An Experimental Study of Brick Veneer with Metal Stud Backup

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Abstract - The results of an experimental program designed for the purpose of evaluating brick veneer walls with metal stud backups are reported. The project included testing of wall ties, flexural testing of full-scale wall systems, and water permeance testing. Six full-scale walls were tested, three with positive pressure and three with negative pressure. The walls were tested to load levels up to three times the load recommended by the metal stud manufacturers. The lateral load test results are reported in the form of deflection profiles at various load levels.

1. INTRODUCTION

The use of metal studs as a backup material for brick veneers has become a widely-used practice in construction in the United States. The wall system gives the same appearance as traditional brick masonry, while the steel stud backup system may be erected with more speed and economy than a backup wythe of masonry. The steel stud system is lighter in weight than masonry backup systems, and may be easily insulated for thermal and sound control.

One area of concern of the steel stud and brick veneer wall system is the large difference in flexural stiffness between the metal stud backup and brick veneer. Although the metal stud has sufficient strength to carry all of the lateral wind loads, it may not do so without experiencing deflections too large for the brick veneer to withstand without flexural failure. According to simple beam theory, the stiff brick veneer, which is tied to the metal stud backup with metal ties, carries substantial lateral load until flexural tensile cracks form. Only after flexural failure of the brick wythe will a significant load be transferred to the metal stud backup. The consequences of flexural failure of the brick veneer are water permeance or, in extreme cases, catastropic structural failure of the wall system.

Most members of the Metal Lath/Steel Framing Association recommend a design criteria for brick veneer walls supported by metal studs in which the stud alone acting as a simple beam resists all lateral load without exceeding a midspan deflection of L/360. The Brick Institute of America, however, does not feel that this design procedure assures sufficient stiffness of the wall system to prevent cracking of the brick veneer. The purpose of the experimental research described herein was to determine whether or not wall systems designed according to Metal/Lath Steel Framing Association criteria would perform adequately.

2. SCOPE OF RESEARCH

The scope of the research project included two experimental phases and development of an analytical model. The subject of this paper includes results of lateral load testing of full-scale wall panels laterally loaded with either positive or negative pressure. Also included are results of water permeance tests of the full-scale panels which were load tested. Due to space limitations, the results of the tie tests are not given.

The analytical phase included the development of mathematical models which predicts the behavior of the walls tested as well as the effects of changes in certain variables.

3. TEST PROGRAM

3.1 Test Specimen

The full-scale lateral load test specimens were constructed according to details shown in Fig. 1. The metal stud was 9.21 cm deep, 240 cm high, and 0.912 mm thick. The strong axis moment of inertia was 22.5 cm^4 and the allowable bending moment was 667 N·m. Gypsum wallboard and gypsum sheathing were screwed to the stud at 20 cm intervals with No. 6 shank self-drilling screws, 2.5 cm long with flared heads.

The wall tie selected was an adjustable tie (Fig. 2) with 0.190 cm thickness backing and wire diameter of 0.437 cm. The axial stiffnes of the tie was measured to be 13 kN/cm in compression and 2.6 kN/cm in tension.

The brick veneer was constructed with Type S portland cement-lime mortar in running bond. The first course of brick was placed in a bed of mortar spread on top of metal flashing. Three weep holes were provided at the base of each wall.

Both the dry wall and the masonry were constructed by contractors familiar with such construction and was observed continuously by at least one of the authors. The walls were constructed and tested in groups of three. The first three walls were tested with positive pressure (i.e. compressed air), the next three, negative pressure (vacuum). The first group of three walls, both the backup dry wall and the masonry veneer, were constructed at the same time. Upon completion of testing of this group of walls, it was observed that the dry wall was still in excellent condition. The test data also indicated very little residual deflection resulting from positive pressure tests. Therefore, the same three dry walls were reused in the second phase of testing. That is, the brick veneer was sawed into pieces and removed, the wire portion of the ties replaced, and new brick veneer constructed. The primary purpose for reusing the dry wall was to eliminate as many variables in the testing program as possible. Reusing the dry walls was the best way to assure that the stiffness of the backup system did not vary between the positive pressure and negative pressure tests. Unfortunately, it was not possible to reuse the brick veneer.

3.2 Quality Control

Quality control of the brick veneer included mortar tests, brick tests, and brick prism tests. Mortar tests included flow, air content, cube strength, and cylinder strength. Brick tests included cold water and boiling water absorption, initial rate of absorption, and compressive strength. Prism tests included compression and flexural tests. Results of quality control tests are shown in Tables 1, 2, and 3. All tests were conducted in accordance with test methods published by the American Society for Testing and Materials.

4. TEST PROCEDURE

4.1 Lateral Load Tests

Lateral load testing was accomplished using a plywood frame equipped

with an electric vacuum cleaner motor and impeller. The chamber was constructed so that it completely surrounded the top and sides of the brick veneer wall with an airspace of approximately 2 cm. In order to seal this air gap, thus minimizing air leaks during tests, a rubber tube was placed between the perimeter of the brick veneer and the inside wall of the test chamber (Fig. 3). Before load testing the walls, the tube was inflated to a pressure of 60 kN/m^2. The purpose of the tube was to provide an air seal without significantly restraining lateral deflection of the brick veneer.

4.2 Water Permeance Tests

The tests for water permeance were an adaption of "Water Permeance of Masonry," ASTM E514-79. However, since the back side of the brick wall was not accessible, it was necessary to modify several of the techniques. The test chamber was clamped to the wall at a distance of approximately 75 cm from the base. This position was chosen so that the region of the wall that was subjected to high flexural stresses would also be exposed to the water permeance chamber. However, the large volume of masonry below the water permeance test chamber absorbed water that would ordinarily collect in the flashing in a standard E514 test. Thus, collection of water in the flashing was not as meaningful as in the standard E514 test. The results are reported, however.

The water for the water permeance test was a closed-loop system. Water was collected at the base of the water permeance chamber and returned to the drum from which water was pumped. In theory, any loss of water from the closed-loop system represents that either absorbed by the wall of that penetrating the wall. In practice, however, it was not possible to seal the perimeter of the water permeance chamber completely. Although every attempt was made to insure a closed system, leaks were inevitable. Therefore, the results of this test phase are lower bond values for water leakage.

