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OFFICE OF RESEARCH ADMINISTRATION

RESEARCH PROJECT INITIATION

Date: April 17, 1972

Project Title: Research Initiation - Compressive Tests of Brick Units to Predict the Strength of Brick Masonry

Project No: E-20-627

Principal Investigator: Dr. Russell H. Brown

Sponsor: National Science Foundation

Agreement Period: From April 1, 1972 Until March 31, 1974*

*18 month budget period plus 6 months for submission of required reports, etc.

Type Agreement: Grant No. GK-32648

Amount: $15,900 NSF funds (E-20-627)
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$22,075 Total

Reports Required: Annual Letter Technical ; Final Report

F.R

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RESEARCH PROJECT TERMINATION

Date: May 13, 1974

Project Title: Research Initiation - Compressive Tests of Brick Units to Predict the Strength of Brick Masonry

Project No: E-20-627

Principal Investigator: Dr. Russell H. Brown

Sponsor: National Science Foundation

Effective Termination Date: 3-31-74 (Grant Expiration)

Clearance of Accounting Charges: by 3-31-74

Grant/~~Contract~~ Closeout Actions Remaining: Final Fiscal Report

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E-20-627

Annual Letter Technical

on

Compressive Tests of Brick Units to Predict the Strength of Brick Masonry

Submitted to the

National Science Foundation
under
Grant GK-32648

by

Russell H. Brown, Principal Investigator
Georgia Institute of Technology
Atlanta, Georgia

INTRODUCTION

The compressive strength of brick masonry walls is currently determined from the compressive strength of standard masonry prisms[1]. The construction and testing of prisms is cumbersome and expensive. The use of prism tests rather than tests of single brick to determine compressive strength was adopted because the standard brick compressive test does not correlate well with that of the brick-mortar assemblage. The discrepancy is probably caused by a difference in failure mode between brick units and prisms.

An investigation was proposed to evaluate the states of stress which produce failure in single brick units and in prisms, and to develop a test using a single brick unit which will reliably predict the compressive strength of a similar element within a wall[2]. Standard tests of individual brick units and of prisms with various types of mortar were conducted to establish base line stress, strain and failure data for the program. Various types of contact material were then used between the loading surfaces of the testing machine and a single brick unit in an attempt to find a material which would provide correlation of the compressive strength and failure mode of a single brick with that of a similar element in a prism. The term "reduced constraint" is introduced to signify the reduction of restraint at the bearing surfaces of the brick specimens.

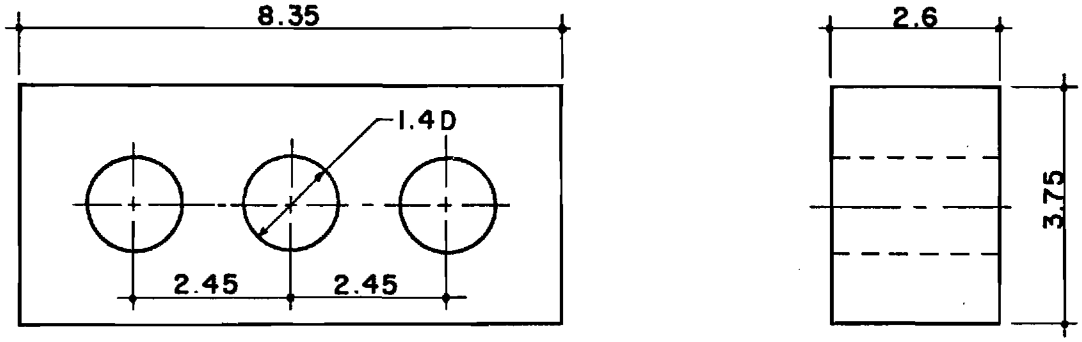
SCOPE

Three types of brick, illustrated in Fig. 1, were used in the investigation, and their properties and descriptions are presented in Table 1. The bricks designated D and G were supplied by Brick Institute of America*and are of the same lot used by D. Watstein[3]. The brick designated C was chosen because it was a relatively low strength brick available locally. Standard compressive strength tests were performed on a minimum of three samples of each type of brick.

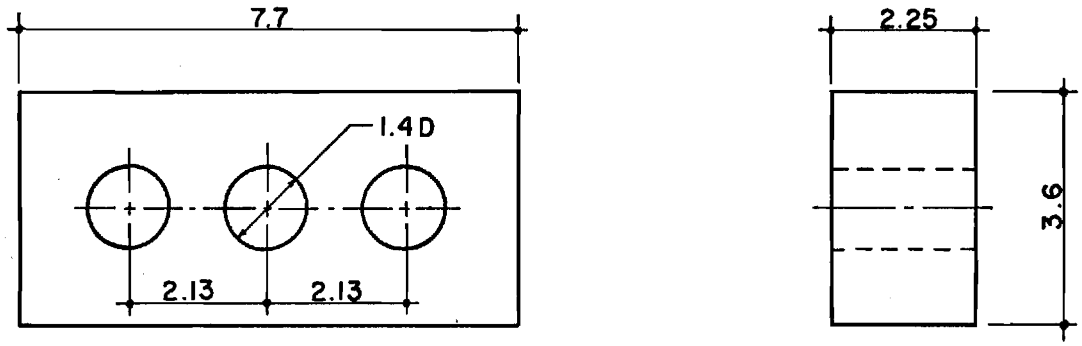
Four types of masonry mortars were used in construction of the prisms. These were types M, S, and N as defined in Specification for Mortar for Unit Masonry, ASTM C270-68, and high-bond mortar made with SARABOND mortar additive (Dow Chemical Company). Three single wythe compressive prisms with a slenderness ratio, h/t, of approximately 5 were constructed with each type of brick and mortar.

Reduced constraint strengths were determined using tetraflouoroethylene (TFE), polyvinyl chloride (PVC), methyl-methacrylate (MM) and neoprene sheet. Cloth inserted (C.I.) neoprene sheet in three thickness was studied further becasue it showed a relatively good correlation to the prism tests in terms of strength and mode of failure.

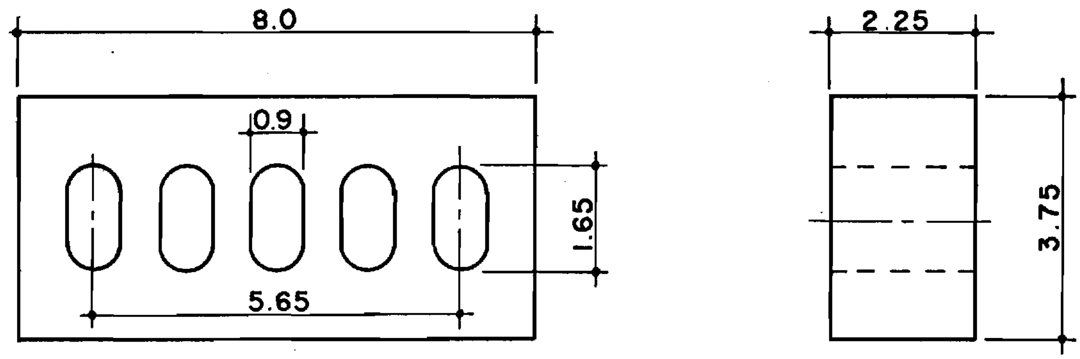
* Formerly Structural Clay Products Institute.



BRICK C
GROSS AREA = 31.3 sq. in.
NET AREA = 27.6 sq. in.
PER CENT CORE = 12.0 %



BRICK D
GROSS AREA = 28.0 sq. in.
NET AREA = 23.2 sq. in.
PER CENT CORE = 17.3 %



BRICK G
GROSS AREA = 30.0 sq. in.
NET AREA = 23.4 sq. in.
PER CENT CORE = 22.0 %

Fig. 1 - Views and dimensions of bricks used in the study.

Table 1 – Properties and Description of Bricks Investigated

		Compressive Strength[a]			Initial Rate of Absorption			
Brick Designation	Source	n[b]	Average value psi	v[e] %	n	Average value g/30 in.^{2}/min.	%	Description of Brick
C[c]	From Tests	6	9,600	0				Extruded, side cut
	Reported by Watstein	-	-	-	-	-	-	
D[d]	From Tests	4	17,750	8.9				Extruded, side cut
	Reported by Watstein	5	12,800	3.0	5	12.5	33.0	
G[d]	From Tests	4	23,100	7.2				Extruded, side cut
	Reported by Watstein	5	25,300	7.7	5	1.3	0	

[a] Determined in accordance with Standard Methods of Sampling and Testing Brick, ASTM C67-66

[b] n = Number of specimens

[c] Bricks supplied by Chattahoochee Brick Company. Properties and designation differ from those tested by D. Watstein.

[d] Bricks supplied by Brick Institute of America. Same lot and designation as those tested by D. Watstein.

[e] v = Coefficient of variation

TEST SPECIMENS

Sample Preparation

The bricks for individual unit tests were inspected to insure that the loading surfaces were relatively level and free from gross surface defects such as holes, cracks or obtrusions. The lateral faces were inspected for cracks. Any defective bricks were rejected. The end bricks for the prisms were selected on the same basis as those for the individual tests, while the interior bricks were rejected only if cracked or chipped.

Samples for standard brick compression tests were cut on a masonry saw and inspected for plane and parallel ends.

All samples were capped with a high strength gypsum in accordance with Section 10, Capping Test Specimens, of Standard Methods of Sampling and Testing Brick, ASTM C67-66, except that the specimens were not coated with shellac. The two end bricks for each prism were capped on one face only prior to prism construction.

Prisms

Three single-wythe masonry prisms were built from each of the three types of brick and four types of mortar and are described in Table 2. They were constructed with whole brick laid in stack bond in a carefully leveled full bed of mortar. The joint thickness was maintained at 3/8-in. Each prism was seven courses high and carefully constructed in a form, as shown in Fig. 2, so as to be plumb and level. The joints on the face of each prism were struck flush. All prisms were cured for 28 days in a laboratory where the temperature was maintained between 65° and 75° F. Relative humidity was not monitored.

Table 2 - Description of Masonry Test Prisms and Their Compressive Strength

Type Brick	Type Mortar	Number of Prisms N	Prism Dimensions: Thickness t, in.	Width w, in.	Height h, in.	h/t	Compressive Strength of Prisms, Average Value psi a	b	Compressive Strength of Mortar, Average Value psi a	b
C	M	3	3.75	8.35	20.5	5.47	5190	-	4760	-
C	S	2	3.75	8.35	19.5	5.20	5090	-	1890	-
C	N	3	3.75	8.35	20.7	5.51	3740	-	1340	-
C	H	3	3.75	8.35	20.6	5.5	4470	-		-
D	M	3	3.65	7.7	17.9	4.92	8540	5150	4760	3290
D	S	0	3.65	7.7	17.7	4.85		4960		1520
D	N	3	3.65	7.7	17.8	4.89	5680	3760	1470	700
D	H	3	3.65	7.7	17.6	4.82	6870	-	1580	-
G	M	3	3.75	8.0	18.1	4.84	6260	5390	4380	3290
G	S	3	3.75	8.0	18.1	4.84	4870	3910		1520
G	N	3	3.75	8.0	18.2	4.86	4270		1400	700
G	H	3	3.75	8.0	18.1	4.84	5840	-		-

a Value determined in this study.

b Value determined by D. Watstein[3].

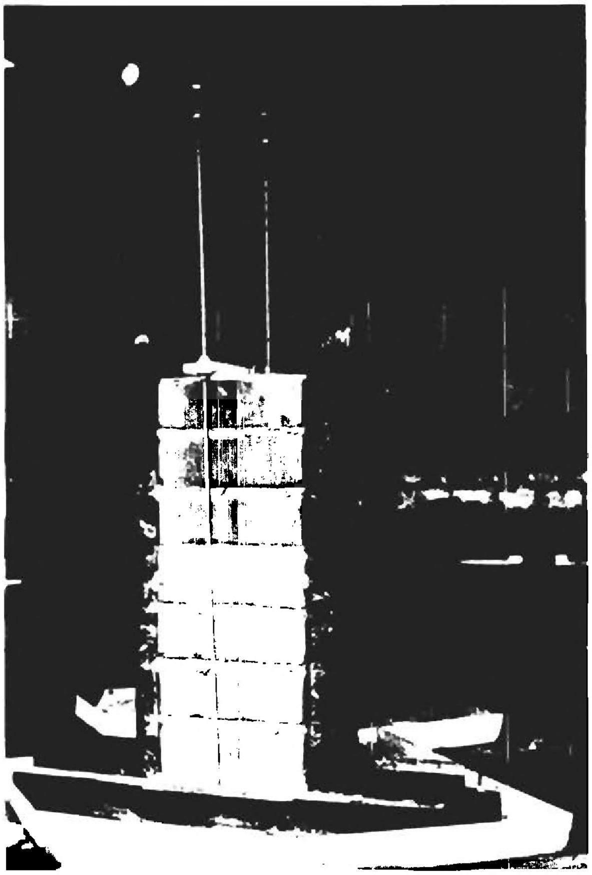


Fig. 2 - Prism in form used for construction.

Mortar

Three 2-in. cubes were made of each type of mortar used to construct the prisms. The cubes were molded in accordance with Section 7,8,10 and 11 of Standard Method of Test for Compressive Strength of Hydraulic Cement Mortars, ASTM C109-64. The cubes were covered with a glass plate for 24 hours after being molded, after which the cubes were removed from the molds and cured in moist curing room for 27 days until tested.

Additional data on properties such as modulus of elasticity and Poisson's ratio will be obtained from compressive tests of 2-in. diameter by 4-in. high cylinders of the mortars.

Instrumentation

Unbonded electrical resistance wire gages were attached to each test specimen at mid-height to measure lateral strain during loading (Appendix).

TEST PROCEDURES

Prisms

The brick masonry prisms were tested in accordance with the applicable provisions of Standard Method of Test for Compressive Strength of Molded Concrete Cylinders, ASTM C39-64. The prisms were loaded in increments, and the load was held constant while strain and vertical deflection readings were taken. Priorty was established such that the peripheral gage would be read first followed by the gages on the faces, and then the gages on the ends. This order may be particularly significant when the strain is increasing rapidly.

Brick

Standard Compressive Tests

The standard compressive tests were performed in accordance with Sections 11 and 12 of ASTM C67.

Compressive Tests with Contact Material

The compressive tests with contact material were conducted as described above, except that a sheet of the particular contact material was placed between the top and bottom of the capped specimen and the upper and lower bearing plates of the testing machine. The loads were applied as described under the test procedure for prisms.

Mortar

The mortar cubes were tested in accordance with Section 12(b) and 12 (c) of ASTM C109.

RESULTS

Compressive strengths of the prisms are shown in Table 2. The values given are the averages based on three tests of each combination of brick and mortar. Values reported by D. Watstein[3] are given for comparison.

The average compressive strength of each type of prism is also presented in Table 3 for comparison with the compressive strength of brick units obtained in reduced constraint tests. Only two samples of type G brick were tested using TFE as a contact material due to a limited supply of the material. Only one sample of each brick was tested with PVC sheet due to poor correlation with prism results. One test with type D brick was conducted with both MM and unreinforced neoprene because neither of these materials appeared to correlate with prism tests. Three thickness of cloth (cotton duck) inserted neoprene sheet were evaluated with the three types of brick.

Stress-strain curves for six tests are presented with photographs taken during and/or after the tests. These particular tests were chosen as some of the best examples, rather than typical examples, of the type of results obtained. Photographs during failure of the prisms were taken to show the location and mode of failure. Post-test photographs were also considered desirable for failure mode analysis for comparison between prism tests and reduced constraint tests. Note was also made of the load and approximate location of surface cracks as they appeared during the reduced constraint tests.

Table 3 - Compressive Strengths of Prisms and Reduced Constraint Specimens

	Average Compressive Strength, psi										
	Prism Tests				Reduced Constraint Tests						
	Mortar Type				Contact Material, Thickness (in.)						
Designation	M	S	N	H	TFE[a] (1/8)	PVC[b] (1/8)	MM[c] (3/8)	U.N.[d] (1/8)	C.I.[e] (3/32)	C.I. (1/8)	C.I. (3/16)
C	5190	4920	3740	4470	3200	10060	-	-	3140	3140	2770
D	8540		5680	6870	3680	13170	14240	6010	5950	5750	4970
G	6260	4870	4270	5840	4230	13670	-	-	6310	6040	5400

[a] Tetrafluoroethylene
[b] Polyvinyl chloride
[c] Methyl-Methacrylate
[d] Unreinforced neoprene
[e] Cloth inserted neoprene

INTERPRETATION OF RESULTS

The proposed tests for the investigation are approximately 90% complete. An attempt was made in conducting the testing to measure as many parameters as practicable although the relevance of such data might not be immediately obvious. Interpretation of the data has been rather superficial and the rationale for some of the results has not been studied. There are, however, some obvious trends in the data and observations which can be commented on at this time.

Comparing the compressive strength data and the mode of failure of individual bricks subjected to the reduced constraint tests, the use of TFE does not appear to eliminate the frictional restraint at the bearing surfaces of the brick specimen. Because of the consistent reduction in compressive strength, it appears that all of the contact materials tested reduced the lateral restraint of the individual bricks. The 1/8-in. thick unreinforced neoprene gave type D brick a compressive strength of less than 1500 psi at initial cracking compared to a minimum of 2000 psi at initial cracking for TFE. Ultimate strength values for type D brick with TFE and unreinforced and C.I. neoprene sheet were comparable. Similar results were obtained with type G brick. The stress-strain curves for TFE and C.I. neoprene sheet shown in Figs. 3 and 4 are almost identical prior to initial crack formation although the ultimate load for TFE is considerably higher.

In contrast to the performance of type G brick with TFE or neoprene, Fig. 5 presents the stress-strain data for PVC. The stress prior to initial cracking is almost double the value observed with TFE at the same level of strain. The performance of MM was similar to PVC and testing of these materials was discontinued.

Of more significance is the comparison of prism and reduced constraint stress-strain curves and failure modes. Continuing to compare the performance of type G brick, Fig. 6 is the stress-strain curve for a prism with type M mortar. It shows

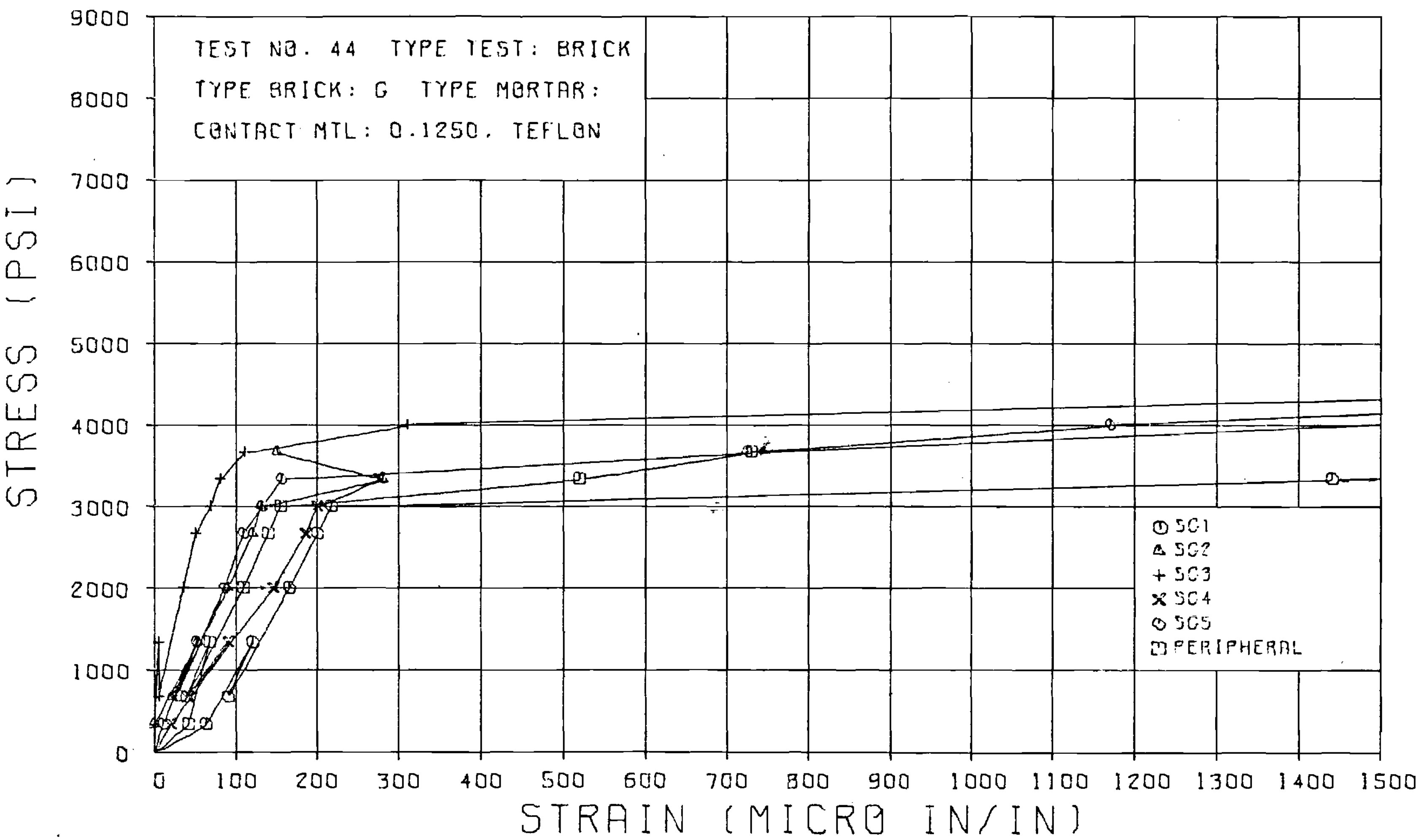


Fig. 3 - Relationship between compressive stress and lateral strain for type G brick with TFE to reduce lateral constraint.

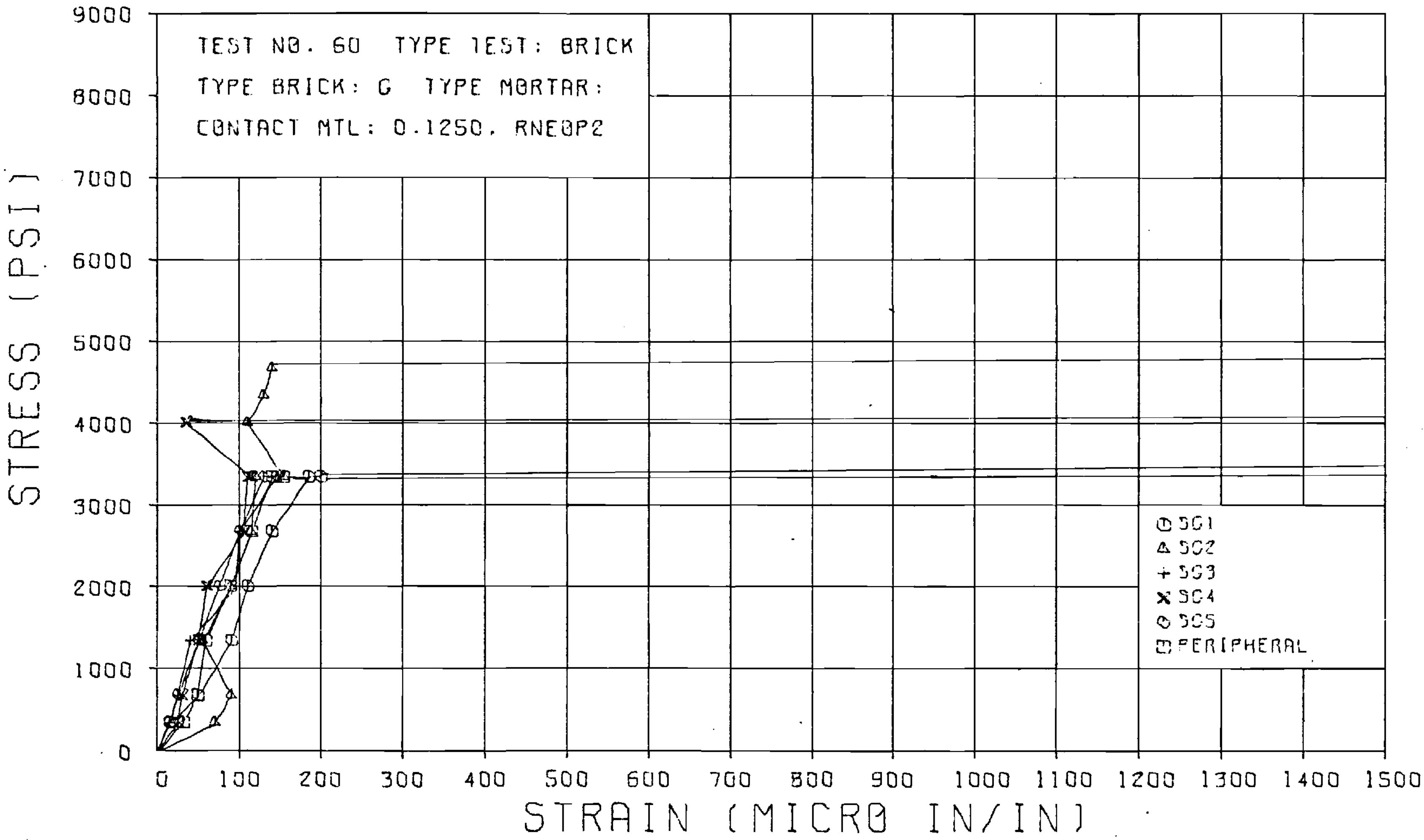


Fig. 4 - Relationship between compressive stress and lateral strain for type G brick with 1/8-in. C.I. neoprene to reduce lateral constraint.

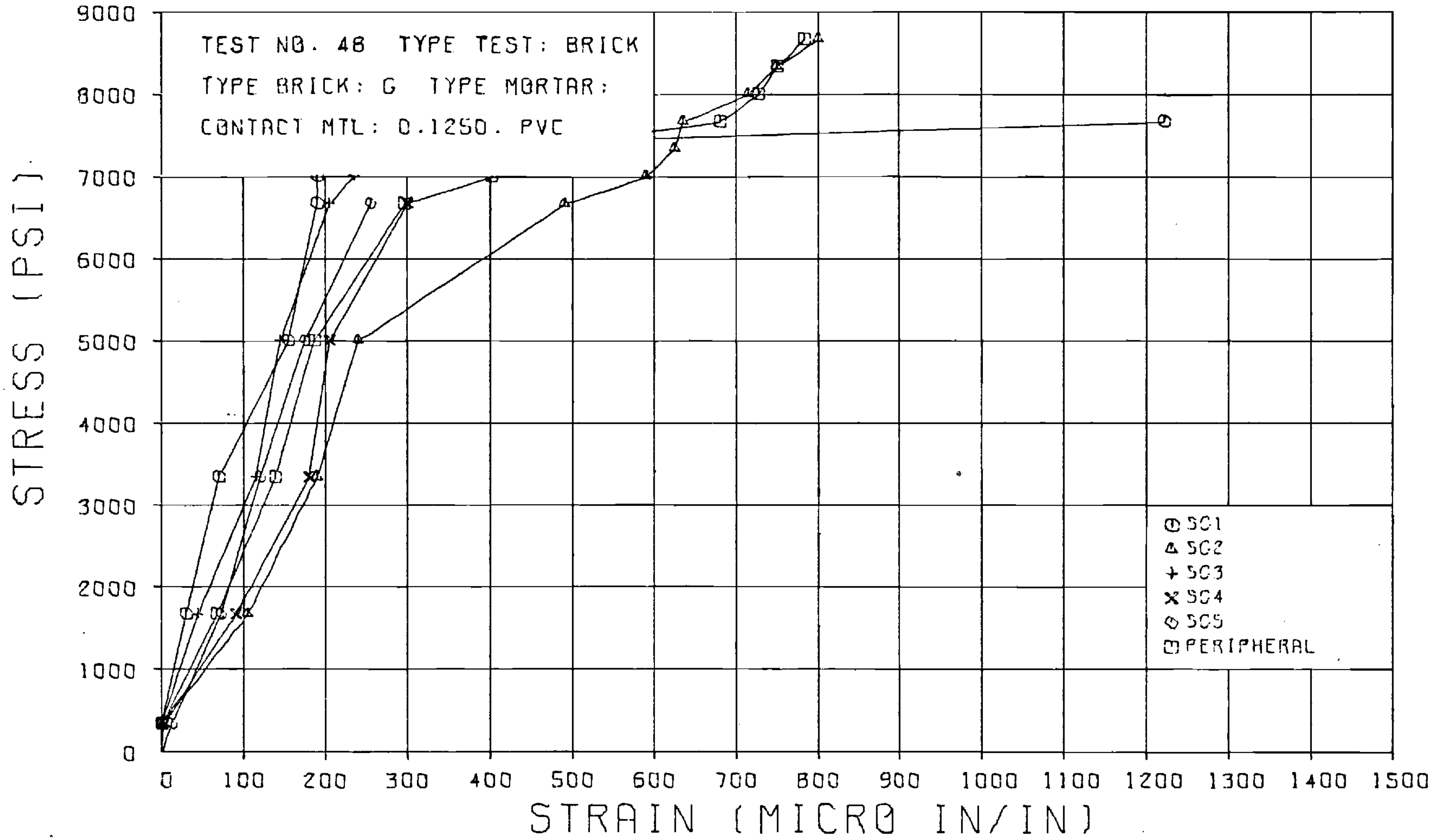


Fig. 5 - Relationship between compressive stress and lateral strain for type G brick with PVC to reduce lateral constraint.

