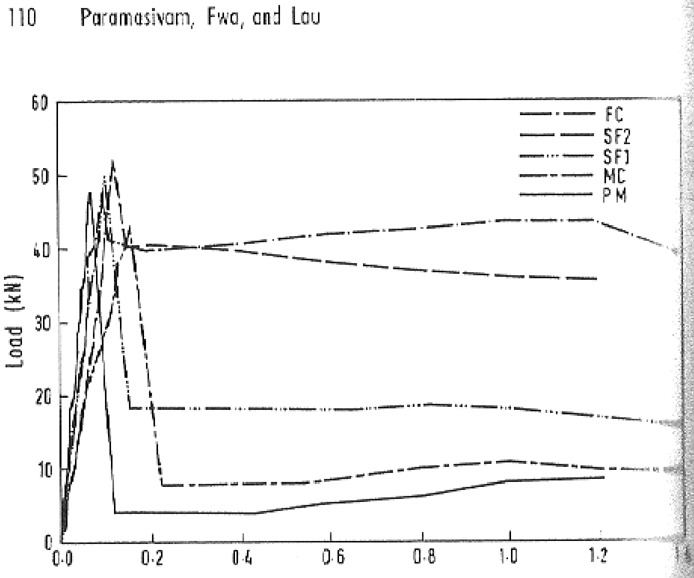
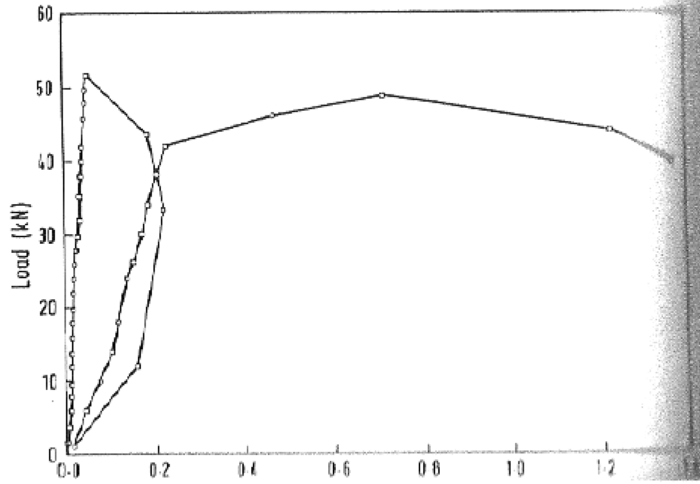


Fig. 6—Comparison of experimental load deflection curves of specimens with different overlay



SP 146-8

Behavior of Ferrocement Moment Resisting Joints

by H. Hammoud and A.E. Naaman

Synopsis: An experimental program was carried out to investigate th behavior of ferrocement bolted moment resisting joints. Eightee ferrocement moment joints and four control ferrocement plates wer tested under third point flexural loading. The moment joints wer fabricated by joining two L-shaped ferrocement elements with bolts The parameters investigated were the number of mesh layers, th corner distance of the first bolt, the number of bolts, and the momen modes (closing corner and opening corner modes). Results describin the load deformation response as well as the failure mode ar presented. As expected, the joints failed by premature cracking alon the corner section of the L-shaped elements. The bending capacity o the joint ranged from 36% to 90% of that of the control plates depending on the test parameters. The joint performance wa improved by more than 50% when a fillet was added, and the failur crack was moved from the corner to one of the legs. The fillet was mor effective for the elements subjected to the opening mode moment, tha for the closing mode moment.

Keywords: Bearings; bolted connections; bolts; composite materials; connections; ferrocement; flexural strength; joints (junctions); moments; panels

H. Hammoud is a Doctoral Candidate and Research Assistant at The University of Michigan, Ann Arbor. He got his Diploma in Civil Engineering from the Universidade Federal do Parana, Brazil, and his M.S.E. in Structural Engineering and his M.S.E. in Applied Mechanics from The University of Michigan, Ann Arbor. His research interests are in ferrocement housing, and in fatigue of concrete structures.

Antoine E. Naaman, FACI, is a professor of civil engineering at the University of Michigan, Ann Arbor. He is a member of various ACI Committees, including 544, Fiber Reinforced Concrete; and 549, Ferrocement and other Thin Reinforced Products. His research interests include prestressed concrete and high-performance fiber reinforced cement-based composites.

INTRODUCTION

The use of bolted joints to transfer loads between ferrocement elements is suggested for numerous applications, yet little technical information has been developed to allow for their implementation. To date only one experimental investigation on ferrocement bolted joints is known to the authors (1). Other experimental investigations deal with ferrocement wet joints (2), and most modeling and analytical work deals with steel joints (3,4,5,6). Applications where bolted ferrocement joints can be used range from water tanks (7), irrigation channels, and roof panels to entirely panelized housing systems where the connections between panels are bolted (8,9). To ensure the economic and safe use of such connections, a clear understanding of the mechanical behavior of ferrocement bolted joints is needed.

