TESTING OF A MODEL COMPOSITE BEAM WITH WEB OPENING

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INTRODUCTION

1.1 General

Composite construction has long been used as an efficient, economical design alternative for bridges and multi-story structures. Composite construction utilizes rolled steel members mechanically connected to reinforced concrete slabs. The mechanical connection is provided by studs welded to the top flange of the steel beam. The studs are later embedded in the concrete slab. When loaded, these composite members act homogeneously allowing for more efficient utilization of the concrete and steel.

Composite floor systems, for example, have grown in popularity because of this efficiency. Savings in steel costs, reductions in the depths of floor members required, and increased floor stiffness are all advantages of using composite floor systems.

To further increase the economy of such systems, designers have begun to reduce and/or eliminate spaces below floor beams and girders previously reserved for heating, ventilation, and utility ducts, by utilizing web openings. These openings, holes cut into the webs of the beams, allow the duct work to pass through the beams rather than under them, resulting in reduced story heights which lead to reduced heights in many multi-story structures.

These beams, however, have a lower strength than do similar beams in which the webs remain intact. Therefore, the strength and behavior of beams with web openings, and even more specifically, composite beams with web openings, must be investigated to determine just what effect opening size, location, and orientation have on the performance of the member. A number of tests on full scale composite members have been conducted, and several design criteria suggested, but a large number of tests investigating all of the parameters and verifying proposed theories have yet to be completed, due in part to the prohibitive cost of fabricating and testing full size members.

The development of model composite beams with web openings that could be used to predict behavior of larger prototype beams would permit more, comprehensive, complete tests of these members to be conducted, and would allow additional important parameters to be explored at a much lower cost. These smaller beams (models) could be fabricated and tested in laboratories not otherwise capable of testing full size composite members, and the results used to verify design criteria for composite members with web openings.

1.2 Review of Previous Work

In 1980, Clawson and Darwin (3,4) published the results of their study of composite beams with web openings. The study included fabricating and testing six, simply-supported, composite beams with concentric, unreinforced, rectangular web openings. The six beams ranged in length from fifteen to twenty four feet and consisted of steel W shapes (W14 x 34, W18 x 45, and W18 x 46) and reinforced concrete slabs four feet wide and four inches thick.

Clawson and Darwin also compared the results of the six tests with values predicted by several ultimate strength theories, one developed and presented in the study. In most cases, the theory provided reasonable, although conservative, predictions of the test beams' ultimate strengths.

In 1981, Scully (7) fabricated and tested a model composite beam with a web opening at Kansas State University. His steel beam, an S4 x 9.5, modeled a prototype W18 x 45 tested by Clawson and Darwin at the University of Kansas (4). The model steel beam and concrete slab provided a geometric scale factor of approximately 4.5 relative to the prototype.

The thickness of the model beam's web was reduced by milling the web in the vicinity of the opening to provide a similar scale factor for web thickness. Mechanical connection between the slab and the beam was provided by steel bolts tapped into the top flange of the steel beam. The results obtained from this model beam test, although somewhat limited, seem to suggest that the behavior of full size composite beams with web openings can indeed be predicted using the results of a model composite beam test.

In 1986, Gattani fabricated and tested another model composite beam with a web opening at Kansas State University (5). The W8 x 10 and 1.82" x 21.82" micro-concrete slab were to model another of the Clawson and Darwin beams (4). The model was a 1:2.2 scale model utilizing threaded steel rods for reinforcement, a micro-concrete mix developed at Kansas State University (8), and model shear studs provided by the Nelson Stud Welding Company. The model beam was instrumented with electronic strain gages similar to those used on the prototype.

Analysis of the results obtained by Gattani indicate that the procedure followed yielded results very near those predicted utilizing the concepts of similitude. The model beam failed in much the same way as the prototype and at a load within 10% of the expected "model" value.

1.3 Objective and Scope

Almost all research in the area of composite beams with web openings has been done on large members requiring special testing equipment. This research has been expensive and limited only to those labs in which large members can be fabricated and tested.

To further investigate the effects of web openings in composite beams, more tests must be conducted on members of different sizes and with different types, locations, and orientations of openings. The first step in developing such a program may very well be the development of experimentally verified modeling techniques.

Therefore, the main objective of this research was to fabricate, test, and analyze another model composite beam with web opening. The results are to be used to further establish the validity of predicting full size member behavior on the basis of model tests and to help establish and refine composite beam modeling techniques.

PRINCIPALS OF MODELING

The theory behind modeling structures, both steel and concrete, and predicting full size member behavior based on tests of the model is well developed and discussed in many texts. All point out how important it is that all structural models be fabricated and tested according to a set of similitude relations. These relations make it possible to accurately predict a prototype's behavior based on the results of an often simpler and less expensive model test. Similitude relations pertaining to a structural model such as a model composite beam are discussed and summarized by Gattanni (5) and are repeated in Table 2.1. The relations presented are based on a stress scale factor of one.

One approach to fabricating, testing through failure, and analyzing a structural model it to employ a "Direct Model" made from materials with properties identical to those used in the prototype. This requirement is often relaxed, however, in the case of reinforced concrete models where the concrete stress-strain relationship, failure strain, and failure mode and the reinforcing steel's yield strength, elasticity, and bond development all become important, to the point where material properties are only required to be similar. As pointed out by Sabnis, Harris, White, and Mirza (6), "...these limitations (material properties being impossible to model exactly) are not serious, as long as the physical properties of the model concrete, including its stress-strain curve and the failure criterion, are compatible with those of the prototype concrete according to the laws of similitude ...."

The preceeding quote clearly points out how vital it is to know as much as possible about the prototype structure and the properties of its components. In attempting to model a beam from the Clawson and Darwin report, important assumptions had to be made concerning the properties of the concrete used simply because those results were not reported. Stress-strain data were supposedly taken but never presented or discussed.

Later, the effect of using a model concrete significantly different from the concrete used in the prototype will be examined and discussed. In lieu of actual data, the modulus of elasticity for the prototype concrete was assumed to be that of normal weight concrete as provided in the ACI Code (1).

DESCRIPTION OF PROTOTYPE BEAM

3.1 General

The composite beam modeled is Beam Number 4 of the University of Kansas tests (4). The fifteen foot long, simply-supported member had a moment-to-shear ratio of three feet at the centerline of the 10.81" by 21.62" rectangular opening. The beam was symetrically loaded as shown in Fig. 3.1.

3.2 Steel Beam

The steel beam portion of the composite member consisted of a W18 x 45 hot-rolled beam made of A36 steel. Tensile coupons cut from the beam were tested and found to have an average static yield strength of 42.81 ksi for the flange steel and 48.71 ksi for the web steel.

The 10.81" by 21.62" opening was centered on a section of the beam where the moment-to-shear ratio, M/V, was three feet. The web opening was flame cut after 3/4" diameter holes had been drilled at each corner. The holes were employed to reduce stress concentrations at the corners of the opening.

3.3 Concrete Slab

The 48" x 4" reinforced concrete slab consisted of normal weight, Portland cement concrete utilizing 3/4" maximum size aggregate and No. 4 transverse and No. 3 longitudinal reinforcing bars. The concrete strength, f'c, as determined by testing six standard, 6" diameter cylinders was 4460 psi on the day the beam was tested. No values for the modulus of elasticity or failure strain of the concrete are reported by Clawson and Darwin (4).

Slab reinforcement consisted of No. 4 and No. 3 Grade 40 reinforcing bars (Fig. 3.2). Tensile tests on samples of the reinforcing steel showed an average yield strength of 54.50 ksi and an ultimate tensile strength of 82.00 ksi.

Mechanical shear connection between the steel beam and the reinforced concrete slab was provided by 48, 3" long, 3/4" diameter studs (Fig. 3.3) welded to the top flange of the steel beam and embedded in the slab (Fig. 3.4).

3.4 Instrumentation

Electrical resistance strain gages were installed on both the steel and concrete at both the high and low moment ends of the web opening. The gages were recessed in from the edges of the opening and the concrete slab to avoid stress concentrations. A total of 26 gages were used on the prototype (Fig. 3.5).

Vertical deflections of the beam were measured at the centerline of the beam and at both ends of the web opening using dial gages graduated in 0.001" increments. Two additional gages, graduated in 0.0001" increments, were used to measure slip between the concrete slab and steel beam at the concrete-steel interface (Fig. 3.6).

DESCRIPTION OF THE MODEL BEAM

4.1 General

The model composite beam was a 1:2.2 scale model of the prototype beam. A comparison of model beam and prototype dimensions and properties is presented in Table 4.1.

