ANALYSIS, DESIGN AND ELASTIC TAILORING OF COMPOSITE ROTOR BLADES

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Final Report
Grant No. NAG-1-638
September 1987

PREFACE

This report summarizes the development of structural models for composite rotor blades. The models are intended for use in design analysis for the purpose of exploring the potential of elastic tailoring. The research has been performed at the Center for Rotary Wing Aircraft Technology, Georgia Institute of Technology. Professor Lawrence W. Rehfield was the Principal Investigator.

Close collaboration with Mark Nixon, Renee Lake, Gary Farley and Wayne Mantay of the Army Aerostructures Directorate, Langley Research Center, was maintained throughout the investigation.

INTRODUCTION

Composite material systems are now the primary materials for helicopter rotor system applications. In addition to reduced weight and increased fatigue life, these materials provide designs with fewer parts which means increased service life and improved maintainability. Also, in terms of manufacturing, it is possible to achieve more general aerodynamic shapes including flapwise variation in planform, section and thickness.

The aeroelastic environment in which rotor blades operate consists of inertial, aerodynamic and elastic loadings. Because of the directional nature of the composite materials, it is possible to construct rotor blades with different ply orientations and hybrid combinations of materials exhibiting coupling between various elastic modes of deformation. For example, if the fibers are placed asymmetrically in the upper and lower portions of the blade, there will be a twist induced by flapwise bending. This provides a potential for improving the performance of a listing surface through aeroelastic tailoring of the primary load-bearing structure. Aeroelastic tailoring of a composite structure involves a design process in which the materials and dimensions are selected to yield specific coupling characteristics which in turn enhance the overall performance of the structure. The design of such advanced structures requires simple and reliable analytical tools which can take into consideration the directional nature of these materials. In this report, a description of analytical models is presented which aid in the design of composite rotor blades.

SUMMARY OF ACCOMPLISHMENTS

Foundation Provided by Previous Work

The present research had its origin in the development and application of a new structural model for composite rotor blades with a single structural cell. The theory is presented in Accomplishment 1, an extensive numerical comparative study appears in Accomplishment 2 and a comparison with box beam experiments is given in Accomplishment 3. This body of knowledge established a sound technology base for applications and design-related studies.

Research Objectives

The present work has three main purposes. They are

1. Support the research underway at the Aerostructures Directorate;
2. Develop simple analytic solutions for beam vibrations for comparison with tests and finite element simulations; and
3. Develop, validate and complete a simple analysis approach for multicell beams.

Item 1 has lead to Accomplishments 5-9 and 13. Item 3 corresponds to Accomplishment 11. Work supporting item 2 was presented in an informal report to the Langley Research Center.

Single Cell Theory

The theory of Rehfield[1] was compared with a finite element simulation of the static response of a model rotor blade[2]. While the results showed generally good agreement, the effect of torsion-related warping was not accounted for. Later a complete analysis was performed[5] which provided excellent agreement. Also, a physical assessment of the various elastic couplings has been made.

A summary of the above results appears in Appendix I, which is the abstract corresponding to Accomplishment 13. Also, a description of the improvements in twisting kinematics over the original theory[1] is provided.

Multicell Theory

Multicell theory requires a new modeling approach. The essential difference between single cell and multicell thin-walled beams is in the analysis of torsion. The innovative approach that has been used[11] is described in Appendix II. This appendix is the abstract for a new paper that has been submitted for presentation at the 29th AIAA SDM Conference.

ACCOMPLISHMENTS

Publications

1. Rehfield, L.W., "Design Analysis Methodology for Composite Rotor Blades," Proceedings of the Seventh DoD/NASA Conference on Fibrous Composites in Structural Design, AFWAL-TR-85-3094, June 1985, pp. (V(a)-1)-(V(a)-15).

2. Hodges, R.V., Nixon, M.W. and Rehfield, L.W., "Comparison of Composite Rotor Blade Models: Beam Analysis and an MSC Nastran Shell Element Model," NASA Technical Memorandum 89024, January 1987.

3. Bauchau, O., Coffenberry, B.S. and Rehfield, L.W., "Composite Box Beam Analysis: Theory and Experiments," Journal of Reinforced Plastics and Composites, Vol. 6, January 1987, pp. 25-35.

Presentations

4. Rehfield, L.W., "Design Issues for Modern Helicopter Rotor System Structures," Memorial Lecture to Honor James Alvin Stricklin, Texas A&M University, College Station, TX, 22 May 1986.

5. Rehfield, L.W., "Some Observations on the Behavior of the Langley Model Rotor Blade," U.S.A. Aerostructure Directorate, Langley Research Center, Hampton, VA, 24 July 1986.

6-9. Rehfield, L.W., "Structural Technology for Elastic Tailoring of Rotor Blades," presented at:

- Army Research Office, Durham, NC, 25 September 1986.
- USA Aeroflightdynamics Directorate, Ames Research Center, Moffett Field, CA, 29 September 1986.
- University of Texas, Arlington, TX, 3 March 1987
- Bell Helicopter Textron, Inc., Ft. Worth, TX, 4 March 1987

10. Hodges, D.H,. and Rehfield, L.W., "Effect of Composite Blade Elastic Couplings on Stability," U.S.A. Aerostructures Directorate, Langley Research Center, Hampton, VA, 12 November 1986.

11. Rehfield, L.W. and Atilgan, Ali R., "Analysis of Multicell Thin-Walled Composite Beam Structures," U.S.A. Aerostructures Directorate, Langley Research Center, VA, 12 November 1986.

12. Rehfield, L.W., "An Overview of Composite Rotor System Research," The Ohio State University, Columbus, OH, 14 January 1987.

13. Rehfield, L.W. and Atilgan, A.R., "A Structural Model for Composite Rotor Blades and Lifting Surfaces," Paper AIAA-87-0769-CP, 28th SDM Conference, Monterey, CA, 6-8 April 1987.

14. Rehfield, L.W., "New Developments in Composite Rotor System Structures," University of California, Davis, CA, 21 May 1987.

APPENDIX I

SINGLE CELL THEORY

A STRUCTURAL MODEL FOR COMPOSITE ROTOR BLADES AND LIFTING SURFACES*

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EXTENDED ABSTRACT

Introduction

Composite material systems are currently primary candidates for aerospace structures. One key reason for this is the design flexibility that they offer. It is possible to tailor the material and manufacturing approach to the application. Two notable examples are the wing of the Grumman/USAF/DARPA X-29 and rotor blades under development by the U.S.A. Aerostructures Directorate (AVSCOM), Langley Research Center.[1]

A working definition of elastic or structural tailoring is the use of structural concept, fiber orientation, ply stacking sequence and a blend of materials to achieve specific performance goals. In the design process, choices of materials and dimensions are made which produce specific response characteristics which permit the selected goals to be achieved. Common choices for tailoring goals are preventing instabilities or vibration resonances or enhancing damage tolerance.

