10:47:25 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 07/10/95

Active

Project #: E-25-578 Cost share #: Rev #: 7
Center # : 10/11-6-P5121-0A0 Center shr #: OCA file #:
Work type : INST
Contract#: NGT-70254 Mod #: SUPPLEPEMENT 3 Document : GRANT
Prime #: Contract entity: GTRC

Subprojects ? : N CFDA: 43.002
Main project #: PE #: N/A

Project unit: MECH ENGR Unit code: 02.010.126
Project director(s):
WEPFER W J MECH ENGR (404)894-3294

Sponsor/division names: NASA / HEADQUARTERS/WASHINGTON, DC
Sponsor/division codes: 105 / 002

Award period: 920701 to 960630 (performance) 960831 (reports)

Sponsor amount	New this change	Total to date
Contract value	11,000.00	77,000.00
Funded	11,000.00	77,000.00
Cost sharing amount		0.00

Does subcontracting plan apply ?: N

Title: INTELLIGENT DESIGN & MANUFACTURING PROCESSES

PROJECT ADMINISTRATION DATA

OCA contact: Anita D. Rowland 894-4820

Sponsor technical contact	Sponsor issuing office
DEB RUSSELL	THERESA CURTIS
(202)358-0970	(202)358-0510
CODE: FEH	CODE: HWG
NASA HEADQUARTERS	ACQUISITION DIVISION
WASHINGTON, DC 20546	NASA HEADQUARTERS
	WASHINGTON, DC 20546

Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
Defense priority rating : N/A N/A supplemental sheet
Equipment title vests with: Sponsor GIT
"THE USE OF TRAINING GRANT FUNDS FOR PURCHASE OF EQUIPMENT IS NOT PERMITTED."
Administrative comments -
SUPPLEMENT 3 AWARDS ADDITIONAL FUNDS AND EXTENDS THE PERIOD FOR ONE YEAR

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

U

NOTICE OF PROJECT CLOSEOUT

SR(48)

Closeout Notice Date 11/05/96

Project No. E-25-578 Center No. 10/11-6-P5121-0A0

Project Director UMEAGUKWU I C School/Lab MECH ENGR

Sponsor NASA/HEADQUARTERS/WASHINGTON, DC

Contract/Grant No. NGT-70254 Contract Entity GTRC

Prime Contract No.

Title INTELLIGENT DESIGN & MANUFACTURING PROCESSES

Effective Completion Date 960630 (Performance) 960831 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory & Related Certificate	N	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

Comments
NOTE USE NASA FORM FOR PATENT.

Subproject Under Main Project No.

Continues Project No.

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other	N
	N

NOTE: Final Patent Questionnaire sent to PDPI.

E-25-578

Georgia Tech

THE GEORGE W. WOODRUFF SCHOOL OF
MECHANICAL ENGINEERING

Georgia Institute of Technology
Atlanta, Georgia 30332-0405
USA

January 19, 1995

Dr. Charles Ume
Georgia Institute of Technology
School of Mechanical Engineering
MARC Room 453
Atlanta, GA 30332

Dr. Frank Six
University Affairs Officer
National Aeronautics and Space Administration
DS01
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

Dear Dr. Six,

The past year has been very productive. Jonathan presented his work at the 1994 ASME International Congress and Exposition/WAM. We anticipate to submit a paper this month for journal publication. Jonathan expects to complete all requirements for the degree of Doctor of Philosophy in Mechanical Engineering by the end of the year. We therefore request a six month extension on the fellowship so that Jonathan may complete the program. If there are any questions or if additional information is needed, please do not hesitate to contact me.

Sincerely,

Dr. Charles Ume

PROPOSALS DUE FEBRUARY 1

NASA Graduate Student Researchers Program Proposal Cover Sheet • Underrepresented Minority Focus

I. Student Information

Name: (Mr/Ms) Lambright (Last) Jonathan (First) P. (MI)

Birth Date: February 15, 1963

Birthplace: Manhattan NY

Home Address: 1258 Spring Hollow S.W.
Atlanta, Georgia 30311

Home Phone: (404) 758-0116

Target Degree: __ MS __ MS/PhD (Joint) X PhD

Discipline: Mechanical Engineering

Department: Mechanical Engineering

Campus Address:

Mail Code:

University: Georgia Institute of Technology

Street Address:

City, State, ZIP: Atlanta, Georgia 30332

Campus Phone: Fax No.:

E-Mail: gt5469c@prism.gatech.edu

Undergraduate GPA: 2.4 Out Of 4.0

Discipline: Mechanical Engineering

Graduate GPA (If Applicable): 3.4 Out Of 4.0

Discipline: Mechanical Engineering

II. Faculty Advisor Information

Name: Charles Ume, Ph.D.

Department: Mechanical Engineering

Campus Address:

Mail Code: 0405

University: Georgia Institute of Technology

Street Address:

City, State, ZIP: Atlanta, Georgia 30332

Campus Phone: (404) 894-7411

Fax Number: (404) 894-9342

E-Mail: charles.ume@me.gatech.edu

Signature: *Date:* 1-27-95

III. Official Responsible for Committing Institution

Name: Janis L. Goddard

Title: Contracting Officer

University: Georgia Tech Research Corporation

Street Address: Georgia Institute of Technology

City, State, ZIP: Atlanta, Georgia 30332-0420

Campus Phone: (404) 894-4817

Signature: *Date:* 1/27/95

I certify that I am a citizen of the United States and I am or will be a full-time graduate student during the period covered by the attached proposal, and that I am a member of one of the following underrepresented minorities:

- ☒ Black Male
- ☐ Black Female
- ☐ Hispanic Male
- ☐ Hispanic Female
- ☐ American Indian Male
- ☐ American Indian Female
- ☐ Pacific Islander Male*
- ☐ Pacific Islander Female*
- ☐ Male with Disability **
- ☐ Female with Disability **

* *A person having origins in any of the original peoples of Hawaii; the U.S. Pacific Territories of Guam, American Samoa, and the Northern Marianas; the U.S. Trust Territory of Paulau; the Islands of Micronesia and Melanesia; and the Phillipines*

** *A disability that limits a major life activity*

Signature: *Date:* 01/17/95

IV. Proposal Information

Type of Proposal:

☐ (1) New ☐ (2) Second Year ☐ (3) Third Year *If Renewal, Designate Grant No.:* **NGT-** 70254

Proposed Start or Renewal Date: July 1, 1995 Expected Completion Date: December 31, 1995

Proposal Title: Intelligent Design of Flat Composite Panels Using Knowledge Based and Case Based Reasoning

V. Submission Information

☐ Headquarters

☒ NASA Centers
- __ Ames/Dryden (ARC/DFRF)
- __ Goddard (GSFC)
- __ Johnson (JSC)
- __ Jet Propulsion Lab (JPL)
- __ Kennedy (KSC)
- __ Langley (LaRC)
- __ Lewis (LeRC)
- X Marshall (MSFC)
- __ Stennis (SSC)

Other Facilities to which this proposal is being submitted:

Center Technical Advisor:

VI. Proposal Checklist

- ☐ Original and 9 Copies
- ☐ Original Transcripts
- ☐ Signed Advisor Evaluation
- ☐ Budget Form
- ☐ University Certifications
  - Suspension and Debarment
  - Drug Free Workplace

VII. NASA Use Only

- ☐ Org/Cpys
- ☐ OT
- ☐ SAE
- ☐ BdgtFrm
- ☐ UCert
- ☐ Returned Proposal

Jonathan P. Lambright
Georgia Institute of Technology
School of Mechanical Engineering
MaRC Box 605
Atlanta, GA. 30332

Intelligent Design of Fiber Reinforced Composites Using Hybrid Knowledge And Case Based Reasoning

Research Progress Report

The 1994 - 1995 school year under the NASA Graduate Student Researchers Program has thus far been very successful. During the past year I have concentrated mainly on performing the actual research outlined in my research proposal. Also, this past year, along with the aid of my advisor, I presented my work at the ASME International Congress & Exposition/Winter Annual Meeting. I anticipate submitting another paper for publication soon.

Courses that I have taken and am currently taking include Case Based Reasoning, and Industrial Mathematics.

During the remainder of the 1994 -1995, and fall quarter of the 1995 - 1996 academic year I plan to complete my research, dissertation writing, and present and defend my research work to my advisor and Thesis Reading Committee. Therefore, by the end of the year I plan to have completed all requirements for the degree of Doctor of Philosophy in Mechanical Engineering. At the completion of all requirements I will submit the required final report and a copy of the final Doctoral Dissertation.

NASA Graduate Student Researchers Program • Underrepresented Minority Focus
Budget Information

I. **Student Stipend** (Maximum of $16,000) $ 8,000.00

II. **Student Allowance** (Itemize if necessary)

Student Allowance Total (Maximum of $3,000) $ 1,500.00

III. **University Allowance** (Itemize if necessary)

University Allowance Total (Maximum of $3,000) $ 1,500.00

Total Requested (Maximum of $22,000) $ 11,000.00

GEORGIA INSTITUTE OF TECHNOLOGY

A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
OFFICE OF THE REGISTRAR - ATLANTA, GEORGIA 30332

CUMULATIVE GRADE REPORT ---- THIS IS NOT AN OFFICIAL TRANSCRIPT

STUDENT NAME: (LAST, FIRST MIDDLE) LAMBRIGHT, JONATHAN PAUL

STUDENT NUMBER: 248-39-3091

DATE OF BIRTH: 15 FEB 63 SEX: M DATE OF ADMISSION: JUN 90

ADMITTED FROM: NORTH CAROLINA AG&TECH STATE UNIVERSITY
GREENSBORO NC 27411

GEORGIA INSTITUTE OF TECHNOLOGY DEGREES AND DATES

JUN 92 MS IN MECHANICAL ENGINEERING

SEE REVERSE SIDE FOR EXPLANATIONS AND INFORMATION

TO: JONATHAN LAMBRIGHT
1258 SPRING HOLLOW SW
ATLANTA
GA 30311

THIS IS A STATEMENT OF THE FINAL GRADES OF THE STUDENT NAMED WHO WAS ENROLLED FOR THE TERM ENDING AS SHOWN.

FRANK E. ROPER, JR.
REGISTRAR

BOX NUMBER: 25469

ACADEMIC STANDING: GOOD

QTR-YEAR/ENDING DATE: FALL 1994 10 DEC 94

COURSE	COURSE NUMBER	DESCRIPTIVE TITLE OF COURSE	HRS SCHEDULED	GRADE	QTR HRS EARNED	QUALITY POINTS
---		SUMMER QUARTER, 1990 GRAD DOCTORS M E				---
M E	4445	AUTOMATIC CONTROL	3	B	3	9
M E	8998	RESEARCH ASSISTANTSHIP	6	V	0	0
M E	9000	DOCTORAL THESIS	9	S	9	0
		QTR AVG 30 GEN AVG 30	3		12	9
		CUMULATIVE GRADUATE TOTALS	3		12	9
---		FALL QUARTER, 1990 GRAD DOCTORS M E				---
M E	6133	ELASTIC YLD DSN-MACH MBR	3	C	3	6
M E	6424	FEEDBACK CONTROL SYS I	3	D	3	3
M E	9000	DOCTORAL THESIS	15	S	15	0
		QTR AVG 15 GEN AVG 20 P	6		21	9
		CUMULATIVE GRADUATE TOTALS	9		33	18
---		WINTER QUARTER, 1991 GRAD DOCTORS M E				---
C E	8104	SPECIAL TOPIC-CIVIL ENGR	4	B	4	12
ICS	4803	SPEC TOPIC-INFO&COMP SCI	3	A	3	12
M E	6170	ENGINEERING DESIGN	5	A	5	20
M E	9000	DOCTORAL THESIS	9	S	9	0
		QTR AVG 37 GEN AVG 30	12		21	44
		CUMULATIVE GRADUATE TOTALS	21		54	62
---		SPRING QUARTER, 1991 GRAD DOCTORS M E				---
C E	8114	SPECIAL TOPIC-CIVIL ENGR	4	A	4	16
M E	9000	DOCTORAL THESIS	17	S	17	0
		QTR AVG 40 GEN AVG 31	4		21	16
		CUMULATIVE GRADUATE TOTALS	25		75	78
---		SUMMER QUARTER, 1991 GRAD DOCTORS M E				---
ISYE	6739	EXPERIMENTAL STATISTICS	4	B	4	12
M E	8013	SEMINAR-MECHANICAL ENGR	1	S	1	0
M E	9000	DOCTORAL THESIS	16	S	16	0
		QTR AVG 30 GEN AVG 31	4		21	12
		CUMULATIVE GRADUATE TOTALS	29		96	90
---		FALL QUARTER, 1991 GRAD DOCTORS M E				---
M E	6790	COMP INTEGR'D MFG SYS I	3	I*	0	0
M E	6790	REMOVE INC 01/08/92	3	A*	3	12
M E	9000	DOCTORAL THESIS	18	S	18	0
		QTR AVG 40 GEN AVG 32	3		21	12
		CUMULATIVE GRADUATE TOTALS	32		117	102
---		WINTER QUARTER, 1992 GRAD DOCTORS M E				---
ISYE	8102	SPEC TOPIC-IND&SYS ENGR	3	A	3	12
M E	6791	COMP INTEGR'D MFG SYS II	3	A	3	12
M E	8011	SEMINAR-MECHANICAL ENGR	1	S	1	0
M E	8501	SPEC PROBLEMS-MECH ENGR	4	A	4	16
M E	9000	DOCTORAL THESIS	10	S	10	0
		QTR AVG 40 GEN AVG 34	10		21	40
		CUMULATIVE GRADUATE TOTALS	42		138	142

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COURSE	COURSE NUMBER	DESCRIPTIVE TITLE OF COURSE	HRS SCHEDULED	GRADE	QTR HRS EARNED	QUALITY POINTS
		CONTINUED FROM PREVIOUS COLUMN				
---		SPRING QUARTER, 1992 GRAD DOCTORS M E				---
ISYE	6302	QUAL CONTROL IN MFG SYS	3	A	3	12
M E	6450	FLEXIBLE AUTOMATION	3	A	3	12
M E	6792	COM INTEGR'D MFG SYS SEM	1	S	1	0
M E	9000	DOCTORAL THESIS	11	S	11	0
MATH	4581	ADV ENGINEERING MATH	3	B	3	9
		QTR AVG 37 GEN AVG 34	9		21	33
		CUMULATIVE GRADUATE TOTALS	51		159	175
---		SUMMER QUARTER, 1992 GRAD DOCTORS M E				---
M E	4180	MECHANICAL ENG DESIGN II	3	V	0	0
M E	9000	DOCTORAL THESIS	18	S	18	0
		QTR AVG 00 GEN AVG 34	0		18	0
		CUMULATIVE GRADUATE TOTALS	51		177	175
---		FALL QUARTER, 1992 GRAD DOCTORS M E				---
M E	6439	CONTROL SYS COMPONENTS	3	V	0	0
M E	9000	DOCTORAL THESIS	18	S	18	0
		QTR AVG 00 GEN AVG 34	0		18	0
		CUMULATIVE GRADUATE TOTALS	51		195	175
---		WINTER QUARTER, 1993 GRAD DOCTORS M E				---
M E	8404	SPEC TOPICS-SYSTEMS&CTRL	4	B	4	12
M E	9000	DOCTORAL THESIS	17	S	17	0
		QTR AVG 30 GEN AVG 34	4		21	12
		CUMULATIVE GRADUATE TOTALS	55		216	187
---		SPRING QUARTER, 1993 GRAD DOCTORS M E				---
M E	9000	DOCTORAL THESIS	19	S	19	0
		QTR AVG 00 GEN AVG 34	0		19	0
		CUMULATIVE GRADUATE TOTALS	55		235	187
---		SUMMER QUARTER, 1993 GRAD DOCTORS M E				---
M E	9000	DOCTORAL THESIS	18	S	18	0
		QTR AVG 00 GEN AVG 34	0		18	0
		CUMULATIVE GRADUATE TOTALS	55		253	187
---		FALL QUARTER, 1993 GRAD DOCTORS M E				---
E E	6154	COMP HARD & SOFT FOR MFG	3	B	3	9
M E	9000	DOCTORAL THESIS	18	S	18	0
		QTR AVG 30 GEN AVG 34	3		21	9
		CUMULATIVE GRADUATE TOTALS	58		274	196
---		WINTER QUARTER, 1994 GRAD DOCTORS M E				---
C S	7332	CASE-BASED REASONING	3	A	3	12
M E	9000	DOCTORAL THESIS	18	S	18	0
		QTR AVG 40 GEN AVG 34	3		21	12
		CUMULATIVE GRADUATE TOTALS	61		295	208

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OFFICE OF THE REGISTRAR - ATLANTA, GEORGIA 30332

CUMULATIVE GRADE REPORT ---- THIS IS NOT AN OFFICIAL TRANSCRIPT

STUDENT NAME (LAST, FIRST MIDDLE) LAMBRIGHT, JONATHAN PAUL

STUDENT NUMBER: 248-39-3091

DATE OF BIRTH: 15 FEB 63 SEX: M DATE OF ADMISSION: JUN 90

COURSE	COURSE NUMBER	DESCRIPTIVE TITLE OF COURSE	HRS SCHED ULED	GRADE	QTR HRS EARNED	QUALITY POINTS
		CONTINUED FROM PREVIOUS PAGE				
---		SPRING QUARTER, 1994 GRAD DOCTORS M E ---				
M E	9000	DOCTORAL THESIS	18	S	18	0
		QTR AVG 00 GEN AVG 34	0		18	0
		CUMULATIVE GRADUATE TOTALS	61		313	208
---		SUMMER QUARTER, 1994 GRAD DOCTORS M E ---				
M E	9000	DOCTORAL THESIS	18	S	18	0
		QTR AVG 00 GEN AVG 34	0		18	0
		CUMULATIVE GRADUATE TOTALS	61		331	208
---		FALL QUARTER, 1994 GRAD DOCTORS M E ---				
M E	9000	DOCTORAL THESIS	18	S	18	0
		QTR AVG 00 GEN AVG 34	0		18	0
		CUMULATIVE GRADUATE TOTALS	61		349	208

--------END OF GRADE REPORT--------

CERTIFICATIONS REGARDING LOBBYING; DEBARMENT, SUSPENSION AND OTHER RESPONSIBILITY MATTERS; AND DRUG-FREE WORKPLACE REQUIREMENTS

Applicants should refer to regulations cited below to determine the certification to which they are required to attest. Applicants should also review the instructions for certification included in the regulations before completing this form. Signature of this form provides for compliance with certification requirements under 31 U.S.C. §1352, "New Restrictions on Lobbying," and 15 CFR Part 26 "Government-wide Debarment and Suspension (Non procurement) and Government-wide Restrictions for Drug-Free Workplace (Grants)." The certifications shall be treated as material representation of fact upon which reliance will be placed when the Department of Commerce determines to award the covered transaction, grant, or cooperative agreement.

1. LOBBYING

As required by §1352, Title 31 of the U.S. Code for persons entering into a grant or cooperative agreement over $100,000, the applicant certifies that:

(a) No Federal appropriated funds have been paid or will be paid by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, in connection with making of any Federal grant, the entering into of any cooperative, and the extension, continuation, renewal, amendment, or modification of any Federal grant or cooperative agreement;

(b) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting an officer or employee of any agency, Member of Congress, and/or an employee of a Member of Congress in connection with this Federal grant or cooperative agreement, the undersigned shall complete Standard Form - LLL, "Disclosure Form to Report Lobbying," in accordance with its instructions;

(c) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers (including subgrants, contracts under grants and cooperative agreements, and subcontracts) and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by §1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

2. DEBARMENT, SUSPENSION, AND OTHER RESPONSIBILITY MATTERS

As required by Executive Order 12549, Debarment and Suspension, and implemented under 15 CFR Part 26, for prospective participants in primary covered transactions.

A. The applicant certifies that it and its principals:

(a) Are not presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency;

(b) Have not within a three-year period preceding this application been convicted of or had a civil judgment rendered against them for commission of fraud or a criminal offense in connection with obtaining, attempting to obtain, or performing a public (Federal, State, or local) transaction or contract under a public transaction; violation of Federal or State antitrust statutes or commission of embezzlement, theft, forger, bribery, falsification or destruction of records, making false statement, or receiving stolen property;

(c) Are not presently indicted for or otherwise criminally or civilly charged by a government entity (Federal, State, or local) with commission of any of the offenses enumerated in paragraph 2.A(b) of this certification; and...

(d) Have not within a three-year period preceding this application had one or more public transactions (Federal, State, or local) terminated for cause or default.

B. Where the applicant is unable to certify to any of the statements in this certification, he or she shall attach an explanation to this application.

C. Certification Regarding Debarment, Suspension, Ineligibility and Voluntary Exclusion — Lower Tier Covered Transactions (Subgrants or Subcontracts)

(a) The prospective lower tier participant certifies, by submission of this proposal, that neither it not its principles is presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from participation in this transaction by any federal department or agency.

(b) Where the prospective lower tier participant is unable to certify to any of the statements in this certification, such prospective participant shall attach an explanation to this proposal.

3. CERTIFICATION REGARDING DRUG-FREE WORKPLACE REQUIREMENTS

- **GRANTEES OTHER THAN INDIVIDUALS**

A. The grantee certifies that it will provide a drug-free workplace by:

(a) Publishing a statement notifying employees that the unlawful manufacture, distribution, dispensing, possession or use of a controlled substance is prohibited in the grantee's workplace and specifying the actions that will be taken against employees for violation of such prohibition;

(b) Establishing a drug-free awareness program to inform employees about—

(1) The dangers of drug abuse in the workplace;

(2) The grantee's policy of maintaining a drug-free workplace;

(3) Any available drug counseling, rehabilitation, and employee assistance programs; and

(4) The penalties that may be imposed upon employees for drug abuse violations occurring in the workplace;

(c) Making it a requirement that each employee to be engaged in the performance of the grant be given a copy of the statement required by paragraph (a);

(d) Notifying the employee in the statement required by paragraph (a) that, as a condition of employment under the grant, the employee will

(1) Abide by the terms of the statement and

(2) Notify the employer of any criminal drug statute conviction for a violation occurring in the workplace no later than five days after such conviction;

(e) Notifying the agency within ten days after receiving notice under subparagraph (d) (2) from an employee or otherwise receiving actual notice of such conviction;

(f) Taking one of the following actions, within 30 days of receiving notice under subparagraph (d)(2), with respect to any employee who is so convicted

(1) Taking appropriate personnel action against such an employee, up to and including termination;

or—

(2) Requiring such employee to participate satisfactorily in a drug abuse assistance or rehabilitation program approved for such purposes by a Federal, State, or local health, law enforcement, or other appropriate agency;

(g) Making a good faith effort to continue to maintain a drug-free workplace through implementation of paragraphs (a), (b), (c), (d), (e) and (f).

B. The grantee shall insert in the space provided below the site(s) for the performance or work done in connection with the specific grant:

Place of Performance (street address, city, county, state, zip code)

____

____

____

____

Check box ☐ if there are workplaces on file that are not identified here.

- **GRANTEES WHO ARE INDIVIDUALS**

The grantee certifies that, as a condition of the grant, he or she will not engage in the unlawful manufacture, distribution, dispensing, possession or use of a controlled substance in conducting any activity with the grant.

As the duly authorized of the applicant, I hereby certify that the applicant will comply with the above certifications.

NAME OF APPLICANT	PR/AWARD NUMBER AND/OR PROJECT NAME
Jonathan P. Lambright	"Intelligent Design of Flat Composite Panels Using Knowledge Based and Case Based Reasoning"
PRINTED NAME AND TITLE OF AUTHORIZED REPRESENTATIVE	
Janis L. Goddard, Contracting Officer	
SIGNATURE	**DATE**
[illegible]	27 January 1995

E 25-578
#2

Georgia Tech

THE GEORGE W. WOODRUFF SCHOOL OF
MECHANICAL ENGINEERING

Georgia Institute of Technology
Atlanta, Georgia 30332-0405
USA

April 25, 1996

Dr. Frank Six
University Affair's Officer
NASA
DS01
George C. Marshall Space Flight Center
Huntsville, AL. 35812

Progress Report

Mr. Johnathan Lambright's Ph.D. Research

Intelligent Design of Fiber Reinforced composites Using Hybrid Knowledge And Case Based Reasoning

Dear Dr. Six:

Mr. Johnathan Lambright has made a tremendrous progress, since the last communication with you. He has written a journal paper that has been accepted for publication in ASME Journal of Mechanical Design. Johnathan has also written the first draft of his Ph.D. thesis. This draft has been corrected, and he is currently revising the thesis based on the recommended changes . He plans to defend his thesis during the Summer quarter.

The final report and a copy of his thesis will be submitted to you sometime during the Summer. If you need any additional information, please do not hesitate to me know. My phone number is 404-894 7411.

Sincerely

Charles Ume
(Associate professor)

E-25-578
#3

Design of Composite Structures Using Knowledge-Based And Case-Based Reasoning

A Thesis
Presented to
The Academic Faculty

by

Jonathan Paul Lambright

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in Mechanical Engineering

October 1996

Design of Composite Structures Using Knowledge-Based And Case-Based Reasoning

Approved:

Charles Ume, Chairman

Nelson Baker

Jonathan Colton

Robert Fulton

Janet Kolodner

DEDICATION

This dissertation is dedicated to my mother Zenola Uldine Lambright and my father Wilden Lambright

ACKNOWLEDGEMENTS

I would like to first thank my advisor and thesis reading committee chairman Dr. Charles Ume for all of his guidance, support, and advice during my stay here at Georgia Tech. I would like to thank Dr. Nelson Baker for his assistance in development of the knowledge base; Dr. Jonathan Colton for his assistance in the design methodology and design of composites areas; Dr. Robert Fulton for his assistance in the design methodology and data abstraction, and Dr. Janet Kolodner for her assistance in case based reasoning and allowing me to use the case based design aid tool (Design-MUSE) developed under her guidance at the College of Computing, AI Group.

I would like to thank all of my committee members for their invaluable input throughout the process. As a result, this research effort has been challenging and of benefit to the academic and industrial communities. Many thanks to Dr. William Wepfer, Claudette Noel, Dr. Jeffrey Donnell, and all of the staff in the School of Mechanical Engineering.

I would like to thank Anthony Jackson (Lockheed Martin Aeronautical), Michael Starbuck (Oak Ridge National Laboratory), and Scott Reeve (Lockheed Martin Aeronautical) for their expert knowledge in design and manufacture of composite structures.

I would like to thank the NASA Graduate Student Researchers Program and the NASA George C. Marshall Space Flight Center for supporting this research: Grant NGT-70254.

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LIST OF SYMBOLS

E_t: Youngs Modulus in Tension

ET: Axial Stiffness

E_{45}: Modulus of +/- 45 Plies

F_c: Design Ultimate Compression Stress

F_t: Design Ultimate Tension Stress

F_{45}: Design Ultimate of +/- 45 Plies

N_x: Axial Load

T: Thickness Per Ply

T_{45}: Thickness of +/- 45 Plies

V: Or

LIST OF ABBREVIATIONS

ADP: Add and Drop Plies

CB: Case Base

CBDA: Case Based Design Aid

CBR: Case-Based Reasoning

DCS: Design Characteristic State

EMI: Energy Materials And Information

KA: Knowledge Acquisition

KB: Knowledge Base

KBS: Knowledge-Based System

LE: Leading Edge

L.E. Less Than or Equal To

IML: Inner Mold Line

TE: Trailing Edge

OML: Outer Mold Line

Summary

A method of using knowledge based and case based reasoning to assist designers during conceptual design tasks of composite structures was proposed. The cooperative use of heuristics, procedural knowledge, and previous similar design cases suggests a potential reduction in design cycle time and ultimately product lead time. The hypothesis of this work is that the design process of composite structures can be improved by using Case-Based Reasoning (CBR) and Knowledge-Based (KB) reasoning in the early design stages. The technique of using knowledge-based and case-based reasoning facilitates the gathering of disparate information into one location that is easily and readily available. The method suggests that the inclusion of downstream life-cycle issues into the conceptual design phase reduces potential of defective, and sub-optimal composite structures. Three industry experts were interviewed extensively. The experts provided design rules, previous design cases, and test problems. A Knowledge Based Reasoning system was developed using the CLIPS (C Language Interpretive Procedural System) environment and a Case Based Reasoning System was developed using the Design MUSE (Memory Utility For Sharing Experiences) environment. A Design Characteristic State (DCS) was used to document the design specifications, constraints, and problem areas using attribute-value pair relationships. The DCS provided consistent design information between the knowledge base and case base. Results indicated that the use of knowledge based and case based reasoning provided a robust design environment for composite structures. The knowledge base provided design guidance from well defined rules and procedural knowledge. The case base provided suggestions on design and manufacturing techniques based on previous similar designs and warnings of potential problems and pitfalls. The case base complemented the knowledge base and extended the problem solving capability beyond the existence of limited well defined rules. The findings indicated that the technique is most effective when used as a design aid and not as a tool to totally automate the composites design process. Other areas of application and implications for future research are discussed.

CHAPTER I

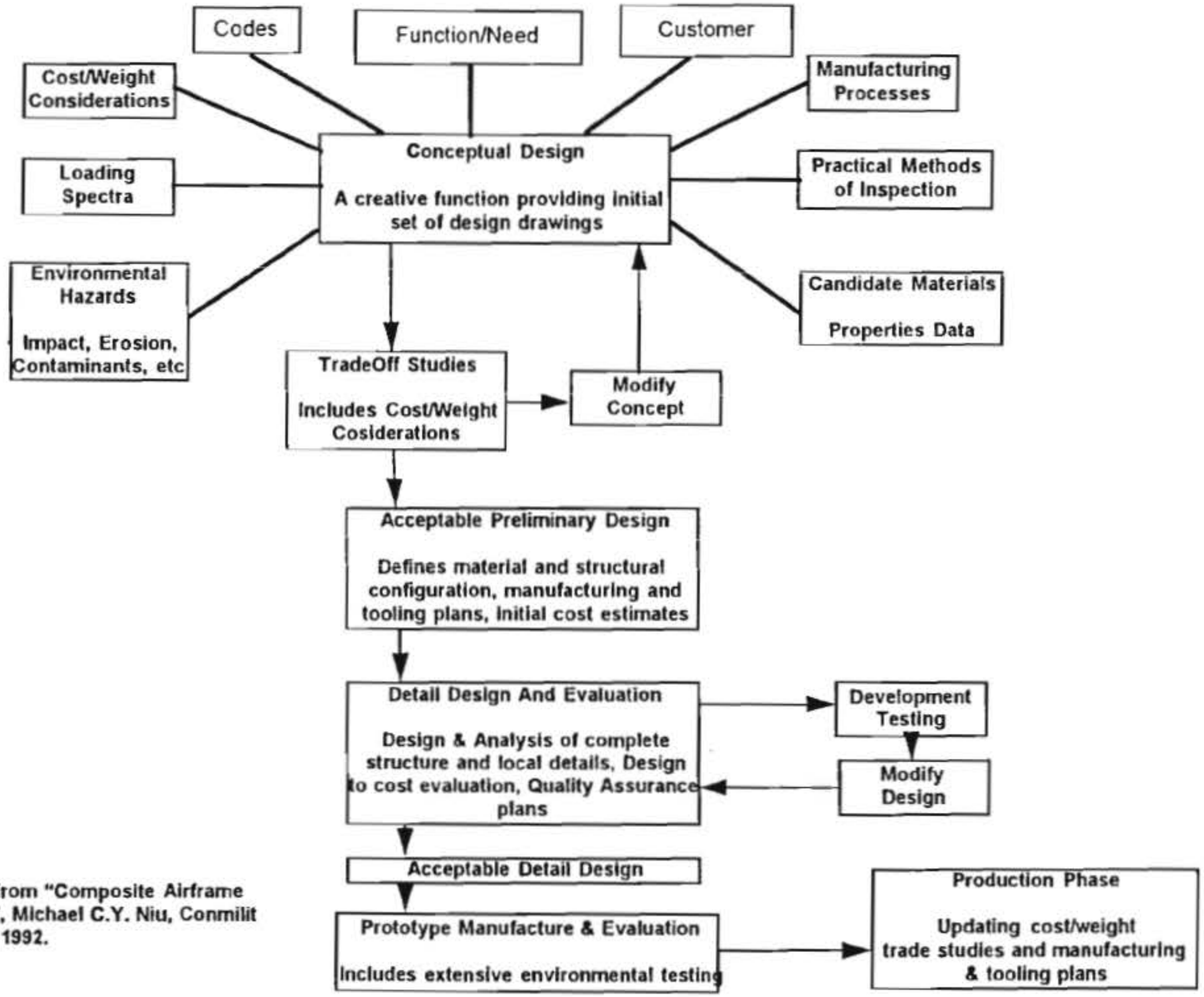
1.0 INTRODUCTION

Within the past few years, designers increasingly have designed parts made from fiber-reinforced composites. They have done so in government defense programs and in the commercial industry. The reasons for their popularity lie in the composite materials' performance characteristics. When designers construct parts out of fiber-reinforced composite materials, they potentially reduce the total weight of the part while maintaining, or even exceeding, the parts' minimum strength requirements. In addition to the high strength-to-weight ratios, composite parts can be custom designed to meet design specifications, such as contour, damage tolerance, operating temperature constraints, and other functional design criteria. These are characteristics which add to the popularity of fiber-reinforced composite structures. Composites have these characteristics because of their highly directional properties.

Consequently, the final design of a composite part can have many different laminate forms. One or more designs may satisfy the functional requirements and specifications; this can be achieved by changing the fiber orientation, ply layup or the fiber/matrix composition. While the availability of different design solutions is good, the designer is confronted with the problem of determining how to approach a particular design situation with the possibility of multiple outcomes. The designer has to determine which design best meets the customer's initial requirements, and can be manufactured affordably without sacrificing quality. To compound the problem, the composites domain is still evolving. A designer's responsibility therefore includes, minimally, the following:

1) Translation of the voice of the customer into functional engineering characteristics;
2) Managing design variability due to composite characteristics;
3) Integration of manufacturing, environmental, cost, and other life-cycle issues into the design process; and
4) Predicting performance results of candidate designs.

Consequently, it is very difficult for a designer to adhere to all of the above issues and produce an optimum design due to the overwhelming amount of design variables and their interactions. Figure 1.1 shows the many tasks and issues involved in composites design.



Extracted From "Composite Airframe Structures", Michael C.Y. Niu, Conmilit Press Ltd., 1992.

Figure1.1: Composites Structure Design Methodology

1.1 Engineering Knowledge Availability and Accessibility Problems

The design of composite structures is in itself a difficult task. There are, however, issues which make the design, development and usage of composite structures an even more difficult task. The composites domain is still evolving. Composites are increasingly being used in aircraft structures where metals previously reigned. New materials and manufacturing techniques are being developed and used in unconventional areas. The domain is growing and changing simultaneously. The engineering knowledge base of composite materials, manufacturing techniques, and usage is increasing substantially. Because of the growth, however, this information that describes how to achieve higher strength-to-weight ratios using hybrid metals and composites, how to minimize delamination in high shear, or how to apply composites to primary structures of commercial aircraft, is not readily accessible, and is often buried inside the details of industry reports. This information is often in the form of heuristic knowledge, rules-of-thumb, experimental test data and reports of test cases and prototypes. This problem makes it difficult for designers, who might otherwise benefit from the availability of this information, to producer optimal designs.

1.1.1 Knowledge From Industry Experiments And Prototypes

Consequently, the task of designers is even more difficult. There may exist similar designs, and production techniques which may give a designer insight into solving new problems. However, gaining access to and interpreting these similar cases is a difficult task. The results of these industry tests, prototypes, and operational designs come in different forms. Some are detailed reports which depict how a structure was designed, what new methods were employed, how it was manufactured and ultimately how it performed in operation. Some of these industry examples describe the overall project but lack the details needed to reproduce the prototype or learn any type of lesson. Some of the similar design cases are simply memories of a designer or engineer with no physical documentation at all. Many of these past designs are documented in a designer's log, as reports, as technical publications, in memory or any combination.

Even if the designer is successful in finding any industry examples which may assist him in solving his new problem, he still has to decipher the information and pull out the lessons which would benefit his project. A task which substantially adds to the product lead time.

1.1.2 Knowledge From Rules-of-Thumb, Heuristics, And Experience

Aside from the knowledge of industrial examples, there exists another body of knowledge which aids designers in their tasks. This knowledge is usually termed rules-of-thumb, or experiential knowledge. Some of it is well known throughout the industry because it is in published form and easily accessible. Some of the knowledge is published yet not easy to access or simply resides in the head of a designer, engineer, or technician. Therefore, most of the heuristic knowledge that would assist a designer in creating successful designs is not easily accessible. An example of the heuristic knowledge would be: *"if the surface of the laminate needs to be smooth, then try using a caul plate during the cure process."* Every designer that may benefit from this type of information may not know it.

Yet, even if the designer had easy access to all of the learned knowledge, it may not be sufficient to produce a satisfactory design. Suppose the designers task is to produce, for the first time, an exchangeable composite counterpart to an all aluminum wing part. If this is the first time that this part is being put into production as a composite material, how is the designer to know the outcome. The experiential knowledge that the designer has access to will help him produce a design. The knowledge, however, will not be able to predict the results of that particular combination of layup pattern, material, cure method, and operational forces. Yet, there may exist a similar previous design which teaches the designer a lesson. That lesson may be applicable to his current problem.

1.1.3 Knowledge Accessibility And Availability During Conceptual Design

The most critical part of the composites design process tends to be the conceptual phase, where the least amount of information is available and the number of variables and combinations increases considerably. In the design and manufacture of composite structures, problems will crop up later in the parts life-cycle if information that is related to downstream processes is not incorporated into the early design stages. These downstream processes include, manufacturing, tooling, operational use, and disposal. This is a common problem in the current design techniques of composite structures. The designer has problems incorporating information from the downstream processes especially as a result of issues mentioned in sections 1.1, 1.1.1, and 1.1.2. Many of the existing composite design methods and tools do not address the issue of bringing in downstream process information at the early stage of the design process. Consequently, technical design, budget, material, and manufacturing problems begin to arise at later stages of the product life cycle. These problems ultimately cause increased lead times, over-expenditure of budgets, and a decrease in product quality and safety.

To compound the problem, experts agree that one of the more difficult tasks is coordination and communication between design and manufacturing. Experts, Niu (1988)(1992), and Appendix B tell of proposed designs that are difficult to manufacture. Experts have also said that it is difficult to find conditions and criteria of the few previous designs that are published.

1.2 Designers Current Design Methods

Designers, therefore, refer to design rules and procedures which help them to make decisions during the design process. Rules exist which aid the designer during the conceptual stage, in evaluating designs during and after the detailed phases, and in predicting performance. Outside these fundamental areas, the applicability of these rules is questionable. Designers can not be sure of how a certain combination of materials, layup, and fabrication will react in new environments and systems. As depicted in section 1.1.2, based on inference rules alone, the performance of the candidate designs cannot be predicted with accuracy. Until better science-based methods and procedures which accurately predict performance regardless of environment, material, or usage are developed, other solutions need to be explored. In the mean time, designers have relied heavily upon lessons learned from experience, as discussed in section 1.1.1. It is common in research and development environments to produce prototype fiber-reinforced composite structures. These prototypes try to predict if certain performance criteria can be met prior to production and operational use. Vital information is collected from these prototypes when tested and placed into operational environments. Information collected from these past experiences serve as ideas, and alternative solutions to future projects and often help to fill the gaps where scientific based solution methods are less accurate. Until solution techniques that cover the entire domain are developed, lessons learned from past experiences are the best alternatives. These past similar design cases are needed to augment the capability of the heuristic knowledge and to fill the gap where rules do not exist.

1.3 Designer Needs

Designers need at their disposal methods and tools that will enhance their design capabilities. They need tools that provide access to the well-defined and newly acquired rules that govern all aspects of the product's life-cycle. Designers also need tools that provide information about previous design scenarios. Although composite design and manufacturing technologies have advanced considerably, there are no complete and proven repositories of information for historical cases, and current domain rules and procedures. Also, there are no tools that are able to incorporate and reason upon experiential knowledge gained from past successful design cases. Table 1.1 shows some of the more popular commercial composites design tools available today.

Table 1.1: Existing Commercial Composite Design Tools

Tool	Pros	Cons
CATIA	Defines ply geometry and layup sequence. Outputs local ply lists, ply tables, and schematic stacking diagrams. IML and OML models.	Does not incorporate life-cycle issues into the design process (e.g., material debulking, thermal expansion, and spring back). Does not contain reference to previous similar designs.
Pro-Engineer	Allows for 3-D parametric design of complex parts.	No predefined routines for design of composite structures. Does not incorporate life-cycle issues into the design process. Does not contain reference to previous similar designs.

1.4 Research Hypothesis

The hypothesis of this work is that the design process of composite structures can be improved by using Case-Based Reasoning (CBR), Kolodner (1993) and Schank (1982), and Knowledge-Based (KB) reasoning Baker (1991) and Parsaye and Chignell (1988) in the early design stages. Specifically, this improvement manifests itself in the form of computer-based tools which advise and assist designers in the design of fiber reinforced composites. The technique facilitates the gathering of disparate information into one location that is easily and readily available. The process improvement metrics are depicted by the methods ability to:

1) provide an increase in the number of potential problem areas detected as compared to current design practices and,

2) provide an increase in the number of new ideas generated as compared to current design practices.

The problem areas of interest are those that were either missed by designers early in the design and had a negative impact on downstream processes or problems which the designer was aware but were difficult to solve. Table 1.2 shows a few of the important issues and potential downstream problems in the composite structure life-cycle.

1.5 Why KB And CB Reasoning

Composites design involves the use of experiential rules and procedures gathered from years of experience, including reference to past similar design situations, quantitative and qualitative analysis, and trade off studies utilizing each to

Table 1.2: Some Important Issues And Potential Problems During The Composite Structure Life-cycle

Issues	*Potential Problems*
Manufacturing Resources	Lack of knowledge of tooling, and curing equipment, their operating specifications, available production times, materials in stock, personnel experienced in certain tasks can cause major problems if not incorporated into the early design stage. Any design can be imagined and created during the design process, but if there are no resources to actually produce the design then much time and budget has been wasted.
Operating Environment	Fiber-reinforced composite structures are used in many types of environments. Structures may potentially be exposed to extreme heat, wind shear forces, hail, and artillery. During design, it is imperative to take into consideration the type of environment the structure will operate in. Structures which operate primarily within battle environments are designed differently than structures used on commercial transport aircraft which simply try to achieve a reduction in weight.

achieve the best blend of cost/weight ratios, loading spectra, environmental considerations, manufacturing processes, and materials. To be useful, design assistant tools for composite structures must be able to duplicate, to a certain degree, the methods used in the design process. Based on the nature of the composites design process and the needs of composites designers, a knowledge base combined with a case based reasoning system is a good choice. Hedburg (1993) shows the trade-offs of hybrid knowledge based systems. Using some data from Hedburg (1993), Table 1.3 shows the advantages and disadvantages of using other techniques combined with KB system technology. Hedburg (1993), pp. 107 states that "*when a system combines a KBS, it can intelligently process a wider variety of information than could be handled by either of the technologies it comprises. Because it can access, organize, and analyze unstructured information that cannot be captured in databases (e.g., free-text data), CBR allows the hybrid system to handle peoples' experiences, or cases. It also enables the system to perform broad, shallow reasoning across these cases by matching new cases with existing ones in the case base*". Table 1.4 shows some of the more popular commercial hybrid knowledge based and case based reasoning systems available today. The rules will provide empirical knowledge to the designer at the earliest stages of the design process. This empirical knowledge includes information on optimal stacking, material choices, tooling and production

Table 1.3: Hybrid Knowledge Based Systems		
A KB Combined With	Pros	Cons
Neural Networks	The system learns/trains itself and provides high-response accuracy.	It often requires prolonged training and offers no explanations for its results.
Case Based Reasoning	The system is able to store, analyze, and process previous experiences/decisions. Inductive systems explain themselves.	There is no standard underlying the adaptive algorithms. The system has difficulty prioritizing cases.
Genetic Algorithms	The system can search an entire domain for a solution, and it breeds on established success paths.	It is developmentally difficult and computationaly expensive.
Virtual Reality	The system can immerse a user in a 3-D environment and remotely simulate movements and situations.	Its applications are mainly used for entertainment or military purposes. The system requires sophisticated equipment.
Multimedia	The system integrates graphics, text, sound, and video. It's simple to use and consists of increasingly commonplace technology.	It accesses stored knowledge unintelligently. The system is resource intensive and expensive.

Table 1.4: Existing Commercial Hybrid KB and CBR Tools		
Tool	Pros	Cons
CBR-Express	Graphical User Interface is user friendly and facilitates the input of data and viewing of results.	Demonstrates more of a key word search rather than true case based reasoning with retrieval algorithms. Limited in case adaptation and partial solutions.
Esteem	Graphical User Interface is user friendly and facilitates the input of data and viewing of results.	Does not provide rule debugging and tracing features. Need to buy ProKappa for added features. Very limited in case retrieval mechanism.

issues, damage tolerance, etc. The cases will provide the designer with information that may otherwise not be represented as well structured heuristics. The cases may show how an unprecedented design or manufacturing technique may be an adequate solution and adapted to fit the designer's current problem. The case may provide details on the materials to use, the way stack the lamina, and the manufacturing issues to be aware of ahead of time. Such information is invaluable to a designer. This type of knowledge is unlikely to be found in text books or corporate design manuals. However, the case is only as good as the lessons that can be learned from its content. Therefore, cases must be used within related domains. For example, cases which depict design and manufacturing of fiber-reinforced composite panels with integral stiffeners for an aircraft outer skin may be useful in the production of light weight composite door panel for automobiles, but not for microprocessor design.

1.6 What Is Knowledge-Based Reasoning?

A knowledge-based system is usually a computer program that relies on a body of knowledge to perform a task typically performed by a human expert. The principal power of a knowledge-based system is derived from the knowledge the system embodies rather than from search and retrieval algorithms. Knowledge-based systems generally deal with a focused task with a rather narrow range of applicability and use highly specific and well-structured knowledge for reasoning.

There are typically 4 parts to a standard knowledge-based system:

1) user interface,

2) knowledge base,

3) working data, and

4) inference engine.

Knowledge-based systems attempt to mimic the problem solving strategy of human experts. Thus the architecture of a knowledge-based system partially resembles how a human expert performs. The long term memory of facts, and rules that represent an experts knowledge is analogous to the knowledge base and working data of the knowledge-based system. The method of reasoning an expert uses to solve problems is analogous to the inference engine of the knowledge-based system. Knowledge Based rules are constructed when well-structured and proven knowledge exists within the domain. The knowledge is used to produce solutions to domain-specific problems. The rules are often represented as If-Then constructs. A more detailed discussion of knowledge-based systems is provided in chapter 4.

1.7 What Is Case-Based Reasoning?

Case-Based Reasoning (CBR) is used in everyday common sense reasoning. In case-based reasoning a reasoner remembers previous situations similar to the current one and uses them to help solve the new problem. For example, during the design of a new commercial transport aircraft wing, a designer remembered from a past program that the 100% composite construction of a primary structural component presented obstacles for which solutions were not yet available. The designer remembered that it took several iterations of prototyping and testing to conclude that application to secondary components was most feasible. Consequently, the designer applied the composite materials to the secondary wing components of the new problem and still achieved the weight savings goal for that section of the aircraft. The designer has used a form of case-based reasoning by using a previous similar design case to help solve his current design problem.

Case-based reasoning suggests a model of reasoning that incorporates problem solving, understanding, and learning and integrates them all with memory processes. Unlike rules, cases in a case-based system may be constructed from well-structured or from incomplete knowledge. In short, a case would describe how a problem was solved, what method was used, whether it was a success or not, and any other domain specific information related to that problem.

While cases cannot represent knowledge in the form of an algorithmic or fixed procedural approach such as rules, they can represent incomplete and poorly structured knowledge, a characteristic which rules do not have. At the core of most case-based reasoning systems exists

1) a library of cases,

2) a vocabulary and indexing scheme,

3) a ranking and retrieval algorithm, and

4) a strategy for case adaptation.

These matters are discussed in further detail in chapter 5.

In the domain of composites, there exist sets of structured analytical and qualitative rules and procedures that are used to obtain solutions to laminate design requirements. However, since the domain itself is still evolving, there are areas where well structured rules do not exist. For instance, composites are being tested on parts of aircraft that are conventionally made from metals. There are no rules that describe to the designer how the composite laminate design will react in the new operating environment when designed under the existing constraints. But a similar previous design case may give the designer clues into its predicted performance, possible pitfalls, and alternative solutions. A similar previous design case can illustrate non-obvious issues that deserve consideration. Therefore, in domains, such as composites where rules do not cover the entire domain, cases can be used to complement the rules and produce a robust problem solving environment.

Using either method alone will produce a less than optimal design. By automating the rules and the process of prior design case retrieval, the design cycle time can be reduced for flat composite panels. This integrated approach uses the advantages of each technique to overcome the disadvantages of using either alone, and it suggests a sequence of problem solving using rules and prior design scenarios. The knowledge in the rule base and case base can be used by less experienced designers and engineers. Valuable time is not wasted in searching for similar previous design cases and the embedded information that is relevant to the current problem. All final design decisions are the responsibility of the designer.

1.8 Research Objectives

The main objective of this work is to demonstrate a computer aided design advisory system using a Knowledge Based and Case Based Reasoning architecture which can potentially:

1) Automate the inclusion of composite structure life-cycle issues into the earliest design stages,

2) Provide access to similar previous design cases,

3) Reduce unforeseen problems and pitfalls, and

4) Ultimately reduce product lead time.

Throughout this work, emphasis will be placed upon the early stages of the composites design process (conceptual); although aspects of the entire life-cycle have been incorporated. The scope of this work is limited to that of flat composite aircraft structure panels. A problem solving strategy is developed which can be expanded, with additional work, to include more complex composites structures with characteristics such as complex curvature, hybrid materials usage, co-consolidated assemblies, and non-conventional manufacturing techniques.

1.9 Research Approach

The approach taken in this research effort begins with a review of related works. A determination of what has been done by others, where the deficiencies are and how this research may help strengthen the deficient areas. Next is an understanding of the current composite structure design and manufacturing processes, coupled with extensive modeling. The modeling effort uses the energy, information, and materials methodology as defined by Pahl & Bietz (1988). Following the modeling, is the knowledge acquisition process from which the rules, procedures, and previous design cases are extracted and structured. The knowledge acquisition involves an interview with three industry experts. Development of the knowledge base and case base, using CLIPS (1993) and Design-MUSE (1994) respectively, follows. A method for knowledge base and case base interaction is developed by use of a Design Characteristic State (DCS) matrix. The Design Characteristic State is an array of knowledge which documents the design specifications, requirements, constraints, and potential problem areas. The DCS encapsulates the common knowledge represented by the KB and the CB through their working data and indexing vocabulary respectively. Finally the resulting prototype system is tested against the stated research objectives.

1.10 The Obstacles

The obstacles to creating a method by which knowledge based and case based reasoning will aid in the flat composite design process are listed in table 1.5. The steps taken in this research to overcome these obstacles are also shown. The results of which are detailed in the remaining chapters.

Table 1.5: Obstacles And Steps Taken To Overcome Them	
Obstacles	*Steps*
Knowledge acquisition in a dynamic domain.	Review of related works, a study of the composite panel life-cycle, and interview of industry experts.
Division of labor between the knowledge base and the case base.	Review of related works, extensive domain modeling, and, a knowledge acquisition and representation strategy.
Interaction between the knowledge base and the case base such that a seamless problem solving strategy is produced.	Review of related works, development of a method for using KB and CB reasoning.
Application of a technique, used mainly in the customer service/help desk area, to life-cycle design.	Review of related works, and development of a prototype design advisory system for use in the design of flat fiber-reinforced composite structures.