A panelized ferrocement housing system using bolted joints was described in two previous publications by Naaman, and Naaman and Hammoud (8,9). Bolted connections were shown to transfer a combination of axial force, moment and shear force between the ferrocement panels. To evaluate analytically the performance of such connections, two approaches can be followed. The first approach would start with a global structural analysis (such as by the finite element method) to identify the forces transmitted by the various joints; then, to verify and supplement the analysis, real size specimens of all the different joint configurations present in the housing unit would have to be tested in the laboratory. This would be a very costly approach. However, an alternative and somewhat more fundamental approach was chosen for this investigation.

Typical joint configurations, that are in reality only parts of the real bolted connections present in the panelized system, were identified. They were reduced to two fundamental joints defined as shear type joint and moment type joint. The moment resisting joint is also often called an axial connection since it transfer axial forces as well. In shear type joints, the load resisting mechanisms are friction an bearing. The friction resistance is usually not reliable, since in mos ferrocement applications it is not economically feasible to control th bolt preload during the life of the structure. If the friction resistance i neglected, the shear type joint is also called a "bearing joint" (Fig. 1).

The main advantage of the second approach is that, as the joint are generic types, the results are general and can be applied in othe ferrocement applications. It should be observed that, in all cases, th bolts are assumed designed to resist and transfer applied force without failure; that is the weak link of the connection is the ferrocemen material itself.

This study focuses on the behavior of moment type ferrocemen joints as observed from experimental tests. These joints were forme by joining two L-shaped ferrocement elements with steel bolts as shown in Figs. 1 and 2. It can be observed that whether a panel is subjected to axial forces or bending moments, the ferrocement materia in the vicinity of the bolts is subjected to flexural moments that can cause some type of localized failure. This is specially critical in the region near the corners of the panels where stress concentrations can cause premature failure. The usual failure modes of moment joints are failure of the bolt due to axial loads (here ruled out), flexural failure of the joined material in the corner region due to stress concentrations, and excessive separation of the joined plates.

The present experimental investigation aims at providing information regarding the ultimate load capacity, failure modes and deformation characteristics of ferrocement moment joints. The study on bearing joints is still under investigation and will be presented in a future publication.

RESEARCH SIGNIFICANCE

A gap exists in the current technical literature with regard to bolted joints and connections in ferrocement elements. The results of this research should lead to a better understanding of the behavior and mechanisms of failure of ferrocement joints, and should help design some guidelines for their use in future construction, particularly in prefabricated ferrocement panelized housing systems.

EXPERIMENTAL PROGRAM

Eighteen ferrocement moment joints and four control ferrocement plates were tested under four point bending (Fig. 3). The specimens, all reinforced with the same type of welded square mesh, were divided in six series (Fig. 4) depending on the number of bolts, the corner distance, the moment mode (closing mode moment and opening mode moment), and whether they had a fillet or not. Control flexural plates with the same thickness and number of layers were also tested along the same clear span and loading set-up.

Test Parameters

The parameters investigated in the experimental program were as follows (Fig. 2):
1) Corner Distance *c*: it is the distance between the center of the first bolt and the outside corner edge of the joint. The two corner distances used were *c*=1.25" and *c*=2.0", i.e., 2.5 to 4 times the thickness of the ferrocement material.
2) Number of mesh layers: specimens with 2, 4, 6 and 8 layers of square welded mesh were tested.
3) Number of bolts: the moment joints were connected by 1 or 2 bolts.
4) Moment mode: most of the specimens were tested in the corner closing mode moment. Some specimens were also tested in the corner opening mode moment.
5) Fillet: due to the relatively poor performance in the opening mode moment, some specimens were also strengthened in the corner region with a fillet.

Mortar

The same mortar mix was used throughout. The cement mortar was fabricated with ASTM Type III high early strength cement. The sand was a graded silica Ottawa sand, ASTM C-109. The mix proportions by weight were: cement=1.0; sand=2.0; water=0.4; melamine based superplasticizer =0.025. The mortar average compressive strength, tested from 3X6 cylinders, was about 8.5 Ksi at 15 days (approximate time of testing).

Reinforcing Meshes

A welded square mesh, with 0.25 in wire spacing, and 0.025 in wire diameter, was used throughout. The mesh yield strength was of the order of 50 ksi.

Bolts

The bolts (fasteners) utilized were standard grade 2 Hex (Screws, 0.5 in in diameter and 2.5 in long (Grade 2, 1/2", 2.5"). E the bolt's shank and threaded portion had a length of 1.25 in.

Fabrication of Specimens

The specimens were assembled from two L-shaped ferrocem elements with a thickness of 0.5 in and a transverse width of 5.0 in; lengths of the L-shaped elements measured along the longitudi direction were 9.75 in along the longer side and 5.75 in along t shorter side (Fig. 5). The control flexural specimens were ferrocem flat rectangular plates 18 in long, 5 in wide and 0.5 in thi (18"x5"x0.5"). The preparation procedure for the different specime was similar and it is described next.