In fabricating the model beam, all "length" dimensions of the prototype became actual dimensions of the model when divided by the scale factor of 2.2. The model beam turned out to be a 6.82' long, simply-supported steel beam and reinforced concrete slab with the centerline of the opening located at a point with M/V ratio equal to a scaled down value of three feet, or 1.36' (Fig. 4.1).

4.2 Steel Beam

The steel beam for the model composite member was a W8 x 10 hot-rolled section of A36 steel. The nearly seven foot section was part of a 20' beam originally purchased for Gattani (5). Coupons taken from the original beam (Fig. 4.2) were tested by Gattani and the results of those tensile tests summarized in Table 4.2.

The opening was cut into the web of the steel beam using a milling machine. 3/8" holes were drilled at each corner of the 4.91" x 9.83" opening, prior to milling, to avoid any unnecessary stress concentrations.

4.3 Concrete Slab

The concrete used in the model slab was a micro-concrete developed at Kansas State University (8). Type I cement, Kaw River sand, and water were used to produce the 135 lb/cu.ft. mix (Table 4.3).

Twenty 3" x 6" cylinders were cast along with the model slab. Fourteen of the cylinders were used to monitor the strength of the concrete slab and to serve as a guide as to when the model beam tests should be conducted (Table 4.4, Fig. 4.3). One of the remaining cylinders was fitted with two electronic strain gages and tested on the same day as the model beam to determine the stress-strain relationship of the micro-concrete (Fig. 4.4). The results of this test, along with tests on the remaining five cylinders, were used to determine the ultimate strength of the model beam concrete. The strength turned out to be 4617 psi or 103.5% of the prototype concrete's strength.

To directly model No. 3 and No. 4 reinforcing bars, complete with similar stress-strain relationships, yield strengths, and ultimate strengths proved to be nearly impossible. Threaded rods were therefore substituted for the "deformed reinforcing bars" required. To model reinforcing strength per foot of slab, 8-32 threaded rods were used as longitudinal reinforcement and 5/16" diameter threaded rods were used transversely (Fig. 4.5). Results of tensile tests run on samples of the threaded rods are summarized in Table 4.2. The yield stress of the rods was determined using the 0.2% offset approach.

Mechanical shear connection between the slab and steel beam was provided by 3/8" diameter studs welded to the top flange of the steel beam. Forty eight, 1-3/8" studs were used, the same number as used on the prototype. The shear, tensile, and push-out capacity of the welded studs were investigated by Gattani (5) and found to be acceptable.

4.4 Instrumentation

As on the prototype, electrical resistance strain gages were installed at both ends of the opening. Gages used on the steel section were 1/8" long while those used on the concrete slab were 1/4" long. Locations of the gages were dictated by the layout used on the prototype as well as space limitations on the smaller beam. A total of

24 strain gages were used on the model beam. The model beam gages, as with those on the prototype, were recessed from the edges of the opening and the edges of the slab (Fig. 4.6). The model has one more longitudinal gage on the top of the concrete slab than did the prototype. This gage was used to obtain data on the stress distribution across the width of the slab.

Vertical deflections of the beam were measured at the centerline of the beam and at the high and low moment ends of the opening using dial gages graduated in 0.001" increments. This procedure was complicated by the testing arrangement of the model beam in that the support points were located on a base beam that also deflected under load (Fig. 4.7). Additional gages were therefore required to correct the vertical displacement values for base beam deflection.

Two additional dial gages were employed to monitor slip between the concrete slab and steel beam. The slip was measured at both ends of the model beam using dial gages graduated in 0.0001" increments.

EXPERIMENTAL PROCEDURE

5.1 General

The model composite beam with web opening was fabricated, tested, and its behavior analyzed in a manner similar to that of the prototype. When the model beam concrete reached the desired strength of 4460 psi plus or minus a few percent, the model beam, base beam, and spreader beam (Fig. 4.7) were moved onto a 300 kip, Emory-Tatnall, hydraulic testing machine. The simply supported beam was loaded through a short spreader beam which rested on bearing plates located on the concrete.

The test program consisted of three parts. The first part involved low, cyclic loads meant to "seat" all of the supports and settle as much freedom of movement out of the system as possible. That completed, slightly heavier loads, still in the elastic region, were used to test the set up, data aquisition instruments, and to obtain elastic data about the member itself. The third and final part of the investigation consisted of an ultimate load test to determine the model beam's ultimate strength and failure mode.

5.2 Elastic Tests

Three elastic tests were conducted on the model composite beam. Before beginning each test, all load was removed from the beam and all strain gages and dial gages zeroed. Load was then applied in 1500 lb. increments until a load of 7500 lbs. had been reached. At each load increment, loading was stopped and all gages read. After reaching a peak load of 7500 lb., the member was unloaded, once again in 1500 lb. increments and with readings being taken at each increment.

5.3 Ultimate Load Test

The ultimate load test began by unloading the beam and once again zeroing all the strain and dial gages. Loading then began in 1.5 kip increments, and as in the elastic tests, readings taken at each load increment. When the relative displacement of the two ends of the opening began to exhibit non-linear behavior, load increment based loading was abandoned in favor of deflection controlled loading. At that point, centerline dial gage deflection was used to determine data collection increments. When the centerline dial gage reached some pre-determined reading, the other gages were read and recorded while the centerline deflection was held constant.

Cracks in the concrete were observed, marked, and noted on the data sheets as they appeared. Load numbers, not load values, were used to identify when the cracks formed and how quickly they progressed through the slab during late stages of the ultimate load test. After failure, the beam was unloaded, clearly marked, and photographed to assist in later analysis of the failure mode.

5.4 Base Beam Deflection Test

Immediately following completion of the ultimate load test on the model composite beam, the model beam was removed from the testing arrangement and a different steel beam inserted in its place. This arrangement was then loaded in the same manner as the model beam and deflections of the base beam recorded at loads up to the failure load of the model beam. Deflection data obtained from this test were later used to correct deflection data taken during the four earlier tests.

5.5 Concrete Cylinder Tests

After the base beam deflection test had been completed, the remaining cylinders of model concrete were tested to determine the strength and stress-strain relationship of the model concrete at the time of testing. The final ultimate strength of the concrete used in the model beam slab, found by averaging the results of the final six cylinders tested, was 4617 psi. The modulus of elasticity of the model concrete, determined experimentally, was 3.41 x 10^6 ksi (Fig. 4.4).

RESULTS OF THE EXPERIMENTAL INVESTIGATION

6.1 General

When an opening is introduced into the web of a member subjected to loading causing shear and moment in the member, the secondary bending moments created by shear being transferred across the opening cause a reduction in the capacity of the beam. This effect, sometimes referred to as the Vierendeel effect, is most pronounced when the opening is located at sections of the beam where shearing forces are large relative to bending moments, or in other words, where the M/V ratio is small.

The openings in the prototype beam and model beam were just such openings, located where the M/V ratios were 3.00' and 1.36' respectively. Such openings are expected to induce relatively large secondary bending moments which lead to large deflections at the high moment end of the opening. This effect was visually evident in the model beam at loads near failure (Fig. 6.1).

6.2 Reduction of Deflection Data

The loading and support system used to test the composite model (Fig. 4.7) required data to be collected for both the model beam and base beam deflection. These values were reduced to yield actual deflection values for all four tests using a Zenith micro-computer and a Multi-Plan program. The program quickly corrected recorded values of model beam deflection for base beam deflection.

6.3 Deflection Results

Although three elastic tests were conducted on the model composite beam with web opening, the results for only one of the tests are included in this report. Results from the three tests were very similar and for the purpose of discussion, only the results of the third elastic test are presented and examined here.

The relative displacement of the two ends of the opening in the elastic range was important to this investigation as it provided a measure of "elasticity" within the composite member. The relative displacement plots for the elastic tests (Fig. 6.2) indicate that the member was indeed acting elastically in the load range used, and it also points out how quickly relative displacement can become significant in beams with web openings.

The deflections of the high moment end, low moment end, and centerline of the beam, presented in Fig. 6.3, also support the idea that the member was acting elastically in the low load range. It is important to note that the greatest deflection was always found at the high moment end of the opening rather than at the centerline of the beam as might have been expected. The least amount of deflection occured at the low moment end of the opening.

During the ultimate load test, and particularly near ultimate load, the relative displacement of the two ends of the openings became quite significant (Fig. 6.4). In fact, the low moment end of the opening had deflected very little while the high moment end ultimately deflected nearly one-half inch.

In the ultimate load test, as in the earlier elastic tests, the high moment end of the opening deflected more than the center of the beam at every load increment (Fig. 6.5). In contrast, the highest deflection in the prototype occured at the centerline at low load levels and then at the high moment end of the opening at loads nearer ultimate. Both sets of results, however, clearly demonstrate the Vierendeel effect in beams with web openings.