* Sponsored by ARO under Contract DAAS29-82-K-0097 and by USA Aerostructures Directorate under grant NAG1-638.

** Professor, Associate Fellow AIAA and NATO Scholar, respectively.

An essential, enabling factor in the design of tailored composite structures is structural modeling that accurately, but simply, characterizes response. Simplicity is needed as cause-effect relationships between configuration and response must be clearly understood and numerous design iterations are required. The objective of this paper is to improve the single closed-cell beam model previously developed by the senior author[2] for composite rotor blades or lifting surfaces and to demonstrate its usefulness in applications.

Modeling Improvements

Two major improvements have been made in the model of Reference 2. They are:

(1) More accurate representation of twisting deformation; and

(2) Simplification of the representation of torsion-related warping.

Outline of the Present Work

An analysis of the behavior of the model Langley rotor blade under three static load cases appears in Reference 1. The model rotor cross section is shown in Figure 1. The same three loading cases have been considered. The first case is bending due to lift and blade weight, the second is pure torque and the third is axial loading due to centrifugal force.

In Reference 1, a classical version of the theory of Reference 2 is compared with an extensive finite element simulation based upon orthotropic shell elements. Attention is focused upon the small discrepancies in the earlier study which are correctly attributed to torsion-related warping. This confirms the findings reported in Reference 3. Also, an assessment of nonclassical effects in bending behavior has been made.

Bending Due to Lift and Blade Weight

Beam deflection results from the bending case appear in Figure 2. Bernouli-Euler, the classical engineering beam theory, results are denoted by "BE." This model is overly stiff. Also presented are three shear deformation models, SD1, SD2 and SD3, and the finite element results.

The shear deformation model S1 is an approximation obtained by setting the coupling stiffness C_{25} and C_{36} in Reference 2 to zero. This is the classical shear deformation model in the spirit of Timoshenko. Clearly it is overly stiff also. This direct transverse shear effect is small for a beam of this slenderness.

The complete theory, which includes all coupling effects, is denoted SD3. It provides good agreement with the finite element results.

The approximation denoted SD2 is obtained by neglecting completely the classical shear deformation effect accounted for in SD1 in favor of the coupling mechanism associated with C_{25} and C_{36}. This model, therefore, includes only deformations due to the transverse shear-bending coupling and the usual bending contribution. The magnitude of this new, unexplored form of elastic coupling is seen to be enormous by comparing SD2 and BE results. This is a finding of major importance in understanding the behavior.

The SD2 or SD3 models are required in this application in order to get sufficiently accurate predictions. This clearly excludes the earlier classical type theory of Mansfield and Sobey[4] from practical use.

<u>Pure Torque</u>

The classical St. Venant torsion theory result (without warping) is compared to the complete beam theory (CBT) and the finite element results in Figure 3. The CBT results, which differ from the classical (CL) only by the warping effect, are in excellent agreement with the finite element analysis. Restrained warping creates a boundary layer zone near the blade root that acts to stiffen the blade and reduce the angle of twist.

<u>Axial Loading Due to Centrifugal Force</u>

This case is of the utmost importance because extension-twist coupling is to be used to control blade stall, an application of elastic tailoring. The discrepancy between analytical predictions and the finite element analysis was the greatest for this case. Classical theory was too soft and it overestimated the twist angle, a condition that is not conservative in view of the stated purpose of the model demonstration.

As in the pure torsion case, the neglect of torsion-related warping is the reason for the discrepancy between coupled beam theory and the finite element analysis.

The twist angle distribution appears in Figure 4. The use of CBT brings the beam theory results in very good agreement with the finite element analysis. The rate of twist distribution is given in Figure 5. Again, the agreement is very good.

Conclusions

In structures designed for extension-twist coupling, a high degree of bending-shear coupling is present which drastically causes the structure to be more flexible in bending. The impact of this effect on system performance must be assessed.

Torsion-related warping is significant enough to warrant its inclusion in the beam analysis. With warping accounted for, the coupled beam theory is extremely accurate and easy to use.

References

1. Hodges, R.V., Nixon, M.W. and Rehfield, L.W., "Comparison of Composite Rotor Blade Models: Beam Analysis and an MSC Nastran Shell Element Model," ARO Dynamics and Aeroelastic Stability Modeling Workshop, Georgia Institute of Technology, Atlanta, GA, 4-5 December 1985.

   To be published as a NASA/AVSCOM Technical Memorandum, 1986.

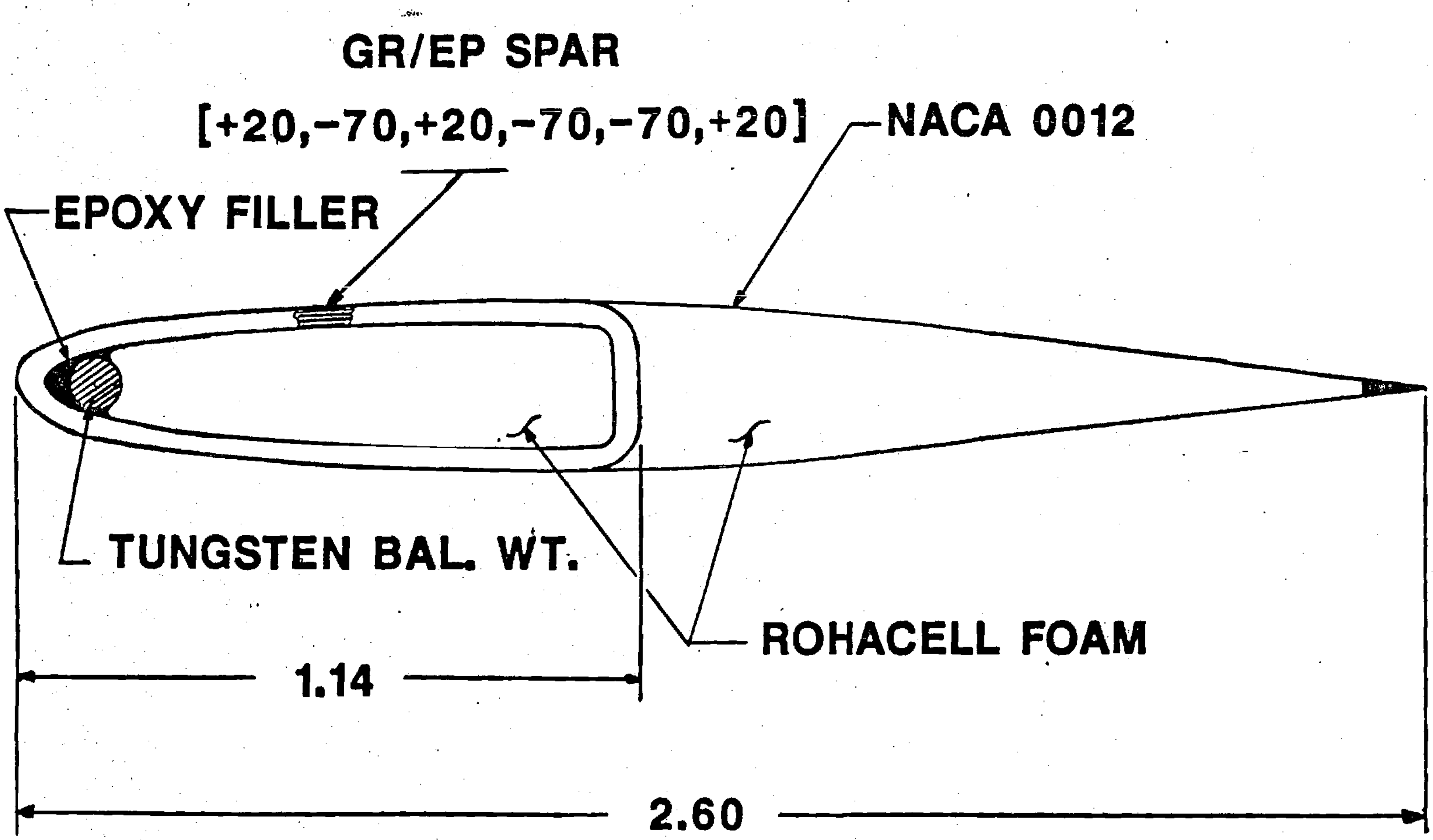
2. Rehfield, L.W., "Design Analysis Methodology for Composite Rotor Blades," Proceedings of the Seventh DoD/NASA Conference on Fibrous Composites in Structural Design, AFWAL-TR-85-3094, June 1985, pp.(V(a)-1)-(V(a)-15).