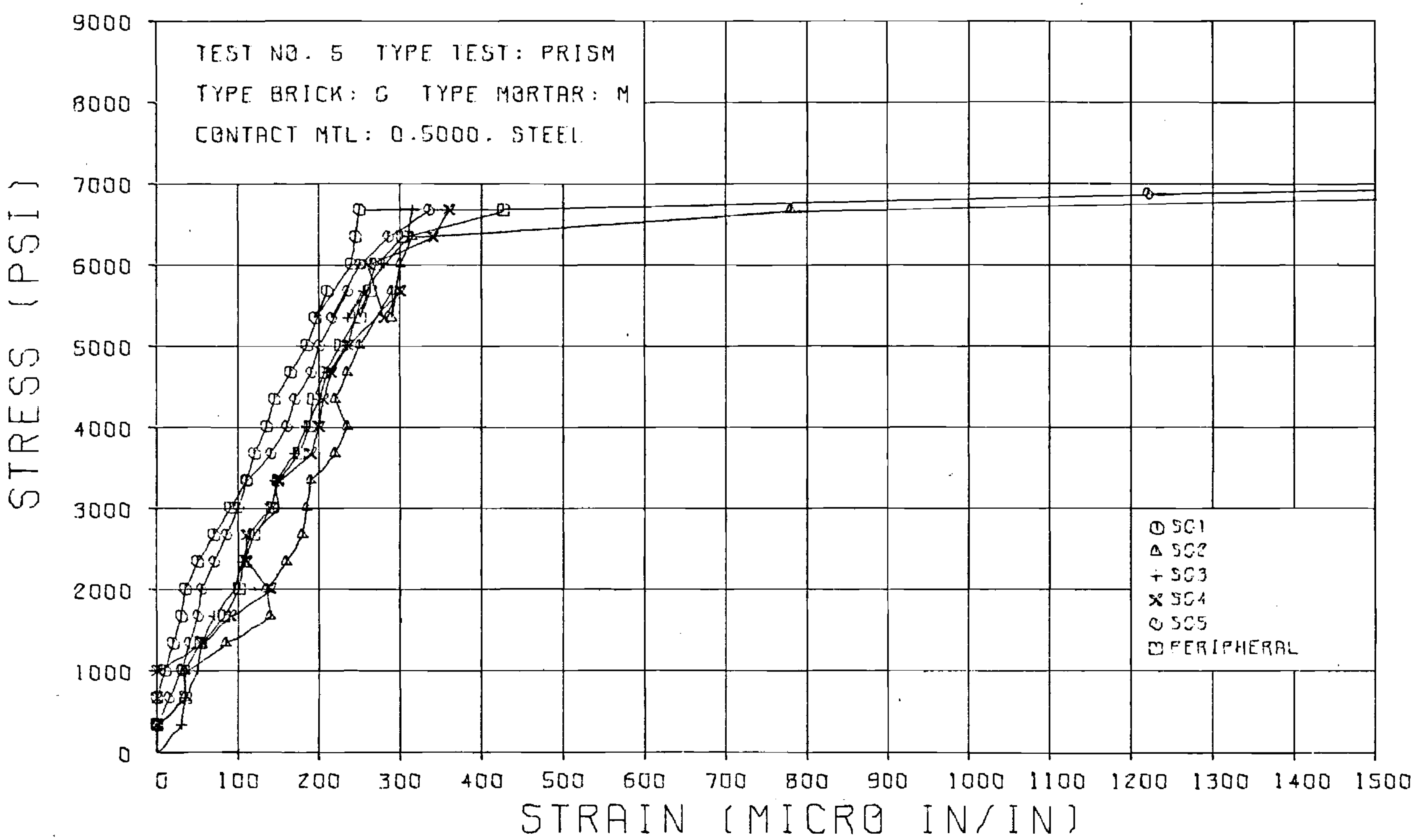


Fig. 6 - Relationship between compressive stress and lateral strain for a prism with type G brick and type M mortar.

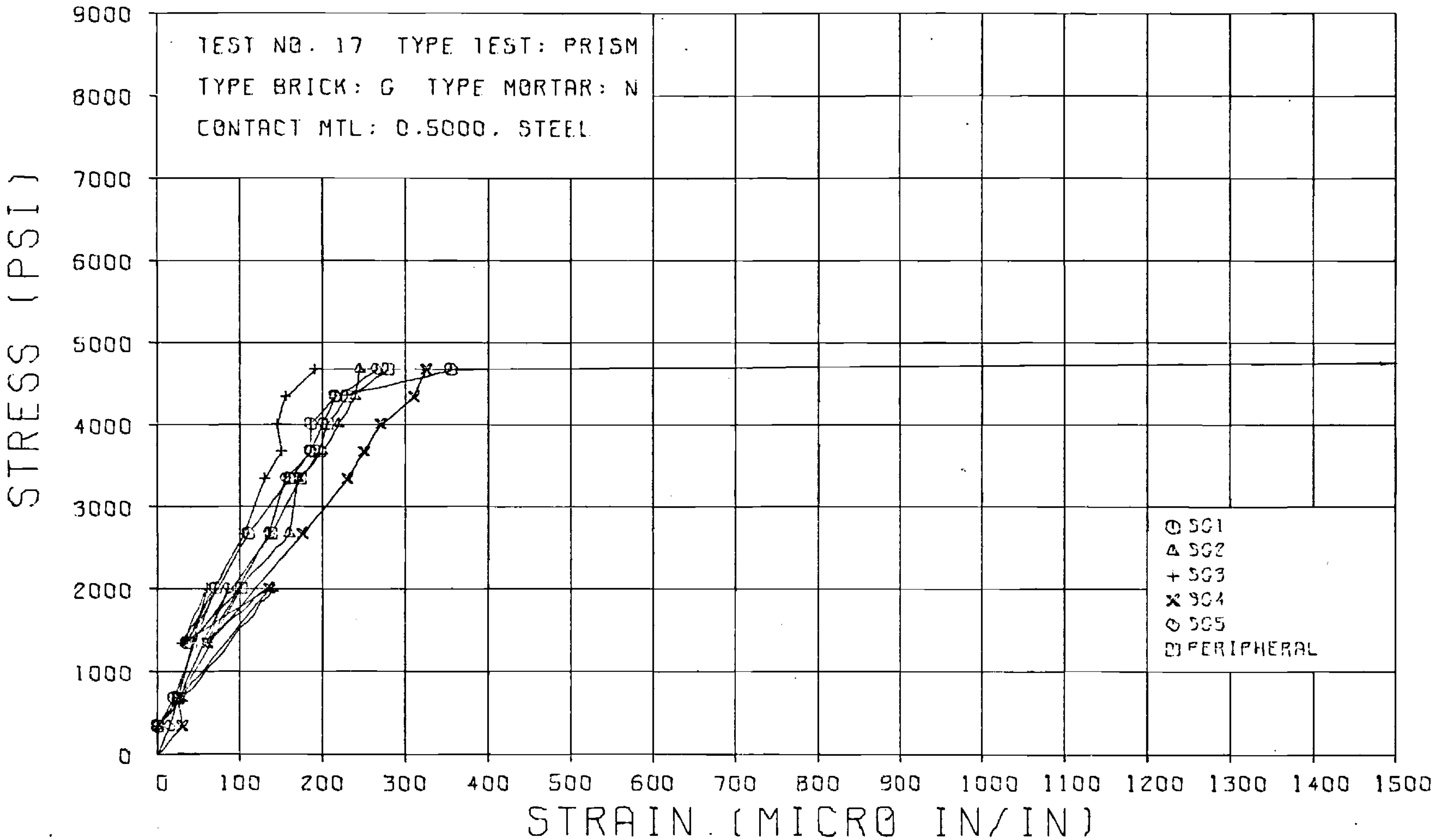


Fig. 7 - Relationship between compressive stress and lateral strain for a prism with type G brick and type N mortar.

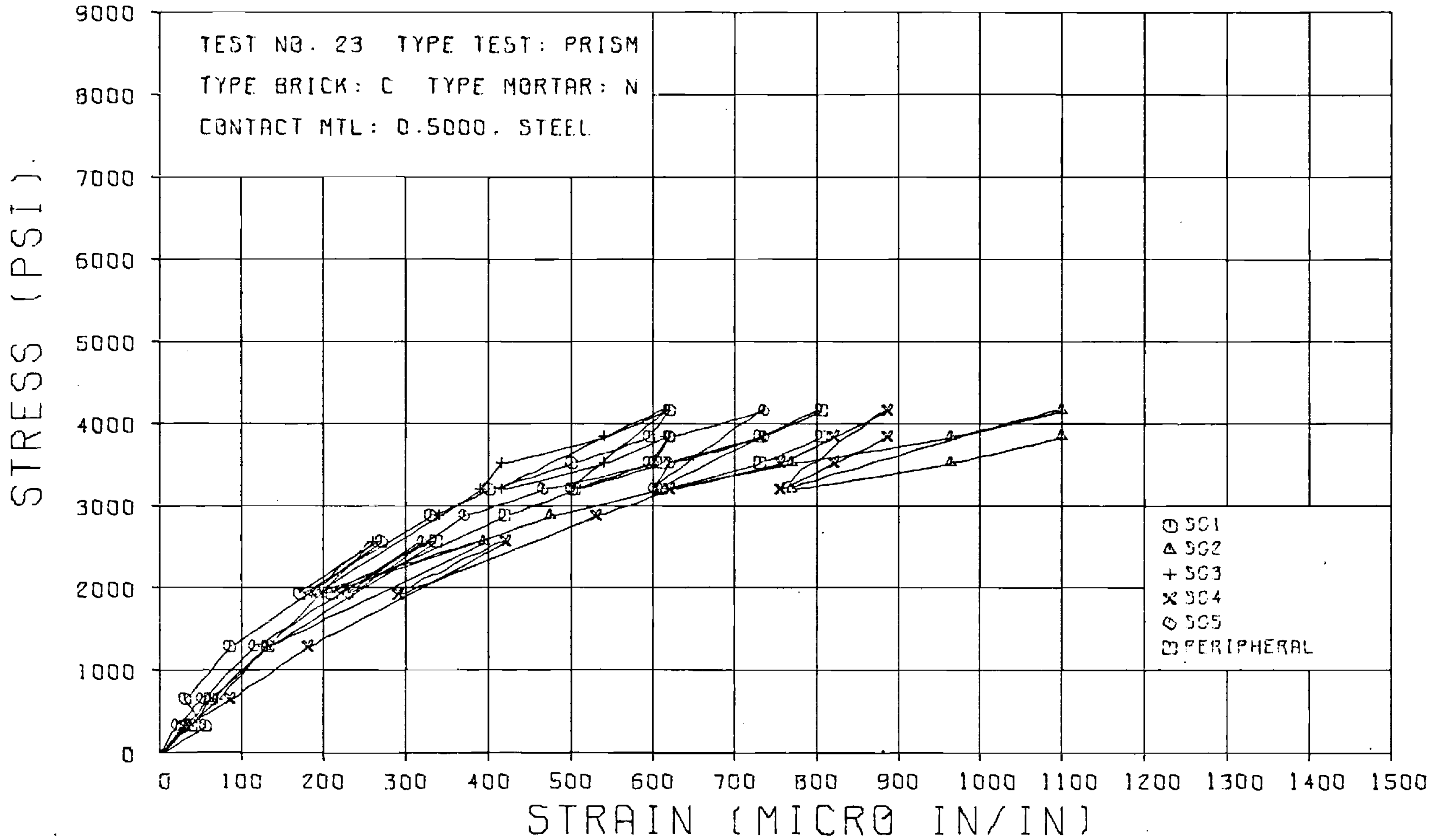


Fig. 8 - Relationship between compressive stress and lateral strain for a prism with type C brick and type N mortar.

very good correlation to the reduced constraint test with C.I. neoprene sheet in 1/8-in. thickness previously discussed (Fig.4). Photographs of these two tests, Fig. 9 and 10 respectively, show the typical tensile splitting mode of failure. Correlation is also good between prisms with type N mortar whose stress-strain curve is shown in Fig. 7 and individual bricks with TFE as the contact material (Fig.3). Again the post-test photographs, Figs. 11 and 12 respectively, show similar modes of failure.

For purposes of contrast, the stress-strain curve for a prism with the low strength brick, type C, and low strength mortar, type N, is shown in Fig. 8. This curve might be compared to that shown in Fig. 6 for a prism with a high strength brick and mortar. A photograph of the low strength prism is shown in Fig. 13.

A comparison of average values in Table 3 shows that the cloth inserted neoprene consistently produced strength values which increased as the thickness of the material was decreased. The strength values also appear consistent with the strength values determined in standard compression tests.

Two discrepancies developed during testing. Three prisms constructed with type D brick and one prism with type C brick from a batch of mortar designated as type S produced compressive strengths consistent with prisms constructed with type M mortar. Cube strength tests of the suspect mortar has substantiated the belief that the mortar was proportioned incorrectly, and was probably type M. The data from these tests has not been included at this reporting, although if included with the data for type M mortar, would not appreciably change those results. The tests with type S mortar will be repeated.

The second discrepancy developed in the use of SARABOND in the high-bond mortar for which the expiration date had been exceeded. A fresh supply of SARABOND was obtained and a considerable increase in cube strength was recorded. However, no significant difference was found in the strength of the prisms. The prism data has been included although the results are questionable. It was also expected that the high-bond mortar would have a higher cube strength than type M mortar. This was not

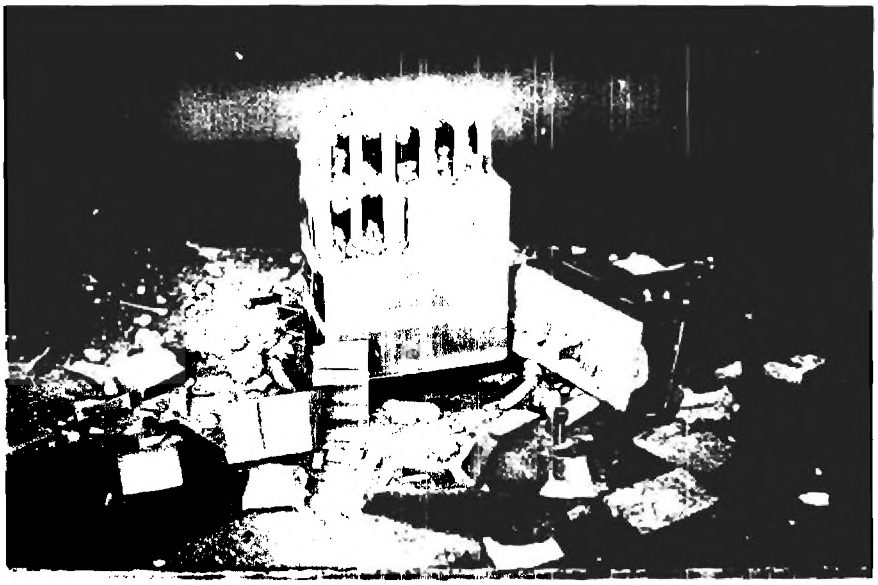


Fig. 9 - View of fractured prism of G brick and M mortar.

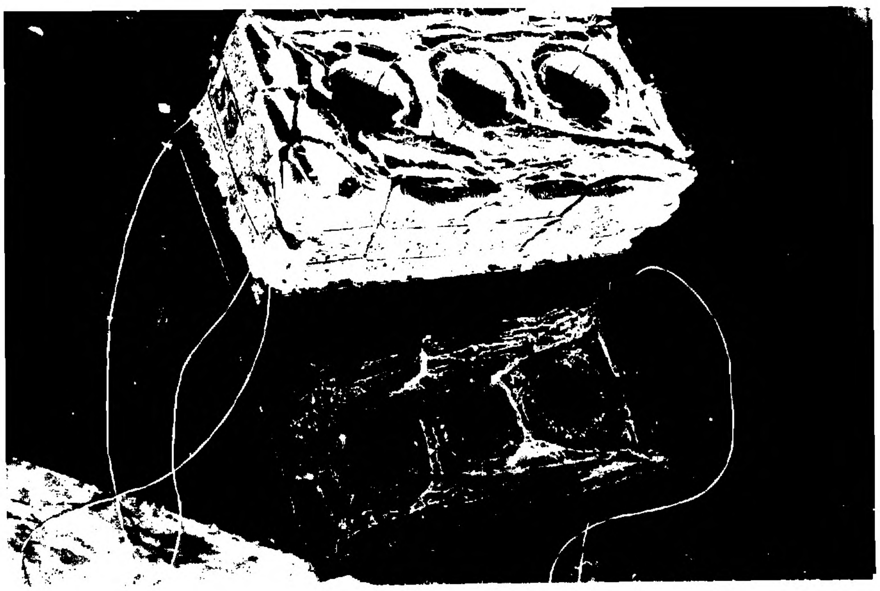


Fig. 10 - View of fractured G brick with 1/8-in. C.I. neoprene contact material.

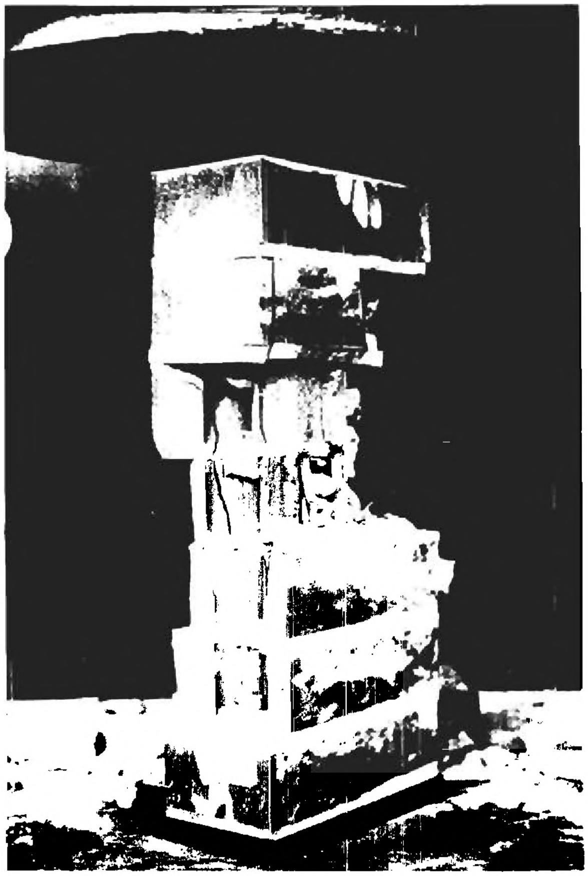


Fig. 11 - View of fractured prism of G brick and N mortar.

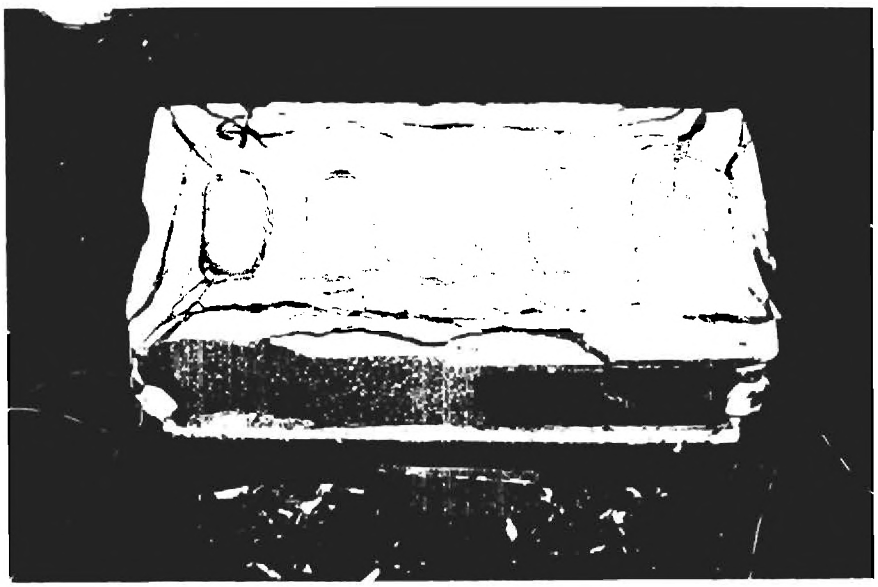


Fig. 12 - View of fractured G brick with 1/8-in. TFE contact material.

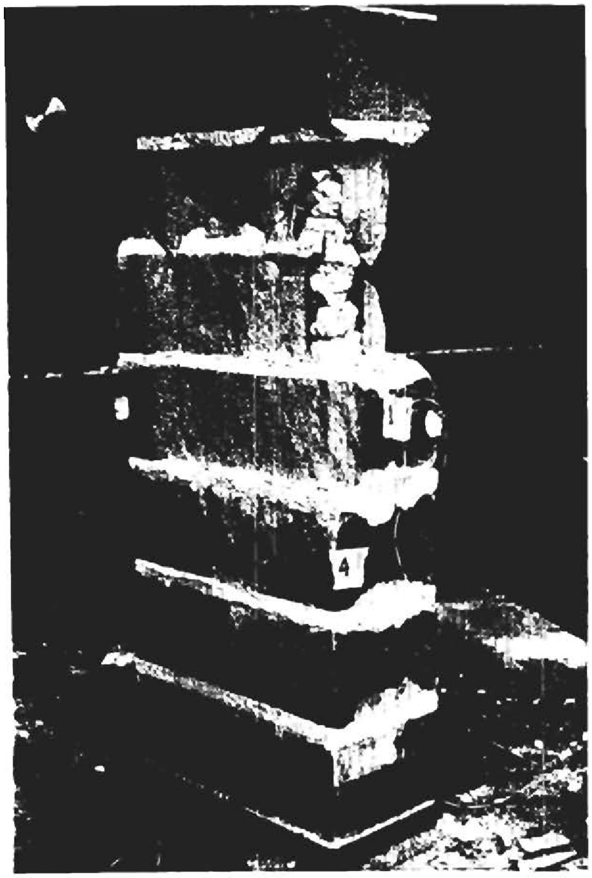


Fig. 13 - View of fractured prism of C brick and N mortar.

the case even with fresh SARABOND.

Comparing the standard compressive strength (ASTM C67) of type G and D bricks reported by Watstein to those reported herein (see Table 1), a significant difference is evident. Since the bricks were from the same source, such a discrepancy is surprising. It appears that the effect of specimen age, moisture content, and core arrangement may have a significant effect on the compressive strength.

SUMMARY AND CONCLUSION

An experimental research program was undertaken to develop a method of testing single bricks to predict the compressive strength of the same element within a wall. The experimental work is approximately 90% complete, with most of the remaining effort in data reduction and interpretation.

Based on limited interpretation of the data compiled at this stage of the research, several tenative conclusions may be reached which depend on a favorable outcome of the remaining tests. These conclusions are as follows:

1) The mode of failure of compressive tests of single bricks using the reduced constraint tests is similar to that of prisms.
2) The most favorable correlation between reduced constraint tests and prism tests was obtained using cloth inserted neoprene as the contact material.
3) By varying the thickness of the contact material, compressive strengths were predictably modified. Such behavior indicates that different contact material thickness may be correlated to corresponding mortar types.
4) Tetraflouroethylene contact material does not appear to completely eliminate frictional restraint on the brick boundaries.
5) Additional basic research needed on several brick related topics include:
   a) Triaxial strength of brick and mortar
   b) Effect of brick age and moisture content on strength
   c) Re-evaluation of the use of gross area as the standard for brick compressive stress computation.

REFERENCES

1. Recommended Practice For Engineered Brick Masonry. Structural Clay Products Institute, 1750 Old Meadow Road, McLean, Virginia, November, 1969.

2. "Compressive Tests of Brick Units to Predict the Strength of Brick Masonry". Brown, Russell H., Proposal to the National Science Foundation Research Initiation Grant Program, December, 1971.

3. D. Watstein, "Relation of Unrestrained Compressive Strength of Brick to Strength of Masonry", Journal of Materials, Vol. 6, No. 2, pp. 304-319.

APPENDIX

Strain Data Acquisition

The strain data for the individual brick specimens and prisms was obatined using unbonded single-wire electrical resistance strain gages. A single continuous strand of bare 0.001-in. diameter copper-nickel alloy wire was attached to insulators at each of the four corners of the brick at mid-height as shown in Fig. A, such that the average transverse strain on each of the unloaded faces and the average transverse strain around the entire periphery of the brick could be measured. The gage was attached to the brick at mid-height of the prisms. The leads from the strain gages were connected through a switching unit to a strain indicator.

Instrumentation Procedure

The type of instrumentation used is almost identical to that used by D. Watstein. Bare 0.001-in. diameter Constantan (Driver-Harris "Advance", 57% copper-43% nickel) was chosen as the gage wire because it is economical, easy to solder, stable at room temperature, provides a resistance of approximately 25-ohms per inch which was thought to be sufficient for accurate readings, and has a gage factor (F = 2.0) which remains constant over a wide range of strain.

The electrical insulators to which the gages were attached at the four corners of the brick were prepared from 0.5-in. I.D. x 0.75-in. O.D. clear methyl-methacrylate (Plexiglas) tubing cut along a diametral plane. The split tubing was then cut into segments 0.5-in. long. The insulator segments were cemented with an epoxy resin to the four corners of a brick at mid-height and held in place with rubber bands. After a curing period for the epoxy, the mid-height of the brick was marked on each insulator and one end of a 0.175-in. bondable terminal (Micro-Measurements CTF-50C) was centered over the mid-height mark and cemented with methyl-2-cyanoacrylate adhesive (Eastman 910) to three of the four insulators as shown in Fig. B. Two terminals were cemented to the fourth insulator, one on each side of the mid-height mark about 1/64-in. apart as shown in Fig. C.

One end of the Constantan wire was temporarily taped in place across the inside end of one of the terminals and a leadwire was held in place to the other end of the same terminal. The gage and lead-wire were then soldered to the terminal simultaneously as shown in Fig. D. It was found to be easier to solder both wires simultaneously to avoid breaking the fine gage wire or overheating the terminal. It is recommended that the terminal and the leadwire be lightly tinned prior to making a solder connection.

After making the initial connection, the free end of the Constantan wire was run over the next corner insulator and aligned with the mid-height mark. A 4.5-oz. weight (tweezers) was hung on the wire on the free side of the insulator to maintain a constant tension on the wire (Fig. E). A leadwire was held to the other end of the terminal and both wires were soldered in place. This same procedure was followed in attaching the gage wire and leadwire to the remaining three terminals. After the final connection, the gage wire was cut off at the fifth terminal. The two adjacent terminals on the fourth insulator as shown in Fig. F should be carefully inspected to insure that they are not shorted.

The five leadwires from the test brick were connected to an Ellis Associates Switch and Balance Unit, Model BS-6, as shown in the schematic in Fig. G. A brick identical to the type being tested was instrumented and connected to the switching unit to serve as a temperature compensator. The switching unit allowed all five strain gages (one gage on each of the four lateral faces plus the peripheral gage) to be read without changing the circuitry. The output from the switching unit was connected to the two-arm bridge circuitry of a BLH Model 120C Strain Indicator permitting the strains to be read directly. In a few cases where differences in gage lengths of the active and compensating gages prevented the strain indicator from being balanced, a variable resistor was attached in parallel allowing the bridge to be balanced.

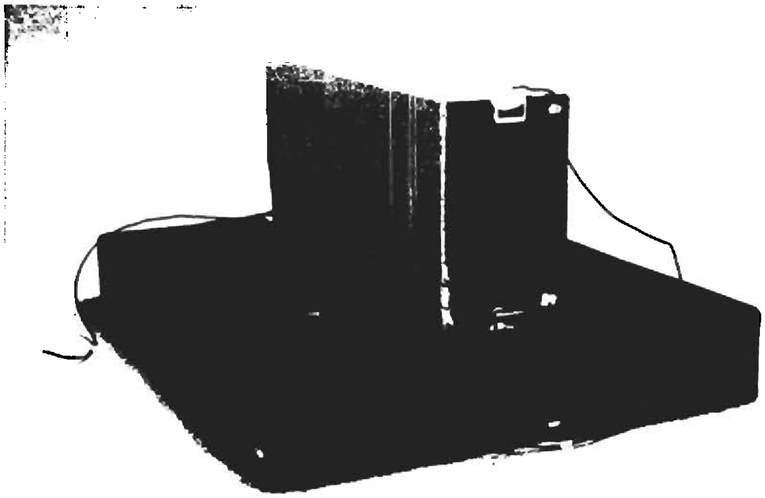


Fig. A - Instrumented brick on instrumentation platform.

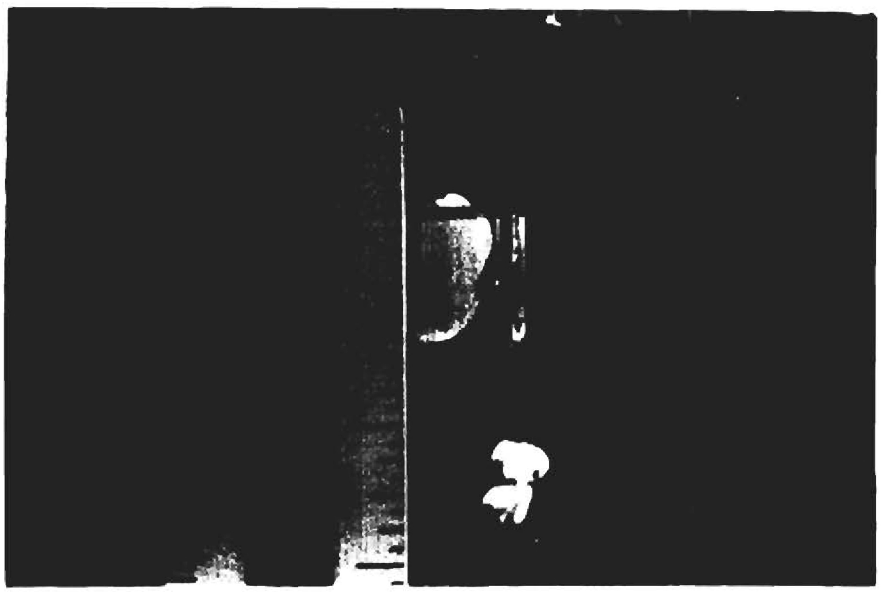


Fig. B - Single insulator on brick with terminal attached.

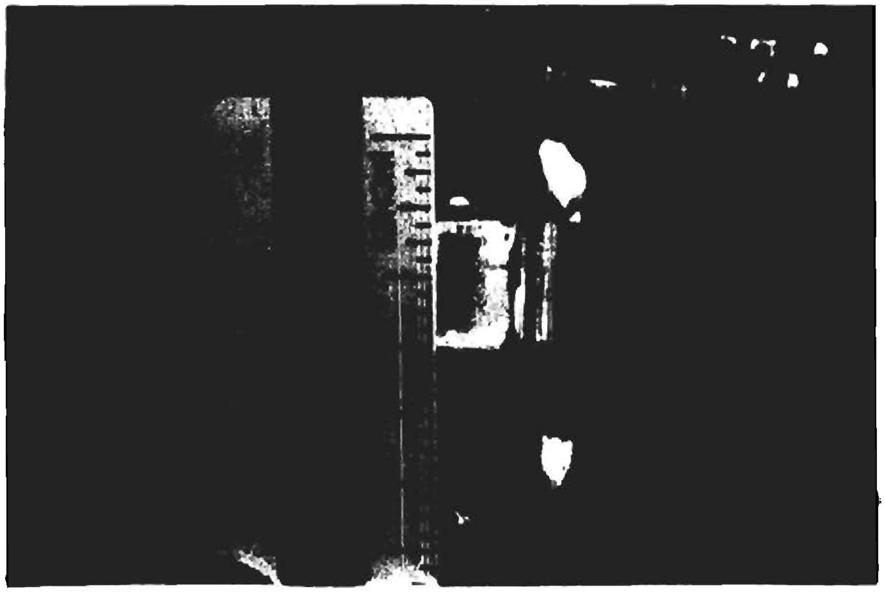


Fig. C - Insulator with double terminals attached.

Fig. D - Initial connection of gage and lead wire.

Fig. E - Tweezers hung to insure equal tension on gage wire.

