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BEHAVIOUR OF BOLTED JOINTS OF CORRUGATED STEEL PLATES

by

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JANUARY, 1988

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REPORT

TO

ALBERTA TRANSPORTATION

ON

BEHAVIOUR OF BOLTED JOINTS

OF

CORRUGATED STEEL PLATES

by

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and

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Abstract

Fifteen tests of lap joints of 3, 5 and 7 mm thick corrugated steel plates were conducted under uniform moment conditions to establish the moment-rotation behaviour of the joints. Low, medium and high torques were used to tighten the bolts. Laps were made with 2, 3 and 4 bolts per complete corrugation. The moment-curvature diagrams for plain plate specimens were established theoretically and verified experimentally.

The lap joint tests show conclusively that correct and incorrect laps exist. Correct lap joints are those in which no bolt is placed on the tension side of the lap at the location where the plates tends to separate when moments are applied, i.e., where prying occurs. These laps are correct for either direction of bending. In incorrect lap joints, tearing occurs transverse to the span from the edge of the bolt holes located on the tension side where prying occurs. This results in reduced ductility. Lap joints with 3 bolts per corrugation are likely to be loaded incorrectly and those with 4 bolts per corrugation will be loaded incorrectly. Improved performance results when the bolts are installed with high torques. To obtain the best performance of a lap joint, 2 bolts in the correct configuration should be used. The size of the bolts and length of the lap should be established to provide a joint with bending resistance more or less equal to that of the plain plate.

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1. Introduction

1.1 General

The University of Alberta, Department of Civil Engineering, has been retained by Alberta Transportation, under agreement CE19/87, dated July 13, 1987, and amended by letter of October 26, 1987, to conduct a project on "Research on Bolted Joints of Corrugated Steel Culverts".

It is generally agreed that bolted lap joints of corrugated steel plates can be made correctly or incorrectly depending upon the placement of the bolts near the edges of the plates. Correctly lapped joints are those in which the plates are assembled so that the bolts closer to the visible edge of the plate are in the valleys of the corrugations and the bolts on the crests of the corrugations are near the hidden edge of the lap as shown in Fig. 1.1, depicting a lap joint of three complete corrugations. The upper plate extends from the left and the 3 bolts on the right hand side of the lap are in the valleys near the visible edge of the lap. From section A-A, for either direction of applied moment, the bolt on the tension face is remote from the edge where the plates tend to separate, i.e., where prying takes place. When the bottom fibres are in tension, prying occurs at B and the valley bolts are remote from this edge; similarly when the top fibres are in tension, prying occurs at T and the crest bolts are remote from this edge.
Fig. 1.2 shows an incorrectly lapped joint in which the

plates are assembled so that the 2 bolts closer to the visible edge of the plate are on the crests of the corrugations and the 3 bolts in the valleys are near the hidden edge. Examining section A-A in Fig. 1.2 reveals that for either direction of applied moment, the bolt on the tension face is adjacent to the edge where prying takes place, i.e., edge B when the bottom fibres are in tension and edge T when the top fibres are in tension. Evidence of failures in the field shows that, when joints are lapped incorrectly, tearing of the plate occurs from the edge of the bolt holes on the tension side. The overall joint deformation is limited, whereas correctly lapped joints can experience substantial deformation without tearing and loss of moment capacity. Tearing at the bolt holes near the hidden edge of a lap is shown in Fig. 1.3.

These field observations have been confirmed by a limited series of pilot tests conducted by Alberta Transportation. A more extensive series of tests is required to quantify the behaviour of correct and incorrect laps and to establish design parameters.

1.2 Objectives

The objectives of this research are:

1. to compare the difference in behaviour of correct and incorrect lap joints.
2. to establish experimentally the moment-rotation behaviour and the ultimate capacity of joints of

different configurations. These configurations include correct and incorrect laps, different joint bolting arrangements (the number of bolts per corrugation), the presence of sloped washers, bolts installed with different torques and different plate thicknesses.

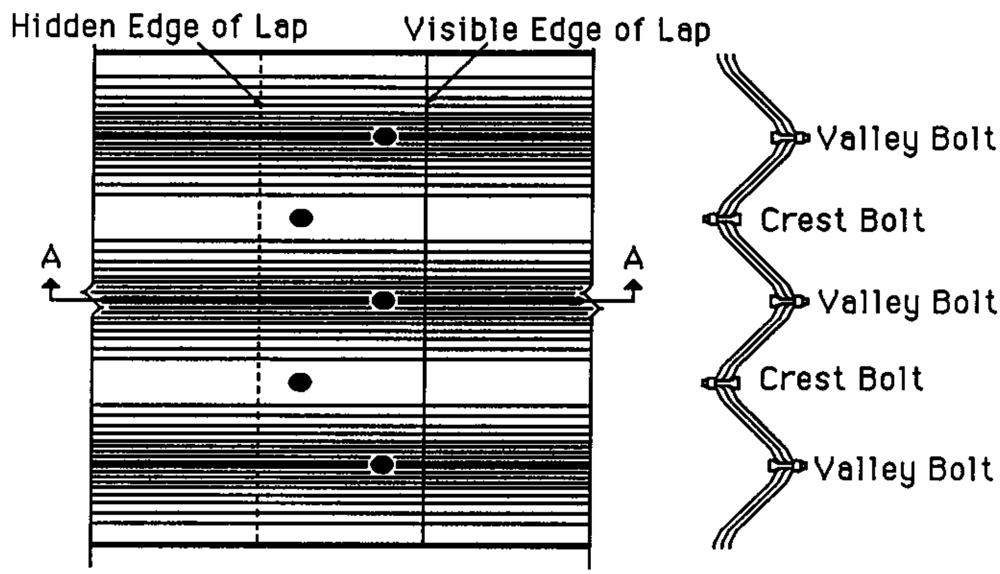
1.3 Scope

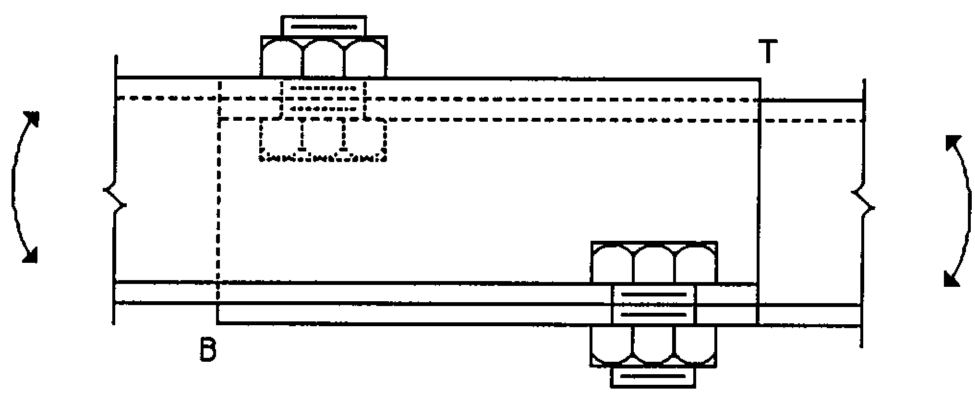
A total of 17 flexural tests on 16 specimens were performed at the I. F. Morrison Structural Laboratory of the University of Alberta. The specimens were tested as simply supported beams with a two-point load system providing two equal shear spans and a constant moment region. Parameters investigated included plate thicknesses, bolting arrangements and lap configurations. Ancillary tests consisted of six tension coupon tests. From the experimental data that includes applied loads, measured deflections, steel strains, gap width and observation of tearing at bolt holes, the behaviour of specimens is determined and conclusions are drawn.

1.4 Personnel

The testing was carried out by Research Associate Raymond W. S. Lee and Chief Laboratory Technican Larry Burden, working under the direction of Professor D. J. Laurie Kennedy. Frequent consultation during the progress of the tests was held with Alberta Transportation personnel including Leonid Mikhailovsky and Helen

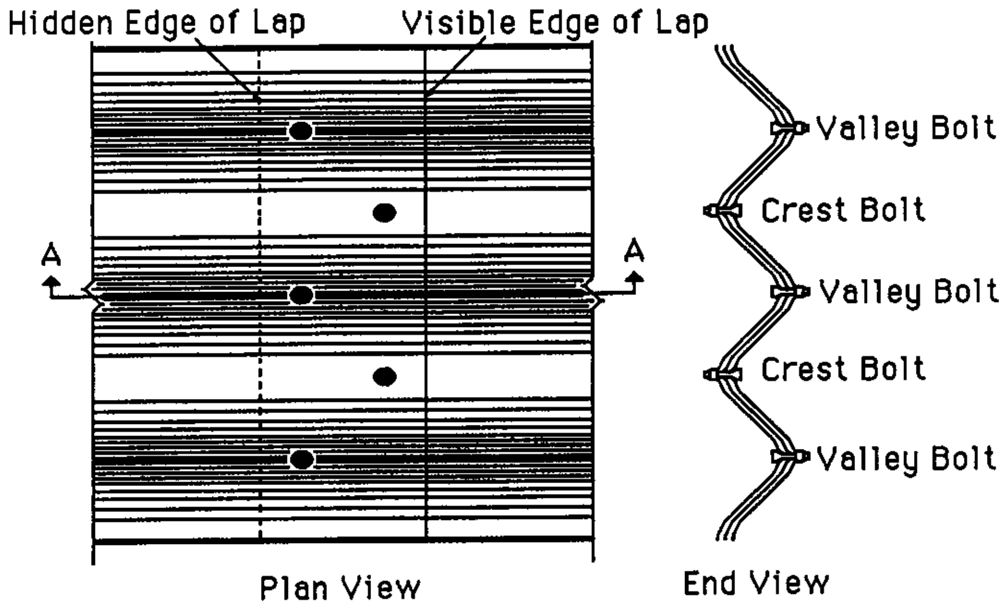
Tetteh-Wayoe who together with Alan Mah observed some of the tests. The test results were analysed and this report written by Lee and reviewed by Kennedy.





