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The seismic renovation and repair potential of ferrocement coatings applied to old brick masonry walls

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ABSTRACT

Older unreinforced brick masonry buildings that were originally designed with little or no provision for lateral loading occur in large numbers in most areas of the world. The risk represented by this old building stock has been recognized as one of the major problems facing the Earthquake Engineer today. The research described in this paper involves the development of an alternate type of upgrading procedure whereby a thin coating of a ferrocement like material is attached to both sides of the masonry. The method is shown to be very effective in the seismic upgrading of such walls for strength, displacement demand and energy dissipation. Enhancement in strength of up to three times is not uncommon. All of the other factors involved in the dynamic behavior of the walls are similarly improved. The results of the testing program shows quite clearly the value of the method for renovation.

INTRODUCTION

One of the major problems facing the earthquake engineers today is that represented by the large number of older masonry structures that were originally designed with little or no provision for lateral loading which can be found in most areas of the world. While some methods of upgrading these brick walls, such as shotcreting, grouting or providing external bracing have been found, in varying degrees, to be effective in actual earthquakes [1 to 3], they have either been quite costly or restricted in use to a certain type of structure.

The research described in this paper involves the development of an alternate type of upgrading procedure whereby a thin coating of a ferrocement like material is attached to both sides of the masonry. In a series of previous studies [4 to 7], it was found that ferrocement had a high potential as a material for increasing the earthquake resistance of a masonry structure. Three series of tests were carried out; the first was to determine the bonding and connector size and spacing by performing standard diagonal split tests, the other two were to study the hysteretic and dynamic behavior of the masonry walls upgraded with ferrocement, using both slow cyclic loading tests and the shake table.

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In the first phase of study, ten pairs of thin ferrocement sheets, each 42 in. x 42 in. x 1/2 in. were subjected to a diagonal split test to determine the buckling behavior, and the required connector size and spacing. Four masonry walls made from old brick were also subjected to diagonal split. In the second group of tests, eight two wythe brick walls each 6 ft. wide 8 ft. high were tested. Half of the walls were coated with a 1/2 in. thick ferrocement overlay on both sides and were subjected to a series of pseudo-static cyclic loading tests. The third phase of the study involved earthquake simulation tests, in which eight additional walls were tested on the shake table under simulated earthquake ground motion. These tests were necessary to investigate the upper strength limits, ductility requirements, strength and stiffness degradation, and energy dissipation characteristics for the masonry walls.

EXPERIMENTAL STUDY I - DIAGONAL SPLIT TEST

The first series of standard diagonal split tests were to determine the connector size and spacing needed to prevent the delamination of the ferrocement from the brick masonry wall. It was determined from these tests that 1/4 in. bolts were required spaced at about 12 in.

The second part of this series of diagonal split tests were performed on four 42 in. x 8 in. wall specimens built from old reclaimed brick using ASTM type M mortar. Three of them were coated on both sides with the coated ferrocement overlay, each using a different size of mesh, as shown in Figure 1, while one bare wall was left as a control. All specimens were placed in a moist room to cure. Those to be coated were removed after 14 days and a 1/2 in. coating of ferrocement was applied. They were then put back into the moist room for an additional 28 days. After curing, each specimen was placed in a 300,000 lb. Universal testing machine, checked for alignment and loaded in diagonal split to destruction.

Fig. 2 shows the strength versus the vertical deflection for the test specimens. As can be seen, the uncoated specimen behaved almost linearly up to the cracking load at which point all load capacity was lost. The coated specimens all showed essentially, linear behavior. At nearly the same slope up to the point at which the brickwork split. This point was indicated by noises from within the specimen and a small drop in load carrying capacity. Visible cracks however did not appear in the ferrocement until after the load reached a value close to the brick cracking load. These small cracks formed in a band between the loaded corners and were more numerous with the smaller size mesh.

EXPERIMENTAL STUDY II - PSEUDOSTATIC TEST

Based on the preliminary diagonal split tests, a 1/2 in. x 1/2 in. x 19 gauge mesh was chosen and used in the ferrocement overlay attached to brick masonry walls. A total of 16 walls each 6 ft. wide, 8 ft. high and 8 in. thick were built from reclaimed old bricks, half of which were coated with a layer of ferrocement on each side. As was defined from earlier tests, 1/4 inch bolts spaced at 12 inches were used to prevent delamination between the coating and masonry wall.

A typical test set-up for a pseudostatic cyclic loading test is shown in Fig. 3. As shown, two wall specimens were mounted on the test base which was anchored to the strong test floor. A ten-ton concrete ballast block was used to represent the overburden loads at the first floor level of a typical two-story masonry building. The block was attached to simulate a pin at the top and a fixed base at the lower end of the wall. A servo hydraulic actuator having a capacity of 55-kip and a 24-inch stroke was horizontally mounted between the heavily braced reaction frame and the ballast block which also acted as a rigid diaphragm. To simulate the usual nonrigid connection between the top of the wall and diaphragm or roof of an old masonry building, the end of the wall was allowed to rotate freely when subjected to out-of-plane loadings.

Sonic displacement transducers, calibrated statically and conditioned within the MTS 406 controller previous to the test, were mounted on the surface of the wall specimen at even intervals from the base as can be seen in Fig. 3. Tests for the in-plane and the out-of-plane behavior of the wall specimens were both carried out, for both coated and uncoated specimens.

Each pair of walls was selected from the results of free vibration tests and were subjected to a series of incremental lateral loading. The loads were controlled by specified displacements produced by the electro-hydraulic actuator. For each loading level, three cycles of saw-tooth type loading were applied at a very low frequency, i.e., 0.02 Hz, to the test specimens. the amplitude of the controlled displacement was gradually increased until the test specimens reached failure. Failure was defined as the load level which produced no loss in frequency with increasing amplitude.

All of the test wall specimens displayed a flexural mode of failure. During the early loading stages flexural cracks were initiated several bricks above the base for the plain wall specimens, while for the wall specimens coated with ferrocement, the damage usually took place somewhat above the connection at the base of the wall. These cracks later spread and allowed for a rocking and up-lifting type of motion about the interior crack in the brick. The difference in the cracking behavior for the coated wall and the plain wall specimens was that no major cracks developed in the coating.