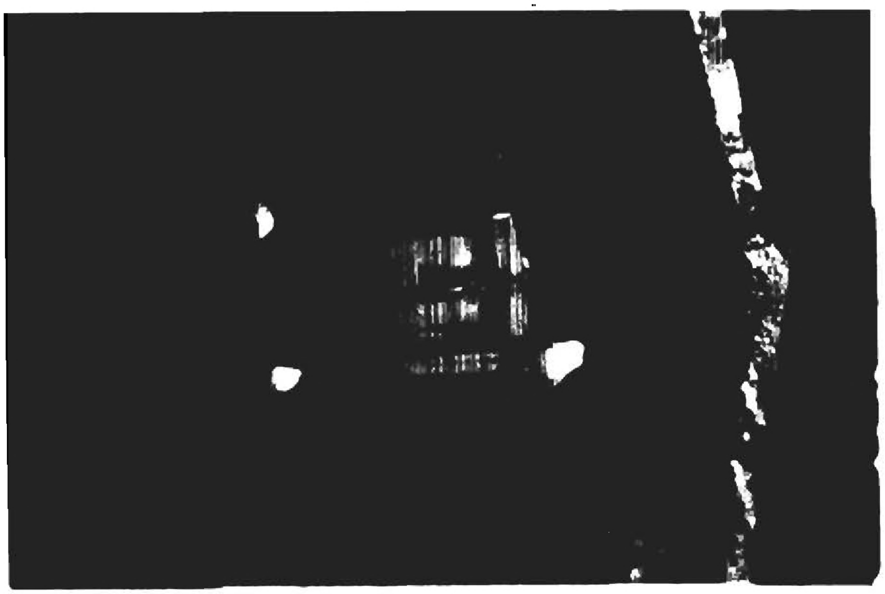


Fig. F - Final connection of gage and lead wire.

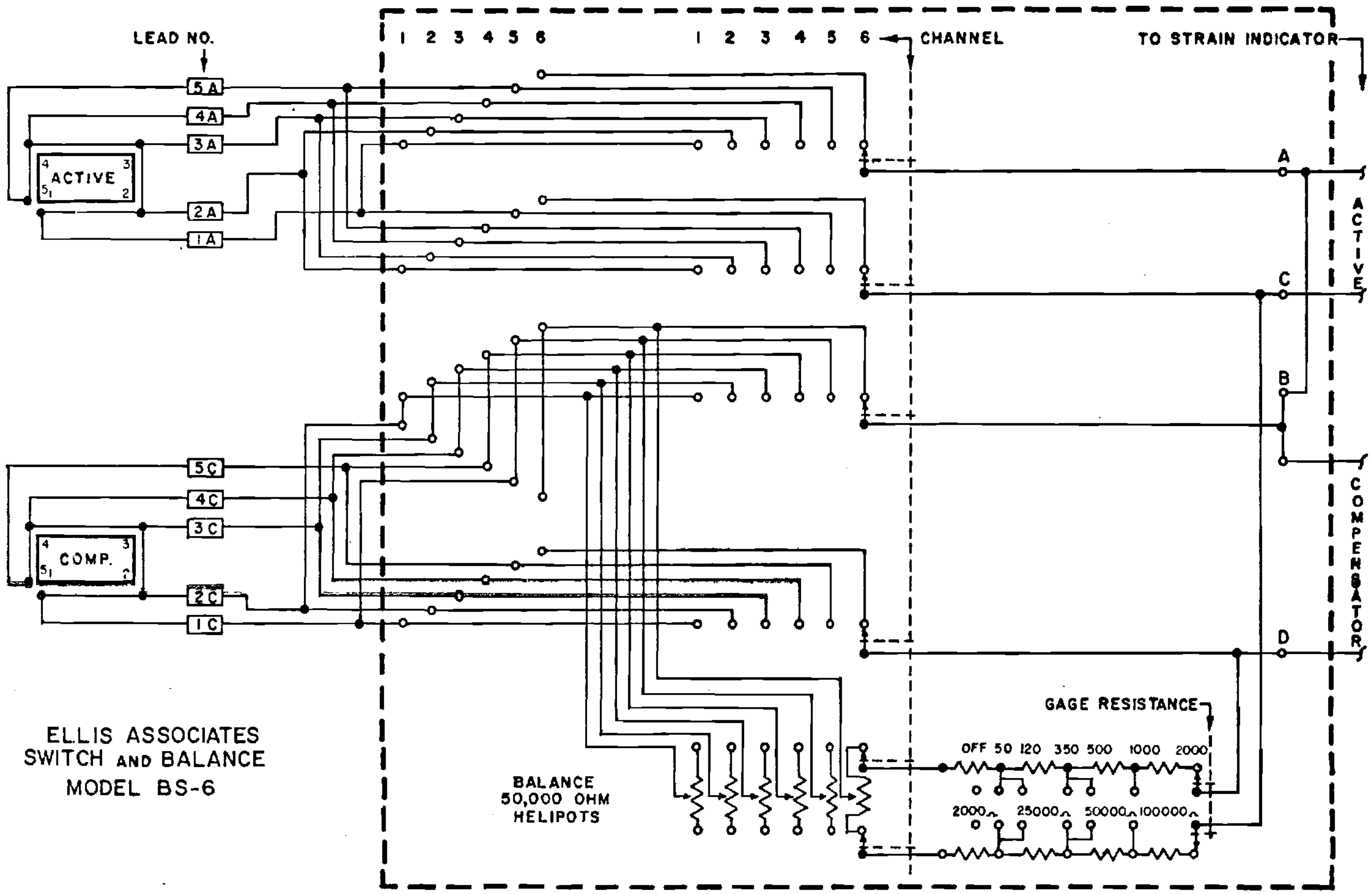


Fig. G. - Schematic of gages and switching unit.

E-20-627

Final Report

on

Compressive Tests of Brick Units to Predict the Strength of Brick Masonry

Submitted to the

National Science Foundation
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by

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INTRODUCTION

The compressive strength of brick masonry walls is currently determined from the compressive strength of standard masonry prisms[1]. The construction and testing of prisms is cumbersone and expensive. The use of prism tests rather than tests of single brick to determine compressive strength was adopted because the standard brick compressive test does not correlate well with that of the brick-mortar assemblage. The discrepancy is probably caused by a difference in failure mode between brick units and prisms.

This investigation was proposed to evaluate the states of stress which produce failure in single brick units and in prisms, and to develop a test using a single brick unit which will reliably predict the compressive strength of a similar element within a wall[2]. Standard tests of individual brick units and of prisms with various types of mortar were conducted to establish bases of comparison for stress, strain and failure data for the program. Various types of contact material were then used between the loading surfaces of the testing machine and a single brick unit in an attempt to find a material which would provide correlation of the compressive strength and failure mode of a single brick with that of a similar element in a prism. The term "reduced constraint" is introduced to signify the reduction of restraint at the bearing surfaces of the brick specimens brought about by the introduction of the contact materials between the capped specimen and the loading platen.

SCOPE

Three types of brick, illustrated in Fig. 1, were used in the investigation, and their properties and descriptions are presented in Table 1. The bricks designated D and G were supplied by Brick Institute of America* and are of the same lot used by D. Watstein[3]. The brick designated C was chosen because it was a relatively low strength extruded brick available locally. Standard compressive strength tests were performed on a minimum of three samples of each type of brick.

Four types of masonry mortars were used in construction of the prisms. These were types M, S, and N as defined in Specification for Mortar for Unit Masonry, ASTM C270-68, and high-bond mortar made with SARABOND mortar additive (Dow Chemical Company) which is herein designated as type H. Three single wythe compressive prisms with a slenderness ratio, h/t, of approximately 5 were constructed with each type of brick and mortar. A total of 39 standard prisms were tested.

Reduced constraint strengths were determined using tetraflouoroethylene (TFE), polyvinyl chloride (PVC), methyl-methacrylate (MM), acrylivin, high impact styrene, and neoprene sheet. Cloth inserted neoprene (CIN) sheet, low density polyethylene (LDP), high density polyethylene (HDP), and polypropylene (PP) in several thicknesses were studied further because they showed a relatively good correlation to the prism tests in terms of strength and mode of failure. A total of 119 bricks were tested with various contact materials.

*Formerly Structural Clay Products Institute.

TEST SPECIMENS

Sample Preparation

The bricks for individual unit tests were inspected to insure that the loading surfaces were relatively level and free from gross surface defects such as holes, cracks or obtrusions. The lateral faces were inspected for cracks. Any defective bricks were rejected. The end bricks for the prisms were selected on the same basis as those for the individual tests, while the interior bricks were rejected only if cracked or chipped.

Samples for standard brick compression tests were cut on a masonry saw and inspected for plane and parallel ends.

All samples were capped with a high strength gypsum in accordance with Section 10, Capping Test Specimens, of Standard Methods of Sampling and Testing Brick, ASTM C67-66, except that the specimens were not coated with shellac. The two end bricks for each prism were capped on one face only prior to prism construction.

Prisms

Three single-wythe masonry prisms were built from each of the three types of brick and four types of mortar and are described in Table 2. They were constructed with whole brick laid in stack bond in a carefully leveled full bed of mortar. The joint thickness was maintained at 3/8-in ($\pm$ 1/32 in). Each prism was seven courses high and carefully constructed in a form, as shown in Fig. 2, so as to be plumb and level. The joints on the face of each prism were struck flush. All prisms were cured for 28 days in a laboratory where the temperature was maintained between 65° and 75° F. Relative humidity was not monitored.

Mortar

Three 2-in. cubes were made of each type of mortar used to construct the prisms. The cubes were molded in accordance with Section 7,8,10 and 11 of Standard Method of Test for Compressive Strength of Hydraulic Cement Mortars, ASTM C109-64. The cubes were covered with a glass plate for 24 hours after being molded, after which the cubes were removed from the molds and cured in moist curing room for 27 days until tested.

Additional data on properties including modulus of elasticity and Poisson's ratio was obtained from compressive tests of 2-in. diameter by 4-in. high cylinders of the mortars.

Brick Cores

Cylindrical cores 7/8 inch in diameter were cut the full height of each type of brick. Each core was then cut on a fine toothed diamond saw to a height of 1 3/4 inches. Care was taken to make the ends parallel, and perpendicular to the longitudinal axis of the cylinder. The specimens were visually inspected with the aid of a square. Chipped, uneven, or non-parallel surfaced specimens were rejected.

TEST PROCEDURES

Prisms

The brick masonry prisms were tested in accordance with the applicable provisions of Standard Method of Test for Compressive Strength of Molded Concrete Cylinders, ASTM C39-64. The prisms were loaded in increments, and the load was held constant while strain and vertical deflection readings were taken. Priority was established such that the peripheral gage was read first followed by the gages on the faces, and then the gages on the ends.

When failure was approaching and strains increased too rapidly to monitor all channels, only the peripheral strain was monitored.

Brick

Standard Compressive Tests

The standard compressive tests were performed in accordance with Sections 11 and 12 of ASTM C67-66.

Compressive Tests with Contact Material (Unrestrained Brick Tests)

The compressive tests with contact material were conducted as described above, except that a sheet of the particular contact material being evaluated was placed between the top and bottom of the capped specimen and the upper and lower bearing plates of the testing machine. The loads were applied and the data acquired as described under the test procedure for prisms.

Flexural and Indirect Tensile Test

Flexural strength (modulus of rupture) was obtained in accordance with Section 6,7, and 8 of ASTM C67-66.

Other techniques of obtaining values representative of the brick tensile strength were split cylinder tests and split brick tests.

The split cylinder tests were performed on 7/8 inch diameter cylinders, 1 3/4 inches in height cored from each type of brick in accordance with applicable provision of ASTM C496-71. Bearing strips of approximately 1/32 inch thickness by 1/4 inch width were used in lieu of the 1/8 inch by 1 inch specified for the larger concrete cylinders.

Split brick test were performed in both the longitudinal and transverse direction using a method similar to that reported by Francis et.al[4]. The test closely resembles the split cylinder test but is performed on the whole brick in its natural shape. A 1/4 inch square bearing strip was placed on the top and bottom of the specimens to apply a line load thus vertically splitting the brick between the bearing strips. The tensile stress at failure was computed from the equation

$$\sigma_t = \frac{2P}{\pi A}$$

where σ_t = tensile stress at failure

P = load at failure

A = area of failure surface, gross

Modulus of Elasticity and Poisson's Ratio

Modulus of elasticity and Poisson's ratio were obtained from 7/8 inch diameter cylinders, 1 3/4 inches in height, cored from each type of brick. Vertical strain gages on diameterically opposite faces were averaged to obtain the elastic modulus of each specimen. The strain from a horizontal strain gage located beneath one of the vertical gages combined with vertical strains provided sufficient information to obtain Poisson's ratio of each type of brick.

Triaxial Tests

Some of the cylinders described in the previous section were subjected to hydrostatic confining pressures and loaded axially in compression to failure. The cylinders were enclosed in surgical tubing to prevent the inclusion of the confining fluid (oil) into the pores of the core samples. The confining pressure for each test was held constant while the specimen was loaded axially to failure. The confining pressures were increased from specimen to specimen with values ranging from 0-4000 psi.

Mortar

Cube Strength

The compressive strength of 2 inch cubes of each type of mortar was obtained in accordance with Section 12(b) and 12 (c) of ASTM C109.

Cylinder Strength and Elastic Properties

Modulus of elasticity, Poisson's ratio and compressive strength were obtained for each type of mortar using 2 inch diameter cylinders, 4 inches in height. Elastic modulus was obtained from vertical strain gages on diametrically opposite faces at midheight. Poisson's ratio was obtained with a horizontal strain gages mounted under one of the vertical gages from which the ratio of horizontal to vertical strain was obtained. All cylinders were eventually loaded to failure.

Instrumentation

Unbonded electrical resistance wire strain gages were attached to each prism and unrestrained compressive specimens at midheight to measure lateral strain during loading. Details of the instrumentation are in Appendix A.

RESULTS

Prisms

Compressive strengths of the prisms are shown in Table 2. The values given are the averages based on three tests of each combination of brick and mortar. Values reported by D. Watstein[3] are given for comparison. A typical stress-strain curve for each type of brick and mortar is given in Appendix B.

Brick

Standard Compressive Tests

Results of Standard compressive tests performed according to ASTM C67-66 are shown in Table 2. Photographs of several speciemns after testing are shown in Fig. 3, 5 and 7.

Unrestrained Compressive Tests

Unrestrained compressive strength of bricks tested with the various types and thicknesses of contact materials are shown in Table 4. Each value represents the average of three tests. Typical stress-strain curves for the contact materials considered most promising are given in Appendix C. Photographs of two specimens after testing are shown in Fig. 4 and 6. Vertical tensile splitting cracks are apparent for both prisms and unrestrained compressive tests.

Flexural and Indirect Tensile Tests

Results of modulus of rupture, split cylinder strength, and both longitudinal and transverse split brick strength are given in Table 3.

Modulus of Elasticity and Poisson's Ratio

The modulus of elasticity and Poisson's ratio of the three types of brick used are given in Table 1. The stress-strain curves from which these values were obtained are presented in Appendix D.

Triaxial Tests

Results of the triaxial tests of brick cores are shown graphically in Fig. E1 of Appendix E. Substantial increases in axial compressive strength resulted from confinement.

Mortar

The compressive strength of 2 inch mortar cubes are given in Table 2. The modulus of elasticity and Poission's ratio of 2 inch diameter cylinders of the four types of mortar used are given in Table 5.

Modes of Failure

Prisms

The prisms exhibited audible cracking prior to failure but usually the cracks did not become visible immediately. Vertical cracks appeared on the front and/or side faces of the bricks on many specimens prior to failure. It appeared that the cracks initiated at approximately midheight of the specimen. Some failures were docile while others were explosive, higher strength prisms having the more explosive tendency.

Standard Compressive Tests

Bricks tested according to ASTM C-67-66 exhibited no lateral tension cracks and all strengths substantially exceeded prism strengths.

Unrestrained Compressive Tests

Bricks tested with contact material between the capped surface and loading platen failed in a manner similar to that of the prisms. Audible cracking occurred prior to failure. Visible tension cracks occurred vertically on all faces. The stress at which the first tension cracks occurred depended on the properties of the contact material for a given type of brick. Thicker, more flexible materials caused cracking at lower stress levels than thinner or stiffer materials.

INTERPRETATION OF RESULTS

Comparison of Prism and Unrestrained Compressive Tests

Since the purpose of this research was to produce a single brick test which would produce results that would accurately predict the prism strength of that brick, a comparison between the two types of tests will be made.

Of the various contact materials tested, those which yielded the most consistent results were LDP, HDP, and PP. Of these materials 1/16 inch LDP was in very close agreement with prisms of type M mortar. Both the compressive strength and the shape of the stress-strain curves compare very favorably (Fig. B1 vs C1, B5 vs C6, B9 vs C11). Such a curve by curve comparison of the data is not a practical means, however, of analyzing the large amounts of data generated herein. But the similarity in the stress-strain curves does indicate that the unrestrained compressive test simulates the conditions that exist in a prism test.

A more efficient means of comparing the large quantities of data for this research program is illustrated in Figs 8 through 11. Here, the compressive strength of prisms is plotted against that of unrestrained bricks. Four graphs are presented, one for each type of mortar. Each point of the graphs represents the result of six tests; the ordinate being the average value of three prism tests, the abcissa being the average value of three unrestrained compressive tests. Four types or thicknesses of contact material are shown on each figure. The deviation of each point from the 45° line is a measure of the deviation of the simulated tests from the prism tests. Of the points shown, 1/16 inch LDP consistently gave the best results.

The Strength Paradox

One very interesting phenomenon which consistently occurred throughout the test program was the reversal of the relative strengths of type G and D bricks. Type G brick when tested in compression according to ASTM C67-66 were always substantially stronger than type D units. However, type G prisms were consistently weaker than those made with type D bricks. The 1/16 inch LDP also yielded stronger D brick results compared to G brick. An explanation for this strength paradox is given in the following paragraphs.

The standard compressive strength test (ASTM C67-66) results in an erroneously high indication of brick compressive strength. During the standard compressive test, the capped brick is in direct contact with a steel bearing surface. Under vertical compressive stress the brick tends to expand laterally more than the steel bearing surfaces. Friction between the surfaces, enhanced by substantial normal forces, restrains the relative lateral slip between the brick and steel thus inducing a lateral compressive stress on the brick. Confining stress substantially increases the apparent compressive strength of brick as illustrated by the results of triaxial tests in Appendix F. This effect is qualitatively illustrated by point A of Fig. 12.

In a prism test, each brick is sandwiched between mortar which tends to expand laterally under vertical compressive stress more than the brick. That is, if Poisson's ratio divided by Young's modulus of the mortar exceeds that of the brick, the mortar expands more than the brick. Friction and bond between the surfaces restrain relative lateral slip resulting in a lateral tensile stress in the brick and a lateral compressive or confining pressure in the mortar. The presence of these lateral stresses explains two phenomena: 1) the vertical tension cracks which occur in bricks within prisms and 2) the ability of mortar, due to confinement, to withstand prism stresses exceeding its cube strength. The stress state in a brick within a prism is qualitatively illustrated by point B of Fig. 12.

In summary, the standard compressive test for brick units (ASTM C67-66) results in a triaxial compressive stress state whereas the prism test results in biaxial lateral tension and axial compression in the bricks. The failure modes are substantially different and the resulting strengths may not be proportional. That is, depending upon the triaxial failure envelops of two brick, one may have a higher standard compressive strength and a lower prism strength than the other. Referring to the qualitative triaxial failure envelops on Fig. 13, brick "A" would have a higher standard compressive strength than brick "B", however, the reverse is true for prism strength.

The conclusion which results from this analysis is that it is not a good practice to use as a standard of compressive strength a test which results in a different failure mode than that which occurs in the element used in a wall. However, in Section 4.2.2.2 of the Brick Masonry Code[1], this practice is permitted.

Prediction of Prism Strength

An equation which predicts the compressive strength of prisms, adopted from Ref. 4 is

$$\sigma_x = \sigma_z = \sigma_y \left[\frac{\beta \nu_m - \nu_b}{1 + \beta\alpha (1 - \nu_m) - \nu_b}\right]$$

where σ_x, σ_z = horizontal stress, positive for tension

σ_y = vertical stress, positive for compression

β = ratio of E_b/E_m

ν_m = Poisson's ratio, mortar

ν_b = Poisson's ratio, brick

α = brick thickness/mortar joint thickness

This equation assumes elastic behavior throughout, uniform lateral stresses in both brick and mortar, and no slip between brick and mortar. Combining this equation with the failure envelop of the bricks, assuming that for lateral tension the failure envelop is a straight line between the unconfined compressive strength and the longitudinal split brick strength, the strength of prisms can be predicted. Using this approach and the measured properties of the materials used herein, the method predicts compressive strengths as shown in Table 5. Variations in elastic properties of mortar from batch to batch were neglected. However, for each type of mortar a different set of elastic properties, Young's Modulus and Poisson's ratio, were used.

Prediction of Unrestrained Brick Strength

The same technique used to predict prism strength can be used to predict the unrestrained brick strength. The properties of mortar are replaced with those of the contact material. Using this method of analysis, the predicted unrestrained brick tests were determined as shown in Table 5.

In spite of the approximations in this model, comparison of Table 4 and Table 5 indicates predicted values usually within ten percent of experimental strengths.

RECOMMENDATIONS

Before making recommendations on predicting prism strength from unconstrained prism tests, it is important to point out that such a method cannot reflect the variations in mortar properties normally expected in masonry construction. A prism test using actual materials for a project is a far better indication of strength than any single brick test. However, due to the difficulty in constructing and testing prisms, a conservative alternative should be available. The present alternative is the standard compressive test

(ASTM C67-66) and has the major shortcoming of having a different failure mode from prisms. A logical improvement is the unrestrained compressive test using contact materials to induce a lateral tensile splitting failure mode.

The contact material which gave the best correlation between unrestrained brick tests and prisms for type M mortar was 1/16 inch LDP. In every case the prism strength exceeded the brick strength, thus the method is conservative (Fig. 8-11). Rather than used other thicknesses of LDP or a completely different. contact material to simulate other type mortars, a scale factor appears to be logical. That is, the results of an unrestrained brick test using 1/16 inch LDP would simulate the prism strength of that brick in a prism of type M mortar. If another type mortar were to be used, the strength would be reduced by a factor. A factor of 5/6 for type S mortar, 2/3 for type N mortar and 1 for type H mortar is reasonable and consistent with the provisions of Sec. 4.2.2.2 of the Brick Masonry Code [1]. The cost of 1/16 inch LDP (Summer '72), is about $15.00 for a 4 ft by 8 ft sheet. It can be cut with scissors and approximately 70 bricks of a nominal 4 inch by 8 inch area can be tested from a single sheet.

It is important to emphasize that although this research involved a large number of tests, they were largely exploratory. A total of only nine tests were performed with any contact material of a given thickness. Before recommending 1/16 inch LDP as a standard, a substantial number of tests with a wide range of brick strengths should be made and compared to prism strengths.

SUMMARY AND CONCLUSIONS

An experimental research project was performed to develop a single brick test which would predict the prism strength of that type of brick. Prisms having a height to thickness ratio of approximately five were constructed using three brick types and four (M,S,N, and organically modified) mortars. Three prisms of each combination of brick and mortar were load tested in compression to failure. The peripheral strain at midheight was recorded at multiple stress levels with unbonded strain gages. The same types of brick were then subjected to unrestrained compressive tests in which contact materials were introduced between the capped brick and the loading platen of the testing machine. Of the contact materials tested (TFE, PVC, MM, CIN, LDP, HDP, PP in various thicknesses), low density polyethylene (LDP) having a 1/16 inch thickness gave the best results. It is recommended that this contact material be singled out for further study on an extensive number of bricks.

Based on the results of the experimental program and analysis of the data, the following conclusions can be drawn:

1) The Standard Compressive Test for Brick (ASTM C67-66) predicts a significantly higher strength than the brick will exhibit in a prism.

2) Lateral tensile stresses are induced in brick in prisms which produced vertical cracks. This failure mode can be simulated by the unrestrained brick tests described herein.

3) It is a questionable practice to attempt to predict prism strength from the results of standard compressive tests. One brick may have a higher standard compressive strength than another but their prism strengths may be just the reverse in relative magnitude.

4) A tri-axial stress failure theory as illustrated by Fig.12 predicts the failure of brick with reasonable accuracy.

5) Prism tests using actual brick and mortar materials are a far better indication of strength than any single brick test.

6) Of the contact materials used in unrestrained brick tests, low density polyethylene of 1/16 inch thickness gave the most promising results.

7) Tentative recommendation, based on the results of limited tests and subject to revision from future tests, are that 1/16 inch LDP unrestrained brick tests be used to predict the prism strength of type M and type H mortar. The result should be multiplied by a factor of 5/6 and 2/3 for type S and N mortar, respectively.

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4. Francis, A. J., Horman, C.B., and Jerrems, L.E., "The Effect of Joint Thickness and Other Factors on the Compressive Strength of Brickwork," SIBMAC Proceedings, Stoke-on-Trent, England, April, 1970, pp. 31-37.

Table 1 - Properties and Description of Bricks Investigated

Brick Designation	n^b	Compressive Strength[a] Average value psi	v^e %	Modulus of Elasticity Average value, psi	Poisson's Ratio Average value psi	n	Initial Rate of Absorption Average value g/30 in. 2/min.
C[c]	6	9,600	0	2.00×10^6	.315	5	26.9
	-	-	-	-	-	-	-
D[d]	4	17,750	8.9	4.5×10^6	.30	5	4.5
	5	(12,800)[f]	3.0			5	(12.5)
G[d]	4	23,100	7.2	6.6×10^6	.23	5	1.6
	5	(25,300)	7.7			5	(1.3)

[a] Determined in accordance with Standard Methods of Sampling and Testing Brick, ASTM C67-66

[b] n - Number of specimens

[c] Bricks supplied by Chattahoochee Brick Company, Atlanta, Ga. Properties and designation differ from those tested by D. Watstein.

[d] Bricks supplied by Brick Institute of America. Same lot and designation as those tested by D. Watstein.

[e] v = Coefficient of variation

[f] Values shown in parentheses are for same type brick determined by Watstein.

Table 2 - Description of Masonry Test Prisms and Their Compressive Strength

Type Brick	Type Mortar	Number of Prisms N	Prism Dimensions: Thickness t, in.	Prism Dimensions: Width w, in.	Prism Dimensions: Height h, in.	Prism Dimensions: h/t	Compressive Strength of Prisms, Average Value psi: a	Compressive Strength of Prisms, Average Value psi: b	Compressive Strength of Mortar, Average Value psi: a	Compressive Strength of Mortar, Average Value psi: b
C	M	3	3.75	8.35	20.5	5.47	5190	-	4760	-
C	S	2	3.75	8.35	19.	5.20	4665	-	1890	-
C	N	3	3.75	8.35	20.7	5.51	3740	-	1340	-
C	H	3	3.75	8.35	20.6	5.5	4470	-	1910	-
D	M	6	3.65	7.7	17.9	4.92	8450	5150	4760	3290
D	S	3	3.65	7.7	17.6	4.82	6580	4960	2600	1520
D	N	3	3.65	7.7	17.8	4.89	5580	3760	1470	700
D	H	3	3.65	7.7	17.6	4.82	6870	-	1580	-
G	M	3	3.75	8.0	18.1	4.84	6620	5390	4380	3290
G	S	3	3.75	8.0	18.1	4.84	4860	3910	2150	1520
G	N	3	3.75	8.0	18.2	4.86	4270	3280	1400	700
G	H	3	3.75	8.0	18.1	4.84	5810	-	3830	-

a Value determined in this study.

b Value determined by D. Watstein[3].

Table 3 - Tensile Strengths of Bricks Investigated

	Split Cylinder Strength			Modulus of Rupture			Longitudinal Split Brick			Transverse Split Brick		
Brick Designation	n	Average Value, psi	v, %	n	Average Value, psi	v, %	n	Average Value, psi	v, %	n	Average Value psi	v, %
C	2	554		5	535.5	38.53	3	306	52.23	3	400	17.48
D	2	1670	11.38	5	1201 (760)[a]	3.88	3	510	11.95	3	765	6.63
G	2	1705	3.23	5	1105 (1080)[a]	8.30	3	583	9.44	2	715	8.38

[a] Value reported by Watstein.

Table 4 - Compressive Strength of Prisms and Reduced Constraint Specimens

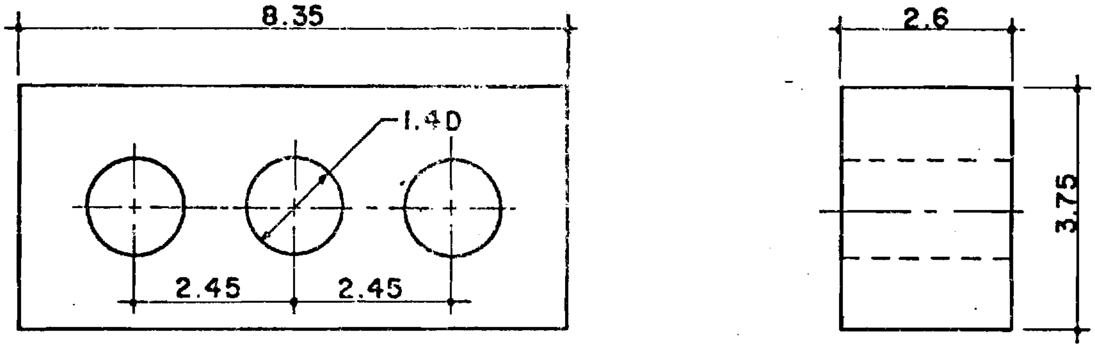
Type Test	Compressive Strength, psi Type Brick C	D	G
Prism - Type M mortar	5190	8450	6620
Type S mortar	4665	6580	4860
Type N mortar	3740	5580	4270
Type H mortar	4470	6870	5810
Unrestrained Brick Tests Contact Material (Thickenss, inches)			
TFE (1/8)	3200	3680	4230
PVC (1/8)	10,060	13,170	13,670
MM (3/8)	-	14,240	-
CIN (3/32)	3140	5950	6310
(1/8)	3140	5750	6040
(3/16)	2770	4970	5400
LDP (1/16)	4270	5703	5524
(3/32)	2347	3892	4613
(1/8)	2055	3482	3433
HDP (1/16)	6520	7160	7650
(1/8)	4690	4780	4870
PP (1/8)	6190	7380	7270
(3/16)	6780	9440	10,100

Table 5 - Compressive Strength of Prisms and Unrestrained Brick Specimens - Predicted.