1.11 Chapter Summary

In this chapter an introduction of current fiber-reinforced composite structure design practices is given. Problems associated with current composites design techniques and tools have been highlighted. A hypothesis of how the joint use of knowledge based and case based reasoning can improve the composites design process has bee stated. Chapter 2 is a detailed literature review of related works. Chapter 3 takes a look at composites design and manufacturing processes and builds the models necessary for system development. Chapter 4 details the knowledge acquisition and structuring for the knowledge base. Chapter 5 details the knowledge acquisition and structuring for the case base. Chapter 6 develops a method for knowledge-based and case-based reasoning using the Design Characteristic State (DCS). Chapter 7 discusses the hardware and software issues surrounding the development of the prototype Composites Design Advisory System (ComDAS). Chapter 8 presents three test problems and the results for the prototype system. Finally, chapter 9 concludes the research followed by appendices and references.

CHAPTER II

LITERATURE REVIEW

This chapter presents a review of work related to this research. There are many noteworthy research efforts within the scope of this work. This review is not intended to include every work which has similarities to this work but only those which are directly related. The review is divided into five different areas of related work:

- Design and Manufacturing of Composite Parts
- Expert/Knowledge Based Systems And Other AI Techniques Applied To Fiber Reinforced Composites Design And Manufacturing
- Case Based Reasoning
- Case Based Design/Manufacturing
- Hybrid Rule Based Reasoning Techniques.

At the end of this chapter in table 2.1 is a view of the ideal fiber-reinforced composites design assistant. Within that table is a listing of deficiencies in the current works as outlined in this chapter. Table 2.1 also shows how the contributions of using the knowledge-based and case-based reasoning approach with the Design Characteristic State (DCS) can strengthen some of the deficient areas.

2.1 Design and Manufacturing of Composite Parts

Potter (1992) asserts that the shape of the design process for composites has become identified with a narrowly defined set of analytical procedures that have tended to squeeze out other equally important considerations, e.g., cost. Potter believes that there is a need to re-establish composites design as a part of a product design process rather than as a separate subject with its roots in mathematical analysis. Potter also believes that the task of the designer is clearly to reflect the needs of the customer in their designs. The design process is described as a process by which customer problems are solved in such a way as to provide a profit to the supplier of components. Potter states that *"Conventially, in aerospace, material and process issues come largely ar or after the design stage. In reality they should come first as they have a major effect on cost and design."* A picture is built up of an ideal design cycle.

McCarty (1993) states that there now exists a sufficient history of composite applications in military, civil and commercial aircraft to provide an adequate technology base such that composites truly represent a viable solution for future designs. Mccarty provides a list of civil and commercial aircraft components comprising key primary structure that have been certified, e.g. the A300-A600 vertical stabilizer certified on March 28, 1988. McCarty lists cost data, vitally important safety issues and economic issues to be addressed before the full utilization of composites in commercial aircraft can be realized.

Like Potter (1992), the research effort described herein aims to make composites design a refection of the entire product lifecycle design process rather than as a separate subject based on flat plate theory mathematical analysis. Also, there is an increased amount of knowledge of composite structures which have been used on military, and commercial aircraft, as McCarty(1993) states, however these experiences are unstructured, raw, and incomplete. A method needs to be employed to turn this data into useful knowledge, an issue this research aims to address.

2.2 Expert/Knowledge Based Systems And Other AI Techniques Applied To Fiber Reinforced Composites Design And Manufacturing

Fathi *et al*. (1991) developed an expert system for the construction of composite parts (EXCOCOM). Components of his expert system are the kernel system module, finite element module, input module, and database module. The system uses the concept of a blackboard architecture.

Pecora *et al*. (1985) have developed the Composite Design Assistant (CDA) Engineering Expert System. It is a Backward Chaining expert system framework written in Prolog and interfaced to a Relational Data Base Management System (RDBMS) called RIM and a laminate analysis code (ADVLAM). It functions as an assistant to the engineer during the design and analysis of composite material structures. Although the CDA utilizes an expert system for production rule implementation, it fails to place any emphasis upon the conceptual design process, yet is supposed to be an assistant to the designer during the entire design and analysis of composite structures.

Ludden et al. (1993) have proposed an integrated knowledge based system to automate the design of laminated composites plates in an object oriented programming environment. The system consists of several different domain specific programs and commercial software packages integrated via a generic interfacing mechanism (Finite Element, Laminated Plate Code). A prototype system dealing with the preliminary design of a laminated plate is demonstrated. A case study is presented and several issues for the improvement of the proposed framework are discussed. Ludden et.al. use the CLIPS expert system shell to implement design rules. They also discuss using case-based reasoning to interpret the results of one or more analyses, also called the Stacking Sequence Expert. While their approach of an object-oriented knowledge-based system and case-based reasoning is to be commended, there seems to be much lacking in the case-based reasoning lists cost data, vitally important safety issues and economic issues to be addressed before the full utilization of composites in commercial aircraft can be realized.

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In their work, Davidson et al. (1993) expanded upon their prototype system. The system is expanded to take the user to a final design. Their system integrates symbolic, numerical and knowledge based tools in an object-oriented programming environment for design synthesis, evaluation and modification. Design modifications and structural optimization are performed using heuristic and experientially derived knowledge bases. Davidson et al. also claim to use case-based reasoning in order to find optimal solutions. While Davidson et.al. recognize the importance of using case-based reasoning in composites design, their discussion, however, indicates methods other than true case-based reasoning.

Rasdorf et al. (1993) describe their work as the integration of several components of engineering software using a relational database. A conceptual finite element material preprocessing system for laminated fiber-reinforced thick composite materials is studied. A materials database is integrated with several software components, including commercially available finite element analysis programs and tools for the design of laminated composite materials. The system, known as the Composites Database Interface (CDI) focuses on assembling, manipulating and using composite materials data resulting in the transfer of 2-D and 3-D composite materials property data into a finite element analysis program. The results of Rasdorf et.al. would be a useful module to plug into the research described herein. A composite materials property database is not the focus of this work, but would make the system more robust.

Karbhari (1992) describes a scheme whereby decisions concerning the composite material's transformation process can be aided through a de-selection process resident on a Decision Support System (DSS), through the use of a hierarchical system that incorporates the major discriminators, for example, shape, material, and form. The scheme Karbhari describes emphasizes the use of simulation and intelligent de-selection to arrive at the optimum design space for a process or structure. Karbhari's Decision Support System is built on a HYPERCARD stack in a Macintosh environment.

Wu (1992) developed a Composite Design Expert (CODEX) system that performs analysis and design of composite laminated plates and struts as well as assessing competing designs. Wu extended the strut optimization expert system to incorporate bolted joint analysis.

Lewis and Jouin (1992) describe a knowledge-based engineering system that reduces the development time and unit costs of the McDonnell Douglas Helicopter Co. advanced technology commercial helicopter, the MDX. They describe their efforts of focusing on automating the task of designing the "trim and drill fixture" component of the MDX tool string. Estimates show that the automation reduces the design time and cost by 50 percent. The knowledge-based engineering tool used in the project is ICAD. Their decision to use ICAD to build the knowledge-based system is good. The knowledge base can infer upon data from the 3D design system. However, a lack of previous similar design situations makes for a less than optimal problem solving environment becuase of the many previous simlar designs which may be helpful in suggesting new design and manufacturing techniques never before considered.

Moore (1992) describes a project at Bell Helicopter which consists of a system to design and manufacture composite bond tools. Tool surface geometry is created on a CAD system, and then downloaded to a knowledge-based system where the tool is designed automatically. The system produces a 3D model of the tool and an exploded drawing of the tool assembly. The graphical data is then uploaded to the CAD system where the tool design drawing is completed and the NC data is automatically created.

Punch et al. (1995) use genetic algorithms to design a laminated (multi-layer) composite material beam. Their approach to design is based on a generate-and-test system and uses a genetic algorithm to perform simulation and optimization. Their initial studies focused on the design of laminated composite beams to maximize their energy absorption. Punch et.al. state *"Our results, though meaningful from our Genetic Algorithm testing viewpoint, were not as accurate from a mechanical design viewpoint as we would have liked."*

The research efforts of expert/knowledge based systems applied to the design of composites cited in this section are commendable. However, there are two main areas of deficiency. The first is that of a lack of access to previous similar design cases, a necessity for good design practice. The second issue is the attempt to automate the design process rather than provide assistance to the designer. The research described herein will provide solutions to these problem areas.

2.3 Case-Based Reasoning

As one of the pioneers of case-based reasoning, Kolodner (1993) provides an in-depth discussion into its origins, methodology, and current state-of-the-art. Kolodner begins by discussing what case-based reasoning is, and how and where it is applicable. Kolodner provides numerous examples of case-based reasoning concepts and cites numerous case studies of case-based reasoners, many of which were developed by her and her staff. Kolodner shows how cases are collected, represented and retrieved and addresses how cases should be used. Kolodner also gives instructions on building a case-based reasoner.

Ketler (1993) presents an introduction to the case-based reasoning process including an example of the creation and consultation use of the case base. Ketler also identifies construction tools for case-based reasoning as well as key concepts. Ketler states that the development of a case base is a three step process: 1) understand problem domain, 2) operationalize indexing mechanism, and 3) provide historic cases. Ketler uses a Help Desk application for systems software to illustrate concepts outlined in the paper. Ketler also provides reference to a few commercial case-based reasoning tools. Ketler provides a good overview of case-based reasoning without getting into the minute details. Finally Ketler states that *"case-based reasoning systems will not compete with rule-based systems but will complement them"*, pp. 7.

Mott (1993) discusses the emerging role of case-based reasoning and its implications from a marketing perspective. Mott states that *"Early experiments pairing CBR with rule-based systems will soon lead to hybrid combinations with other* *"close approximation" technologies, such as neural networks, fuzzy logic systems, genetic algorithms, and so forth", pp. 97.* Mott also states that *"everybody knows that if you can model a problem domain perfectly with rules that is the best approach. It is the last 20% of most domains - the component of judgement, intuition, intelligent guesswork, or whatever - that confounds rule-based systems and causes all the problems"*, pp. 98. This concept corresponds directly with what is stated in chapter I of this research effort concerning the composites design domain having well defined rules for traditional plate theory but not nearly enough to define the characteristics of the entire domain. Also, in direct agreement with the hypothesis of this research, Mott states that *"the obvious answer is to model the domain with rules as far as you can, then apply case-based reasoning to handle the boundary region exceptions and special or subtle contexts", pp. 98.* Mott sites organizations which have used case-based reasoning applications to assist in solving problems, e.g. Digital Equipment Corp., Lockheed, and the Toronto Stock Exchange. Finally, Mott states that *"more elaborate manifestations of CBR are likely to show up in the traditional engineering domains of design, planning and scheduling and process control", pp. 102.*

Yoon et al. (1993) illustrate the case-based reasoning technique as applied to the problem of emulating the decision process of service coordinators dispatching technicians. Yoon describes a system, SERVICE, which is being developed for the Southern region of a company whose products include electron accelerators and associated equipment used for radiation treatment in cancer therapy. SERVICE was developed using CBR Express by the Inference Corp. One important point Yoon makes is that *"One of the key factors influencing the applicability of CBR to a particular domain is the existence of a prior case base", pp. 79.* The company Yoon is involved with has for the past 2 years recorded all incoming service requests and their disposition in a database. This is considered an ideal situation and is the exception rather than the rule in today's industry.

Kolodner and Domeshek (1993) consider three issues: 1) What sort of content should be captured in a design case?, 2) How should the content of a complex case be segmented into chunks for use?, and 3) How should the resulting chunks be indexed for retrieval? Kolodner and Domeshek talk about Archie-II, a case-based design aid for architects. Kolodner and Domeshek state that in Archie-II, they focus on raising design issues, proposing responses to design issues, and identifying pitfalls and opportunities. Archie-II presents retrieved material to the user; the user bears the responsibility for understanding and applying (or ignoring) the information presented. Kolodner and Domeshek state *"we* *believe that systems like Archie-II, that make evaluative information available to designers early in design, can contribute to designers awareness of the downstream implications of their decisions"*, pp. 90.; an axiom shared by this research effort. Kolodner and Domeshek provide screen shots of Archie-II and describe its functionality. Archie-II contains about 150 stories and a similar number of guidelines.

2.4 Case-Based Design/Manufacturing

Design-MUSE, Kolodner and Domeshek (1994), is the Design Memory Utility for Sharing Experiences. It is a shell intended to ease construction of Case-Based Design Aids (CBDAs) and was developed at the Georgia Institute of Technology, College of Computing. The project was directed by Dr. Janet Kolodner and Dr. Eric Domeshek. Case-based design aids are a class of computer systems intended to aid designers by providing easy access to prior design experiences and the lessons that can be learned from those experiences. Design-MUSE incorporates three levels of privileges, define, modify, and browse. Therefore, with Design-MUSE a user can either build their own domain specific case-based design aid or simply be an end user. Design-MUSE is a Macintosh application written in Mac Common Lisp, and implements a user-friendly graphical user interface. Design-MUSE was the tool used in this research effort to build the case-based reasoning portion of the architecture. More details on the functionality of Design-MUSE can be found in chapter 7.

Ullman (1994) discusses the work to date and organizes by importance the issues related to design history, design intent, and design rationale systems. Ullman lists thirteen issues key to the development of systems that manage design information evolution. Ullman's tenth issue states that *"The major issue in developing a design intent system is to determine when information can be managed as direct history, as designer input rationale, as modeled parameters, as automatically parameterized by the system or as requiring inference. It is suspected that a successful design intent system will utilize all of these types"*, pp. 257. This issue supports a basic concept of this work; that is a true design advisory system will use multiple design representation and solution finding mechanisms in order to assist in solving design problems.

Michelena and Sycara (1994) developed a methodology for physical synthesis of design components and sub-assemblies retrieved under a case- based design framework. The goal of their work was to provide a case-based design system with reasoning mechanisms for design synthesis at the configuration level.

Hinkle and Toomey (1995) have developed CLAVIER which is a case-based reasoning system that assists in determining efficient loads of composite material parts to be cured in an autoclave. Clavier uses CBR to match a list of parts that need to be cured against a library of previously successful loads and suggests the most appropriate next load. Clavier is a stand-alone application written in Macintosh Common Lisp. Clavier also has facilities for capturing and tracking pertinent shop floor data, such as the part production schedule that drives the shop, the number and work shifts of shop personnel, and the supply of material and other resources. In an explanation of why case-based reasoning was chosen Hinkle and Toomey state *"in talking with the expert autoclave operators, it became clear to us that sometimes even they are forced to use trial-and-error methods. When they encounter a new situation, they cannot predict what molds it will be compatible with without testing several possibilities in the autoclave. A constructive rule-based approach to load generation was found infeasible because even the experts did not have the first principles needed for such an approach"*, pp. 70. So, here is a situation of composites curing, much like its design counterpart, where frequent trial-and-error methods must be employed to predict performance. Clavier has been in continuous daily use at Lockheed's Composites Fabrication Facility in Sunnyvale, California since September 1990, and has virtually eliminated the production of low quality parts that must be scraped.

Maher and Zhang (1993) propose a hybrid case-based design process model, CADSYN, which is to integrate specific design situations and generalized domain knowledge. In discussing case-based design as hybrid systems, Maher and Zhang state that *"a hybrid case-based design system raises the issue of integrating different types of knowledge and reasoning methods within the framework of case-based reasoning"*, pp. 98. CADSYN provides a process model for design in which case-based reasoning is combined with a generalized decomposition approach. A hotel design problem is presented to illustrate transformation as constraint satisfaction. The specific cases are represented as attribute-value pairs and domain knowledge is represented by generalized design concepts and constraints. Maher and Zhang don't provide specifics on software and hardware of the CADSYN environment, neither on performance results.

Pu (1993) reviews some of the important issues concerning the application of case-based reasoning techniques to the design domain. Pu gives an overview of case-based reasoning and case-based design systems. Pu gives a status of the case-based design field, with surveys of existing case-based design systems and a summary from the first workshop held on the subject, first International Workshop on Case-Based Design Systems, June, 1992, Carnegie Mellon University.

Hua et.al.(1992) focus upon the formulation of design knowledge within the building domain. The representations used within their research used to formulate building design knowledge include production rules, shape grammars, prototypes and cases. Hua et.al. argue that search for a solution that accommodates several aspects is best carried out through iterative refinement of cases, and that a precise geometrical model of the case is required to link different aspects. Hua et.al. state that this leads them to employ cases as a design knowledge representation and adaptation as a reasoning methodology for design. Hua et.al. have implemented a prototype system for case-based architectural design. In their system, original cases are created through an AutoCAD interfacing program and stored as AutoCAD drawings. The technique that Hua et.al have presented is worth noting, but a formal methodology for integration between the solution methods is lacking.

Fischer and Nakakoji (1994) state that their research is based on the assumption that design problems are best solved by fostering co-operative problem-solving between humans and integrated, domain-oriented, knowledge-based design environments. Fischer and Nakakoji state that combining knowledge-based systems and innovative human-computer communication techniques empowers designers to produce better products by amplifying their creative skills. They state that their environment has three mechanisms which provide information that gives rise to ideas that are both valuable and innovative, (Construction Analyzer, Catalogue Explorer, and Case Deliverer). The design objects stored in the catalogue can be used for providing a solution to a new problem, warning of possible failures, and evaluating and justifying a decision. Fischer and Nakakoji illustrate their concepts by providing examples and screenshots from their prototype system Janus. Janus supports the design of kitchen floors, is implemented in Common Lisp and runs on Symbolic Lisp machines.

Barber et.al. (1992) describe ASKJEF which is a prototype AI system that helps software engineers in designing human-machine interfaces. ASKJEF contains two cooperating modules: memory and interface. The memory module manages different types of knowledge and the interface module interprets the designer's actions. ASKJEF provides a memory of interface design examples, primitive domain objects, and design principles, guidelines, errors and stories. The design examples within ASKJEF are represented graphically and decomposed temporally, and it uses text, graphics, animation and voice to present relevant information to the designer. ASKJEF runs in Microsoft Windows 3.0 and uses the ART-IM knowledge tool from Inference Corp. Barber et.al. provide an example of ASKJEF using the design of a customer-activated terminal (CAT) for a fast food restaurant.

Domeshek et.al. (1994) describe MIDAS (Memory for Initial Design of Aircraft Subsystems), a system that applies insights and techniques from case-based reasoning to aid engineers in the design of utility subsystems early in the development of a new aircraft concept. MIDAS is an instance of a general class of systems called Case-Based Design Aids (CBDA's). In building their case base, Domeshek et.al. describe problems of acquiring knowledge from the design experts as *"the expert seemed as reluctant to tell his personal stories as he was eager to share his personal library."* Their solution to the case acquisition problem combined a review of the experts personal collection of books, journals, documents and clippings supplemented with the experts stories. Their approach is very similar to the knowledge acquisition approach utilized within this work. However, the work described within this document began the knowledge acquisition process with interviews and reference to books, journals, and other documents simultaneously. The MIDAS case library was developed by one of the Lockheed employees. It is worth noting that the same case-based design aid tool (Design-MUSE) used within this research, was used to build MIDAS. MIDAS is a commendable project, however, the addition of rules to handle the well-defined subsystems knowledge would make a more efficient system.

Kolodner and Domeshek (1992) summarize the current status of a project to construct a design aiding system for architects. Their system, ARCHIE II is an application of case-based reasoning techniques to the task of assisting human designers. Kolodner and Domeshek(1992) focus upon design aiding, and the choice of case-based techniques. In discussing the choice of case-based reasoning techniques, they state that the rationale is that people are good at figuring out what to do in new situations largely because they are able to remember and adapt things they did (or saw others do) in similar previous situations. Kolodner and Domeshek (1992) describe the ways which design cases can be carved up for presentation to designers and how the resulting pieces can be indexed and organized so as to make them available at appropriate times in the design process. They have identified three classes of chunks worth presenting to designers;

1) Stories: goal-focused evaluative case descriptions that teach lessons by example,

2) Documentation: information clustered according to decompositions in terms of structural components and functional systems, and

3) Guidelines: provide a way of relating parts of cases to one another.

Archie-II exists as a set of dozens of analyzed stories and their accompanying guidelines, a preliminary vocabulary for

describing those stories, and an interface prototype developed in Supercard on and Apple Macintosh. The systems stories are drawn from a set of Post-Occupancy Evaluation reports prepared by architectural consulting firms as part of procurement review processes of various government agencies. Kolodner and Domeshek (1992) have received interest and encouragement from architects who have seen the system.

Kolodner et. al. (1994) discuss the progress they have made in implementing Case-Based Design Aids (CBDA's) and focus on the generalization of their original system (first developed to support architects with the conceptual design of buildings, ARCHIE and ARCHIE-II) into a tool kit applicable to a wide range of design domains. In discussing their motivation for CBDA's, they state that they conceived of CBDA's as a way to apply some of the insights and techniques developed in the AI paradigm of case-based reasoning so as to have a real effect on the quality of design processes, particularly conceptual design. They have redirected their efforts to building tools intended to aid people doing design. In particular, learning how to segment and index large complex cases in domains where no clear causal models are available. Their CBDA toolkit supports three different classes of users:

1) end users who simply browse through the available materials,

2) expert users authorized to expand the collection

of materials in the library, and

3) system administrators authorized to redefine the available data structures.

Their CBDA tool kit has three main GUI window interfaces: designs, lessons and sources. The design window organizes and presents documentation describing particular facts. The lessons window organizes and presents the evaluative material that allow users to learn interesting lessons from the artifacts. The sources window allows all information in the system to be tied to citations identifying where the information came from. One of their most recent CBDA's is MIDAS, (Domeshek et.al. 1994). Knowledge within MIDAS is segmented into linked problems, responses, and stories, much like the work described herein. The case-based reasoning work of the research described herein is largely based upon the concepts outlined by the work of Kolodner et.al. (1994). The CBDA tool which resulted from Kolodner et.al. (1994) is used in this research to build the case-based reasoning prototype for flat panel composites.

Colton and Dixon (1996) describe a process of anchoring and adjustment design. Anchoring and adjustment and deltaspecs are presented as concepts for modeling design scenarios where previous re-design solutions form the basis for a new design. The anchor provides the basis for the re-design and may consist of a collection of previous design solutions (ideas, components, devices and solution principles). Colton and Dixon state that the deltaspecs represent the difference between the specifications for the new design and the current version of the design solution and guide the adjustment of the anchor toward the final solution. A case study on the design of the Scanning Tunneling Microscope (STM) is presented. The results of the STM case study satisfied all of the goals outlined as characteristics of an ideal design method. These characteristics are:

1) Guides a designer through a broad and exhaustive search of possible solution concepts,

2) Evaluates solution ideas in an objective manner,

3) Guides a designer to an optimum solution utilizing the tasks limited resources, and

4) Anticipates and works with the cognitive limitations of the human designer.

In comparison to the work of this research effort, the previous re-design solutions described in Colton and Dixon, which form the basis for new designs, can be likened to cases of similar previous designs described herein.

2.5 Hybrid Rule-Based/Knowledge Based and Case Based Reasoning Techniques

Chi and Kiang (1993) demonstrate the importance of hybrid rule- and case-based reasoning. They state that a case- based reasoning system is appropriate for an experience-rich domain while a rule-based system performs reasonably well in a knowledge-rich application environment. In their paper, a Multi-agent Cooperative Reasoning System (MCRS), which integrates an inductive reasoning agent and a deductive reasoning agent is proposed to solve problems through the cooperation of both agents. An architecture and inference mechanism of the MCRS are presented. However, Chi and Kiang do not discuss how the communication interface between the case base and knowledge base operate. The way and type of data that is passed between the knowledge base and case base is not explained. Also, much effort is given to building a case-based reasoning system using frames in Prolog and devising a matching algorithm.

Liu et al. (1994) describe an integrated approach for solving the route finding problem. Liu describes their work as having integrated Dijkstra's algorithm with a knowledge-based and case-based approach. Liu states that knowledge about the geographical information and past cases are used to help Dijkstra's algorithm in finding a solution. A prototype system called R-Finder was implemented for route finding in Singapore. Although Liu et.al. describe a problem solving sequence, (case base-->Dijkstra's Algorithm-->knowledge base) they fail to provide any hint of the way data is passed between the modules, and the way each is implemented. Also, it is not clear how each reasoner benefits the problem solving approach.

Hamada et al. (1995) developed an optimization problem solver to combat scheduling issues in their steel making plant. The system consists of 1) a procedural approach (an optimization algorithm library that includes many operations research methods), 2) K1, an object oriented rule-based system, and 3) C1, a Genetic Algorithm developers kit. They applied the system to an actual problem that occurs in one of their steel making processes. Hamada et. al. state that *"it is generally difficult or insufficient to use only one method to solve realistic engineering problems because of their nonlinearity and complexity."* The research described within is in agreement with this statement. They evaluated the system's performance by comparing system-made schedules with man-made schedules for several dozen of cases that were not used to tune genetic algorithm parameters. The system proved superior in the categories of schedule quality, and schedule make time. The results show that the solver reduces the human workload and produces efficient schedules. Operators gave the system high remarks, but commented that the expert system rules and the genetic algorithms evaluation function should be changed on-screen, because the operational constraints vary daily.

Many of the above mentioned works concentrate on the improvement of the composites design process. Many different types of computer aided techniques are employed. Some of these works use knowledge-based systems technology. Others use only quantitative analysis. However, none of these works has attempted to use knowledge based reasoning coupled with case-based reasoning with an emphasis upon the entire flat composite panel life cycle. Kolodner et.al(1994)(1992), however, do realize the importance of applying the use of case-based reasoning during the conceptual design process. This is a concept shared by this work as it focuses upon the design of composite structures in the early design stages with emphasis upon downstream processes impacted by early decisions.

Table 2.1 lists the features of an ideal design assistant for fiber-reinforced composite structures. The table also shows the holes in current works which need to be filled to achieve the ideal system. Also is shown how the use of knowledge-based and case-based reasoning can help fix the deficiencies. A checked box in the *Ideal Design Assistant* column indicates a feature which is desired from an ideal system. A checked box in the *Defficiencies* column indicates a defficiency that exists in current works. A checked box in the *Contributions* column indicates areas where the knowledge-based and case-based reasoning technique can help strengthen

Table 2.1: The Ideal Fiber-Reinforced Composites Design Assistant			
	Ideal Design Assistant	Deficiencies in Current Works	Contributions by Using Knowledge-Based And Case-Based Reasoning
Knowledge of domain commensurate with scope of design assistant.	✓		
Automation of repetitive procedural tasks.	✓		
Easy-to-use interface.	✓	✓	
Data storage capability.	✓		
Ability to suggest multiple solution techniques.	✓	✓	✓
Capability of providing previous similar design cases.	✓	✓	✓
Ability to reason upon temporal design information provided by user.	✓		
2-D and/or 3-D design.	✓		
Ability to reason upon incomplete design information.	✓	✓	✓
Provide a design history log.	✓	✓	
Modularity.	✓		
Expandability.	✓		
Ability to suggest solutions from both heuristic knowledge and previous similar designs.	✓	✓	✓
Help facility for users.	✓		

the defficiencies. In chapter nine, table 9.1 compares the ideal composites design assistant to the prototype produced from this research effort. Table 9.1 lists the short-falls of the prototype composites design advisory system from the ideal composites design advisory system. The features listed as ideal for a composites design advisory system were compiled from three different sources:

1) most common features listed throughout literature review as desireable, or needed in an automated or semi-automated design system,

2) input from industry experts when asked what features were most desired in a composites design advisory system, and

3) guidelines from text which discuss developing design advisory or knowledge-based and case-based reasoning systems, e.g. Kolodner (1993) and Parsaye and Chignell (1988).

2.6 Chapter Summary

A detailed literature review of related research works has been given. Topics covered included, Design and Manufacturing of Composite Parts, Expert/Knowledge-Based Systems And Other AI Techniques Applied To Fiber Reinforced Composites Design And Manufacturing, Case-Based Reasoning, Case-Based Design/Manufacturing, and Hybrid Rule-

Based/Knowledge-Based and Case-Based Reasoning Techniques. Chapter three discusses the flat composite panel life cycle. It will be the foundation upon which a solution strategy for cooperative knowledge-based and case-based reasoning is built and the template for the prototype advisory design tool is built. Studying the life-cycle will give insight into where and why rules and procedures are used, when and what type of decisions are made, and where reference to previous similar design cases takes place.

CHAPTER III

FLAT COMPOSITE PANEL DESIGN

3.1 The Panel Life Cycle

The composite panel design process is complex. The conventional process for creating a panel from conception to delivery can be divided into six sub tasks. Those sub tasks are the Specification, Conceptual, Detailed, Testing, Manufacture, and Operational phases. These six sub-tasks may not represent the categories each designer utilizes, but they are a good representation for most. Each phase is explored in detail below. Realistically, these phases overlap in specific areas. For clarity, these divisions are used throughout this work.

3.1.1 Design Specification Phase

Every product starts out as an idea in someone's mind. In order for that idea to become a physical reality, the owner has to communicate that idea in terms of functional and physical relationships. These relationships describe the idea in terms of the owner's requirements, needs, and wishes. It is here that the design first begins to become a reality. These descriptions are termed specifications, and they represent the voice of the customer.

During the flat panel design specification phase, the customer may voice requirements and wishes concerning final product weight, material, functionality, geometry, available budget, production volume, and operational loads. These requirements are recorded according to their respective dimensional units. For example, loads are recorded in lbs. or kgs. Geometry is described in inches, or centimeters, length, width, height, radii, etc. These specifications then are used in the design phase.

3.1.2 Conceptual Design Phase

During the conceptual design phase, the customer's requirements are transformed into the beginning concept. From the flat panel conceptual design phase a designer expects to obtain a preliminary laminate lay-up. This lay-up consists of the number of individual 0,90,and +-45 degree plies, their orientation, and their material content. In order to obtain this concept, the designer needs quantitative data. This data includes the material properties and loading requirements. As an example of how this quantitative data is used to obtain a concept, equation 3.1 represents a method of determining the number of 0 plies required for a composite laminate based upon material properties and loading spectra.

Equation (3.1) : Number of 0 Plies:

Maximum of

$$N_x - (F_{45} * T_{45}) / T * (F_t \vee F_c)$$

and

$$ET_a - (E_{45} * T_{45}) / T * (E_t \vee E_c)$$

Where: N_x is Axial Load
F_{45} is Design Ultimate of +/- 45 plies
T_{45} is Thickness per 45 ply
T is Thickness per ply
F_t is Design Ultimate Tension Stress
F_c is Design Ultimate Compression Stress
ET_a is Axial Stiffness
E_{45} is Modulus of +/- 45 plies
E_t is Youngs Modulus in Tension
E_c is Youngs Modulus in compression

However, before an acceptable conceptual or rough design is developed, the designer must take into consideration qualitative issues as well. Some of those issues include the environment in which the product will operate, the mode of manufacture, mating parts and materials, damage tolerance, and maintenance. Each of these issues affects the outcome of the conceptual design, and the designer has to design the product accordingly.

The knowledge which addresses these issues is collected from various sources. The environment in which the product will operate is obtained from the customer during the design specification phase. The mode of manufacture is obtained through a collaboration with the manufacturing department and possibly outside suppliers. The designer then uses empirical data, company standards, and published knowledge to address the qualitative issues as related to the voice of the customer.

3.1.3 Detailed Design Phase

The flat panel detailed design phase entails a detailed force/stress analysis. This phase usually is conducted with the use of laminate plate code 3-D geometrical analysis and finite element analysis. It is during this phase that the laminate is analyzed to assure that it can withstand the operational loads, temperatures, and impact forces given as specifications and constraints earlier in the design process.

3.1.4 Testing

Testing of fiber-reinforced composite lamina is to validate the performance predictions that were produced in the detailed design phase. Also, the testing phase attempts to bring unforeseen problem areas to the surface prior to final production and placement of the lamina in its final operating environment. Testing may occur with full scale prototypes or with small coupon samples which represent the material properties and behavior of a full size laminate.

3.1.5 Flat Panel Manufacture

Tooling required for lamina layup and cure methods, such as autoclave curing, make up much of the manufacture phase of a flat composite panel. Tooling is often used as a die or pattern upon which the lamina may be layed up. Most lamina layed up using tooling are cured by large ovens termed as autoclaves. It is imperative during design that manufacturing resources, such as tooling and cure methods, be incorporated into the earliest stages of the design process and throughout the entire product life cycle.

3.1.6 Operational Phase

The operational phase encompasses delivery to the customer, actual use by the customer, maintenance, and customer feedback. During this stage of the panel life cycle, important information is transferred back to the product development team. Much of this information comes from the customer in the form of verbal feedback on the product's performance. Such feedback is invaluable to the product development team and should be used for future reference.

3.2 Flat Panel Life Cycle Model

There is interaction between the different phases of the product's total life cycle. The interaction occurs at different levels of each phase. For example, interaction between the conceptual phase and the manufacturing phase should occur at the beginning of the conceptual phase and not at the end. Available manufacturing resources should be integrated into any design problem at the earliest stage of design. Structures which could not be designed due to a lack of attention to manufacturing capability and constraints has been a typical statement from our experts. These interactions throughout the product life-cycle must be modeled to aid in the development of a flat panel fiber-reinforced composite design assistant.

During the complete product life cycle, energy, materials, and information (EMI) are transferred between the life-cycle phases. For example, information includes the customer's requirements, materials include the fiber and resin, and energy includes the heat required to cure the laminate. Figure 3.1 displays a model of the manufacturing operation of the composite flat panel and the associated energy, material and information flow. The models were partly created using the Pahl & Beitz (1988) theory of showing how energy, materials, and information flow as integrated

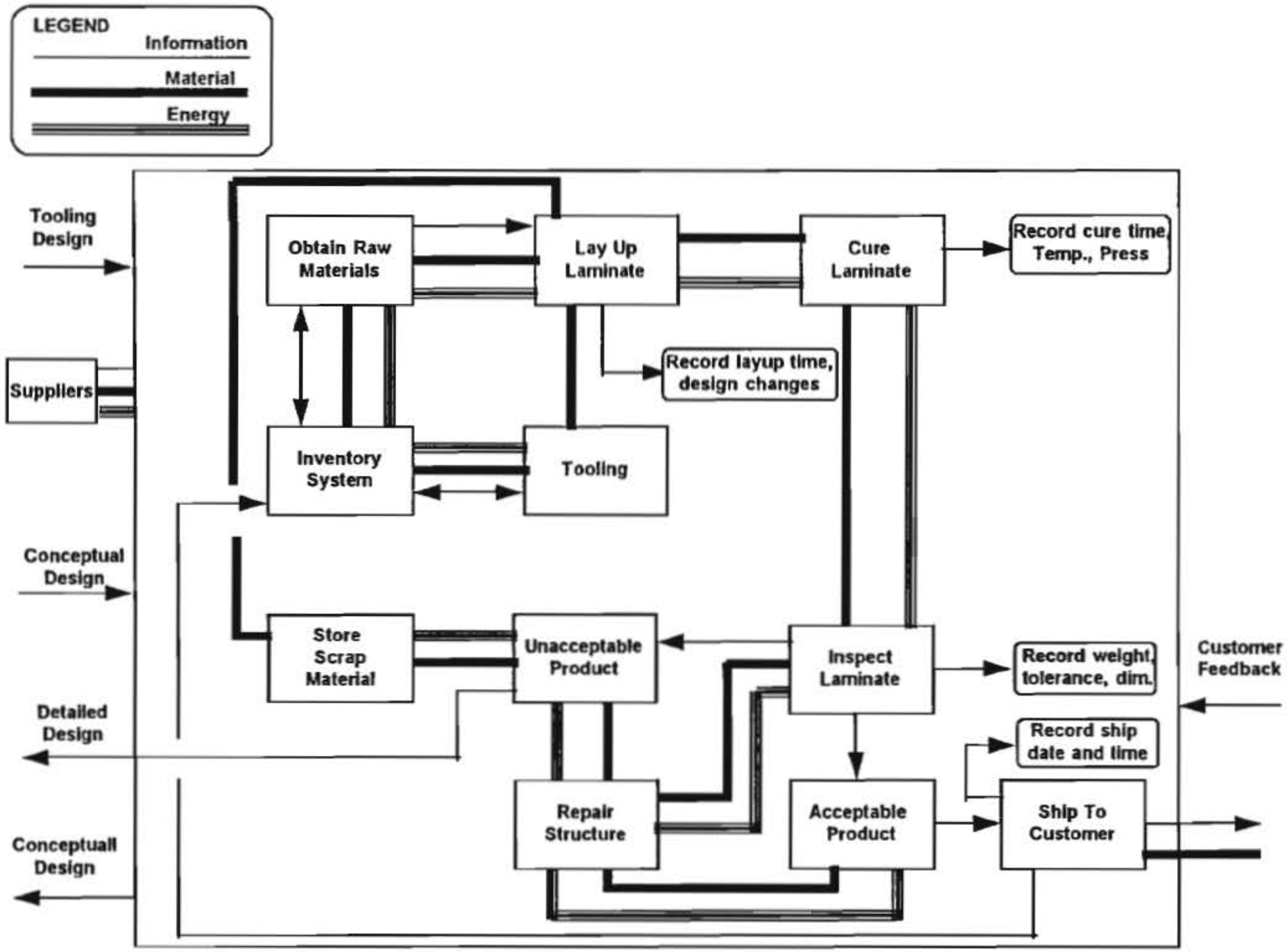

Figure 3.1:Composite Structure Production EMI Model

attributes of the function-to-form design methodology (1). The models were constructed through the aid of the composites design experts mentioned earlier. Based upon research, course work, industrial experience, and interviews with experts,conceptual models were developed by the researcher then reviewed by the experts. Corrections to the models were made as required. The labeled boxes indicate processes that occur throughout the life-cycle of the composite structure. Lines which connect these process indicate the direction of flow of either energy, materials, or information. Details on how the knowledge used in the models was gathered are provided in chapter 4. The models which depict the remaining phases of the product life cycle are shown in appendix A.

These models show how information, material, and energy flow between the sub-process of each life cycle phase. These models are indispensable in understanding the entire flat composite panel life cycle. By developing and studying these models, an understanding is obtained of where empirical knowledge, heuristics, and design history are used.

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(1) The concept of showing how information, material, and energy flow in the life-cycle model was adopted from "Engineering Design", G. Pahl and W. Beitz, 1988

3.2.1 Application of Empirical and Heuristic Knowledge

Empirical and heuristic knowledge is often used during the life cycle of a flat composite panel. Within this work empirical and heuristic knowledge are referred to as rules. These rules are used at varied stages in the product's life cycle on many different issues. The rules cover qualitative and quantitative product life cycle issues.

By studying the life cycle models, a determination is made of where these rules are applied and why. For example, during the conceptual design phase, rules are applied after the design specifications are acquired and before a rough layout is completed. During that phase, rules check the customer's requirements and specifications against known limitations of material, financial, manpower, and manufacturing resources.

The process of incorporating these issues in the early stages of the product life cycle has been the topic of many research efforts. When rules are used to address these issues at this early stage of the design process, the potential for problems downstream of the product life cycle is reduced.

3.2.2 Application of Historical Design Information

When designing composite structures, designers often refer to similar previous design cases. In so doing, the designer can compare previous case issues to current problems, such as materials used, manufacturing techniques, and stacking sequence comparisons. The designer then has greater insight into the performance of similar designs. Consequently future mistakes can be avoided.

A major benefit derived from referring to similar cases is the ability to reduce time and costs involved in designing, prototyping, testing, and redesign. If a designer can see what pitfalls have arisen in previous similar designs, those mistakes can be avoided in the current design. By studying the life-cycle model in figure 3.2, one sees that, during the conceptual phase, designers refer to previous design cases after specifications are gathered, during tradeoff studies and through reference to customer feedback. The remaining models which include reference to applied rules and procedures are included in appendix B.

These models are the building blocks needed in cooperatively using knowledge-based and case-based reasoning in flat composite panel design. The models show where rules and previous designs are employed throughout the product life cycle. These models are used as the foundation for a solution strategy and for the flat composite panel design advisory system. Details of the prototype are provided in chapter 6. The following chapter discusses the acquisition, manipulation and representation of the knowledge used within the product

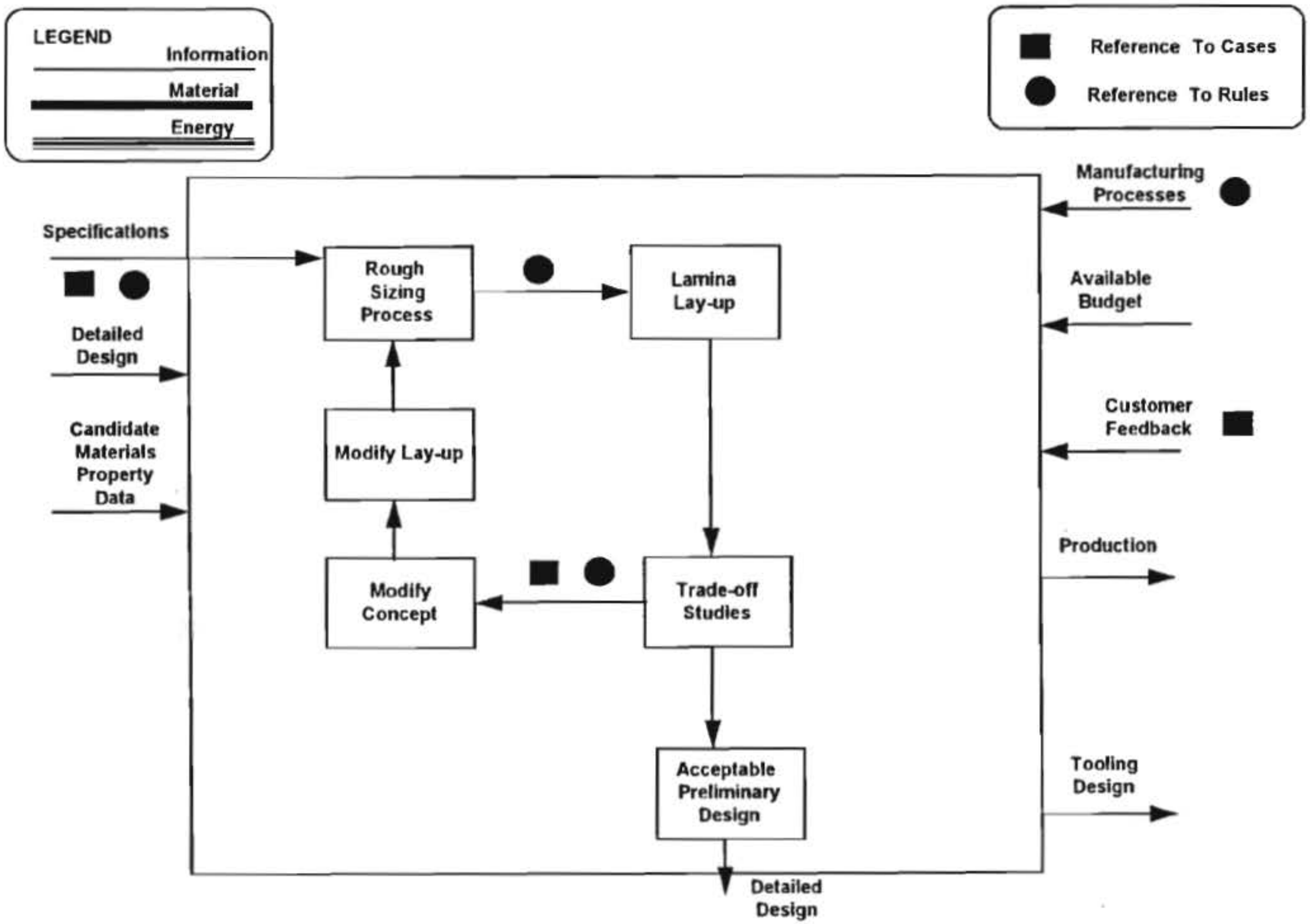


Figure 3.2: Composite Structure Conceptual Design EMI Model w/ Reference to Cases and Rules

life cycle. This knowledge represents rules and procedures used during the life-cycle phases as represented by figure 3.2.

3.3 Chapter Summary

Within this chapter has been presented a review of the fiber-reinforced composites design phases. A discussion of the events which happen within each phase and the interactions among the phases has been given. A method of modeling the life-cycle of the composite structure using a technique which consists partially of the Pahl & Bietz (1988) methodology. The models are used as the building blocks for development of a knowledge based and case based reasoning technique used for fiber-reinforced composite structure design.

Chapter four details the knowledge acquisition and representation process used throughout this research. The acquired knowledge centers around the models which were described within this chapter.

CHAPTER IV

KNOWLEDGE ACQUISITION AND REPRESENTATION

In order to understand the many events associated with the life-cycle of any complex domain, related knowledge must be gathered, structured, and used. Herein, knowledge of composite structure design is gathered to aid in the understanding of the life-cycle process. That knowledge is then put into a useable form or structure such that it can potentially become applied knowledge. The knowledge acquisition and representation carried out here is used to help develop the knowledge-based and case-based reasoning approach. Without the knowledge and a suitable representation a method could not be created. This work is not meant to explicitly define nor to alter the functionality of Knowledge-Based Reasoning; only to use it and prove its worth in suggesting a problem solving strategy when cooperatively used with Case-Based Reasoning. Below is a description of the way that the knowledge was gathered and structured for this work.

4.1 What is Knowledge and The Knowledge Base?

Knowledge can be described as an accumulation of facts, a set of rules, relationships between facts, an association of facts to rules, and experience. One definition of a knowledge base, Baker (1991) and Parsaye and Chignell (1988), can be described as a computer program which incorporates knowledge to perform tasks that an expert usually performs. A typical knowledge base consists of a set of rules, factual knowledge or working data, an inference engine, and a user interface. The working data includes mainly temporal information which describes the characteristics surrounding the knowledge base domain. The rules use this working data to infer solutions. The path by which rules take in order to infer these solutions is performed by the inference engine. Finally, the user interface allows the user to query the knowledge base, supply information, and receive advice. Figure 4.1 shows a typical rule-base knowledge structure.

4.2 The Role of Knowledge

Knowledge is of key importance within the life cycle of flat panel composite structures. People using knowledge is what transforms an idea into a physical product. Flat composite panel design knowledge is used in many different areas throughout the product's life cycle. For example, the detailed design phase uses knowledge from the preliminary design phase, and the preliminary phase uses knowledge from the specifications and manufacturing phases. Consequently, the knowledge is represented in different forms in order to be

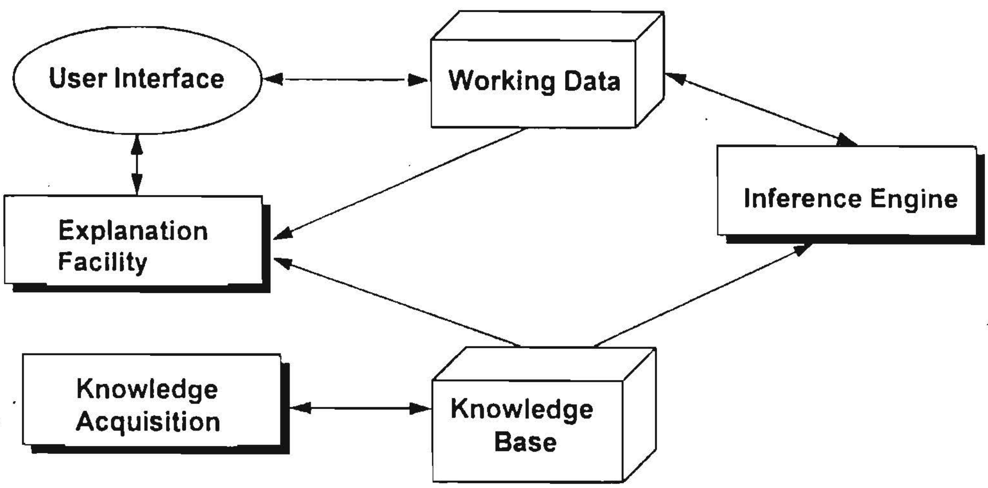


Figure 4.1: A Typical Rule-Based Knowledge Architecture

Source: Baker (1991)

accessible in different areas of the product's life cycle. This knowledge must be organized, up to date, and readily available.

This leads to the discussion of acquiring, organizing, and making available knowledge used in the development of flat composite panels. This work is based upon the cooperative use of knowledge-based and case-based reasoning. Cases are also knowledge, but this chapter is devoted to the knowledge found in rule-based knowledge systems. The knowledge contained in case- based reasoning systems and its relation to this work is covered in chapter 5.

Below is a detailed discussion of the way the knowledge-based system for the design of flat composite panels was constructed. It includes the knowledge acquisition process, knowledge organization, and knowledge representation schemes. These steps and others are critical and necessary for the development of a complete knowledge-based system. Most of the acquired knowledge is focused upon the conceptual phase and its interactions with other downstream phases. This knowledge includes quantitative preliminary sizing and qualitative life cycle issues. Therefore, detailed analytical methods were not included as part of the knowledge acquisition process, but their role in the complete product life-cycle is incorporated. The reasoning is that there are many analytical detailed composite design tools but few that concentrate upon empirical and heuristic knowledge applied during the conceptual design phase and its downstream impact.

4.3 Knowledge Acquisition

Knowledge acquisition traditionally has been the bottleneck in rule-based knowledge and expert systems development. This typically has resulted because of the following three reasons:

a) Relating experience to rules of expertise is not an easy task.

b) Experts are hard pressed to describe expertise in a systematic manner.

c) Expertise given in a rationally structured form is an idealistic and usually un-achievable goal.

These facts are especially true within the composites design domain because of its complexity and continued evolution. Therefore, there has to be continuous interaction between the Knowledge Engineer (KE) and the expert in order to develop an accurate representation of the domain knowledge.

In knowledge-based systems development, the expert provides the needed domain knowledge in the form of design approaches and methods, general rules of thumb learned through experience, and collected data. The knowledge engineer interviews the expert, organizes the extracted knowledge into well-structured production rules, and then passes them on to the programmer. The programmer then encodes the rules and factual data into the selected software environment, see figure 4.2.

4.3.1 Experts

The experts who provided their knowledge for this research work were from industry and academic environments,

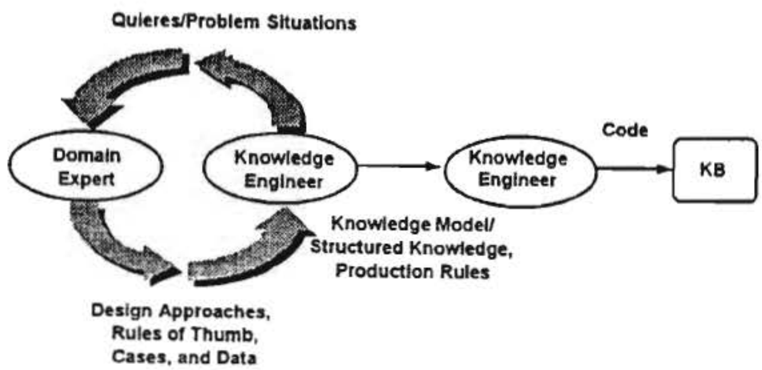


Figure 4.2: Knowledge Acquisition And Engineering Model
Source: Baker (1991)

see appendix B. Their backgrounds spanned areas of composites from conceptual and detailed design, manufacturing, advanced processes, and theoretical modeling.

It was imperative to obtain a diverse source of knowledge so that the domain was well covered and more than one expert's view could be analyzed. The industry experts each have several years of design and manufacturing experience in the composites industry. A total of three industry experts were interviewed. The knowledge gathered from the experts was supplemented with knowledge from Niu (1988)(1992), and the researchers' industrial and academic experience. Often times, information from Niu (1988)(1992) served as a springboard for formulating questions for the experts.

4.3.2 Technique

The method used in this research for acquiring and structuring the knowledge was adopted from Baker (1991) and Parsaye and Chignell (1988). The knowledge elicitation technique was completed using traditional knowledge acquisition. Each industry expert was interviewed in an office or shop floor environment. In order to keep the process somewhat organized, each session started with a particular set of topics that needed to be covered. A specific protocol was not used for the interviews, but rather a collection of techniques extracted from Baker (1991), Manivannan (1992), and Parsaye and Chignell (1988). Each interview began with clarification of any issues that were brought up in the prior interview. The interview then progressed with a broad issue or topic allowing the expert to go into the details related to that topic. Consequently, additional questions would arise which would later be brought up for the expert's elaboration. During the interview, knowledge from the expert was written in a journal. Because most areas were secured, no tape recorders, or cameras were allowed.