6.4 Strain Results

Load vs. strain results, plotted for loads in the elastic range at various locations at the high and low moment ends of the opening (Fig. 6.6-6.10), again indicate that the member acted elastically at low loads. Of particular interest is Fig. 6.9 which clearly shows the bottom fiber of the steel beam to be in compression at the low moment end of the opening. This, in an area normally expected to be in tension, once again demonstrates the effect of Veirendeel bending moments caused by shear being transferred across an opening.

A complete strain distribution across a vertical section of the composite member (Fig. 6.11) at one of the elastic loads clearly shows how the Vierendeel effect changes the strain distribution in a member. Figures 6.12-6.14 show strains plotted at loads outside the elastic range which can be used to determine the strain profile at early yield, late yield, and at ultimate load, but no attempt has been made to complete the profiles as the amount of strain data collected would make such an attempt mere conjecture.

The behavior of the composite member during the ultimate load test, in terms of strain in the member, is presented graphically in Fig. 6.15-6.19. Of particular importance are Fig. 6.16 and Fig. 6.19 which show portions of the steel beam nearing its yield strain at the high moment end, top tee and the low moment end, bottom tee, respectively. Figure 6.15, a plot of the strains in the concrete slab during the ultimate load test, shows that the concrete remained well below its ultimate strain limit in compression while going into tension at the bottom of the slab at the high moment end and at the top of the slab at the low moment end.

6.5 Slip between Slab and Beam

While the slip of the concrete slab relative to the steel beam was measured in both the elastic and the ultimate tests, the results of only the ultimate test are considered due to insignificant slip recorded during the elastic tests.

Slip between the slab and beam seemed to occur around what might be considered "first yield" of the model composite member. Later, at loads nearing ultimate, the slip measured at the end of the beam nearer the opening began to increase significantly with each "deflection" increment. It was only at loads within two kips of ultimate that significant slip at the far end of the beam was detected (Fig. 6.20).

6.6 Behavior of Model Beam during Ultimate Load Test

Since the model beam, like the prototype, had a relatively low M/V ratio, that is, high shearing forces accompanied by smaller moments, it was highly subject to secondary bending moments. This was quickly demonstrated at low loads by the fact that the bottom fiber of the steel beam at the low moment end of the opening was in compression rather than tension, while the bottom tee at the high moment end had fibers in both tension, as expected, and compression (Fig. 6.11).

As in the prototype, first yield occurred in tension at the high moment end, top tee, near the opening. Shortly thereafter, the slab began to separate from the beam and cracks began to develop in the concrete slab. The first cracks occurred on top of the slab at the low moment end of the opening indicating secondary bending moments sufficient to produce tension in a region which would experience compressive stresses in a normal composite beam.

Cracks then began to develop in the bottom of the slab near the centerline of the opening. These cracks propagated out towards the edge of the slab ultimately resulting in a diagonal tension crack which went through the slab and marked the failure and ultimate strength of the composite member. Photos taken after removing the beam from the testing machine reveal that the ultimate failure mode of the model was similar to that observed in the prototype (Fig. 6.21-6.24).

6.7 Comparison of Model and Prototype Results

In comparing results of a model test to results obtained from the prototype, it is important to keep in mind the similitude requirements and the effects of not adhering to them exactly. In terms of ultimate load, the expected load should be smaller than the prototype load by a factor of the linear scale factor squared. In this case, a scale factor of 2.2 would yield a predicted ultimate strength of 19.2 kips. The ultimate strength of the model beam proved to be 21.2 kips or 10.4% larger than predicted by similitude. The ultimate model load would have been a perfect value if the model had been designed with a scale factor of 2.10.

Another important parameter to consider when comparing results of model tests with those of a prototype is the behavior of the member in terms of deflections. To be valid, however, such considerations must be based on models made with materials clearly meeting the requirements of similitude. In this case, one of the assumptions made in fabricating the model member was that the modulus of elasticity of all materials used in the model and their counterparts in the prototype were the same. If this requirement were not met, then all values affected by the stress-based scale factor (force per area (model) = force per area (prototype) / scale factor for stress) would not be affected by only the linear scale factor. In terms of deflections, the fact that the modulus of elasticity of the model concrete was probably significantly lower than that of the prototype concrete means that deflections of the model would over-predict deflections of the prototype. In other words, the deflections of the model beam would be larger than predicted by following the similitude requirements presented in Chapter 2.

For this model member, the high moment end deflection, when compared to that of the prototype, yielded a scale factor of 1.34 rather than 2.20, and the centerline deflections yielded a scale factor of 1.55. The differences in scale factors for deflections at the high moment end and centerline are probably due to the difference discussed earlier between modulus of elasticity values. The model concrete slab, if less-stiff because of the model concrete, contributes more to the overall stiffness of the member at the opening than at the centerline of the beam. Therefore, deflections at the opening would tend to be greater, even in scale, than those elsewhere along the beam.

6.8 Horizontal Strain Distribution in Concrete Slab

While not reported in the Clawson and Darwin report (4), the strain distribution in the model concrete slab at the high moment end of the opening is presented here, more for information and further reference than for analysis. The distributions for several loads are shown in Fig. 6.25 and they clearly demonstrate how difficult it is to determine the contribution concrete makes to the overall strength of composite members. It should be noted that both model and prototype slabs exceed the maximum effective width as defined by specifications for composite design (1).

An attempt was made to determine whether or not the strain immediately above the steel beam at the middle of the slab could be predicted based on the distribution along the top of the slab. It was concluded that more instrumentation would be required, especially above the beam at both the top and the bottom of the slab, to confidently predict the actual distribution.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 Summary

The main objective of this research and report was to fabricate, test, and analyze a model composite beam with web opening, and to use the results to further establish modeling as a tool of research in this area. The development of model composite beams with web openings that would accurately predict the behavior of large composite members would permit more, comprehensive, complete tests to be run on a large number of model beams. The results of these more economical model tests could then be used to verify design criteria for composite members with web openings.

The model fabricated for this investigation was a 6.82' long, simply-supported, W8 x 10 steel beam and 1.82" x 21.82" reinforced concrete slab. The model composite member provided a geometric scale factor of 2.2 between the model and prototype. The steel beam and reinforced concrete slab were fabricated and tested just as the prototype was at the University of Kansas in 1980 (4).

7.2 Conclusions

The results of the model composite beam tests, while not exactly what was predicted by the laws of similitude, do seem to indicate that modeling composite beams, although complicated, is indeed a viable alternative to fabricating and testing large, full sized members. When doing so, however, it is vitally important to fabricate the model using materials with properties very similar to those of full sized members.

7.3 Recommendations for Further Study

The requirement that material properties be similar in both prototype and model complicates the modeling of composite beams with web openings. Finding steel with similar properties is usually no great problem, but designing and fabricating a reinforced concrete slab with suitable model materials is. The development of a micro-concrete mix with suitable ultimate strength, modulus of elasticity, and failure strain, both in tension and in compression, would make that particular problem manageable. Further work in deforming and annealling steel wires to be used as model reinforcing would also be beneficial.

As the popularity of composite floor systems has grown, so has the demand for faster, easier, more economical ways of constructing them. This has led to the development of "ribbed construction" where corrogated sheet metal is used as formwork. The sheeting remains as a part of the floor system. Work has begun on the effect of web openings on such systems, but here, as with regular flat slab systems, additional tests must be run to verify existing criteria or to develop new guidelines.

Finally, this investigation sought to model a W18 x 45 with a four inch concrete slab. Presently, however, most web openings in composite members are found in deeper members, often members greater in depth than most average floor beams and in some cases, even plate girders. Modeling, as a tool to predict the behavior of these large members, would allow tests to be conducted and predictions of member behavior made without actually testing huge beams. One might even argue that the "prototype" W18 x 45 is but a model of the more often used, heavier, deeper shapes.

