CYCLIC LOADING OF EXTERNALLY REINFORCED MASONRY WALLS CONFINED BY FRAMES

W.K. Tso[1], A. Rutenberg[2] and A.C. Heidebrecht[3]

SUMMARY

Experimental results are presented on three externally reinforced concrete block walls subjected to in-plane cyclic lateral loading, the walls being confined by flexible steel frames. All three specimens were of similar construction, the varying parameter being the steel reinforcement ratio in the outer skins. The load deflection curves, stiffness degradation characteristics, energy absorption capacity as well as axial stress in the confining frame columns are discussed. The externally reinforced walls held their integrity even under a large number of cycles of reversed load. In this respect, externally reinforced masonry behaves under cyclic loading at least as well as internally reinforced masonry. It is concluded that changes in steel reinforcement ratios do not materially affect the failure load although this ratio may have an important effect on the stiffness degradation and the energy absorption capacity of the assembly. The evaluation of the axial forces in the columns on the basis of the truss analogy appears to be substantiated by the test results.

---

1) Associate Professor, Department of Civil Engineering and Engineering Mechanics, McMaster University, Hamilton, Ontario Canada.

2) Visiting Associate Professor, Department of Civil Engineering and Engineering Mechanics, McMaster University, Hamilton, Ontario, Canada; on leave from Technion-Israel Institute of Technology, Haifa, Israel.

3) Professor, Department of Civil Engineering and Engineering Mechanics, McMaster University, Hamilton, Ontario, Canada.

INTRODUCTION

As a result of poor earthquake resistance of unreinforced masonry structures, only reinforced masonry is recommended for use in active seismic regions. Whereas new structures can be designed to be either internally or externally reinforced, the former is impracticable for repairing walls already damaged by an earthquake, or strengthening walls of existing buildings. The purpose of this paper is to investigate the behaviour of externally reinforced masonry structures of a particular type, namely, walls confined by steel frames. The behaviour of damaged in-filled frames repaired by means of external reinforcement was reported elsewhere [1], and the present paper focuses on newly built panels.

Experimental results on three panels of externally reinforced concrete blocks subjected to in-plane cyclic lateral loading are reported. The adequacy of the system is evaluated on the basis of ductility, stiffness degradation characteristics, energy absorption and overall damage pattern. To evaluate the influence of the frame, the axial forces in the columns of the steel frame method were calculated by means of the truss analogy [2].

TEST ARRANGEMENT

Each test specimen was an approximately half-scale representation of a single storey wall. The dimensions of the specimens were 6' 8" long and 4' 8" high, constructed using 6" x 8" x 16" hollow concrete blocks, with an average strength of 1200 psi based on gross area. The walls were externally reinforced with a welded steel wire fabric (varying in weight with each specimen) and bonded to each side of the block wall by means of one inch thick layer of 1:3 sand-cement mortar applied in two coats. In addition seven 1/4" diameter bolts with 2" x 2" x 1/8" plates welded to their ends were driven through the joints of the blocks further to improve bonding. The relevant data for the mortar and steel reinforcement is given in Table I. The steel frame consisted of four 8" x 8" column I-sections welded together, with slits cut along the webs of the frame columns to increase their flexibility. The frame was anchored to a steel beam which, in turn, was rigidly attached to the test floor. The load was applied by means of a hydraulic jack acting horizontally on the upper corner of the frame. The jack was actuated by means of a M.T.S. servo-controlled hydraulic system capable of push-pull acting to provide the cyclic load function. Stroke displacement was the controlling parameter in all tests. Mechanical dial gauges were used to measure deflections at various points of the system. In order to evaluate the participation of the steel frame in the composite action of the panel, eight foil-type resistive strain gauges were placed vertically at mid-height of each column. The general test set up is shown in Fig. 1.

In each test the specimen was subjected to several cycles of reverse loading. The load-displacement curve for each cycle was measured and the axial strains in the strain gauges were recorded. In addition, the damage pattern was observed. The energy absorption per cycle and the secant stiffness of the panel were deduced from the load-displacement curve. The axial forces in the columns were determined from the strain measurements and the stresses in the compressed diagonals of the masonry panel were computed.

EXPERIMENTAL RESULTS

The load-displacement curves for the final cycles of the three specimens are shown in Fig. 2, Fig. 3 and Fig. 4. A lateral force of 108 kip was reached after 16 cycles in specimen A, and after 17 cycles in specimen C; a force of 114 kip after 17 cycles was reached for specimen B. All specimens suffered a substantial loss in stiffness with increasing cycle displacement. This can be seen in Fig. 5, Fig. 6 and Fig. 7 in which the secant stiffness for increasing and decreasing loads are defined. Panels A and B which were more heavily reinforced suffered less than panel C whose stiffness was degrading at a much faster rate. Also there was a slight stiffness degradation for repeated cycles in which the displacement was kept the same as in the previous cycle. The energy absorption capacity of each of the three specimens is given in Fig. 8, Fig. 9 and Fig. 10 respectively, and it can be seen that for panels A and B there is an increase of energy absorption per cycle as the cycle displacement increases. However, subsequent cycles of similar displacements tended to give a lower value of energy absorption capacity. The behaviour of panel C was quite different. There was a marked loss of energy absorption capacity per cycle for displacements larger than 0.45" corresponding to an angle of rotation = 0.43°. On the whole the behaviour of panels A and B was in line with a previous experiment [1], whereas panel C showed a marked deterioration in terms of stiffness and energy absorption. The main observed damage of the three specimens consisted of long cracks along the compressed diagonals of the reinforcing mortar skins, loss of bond between the skins and the blocks and local crushing of the skin and the blocks at compressed corners. The removal of the two reinforcing skins revealed cracking of some blocks, and of mortar along vertical and horizontal joints. Internal vertical cracks in many blocks were also observed. The observations reported in [1] regarding the out-of-plane strength and stiffness of the damaged panels were substantiated in the present series of tests: all three panels were capable of resisting a concentrated load of 10 kips after they had been damaged by a large number of cycles of in-plane loading.

For all specimens the axial forces in the tensioned columns of the frames as based on the measured axial strains, were found to be in good agreement at all load levels with the truss analogy for in-filled frames [2]. This can be seen in Fig. 11. At maximum load, the computed axial strains in the compressed diagonals of the panel ranged between 0.0022 and 0.0033.

Further, from the forces calculated using the truss analogy, the stress along the compressed diagonals was found to be about 850 psi, based on an equivalent strut width of 20% the length of the diagonal [3]. To obtain this stress value, the gross area of the strut was taken.