Shown in Fig. 4(a-d) are the hystertic loops corresponding to either uncoated or coated walls in the cyclic loading tests. As shown for the out-of-plane test, both the coated and uncoated walls behaved in a ductile way, except that the uncoated walls had a much lower loading capacity and a very poor energy dissipation capacity. For the uncoated walls subjected to the in-plane loadings, the strength for one end dropped immediately after the first loading cycle while the strength for the other end of the wall specimen showed an increase. This nonsymmetric pattern was produced in subsequent loading cycles and reflected in the hysteretic loops because the loss of the resistance at one end of the wall, where sliding occurred when loading was applied. For the coated walls under in-plane loadings, elastic behavior was realized in the early loading stages. When the loading intensity was increased, the specimens started to yield at one end of the wall. Good energy dissipation was noted in the hysteretic loops.

EXPERIMENTAL STUDY III-SIMULATED EARTHQUAKE TEST

The basic test set-up was similar to the pseudostatic test except that the wall specimens were located on the shaking table. The shaking table constructed of a composite sandwich plate coated by ferrocement, has five degrees of freedom, of which three (vertical, lateral and roll) can be individually programmed.

Transducers, including accelerometers and sonic displacment transducers were both utilized in the shake table tests. The accelerometers used in the experiment were conditioned by PCB-conditioners/amplifiers with sensitivity of 5 V/g and with 0-50 Hz low-pass filters. These accelerometers were calibrated dynamically with respect to a reference whose calibration factor has been certified by the manufacturer, while the tempsonics used in this experiment were calibrated in the same manner as in the pseudostatic tests. The data acquisition and processing system employed was a digital PDP 11/34 minicomputer, a spectrum analyzer and several x-y recorders, that are a part of the shake table control system.

After pairs of walls showing the nearest frequency response were selected based on a vibration test, a banded white noise excitation having a frequency range of 0 to 20 Hz and time duration of 40 seconds was applied. From this preliminary white noise test, modal frequency, mode shape and modal damping factor could be estimated. To determine the failure mode, a series of incremental levels of simulated earthquake component with increasing intensity based on attenuated N-S component of the 1940 El Centro Earthquake, was applied to the wall specimens.

The physical behavior of both the coated and uncoated wall specimens was similar to the results observed in the pseudostatic loading test. A first crack was formed near the base in the early loading stages, and then the cracks propagated through the wall gradually corresponding to the intensity increase of the subsequent loadings. Typical response time history for the relative displacement corresponding to each temposonic transducer mounted on the wall specimens shown in Fig. 5.

DISCUSSION OF THE TEST RESULTS

The general characteristics discussed in this section consist of the hysteretic behavior including the ultimate strength and strength deterioration, stiffness degradation, energy dissipation, ductility, and general dynamic behavior such as frequency response and the variation of the damping factor for both the plain and coated walls. The only parameter considered was the effect of ferrocement overlay while other parameters such as overburden load, mortar strength, and the size of wire mesh were held constant.

The in-plane strength is improved by about 3 times when the brick wall specimen is coated by the ferrocement overlay. Considerable improvement in the flexural strengths of the coated walls was also indicated in the results of the pseudostatic tests. Fig. 6 (a,b) shows the hysteretic envelopes taken from the cyclic loading test results for the plain and the coated walls when subjected to both in-plane and out-of-plane loadings. Each point shown in the hysteretic envelopes was obtained from the hysteresis loops by averaging the absolute extreme values of the six peaks of three cyclic of loadings and the corresponding absolute values of the relative lateral displacement for each test stage. It can be seen that the ultimate strength of the masonry wall was upgraded by 3 to 4 times by the ferrocement overlay.

The hysteretic stiffness was defined as the slope of the hysteretic envelope. It is obvious that not only was the initial stiffness of the coated wall specimens improved but the degradation of stiffness was reduced during each incremental loading step. The improvement in the initial stiffness of the coated wall specimen loaded out-of-plane under simulated Earthquake loading was about two times.

Ductility, an important indicator of earthquake resistant ability, was obtained from the hysteretic envelopes and defined as the ratio of the maximum displacement at the failure point to the extrapolated displacement corresponding to the same loading point, which was noted in the envelopes. According to this definition, the ductility for the walls in the out-of-plane test was found to be 6.70 and 9.50 for the plain and coated walls respectively, while in the in-plane test, it was 3.50 and 4.00. It is evident that the ductility of the masonry walls was improved by the application of ferrocement coatings.

The energy dissipation capacity is taken as the average area contained in the hysteresis loops for three cycles of repeated loading for each stage of test. It can be seen in the hysteretic loops that in general, in the early loading stages, the energy dissipated in both the plain and the coated walls is very small since the response was still in the elastic range. In the later loading stages, significant dissipation of energy was found in the coated wall specimens, particularly for the wall specimen in the out-of-plane test. The energy dissipation capacity of masonry brick wall improved 3-6 times by the ferrocement overlay.

A banded white noise test with very small amplitude was performed after each level of simulated earthquake test loading. The frequency was then taken directly from a spectrum analyzer and from this data, a degradation curve of frequency with respect to the loading intensity was determined for both the coated and plain walls. The natural frequency was found to decrease with an increase of loading intensity. The degrading rate of frequency for the coated wall specimens appeared to be slower than for the plain wall specimens. With the ferrocement coatings, the wall specimens become more stiff and had a higher frequency.

The damping factor for both the coated and plain walls was calculated [7] and plotted against the corresponding loading intensity. Generally, the damping factor is increased corresponding to the increase of loading intensity. Higher damping was found in the wall specimens coated by ferrocement, especially during the later loading stages.