Section A-A

Figure 1.1 Correct Lap Joint



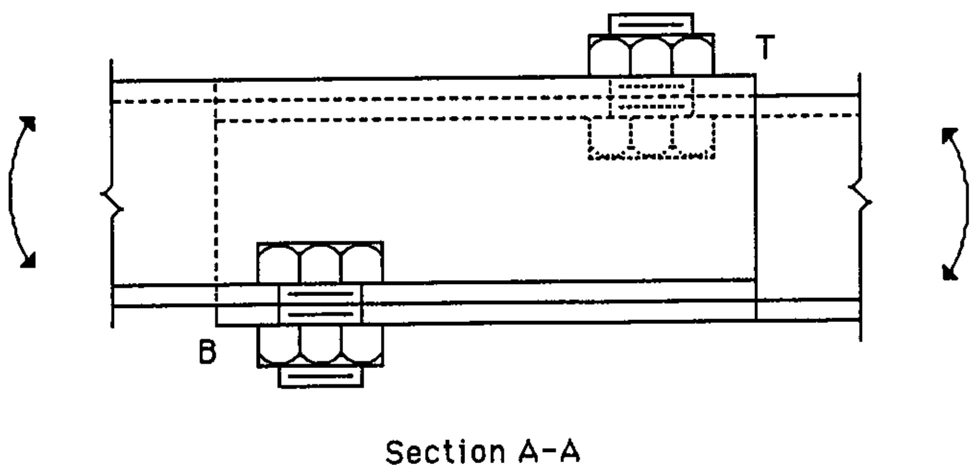


Figure 1.2 Incorrect Lap Joint

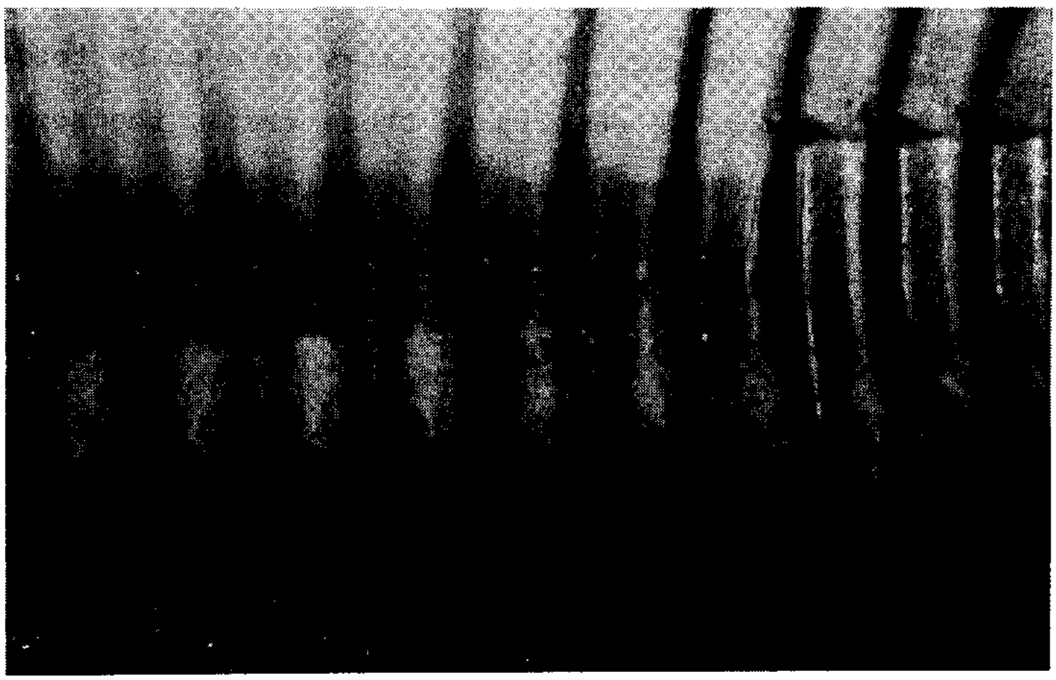


Figure 1.3 Tearing at Bolt Holes

2. Experimental Program

2.1 General

Initially, it was proposed that a total of 12 flexural tests be conducted on lapped corrugated steel plates of 3, 4, 5, 6 and 7 mm thickness as shown in Table 2.1. A correct lap and incorrect lap on 5 mm plates were to be tested first and, subject to the results of these tests, the series was to be modified as seen fit. In the initial test setup, used for one test on the 5 mm plate with correct lap and two tests on 5 mm plate with incorrect lap (the second of these two tests was a continuation of the first), with a span of 4.4 m, the specimens proved to be too flexible. The test setup was then modified to provide a 1.7 m span with a constant moment region of 0.6 m. This setup proved to be sufficiently stiff although the space available for instrumentation was limited. At this time, and subsequently during the 2 months period of experimental testing, the program was revised extensively. A total of 17 flexural tests was done on 16 specimens with the last 14 tested on a test span of 1.7 m. The final testing program is shown in Table 2.2. The original objective of the program to establish experimentally the moment-rotation relationship for correct and incorrect lap configurations for several different thicknesses of plate material was expanded and revised to include the following aspects:

1. to establish the effects of high (500 N.m), medium (250

N.m) and low (50 N.m) bolting torques on the strength of correct and incorrect laps.

2. as a bench mark, to determine the moment-curvature relationship for the 5 mm plate in bending.
3. to establish the effects of different bolting configurations of 2, 3 and 4 bolts per corrugation and with correct and incorrect laps on 7 mm plates.
4. to observe the development of tearing at the bolt holes and the opening of the gap between the lapped plates on the tension side where prying occurs.

In addition, tension tests were performed on 6 coupons to establish material properties.

As discussed, the test series was designed to evaluate the effects of different plate thicknesses, of correctly and incorrectly lapped joints, of low, medium and high torques on the bolts and 2, 3 and 4 bolts per corrugation for the 7 mm thick plates. In this limited series of tests, it was virtually impossible to carry out sufficient tests to provide a statistical basis for the evaluation of the different parameters. The approach used, which provided much useful information, but more tests would be required to assess the parameters statistically.

2.2 Test Specimens

All the test specimens listed in Table 2.2 were about 760 mm wide containing 5 complete corrugations. It was originally planned that Alberta Transportation would bolt these specimens together with correct and incorrect lap as required and with whatever torques were deemed appropriated. Subsequently, Alberta Transportation asked that the University of Alberta research group take responsibility for assembling the specimens. The program for the specimens was also modified to include many more 7 mm plates with special bolting arrangements than originally anticipated. Also as discussed previously, because of the flexibility of the 4.4 m span specimens, the test span was reduced to 1.7 m for the last 14 specimens tested. For each thickness of plate, the thickness, t, depth, d, and pitch, p, were measured to determine the geometric properties of the cross-section. These measurements together with the material properties obtained from the tension coupon tests allow the theoretical moment-curvature relationship for the corrugated plates to be obtained.

The specimens tested, with one exception, have an alphanumeric designation as shown in Table 2.2. The standard designation such as 5C2M indicates, in order, that the plate thickness is 5 mm, the lap is made correctly, there are 2 bolts per complete corrugation (one in the valley and one on the crest) and that the torque applied was of medium value, i.e., 250 N.m per bolt. Other torque designations are H for the high torque of 500 N.m and L for the low torque of 50 N.m. Two of the 5 mm plate tests carry the additional designator ".1" indicating these specimens were tested on the initial 4.4 m span. Five of the 7 mm plate specimens carry additional designator letters C, V and W. The C indicates that 2 of the 3 bolts are on the crest, the V indicates that 2 of the 3 bolts are in the valley, and the W indicates that the valley bolts were installed with sloped washers conforming to the shape of the corrugations.

The exception to the alphanumeric designation is Specimen 5000, a plain corrugated 5 mm thick specimen with no lap. This specimen was tested to confirm the moment-curvature relationship as could be deduced, in part, from the measured geometry of the corrugations and the stress-strain characteristics of the galvanized steel.

Apart from Specimens 5C2M.1 and 5I2M.1, all the bolts used had four small radial ribs on the underside of the head. All bolts were cleaned by wire-brushing and the threads were lubricated before installation to minimize the variation in bolt tension with torque. The bolts were torqued using a torque wrench (supplied by Alberta Transportation) applied to the nuts. The torque wrench was easily used by placing the heads of the bolts in the valleys and the nuts on the crests.

The bolting arrangements for the 7 mm plate specimens with 3 or 4 bolts per complete corrugation are shown in Figs. 2.1 to 2.5. Of particular interest are sections A-A on each of the figures which show the direction of the applied moment in the test. The designation C for correct lap and I for incorrect lap is based on Figs. 1.1 and 1.2 as if only 2 bolts were used per corrugation.

Examining section A-A in Fig. 2.1 for "correctly" lapped specimen 7C3MC shows that the lap is indeed correct for the direction of the applied moment in the test. If, however, the moment had been reversed, as it could be in the field, then the bolt at location T would be on the tension side where prying occurs. Under this circumstance, the lap becomes an incorrect lap. Therefore, one-half the time on the average, this 3 bolts per corrugation lap would behave incorrectly. Section A-A in Fig. 2.2 for "correctly" lapped specimen 7C3MV shows, when the third or extra bolt is placed in the valley, that the lap immediately becomes incorrect for the direction of moment used in the test. The third bolt at location B is on the tension side where prying occurs. The lap would be correct were the moment reversed in direction with no bolt at location T.

For Specimen 7I3MC, section A-A in Fig. 2.3 shows that the lap is incorrect for both directions of applied moment, the bolt at B is on the tension side for the test condition and the bolt at T is on the tension side where prying occurs for the reversed moment. Similarly, Fig. 2.4 for Specimen 7I3MV shows that, when the first 2 bolts are installed incorrectly, the addition of the third bolt does not change the situation, the lap is incorrect for both directions of moment.

It is obvious from Fig. 2.5 that a 4-bolt connection will always have bolts on the tension side where prying occurs.

Examination of the prying in the lapped joints shows, therefore, that 2-bolt connections, can be made correctly and incorrectly, 3-bolt connections will be incorrect for at least one direction of moment, and a 4-bolt connection will always be incorrect.

2.3 Test Setup

Fig. 2.6 is a photograph of the test setup used for the final 14 tests. The two point loading system provided a constant moment region of 0.6 m with equal shear span on either side of 0.55 m. This test setup was designed based on the 250 mm stroke of the two hydraulic jacks, the capacity of the load cells with the smaller two having a 45 kN capacity, the predicted flexural strength of the 7 mm corrugated plate and the predicted total deflection of the 3 mm specimen. The loading jacks of equal piston area were pressurized from a common manifold thus ensuring that the loads were essentially equal. The jacks reacted against a steel frame bolted to the laboratory strong floor while the reaction assemblies were supported by a distribution beam resting on the strong floor. A hydraulic system consisting of a reservoir, control console, control valves and control manifold was used to supply pressure to the jacks. Load increments were controlled using the main pressure gauge. Each reaction and load point was provided with knife edges to allow unrestricted rotation and with rollers to accomodate the lateral movement that occurred as the specimen deflected. The lateral movements were substantial and the changes in the shear span (of up to 80 mm) due to the load points moving inward and the reactions moving outward were taken into account in determining the applied moment. Corrugated steel loading blocks, provided by Alberta Transportation were placed between the specimen and the knife edge assemblies to give uniform bearing on the specimen. It was necessary to plaster these blocks in place to provide the uniform bearing required. In Fig. 2.6, it is seen that the knife edges at the loading points were tilted outwards (about 7°) initially to compensate partially for the large angle of rotation of the specimen that occurred at these locations. Because of the lap in these specimens, one of the reactions was placed higher than the other by an amount equal to the thickness of the test specimen so that the specimen was positioned horizontally. Load cells were provided at each reaction and load point. Fig. 2.7 shows the significant rotations that occurred at the reaction during the course of the test. Fig. 2.8 shows the central portion of a test specimen at about the maximum deformation. The rotation of the knife edge and inward movement of the jacking assembly is clearly visible.

2.4 Instrumentation

For each flexural test, measurements of loads and reactions, specimen vertical deflections, roller movements, steel strains and gap width were made as the specimen was loaded. By measuring the loads and the reactions, a check on statics was obtained.