4.3 Instrumentation

The brick veneer and dry wall panels were instrumented with mechanical dial gages accurate to within 0.025 mm. A sufficient number of dail gages was attached in order to obtain a complete deflection profile of both walls. The gages which measured the brick veneer deflection were mounted on the metal stud side of the wall system, and had extensions which passed through holes drilled in both layers of gypsum board to permit contact with the brick. Dial gages intended to monitor dry wall deflection were mounted adjacent to those used to measure brick veneer deflection. Gages were located at approximately the height of the wall ties. It was, therefore, possible to determine the difference in wall deflection at the tie location. A total of 20 dial gages was used on each wall test.

Lateral load was monitored by a manometer mounted on the lateral loading chamber. The manometer was accurate to within 0.5 mm resulting in pressure readings accurate to within 5 N/m^2.

4.4 Test Sequence

Each wall was tested according to the following procedure.

1. Precondition for water permeance, 24 hours.

2. Allow wall to dry, 24 hours.

3. Perform first water permeance tests, 3 hours, remove water permeance chamber.

4. Attach lateral load chamber, load test wall to one time design load, unload, remove chamber, attach water permeance chamber, seal with caulking compound.

5. Perform second water permeance test, 3 hours, remove water permeance chamber.

6. Attach lateral load chamber, load test wall to 2 times design load, unload, remove lateral load chamber, attach water permeance chamber, seal with caulking compound.

7. Perform third water permeance test, 3 hours, remove water permeance chamber.

8. Attach lateral load chamber, load test to three times design pressure.

Dial gages were read at load increments of 0.25 kN/m^2 both during loading and unloading. Residual deflections were recorded at the end of each load test. At the beginning of the next day's test, the initial readings of the dial gages were zeroed. Therefore, a wall which deflected 10 mm on the second day of testing and which experienced a 1 mm residual deflection at the end of the first day's test would have experienced an absolute deflection of 11 mm.

5. TEST RESULTS

5.1 Results of Lateral Load Tests

The best representation of lateral load test results are deflection profile graphs at increasing load levels. Space limitations do not permit inclusion of all of these graphs. However, Figs. 4-8 illustrate typical results. This group of 5 figures includes deflection profiles of both brick veneer walls and dry walls.

The behavior shown in Fig. 4 was generally characteristic of three of the walls tested (Wall No. 1, 3, and 5). That is, the deflected shape was a continuous smooth curve up to a lateral load level between 2.5kN/m^2 and 2.74 kN/m^2, after which a flexural tensile crack formed which completely altered the deflection profile and magnitude. Figure 5 shows the corresponding dry wall deflection. Although it remained a smooth continuous curve, the dry wall deflection increased markedly at the load level corresponding to cracking of the brick veneer. Figure 4 also illustrates how the top of the brick veneer moves laterally due to the absence of a positive lateral support. Figure 1, Detail A, illustrates that the top of the brick veneer is supported elastically by a neoprene pad, friction fit between the top of the brick veneer and the bottom of the shelf angle above. The magnitude of the top end deflection increased in proportion to the load up to a value of approximately 2.5 mm before cracking. After cracking, no appreciable top deflection was observed with increased loading.

Figure 6 illustrates the deflection profile of Wall No. 2, the only wall to experience flexural failure at a load less than twice the design load. This wall experienced flexural failure at a load between 1.25 and 1.50 kN/m^2. Otherwise, its behavior was very similar to that of Walls 1, 3, and 5.

Figures 7 and 8 illustrate the deflection profiles of the brick veneer wall and dry wall of Wall No. 4, respectively, at three times design load. The behavior of this wall was similar to that of Wall No. 6, in that flexural failure of the brick veneer did not occur. Large top end deflections were observed, reaching a magnitude of 1.35 cm. Wall No. 6, though similar in behavior, experienced a top deflection of 2.15 cm. Figure 8 shows that the deflected shape of the dry wall remained continuous and did not possess the characteristic large increase in deflection associated with cracking of the brick veneer.

5.2 Results of Water Permeance Tests

The results of the water permeance tests summarized in Table 4 were generally disappointing to the authors. Because of the imperfections of the test method, or at least in the authors' ability to perform the test, the data is not completely reliable.

In spite of the uncertainties associated with the water permeance tests, a few observations are still possible. In the first group of three walls, Wall No. 2 had the highest rate of leakage measured by either method, and also had the worst performance in resisting lateral load.

Another observation from Table 4 concerns Wall No. 2, the only wall that experienced a flexural crack prior to a water permeance test. This wall showed more change in water leakage after the load to one time design load than it did after the flexural crack. That is, contrary to what was expected, a flexural crack did not cause a substantial increase in leakage. The authors do not believe that this is generally true. In this test, the forces that produced the crack were not present during the water permeance test. The crack was able to close under the self-weight of the wall, in the absence of other forces that would tend to prevent a reclosing.

If one chooses to evaluate the data without regard to its uncertainty, he might conclude from Table 4 that water permeance increases in walls subjected to one time design load. At least, this is so for four of six walls. In the other two walls, the loss of water was the same both days. If the change in water loss were in fact due to loading, then one might expect the loss of water on the third day of tests to be even greater. This was true in three of six walls. However, in two of the walls, the third day loss was smaller than that obtained on the second day.

6. ANALYSIS OF DATA

6.1 Development of Mathematical Model

A mathematical model was developed using simple beam theory in which the two walls were treated as vertical beams connected by linear springs. Boundary conditions of the beams were chosen to match the conditions of tests as closely as possible. The brick veneer was treated as pinned at

the base, and free at the top. The dry wall was considered simply-supported at the base and the top. The modulus of elasticity of the masonry in flexure was measured experimentally from a beam cut from Wall No. 1 and was, $E_m = 6030\ MN/m^2$.

The metal stud dry wall was modeled first as a beam having a moment of inertia equal to that of the stud alone, then, as a transformed beam having a moment of inertia corresponding to the metal stud acting compositely with the gypsum wall board. Respective values of moment of inertia were 22.5 cm^4 and 57.9 cm^4.

The most difficult feature of the test specimens to mathematically model was the stiffness of the neoprene support at the top of the veneer wall. Other sources of uncertainty were the amount of composite action between gypsum boards and metal studs and the degree of end rotational restraint provided at the top and bottom of the metal stud wall.