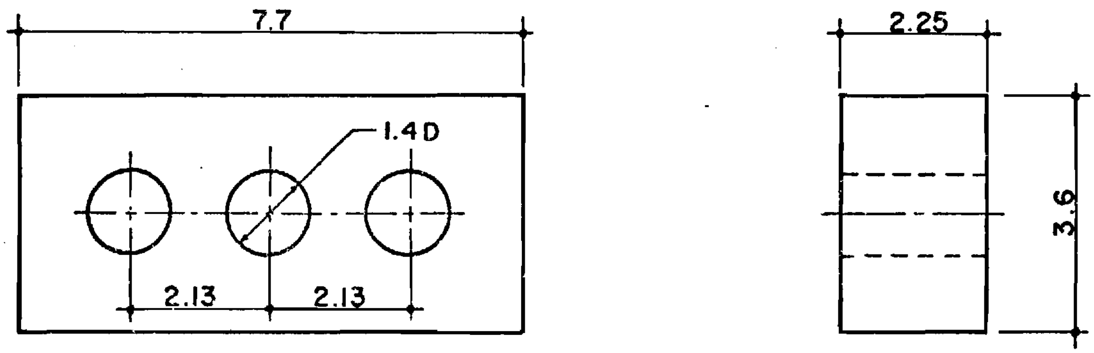
Type Test			Compressive Strength, psi		
			Type Brick		
	E,[a] ksi	ν[b]	C	D	G
Prism - Type M mortar	2000	.3	7300	6810	6970
S	1500	.3	5420	6140	6600
N	1000	.3	4250	5570	6260
H	2000	.3	7300	6810	6970
Unrestrained Brick Tests Contact Material (Thickness, inches)					
LDP (1/16)	35	.5	4480	7780	9820
HDP (1/16)	115	.5	4520	7810	9850
HDP (1/8)	115	.5	3370	5510	6730
PP (1/8)	150	.25	5180	9160	11720

[a]Modulus of elasticity of mortar for prism tests and of contact material for unrestrained brick tests

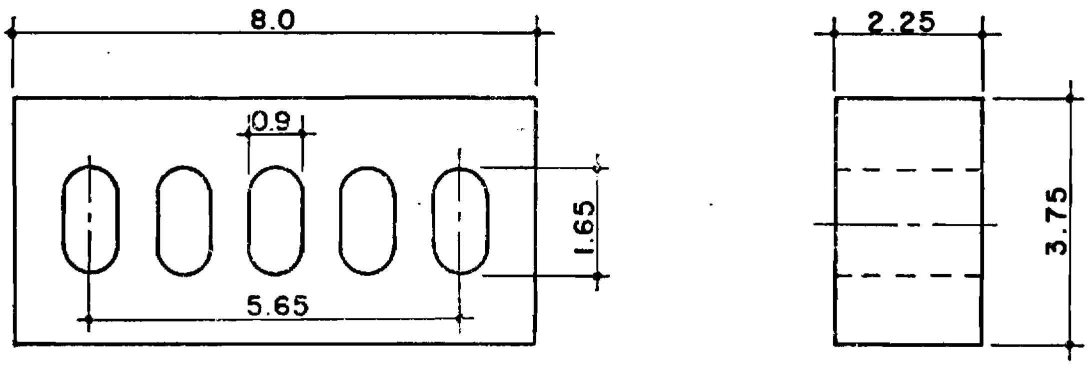
[b]Poisson's ratio



BRICK C
GROSS AREA = 31.3 sq. in.
NET AREA = 27.6 sq. in.
PER CENT CORE = 12.0 %



BRICK D
GROSS AREA = 28.0 sq. in.
NET AREA = 23.2 sq. in.
PER CENT CORE = 17.3 %



BRICK G
GROSS AREA = 30.0 sq. in.
NET AREA = 23.4 sq. in.
PER CENT CORE = 22.0 %

Fig. 1 - Views and dimensions of bricks used in the study.

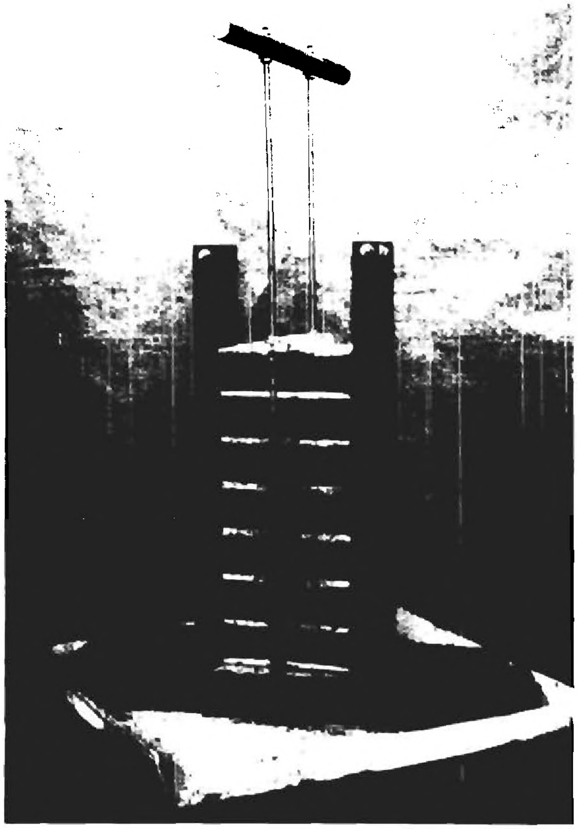


Fig. 2 Prism in form used for construction

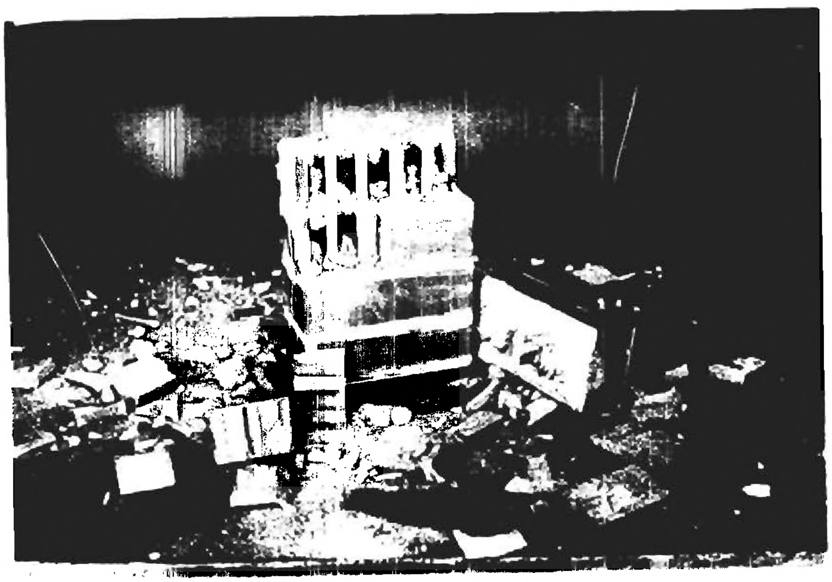


Fig. 3 View of fractured prism of G brick and M mortar

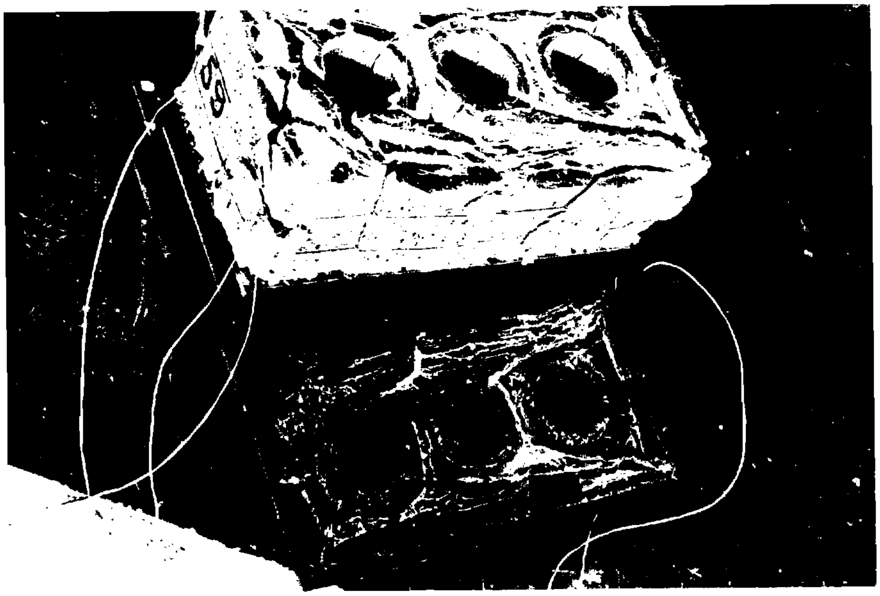


Fig. 4 View of fractured G brick with 1/8 in. CIN contact material

Fig. 5 View of fractured prism of G brick and N mortar

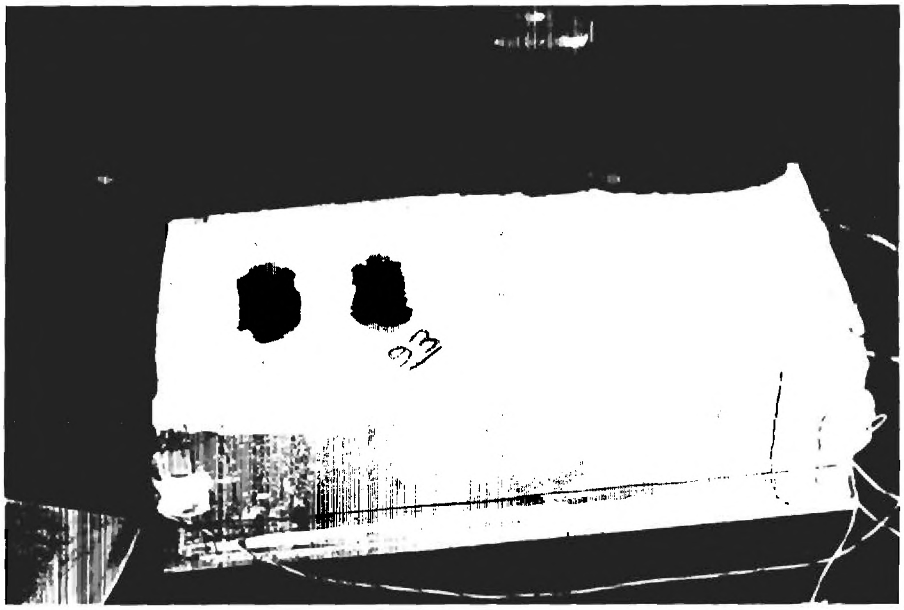


Fig. 6 View of fractured G brick with 1/16 in. LDP contact material

Fig. 7 View of fractured prism of C brick and N mortar

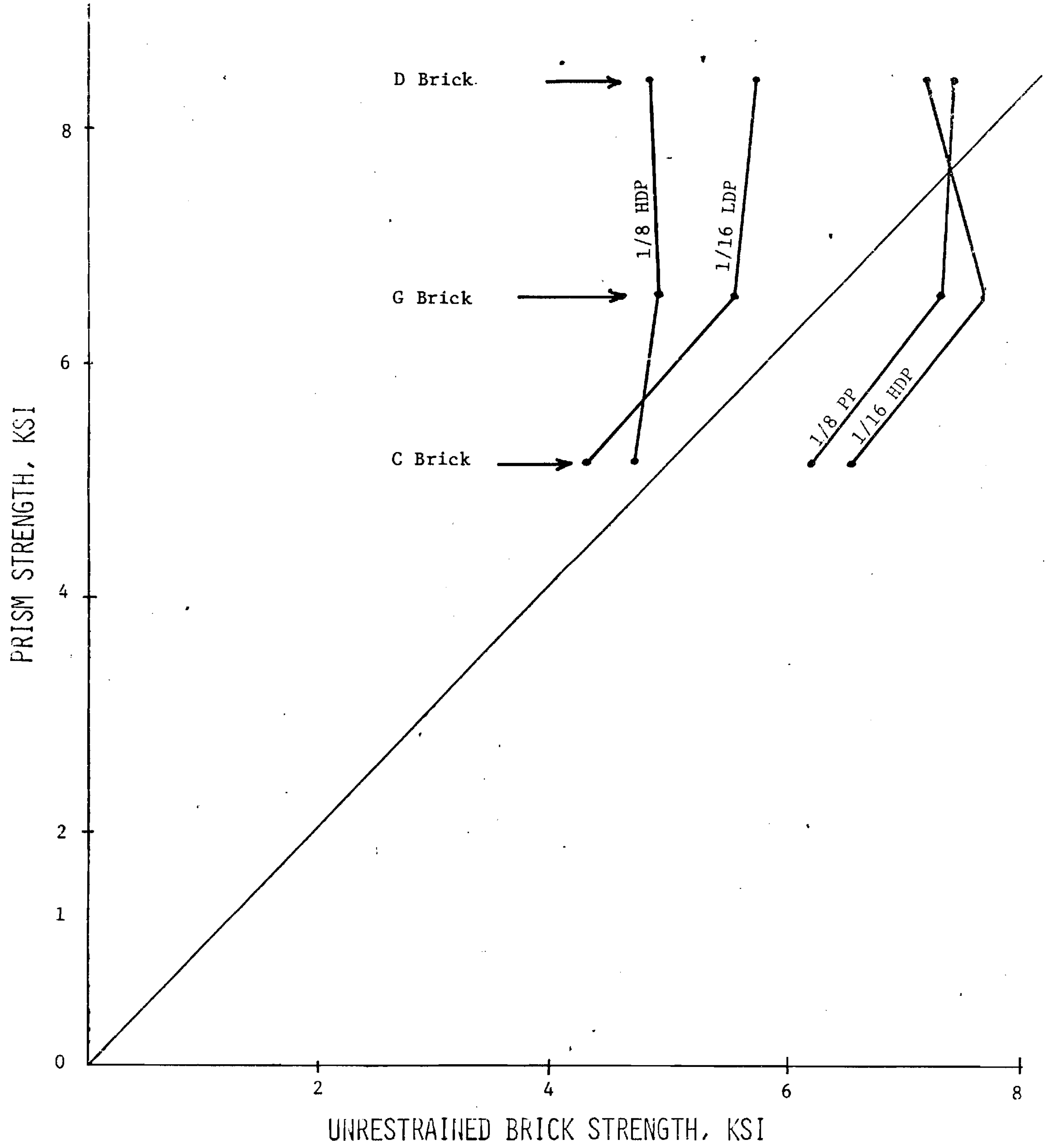


Fig. 8, Prism Strength vs Unrestrained Brick Strength, Type M Mortar

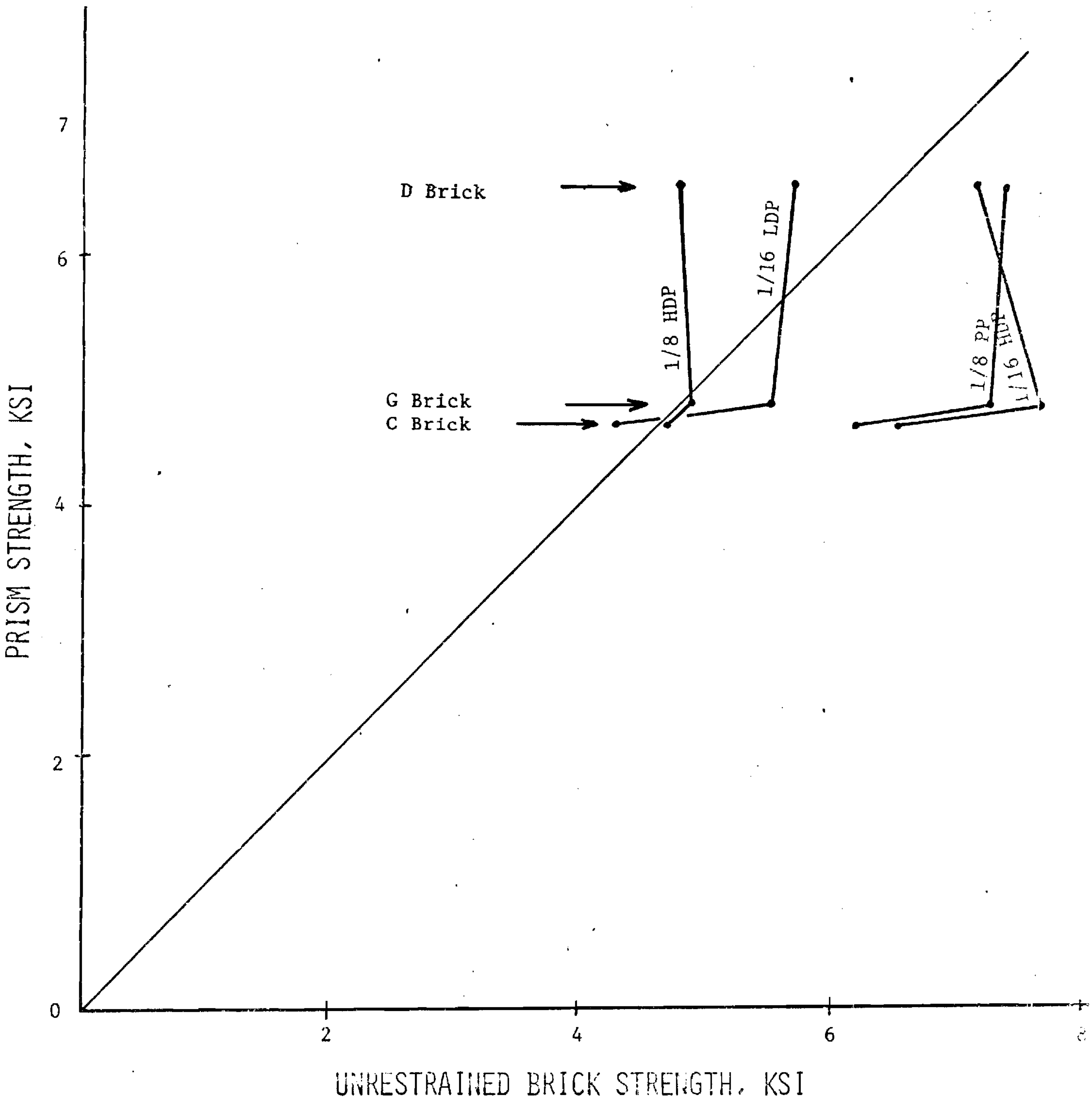


Fig. 9, Prism Strength vs Unrestrained Brick Strength, Type S Mortar

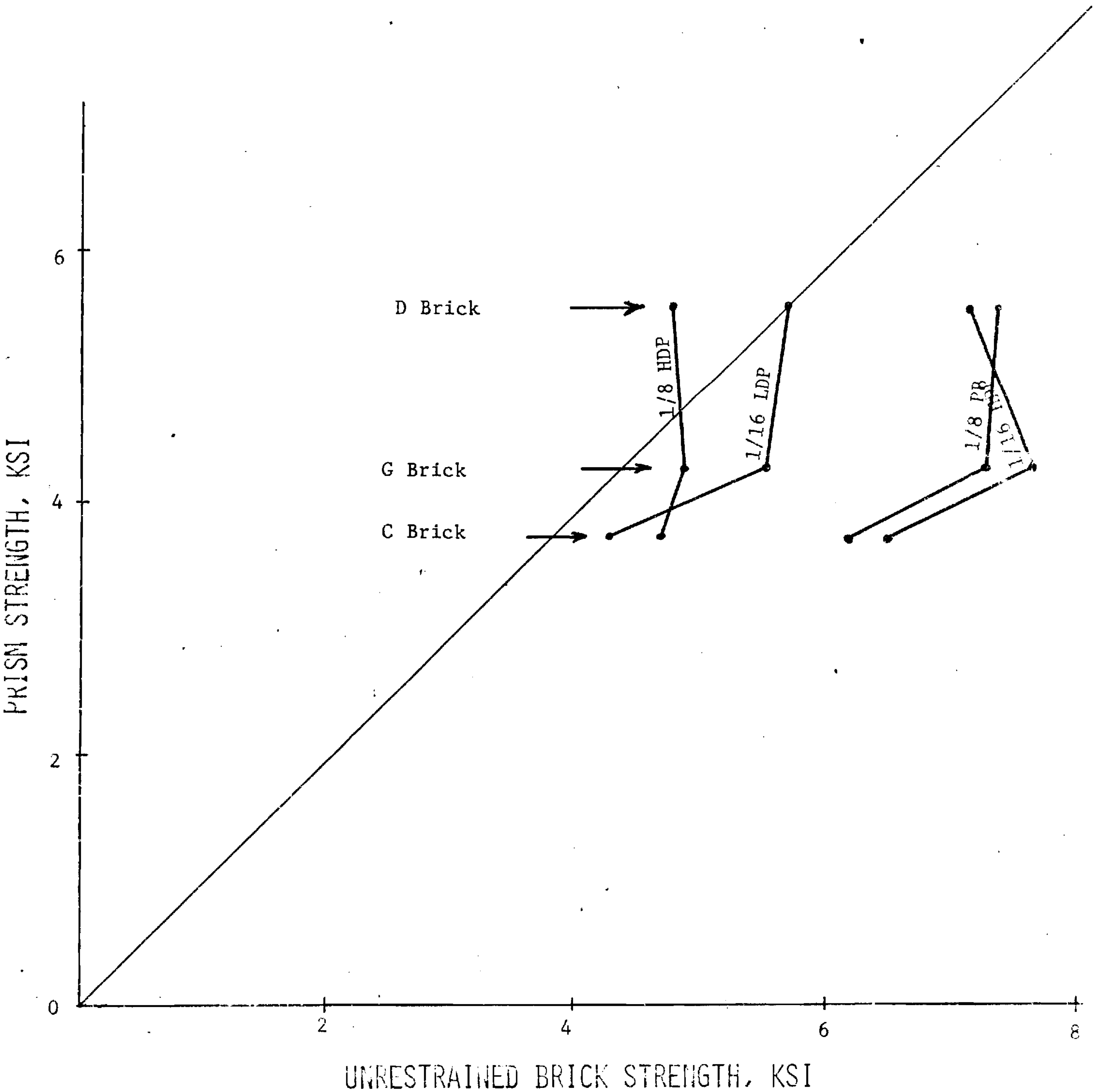


Fig. 10, Prism Strength vs Unrestrained Brick Strength, Type N Mortar

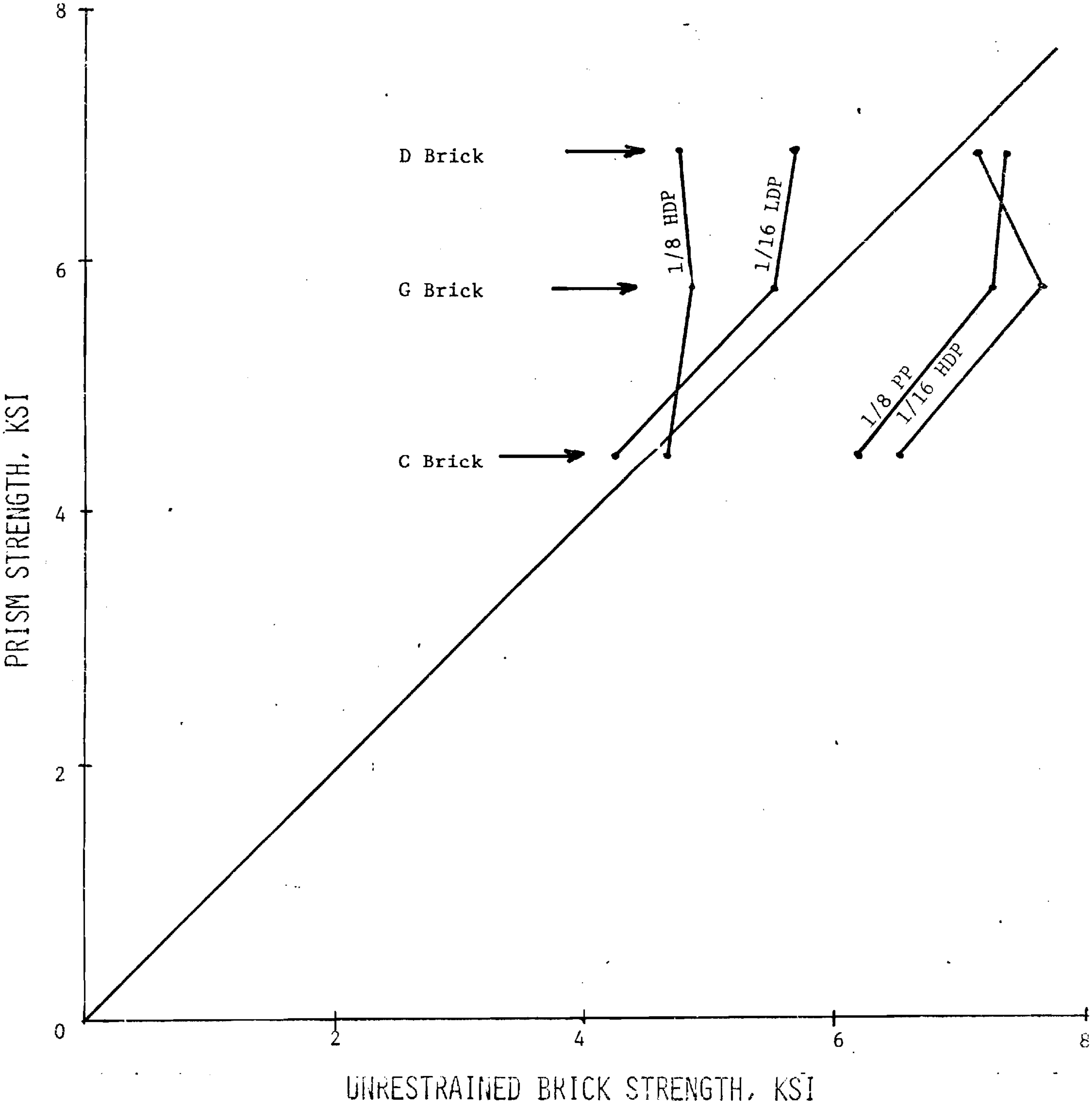


Fig. 11, Prism Strength vs Unrestrained Brick Strength
Type H Mortar

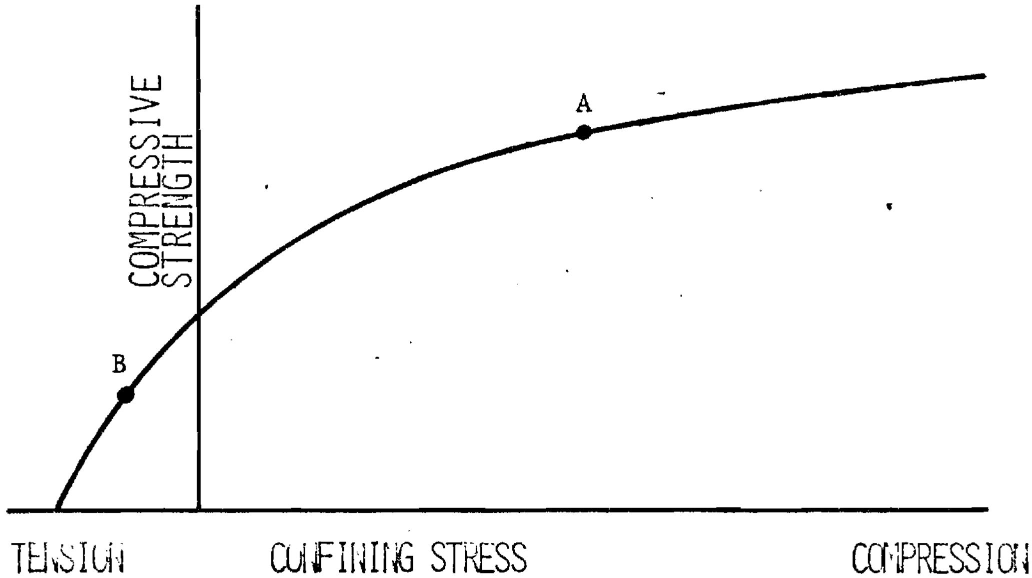


Fig. 12, Triaxial Stress State of Prisms and Standard Compressive Tests

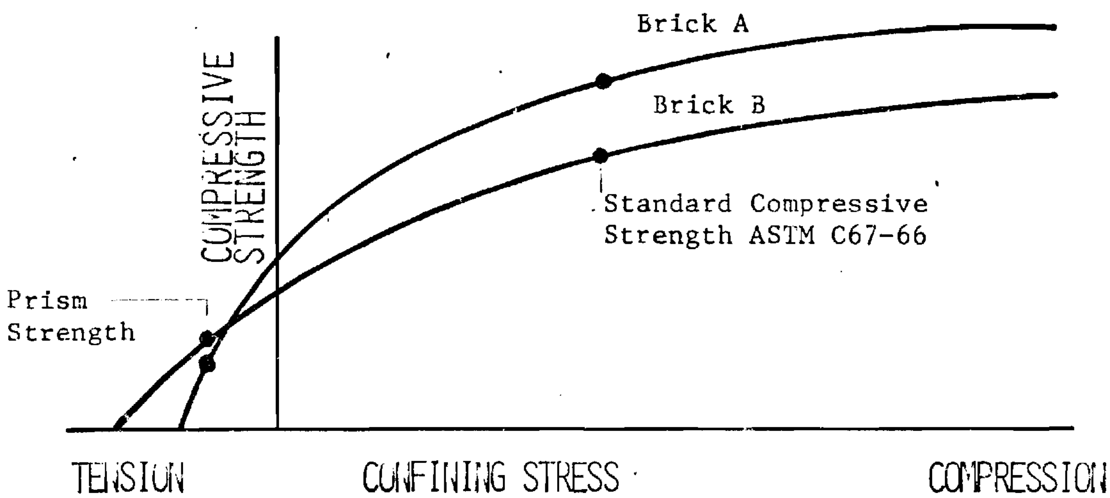


Fig. 13, Strength Reversal - Prism Strength vs Standard Compressive Strength

APPENDIX A

INSTRUMENTATION

Strain Data Acquisition

The strain data for the individual brick specimens and prisms was obtained using unbonded single-wire electrical resistance strain gages. A single continuous strand of bare 0.001-in. diameter copper-nickel alloy wire was attached to insulators at each of the four corners of the brick at mid-height as shown in Fig. A1, such that the average transverse strain on each of the unloaded faces and the average transverse strain around the entire periphery of the brick could be measured. The gage was attached to the brick at mid-height of the prisms. The leads from the strain gages were connected through a switching unit to a strain indicator.

Instrumentation Procedure

The type of instrumentation used is almost identical to that used by D. Watstein. Bare 0.001-in. diameter Constantan (Driver-Harris "Advance", 57% copper-43% nickel) was chosen as the gage wire because it is economical, easy to solder, stable at room temperature, provides a resistance of approximately 25-ohms per inch which was thought to be sufficient for accurate readings and has a gage factor (F = 2.0) which remains constant over a wide range of strain.

The electrical insulators to which the gages were attached at the four corners of the brick were prepared from 0.5-in. I.D. x 0.75-in. O.D. clear methl-methacrylate (Plexiglas) tubing cut along a diametral plane. The split tubing was then cut into segments 0.5-in. long. The insulator segments were cemented with an epoxy resin to the four corners of a brick at mid-height and held in place with rubber bands. After a curing period for the epoxy, the mid-height of the brick was marked on each insulator and one end of a 0.175-in. bondable terminal (micro-Measurements CTF-50C) was centered over the mid-height mark and cemented with methyl-2-cyanoacrylate adhesive (Eastman 910) to three of the four insulators as shown in Fig. A2. Two terminals were cemented to the fourth insulator, one on each side of the mid-height mark about 1/64-in. apart as shown in Fig. A3.

One end of the Constantan wire was temporarily taped in place across the inside end of one of the terminals and a leadwire was held in place to the other end of the same terminal. The gage and lead-wire were then soldered to the terminal simultaneously as shown in Fig. A4. It was found to be easier to solder both wires simultaneously to avoid breaking the fine gage wire or overheating the terminal. It is recommended that the terminal and the lead-wire by lightly tinned prior to making a solder connection.