Eight LVDT's with a stroke of ±75 mm were used to measure the vertical deflections in the constant moment region. A pair of LVDT's was located immediately under the north load point (300 mm from the centerline of the specimen), and another 2 pairs of LVDT's were placed 85 mm each side of the centerline of the specimen (each pair was 25 mm away from the edge of the lap). The remaining 2 LVDT's were positioned 192.5 mm each side of the centerline of the specimen. The average reading of a pair of LVDT's located in the same position in the longitudinal direction was taken to be the actual deflection of the specimen at that particular location. To avoid damage to the LVDT's located under the specimen, thin spring-loaded copper wire was used to attach the specimen to the rod of the LVDT's. A mechanical dial gauge reading to 0.001 in. was used to provide a rough check of the centerline deflection.

At both the reactions and the load points, dial gauges reading to 0.01 mm were positioned against the roller plates to measure horizontal movements.

Six electrical resistance strain gauges were used to measure steel strains. They were all located midway between the south load point and the centerline of the specimen, that is, 150 mm from the centerline. Three strain gauges were applied to the extreme compression fibre and the other three to the extreme tension fibre of the specimen.

The locations of the dial gauges, strain gauges and LVDT's are shown in Fig. 2.9.

All electrical instrumentation, including load cells, LVDT's and strain gauges were calibrated before being used. Load cells were loaded in the 1000 kN Material Testing Systems (MTS) to define the linear relationship between the change in output voltage and the change in load for each load cell. The output voltage of each LVDT was measured for the full range of displacement to allow calculation of the calibration factor. Each strain gauge was calibrated, using a 50 000 ohm resistor, after the Wheatstone bridge was balanced.

During the test, dial gauge readings and gap width measurements were recorded manually, while the output from electrical resistance strain gauges, LVDT's and load cells were recorded automatically on the Data General Eclipse S/120 data acquisition computer system in the laboratory. With each strain gauge, LVDT and load cell being assigned an individual channel in the Eclipse system, a total of 23 data acquisition channels were used for each test. The data were subsequently transferred to and processed on the University of Alberta main computer system, an Amdahl 5860.

2.5 Test Procedure

After the strain gauges were applied, the specimens was positioned in the testing frame using a fork lift truck and then carefully aligned and levelled. The loading and reaction blocks with matching corrugated shapes were then positioned and plastered in position to provide a complete contact with the surface of the specimen. All the instruments were positioned and hooked up to the data acquisition system. At the beginning of any test, all electrical instrumentation readings were initialized to zero using the testing software of the Eclipse system. Initial reading of the dial gauges were recorded manually. During the test, certain loads, reactions and deflections were monitored continually on the data acquisition screen. When the required load or deflection was reached, the hydraulic system valves was closed to maintain the load and a complete set of readings was taken. The output for the two load cells and two reaction load cells was used to check the statics of the system. The overall behaviour of each specimen was monitored during the test by plotting the load versus the average deflection readings of the LVDT's located near the edge of the joint. In the elastic range, load increments of 2 kN and 4 kN per jack was used for the 5 mm and 7 mm plates respectively. When the specimen started to behave inelastically, the test increments were selected based on the vertical deflection that was occurring. The LVDT's and dial gauges were reset when they reached their limits. The jacks were plumbed at every test increment and the horizontal movements were adjusted if necessary by adjusting the lead on a threaded rod attached to each of the roller plates. The adjusting rods are visible in Figs. 2.7

and 2.8. When large deflections were reached, the specimen was carefully examined for the presence of tearing at the bolt holes. Fig. 2.10 shows a specimen under load. At the end of any test, the permanent deformation and the deformed shape of the specimen were measured. A written record was kept.

2.6 Ancillary Tests

Tension coupons were cut from the flat portion of the corrugated steel plates provided by Alberta Transportation to determine the stress-strain characteristics of the plate material. A total of 6 tension coupons, two 3 mm, two 5 mm and two 7 mm thick were tested. The coupons were machined to provide a gauge length of 200 mm and a reduced section of 25 mm in width with the full thickness of the plate. The cross-sectional areas of the coupons were determined prior to testing from measurements of the gauge width and thickness using a digital micrometer. The tension coupons were tested in the 1000 kN capacity MTS testing machine. Strains up to about 2% were measured with a pair of strain gauges mounted on opposite faces of each coupon. An extensometer with a gauge length of 50 mm and capable of measuring strains up to 20% was also employed to measure strain in the central portion of the coupon. When the limit of the extensometer was exceeded, larger strains were measured over a gauge length of 200 mm between a pair of pre-punched holes using a caliper and a scale.

Table 2.1 Proposed Lapped Joint Testing Program

Test #	Plate Thickness (mm)					Test Condition
	3	4	5	6	7	
1	X					Correct lap
2		X				Correct lap
3			X			Correct lap
4				X		Correct lap
5					X	Correct lap
6			X			Incorrect lap
7			X			Washer correct
8			X			Washer incorrect
9			X			Low torque - washers
10			X			High torque - washers
11			X			Low torque - no washers
12			X			High torque - no washers

Table 2.2 Testing Program

Specimen Designation	Test Date	Plate Thickness (mm)	Lap Configuration		No. of Bolts per Corrugation		Bolting Torque (N.m)	Comments
			Correct	Incorrect	Valley	Crest		
3C2M	Oct 1	3	✓		1	1	250	
5000	Oct 6	5	-	-	-	-	-	Plain specimen, no joint
5C2H	Oct 13	5	✓		1	1	500	
5C2M.1	Sep 3	5	✓		1	1	250	Tested on 4.4 m span
5C2M	Sep 28	5	✓		1	1	250	
5C2L	Sep 24	5	✓		1	1	50	
5I2M.1	Sep 8	5		✓	1	1	250	Tested on 4.4 m span
5I2M.1	Sep 9	5		✓	1	1	250	Continuation
5I2M	Sep 29	5		✓	1	1	250	
5I2L	Sep 22	5		✓	1	1	50	
7C2M	Oct 5	7	✓		1	1	250	
7C3MC	Oct 16	7	✓		1	2	250	
7C3MV	Oct 15	7	✓		2	1	250	
7C3MVW	Oct 22	7	✓		2	1	250	Sloped washers on valley bolt heads
7I3MC	Oct 19	7		✓	1	2	250	
7I3MV	Oct 20	7		✓	2	1	250	
7I4M	Oct 8	7		✓	2	2	250	

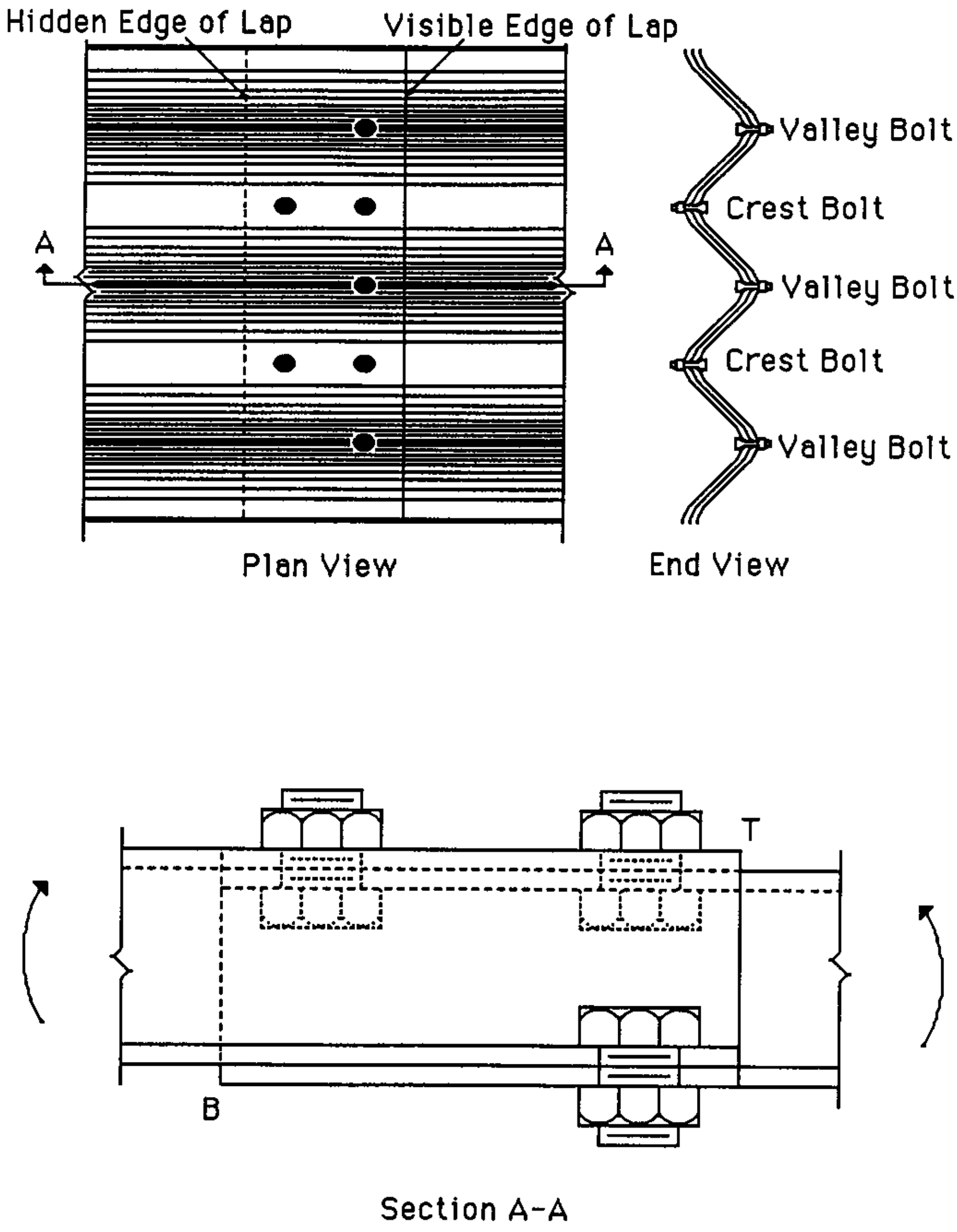
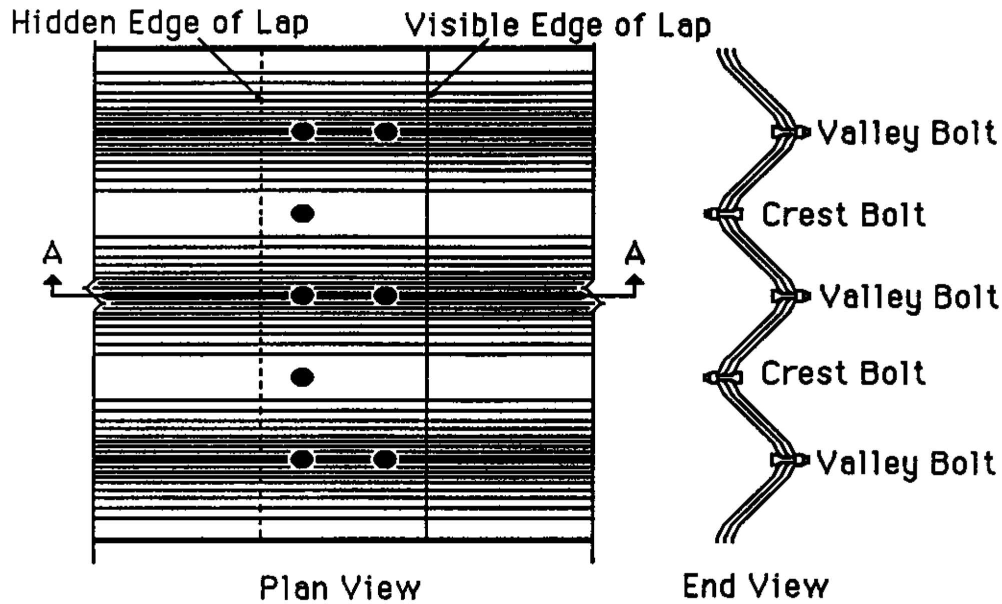


