Composite Slabs Subjected to Repeated Point Loading

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by

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ABSTRACT

Composite slabs have been and still are primarily used in office and apartment buildings where the design load is based on equivalent uniformly distributed static loading. The use of composite slabs in the construction of warehouses and indoor parking garages has been limited due to the lack of behavioural and strength information of composite slabs subjected to repeated point loading. This paper presents results of tests recently carried out at the University of Waterloo on composite slabs subjected to repeated point loading. Based on these tests, both simple and double span specimens were able to sustain repeated point loads of 75% of static ultimate for at least 1.25 million cycles. The mode of failure in all cases was shear-bond with no early end-slip prior to ultimate load.

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INTRODUCTION

Composite slab construction refers to a structural slab system created by compositely combining the structural properties of concrete and cold formed steel decking. To develop the required composite action (mechanical interlocking resistance) between the concrete and steel deck, the steel deck must be able to resist horizontal shear and vertical separation between the concrete and steel deck. To achieve this, most common composite steel decks on the market today utilize a fixed pattern of embossments.

To date, composite slabs are primarily used in office and apartment buildings, where the design load is assumed to be an equivalent uniformly distributed static load. This is due to the fact that testing of composite slab systems over the past 20 years has almost entirely been carrier out on slab elements subjected to static line loading. It has been well established and substantiated by a number of researchers [1,2,3] that shear-bond is the most common mode of failure of composite slabs when subjected to static line loading and that laboratory performance tests must be carried out to establish the shear-bond resistance of any composite slab system. Based on numerous composite slab laboratory performance tests subjected to static line loading, design Standards have recently been published in North America [4,5,6]. These Standards give performance and design criteria for composite slabs subjected to static line loading only.

The use of composite slabs in the construction of warehouses and indoor parking garages is limited due to the lack of conclusive information on the behaviour of composite slabs subjected to repeated point loading. Such repeated point loading could be the result of fork lift truck and automobile wheel loading (see Figure 1.). The technical literature does not contain conclusive information on repeated point loadings of composite labs, however, some noteworthy references related to the topic are [7,8,9,10,11,12].

The subject of this paper is to present results of an extensive experimental study of a composite slab system subjected to repeated point loading. The study was carried out at the University of Waterloo, by R. Suleiman [13]. The objective of the study was to establish standard test procedures and possible design criteria for composite slabs subjected to repeated point loading. It was initially realized that, since laboratory performance tests must be carried out to establish the structural resistance of any composite slab system under static loading, it is absolutely essential that similar tests be conducted under repeated point loading. Furthermore, testing is required since no two composite slab systems are the same, i.e., pattern, depth and size of embossments are different, and the mode of failure can either be shear-bond or tearing of the steel deck, especially under repeated loading.

SHEAR-BOND FAILURE

Since shear-bond is the most predominant mode of failure with composite slabs subjected to concentrated static line loading [1,14,15], it is important to briefly review certain behavioural characteristics. Typical load-deflection and end-slip curves, as shown in Figure 2, are used to discuss the behaviour of composite slabs. Generally, composite slabs behave in two different ways with respect to end-slip, i.e., 1) no end-slip prior to ultimate load is experienced, as indicated by curve 1 of Figure 2, and 2) where end-slip is experienced prior to ultimate load, as indicated by curve 2 of Figure 2. This difference in behaviour concerning possible early end-slip is extremely important when a composite slab is subjected to repeated loading. Should the maximum repeated load be greater than the load at which early end-slip occurs, then the system would not be able to experience its anticipated fatigue life.

Based on the fact that early end-slip can occur with composite slabs, it is essential that, prior to conducting repeated load tests, a companion static test be carried out to establish the maximum repeated load level in relation to end-slip. For a more detailed explanation of the various regions shown in Figure 2, see References [13,14,16].

TESTING PROGRAM

The testing program was initially established in consultation with an ad-hoc committee under the auspices of the Canadian Sheet Steel Building Institute (CSSBI) with Mr. C. Fung as project coordinator. This was done in an effort to help the researchers create an appropriate laboratory test set-up that would reflect, as much as possible, actual practice in the field. The committee also decided that the fatigue life for composite slabs subjected to repeated point loading be 1.25 million cycles. Testing was to be carried out on both single and double span specimens, subjected to both static and repeated point loading. The reason for testing both single and double span specimens was to obtain comparative results with the intention of recommending one performance test set-up to establish the fatigue resistance of composite slabs.

Description of Test Specimens

All single span specimens were approximately 2200 mm long with an average overall slab depth of 150 mm and a slab width of 1600 mm. All double span specimens were identical in geometric detail to the single span specimens with the exception that they were approximately 4400 mm in length with the interior support positioned symmetrically.

Composite steel decks were nominally 75 mm in depth and 0.91 mm in thickness and of embossment type (see Figure 3). Since a number of different shipments of composite deck were received from the manufacturer during the course of the study, some embossment depth variation was experienced. Also, the steel decks had a phosphate-treated surface finish and the mechanical properties of the steel conformed to ASTM A446 Grade A material.

Normal density concrete, supplied by a local ready-mix plant, was used with all specimens. The specimens were cast with the steel decks supported along the length so that the overall depth of the concrete remained constant over the entire span length. It should be acknowledged that this does not occur in actual field installations where the system is generally not supported throughout casting, but rather at its ends or, perhaps, at some interior locations provided by shoring. Due to the effect of deflection caused by the wet concrete during the construction stage, the nominal depth of the composite section is increased in actual construction practice. In design, nevertheless, this slight increase in depth and consequently in stiffness can be regarded as an additional factor of safety. Welded wire fabric consisting of No. 6 wires (152 mm x 152 mm) was used as supplementary reinforcement in all specimens, which is commonly used as shrinkage reinforcement.

Test Equipment and Instrumentation

In general, fatigue testing equipment, regardless of complexity, consist of the same basic elements. A test system loads the specimen through the load train, commands and programs the test through controls, monitors the test through sensors and communicates with the investigator by means of read out devices. The load train consisted of a test frame, specimen and an MTS electrohydraulic servo drive system.

Instrumentation consisted of various sensors used in monitoring specimen behaviour and recording devices used to communicate the behaviour to the investigator, i.e., deflection monitoring devices such as mechanical dial gauges (0.01/mm) and displacement transducers. Three mechanical dial gauges were placed along the midspan centreline of the loaded span, positioned as shown in Section A-A of Figure 4. One dial gauge was placed at the centre of each composite slab support beam, including the external support beam of the unloaded span of the double span specimens and one at the centre of the unloaded span for double span specimens. For static testing only, two dial gauges were positioned at each end of both the single and double span specimens for measuring possible horizontal end-slip and were placed at 1/3 of the specimen width from each side of the specimen. Three displacement transducers were placed along the midspan centreline of the loaded span, as shown in Section A-A of Figure 4. For static testing only, one displacement transducer was placed at each end of single span specimens and only at the loaded end of double span specimens. The transducers were located at the centre of the specimen width in order to measure possible horizontal end-slip

Electrical strain gauges were attached to the steel decks in the longitudinal direction parallel to the deck corrugations. In general, the gauges were placed over only one-half of the specimen width on the flat areas of both the top and bottom flanges of the steel deck. The strain gauges were placed along the transverse midspan centerlines of both loaded and unloaded spans and for double span specimens, strain gauges were also placed on the steel deck along the interior support beam.

Test Set-Up

All slab specimens were placed on pin and roller reactions which in turn rested on W200 x 27 support beams. The test set-up for the single and double span specimens is shown in Figures 4 and 5, respectively. Steel beams were used to transfer the load from the slab to the support columns, thus creating a similar condition to that found in actual field practice. In each case, the bottom flange of each beam was rigidly clamped on both sides to the support columns to prevent horizontal and vertical movement.

For repeated load tests, it was also necessary to restrict horizontal movement of the pin reactions. This was achieved by clamping small steel plates to the top flange of the steel beams on either side of the bar used as the pin reaction. In certain cases the same procedure was also used for roller reactions, although some space was left between the roller reactions and the steel plates to allow for movement of the rollers.

Loading of the slabs was accomplished by applying a concentrated point load at the geometrical center of the specimen. The load cell and hydraulic actuator formed the loading component of the drive system with a cylindrical extension connected to the bottom of the load cell onto which a steel plate was bolted. This was necessary due to limitations on the available stroke in the hydraulic actuator. A 200 mm x 200 mm x 20 mm neoprene pad was placed between the metal plate and the contact surface of the concrete to provide a relatively uniform bearing surface between the concrete and the applied load. Figure 6 shows a photograph of the testing frame set-up.

TEST RESULTS

It is not the intention of this paper to discuss the results of each individual test but rather present some typical results and an overall summary of the test results in general. The reader is referred to Reference [13] for more detailed information. Using the composite deck shown in Figure 3, eight single and four double span slab specimens were tested.

Failure Mode

Based on the test results, the primary mode of failure experienced with all specimens was shear-bond, which was identified as an approximately diagonal crack either under or near the concentrated load, causing end-slip only at ultimate load, i.e., no early end-slip prior to ultimate load occurred. However, in no case was there disengagement of the concrete shear span from the steel deck. In fact, the specimens remained extremely well interlocked, even after failure. Moreover, the ultimate load was defined as the largest load attained by the specimen. Figure 7 shows the shear-bond failure of specimen W4-DD, which can be considered typical for all other specimens. The characterization of this composite slab system failing in shear-bond is similar to other embossment type systems failing in the same mode when subjected to static line loading, as reported in References [1,2,3,14,15].