CONCLUSIONS

Brief conclusions that can be drawn from the results of these tests are as follows: (1) The mode of failure for both the coated and plain wall specimens subjected to either in-plane or out-of-plane loading was flexural. (2) The original stiffness of coated masonry walls was increased up to two times as much as that for the uncoated walls. (3) The shear strength is increased about 1.5-2 times, and the flexural strength of masonry walls in terms of moment capacity is increased about three times by the ferrocement reinforcement. (4) The energy dissipation capacity and ductility are improved when ferrocement coatings are applied. (5) With the ferrocement coatings, the wall specimens become more stiff and have a higher natural frequency. (6) The damping factor increased corresponding to the loading intensity. In the in-plane test, the coated wall specimens appeared to have higher damping than the plain wall specimens at the same loading intensity. (7) It is evident that ferrocement is an appropriate material able to significantly improve the dynamic resistance of brick masonry.

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Fig. 1 The Ferrocement Overlay Attached to the Masonry Wall

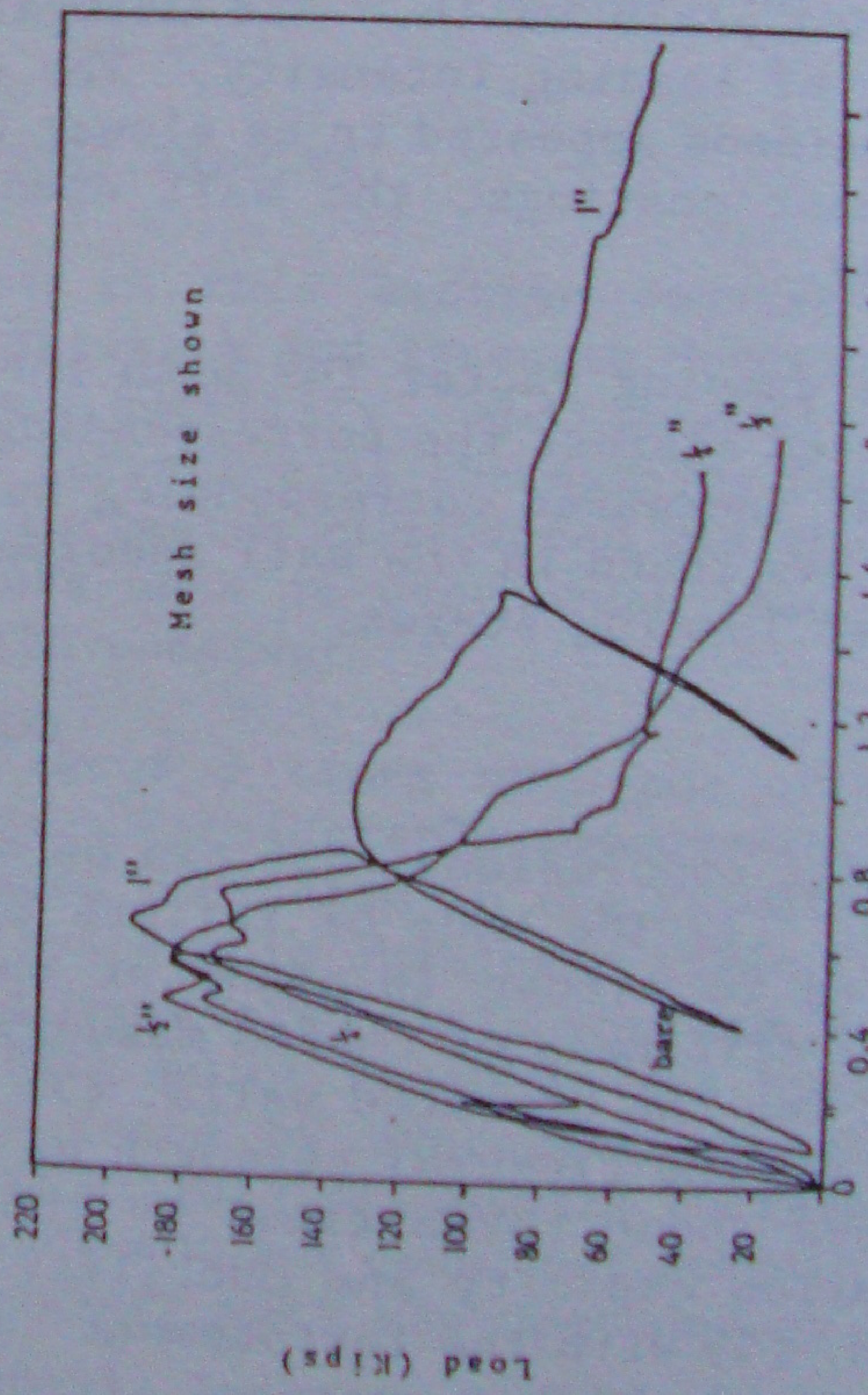

Fig. 2 Load vs Vertical Deformation for Diagonal Split Test

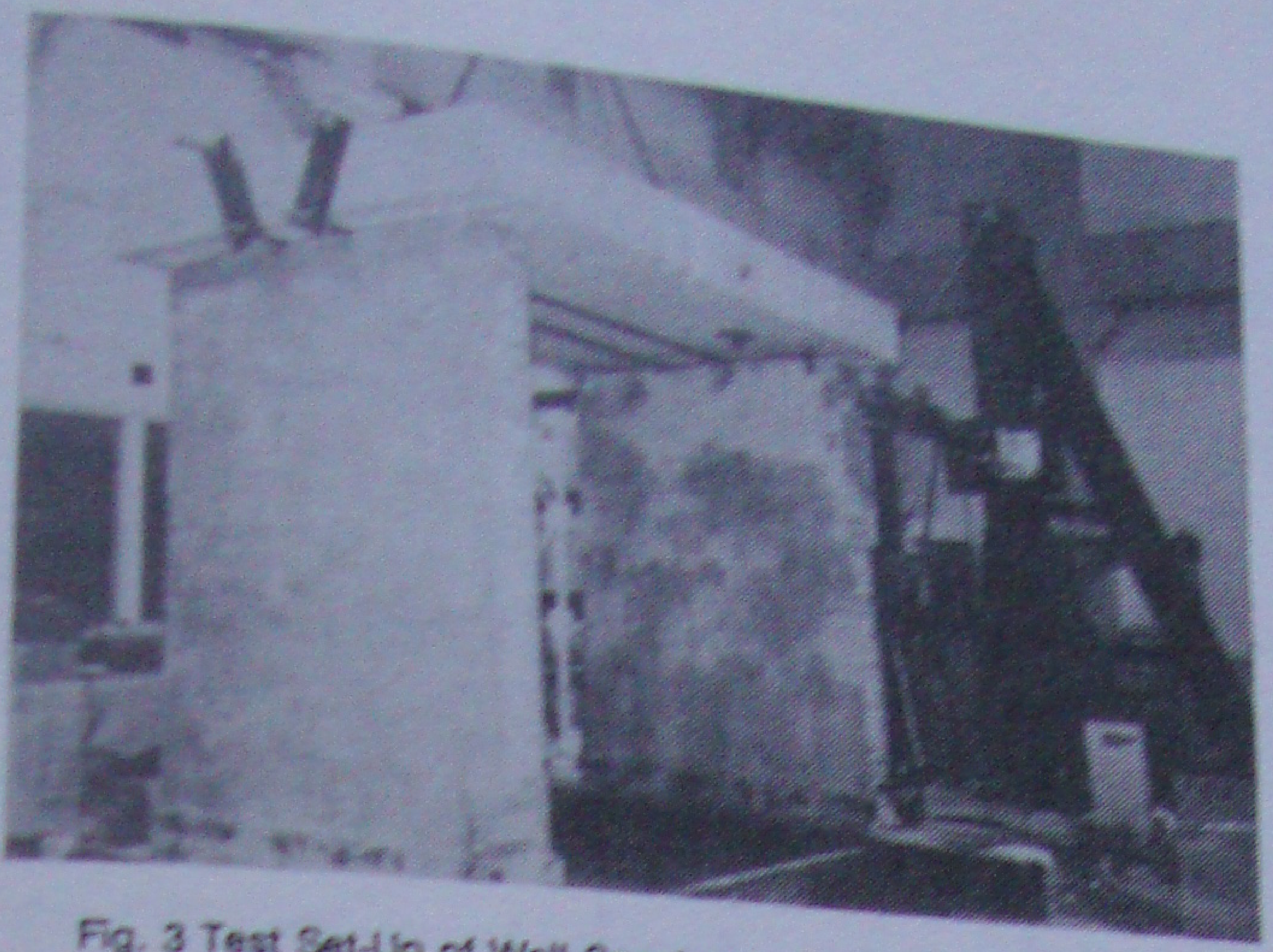

Fig. 3 Test Set-Up of Wall Specimens in Cyclic Loading Test

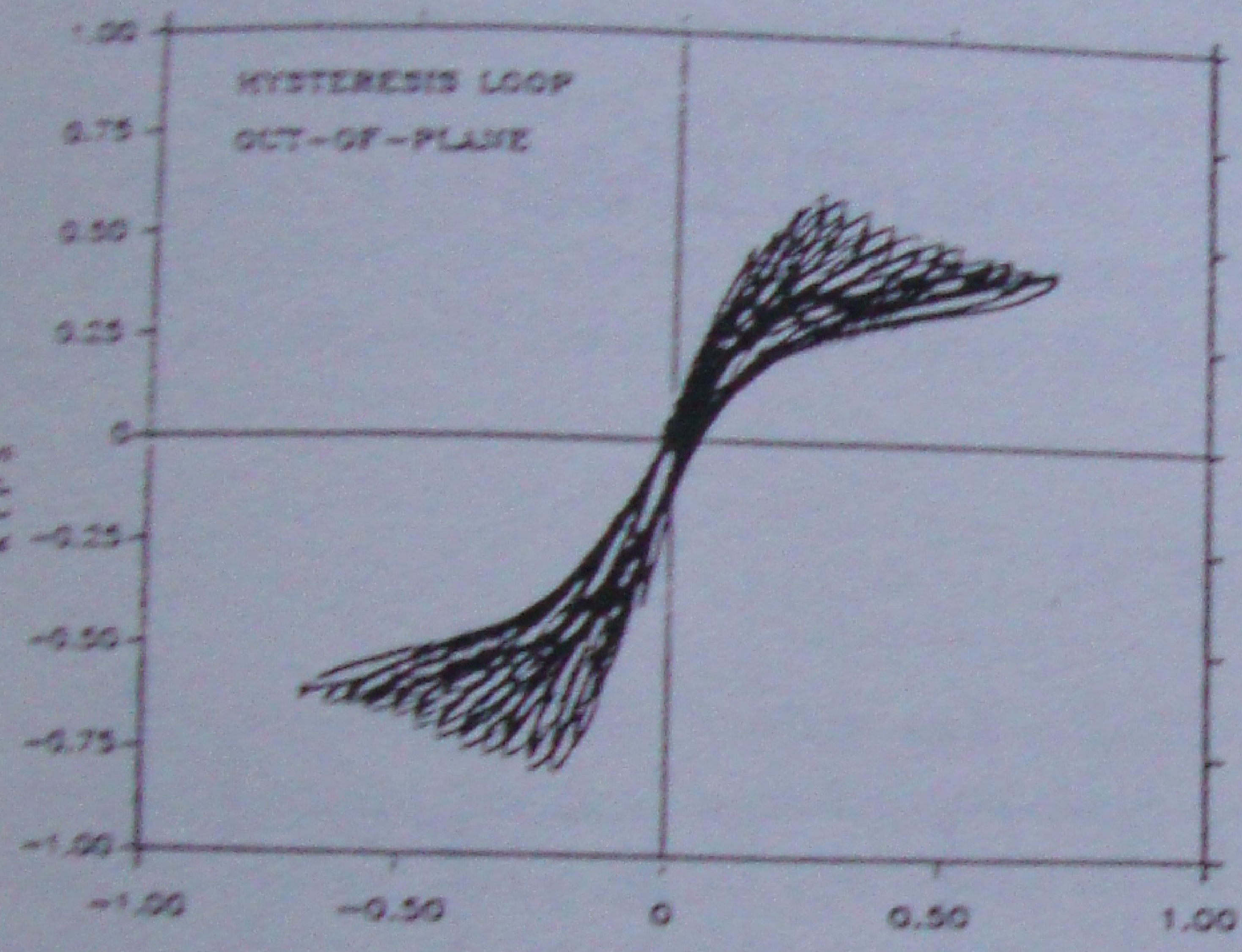

Fig. 4(a) Typical Hysteresis Loops for Plain Wall in Out-of-plane Test

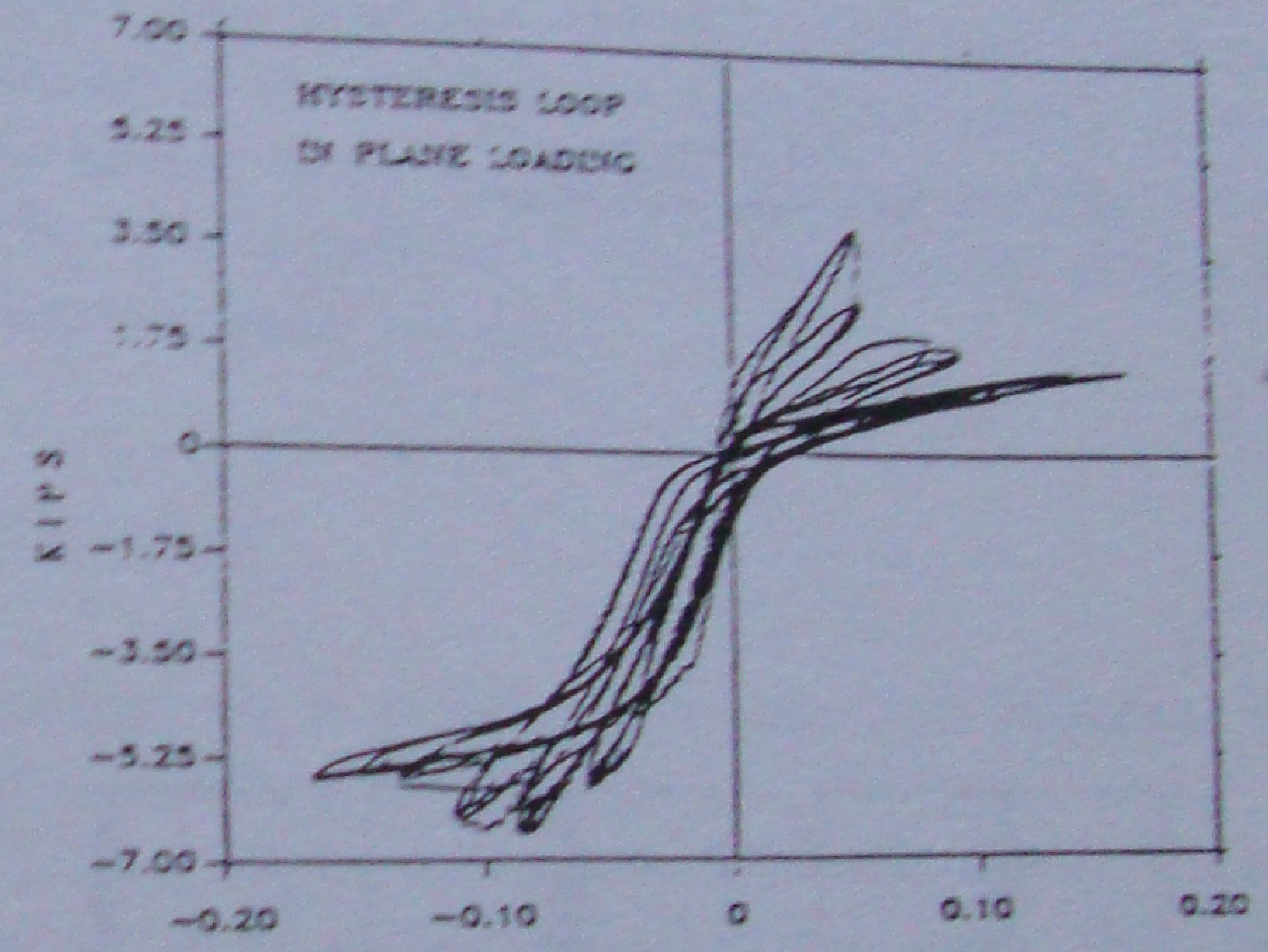