Figure 2.1 Bolting Arrangement for Specimen 7C3MC



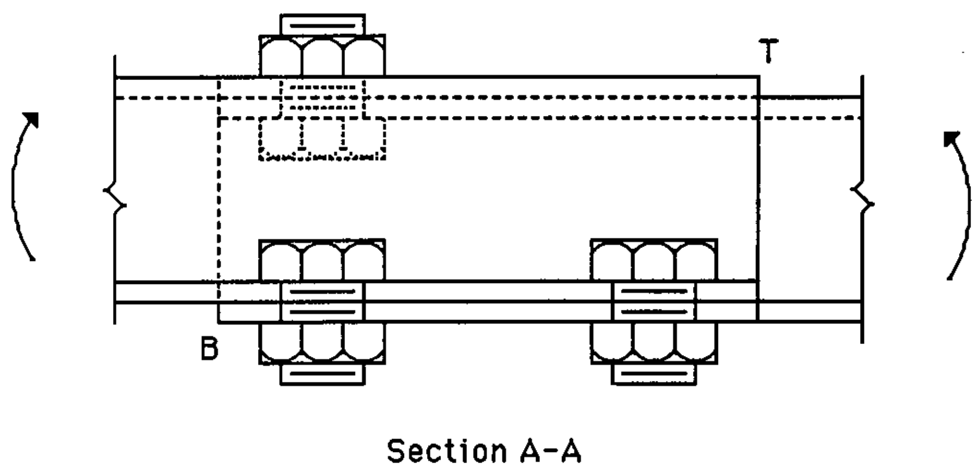


Figure 2.2 Bolting Arrangement for Specimens 7C3MV and 7C3MVW

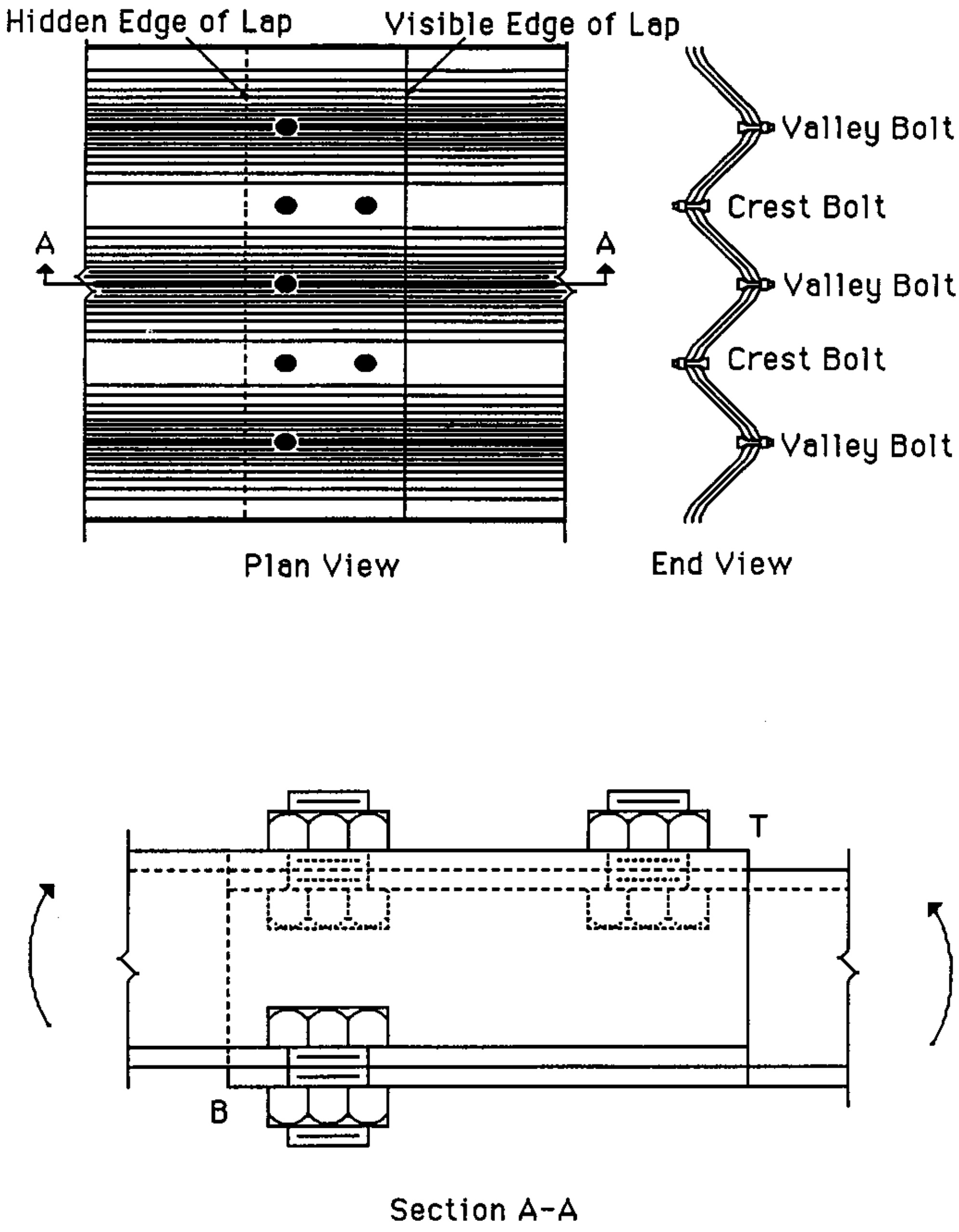
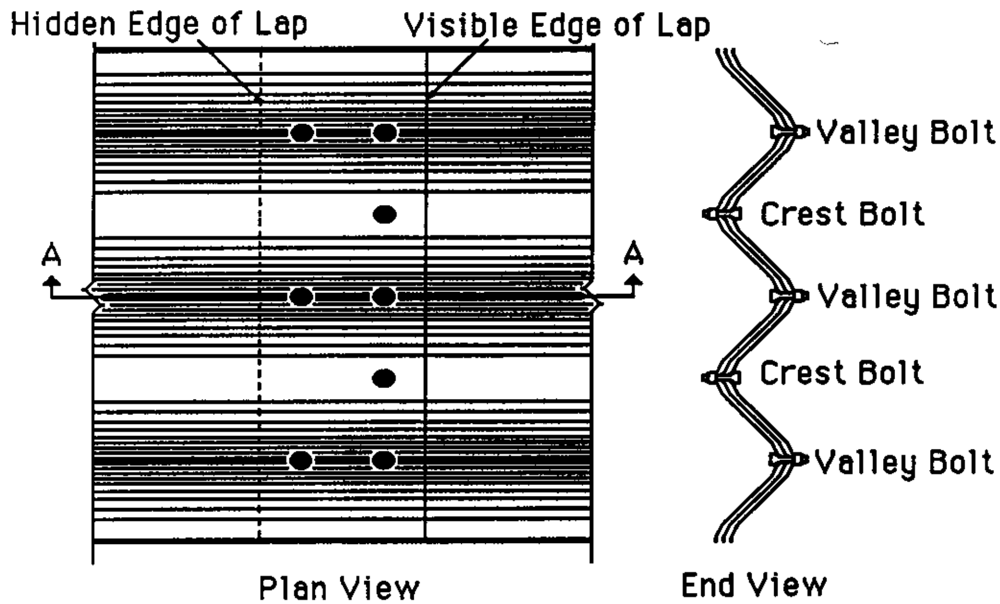


Figure 2.3 Bolting Arrangement for Specimen 7I3MC



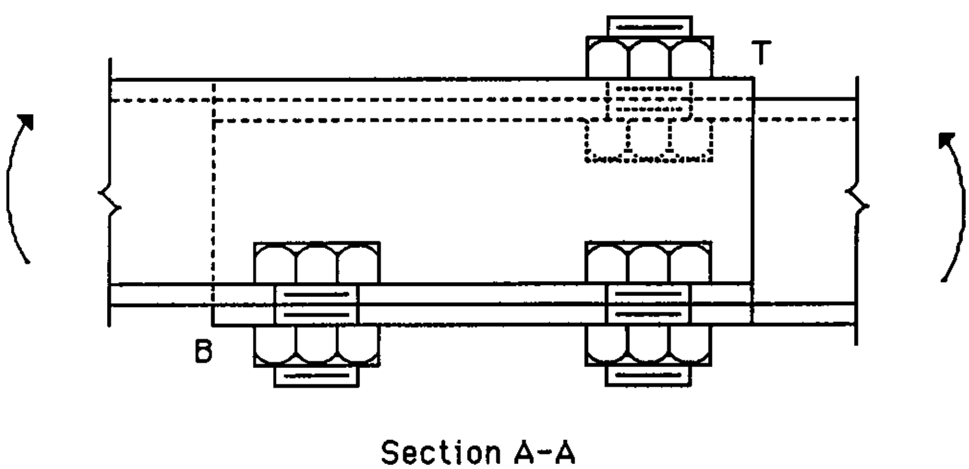
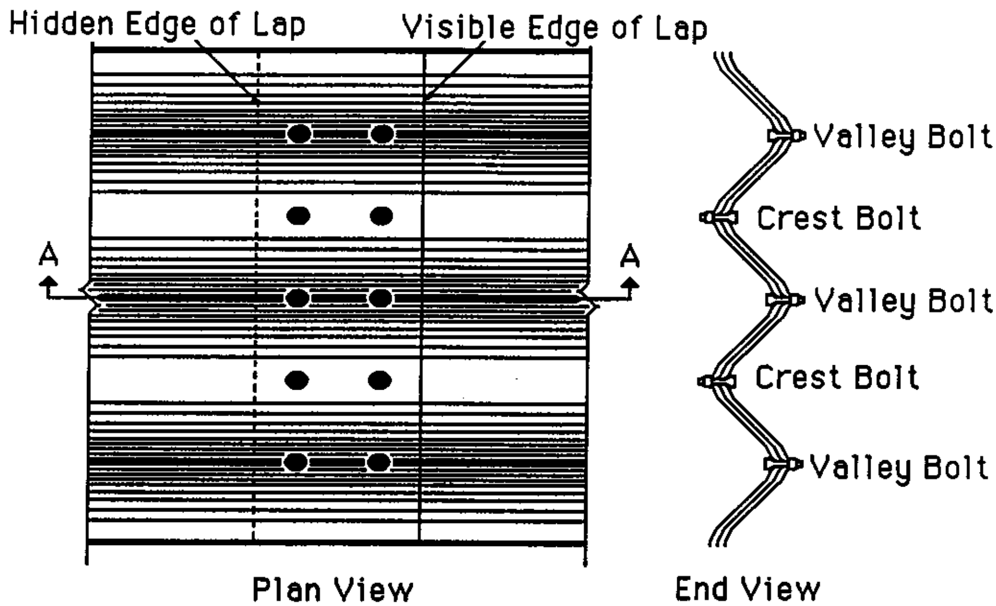
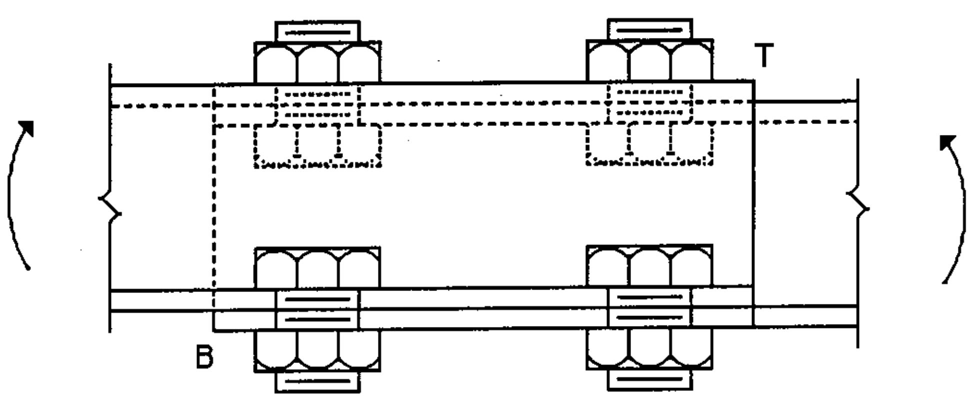