The mathematical model was capable of modification which permitted the placement of an internal hinge in the brick veneer wall. This moment release allowed the model to predict post cracking behavior of the wall system. Results of the model with and without an internal hinge are presented in Figs. 9 and 10.

6.2 Model Notation

Several terms were defined in the development of the mathematical model:

A = relative flexural stiffness of masonry to axial stiffness of one wall tie

= $E_m I_m / KL^3$

where E_m = modulus of elasticity of masonry (see section 6.1)

I_m = moment of inertia of a strip of masonry having a width equal to the horizontal tie spacing

K = axial stiffness of a single wall tie (see section 3.1)

L = height of brick veneer

B = relative flexural stiffness of brick veneer to flexural stiffness of backup drywall

= $E_m I_m / E_s I_s$

where E_s = modulus of elasticity of steel
= 203 GN/m^2

I_s = moment of inertia of backup system

KE = axial stiffness of elastic support at the top of the brick veneer

K/KE = ratio of axial stiffness of interior ties to elastic support at top of wall

7. DISCUSSION

The behavior of the wall system tested was complex and difficult to model. Probably the most meaningful way to evaluate the effectiveness of the wall system is to compare the bending moment in the brick veneer wall backed up by the metal stud system to that of the brick veneer wall as if it resisted all lateral load alone. The difference in these bending moments represents the amount by which the backup system reduces the load carrying requirements of the brick veneer alone. Using the values of wall stiffness, end support stiffness, composite action of metal stud wall, boundary conditions, etc., which best fit the mathematical model to the experimental data, the bending moments in the brick veneers were calculated (Figs. 11, 12, and 13). Lines which are identified "brick wall only" are plots of the moments in the brick wall without backup. An example of the usefulness of such a plot may be illustrated from Fig. 11. The maximum nondimensionalized moment, M/QL^2 for B = 4.712, A = .0071, K/KE = 0 is found from the graph to be 0.075. If the brick veneer resisted all of the load, the value would be 0.125. Therefore, according to the model, the bending stress of the "backed up" wall would be 60% of a wall which was not backed up.

The effect of the stiffness of the support at the top of the brick wall can be illustrated by Fig. 12. A wall having K/KE = 0, which corresponds to a rigid end spring, has nondimensionalized maximum moment of 0.103. The same wall having K/KE = 100, corresponding to an extremely flexible top spring, has a nondimensionalized moment of 0.050. The same wall without backup has a nondimensionalized moment of 0.125. Thus, a wall with stiff lateral support at the top would have 83% of the stress of a wall without backup. The same wall with very flexible top support would have only 40% as much flexural stress as a wall without backup. It is therefore expected that brick veneers supported by shelf angles with flexible support at the top can be expected to perform better than those which have stiffer lateral support. The effect of K/KE is not as great when the ties are stiffer, as shown in Fig. 11. Here there is little difference between values corresponding to K/KE = 0 and K/KE = 100.

The effect of relative flexural rigidity is shown in Fig. 13. When the brick veneer is 4.712 times stiffer than the dry wall (no composite action), the nondimensionalized moment is 0.075, compared to 0.125 with no backup. When the relative flexural stiffness decreases to 1.828 (full composite action), the nondimensionalized moment decreases to 0.053. Thus, for B = 4.712, the veneer carries 60% as much bending moment as it would without backup. When B is decreased to 1.828, the percentage decreases to 42%. The authors feel that, due to partial composite action, the actual value is probably near 55%.

Figure 13 also illustrates that the use of relative stiffness (EI) as a means of distributing load to each wythe is not a good method of design. For example, a value of B = 1 would imply equal distribution of lateral load to each wythe, thus a 50% reduction in bending stress. However, Fig. 13 illustrates a 70% reduction for B = 1. Similar inaccuracies are observed for other values of B.

The forces in the wall ties were found to be non-uniform. In fact, analysis shows that ties can even have different signs depending upon boundary conditions at tie location. According to the computer model, the forces in the ties ranged from 0 up to values as high as 20% of the total force on the entire wall. Thus, since there were a total of 14 ties in the

wall, the practice of distributing load equally to all the ties would result in a maximum of only 7% of total wall load per tie. A second implication of unequal tie force distribution is that the backup wythe is not uniformly loaded. In fact, the distribution of load on the backup wythe is much larger near the supports than it is near midspan. Since the backup wall is much stiffer in resisting lateral force near a support, it is logical that more force would be attracted to these locations.

8. SUMMARY AND CONCLUSIONS

An experimental and analytical study was performed on brick veneer walls with metal stud backup. A mathematical model was developed in order to explain the behavior of the walls tested as well as predict the effects of other variations in the wall construction. Based on the test results and the computer model, the following conclusions were reached:

1. Test results showed that all six walls tested were capable of resisting their design lateral wind load without flexural cracking; five of six walls reached twice design load without flexural cracking; and two of six walls reached three times design load without cracking.

2. Water permeance tests performed on the walls were inconclusive due to experimental problems with the test method.

3. The modulus of elasticity of the brick masonry tested was significantly lower than would have been obtained by calculations from present USA standards.

4. In the walls tested, it appears that the metal stud backup reduced the flexural stress on brick veneer about 45% compared to that of a veneer without backup.

5. Forces in the wall ties are nonuniform, even when wind pressure is uniformly distributed. The practice of distributing force to ties uniformly in design appears to substantially underestimate maximum tie forces.

6. Composite action between the metal studs and gypsum sheathing, though partially present, does not significantly alter the load which must be resisted by the brick veneer.

7. The use of flexural rigidity as measured by the value EI as a means to distribute lateral load to each wythe is inaccurate. Such factors as tie stiffness, span difference between the two wythes, and boundary conditions have as much effect as relative rigidity on distribution of lateral load.