After making the initial connection, the free end of the Constantan wire was run over the next corner insulator and aligned with the mid-height mark. A 4.5-oz. weight (tweezers) was hung on the wire on the free side of the insulator to maintain a constant tension of the wire (Fig. A5). A leadwire was held to the other end of the terminal and both wires were soldered in place. This same procedure was followed in attaching the gage wire and lead-wire to the remaining three terminals. After the final connection, the gage wire was cut off at the fifth terminal. The two adjacent terminals on the fourth insulator as shown in Fig. A6 should be carefully inspected to insure that they are not shorted.

The five leadwires from the test brick were connected to an Ellis Associates Switch and Balance Unit, Model BS-6, as shown in the schmatic in Fig. A7. A brick identical to the type being tested was instrumented and connected to the swtiching unit to serve as a temperature compensator. The switching unit allowed all five strain gages (one gage on each of the four lateral faces plus the peripheral gage) to be read without changing the circuitry. The output from the switching unit was connected to the two-arm bridge circuitry of a BLH Model 120C Strain Indicator permitting the strains to be read directly. In a few cases where differences in gage lengths of the active and compensating gages prevented the strain indicator from being balanced, a variable resistor was attached in parallel allowing the bridge to be balanced.

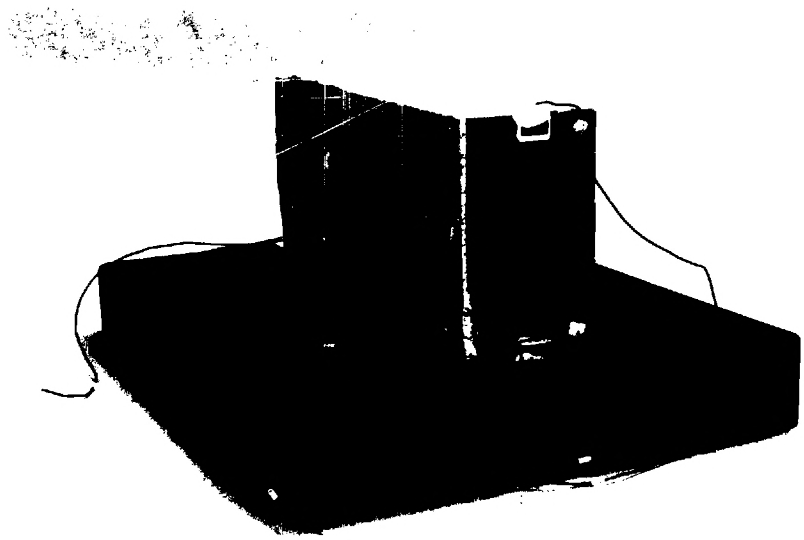


Fig. A1 Instrumented brick on instrumentation platform

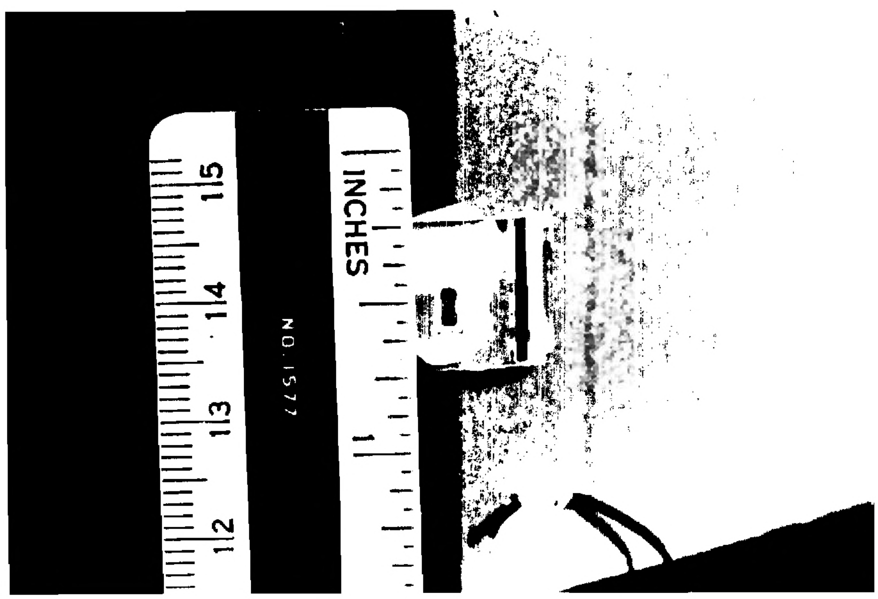


Fig. A2 Single insulator on brick with terminal attached

Fig. A3 Insulator with double terminals attached

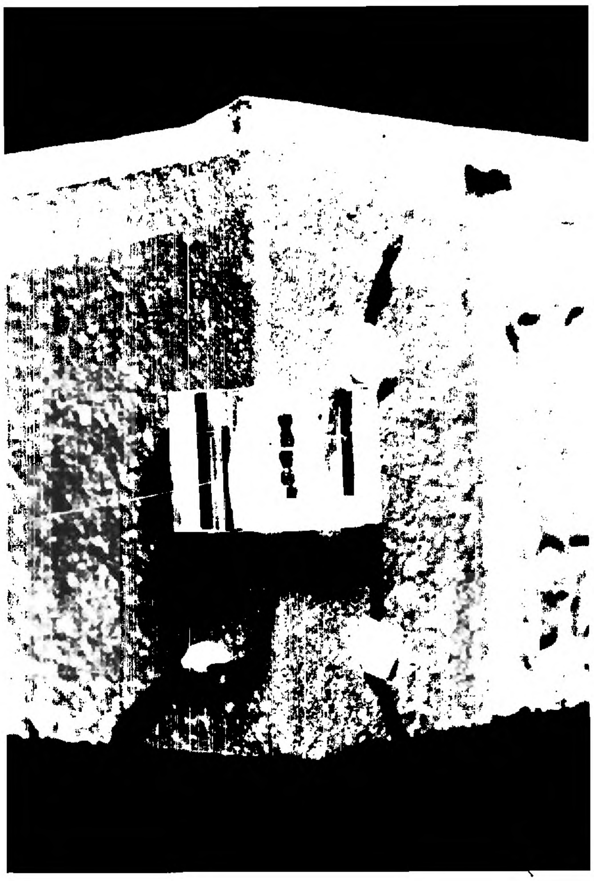


Fig. A4 Initial connection of gage and lead wire

Fig. A5 Tweezers hung to insure equal tension on gage wire

Fig. A6 Final connection of gage and lead wire

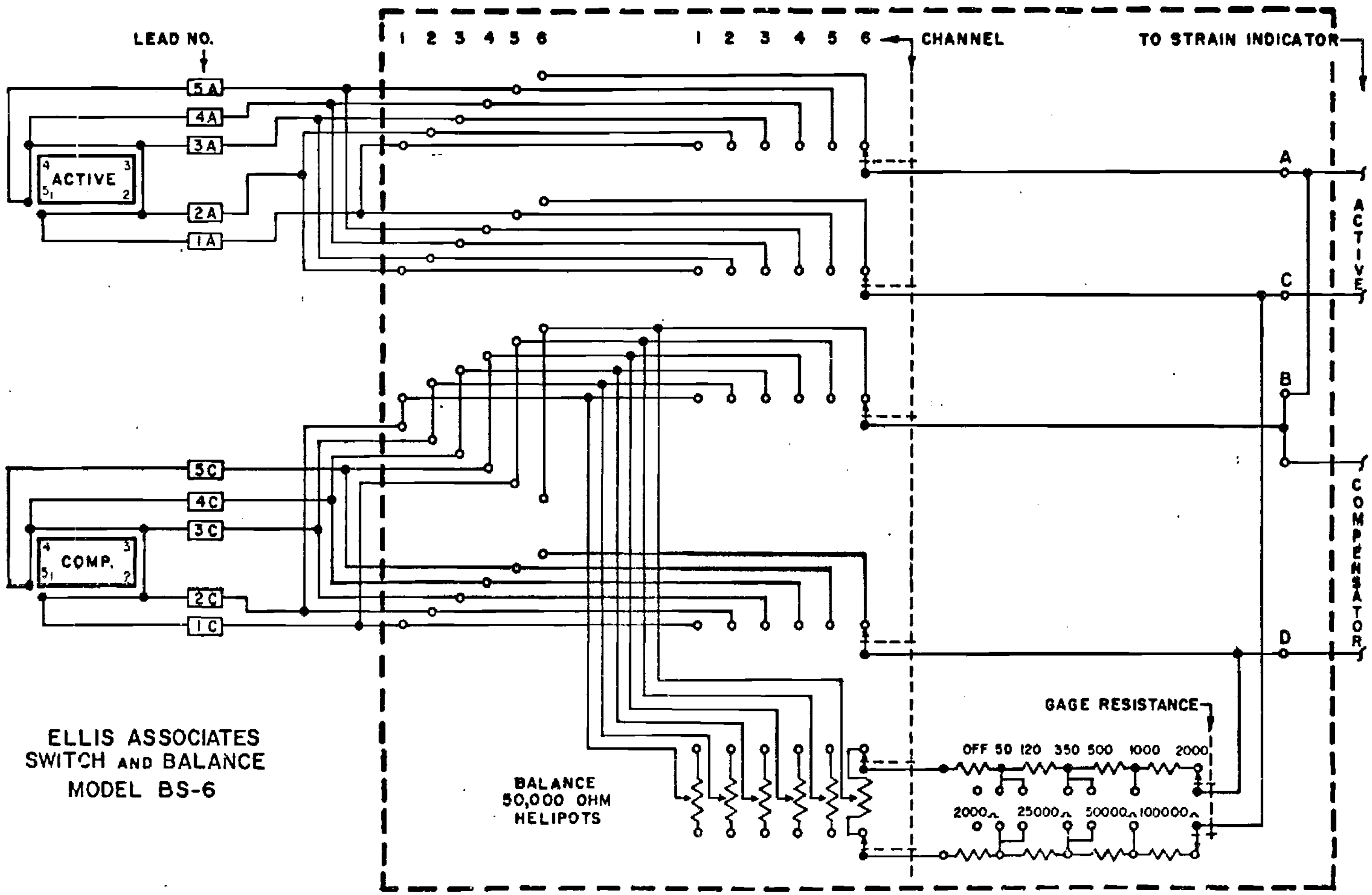
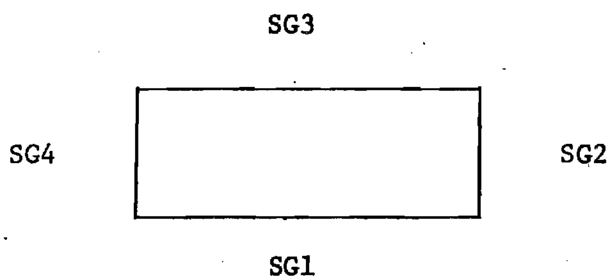


Fig. A7 – Schematic of gages and switching unit.

APPENDIX B

Stress-Strain Curves for Prism Tests

The following curves show the stress-strain curves measured from prism tests. Although three prisms were tested for each type brick and mortar, only one curve is presented for the sake of brevity. Each graph has two legends: one indicates the materials used in the particular test, the other identifies the symbols used on the curves. The symbols SG1 through SG4 are the strains on the faces of the brick indicated below. The symbol SG5 is the strain around the total periphery, and the "peripheral" symbol is the average of SG1 through SG4.