Figure 2.4 Bolting Arrangement for Specimen 7I3MV





Section A-A

Figure 2.5 Bolting Arrangement for Specimen 7I4M

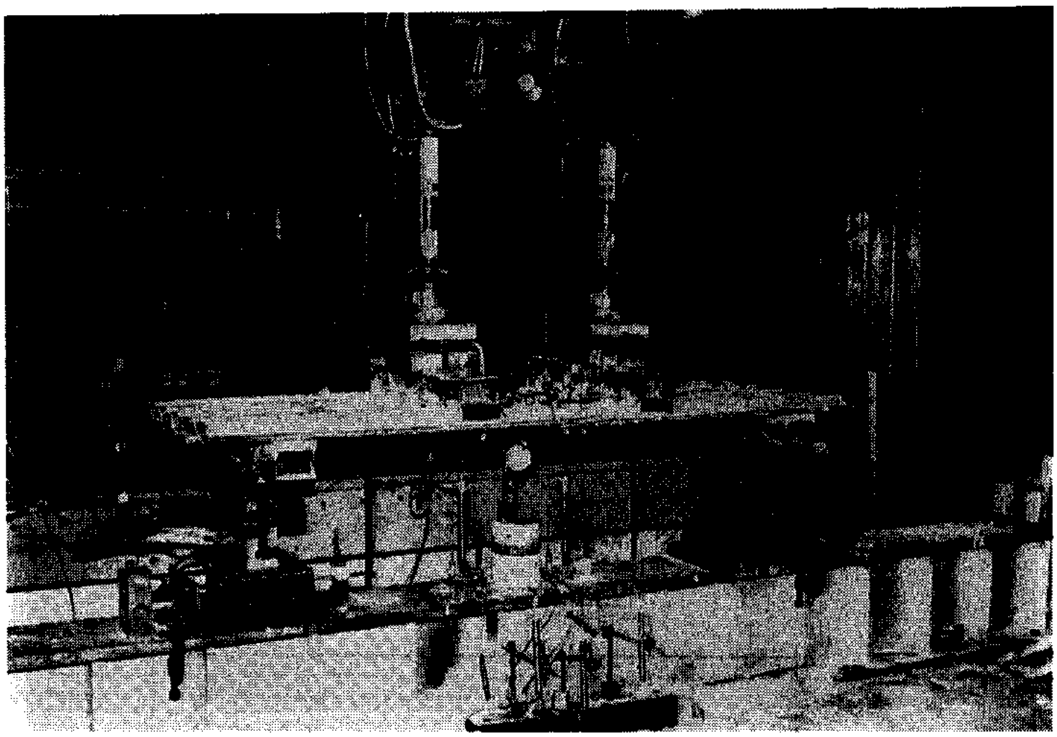


Figure 2.6 Test Setup

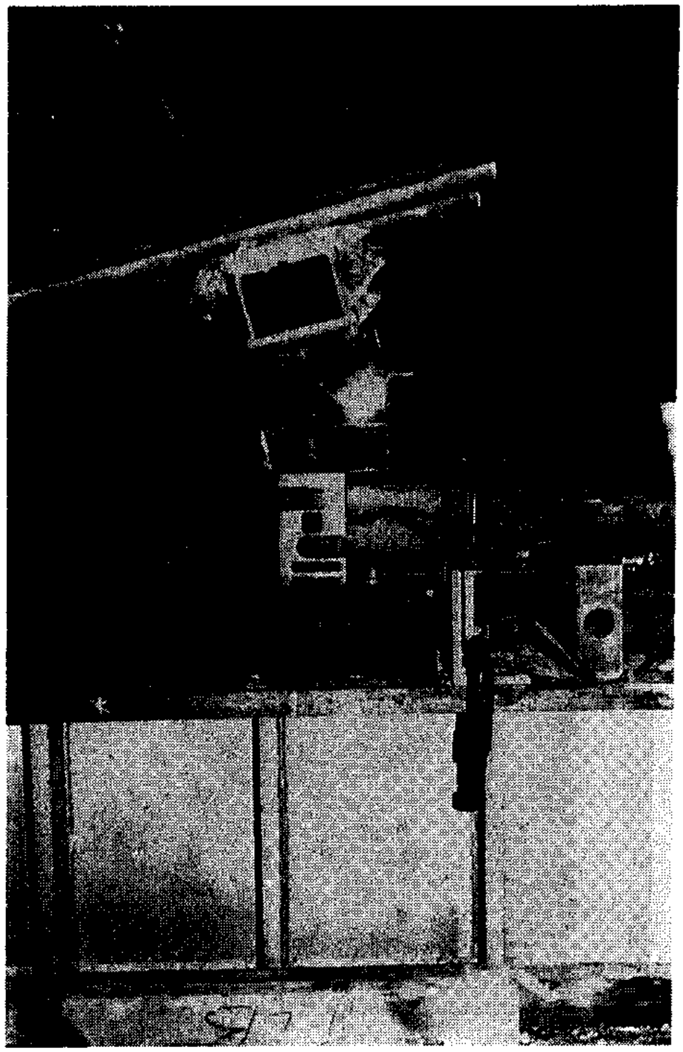


Figure 2.7 Reaction Assembly

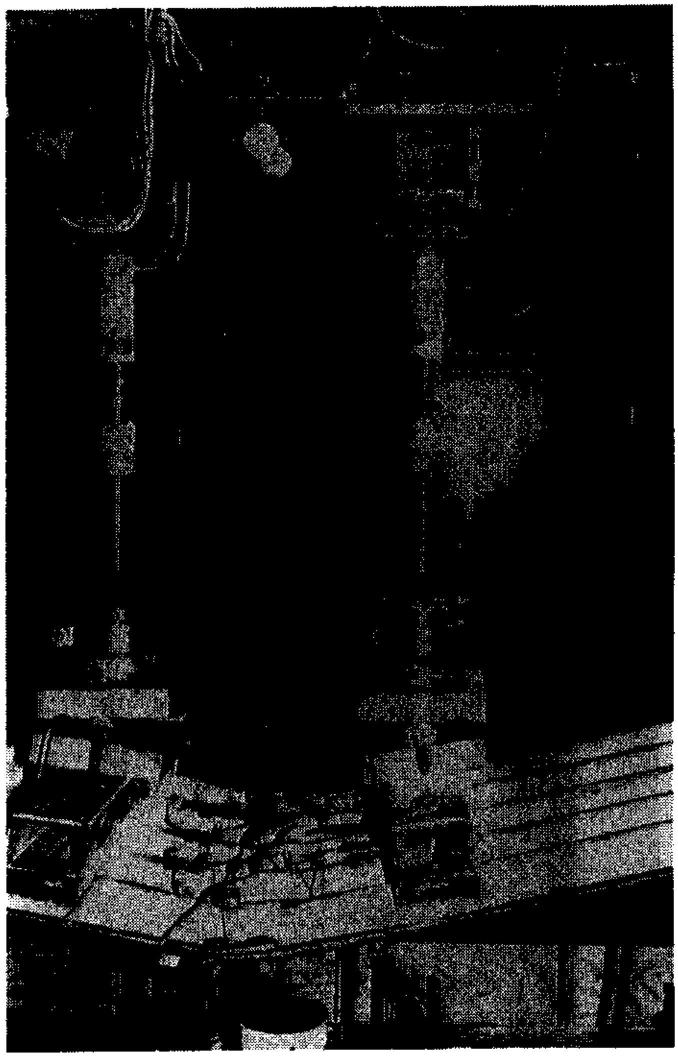


Figure 2.8 Loading Assemblies

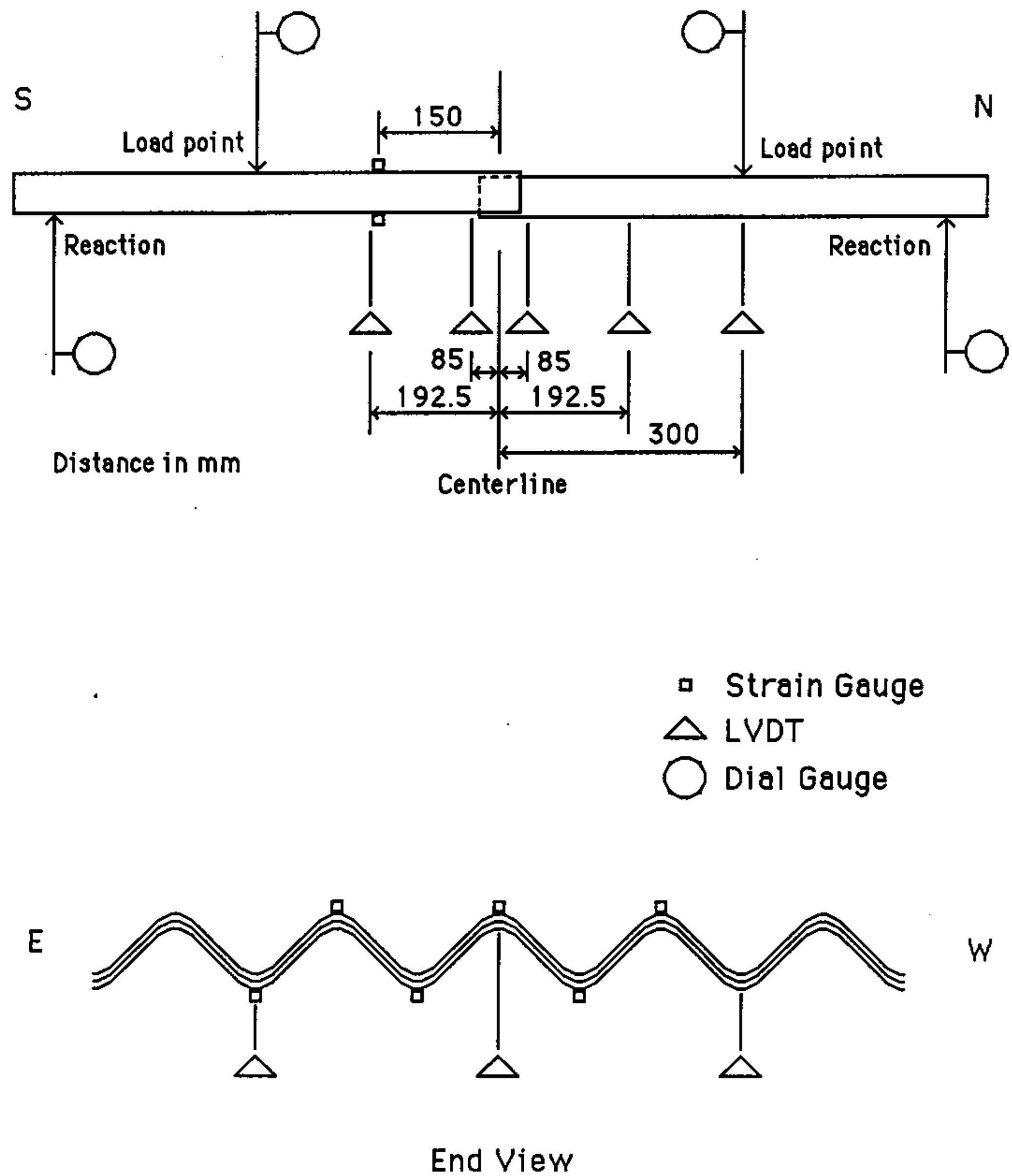


Figure 2.9 Schematic Diagram of Instrumentation on a Specimen

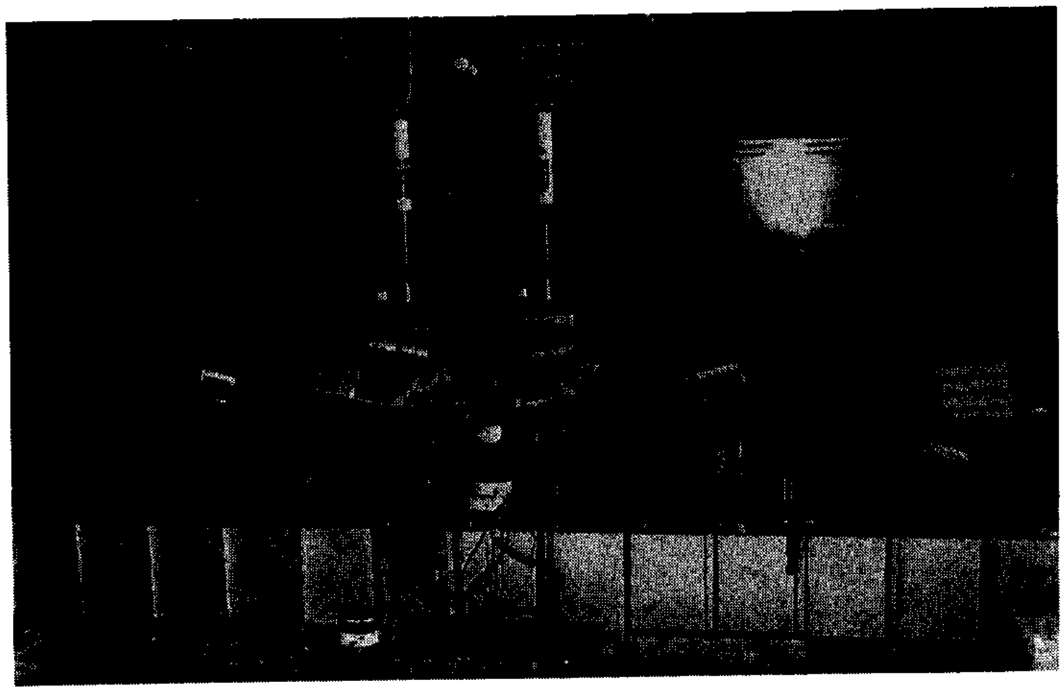


Figure 2.10 Specimen under Load

3. Discussion and Analysis of Test Results

3.1 Ancillary Tests

Stress-strain curves for coupons cut from each of the 3, 5 and 7 mm thick plates are shown in Figs. 3.1 to 3.3 respectively. The average modulus of elasticity, based on the strain gauges readings, and obtained using the method of least squares, was determined to be 203 900, 206 300 and 207 700 MPa, and the average static yield strength was 260.6, 232.7 and 266.9 MPa for the 3, 5 and 7 mm coupons respectively. It is noted that yield strength for the 5 mm coupons is significantly lower than that of the other 2 thicknesses. About 20 thickness measurements showed that the average thickness of the 3 and 7 mm thick tension coupons was within about 1.5% of the actual thickness of the test specimens obtained from about 30 measurements. On the other hand, the 5 mm thick tension coupons were 4% thinner than the specimens tested. This suggests that the 5 mm coupons may not have been cut from the same material as the test specimens. The test results of the 5 mm thick coupons were therefore not used in the analysis that follows. The actual measurements of the specimens and tension coupons are given in Table 3.1.

3.2 Geometric Properties and Strength of Cross-section

Table 3.2 gives measurements of the depth of the cross-section measured from the line joining the crests to the top of the valley, and the pitch, as the distance crest to crest, for the 3, 5 and 7 mm thick specimens. Based on the plate thickness measurements given in Table 3.1 and the depth and pitch measurements from Table 3.2, the cross-sectional properties for each corrugated plate can be calculated. It was assumed that the cross-sections were symmetric about the mid-depth and that the cross-section consisted of two 45° circular arcs joined by a straight line segment. As the crest to crest distance, or pitch, did not vary significantly, an average value of 155.5 mm was used for all plate thicknesses. The calculated moment of inertia, elastic section modulus and plastic section modulus per meter width for the 3 corrugated plates are given in Table 3.2.

Sample calculations for these section properties for the 5 mm plate are given in Appendix A.

Blodgett (1934) gives an expression for calculating the moment of inertia of corrugated plates. The values in parenthesis in Table 3.2, based on Blodgett's expression, are at the most 0.7% greater than those calculated here.

The yield moment and fully plastic moment obtained from the calculated section properties and the static yield strength obtained from the tension coupons are also given in Table 3.2. Due to the incongruity between the 5 mm coupon thickness and the 5 mm corrugated plate thickness, the yield strength for the 5 mm corrugated plate was deduced from the moment-curvature relationship as discussed subsequently. This value of about 264 MPa is the same as the average of that for the 3 and 7 mm thick coupons.

3.3 Flexural Test on Plain Specimen

Fig. 3.4 shows the experimental relationship between moment and curvature for the 5 mm corrugated steel plate. The theoretical relationship plotted in the diagram is obtained using the measured geometric properties but fitted to have the same maximum moment as that obtained experimentally. The close correlation between the experimental and theoretical curves in the elastic region confirms both the calculation of the moment of inertia and the value of the modulus of elasticity. In the area of the knee of the curve, the experimental values are up to 1.10 times the theoretical values.