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Table 2.1

Similitude Relationships

Parameter	Dimensions	Scale Factor
1. Geometry:		
Linear dimension, L	L	S_L
Area, A	L^2	S_L^2
Moment of Inertia, I	L^4	S_L^4
Linear displacement, δ	L	S_L
2. Materials and related Parameters:		
Stress, σ	FL^{-2}	$S_E = 1$
Modulus of Elasticity, E	FL^{-2}	$S_E = 1$
Poisson's ratio, ν	---	1
Density, ρ	FL^{-3}	$S_E/S_L = 1/S_L$
Strain, ϵ	---	1
3. Loading:		
Concentrated force, P and Shear force, V	F	$S_E S_L^2 = S_L^2$
Pressure or uniformly distributed load, q	FL^{-2}	$S_E = 1$
Line load, w	FL^{-1}	$S_E S_L = S_L$
Moment, M	FL	$S_E S_L^3 = S_L^3$
Moment-Shear ratio, M/V	L	S_L

Table 4.1

Comparison of Model and Prototype Beams

Section Properties	W18x45	W8x10	Scale Factor
Steel Section:			
Depth, d, in.	17.88	7.89	2.29
t_w, in.	0.343	0.170	2.12
t_f, in.	0.490	0.205	2.39
b_f, in.	7.5	3.94	1.90
A_f, in^2	3.68	0.810	2.13
A, in^2	13.20	2.96	2.14
I, in^4	706	30.8	2.19
Composite Section:			
Depth, d, in.	21.88	9.71	2.25
I, in^4	1800	74.8	2.21

Table 4.2

Properties of Steel used in Model Beam

Specimen	Yield (ksi)	Static Yield (ksi)	Ultimate (ksi)
Flange No. 1	46.78	41.91	61.29
Flange No. 2	46.30	43.03	61.10
Web No. 1	55.77	52.41	66.90
Web No. 2	48.23	44.08	62.08
Reinforcing Steel:			
5/16"-18	84.13	---	92.69
8-32	90.71	---	97.14

Table 4.3

Micro-Concrete Mix Proportions

Material	Relative Weight
Water	1
Type I cement	2
Sand (passed No. 16 sieve) . .	4

Table 4.4

Compressive Strength of Model Concrete

Ultimate Load (kips)	Average Strength (ksi)	Age (Days)	% Desired Strength
23.0 25.2	3.41	3	76.46%
28.8	4.07	5	91.37%
29.5 29.6	4.18	6	93.72%
30.2 29.7	4.24	7	94.96%
32.8 31.5 30.8 31.4	4.47	9	100.3%
31.7 31.4 33.9	4.57	11	102.6%
32.8 32.8 31.6 32.4 33.4 32.8	4.62	13	103.4%