CONCLUSIONS

From the measured and observed behaviour of the three test specimens, the following conclusions may be drawn: (i) externally reinforced block wall construction is a viable method of reinforcing masonry walls. It strengthens the walls and increases its resistance to cyclic loading; (ii) the ultimate load does not appear to be strongly dependent on the steel ratio in the reinforcing skins; (iii) degradation of stiffness and energy absorption capacity may depend on the steel reinforcement ratio; (iv) the analysis of externally reinforced block wall panels with flexible confining frames may be based on the truss approximation for in-filled frames; (v) the out-of-plane behaviour of damaged walls appears to be satisfactory in view of the large ratio of the failure load to the dead weight of the panel. Therefore, the danger of fall-out of debris commonly associated with unreinforced masonry after reverse loading is unlikely.

It appears that externally reinforced block walls behave to some extent like sandwich panels. The external reinforcing layers are the stressed skins of the panels resisting most of the in-plane lateral loading. Yet, the effectiveness of this arrangement to resist combined vertical and lateral loads, with or without a confining frame remains to be investigated.

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of the National Research Council of Canada for a research program in earthquake engineering at McMaster University. The material presented above forms a part of the investigation under this program. The donation of masonry blocks by J. Cooke Ltd. of Burlington is gratefully acknowledged.

REFERENCES

1. Tso, W.K., Pollner, E., and Heidebrecht, A.C., "Cyclic Loading on Externally Reinforced Masonry Walls", Paper No. 144, Proceedings 5th World Conference on Earthquake Engineering, Rome, 1973.

2. Polyakov, S.V., "On the Interaction Between Masonry Filler Walls and Enclosing Frame When Loaded in the Plane of the Wall", Translations in Earthquake Engineering, Earthquake Engineering Research Institute, San Francisco, 1960, p. 36.

3. Stafford-Smith, B., "Lateral Stiffness of In-filled Frames", Journal of the Structural Division, ASCE, Vol. 88, ST6, 1962, p. 183.

		SPECIMEN A	SPECIMEN B	SPECIMEN C
Mesh Reinforcement	Spacing & Gauge	6"x6";~6G	4"x4";~9G	6"x6";~10G
	lb/100 sq.ft.	2 x 42	2 x 39	2 x 20
Joint Mortar Strength* (psi)		725	825	1195
Skin Mortar Strength* Coat I (psi)		2000	2040	2110
Skin Mortar Strength* Coat II (psi)		2520	3035	2825