3. Bauchau, O., Coffenberry, B.S. and Rehfield, L.W., "Composite Box Beam Analysis: Theory and Experiments," to appear in the January 1987 issue of the Journal of Reinforced Plastics and Composites.

4. Mansfield, E.H. and Sobey, A.J., "The Fibre Composite Helicopter Blade, Part 1: Stiffness Properties, Part 2: Prospect for Aeroelastic Tailoring," Aeronautical Quarterly, May 1979, pp. 413-449.

FIG. 1

MODEL ROTOR CROSS SECTION



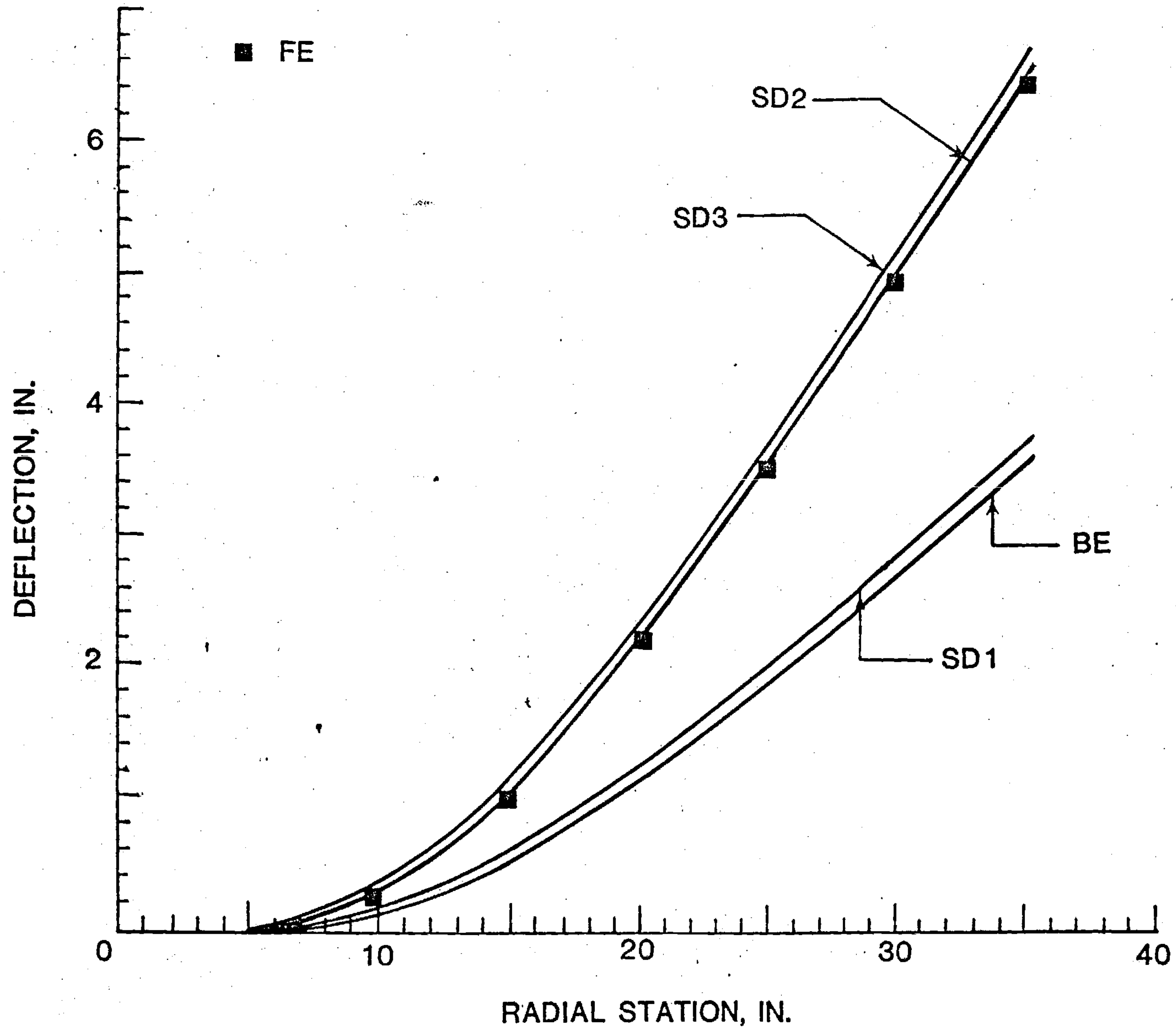


FIGURE 2
BEAM DEFLECTION DUE TO
LIFT AND BLADE WEIGHT

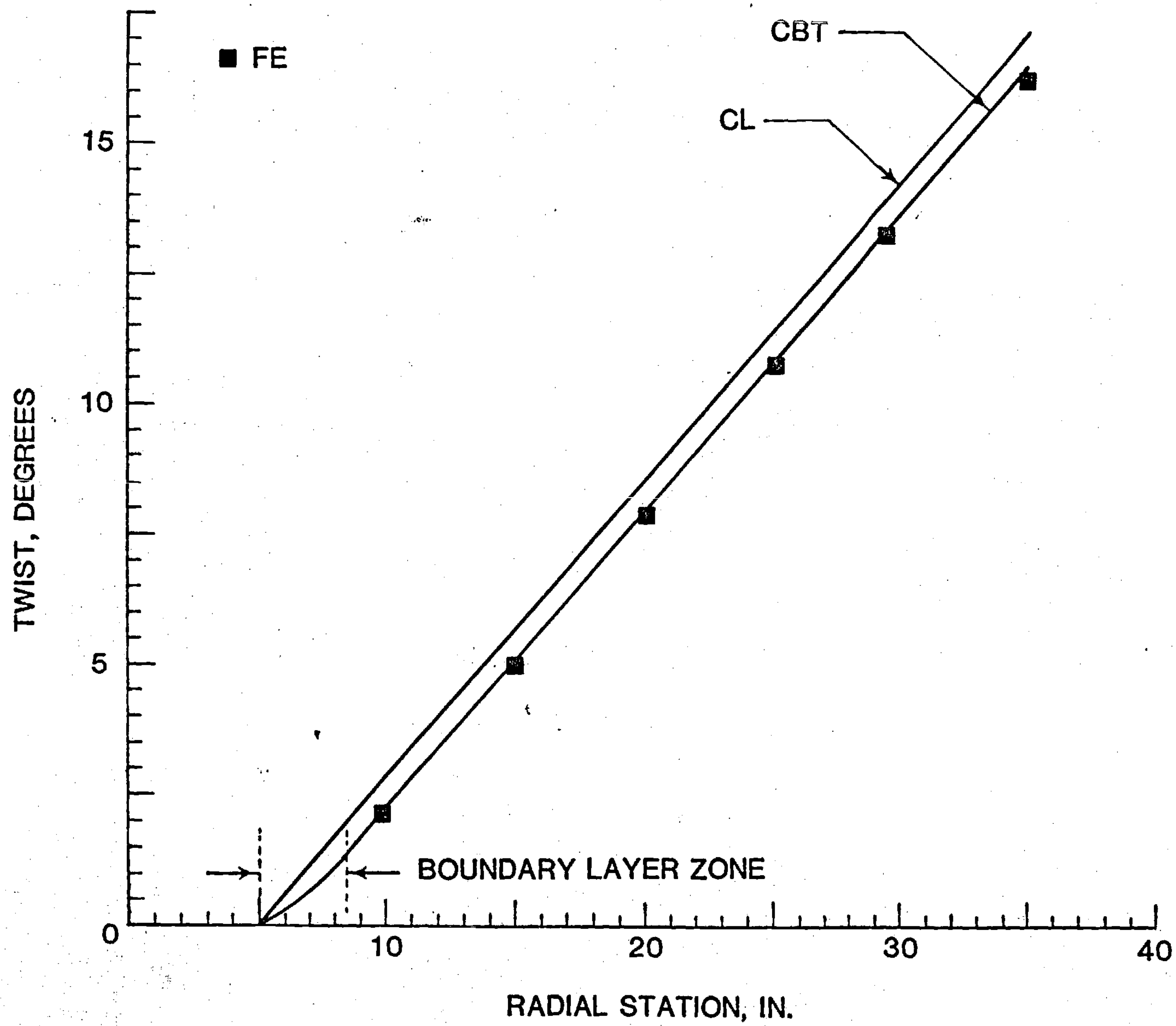


FIGURE 3

TWIST DUE TO APPLIED TORQUE

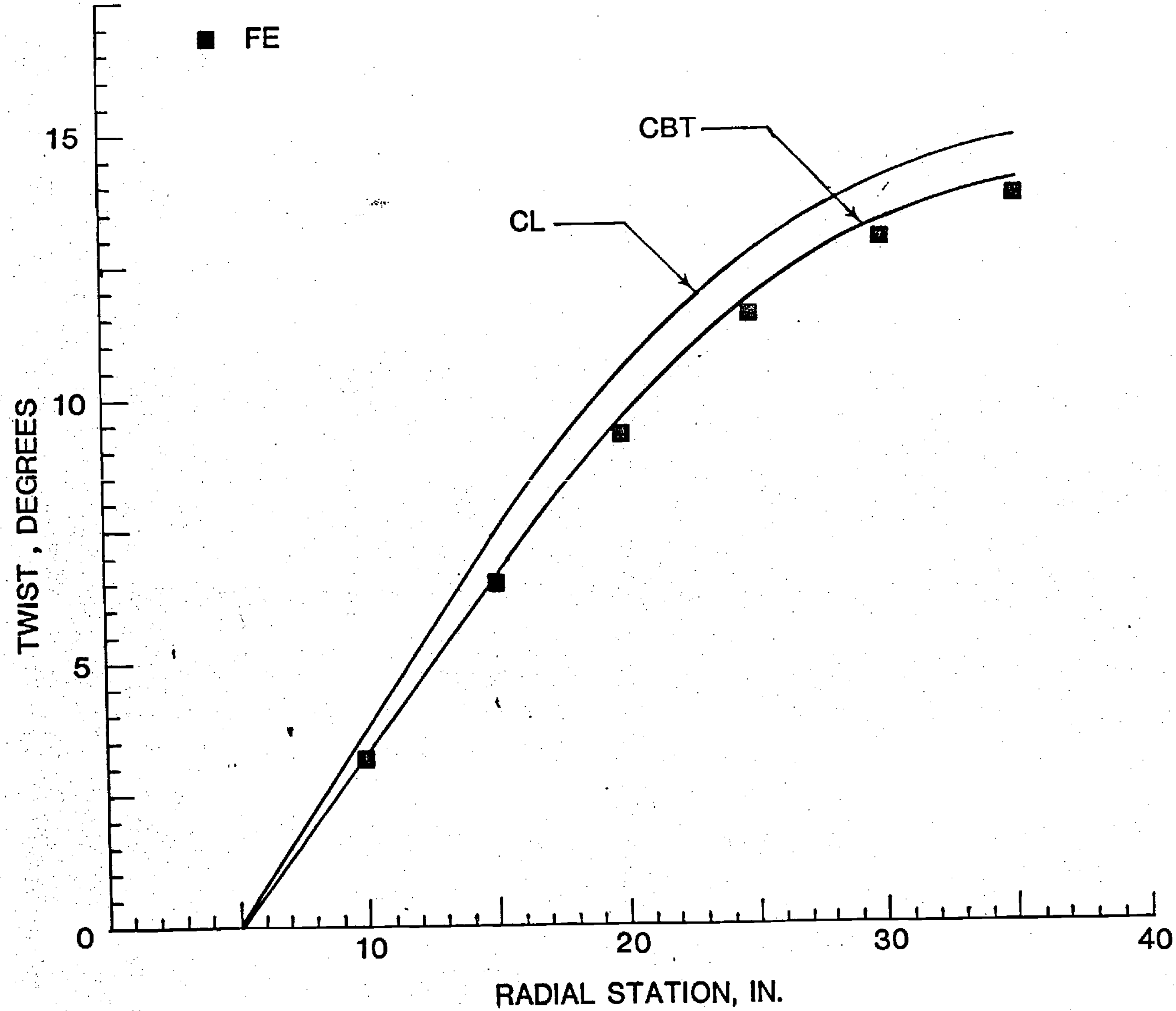


FIGURE 4

TWIST DUE TO CENTRIFUGAL FORCE

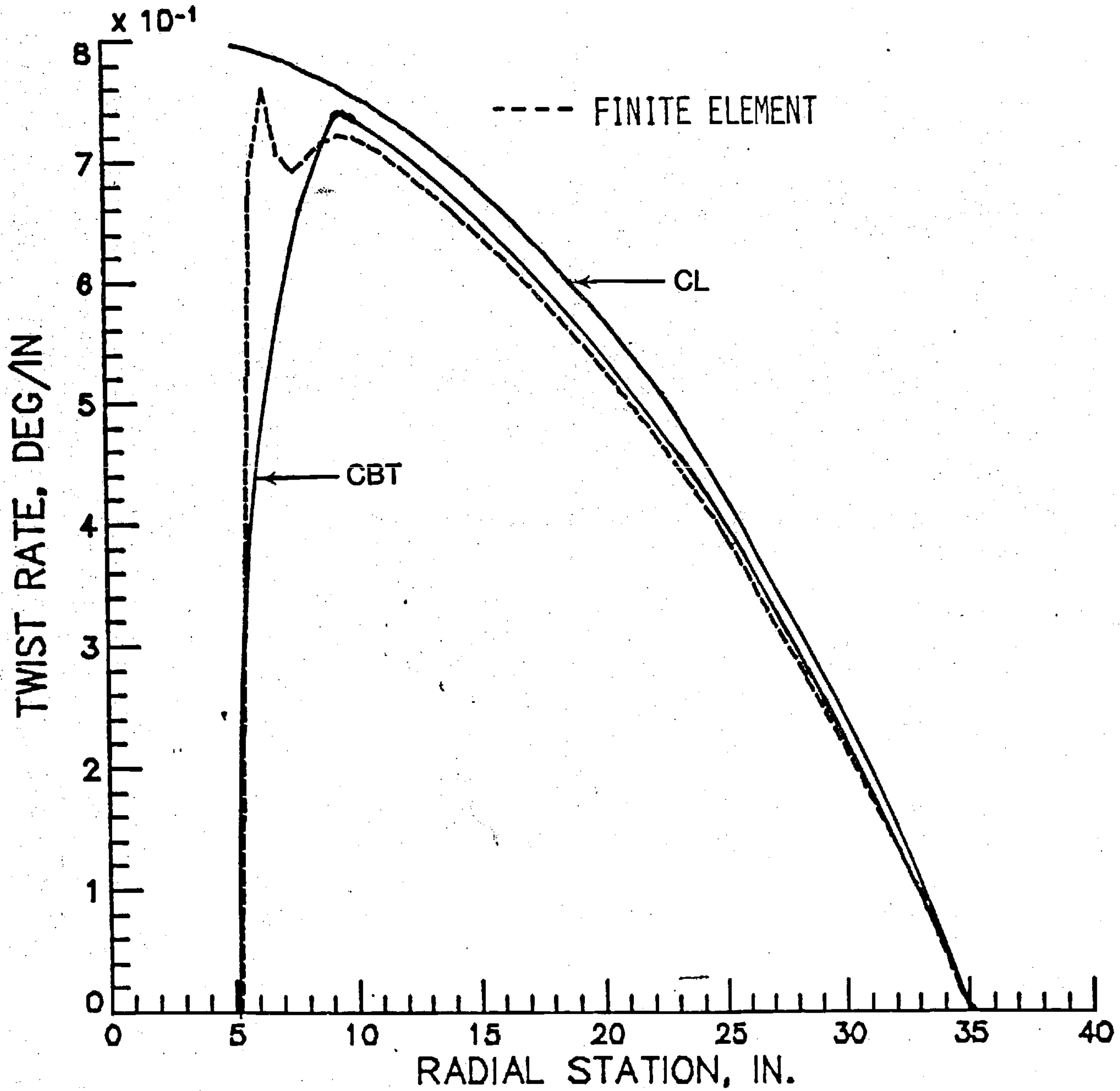


Figure 5. - Twist rate due to centrifugal force.

APPENDIX II

MULTICELL THEORY

STRUCTURAL MODELING FOR MULTICELL COMPOSITE ROTOR BLADES

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** Professor, Associate Fellow AIAA and NATO Scholar, respectively.