9. ACKNOWLEDGEMENTS

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TABLE 1 - BRICK PROPERTIES

SAMPLE	COMPRESSIVE STRENGTH (MN/m^2)	ABSORPTION (%) 5 Hr. COLD	ABSORPTION (%) 24 Hr. COLD	ABSORPTION (%) 5 Hr BOIL	SATURATION COEFFICIENT	INITIAL RATE OF ABSORPTION ($g/194\ cm^2$)
1	117	5.28	5.33	7.35	.73	7.8
2	119	5.53	5.81	7.99	.73	13.5
3	129	5.57	5.80	7.95	.73	12.0
4	141	5.10	5.47	7.36	.74	9.5
5	139	5.02	5.28	7.27	.73	9.0
Mean	129	5.30	5.54	7.58	.73	10.4

TABLE 2 - PRISM PROPERTIES

Wall No.	Test Type	No. of Tests	Mean Stress (MN/m^2)	Coef. of Variation
1, 2, 3	Compression	3	27.8	5.7%
	Bending	3	0.61	18.5%
4, 5, 6	Compression	3	35.6	6.8%
	Bending	3	1.01	16.3%

TABLE 3 - MORTAR PROPERTIES

Wall No.	Batch No.	Type Test	No. of Tests	Mean Stress MN/m^2	Coef. of Variation %
1, 2, 3	6	Cube, Comp.	3	20.8	2.6
	8	Cube, Comp.	3	21.8	2.4
		Cube, Splitting	3	1.34	20.5
		Cylinder, Comp.	3	15.0	5.9
		Cylinder Splitting	3	1.92	22.7
4, 5, 6	3	Cube, Comp.	3	12.1	11.1
		Cube Splitting	3	1.37	18.1
		Cylinder, Comp.	3	10.8	5.6
		Cylinder Splitting	3	1.85	14.7
	7	Cube, Comp.	3	15.4	8.6
		Cube, Splitting	3	1.53	3.7
		Cylinder, Comp.	3	12.3	4.0
		Cylinder Splitting	3	1.89	26.7

TABLE 4 - WATER PERMEANCE TEST RESULTS

Wall No.	Loss of Water - System (liters)			Water Collected on Flashing (liters)		
	1 day	2 days	3 days	1 day	2 days	3 days
1	1.3	1.6	2.0	0	0	0
2	2.3	3.9	1.9	0.28	0.57	0.02
3	1.0	1.0	0.7	0	0	0
4	0.5	0.8	0.9	0	0	0
5	1.8	2.0	3.0	0.66	0.15	1.23
6	0.5	0.5	0.5	0	0	0

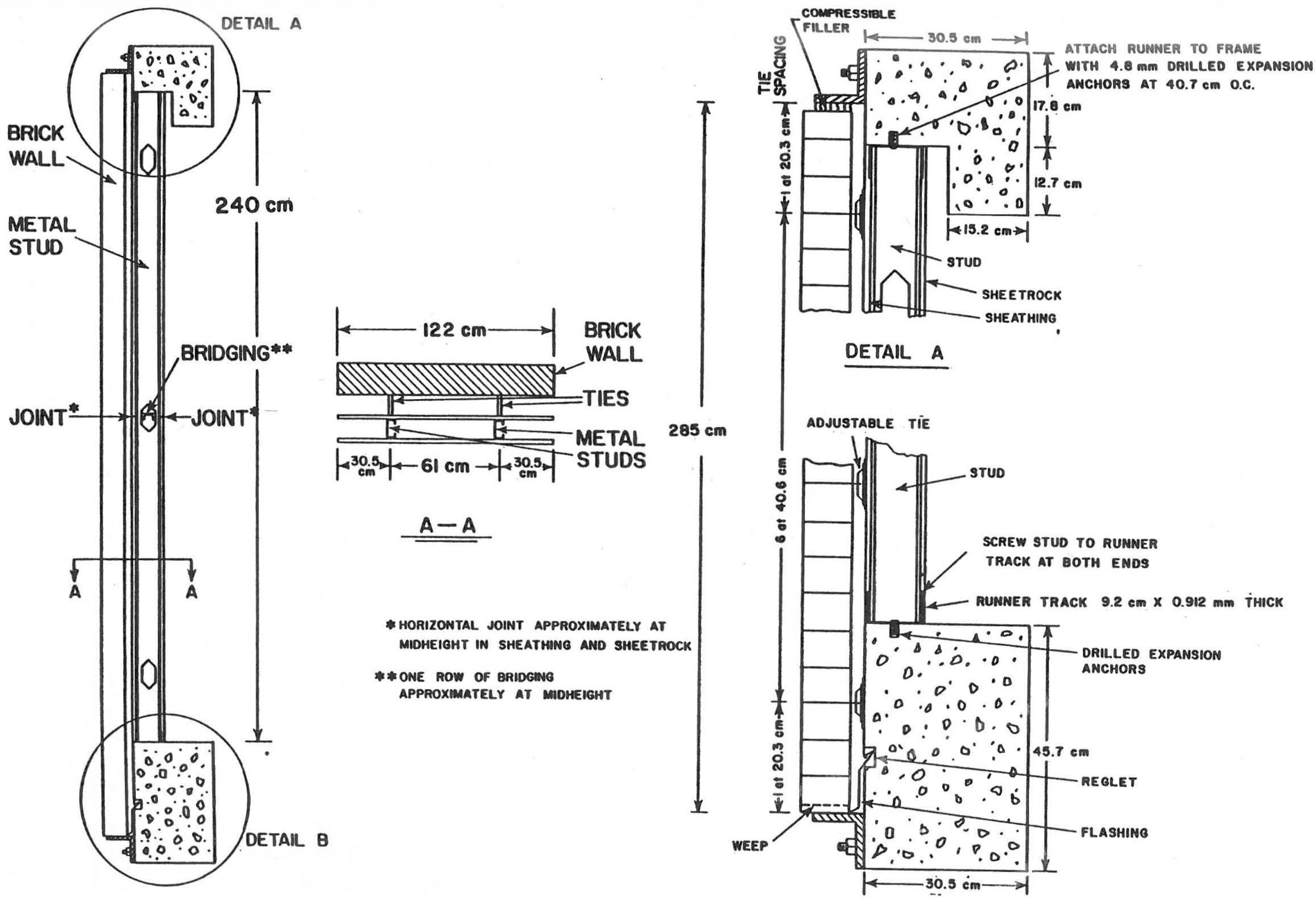

Fig. 1 Typical Brick Veneer/Steel Stud Wall
Tested for Lateral Load and Water Permeance