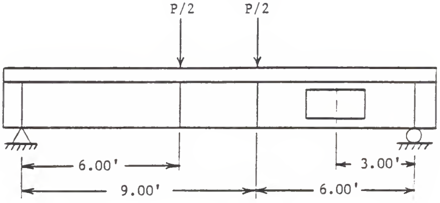


Fig. 3.1 Prototype -- Beam No. 4

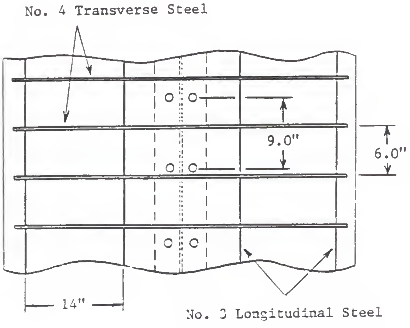


Fig. 3.2 Plan View of Prototype Slab, Reinforcing Steel, and Studs

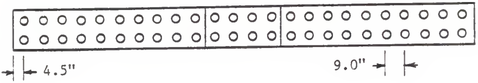


Fig. 3.3 Prototype Shear Stud Locations

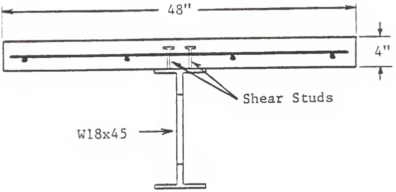


Fig. 3.4 End View of Prototype Beam and Slab

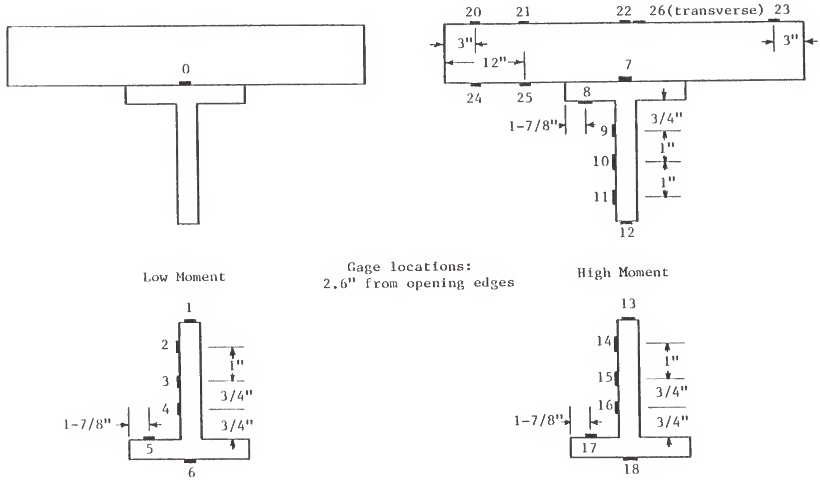


Fig. 3.5 Strain Gage Locations for Prototype Beam

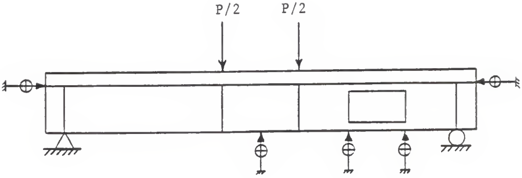


Fig. 3.6 Dial Gage Locations for Prototype Beam

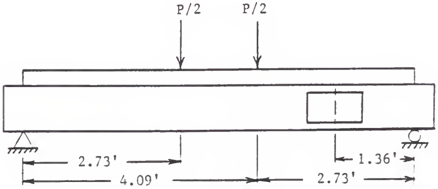


Fig. 4.1 Layout of the Model Beam

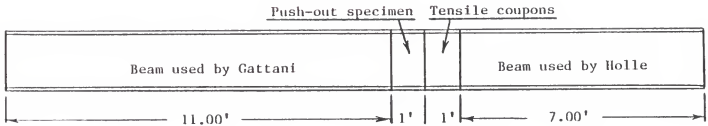


Fig. 4.2 Location of Model Beam and Coupons on Original 20' Long W8 x 10

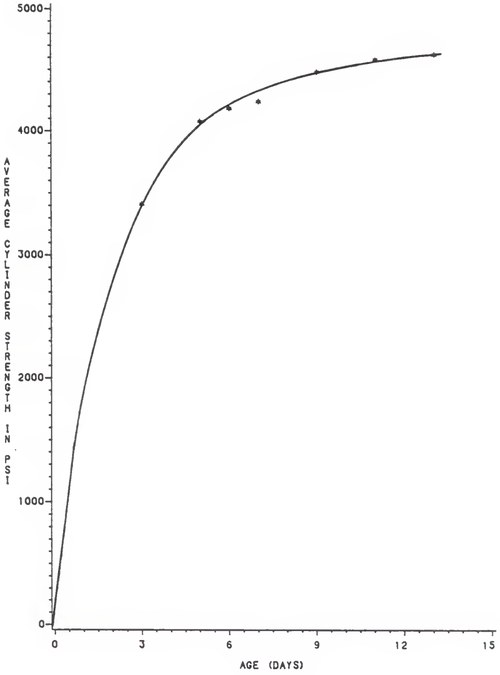


Fig. 4.3 Strength vs. Age Curve for Model Concrete

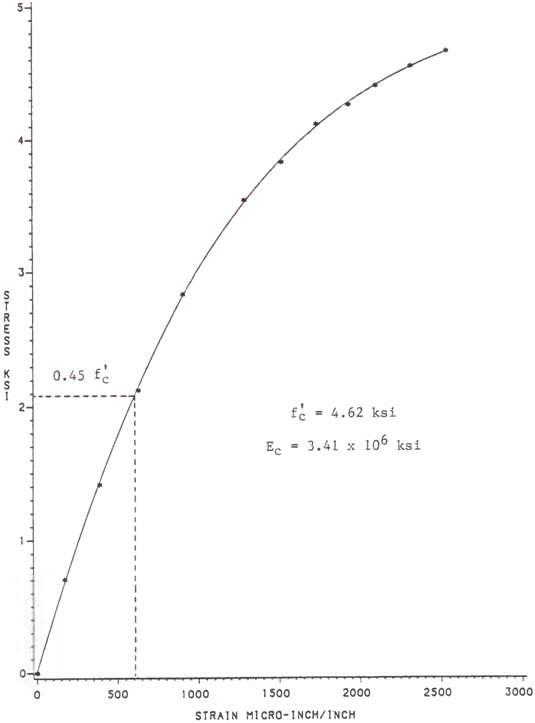


Fig. 4.4 Stress-Strain Curve for Model Concrete

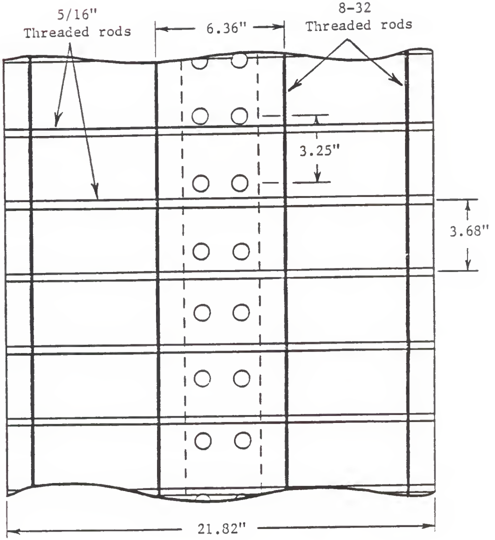


Fig. 4.5 Plan View of Model Slab, Reinforcing Steel, and Studs

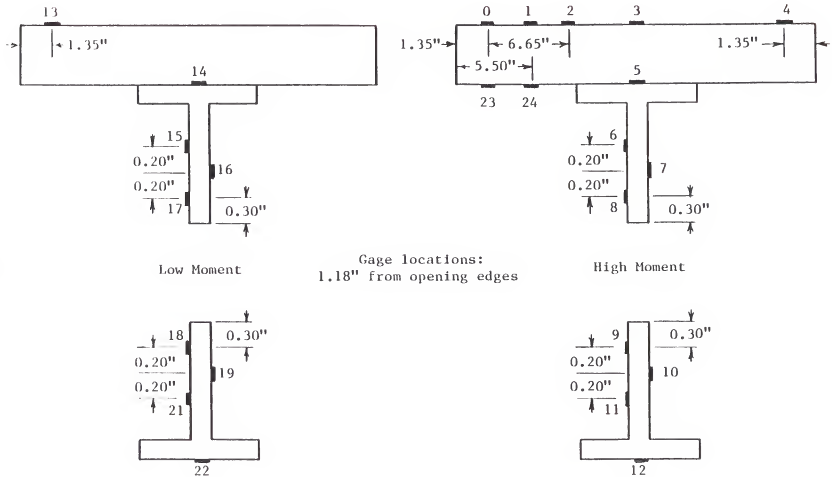


Fig. 4.6 Strain Gage Locations for Model Beam

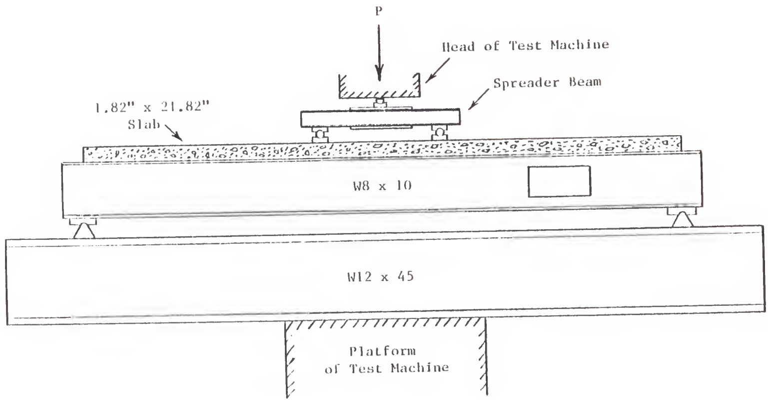


Fig. 4.7 Model Beam Testing Arrangement

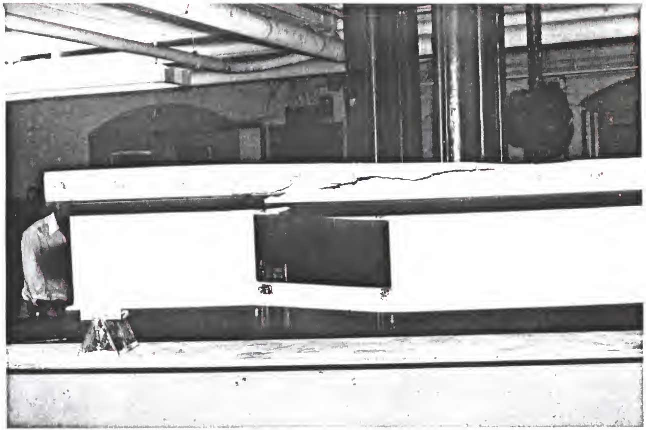


Fig. 6.1 Model Beam After Completion of the Ultimate Load Test

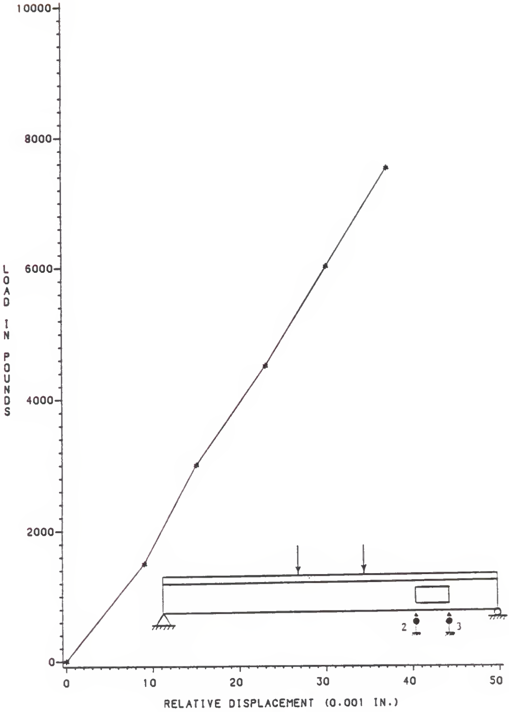


Fig. 6.2 Elastic Load vs. Relative Displacement Between Points 2 and 3

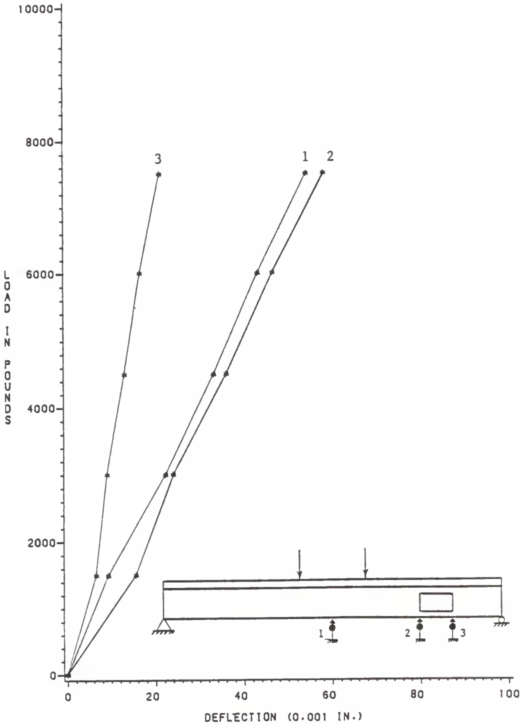


Fig. 6.3 Elastic Load vs. Deflection Curves for Model Beam

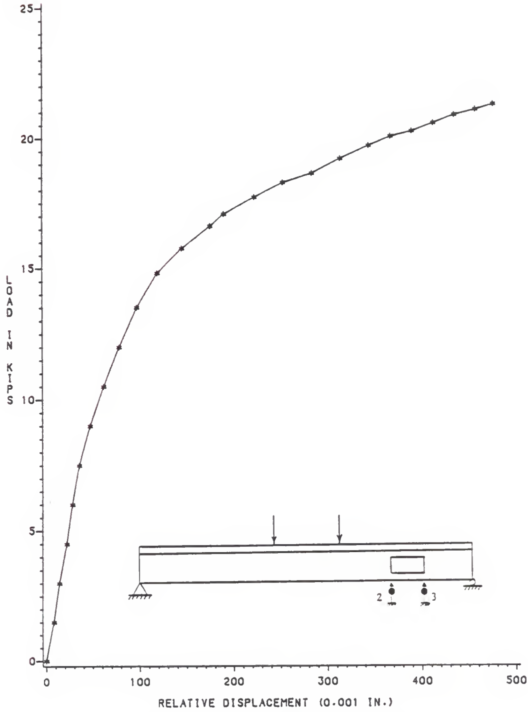


Fig. 6.4 Load vs. Relative Displacement Between Points 2 and 3 -- Ultimate Load Test