* at 14 days

TABLE I

STEEL REINFORCEMENT DATA AND MORTAR CUBE STRENGTH - SPECIMENS A, B AND C

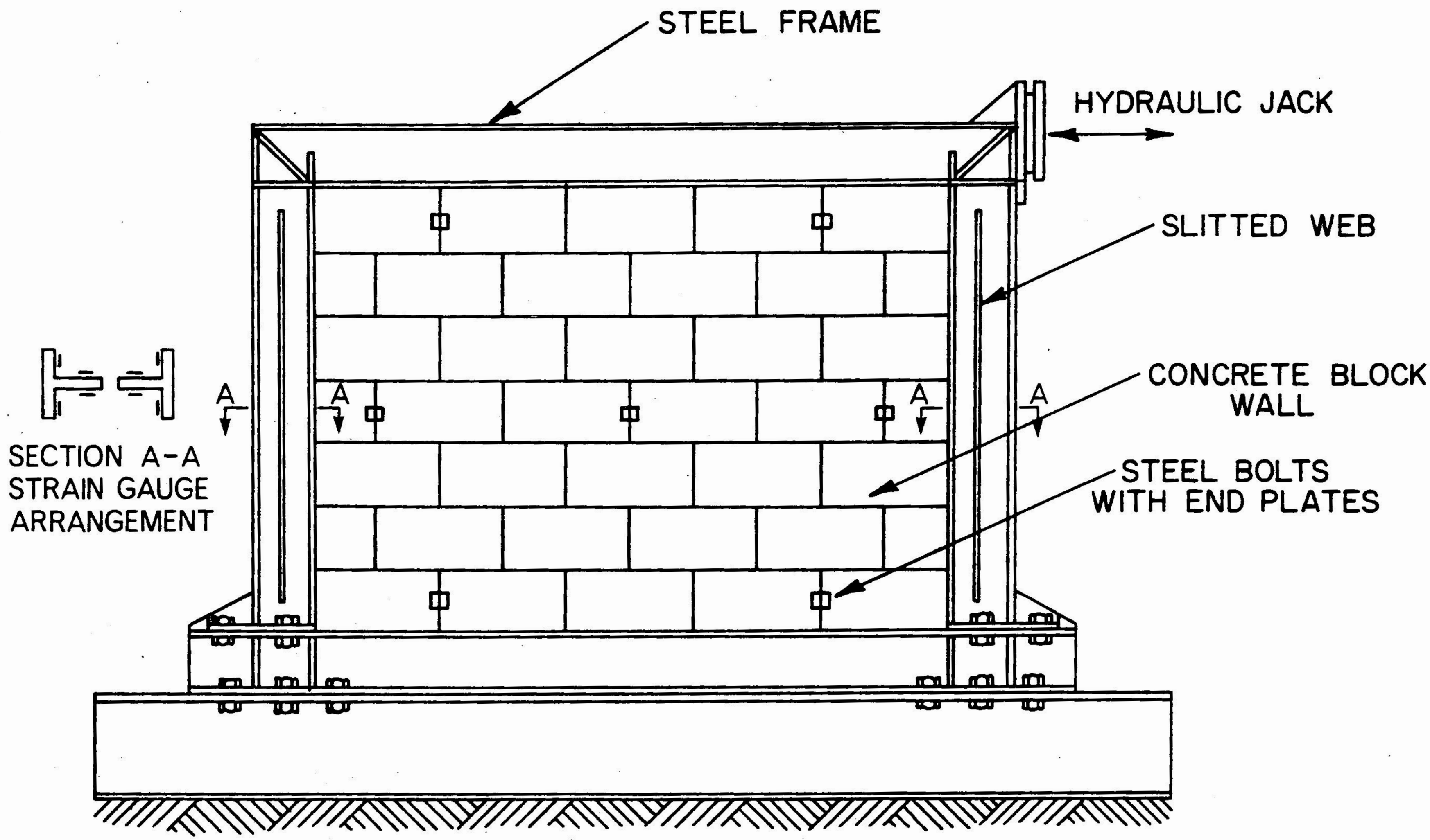

FIG. 1 - TEST SET UP

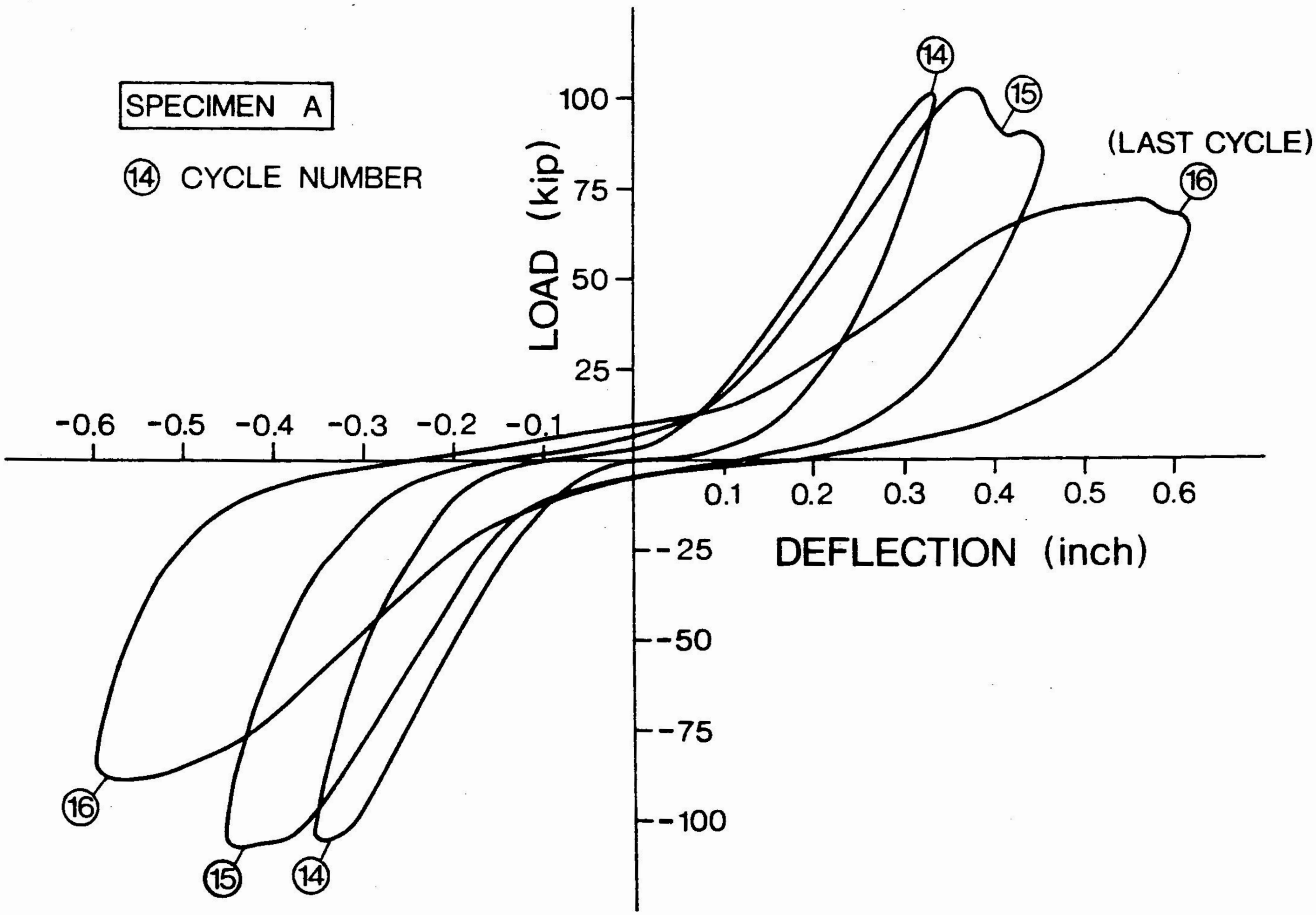