There was an average of four interviews with each industry expert. Each interview lasted approximately fifty minutes and the length of time between each interview was approximately two to three weeks. Each interview topic usually progressed along a flat composite panel life cycle spectrum. That is the experts were usually asked about how they handle customer requirements and specifications first. The final interviews were usually related to tooling and manufacturing, although this topic came up often in the conceptual, detailed, and testing phase discussions.

Out of this knowledge elicitation process came raw knowledge. This knowledge was unorganized and incomplete. At this point the knowledge was organized into sections or chunks. These chunks were based upon where the knowledge fit into the flat composite panel design and manufacture process, how it related to other knowledge, and what issues it represented. Table 4.1 lists the sections into which the knowledge was divided. The scope of each section of knowledge is as follows:

Laminate Layup: limited to procedures and knowledge which describes how to layup a non-complex laminate. The procedural knowledge calculates a rough number of 0's, 45's, and 90's needed.

Material: knowledge which describes how certain materials may act in different environments, but not material characteristics.

Table 4.1: Organization of Knowledge	
Laminate Layup	Aircraft
Material	Features
Loading	Environment
Manufacture	Cure
Tooling	Geometrical
Failure	

Loading: limited to simple loads which can be used to calculate layup or predict laminate performance under operation.

Manufacture: knowledge which describes composites structure manufacturing techniques such as hand layup, filament winding or fiber placement. This section is mainly limited to hand layup.

Tooling: knowledge which describes composite tooling to the extent that it may potentially affect structure design.

Failure: knowledge which describes manufacturing, cure, and operational situations which may potentially produce failure in a composite structure.

Aircraft: knowledge which conceptually describes military and commercial aircraft and their differences.

Features: knowledge which describes features of simple composites structures, such as drilled holes, and how they may affect design.

Environment: knowledge which describes how the operating environment may potentially affect composite structure design.

Cure: knowledge which describes how composite structures are cured. This section is limited to mainly autoclave cured structures.

Geometrical: knowledge which describes how the geometry of a structure, mostly non-complex, and small curvature, will affect its design, manufacture, and operational use.

The knowledge that resulted from the above analysis was more organized than the raw knowledge. Most of the conflicting and redundant knowledge was eliminated. The redundant knowledge was eliminated by choosing the set which provided more information or had more associated consequents. The conflicting knowledge, although there was not much, was corrected by referring back to the industry experts. It usually turned out to be a need for supplemental knowledge and clarification rather that conflicting knowledge. This knowledge is now considered digested knowledge.

At this point, the process of knowledge conceptualization was performed upon the digested knowledge. This method imposed a structure, knowledge representation scheme and resulted in partitioned knowledge. First, each section of knowledge gathered was decomposed into a hierarchy. The hierarchy was based upon physical descriptions of the extracted knowledge. After each hierarchy was generated, an attributes list was constructed.

For each element in the outer most leaves of the hierarchy, a list of attributes, which described that particular component, was generated and placed next to that component. Most of these attribute lists occurred towards the lower nodes of the hierarchy tree. Figure 4.3 shows an example of one hierarchy. Appendix C shows the remaining hierarchical decompositions. The knowledge elicitation and conceptualization were performed by hand with the use of research journals. The questions put to the experts were written in the journals followed by the answers which were given. The organization and structuring of the knowledge were also performed by hand in the same journals used for the interviews. Therefore, the entire Conceptual Knowledge Model

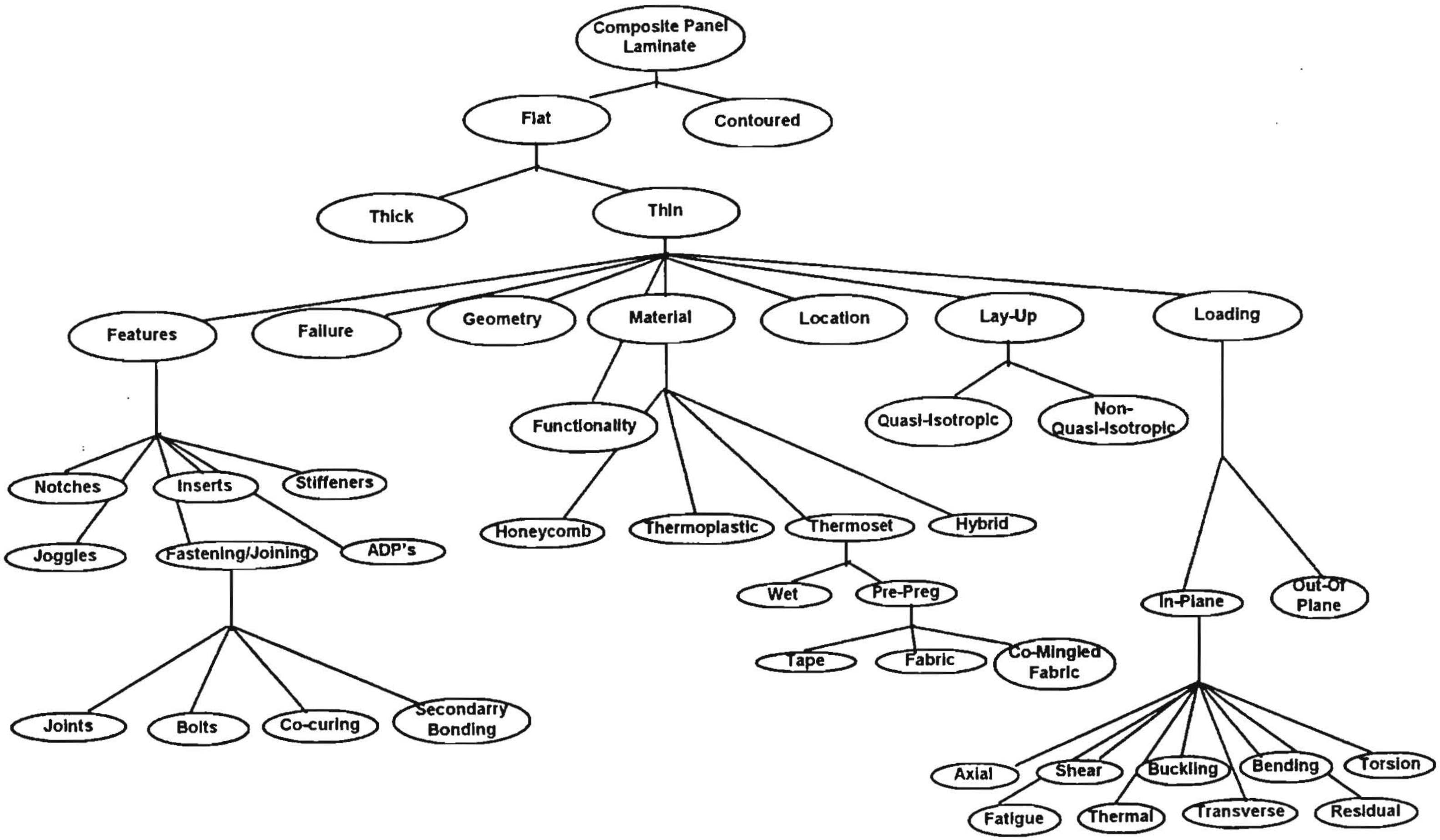


Figure 4.3: Composite Panel Laminate Hierarchical Decomposition

is contained in the research journals.

These hierarchical decompositions were invaluable to the development of the knowledge base. The hierarchies not only organized and structured the knowledge but aided in the development of the rules and the identification of factual knowledge from experiential knowledge. This comprises the Conceptual Knowledge Model Implementation. The required knowledge is now organized and usable. The final forms in which the knowledge was implemented are discussed below in section 4.4.

4.4 Knowledge Representation

4.4.1 Rules

From all the elements which comprise the knowledge model, and the interviews with the experts, the production rules were generated. Most of these rules were structured as "If-Then" constructs. Each rule had at least one antecedent and consequent. Figure 4.4 shows a typical rule constructed from the acquired knowledge. These rules were organized according to the divided chunks or sections of knowledge as represented in table 4.1. Appendix E shows the remaining rules that were generated from the acquired knowledge. These are the rules which are implemented in the knowledge base portion of the design advisory system. The rules give guidance to the designer during the design process based upon customer requirements and factual information. Table 4.2 provides a list of rule types generated from the knowledge and how they were organized. Appendix G is a list of all rules generated from the knowledge acquisition and used in the research.

If Residual Stress or Built-In Strains Are Induced Within The Part As A Result of Tooling

Or Close Dimensional Tolerances Are To Be Held On The Part

Then Consider The Use of Low CTE Tooling Such As Carbon/Graphite Composite or Ceramic

Figure 4.4: A Typical Rule Constructed From Acquired Knowledge

4.4.2 Classes

Much of the acquired knowledge was structured such that it could be represented in the form of association with a particular class. These groupings were taken advantage of when actually developing the prototype advisory tool. Specifically, these classes were represented with an object-oriented structure; i.e., a parent child relationship. Figure 4.5 shows how some knowledge was structured into a class hierarchy. Chapter 6 discusses how the class structures were implemented into the prototype advisory system.

Table 4.2: Rules Created From Knowledge Acquisition Process And Used In Research.	
Grouping	*Description*
Manufacturing Rules	Describe parts of the composites manufacturing process.
Failure Rules	Describe situations which might induce failure within a composite structure.
Environment Rules	Describe effects upon structures based upon the environment in which used.
Material Rules	Describe material behavior and effects in certain situations.
Loading Rules	Describe the effects of particular loading types.
Life-Cycle Issue Rules	Describe certain life-cycle issues of the laminate.
Geometric Rules	Describe effects based upon the shape of the structure.
Manufacturing/ Tooling Rules	Integrate tooling and manufacturing for a composite structure.
Features Rules	Describe how physical features affect performance.
Lamina Lay-up Rules	Describe effects that result from how a laminate is actually layed-up.

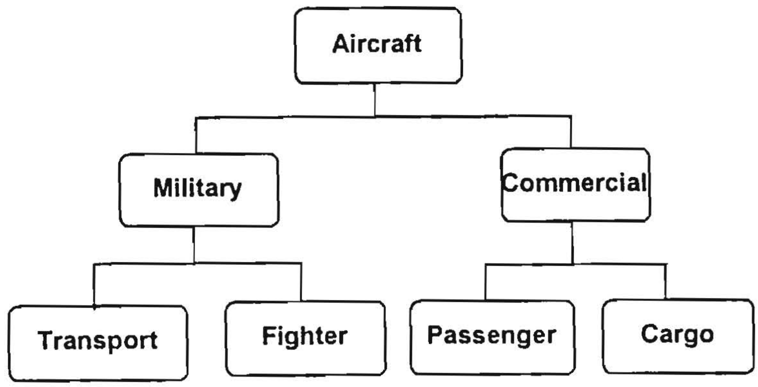


Figure 4.5: Simple Aircraft Class Structure

4.4.3 Procedural Knowledge

Apart from the rules and classes, other forms of knowledge were represented. Part of the acquired knowledge consisted of mostly quantitative data and needed to be expressed in procedural form. This knowledge consisted mainly of the laminate synthesis procedures (i.e., the quantitative method which uses the design load requirements, and material properties in order to produce a first cut at the panel ply arrangement). Equation 3.1 shows an example of the acquired procedural knowledge. The remaining procedural knowledge used in the composites design advisory system is shown in appendix G.

4.4.4 Factual Knowledge

Much of the acquired knowledge was represented as factual knowledge. Sometimes this knowledge is termed working data. Rules often use the factual knowledge in order to draw inference upon the current problem being solved. Values of factual knowledge often change over time. For example, the availability of a certain material or status of a design can be represented as factual knowledge.

4.5 A Knowledge Acquisition And Representation Example

A brief example of the process described above is as shown below. This example represents actual knowledge used within this research.

a) Question to the expert:

"Does moisture have an effect upon composite structures"?

b) Response from expert written in journal or (Raw Knowledge):

"Moisture affects all plastic-based composites. Thermoplastics pick up less than thermosets. 3% to 5% of weight. For BMI's, approximately 1% of weight is moisture. Moisture does not go into plastic as free moisture. Weight gain is a problem. The composite swells a little. Hasn't created any serious problems. Worry about when doing a bonded

repair. Then you have to dry out surface for bonded repair. Moisture does affect the properties. Approximately 5% to 10% or even 40% to 50% @ higher temps; e.g. average epoxy system at 180 degrees wet gets 15% to 20% reduction in matrix dominated properties (compression and shear). Moisture makes it a little softer."

c) The knowledge was grouped under "Environment Knowledge" within the journal.

d) A rule created from the knowledge is as follows:

"*(Antecedent)*

If using a thermoplastic material

(Consequent)

Then expect to pick up 0.3% to 0.5% of the structures weight in moisture. Expect a 5.0% to 10.0% reduction in material properties."

e) A *class* created from such knowledge would include one for materials. Where the material would be structured into different types (e.g. thermoplastic or thermoset). Each instance of a type would have attributes such as weight, and properties (e.g. yield strength, modulus).

f) *Factual* knowledge would include information such as which materials are actually in stock, and the type of environment in which the structure would be used.

This knowledge acquisition process is necessary in the development of a design advisory system for flat composite panels using knowledge-based and case-based reasoning.

4.6 Chapter Summary

Within this chapter has been described a process for acquiring knowledge for use in understanding the composites life-cycle and for building the design advisory system. The chapter describes how the knowledge was gathered from industry experts, and organized for later use. The following chapter discusses knowledge in the form of historical design cases and their relationship to this work.

Chapter V

CASE-BASED REASONING

Chapter 1 discussed the frequent reference to and use of previous similar designs when designing and manufacturing composites structures. Also, chapter 1 discussed the reasons that case based reasoning was the best candidate to capture and emulate this part of the design process. This chapter is devoted to defining the role of case-based reasoning within this work. This work is not meant to explicitly define nor to alter the functionality of Case-Based Reasoning; only to use it and prove its worth in suggesting a problem solving strategy when cooperatively used with Knowledge-Based Reasoning. An in-depth and complete discussion of Case-Based Reasoning can be found in Kolodner (1993). Below is a discussion of case-based reasoning and a description of how the cases for this work were acquired, structured, indexed, and used.

5.1 What is Case-Based Reasoning?

In brief, Case-Based Reasoning (CBR) is used everyday by people in day-to-day situations. One often faces conditions where problems arise and decisions have to be made. Many of these problems and decisions have been faced before. One remembers mistakes from previous occasions and avoids them in later similar situations. Also, one may borrow solutions from previous similar cases. This is a basic tenant of Case-Based Reasoning. Kolodner (1993) states that "*In case-based reasoning, a reasoner remembers previous situations similar to the current one and uses them to help solve the new problem ... remembered cases are used to suggest a means of solving the new problem, to suggest a means of adapting a solution that doesn't quite fit, to warn of possible failures, and to interpret a situation*".

Case-Based Reasoning is a way of adapting old solutions to meet new demands. In Case-Based Reasoning old experiences stored in memory are assigned indexes so that they can be recalled under later appropriate circumstances. When old experiences do not completely match current problem situations, adaptation may be performed to compensate for the differences between an old situation and a new one. In chapter 1 was introduced the core components of most case-based reasoning systems.

1)a library of cases,

2)a vocabulary and indexing scheme,

3) a ranking and retrieval algorithm, and

4) a strategy for case adaptation.

Below is a discussion of each component and how this work makes use of them to develop an architecture for conceptual design of composite structures.

5.1.1 What Is A Case?

Kolodner (1993) states that "*A case is a contextualized piece of knowledge representing an experience that teaches a lesson fundamental to achieving the goals of the reasoner.*" Cases represent specific knowledge tied to specific situations. Cases represent knowledge at an operational level. They make explicit how a task was carried out or how a piece of knowledge was applied or what particular strategies for accomplishing a goal were used. Cases can come in many different shapes and sizes, covering large or small time slices, and associating solutions with problems, and outcomes with situations. Cases worthy of recording are cases that teach a useful lesson. Useful lessons are those that have the potential to help a reasoner achieve a goal or set of goals more easily in the future or that warn about the possibility of a failure or point out an unforeseen problem. The case shown in table 5.1 depicts the types of cases extracted from experts and published text for use within this work. The case in table 5.1, however, is unstructured and may seem useless, yet, it has all of the components needed for a good case. Further below is a discussion of how this case is made useful in the composites case-based reasoning environment.

Table 5.1: Boeing 727 Elevator Sample Design Case
Boeing 727 Elevator Results: BRN9834j89 Panel Material Form: Nomex honeycomb sandwich panel Number of Ribs: 4 Rib material: Honeycomb stabilized webs Spars: Solid laminates Panel skin: graphite fabric at 45 degrees and unidirectional tape at 90 degrees on outer layer of face sheet for smooth and nonporous surface. Inner face sheet: Outer layer is fabric Weight of metal elevator: 85lbs Maximum target composite elevator weight: 75 lbs Final composite weight: 60lbs Porosity and smoothness issues resolved.

5.1.1.1 Component Parts of Cases

There are three major parts to any case, though every case may not contain all of these components.

1) Problem/situation description: The state of the world at the time the case was happening and, what problem needed solving at that time. There are three major components of a problem description:

a) Goals to be achieved in solving a problem.

The goals in a problem description describe the aims of the actor in the situation.

b) Constraints.

Constraints are the conditions put upon the goals.

c) Features of the problem situation and relationships between its parts.

Features of the problem situation holds any other descriptive information about the situation relevant to achieving the situations goals.

2) Solution: The solution to the problem specified in the problem description, and/or the reaction to its situation.

3) Outcome: The resulting state of the world when the solution was carried out.

Table 5.2 shows how the case in table 5.1 is structured according to the case components discussed above.

5.1.2 What Are Indexes?

Indexing is the process of assigning labels to cases when they are entered into a case library so that they can be retrieved at appropriate times. These labels tell under what circumstances the case might have a lesson to teach. Indexing has to anticipate the vocabulary a retriever might use. Indexing has to be performed by concepts that are normally used to describe the items being indexed, whether they are surface features or something more abstract. Indexing has to anticipate the circumstances in which a retriever is likely to want to retrieve something (i.e., the task context in which it will be retrieved) and the descriptors the retriever is likely

Table 5.2: Boeing 727 Elevator Sample Design Case: Case Components	
Problem Situation	
Description The elevators on the Boeing 727 need to be designed such that they are constructed of non porous, smooth and light weight material. The maximum weight of the composite elevator must not exceed 75 lbs.	*Goals:* Design composite elevator. Minimize porosity. Smoothness. Reduce weight. *Constraints:* Maximum weight of 75lbs *Features:* Metal equivalent weight of 85 lbs.
Solution Construct the elevators out of Nomex honeycomb sandwich panels with graphite epoxy face sheets for surface panels and four ribs. The ribs are constructed of honeycomb stabilized webs, and the spars are solid laminates. The skin panel facesheets have a layer of graphite fabric oriented at 45 degrees and a single layer of unidirectional tape at 90 degrees. The tape is used as the outer layer of the exterior facesheet to provide a smooth, nonporous surface. The outer layer of the inner facesheet is fabric.	
Outcome Overall weight savings of 29%, and a 25.6% structural savings.	

to have available to describe the item to be retrieved. Table 5.3 shows the indexes and dimensions that are used for the sample case of tables 5.1 and 5.2.

Table 5.3: Dimensions and Indexes For Boeing 727 Elevator Sample Design Case	
Dimensions	*Indexes*
Material Form	Sandwich construction.
Life-cycle Issues	Weight savings, fiber breakout, and porosity.
Surface Attributes	Smoothness.
Part Type	Elevators.

5.1.3 Case Retrieval

There are two important components to case retrieval, matching and ranking of cases, and retrieval algorithms. Retrieval algorithms direct search to appropriate places in memory, accessing cases with some potential to be useful, however the matching and ranking heuristics choose useful cases from that selection. The process of choosing the most useful cases from a case library begins while searching for partially-matching cases when search processes ask matching functions to compute the degree of match along certain indexing dimensions. Based on the series of dimensional matches, search functions collect a set of cases that partially match the new situation. After this set has been collected, a more comprehensive evaluation of degree of match is done, this time taking into account the importance of match along each dimension. This is referred to as ranking.

This work was accomplished with the aid of Design-MUSE, Domeshek and Kolodner(1993), which is a case-based design tool for building case-based reasoning systems. Design-Muse has built into it matching and ranking and case retrieval algorithms, which this work took full advantage of. This work did not create or modify any of these algorithms but used what was built into Design-MUSE. Therefore, a more detailed discussion on case retrieval can be found in Kolodner (1993) and for Design-MUSE in Domeshek and Kolodner (1993).

5.1.4 Case Adaptation

Usually there is no solution that fits perfectly the new problem situation and must be adapted to be made applicable. In adaptation, one manipulates a solution that isn't exact for the current problem. Adaptation may be as simple as substituting one component of a solution for another or as complex as modifying the overall structure of a solution.

For example, a wing is designed for a military transport aircraft and the goals are to make it lighter than its metallic counterpart, yet just as strong. A case-based reasoning system retrieves a similar case, the Boeing 727 elevator sample design case as shown in figure 5.2. However, for the new problem situation porosity and smoothness are not an issue. The designer, therefore, uses the same approach as that of the Boeing 727. The designer chooses to apply composites to the elevator components but eliminates the use of a single layer of unidirectional tape on the outer surface. This type of adaptation is termed structure modification.

In adaptation, the whole structure of a solution can be adapted or some piece of the solution can be adapted without changing the overall solution structure. Adaptation can take several forms: something new might be inserted into the old solution, something might be deleted from it, some item might be substituted for another, or some part of the old solution might be transformed. This work does not currently employ adaptation techniques but should be implemented in future research efforts. Kolodner (1993) discusses in detail the elements, types, and uses of adaptation.

5.2 Composites Design And The Role Of Case-Based Reasoning

Composite materials have been around for some time. However, only within the past few years have composite materials been used widely in our commercial and industrial society. Their use has been mostly on military aircraft. The domain itself however, is still evolving due to its own complexity, diversity, and efforts to apply it to different domains. The current rules therefore do not cover the entire domain characteristics, and designers therefore refer to previous similar designs to help formulate a solution to a current problem. Many of these previous designs are in the form of notes, sketches from a designer's journal, technical reports and publications, or memorization of specific solutions and outcomes related to a specific past design.

The design of composite structures is therefore a prime subject for Case-Based Reasoning. Case-Based Reasoning applied to the domain of composites design:

1) Gives structure and organization to previous designs;
2) Provides an indexing mechanism for each case;
3) Automates the retrieval process, thereby reducing search and consequently design time; and
4) Allows storage of newly created design cases for future reference.

5.3 A Case-Based Reasoning Architecture For Composites Design

Below is a discussion of acquiring and structuring composites design cases for use in a Case-Based Reasoning System.

5.3.1 Indexing Vocabulary

Table 5.4 presents the indexing dimensions and corresponding vocabulary developed in building a Case-Based Reasoning System for composites design. The vocabulary and indexing dimensions shown below were created using a combination of sources and techniques. Kolodner (1993) (1994) provided much of the protocol and technique necessary to build the indexing dimensions and vocabulary. Interviews with the experts, Niu (1988)(1992), and the researchers industrial experience provided the actual data necessary to create the indexing dimensions and populate them with the vocabulary. Much of the vocabulary consist of attributes which describe characteristics of the entire composite panel life-cycle. Therefore, interviews with industry experts, literature research, and organizing factual knowledge for the knowledge base facilitated the development of the indexing dimensions and vocabulary.

5.3.2 Case Acquisition

The cases were all extracted from published works in the area of composites applied to aircraft design. The cases were extracted from published textbooks such as Niu (1988)(1992), technical reports, professional technical publications, and stories from designers. Most of the published sources provided sections which gave details for and discussed

Table 5.4: Vocabulary And Indexing Dimensions for composites Design	
Indexing Dimensions	*Vocabulary*
Part Type	beam, skin, bulkhead, compression panel, control surface
Operational Temp	high, medium, low
Operational Load	high, medium, low
Loading	Part Category: (primary, secondary), Static Directional: (torsional, axial, bi-axial, shear, bending, buckling, impact) Spatial: span-wise, asymmetric Dynamic: acoustic, torsional, axial, bi-axial, shear, bending Fatigue: torsional, axial, bi-axial, shear, bending
Material	Graphite/Epoxy, Boron/Epoxy, Kevlar, Aluminum, Titanium, Berylium, carbon epoxy
Material Form	fabric, tape, honeycomb core, commingled fabric, fiber tows
Location	fuselage, wing, tail, nose, landing gear, aileron, flap, rudder, main body, under body, elevator
Surface Attributes	smoothness, porosity
Material Characteristics	thermoset, thermoplastic, water resistance, water sensitivity, corrosion resistance, toughness, damage tolerance, color, material incompatibility, dissimilar materials
Operational Environment	Temperature Range: Weather: rain, snow, sun, hail, sand, moisture, lightning Chemicals: corrosive, acidic, benign
Laminate Characteristics	thick, thin, flat, contoured, quasi-isotropic, non-quasi-isotropic
Part Features	fasteners, joggles, stiffeners, notches, inserts
Manufacturing Processes	hand layup, fiber placement, filament winding, tape layup, automated, manual
Tooling	metallic, non-metallic
Cure Process	pressure vessel, pultrusion, oven, autoclave, resin injection molding
Testing	non-destructive testing
Inspection	coordinate measuring machine, visual, laser
Failure	longitudinal tension, longitudinal compression, transverse tension, transverse compression, in-plane shear, delamination, sub-laminate buckling, interlaminar shear, interlaminar tension

previous design cases, but had no structure. A journal was used to facilitate the organization of each case (see section 5.4). The methodology used for finding and structuring these cases was adopted from Kolodner (1993). Each case was analyzed to be certain it was in accord with the scope of this work and that there was enough information to potentially teach a lesson when retrieved at the appropriate time. Subsequently each applicable case was then separated into three parts - the problem, response, and story - as outlined below.

5.4 Structuring The Knowledge/And Building Cases

The cases collected for this work were structured using the methodology as outlined in the Domeshek and Kolodner(1994). Each case was partitioned into three different sections:

1) Case Problem,
2) Case Response, and
3) Case Story

The cases were represented as stories with linked problems and responses. The stories are very detailed individual descriptions of how a particular composite structure was designed, what materials and manufacturing processes were used, and whether its performance was successful or not and why. Stories describe cases as a designer may illustrate them. Stories give a description of why the design was needed, what approach was taken, and any unexpected results. The case problems indicate a general problem situation, e.g., *Problem: Design A Vertical Fin With Weight Reduced By 25%*. The case response represents an approach to solving the problem, but not at a detailed level, e.g., *Use Fiber Reinforced Composite Material With HoneyComb Construction*. Each story is linked to at least one problem and response, but may be linked to many more. Multiple links - story to problem, story to response, and problem to response - are allowed when one is related to the other and can provide beneficial information to the case. Each case was indexed using the vocabulary shown above so that it may be retrieved at the appropriate time. Table 5.5 shows the Boeing 727 elevator sample design case and how it was structured for use within the Design-MUSE Case Based Reasoning System. Table 5.6 shows the Boeing 727 elevator sample design as a complete and useful case with lessons to be learned. The remaining cases are implemented within the Composites Design Advisory System (ComDAS). Appendix H is a listing of the composites design cases collected for this work.

Table 5.5: Problems, Responses, and Stories For The Boeing 727 Elevator Sample Design Case

Problem:	Design the elevators of an aircraft wing such that they are non-porus and light weight.
Response:	Construct the elevators out of composite material to achieve strength and weight reduction. Minimize porosity through surface material characteristics.
Stories:	On the Boeing 727 elevators were constructed using Nomex honeycomb sandwich panels with graphite epoxy face sheets for surface panels and four ribs. The ribs are constructed of honeycomb stabilized webs, and the spars are solid laminates. The skin panel facesheets have a layer of graphite fabric oriented at 45 degrees and a single layer of unidirectional tape at 90 degrees. The tape is used as the outer layer of the exterior facesheet to provide a smooth, nonporous surface. The outer layer of the inner facesheet is fabric. There resulted an overall weight savings of 29%, and a 25.6% structural savings. The lessons learned were that 1) using sandwich covers allows the elimination of most needed ribs, 2) fabric is more resistant to fiber breakout during drilling processes, and 3) tape can be used where smooth and nonporous surfaces are necessary.

Table 5.6: Boeing 727 Elevator Sample Design Case As A Useful Design Case	
Problem Situation:	The elevators on the Boeing 727 need to be designed such that they are constructed of non porous and light weight material.
Solution:	Construct the elevators out of Nomex honeycomb sandwich panels with graphite epoxy face sheets for surface panels and four ribs. The ribs are constructed of honeycomb stabilized webs, and the spars are solid laminates. The skin panel facesheets have a layer of graphite fabric oriented at 45 degrees and a single layer of unidirectional tape at 90 degrees. The tape is used as the outer layer of the exterior facesheet to provide a smooth, nonporous surface. The outer layer of the inner facesheet is fabric.
Result\Outcome:	Overall weight savings of 29%, and a 25.6% structural savings.
Lessons Learned:	Using sandwich covers allows the elimination of most needed ribs. Fabric is more resistant to fiber breakout during drilling processes. Tape can be used where smooth and nonporous surfaces are necessary.
Indexes:	Sandwich construction Weight savings Fiber Breakout Porosity Smoothness Elevators

5.5 Chapter Summary

This chapter gives a brief review of case-based reasoning. Also, a discussion of the way that cases were acquired, structured, and indexed is included. The chapter explains the way that cases are partitioned into *problems*, *responses*, and *stories*. Chapter 6 details a method for using cooperative knowledge-based and case-based reasoning as design aid tools. Chapter seven details how these structured cases were implemented into the Design-MUSE(1994) Case-Based Reasoning shell and combined with a knowledge-based system for the design of flat composite panel structures.

CHAPTER VI

A METHOD FOR COOPERATIVE KNOWLEDGE-BASED AND CASE-BASED REASONING

Chapters 4 and 5 have outlined the knowledge-based and case-based reasoning schemes used within this work. Each system performs specific tasks to aid in the design of composite structures. While each of these systems individually can aid a designer in designing a composite structure, it would be inefficient to use them in that manner as described in chapter 1. Therefore, a method which enables the knowledge base and the case base to be integrated and work cooperatively is needed. This chapter describes how that method was developed and implemented within this work.

Using cooperative knowledge-based and case-based reasoning in problem solving environments is not specific to flat panel composites. The concept is germane to almost every domain that has a history and structure relative to solving related problems; yet there are no strategies of using them cooperatively. This research suggests a method for problem solving environments using cooperative knowledge-based and case-based reasoning. Below is a step by step description of the method. Figure 6.1 shows the architecture for the knowledge-based and case-based reasoning method while figure 6.2 shows the steps needed to develop a cooperative knowledge-based and case-based reasoning design advisory system. The architecture begins with the designer obtaining all specifications, constraints and other pertinent information about the design problem. This knowledge helps to form the first Design Characteristic State (DCS) using attribute-value pairs akin to those of the knowledge base factual data and case base indexing dimensions and vocabulary. The knowledge base queries the user for information, (factual data), necessary to trigger the rules. The knowledge base then displays any recommendations that were generated. Using the DCS developed from the specifications and constraints, the case base search index is populated and a search of cases initiated. The user can then review any of the cases which were retrieved by the case base. If a new search using arts of the first DCS is desired, the user can modify the existing DCS by either adding, or taking away specifications based upon output from the case base and knowledge base. The decision to implement any of the ideas, warnings, or solutions is the responsibility of the designer.

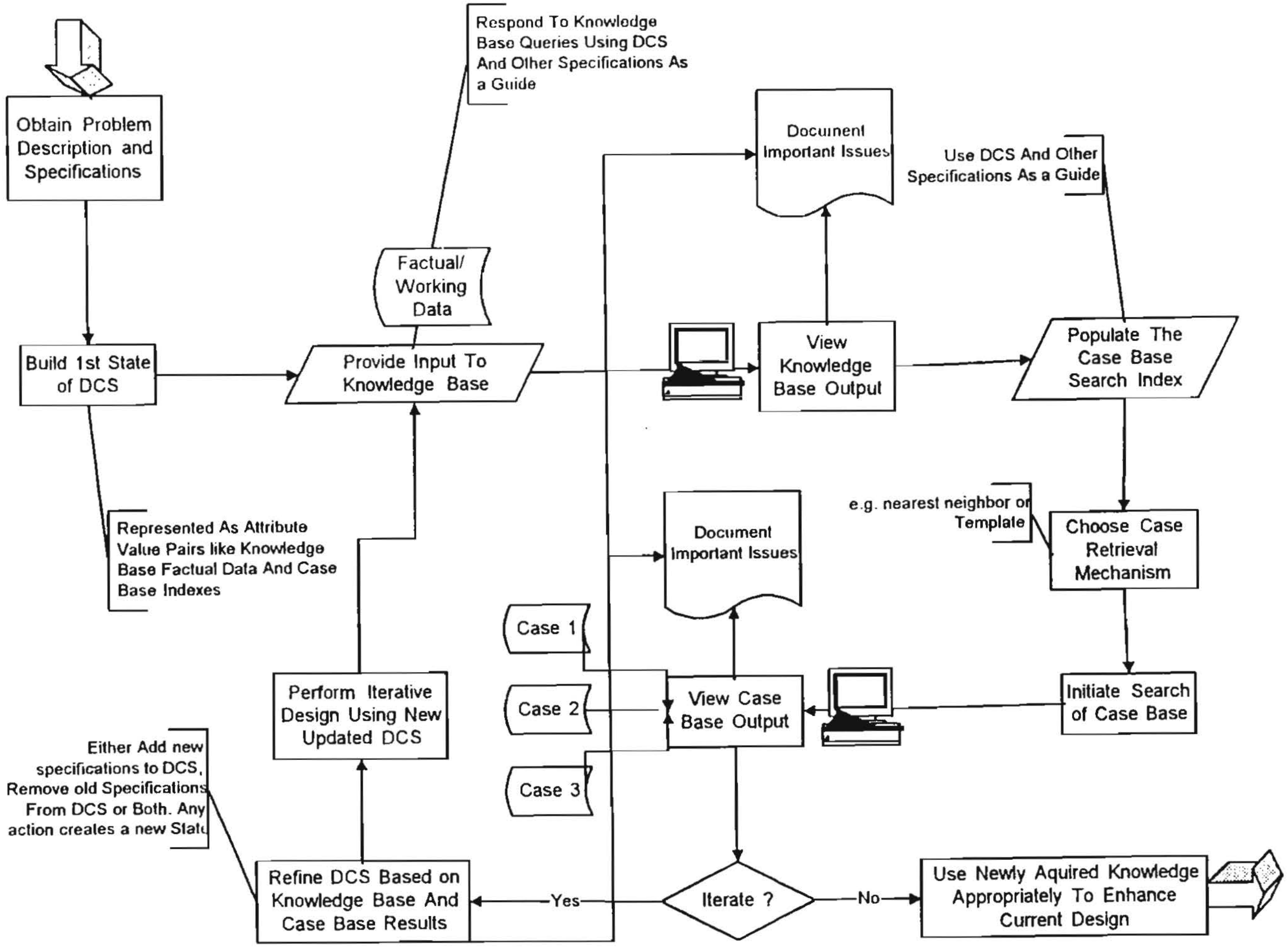


Figure 6.1: A Process Model For The Knowledge-Based And Case-Based Reasoning Method For Design

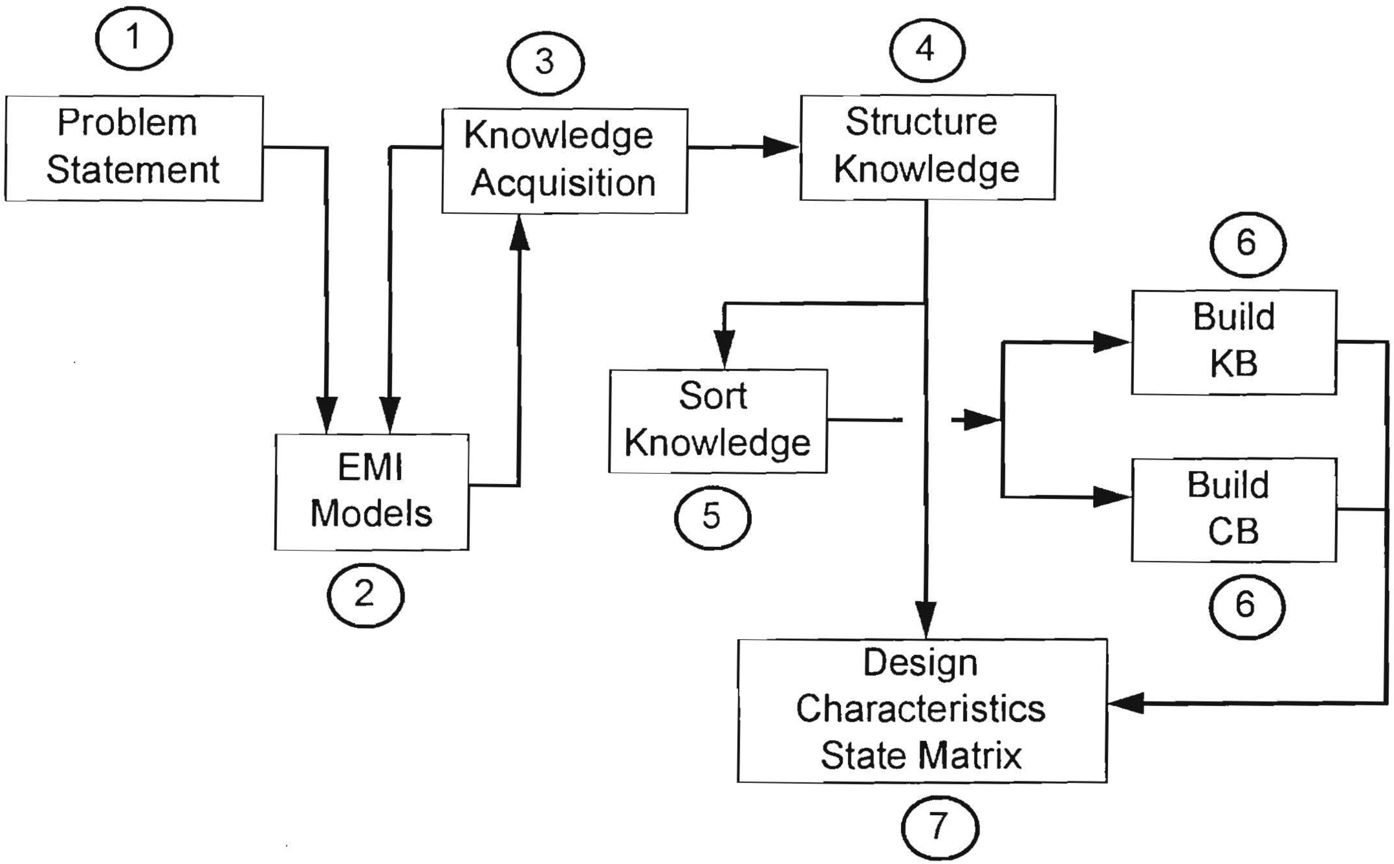


Figure 6.2: A Method For Knowledge-Based And Case-Based Reasoning Design Advisory Systems

6.1 Understanding The Domain

In order to use the method of cooperative knowledge-based and case-based reasoning, there must to be an understanding of the domain targeted. Depending upon the application, this understanding may relate to only a portion of a larger domain. For example, understanding the domain targeted means knowing the sub-phases into which the domain is broken, the interaction of those sub-phases with each other, the decisions that are made and when, and the actions that take place as a result of earlier decisions.

6.1.1 Modeling The Selected Domain

Modeling helps one to understand the processes involved in an operation and the decisions that are made during those processes. In using Knowledge-Based and Case-Based Reasoning, it is important that a model of the domain process be built. Figures 3.1 and 3.2 represent the EMI models built for this work. Modeling the process will give insight as to where empirical rules and procedural processes are used, as well as where reference to previous design cases take place. Consequently, process information used with the rules and cases is known. Therefore, to acquire this knowledge, the model must show the different phases of the process, and the energy, material and information flows between and within the different phases.

6.2 Acquiring Knowledge

In order to use cooperative Knowledge-Based and Case-Based Reasoning in problem solving, knowledge must be acquired. This knowledge is the domain knowledge which experts use to make decisions and solve problems. The knowledge is in the form of rules, procedures, and previous design cases, although this knowledge is typically unstructured. A formal knowledge acquisition procedure must be used to acquire the rules and the cases. However, there are natural similarities between the structuring of the Knowledge Base's data and the Case-Based Reasoning data. Therefore the time required to perform knowledge acquisition and structuring for rules and cases is shortened. The time used during the Knowledge Base knowledge acquisition process can be used for the Case Based Reasoning process as well. This concept is explained in further detail below.

The method described here will assume that the knowledge acquisition process is through interviews with experts and extraction from published texts and reports. The interview protocol, Walters and Nielsen (1988), and Parsaye and Chignell (1988), should be as follows:

a) Interviewer selects domain experts, text and reports from which to acquire knowledge.

b) Interviewer plans types of questions, interview dates and times, with experts.

c) Interviewer asks the expert questions based upon the type and depth of knowledge desired. (The depth of questions and the order in which they are given is left to the interviewer, as each may have different goals to accomplish. For example, within this work the questions to the expert began with the conceptual design phase and progressed through the manufacture phase - a natural life-cycle chronology. However, questions concerning the manufacturing phase were posed to the expert during certain conceptual design phase questions.)

d) The expert answers questions asked by the interviewer. These answers may come in different forms. For example, one expert may choose to solve a related problem in writing in order to illustrate his point, while another may choose to give only a verbal response.

e) The interviewer records the expert's responses to the questions. The interviewer has several media to choose from for recording responses during the interview, journals, tape recorders, video recorders, computers, etc.

During the interviews, the expert can be asked to provide accounts of previous design cases. These cases can be given to the interviewer through the expert's personal journal or by verbal communication. During the knowledge acquisition process, experts are usually asked to solve a few problems. These problems could be previous design cases. In addition to the interviewer's acquiring knowledge from the expert's thought and decision process, he acquires previous design cases as well.

6.2.1 Knowledge-Based Factual Data and Case-Based Indexing Dimensions And Vocabulary

During the entire interview process, the expert will be using terminology related to the domain. This is an opportune time for the interviewer to begin creating the domain dimensions and corresponding vocabulary which will be used to index the previous design cases. This terminology will relate very closely to the working knowledge of the knowledge base. The case base dimensions are to knowledge base facts as case base vocabularies are to knowledge base fact values. Table 6.1 shows the requirements of the knowledge base factual data and case base indexing dimensions and vocabulary attribute-value pairs. The entire attribute-value pair set for each the knowledge base and case base is not fully represented in the table as it is used to only to illustrate their similarities. Table 6.1 was generated using the models described in chapter 3, the working data of the knowledge base described in chapter

Table 6.1: Requirements of Knowledge-Based Factual Data and Case-Based Indexing Dimensions And Vocabulary Attribute Value Pairs

Potential Knowledge Base Factual Data Value	***Knowledge Base Factual Data Attributes***		***Case-Based Indexing Dimensions***	***Case-Baed Vocabulary***
beam, skin, bulkhead, compression panel, control surface	Functionality	<>	Part Type	beam, skin, bulkhead, compression panel, control surface
			Operational Temp	high, medium, low
			Operational Load	high, medium, low
5 x 10E6	axial_load shear_load transverse_load shear_stiffness axial_stiffness	<>	Loading	Part Category: (primary, secondary), Static Directional: (torsional, axial, bi-axial, shear, bending, buckling...) Spatial: span-wise, asymmetric Dynamic: acoustic, torsional, axial... Fatigue: torsional, axial, bi-axial...
Graphite/Epoxy, Boron/Epoxy, Kevlar, Aluminum, Titanium, Berylium...	Material	<>	Material	Graphite/Epoxy, Boron/Epoxy, Kevlar, Aluminum, Titanium, Berylium...
simple, complex	Shape			
fabric, tape, honeycomb core, commingled fabric, fiber tows	Material_Form	<>	Material Form	fabric, tape, honeycomb core, commingled fabric, fiber tows
fuselage, wing, tail, nose, landing gear, aileron, flap, rudder, main body, under body, elevator	Position	<>	Location	fuselage, wing, tail, nose, landing gear, aileron, flap, rudder, main body, under body, elevator
$[45,90,90,0]_s$	Stacking			
3.5 hours	Production_time			
4	Number pf productic parts		Surface Attributes	smoothnes, porosity
thermoset, thermoplastic,	Type-of_plastic	<>	Material Characteristics	thermoset, thermoplastic, water resistance, water sensitivity, corrosion resistance, toughness, damage tolerance, color, material incompatibility...
rain, snow, sun, hail, sand, moisture, lightning	Environment	<>	Operational Environment	Temperature Range: Weather: rain, snow, sun, hail, sand, moisture, lightning Chemicals: corrosive, acidic, benign
			Laminate Characteristics	thick, thin, flat, contoured, quasi-isotropic, non-quasi-isotropic
fasteners, joggles, stiffeners, notches, inserts	Features	<>	Part Features	fasteners, joggles, stiffeners, notches, inserts
hand layup, fiber placement, filament winding, tape layup, automated, manual	Equip_name	<>	Manufacturing Processes	hand layup, fiber placement, filament winding, tape layup, automated, manual
pressure vessel, pultrusion, oven, autoclave, resin injection molding	Method	<>	Cure Process	pressure vessel, pultrusion, oven, autoclave, resin injection molding
CMM, visual, laser	Inspection	<>	Inspection	CMM, visual, laser
			Failure	longitudinal compression/tension, interlaminar shear...
		<>	Testing	non-destructive testing

4, and the indexing dimensions of the case base as described in chapter 5. The knowledge base factual data attributes tend to outnumber the indexing dimensions of the case base. The reasoning behind this is that the knowledge base sometimes reasons about knowledge at a lower level of granularity than that of the case base, see tables 7.1 and 7.2 also. Hence, additional descriptors are needed for the knowledge base to define these extra details. For example, consider this piece of code from the knowledge base part of the prototype system developed under this research.

```
(printout t "Please input the axial load")
(send [current_design] put-axial_load (read)) crlf
(printout t "Please input the shear load")
(send [current_design] put-axial_load (read)) crlf
```

Here the knowledge base is asking the user to input values for the axial load and shear loads that the composite structure will most likely experience so that a rough estimate of the laminate layup configuration may be calculated. The corresponding factual data attributes are *axial_load* and *shear_load*. The case base, however, would probably not need a dimension which provides numeric values for each type of applied load because it is highly unlikely that a designer would want to enter a search index into the case base along this dimension. The procedures in the knowledge base are very good at performing these calculations. The case base contents are better at providing information related to novel techniques rather than numeric values used in procedural calculations. However, it is an important and necessary part of the knowledge base structure. A useful indexing dimension for the case base along the lines of loading would, however, be *loading-type*. With a possible value of *axial* or *shear*.

As another example of knowledge base factual data and case base indexing vocabulary similarities, during the early stages of design one often tries to determine the type of material that will be used for the composite structure. The type of material used can affect other aspects of the product's life-cycle. Therefore, here is an area where rules, as discussed in chapter 4, can be applied during the design process. An example rule would be:

IF the fiber-reinforced composite structure has to be damage tolerant
THEN use +/- 45 fabric as the outer plies.

The working knowledge or factual data, as discussed in chapter 4, used within this rule would include the *material_form* used. Which in this case is recommended to be *fabric*. The indexing dimensions described in chapter 5 include a section for *material_form* as well. The vocabulary describing the material form indexing dimension includes attributes such as fabric, tape, and honeycomb. These are all descriptions of types of fabric forms and coincide directly with the factual data of the knowledge base.

Appropriate analogies are that case base indexing dimensions are to knowledge base facts, as case base vocabularies are tc knowledge base factual data values. Consequently, the knowledge base working data and case base indexing vocabulary and dimensions can be developed simultaneously. This makes structuring the knowledge of KB and CB systems much easier. During the knowledge conceptualization phase is a good time to refine the vocabulary. See figure 6.3.

6.3 Structuring Knowledge

Knowledge must be structured according to how it supports reasoning needed to be done. If the knowledge is not structured correctly it will be useless to the knowledge base and the case base. Within this work several forms of knowledge were extracted during the knowledge acquisition process. The acquired knowledge warranted that it be structured into different forms according to its use. As discussed in chapters 4 and 5 and section 6.2, those forms included class structures, rules or If-Then constructs,

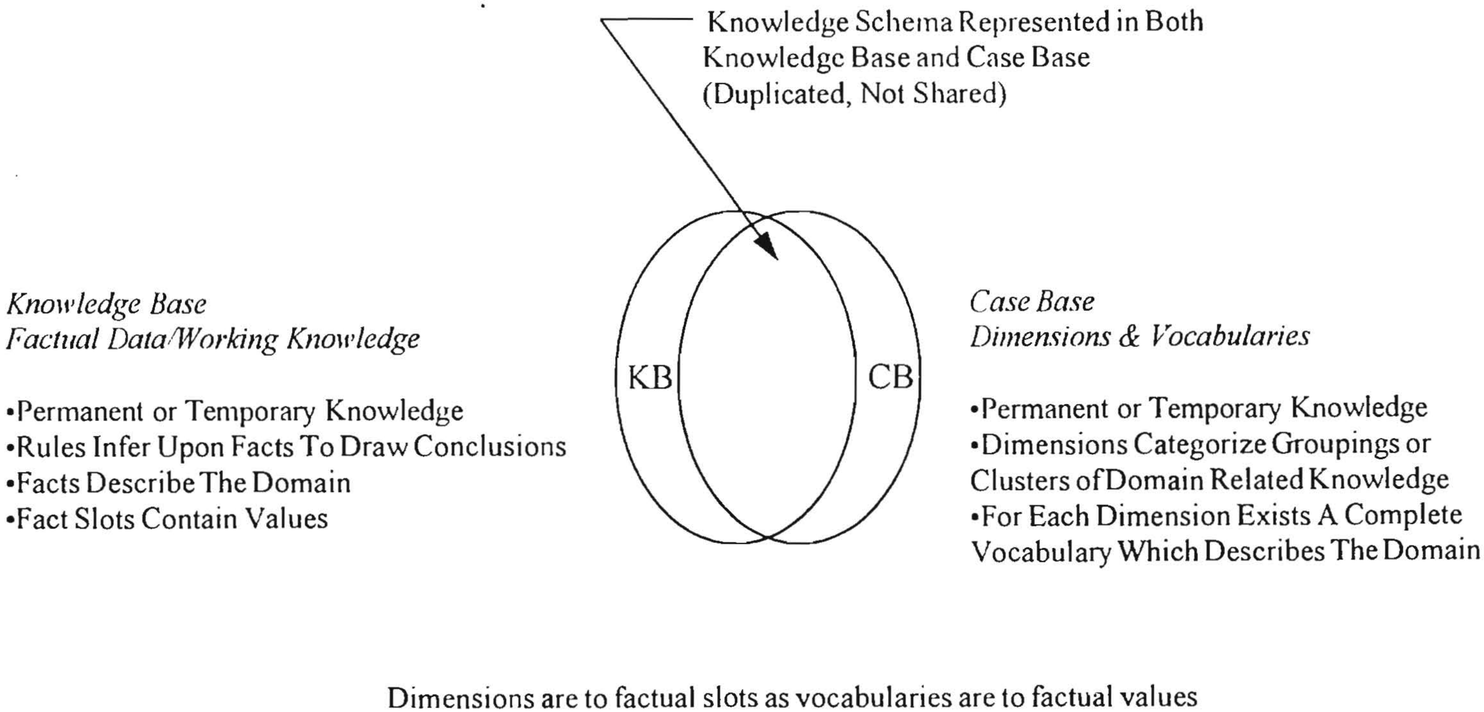


Figure 6.3: Dual Knowledge Acquisition For The Knowledge Base And Case Base

procedural knowledge, dimensions and vocabularies, factual data, free form-text, indexes, problems, stories, and responses. Some of the knowledge overlaps between forms, and knowledge within one form may be used by another. It is left to the knowledge engineer to determine which extracted knowledge is structured into which form.