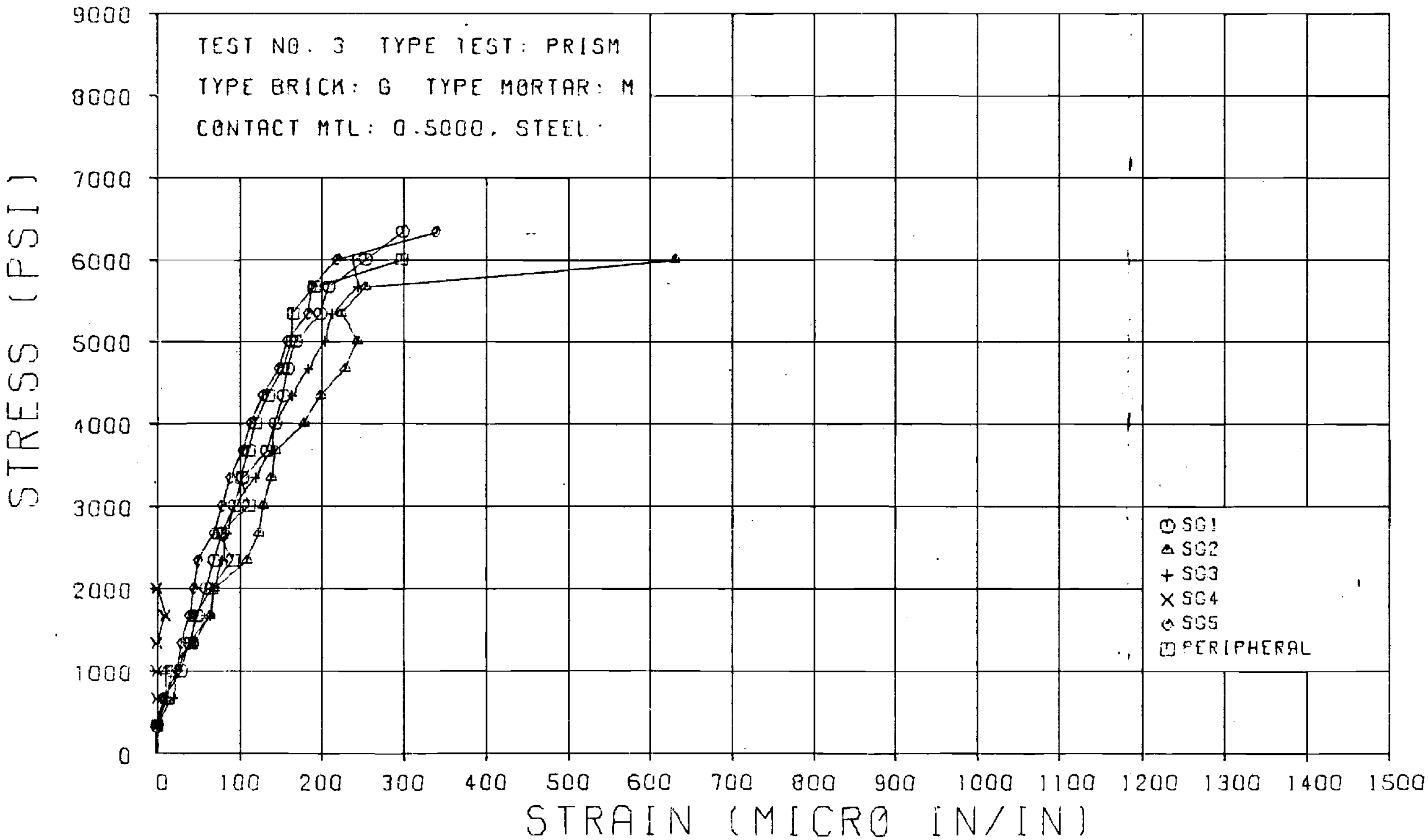


Fig. No. B1 Compressive Stress - Lateral Strain Type G Brick and Type M Mortar

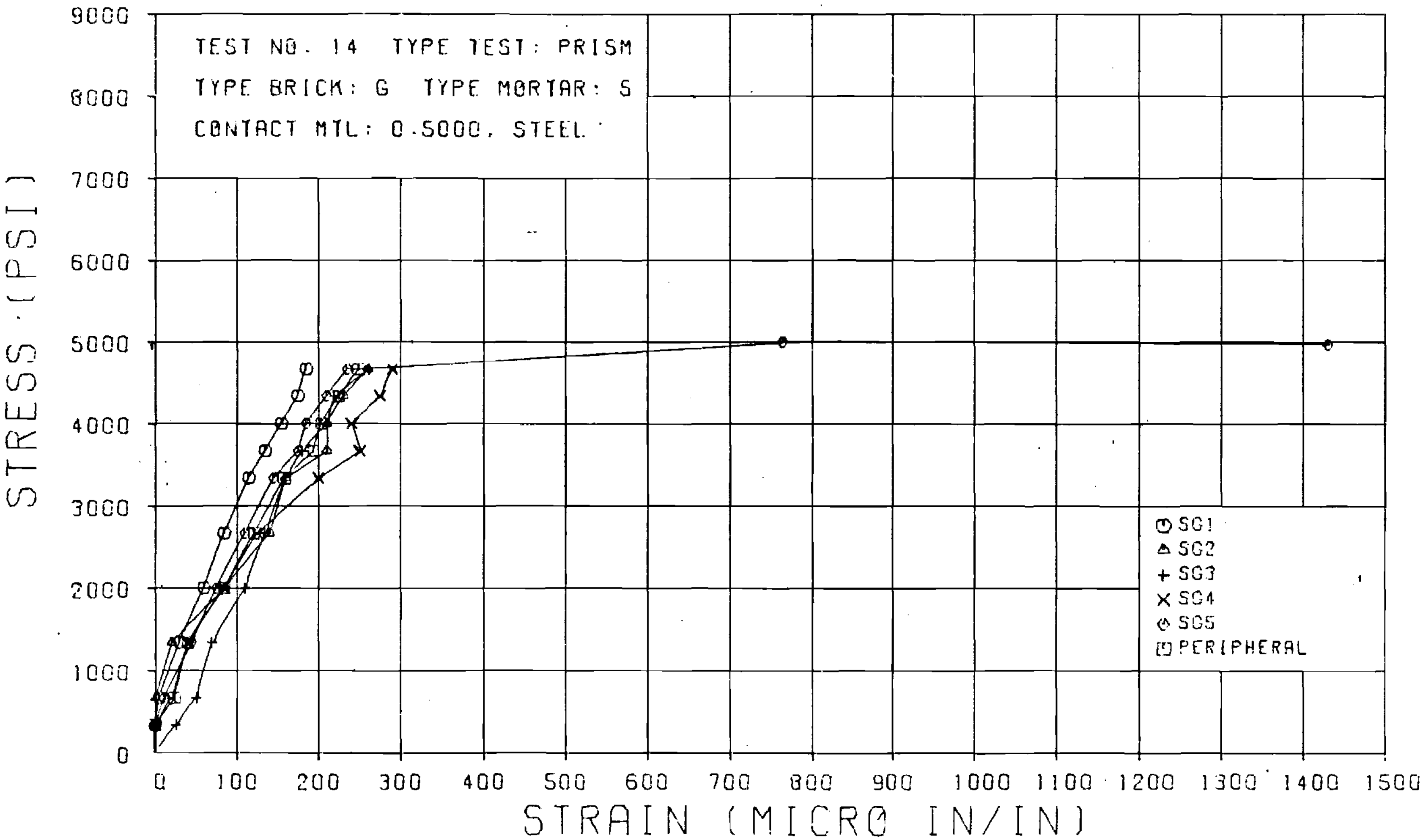


Fig. No. B2 Compressive Stress - Lateral Strain Type G Brick and Type S Mortar

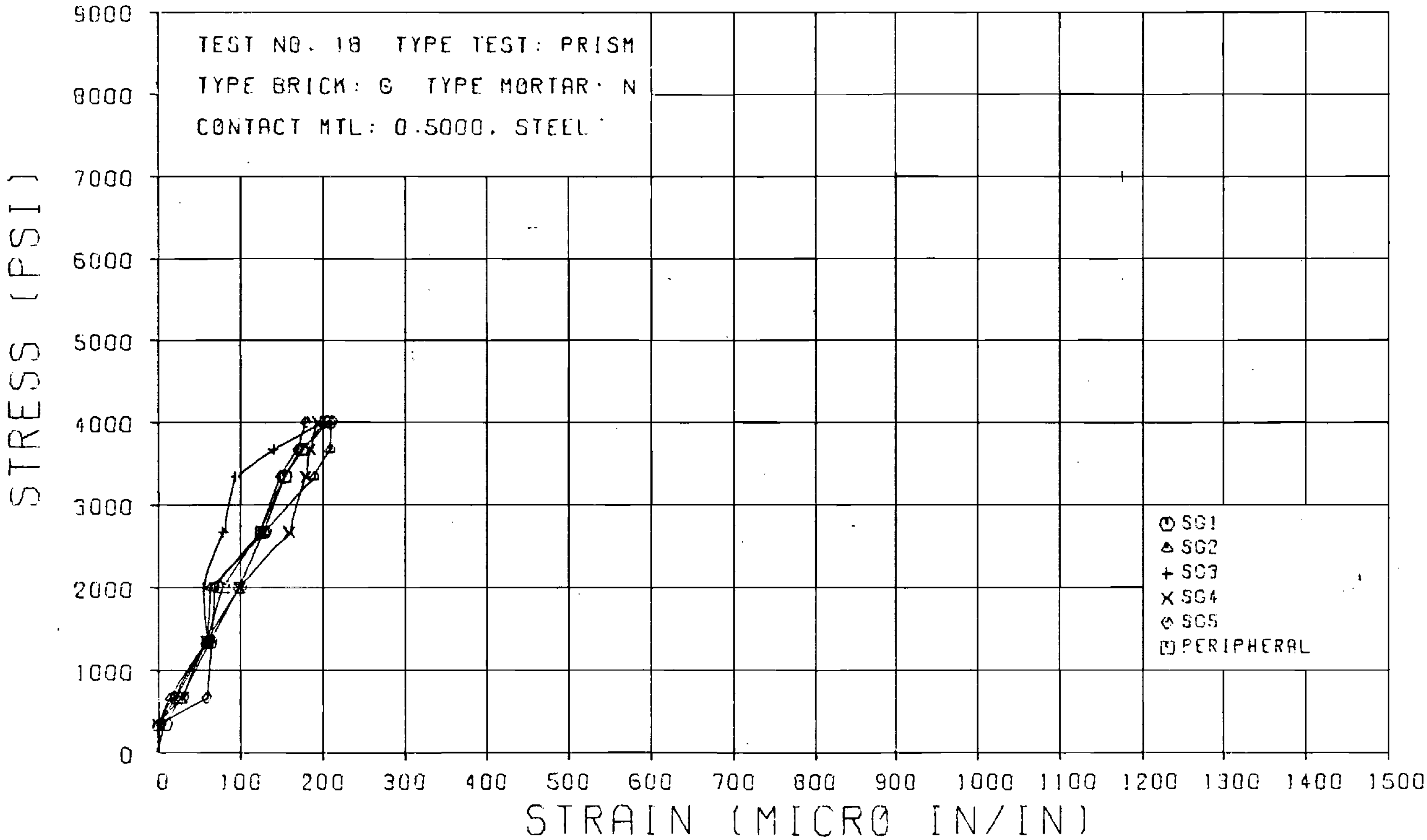


Fig. No. B3 Compressive Stress - Lateral Strain Type G Brick and Type N Mortar

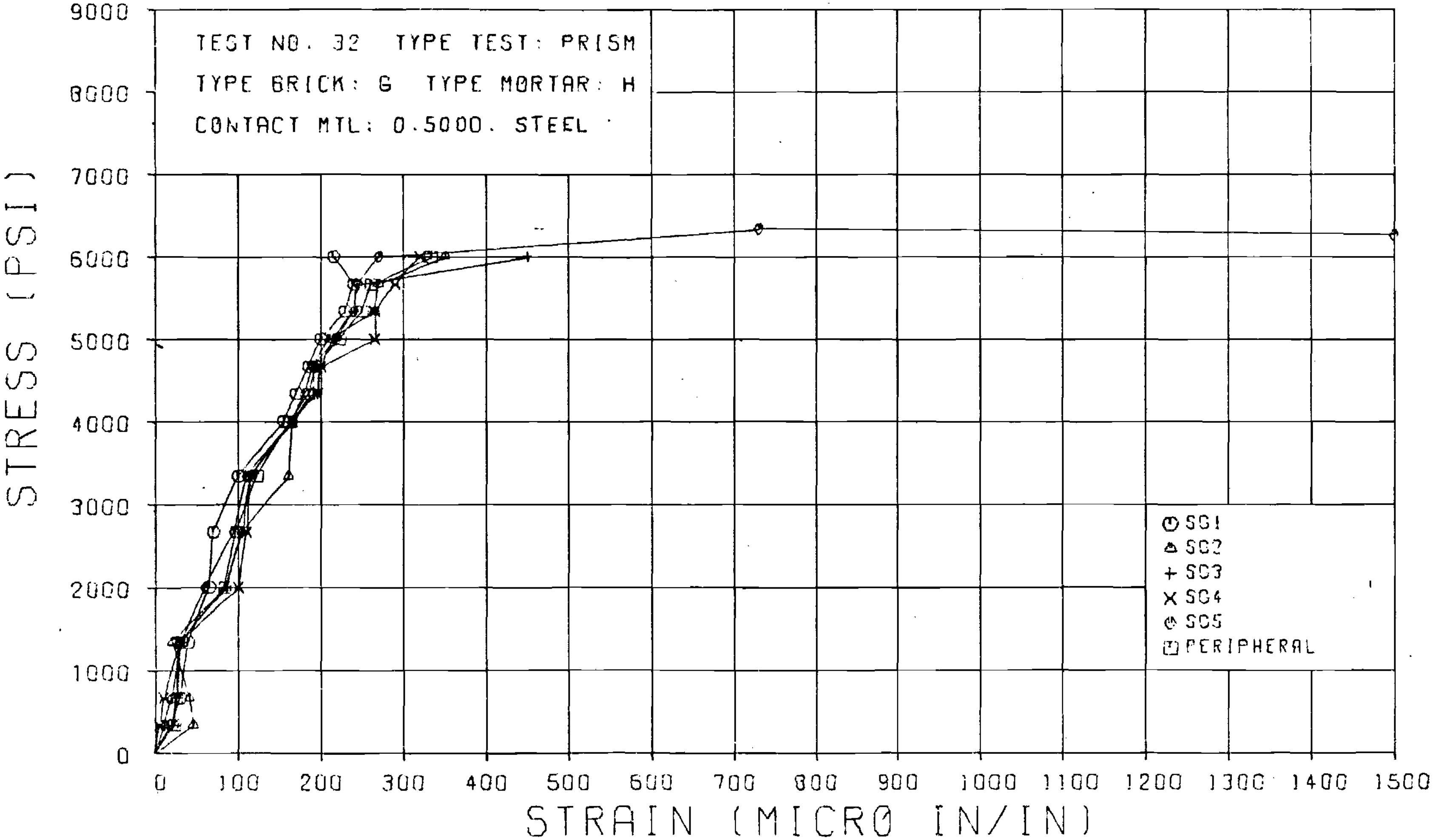


Fig. No. B4 Compressive Stress - Lateral Strain Type G Brick and Type H Mortar

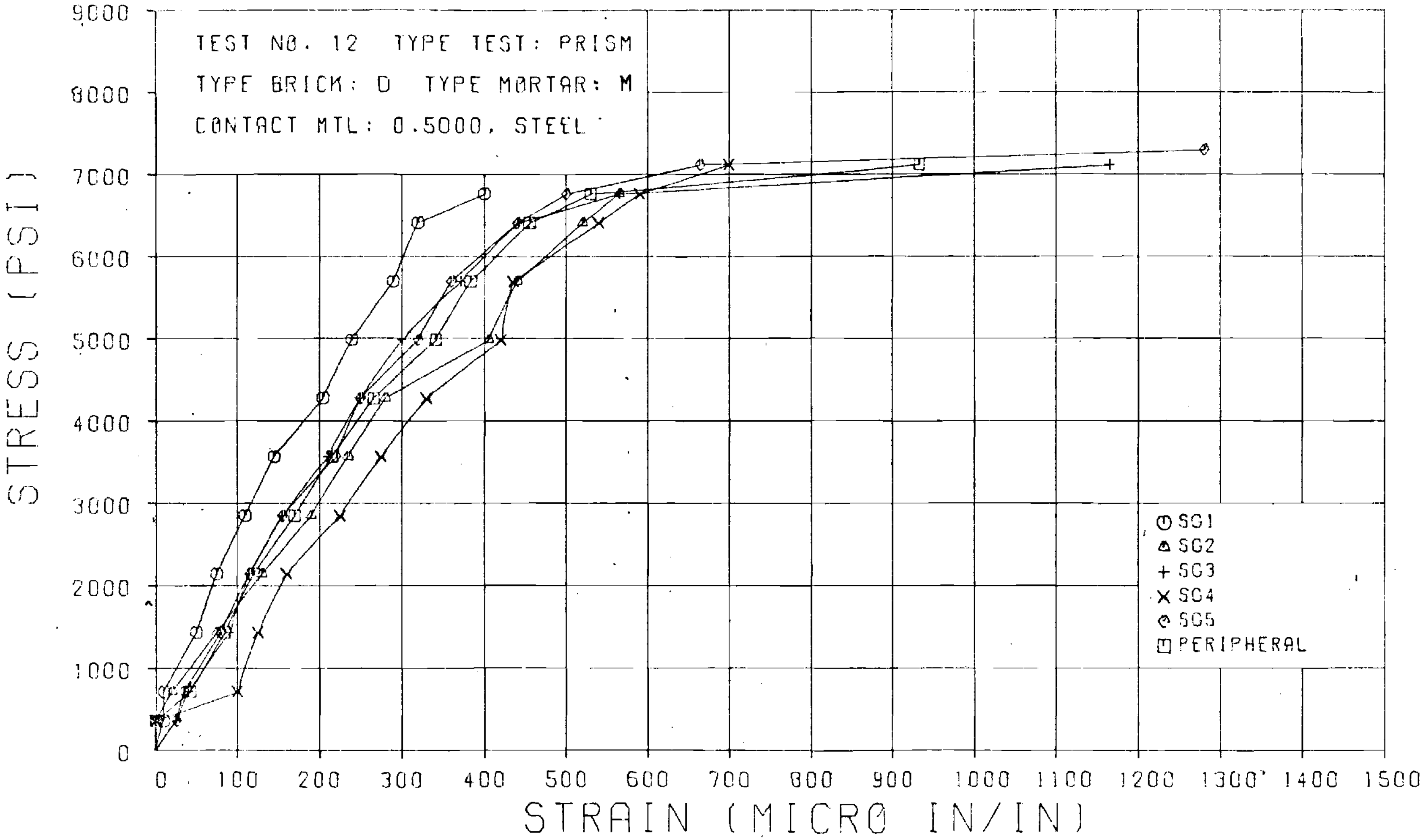


Fig. No. B5 Compressive Stress - Lateral Strain Type D Brick and Type M Mortar

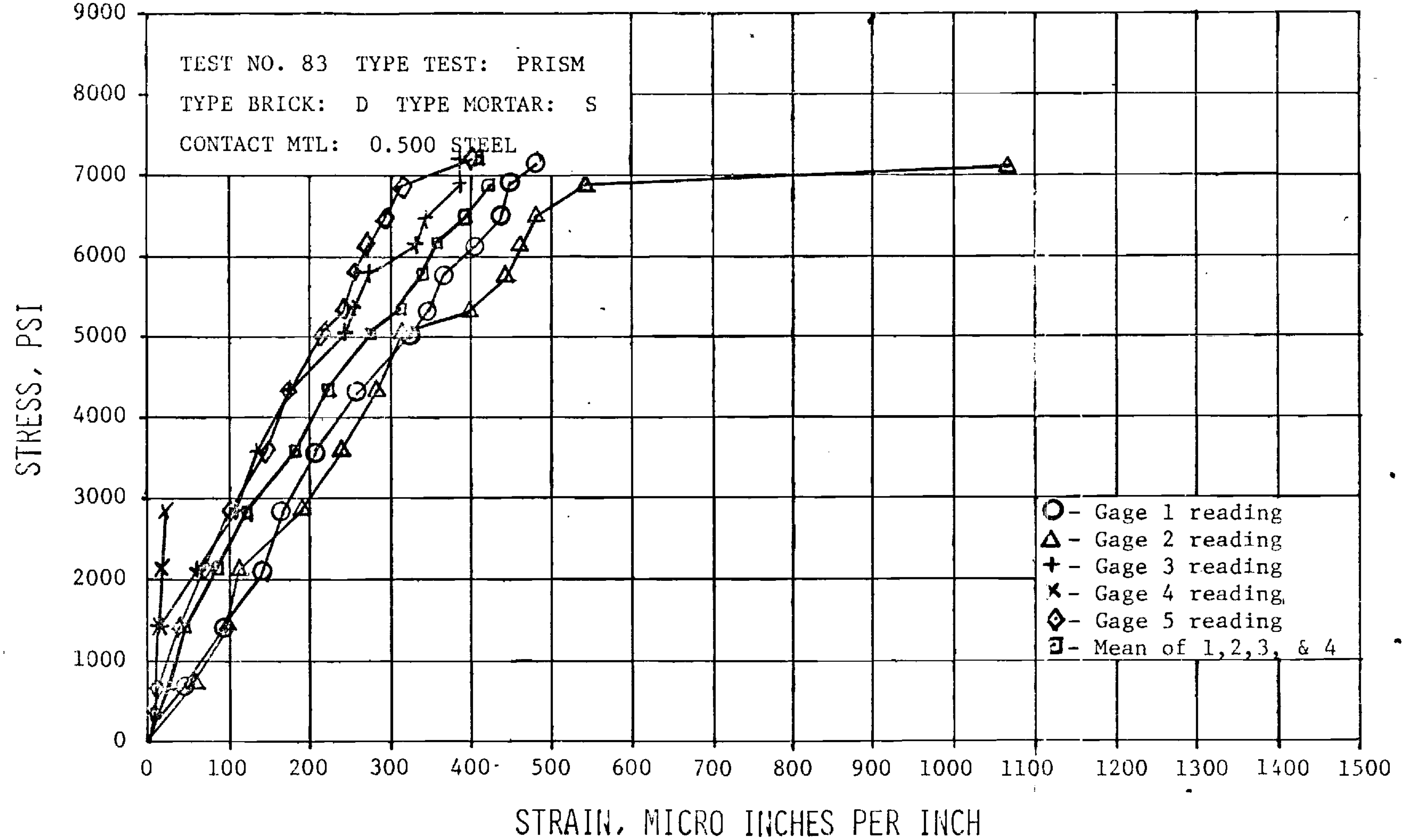


Fig. No. B6 Compressive Stress - Lateral Strain Type D Brick and Type S Mortar

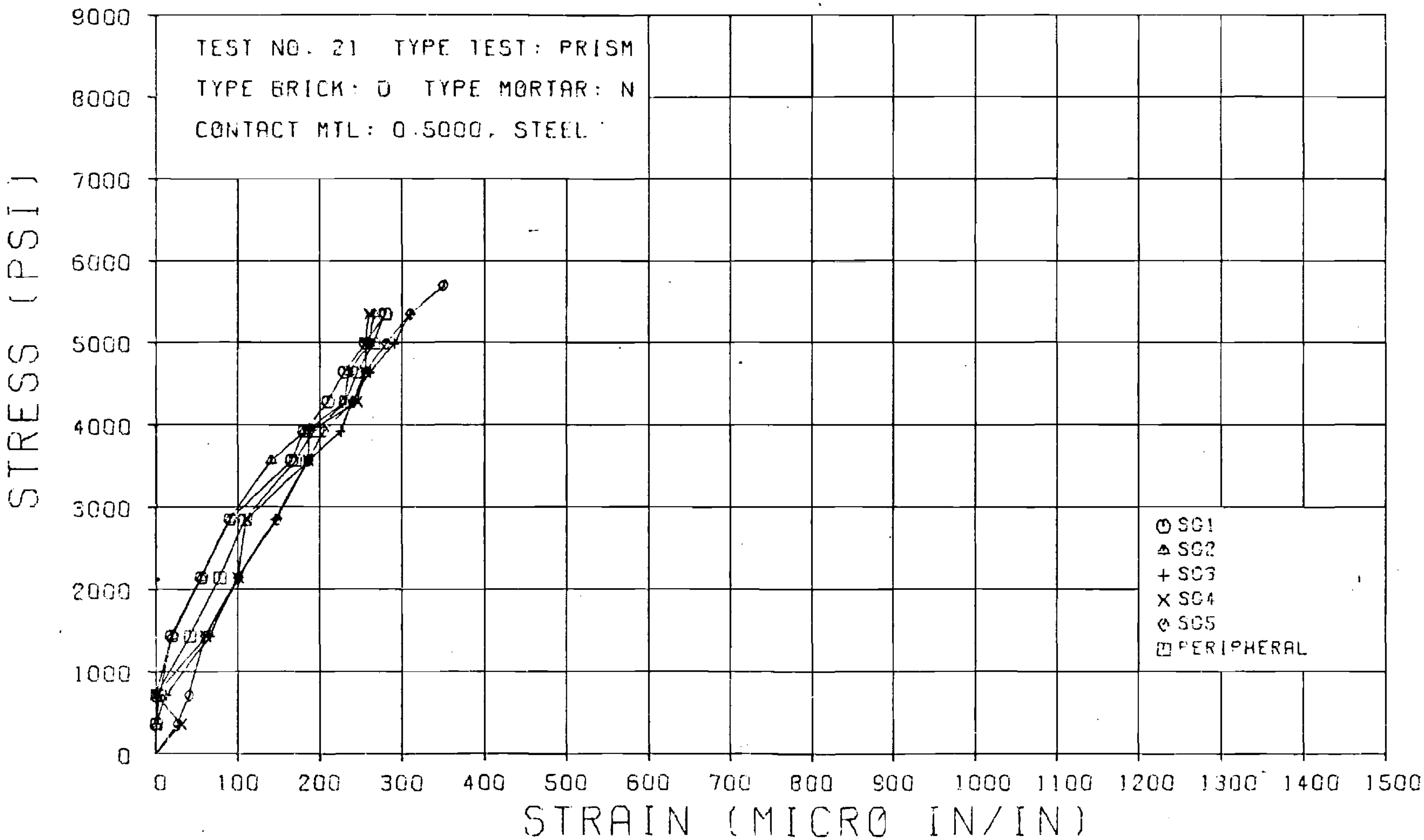


Fig. No. B7 Compressive Stress - Lateral Strain Type D Brick and Type N Mortar

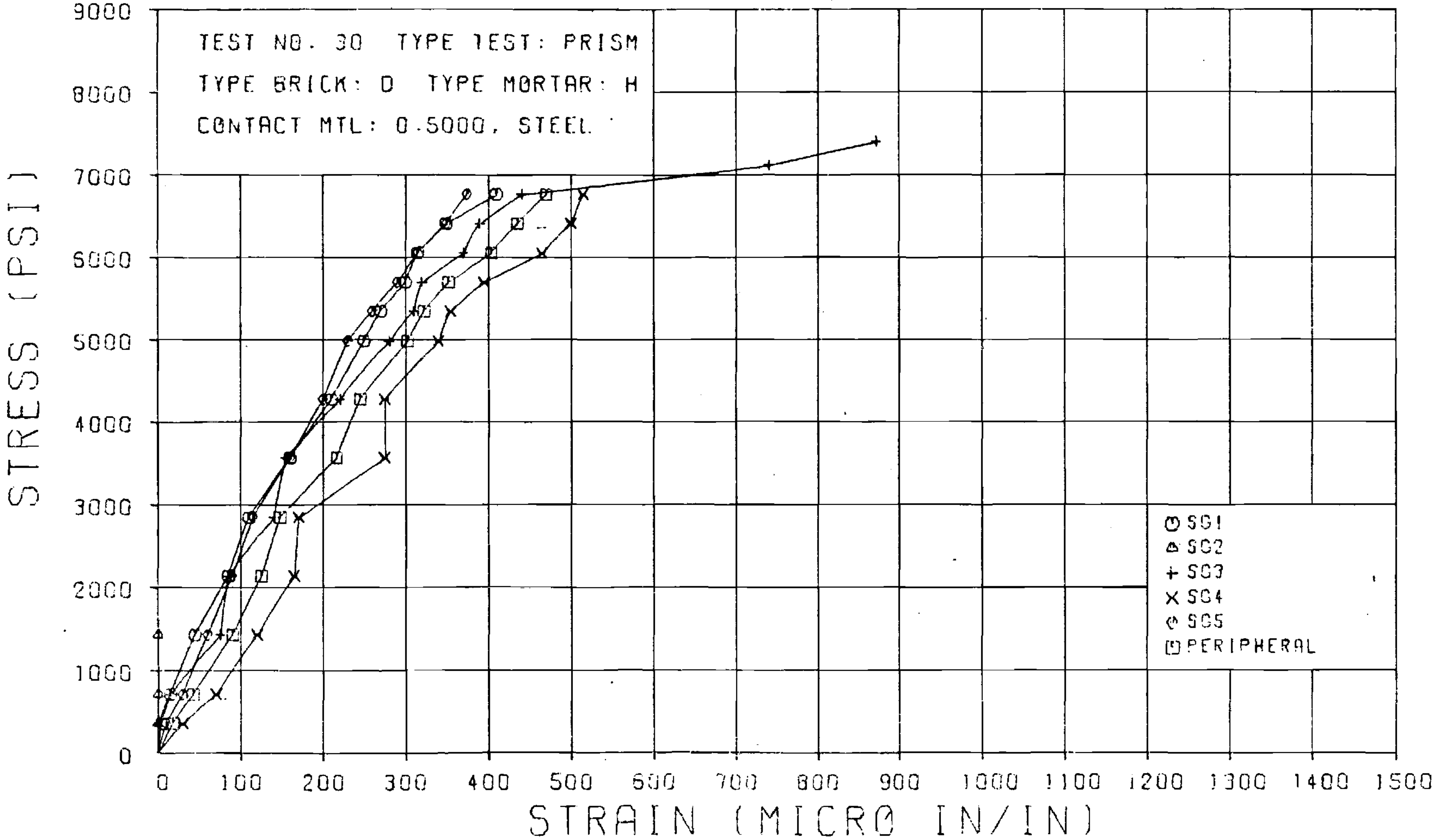


Fig. No. B8 Compressive Stress - Lateral Strain Type D Brick and Type H Mortar

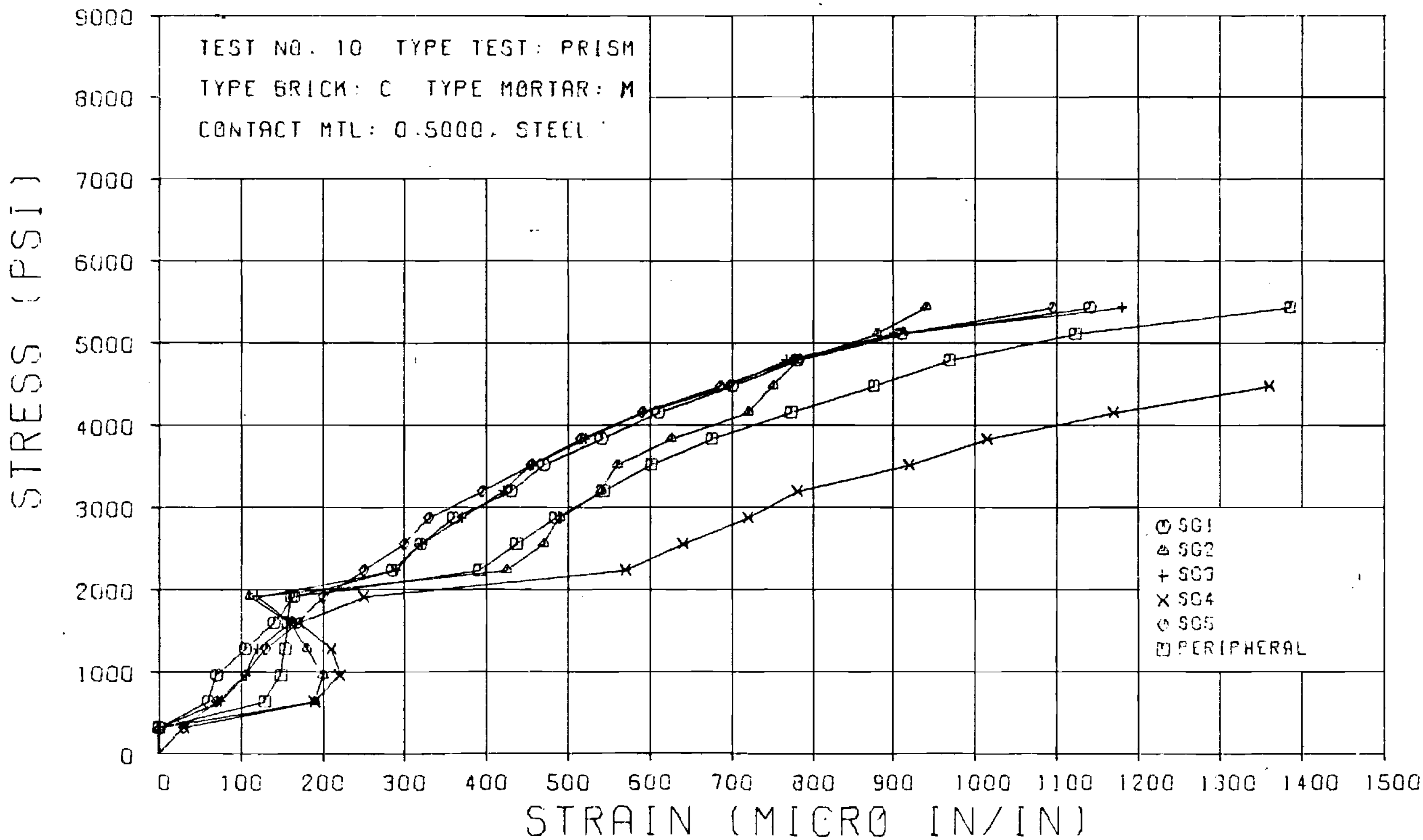


Fig. No. B9 Compressive Stress - Lateral Strain Type C Brick and Type M Mortar

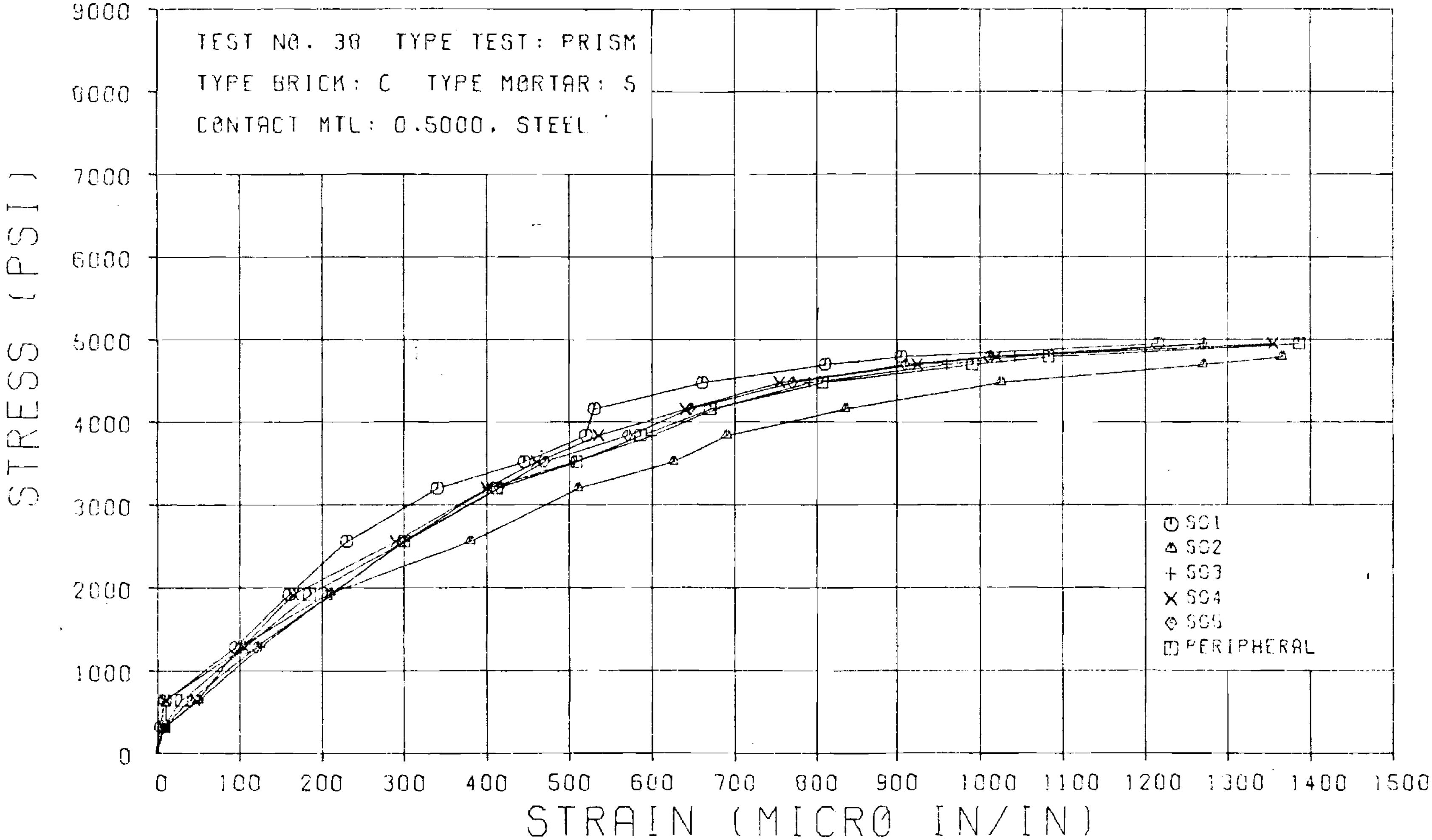


Fig. No. B10 Compressive Stress - Lateral Strain Type C Brick and Type S Mortar

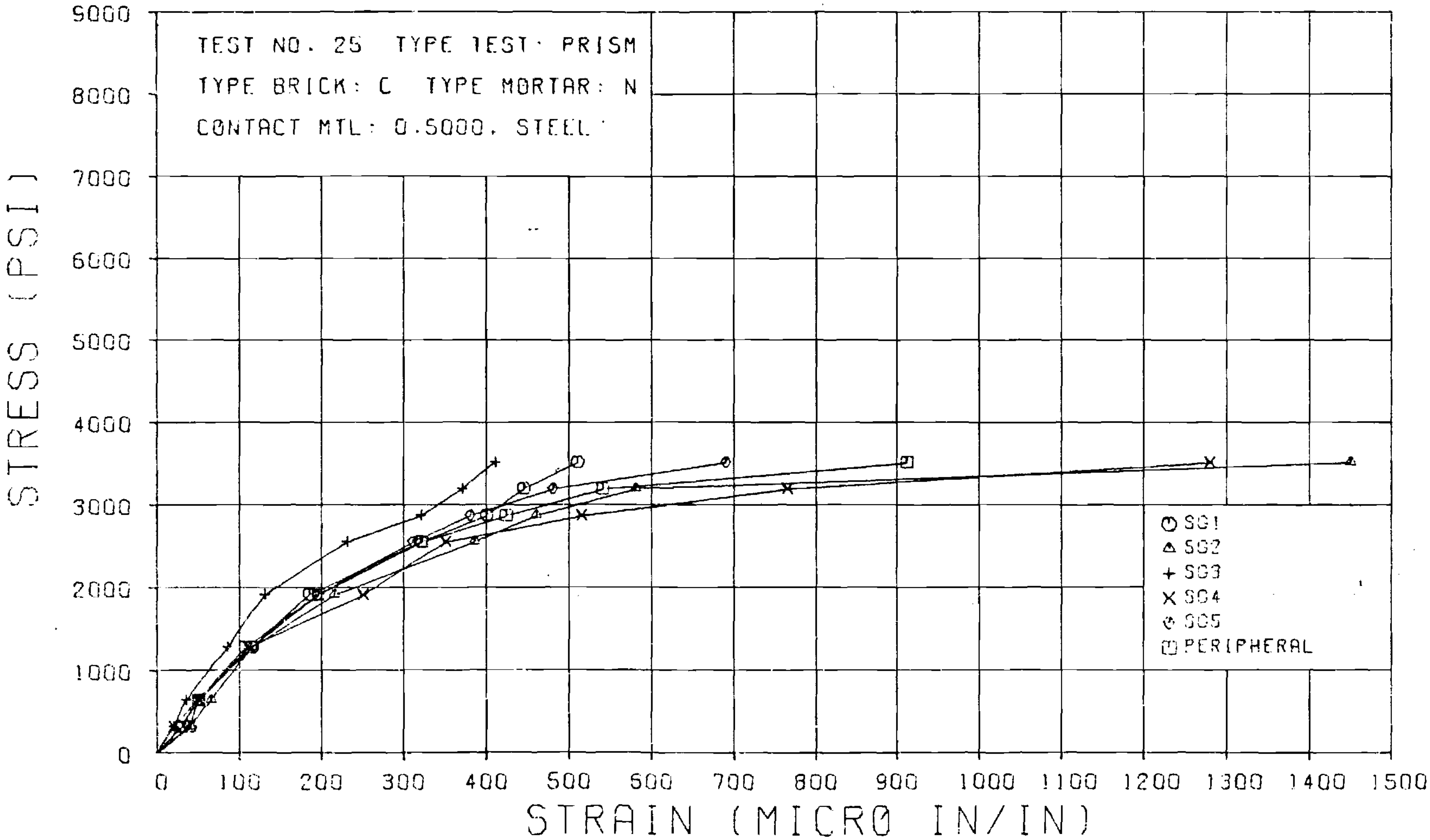


Fig. No. B11 Compressive Stress - Lateral Strain Type C Brick and Type N Mortar

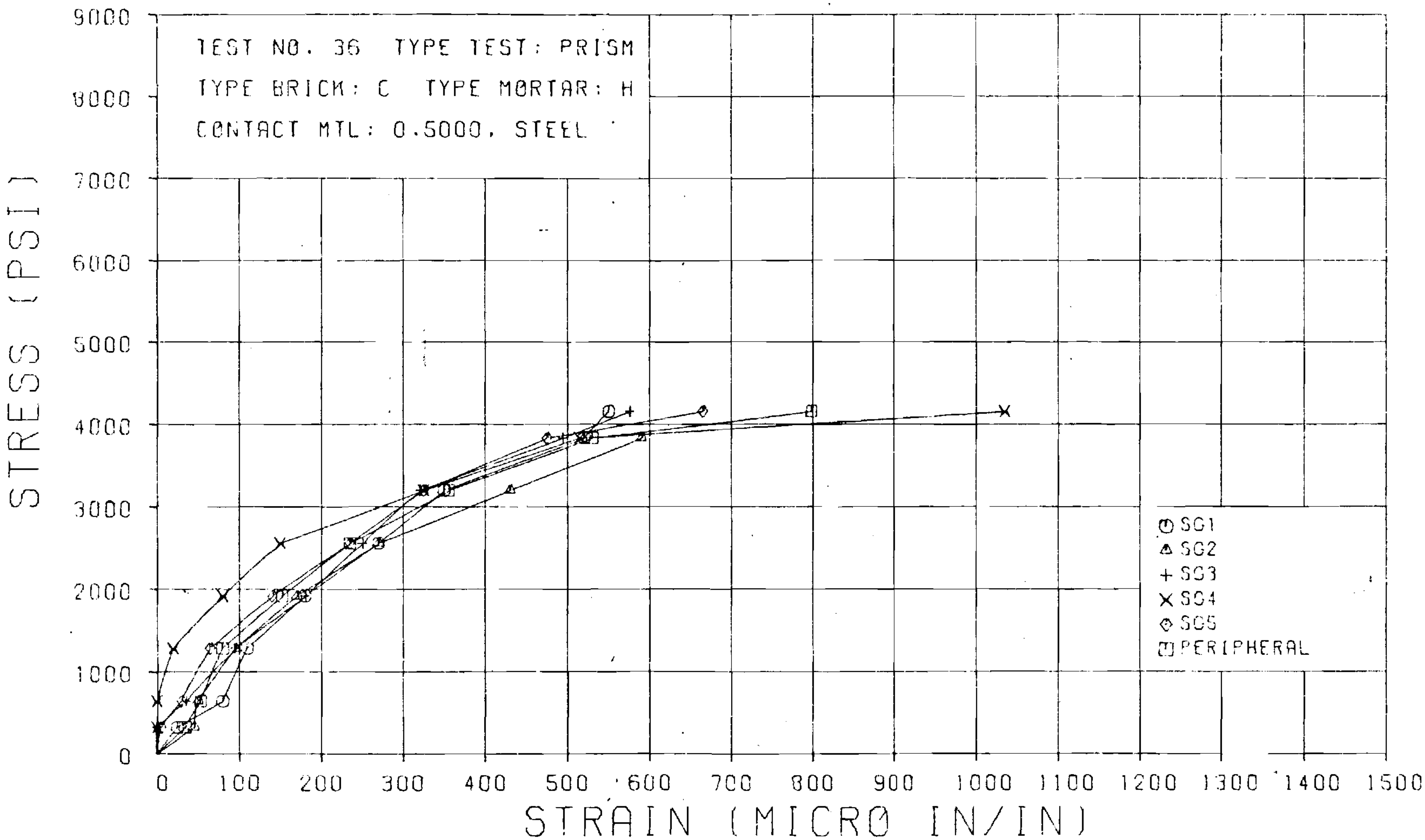


Fig. No. B12 Compressive Stress - Lateral Strain Type C Brick and Type H Mortar

APPENDIX C

Stress-Strain Curves for Unrestrained Compressive Tests

The following curves show the stress-strain curves measured from unrestrained brick tests. Although three bricks were tested for each type brick and contact material, only one curve is presented for the sake of brevity. The strain indicated on each graph is the total strain around the entire brick periphery. The abbreviations used for contact materials are as follows:

LDP - low density polyethylene

HDP - high density polyethylene

PP - polypropylene

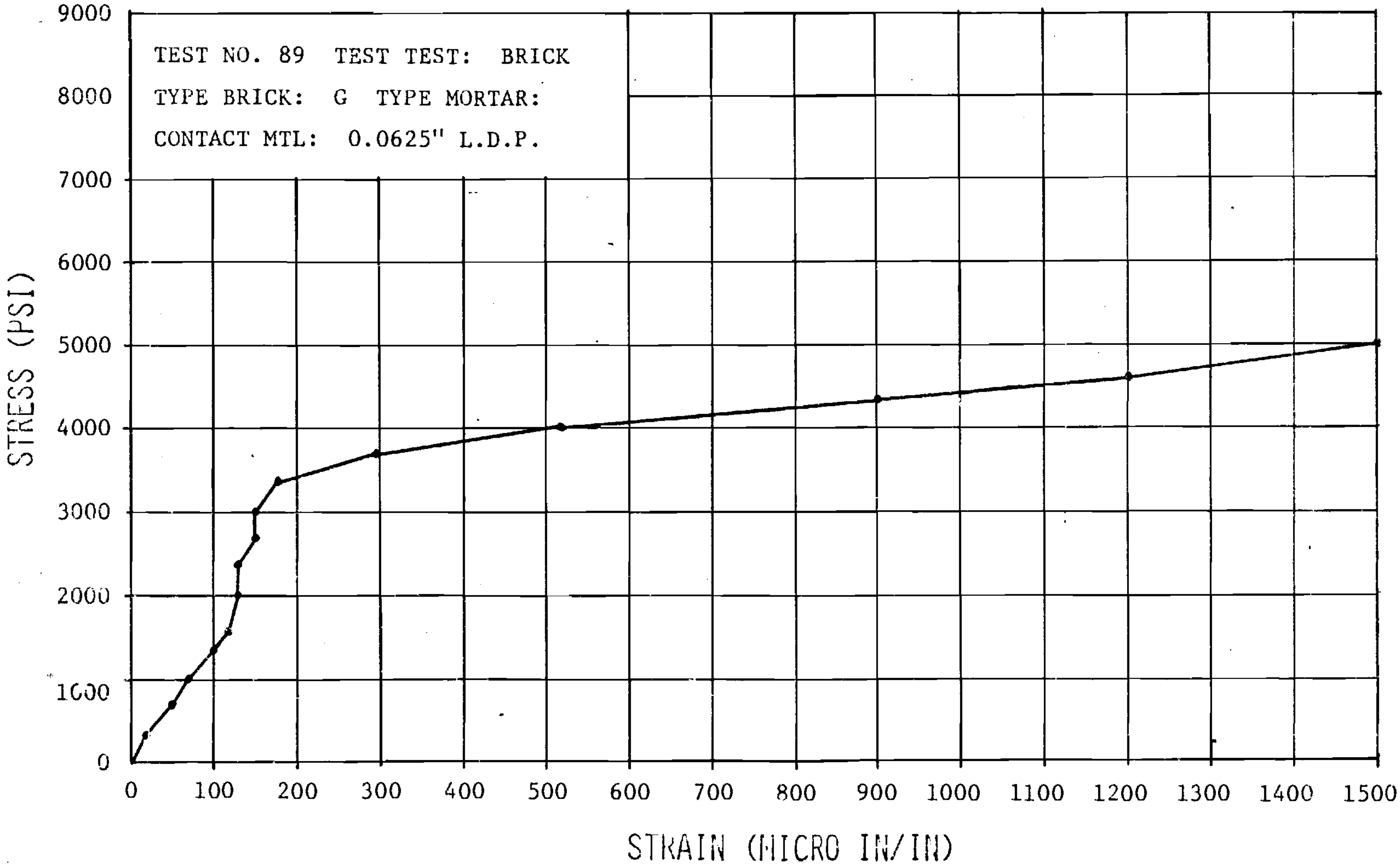


Fig. No. C1 Compressive Stress - Lateral Strain Type G
Brick and 1/16 LDP Contact Material