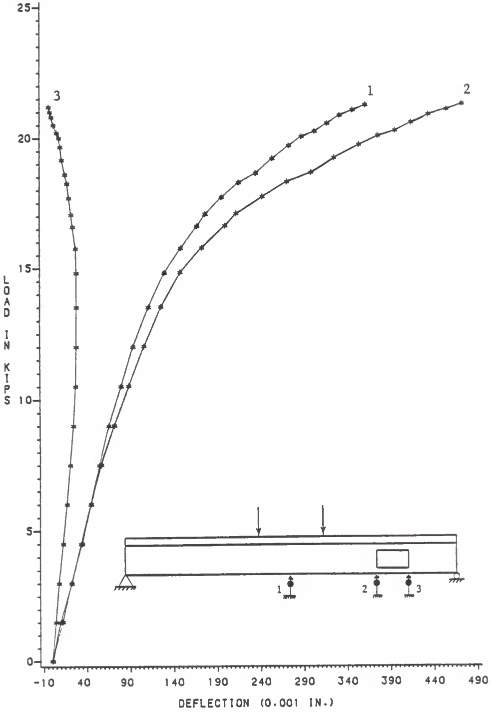


Fig. 6.5 Load vs. Deflection Curves for Model Beam (Ultimate Load Test)

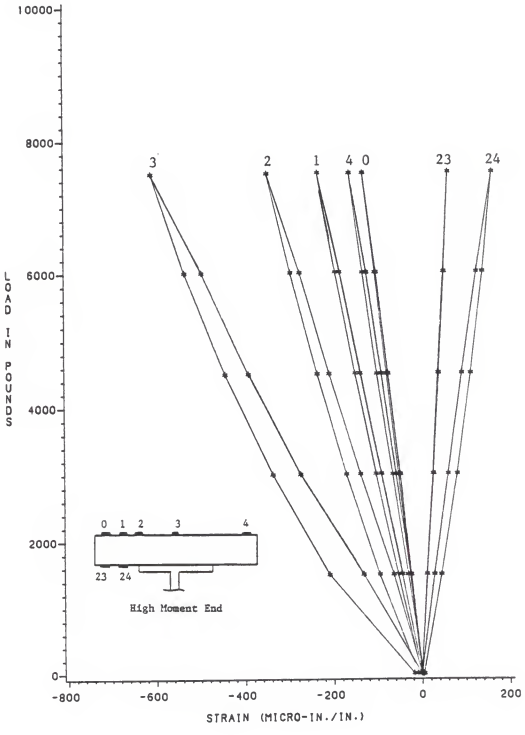


Fig. 6.6 Elastic Load vs. Strain Curves for Model Beam (Concrete -- High Moment End)

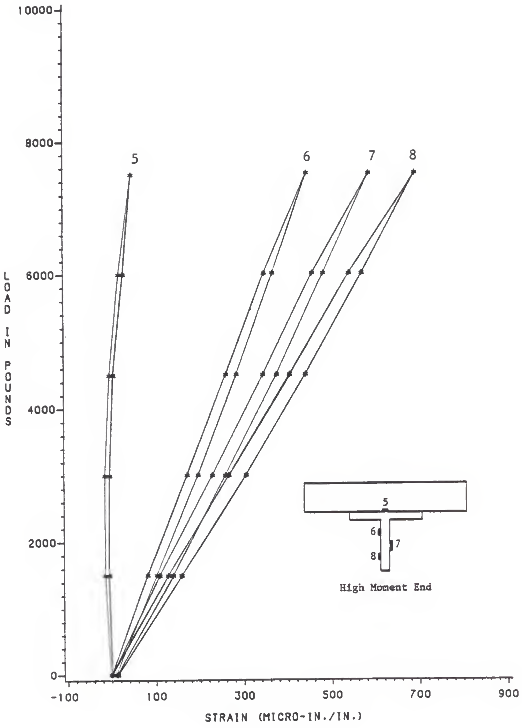


Fig. 6.7 Elastic Load vs. Strain Curves for Model Beam (Steel -- High Moment End, Top Tee)

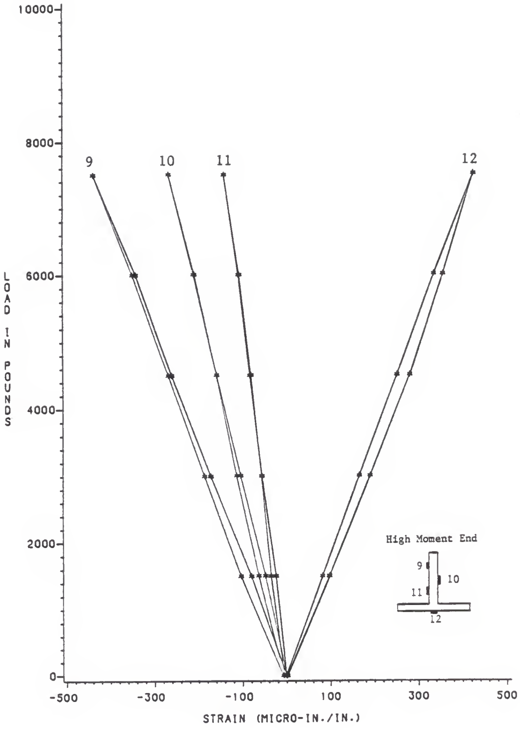


Fig. 6.8 Elastic Load vs. Strain Curves for Model Beam (Steel -- High Moment End, Bottom Tee)

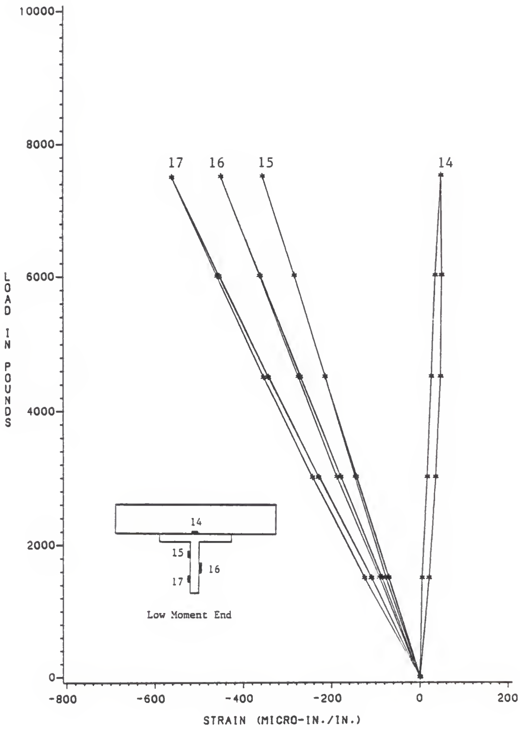


Fig. 6.9 Elastic Load vs. Strain Curves for Model Beam
(Steel -- Low Moment End, Top Tee)

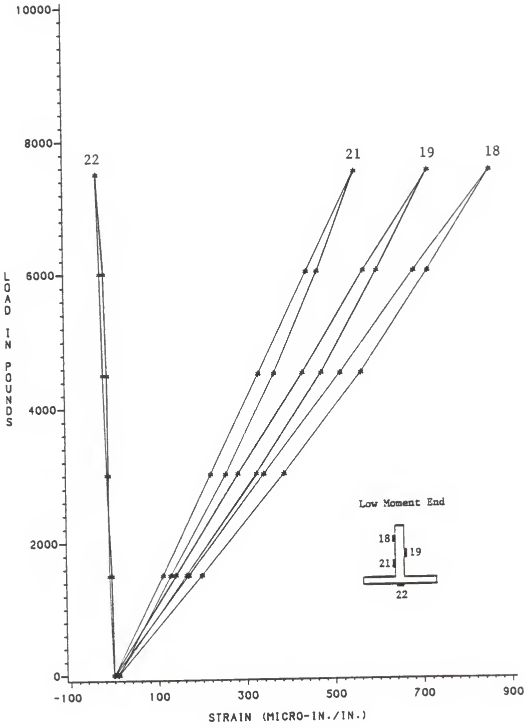
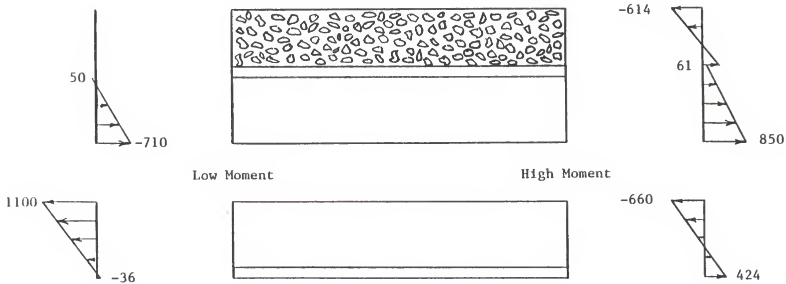
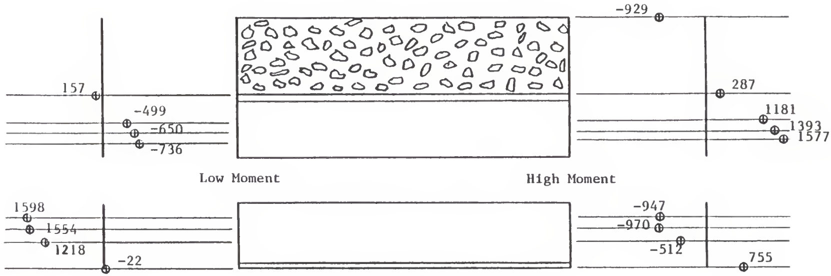


Fig. 6.10 Elastic Load vs. Strain Curves for Model Beam
(Steel -- Low Moment End, Bottom Tee)



Strain Units: Micro-in./in.