6.4 Providing A Link Between The Knowledge Base And The Case Base

The knowledge base and case base must use the same working knowledge at discrete points in time. Otherwise, incorrect information may be used by either and therefore an incorrect solution may result. The Design Characteristic State (DCS) addresses the issue of ensuring that the data is consistent between the knowledge base and the case base. The DCS is described in further detail below.

6.4.1 Design Characteristic State

The Design Characteristic State (DCS) is an array of knowledge which documents the design specifications, requirements, constraints, and potential problem areas, see figure 6.4(a). The DCS encapsulates the common knowledge represented by the KB and the CB through their working data and indexing vocabulary respectively, see chapters 4 and 5, and section 6.2. The DCS describes the world at a discrete point in time. Since much of design information is temporal, a DCS is dynamic and its contents may change several times during the design and manufacturing processes. Since the DCS uses the working data and indexing vocabulary from the knowledge base and case base, only one repository of data is needed for both systems. The DCS is needed to keep the data that describes the design consistent across the knowledge base and the case base. If the information which describes the design is not the same for input to the knowledge base and case base, then erroneous output may result.

6.4.1.1 Knowledge Representation Within The DCS

Section 6.2 discussed how the attribute-value pairs of the factual data of the knowledge base and indexing dimensions and vocabulary of the case base were very similar. The sample elements of figure 6.4(a) represent the knowledge base factual data and case base indexing dimensions and vocabulary. For example, the second element of figure 6.4(a) indicates the material that was chosen for a design. Chapter 4 and, section 6.2 showed how *material is graphite/epoxy* is represented as factual data within the knowledge base. Chapter 5 and, section 6.2 showed how there exists a indexing dimension of *material* with vocabulary of *graphite/epoxy, nomex, kevlar, and bismalemide.* Therefore, the entrant of *material is graphite/epoxy* in figure 6.4(a) can represent data from both the knowledge base and the case base and facilitates consistency of data between the two during a design session.

The DCS therefore, represents the design knowledge in the form of attribute-value pairs resulting from the knowledge base working data and case base indexing vocabulary. In the example shown above, the attribute would be *Material* and the value would be *Graphite/Epoxy*. If there are attribute-value pairs that are not similar between the knowledge base and case base then two elements are added to the DCS. One from the knowledge base and one from the case base. Or it may be an opportunity to expand either the knowledge base working data or the case base indexing dimensions and vocabulary.

The limitation of the DCS is that it currently represents only text-based attribute-value pairs. The DCS cannot presently represent procedural knowledge as documented in chapters three and four. However, a method for representing procedural knowledge in the DCS could possibly be developed. An example of how the DCS might represent procedural knowledge is as follows:

Number_of_45s is $(N_x - F_{45} * T_{45} / T * F_t)$

The attribute would be *Number_of_45s*. This is the number of 45 degree plies used in the laminate. The value $((N_x - F_{45} * T_{45} / T * F_t))$ is a single list of elements which describe the procedure calculating the number of 45 degree plies. The recipient of the value would have to extract the procedure from the list in order to use it. This could potentially be the subject of follow-on research. Another limitation of the DCS is that it is not implemented in software. The DCS is currently implemented on paper by the user and its contents are transferred to the knowledge base and case base manually through their user interfaces.

6.4.1.2 Using The DCS As A Design History Matrix

As a design progresses, some of the original design information may change, such as materials to use, or how to join two components. This design information may also change if the designer elects to perform trade studies on the design configuration, thereby resulting in multiple design iterations. The DCS can be used to document the design specifications, constraints, and problem areas for each trade study or design iteration. This would create an attribute-value based design history tree. The notation of the DCS is therefore S_{ij}; where S stands for state, the first subscript (i) represents the ith design characteristic state generated, and the second subscript (j) represents the jth element of the ith state. Figure 6.4 shows an example of a DCS. Figure 6.4(b) shows a matrix of Design Characteristic States. This situation would result from a design which had more than one iteration during the conceptual design. $S_{1,1-j}$ indicates the first DCS generated and $S_{i,i-j}$ the last. Therefore, the DCS in

S_1

1) Part Function is Access Panel
2) Material is Graphite/Epoxy
3) Layup is $[45,90,-45,0]_S$
4) Cure Method is Autoclave
5) Aircraft is Fighter
6) Issue is High Damage Tolerance
7) Issue is Low Cost
8) Requirement is 30% Weight Reduction
9) Constraint is Thickness < 0.25

(a)

$$\begin{vmatrix} S_{11} & S_{12} & \cdots & S_{1j} \\ S_{21} & S_{22} & \cdots & S_{2j} \\ \vdots & & & \\ S_{i1} & S_{i2} & \cdots & S_{ij} \end{vmatrix}$$

(b)

Figure 6.4: Sample Design Characteristic State

figure 6.4(a) would encompass the entire top row of figure 6.4(b). Subsequent states would follow in chronological order. Within this work only two states were generated for each test problem solved, as the intent was to prove the hypothesis and not conduct an elaborate detailed design of a composite structure.

6.5 Chapter Summary

This chapter describes a method to build a cooperative knowledge-based and case-based reasoning architecture. Included are the steps that were developed and used within this work to build the Composites Design Advisory System. The main tasks discussed are understanding the domain, building models, acquiring and structuring knowledge, and developing the Design Characteristic States. An important fact is that the method is independent of any domain. Chapter 7 discusses the hardware and software related issues and how the Composites Design Advisory System (ComDAS) was built.

CHAPTER VII

PROTOTYPE DESIGN ADVISORY SYSTEM

7.1 ComDAS

A Composites Design Advisory System (ComDAS) was developed during the course of this research work. The purpose of the design advisory tool was to implement the method of using cooperative knowledge-based and case-based reasoning in a computer aided design environment. Therefore the system assists a designer during flat composite panel design. It is not intended to automate completely the design process. Figure 7.1 shows the use of the developed method within the conceptual design process of composite structures. Following is a discussion of the system requirements and implementation details.

7.2 System Components

Several components were needed to create the prototype design advisory system. These components were as follows: a computing platform for development purposes; a knowledge-based system shell to support knowledge base development; a user interface for data entry and feedback; and a case-based reasoning shell to support cb development. Below is a

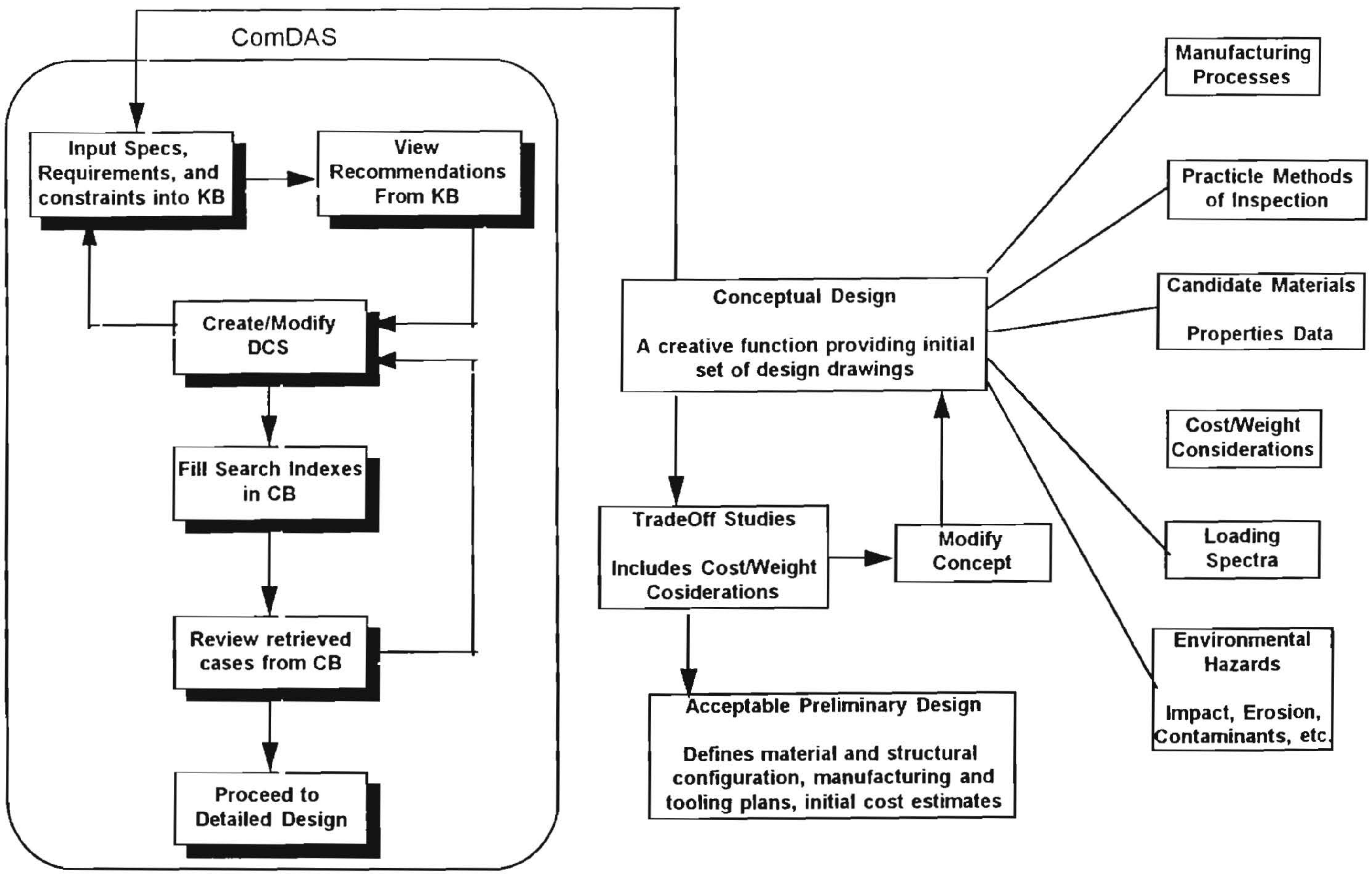


Figure 7.1: A Method of Using Knowledge Based And Case Based Reasoning As A Design Aid During Conceptual Design

discussion of each of these components and how they were developed into the COMposites Design Advisory System (ComDAS).

7.2.1 Platform

A Macintosh Power PC was used as the computing platform for system development. This platform was chosen for several reasons. First, it is a platform that is rapidly finding its way onto the desks of researchers, scientists and engineers. Therefore, compatibility with existing systems is an important consideration. Secondly, the most complete case-based design reasoning shell, (Design MUSE), runs on this platform as well as one of the well known knowledge based system shells (CLIPS). Finally, it is a relatively easy system on which to develop applications.

7.2.2 Rule-Based System

The rule-based system of ComDAS was developed using the CLIPS (C Language Integrated Production System; Version 5.1 for Macintosh) expert system shell (1993). A survey was conducted of knowledge-based system shells. In looking for the knowledge base shell, criteria were as follows:

a) easy implementation of production rules,
b) capable of representing different types of knowledge,
c) relatively easy portability between platforms,

d) product, and application development support, and

e) low cost.

CLIPS was developed by the Software Technology Branch, NASA/Lyndon B. Johnson Space Center. It allows for the creation of production rules, procedural functions, factual knowledge, object-oriented structures, rule verification and a control structure into a working expert/knowledge-based system. Within this research, CLIPS was used as a shell to support KB development. It was not intended to modify any parts of the software or attempt to port it to other platforms.

Chapter 4 discussed the acquisition, manipulation, and representation of the knowledge associated with flat composite panel design and manufacture. That knowledge and its structure were used to build and populate the knowledge-based system. The rules that were constructed in chapter 4 were implemented as rules in the system. The class structures developed in chapter 4 were implemented as object-oriented class structures in the system. The procedural knowledge acquired in chapter 4 was implemented as functions in the system. Appendix E has a complete representation of the acquired knowledge in CLIPS code. CLIPS runs on Macintosh, DOS, VAX VMS, and UNIX platforms.

The rules in the knowledge base were grouped according to functionality, e.g. manufacturing, layup, structural and tooling. The inference mechanism that was implemented was forward chaining. The system begins by asking the user for design specifications and constraints. Table 7.1 shows the initial queries from the knowledge base.

Table 7.1: Initial Query Set From Knowledge Base During Run Time	
1	Input the design name.
2	Input the part name.
3	Input the part functionality, e.g., compression panel.
4	Input the operating environment, e.g., hail or sand.
5	Input the maximum operating temperature.
6	Input the preferred material.
7	Input any mating materials.
8	Input the aircraft type.
9	Input the axial load.
10	Input the transverse load.
11	Input the shear load.
12	Input the axial stiffness.
13	Input the transverse stiffness.
14	Input the shear stiffness.

The queries are presented during every session with the knowledge base. It is possible that some of these queries may not be relevant to the current design. However, the designer can simply enter 0 for numeric values or an empty list for textual values where not applicable to the design. This tends to be a simpler method as opposed to asking the designer if a particular issue is relevant to his design then prompting for the input. After this initial input is given by the user, the knowledge base transforms some of the information into factual data which is used by the rules to infer solutions. Also, the knowledge base performs an initial ply layup calculation. Input does not have to be given to each query. For example, if the designer does not yet know the loading spectra, then the knowledge base will not calculate an initial ply layup. The knowledge base will only use information it is given. After this initial set of queries, the knowledge base allows the user to input issues that are relevant to the design. Table 7.2 lists these additional queries where the user may specify issues related to the design. The queries are not ranked in any order of importance, only the sequence in which they are presented to the user.

The user is allowed to pick those issues that are pertinent to the design problem being solved. Once all information about the current design problem is given, the knowledge base forward chains to a set of design and manufacturing recommendations. The suggestions from the knowledge base are based only upon the information given by the user. Figure 7.2 shows a sample session with the knowledge base. The figure is an actual screen print of the Composites

Table 7.2: Final Set of Queries From Knowledge Base			
Set1	*Laminate Issues*	Set3	*Geometric Issues*
	laminate surface to be smooth on one side		part contains contours
	laminate surface to be smooth on both sides		part has compound contours
	laminate surface to be flat		part contains radii
	lamina adjacent to bonded joint		part contains sharp contour changes
	lamina fiber orientation parallel to direction of loading		close dimensional tolerances on part
	lamina fiber orientation 45 to direction of loading		part has abrupt changes in cross section
Set2	*Requirement Issues*	Set4	*Manufacturing And Tooling Issues*
	part needs to be light		higher temperature needed
	part needs to be stiff		cte of tool different from composite
	fatigue loading		spring-in
	increase stability		rapid heat transfer needed
	free edge effects		residual strains
	poisson ratio effects		built-in strains
	thermal expansion effects		part requires uniform temperature distribution during cure
	high mechanical strength needed		internal residual stress
	low cte needed		tool cte to be compatible with part
	delamination at a joint		part cure temperature is high
	part to be damage tolerant		part requires joining
	part must withstand impact resistance		cocuring is possible
			inspection needed prior to assembly

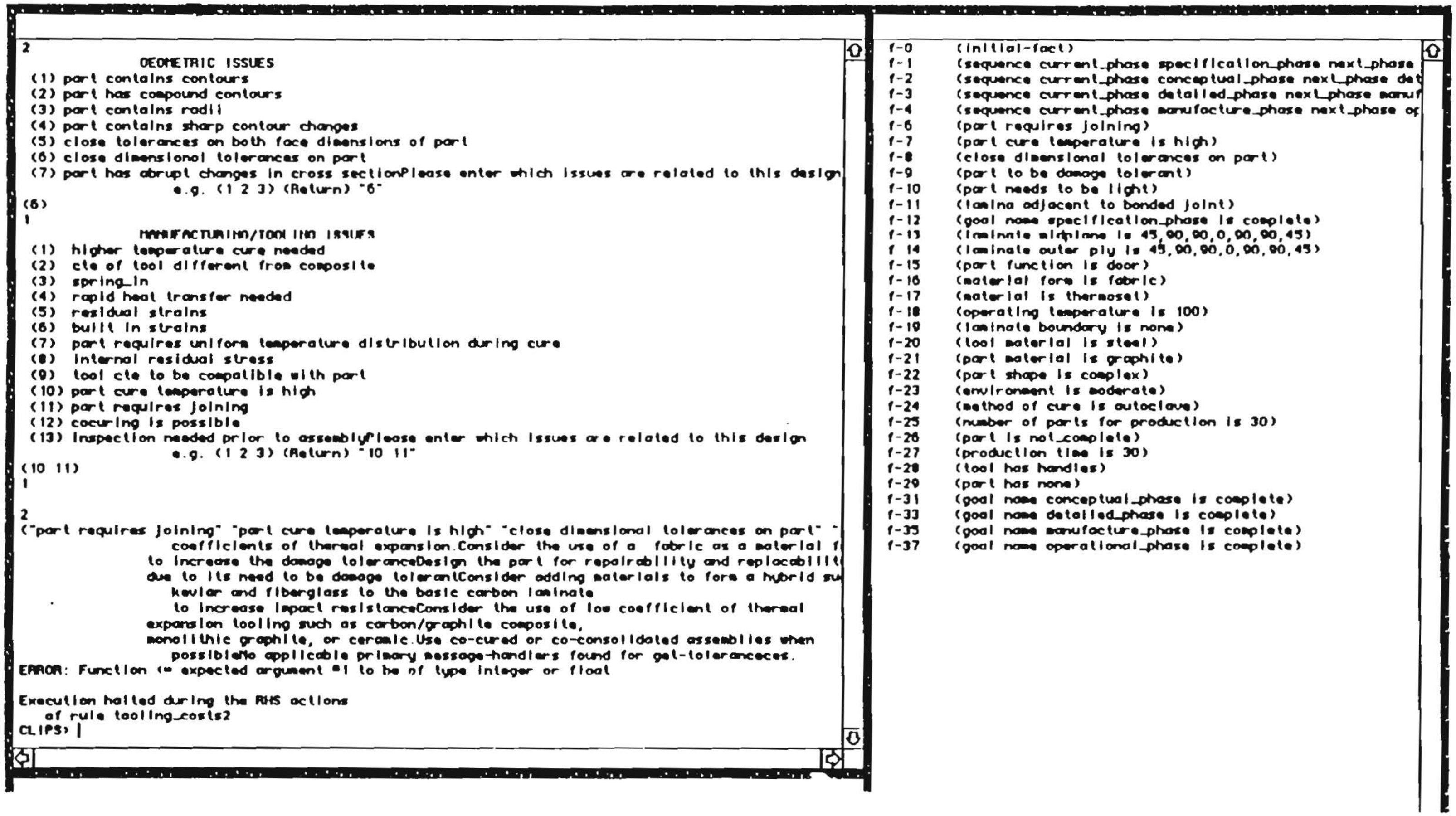


Figure 7.2: A Sample Session With The ComDAS Knowledge Base

Design Advisory System (ComDAS) knowledge base. The left side of the figure shows how the user interacts with the knowledge base during run-time. The user answers queries asked by the system and inputs criteria relevant to the current problem. The lower part of the figure's left side shows the output of the knowledge base and suggestions to the user. The right side of figure 7.2 shows factual data which was used to trigger and fire rules contained within the knowledge base.

7.2.3 Case-Based Reasoning System

The case-based reasoning shell was Design-MUSE (Design Memory Utility For Sharing Experiences) V.2.0. A survey was conducted of case-based reasoning shells. In looking for the case-based reasoning shell, criteria were as follows:

a) easy structuring and implementation of cases,

b) user friendly interface,

c) relatively easy portability between platforms,

d) product, and application development support, and

e) low cost.

Design MUSE was developed at the Georgia Institute of Technology's College of Computing under the direction of Dr. Janet Kolodner. It is a shell intended to ease construction of Case Based Design Aids (CBDAs). Within this research, Design MUSE was used as a shell to support CB development. It was not intended to extensively modify the software or attempt to port it to other platforms, but to use it in building the prototype and consequently aid in proving the research hypothesis.

CBDAs are an experimental class of computer systems used to aid designers by providing easy access to prior design experiences and the lessons that can be learned from those experiences. CBDAs are primarily aimed at aiding design in the very earliest stages of very complex design tasks. Design-MUSE is written in Macintosh Common Lisp and is window-based and menu driven. The major purpose of the CBDA is to provide designers easy access to two types of information 1) documentation describing existing designs, and 2) lessons that can be learned from those designs. Access to both documentation and lessons learned is provided through two major methods: 1) searching, through the contents of the library for items that match user-specified queries, and 2) exploring connections leading off from retrieved items. The major windows of Design-MUSE are as follows:

a) the notebook window (figure 7.3)

The notebook window is the gateway to the contents, designs, lessons, history, and help sections. This is usually the first window a user will see when using the case base part of ComDAS. Here the user logs in with a user name and password. Entry into the case base is not allowed if the user name and password are not valid.

b) the find window (figure 7.4)

The find window provides a way of specifying search queries, much as you would in a form-driven database system. The user specifies searches using the indexing dimensions and vocabulary as discussed in chapters 5 and 6. The user chooses a value for each indexing dimension listed in the window and then clicks on the search button. The user need not choose a value for each indexing dimension in the find window. Only those for which a value exists. A search can be made with partial information. The results of a search from the find window are retrieved by the system and the information is displayed in the library window.

c) the object classes window (figure 7.5)

the object classes window is divided into two panes. The class pane allows for the display of all object class definitions. The object pane allows for the creation and editing of any type of data object in the system.

d) the library window (figure 7.6)

The library window is composed primarily of three panes, one for each of the three major types of information in the system: problems, responses, and stories. This is where the user views the cases that were retrieved during the search that was initiated by the find window. The user may scroll through either the problems, responses, or stories shown in the window. Stories are displayed in the center of the window and problems and responses are displayed on the left and right respectively. At this point a user can view other information related to the retrieved cases. For example, figures, if attached, and annotations.

e) the source window

The source window displays citations to tell where information in the system came from. Domeshek (1994) explains in greater detail the operation of Design-MUSE and building a Case Based Design Aid.

7.2.4 User Interface

The user interface was developed using the resources of the knowledge base and case base reasoning shells. An elaborate user interface was not implemented as this work was primarily to demonstrate the feasibility of the concept. Therefore, most of the user interface is implemented through keyboard interaction, and menus from which choices may be selected. Output is in the form of text or graphics. During a session with the knowledge base a user is prompted by the system. The knowledge base waits for input from the user and continues only after receiving such. Therefore the system is user friendly as it utilizes prompts and queries from the knowledge base for input, and a Graphical User Interface (GUI) for the case base. A users' manual for full operation of Design-MUSE is contained in Domeshek (1994).

Currently the knowledge base and case base run independently, but they are connected through the Design Characteristic State. Future research efforts include a seamless integration of the two.

7.3 Intended User

The system was developed to assist designers in the design of composite structures, not to completely automate their tasks. Therefore any user of ComDAS would need a fairly high level of understanding of composites design in order to achieve positive results from the system. The user must have an understanding of the problem at the level that specifications, such as initial geometry requirements, usage environment, mating structures, special features, and production amount, are known.

7.4 Development Time

The amount of time expended in developing the knowledge base and the case base was approximately 12 man-months. This included time for interviewing experts, finding cases, structuring knowledge, setting up software and hardware systems, and coding. Development time may vary depending upon the application domain, and resources.

7.5 Chapter Summary

This chapter discusses the software and hardware used in development of a prototype Composites Design Advisory System (ComDAS). A description is given of how CLIPS is used as the knowledge-based system shell and Design-MUSE as the case-based reasoning shell. Also discussed are the major windows which are displayed when the system is running and what the user should expect during a session with ComDAS. Chapter 8 shows the results of using ComDAS to test the method of knowledge-based and case-based reasoning to aid designers. Three tests were performed using different structural composite design problems. The successes and limitations are noted.

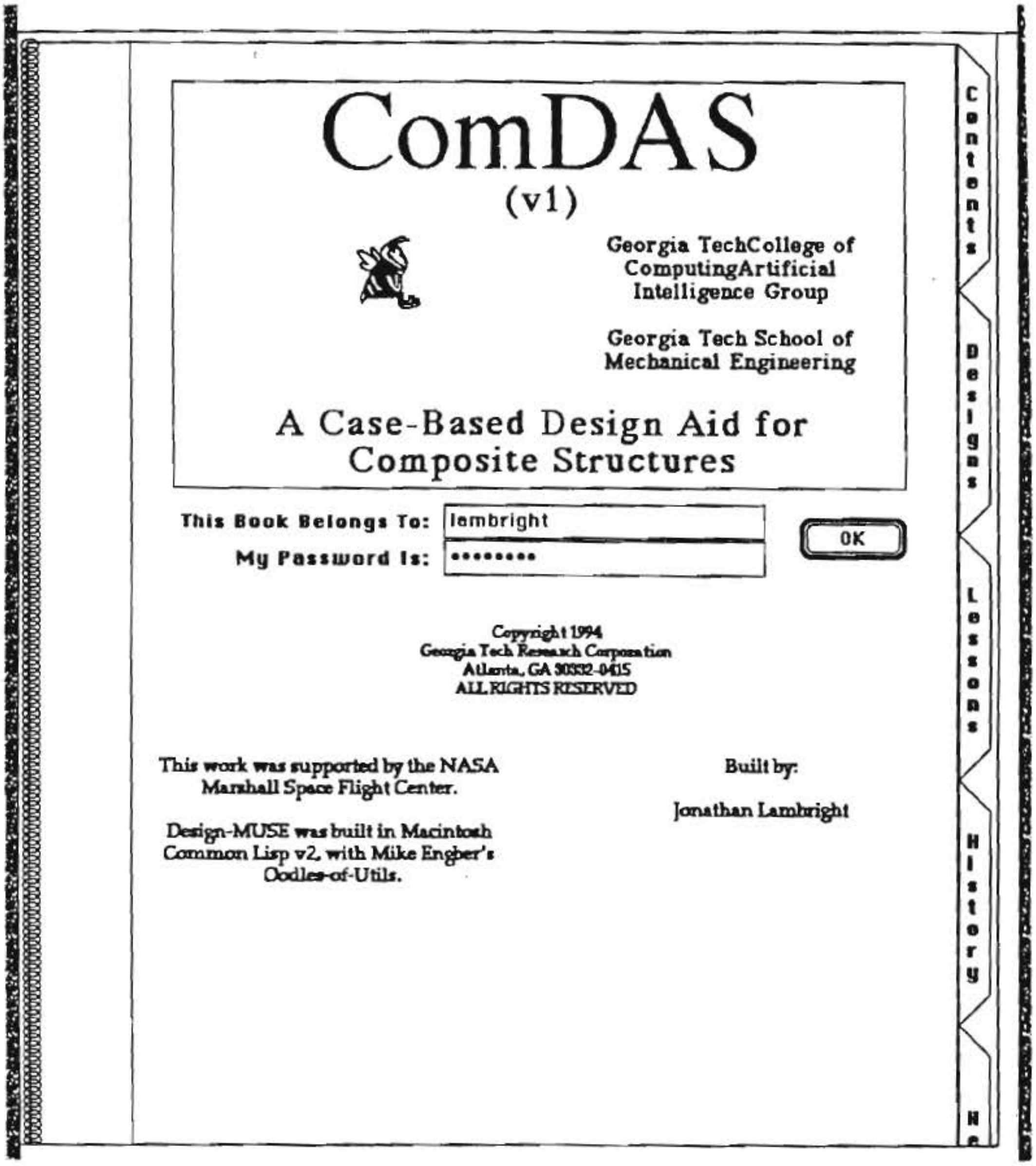


Figure 7.3: Design MUSE Library Window

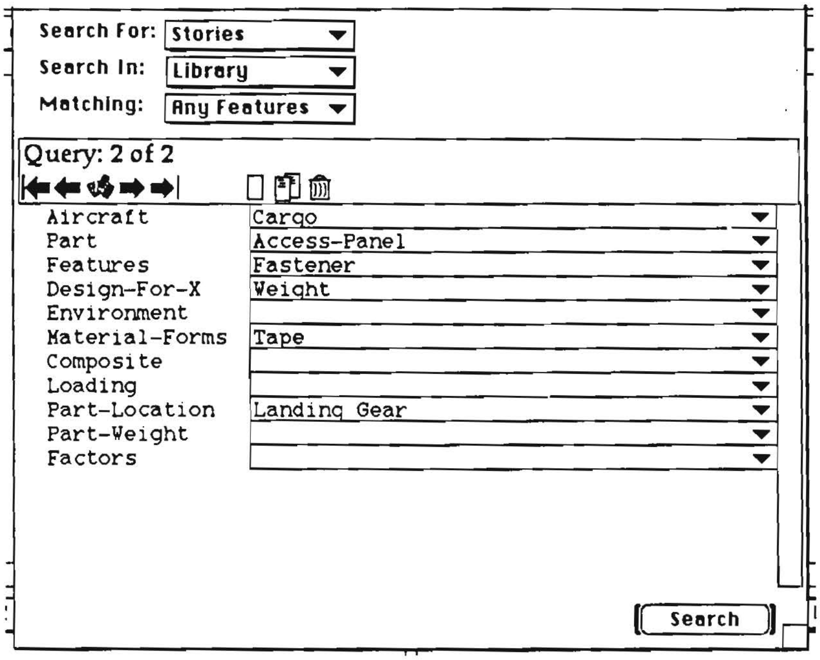


Figure 7.4: Design MUSE Find Window

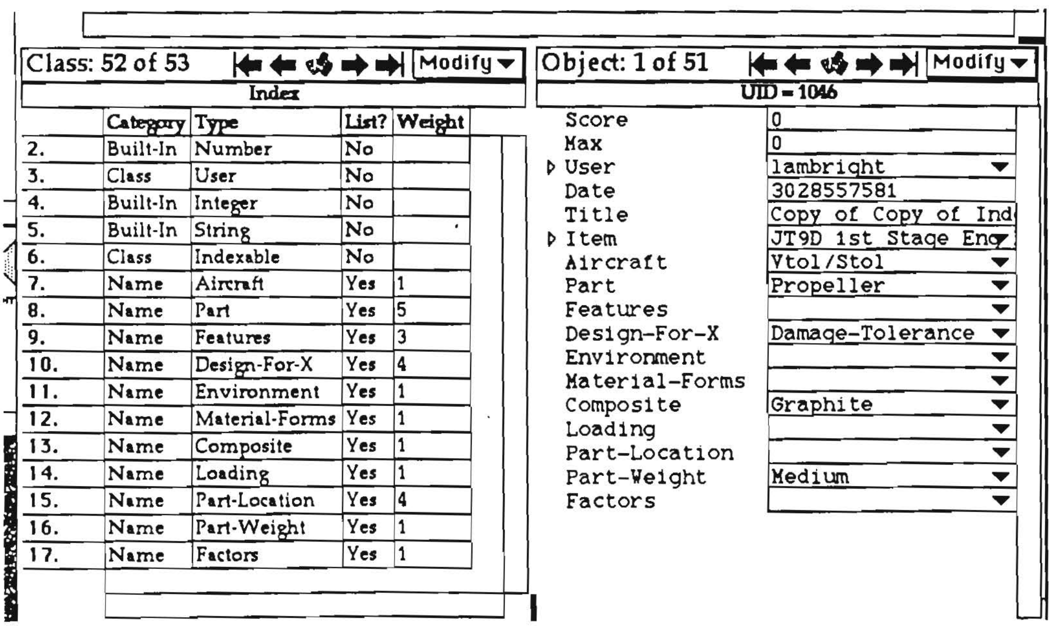


Figure 7.5: Design MUSE Object Classes Window

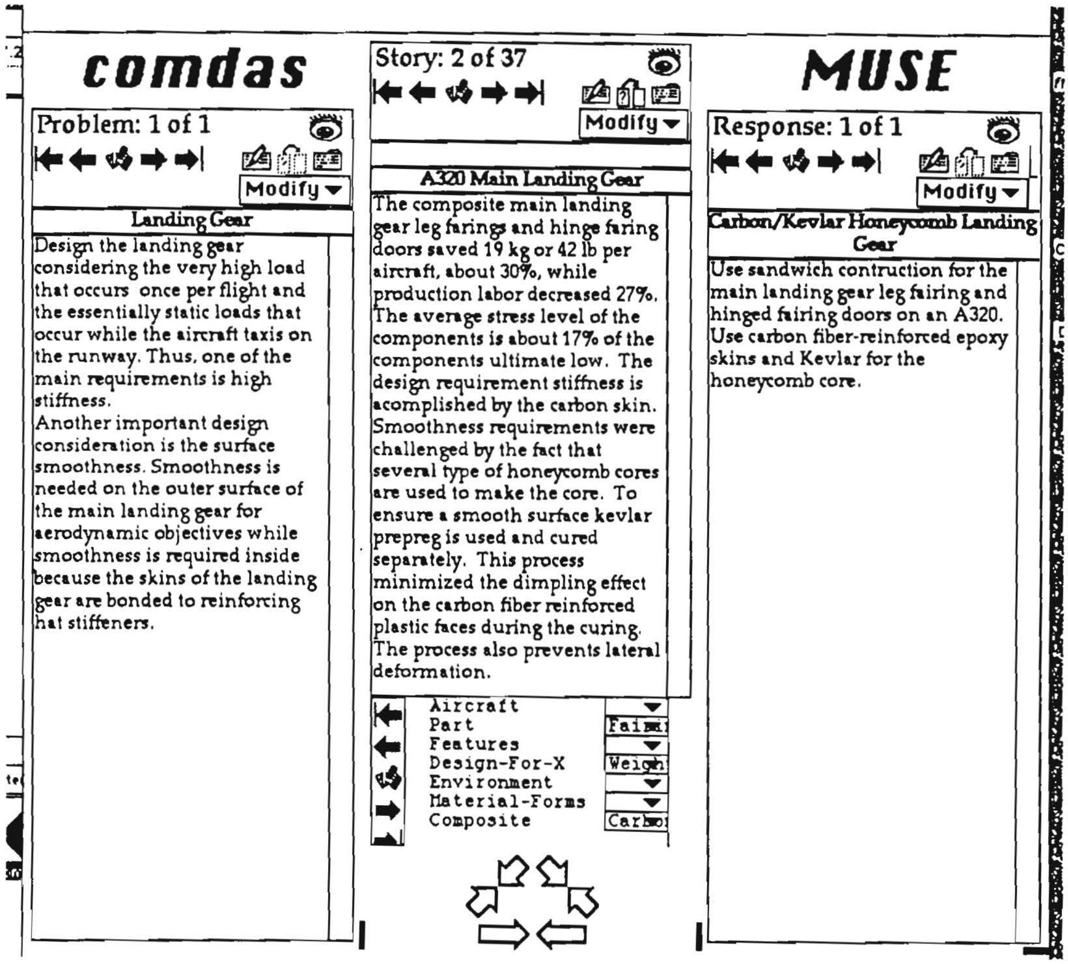


Figure 7.6: Design MUSE Case Viewing Window

CHAPTER VIII

RESULTS/DISCUSSION

ComDAS was tested with three different composite structural design problems. These problems were real life design cases, provided by the experts who provided the knowledge for this research. A solution to each problem was attempted using four different methods:

a. Current design technique.

   A designer solves the conceptual and preliminary design by hand, the structure is manufactured and tested. It is assumed that detailed design would be accomplished by Computer Aided Design (CAD) tools. This research does not cover detailed design.

b. A stand-alone knowledge base.

   The case base part of ComDAS is not invoked and results are taken only from the knowledge base.

c. A stand-alone case base.

   The knowledge base part of ComDAS is not invoked and results are taken only from the case base.

d. A knowledge-based and case-based reasoning system using DCS.

   Input is given to the knowledge base and the case base and results are taken from both to form a solution.

Figure 8.1 depicts the process flow used when ComDAS is invoked as a design advisory system. Each design problem is presented below along with its specifications, solution methods, and results. ComDAS currently does not have a repository of materials and their properties, and will not suggest the use of a particular material. Therefore, in each problem the material which was used in the final production was used as input into ComDAS. For example, if the original design used Graphite/Epoxy tape, then the properties of this material were entered into the working data of the rule base prior to running the system. These material properties were used to generate the first cut at the number of 0, 90, and 45 degree plies. However, based upon design requirements, ComDAS is able to suggest various material types. For example, if one of the requirements is to design for damage tolerance, ComDAS may suggest the use of fabric on the outer surfaces.

Each design problem below may have different specification data. For example, one problem may provide the loading conditions while another may not. This makes no difference to ComDAS as long as there is enough information to describe the design conceptually. Often during the early stages of design, information is unavailable and a designer has to use what is given. Following are three design problems

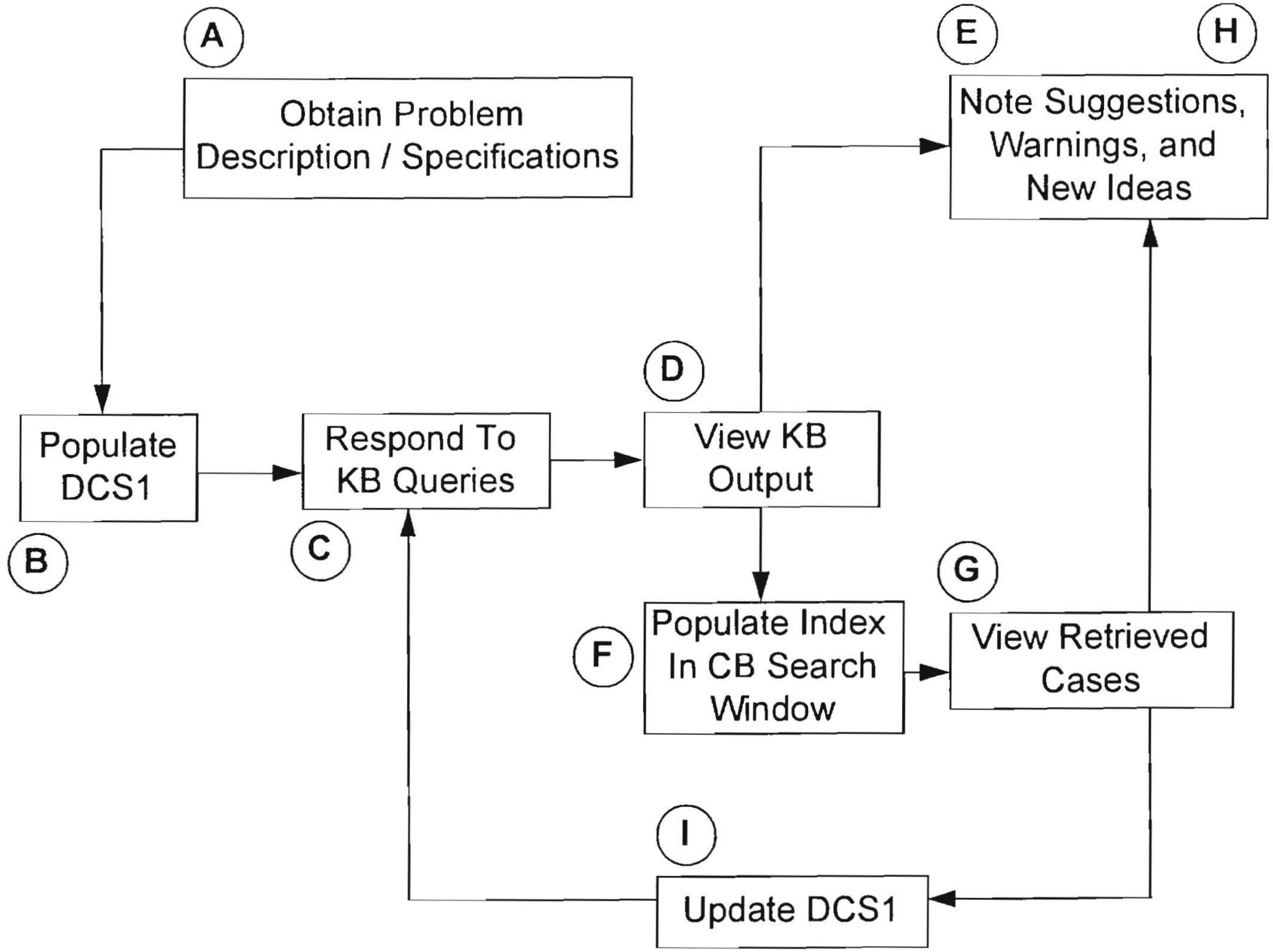


Figure 8.1: Process Flow When Using ComDAS As A Design Advisory System

used to test ComDAS.

Appendix D contains the original problem definitions for the following three test cases. Each problem was described using a standard template generated by the researcher with input from the experts and Niu (1988)(1992). Using this template assisted in making sure that the information used to define the problem was complete and common across all three test cases. The templates were then given to the experts to provide one test case each.

8.1 Design Problem 1

The first design problem is a landing gear door, figure 8.2. Appendix D shows the original problem specifications as given by the expert. The design specifications were extracted from the original problem statement and are shown in table 8.1. These specifications are used to formulate the first DCS for problem 1. Consequently the specification data is consistent throughout the session with the design advisory system. The production results from an actual commercial program which produced this part are shown in table 8.2 and serve as the base from which design advisory system results are measured. Specifically, the results of the knowledge base and case base are compared to that of the actual production results. The comparison looks to see if the knowledge base and case base can predict potential materials, material forms,

Table 8.1: Design Problem 1 Specifications /Landing Gear Door	
Aircraft Type	Fighter
Description	Landing Gear Door
Function	Moldline Door
Loading Spectra Units	psi
Criteria	1) Carry airload pressures in open and closed positions 2) Meet deflection criteria to prevent door from hitting the gear in the open position and to prevent gaps in the closed position.
Loading Spectra	Normal pressure of -10 to +5 psi
Potential Problem Areas	1) Deflection criteria with air pressure loads, no periphial attachments. 2) Fixed lug locations, interference with internal structure 3) Stiffener Pattern 4) Flat plate bending
Important Issues	Weight, Damage tolerance

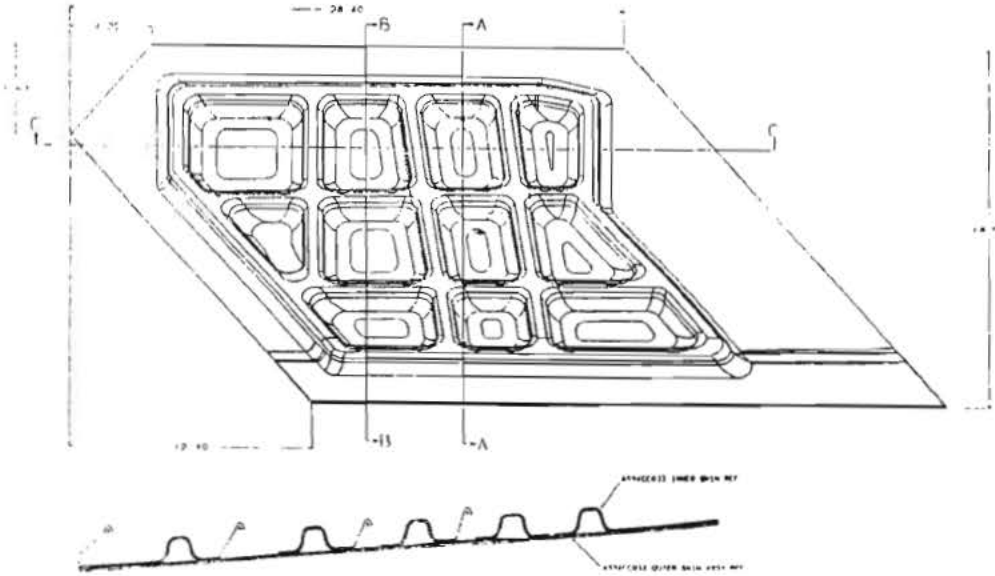


Figure 8.2: Design Problem 1; Landing Gear Door

stacking sequence, cure method, tooling, layup method and especially problems encountered during the product life-cycle as shown in table 8.2. The stand-alone knowledge base results are shown in table 8.3. These are the actual recommendations from the knowledge base after given input by the designer. The DCS was used to respond to queries from the knowledge base and populate the case base search index. The stand-alone case base results are shown in tables 8.4 and 8.5. These are more readable versions of the actual screen prints shown in figures 8.5 and 8.6. These are the actual cases retrieved from the case base as a result of the designer populating the search index window using the DCS. The cases are divided into their problem statements, responses, and stories as discussed in chapter 5. Table 8.6 tabulates and compares the results from ComDAS to that of the original production results. Within this chapter, the notation of DCS(Px,S_i) will be used to denote "Design Characteristic State of (Problem x, State i)." The specifications used as input to the knowledge base and case base for problem 1 are contained in DCS(P1,S_{13}), (see figure 8.3).

S_1

1) Part Function is Moldline Door
2) Part Name is Landing Gear Door
3) Aircraft is Fighter
4) Material is Carbon Thermoplastic
5) Issue is High Damage Tolerance
6) Issue is Weight
7) Issue is Deflection Criteria
8) Issue is Interferance
9) Fixed Lug Locations
10) Lug Padups To Carry Flat Plate Bending

Figure 8.3: DCS ($P1, S_{1j}$), Landing Gear Door

Table 8.2: Production Program Results of Problem 1	
Materials	Intermediate modulus carbon/thermoplastic
Material Forms	Unidirectional tape prepreg
Stacking Sequence	skin = $(45,90,-45,0,0,-45,90,45)_s$ 4 +45s, 4 -45s, 4 90s, 4 0s
Cure Method	Diaphragm forming.
Tooling	Female tool for outer-skin, male tool for stiffeners.
Other Layup Issues	Stiffeners are same layup. Edgeband is a combination of skin and stiffener layup.
Layup Method	Collate plies; form stiffeners, skin separately; bond together.
Special features	Padups under the lugs.
Problem Encountered	1) Deflection criteria with air pressure loads, no periphial attachments. 2) Fixed lug locations, interference with internal structure. 3) Stiffener Pattern. 4) Flat plate bending.
Total Time to Produce	320 hours
CAD Tools	CATIA, IDEAS FEA

Table 8.3: Stand-Alone KB Results of Problem 1	
Recommendations	"Take extra concern over effects of differing coefficients of thermal expansion. Consider the use of fabric as a material form. Consider the use of +- 45 fabric on the outer surface to increase damage tolerance. Design the part for repairability and replaceability due to its need to be damage tolerant. Consider adding materials to form a hybrid such as kevlar and fiberglass to the basic carbon laminate to increase impact resistance. Consider the use of low coefficient of thermal expansion tooling such as carbon/graphite composite, monolithic graphite or ceramic. Use co-cured or co-consolidated assemblies when possible. Beware of severe residual built-in strains in the laminate due to contraction during the cool down from peak cure cycle temperature."
Stacking Sequence	skin = $(45,90,-45,0,0,-45,90,45)_s$ 4 +45s, 4 -45s, 4 90s, 4 0s

Table 8.4: Stand-Alone CB Results of Problem 1, Case 1	
Retrieved Case #1	<u>Problem</u> "Design the landing gear considering the very high load that occurs once per flight and the essentially static loads that occur while the aircraft taxis on the runway. Thus, one of the main requirements is high stiffness. Another important design consideration is the surface smoothness. Smoothness is needed on the outer surface of the main landing gear for aerodynamic objectives while smoothness is required inside because the skins of the landing gear are bonded to reinforcing hat stiffeners." <u>Response</u> "Use sandwich construction for the main landing gear leg fairing and hinged fairing doors on an A320. Use carbon fiber-reinforced epoxy skins and kevlar for the honeycomb core." <u>Story</u> "The composite main landing gear leg fairings and hinge fairing doors saved 19kg or 42lb per aircraft, about 30%, while production labor decreased 27%. The average stress level of the components is about 17% of the components ultimate low. The design requirement stiffness is accomplished by the carbon skin. Smoothness requirements were challenged by the fact that several types of honeycomb cores are used to make the core. To ensure a smooth surface kevlar prepreg is used and cured separately. This process minimized the dimpling effect on the carbon fiber reinforced plastic faces during the curing. The process also prevents lateral deformation."

Table 8.5: Stand-Alone CB Results of Problem 1, Case 2	
Retrieved Case #2	<u>Problem</u> "Design the main landing gear strut door." <u>Response</u> "Use graphite/epoxy material" <u>Story</u> "4 pounds and $2,000 per aircraft were saved by using the graphite epoxy material over the existing aluminum material. All chemical milling and material removal operations were eliminated with the exception of edge trim. The number of tools necessary to fabricate the part was reduced by 55. The complexity of the part was also reduced as the number of Z-members was reduced by 26."

8.1.2 KB And CB Results For Problem 1

The result of the scenario is a combination of the stand-alone knowledge and case bases and the accompanying design characteristic states. The solution is simply an addition of the knowledge base and case base results as found above, yet creates a very powerful result in problem solving situations. The DCS helped to maintain consistency of design data throughout the design. Without the DCS one cannot determine whether a designer would have been able to convey properly the intent of the design requirements, specifications, and constraints between the knowledge base and the case base. After the suggestions, insights, and potential pitfalls are given through the KB and CB, a new DCS is formed, DCS(P1,$S_{[illegible]}$) (see figure 8.3). This DCS reflects a new state of the design where form potentially has been tied to function, and recommendations of potential problem areas and solutions have been incorporated into the design. The content of the DCS reflects the design in terms of the factual data of the KB and vocabulary of the CB. The new DCS includes the original ten issues as illustrated in figure 8.3. The additional four elements, eleven through fourteen, are the result of suggestions from the knowledge base (table 8.3) and insights from the cases retrieved from the case base (tables 8.4 and 8.5). The DCS itself is not implemented digitally within the design advisory system and can exist simply in a designer's journal. Therefore, the responsibility of updating the DCS is left to the designer so as not to create a totally automated system but one that includes the user in making critical decisions. The designer can now populate the DCS according to those suggestions and insights which he/she thought to be most relevant to the problem. At this stage the designer can use this DCS and proceed to the late preliminary and detailed design phases or use DCS($P1,S_{2j}$) as input back into the knowledge base and case base for further iterative analysis. The resulting DCS($P1,S_{2j}$) is shown below in figure 8.4.