Strength Behaviour

To establish the ultimate load and end-slip characteristics, one single and two double span specimens were first tested statically. Since shear-bond was the mode of failure and in neither test did early end-slip occur, the maximum repeated load level was determined on the basis of the ultimate failure load in conjunction with a weighted load factor, as follows:

$$P_{mr} = \frac{P_{ue}}{WL} \tag{1}$$

where $$WL = \frac{1.25P_D + 1.5P_{ue}}{P_D + P_{ue}}$$

P_{mr} = maximum repeated load

P_{ue} = maximum ultimate static load

WL = weighted load factor

P_D = dead load of composite slab

1.25 and 1.5 are dead and live load factors respectively, which are consistent with limit states design and the National Building Code of Canada [17].

Experimental test results for single and double span specimens all having failed in shear-bond, are summarized in Tables 1 and 2, respectively. As listed in Table 1, the ultimate static load of the single span specimen W1-SSwas 71.9 kN and 81.9 kN of the double span specimen W10-DS (see Table 2). Based on these two tests, the double span specimen was able to carry approximately 14% more load than the single span specimen. It should be noted that the double span specimen behaved essentially as two single span specimens since only marginal negative reinforcement (welded wire mesh) was located over the interior support and shear-bond failure occurred at the exterior end of the loaded span.

Ideally, the behavior of a specimen under repeated load is best represented by constructing an S - N (fatigue strength vs number of cycles) curve, however, this requires the testing of numerous specimens at different load levels. Since repeated load tests of composite slabs are expensive and time consuming to run, it is most desirable to reduce the number of tests to an absolute minimum, i.e., select the proper maximum repeated load that can be maintained throughout the desired fatigue life, knowing that a higher load would fail the specimen before reaching the fatigue life. This of course is almost impossible to achieve consistently, especially when shear-bond is the mode of failure, hence, one must be prepared to carry out a number of tests.

Initially, repeated load testing was carried out by using the weighted load factor method of Equation 1 to establish the maximum starting repeated load and cycling the specimen at 3 cycles per second until the fatigue life of 1.25 million cycles was reached. After having reached the fatigue life, the specimen was then statically tested until failure. This was done in the case of the two single span specimens W5-SD and W6-SD, the results of which are summarized in Table 1. As can be observed, both specimens carried their maximum repeated loads, P_{mr}, through the fatigue life. What is of interest to note is that the final static ultimate load, P_{uer}, after both specimens had been subjected to their respective P_{mr} repeated loads over 1.25 million cycles, was in both cases larger than the ultimate load of the companion 1 - cycle static load specimen W1-SS. This may be, at least in part, be attributed to the fact that the fatigue strength of some materials can be increased or "coaxed" by subjecting the specimen to a repeated load below its fatigue limit, after which a final static load test is carried out. The percent load increase of specimens W5-SD and W6-SD in comparison with specimen W1-SS without a load history is only about 8%. The same observation can be made in the case of the double span specimen W4-DD subjected to repeated load in comparison with its companion static load specimen W10-DS, where the percent load increase is about 16% (see Table 2).

In an effort to reduce the number of repeated load tests to a minimum, it was decided to use an "increasing load approach" with the remaining specimens. With this approach, the specimen was subjected to the first maximum repeated load as established by Equ. 1, and tested until 1.25 million cycles were reached. The maximum repeated load was then increased a certain increment and the test repeated until another 1.25 million cycles were reached. This procedure was repeated until the specimen finally failed. The absolute maximum repeated load of the specimen can then be taken as the last increment of repeated load that was successfully maintained over the fatigue life. Two single span specimens, namely, W11-SD and W12-SD were subjected to this approach, the results of which are summarized in Table 1 and one double span specimen, W7-DD, given in Table 2. An interesting observation can be made by comparing the results of specimen W5-SD with those of specimen W11-SD, both summarized in Table 1. i.e., the maximum repeated load in the case of specimen W5-SD was 44.5 kN after 1.25 million cycles, which was also the initial maximum repeated load for specimen W11-SD, however, specimen W11-SD was able to sustain an absolute maximum repeated load of 53.3 kN after 3.75 million cycles, which is an increase in load of about 20%. This same comparison can be made between single span specimens W6-SD and W12-SD, where the initial maximum repeated load was 48.9 kN and the final repeated load for specimen W12-SD was 57.7 kN after about 3.75 million cycles, an increase in load of about 18%.

Repeated loads below the fatigue limit seem to have a favourable effect on the fatigue life of a specimen when the repeated loading is increased. For example, the single span specimen W8-SD (Table 1.) with no load history, was subjected to a repeated load of 74% of ultimate static load and failed after only 18 160 cycles. In contrast, an identical specimen (W11-SD) previously loaded for 1.25 million cycles each at 62 and 68 percent of ultimate static load, respectively, sustained repeated loading at 75 percent of ultimate static load for another 1.25 million cycles without failure.

Deflection Behaviour

Comparisons between experimental and calculated maximum deflections were made and are summarized in Table 3, using beam and slab theories as follows:

Beam Theory:

$$\text{Single Span} \qquad \Delta_{cb} = \frac{P_{ue}L^3}{48E_cI_{cc}B} \qquad\qquad \text{Double Span} \qquad \Delta_{cb} = \frac{P_{ue}L^3}{67E_cI_{cc}B} \tag{2}$$

where

P_{ue} = ultimate experimental load

L = span length

E_c = modulus of elasticity of concrete

I_{cc} = moment of inertia based on cracked equivalent concrete section

B = width of test specimen

Slab Theory:

An approximate slab theory equation, taken from Reference [18], was used for both single and double span specimens to compute maximum deflections, and is given by

$$\Delta_{cs} = \frac{P_{ue}L^2}{5E_c t_c^3}. \tag{3}$$

where t_c is the depth of concrete above the top of steel deck. Table 3 summarizes, for both single and double span specimens, the maximum experimental deflections as well as the calculated deflections based on the slab theory, Equ. 3, and the beam theory, Equ. 2. As can be observed from Table 3, the experimental deflections did not agree with the beam theory, hence, single and double span specimens did not behave as beams. However, the deflections calculated according to the slab theory, Equ. 3, were in good agreement with the experimental deflections. Therefore, it can be concluded that single and double span specimens behaved as slabs with respect to deflections.

Concerning the stiffness of the static load tests, Figure 8 shows the load-deflection behaviour of single span specimen W1-SS and the load-deflection behaviour of double span specimen W10-DS is shown in Figure. 16. Both specimens showed similar deflection characteristics, with the actual average curves falling between the uncracked and cracked calculated deflections, a behaviour characteristic of composite slabs [14].

The load-deflection behaviour of specimens subjected to repeated loading for one fatigue life (1.25 million cycles), followed by a final static load, was in all cases similar to the one cycle static tests. This is illustrated in Figure 10 for single span specimen W5-SD and in Figure 17 for double span specimen W4-DD. A moderate continuous increase in deflection was experienced with an increase in number of cycles under constant loading. Figure 11 shows this behaviour for specimen W5-SD.

In the case of specimens being subjected to the "increased load approach", load-deflection curves are shown in Figures 15 and 18 for single span specimen W12-SD and double span specimen W7-DD, respectively. The stiffness of both specimens remained virtually the same during the different stages of repeated load cycling, and only at failure did the stiffness change. Also, the double span specimen W7-DD was more stiff in comparison to the single span specimen W12-SD, indicting the presence of some continuity and restraint over the interior support.

The irrecoverable deflection (Δ_{er}) experienced by the single span specimens was larger in comparison to the double span specimens. Furthermore, Δ_{er} increased for double and single span specimens when the number of cycles and/or the maximum repeated load increased. (See Tables 1 and 2).

Steel Stresses

Neither of the static load specimens, W1-SS (single span) or W10-DS (double span) yielded at any point, as evidenced by the strain gauge results. This can be observed for specimen W1-SS in Figure 9, for example. However when specimens W5-SD and W6-SD (both single span) and W4-DD (double span) were subjected to a final cycle static load, after repeated loading for approximately 1.25 million cycles, the steel deck yielded at the bottom fiber under the point of load application. Figure 13 shows this behaviour for specimen W5-SD. The repeated loading produced locked-in stresses which in turn resulted in irrecoverable deflections. These locked-in steel stresses ranged from 8 to 25% of the yield strength after 1.25 million cycles for specimens W5-SD, W6-SD and W4-DD. Figures 12 and 13 verify this for specimen W5-SD. Also, the steel stresses increased only marginally as the number of repeated load cycles increased, an example of which is illustrated in Figure 14 for specimen W5-SD. Hence, the steel deck yielded under the point of load application prior to failure, when the final cycle static load was applied.

Moments

The maximum experimental moments were calculated by using experimental stresses (strain gauge results) and yield strength values obtained from coupon tests, namely

$$M_{st} = \frac{F_{se}\, I_{cc}}{c} \tag{4}$$

where $F_{se} = \epsilon_s E_s$,
ϵ_s = measured strain in steel deck,
E_s = modulus of elasticity of steel,
I_{cc} = moment of inertial of composite slab based on equivalent cracked concrete section,
c = distance from neural axis of composite section to bottom fibre of steel deck.
The experimental moments were calculated based on equilibrium, as follows:

Single Span $\qquad$ Double Span

$$M_{ue} = \frac{P_{ue}L}{4B} \qquad M_{ue} = \frac{13P_{ue}L}{64B} \tag{5}$$

Another expression for calculating moments in slabs subjected to point loading at the center, reported in Reference [18], was used to establish a possible effective slab width. This is accomplished in the following manner:

The maximum moment in the span direction is

Single Span $\qquad$ Double Span

$$M_{ol} = \frac{P_{ue}L}{4B_e} \qquad M_{ol} = \frac{13P_{ue}L}{64B_e} \tag{6}$$

and the maximum moment in the support direction is

$$M_{ob} = M_{ol} - 0.0676P_{ue} \,, \tag{7}$$

where B_e = effective width of slab.