An essential, enabling factor in the design of tailored composite structures is structural modeling that accurately, but simply, characterizes response. Simplicity is needed as cause-effect relationships between configuration and response must be clearly understood and numerous design iterations are required. The objective of this paper is to present a new multicell beam model for composite rotor blades and to validate predictions based upon the new model by comparison with a finite element simulation in three benchmark static load cases.

Outline of the Present Work

The most significant difference between single cell and multicell thin-walled beams is in the analysis of torsion. The first step is to determine the shear center of the multicell section which is needed to establish the twisting kinematics. In the present approach, an innovative application of the unit load theorem is employed which utilizes the St. Venant torsion solution as a basis. This approach leads to closed form expressions for the coordinates of the shear center that are in terms of physically meaningful parameters.

Torsion-related warping, which earlier works[2,3,4] on single cell theory indicate is important, is determined in a manner similar to that of Benscoter.[5] In contrast to obtaining the stiffness matrix using the principle of virtual work[2], the unit load theorem is employed also to find the flexibility matrix, which is inverse of the stiffness matrix. Therefore, flexibilities are directly found, which is convenient for application.

After the above analytical steps are completed, the global beam theory is created in a manner similar to the single cell case.[2]

Application

The present model is applied to a two cell beam. The model cross section is shown in Figure 2. The benchmark static load cases appear in Figure 3. The first case is bending due to a tip load, the second is pure torque and the third is axial loading due to a centrifugal force.