The reinforcing mesh was cut to the proper dimensions, a bent to conform to the final specimen shape (Fig. 5). Plexiglas mol were used, and steel pins (of same diameter as the bolts) were glued the internal walls of the molds in the locations of bolt holes. This wa done to produce smooth lateral surfaces around the hole. Th reinforcing mesh was then carefully placed inside the mold to fit th glued pins in the position of the holes. The internal surface of the mo and the pin external surface were oiled to facilitate specimen and p removal after hardening of the cement.

The mortar was prepared in a food type mixer. The cement an sand were mixed first, then water and melment were added to th solution. The molds were then placed into a vibrating table and th mortar was poured. The specimens were removed from the forms 2 hours after pouring. The steel pins were then removed from th specimens, and the specimens were placed in a water tank where the cured for about 14 days. Before testing on the 15th day, they wer coated with a lime solution to facilitate observation of cracking.

In the final stage of preparation of the moment joints, pairs o ferrocement L-shaped elements were connected with bolts through the holes. The bolts were tightened with a torque wrench to a torque valu between 450 lbs-in and 500 lbs-in. This was the maximum torque valu that could be manually applied with reasonable effort.

Instrumentation and test Set-up

All the specimens were tested in a machine with 30 Kips capacity in tension and compression. The specimens were tested under displacement control. The rate of loading was 0.06 inch/min for all tests.

The data collection was achieved by means of a non-contacting motion measuring instrument connected to a data acquisition system controlled by a computer. The system consists of a central control unit, a set of infrared sensitive cameras, and infrared emitting markers (or targets). The markers are attached to the specimen and the camera can sense their positions in the tri-dimensional coordinates. The software can record the positions of the markers relative to a XYZ reference frame which is also automatically built by the system. The system also contains channels that accept analog input data such as load and displacement transducers.

The data collection was carried at a rate of 1 Hertz for all test specimens. Measurements of loads and displacements were recorded. The displacements were measured by both the infrared markers, and by conventional LVDT's (Linear Voltage Differential Transducer). The markers were glued to the specimens with 'Rubber Silicone' just before testing. The LVDTs were placed in proper fixtures attached to the specimens.

The joined L-shaped ferrocement elements formed a flexural member that was tested under four point loading. Thus, the joint at midspan transferred moment only. The specimen was simply supported with a clear span of 15 in, and the loads were applied at a distance of 5.0 in from the supports, through a spread beam. Specimens were tested under two different positions, so as to apply moments in the opening corner mode and closing corner mode (Fig. 3).

Six infrared markers and two LVDT's were utilized in the data collection. The six markers were placed along the sides of the two joined faces of the specimens, three on each face. This configuration was chosen to obtain relevant data on the joint opening and assembly displacement. The first pair of targets was placed in the corner portion of the plate, the second pair along the portion between the corners and the level of the first bolt, and the third pair at the same level as the first bolt. The two LVDT's were utilized to backup the data obtained from the markers. One LVDT was used to measure deflection and the other one was used to measure joint opening.

The control flexural specimens were subjected a third point loading with a span of 15 in between supports. The test set-up, including dimensions, was identical to the one used for the moment joints. Four infrared markers were placed along the constant moment region of the specimen, two of them directly under the points of load application and two others closer to mid-span. Two LVDT's were also utilized to backup the values measured by the infrared markers.

TESTS RESULTS

Cracking and Failure Modes

As mentioned above, eighteen ferrocement moment joints anc four control ferrocement plates were tested in bending. All specimens failed by cracking of the ferrocement plate. Four different location o cracks were observed, depending upon the moment mode and the presence or not of the fillet (Fig. 6). For the specimens without fillet an subjected to the closing mode moment, premature crack occurred i the vicinity of the corner in one of the legs. When a fillet was added, th crack occurred at the ends of the fillet, in one of the legs. For th specimens without fillet subjected to the opening mode moment, diagonal crack formed and propagated along the corner itself. In th three cases mentioned above, once the crack opened, it propagate rapidly and no other cracks were observed to continue opening in tl plate. For the specimens with fillet subjected to the opening mome mode, a number of small cracks occurred in the region below tl application of the load. These cracks opened gradually as the load w increased, until flexural failure of the plate occurred.

The test parameters as well as the failure loads observed in specimens tested are summarized in Table 1. The ratio between t joint capacity and that of corresponding control specimen is a presented. The following observations were made.

In Series A, the specimens were joined with 2 bolts, the cor distance was 2.0 in (c=2.0"), the distance between bolts was 2.((b=2.0"), the specimens were loaded in the closing corner mode they did not have a fillet. In this series, the four specimens failec premature cracking in the corner region. The ratios between ultimate strength of the moment joints and that of the control specir were 0.52, 0.78, 0.4 and 0.44 for the specimens reinforced with 2, and 8 layers respectively. The lower strength value observed ir specimen reinforced with 6 layers was probably due to misalignmer the set-up.

In series B, the specimens were joined with 2 bolts, the c distance was 1.25 in (c=1.25"), the distance between bolts was 2. (b=2.75"), the specimens were loaded in the closing corner mode they did not have a fillet. The four specimens tested in this series failed by premature cracking in the corner region. The ratios between the ultimate strength of the moment joints and that of the control specimens were 0.65, 0.6, 0.82 and 0.68 for the specimens reinforced with 2, 4, 6 and 8 layers respectively. On the average, when compared with series A, the specimens of series B showed higher ultimate strength values. Since the only difference between these two series is the corner distance, it can be concluded that the smaller corner distance of Series B causes an increase in the ultimate capacity of the joint.