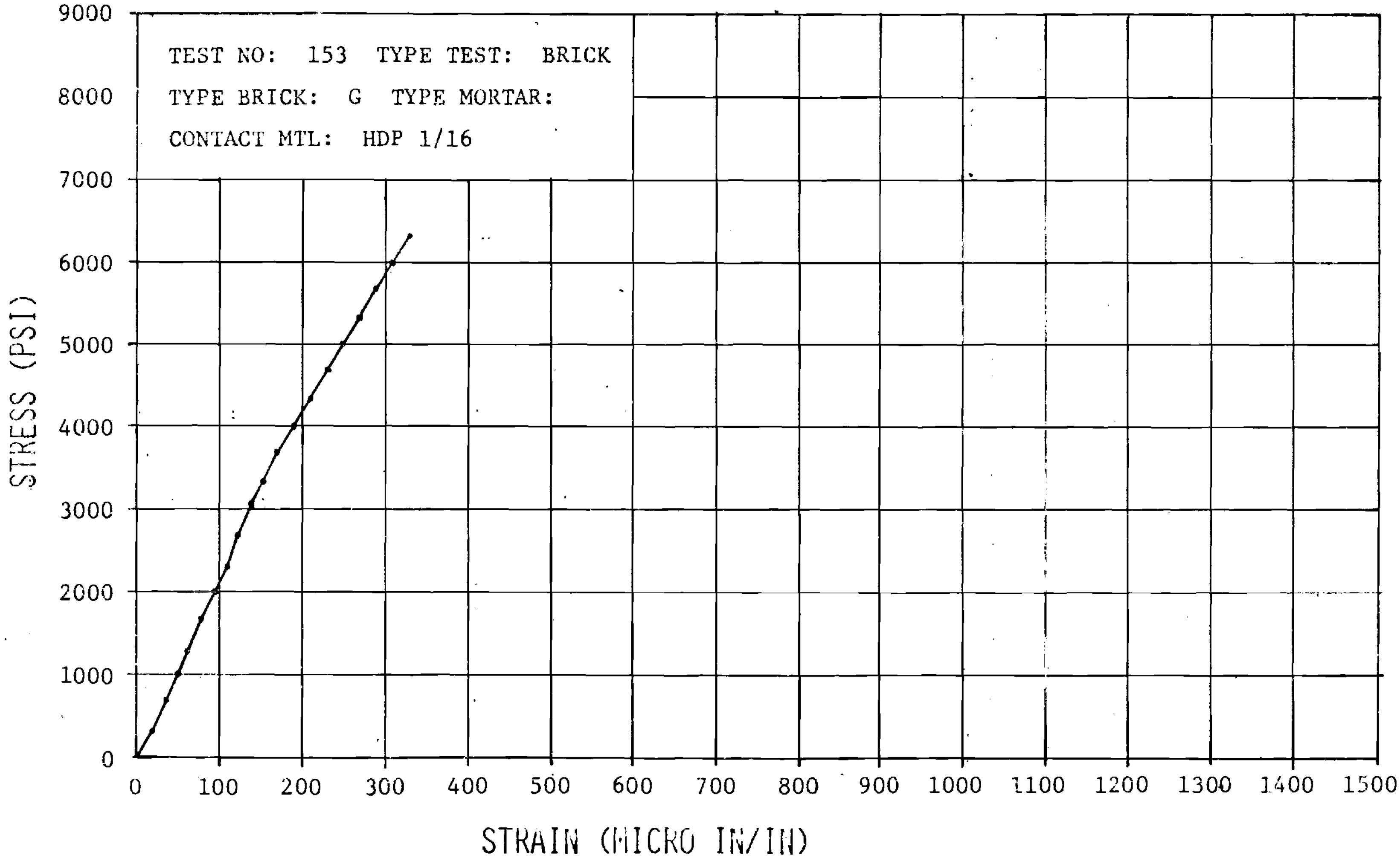


Fig. No. C2 Compressive Stress - Lateral Strain Type G
Brick and 1/16 HDP Contact Material

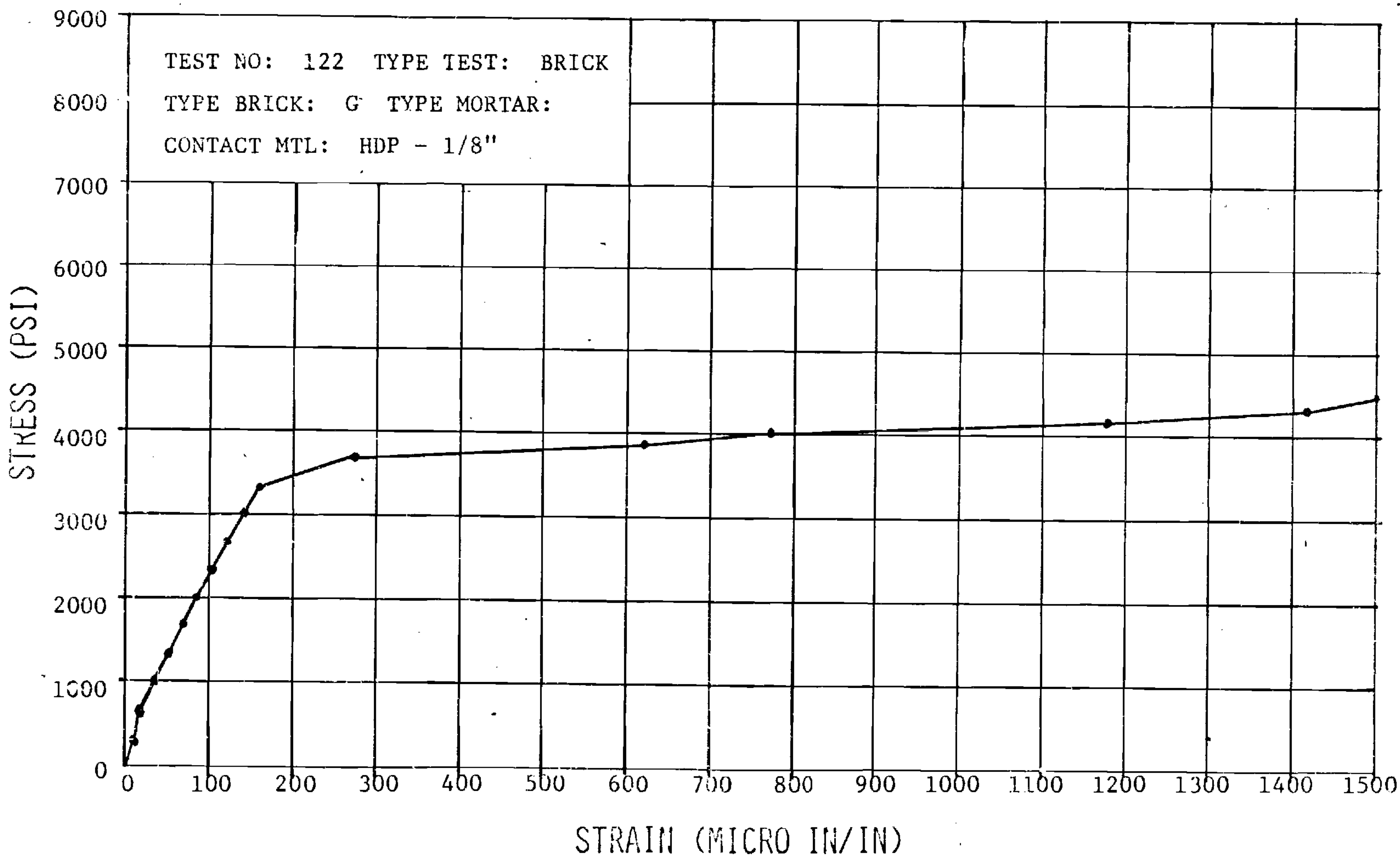


Fig. No. C3 Compressive Stress - Lateral Strain Type G
Brick and 1/8 HDP Contact Material

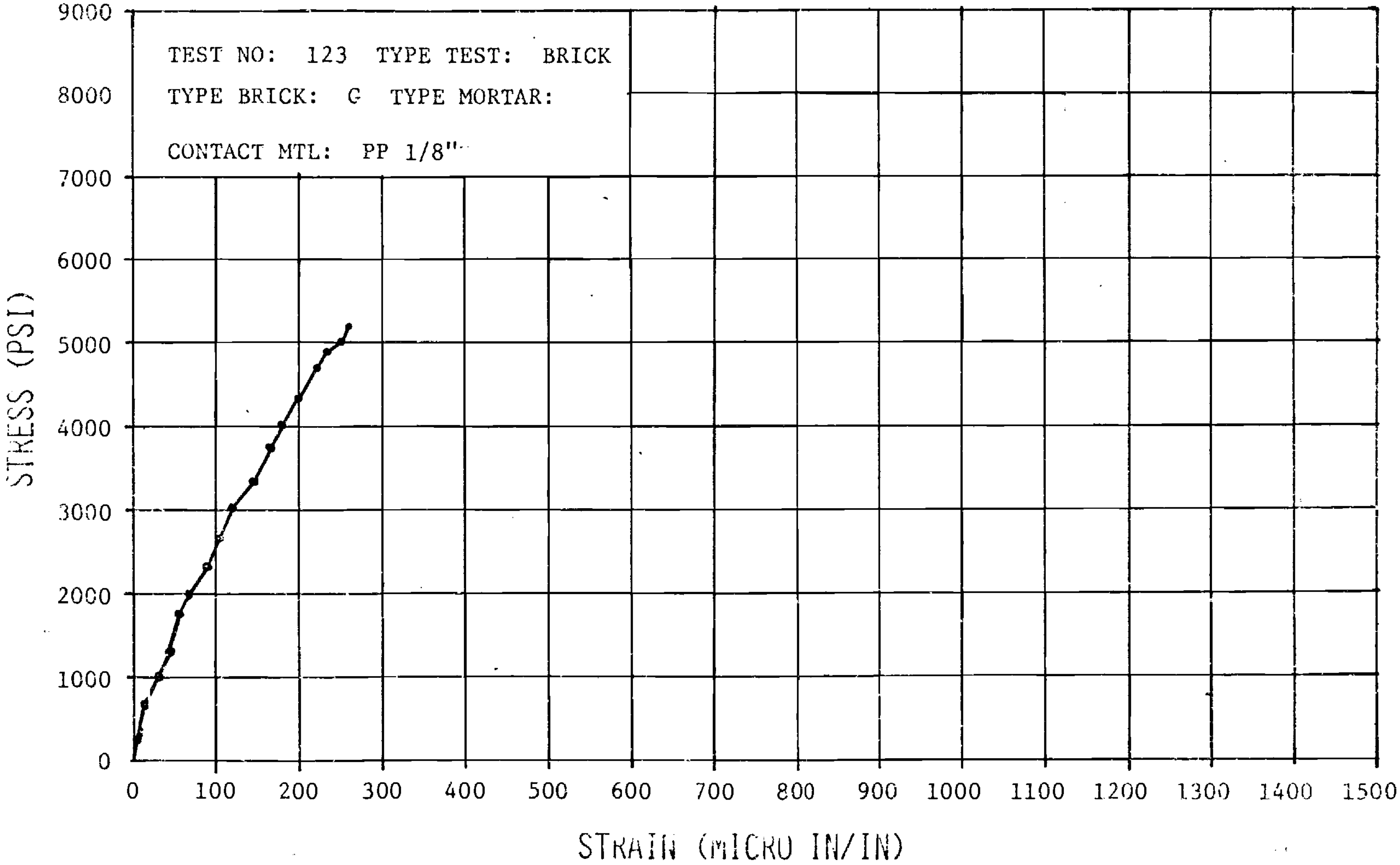


Fig. No. C4 Compressive Stress - Lateral Strain Type G
Brick and 1/8 PP Contact Material

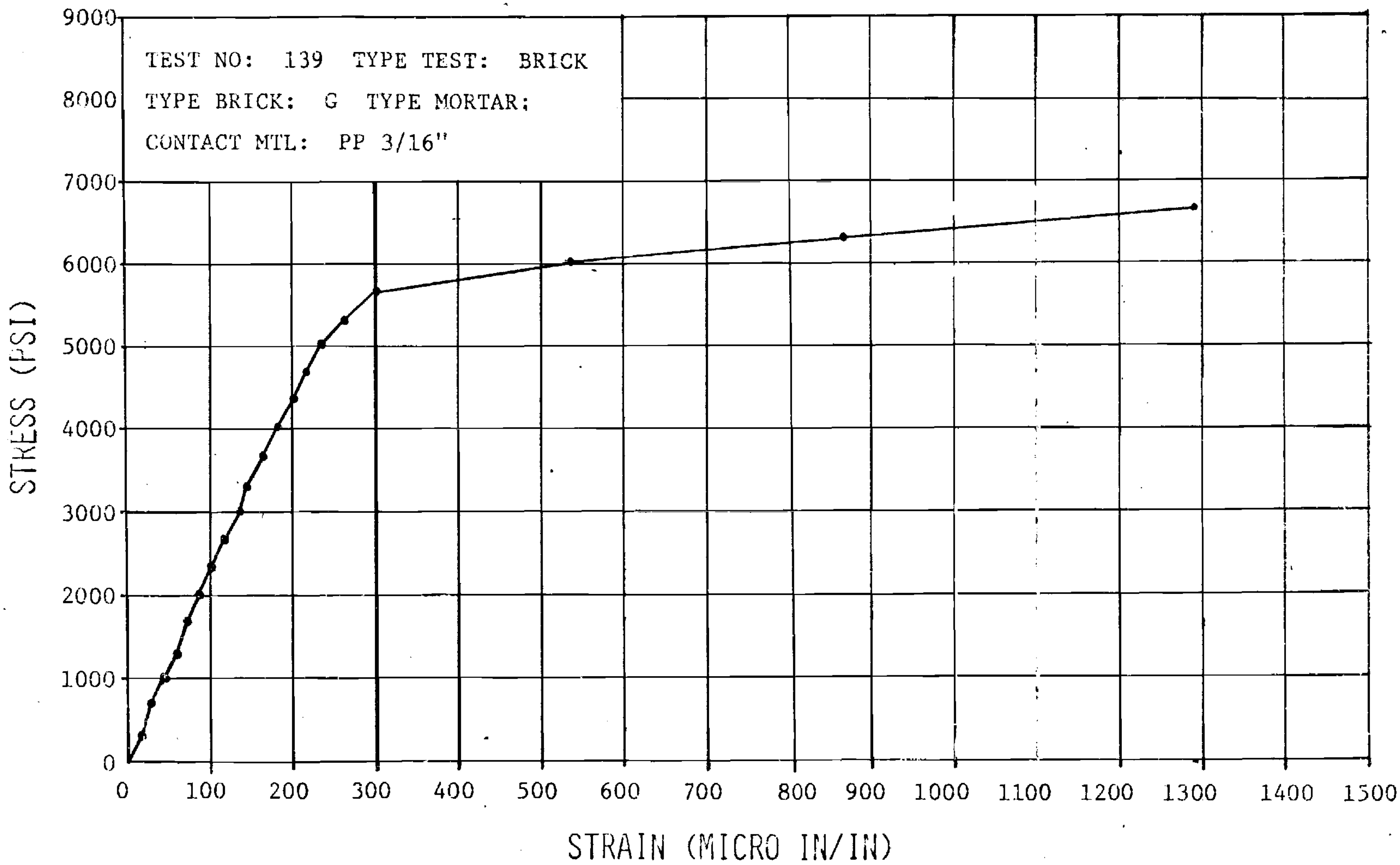


Fig. No. C5 Compressive Stress - Lateral Strain Type G Brick and 3/16 PP Contact Material

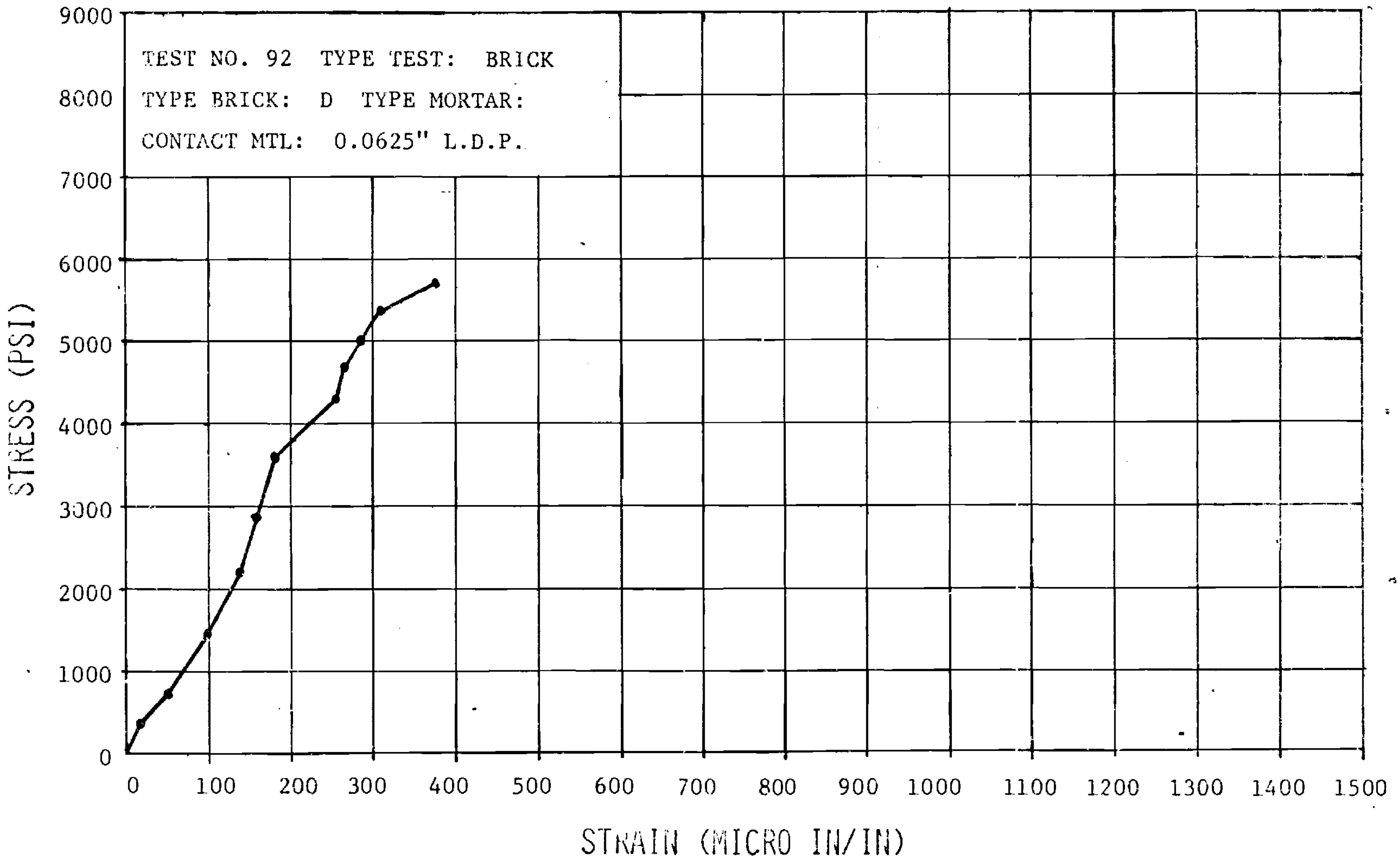


Fig. No. C6 Compressive Stress - Lateral Strain Type D Brick and 1/16 LDP Contact Material

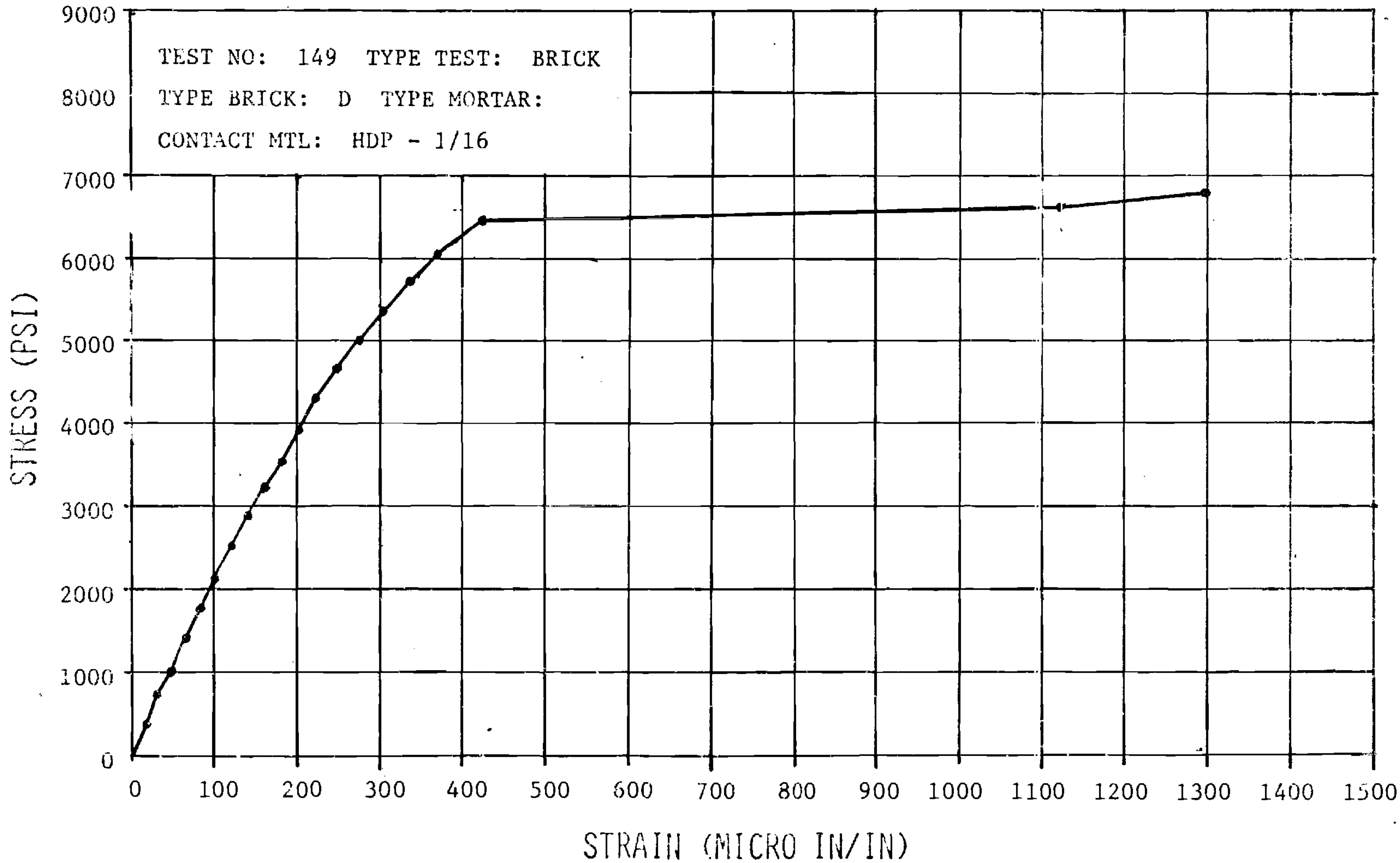


Fig. No. C7 Compressive Stress - Lateral Strain Type D
Brick and 1/16 HDP Contact Material

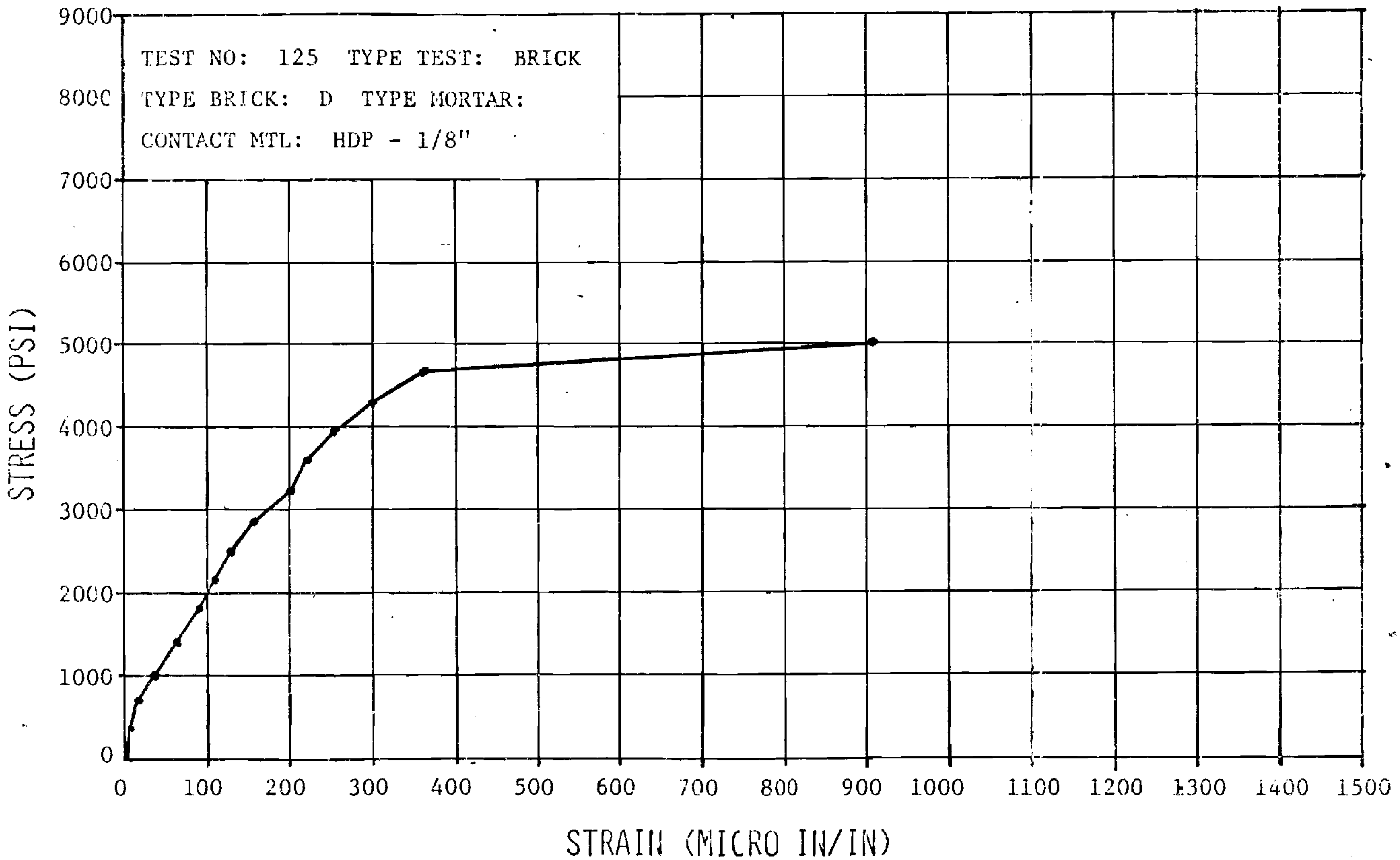


Fig. No. C8 Compressive Stress - Lateral Strain Type D Brick and 1/8 HDP Contact Material

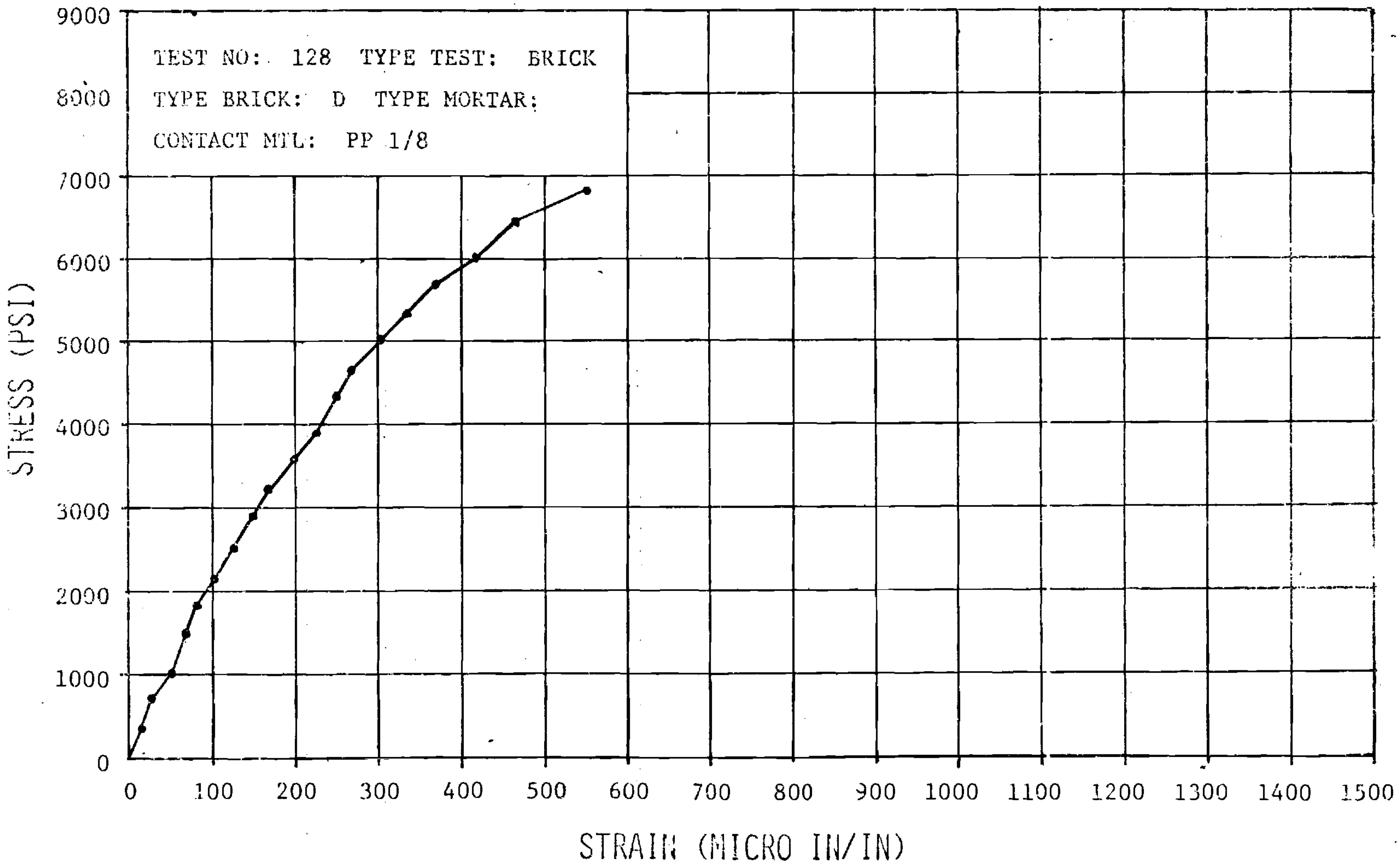


Fig. No. C9 Compressive Stress - Lateral Strain Type D
Brick and 1/8 PP Contact Material