The predictions are compared with an extensive finite element simulation[6] based upon orthotropic shell elements. They are found to be in very good agreement as can be seen in Figures 4, 5 and 6.

Concluding Remarks

A multicell beam theory is developed and validated. Predictions based upon the new model are compared with an extensive finite element simulation as the means of validation.

References

1. Hodges, R.V., Nixon, M.W. and Rehfield, L.W., "Comparison of Composite Rotor Blade Models: Beam Analysis and an MSC Nastran Shell Element Model," NASA Technical Memorandum 89024, March 1987.

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5. Benscoter, S.U., "A Theory of Torsion Bending for Multicell Beams," Journal of Applied Mechanics, March 1954, pp. 25-34.

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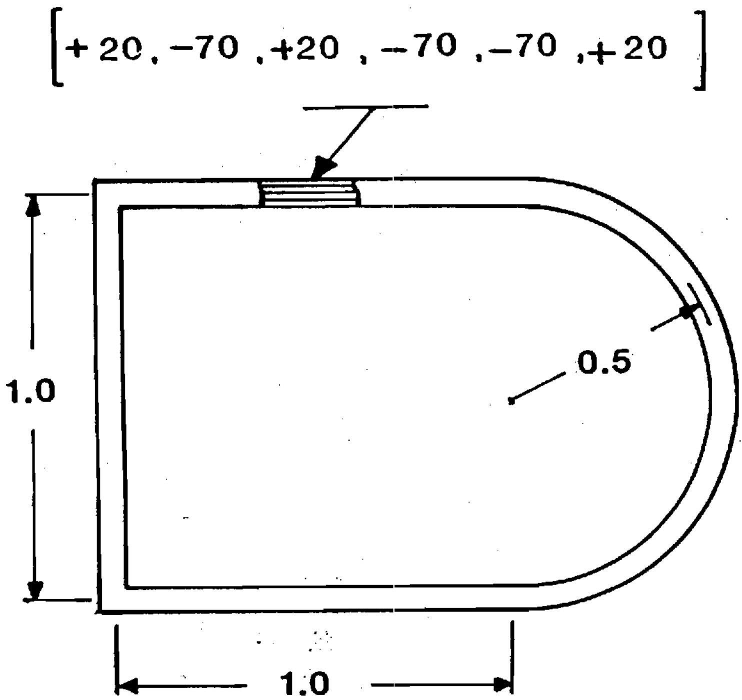


FIGURE 1. SINGLE CELL BEAM CROSS SECTION

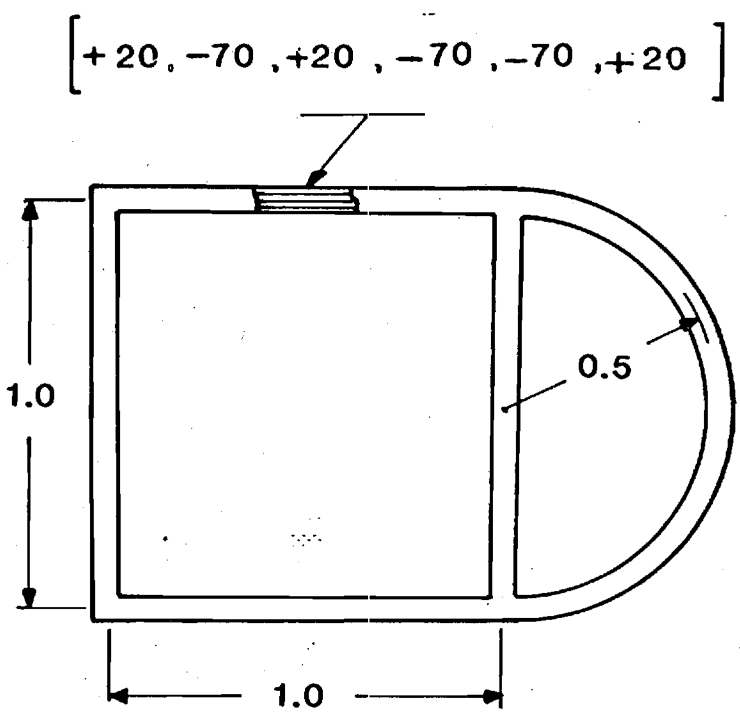
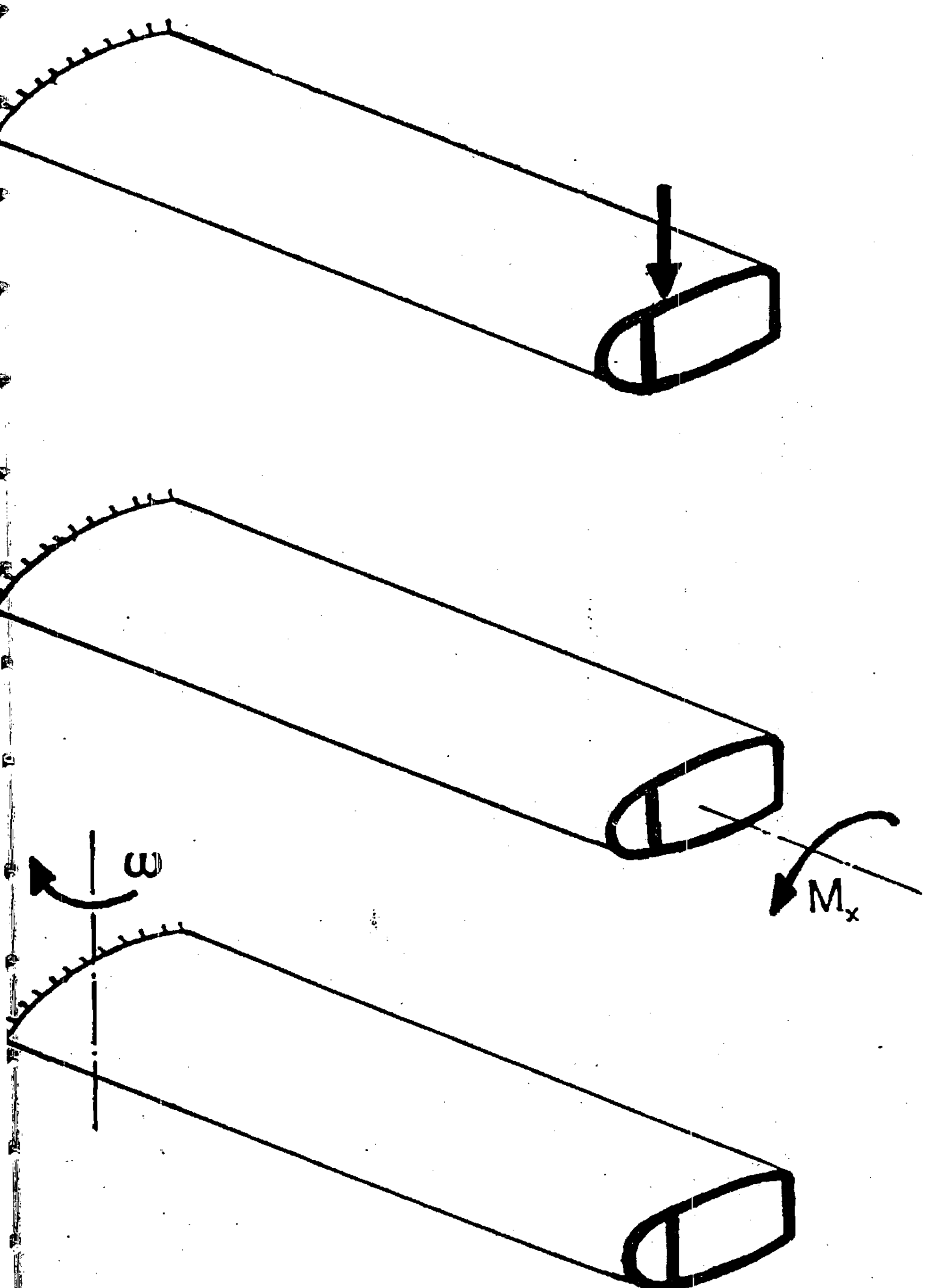