Fig. 4(c) Typical Hysteresis Loops for Plain Wall in In-plane Test

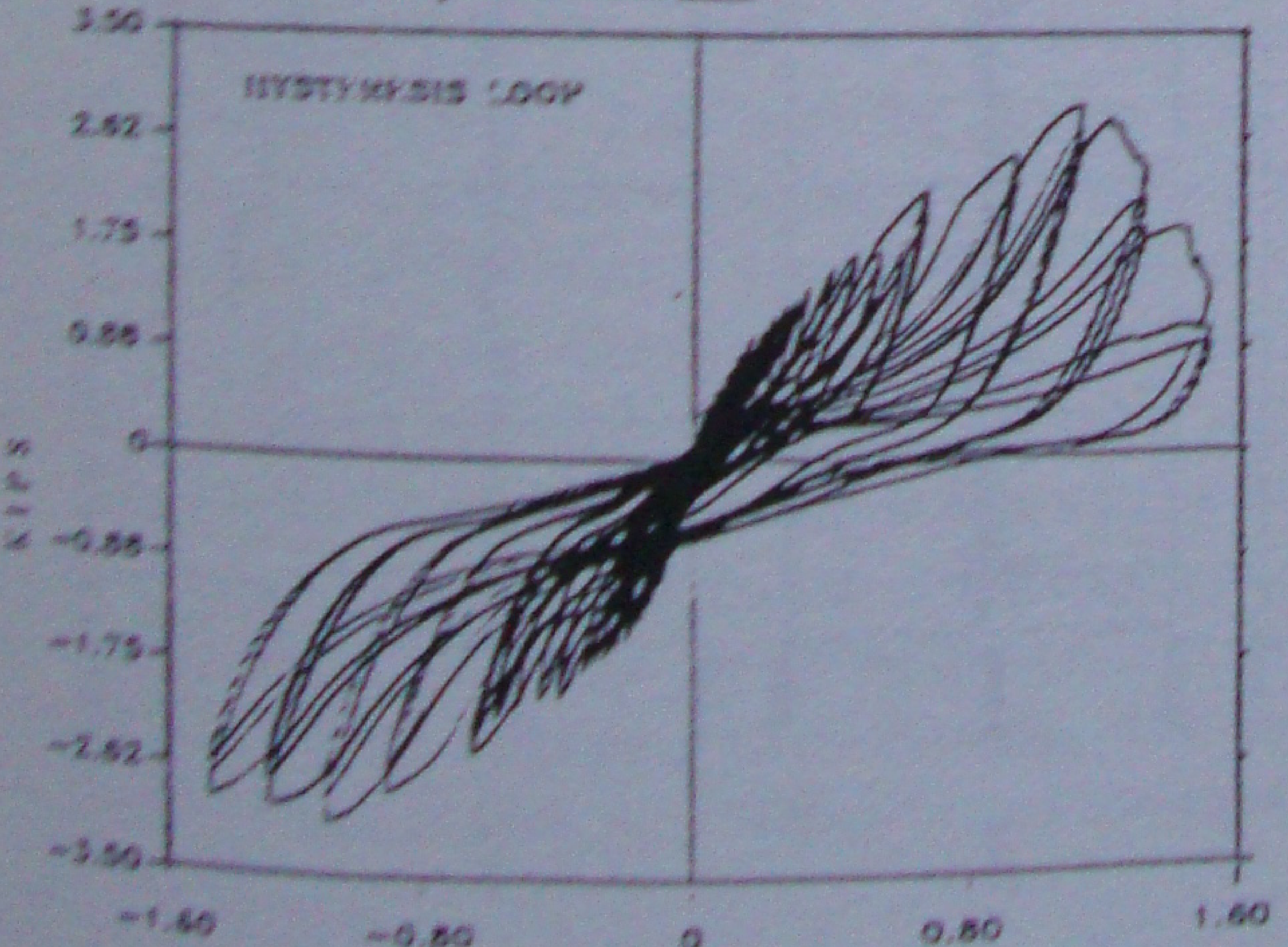

Fig. 4(b) Typical Hysteresis Loops for Coated Wall in Out-of-plane Test

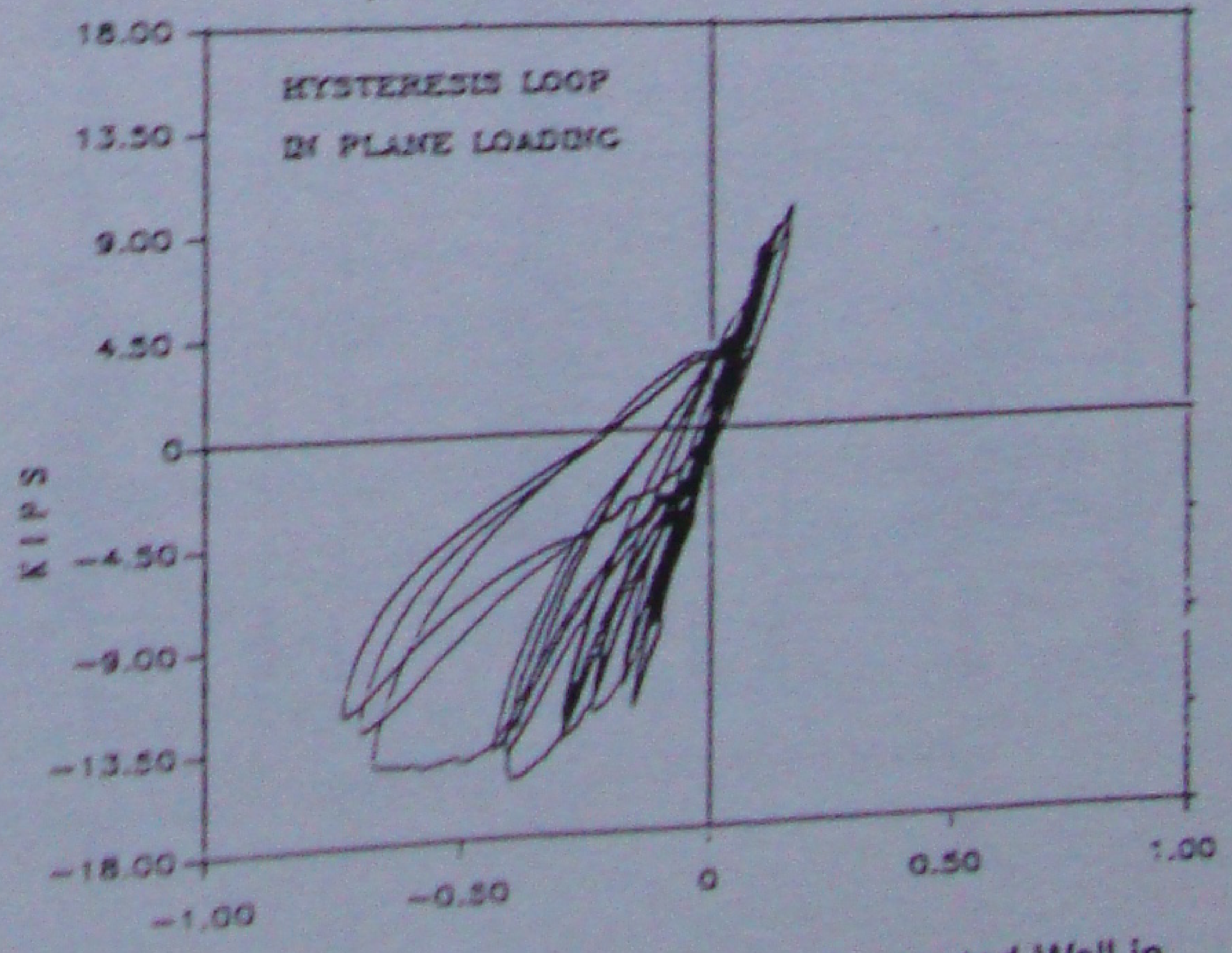

Fig. 4(d) Typical Hysteresis Loops for coated Wall in In-plane Test

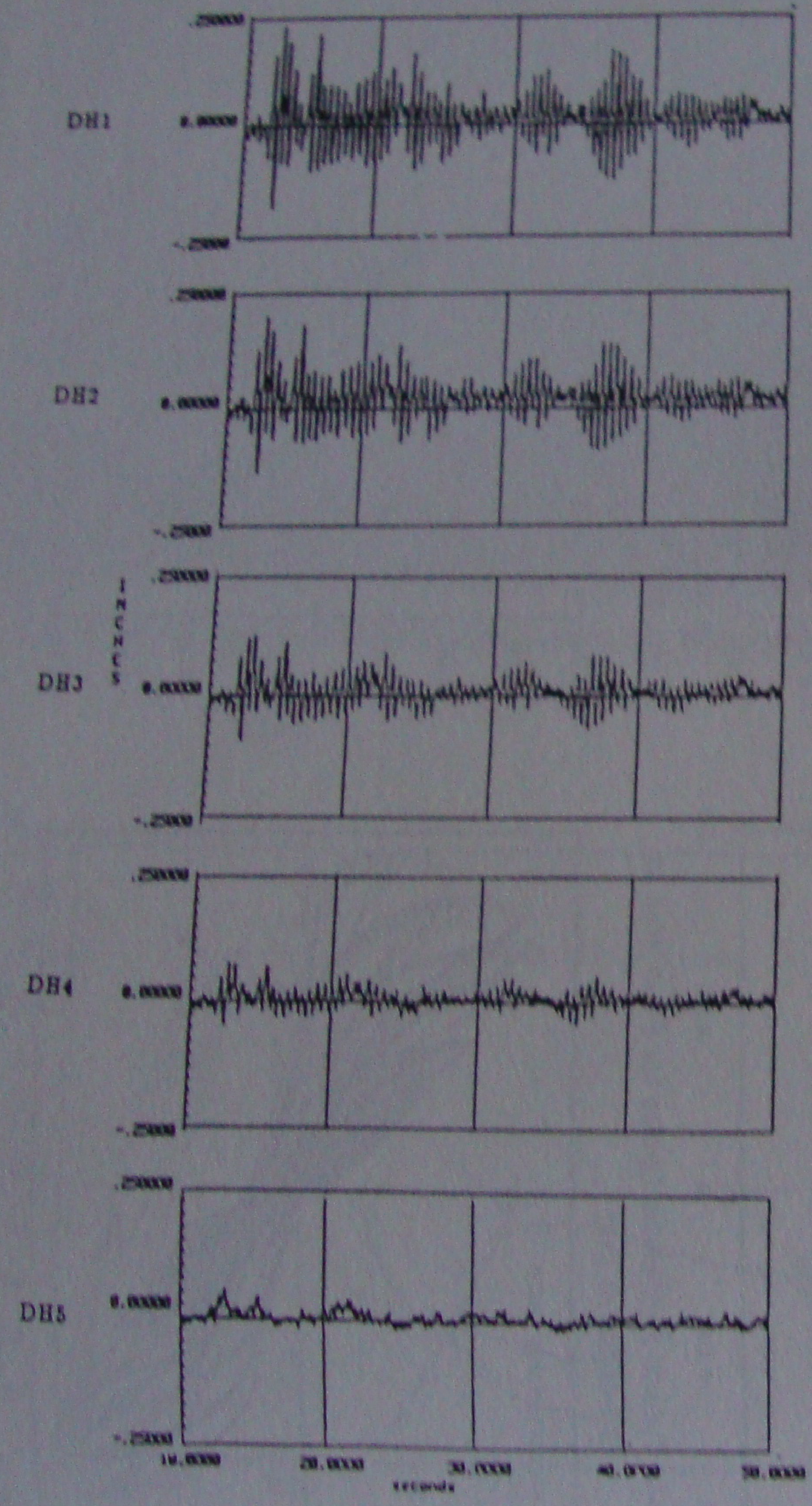

Fig. 5 Time Histories of Displacement Response for Plain Wall in Shake Table Test