The theoretical non-dimensionalized moment-curvature relationships based on the calculated section properties for the 3 and 7 mm corrugated plate are given in Fig. 3.5. The partial experimental corroboration of the moment-curvature relationship for the 5 mm plate based on measured cross-sectional properties, suggests that it is valid to use the theoretical relationships for the 3 and 7 mm plates in the analyses of structures composed of these plates.

3.4 Flexural Tests on Specimens with Lap Joints

3.4.1 General

As noted in Section 2.1, in the initial test setup with a span of 4.4 m used for testing Specimen 5C2M.1 and 5I2M.1, the specimens proved to be too flexible and the limits of the jacks were reached before failure occurred. For Specimen 5I2M.1, the jacks were reset and approximately 100 mm additional deflection was obtained above the 290 mm obtained in the first loading. For subsequent tests the span was reduced to 1.7 m with a constant moment region of 0.6 m. In the first two tests as well, some difficulties were encountered with the readings of the load cells mounted beneath the jacks and the load cells were therefore replaced.

The ultimate moment capacity, including the self-weight, and taking into account the change in the shear span of the specimen during testing, is given in Table 3.3 for all the specimens, both in absolute terms and also non-dimensionalized by dividing by the calculated plastic moment capacity of the plain corrugated plate.

3.4.2 Load-deflection Diagrams

Experimental load-deflection diagrams are given in Figs. 3.6 to 3.10 for tests of 5 mm thick specimens with lapped joints. The two curves on each figure labelled North and South, give the deflections near the north and south edges of the lap of the specimen that was oriented longitudinally in the north-south direction. It is seen from Figs. 3.6, 3.7 and 3.8 that increasing the torque increases the stiffness of that portion of the curve before general yielding takes place. In fact, the specimen with low torque (Fig. 3.6) tends to exhibit a bilinear response in this region. Comparing Fig. 3.9 with 3.6 and Fig. 3.10 with 3.7, it is seen that the decrease in load after reaching the maximum load is much more pronounced for the specimens with incorrect laps. In these specimens, tearing occurred at location B (see Fig. 1.2) starting on either side of a bolt head and spreading transversely across the specimen. As loading continued, other tears developed at other bolt holes. With this tearing, the test load could not be maintained and dropped off gradually. Fig 3.11 shows tears at the locations marked 2. Bakht and Agarwal (1987) report the results of one flexural test with single point loading in which tearing was observed, but no numeric or graphical data was reported.

The load-deflection curves for the 7 mm thick specimens given in Figs. 3.12 to 3.18 exhibit similar behaviour to that of the 5 mm thick specimens. Examination of these figures shows that the addition of extra bolts did not increase the capacity of the lapped joint and, as a matter of fact, tended to reduce the capacity, particularly when the extra bolt was in an incorrect location, i.e., on the tension side where prying occurred. In these cases, tearing occurred at the bolt head at these locations. Furthermore, increasing the number of bolts did not increase the initial stiffness of the joints.

3.4.3 Moment-rotation Diagrams

Moment-rotation diagrams for the three thicknesses of lapped joints are given in Figs. 3.19 to 3.25. The moments plotted are per meter width of plate, include the self weight moment and also have been corrected by taking into account the increase in the shear span as the specimens deflected.

The rotations had been deduced from the deflection measurements taking into account the constant curvature of the corrugated plates in the constant moment region as determined from the strain gauges readings in this region.