Different experimental expressions of calculaing the effective width, B_e, of a slab of infinite width can be found in Reference [19]. For example, B_e can be taken as 0.78L for the loading and boundary conditions of the study by Suleiman [13], however, $B_e = 0.75L$ was selected as an average value. By making the appropriate substitutions, Equ. 6 can be simply expressed as

Single Span $\qquad$ Double Span

$$M_{ol} = \frac{P_{ue}}{3} \qquad M_{ol} = \frac{13}{48}P_{ue} \tag{8}$$

To compute the maximum moment based on yielding of the steel deck, the following expression was used:

$$M_{uy} = A_s F_{ye} \left(d - \frac{a}{2} \right), \text{ where } a = \frac{A_s F_{ye}}{0.85 f'_c b} \quad (9)$$

Comparisons of maximum moments for both single and double span specimens are shown in Table 4. It should be noted that the calculated moments of Table 4 include a dead load component, which is not included in the equations above. As can be observed from Table 4 in comparing the results of M_{st} and M_{uy}, none of the specimens reached the calculated yield moment. In comparing the calculated moments, M_{ue} and M_{ol} with the experimental moments based on strain gauge results, M_{st}, the slab moments, M_{ol}, of Equ. 8 result in a better correlation with the experimental values than the beam moments, M_{ue}, of Equ. 5. The difference between calculated beam and slab moments is only marginal since the failure mode was shear-bond in all cases, with the failure crack extending almost straight across the width of the specimens. This suggests that in the case of maximum moment, the slab influence was only marginal.

Using strain gauge results, the distribution of moments across the width of specimens was also investigated at the center of single span and loaded double span specimens. It as observed that the moment reached a maximum under the point of load application and decreased towards the edges of the slab to approximately 60% of the ultimate moment. The reader is referred to Reference [13] for more detailed information relating to this topic.

CONCLUSIONS

Based on the study by Suleiman [13] the following conclusions and observations can be made:

Single Span Specimens

(1) The mode of failure of all one cycle static load specimens was shear-bond without yielding of the steel deck.

(2) The mode of failure of the specimens loaded repeatedly for 1.25 million cycles, after which a final static load was applied, also was shear-bond with evidence of yielding in the steel deck.

(3) Shear-bond was also the mode of failure with those specimens that were subjected to an increasing repeated load approach.

(4) Early end-slip prior to ultimate load was not experienced.

(5) Specimens that were loaded to failure after being subjected to 1.25 million cycles of repeated loading failed at a higher final static load (approximate 8%) than the specimen which was subjected to a one cycle static load.

(6) Specimens could sustain a maximum repeated load of approximately 75% of ultimate static load exceeding 1.25 million cycles without failure, based on the increasing repeated load approach.

(7) The stiffness of the repeated load specimens remained relatively constant throughout the cycling history. A change in stiffness was only experienced at failure, but even then, the reduced stiffness of the specimens shows that the slab system was still well interlocked.

(8) During the repeated load application, permanent deflection (irrecoverable) occurred. Most of this permanent deflection was experienced in the first 100 000 cycles. The rate of increase in permanent deflection became smaller as the number of cycles increased. Different specimens subjected to repeated loading of 1.25 million cycles showed approximately the same magnitude of permanent deflection.

Double Span Specimens

1. Similar to single span specimens, the failure mode was shear-bond (see items (1), (2) and (3) above).

2. Early end-slip prior to ultimate load was not experienced as was the case with single span specimens

3. One specimen which was loaded to failure after being subjected to 1.25 million cycles of repeated loading failed at a higher final static load (approximately 16%) than the specimen which was subjected to a one cycle static load.

4. The same conclusion can be drawn as in item (6) above for single span specimens.

5. The stiffness behaviour was similar to single span specimens described in item (7) above.

6. Concerning irrecoverable deflections, the same behaviour was observed as with single span specimens, discussed in item (8) above.

7. Shrinkage mesh does to some degree serve as negative reinforcement at midsupport of double span specimens. Based on the double span specimens tested, no visible cracks occurred at the interior support prior to ultimate load for both static and repeated loading.

RECOMMENDATIONS

The following recommendations are based on the study by Suleiman [13]:

1) Since single span specimens give conservative results and are less expensive to conduct in comparison to double span specimens, it is recommended that single span specimens be tested.

2) To reduce the number of repeated load tests to a minimum, the increasing load approach is recommended, using the weighted load factor method presented herein.

3) Maximum moments should be calculated in accordance with the slab approach given herein.

4) Maximum deflections should be calculated in accordance with the slab approach given herein.

REFERENCES

[1] Schuster, R.M., "Composite Steel-Deck Reinforced Concrete Systems Failing in Shear-Bond", Preliminary Report, Ninth Congress of the International Association for Bridge and Structural Engineering Zurich, Switzerland, 1972, pp. 185-191.

[2] Porter, M.L., "The Behaviour and Analysis of Two-Way Simply Supported Concrete Composite Floor Slabs Constructed with Cold-formed Steel Decking, Ph.D. Thesis, Iowa State University, Ames, Iowa, 1974.

[3] Luttrell, L.D., and Davison, J.H., "Composite Slabs with Steel Deck Panels", Proceedings of the Second Specialty Conference on Cold formed Steel Structures, University of Missouri, Rolla, Oct. 1973. pp. 573-603.

[4] ASCE Standard, "Specifictions for the Design and Construction of Composite Slabs" , Technical Council of Codes and Standards, Division of the American Society of Civil Engineers, New York, New York, October, 1984.

[5] Standard for Composite Steel Deck, Canadian Sheet Steel Building Institute, Willowdale, Ontario, Canada, July 1984.

[6] Testing Criteria for Composite Slabs, Draft Bulletin, Canadian Sheet Steel Building Institute, Willowdale, Ontario, Canada, May 1985.

[7] Nouw, Kenneth W., "Fatigue Testing of Light Metal Forms", Engineering Research Institute, Iowa State University, Ames, Iowa, January, 1969, ERI-348, Project 741.

[8] Climenhaga, J.J. and Johnson, R.P. "Fatigue Strength of Form Reinforced Composite Slabs for Bridge Decks", I.A.B.S.E., 35-1, 89-101, 1975.

[9] Borowski, R., Bryman, M., Hendrata, C. "Strength and Behaviour of Composite Steel-Deck Reinforced Concrete Floor Slabs Subjected to Repeated Loads", Report Prepared for Heads of Floor Systems at University of Waterloo, March, 1977.

[10] Abdel-Sayed, G., Temple, M.C. and Madugula, M.K.S., "Response of Composite Slabs to Dynamic Loads", Canadian Journal of Civil Engineering, Vol. 1, No. 1, 1974, pp. 62-70.

[11] Roeder, Charles W. "Point Loads on Composite Deck Reinforced Slabs", Journal of the Structural Division, ASCE, Vol. 107, No ST 12 Paper No. , December, 1981, pp. 2421-2429.

[12] Temple, M.C., and Abdel-Sayed, G., "Fatigue Experiments on Composite Slab Floors", Proceeding of the Fourth International Specialty Conference on Cold-Formed Steel Structures, University of Missouri-Rolla, Mo., June, 1978, pp. 871-891.

[13] Suleiman, R.E., "Behaviour of Composite Slabs Subjected to Repeated Point Loading", M.A.Sc. Thesis, University of Waterloo, Waterloo, Ontario, 1983.

[14] Schuster, R.M., "Strength and Behaviour of Cold-Rolled Steel-Deck Reinforced Concrete Floor Slabs", Ph.D. Thesis, Iowa State University, Ames, Iowa, 1970.

[16] Schuster, R.M., "Composite Steel-Deck Concrete Floor Systems", Journal of the Structural Division, ASCE, Vol. 102, No. ST 5, Proc. Paper 12116, May, 1976, pp. 899-917.

[16] Schuster, R.M. and Ling, W.C., "Mechanical Interlocking Capacity of Composite Slabs", Fifth International Specialty Conference on Cold Formed Steel Structures, St. Lousi, Missouri, U.S.A., Nov., 1980, pp. 387-407.

[17] "National Building Code of Canada", National Research Council of Canada, Ottawa, Canada, 1985.

[18] Westergaard, H.M., "Computation of Stresses in Bridge Slabs Due to Wheel Loads", Public Roads, Vol. 11, No. 1, March, 1930.

[19] Morris, Clyde, T., "Concentrated Loads on Slabs", Ohio Engineering Experiment Station Bull. 80. Nov. 1933.