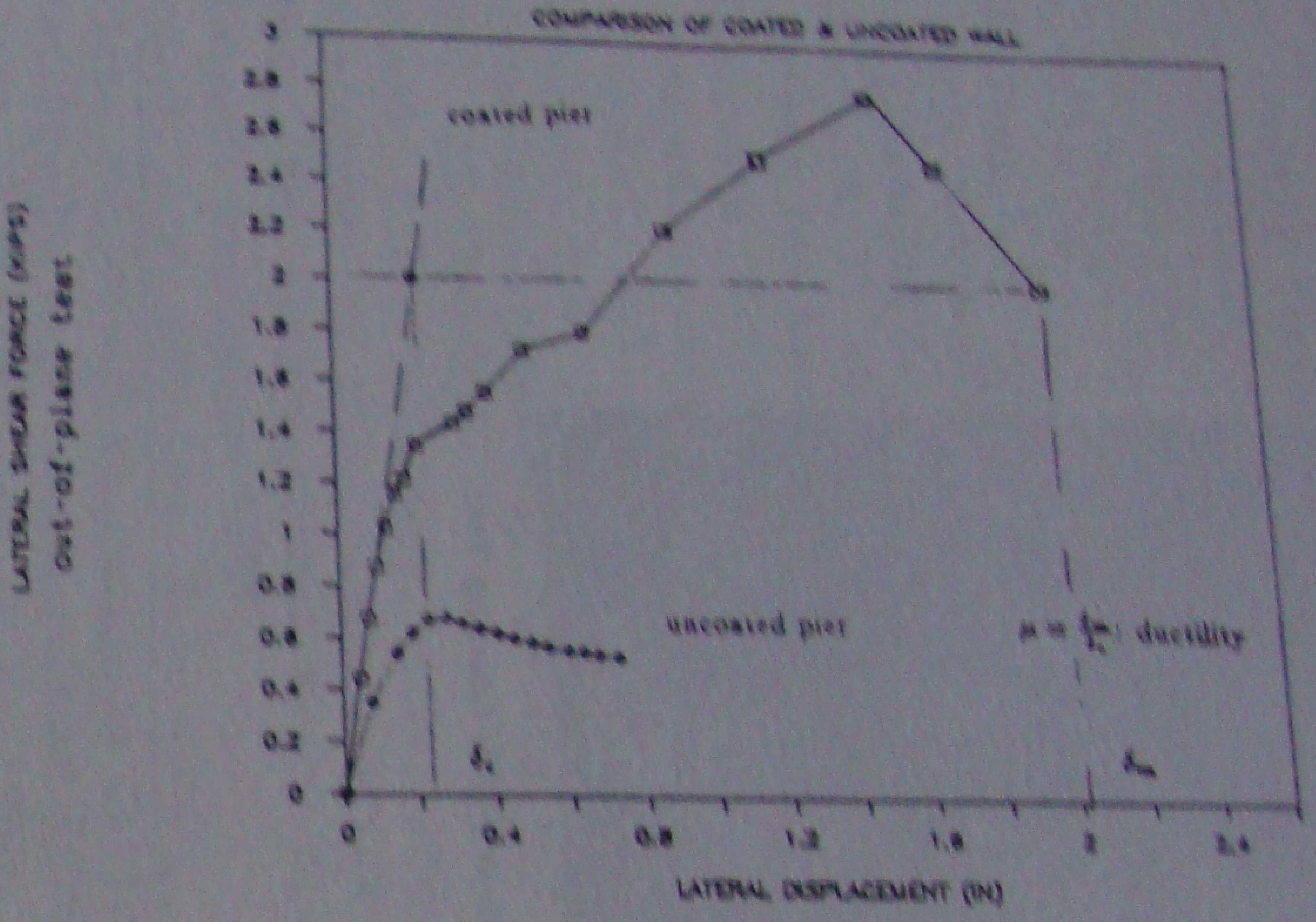

Fig. 6(a) Hysteresis Envelope for out-of plane test

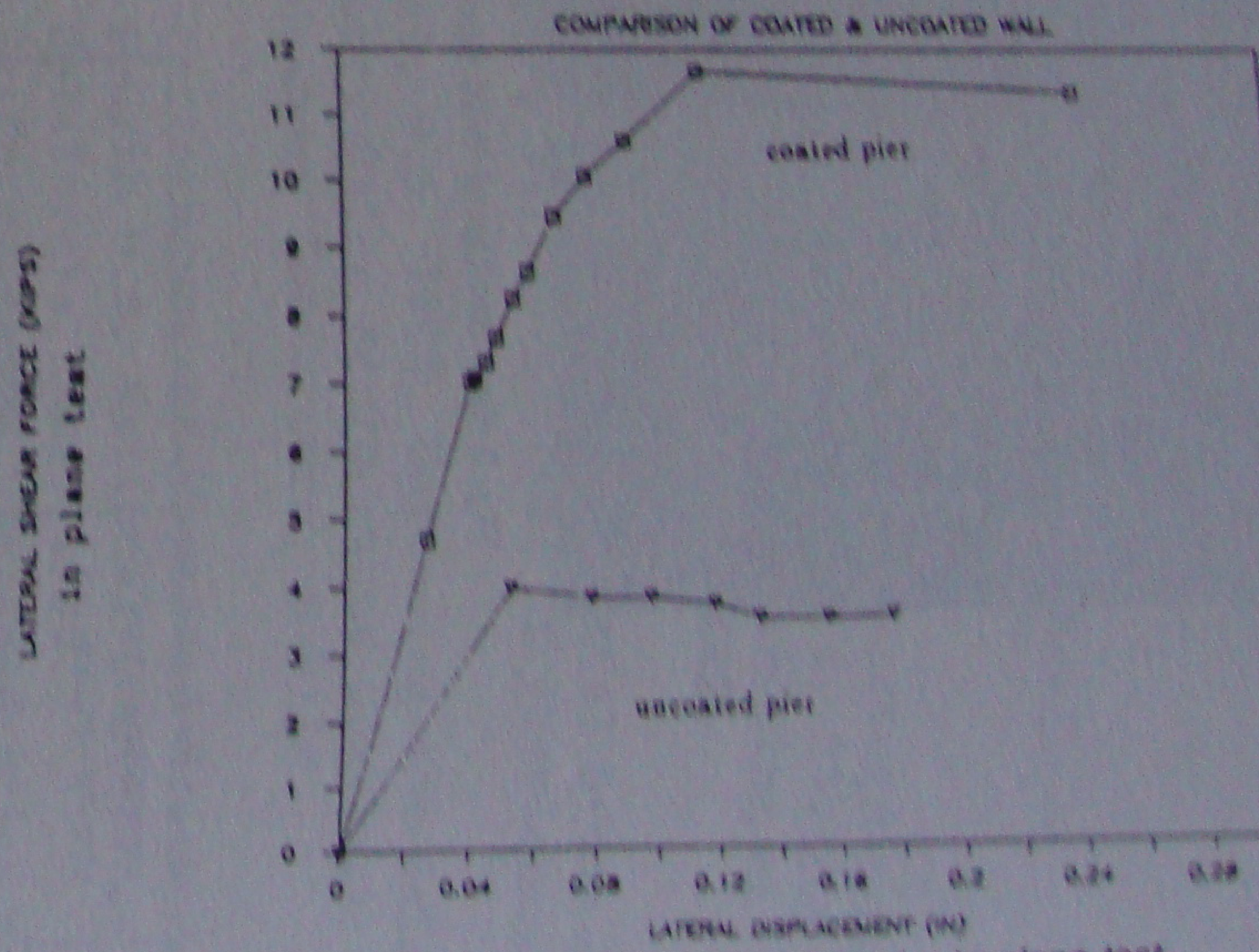

Fig. 6(b) Hysteresis Envelope for in plane test