FIGURE 2. TWO CELL BEAM CROSS SECTION

FIGURE 3. GENERIC STATIC LOAD CASES



TIP LOAD

PURE TORSION

CENTRIFUGAL LOADING

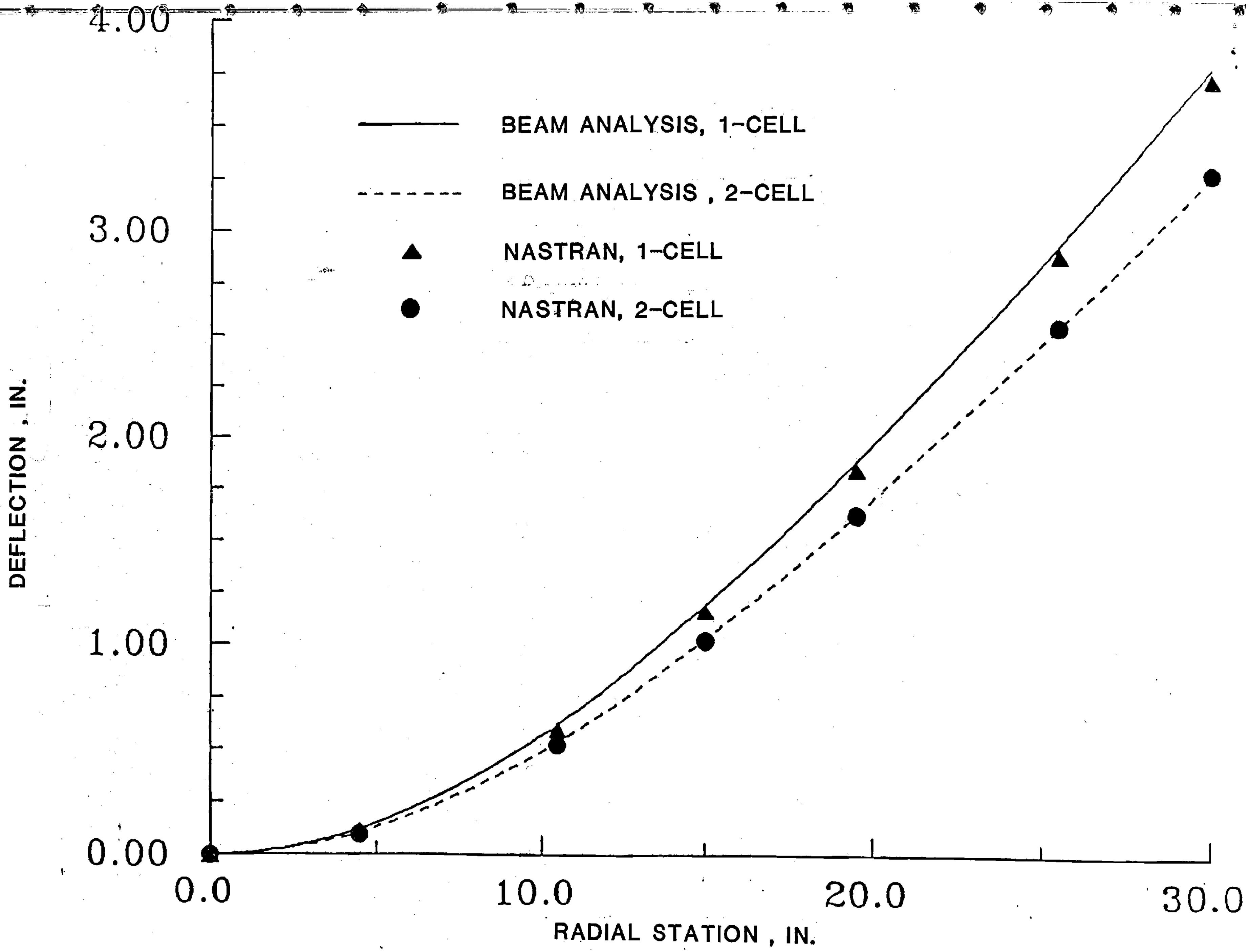