In series C, the specimens were joined with only 1 bolt, the corner distance was 1.25 in (c=1.25"), the specimens were loaded in the closing corner mode and they did not have a fillet. Failure was by cracking around the corner region. The joint strength obtained corresponds to 0.85, 0.62, 0.72 and 0.45 of the strength of the control plates, for the specimens reinforced with 2, 4, 6 and 8 layers respectively. The lower strength value observed in the specimen reinforced with 8 layers was probably due to misalignment in the set-up. The only difference between series B and C is that, in the former 2 bolts were used, while in the latter only 1 bolt was utilized. Results indicate that the addition of the second bolt away from the corner did not influence the joint strength, since on the average, the relative strength for these two series was very similar. Furthermore, the higher load values observed for series C when compared with series A confirm the fact that the smaller corner distance causes an increase in strength.

In Series D and D', the corner distance was 1.25 in (c=1.25"), the specimens were loaded in the opening corner mode, and they did not have a fillet. The two specimens failed by a very premature cracking of the corner region. In series D, one specimen reinforced with 4 layers of square mesh was tested and it had a single bolt. For this specimen, the joint strength obtained corresponds to 0.38 of the strength of the control specimen. In series D', one specimen reinforced with 4 layers of square mesh was tested and it had two bolts. For this specimen, the joint strength obtained corresponds to 0.36 of the strength of the control specimen. The fact that the two values are almost identical suggest that the second bolt is not effective. Furthermore, the strength was smaller than that of the 4 layers specimens of series A, B and C tested under the closing mode moment; this suggests that, everything else being equal, the opening mode moment is more critical that the closing mode moment.

In series E and E', the four specimens tested had a fillet, had 1 bolt, and due to the presence of the fillet, the corner distance was 1.75 in (c=1.75'). In series E, two specimens, reinforced with 4 and 6 layers, were tested in the closing mode moment. The two specimens tested in the closing mode failed by cracking in the corner region at the edge of the fillet. Strength values were 58% and 60% of the strength of the corresponding control specimens for the 4 layer and 6 layer specimens respectively. These values are smaller than those for the specimen without fillet, but this could also be partially caused by the increase corner distance. The two specimens of series E', tested in the openin mode, failed in the leg regions, away from the corner and under the third points. For these specimens, the strength ratios obtained were 90% and 83% for the 4 layer and 6 layer specimens respectively. The failure mode observed in these two specimens suggests that the specimens attained almost the full flexural capacity and that the fille was very effective in eliminating cracking in the corner region.

Load-Deflection Response

Typical load vs. midspan deflection curves for specimens subjected to the closing mode moment and without a fillet are shown in Fig. 7. The curves are for specimens reinforced with 6 and 8 layers of mesh having different number of bolts and corner distance. The increase in strength with the decrease in corner distance is clearly illustrated. Typical load vs. midspan deflection and load vs. joint separation (at level of corner) for specimens reinforced with 2 layers of mesh are shown in Fig. 8. It can be observed that a decrease in corner distance caused an increase in strength and a decrease in joint separation. Typical load vs. midspan deflection for the specimens with a fillet are shown in Fig. 9. The curves correspond to specimens reinforced with 4 and 6 layers of mesh. It can be seen that the presence of the fillet in the opening mode moment is more effective than in the closing mode moment. Photographs of typical specimens after failure are shown in Fig. 10.

CONCLUSIONS

The following conclusions can be drawn from this experimental investigation:

1. As anticipated, the critical region of ferrocement joints is the corner region where premature cracking and failure occurred at load ranging from 36% to 85% of the theoretical flexural capacity of the section.

2. The opening mode moment is more critical to the joint than the closing mode moment. The capacity of the joints without fillet subjected to the opening moment and closing moment modes correspond, on the average, to 37% and 60% of the capacity of the control specimens respectively.

3. A decrease in the corner distance from c=2.0" to c=1.25" causes an increase of approximately 12% in the capacity of the joints subjected to the closing moment mode.

4. Since joint failure generally occurred in the corner, the addition of a second bolt away from the corner did not contribute to the strength of the joint whether a closing moment or an opening moment was applied.

5. The use of a fillet is very effective in preventing stress concentration in the corner region, and in transferring cracking and failure from the corner region to the legs of the specimen. For joints subjected to the opening mode, the addition of the fillet caused a strength increase of the joint from 36% to 90% of the control strength. For the joints in the closing mode, however, no significant effect was observed, because the main crack simply moved to the end of the fillet.

6. The addition of mesh layers causes an increase in the absolute strength of the joints. The efficiency of the joints (strength ratio), however, showed variable trends with the increase of the number of mesh layers.

REFERENCES

1. Krishnamoorthy, T. S., Parameswaran, V. S., Neelamegam, M. and Balasubramaniam, K., "Investigation of Precast Ferrocement Planks Connected by Steel Bolts," ACI Special Publication, SP-124, pp. 389-403.