Fig. 6.11 Strain Distribution in Model Beam -- Elastic Range



Strain Units: Micro-in./in.

Fig. 6.12 Strain Distribution in Model Beam -- First Yield

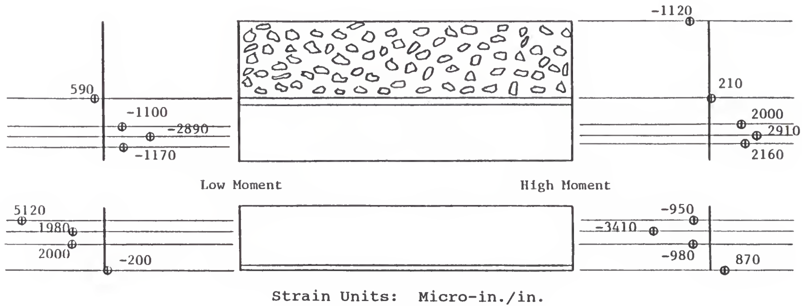


Fig. 6.13 Strain Distribution in Model Beam -- Late Yield

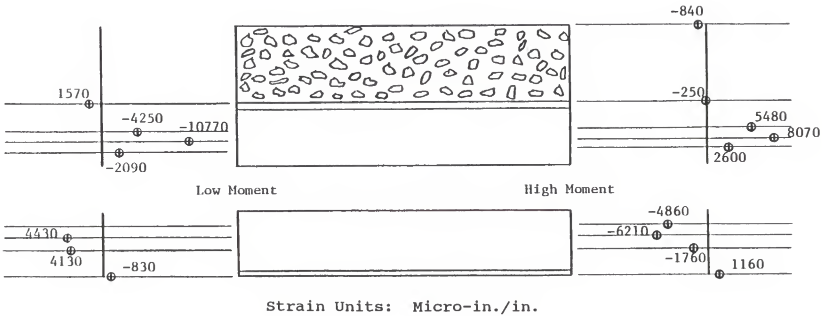


Fig. 6.14 Strain Distribution in Model Beam -- Ultimate Load

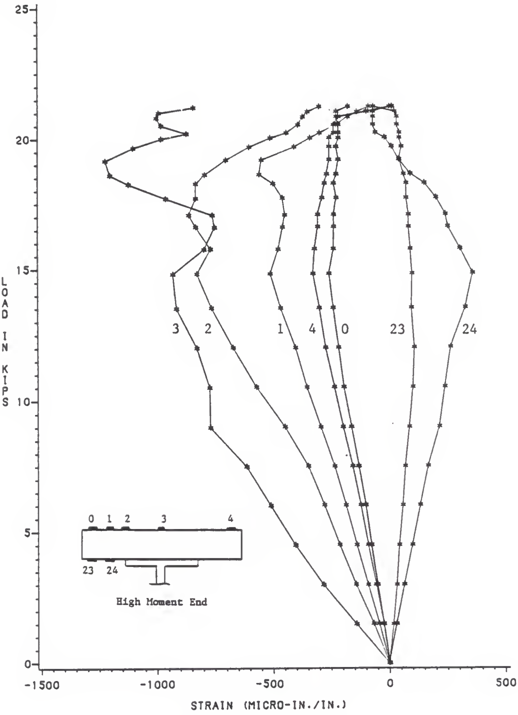


Fig. 6.15 Load vs. Strain Curves for Model Beam - Ultimate Load Test
(Concrete -- High Moment End)

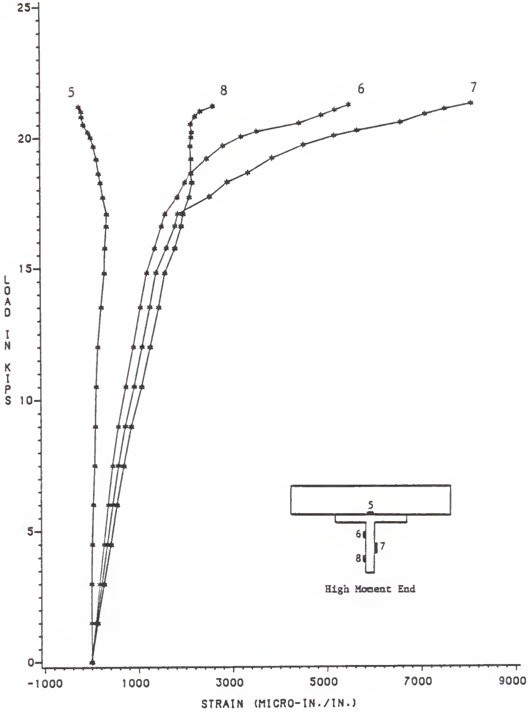


Fig. 6.16 Load vs. Strain Curves for Model Beam - Ultimate Load Test
(Steel -- High Moment End, Top Tee)

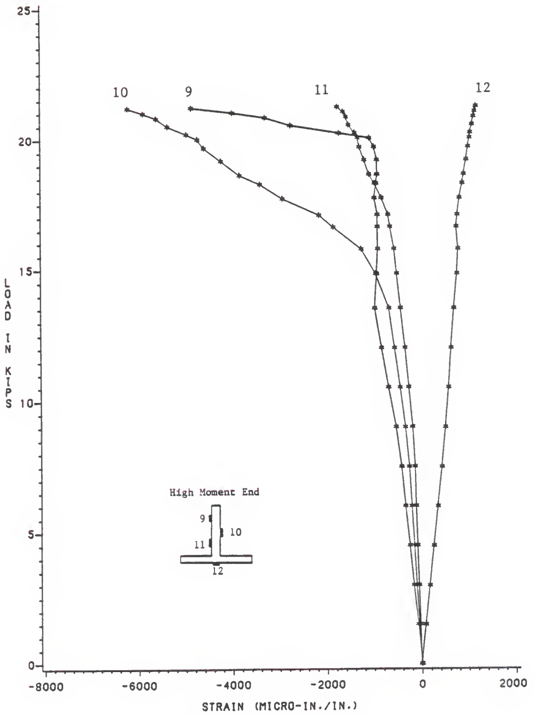


Fig. 6.17 Load vs. Strain Curves for Model Beam - Ultimate Load Test
(Steel -- High Moment End, Bottom Tee)

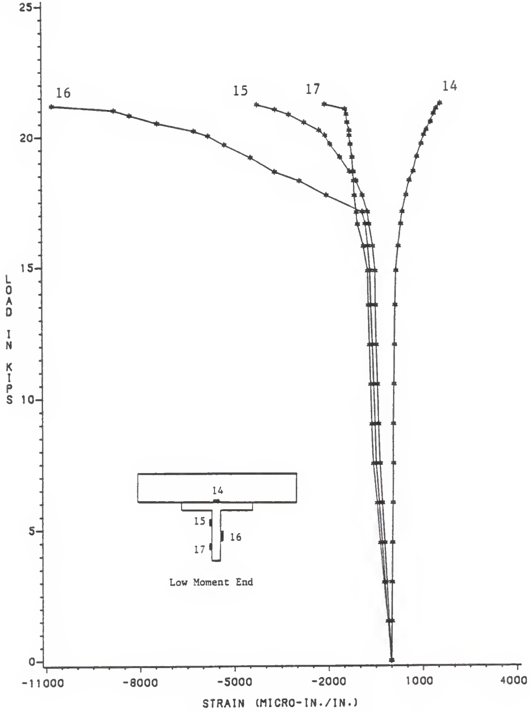


Fig. 6.18 Load vs. Strain Curves for Model Beam - Ultimate Load Test
(Steel -- Low Moment End, Top Tee)