NOTATIONS

A_s	Cross-sectional area of steel deck mm^2/m of width
a	$A_s F_{ye}/0.85 f'_c b$
B	Width of composite slab, mm
b	Unit width of composite slab - 1000 mm
D	Depth of composite specimen (from lowest point of steel deck to top of concrete), mm
d	Effective depth of composite slab (from top of concrete to c.g.s.) m
E_c	Modulus of elasticity of concrete, MPa
E_s	Modulus of elasticity of steel deck, MPa
ϵ_{s_t}	Measured experimental steel deck strain, micro mm/m
f'_c	Compressive test cylinder strength of concrete, MPa
F_{se}	Calculated experimental stress in steel deck, MPa
F_{ye}	Yield strength of steel deck obtained from standard coupon tests, MPa
I_{cc}	Moment of inertial of composite section based on equivalent cracked concrete section, mm^4/m of width
L	Length of span, mm
M_{ol}	Maximum moment in span direction, based on slab action, kN.m/m
M_{ob}	Maximum moment in support direction, based on slab action, kN.m/m
M_{ue}	Maximum moment based on equilibrium, kN.m/m
M_{st}	Maximum moment based on experimental stress, kN.m/m
M_{uy}	Ultimate moment based on yielding of steel, kN.m/m
N	Number of cycles
P_e	Applied experimental load, kN
P_{ue}	Ultimate experimental static load, based on one cycle , kN
P_{mr}	Maximum repeated load, kN
P_{uer}	Ultimate experimental static load after (N) cycles of repeated load, kN.
t	Nominal steel deck core thickness, mm
t_c	Depth of concrete above top of steel deck, mm
Δ_{er}	Irrecoverable midspan deflection, mm
Δ_{es}	Experimental midspan deflection, mm
Δ_{cb}	Calculated midspan deflection, based on beam theory, mm
Δ_{cs}	Calculated midspan deflection, based on slab theory, mm

Table 1: Test Results of Single Span Specimens

Specimen No.	Specimen Designat.	Emboss. Group (a)	P_{mr} (kN)	N (Cycles)	P_{ue} (kN)	P_{uer} (kN)	Δ_{er} (mm)	Mode of Failure
Static Load								
1	W1-SS	1	-	1	71.9	-	-	Shear-Bond
Repeated Load								
2(b)	W2-SD	2	48.9	11 620	-	45.8	-	Shear-Bond
3	W5-SD	2	44.5	1 250 000	-	76.8	1.70	Shear-Bond
4	W6-SD	2	48.9	1 270 000	-	78.5	1.80	Shear-Bond
5	W8-SD	3	53.2	18 160	-	45.0	-	Shear-Bond
6	W9-SD	3	48.9	3 672 800	-	41.0	-	Shear-Bond
7	W11-SD	4	44.5	1 250 000	-	-	1.80	
			48.9	1 250 000	-	-	2.00	
			53.3	1 250 000	-		2.30	
			57.7	279 720	-	57.5	-	Shear-Bond
8	W12-SD	4	48.9	1 250 000	-	-	1.60	
			53.3	1 250 000	-	-	2.00	
			57.7	1 260 110	-	-	2.15	
			62.3	18 670	-	57.5	-	Shear-Bond

(a) Embossment depth (Group 1 - 1.86 mm; Group 2 - 1.85 mm; Group 3 - 1.65 mm; Group 4 - 1.88 mm)

(b) Test not considered reliable - problem with testing equipment.

Table 2: Test Results of Double Span Specimens

Specimen No.	Specimen Designat.	Emboss. Group (a)	P_{mr} (kN)	N (Cycles)	P_{ue} (kN)	P_{uer} (kN)	Δ_{er} (mm)	Mode of Failure
Static Load								
1(b)	W3-DS	1	-	1	65.4	-	-	Shear-Bond
2	W10-DS	4	-	1	81.9	-	-	Shear-Bond
Repeated Load								
3	W4-DD	2	44.5	1 250 000	-	94.8	1.00	Shear-Bond
4	W7-DD	3	57.8	2 590 000	-	-	2.90	
			62.3	1 240 000	-	-	3.30	
			66.7	490 670	-	-	3.90	
			77.8	2 110	-	66.5	-	Shear-Bond

(a) See Footnote of Table 1

(b) Test not considered reliable - problem with testing equipment

Table 3: Comparison of Maximum Experimental and Calculated Deflections for Single and Double Span Specimens

Specimen Designation	Δ_{es} (mm)	Δ_{cs} (mm) Equation 3	Δ_{cb} (mm) Equation 2
Single Span			
W1-SS	6.10	6.30	4.40
W5-SD	7.60	7.70	5.90
W6-SD	7.70	7.90	6.10
Double Span			
W3-DS	5.00	5.30	2.70
W4-DD	8.20	8.50	4.80
W7-DD	6.00	6.30	3.30
W10-DS	5.20	6.60	3.40

Note: Deflections of Loaded Span for Double Span Specimens

Table 4: Comparison of Maximum Moments of Single and Double Span Specimens

Specimen Designation	M_{st} (kNm/m) Equation 4	M_{ue} (kNm/m) Equation 5	M_{0l} (kNm/m) Equation 8	M_{uy} (kNm/m) Equation 9
Single Span				
W1-SS	28.37	25.10	25.50	38.21
W5-SD	29.55	26.71	27.14	39.42
W6-SD	29.55	27.26	27.70	39.42
Double Span				
W3-DS	21.47	18.27	18.57	39.96
W4-DD	28.54	26.11	26.54	40.82
W10-DS	23.91	22.67	23.04	40.55

Note: Dead load moments are included in the moment calculations.

FIGURES

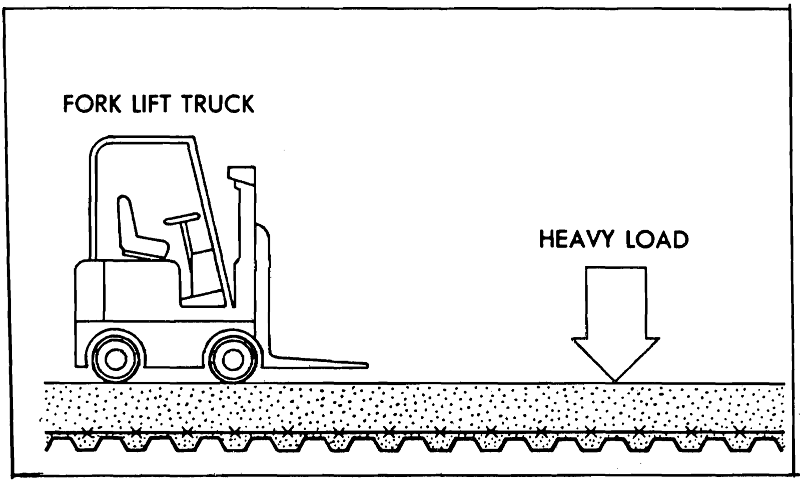

Figure 1. Schematic of Typical Composite Slab System Subjected to Point Loading.

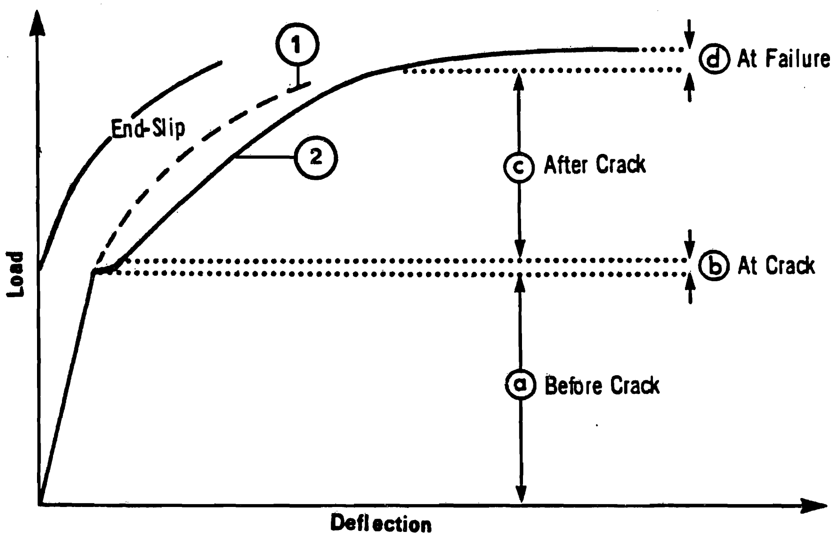

Figure 2. Typical Load-Deflection and End-Slip Curves.