2. Paramasivam, P. and Mansur, M. A., "Tensile and Flexural Behavior of Joints in Ferrocement Construction," ACI Journal, Vol. 82, 1985, pp. 710-715.

3. Holmes, M, and Martin, L.H., "Analysis and Design of Structural Connections - reinforced concrete and steel," Ellis Horwood, England, 1983.

4. Bickford, John H., "An Introduction to the Design and Behavior of Bolted Joints," Decker, 2nd Edition, 1990.

5. Kulak, G. L., Fisher, J. W., and Struik, J. A. H., "Guide to Design Criteria for Bolted and Riveted Joints," Wiley, 2nd Edition, 1987.

6. Blake, A. " Design of Mechanical Joints," Decker, 1985.

7. Paramasivam, P. and Nathan, G. K., "A Prefabricated Ferrocement Water Tank," ACI Journal, Vol. 81, 1984, pp. 580-586.

8. Naaman, A. E., "Ferrocement Housing: Toward Integrated Hig Technology Solutions," Journal of Ferrocement, Vol. 19, No. 2, 198 pp. 141-149.

9. Naaman, A. E. and Hammoud, H., "Ferrocement Prefabricate Housing: The Next Generation," Journal of Ferrocement, Vol. 22, No. January 1992, pp. 35-47; also published in the proceedings of th Fourth International Symposium on Ferrocement, La Havana, Cub October 1991.

TABLE 1 — SUMMARY OF RESULTS

Series	Moment Mode	Number of Bolts and Distances	Number of Layers	Ultimate Strength (lbs-in)	Joint/ Control Ratio
A	Closing	2 Bolts c=2.0" b=2.0"	2	151.5	0.52
			4	381.0	0.78
			6	314.5	0.40
			8	524.0	0.44
B	Closing	2 Bolts c=1.25" b=2.75"	2	187.7	0.65
			4	294.5	0.60
			6	626.7	0.82
			8	806.0	0.68
C	Closing	1 Bolt c=1.25"	2	248.2	0.85
			4	304.5	0.62
			6	552.2	0.72
			8	528.0	0.45
D	Opening	2 Bolts c=1.25" b= 2.75"	4	185.7	0.38
D'	Opening	1 Bolt c=1.25"	4	177.2	0.36
E	Closing	1 Bolt, fillet c=1.75"	4	286.5	0.58
			6	467.7	0.60
E'	Opening	1 Bolt, fillet c=1.75"	4	445.5	0.90
			6	634.7	0.83
Control	------	-------- ---	2	290.0	1.00
			4	489.7	1.00
			6	767.5	1.00
			8	1175.0	1.00

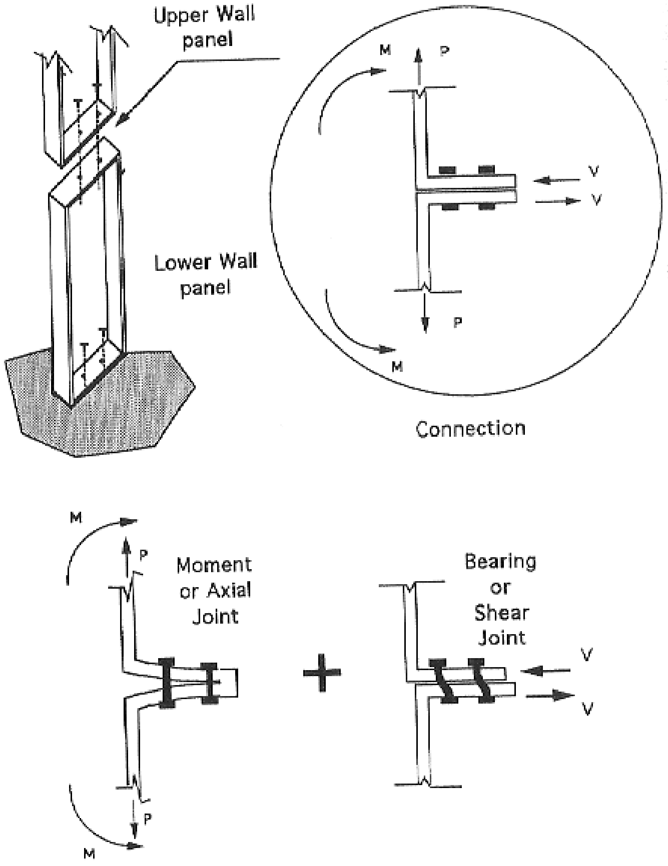
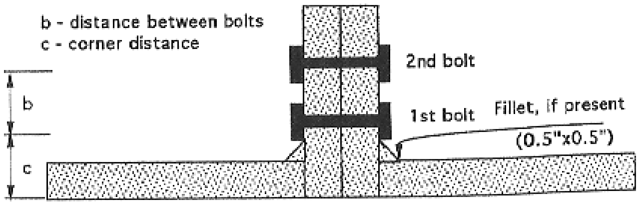
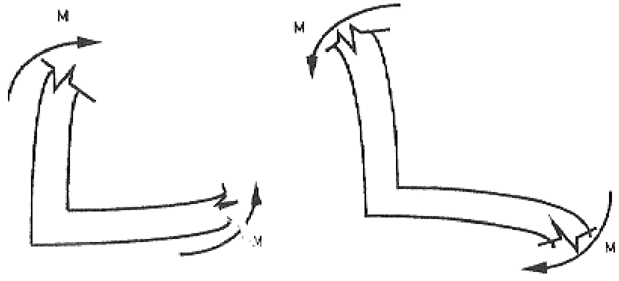