3.4.3.1 Effects of Thickness

The three moment-rotation curves in Fig. 3.19 for correctly lapped joints with 2 bolts and with a medium torque of 250 N.m applied to the bolts show, as would be expected, that the moment capacity increases with increasing thickness. After a more or less linear portion, with the thicker plates showing greater stiffness, the moment-rotation curves gradually decrease in slope and finally exhibit large plastic deformations at more or less constant moment. In general, the specimens were deformed as far as deemed practicable at the time, and the lesser rotations obtained for the 3 and 7 mm thick plates as compared to that for the 5 mm plate should not be construed to indicate that the 3 and 7 mm plates have lesser rotation capacity. There were no significant signs of local distress in any of these three tests. The maximum moments obtained were 0.96, 0.90 and 1.08 times the plastic moment capacity of the plain corrugated plate, obtained as discussed in Section 3.2, for the 3, 5 and 7 mm specimens respectively. Further tests, corroborated by tension coupon tests, would establish whether or not these ratios vary with thickness. It is expected that the moment capacity of a correctly lapped joint is comparable to that of the plain plate provided that the joints are well proportioned both with respect to lap length and bolt capacity.

3.4.3.2 Effects of Correct and Incorrect Laps

Fig. 3.20 shows for 5 mm specimens, the results of two tests with medium torque and with correct and incorrect laps (tests 5C2M and 5I2M) and also the results of two tests with low torque and with correct and incorrect laps (tests 5C2L and 5I2L). In each case, the incorrect laps give maximum moments that are essentially identical to that obtained with the correct lap. The curves with the same torques essentially duplicate one other up to the maximum capacity. The difference between correct and incorrect laps is that the correctly lapped joints exhibit great ductility (irrespective of the torquing procedure) while the incorrectly lapped specimens have limited ductility. Shortly after the maximum moment is reached, the steel plate for the incorrectly lapped specimens was observed to tear from either side of one or more of the bolt heads at location B (Fig. 1.2), where the bolt is on the tension side where prying occurs. This tearing causes a reduction in the moment capacity of the plate where the tensile stresses are maximum.

Incorrect laps therefore do not change the behaviour up to the maximum moment but cause significantly reduced ductility thereafter and a loss of moment capacity. The reduced ductility and loss of moment capacity result from the tearing of the steel and loss of cross-sectional area at the location where the maximum moment exists.

3.4.3.3 Effects of Bolt Torque

The effect of varying the torque used to tighten the bolts can be discerned from Figs. 3.21 and 3.22 that are plotted for joints with correct laps and incorrect laps respectively. In Fig. 3.21 with correctly lapped joints, it is seen that increasing the torque improves the behaviour by making the joint both stiffer and stronger. The increase in strength is about 12% when the torque is increase from 50 N.m to 500 N.m, with the joint made with a torque of 250 N.m falling in between.

In any joint, little or no separation of the lapped plates occurs until the tension in the bolts due to prying action exceeds the tension developed due to torquing. In the joints made with low torque, this action occurs at a much lower moment than in the joints made with medium or high torque and results in increased flexibility of the joint, i.e., a flatter moment-rotation diagram. It is also noted in Fig. 3.21 that the two tests with medium torque 5C2M and 5C2M.1 conducted on two different shear spans are virtually identical.

In Fig. 3.22 for incorrectly lapped joints, it is seen that when the bolts are tightened with a low torque, the specimen exhibits increased flexibility as was the case for the correctly lapped joints. The test curves for two different shear spans, tests 5I2M and 5I2M.1 are again in close correspondence. Test 5I2M.1 was stopped when the maximum deflection was limited by the test setup.

3.4.3.4 Effects of Number of Bolts per Corrugation

The effects of the number of bolts per corrugation can be deduced from Fig. 3.23 and 3.24. As stated previously, when 3 bolts per corrugation are used , the bolting configuration is incorrect for at least one direction of applied moment. (See Figs. 2.1 to 2.5 and related discussion). Starting with a correct 2-bolt configuration, for the test setup used, when the third bolt is placed on the crest, the total configuration performs as a correctly lapped joint. However if the third bolt is placed in the valley, the total configuration performs as an incorrectly lapped joint. Of course, if the first two bolts are in an incorrect configuration, the joint acts as an incorrectly lapped joint irrespective of the location of the third bolt. A 4-bolt joint will necessarily have a bolt at location B (Fig. 2.5), on the tension side where prying occurs, and therefore must be considered to be incorrectly lapped.

Fig. 3.23 compares the moment-rotation behaviour of a correctly lapped 2-bolt joint and a 4-bolt joint, the difference in initial stiffness between the 2 joints is not considered to be significant. The 4-bolt joint appears to be about 9% weaker than the 2-bolt joint. This reduced strength is attributed to the reduced cross-sectional area on the tension side of the connection at the critical location B. Furthermore, with continued loading, tears occurred on either side of bolt heads at this location. Although the moment had not decreased substantially when the test was terminated, it is postulated that with further rotation the moment would have dropped off more and more rapidly. Using 4 bolts therefore, does not provide an advantage and in fact appears to be disadvantageous.

The curve for test 7C2M has also been plotted in Fig. 3.24 where all the test curves on joints with 3 bolts are given. Test 7C3MC, tested in a correct configuration, displays essentially the same behaviour as the 2-bolt joint. No tearing was observed. The remaining 3 tests 7C3MV, 7I3MC and 7I3MV, all tested in an incorrect configuration, exhibit similar behaviour among themselves. Tearing occurred at location B in all three tests. These tears, as evident from test 7I3MC, sooner or later lead to a significant decrease in the moment capacity. The maximum strength ranged from 33.5 to 36.3 kN.m per meter width, or about 86% to 94% of the 2-bolt joint strength whereas in test 7C3MC, tested in a correct configuration, 95% of the 2-bolt joint strength was obtained.

The softer behaviour exhibited by specimen 7I3MV is attributed to the fact that the bolt holes were somewhat oversize. It was noted, when the bolts were torqued, that the heads were pulled slightly into the holes. From the limited data available, there does not appear to be significant differences in the behaviour of the various 3-bolt joints tested in an incorrect configuration.

3.4.3.5 Effects of Washers

Fig. 3.25 compares the moment-rotation relationship for tests 7C3MVW and 7C3MV tested with and without washers respectively. The washers were located only under the heads of the bolts in the critical location B where tearing had been observed to occur. The test curves are essentially identical. Although no tearing was observed during the test when the washers were used on the assembly, small tears, 2 to 3 mm in length, were observed leading from the edges of the bolt holes in the critical location when the washers were removed after the test.

3.4.4 Moment versus Gap Opening

The opening of the gap at location B as a function of the applied moment is plotted in Fig. 3.26 for the tests on 5 mm thick lapped plates and in Fig. 3.27 for the tests on 7 mm thick lapped plates. The gaps were measured by inserting a tapered wedge into the gap, marking the depth of the insertion and then measuring the width of the wedge at this mark to the nearest 0.5 mm. Fig. 3.28 shows the gap opening of a specimen.

The curves show that an initial gap, from 1.5 mm to 4.5 mm wide, existed as the two corrugated plates did not nest perfectly. Fig. 3.26 shows, as may be expected, that the gap opens up at relatively low moments in joints where the bolts are installed with a low torque. All of the joints in Fig. 3.27 were bolted with the same torque. The somewhat earlier opening of the gap in specimen 7I3MV is attributed to the oversize holes (30 mm diameter versus 25 mm) in this specimen.

Table 3.1 Thickness Measurements

3 mm				5 mm				7 mm			
Tension Coupon		Test Specimen		Tension Coupon		Test Specimen		Tension Coupon		Test Specimen	
No.	t	No.	t	No.	t	No.	t	No.	t	No.	t
3.a	3.25	3C2M	3.30	5.a	5.08	5000	5.28	7.a	7.19	7C2M	7.09
	3.28		3.30		5.11		5.26		7.21		7.11
	3.28		3.33		5.08		5.26		7.16		7.14
	3.25		3.28		5.05		5.28		7.19		7.11
	3.25		3.28		5.08		5.28		7.21		7.11
	3.23		3.33		5.08	5C2L	5.31		7.24	7C3MC	7.16
	3.23		3.30		5.05		5.31		7.16		7.14
	3.28		3.33		5.03		5.28		7.16		7.11
	3.25		3.30		5.03		5.28		7.21		7.11
	3.23		3.30		5.08		5.28		7.21		7.11
3.b	3.25			5.b	5.05	5C2M	5.26	7.b	7.19	7C3MV	7.09
	3.25				5.11		5.28		7.16		7.11
	3.28				5.08		5.28		7.16		7.11
	3.28				5.08		5.31		7.19		7.09
	3.25				5.08		5.31		7.19		7.06
	3.25				5.11	5C2H	5.28		7.21	7C3MVW	7.06
	3.23				5.11		5.33		7.21		7.14
	3.23				5.08		5.31		7.24		7.09
	3.25				5.05		5.28		7.19		7.09
	3.25				5.08		5.28		7.16		7.11
						5I2L	5.31			7I3MC	7.09
							5.26				7.09
							5.28				7.11
							5.23				7.11
							5.28				7.14
						5I2M	5.28			7I3MV	7.11
							5.28				7.14
							5.26				7.09
							5.31				7.11
							5.31				7.11
										7I4M	7.11
											7.11
											7.11
											7.09
											7.09
Ave.	3.25		3.30		5.08		5.28		7.19		7.11

Table 3.2 Material and Geometric Properties of Corrugated Plates

Specified Plate Thickness	Measured Plate Thickness t mm	Depth d mm	Pitch p mm	Area $x10^3mm^2/m$	Moment of Inertia I $x10^6mm^4/m$	Elastic Section Modulus S $x10^3mm^3/m$	Plastic Section Modulus Z $x10^3mm^3/m$	$\frac{Z}{S}$	Static Yield Strength F_y MPa	Yield Moment M_y kN.m/m	Fully Plastic Moment M_p kN.m/m
3	3.30	50.26	155.50	4.06	1.203 (1.212)	44.92	62.24	1.39	260.6	11.71	16.22
5	5.28	50.53	155.50	6.51	1.979 (1.989)	70.93	100.81	1.42	263.8	18.71	26.59
7	7.11	49.65	155.50	8.75	2.612 (2.632)	92.04	134.56	1.46	266.9	24.57	35.91

Table 3.3 Ultimate Moment Capacity

Specimen Designation	Ultimate Moment (kN.m)	Ultimate Moment per Meter Width M_u (kN.m/m)	$\frac{M_u}{M_p}$
3C2M	11.85	15.59	0.96
5000	20.19	26.57	1.00
5C2H	19.37	25.49	0.96
5C2M.1	17.93	23.59	0.89
5C2M	18.14	23.87	0.90
5C2L	17.23	22.67	0.85
5I2M.1	17.92	23.58	0.89
5I2M	17.95	23.62	0.89
5I2L	17.11	22.51	0.85
7C2M	29.44	38.74	1.08
7C3MC	28.11	36.99	1.03
7C3MV	27.60	36.32	1.01
7C3MVW	26.79	35.25	0.98
7I3MC	25.46	33.50	0.93
7I3MV	26.31	34.62	0.96
7I4M	26.93	35.43	0.99