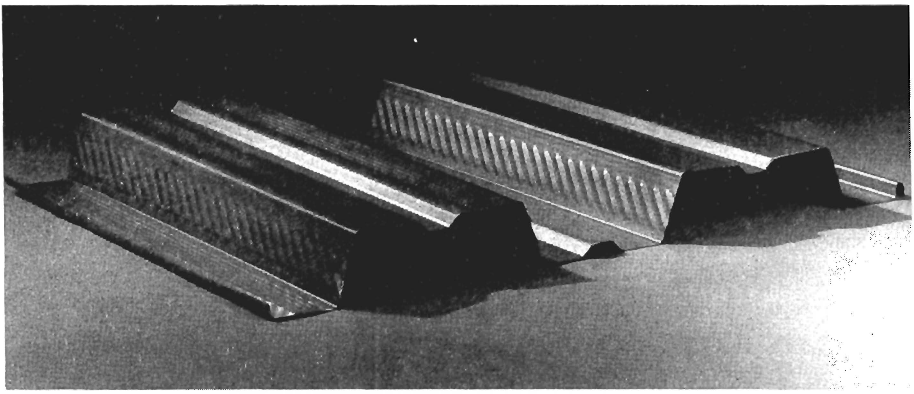

Figure 3. Photograph of Composite Deck Tested

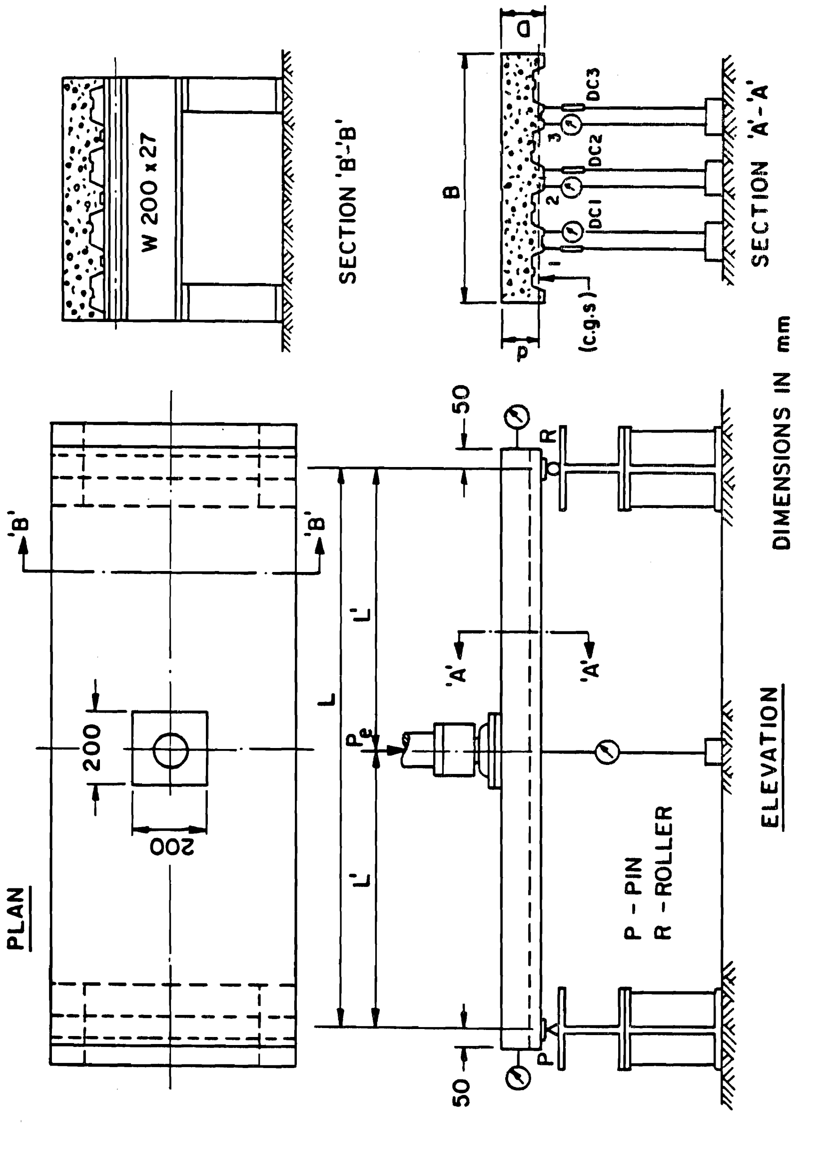

Figure 4. Typical Test Set-Up for Single Span.

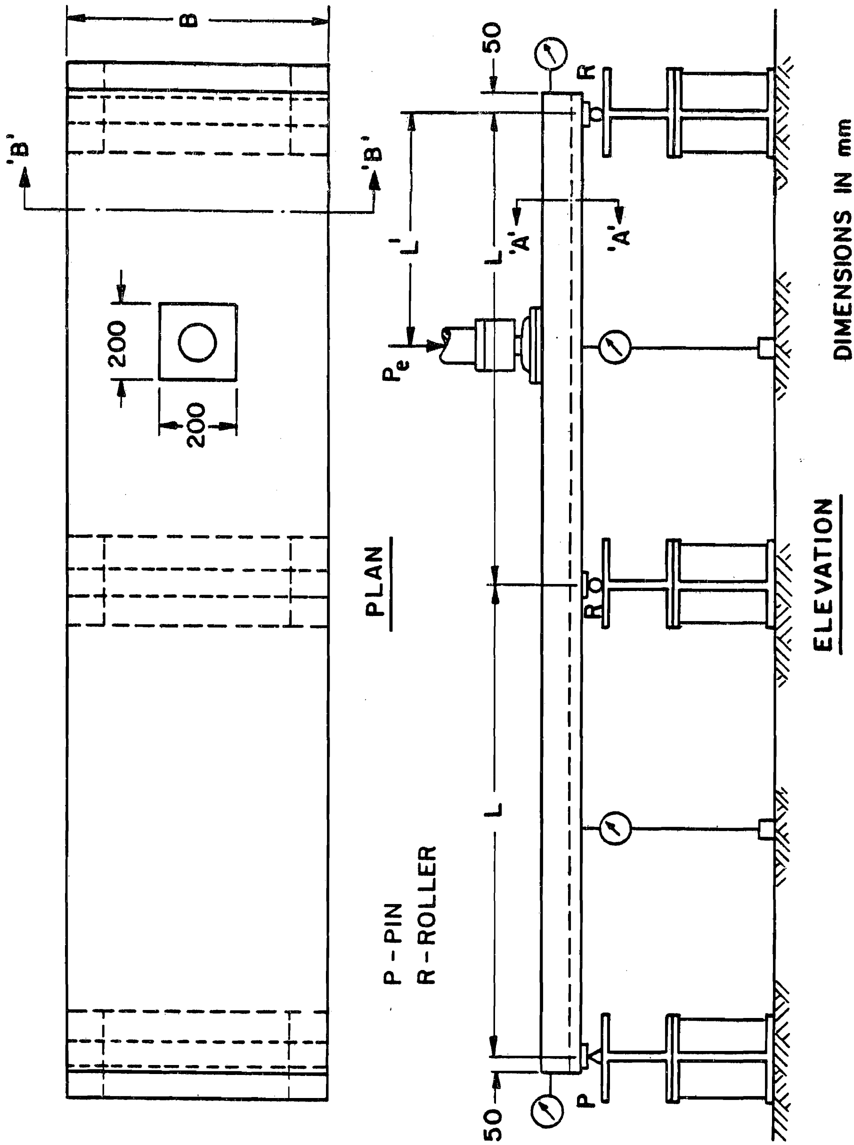

Figure 5. Typical Test Set-up for Double Span. (See Fig. 4 for Sections A-A and B-B).

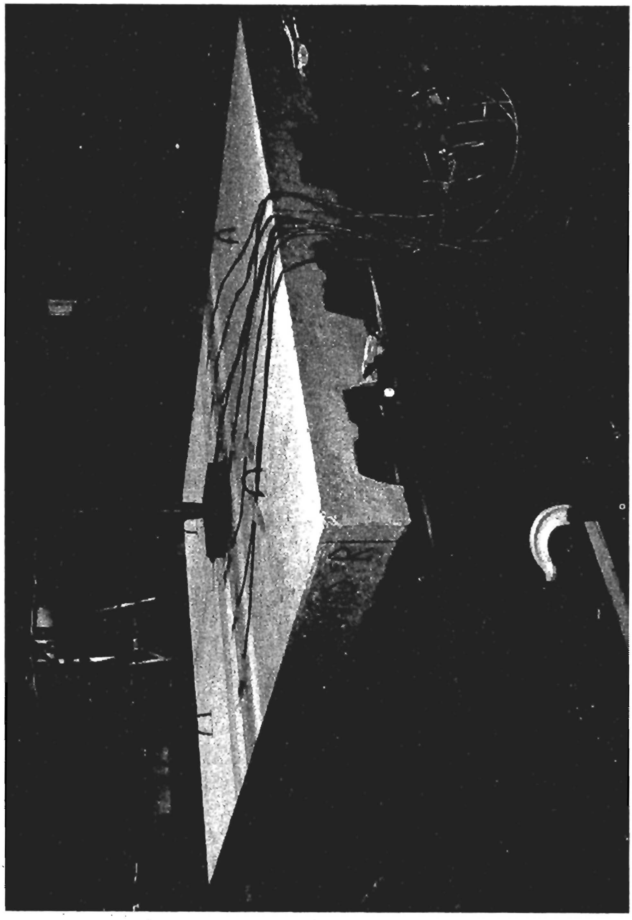

Figure 6. Photograph of Testing Frame with Single Span Specimen in Position.

Figure 7. Typical Shear-bond Failure, Showing Failure Crack.

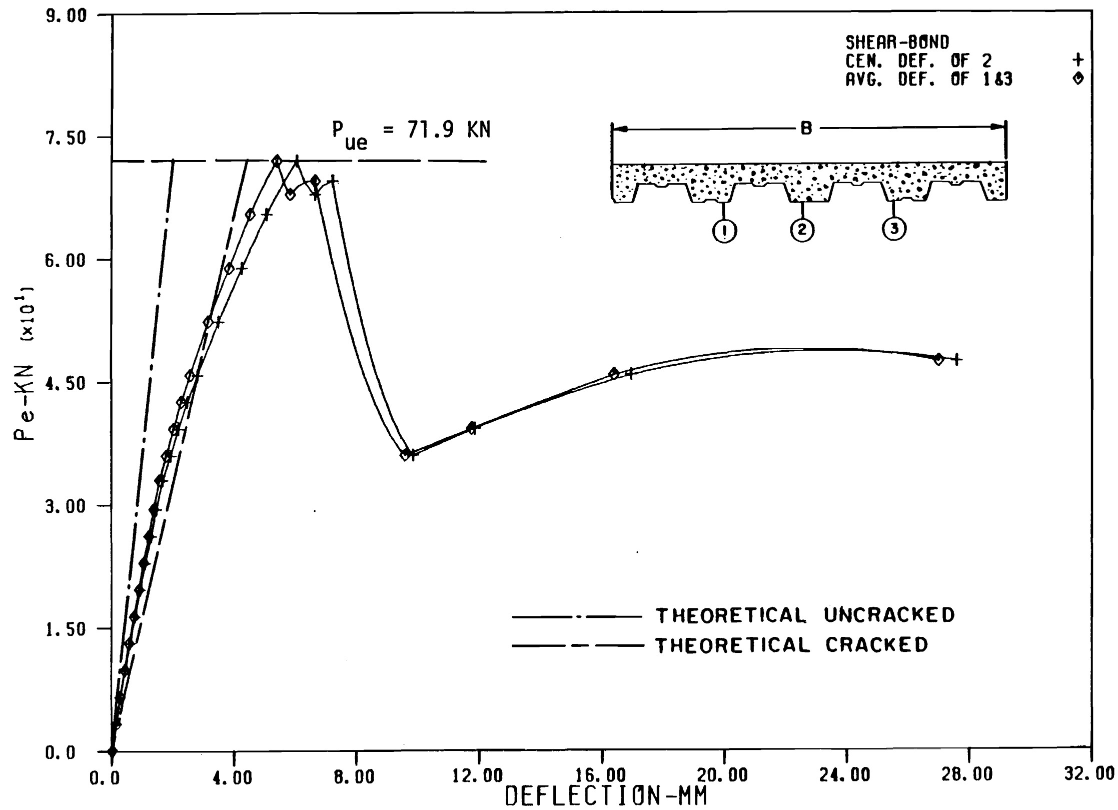

Figure 8. Load-Deflection Curves of Specimen W1-SS (Single Span and Static Load).