S_2

1) Part Function is Moldline Door
2) Part Name is Landing Gear Door
3) Aircraft is Fighter
4) Material is Carbon Thermoplastic
5) Issue is High Damage Tolerance
6) Issue is Weight
7) Issue is Deflection Criteria
8) Issue is Interferance
9) Fixed Lug Locations
10) Lug Padups To Carry Flat Plate Bending
11) Material Form is Fabric
12) Issue is Differing Coefficients of Thermal Expansion
13) Co-Cured / Co-Consolidated Assemblies
14) Stacking $(45, 90, -45, 0, 0, -45, 90, 45)_s$

Figure 8.4: DCS(P1,S_{2j}), Landing Gear Door

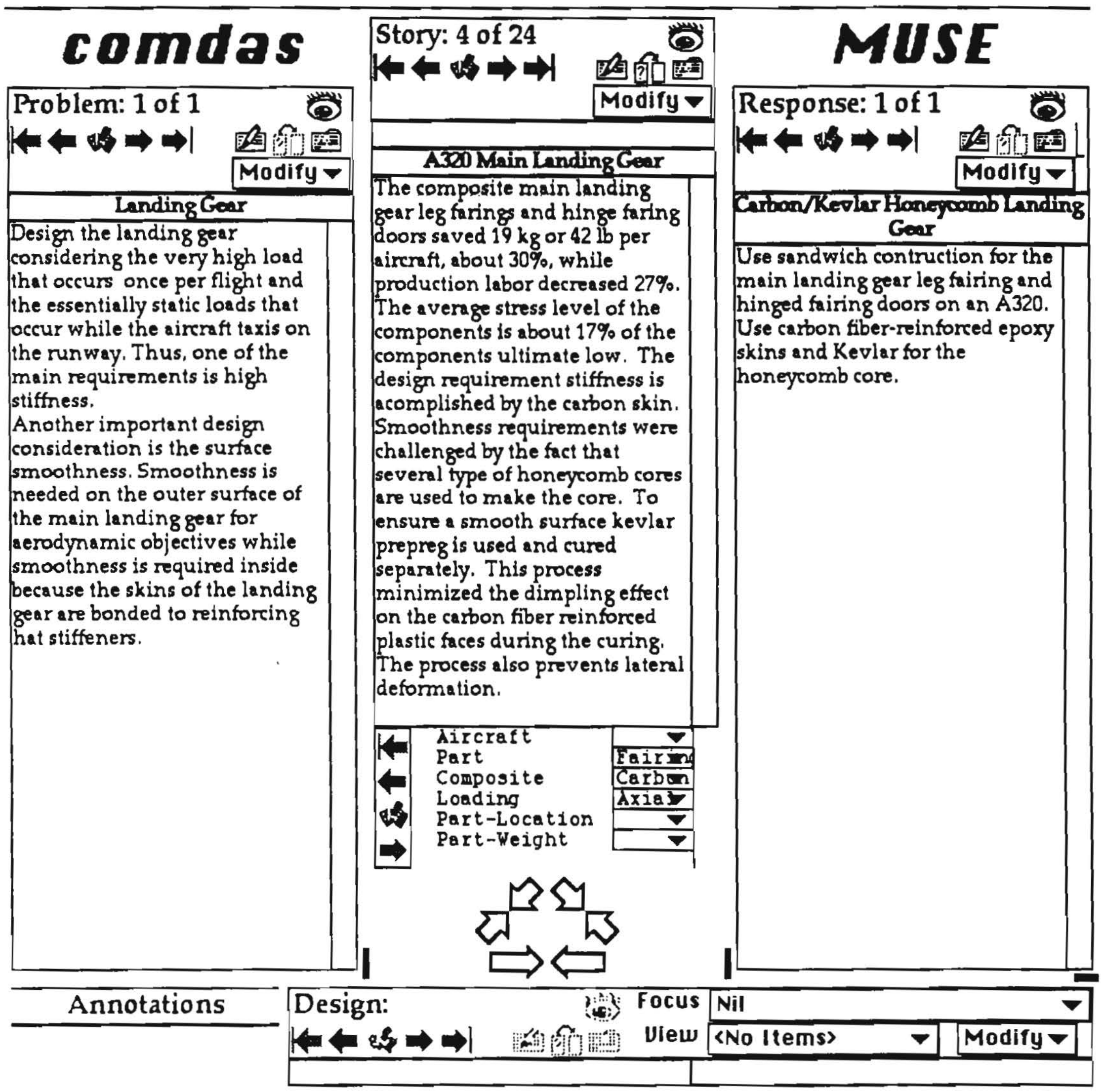


Figure 8.5: Retrieved Case #1 From Case Base on Problem 1

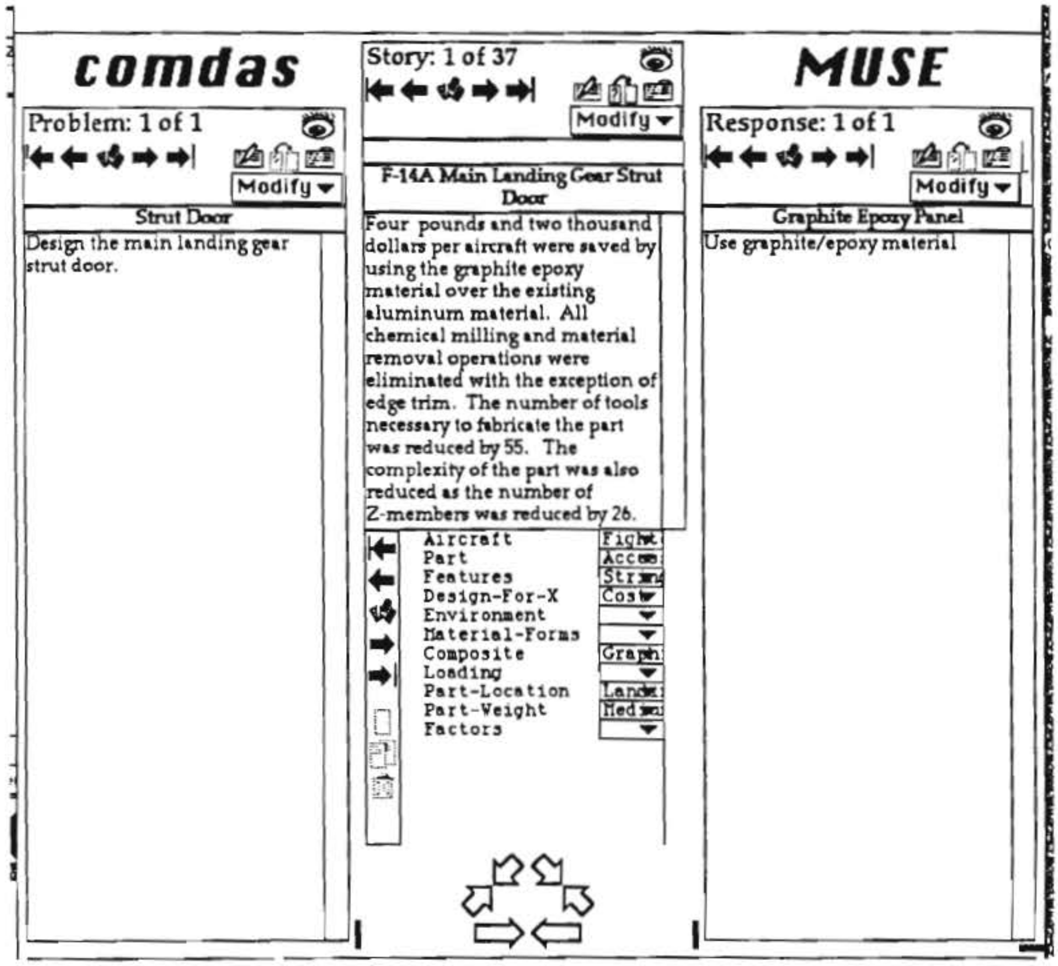


Figure 8.6: Retrieved Case #2 From Case Base on Problem 1

8.1.3 Discussion of Problem 1 Results

Table 8.6 tabulates and compares the results obtained from the design advisory system. The knowledge base performed very well at providing rules of thumb and heuristics according to the design specifications that were input. The knowledge base provided rules which aided in creating a light structure but put emphasis upon the design requirement of damage tolerance and deflection criticality. Specifically, the knowledge base suggested the use of +/-45 fabric on the outer surface to increase damage tolerance, and the use of a hybrid such as kevlar and glass to the basic carbon laminate to increase impact resistance. Also the knowledge base calculated the same number of plies as the human designer. The knowledge base, however, was not able to predict the stiffener pattern problem. A previous design case may have been of assistance at this point. However, the knowledge base did not and could not provide previous related designs. The designer would have to rely solely upon the results of the knowledge base. Though this is not considered a bad idea, especially since the knowledge for the knowledge base was gathered from the expert, it does creates a less than optimal problem solving environment. The important fact is that since the domain itself is still growing, the rules of thumb and heuristics don't always represent the possible outcomes of

Table 8.6: Comparison of ComDAS Results to Actual Production Results \ Problem 1

	Actual Production Results	*ComDAS*	
		Case-Based Contribution	*Knowledge-Based Contribution*
Problem Areas Missed in Conceptual Design	1) Manufacturing constraints on stiffener pattern.	1) Manufacturing constraints on stiffener pattern.	1) Manufacturing constraints on stiffener pattern.
Potential Problem Areas Picked Up in Conceptual Design	None	1) Non-smooth surfaces can increase dimpling effect on the laminate surface and consequently lateral deformation.	1) Part should be damage tolerant and therefore designed for repairability and replaceability. 2) Potential of severe residual built-in strains in laminate due to contraction during cool-down from peak cure cycle temperature.
New Ideas Generated	None	1) Stiffness criteria could be accomplished using carbon skin and a kevlar honeycomb construction. 2) Kevlar prepreg could be used and cured separately to ensure a smooth surface, minimize the dimpling effect on the laminate faces, and help prevent lateral deformation. 3) Titanium drive fitting could be used to control the transfer of load onto the skins and to minimize residual stresses in the adhesive joint due to thermal incompatibility.	1) Use of +/-45 fabric on the outer surface to increase damage tolerance, and the use of a hybrid such as kevlar and glass to the basic carbon laminate to increase impact resistance.

manufacturing and operational conditions. Therefore, previous similar cases which depict the design, manufacturing and operational results would compliment the knowledge base well.

The case base was very successful in retrieving cases of similar context. Those retrieved cases gave descriptions of how a landing gear door was constructed on other aircraft and what problems were encountered. One retrieved case described that a weight and labor reduction could be realized in the main landing gear door assembly by 30% and 27% respectively. Also the retrieved case showed how the stiffness criteria could be accomplished using carbon skin and a kevlar honeycomb construction.

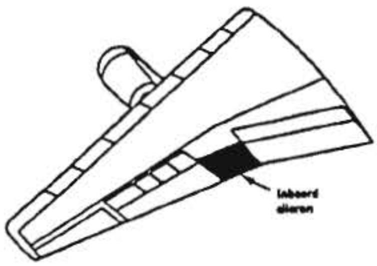
The retrieved case depicted how a kevlar prepreg is used and cured separately to ensure a smooth surface, minimize the dimpling effect on the laminate faces, and help prevent lateral deformation. This was a requirement not picked up in the initial specifications or the knowledge base. Another case described how a titanium drive fitting was designed to control the transfer of load onto the skins and to minimize residual stresses in the adhesive joint due to thermal incompatibility. Recommendations from the knowledge base warned of effects from differing coefficients of thermal expansion. These recommendations from the knowledge base and case base compliment each other. The case base, however, could not provide the heuristic knowledge that links the manufacturing issues to the design specifications or warnings on environmental, and configuration layup related issues, unless spelled out specifically in one of the retrieved cases.

The combined results of the knowledge base and case base provide a more robust problem solving environment. Where the knowledge base could not apply heuristics and warnings to unforeseen potential problem areas, the case base provided real-life results of similar designs that addressed those areas. The decision to adopt any of the recommendations and methods from the case base and or knowledge base is left to the designer. The designer has several choices available. The designer could elect to use one of the case solution techniques in combination with the knowledge base recommendations; use combinations of case solutions with knowledge base recommendations; or use only knowledge base recommendations. The designer could also seek more detailed knowledge of the retrieved cases design and manufacturing techniques. According to our expert's opinion, the potential lead time savings of using this method is estimated at 10% to 15% when used with conventional techniques.

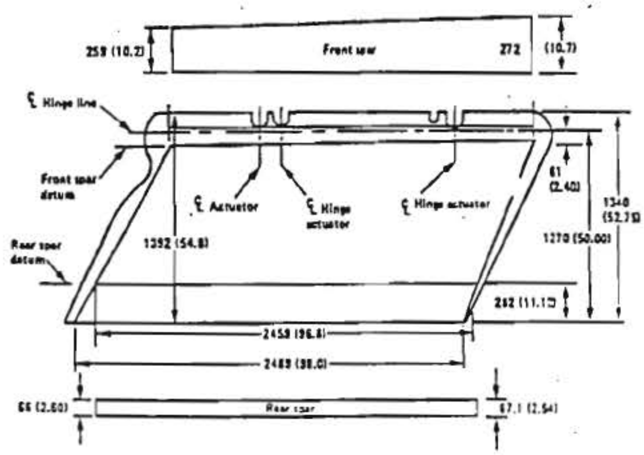
8.2 Design Problem 2

The second design problem is an aileron, figure 8.7. The initial specifications are shown in table 8.7. The designer's results are shown in table 8.8. The stand-alone knowledge base results are shown in table 8.9 and the stand-alone case base results in tables 8.10, 8.11, and 8.12. These are more readable versions of the actual screen prints shown in figures 8.9, 8.10, and 8.11. Appendix D shows the original problem specifications as given by the expert. The production results from the actual commercial program which produced this part are shown in table 8.8. Table 8.13 tabulates and compares the results from ComDAS to that of the original production results. The specifications used as input to the knowledge base and case base for problem 2 are contained in DCS(P2,S_{1j}), (see figure 8.8). The final DCS resulting from one session with ComDAS is shown in figure 8.12.

Table 8.7 Design Problem 2 Specifications/Aileron	
Aircraft Type	Commercial Passenger
Description	Aileron (Control Surface)
Function	Control Rolling of Aircraft
Operating Temperature	219.3K (-65F) < T < 355K (181F)
Loading Spectra Units	psi
Important Issues	Tolerance to Foreign Object Damage (Hail Impact), Non-Separation From Aircraft After Failure or Jam. Must be interchangeable with existing metal aileron. Protect against lightning strikes. Use fasteners for skin to rib/spar joining. Moisture accumulation.



Inboard aileron location on L-1011 wing.



Inboard aileron dimensions (All dimensions shown in mm (in)

Figure 8.7: Design Problem 2, Aileron

S1

1) Part Function is Control Rolling
2) Part Name is Aileron
3) Material is Graphite/Epoxy
4) Aircraft is Passenger
5) Operating Temperature is -65F<T<181F
6) Issue is Damage Tolerance
7) Issue is Interchangeability
8) Issue is Moisture
9) Issue is Lightning

Figure 8.8: Design Problem 2, DCS(P2, S_{12})

Table 8.8 Production Program Results of Problem 2	
Materials	Graphite/Epoxy Unidirectional Tape (Covers and front spar). Graphite/Epoxy bi-directional fabric (ribs). Kevlar and Nomex Core (Trailing Edge Wedge). Aluminum (Rear Spar).
Material Forms	Single Piece Upper And Lower Covers(Tape). Ribs(Fabric). Trailing Edge Wedge (Honeycomb Construction).
Stacking Sequence	12 Plies of 0.019cm per ply tape.
Cure Method	Conventional bagging and formed rubber bags used on both male and female tools.
Tooling	Graphite fabric ribs made using both male and female tooling.
Other Layup Issues	
Layup Method	
Special features	Mechanical Fasteners(Triwing Titanium screws and stainless steel Hi-lok collars).
Problems Encountered	Parts made in the female tool using a conventional vacuum bag or formed rubber bag showed evidence of bridging and porosity in the radii of the rib. Parts made in the male tool showed no evidence of bridging in the radii; however the parts did have large dimensional variance. The dimensional problem made using a male tool appeared to be correctable by tool development, however, the accumulation of tolerances to the outside mold lines for the ribs and spar could be a problem.
Total Time to Produce	
CAD Tools	CATIA

Table 8.9: Stand-Alone KB Results of Problem 2	
Recommendations	"Consider the use of a fabric as a material form. Severe residual or built in strains can be induced in the laminate due to contraction during the cool-down from peak cure cycle temperature. Specify that either the tool surface side of the laminate is to be used, use tape as a material form for the outer plies or use a caul plate during the cure cycle for smoothness. Consider the addition of fasteners. Take extra concern over the effects of differing coefficients of thermal expansion. Consider adding materials to form a hybrid such as kevlar and fiberglass to the basic carbon laminate to increase impact resistance. Avoid sharp changes in the surface contours and avoid tight radii. Use cocured or co-consolidated assemblies when possible."
Stacking Sequence	"This option not invoked for the aileron as sufficient amount of information not given."

Table 8.10: Stand-Alone CB Results of Problem 2, case 1	
Retrieved Case #1	<u>Problem</u> "Evaluate the viability of composite control structures such as foreflaps. These types of parts are relatively small and lightly loaded, however they are subjected to extreme environmental effects." <u>Response</u> "A traditional rib-stiffened aluminum foreflap has been redesigned as a monocoque structure with boron-epoxy, aluminum honeycomb skins, and titanium end attachments." <u>Story</u> "Control surfaces such as foreflaps are small and lightly loaded, however they experience extreme environmental effects. Thus they do not provide much opportunity for weight savings, however, they are excellent sources of data on the durability and reliability of composite materials. A foreflap was designed for the Boeing 707 out of a boron/epoxy composite, aluminum honeycomb skins and titanium attachments. The part was able to pass stress tests, however it was not cost effective."

Table 8.11: Stand-Alone CB Results of Problem 2, case 2	
Retrieved Case #2	<u>Problem</u> "Demonstrate potential weight savings of composite materials and compare the advantages of boron/epoxy and graphite/epoxy composites. Also reduce the number of parts." <u>Response</u> "The original forged aluminum rib was used and a boron/epoxy skin was applied over it. The skin and other small parts were laminated from four layers of boron pre-pregs. A full-depth honeycomb core was used to provide skin stability. The composite assemblies were bonded together with a film adhesive." <u>Story</u> "The landing flap of an A-4 aircraft was constructed from boron-epoxy composite material. The landing flap typifies most airframe construction in that it has lightgage, stiffened-skin panels and concentrated load fittings. The composite part was designed to be interchangeable with the original aluminum design. Static and fatigue tests were conducted to simulate the landing approach condition. The boron flap withstood the fatigue spectrum tests without visible damage and then withstood a static load equal to 181% of the design limit load. The part was 21% lighter than the aluminum version and had only 55 components as opposed to 280 in the aluminum flap."

Table 8.12: Stand-Alone CB Results of Problem 2, case 3	
Retrieved Case #3	Problem Demonstrate potential weight savings of composite materials and compare the advantages of boron/epoxy and graphite/epoxy composites. Also reduce the number of parts. Response A matched-die mold rib was used and the skins and other small parts were laminated from graphite prepregs. A full-depth honeycomb core was used to provide skin stability. The composite parts were bonded with a film adhesive. Story The landing flap of an A-4 aircraft was constructed from boron-epoxy composite material. The landing flap typifies most airframe construction in that it has lightgage, stiffened-skin panels and concentrated load fittings. The composite part was designed to be interchangeable with the original aluminum design. The flap was successfully tested, failing at the 160% of the design load limit. The flap provided a 47% savings in weight and required only 7 components, as opposed to 280 in the aluminum version.

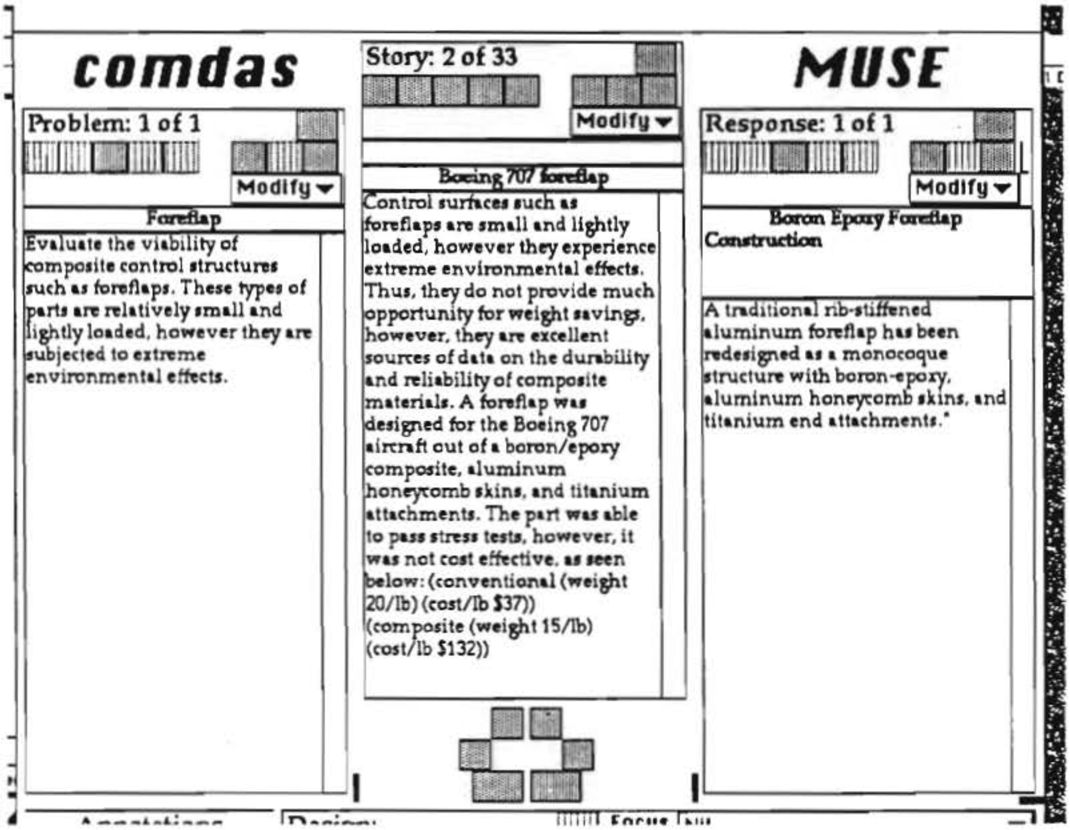


Figure 8.9: Retrieved Case #1 From Case Base on Problem 2

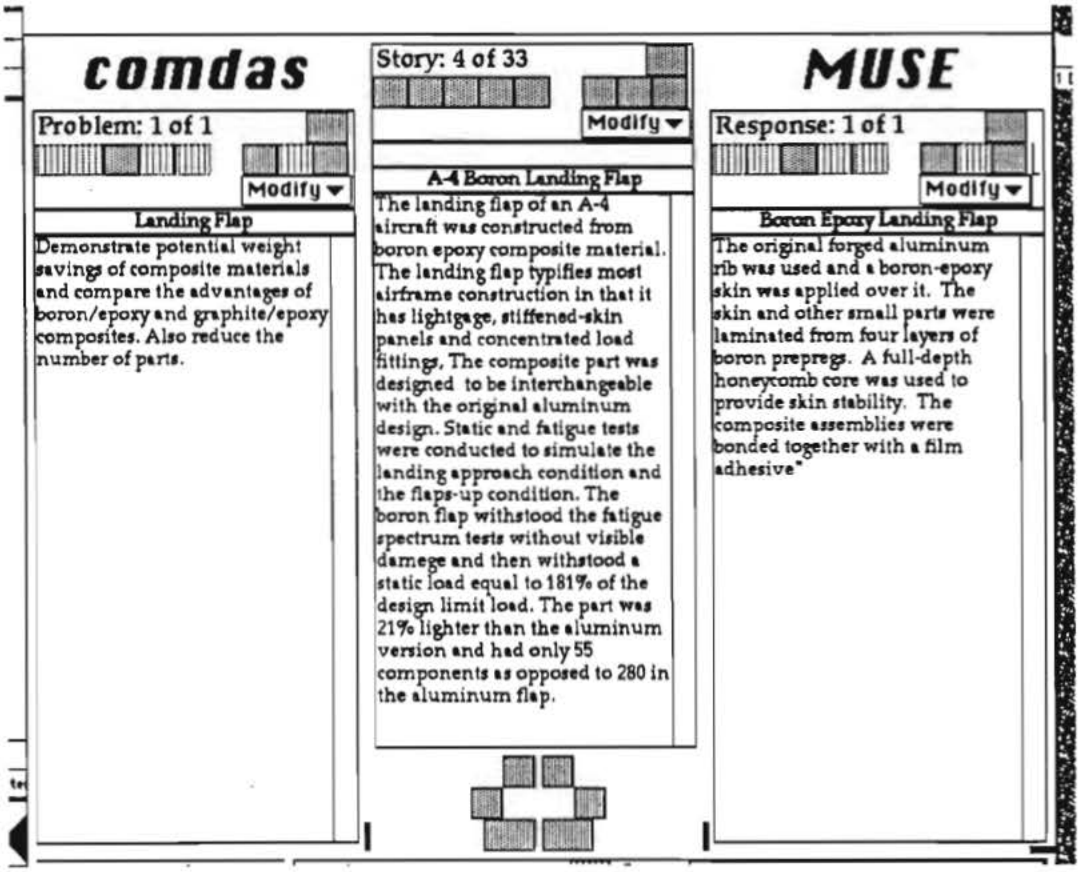


Figure 8.10: Retrieved Case #2 From Case Base on Problem 2

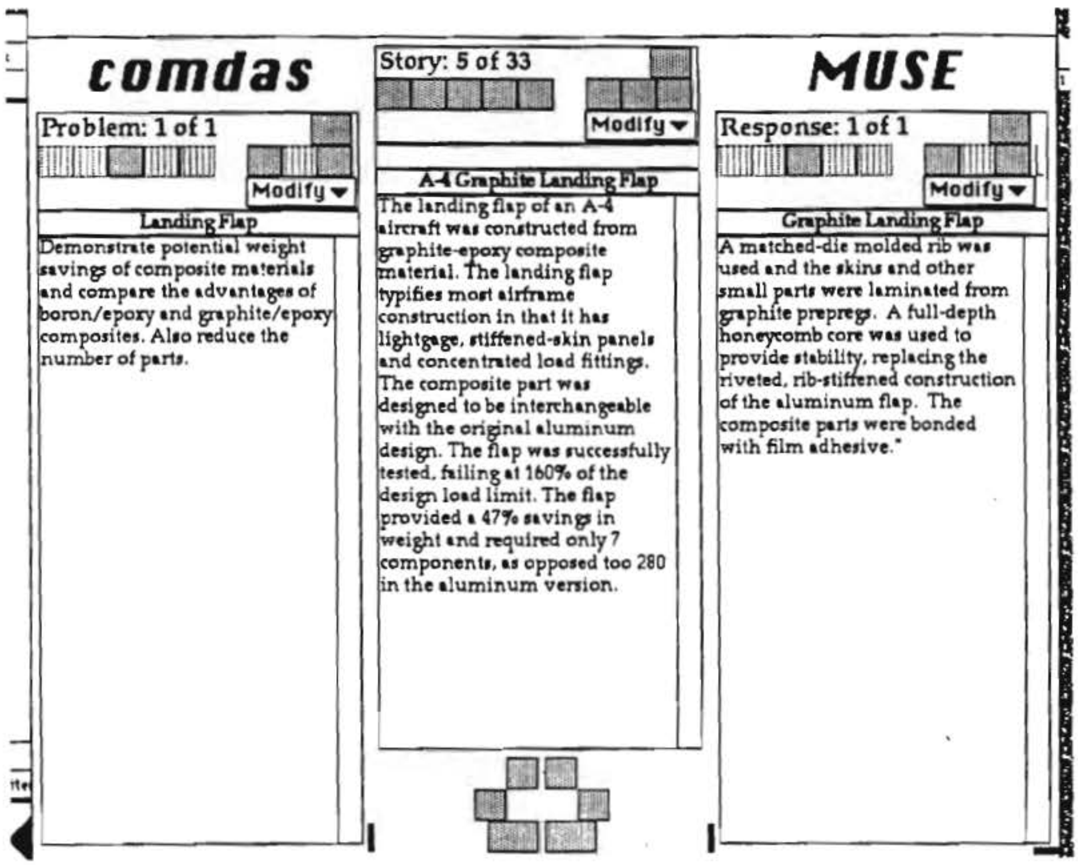


Figure 8.11: Retrieved Case #3 From Case Base on Problem 2

S2

1) Part Function is Control Rolling
2) Part Name is Aileron
3) Material is Graphite/Epoxy
4) Aircraft is Passenger
5) Operating Temperature is -65F<T<181F
6) Issue is Damage Tolerance
7) Issue is Interchangeability
8) Issue is Moisture
9) Issue is Lightning
10) Material Form is Fabric or Tape
11) Material is Hybrid
12) Co-cured or Co-consolidated assemblies or fasteners for bonding
13) Issue is Differing Coefficients of Thermal Expansion

Figure 8.12: Design Problem 2, DCS(P2,S_{2j})

8.2.1 Discussion of Problem 2 Results

Table 8.13 tabulates and compares the results from ComDAS to that of the original production results. The knowledge base results concurred with that of the designer in using tape as a material form for the outer plies. It also suggested using a caul plate during the cure cycle. The use of a caul plate may have helped to reduce the problems of bridging and porosity in the radii of the rib and the large dimensional variance. The knowledge base also warned about severe residual or built in strains due to contraction. This may also have contributed to the bridging in the radii of the

Table 8.13: Comparison of ComDAS Results to Actual Production Results \ Problem 2			
	Actual Production Results	*ComDAS*	
		Case-Based Contribution	*Knowledge-Based Contribution*
Problem Areas Missed in Conceptual Design	1) Bridging and porosity in the radii of the rib as a result of parts made in the female tool using a conventional vacuum bag or formed rubber bag. 2) Large dimensional variance.	1) Large dimensional variance.	1)Large dimensional variance.
Potential Problem Areas Picked Up in Conceptual Design	none	1) A foreflap was designed for the Boeing 707 out of a boron/epoxy composite, aluminum honeycomb skins and titanium attachments. The part was able to pass stress tests, however it was not cost effective.	1) Avoid the sharp changes in surface contours and tight radii. Insufficient curing and porosity may result. 2) Beware of severe residual or built-in strains due to contraction.
New Ideas Generated	none	1) Boron/Epoxy material instead of Graphite/Epoxy. 2) A reduction in parts as a result of using composites and co-consolidated assemblies decreases weight and complexity and was proven on the A-4.	1) Use of a hybrid such as kevlar and glass added to the basic carbon laminate to increase impact resistance. 2) Use of a caul plate during cure cycle.

rib. The knowledge base suggested adding materials to form a hybrid such as kevlar and glass to the basic carbon laminate. This suggestion is in direct agreement with design results of flaps on other aircraft.

The results of the case base were complimentary to those of the knowledge base. The case base retrieved three successful designs one of which was not cost effective. Two of the cases demonstrated how the number of parts could be reduced from the original design.

8.3 Design Problem 3

The third design problem is a rudder. The initial specifications are shown in table 8.14. This problem is an example of not having much information during the early design stages. The production program results are shown in table 8.15. The stand-alone knowledge base results are shown in table 8.16. The stand-alone case base results are shown in tables 8.17, 8.18, 8.19 and 8.20. These are more readable versions of the actual screen prints shown in figures 8.15, 8.16, 8.17, and 8.18. Appendix D shows the original problem specifications as given by the expert. The production results from an actual commercial program which produced this part are shown in table 8.8. Table 8.21 tabulates and compares the results from ComDAS to that of the original production results. The specifications used as input to the knowledge base and case base for problem 3 are contained in DCS(P3,S_{1j}), (see figure 8.14). The final DCS resulting from one session with ComDAS is shown in figure 8.19.

Table: 8.14: Design Problem 3 Specifications/Rudder	
Aircraft Type	Commercial Passenger
Description	Rudder (Control Surface)
Function	Control Steering Aircraft
Operating Temperature	
Loading Spectra Units	psi
Loading Spectra	
Important Issues	

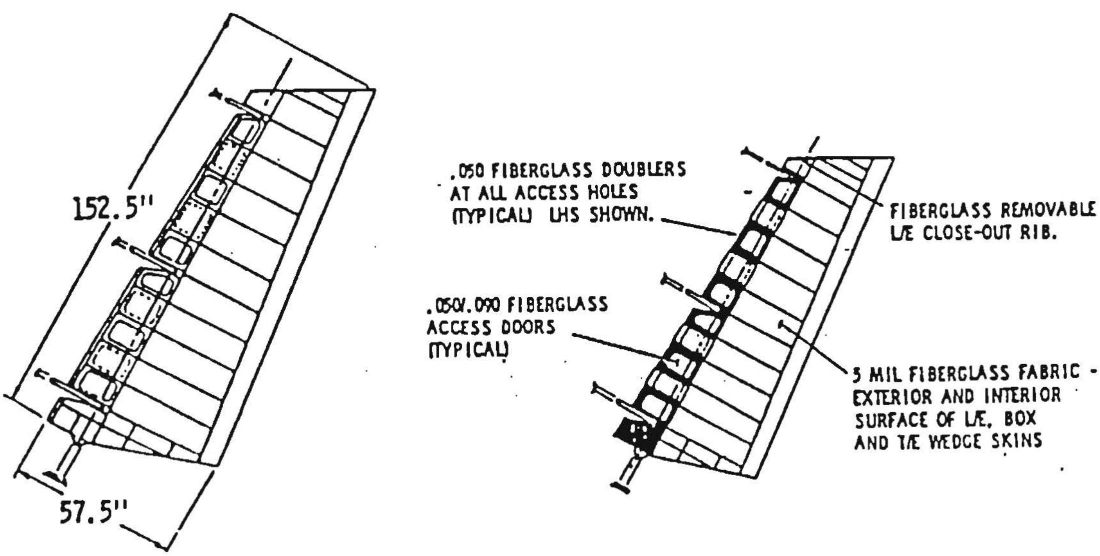


Figure 8.13: Design Problem 3, Rudder

S1

1) Part Function is Control Steering
2) Material is Graphite/Epoxy
3) Part Name is Rudder
4) Aircraft is Passenger

Figure 8.14: Design Problem 3, DCS(P3,S_{1j})

Table 8.15: Production Program Results of Problem 3

Design Concept	Integrally molded L.E. skin panels, center box skin panel. T.E. Wedge and Rear spar precured. Rib webs & spar webs precured laminates. Hinge ribs precured.
Materials	Graphite/Epoxy
Material Forms	
Stacking Sequence	
Cure Method	Conventional bagging and formed rubber bags used on both male and female tools.
Tooling	L.E. Skin: Fiberglass female with aluminum flange bars. Bag pressure autoclave. Center box skin panels aluminum and graphite tooling expansion & autoclave pressure. T.E. Wedge & Rear Spar: Aluminum tool bag an autoclave pressure. Rib Web & Spar Web: Flat pattern aluminum bag and autoclave pressure. Hinge Rib: Female graphite epoxy tools, rubber plug inserts, bag and autoclave pressure.
Other Layup Issues	
Layup Method	
Special features	Assembly by rivet bonding and adhesive.
Problems Encountered	
Total Time to Produce	
CAD Tools	CATIA

Table 8.16: Stand-Alone KB Results of Problem 3	
Recommendations	"Put the +-45s on the outer surface. Consider the use of low CTE tooling such as carbon/graphite composite, monolithic graphite, or ceramic. Consider the use of a fabric as a material form. Severe residual or built-in strains can be induced in the laminate due to contraction during the cool-down from peak cure cycle temperature. Specify that either the tool surface side of the laminate is to be used, use tape as a material form for the outer plies or use a caul plate during the cure cycle for smoothness. Consider the addition of fasteners. Take extra concern over the effects of differing coefficients of thermal expansion. "
Stacking Sequence	"This option not invoked for the rudder as sufficient amount of information not given."

Table 8.17: Stand-Alone CB Results of Problem 3, case 1	
Retrieved Case #1	<u>Problem</u> "To demonstrate the viability of composite construction in the design and manufacture of a practical structural component of significant size. Maneuver loads are the primary design case of the rudder, a case characterized by combinations of compression, shear, and tension loads. The engine failure case is the most critical design case. Consider also the air turbulence around a rudder with significant deflection; this is a case of high vibration at the points where the control surface and the fuselage meet. This aerodynamic loading may also cause fatigue damage to the aircraft." <u>Response</u> "A four-ply laminate was used. The skin design tailored laminate to provide strength and stiffness in critical areas by adding plies. A titanium drive fitting was designed to control the transfer of load onto the skins and to minimize residual stresses in the adhesive joint. This minimized residual stresses caused by thermal incompatibility. A honeycomb sandwich structure allowed maximal weight reduction. FM40 and FM96 adhesives were chosen because they meet the temperature requirements of the rudder. These were used to bond the skin to the honeycomb core and to join the honeycomb core to the edge members." <u>Story</u> "The rudder is a control surface on the tail of an aircraft. This design replaced the traditional aluminum or beryllium part with a boron/epoxy composite version. 50 rudders were constructed and 45 were retrofitted into in-service F-4 aircraft for long term service tests. The remaining five were subjected to various ground test programs."

Table 8.18: Stand-Alone CB Results of Problem 3,case 2	
Retrieved Case #2	Problem "To demonstrate the viability of composite construction in the design and manufacture of a practical structural component of significant size. Maneuver loads are the primary design case of the rudder, a case characterized by combinations of compression, shear, and tension loads. The engine failure case is the most critical design case. Consider also the air turbulence around a rudder with significant deflection; this is a case of high vibration at the points where the control surface and the fuselage meet. This aerodynamic loading may also cause fatigue damage to the aircraft." Response "Carbon/fiber composites were used for both the skin and sub-structure. Instead of using conventional fastening techniques to attach the parts, they were bonded using adhesive." Story "The significant reduction in weight, number of components, number of parts, and cost was achieved by building the A310 rudder out of a nomex core and carbon and graphite facing sheets. Specifically, weight was decreased 45kg or 99lbs compared to a light alloy rudder. This twenty percent saving was one of the major goals of this program. The other major objectives was to reduce production cost. The composite configuration was only ninety percent of the cost of the metallic design; however, this material portion of the material cost increased from twelve to thirteen percent of the overall cost. This decrease in cost was mainly attributable to the decrease in the assembly effort."

Table 8.19:	Stand-Alone CB Results of Problem 3, case 3
Retrieved Case #3	<u>Problem</u> "Design the tail boom and vertical fin of a helicopter. Design such that life-cycle costs are reduced and part count is minimized." <u>Response</u> "A semi-monocoque configuration using a sandwich wall construction can be used to build a composite tail boom. The wet filament winding process can be used to fabricate the tail boom." <u>Story</u> "The purpose of this program was to design and fabricate a primary structural component for a helicopter using composite materials. The component selected was the tail boom and vertical fin of the AH-1G Cobra helicopter. The composite tail boom was required to meet the existing metal tail boom structural design and stiffness criteria, and to be interchangeable with the metal tail boom. The design objectives were to reduce the life cycle costs, to minimize the parts count, and lower the overall weight of the existing structure. The composite tail boom structure is a semi-monocoque configuration using a sandwich wall construction. The inner and outer skins are fabricated of Thornel 300 graphite filaments with epoxy resin, and the sandwich core is Nomex honeycomb. The filament winding technique was used in the fabrication of the major components. the composite tail boom successful satisfied the design criteria and objectives."

Table 8.20:	Stand-Alone CB Results of Problem 3, case 4
Retrieved Case #4	<u>Problem</u> "Design a stabilizer fin, which must be stiff and strong to withstand acoustic fluttering. The part is an all moving surface serving the functions of both elevator and aileron." <u>Response</u> "Thornell 300 and Narmco 5208 carbon-epoxy unidirectional tape was used. Caps, webs, stiffeners, and rib attachments were cured in an autoclave. The spars were molded in a steel matched-die tool using a thermal elastomeric process." <u>Story</u> "A vertical fin for a Lockheed commercial air transport was constructed using carbon-epoxy composites. The use of composites resulted in a 25% decrease in weight over all-metal designs. The number of ribs was reduced from 17 to 11 and the number of parts and fasteners was reduced 72% and 83% respectively."

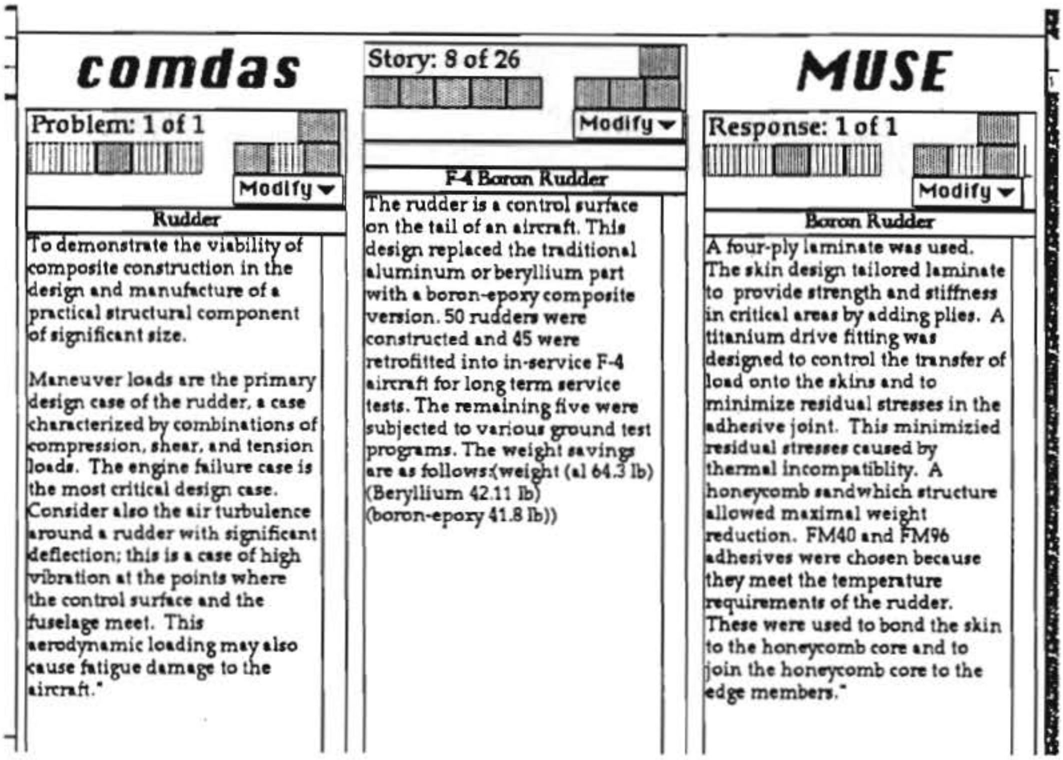


Figure 8.15: Retrieved Case #1 From Case Base on Problem 3

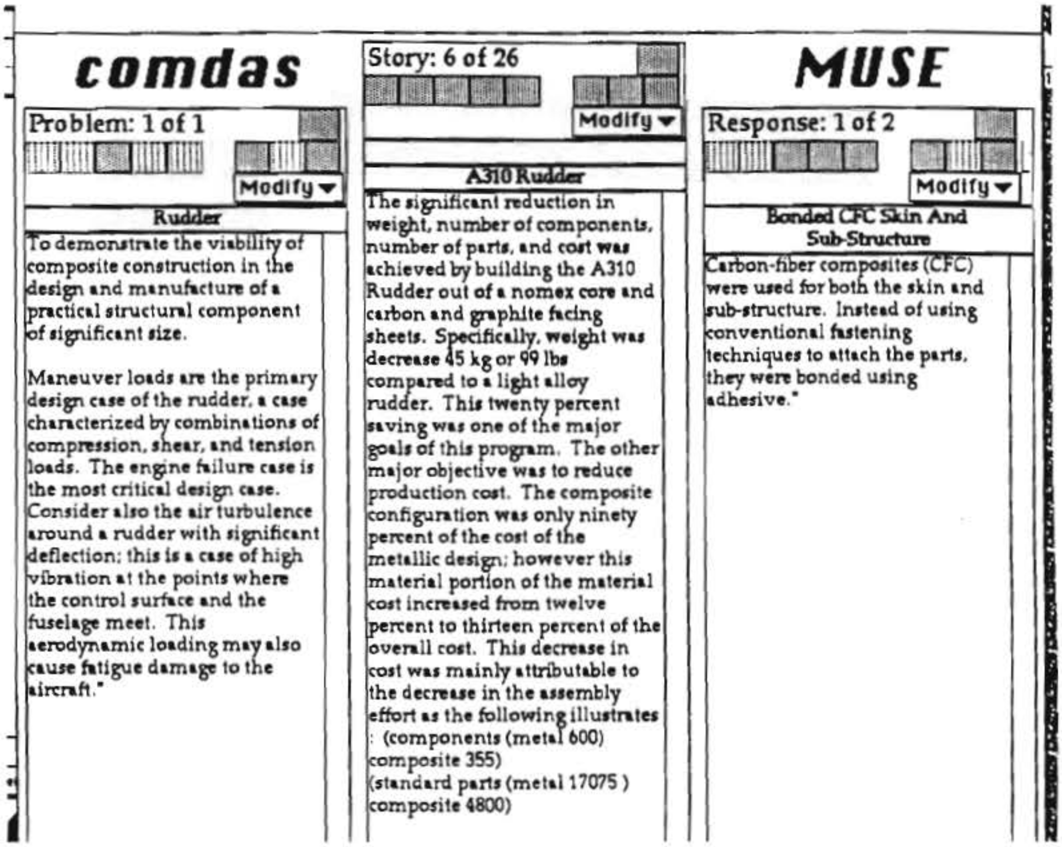


Figure 8.16: Retrieved Case #2 From Case Base on Problem 3

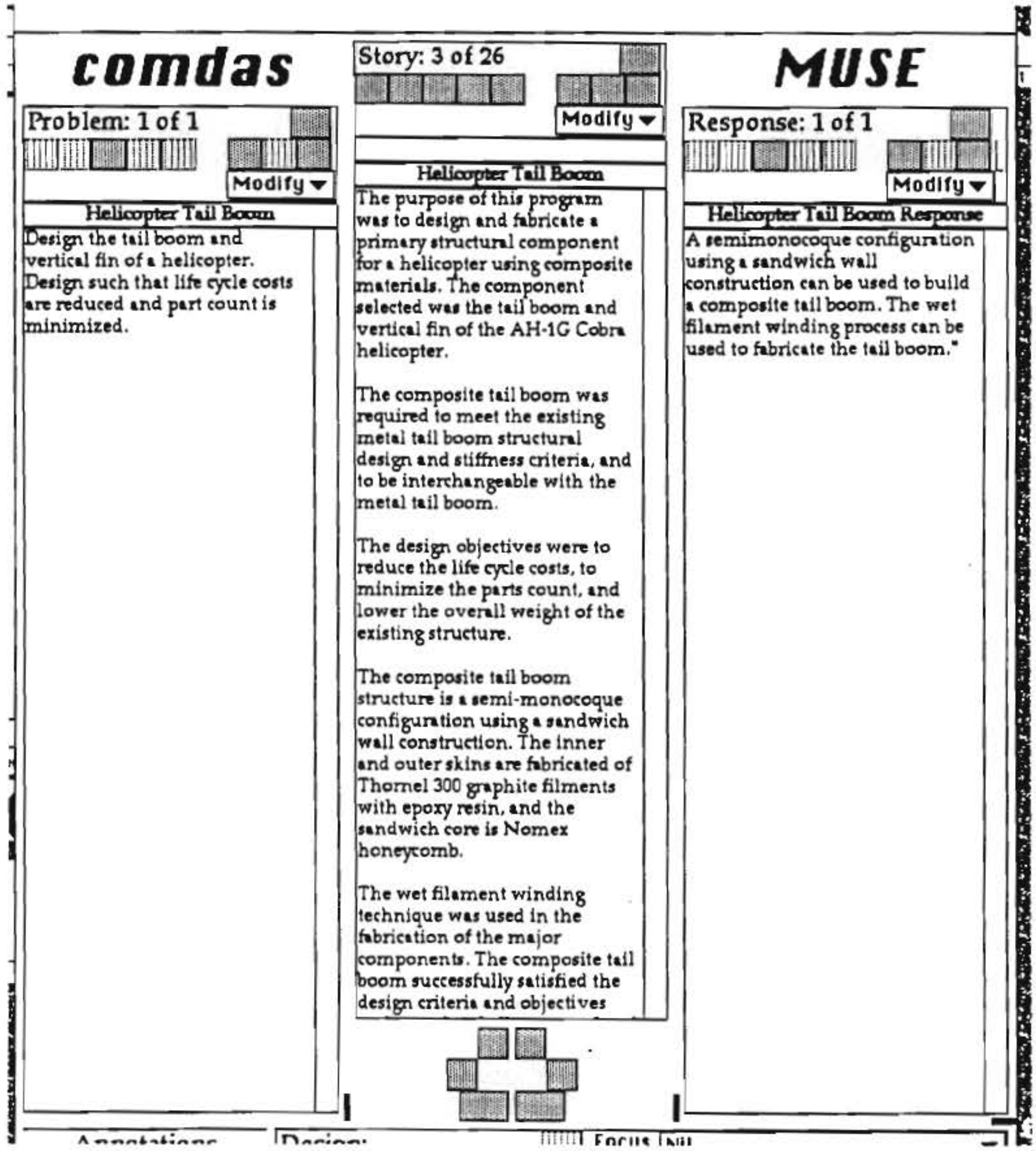


Figure 8.17: Retrieved Case #3 From Case Base on Problem 3

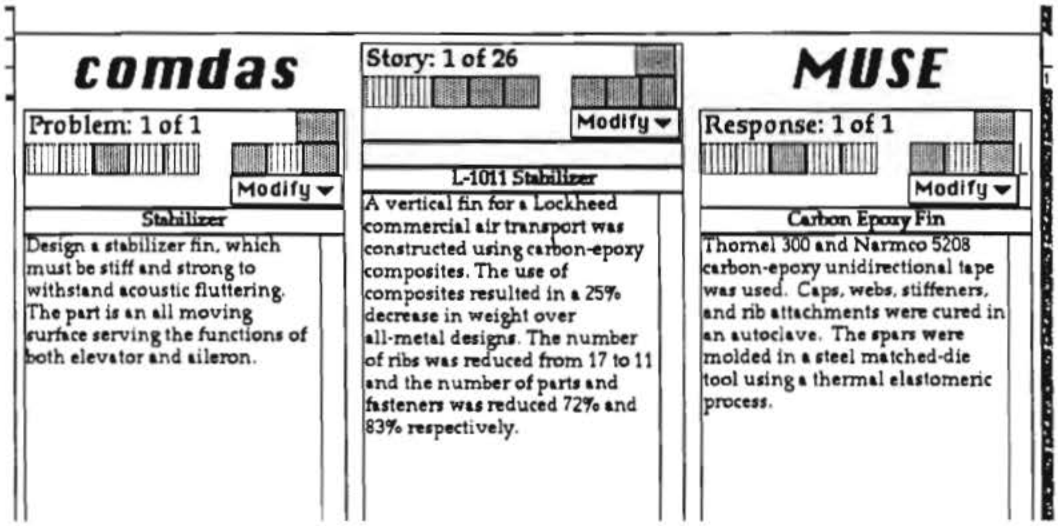


Figure 8.18: Retrieved Case #4 From Case Base on Problem 3

S2

1) Part Function is Control Steering
2) Material is Graphite/Epoxy
3) Part Name is Rudder
4) Aircraft is Passenger
5) +- 45 Lamina on Outer Surface
6) Material Form is Fabric or Tape
7) Issue is Differing Coefficients of Thermal Expansion
8) Fasteners or adhesive for bonding
9) Use Titanium Drive Fitting

Figure 8.19: Design Problem 3, DCS(P3,S_{2j})

8.3.1 Discussion of Problem 3 Results

Table 8.21 tabulates and compares the results from ComDAS to that of the original production results. The case base was very successful in retrieving four cases which were very similar in design to problem 3. The cases suggested ideas of addressing vibrational and flutter loads experienced by the rudder. Also the cases depicted how designers minimized residual stresses (a point brought out in the suggestions of the knowledge base) and used adhesives rather than fasteners to bond skins to honeycomb cores and the cores to the edge members. The knowledge base helped to address the issue of

Table 8.21: Comparison of ComDAS Results to Actual Production Results \ Problem 3

	Actual Production Results	*ComDAS*	
		Case-Based Contribution	*Knowledge-Based Contribution*
Problem Areas Missed in Conceptual Design	none	none	none
Potential Problem Areas Picked Up in Conceptual Design	none	1) Maneuver loads are the primary design case of the rudder, a case characterized by combinations of compression, shear, and tension loads. The engine failure case is the most critical design case. Consider also the air turbulence around a rudder with significant deflection; this is a case of high vibration at the points where the control surface and the fuselage meet. This aerodynamic loading may also cause fatigue damage to the aircraft.	none
New Ideas Generated	none	1) "A four-ply laminate was used. 2) A titanium drive fitting was designed to control the transfer of load onto the skins and to minimize residual stresses in the adhesive joint. This minimized residual stresses caused by thermal incompatibility. 3) A honeycomb sandwich structure allowed maximal weight reduction. 4) Carbon/fiber composites were used for both the skin and sub-structure. 5) Instead of using conventional fastening techniques to attach the parts, they were bonded using adhesive. 6) The significant reduction in weight, number of components, number of parts, and cost was achieved by building the A310 rudder out of a nomex core and carbon and graphite facing sheets. 7) A semi-monocoque configuration using a sandwich wall construction can be used to build a composite tail boom. The wet filament winding process can be used to fabricate the tail boom.	none

built-in residual stresses by suggesting the use of low coefficient of thermal expansion tooling such as carbon/graphite composite, monolithic graphite, or ceramic.