FIG. 2 - LOAD DEFLECTION CURVES - SPECIMEN A

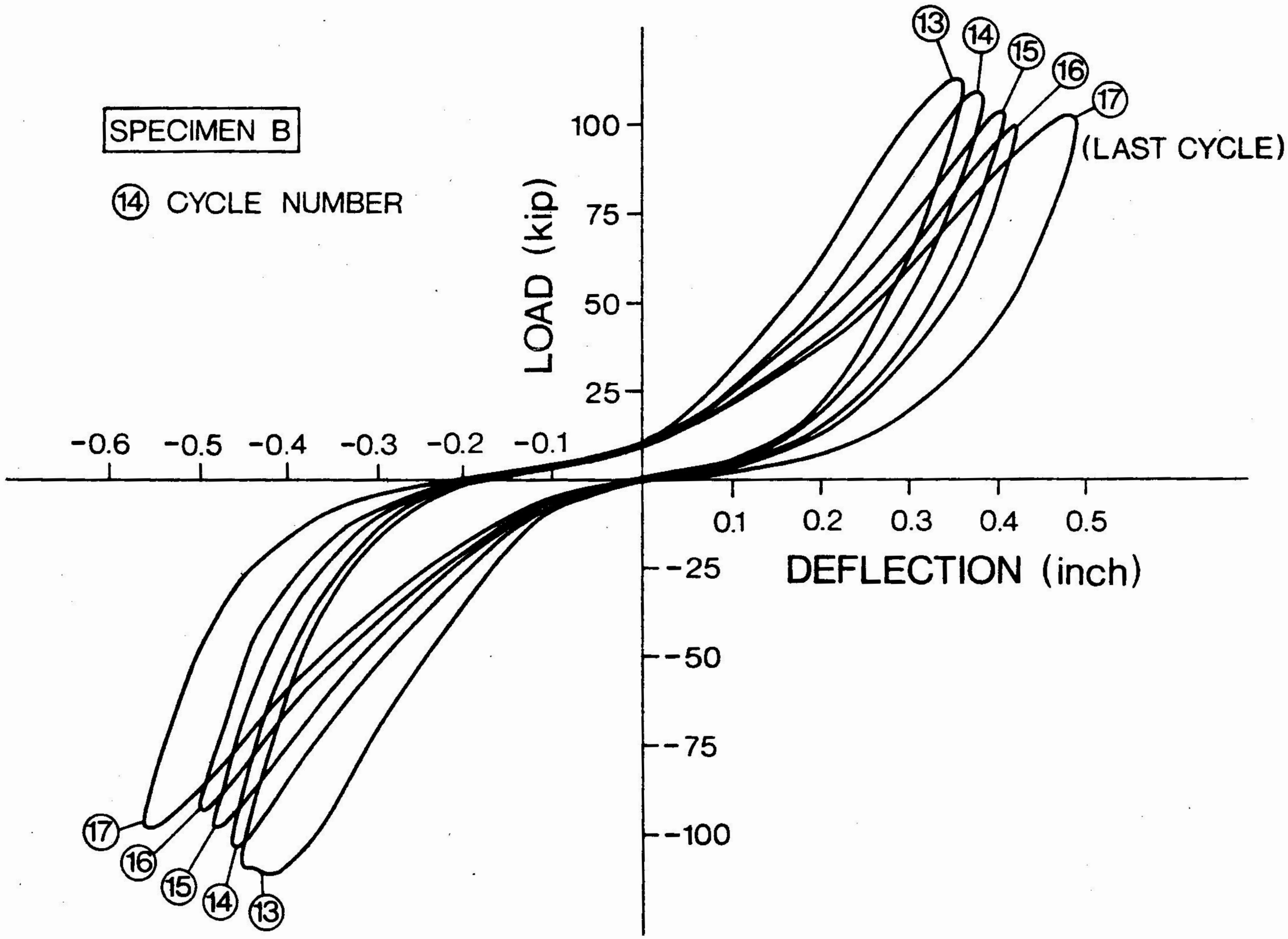

FIG. 3 - LOAD DEFLECTION CURVES - SPECIMEN B

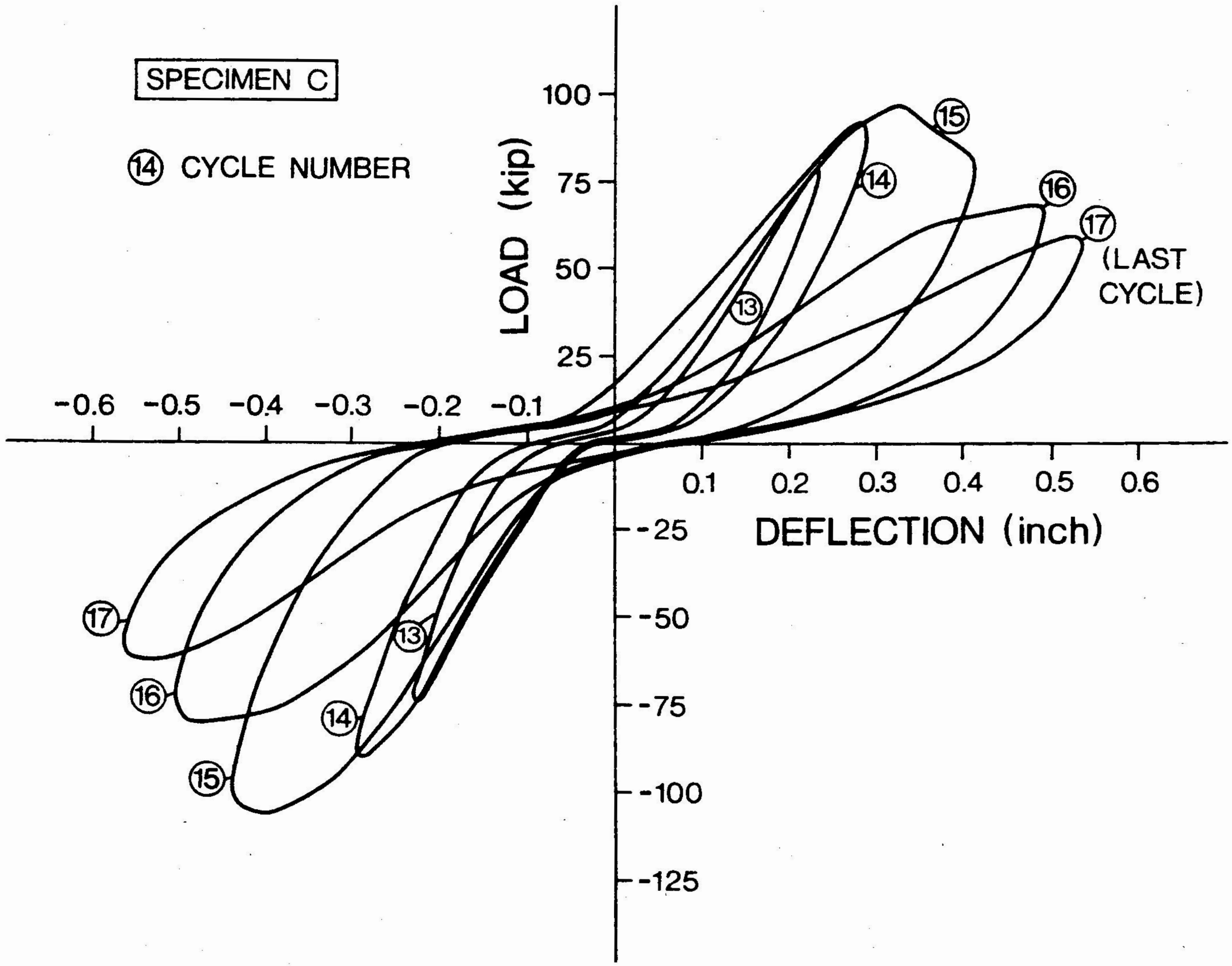