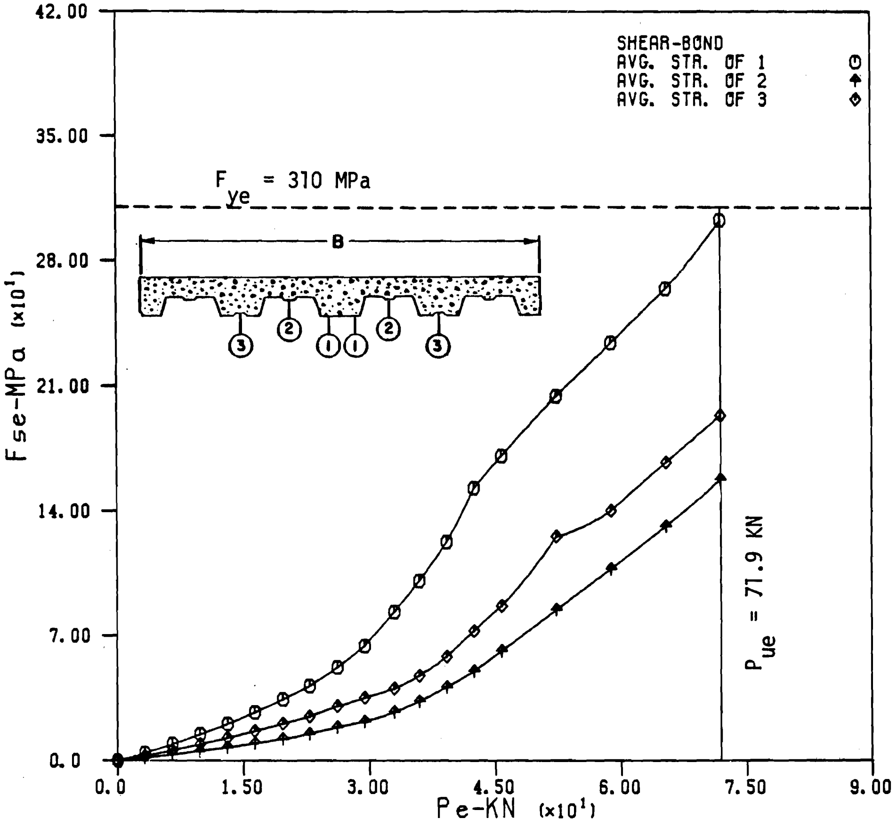

Figure 9. Experimental Steel Stresses Versus Applied Static Load of Specimen W1-SS.

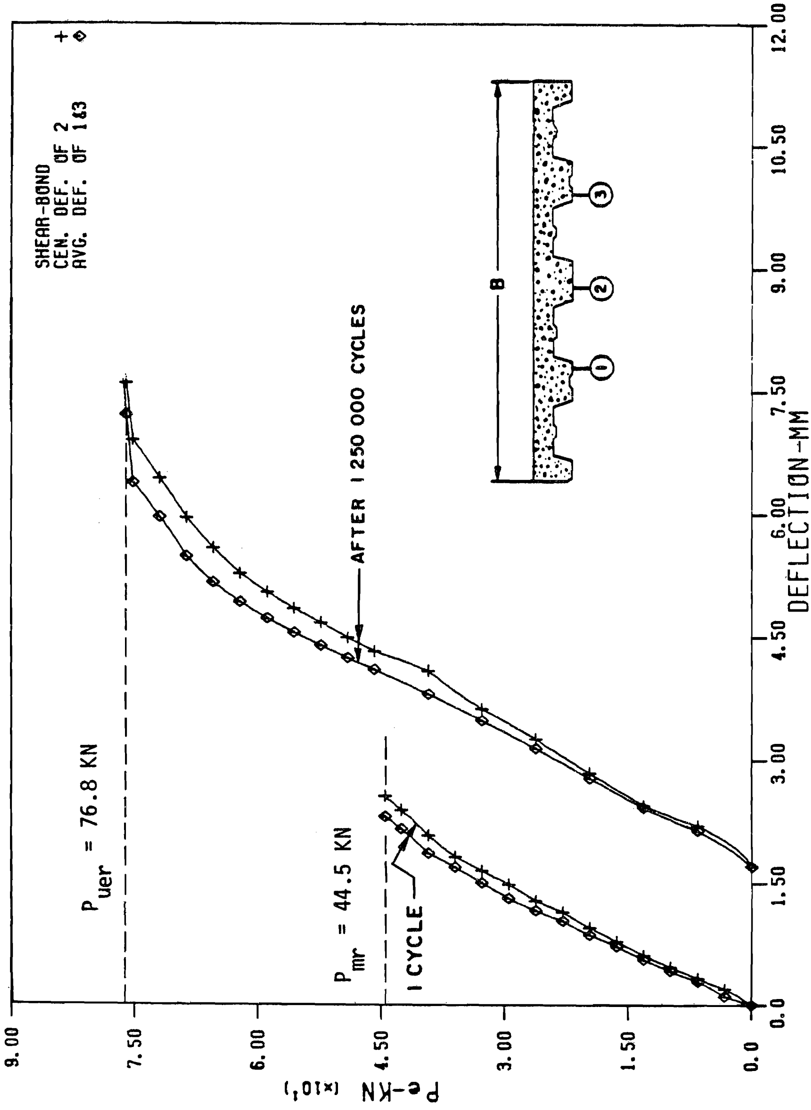

Figure 10. Load-Deflection Curves for Specimen W5-SD (Single Span and Repeated load).

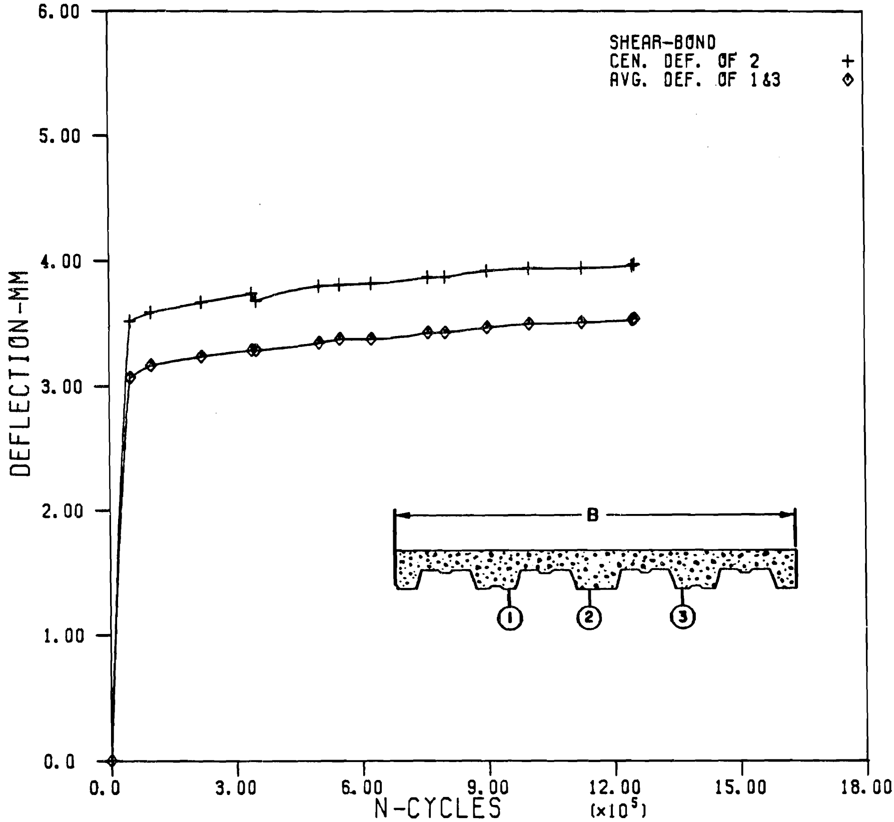

Figure 11. Deflection Versus Number of Cycles of Specimen W5-SD.