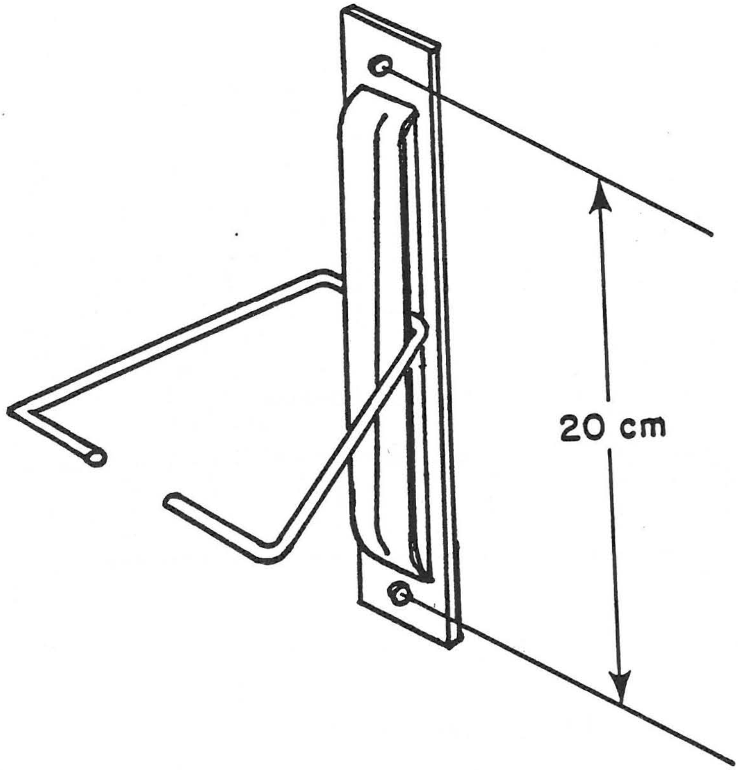

Fig. 2 Adjustable Wall Tie Used in Full-Scale Lateral Load Tests

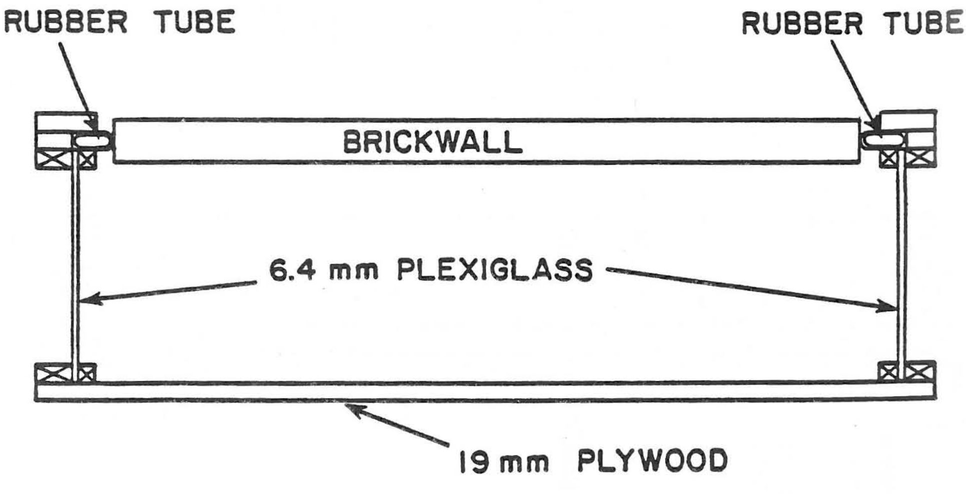

Fig. 3 Cross Section Through Brick Wall and Lateral Loading Chamber Illustrating Inflatable Rubber Tube