8.4 Further Discussion of Results

8.4.1 System Performance

Figure 8.20 graphs the results found in tables 8.6, 8.13, and 8.21. Specifically, figure 8.20 shows the number of *problem areas missed in conceptual design, potential problem areas picked up in conceptual design, and new ideas generated during conceptual design* by the actual production programs and the knowledge-based and case-based reasoning method. The number of potential problem areas detected were measured by tallying the number of recommendations from both the knowledge base and case base which directly addressed problems that the designer and engineers had during the prototype stage. The number of new ideas generated were measured by the number of recommendations from both the knowledge base and case base which depicted design and manufacturing techniques other than those used in the actual production program. It is important to note that as the design information available during the beginning of the design decreased, see test problem 3, the amount of new ideas generated by retrieved cases from the case

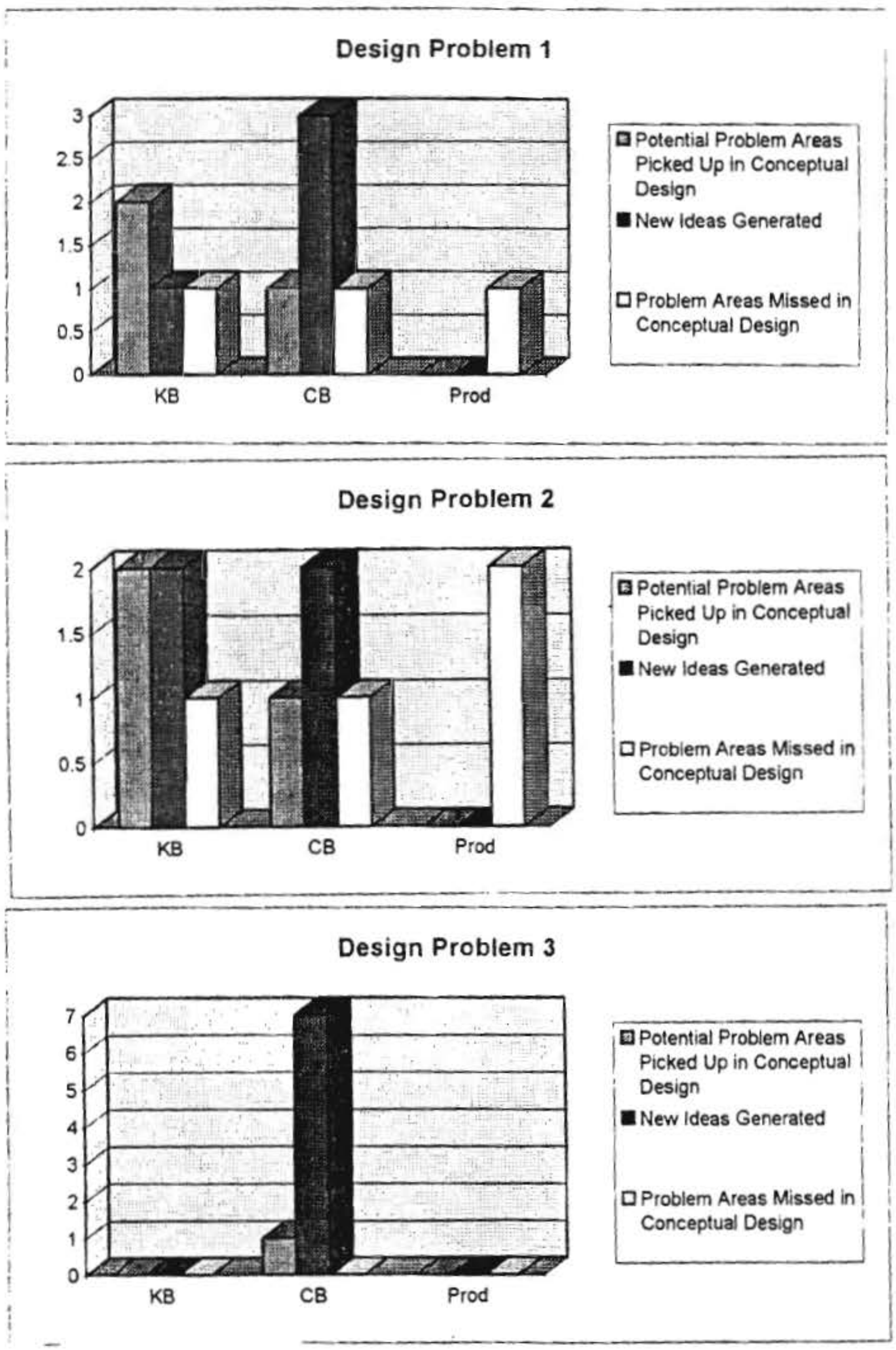


Figure 8.20: Comparison of Production, Knowledge Base, Case Base And Results from ComDAS

base increased. This is made possible through the fact that the case-based reasoning part of ComDAS is capable of reasoning upon incomplete information. The knowledge base however, does not have this capability. One can see that when detailed design information was available during the beginning of the design process, see problem 1, the amount of information provided by the knowledge base increased. This is because the knowledge base infers solutions based upon well-structured and not incomplete knowledge. These are characteristics of the knowledge base and case base which were discussed in chapters 1, 4, and 5 and part of the reasons why these two reasoning methods were chosen for this research.

The original hypothesis of this research was that the design of flat panel fiber reinforced composite structures could be improved with the aid of a knowledge-based and case-based reasoning system. The results shown above have proven this hypothesis to be true under certain conditions as explained below.

8.4.2 Design Automation vs. Design Advisory

First, as believed, the knowledge-based and case-based reasoning method with the DCS is not capable of automating the entire conceptual design process for flat panel composite structures. The nature of the domain precludes taking the human designer out of the design process. But, based upon system results, and as suspected, it has proven to be an excellent assistant to the designer. Specifically, the results of the method provided the designer with new ideas for solving the problem. The system also warned the designer of potential problems which may result under certain conditions and how to address them. The method also proved to be better as a design advisory system than either the knowledge base or case base individually. Tables 8.6, 8.13, and 8.21 show the results of the separate use of the knowledge base and the case base, but also show that a more robust problem solving environment is created when the two are combined.

8.4.3 System Usability

The software that resulted from this research is a prototype system. Additional work needs to be conducted to turn it into a production system, as discussed in chapter 9. Currently the system is relatively easy to use. The knowledge base is query driven. The user only responds to the questions asked by the knowledge base. The amount of time it took to respond to all of the questions asked by the knowledge base for each test case shown above, was, on average 15 minutes. This is a minimal amount of time to invest compared to the potential time savings from the knowledge base's suggestions. The case base was also easy to use. The user inputs information into the *find* window only. The number of cases retrieved from the case base depends upon the information given, the number of cases in the case base, and the retrieval mechanism invoked. Consequently, the amount of time needed to review the retrieved cases will vary. For the test cases shown above, the time required to review the retrieved cases was, on average, 10 to 20 minutes. Again, a minimal amount of time to invest compared to the potential time savings which may result from the case base's suggestions.

Therefore, the system is not difficult to use. It does require that the user have a working knowledge of the design of composite structures. The system is easy to learn and is not at all complicated. The majority of the system matches the user's intuition and normal ways of practice. The part of the system that is not very intuitive is that of building and refining the DCS. This part the research could use improvement such that the user is not burdened with this responsibility. This matter is addresses in chapter 9 section 2. The screen layouts of the system are fairly simple, and easy to navigate once the user is shown how. It is the researcher's opinion that a designer would take the time to provide the design advisory system with all of the information required.

8.4.4 Case Base Vocabulary And Weighting Issues

During the first run of problem #1 it was observed that it was very difficult to describe most of the problem in the case base side of ComDAS. A review of the then current indexing vocabulary and dimensions was conducted. It was determined that the indexing dimensions and vocabulary was not complete. It did not include all of the vocabulary by which a designer would describe the design characteristics. Therefore, the vocabulary was expanded which resulted in a modification to the search indexing structure and a refinement of existing cases index. Also, during the first run of problem #1 the retrieved cases did not seem to match the issues of the design problem. After analyzing the system, it was determined that the index weightings of the index class were not correct, (see figure 7.4). For example, a higher weighting was assigned to the *Design-For-X* index type than for *environment*. However, the current system would yield more information based upon environment issues rather than designing for a particular effect, such as assembly. The weightings were changed to provide a higher weight to *environment* and a lower weight to *Design-For-X*. The system then began to retrieve cases commensurate with the current design problem.

8.4.5 Knowledge Base Accurate Knowledge Representation Issues

One observation of using the stand-alone knowledge base is that it is difficult for the user to fully describe the design. Although the knowledge base works off of a detailed set of factual knowledge, it's not easy to represent the intent of the designer by just a knowledge base. A knowledge base can only partially represent the meaning of natural language constructs and phrases. For example, the designer's description of design problem 1 (appendix F) reads as follows: *"Design a composite part/structure to be a landing gear door. It must carry airload pressures in open and closed positions. It must meet deflection criteria to prevent the door from hitting the gear in the open position and to prevent gaps in the closed position. It must be attached to the gear assembly by three lugs".*

This is an accurate description of what is required and where the potential problem areas lie. Though most of the information within the statement can be represented in the knowledge base (e.g., (function as door), (airload pressures), (deflection critical), (mating hinges)), some of the voice of the customer is lost in the transition. Such as, it is obvious that deflection is an important issue, but it is not possible to tell the system why. Or, that airload pressures are significant, but how can the system know this condition is true for both the open and closed positions. The first thought to resolve this problem would be to create a more detailed and descriptive factual knowledge set that would be understood by the knowledge base. This has been the discussion of many research efforts. This begs the question: How does one create a knowledge representation mechanism without an inclusion of and interpretation of the entire english vocabulary? It is not within the purview of this research and is in itself a difficult problem to solve.

8.4.6 The Design Characteristic State

The Design Characteristics State (DCS) performed well at representing the attribute-value pair knowledge from both the knowledge base and the case base. By using the DCS only one repository of design information was needed for each test case. For each test case a maximum of two states were generated. The intent was only to support proof of the hypothesis. Multiple design iterations and trade studies can be supported using the DCS but are not necessary for this proof see section 6.4.

Together the results of the knowledge base and case base can aid a designer in the design process and potentially reduce the product lead time. The method has proved to be better than the individual systems alone and an excellent assistant to the human designer. However, there are limitations as discussed in section 8.5. At this stage of the research, it is difficult to quantify the potential design and manufacturing time savings. However, it has been agreed by the experts that if these rules and cases were presented during the original design problem attempt, it is highly probable that design time could have been reduced. The results of ComDAS were reviewed by the experts and received excellent reviews. The experts stated that this is a great prototype system, but would need more detail to develop into a production tool. The detail is that of being able to represent more complex designs.

8.5 Issues For Development Across Other Domains

Below is a discussion of various issues pertaining to the development of such systems as design advisory applications and repositories for design information.

8.5.1 Acquisition And Structuring of Previous Design Cases

The case base library which resulted from this work currently contains approximately 65 cases. Most of these cases were extracted from published books, reports, and designer journals. The indexes of each case are those descriptors which depict the important characteristics of a case and the potential lessons that may be learned, see chapter 5. An important issue in development of case libraries for design advisory purposes is that of who extracts the cases, builds the indexes, and structures them into the library. In order to determine what lessons a case may potentially teach, the knowledge engineer must have a very good working knowledge and understanding of the problem domain. Therefore, it is important that an individual with experience within the selected domain be selected to perform the case acquisition and structuring. If the cases are not indexed and structured correctly, the wrong information may be sent back to the user at case retrieval time. This may be a benefit to large corporations that have documented many previous design cases and need to put them into one easily accessible repository. The company can choose an existing experienced employee to perform the case acquisition, indexing, and structuring to build the case library. This saves time and money from having to hire an outside consulting firm that may not have the needed experience in that particular domain. It may be a good practice for companies to start having their designers and engineers document all of their designs for integration into a case library. This would facilitate the populating of the case library that could be accessed by other employees when necessary.

8.5.2 Number of Rules And Cases Needed

In building these types of systems there is always the question of how much information is enough. How many rules and/or cases are needed to build a knowledge-based or case-based system? There is no formula or magical number that can be used to determine the number of rules and cases needed. The most important detail to remember here is that it is the content of the knowledge that matters most. For example, 5 design cases that teach several lessons, are well documented, and indexed correctly are far better than 15 that give no insight nor teach any lessons. In developing new applications it is always a good idea to start out with a subset of the domain knowledge and build from there. This reduces the initial number of rules and cases and facilitates the knowledge acquisition process, software development, testing and knowledge validation.

8.5.3 Knowledge Base And Case Base Order of Execution

Within this work, the information contained in the DCS was fed into the knowledge base first. The user has the option of taking results from the knowledge base, adding them to the DCS, and inputing this data into the case base. The user could also use the same input data for the case base as for the knowledge base. The reasoning for feeding results from the knowledge base to the case base is that the heuristics or rules-of-thumb from the knowledge base provide the core domain knowledge. If necessary, the rules can explain the reasoning behind the results from the knowledge base. It is fairly straight forward to develop attribute-value pairs from the results of the knowledge base. The case base knowledge however, may not be intuitively obvious as input to the knowledge base since much of its content is free form text. The task of using case base knowledge as input to the knowledge base may be difficult, yet not impossible, especially if the process of transferring the DCS data contents is totally automated. However, there may be substantial benefits of feeding output from the case base into the knowledge base. For example, suppose that the cases were structured well enough that such that rules could be created from their output. Several of these rules could potentially create algorithms or procedures. These could be algorithms or procedures that are not included in the rule base. Therefore, a totally different method of problem solving could be generated from feeding knowledge into the case base prior to the knowledge base. The hurdle is being able to structure the cases well enough or having an elaborate natural language interpreter, such that rules can be generated from the case text.

8.5.4 Temporal Issues of Acquired Knowledge

The test cases used within this research were all fairly recent designs from industry. The landing gear door was designed in 1992, and the aileron and rudder in 1989. All of the similar design cases retrieved during the system tests were originally designed and manufactured prior to 1989. The majority of these retrieved cases were programs which were initiated in the late 70's to mid 80's. However, one of the metrics for this research is to measure the number of potential problems generated from the system vs. those not picked up by the designer during the actual production program, see sections 1.4 and 8.4.1. If the cases retrieved were designed and developed after those of the test designs, then based upon the metrics used, a fair comparison would not have resulted. The cases may have given information concerning a design or manufacturing technique that was not even available to or known by the designer. This has not been the case with this research, however, it is an issue which should be taken into consideration when developing such systems. The issue is that if new similar design cases are used to provide design and manufacturing insight to a design that was started prior to the retrieved case, then a different metric for determining effectiveness needs to be used.

8.6 Limitations

Table 8.22 compares the ideal system of table 2.1 to the prototype developed under this research. Overall the knowledge base and case base performed very well as a design aid for flat panel composite structures. The main limitation of the system is that construction and refinement of the DCS is not fully automated. During the system tests, the design requirements, specification, and constraints had to be manually transferred from the knowledge base to the case base and back. Although this is not necessarily a problem, it is preferred to have a nearly seamless integration between the knowledge base and the case base. Each could transfer the requirements to the other transparently to the user. Rules would be fired and cases retrieved when needed. This, however, is not a simple task and can possibly become the topic of a future research problem. The researcher's suggestion for overcoming this is to create an Application Programming Interface (API) for each piece of software specifically for the elements in the Design Characteristic State. But, there would also need to be some sort of natural language interpretation component as the information passed between the knowledge base and case base may have the same meaning but not necessarily use the same descriptors.

Other limitations were encountered, but were minor and overcome. For example, the CLIPS environment is sensitive to

Table 8.22: Comparison of ComDAS With Ideal Fiber-Reinforced Composites Design Assistant

	Ideal Design Assistant	ComDAS	
			Short-falls from Ideal System
Knowledge of domain commensurate with scope of design assistant.	✓	✓	Limited conceptual design capability implemented in prototype. Scope needs to be broadened for production system.
Automation of repetitive procedural tasks.	✓	✓	
Easy-to-use interface.	✓		Knowledge base interface would be better implemented as a GUI.
Data storage capability.	✓		ComDAS only has factual data storage capability for the knowledge base. Nothing along the lines of a database.
Ability to suggest multiple solution techniques.	✓	✓	
Capability of providing previous similar design cases.	✓	✓	
Ability to reason upon temporal design information provided by user.	✓	✓	
2-D and/or 3-D design.	✓		ComDAS does not have 2-D or 3-D graphical design capability.
Ability to reason upon incomplete design information.	✓	✓	
Provide a design history log.	✓		ComDAS does not have a design history log except for the DCS as described in chapter 6.
Modularity.	✓		Porting Design-MUSE to another platform may require a substantial investment of man-hours because of its complexity.
Expandability.	✓	✓	
Ability to suggest solutions from both heuristic knowledge and previous similar designs.	✓	✓	
On-line help facility for users.	✓		ComDAS does not yet have an on line help facility.

the number of modules loaded at one time and thus aborts when that limit is reached. The researcher suspected that there may be an internal memory management solution to this problem. This problem was overcome by loading in 3 to 4 modules at a time. Also the Design MUSE environment is written in lisp and as the number of cases increase the run-time speed decreases.

8.7 Chapter Summary

Within this chapter has been presented three design problems. These problems were used to test the prototype Composites Design Advisory System (ComDAS). For each problem, the design specifications were given, actual production results were displayed, and the results from the knowledge base and case base components of ComDAS were presented. The results of ComDAS were compared to that of the actual production programs. Discussion of the results and other issues related to the performance of the prototype are also given. Chapter 9 concludes the research.

CHAPTER IX

CONCLUSIONS

The beginning objectives of this research have been met and additional observations and insights have been encountered. A description of how these objectives were met is as follows:

a. A prototype computer-aided design advisory system using a Knowledge-Based and Case-Based Reasoning method was developed (ComDAS).

b. The system provided a means for gathering disparate knowledge into one easily and readily available location.

c. The system automated the inclusion of composite structure life-cycle issues into the earliest stages of the design process by allowing the user to input design information. This objective was accomplished by way of the knowledge base.

d. The system included a case base which provided access to similar previous design cases.

e. In prototype tests, the system successfully provided the designer with information related to life-cycle issues based upon input data. The system also helped to suggest areas where there may be potentially unforeseen problems, and pitfalls.

f. Based on (a) through (d) above, and input from experts, the resulting system may assist in the reduction of product lead time.

Additional accomplishments and insights as a result of addressing some of the obstacles were as follows:

a. Knowledge acquisition and structuring of the knowledge base and case base architecture were facilitated by their complimentary features.

b. Division of labor between the knowledge base and the case base became clear through the interviews with the experts and the development of the Energy, Materials, and Information models.

c. Interaction between the knowledge base and the case base was facilitated through their working data and vocabulary and dimensions.

d. A method for developing knowledge-based and case-based reasoning systems to assist in conceptual design environments was created.

9.1 Potential Areas of Application

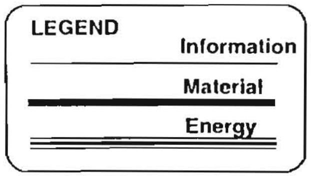
The method of using knowledge-based and case-based reasoning to assist in design environments is applicable to areas other than aircraft design. For example, printed circuit board design, automobile design, aerospace design, ship design, sporting goods design, and rail car design. Based on review of trade magazines and journals, there has been a considerable amount of effort in applying the use of composites to the above mentioned domains. The characteristic they share with this research is that of a limited amount of heuristic knowledge which can be applied to the composites design process. Also, the prototyping and testing programs may prove to be useable design cases for future projects. The actual implementation between these areas may be different, but the underlying method would be the same. One important criterium exists in determining the use of knowledge-based and case-based reasoning to a particular domain. That is to ensure the character of the application area fits that of rule based and case based reasoning. For example, if there existed a domain with a lot of data and very little heuristic knowledge or history, then neural networks or genetic algorithms may be a better solution.

9.2 Future Research

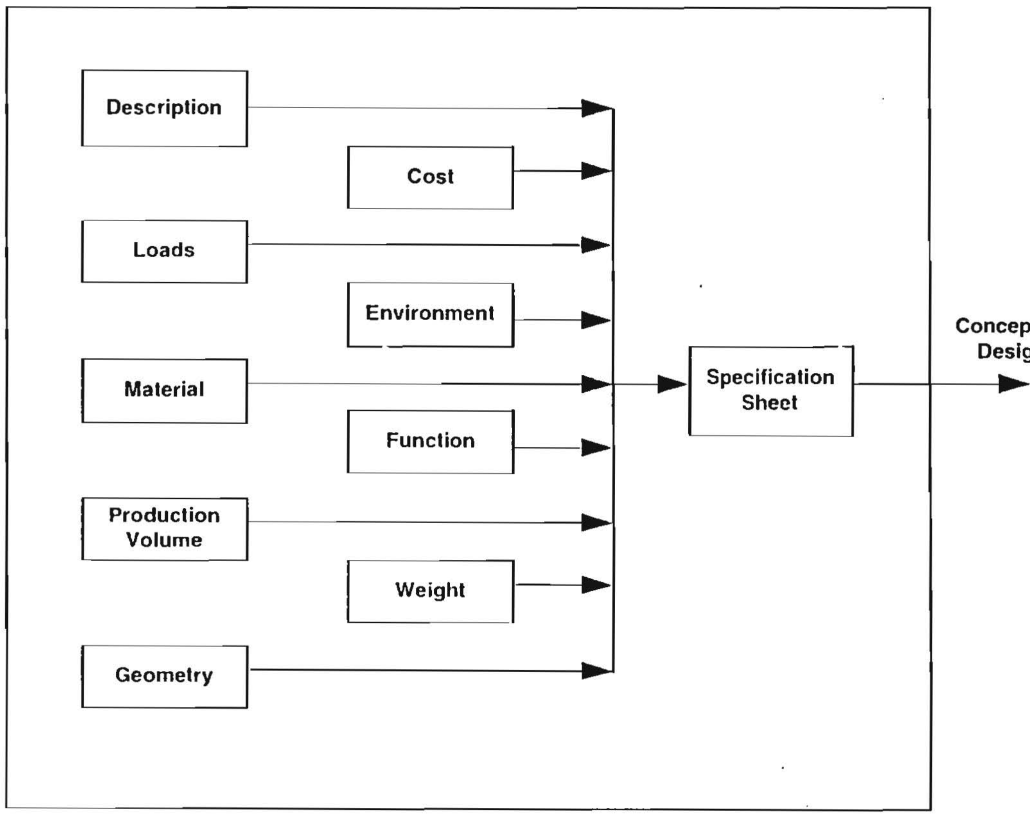
There are a few research efforts that could be extensions of this research project. Some would simply be modifications to the existing work for greater efficiency. Others would expand the research beyond its current scope. The first would be that of creating a seamless integration between the knowledge base and the case base. This would allow for the

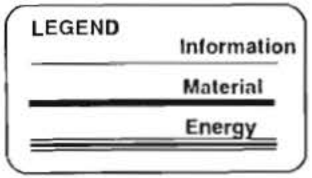
Appendix A

Product LifeCycle EMI Models

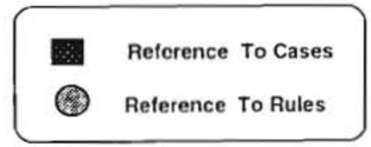


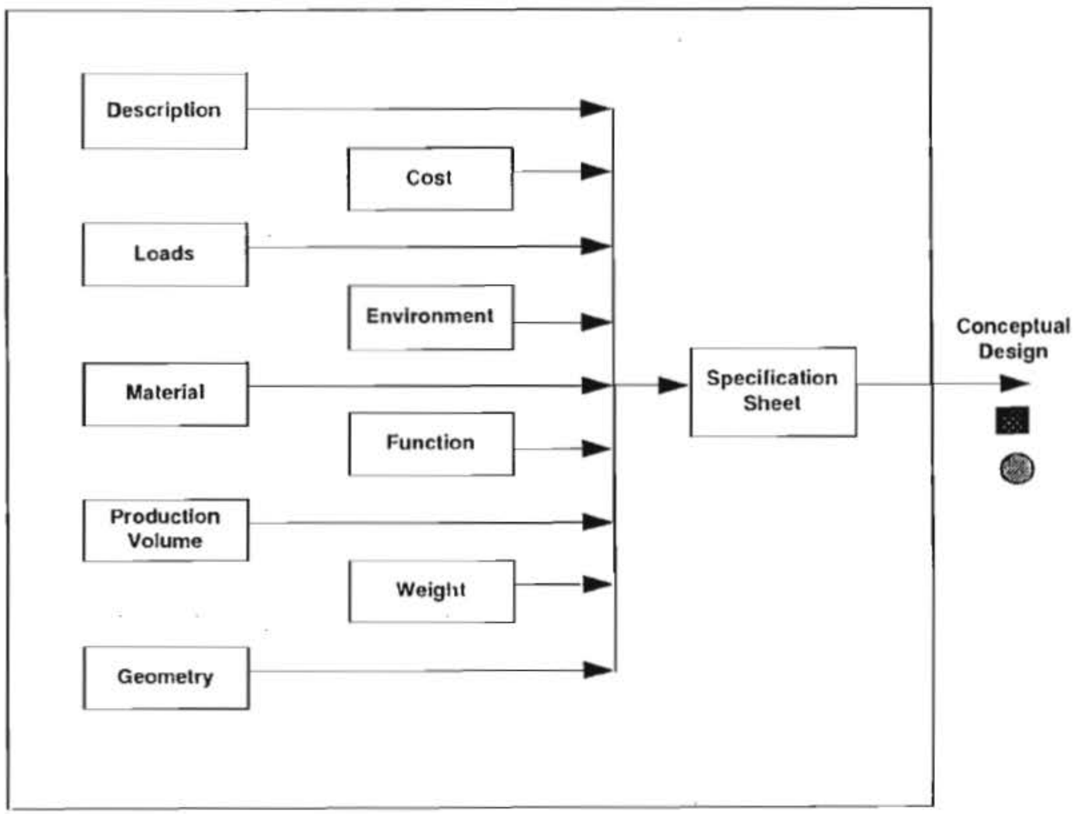
COMPOSITE PANEL SPECIFICATION DESIGN



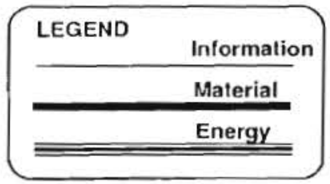


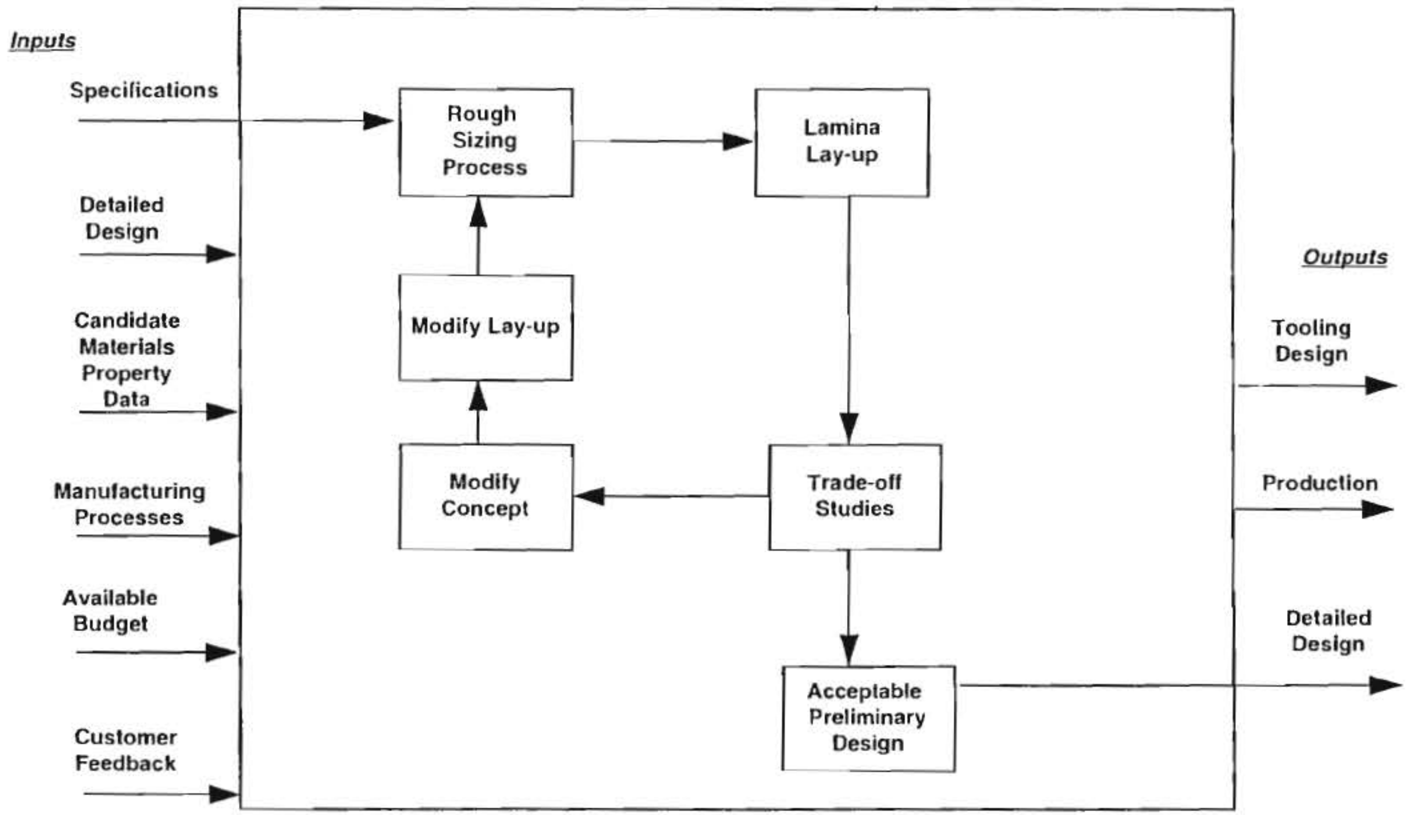
COMPOSITE PANEL SPECIFICATION DESIGN



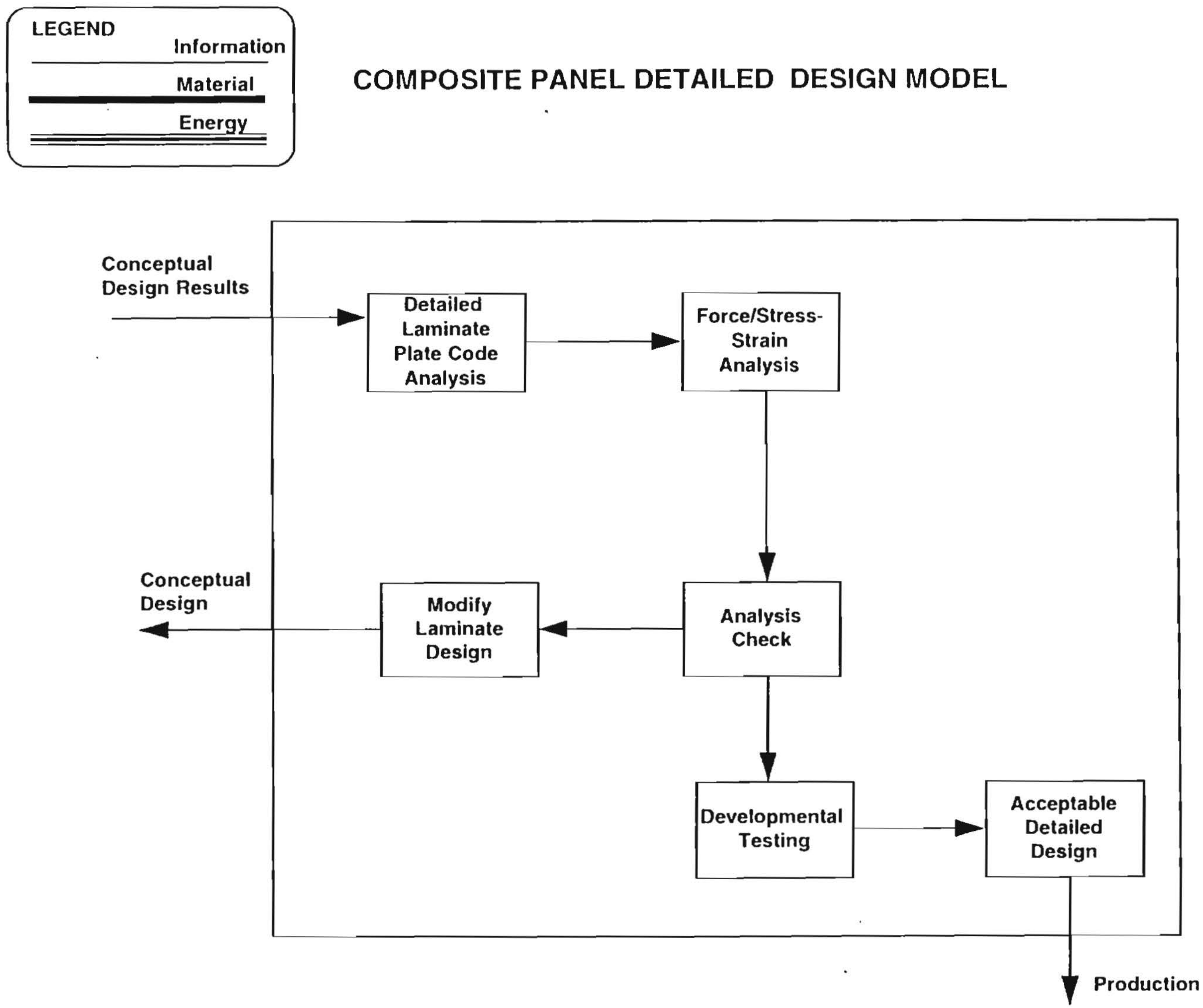


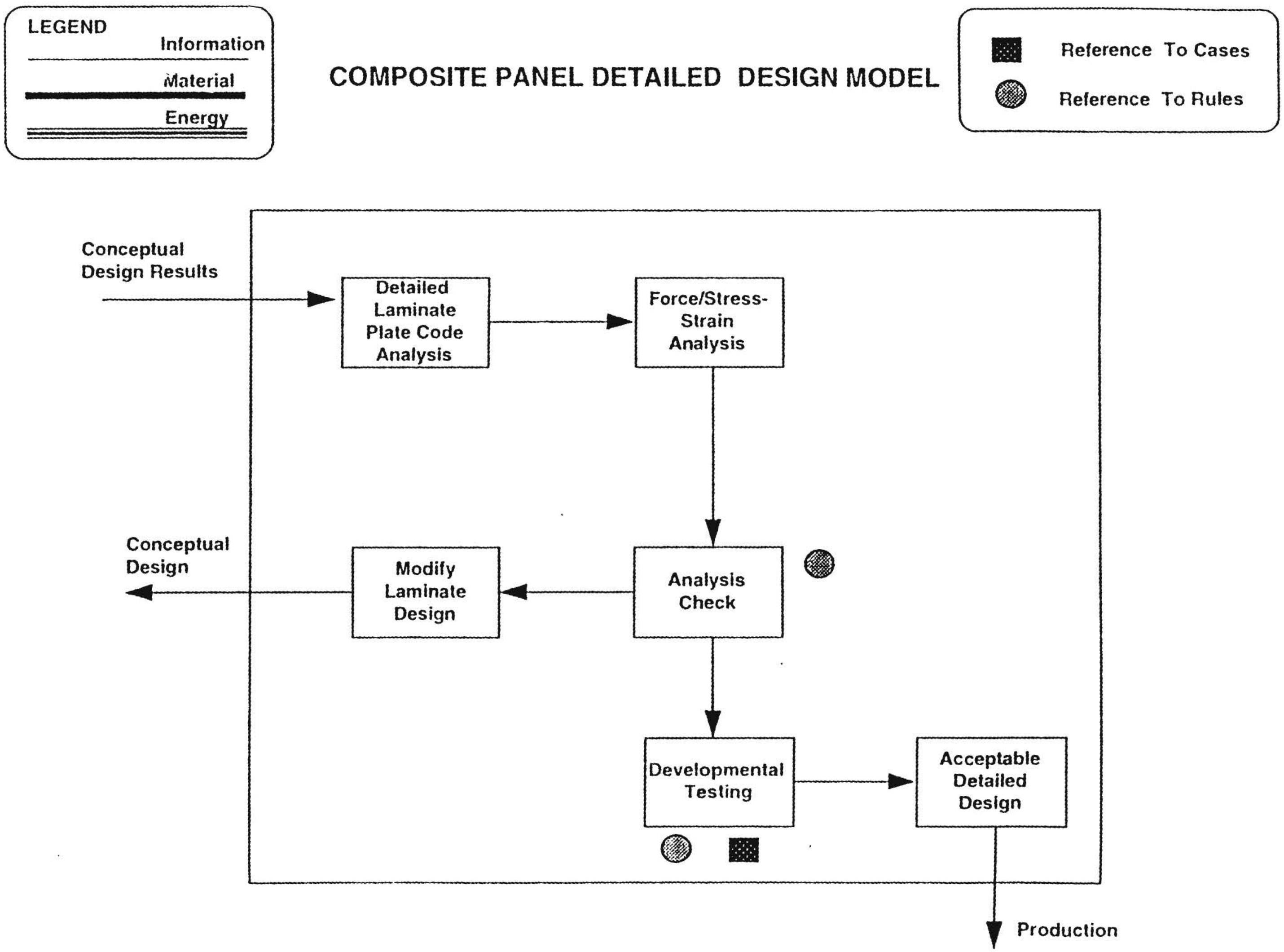
COMPOSITE PANEL CONCEPTUAL DESIGN MODEL





COMPOSITE PANEL DETAILED DESIGN MODEL

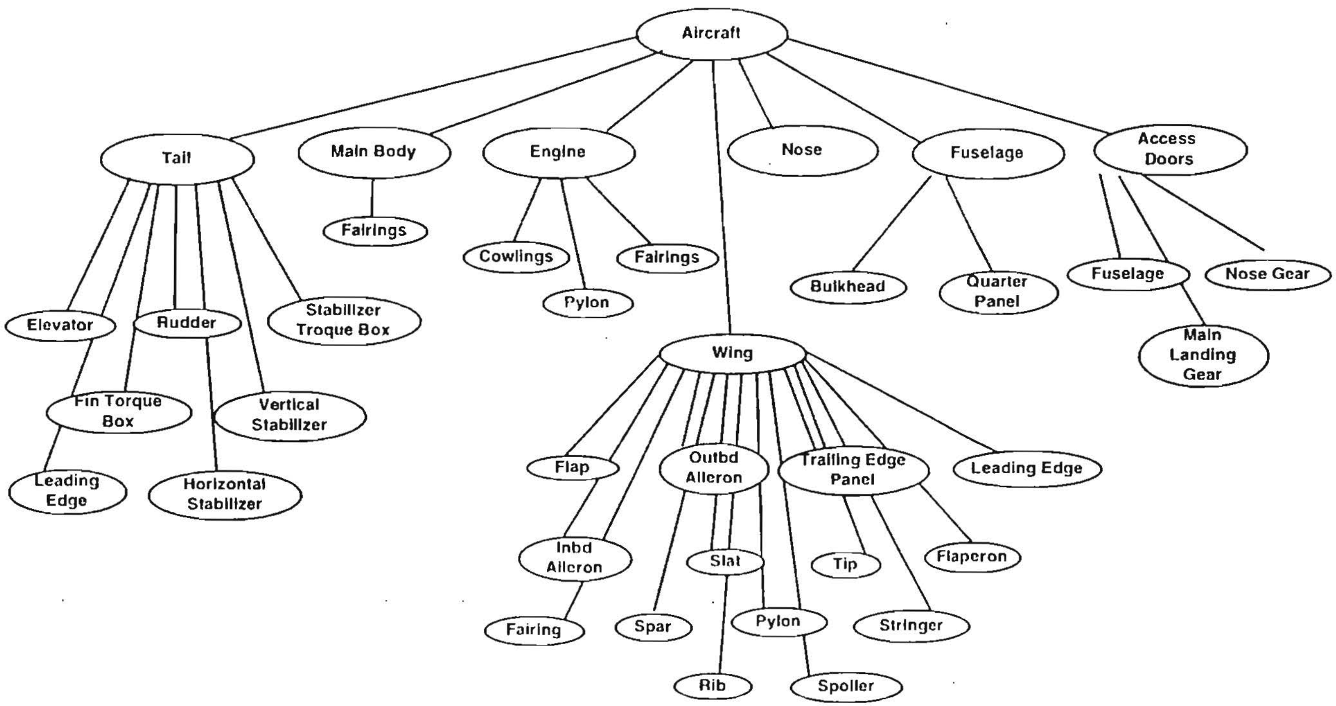



LEGEND
Information
Material
Energy
COMPOSITE PANEL DETAILED DESIGN MODEL
Reference To Cases
Reference To Rules
Conceptual Design Results
Detailed Laminate Plate Code Analysis
Force/Stress-Strain Analysis
Conceptual Design
Modify Laminate Design
Analysis Check
Developmental Testing
Acceptable Detailed Design
Production

Appendix C

Hierarchical Decompositions From Knowledge Acquisition

AIRCRAFT HIERARCHICAL DECOMPOSITION



Composite Panel Design Problem

Problem Description

Design a composite part/structure to *be a landing gear door. Must carry airload pressures in open and closed positions. Must meet deflection criteria to prevent door from hitting the gear in the open position and to prevent gaps in the closed position. Attached to gear assembly by 3 lugs*

What Are The Design Specifications/Requirements?

What is the function of the part/structure? *moldline door*

e.g. bulkhead, stabilizer, shear panel, etc...

What is the loading spectra? Units *psi*

Axial Load ____ Transverse Load ____
Shear Load ____ Axial Stiffness ____
Transverse Stiffness ____ Shear Stiffness ____
Other ____ Other *Normal pressure of -10 to +5 psi*

What are the most important issues?
If more than 2, please rank in ascending order of importance.
Cost ____ Weight *1* Damage Tolerance *2*
Environmental Hazards ____ Repairability ____
Manufacturability ____ Design/Mfg. Time ____
Mating With Dissimilar Materials ____ Assembly ____
CoCuring ____ Recyclability ____ Tooling ____
Life Time ____ Other ____

What Were The Results?

Materials Used *Intermediate Modulus Carbon / Thermoplastic*

Material Forms Used *Unidirectional tape prepreg*

e.g. honeycomb, fabric...

Stacking Sequence *Skin = $(45, 90, -45, 0, 0, -45, 90, 45)_s$*
No. of +45's *4* No. of -45's *4* No. of 90's *4*
No. of 0's *4* Other *Stiffeners are same layup. Edgeband is combination of skin and stiffener layup*
Cure Method *Diaphragm forming in a heated press*
Tooling Method *Female tool for outer skin; Male for stiffeners*
Layup Method *Collate plies; form stiffeners & skin separately; bond together*

Any Special Features? Padups under the lugs to carry flat plate bending. Intersecting hat stiffeners

e.g. fasteners, joggles, inserts, etc...

What Problems Were Encountered?
1. Deflection criteria with air pressure loads, no peripheral attachments
2. Fixed lug locations, Interference with internal structure
3. stiffener pattern

How Were They Solved?
1. Used intersecting stiffeners.
2 Had to arrange stiffener pattern to be within certain periphery and close enough to lugs to minimize local bending
3. Had to work within manufacturing constraints on forming stiffeners, spacings

Estimate The Amount of Time it Took To:
Prepare a conceptual design ________
Obtain a detailed design ________
Research past similar designs ________
Build a prototype ________
Test ________
Build Final Part ________

or

Estimate The Time It Took From The Product Conception Through The Point of Final Production; Including Time For Testing, Prototyping, and Mistakes 3200 hrs

What Computer Aided Design Tools Were Used? CATIA, IDEAS finite element analysis

Additional information related to this particular problem is welcome and may be attached, e.g. figures, data, charts, notes...

X ________
Designer or Engineer

Any Special Features? Fasteners

e.g. fasteners, joggles, inserts, etc...

What Problems Were Encountered? Bridging & porosity in radii of the rib.

Large dimensional varience

How Were They Solved? Dimensional varience correctable in tool development.

Estimate The Amount of Time it Took To:
Prepare a conceptual design ______
Obtain a detailed design ______
Research past similar designs ______
Build a prototype ______
Test ______
Build Final Part ______

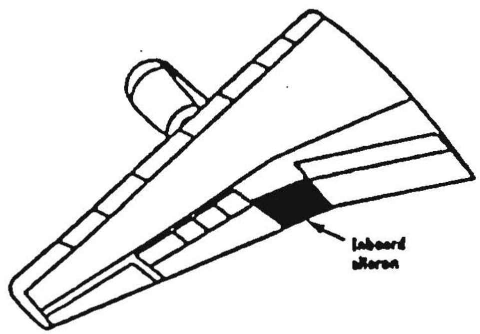
or

Estimate The Time It Took From The Product Conception Through The Point of Final Production; Including Time For Testing, Prototyping, and Mistakes 200 hrs

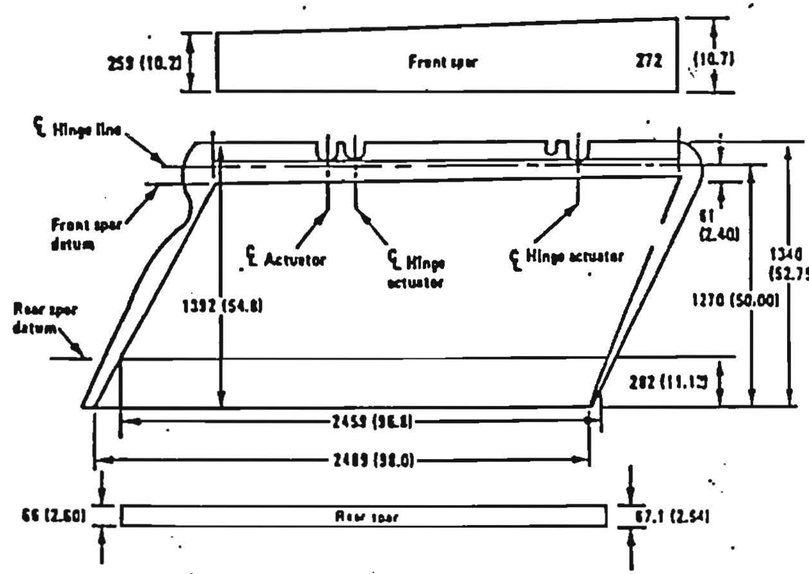
What Computer Aided Design Tools Were Used? CATIA

Additional information related to this particular problem is welcome and may be attached, e.g. figures, data, charts, notes...

X______________________
Designer or Engineer



Inboard aileron location on L-1011 wing.



Inboard aileron dimensions (All dimensions shown in mm (in)

Composite Panel Design Problem

Problem Description

Design a composite part/structure to control steering of a commercial passenger jet airliner.

What Are The Design Specifications/Requirements?

What is the function of the part/structure? Rudder (control surface)
e.g. bulkhead, stabilizer, shear panel, etc...

What is the loading spectra? Units —

Axial Load ____ Transverse Load ____
Shear Load ____ Axial Stiffness ____
Transverse Stiffness ____ Shear Stiffness ____
Other ____ Other ____

What are the most important issues?
If more than 2, please rank in ascending order of importance.
Cost ____ Weight ____ Damage Tolerance ____
Environmental Hazards ____ Repairability ____
Manufacturability ____ Design/Mfg. Time ____
Mating With Dissimilar Materials ____ Assembly ____
CoCuring ____ Recyclability ____ Tooling ____
Life Time ____ Other ____

What Were The Results?

Materials Used Graphite Epoxy

Material Forms Used ____
e.g. honeycomb, fabric...

Stacking Sequence —
No. of +45's ____ No. of -45's ____ No. of 90's ____
No. of 0's ____ Other ____

Cure Method Conventional Bagging
Tooling Method ____
Layup Method ____

Any Special Features? Assembly of rivet bonding and adhesive

e.g. fasteners, joggles, inserts, etc...

What Problems Were Encountered?

How Were They Solved?

Estimate The Amount of Time it Took To:
Prepare a conceptual design
Obtain a detailed design
Research past similar designs
Build a prototype
Test
Build Final Part

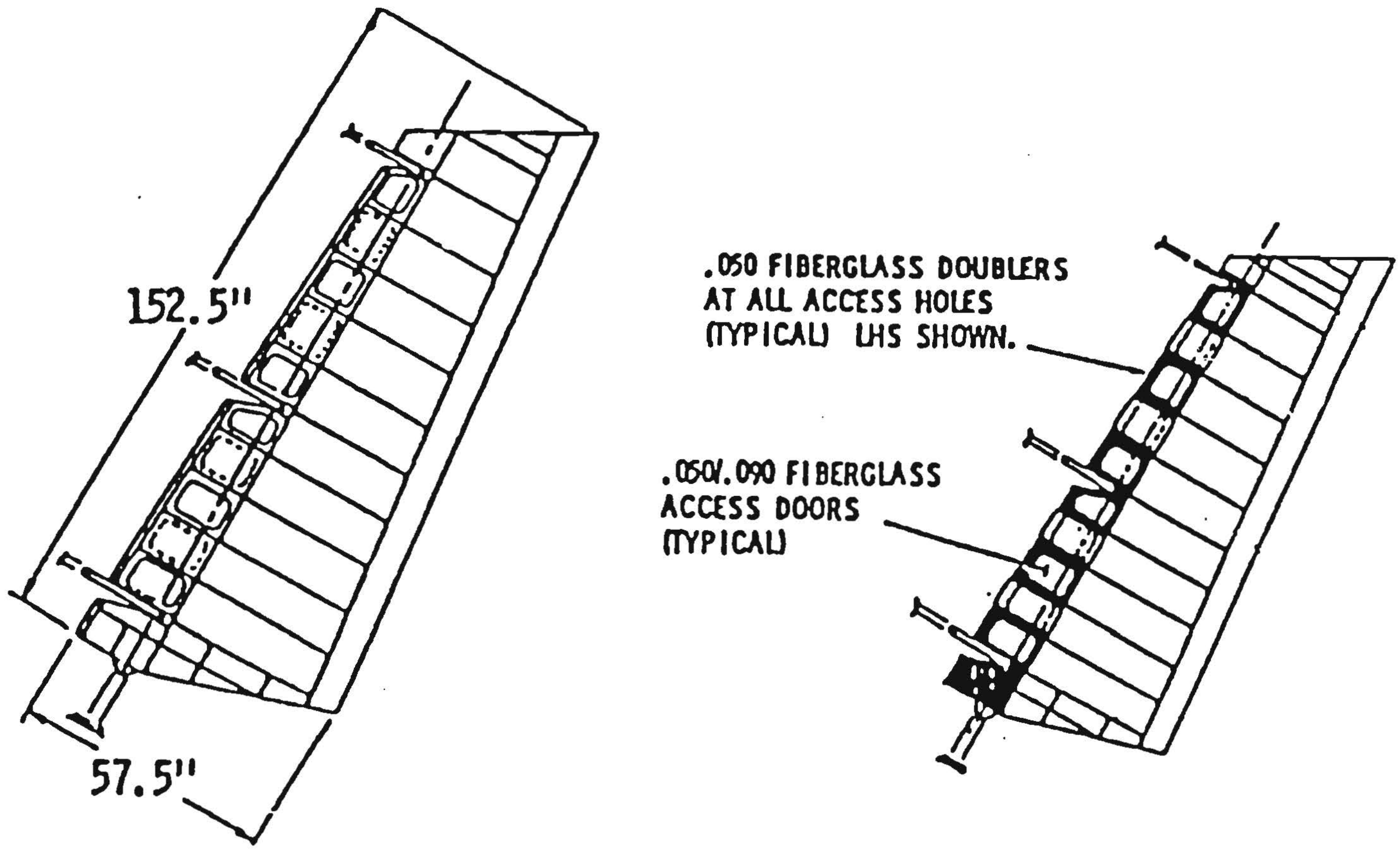
or

Estimate The Time It Took From The Product Conception Through The Point of Final Production; Including Time For Testing, Prototyping, and Mistakes

What Computer Aided Design Tools Were Used?