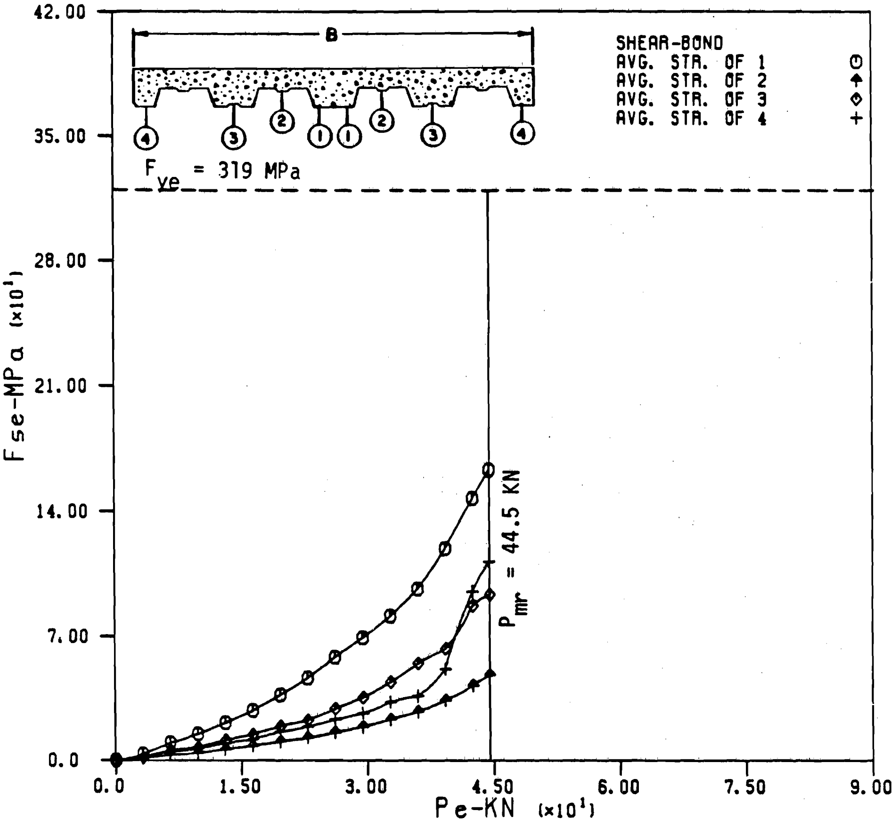

Figure 12. Experimental Steel Stresses Versus First Cycle Static Load of Specimen W5-SD.

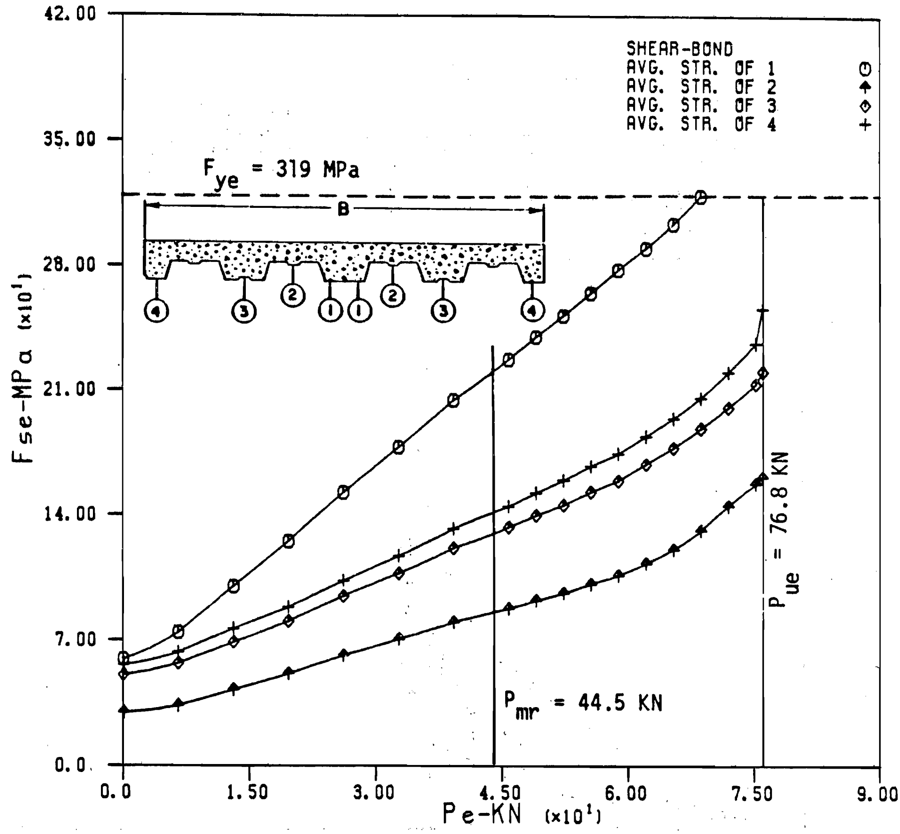

Figure 13. Experimental Steel Stresses Versus Applied Load After 1.25 Million Cycles of Specimen W5-SD.

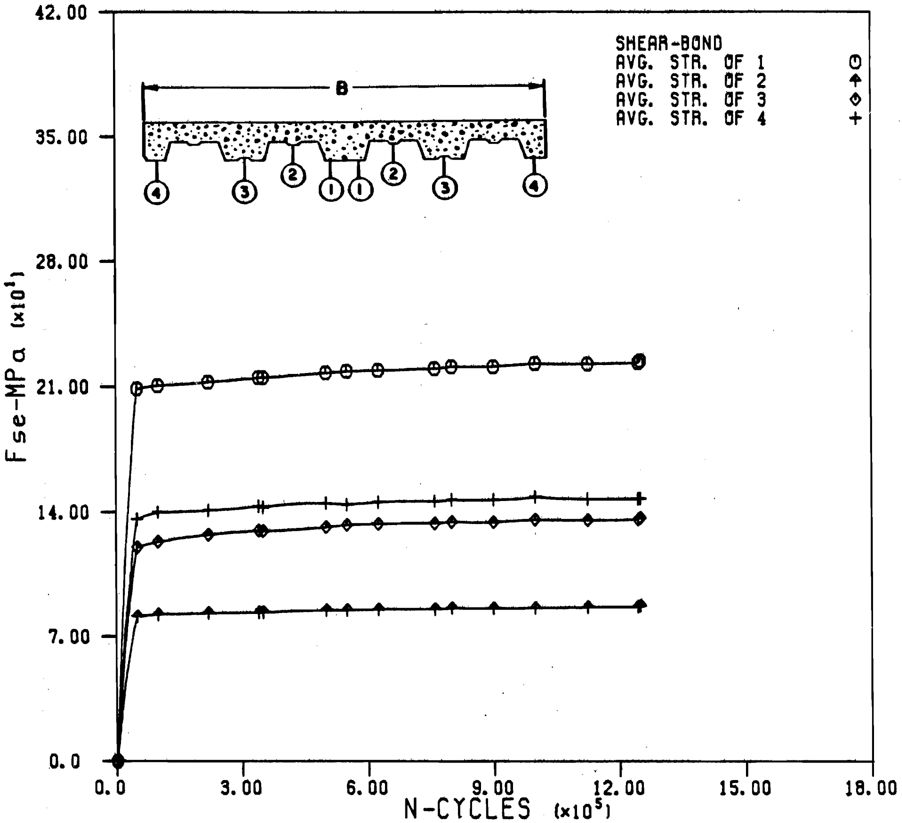

Figure 14. Experimental Steel Stresses Versus Number of Cycles of Specimen W5-SD.

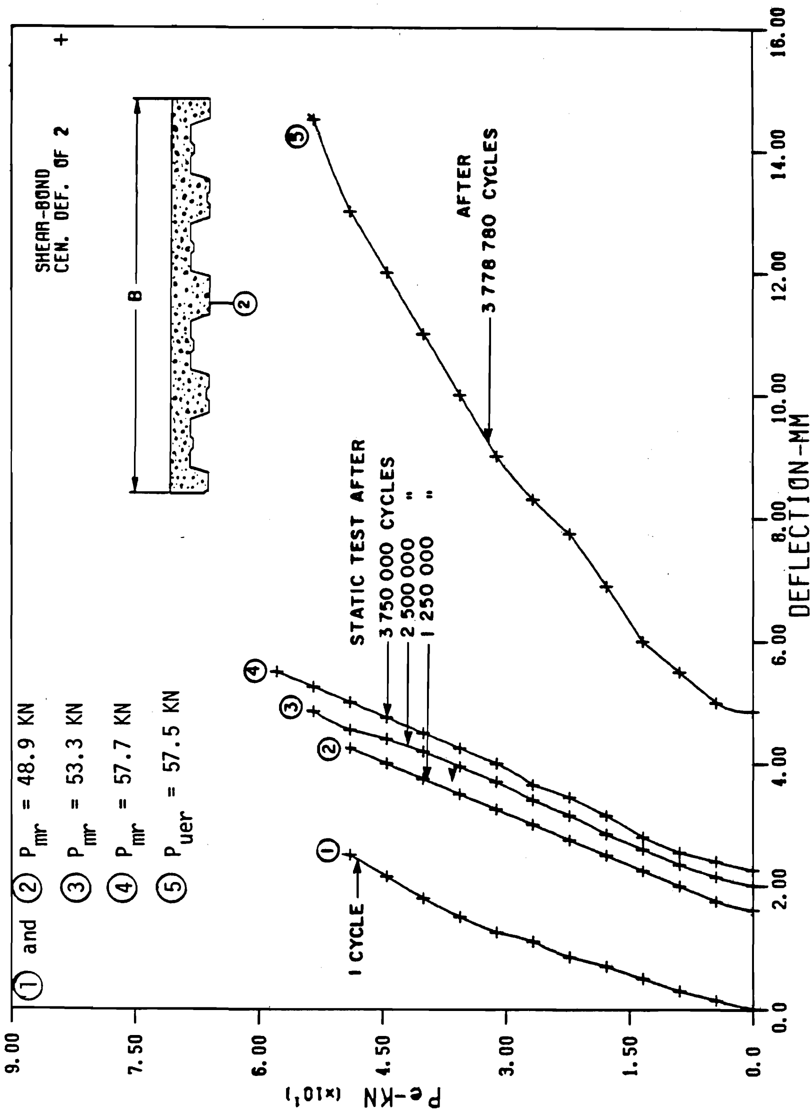

Figure 15. Load-Deflection Curves of Specimen W12-SD (Single Span with Repeated Load)