FIG. 4 - LOAD DEFLECTION CURVES - SPECIMEN C

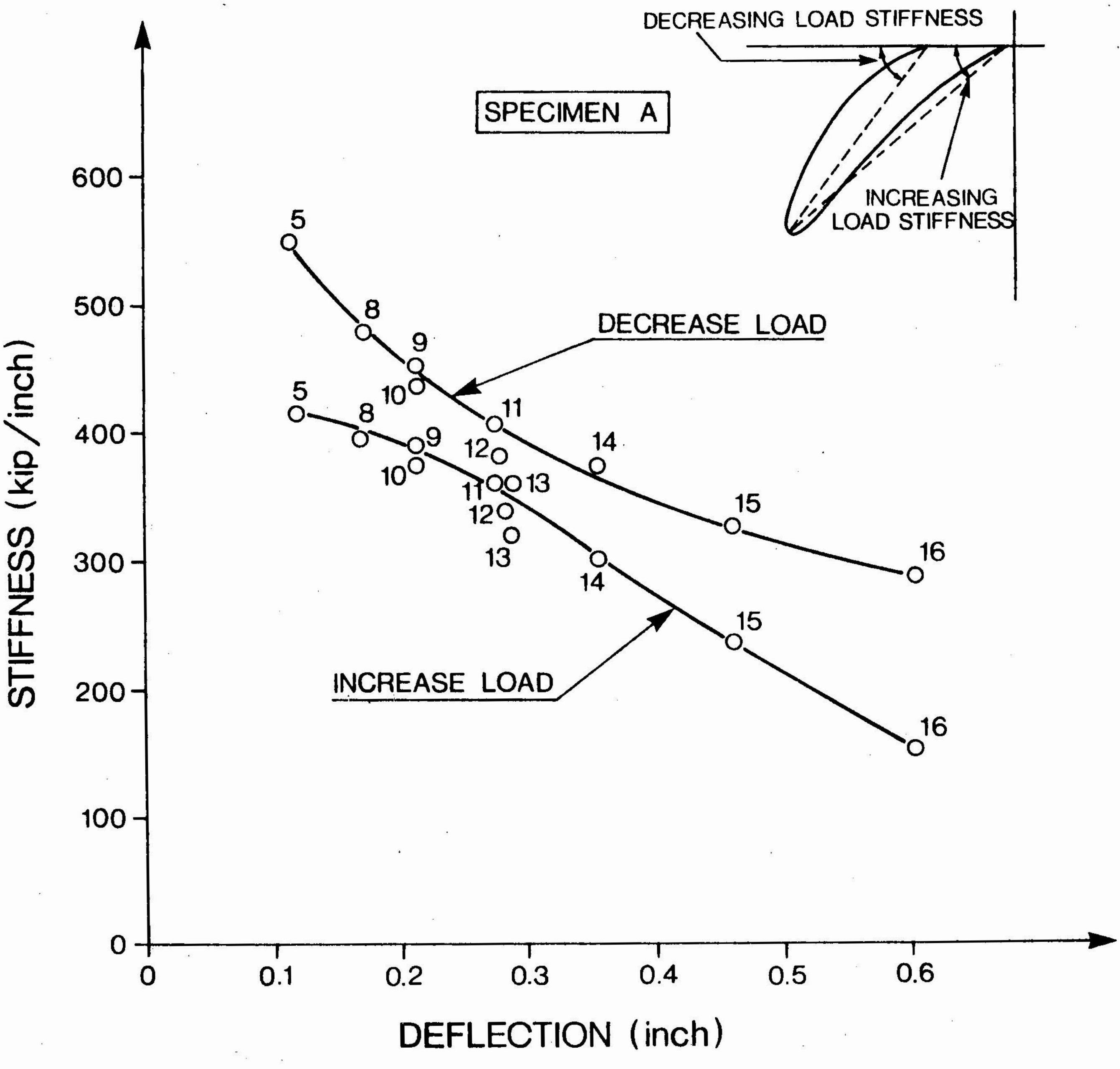

FIG. 5 - STIFFNESS DEGRADATION CURVES - SPECIMEN A

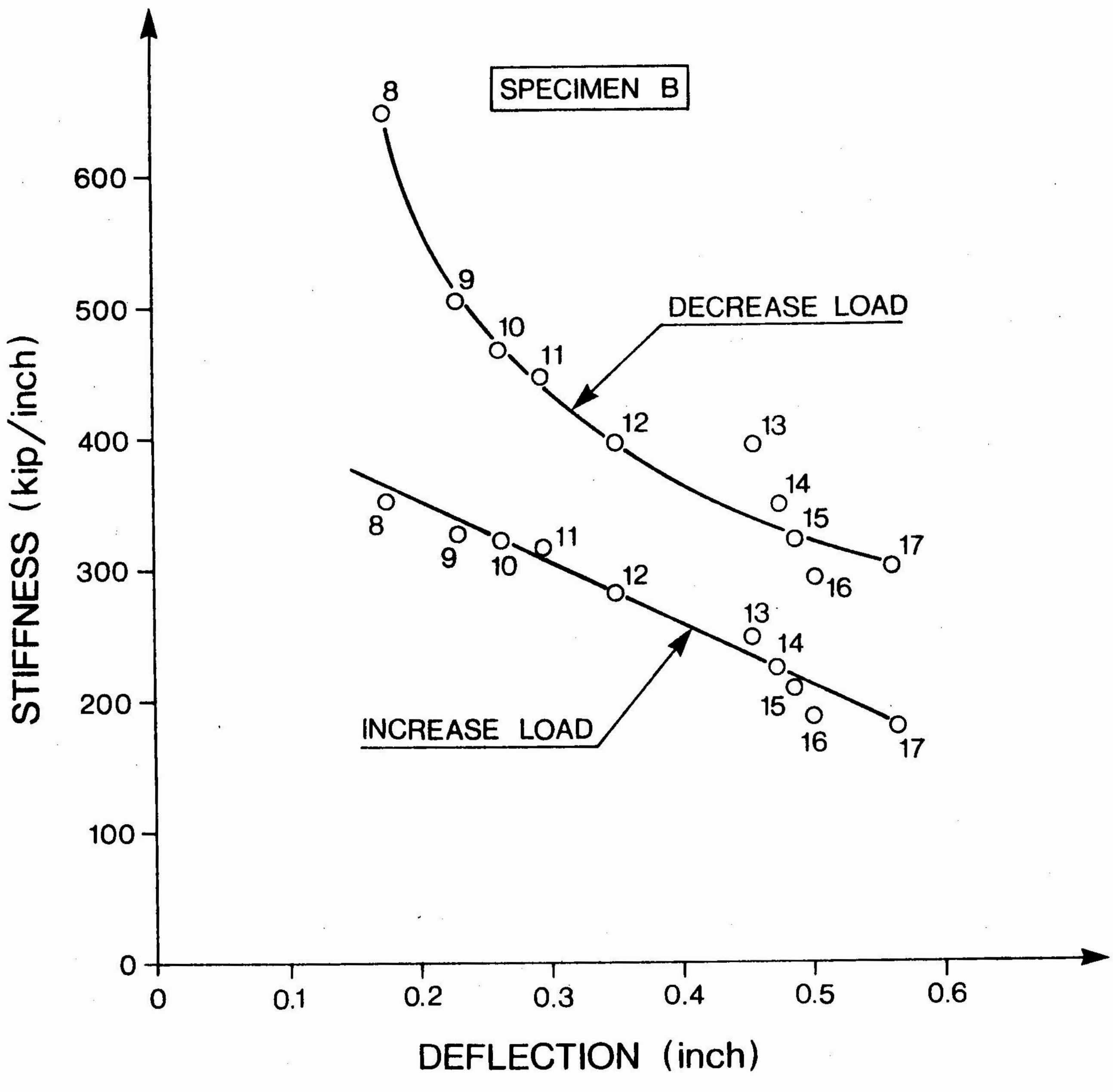