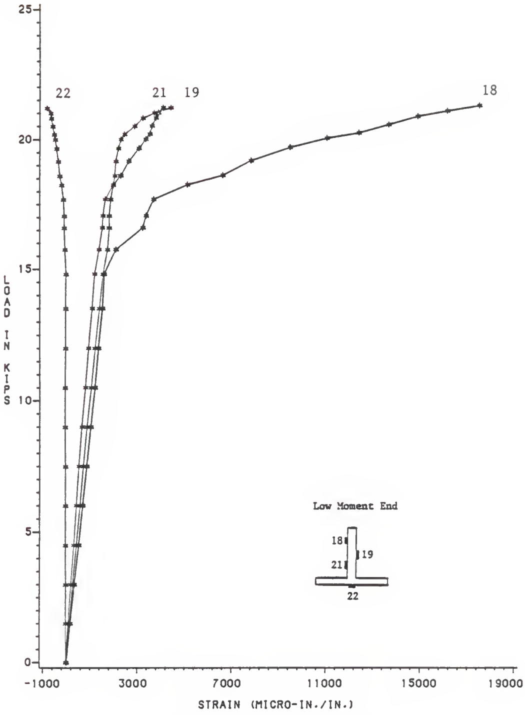


Fig. 6.19 Load vs. Strain Curves for Model Beam - Ultimate Load Test
(Steel -- Low Moment End, Bottom Tee)

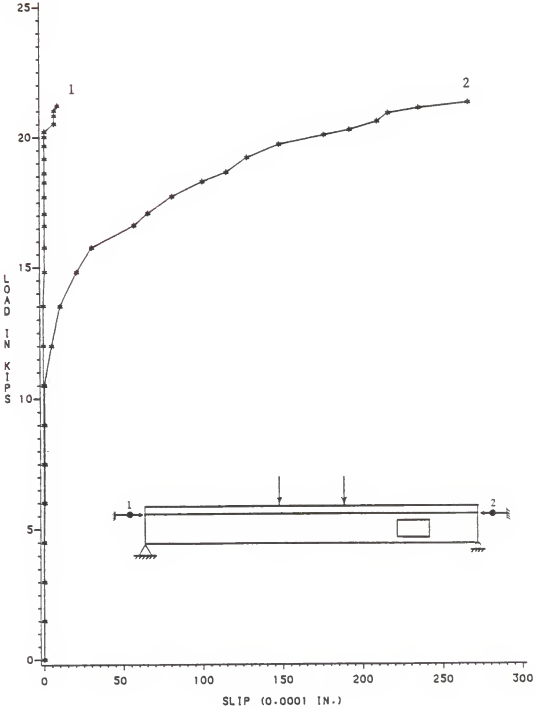


Fig. 6.20 Load vs. Slip Curves for Model Beam - Ultimate Load Test

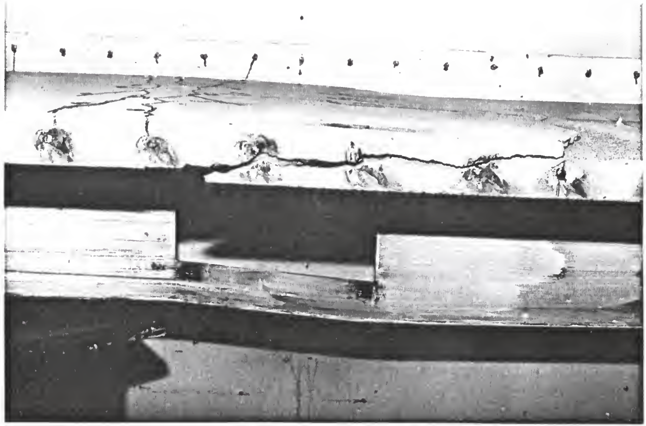


Fig. 6.21 Crack Pattern of Model Beam Slab

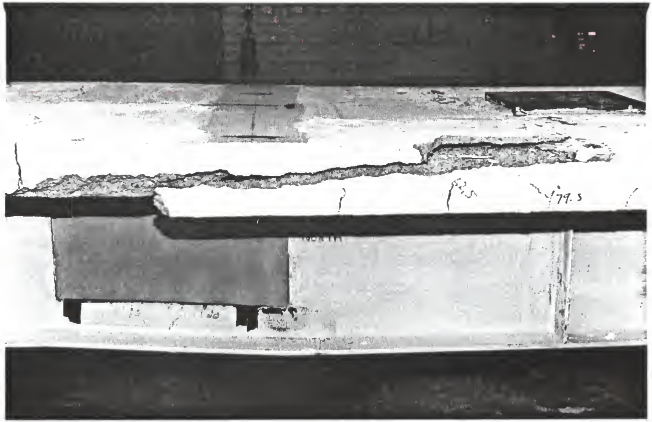


Fig. 6.22 Crack Pattern of Prototype Beam Slab

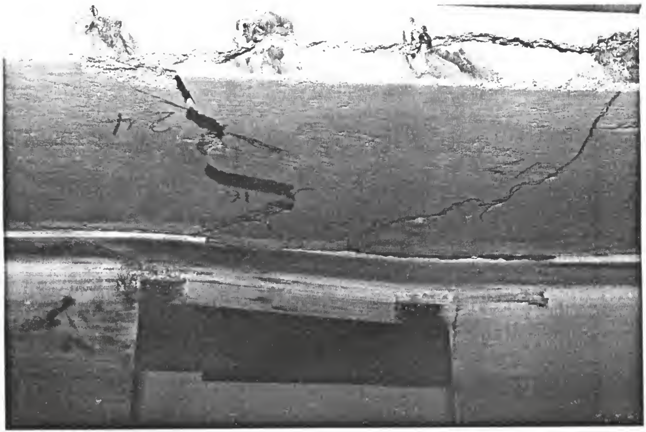


Fig. 6.23 Crack Pattern of Model Beam Slab

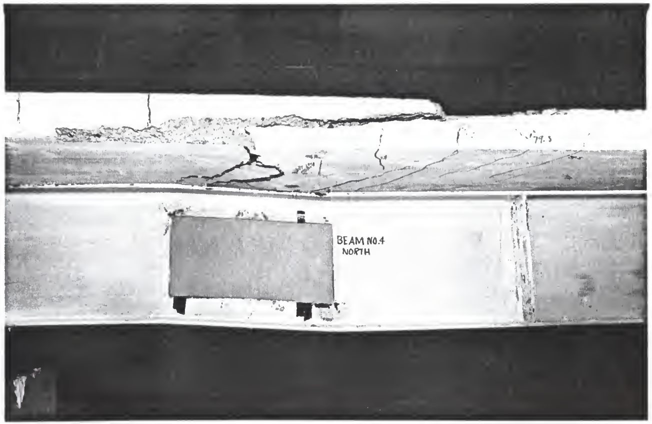


Fig. 6.24 Crack Pattern of Prototype Beam Slab

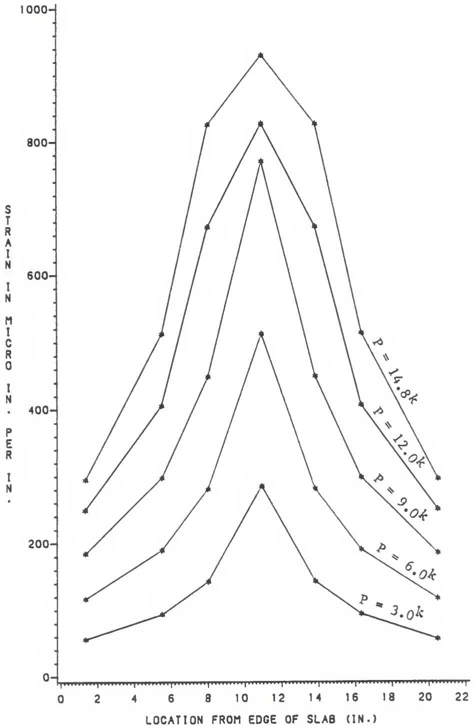


Fig. 6.25 Horizontal Strain Distribution at the Top of the Model Beam Slab

TESTING OF A MODEL COMPOSITE BEAM
WITH WEB OPENING

By

Brian G. Holle

B.S., Kansas State University, 1986

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1987

ABSTRACT

This project consisted of fabricating, testing, and analyzing a model composite beam with web opening, a member that would provide a geometric scale factor of 2.2 relative to the prototype. The model beam, which utilized model shear studs, a micro-concrete mix, threaded steel rods, and a W8 x 10, A36 steel beam, had an opening with centerline M/V ratio of 1.36 feet.

The model beam was tested to failure and the results of the tests used to compare behavior of the model beam to that of the prototype. Deflection and strain data seemed to compare favorably while the failure mode of the model was nearly identical to that of the prototype.

Recommendations for further study are presented based on the results of the model beam test. They include further work in developing suitable model materials, especially for the case where reinforced concrete is to be considered, in pursuing composite designs utilizing "ribbed" slabs and web openings, and in modeling even larger, deeper members in which openings become even more appealing.