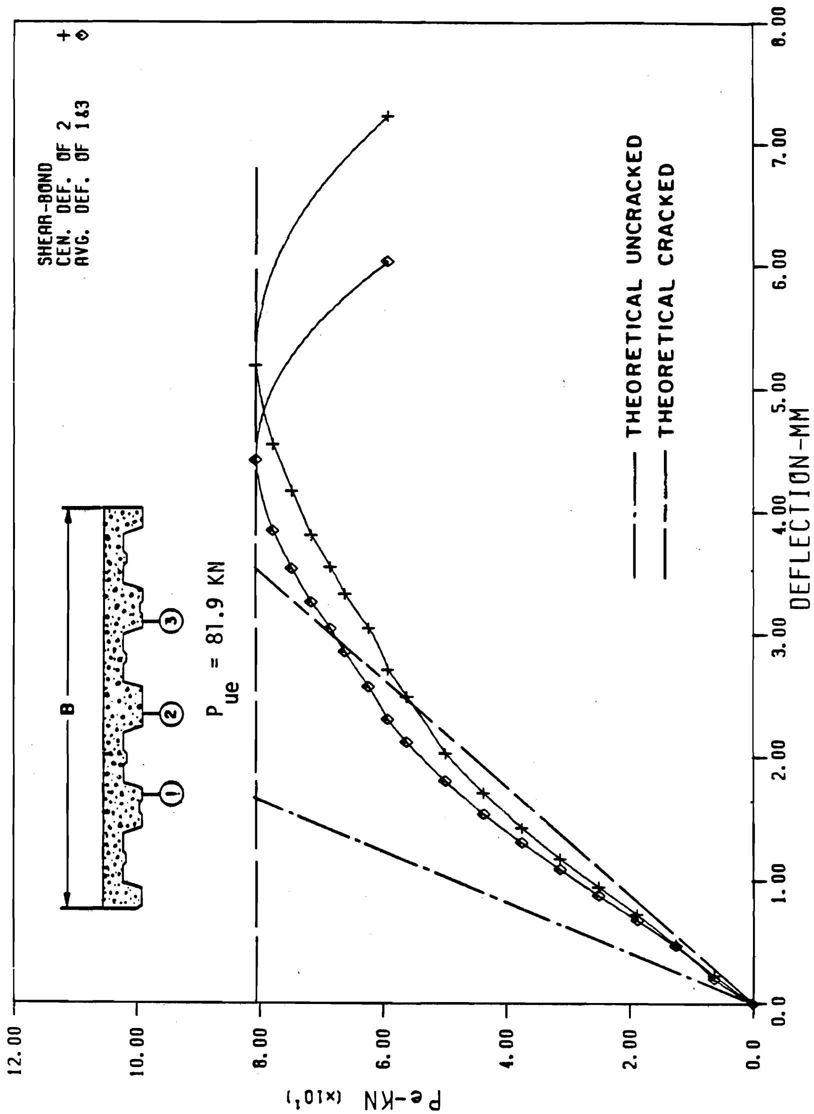

Figure 16. Load-Deflection Curves at Center of Loaded Span of Specimen W10-DS (Double Span and Static Load)

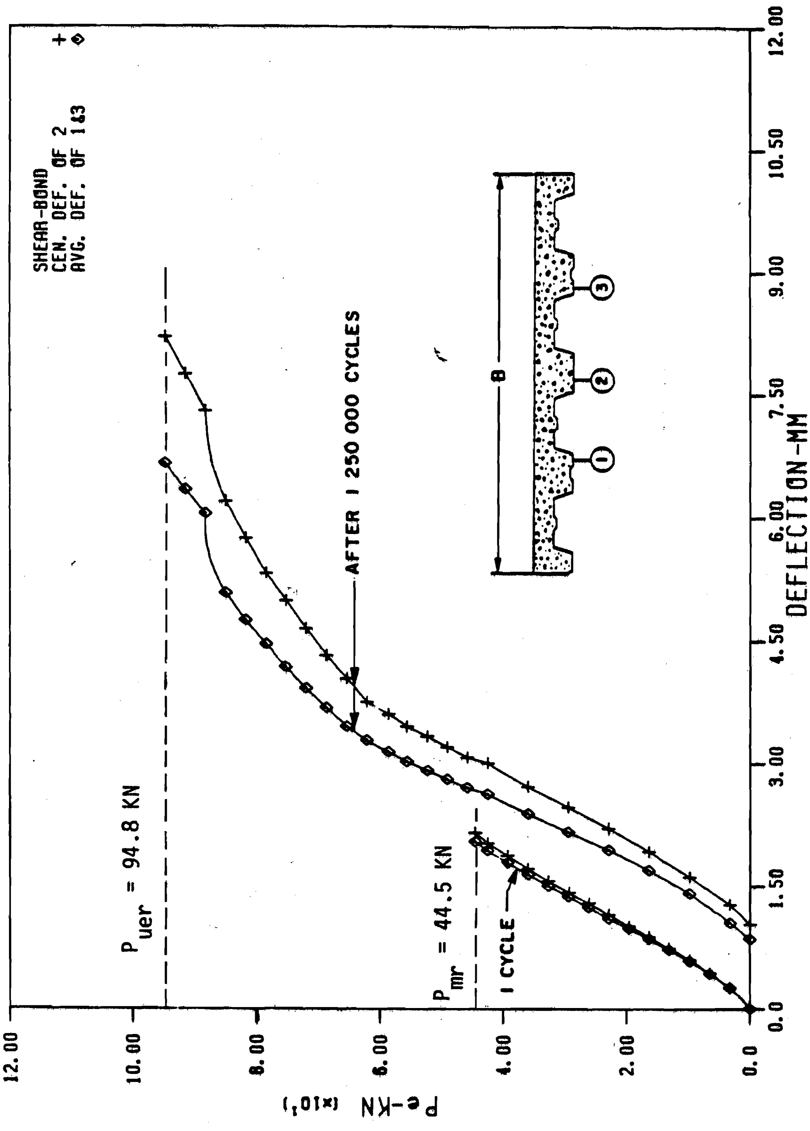

Figure 17. Load-Deflection Curves at Center of Loaded Span of Specimen W4-DD. (Double Span and Repeated Load)

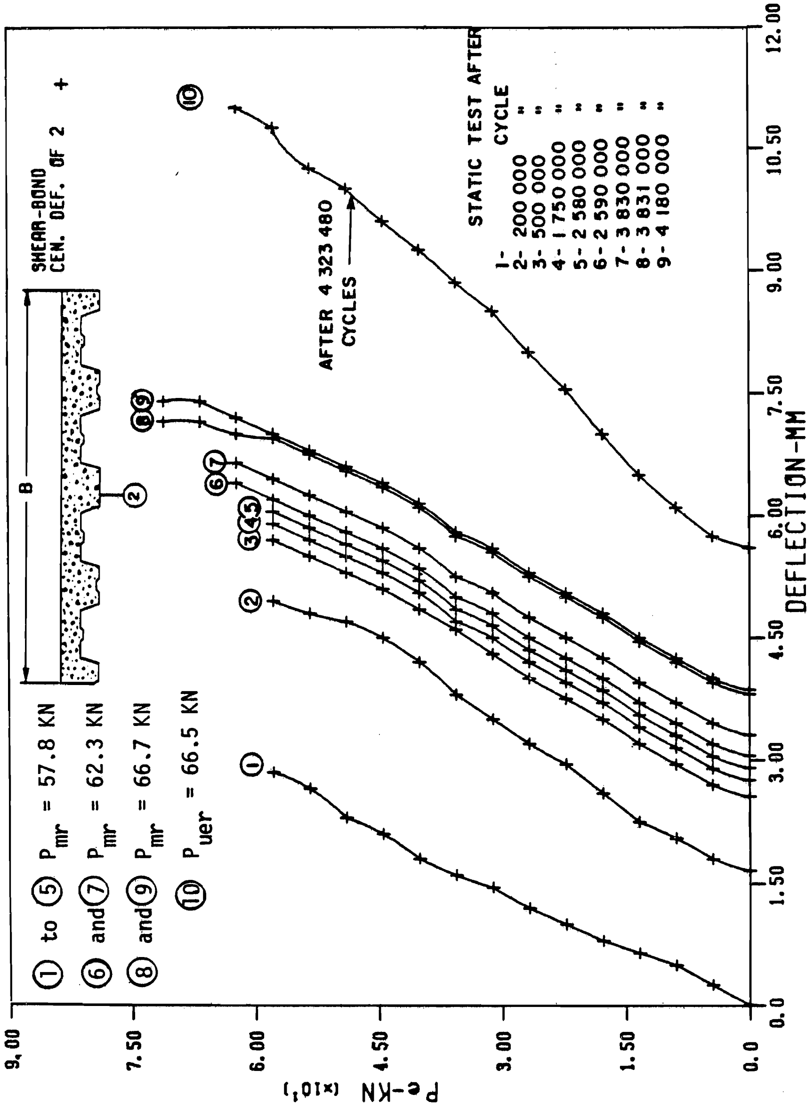

Figure 18. Load-Deflection Curves at Center of Loaded Span of Specimen W7-DD (Double Span and Repeated Load)