FIG. 6 - STIFFNESS DEGRADATION CURVES - SPECIMEN B

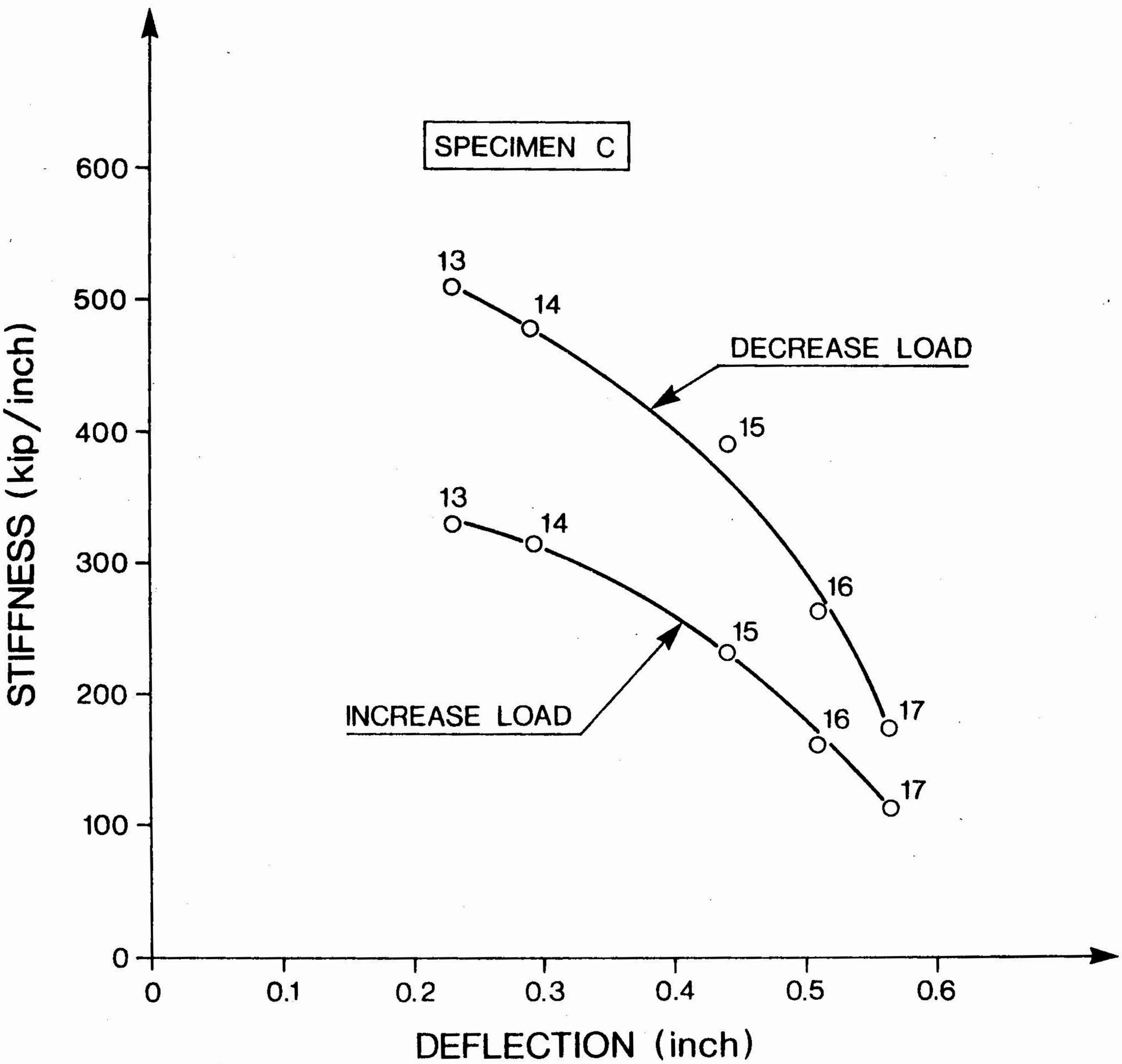

FIG. 7 - STIFFNESS DEGRADATION CURVES - SPECIMEN C

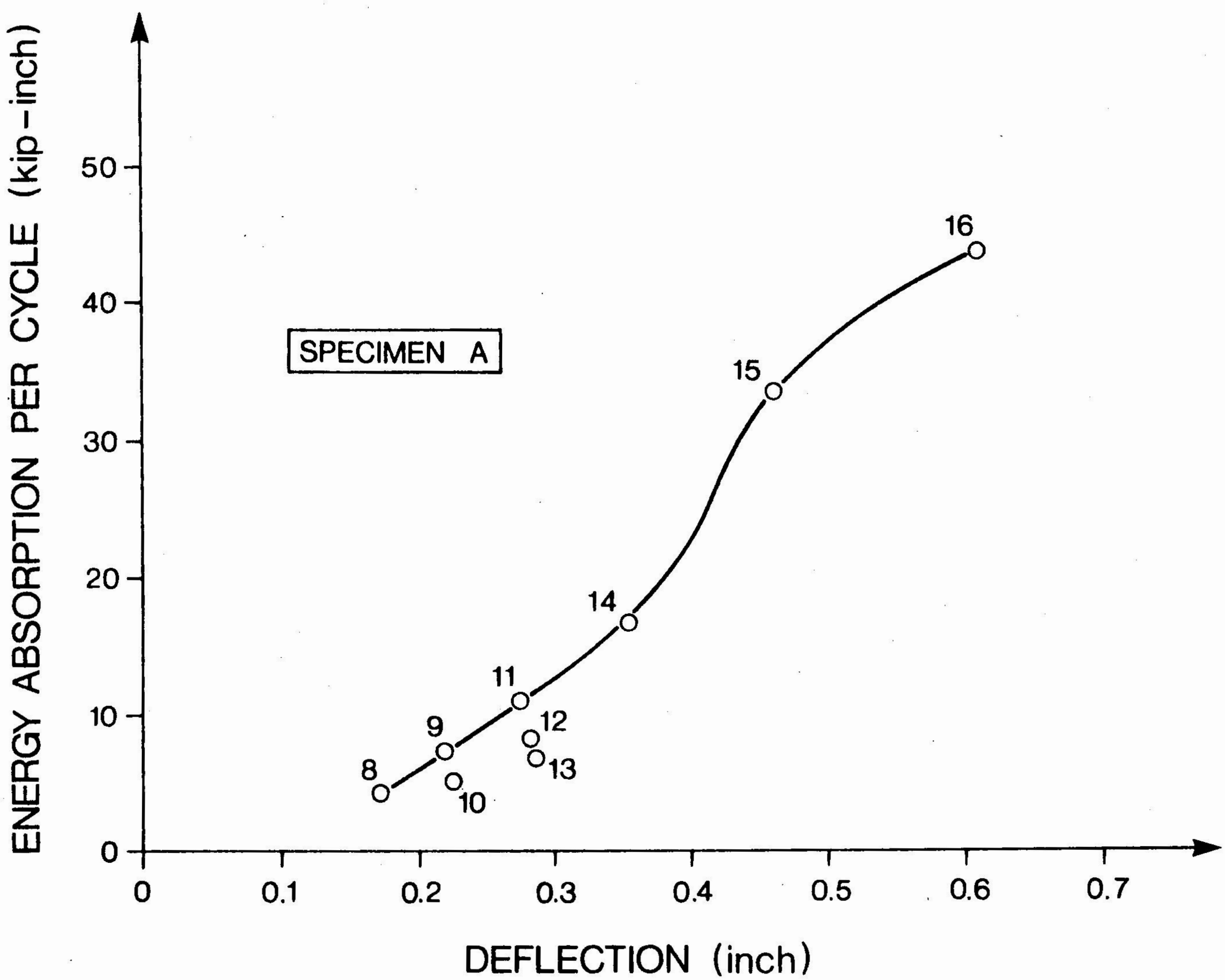