Fig. 1—Fundamental types of joints

Specimen Geometry



Moment Mode



Closing Mode Moment

Opening Mode Moment

Fig. 2—Test parameters

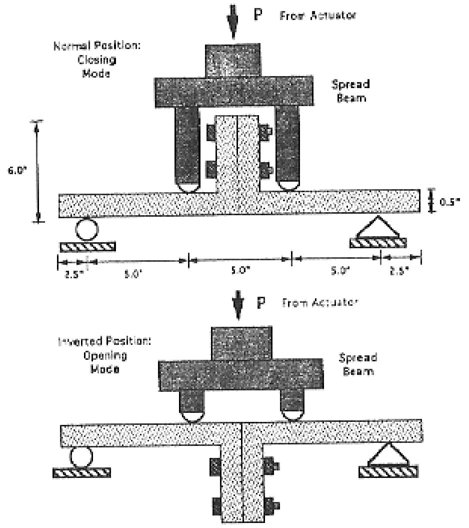
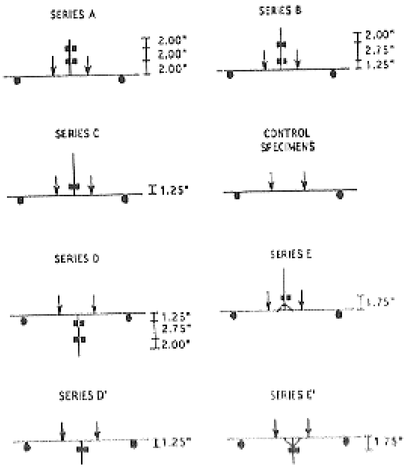
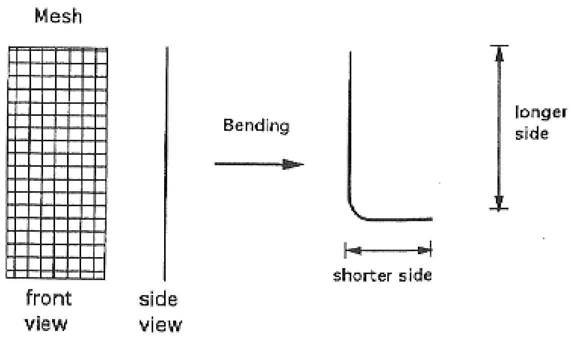
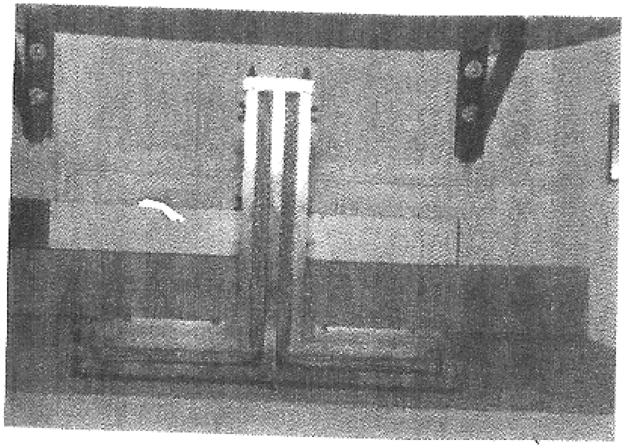


Fig. 3—Test set-up







[illegible]