Additional information related to this particular problem is welcome and may be attached, e.g. figures, data, charts, notes...

X
Designer or Engineer



Design Problem 3, Rudder

Appendix E

List of Rules Generated From Knowledge Acquisition Process

Laminate Layup Rules

If the laminate is not balanced
and there is not a 0 or 90 ply about the midplane
Then the laminate must be balanced before continuing

If the laminate is not symmetrical about the mid-plane
Then the laminate must be balanced before continuing

If the outer ply of the laminate is 0 or 90
and the part function is compression panel
Then redo the laminate design

If the outer ply of the laminate is 0 or 90
and the part function is compression panel
and the ply form is fabric
Then redo the laminate design

If the number of 0 plies < 8% of total plies
or the number of 90 plies < 8% of total plies
or the number of +45 plies < 8% of total plies
or the number of -45 plies < 8% of total plies
Then redo the laminate design

IF the number of + 45 plies < 40% of total plies
or the number of -45 plies < 45% of total plies
Then redo the laminate design

IF the laminate thickness < 0.14 in
Then redo the laminate design
(Cumulative_Tolerance_Rules)

IF the part function is a fuel tank
and the laminate thickness < 0.08 in
Then redo the laminate design

IF there are more than 4 plies of the same orientation together
Then redo the laminate design

If the lamina position is adjacent to a bonded joint

and the lamina fiber orientation is not parallel to the direction of loading
or the lamina fiber orientation is not +- 45 to the direction of loading
Then redo the laminate design

If the angle between adjacent plies > 60 degrees
and the ply form is not fabric
and the number of plies > 16
Then redo the laminate

If the number of laminate plies < 7
The redo the laminate design

If the distance between the ADP steps is not ar least between .15 and .25 in
or the ADP's are not tapered
or the ADP slope angle is > 10 degrees
or the ADP's is > 10 plies based on ply thickness of 0.005 in/ply
or the ADP occurs on the outer surface
Then redo the ADP's

Loading Rules
If increase stability is needed
Then put +- 45's on the outer surface

If the part function is a compression column
Then put 0 or 90 plies on the outer surface or as far away from the midplane as possible

If the material chosen if thermoplastic
and the operating temperatures are high
Then investigate the design for creep effects

If there is a boundary where the composite laminate meets metal
Then check for induced stresses due to a high poissons ratio

If free edge effects are of concern
Then either minimize the angle between adjacent tape plies

or use unitape as a material form

If fatigue loading is present
Then check the design features which cause premature failure

If poisson ratio effect is considerable
or if there are bonded parts
Then use 90 degree plies in the laminate and reduce the number of 0 degree plies in the laminate

If either a steel or aluminum tool is being used for manufacture cure
Then severe residual or built-in strains can be induced in the component due to contraction during cool-down from peak cure cycle temperature

<u>Material Rules</u>

If a light and stiff structure is needed
and the part is not primary
Then consider using a honeycomb construction

If the part function is a fairing
or the part function is a close out
and the part is not primary
Then consider using a honeycomb construction

If honeycomb construction is used in the part
Then take precaution for affects due to moisture

If the part usage temperature range is 200F g.e. x l.e. 350F
and a material has not been selected
Then consider the use of BMI's

If the laminate is a hybrid
Then take precaution for possible internal thermal expansion effects

If a laminates' core material is aluminum
Then ensure it is isolated from carbon laminates

If thermal expansion effects are of concern
Then use symmetrical laminates or increase the number of plies in the 90 degree direction

If the shape of the part is complex
Then consider the use of a fabric as a material form

If the surface of the laminate needs to be smooth or flat
Then specify the tool surface side of the laminate or use tape as a material form for the outer plies or use a caul plate during cure.

If the shape of the part is simple and high mechanical strength is needed
Then consider the use of tape as a material form

If honeycomb construction is used in the part
Then the structure can be fabricated either by co-curing the components together or utilizing secondary adhesive bonding

If the parts usage temperature g.e. 350F
Then use thermoset materials

If the parts usage temperature is 350F > x l.e. 700F
Then use thermoplastic or polymide materials

IF a low CTE is needed
    and the part can use metal as a material form
Then consider the use of Invar 36 or Invar 42 as material

<u>Failure Rules</u>

If the part function is a compression panel
    and the part loading is fatigue
Then take into consideration that cracks may develop between the 0 an 90 plies. This may cause delamination

If there is a concern of delamination at a joint
Then consider the addition of fasteners

If the laminate contains either a hole or other strength reducing features
Then the strength retention is increased by adding +- 45 plies to the orientation. Load carry capacity may be reduced

If the laminate loading is fatigue
and the laminate has notches
or the laminate has sharp corners
or the laminate has abrupt changes in cross section
or the laminate has local ply padups
or the laminate has fastened joints
or the laminate has joggles
Then take into consideration the possibility of premature failure

Environment Rules
If the material is thermoplastic
Then expect to pick up .3% to .5% of the structures weight in moisture. Expect a 5% to 10% reduction in material properties

If the material is BMI
Then expect to pick up 1% of the structures weight in moisture. Expect a 5% to 10% reduction in material properties (mainly matrix dominated properties, compression and shear). At higher temperatures expect even a 40% to 50% reduction

If lightening strikes may occur at the altitude the craft is operating
Then do not use aluminum cores in areas where strikes may occur

If the part usage environment is space
and one of the material forms is honeycomb
Then one face sheet having widely spaced small perforations to release trapped air should be used.

Life Cycle Rules
If the part has to withstand any amount of damage tolerance
Then consider the use of +-45 fabric on the outer surface

If the part has to withstand any amount of damage tolerance
Then design for repairability and replaceability

If damage tolerance is of any concern
    or if specifically impact resistance
Then consider adding materials to form a hybrid such as kevlar and fiberglass to the basic carbon laminate

<u>Geometric Rules</u>

If the part is to contain any contours or radii
Then avoid shape changes in the surface contours and avoid tight radii

If the part must adhere to tolerances
Then the tolerances should be as large as the use function of the part will allow

If the part must have sharp contour changes
Then use woven fabric as a material form

If close tolerance needs to be held on both face dimension
Then consider using a matched mold die for manufacture

<u>Manufacturing Rules</u>

If the part requires joining of some type
Then use cocured or coconsolidated assemblies when possible

If the parts material form is honeycomb
Then thermoset laminates may be cocured together with the honeycomb core

If the parts material form is honeycomb
    and cocuring is not possible
Then an adhesive layer can be placed between the precured laminates and the core, then the assembly heated to cure the adhesive layer

If the part material form is honeycomb
    and the sandwich panel is cocured
    and a smooth surface on the bag side is needed
Then use a caul plate to reduce dimpling

If inspection of part components is needed prior to assembly
or a smooth surface on both sides are needed
and the material form is honeycomb
Then consider secondary curing

If the part contains edge close outs
and the material form is honeycomb
Then the core must be carved at about 30 degrees or less to minimize angular bond pressure loading

If the method of cure is autoclave
and the number of parts for production is small
and the cure temperature is 1.e. 400F
Then use laminated tools

If the method of cure is autoclave
and the part is a prototype
or the part is a development part
and time for production is short
and the number of parts for production is small
Then use plaster or casted tools

If the method of cure is autoclave
and the length of production runs is long
or higher temperature cure is needed
or rapid heat transfer is needed
Then use machined metal tools

<u>Manufacturing/Tooling Rules</u>

If the CTE of the tool is different from the CTE of the composite
Then try to minimize the difference between the two CTE's

If the tool has a built in angle
or there may be affects of closure or spring-in after cure
Then design the tool to have a draft angle of 1 to 2 degrees

If the part is a prototype

or the part is a development part
or the production time is short
Then keep tooling costs as low as possible

If the part is long and slender
or the shape is complex
Then take extra concern over the affects of differing CTE's

If residual or built-in strains are induced within the part as a result of tooling
or close dimensional tolerances are to be held on the part
Then consider the use of low CTE tooling such as carbon/graphite composite, monolithic graphite, ceramic, etc

If tooling tolerances are l.e. 0.025in
and the laminate is thin
Then tooling costs may be very expensive

If the production run is long
Then the tool should be constructed of steel. The second choice is aluminum tooling made of heavy roll-formed machined plate

If the production run is short
or the part is a prototype
or the part is a development part
Then consider the use of non-metallic tooling

If the tool weighs over 40lbs
or the tool is constructed of composite material
Then make sure there are handling features on the tool

If the laminate is flat
or the laminate is considered small
and the laminate part is without tight tolerances
or the cure temperature l.e. 400F
Then consider the use of an aluminum tool

If the production run is large

or the part requires severe radius forming
or the part is considered large
Then consider the use of steel or titanium as a tool material

If the part cure requires a relatively uniform temperature distribution during cure
or if build-up of internal residual stresses needs to be prevented
or the CTE of the tool needs to be compatible with the part
Then consider the use of graphite mold tooling

If the parts cure temperature is high
or the part requires tight dimensional tolerances
or the part has compound contours
and the part is considered large
Then consider the use of a ceramic tool

Features Rules

If the part has notches
or the part has sharp corners
or the part has abrupt changes in cross section
or the part has fastened joints
or the part has joggles
and the part loading is fatigue
Then premature failure may result

If the part includes mechanically fastened joints
Then in that location use at least 40% +-45 plies to maximize bearing strength

Appendix F

Procedural Knowledge Used In Knowledge Base Used To Calculate Initial Number of Laminate Plies

The number of +/- 45 plies used as a first cut for conceptual design shall be the maximum of:

$$N_{xy}/T*F_{xy}$$

and

$$GT/T*G$$

The number of 0 plies used as a first cut for conceptual design shall be the maximum of:

$$N_x-(F_{45}*T_{45})/T*(F_t \vee F_c)$$

and

$$ET_a-(E_{45}*T_{45})/T*(E_t \vee E_c)$$

Number of 90 plies used as a first cut for conceptual design shall be the maximum of:

$$N_y-(F_{45}*T_{45})/T*(F_t \vee F_c)$$

and

$$ET_t - (E_{45} * T_{45}) / T * (E_t \vee E_c)$$

Appendix G

CLIPS Code From Knowledge Based Part of ComDAS

```
;;      -----------------------------------------------------------
;;      -----------------------------------------------------------
;; This file is the control file. It determines when a phase is
;; complete and which phase to go to next. It controls the flow
;; from beginning to end.
;;
;; Developed By: Jonathan P. Lambright
;; For: COMDAS (Composites Design Advisory System)
;; Date: 09/30/94
;; Source: CLIPS, V. 5.0, MAC
;; File: control.clp
;;      -----------------------------------------------------------
;;      -----------------------------------------------------------
;;
;;


;;      -----------------------------------------------------------
;;      -----------------------------------------------------------
;; Start the system
;;      -----------------------------------------------------------
;;      -----------------------------------------------------------
;;      -----------------------------------------------------------
;;      -----------------------------------------------------------
;; Rules That Control The Flow Between Phases
;; This method of control was adopted from Dr. Nelson Bakers
;; Knowledge Based Systems Class, Spring 1991.
;;      -----------------------------------------------------------
;;      -----------------------------------------------------------
   (deffunction calc_num_of_45s (?shear ?thickness ?des_ult_shear
                    ?shear_mod ?shear_stiff ?answer))
   (deffunction calc_num_of_0s (?axial ?des_ult_45 ?thick_45
                    ?thickness ?des_ult ?axial_stiff
                  ?mod_of_45 ?young_mod ?answer))
   (deffunction calc_num_of_90s (?transverse ?des_ult_45 ?thick_45
                    ?thickness ?des_ult ?transverse_stiff
                  ?mod_of_45 ?young_mod ?answer))
   (deffunction get_issues ())

 (defrule system_start
    (initial-fact)
=>
   (assert (sequence current_phase specification_phase next_phase conceptual_phase)
)  (assert (sequence current_phase conceptual_phase next_phase detailed_phase))
```

```
   (assert (sequence current_phase detailed_phase next_phase manufacture_phase))
   (assert (sequence current_phase manufacture_phase next_phase operational_phase)
)   (assert (goal name specification_phase is active)))


(defrule switch_phases
   (goal name ?any is complete)
   (sequence current_phase ?any next_phase ?next)
=>
   (assert (goal name ?next is active)))

;;      ----------------------------------------------------------
;;      ----------------------------------------------------------
;; Specification Phase
;;      ----------------------------------------------------------
;;      ----------------------------------------------------------

(defrule specification_phase
   ?goal <- (goal name specification_phase is active)
=>
   (retract ?goal)
   (make-instance [current_customer] of customer)
   (make-instance [current_material] of material)
   (make-instance [current_tooling] of tooling)
   (make-instance [current_cure_equip] of cure_equipment)
  (printout t "Please Enter The Company Name ")
   (send [current_customer] put-name (read)) crlf
  (printout t "Please Enter The Company Address ")
   (send [current_customer] put-address (read)) crlf


   (make-instance [current_design] of design)
  (printout t "Please input the design name ")
   (send [current_design] put-design_name (read)) crlf
  (printout t "Please input the part name ")
   (send [current_design] put-part_name (read)) crlf
   (printout t "Please input the parts functionality ")
   (send [current_design] put-functionality (read)) crlf
   (printout t "Please input the operating environment ")
   (send [current_design] put-environment (read)) crlf
   (printout t "Please input the operating temperature ")
   (send [current_design] put-operating_temp (read)) crlf
   (printout t "Please input the prefered material ")
```

```
(send [current_design] put-prefered_material (read)) crlf
 (printout t "Please input the mating materials ")
(send [current_design] put-mating_materials (read)) crlf
 (printout t "Please input the aircraft type ")
(send [current_design] put-aircraft_type (read)) crlf
 (printout t "Please input the axial load ")
(send [current_design] put-axial_load (read)) crlf
 (printout t "Please input the transverse load ")
(send [current_design] put-transverse_load (read)) crlf
 (printout t "Please input the shear load ")
(send [current_design] put-shear_load (read)) crlf
 (printout t "Please input the axial stiffness ")
(send [current_design] put-axial_stiffness (read)) crlf
 (printout t "Please input the transverse stiffness ")
(send [current_design] put-transverse_stiffness (read)) crlf
 (printout t "Please input the shear stiffness ")
(send [current_design] put-shear_stiffness (read)) crlf
(get_issues)
(assert (goal name specification_phase is complete)))
;;    ------------------------------------------------------------
;;    ------------------------------------------------------------
;; Conceptual Phase
;;    ------------------------------------------------------------
;;    ------------------------------------------------------------


(defrule conceptual_phase
   ?goal <- (goal name conceptual_phase is active)
=>
   (retract ?goal)
   (calc_num_of_45s   (send [current_design] get-shear_load)
                 (send [current_material] get-thickness_per_ply)
                  (send [current_material] get-design_ultimate_shear_stress)
                 (send [current_material] get-shear_modulus)
                 (send [current_design] get-shear_stiffness)
              answer)

   (calc_num_of_0s    (send [current_design] get-axial_load)
                  (send [current_material] get-design_ult_of_45_plies)
                  (send [current_material] get-thickness_per_ply_of_45)
                 (send [current_material] get-thickness_per_ply)
                  (send [current_material] get-design_ultimate_comp_stress)
                 (send [current_design] get-axial_stiffness)
```

```
                    (send [current_material] get-modulus_of_45_plies)
                   (send [current_material] get-youngs_mod_comp)
                 answer)

   (calc_num_of_90s    (send [current_design] get-transverse_load)
                    (send [current_material] get-design_ult_of_45_plies)
                    (send [current_material] get-thickness_per_ply_of_45)
                    (send [current_material] get-thickness_per_ply)
                    (send [current_material] get-design_ultimate_comp_stress)
                    (send [current_design] get-transverse_stiffness)
                    (send [current_material] get-modulus_of_45_plies)
                   (send [current_material] get-youngs_mod_comp)
                 answer)

   (assert (goal name conceptual_phase is complete)))

;;     ------------------------------------------------------------
;;     ------------------------------------------------------------
;; Detailed Phase
;;     ------------------------------------------------------------
;;     ------------------------------------------------------------

(defrule detailed_phase
   ?goal <- (goal name detailed_phase is active)
=>
   (retract ?goal)
   (assert (goal name detailed_phase is complete)))

;;     ------------------------------------------------------------
;;     ------------------------------------------------------------
;; Manufacture Phase
;;     ------------------------------------------------------------
;;     ------------------------------------------------------------


(defrule manufacture_phase
   ?goal <- (goal name manufacture_phase is active)
=>
   (retract ?goal)
   (assert (goal name manufacture_phase is complete)))

;;     ------------------------------------------------------------
;;     ------------------------------------------------------------
```

```
;; Operational Phase
;;      ----------------------------------------------------------------
;;      ----------------------------------------------------------------

(defrule operational_phase
   ?goal <- (goal name operational_phase is active)
=>
   (retract ?goal)
   (assert (goal name operational_phase is complete)))
```

```
;;     -------------------------------------------------------------
;;     -------------------------------------------------------------
;; This file is the functions file. It contains all of the
;; functions which are required in COMDAS.
;;
;; Developed By: Jonathan P. Lambright
;; For: COMDAS (Composites Design Advisory System)
;; Date: 10/01/94
;; Source: CLIPS, V. 5.1, MAC
;; File: funcs.clp
;;     -------------------------------------------------------------
;;     -------------------------------------------------------------
;;
;;


;;     -------------------------------------------------------------
;;     -------------------------------------------------------------
;; Calculate the number of +- 45 plies.
;;     -------------------------------------------------------------

(deffunction calc_num_of_45s (?shear ?thickness ?des_ult_shear
                    ?shear_mod ?shear_stiff $?answer)
(bind $?answer (max (/ ?shear (* ?thickness ?des_ult_shear))
             (/ ?shear_stiff (* ?thickness ?shear_mod))))
(printout t $?answer)
(send [current_design] put-layup $?answer))

;;     -------------------------------------------------------------
;;     -------------------------------------------------------------
;; Calculate the number of 0 plies.
;;     -------------------------------------------------------------
(deffunction calc_num_of_0s (?axial ?des_ult_45 ?thick_45
                    ?thickness ?des_ult ?axial_stiff
                   ?mod_of_45 ?young_mod $?answer)
(bind $?answer (max (/ (- ?axial (* ?thick_45 ?des_ult_45))
             (* ?des_ult ?thickness))
             (/ (- ?axial_stiff (* ?mod_of_45 ?thick_45))
             (* ?thickness ?young_mod))))
(printout t $?answer)
(send [current_design] put-layup (mv-append (send [current_design]
                          get-layup) $?answer)))
;;     -------------------------------------------------------------
;;     -------------------------------------------------------------
```

```
;; Calculate the number of 90 plies
;;    ------------------------------------------------------------
(deffunction calc_num_of_90s (?transverse ?des_ult_45 ?thick_45
                    ?thickness ?des_ult ?transverse_stiff
                  ?mod_of_45 ?young_mod $?answer)
(bind $?answer (max (/ (- ?transverse (* ?thick_45 ?des_ult_45))
             (* ?des_ult ?thickness))
             (/ (- ?transverse_stiff (* ?mod_of_45 ?thick_45))
             (* ?thickness ?young_mod))))
(printout t $?answer)
(send [current_design] put-layup (mv-append (send [current_design]
                                get-layup) $?answer)))
```

```
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
;; This file contains all of the rules associated with the laminate
;; layup
;;
;;
;; Developed By: Jonathan P. Lambright
;; For: COMDAS (Composites Design Advisory System)
;; Date: 09/30/94
;; Source: CLIPS, V. 5.1, MAC
;; File: lamrul.clp
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
;;
;;
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
;; Turn The Customers Requirements And Current Resources Into
;; Factual Information To Be Used By The Rules.
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
(defrule get_laminate_info
   (goal name specification_phase is complete)
=>

(bind ?count 1)
(bind ?count1 1)
(bind ?count2 1)
(bind ?count3 1)
(bind ?count4 1)
(bind ?count5 1)
(bind ?count6 1)
(bind ?count7 1)
(bind ?count8 1)
     (if (integerp (/ (length (send [current_design] get-stacking)) 2))
     then (assert (laminate midplane is none))
     else (assert (laminate midplane is
                    =(nth (+ (/ (length (send [current_design] get-stacking)) 2) .5)
                       (send [current_design] get-stacking)))))

   (if (integerp (/ (length (send [current_design] get-stacking)) 2))
     then (assert (laminate midplane is none))
     else (assert (laminate midplane is
```

```
              =(nth (+ (/ (length (send [current_design] get-stacking)) 2) .5)
                 (send [current_design] get-stacking)))))

   (while (< ?count (length (send [current_design] get-stacking)))
     (if (> (abs (- (nth count? (send [current_design] get-stacking))
               (nth (+ ?count 1) (send [current_design] get-stacking)))) 60)
       then (assert (angle between adjacent ply greater than 60)))
    (bind ?count (+ ?count 1)))

   (send [current_design] put-thickness (* (send [current_material]
get-thickness_per_ply)
        (length (send [current_design] get-stacking))))

  (assert (laminate outer ply is =(nth 1 (send [current_design] get-stacking))))

  (assert (laminate outer ply is =(nth (length (send [current_design] get-stacking))
                              (send [current_design] get-stacking))))

   (while (<= ?count1 (length (send [current_design] get-functionality)))
     (assert (part function is =(nth ?count1 (send [current_design]
get-functionality))))
    (bind ?count1 (+ ?count1 1)))

   (while (<= ?count2 (length (send [current_design] get-material_form)))
     (assert (material form is =(nth ?count2 (send [current_design]
get-material_form))))
    (bind ?count2 (+ ?count2 1)))

   (assert (material is =(send [current_material] get-type_of_plastic)))

   (assert (operating temperature is =(send [current_design] get-operating_temp)))

   (while (<= ?count3 (length (send [current_design] get-mating_materials)))
     (assert (laminate boundary is =(nth ?count3 (send [current_design]
get-mating_materials))))
    (bind ?count3 (+ ?count3 1)))

   (assert (tool material is =(send [current_tooling] get-material)))

   (while (<= ?count4 (length (send [current_design] get-material)))
     (assert (part material is =(nth ?count4 (send [current_design] get-material))))
    (bind ?count4 (+ ?count4 1)))
```

```
(while (<= ?count5 (length (send [current_design] get-shape)))
   (assert (part shape is =(nth ?count5 (send [current_design] get-shape))))
  (bind ?count5 (+ ?count5 1)))

(while (<= ?count6 (length (send [current_design] get-environment)))
   (assert (environment is =(nth ?count6 (send [current_design] get-environment))))
  (bind ?count6 (+ ?count6 1)))

(assert (method of cure is =(send [current_cure_equip] get-method)))

(assert (number of parts for production is =(send [current_design]
get-parts_for_prod)))

(assert (part is =(send [current_design] get-part_status)))

(assert (production time is =(send [current_design] get-production_time)))

(while (<= ?count7 (length (send [current_tooling] get-features)))
   (assert (tool has =(nth ?count7 (send [current_tooling] get-features))))
  (bind ?count7 (+ ?count7 1)))

(while (<= ?count8 (length (send [current_design] get-features)))
   (assert (part has =(nth ?count8 (send [current_design] get-features))))
  (bind ?count8 (+ ?count8 1))))
```

```
;;    ------------------------------------------------------------
;;    ------------------------------------------------------------
;; This file queries the user and extracts information relating to
;; design, manufacturing, and operational issues.
;;
;; Developed By: Jonathan P. Lambright
;; For: COMDAS (Composites Design Advisory System)
;; Date: 01/08/95
;; Source: CLIPS, V. 5.0, MAC
;; File: issues.clp
;;    ------------------------------------------------------------
;;    ------------------------------------------------------------
;;
;;

(deffunction get_issues ()
  (bind S?issues1 (mv-append "Part must be damage tolerant"


))

  (bind S?laminate_issues (mv-append
            "laminate surface to be smooth"
            "laminate surface to be smooth on both sides"
            "laminate surface to be flat"
            "lamina adjacent to bonded joint"
              "lamina fiber orientation parallel to direction of loading"
              "lamina fiber orientation 45 to direction of loading"))

  (bind S?requirement_issues (mv-append
            "part needs to be light"
            "part needs to be stiff"
            "fatigue loading"
            "increase stability"
            "free edge effects"
            "poisson ratio effects"
            "thermal expansion effects"
            "high mechanical strength needed"
           "low cte needed"
            "delamination at a joint"
            "part to be damage tolerant"
              "part must withstand impact resistance"))
```

```
(bind $?geometric_issues (mv-append
            "part contains contours"
            "part has compound contours"
            "part contains radii"
            "part contains sharp contour changes"
             "close tolerances on both face dimensions of part"
             "close dimensional tolerances on part"
             "part has abrupt changes in cross section"))

(bind $?mfg_tooling_issues (mv-append
            "higher temperature cure needed"
              "cte of tool different from composite"
            "spring_in"
            "rapid heat transfer needed"
            "residual strains"
            "built in strains"
               "part requires uniform temperature distribution during cure"
             "internal residual stress"
              "tool cte to be compatible with part"
             "part cure temperature is high"
             "part requires joining"
             "cocuring is possible"
              "inspection needed prior to assembly"
          ))


 (bind ?count9 1)
 (bind ?count10 1)
 (bind ?count11 1)
 (bind ?count12 1)
 (bind ?count13 1)

 (printout t "              LAMINATE ISSUES" crlf)
  (printout t " (1) " (nth 1 $?laminate_issues) crlf
             " (2) " (nth 2 $?laminate_issues) crlf
             " (3) " (nth 3 $?laminate_issues) crlf
             " (4) " (nth 4 $?laminate_issues) crlf
             " (5) " (nth 5 $?laminate_issues) crlf
             " (6) " (nth 6 $?laminate_issues)) crlf

  (printout t "Please enter which issues are related to this design
             e.g. (1 2 3) (Return) ")
  (bind $?laminate_issue_list (str-explode   (read)))
```

```
    crlf
     (printout  t  $?laminate_issue_list)  crlf
    (while  (<=  ?count9  (length  $?laminate_issue_list))
       (printout t crlf $?count9 crlf)
        (send [current_design] put-issues (nth (nth ?count9 $?laminate_issue_list)
$?laminate_issues))
      (bind ?count9 (+ ?count9 1)))


 (printout t "              STRUCTURE REQUIREMENT ISSUES" crlf)
    (printout  t  " (1)   " (nth  1  $?requirement_issues)  crlf
                 " (2)  " (nth 2 S?requirement_issues) crlf
                 " (3)  " (nth 3 $?requirement_issues) crlf
                 " (4)  " (nth 4 S?requirement_issues) crlf
                 " (5)  " (nth 5 S?requirement_issues) crlf
                 " (6)  " (nth 6 S?requirement_issues) crlf
                 " (7)  " (nth 7 S?requirement_issues) crlf
                 " (8)  " (nth 8 S?requirement_issues) crlf
                 " (9)  " (nth 9 S?requirement_issues) crlf
                 " (10) " (nth 10 $?requirement_issues) crlf
                 " (11) " (nth 11 $?requirement_issues) crlf
                 " (12) " (nth 12 $?requirement_issues)) crlf

   (printout t "Please enter which issues are related to this design
              e.g. (1 2 3) (Return) ")
   .(bind $?requirement_issue_list (str-explode   (read)))
   crlf
    (printout  t  $?requirement_issue_list)  crlf
   (while  (<=  ?count10  (length  $?requirement_issue_list))
      (printout t crlf $?count10 crlf)
      (send [current_design] put-issues (mv-append (nth (nth ?count10
$?requirement_issue_list)  $?requirement_issues)
                                          (send [current_design] get-issues)))
     (bind ?count10 (+ ?count10 1)))


(printout t "              GEOMETRIC ISSUES" crlf)
   (printout  t  " (1) " (nth 1 $?geometric_issues) crlf
                " (2) " (nth 2 S?geometric_issues) crlf
                " (3) " (nth 3 S?geometric_issues) crlf
```

```
        " (4) " (nth 4 $?geometric_issues) crlf
        " (5) " (nth 5 $?geometric_issues) crlf
        " (6) " (nth 6 $?geometric_issues) crlf
        " (7) " (nth 7 $?geometric_issues)) crlf

 (printout t "Please enter which issues are related to this design
        e.g. (1 2 3) (Return) ")
 (bind $?geometric_issue_list (str-explode   (read)))
 crlf
  (printout  t  $?geometric_issue_list)crlf
 (while (<= ?count11 (length $?geometric_issue_list))
    (printout t crlf $?count11 crlf)
    (send [current_design] put-issues (mv-append (nth (nth ?count11
$?geometric_issue_list)  $?geometric_issues)
                                  (send [current_design] get-issues)))

    (bind ?count11 (+ ?count11 1)))



(printout t "              MANUFACTURING/TOOLING ISSUES" crlf)
  (printout t " (1)   " (nth 1 $?mfg_tooling_issues) crlf
          " (2)  " (nth 2 $?mfg_tooling_issues) crlf
          " (3)  " (nth 3 $?mfg_tooling_issues) crlf
          " (4)  " (nth 4 $?mfg_tooling_issues) crlf
          " (5)  " (nth 5 $?mfg_tooling_issues) crlf
          " (6)  " (nth 6 $?mfg_tooling_issues) crlf
          " (7)  " (nth 7 $?mfg_tooling_issues) crlf
          " (8)  " (nth 8 $?mfg_tooling_issues) crlf
          " (9)  " (nth 9 $?mfg_tooling_issues) crlf
          " (10) " (nth 10 $?mfg_tooling_issues) crlf
          " (11) " (nth 11 $?mfg_tooling_issues) crlf
          " (12) " (nth 12 $?mfg_tooling_issues) crlf
          " (13) " (nth 13 $?mfg_tooling_issues)) crlf

 (printout t "Please enter which issues are related to this design
        e.g. (1 2 3) (Return) ")
 (bind $?mfg_tooling_issue_list (str-explode   (read)))
 crlf
  (printout  t  $?mfg_tooling_issue_list)  crlf
 (while (<= ?count12 (length $?mfg_tooling_issue_list))
    (printout t crlf $?count12 crlf)
    (send [current_design] put-issues (mv-append (nth (nth ?count12
```

```
$?mfg_tooling_issue_list)  $?mfg_tooling_issues)
                                    (send [current_design] get-issues)))
      (bind ?count12 (+ ?count12 1)))




    (printout t (send [current_design] get-issues))

(while (<= ?count13 (length (send [current_design] get-issues)))
      (bind $?the_issue (str-explode (nth ?count13 (send [current_design]
get-issues))))
      (assert ($?the_issue))
      (bind ?count13 (+ ?count13 1))))
```

```
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
;; This file is the initial setup file. It is used as a query to
;; the manufacturing floor, designers, and engineers to determine
;; important information such as the type of cure processes available,
;; available material, tooling, etc...
;;
;; Developed By: Jonathan P. Lambright
;; For: COMDAS (Composites Design Advisory System)
;; Date: 09/30/94
;; Source: CLIPS, V. 5.0, MAC
;; Credits: Dr. Nelson Baker, Georgia Tech, CE. Dept.
;; File: setup.clp
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
;;
;;


(defrule resources_info
   (initial-fact)
=>
   (make-instance [current_resources] of resources)
   (printout t "Please Enter The Types of Material Available.")
   (send [current_resources] put-material (read))
   (printout t "Please Enter The Types of Material Forms Available.")
   (send [current_resources] put-material_forms (read))
   (printout t "Please Enter The Types of layup Available.")
   (send [current_resources] put-layup (read))
   (printout t "Please Enter The Types of cure Available.")
   (send [current_resources] put-cure (read))
   (printout t "Please Enter The Types of Tool Material Available.")
   (send [current_resources] put-tool_material (read))
   (printout t "Please Enter The Weight of The Tool.")
   (send [current_resources] put-tool_weight (read))
   (printout t "Are There Any Inspection Capabilities Available?.")
   (send [current_resources] put-inspection (read)))
```

```
;;      ---------------------------------------------------------------
;;      ---------------------------------------------------------------
;; A Loader file to automatically load other individual files
;; associated with ComDAS.
;;
;;
;; Developed By: Jonathan P. Lambright
;; For: COMDAS (Composites Design Advisory System)
;; Date: 09/27/94
;; Source: CLIPS, V. 5.1, MAC
;; File: loader.clp
;;      ---------------------------------------------------------------
;;      ---------------------------------------------------------------
;;
;;


;;(watch  facts)
;;(watch  rules)

(load  "myclas.clp")
(load  "control.clp")
(load  "funcs.clp")
(load  "lamrul.clp")
(load  "rules1.clp")
(load  "rules2.clp")
(load  "rules3.clp")
(load  "rules4.clp")
(load  "rules5.clp")
(load  "rules6.clp")
(load  "rules7.clp")
(load  "issues.clp")
```

```
;;      ----------------------------------------------------------
;;      ----------------------------------------------------------
;; Construction of Class Structures
;;
;;
;; Developed By: Jonathan P. Lambright
;; For: COMDAS (Composites Design Advisory System)
;; Date: 09/22/94
;; Source: CLIPS, V. 5.1, MAC
;; File: myclas.clp
;;      ----------------------------------------------------------
;;      ----------------------------------------------------------
;;
;;

;;      ----------------------------------------------------------
;;      ----------------------------------------------------------
;; Customer Class Structure
;;      ----------------------------------------------------------
;;      ----------------------------------------------------------

(defclass customer (is-a USER)
   (concrete)
   (slot name (type STRING))
    (slot address (multiple))
    (slot designs (multiple)))
;;      ----------------------------------------------------------
;;      ----------------------------------------------------------
;; Design Class Structure
;;      ----------------------------------------------------------
;;      ----------------------------------------------------------

(defclass design (is-a USER)
   (concrete)
   (slot design_name)
    (slot part_name (multiple))
     (slot functionality (multiple))
    (slot environment (multiple))
    (slot operating_temp (multiple))
    (slot material (multiple) (default graphite))
    (slot prefered_material (multiple))
    (slot material_form (multiple) (default fabric))
    (slot mating_materials (multiple))
```

```
(slot aircraft_type (multiple))
(slot axial_load)
(slot transverse_load)
(slot shear_load)
(slot axial_stiffness)
(slot transverse_stiffness)
(slot shear_stiffness)
(slot thickness (default .5))
(slot operating_temp_low (default 100))
(slot operating_temp_high (default 500))
(slot features (multiple)(default none))
(slot shape (multiple)(default complex))
(slot stacking (multiple)(default 45,90,90,0,90,90,45))
(slot parts_for_prod (default 30))
(slot part_status(default not_complete))
(slot production_time(default 30))
(slot issues (multiple))
(slot layup (multiple)))
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
;; Aircraft Class Structure
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
(defclass aircraft (is-a USER)
   (concrete)
   (slot type (multiple))
   (slot tail (multiple))
   (slot main_body (multiple))
   (slot engine (multiple))
   (slot nose)
   (slot fuselage (multiple))
   (slot access_doors (multiple)))

;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
;; Material Class Structure
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
(defclass material (is-a USER)
   (concrete)
   (slot type (multiple)(default graphite))
   (slot type_of_plastic(default thermoset))
   (slot design_ultimate_ten_stress (default 30000))
```

```
    (slot design_ultimate_comp_stress (default 30000))
    (slot design_ultimate_shear_stress (default 30000))
    (slot youngs_mod_tension (default 25000))
    (slot youngs_mod_comp (default 25000))
    (slot shear_modulus (default 25000))
    (slot thickness_per_ply (default 0.008))
    (slot thickness_per_ply_of_45 (default 0.008))
    (slot modulus_of_45_plies (default 25000))
    (slot design_ult_of_45_plies (default 30000)))

;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
;; Tooling Class Structure
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
(defclass tooling (is-a USER)
   (concrete)
    (slot material(default steel))
    (slot weight(default 300))
    (slot type(default ffff))
    (slot features (multiple)(default handles)))


;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
;; Layup Equipment Class Structure
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
(defclass lay_up_equipment (is-a USER)
   (concrete)
    (slot equip_name (multiple)(default hand))
    (slot type(default hand)))

;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
;; Cure Equipment Class Structure
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
(defclass cure_equipment (is-a USER)
   (slot concrete)
    (slot cure_temp(default 600))
    (slot method(default autoclave)))
;;      ------------------------------------------------------------
```

```
;;     ----------------------------------------------------------
;; Resources Class Structure
;;     ----------------------------------------------------------
;;     ----------------------------------------------------------

(defclass resources (is-a USER)
   (concrete)
    (slot material (multiple))
    (slot material_forms (multiple))
    (slot layup (multiple))
    (slot cure (multiple))
    (slot tool_material (multiple))
    (slot tool_weight (multiple))
    (slot inspection (multiple)))
```

```
;;      ------------------------------------------------------------
;; Manufacturing Rules
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------

(defrule  co_curing
   (part requires joining)
=>
   (printout t "Use co-cured or co-consolidated assemblies when
              possible")) crlf

(defrule  honeycomb5
   (material form is honeycomb)
=>
   (printout t "Thermoset laminates may be co-cured together with
            the honeycomb core")) crlf

(defrule  honeycomb6
   (material form is honeycomb)
   (not (cocuring is possible))
=>
   (printout t "An adhesive layer can be placed between the precured
              laminates and the core, then the assembly heated to cure
               the adhesive layer.")) crlf

(defrule  honeycomb7
   (material form is honeycomb)
   (cocuring is possible)
   (laminate surface to be smooth)
=>
   (printout t "Can possibly use a caul plate to reduce dimpling.")) crlf

(defrule  secondary_curing
   (material form is honeycomb)
   (inspection needed prior to assembly)
   (laminate surface to be smooth on both sides)
=>
   (printout t "Consider secondary curing")) crlf

(defrule  edge_close_out
   (part has edge closeouts)
   (material form is honeycomb)
=>
```

```
(printout t "Because of the edge closeouts and the honeycomb core,
        the core must be carved at about 30 degrees or less
         to minimize angularbond pressure loading.")) crlf
```

```
;;      ---------------------------------------------------------
;;      ---------------------------------------------------------
;; Failure Rules
;;      ---------------------------------------------------------
;;      ---------------------------------------------------------

(defrule  delamination1
   (part function is compression_panel)
   (part loading is fatigue)
=>
   (printout t "Take into consideration that cracks may develop
              between the 0 and 90 plies. This may cause
              delamination")) crlf

(defrule  delamination2
   (delamination at a joint)
=>
   (printout t "Consider the addition of fasteners")) crlf

(defrule  strength_reducing_features
   (or (part has notches)
       (part has sharp corners)
       (part has fastened joints)
       (part has abrupt changes in cross section))
=>
   (printout t "Strength retention is increased by adding +- 45's
             to the orientation. Though the load carrying capacity
            may be reduced.")) crlf

(defrule  fatigue_loading1
   (part loading is fatigue)
   (or (part has notches)
       (part has sharp corners)
       (part has abrupt changes in cross section)
       (part has local ply pad ups)
       (part has fastened joints)
       (part has joggles))
=>
   (printout t "Take into consideration the possibility of
              premature failure")) crlf
```

```
;;      -----------------------------------------------------------
;;      -----------------------------------------------------------
;; Environment Rules
;;      -----------------------------------------------------------
;;      -----------------------------------------------------------

(defrule  moisture1
    (material is thermoplastic)
=>
   (printout t "Due to moisture, expect to pick up .3% to .5% of the
            structures weight in moisture. Expect a 5% to 10%
             reduction in material properties, mainly
            matrix dominated properties; compression and shear
           At higher temperatures expect even a 40% to 50%
           reduction.")) crlf

(defrule  moisture2
   (part material is BMI)
=>
   (printout t "Due to the use of BMI material, expect to pick up
            1% of the structures weight in moisture. Expect a
            5% to 10% reduction in material properties, mainly
            matrix dominated properties; compression and shear
           At higher temperatures expect even a 40% to 50%
           reduction.")) crlf

(defrule  lightning_strikes
   (environment is lightning)
=>
   (printout t "Do not use aluminum cores in the area where lightning
            may occur")) crlf

(defrule  space_use
   (environment is space)
   (material form is honeycomb)
=>
   (printout t "Use one face sheet having widely spaced small perforations
            to release trapped air.")) crlf
```

```
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
;; Material Rules
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
(defrule honeycomb1
   (and (part needs to be light)
        (part needs to be stiff)
        (not (part is primary)))
=>
   (printout t "Consider using a honeycomb construction")) crlf

(defrule honeycomb2
   (and (or (part function is fairing)
            (part function is close_out))
        (not (part is primary)))
=>
   (printout t "Consider using a honeycomb construction")) crlf

(defrule honeycomb3
   (material form is honeycomb)
=>
   (printout t "Consider the effects due to moisture")) crlf

(defrule BMI
    (initial-fact)
=>
   (if (and (> (send [current_design] get-operating_temp_low) 200)
          (< (send [current_design] get-operating_temp_high) 350))
     then (printout t "Consider the use of BMI's as a material"))) crlf

(defrule thermal_expansion_effects
   (part material is hybrid)
=>
   (printout t "Take precaution for possible internal thermal
            expansion effects")) crlf

(defrule aluminum_core
  (part has aluminum core)

=>
```

```
   (printout t "Make sure aluminum core is isolated from carbon
           laminates")) crlf

(defrule thermal_expansion_effects
   (thermal expansion effects)
=>
   (printout t "use symmetrical laminates or increase the number
            of plies in the 90 direction")) crlf

(defrule fabric1
   (part shape is complex)
=>
   (printout t "Consider the use of a  fabric as a material form")) crlf

(defrule smooth_laminate
   (or (laminate surface to be smooth)
       (laminate surface to be flat))
=>
   (printout t "Specify that either the tool surface side of the
           laminate is to be used, use tape as a material
           form for the outer plies, or use a caul plate during
           the cure cycle")) crlf

(defrule tape1
   (part shape is simple)
   (high mechanical strength needed)
=>
   (printout t "Consider the use of tape as a material form")) crlf

(defrule honeycomb4
   (material form is honeycomb)
=>
   (printout t "The structure can be fabricated either by
             cocuring the components together or utilizing
           secondary adhesive bonding")) crlf

(defrule invar_material
   (low cte needed)
   (metal permitted as material form)
=>
   (printout t "Consider the use of Invar 36 or Invar 42 as a
             material form")) crlf
```

```
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
;; Loading Rules
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------

(defrule stability
    (increase stability)
=>
   (printout t "Put +- 45's on the outter surface")) crlf

(defrule compression_column
   (part function is compression column)
=>
   (printout t "Put 0 or 90 plies on the outer surface or as far
            away from the midplane as possible")) crlf

(defrule creep_effects
    (material is thermoplastic)
   (operating temperature is high)
=>
   (printout t "Investigate the design for creep effects")) crlf

(defrule induced_stresses
   (Laminate boundary is metal)
=>
   (printout t "Check for induced stresses due to a high Poissons ratio")) crlf

(defrule free_edge_effects
   (free edge effects)
=>
   (printout t "Minimize the angle between adjacent tape plies or
             use unidirectional tape as a material form")) crlf

(defrule fatigue
   (fatigue loading)
=>
   (printout t "Check design features which cause premature failure")) crlf

(defrule Poisson_effect
   (poisson ratio effect)
   (part has bonded joints)
```

```
=>
   (printout t "Use 90 plies in the laminate and reduce the
                number of 0 plies in the laminate")) crlf

(defrule  induced_strains
   (or (tool material is steel)
       (tool material is aluminum))
=>
   (printout t "Severe residual or built-in strains can be induced
            in the laminate due to contraction during the
             cool-down from peak cure cycle temperature")) crlf
```

```
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
;; Laminate Layup Rules
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
(defrule balanced_layup
   (not (laminate is balanced))
   (not (laminate midplane is a 0))
   (not (laminate midplane is a 90))
=>
   (printout t "The laminate is not balanced")) crlf

(defrule  symmetrical_laminate
   (not (laminate is symmetrical))
=>
   (printout t "The laminate is not symmetrical")) crlf

(defrule  outer_ply_1
   (or   (laminate outer ply is 0)
         (laminate outer ply is 90))
   (not (part function is compression panel))
=>
   (printout t "The laminate has a 0 or 90 outer ply but is not a
               compression panel")) crlf

(defrule  outer_ply_2
   (or   (laminate outer ply is 0)
         (laminate outer ply is 90))
   (part function is compression panel)
   (not (material form is fabric))
=>
   (printout t "The outer ply should be constructed of fabric")) crlf

(defrule  check_laminate_thickness
    (initial-fact)

=>
   (if (< (send [current_design] get-thickness) 0.04)
       then (printout t "Check the laminate thickness"))) crlf

(defrule  fuel_tank_thickness
```

```
   (part function is fuel tank)
=>
    (if (< (send [current_design] get-thickness) 0.08)
        then (printout t "Check the laminate thickness for a fuel tank"))) crlf

(defrule  adjacency_to_bonded_joint
   (lamina adjacent to bonded joint)
   (or (not (lamina fiber orientation parallel to direction of
         loading))
       (not (lamina fiber orientation 45 to direction of loading)))
=>
   (printout t "Check the adjacency to the bonded joint")) crlf

(defrule  adjacent_ply_angle
   (angle between adjacent ply greater than 60)
   (not (material form is fabric))
=>
   (if (> (+ (nth 1 (send [current_design] get-layup))
           (nth 2 (send [current_design] get-layup))
           (nth 3 (send [current_design] get-layup))) 16)
      then (printout t "Check the adjacency angles of the plies"))) crlf

(defrule  number_of_plies
    (initial-fact)
=>
   (if  (< (+ (nth 1 (send [current_design] get-layup))
              (nth 2 (send [current_design] get-layup))
              (nth 3 (send [current_design] get-layup))) 7)
      then (printout t "Check the number of plies"))) crlf
```

```
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
;; Life Cycle Issue Rules
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------

(defrule  damage_tolerance1
   (part to be damage tolerant)
=>
   (printout t "Consider the use of +-45 fabric on the outer surface
            to increase the damage tolerance") crlf

   (printout t "Design the part for repairability and replacability
            due to its need to be damage tolerant")) crlf

(defrule  damage_tolerance2
   (or (part to be damage tolerant)
       (part must withstand impact resistance))
=>
   (printout t "Consider adding materials to form a hybrid such as
               kevlar and fiberglass to the basic carbon laminate
               to increase impact resistance")) crlf


;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
;; Geometric Rules
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------

(defrule  shape_contours1
   (or (part contains contours)
       (part contains radii))
=>
   (printout t "Avoid sharp changes in the surface contours and
            avoid tight radii")) crlf

(defrule  shape_contours2
   (part contains sharp contour changes)
=>
   (printout t "Consider the use of woven fabric as a material form
            to combat the charp contour changes.")) crlf
```

```
(defrule  tolerances1
   (close tolerences on both face dimensions of part)
=>
   (printout t "Consider using a matched mold dye")) crlf
```

```
;;     ------------------------------------------------------------
;;     ------------------------------------------------------------
;; Manufacturing/Tooling Rules
;;     ------------------------------------------------------------
;;     ------------------------------------------------------------
(defrule  laminated_tools
   (method of cure is autoclave)
   (number of parts for production is small)
=>
   (if (<=  (send [current_cure_equip] get-cure_temp) 400)
      then (printout t "Consider the use of laminated tooling."))) crlf

(defrule  casted_tools
   (method of cure is autoclave)
   (number of parts for production is small)
   (or (part is prototype)
      (part is development))
   (production time is short)
=>
   (printout t "Consider the use of plaster or casted tooling.")) crlf

(defrule  machined_metal_tools
   (method of cure is autoclave)
   (production time is long)
   (or (higher temperature cure needed)
      (rapid heat transfer needed))
=>
   (printout t "Consider the use of machined metal tooling.")) crlf

(defrule  different_ctes1
   (cte of tool different from composite)
=>
   (printout t "Try to minimize the difference between the two
                coefficients of thermal expansion.")) crlf

(defrule  tool_draft_angle
   (or (tool has built in angle)
      (spring_in))
=>
   (printout t "Design the tool to have a draft angle of 1 to 2
           degrees.")) crlf
```

```
(defrule  tooling_costs1
   (or (part is prototype)
       (part is development))
       (production time is short)
=>
   (printout t "Try to keep the tooling costs as low as possible.")) crlf

(defrule  different_ctes2
   (or (part shape is complex)
       (part shape is long)
       (part shape is slendor))
=>
   (printout t "Take extra concern over the effects of differing
               coefficients of thermal expansion".)) crlf

(defrule  low_cte_tooling
   (or (residual strains)
       (built in strains)
       (close dimensional tolerances on part))
=>
   (printout t "Consider the use of low coefficient of thermal
             expansion tooling such as carbon/graphite composite,
             monolithic graphite, or ceramic.")) crlf

(defrule  tooling_costs2
(initial-fact)
=>
   (if (and (< (+ (nth 1 (send [current_design] get-layup))
          (nth 2 (send [current_design] get-layup))
          (nth 3 (send [current_design] get-layup))) 16)
        (<= (send [current_tooling] get-toleranceces) 0.025))
      then (printout t "Tooling costs may be very expensive."))) crlf

(defrule  steel_tooling
   (number of parts for production is long)
=>
   (printout t "Consider the use of steel tooling. The second choice
             is that of aluminum tooling made of heavy roll-formed
            machined plate.")) crlf

(defrule  non_metallic_tooling
   (or (number of parts for production is short)
       (part is prototype)
```

```
      (part is development))
=>
    (printout t "Consider the use of non-metallic tooling.")) crlf

(defrule  tool_handling_features
   (tool material is composite)

=>
     (if (> (send [current_tooling] get-weight) 40)
   then (printout t "Make sure there are handling features on the tool."))) crlf

(defrule  aluminum_tooling
   (not (close dimensional tolerances on part))
   (or (shape is flat)
      (shape is small))
=>
    (if (> (send [current_cure_equip] get-cure_temp) 400)
         then (printout t "Consider the use of aluminum tooling."))) crlf

(defrule   steel_or_titamium_tooling
   (or (number of parts for production is long)
       (part requires severe radius forming)
      (shape is large))
=>
   (printout t "Consider the use of steel or titanium tooling.")) crlf

(defrule  graphite_mold_tooling
   (or (part requires uniform temperature distribution during cure)
       (internal residual stress)
       (tool cte to be compatible with part))
=>
   (printout t "Consider the use of graphite mold tooling.")) crlf


(defrule  ceramic_tooling
   (or (part cure temperature is high)
       (close dimensional tolerances on part)
      (part has compound contours))
  (shape is large)
=>
   (printout t "Consider the use of ceramic tooling.")) crlf
```

```
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------
;; Features Rules
;;      ------------------------------------------------------------
;;      ------------------------------------------------------------

(defrule  fastened_joints
   (part has mechanically fastened joints)
=>
   (printout t "In the location of the mechanically fastened joint
            use at least 40% of +- 45 plies to maximize the
            bearing strength.")) crlf
```

Appendix H

A Listing of Cases Collected For Use Within The Case-Based Reasoning System

****

//This is what the actual code looks like after building a story with links to problems and responses. The remaining stories list only the text.

****

```
(in-package "MUSE")
(progn
(make-instance 'story
   :uid '6
   :date '3023972849
   :movie 'NIL
   :pict 'NIL
   :text '"In 1973, Dowty Rotol designed a number of airfoils known as the ARA-D
(Aircraft Research Association) airfoils. The objective was to have good aerodynamic
efficiency while employing composite materials. The result was a group of airfoils that had
better lift coefficients than the conventional NACA series 16 or NACA series 65 airfoil
sections. This meant that for a certain propeller diameter, the chord could be shortened
giving rise to a reduced weight and centrifugal twisting moment (CTM). Higher loadings at
higher Mach numbers were possible  because the blades displayed a more uniform pressure
distribution. The section also reduced cruise drag and improved take-off qualities
significantly. Because of a lower CTM, the hubs and pitch change mechanisms could be
smaller and thus, lighter."
   :summary '""
   :title '"1973 Dowty Rotol Propeller"
   :class '#n(STORY-CLASS POINT)
   :outcome '#n(OUTCOME POSITIVE)
   )
 (persistent-object-slot '6 'LINKS '(351 148))
 (persistent-object-slot '6 'USER '4)
 (persistent-object-slot '6 'INDEXES '(1010))
 )
```

Title: 1965 Dowty Rotol Propeller

Dowty Rotol started work on composite propeller blades in 1965. Designed for an oceanic environment, these large glass fiber blades had erosion and corrosion problems in this harsh surrounding.