FIG. 8 - ENERGY ABSORPTION CURVE - SPECIMEN A

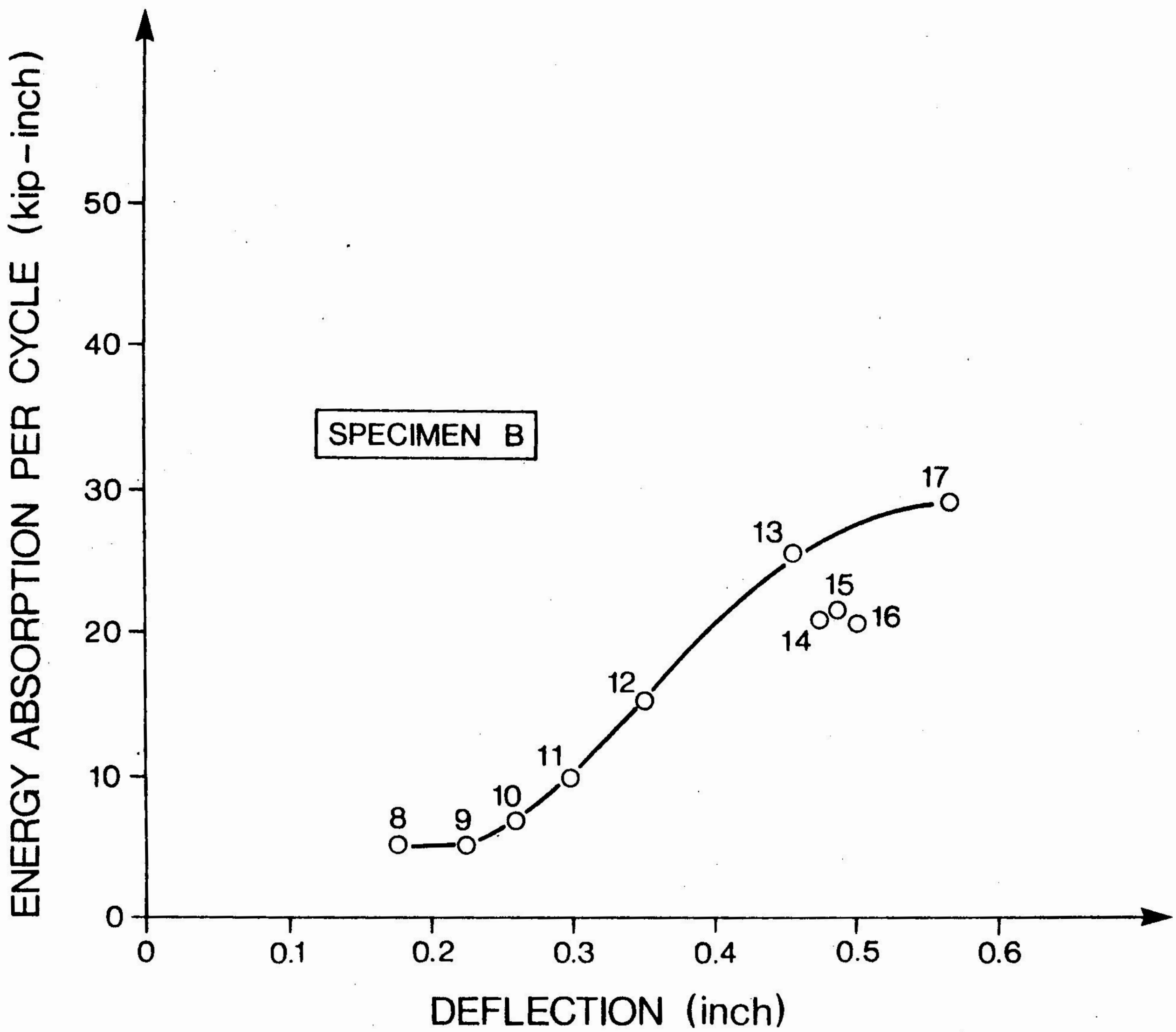

FIG. 9 - ENERGY ABSORPTION CURVE - SPECIMEN B

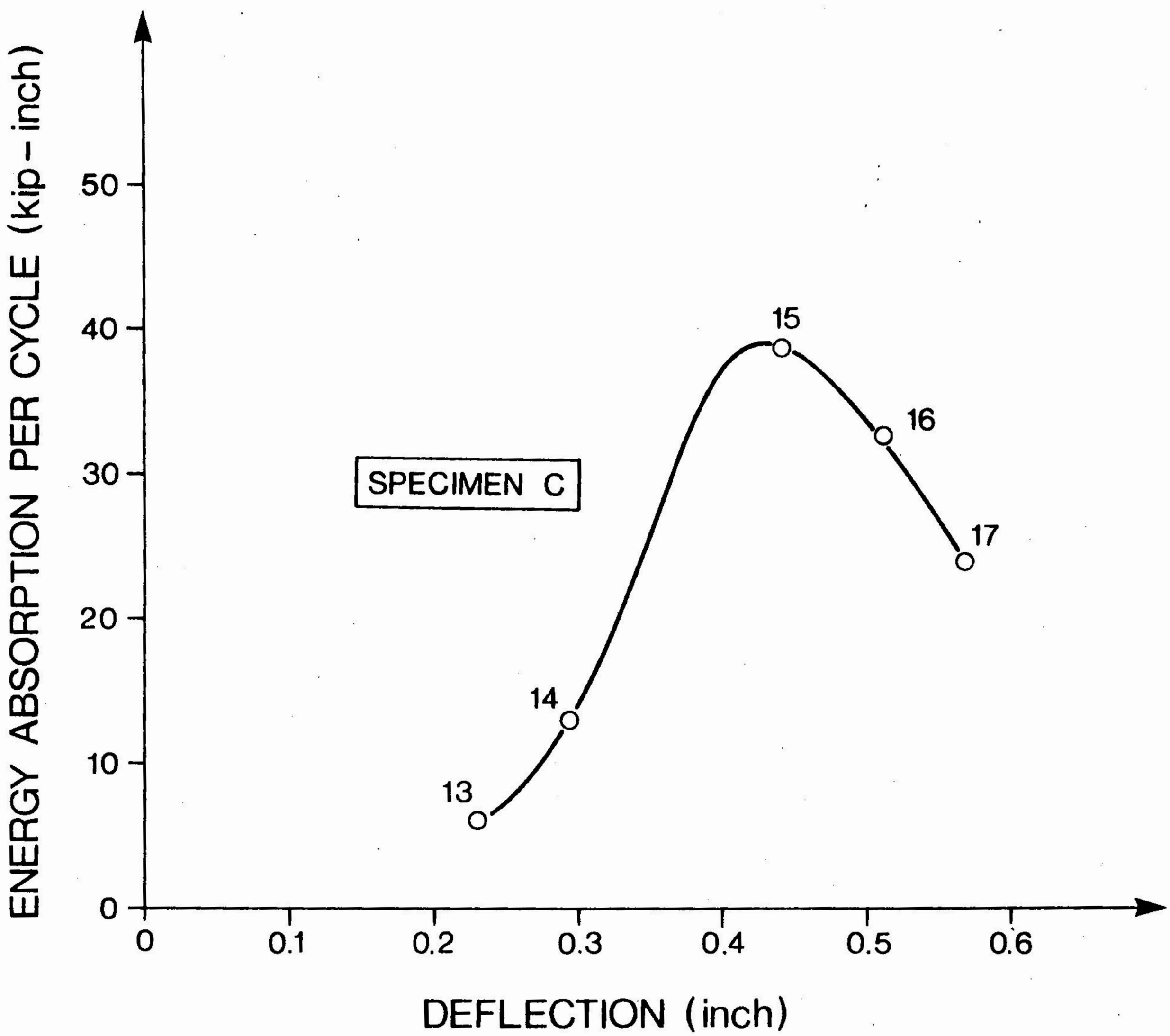