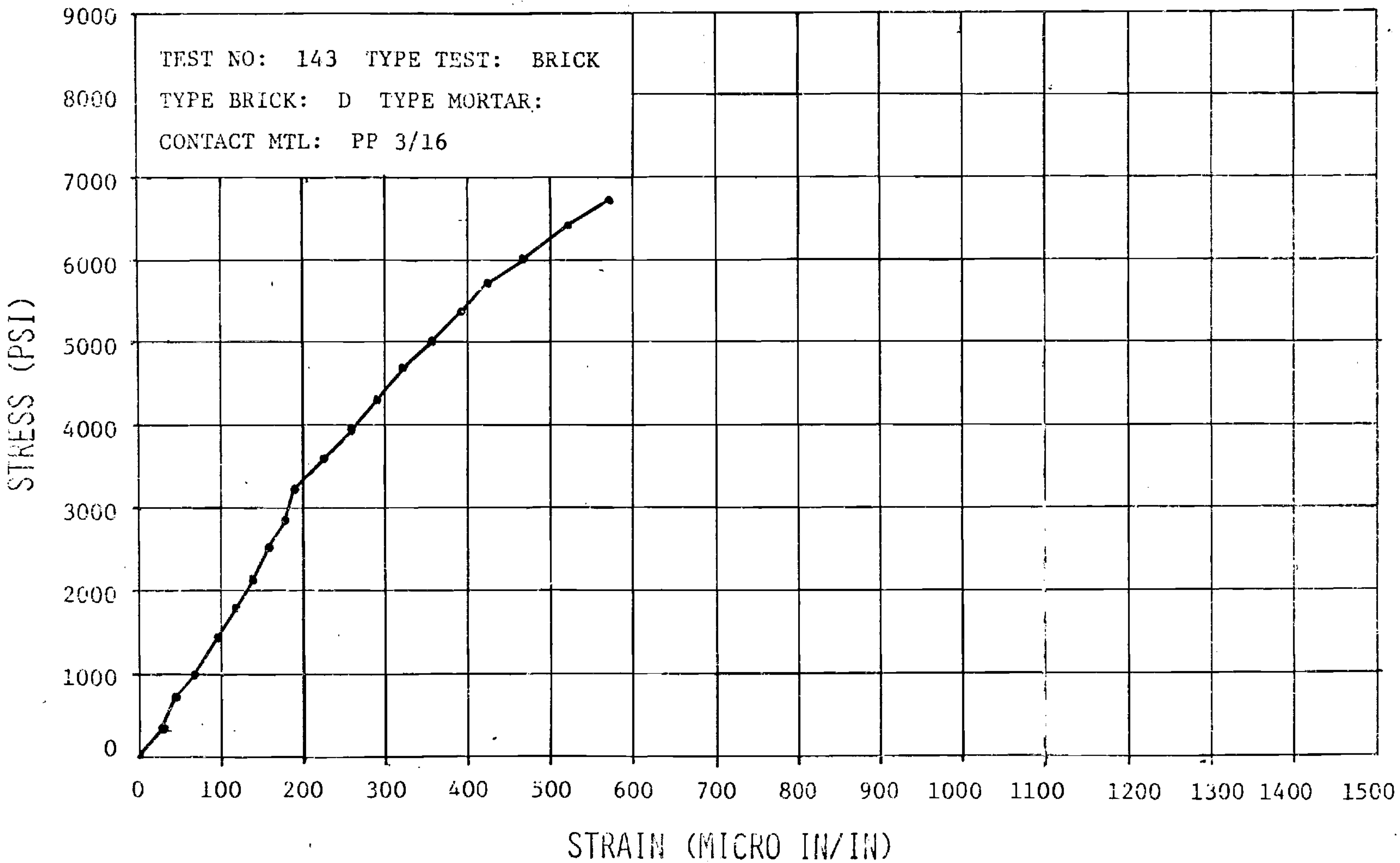


Fig. No. C10 Compressive Stress - Lateral Strain Type D Brick and 3/16 PP Contact Material

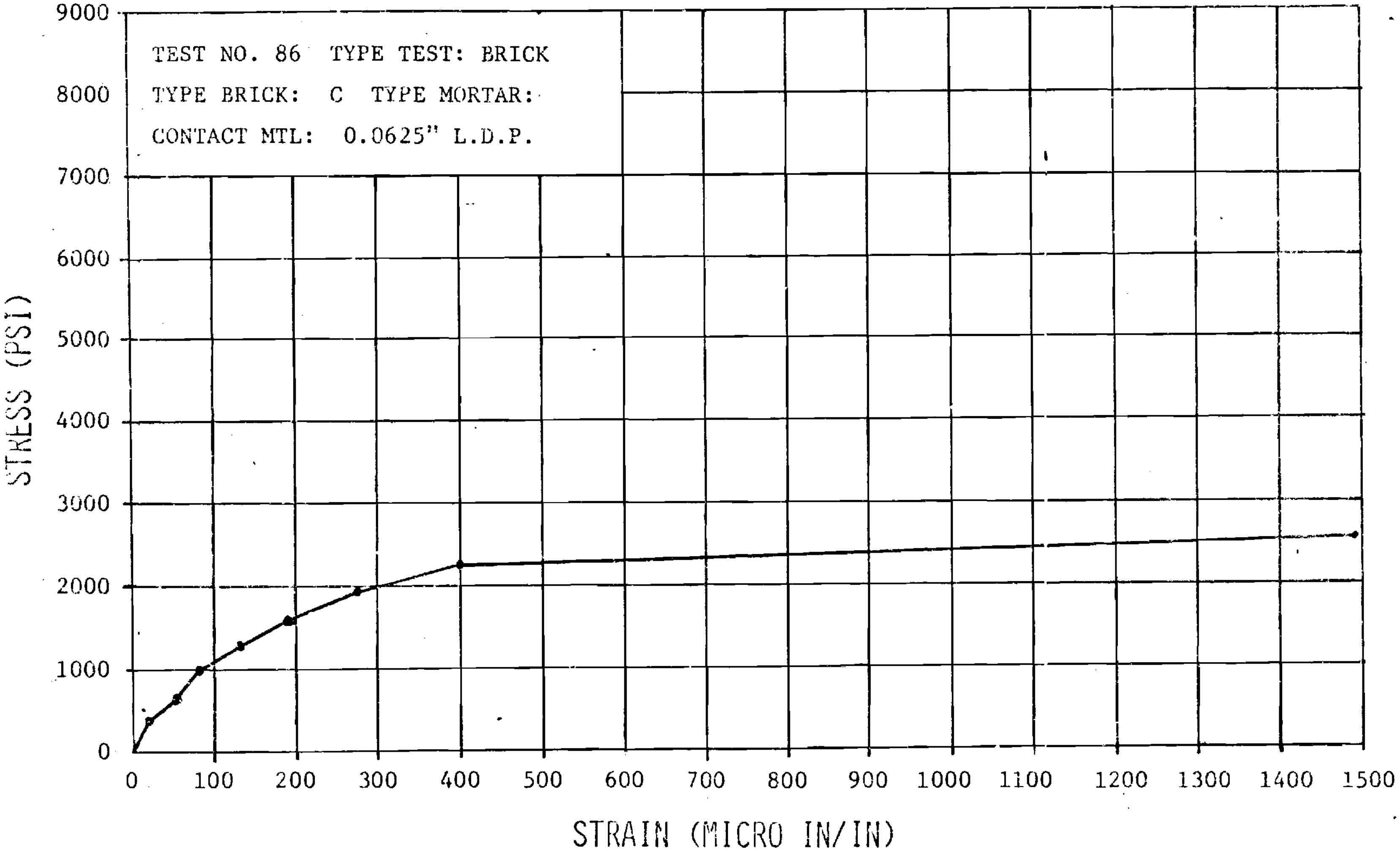


Fig. No. C11 Compressive Stress - Lateral Strain Type C Brick and 1/16 LDP Contact Material

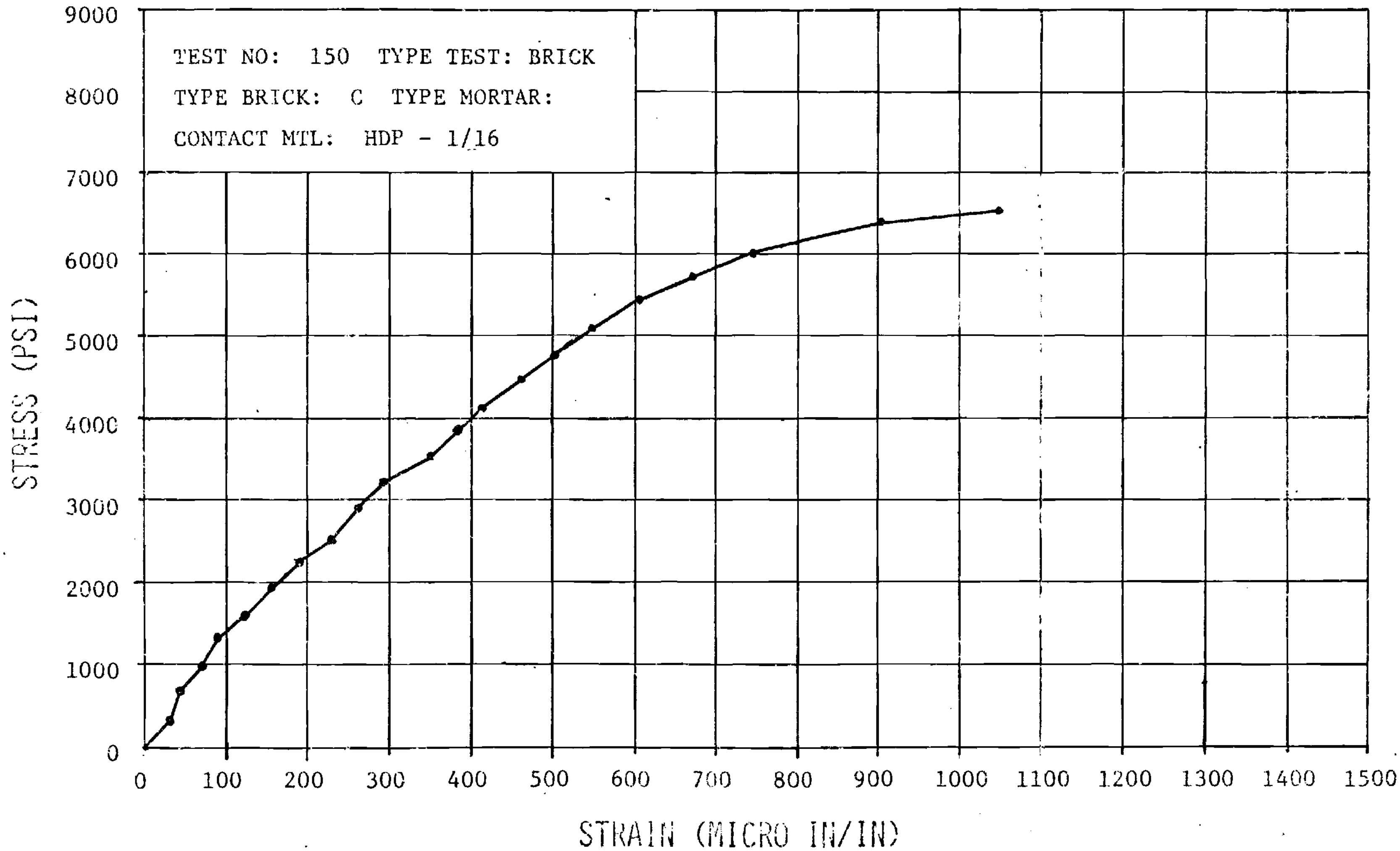


Fig. No. C12 Compressive Stress - Lateral Strain Type C
Brick and 1/16 HDP Contact Material

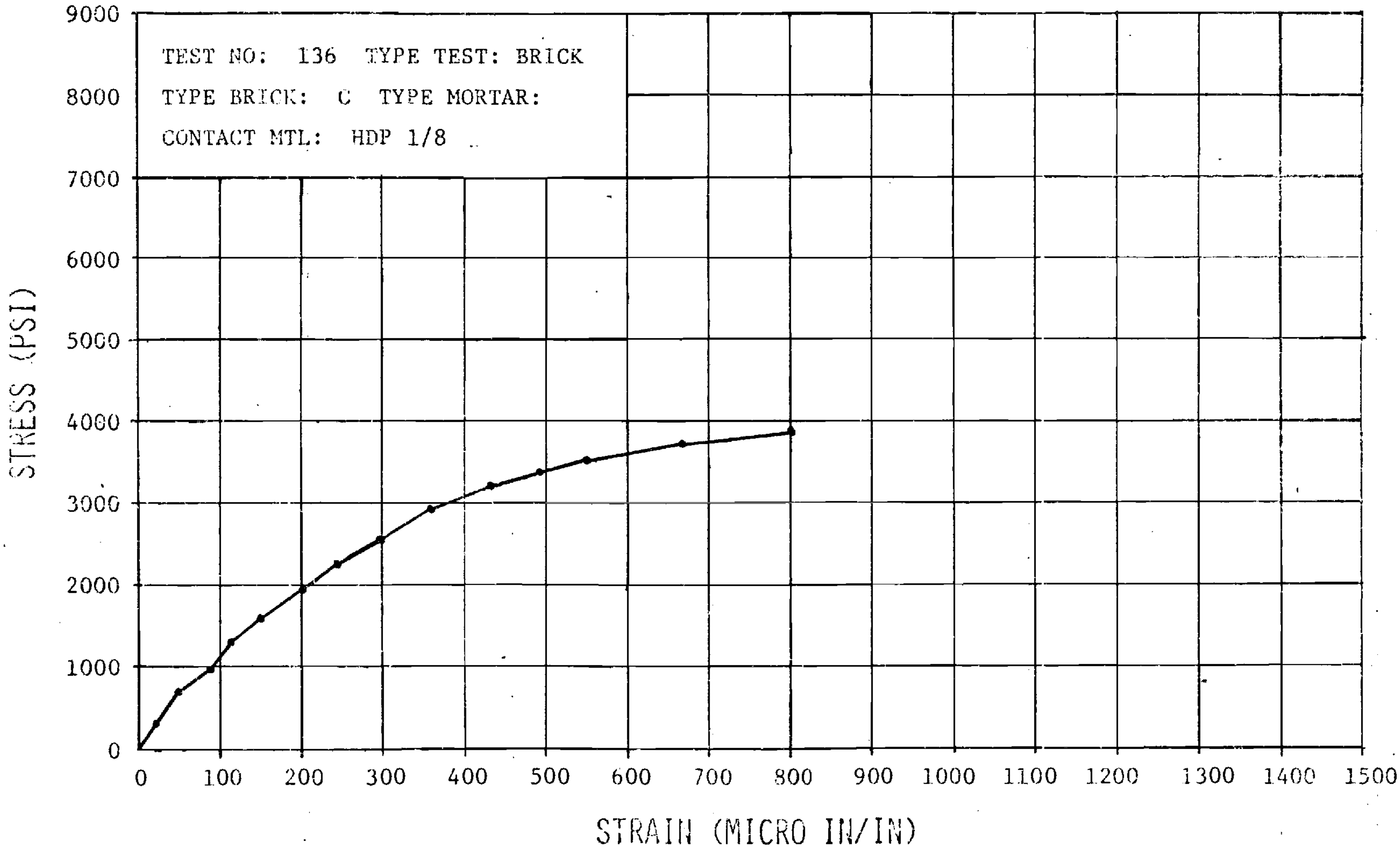


Fig. No. C13 Compressive Stress - Lateral Strain Type C
Brick and 1/8 HDP Contact Material

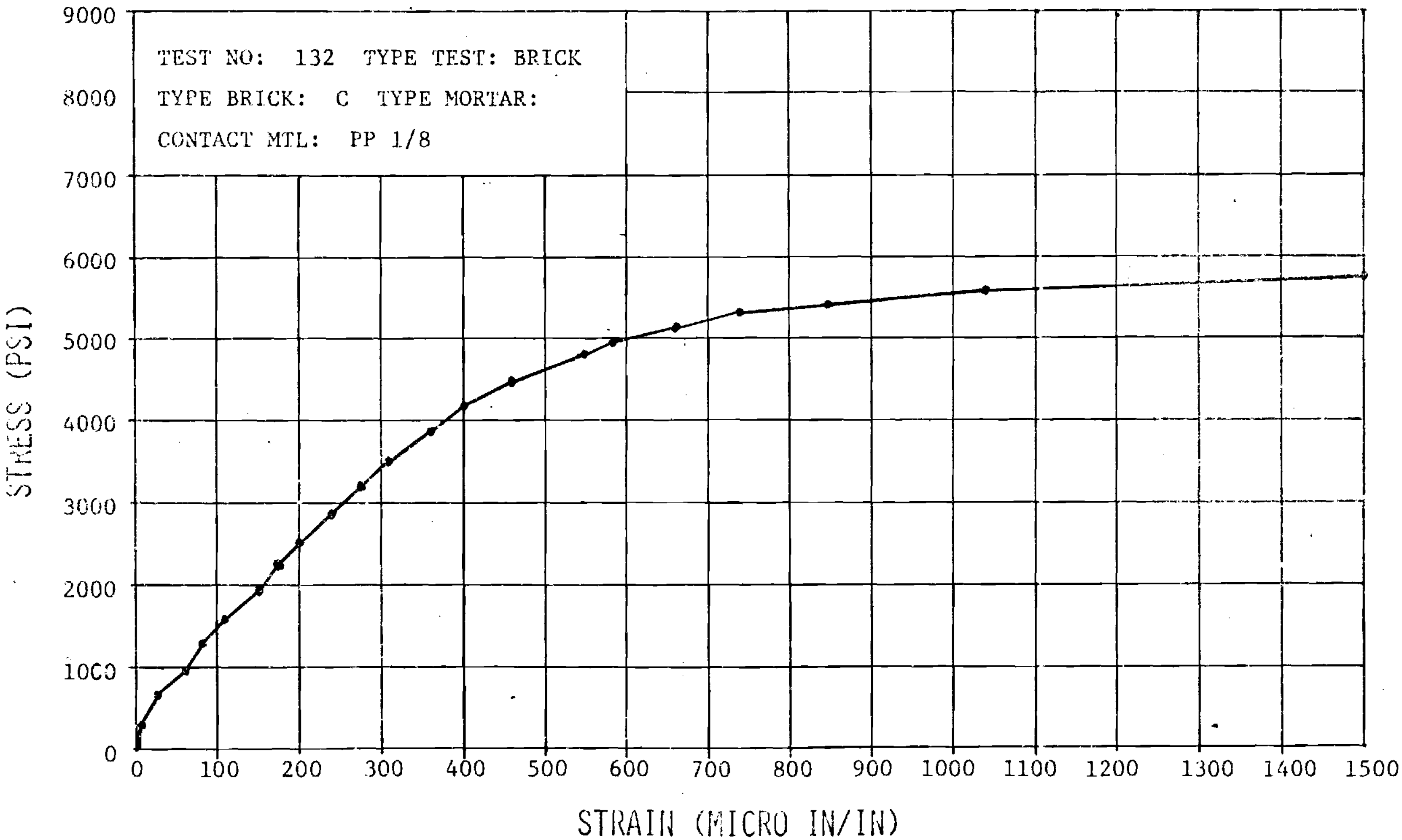


Fig. No. C14 Compressive Stress - Lateral Strain Type C
Brick and 1/8 PP Contact Material

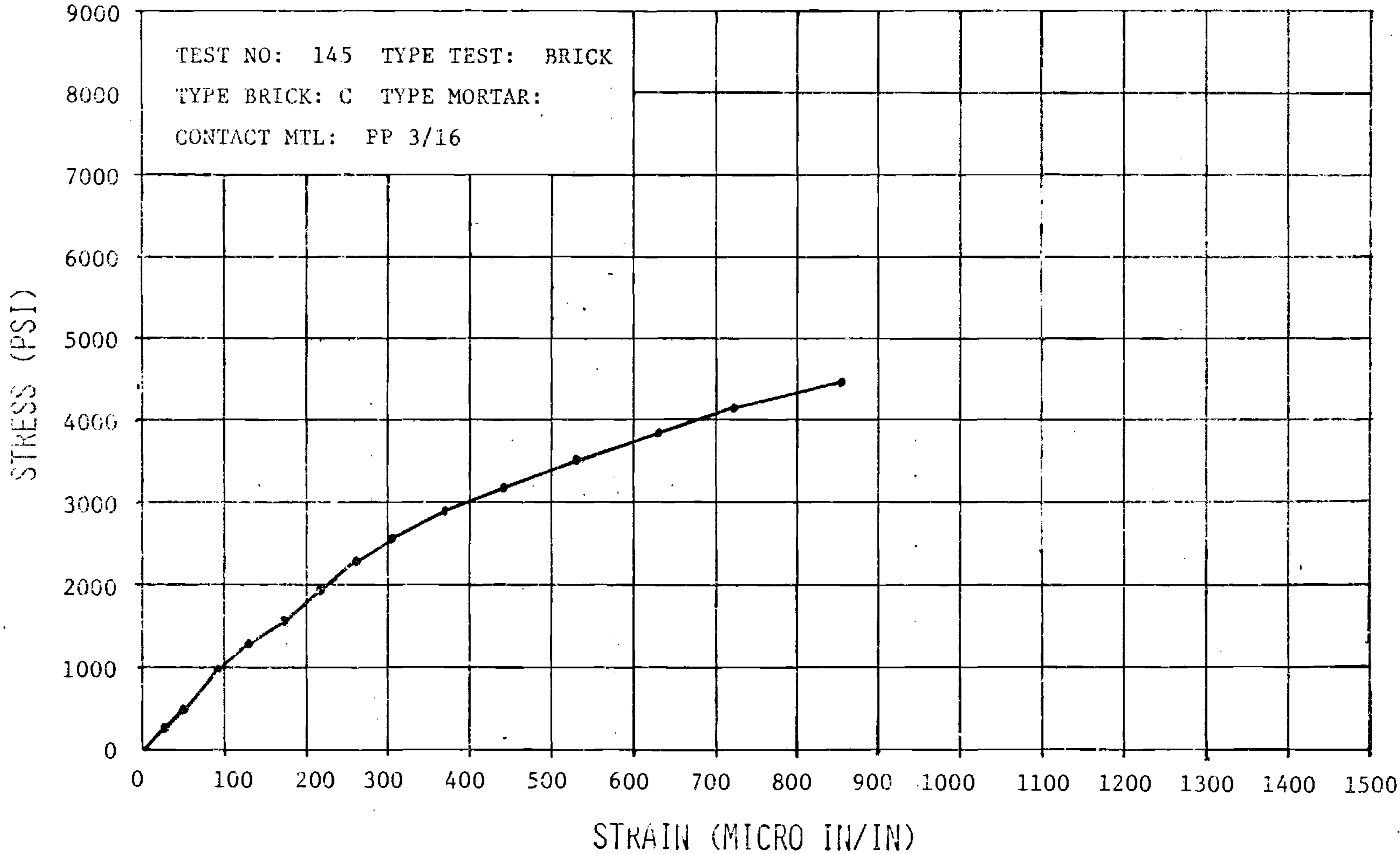


Fig. No. C15 Compressive Stress - Lateral Strain Type C
Brick and 3/16 PP Contact Material

APPENDIX D

Stress-Strain Curves for Brick Cylinders

The following curve represents vertical and horizontal strains from 7/8 inch diameter cores, 1 3/4 inches in height taken from each type of brick. Modulus of elasticity was obtained from the slope of the line corresponding to vertical strain. Poisson's ratio is the ratio of horizontal to vertical strain.

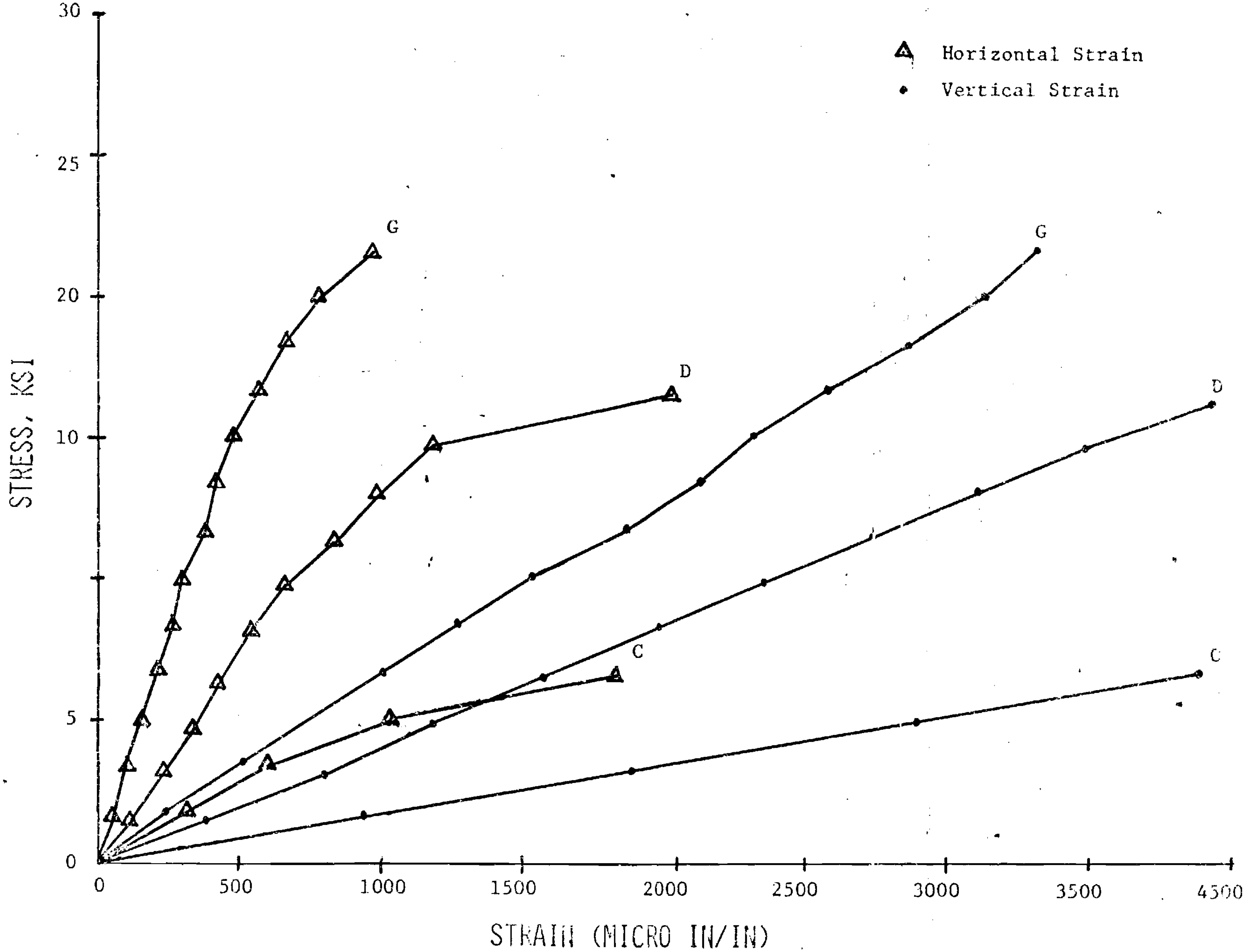


Fig. D1, Stress - Strain Curves For Brick Cylinders

APPENDIX E

Triaxial Strength of Brick

The following graph represents data from triaxial tests of 7/8 inch diameter cylinders, 1 3/4 inches in height. Cylinders cored from two of each type of brick were tested. The data point for type G brick, sample 1 (G1) under a confining pressure of 4 ksi was probably faulty and hence is illustrated with a dashed line.

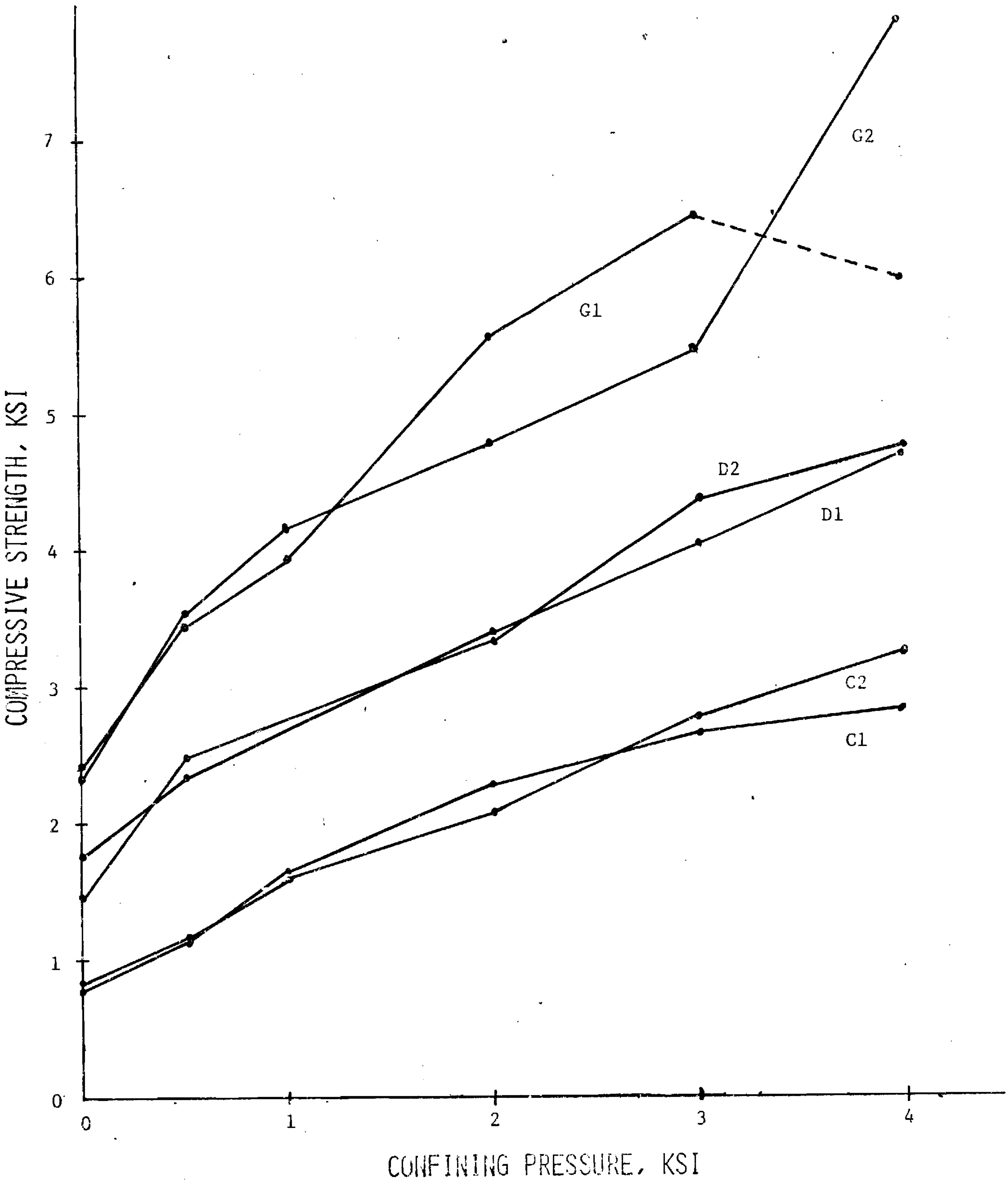


Fig. F1, Compressive Strength vs Confining Pressure for Brick Cylinders