Title: 1978 Dowty Rotol Propeller

In 1978, Dowty Rotol designed a propeller blade similar to blades used today. The results of the program were a reduction of weight by 50% compared to conventional duraluminum designs. With propeller actuation and control system complexities simplified by a lighter blade, the overall propeller system costs decreased despite of the fact that the composite blades themselves were slightly more expensive than duraluminum blades. Furthermore, the lower propeller weight means a lower power requirement for rapid pitch changes essential in today's power plants. Also, the propeller governor may be reduced in size and thus weight because it has a lower work requirement due to lower blade mass.

Acoustic considerations also improved with the composite blades. Because 6 composite blades could be utilized in a hub rather than 4, the propeller tip speed is lower, a large noise factor. A 6-bladed duraluminum propeller would require a prohibitively large blade.
An interesting aspect of the hub end of the propeller is that the ring-shaped glass fiber wedges are trapped between the inner and outer metal sleeves. These wedges are pulled tightly by centrifugal forces that are on the blade. As a result, these wedges may carry load in any direction and the structural integrity does not relate to adhesive properties to the metal components.
Considerable testing was conducted to prove the absolute impossibility of a structural failure. Thus, the fatigue was a critical issue. Since the blades were lighter, the centrifugal loads were not as great which helped in preventing fatigue damage. Tests exceeded 115% overpower and 126% overspeed. Severe flexural fatigue tests were done to expose the blades to vibratory loads higher than possible in actual use. Over 100x10E6 cycles were executed and proved an infinite fatigue life.
Lightning strike tests were conducted at peak currents of about 200 kilo amps and action integrals of 2x10E6 amps^2 seconds. A strip of aluminum braid molded into each of the 2 blade surfaces and earthed to a metallic root serve as the lightning strike protection of the blade. Nine full threat strikes prove that the configuration is valid since the only damage was minor vaporization of the polythurene erosion coat at the tip of the propeller blade.
A bird carcass of 4 lb was thrown into the composite propeller operating at take off speed. After repeated tests, the only damage was a minor nick in the filed replaceable protective strip located on the propellers leading edge. Tests of a wheels up landing generated only minor debris. Also, rig and flight testing was conducted to verify the vibrations, control responses, and de-icing characteristics of the blades.

Prevention from erosion due to water, sand, or dust was achieved by spraying the blade with a polyurethane coating, the thickness of such a coating being determined by environmental factors. Also, , a nickel leading edge sheath is bonded to the polyurethane coating to protect the outboard edge of the de-icer boot. In cases where the de-icer boot cannot provide good protection of the inboard sheath, the de-icer boot may have stainless steel petals bonded to its top.

Title: A-4 Boron Landing Flap

The landing flap of an A-4 aircraft was constructed from boron epoxy composite material. The landing flap typifies most airframe construction in that it has light gage, stiffened-skin panels and concentrated load fittings, The composite part was designed to be interchangeable with the original aluminum design. Static and fatigue tests were conducted to simulate the landing approach condition and the flaps-up condition. The boron flap withstood the fatigue spectrum tests without visible damage and then withstood a static load equal to 181% of the design limit load. The part was 21% lighter than the aluminum version and had only 55 components as opposed to 280 in the aluminum flap.

Title: A-4 Graphite Horizontal Stabilizer

A graphite-epoxy horizontal stabilizer for the A-4 Skyhawk was constructed and its performance compared with the equivalent metal structure. The composite part weighed 28% less than the all-metal counterpart. A series of tests on the substructure were performed. The I-beams were successfully tested statically and in fatigue. The box-beam component was successfully tested statically. The stabilizer failed at 74% DLL in a down bending condition. Failure was initiated by a non-uniform bolt loading in the joint between the stabilizer and the fuselage.

Title: A-4 Graphite Landing Flap

The landing flap of an A-4 aircraft was constructed from graphite-epoxy composite material. The landing flap typifies most airframe construction in that it has light gage, stiffened-skin panels and concentrated load fittings. The composite part was designed to be interchangeable with the original aluminum design. The flap was successfully tested, failing at 160% of the design load limit. The flap provided a 47% savings in weight and required only 7 components, as opposed too 280 in the aluminum version.

Title: A-7 Speed Brake

The speed brake serves as a speed limiting device as an aircraft is in a dive. As a result, the speed brake gets very high aerodynamic loading. The maximum load for the 2.7m long and 1.83m wide (total area: 2.3 square meters) is 204,437 N (46,000 lb), a load limited by the hydraulic actuator. On the A-7, the speed brake is found on the bottom of the fuselage forward of the doors of the main landing gear. The original configuration was 7075-T6 aluminum sheet metal with machined forgings, a configuration with tremendous complexity.
A 40% weight savings was gained by reducing the part from 56kg (123.4 lb) to 33.5 kg (73.9 lb) employing graphite-epoxy material with a density of 1604.9 kg/m^3. It is important to note that since the number of parts decreased significantly, production costs can be expected to decrease as well.

Title: A300 Air Conditioning Inlet Fairing

The air conditioning inlet fairing of the A300 was originally a light alloy. This material was changed to a sandwich construction of Kevlar skin and a Nomex honeycomb core to reduce weight and production costs since this part is very complex to produce. Production costs did indeed decrease and 14 kg or 30.9 lb was saved per aircraft.

Title: A300 Spoiler

Sandwich structure was used for the spoilers asymmetric loading rather than monolithic structure because the monolithic configuration would have required close spacing of the ribs to support the skins correctly, resulting in higher costs.
A brief survey of the manufacturing methods of the A300 spoiler follows: 1) Begin with the spoiler lower shell laminate. 2) Bond the composite re-inforced plastic box to the sub-assembly, 3)Finish-mill the honeycomb core, 4) Bond the upper skin to the structure, 5) Fit the main hinge and actuator fittings to the box with blind bolts.

Title: A300/310 Apron Fairing

The A300/310's carbon fiber apron fairing reduced the aircraft weight 15 kg or 33 lb from the original glass fiber construction.

Title: A310 Engine Pylon Fairings

Using a kevlar prepeg fabric on the A310's engine pylon fairings saved a total of 7.5kg or 16.5lb per aircraft over a glass fiber construction, a savings worth the Kevlars higher cost. These engine pylon fairings give aerodynamic continuity between the lower wing surface and the pylon so that the best airflow is developed at the wing and engine connection.

Title: A310 Airbrakes

Using composite structure in the inner and outer brakes of the A310 saved 3kg or 77lb per aircraft. Note that air brakes have more than one objective. The inner air brakes serve as brakes only. However, the outer brakes also function as spoilers. As a result, the inner and outer brakes are frequently used for takeoff and landing.
Differing thicknesses of plies are used for the unidirectional prepreg carbon tape of the skins. Near the actuator attachment, as many as 26 plies were used while as few as 8 were necessary at the trailing edge (a titanium section that takes high flexural loads to protect the trailing edge).

Title: A310 FLAP TRACK FARINGS

The flap track fairings on the A310, parts that permit the flaps to move, were originally made with a glass fiber sandwich construction. Weight and cost savings were driving factors to change the material to kevlar. Another reason was that the aramid fibers had special stiffness advantages over glass fiber. Furthermore, the aramid provided a consistency of aerodynamic form. The aluminum core were chosen over the previous nomex core because of aluminum's higher shear transfer ability, better acoustic fatigue characteristics, and lower cost. Also, the aluminum core may be compressed by impact without delamination.

Title: A310 Rudder

The significant reduction in weight, number of components, number of parts, and cost was achieved by building the A310 Rudder out of a nomex core and carbon and graphite facing sheets. Specifically, weight was decrease 45 kg or 99 lbs compared to a light alloy rudder. This twenty percent saving was one of the major goals of this program. The other major objective was to reduce production cost. The composite configuration was only ninety percent of the cost of the metallic design; however this material portion of the material cost increased from twelve percent to thirteen percent of the overall cost. This decrease in cost was mainly attributable to the decrease in the assembly effort as the following illustrates : (components (metal 600) composite 355)
(standard parts (metal 17075) composite 4800).

Title: A310 Wing and Fuselage Fairings

To save 13 kg or 28.7 lb. per aircraft, the wing and fuselage faring on the airbus A310 was altered from a glass fiber construction to a construction with kevlar skins and a nomex sandwich core.

Title: A320 Main Landing Gear

The composite main landing gear leg fairings and hinge faring doors saved 19 kg or 42 lb per aircraft, about 30%, while production labor decreased 27%. The average stress level of the components is about 17% of the components ultimate low. The design requirement stiffness is accomplished by the carbon skin. Smoothness requirements were challenged by the fact that several type of honeycomb cores are used to make the core. To ensure a smooth surface kevlar prepreg is used and cured separately. This process minimized the dimpling effect on the carbon fiber reinforced plastic faces during the curing. The process also prevents lateral deformation.

Title: A37B Landing Gear

The use of borsic/aluminum and boron/epoxy material was studied for use in the main landing gear of the A37B. The boron/epoxy configuration was successfully full size tested for hydraulic pressure containment, a design load case, and static structural strength.

Title: ASW22B Hi Performance Glider

The use of composites in the ASW22B permitted a first and second place finish in the 1987 world gliding championships. According to the designer, the ASW22B could only be built the way it was. Glass fiber is typically used when it is clearly better than carbon and aramid fibers. In the ASW22B, no components were considered to be replaced by glass fiber. From experience a 30% weight savings is really on 25% when glass fiber is replaced with carbon and aramid. This is because the exact desired thickness of carbon and aramid may not be available, or the design thickness must be slightly bigger to accommodate hail damage or ground handling problems experienced by gliders.

Comparing a glass fiber/epoxy design with a carbon/aramid epoxy, one notes that the glass fiber/epoxy would weigh 67.5 kg of the 150 kg aircraft structure or 45% of the total. The carbon/aramid epoxy would weigh only 39.4 kg or 26% of the aircraft weight. A unique attribute of hi performance gliders it that minimum weight is not always advantageous. Because the glider has to take advantage of thermal gradients, certain discrete weights are optimal. However, the weight savings generated by structure may be used to improve crash protection, pilot comfort, or landing gear characteristics.

The cost differences of glass fiber/epoxy and carbon/aramid are quite large. In 1987, glass fiber cloth averaged about 25 dm per kg (German deutsche marks) while aramid and carbon cloth was 250 dm per kg. Resin requirements for the carbon/aramid configuration was about 10 kg less than the glass fiber configuration. However, the overall carbon/aramid material costs was still 7500 dm more than the glass/epoxy aircraft. Glass/aramid was used in the vertical stabilizer because carbon would adversely effect the vhf radio antenna mounted within the structure aramid/hard foam was selected as the material for the rudder, ailerons, and flaps because this material displays a high degree of rigidity and lightness.

Title: B-1 Horizontal Stabilizer

The original objective of this design of a composite B-1 horizontal stabilizer was to achieve the absolute minimum weight. This was changed to low cost at low weight. The actual weight savings was 15% for the flight worthy stabilizer and 21% for the box. Cost savings were expected to be 17% during the production runs. Failure of the full scale static horizontal stabilizer occurred at 132% of the design ultimate load. Fatigue tests showed that the part may withstand a life of twice that of the expected life of the entire B-1.

Title: B/Sic-Ti6A1-4V Gas Turbine Engine Fan and Compressor Blades

Two full scale airfoil shapes and three full scale fan blades were successfully designed, fabricated and tested. A 30% weight reduction was observed using 50 v/o/b/sic-ti6AL-4V material over monolithic titanium. The dynamic characteristics of the titanium metal matrix composite were found to be predictable, increasing the confidence in using this material and design. Defects in the titanium composite blades were short random filaments (less than 5 diameters long), long random filaments, lines of filament fracture, incomplete consolidation or bonding, filament surfacing in machined areas, and surface irregularities. The reasons for the defects have been determined so the defects can be resolved. It was found that ultrasonic and regiographic inspection methods were good at detecting surface problems.

Title: Boeing 707 Floor Beam

An aluminum web-stiffened floor beam from a Boeing 707 commercial aircraft was replaced with one constructed of Boron filament-epoxy composite. The composite beam had the same design constraints as the original metal part, including load-bearing capabilities, size, and stiffness. The composite part was constructed using boron filament-epoxy flanges with a titanium - aluminum honeycomb web. The beam was subjected to various load tests and performed comparably to its aluminum counterpart. The use of composite materials had the following effects: (weight (aluminum 16.5) (composite 9.17))
(fasteners (aluminum 458) (composite 22))
(parts (aluminum 41) (composite 22))
(cost (aluminum $10/lb) (composite $106/lb)).
$352.00 per pound of weight saved.

Title: Boeing 707 foreflap

Control surfaces such as foreflaps are small and lightly loaded, however they experience extreme environmental effects. Thus, they do not provide much opportunity for weight savings, however, they are excellent sources of data on the durability and reliability of composite materials. A foreflap was designed for the Boeing 707 aircraft out of a boron/epoxy composite, aluminum honeycomb skins, and titanium attachments. The part was able to pass stress tests, however, it was not cost effective, as seen below:
(conventional (weight 20/lb) (cost/lb $37))
(composite (weight 15/lb) (cost/lb $132)).

Title: Boeing 737 Spoiler

Aluminum spoilers in a Boeing 737 aircraft were replaced with a graphite/epoxy composite component. The part is non-critical so it was used in actual flight tests. These tests provided a wide spectrum of load degree and duration. The spoilers were tested for compression, flexure, shear, humidity effects, thermal cycling, and other environmental effects. The composite spoiler is slighter stiffer than the traditional aluminum design, but is capable of withstanding comparable loads with equivalent success. Additionally, the part is 15% lighter than the aluminum counterpart.

Title: Bonded CFC Skin and Sub-Structure Fin provide the greatest decrease in weight, carbon-fiber composite (CFC) material was used for both the skin and sub-structure of the wing. To facilitate construction and reduce manufacturing costs the parts were bonded together using adhesive rather than conventional fasteners. The resulting wing provided a 12% decrease in weight compared to an all-metallic wing as well as a significant reduction in the number of parts required. The use of composites also reduced the corrosion rate of the wing, decreasing servicing and inspection rates.

The wing was built to better tolerances than previously possible. This is an improvement in quality and increases airplane performance. The company implementing this technology is at a tremendous technological advantage. Corrosion problems were decreased. This leads to lower servicing and inspection times.

Title: Borsic/Al 3rd Stage Gas Turbine Rotor Blades

The Borsic/Al fan blades of the F100-PW-100 IED engine were 33% lighter than the conventional titanium design, a reduction due to the low density of the borsic/al metal matrix composite. Weight savings were also possible by the removal of the part-span shroud found in titanium blades because of the borsic/al's better stiffness characteristics. Additionally, the Borsic/Al blade experienced better aerodynamic properties. To prevent damage from foreign objects and erosion problems a nickel-cobalt leading edge shied was used for protection.

The blade successfully achieved their required capability of 177C (350F) at redline of 10500 RPM and 316C (600F) at 8600 RPM.

Title: Borsic/Al Blades on JT8D Turbo Fan Engine

Use of borsic/al metal matrix composite was highly successful in the Pratt & Whitney JT8D turbo fan engine. Each of the 30 borsic/al blades weighed 439 g (15.5 oz) compared to 737 g or 25 oz for the titanium blades, a 40% weight savings. A two hour flight test run confirmed the effectiveness of the borsic/al rotor blades in the JT8D turbo fan engine, the largest rotating engine component composed of a metal matrix composite when this attempt was tried (size=101.6 cm or 40 in). The 40% weight savings was possible due to borsic/al high modulus, high strength, and low density.

Mid-span shrouds found in titanium configurations are not necessary with borsic/al because of its increased stiffness to mass ratio. Titanium blades require the mid-span shrouds for stiffness and flutter abatement.

Title: C-130 Wing Box

Boron-epoxy was used to reinforce the center wing structure in a C-130 transport aircraft. The part was required to have equivalent strength and stiffness as the original aluminum part as well as equivalent fatigue life. The part was evaluated in laboratory and flight tests. The part had a residual static strength of 109% of design ultimate. The part was also fatigue tested to 40,000 hours and static tested to 133% design load limit. In addition to successfully meeting load requirements, the part weighed 500 lbs less than the all aluminum part.

Title: C-4 Missile Equipment Bay Structure

After designing graphite/epoxy and fiber glass sandwich panels for the equipment based structure for the C-4 missile, testing was executed. The full scale tests component withstand 110% of the design ultimate load and saved 23% in weight compared to the aluminum configuration. Boron/epoxy, graphite/epoxy, hybrid boron/graphite/epoxy, boron aluminum, aluminum, and titanium materials were all considered before graphite/epoxy as selected based on cost and weight saving issues. Note that graphite/epoxy is one of the least expensive composite materials with the exception of fiberglass.

Title: C-5 Leading Edge Slat

A leading edge slat is a controlled surface on the wing of the aircraft. Slats are extended at low speeds to generate additional lift, and are subject to extreme loads. The boron slat is physically and functionally interchangeable with the corresponding aluminum slat. The structural integrity of the slat was demonstrated in a series of laboratory and flight tests experiments. The slats were also installed on operational C-5 aircraft without failures. The composite design resulted in a slat that weighed 21% less than the original aluminum slat, and had 1/10 the number of detail parts and 1/4 the number of fasteners.

Title: CFC and Metal Sub-Structure Fin

In order to reduce part weight, a carbon-fiber composite skin was used to replace the usual metal skin of the wing. The composite skin was joined to a traditional metal sub-structure using conventional fastening techniques. The weight of the part did decrease, however, manufacturing costs increased greatly. This was due to the difficulty of fastening the metal to the composite skin.

Title: CFC Skin and Sub-Structure Fin

To eliminate as much weight as possible, both the metal skin and sub-structure of the wing were replaced with carbon-fiber. The skin was attached to the sub-structure using conventional fasteners. The design greatly reduced the weight of the part, however, manufacturing costs were significantly increased. This was due to the difficulty in drilling fastener holes into the composite materials.

Title: F-100 Wing Skin

In order to evaluate viability of composite materials and potential for weight savings, a composite wing skin for the F-100 was constructed of boron-epoxy composite material. The wing skin tapers in thickness from .34 in at the outboard into 1.06 in at the inboard end. The variation in thickness required that a specific curing method be used to compensate for varying exothermic reactions. The design provided several primary benefits: (usefulness of boron-epoxy in large, complex major air-vehicle structural components. Practicality and effectiveness of the metal inlay reinforcement techniques. Significant weight savings (21.9%)).

Title: F-111 Horizontal Stabilizer Fin

The horizontal stabilizer fin for the F-111 fighter was constructed out of a boron-epoxy composite in order to reduce weight. The part experiences significant flutter loading and must therefore be stiff and strong. The part was fatigue tested to 4 life times of the horizontal loading spectrum, and passed. Then, the component was loaded to static failure, which occurred at 75% of the design maximum. The primary cause of failure was found to be a design deficiency in the aft spar-to-hub fitting joint. The use of composite materials for both the outer skin and underlying support resulted in a 27% weight savings.

Title: F-14 Overwing Faring

By employing a hybrid mixture of composites for the overwing faring of the F-14 aircraft, a cost savings was projected to be at 40% for the 100th production part. Weight savings of the hybrid graphite fiberglass-epoxy material was 26% which meant a savings of 43.5 kg or 96 lb. This was significantly higher than the initial goal of 16% weight savings or 21.8 kg (48 lb).

The design of the 2.13 m (7.0 ft) long overwing faring was tested and confirmed by 72 coupon tests and 28 element tests all at 149C. Fatigue tests of 20,000 cycles at limit load found that the residual strength was 121% of the design ultimate low at 149C. A full scale static test of the full overwing faring revealed that initial failure occurs at 116% of the design ultimate load. The part will continue to carry the load until it reaches 127% of the design ultimate load.

Title: F-14A Horizontal Stabilizer

The F-14A stabilizers are all moving surfaces which pivot about shafts protruding from the fuselage sides. The boron-epoxy design resulted in a 19% weight savings over an all titanium design. The part was tested to failure at 109% of design load ultimate. The part has been in flight service since 1970, over 300 sets have been completed. The F-14 fleet has accumulated over 250,000 flight hours without malfunctions in the composite stabilizer box.

Title: F-14A Main Landing Gear Strut Door

Four pounds and two thousand dollars per aircraft were saved by using the graphite epoxy material over the existing aluminum material. All chemical milling and material removal operations were eliminated with the exception of edge trim. The number of tools necessary to fabricate the part was reduced by 55. The complexity of the part was also reduced as the number of Z-members was reduced by 26. Static and fatigue tests validated the design.

This very small part emphasizes the importance of using composite materials for even very small parts. While 4 lbs is only a little weight, although this 4 lbs is extra payload or extra fuel, the costs dramatically decreased with this ordinary part.

Title: F-15 Composite Wing

The F-15 composite wing was constructed from boron-epoxy composites. Both the inner torque box and outer skin were constructed from composites. The skins are primarily boron-epoxy and the internal substructures are graphite-epoxy. The torque box construction combined boron-epoxy with conventional metal parts. The composite design was subjected to a battery of stress and fatigue tests and its performance was equivalent to traditional designs. The composite construction resulted in a 25% decrease in weight.

Title: F-4 Boron Rudder

The rudder is a control surface on the tail of an aircraft. This design replaced the traditional aluminum or beryllium part with a boron-epoxy composite version. 50 rudders were constructed and 45 were retrofitted into in-service F-4 aircraft for long term service tests. The remaining five were subjected to various ground test programs. The weight savings are as follows:(weight (al 64.3 lb) (Beryllium 42.11 lb) (boron-epoxy 41.8 lb)).

Title: F-4 Graphite and Boron Rudder

An F-4 rudder was constructed using structural composites with polymide matrix. The rudder was subjected to 400% of design load limit without catostrophic failure. The F-4 rudder is torsional-stiffness critical.

Title: FB-111 Boron-Epoxy Wing Box Extension

A complete report that includes the examination of many structure issues including access covers, control surface mountings, contoured surface mountings, contoured surfaces, fuel pressurization, and a 177C operating environment may be found in Grumman Advanced Development Report ADR 02-0471.1

Title: Helicopter Rotor Blade (Main)

The objectives of this program were to design a composite main rotor blade in the multi-tubular spar configuration. The blades must be interchangeable (in pairs) with the production metal blades on the AH-1G helicopter.

The blades must have increased fatigue life, be invulnerable to the 23mm ballistic threat, have low radar cross section and low fabrication costs.

The wet filament winding, co-curing process was modified while fabricating the early test blades to improve the ease and repeatability of manufacturing.

Laboratory ground, and flight tests demonstrated that the wet-filament, cocured blade satisfied, and in some cases surpassed, all objectives and could be adapted for Army service.

Title: Helicopter Tail Boom

The purpose of this program was to design and fabricate a primary structural component for a helicopter using composite materials. The component selected was the tail boom and vertical fin of the AH-1G Cobra helicopter.

The composite tail boom was required to meet the existing metal tail boom structural design and stiffness criteria, and to be interchangeable with the metal tail boom.

The design objectives were to reduce the life cycle costs, to minimize the parts count, and lower the overall weight of the existing structure.

The composite tail boom structure is a semi-monocoque configuration using a sandwich wall construction. The inner and outer skins are fabricated of Thornel 300 graphite filaments with epoxy resin, and the sandwich core is Nomex honeycomb.

The wet filament winding technique was used in the fabrication of the major components. The composite tail boom successfully satisfied the design criteria and objectives and completed all structural and flight tests.

Title: JT9D 1st Stage Eng Blades - STOL

Concern for damage from foreign objects is a central issue for the 1st stage fan blades of a Pratt & Whitney JT9D gas turbine engine that may be used in a Short Take-Off and Landing (STOL) vehicle. Five blades of Modmor II graphite fiber-BP-907 epoxy-resin and five boron fiber-BP-907 epoxy resin blades were fabricated and tested. Tests included impact velocities of 216 m/s (707 ft/s) with angles of impact up to 30 degrees. Foreign impact objects included ice balls, gelatin balls simulating birds, starlings, and gravel. Both materials performed similarly. The damage threshold was found to be somewhere between 40g and 105g (1.4 - 3.7 oz) for the graphite-epoxy blades and 45g to 130g (1.6 - 4.6 oz) for the boron-epoxy configuration. As a result, it was concluded that these two types of blades were not suitable for jet engines for a STOL aircraft.

Title: L-1011 Fairing Panels

Composite material was desirable for the wing-to-body fairing panels, the wing-to-body fillet panels, and the engine panels of a L-1011. All three were constructed of a similar configuration: a honeycomb panel of 3-ply kevlar fabric facings and a Nomex core. The size of the engine honeycomb fairing panels was between 152cm X 203cm (60in X 80in). The ultimate loads for the wing-to-body fairing panel was 8273PA (1.2 psi) internal pressure. The ultimate external pressure loads were 16,546Pa (2.4psi). Static testing for the wing-to-body fairings was successful.

Title: L-1011 Stabilizer

A vertical fin for a Lockheed commercial air transport was constructed using carbon-epoxy composites. The use of composites resulted in a 25% decrease in weight over all-metal designs. The number of ribs was reduced from 17 to 11 and the number of parts and fasteners was reduced 72% and 83% respectively.

Title: TF-30-P-9 3rd Stage Fan Blades

The 3rd stage fan of the TF-30-P-9 was and early application of BORSIC/Al composite material. It was found that weight was reduced and there was a potential for increasing the fan tip speed. Two full sets of blades were produced and were successfully structurally and aerodynamically tested for over 500 hours.

Although the 3rd stage had a higher temperature environment (about 243C or 470C) then the 1st or 2nd stage, the 3rd stage does have to contend with the foreign objects like birds and ice.

Title: Westland Helo MR Blades

In 1970, Westland Helicopters Limited began comparing the differences between its metal and composite tail rotors on the Sea King. Two positive outcomes were noted: the fatigue life improved significantly and production consistency Was higher and thus less costly. Westland also found that a Mach Number of 0.97 was possible at the tip of the advancing blade and at high incidence (20C to 22C). The retreating blade managed to stay out of blade stall, too. This was because of a strong vortex action produced by the tip design. Additionally, thrust increased 30%, an improvement also positively affecting the top speed.

The advanced shape of the airfoil would have been possible to manufacture economically using metal materials, especially for helicopters ranging from 8800lb (Lynx) to 16000lb (W30-300 and EH 101). One critical success factor in this process was Computer Aided Design (CAD). CAD allowed the designer to quickly compare the overall view of the blade to a view of the detailed layup.

Carbon fiber reinforced plastic is absent form these rotor blades. Instead, a high performance prepreg known as Ciba-Geigy Fiberdux 913 is used. While CFRP is an efficient material, its use in thick sections like this on should be avoided because of its explosive fracture characteristics. In contrast, glass-carbon like Ciba-Geigy Fiberdux 913 has an acceptably high modulus. Like CRFP glass-carbon has a fiber-dominated failure mechanism, although its fiber failure is progressive rather than instantaneous (and thus catostrophic) as is the case in CFRP).

Title: Wing Upper Surface

Wing upper surfaces (compression panels) offer potential for weight savings with the use of advanced composites because of their high intensity of compressive loading. A unidirectional boron composite was used to resist the major portion of the compressive load, with conventional metals used for secondary load carrying. The part was constructed in a honeycomb sandwich and stress tests demonstrated the ability of the design to carry the specified loads. The composite panel proved to be 53% lighter than a conventional titanium design, at a cost of $52 per pound saved.

(in-package "MUSE")

//This is what the actual code looks like after building a problem linked to a story. The remaining problems list only the tex'

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a structure capable of dealing with induced flexural and torsional deformation and high
compression loads on the skins. Outer brakes may serve as spoilers and would therefore
have similar design considerations."
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Title: Aircraft Wing

Design a wing with minimum mass without drastically increased manufacturing.

Title: Apron Fairing

Design the apron fairing. Since the tail area of an aircraft has considerable movement possibilities about the horizontal axis, it is difficult to maintain an aerodynamic seal between the tail and the fuselage. Thus, the apron fairing must have a considerable amount of flexibility.

Title: Compression Panel

Design a compression panel for a wing upper surface. The part must withstand high compression loads as well as preserve the stiffness of the traditional material.

Title: Engine Pylon Fairings

Design engine pylon fairings considering the high frequency vibration generated by engine noise and the temperature effects of the engine. Ensure substantial flexibility to permit movement between the pylon and the wing during large gusts.

Title: Equipment Bay

Design an equipment bay structure, secondary structure, for a cargo or payload carrying aircraft.

Title: Fairing Panels

Design fairing panels for a commercial air transport aircraft.

Title: Flap Track Fairings

Design flap track fairings.

Title: Floor Beam

Replace a web stiffened aluminum floor beam with one constructed of composite materials. Critical aspects of the design are: fixed depth equal to metal counterpart, equivalent stiffness, and beam fixity of 33%.

Title: Foreflap

Evaluate the viability of composite control structures such as foreflaps. These types of parts are relatively small and lightly loaded, however they are subjected to extreme environmental effects.

Title: Gas Turbine Engine Rotor Blades

Design gas turbine rotor blades. Consider the vibration and flutter problems and avoidance of certain natural frequencies. Also consider the high aerodynamic loading and high temperature environment, of as much as 600F. The blades also undergo high centrifugal loading and must not experience creep. Other considerations include: bending fatigue, thermal shock, salt corrosion, sand corrosion, foreign object damage, combined stress/fatigue.

Title: Helicopter Rotor Blades

Design helicopter rotor blades. Avoid the rotor speed harmonics."

Title: Helicopter Tail Boom

Design the tail boom and vertical fin of a helicopter. Design such that life cycle costs are reduced and part count is minimized.

Title: Hi-Performance Glider

Design structures for a super high performance glider. Gain any possible weight advantage savings regardless of cost. An interesting technical challenge in high performance gliders is that structures are only about 250 kg to begin with and about 100 kg is fixed equipment such as wheels, tires, instruments, etc. Thus, only 150 kg of the structure can be considered for weight savings.

Title: Inlet Fairing

Design the air conditioning inlet fairing. The air conditioning inlet fairing is an excessively complex part and is thus expensive to manufacture from a tooling perspective. The objective is to use composite materials to reduce weight and production costs. Aerodynamic and static loads are both low.

Title: Landing Flap

Demonstrate potential weight savings of composite materials and compare the advantages of boron/epoxy and graphite/epoxy composites. Also reduce the number of parts.

Title: Landing Gear

Design the landing gear considering the very high load that occurs once per flight and the essentially static loads that occur while the aircraft taxis on the runway. Thus, one of the main requirements is high stiffness.
Another important design consideration is the surface smoothness. Smoothness is needed on the outer surface of the main landing gear for aerodynamic objectives while smoothness is required inside because the skins of the landing gear are bonded to reinforcing hat stiffeners.

Title: Leading Edge Slat

To demonstrate the feasibility of using composites on large structural components, design a leading edge slat constructed from composite materials.

Title: Overwing Fairing

Design the overwing fairing.

Title: Propeller Rotor Blades

Design propellers that maximize cruise speed while maintaining the fuel economy of propellers. High power implies a larger propeller blade area or more propeller blades. The propeller diameter is limited by land gear clearance so propeller alternatives are usually using more blades or using wider blades. A consequence of more blades is a more complex and heavier hub. Wider blades causes a larger centrifugal twisting moment (CTM), a moment that can be minimized by using counterweights which add to the weight of the aircraft.

The blade should weigh significantly less than the conventional duralumin blade. The composite blades should also be completely interchangeable with existing metal blades. the blades and hub must be able to deal with complicated steady and vibratory stresses that result from the centrifugal force and thrust-bending of the blades. Furthermore, aerodynamic twisting moments as well as frequency effects (flexure, fundamental, harmonic, and torsional) are important.

Title: Rudder

To demonstrate the viability of composite construction in the design and manufacture of a practical structural component of significant size.

Maneuver loads are the primary design case of the rudder, a case characterized by combinations of compression, shear, and tension loads. The engine failure case is the most critical design case. Consider also the air turbulence around a rudder with significant deflection; this is a case of high vibration at the points where the control surface and the fuselage meet. This aerodynamic loading may also cause fatigue damage to the aircraft.

Title: Speed Brake

Design the highly-loaded speed brake, a secondary structure not critical to flight safety. The speed brake's high aerodynamic loading must handle a load of 204,437 N (46,000 lb) or 88,836 Pa, a loading that is determined by the hydraulic actuator's maximum loading capability.

An example of an all metallic (7075-T6) aluminum) construction is shown to show the complexity of the 300 detail parts of the 56 kg or 123.4 lb part.

Title: Spoiler

Construct a composite spoiler for a commercial aircraft. The spoiler must provide equivalent functionality as its aluminum counterpart and handle the equivalent loads without failure. Consider the asymmetric loading of the skins.

Title: Stabilizer

Design a stabilizer fin, which must be stiff and strong to withstand acoustic fluttering. The part is an all moving surface serving the functions of both elevator and aileron.

Title: Strut Door

Design the main landing gear strut door.

Title: Wing And Fuselage Fairings

Design a wing and fuselage fairing that is sufficiently strong to withstand the aerodynamic forces present while at the same time is sufficiently flexible enough to move as the wing is deflected.

Title: Wing Box

Use composite material to selectively reinforce the center wing structure of a large aircraft. The reinforced wing box must have equivalent strength and stiffness as the all-aluminum wing box. Also, the part must have a fatigue life of 40,000 flight hours as well as equivalent limit-load capability.

An important design consideration is that of using an adhesive bonded joint within the wing box. The adhesive bonded joint has to be designed so that it will withstand the shear force applied by the spars to the skin as the wing bends in flight as well as the \\\"pull-off\\\" force from the skin to the spars which comes from aerodynamic and tank pressures.

Title: Wing Skin

Construct a wing skin from composite materials to evaluate weight savings potential and demonstrate the viability of composite materials in aircraft construction.

****

//This is what the actual code looks like after building a response linked to a story. The remaining responses list only the text.

****

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   :date '3024498563
   :movie 'NIL
   :pict 'NIL
   :text '"The horizontal stabilizer of a high performance glider was built with carbon fiber
sandwich construction with an aramid fiber sandwich elevator. The vertical stabilizer was
made of a glass/aramid sandwich construction. The rudder, ailerons, and flaps were made
of aramid/hard foam.\"
  "
   :summary '""
   :title '"Aramid Fiber Sandwich Elevator (Glider)"
   )
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 (persistent-object-slot '188 'USER '4)
 )
```

Title: B/SIC-Ti6A1-4V Engine/Compressor Blades

Use 50 volume percent B/SiC-Ti 6A1-4V composite material for gas turbine engine fan and compressor blades. Make the titanium metal matrix composite blades using a closed die, vacuum hotpressing technique.

Title Bonded CFC Skin And Sub-Structure

Carbon-fiber composites (CFC) were used for both the skin and sub-structure. Instead of using conventional fastening techniques to attach the parts, they were bonded using adhesive.

Title: Boron Compression Panel

A unidirectional boron composite was used to construct the wing upper compression panel. A honeycomb sandwich construction was used, along with conventional metals for secondary load carrying.

Title: Boron Epoxy Floor Beam

A composite floor beam was constructed from boron filament-epoxy flanges and a titanium-aluminum honeycomb web. Boron tapes were loaded into a mold and the part was cured under vacuum in an autoclave.

Title: Boron Epoxy Foreflap

A traditional rib-stiffened aluminum foreflap has been redesigned as a monocoque structure with boron-epoxy, aluminum honeycomb skins, and titanium end attachments.

Title: Boron Epoxy Landing Flap

The original forged aluminum rib was used and a boron-epoxy skin was applied over it. The skin and other small parts were laminated from four layers of boron prepregs. A full-depth honeycomb core was used to provide skin stability. The composite assemblies were bonded together with a film adhesive.

Title: Boron Epoxy Landing Gear

Use boron/epoxy for the outer cylinder, inner cylinder, and side brace of the main landing gear. Use metallic attachment fittings.

Title: Boron Epoxy Stiffened Panel

The design incorporated two types of stiffeners to stabilize the boron skins. Large stiffeners were used in large open bays with smaller sandwich beam stiffeners between large stiffeners and beams. The entire structure was bolted together.

Title: Boron Epoxy Wing Box Extension

Use boron/epoxy face sheets and aluminum honeycomb structure for main parts. The structure is all-bonded except for some fasteners for resisting fuel pressure loads on the center spar. The inboard lower access panel uses a solid laminate cover and honeycomb stiffeners capped with boron for reinforcement.

Title: Boron Epoxy Wing Skin

A boron/epoxy composite was used to construct the wing skin. The degree of load required that metal reinforcement was necessary to increase laminate strength. This was accomplished by interleaving titanium plies.

Title: Boron Full Depth Sandwich

The boron composite skins were stabilized by the aluminum honeycomb core which extended the full depth of the stabilizer. Since the pivot area load distribution was comparatively uniform because of the full-depth core material, a disc-shaped plate was introduced for bending, shear, and torsion load redistribution from the stabilizer surface to the pivot structure.

Title: Boron Rudder

A four-ply laminate was used. The skin design tailored laminate to provide strength and stiffness in critical areas by adding plies. A titanium drive fitting was designed to control the transfer of load onto the skins and to minimize residual stresses in the adhesive joint. This minimized residual stresses caused by thermal incompatibility. A honeycomb sandwich structure allowed maximal weight reduction. FM40 and FM96 adhesives were chosen because they meet the temperature requirements of the rudder. These were used to bond the skin to the honeycomb core and to join the honeycomb core to the edge members.

Title: Boron Sandwich Panel

The sandwich panel design incorporated aluminum honeycomb core to stabilize the boron skins. The panels, in turn, were stabilized by the spars, ribs, or stiffeners. The sandwich terminated at the spar to allow variation in panel thickness to suit load magnitude or panel stability requirements. The inner skin was held to minimum thickness for design efficiency, The sandwich also terminated near the pivot area, where the outer skin thickness was greatest and the spars and ribs converged. The spar orientations provided direct load paths from the most highly loaded portions of the surface to the pivot shaft at the outboard bearing, and the spar locations straddled the maximum thickness of the airfoil section.

Title: Boron Slat

A leading edge slat for a C-5 was constructed from boron composite material. The design was entirely new, not a substitution of boron for aluminum in an existing design.

Title: Boron/Epoxy Fin

The stabilizer covers were designed using boron-epoxy composite configured so that there were no mechanical fasteners through the boron. In regions of high-shear transfer between the substructure and the covers, it was necessary to use mechanical fasteners and titanium was carried over these areas. The cover configuration has a titanium peripheral boundary forming the edge splice at the root rib, beams, and tip; and an integral titanium splice plate covers the pivot regions. The outboard forward corner of this splice plate extends forward along the flange of the outboard rib to meet the leading -edge splice so that mechanical fasteners can be provided in this region. The layups themselves are made to the established Grumman pattern of 0 degrees, 90 degrees, and +/- 45 degrees layer orientation with the 0 degree direction along the 50% chord line. The boron in the inboard area immediately forward of the pivot shaft is isolated from the main boron layup.

Title: Boron/Epoxy Wing Box

A wing box was reinforced in the spanwise direction with unidirectional boron-epoxy composite material. The composite was bonded to the skins and stringers of each wing box.

Title: Boron/Graphite Wing Construction

A composite wing for the F-15 was constructed of boron-epoxy and graphite-epoxy composites. The wing consisted of an inboard section, divided into three cells designed to serve as a fuel tank, and an outboard section incorporating the outer pylon support structure, fuel surge tank, and space for misc. electronic components. The upper and lower skins are primarily boron-epoxy. The upper skin is removable to facilitate wing assembly and maintenance, while the lower skin is permanently attached with mechanical fasteners. The wing is shoulder mounted by metal spars with lugs at the inboard end. Substructures are graphite-epoxy in locations were significant weight may be saved. The inner main structural torque box section contains seven graphite-epoxy ribs and the full-depth pylon rib. The ribs are attached to the upper skin and the stiffener flanges. The front spar is existing aluminum structure. The intermediate and main spars have titanium caps and graphite-epoxy webs. The inboard torque box skins are spliced at the intermediate spar. The upper skins are think honeycomb sandwich panels with boron-epoxy hat stiffeners. The lower skins are boron-epoxy sandwich construction with boron-graphite-epoxy stiffeners.

Title: Borsic/Al 3rd Stage Gas Turbine Rotor Blades

Use BORSIC/Aluminum fan blades for the Pratt & Whitney F100-PW-100 Third Stage fan blade. Use a nickel cobalt-plated leading edge shield. The average chord was 5.3 cm (2.1 in) and the length was 17 cm (6.7 in). The root of the rotor blade is shown in the figure.

Title: Borsic/Al Gas Turbine Rotor Blades

Use the high modulus, high strength BORSIC fiber reinforced aluminum composite, a metal matrix composite material, for the Pratt & Whitney JT8D turbofan engine. Do not include the mid-span shrouds found in titanium blades.

Title: Borsic/Al TF30-P-9 3rd Stage Fan Blades

Use BORSIC/Aluminum composite material for the fan blades of the third stage of the TF30-P-9.

Title: Carbon Epoxy Fin

Thornel 300 and Narmco 5208 carbon-epoxy unidirectional tape was used. Caps, webs, stiffeners, and rib attachments were cured in an autoclave. The spars were molded in a steel matched-die tool using a thermal elastomeric process.

Title: Carbon Fiber Apron Fairing

Use a carbon fiber laminate for the apron fairing. The apron fairing is composed of several different types of fabrics laid under ±45°, 0°, and 90° orientations and unidirectional tape.

Title: Carbon Fiber Hard Foam Sandwich Wing (Glider)
The wing of a high performance glider was built with carbon fiber/hard foam sandwich skin and carbon fiber spar caps. The figure above shows the wing structure:

Title: CArbon Propeller Blades

Use 2 carbon fiber spars to carry the main loads and a polyurethane foam filling for propeller blades. For the airfoil shell, use glass fiber-reinforced resin with a polyurethane coating to protect against erosion. On the leading edge, use a nickel alloy. At the blade root, use glass fiber wedges.

Title: Carbon Skin/Nomex Core Rudder

Build the rudder side panels out of carbon and glass fiber epoxy prepreg. Bond the panels to a Nomex core as shown above. Note that the lower part of the rudder has a Nomex core with the following 4 plies (from exterior to interior):
1) Carbon-Fiber Re-Inforced Plastic Fabric, Orientation: ±45°
2) Carbon-Fiber Re-Inforced Plastic Fabric,
Orientation: 90°
3) Carbon-Fiber Re-Inforced Plastic Fabric,
Orientation: ±45°
4) Graphite-Fiber Re-Inforced Plastic Fabric,
Orientation: 0° / 90°

Also note that the upper part of the rudder has a Nomex core and 2 plies with a carbon fabric re-inforced plastic sheet oriented at ±45° on the outside and a graphite fiber re-inforced plastic fabric oriented at 0° and 90° on the inner side of the sandwich facings.

Where the actuator is attached (an area that requires high stability in compression loads), use glass fiber fabrics and increase the number of carbon fiber layers. The sandwich panels are bonded at once while the side panels are bolted together at the trailing edge. The front spar has each of the side panels bolted to it. End ribs fitted to the upper and lower ends close off the rudder box. Hinge fittings and the actuator are bolted to the side panels and spar. No additional ribs are necessary.

Title: Carbon/Kevlar Honeycomb Landing Gear

Use sandwich construction for the main landing gear leg fairing and hinged fairing doors on an A320. Use carbon fiber-reinforced epoxy skins and Kevlar for the honeycomb core.

Title: CFC And Metal Substructure

A carbon-fiber composite (CFC) skin was applied over traditional metal substructure using conventional fastening techniques.

Title: CFC Skin And Substructure

The wing was constructed of carbon-fiber composite (CFC) outer skin and substructure. The skin was attached to the substructure using conventional fasteners.

Title: Graphite Epoxy Panel

Use graphite/epoxy material

Title: Graphite Epoxy Spoiler

A composite spoiler was constructed using graphite-epoxy. A full-depth sandwich construction was used. The skin was constructed of graphite-epoxy and the aluminum end ribs were replaced with fiberglass. The aluminum hinge fittings, spar, and honeycomb core were retained from the original design.

Title: Graphite Epoxy Stabilizer

A multi-shear solid-laminate skin was selected and attached to a rigid substructure of spars, ribs, and honeycomb shear webs to stabilize the skin against buckling. The honeycomb web assemblies consisted of graphite laminate facings supported by .635 cm thick fiberglass hexagonal honeycomb cores. At rib and shear-web intersections, the web assemblies were bonded together with precured graphite laminate attach angles. The upper and lower skin panels were fabricated on the plastic laminating mold. A high-temperature fiberglass-epoxy layup was laminated and cured against the pattern. After the laminate was cured, it was fitted with three steel joggle strips along the skin leading edge, and joined to the metal backup structure through metal supporting tabs. The joggle strips formed a net molded step in the cured skin panels. The individual laminate for the skin panels were placed on the layup in accordance with the requirements of a FACT sheet. The final fabrication operation for the skin panels was the edge trim. The skin panels were mechanically attached to the attach angles to enhance the bond performance and provide a fail-safe load path.

Title: Graphite Landing Flap

A matched-die molded rib was used and the skins and other small parts were laminated from graphite prepregs. A full-depth honeycomb core was used to provide stability, replacing the riveted, rib-stiffened construction of the aluminum flap. The composite parts were bonded with film adhesive.

Title: Graphite or Boron BP-907 1st Stage Engine Blades

Use Modmor II graphite fiber/BP-907 epoxy resin or boron fiber/BP-907 epoxy resin in the form of prepreg tape for the 1st stage of the JT9D gas turbine engine. Use a metal leading edge sheath.

Title: Graphite/Boron Rudder

The rudder was constructed with boron skins, graphite spar/rib, and fiberglass polyimide honeycomb core. Polyimide adhesives were used to withstand temperature ranges. The graphite spar was cured and postcured using the processing cycle describe in (XXX). The prepreg layup used the boiling-point pyrolidone solvent to improve handle ability and tack.

Title: Graphite/Epoxy Facings, Fiberglass/Phenolic Core Sandwich

Use graphite/epoxy face sheets for a honeycomb sandwich conical shell to be used as panels in an equipment bay. Use fiberglass-reinforced phenolic core. For the base frame component, use an aluminum ring at the upper end and a graphite/epoxy ring for the outer cylinder.

Title: Graphite/Epoxy Speed Brake

Use graphite epoxy with a density of 1604.9 kg per cubic meter. For shear webs, use a ±45° orientation. Pressure panels with honeycomb face sheets have a quasi-isotropic orientation. Beam flanges were laid in the 0° orientation. Beam intersections and fittings used 0°, 90°, and ±45° orientations.

Title: Helicopter Rotor Blade Response (Main)

For a multi-tubular spar configuration, wet filament winding, cocuring can be used to improve the ease and repeatability of manufacturing.

Title:

High performance prepegs based on Cib-Geigy Fiberdux 913 were used. These prepegs have high toughness and low bleed resin. Courtaulds XAS carbon and 'E' glass were used as resins. Specific materials used in the Lynx W-30 were:
- Ciba-Geigy Fiberdux Carbon 913C XAS 5
- Ciba-Geigy Fiberdux Hybrid 913C XAS/913GE10
- Nickel Coated Carbon Prepeg
- Cyanamid-Fothergill Cymet (Cycom 919 resin), a unidirectional prepeg
- Ciba-Geigy Fiberdux 913G 7781

Title: Helicopter Tail Boom Response

A semi-monocoque configuration using a sandwich wall construction can be used to build a composite tail boom. The wet filament winding process can be used to fabricate the tail boom.

Title: Hybrid Fiberglass, Graphite/Epoxy, Boron/Epoxy, Overwing Fairing

Use a hybrid mixture of composites including fiberglass, graphite, and boron/epoxy. Use a hybrid graphite/fiberglass/epoxy for the laminate.

Title: Hybrid Laminate Spars & Ribs; Boron/Epoxy Skin

Use hybrid laminates for low-cost/high-strength (LHS) graphite with 0°, 90°, and ±45° orientations for the sine-wave spars and ribs. Use boron/epoxy pads with LHS graphite/epoxy for the skin over the beams to provide the required stiffness and bending strength.

Title: Kevlar & Nomex Air Conditioning Fairing

Use 3 plies of 181 Kevlar prepreg for the air conditioning inlet fairings' outer skin and 2 plies for the inner skin. Use a Nomex honeycomb core for the fairing's sandwich construction.

Title: Kevlar & Nomex Wing And Fuselage Fairings

Use 181 Kevlar prepregs for the skins of the A310 wing and fuselage fairing construction and use Nomex for the fairing's core. For the inner skins, use thicknesses of 1 or 2 plies depending upon the location and use 2 or 3 plies for the outer skins.

Title: Kevlar Flap Track Fairings

Build the nose of the flap track fairing of the A310 as a solid laminate with Kevlar prepreg and Kevlar dry fabric. Use up to 20 plies for the nose flap track fairing. For the fixed fairing shell, use a sandwich construction composed of an aluminum honeycomb middle and 2 plies of Kevlar prepreg on the inner and outer faces. Make the moveable fairing shell and rear cover shell like the fixed fairing shell. For the cone shell, use plies of Kevlar prepreg and Kevlar dry fabric. This configuration is displayed in the above figure.

Title: Kevlar Skins/Nomex Core Engine Pylon Fairings

Use 181 Kevlar prepreg fabric in a sandwich construction to build engine pylon fairings for the Airbus A310. Use 3 plies for the outer skin and 2 plies for the inner skin; separate the skin by a Nomex honeycomb core.

Title: Kevlar/Nomex Fairing Panels

For the wing-to-body fairing panels, the wing-to-body fillet panels, and the engine fairing panels, use a honeycomb panel of 3-ply Kevlar fabric facings of 0.051 cm thickness and a Nomex core. For the wing-to-body fairing panels and fillets, use a 121°C cure, 71° service epoxy (Hexcel F 155). For the center engine fairing panels, use a 177°C cure, 149°C service epoxy (Hexcel F 161).

Title: Large, Glass Fiber Propeller Blades

Make large, slow running propeller blades out of glass fiber-reinforced resin.

Title: Monocoque Glass/Carbon/Aramid Fuselage (Glider)

The fuselage of a high performance glider was built of monocoque structure of glass and carbon fiber aramid sandwich.

Title: Narrow Propeller Blades

Use narrow propeller blades and a buff leading edge. The planform view and cross section view of the Aircraft Research Association (ARA) airfoil is shown and compared to the typical propeller blade.

Title: Prepreg Carbon/Epoxy & Nomex Spoiler

Use sandwich structure for the asymmetric loading of the spoiler. Use a unidirectional prepreg carbon fiber epoxy tape for the upper and lower skin. Bond the skins to a Nomex honeycomb core. Use carbon fiber re-inforced plastic for the spoiler box. This is illustrated above. Refer to the key below:
1) Nomex honeycomb core
2) Top skin
3) Shell
4) Ti Trailing Edge
5) Side Rib
6) Connecting rib
7) Jack attachment bracket
8) Center hinge arm
9) Sliders
10) Various fasteners
11) Sliders reinforcement
12) CFRP Box
13) Stop bracket
14) Al Outer Hinge Arm

Title: Unidirectional Carbon Prepreg Airbrakes

Use monolithic structure for the inner and outer airbrakes of a commercial air transport. Build the skins and ribs of unidirectional prepreg carbon tape with differing thicknesses. Bolt the metal front spar and the integral machined hinges and brackets to the composite structure.

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