FIG. 10 - ENERGY ABSORPTION CURVE - SPECIMEN C

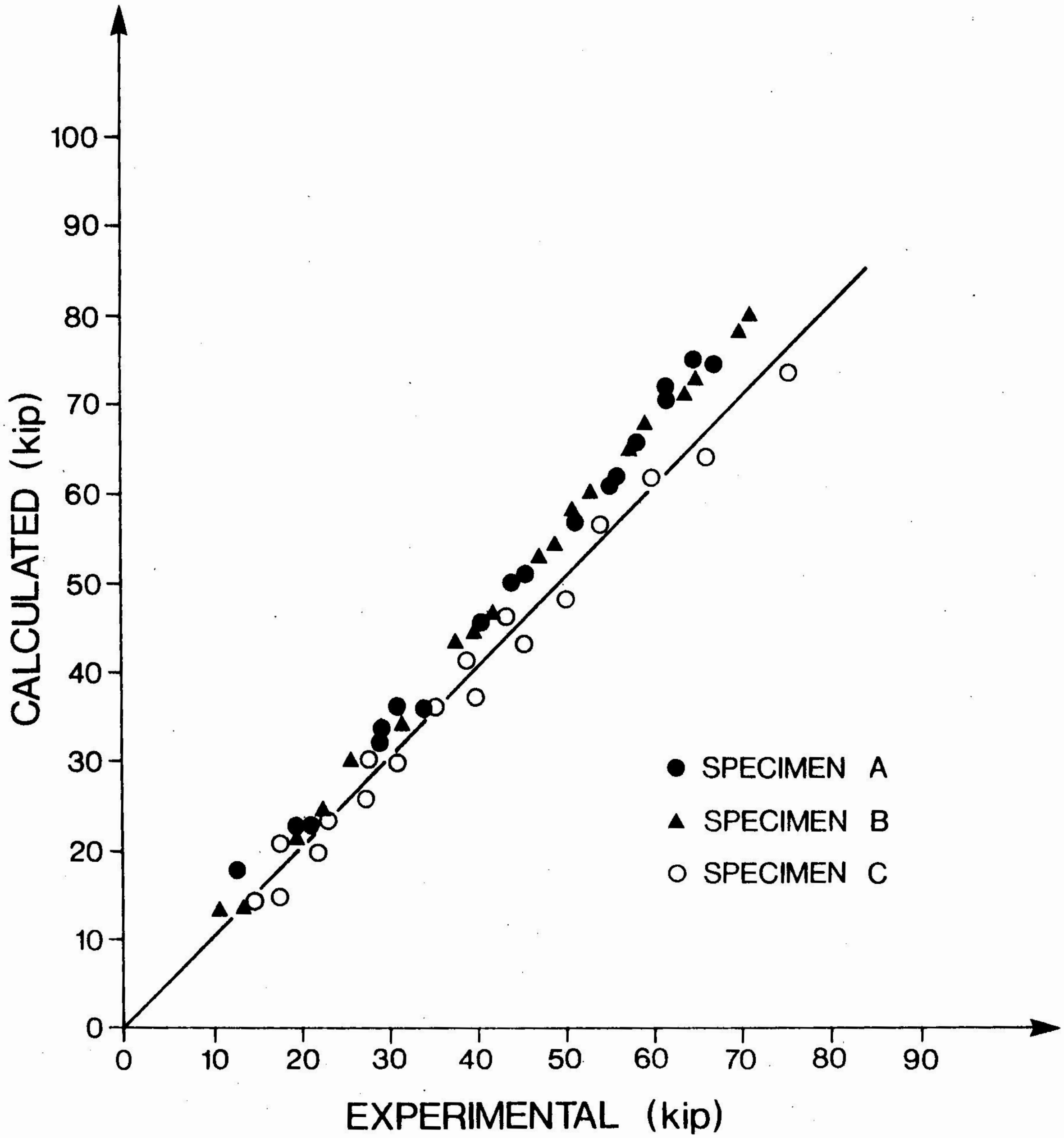

FIG. 11 - AXIAL FORCES IN TENSIONED COLUMNS - COMPARISON WITH TRUSS ANALOGY (SPECIMENS A, B AND C)