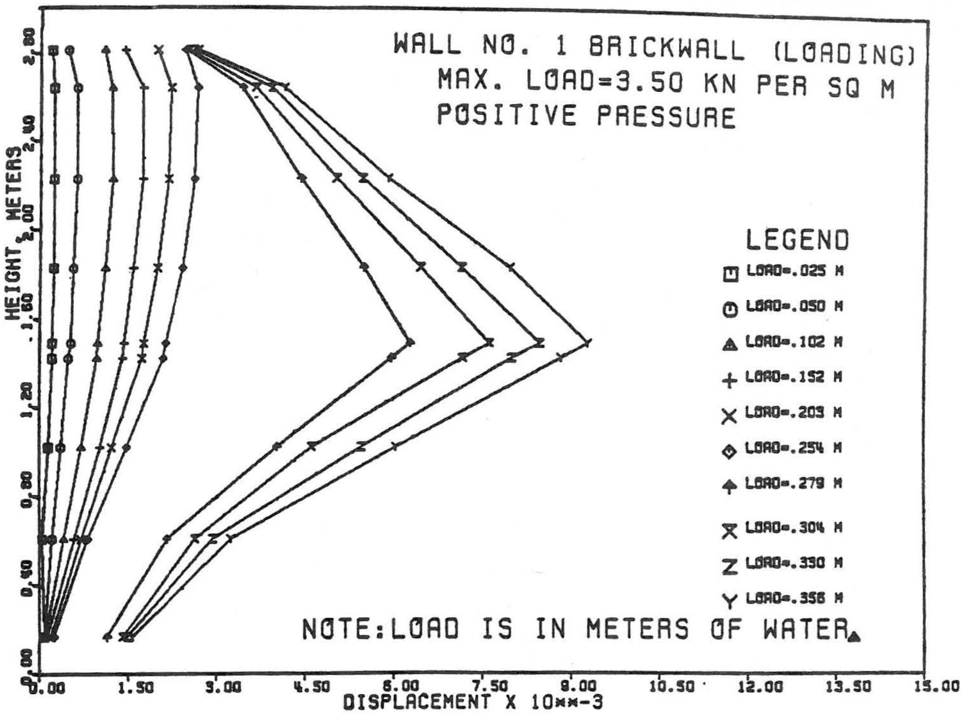

Fig. 4 Brick Wall Displacement Profile to 3 Times Design Load for Wall No. 1

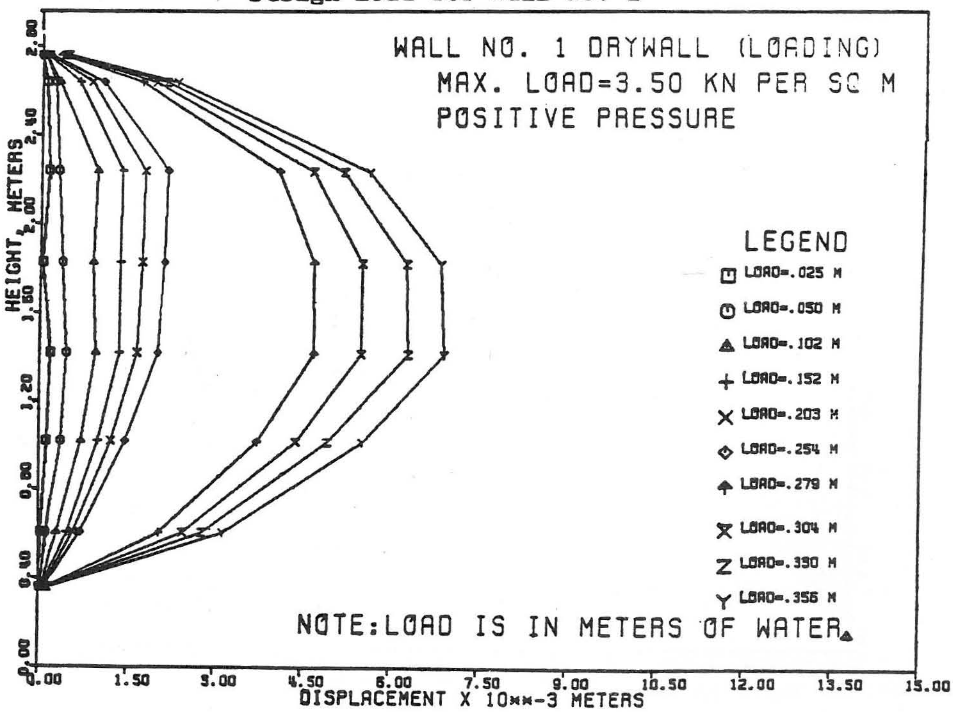

Fig. 5 Drywall Displacement Profile to 3 Times Design Load for Wall No. 1

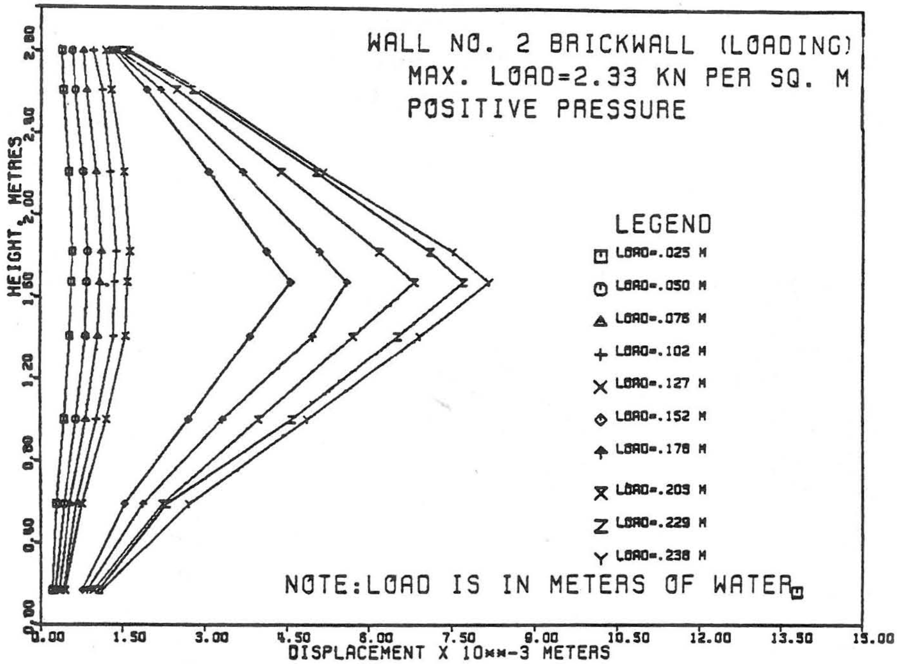

Fig. 6 Brick Wall Displacement Profile to Twice Design Load for Wall No. 2

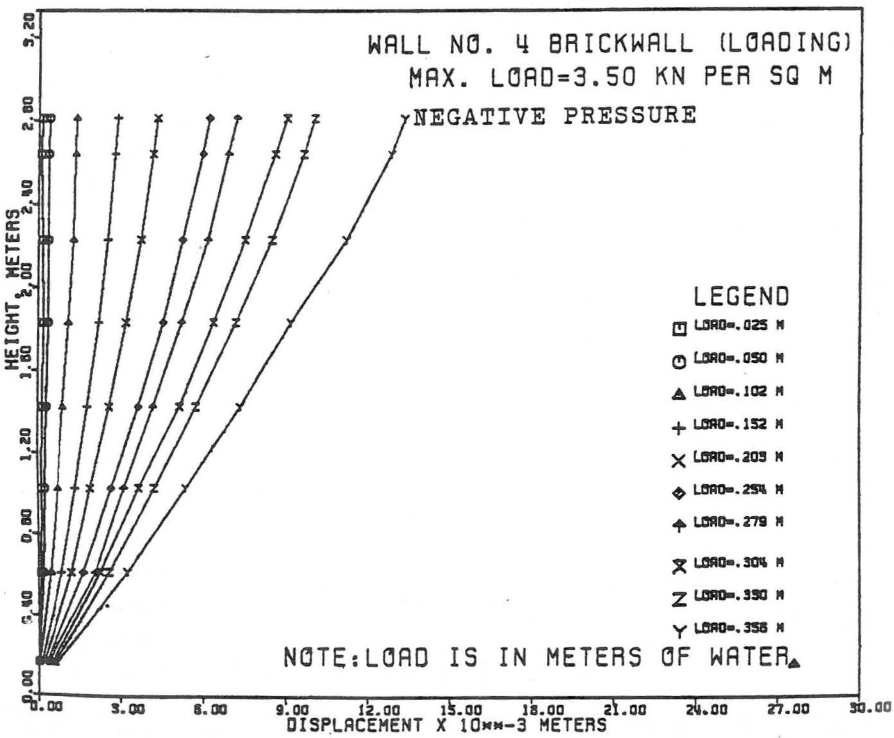

Fig. 7 Brick Wall Displacement Profile to 3 Times Design Load for Wall No. 4