FIGURE 4. DEFLECTION DUE TO TIP LOAD

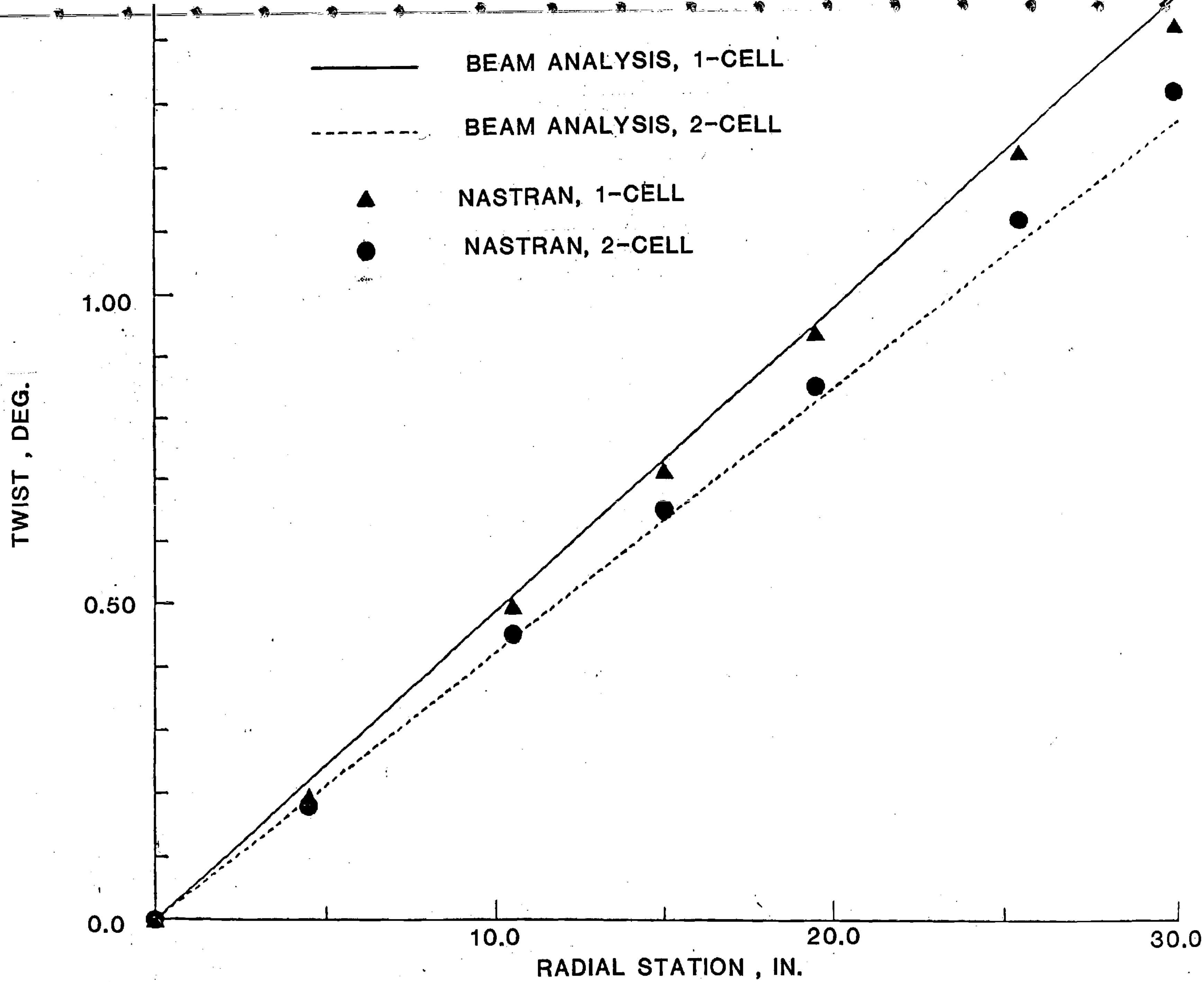


FIGURE 5. TWIST DUE TO PURE TORQUE

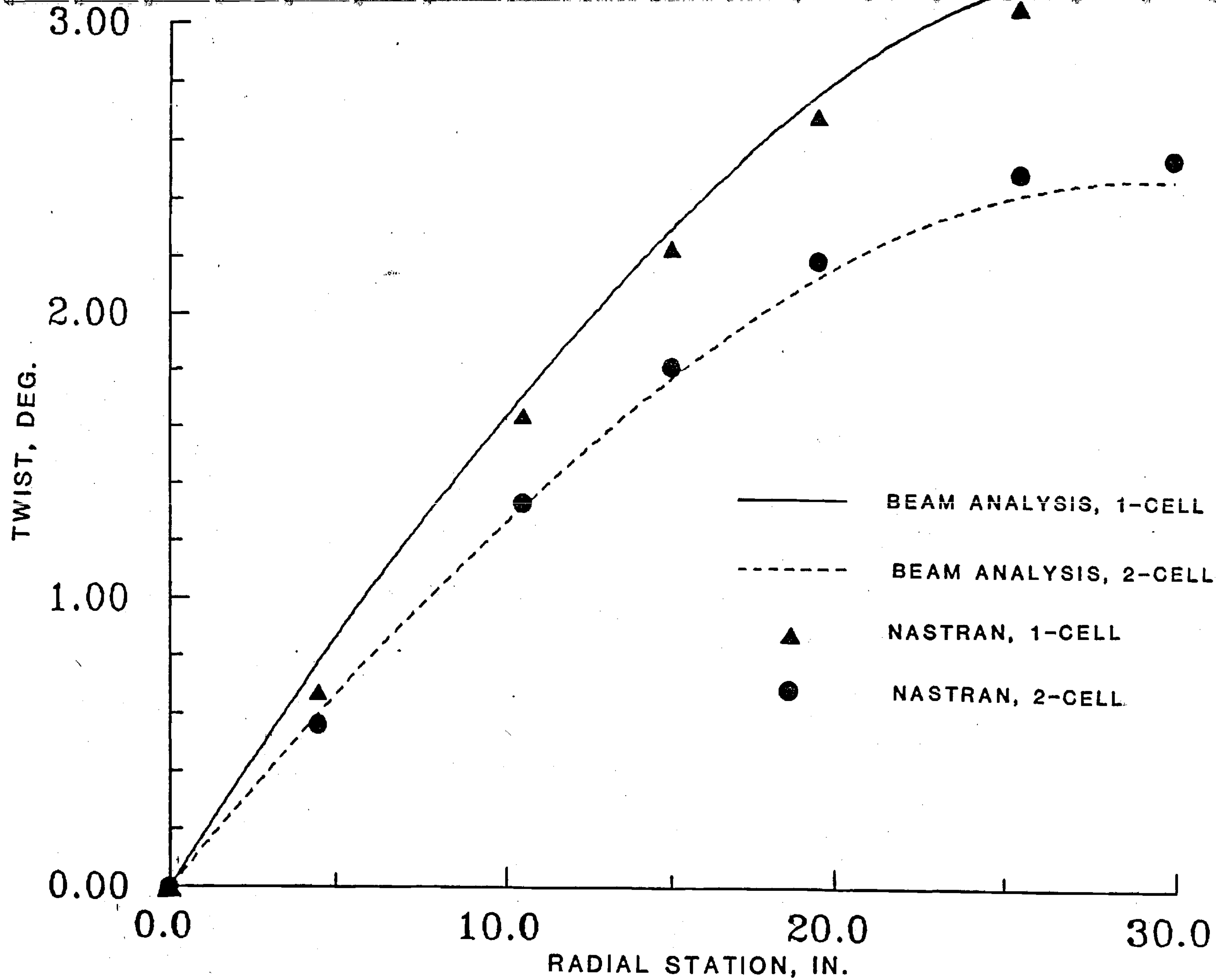


FIGURE 6. TWIST DUE TO CENTRIFUGAL FORCE