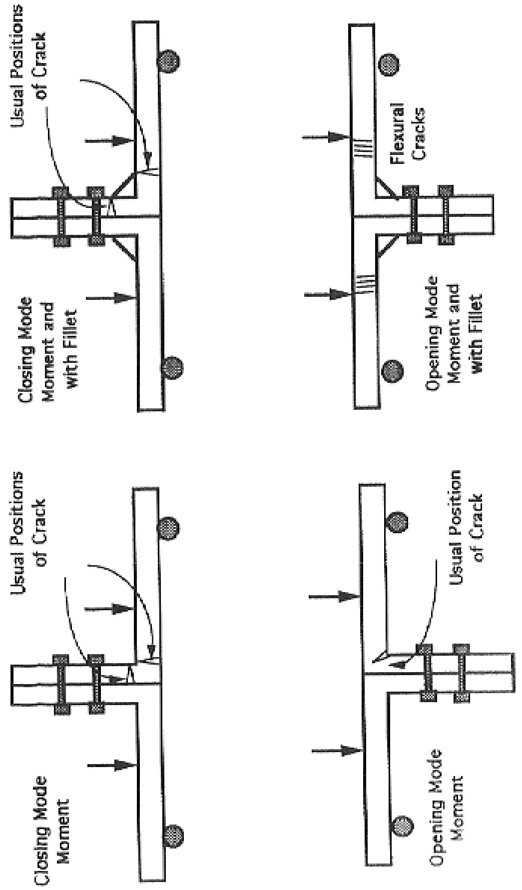
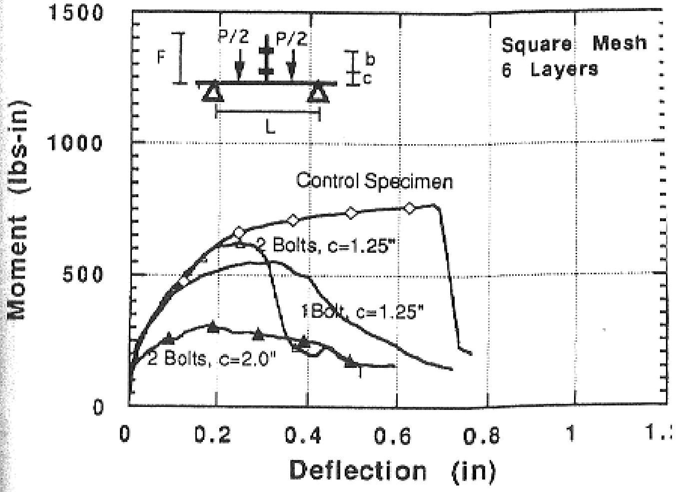
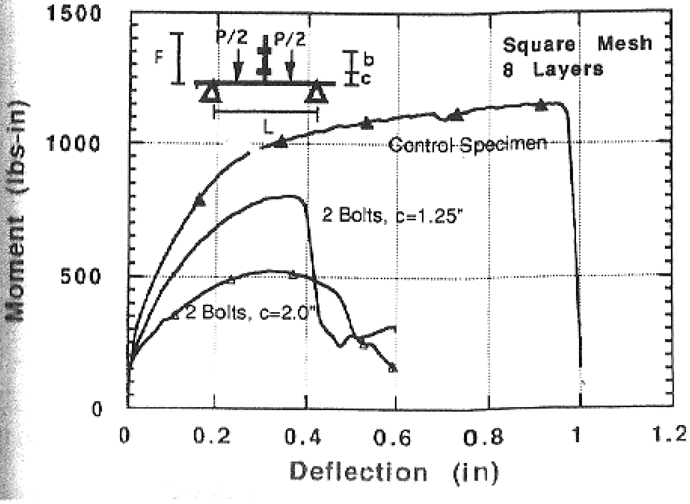