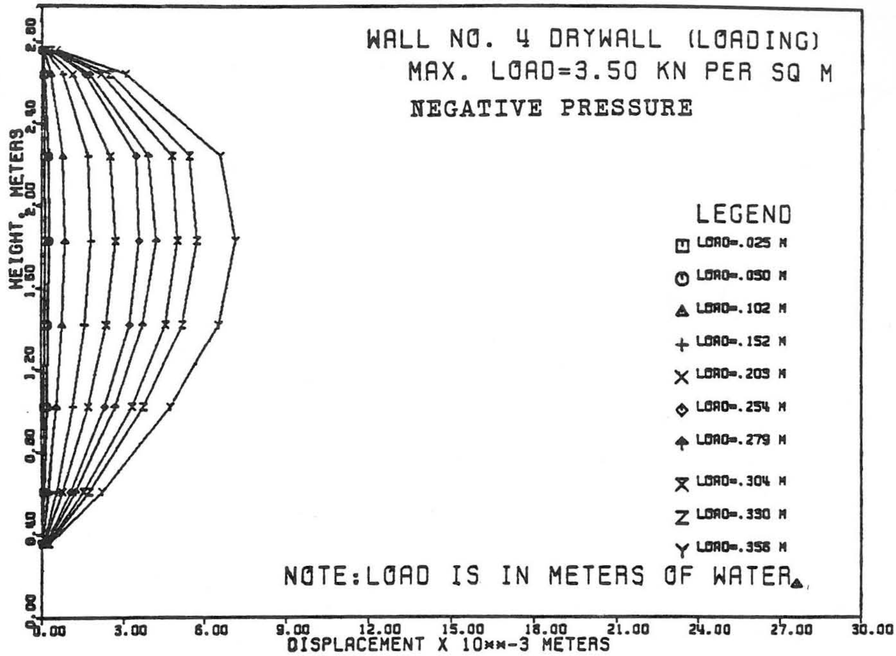

Fig. 8 Drywall Displacement Profile to 3 Times Design Load For Wall No. 4

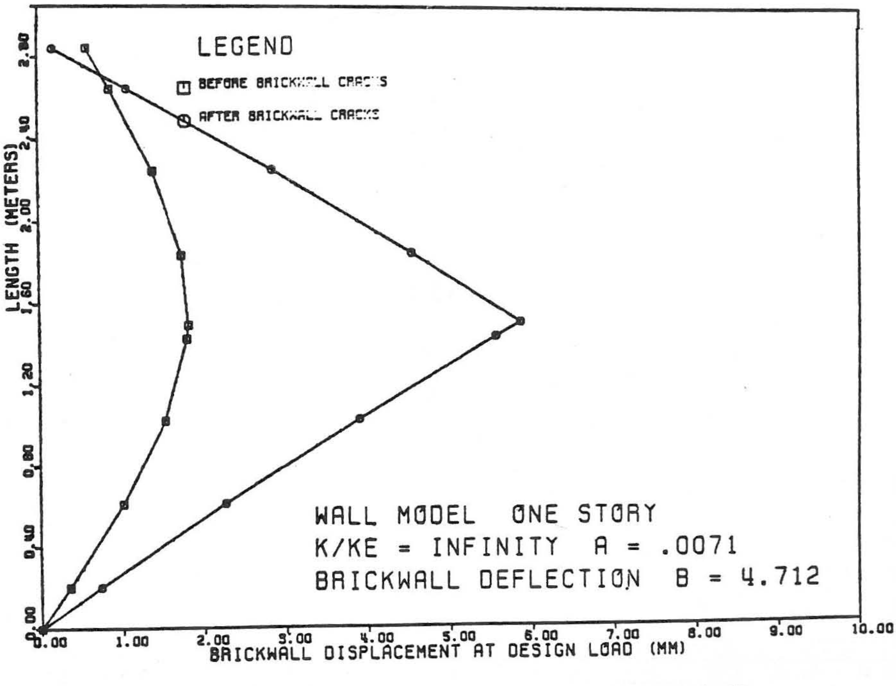

Fig. 9 Computed Displacement Profile of Brick Veneer at Design Load (1.17 kN/m^2) Before and After Cracking

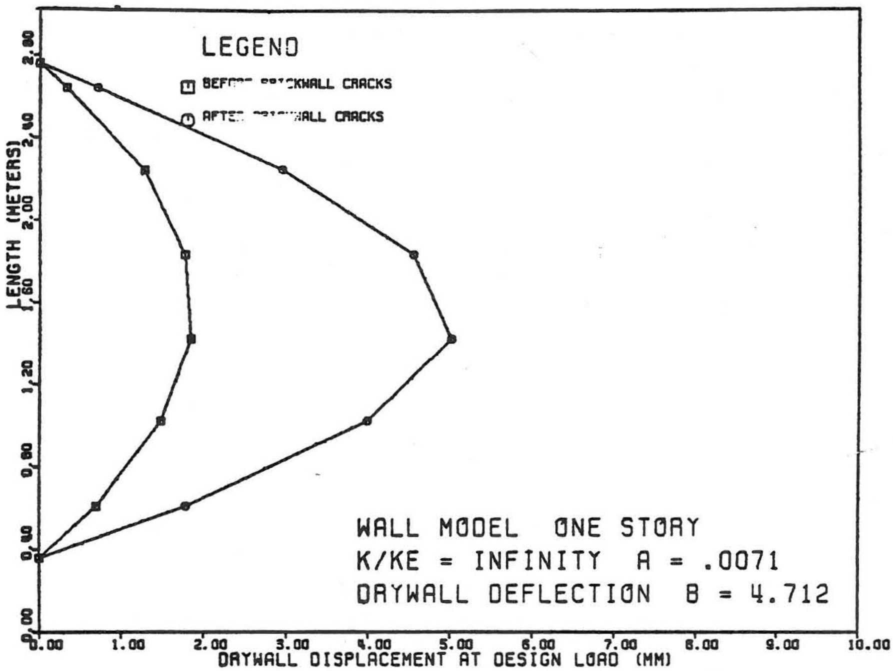

Fig. 10 Computed Displacement Profile of Drywall at Design Load (1.17 kN/m^2) Before and After Cracking of the Brick Veneer

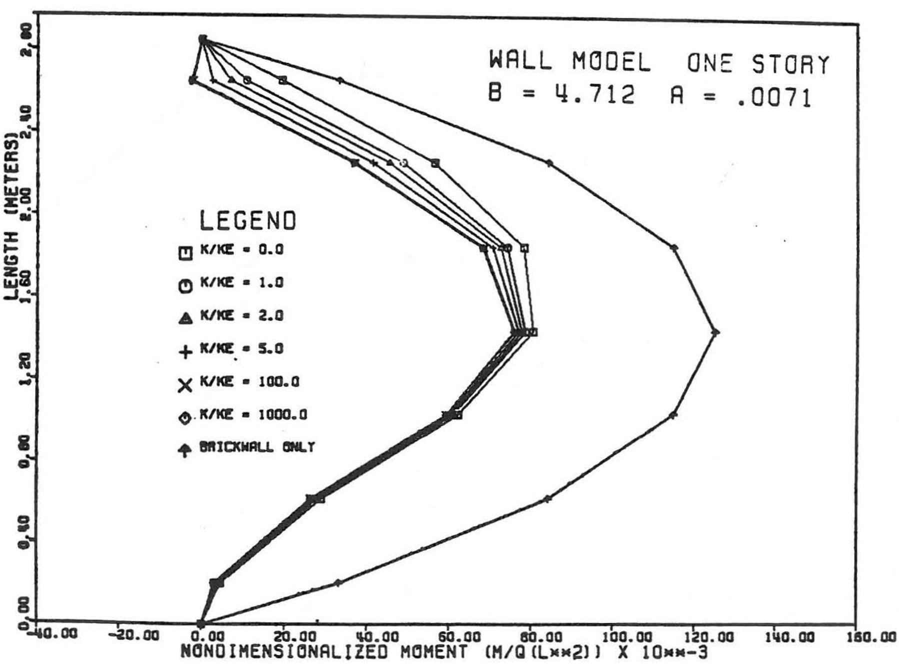

Fig. 11 Nondimensionalized Bending Moment Diagram of Brick Veneer for Various Ratios of K/KE with Stiff Ties

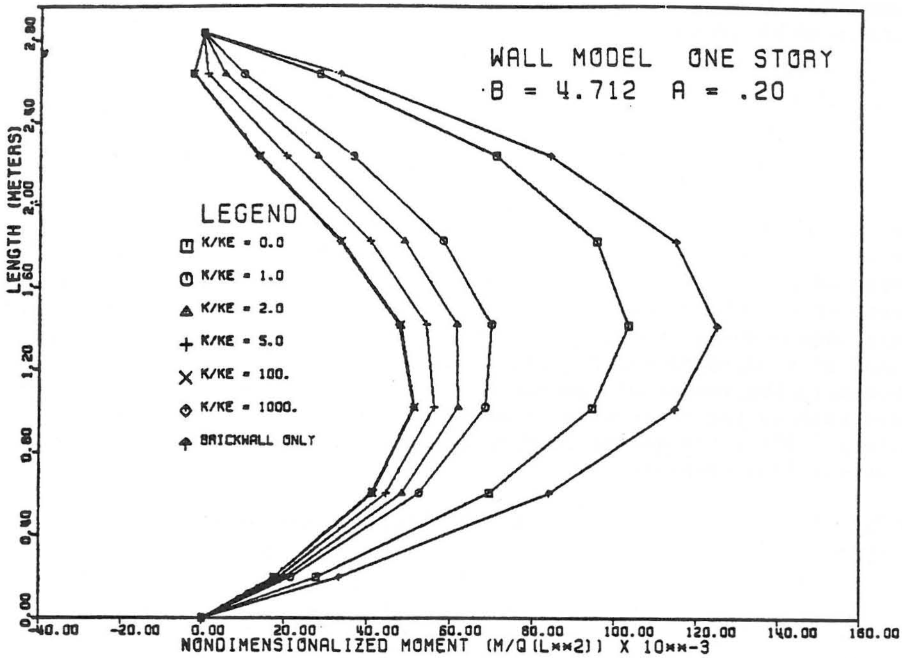

Fig. 12 Nondimensionalized Bending Moment Diagram of Brick Vener for Various Ratios of K/KE with Flexible Ties

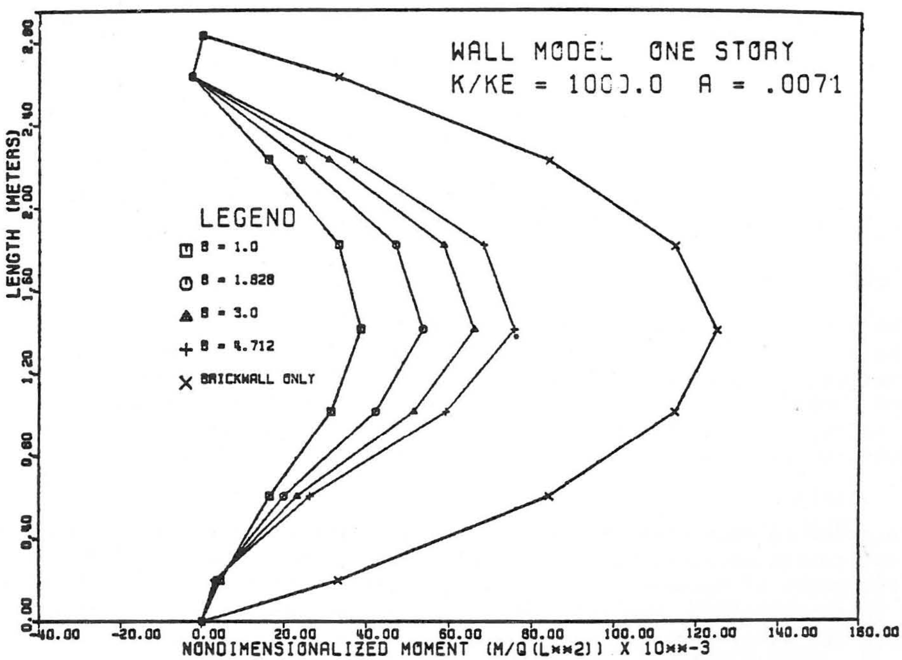

Fig. 13 Nondimensionalized Bending Moment Diagram of Brick Veneer for Various Ratios of Flexural Stiffness with Stiff Ties