Fig. 6—Observed failure modes





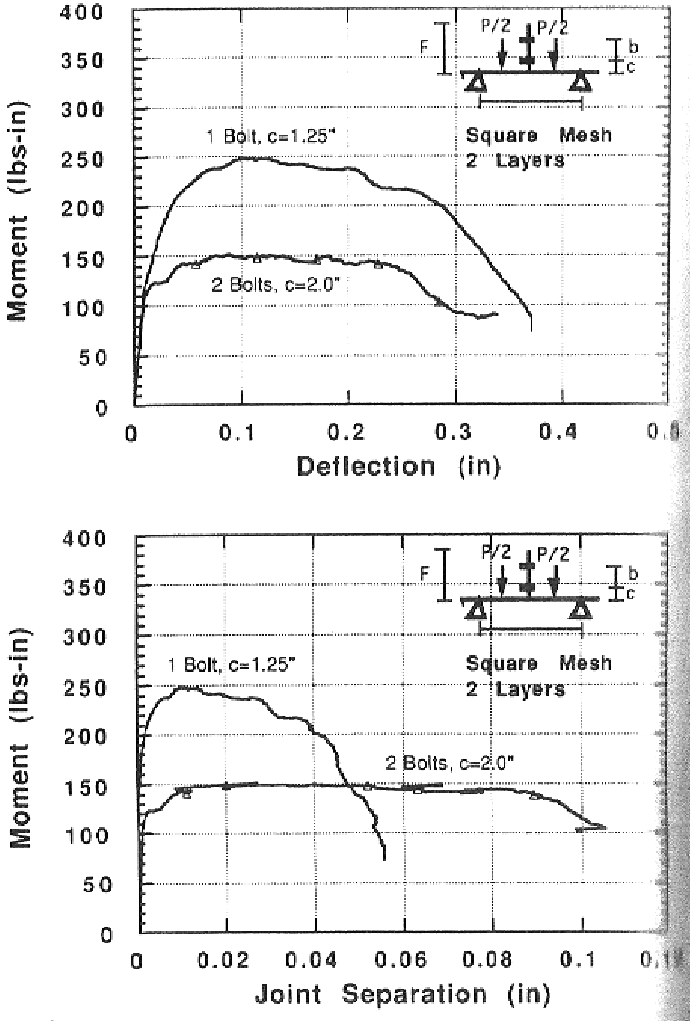


Fig. 8—Typical load-deflection and load-separation curves

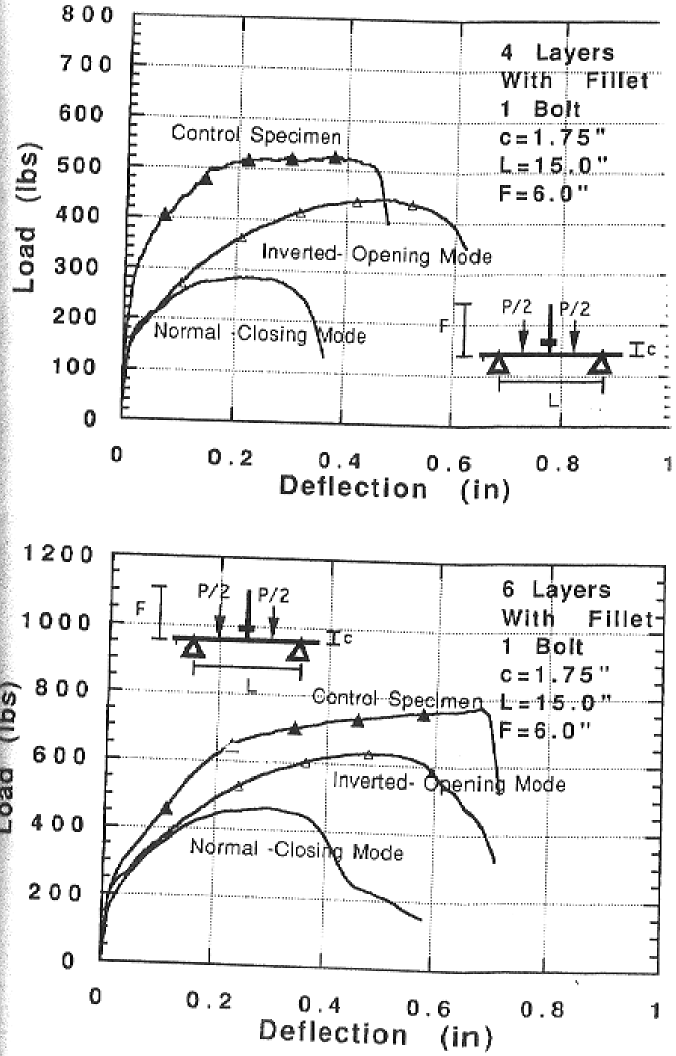


Fig. 9—Typical load-deflection curves for specimens with a fillet

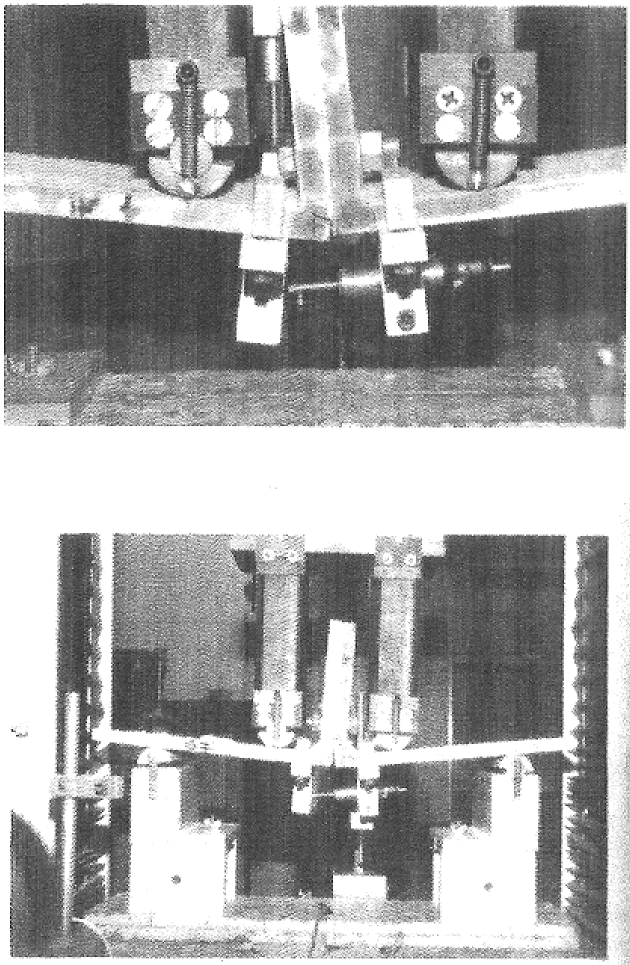


Fig. 10—Typical specimens after failure

Statistical Evaluation of the Physical Properties of Wood Fiber-Cement Composites

by P. Soroushian, S. Marikunte, and J.P. Won

Synopsis: A comprehensive experimental program based on the statistic concepts of fractional factorial design was conducted to investigate the effect of various mix variables on the physical properties of wood fiber reinforce cement composites. The variables investigated were: fiber type, fiber content pozzolanic admixture, and silica sand content. The composites wer produced through slurry-dewatering and effect of the above variables on th following properties were studied: specific gravity, water absorption anc moisture movement.

Keywords: Admixtures; composite materials; fibers; physical properties; pozzolans; sands; silica; statistical analysis