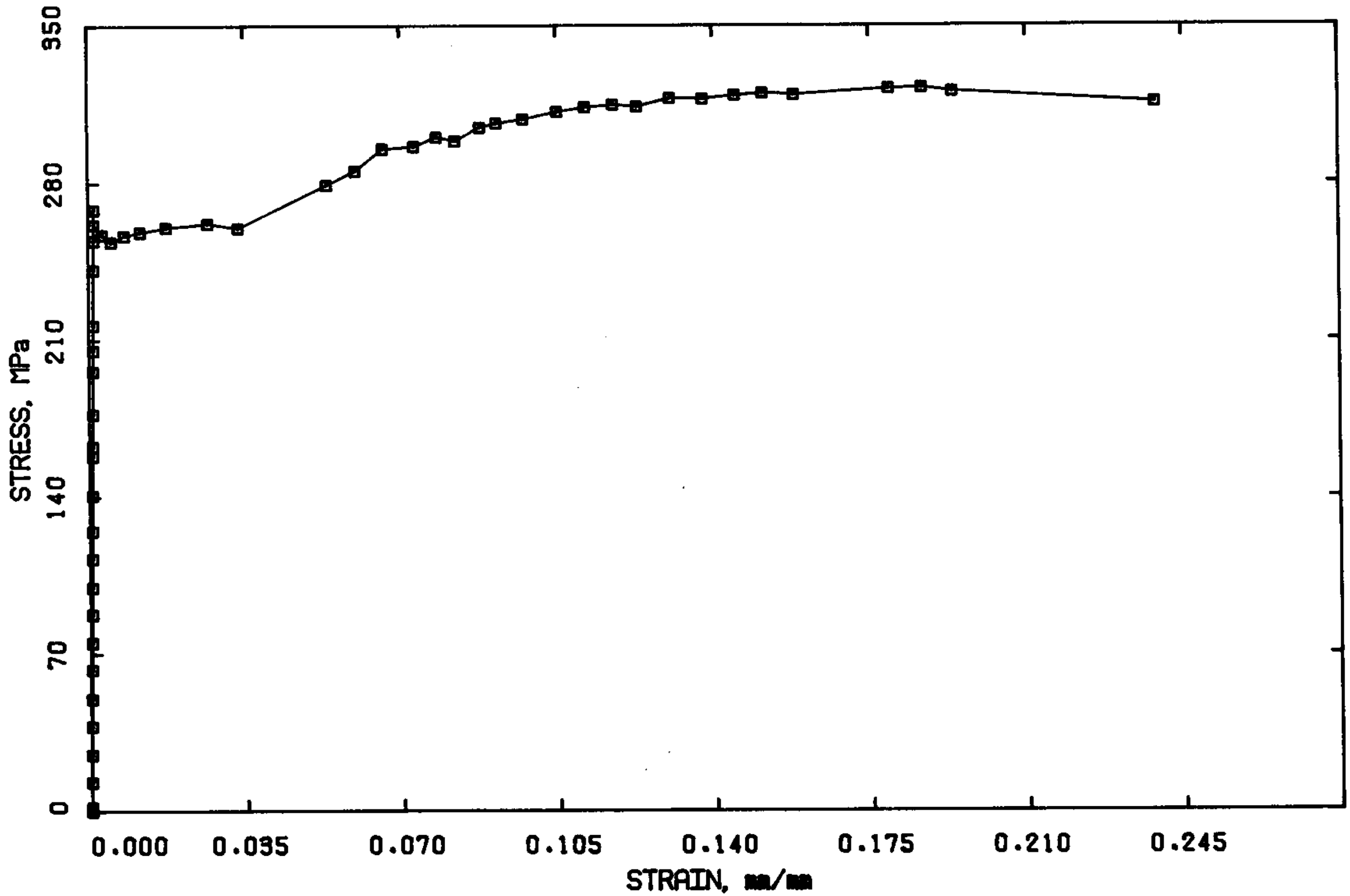


Figure 3.1 Stress Strain Curve for 3 mm Plate

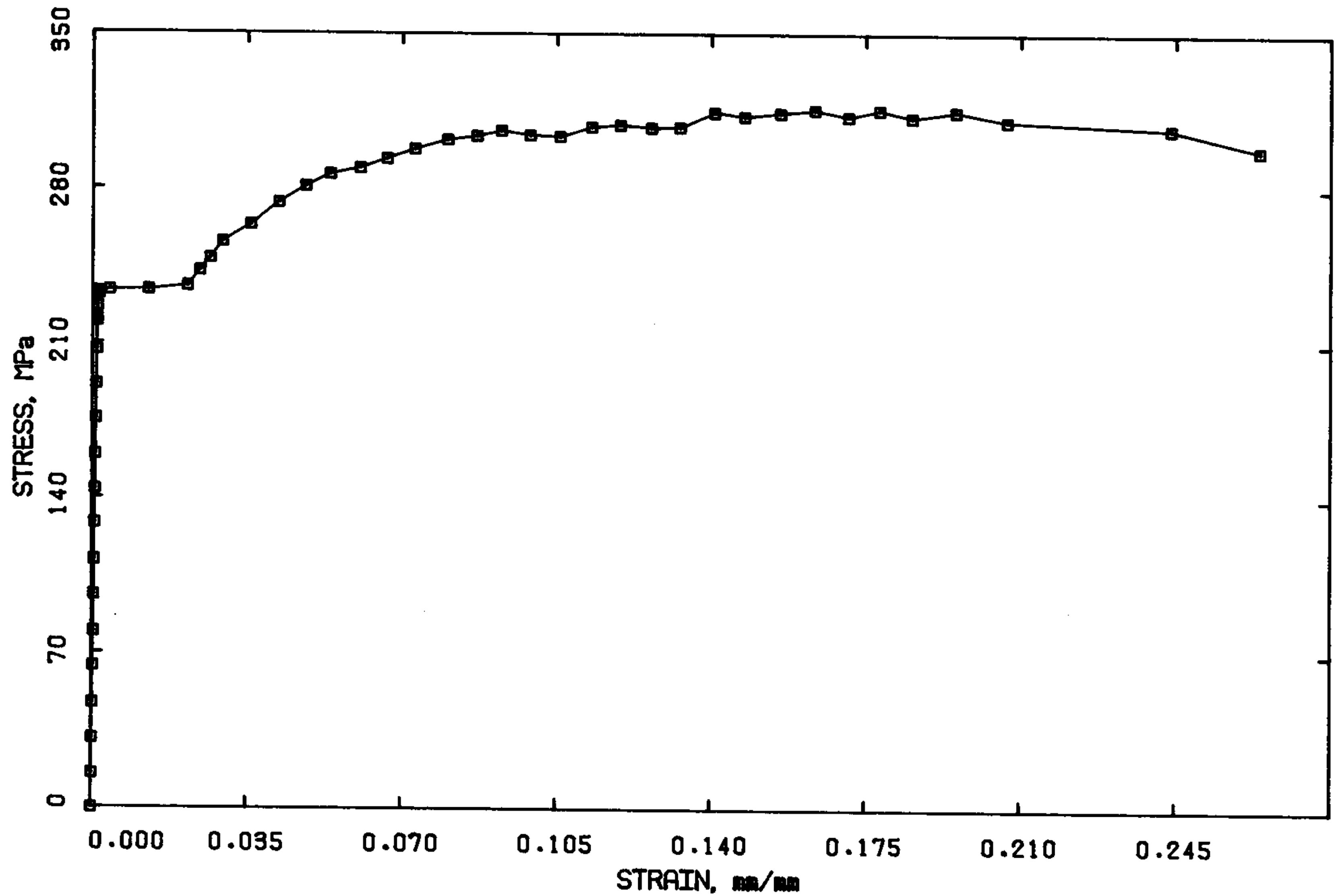


Figure 3.2 Stress Strain Curve for 5 mm Plate

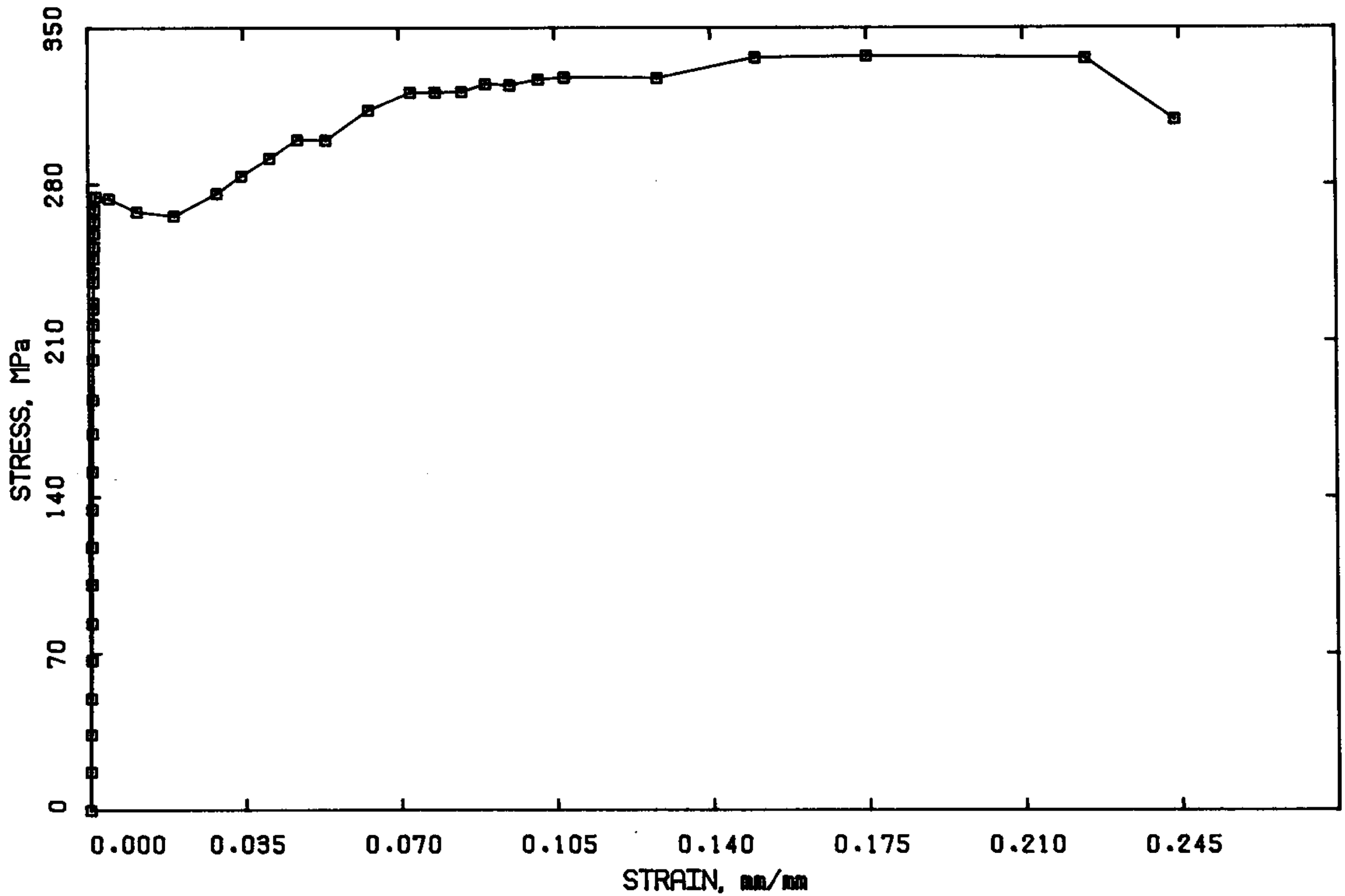


Figure 3.3 Stress Strain Curve for 7 mm Plate

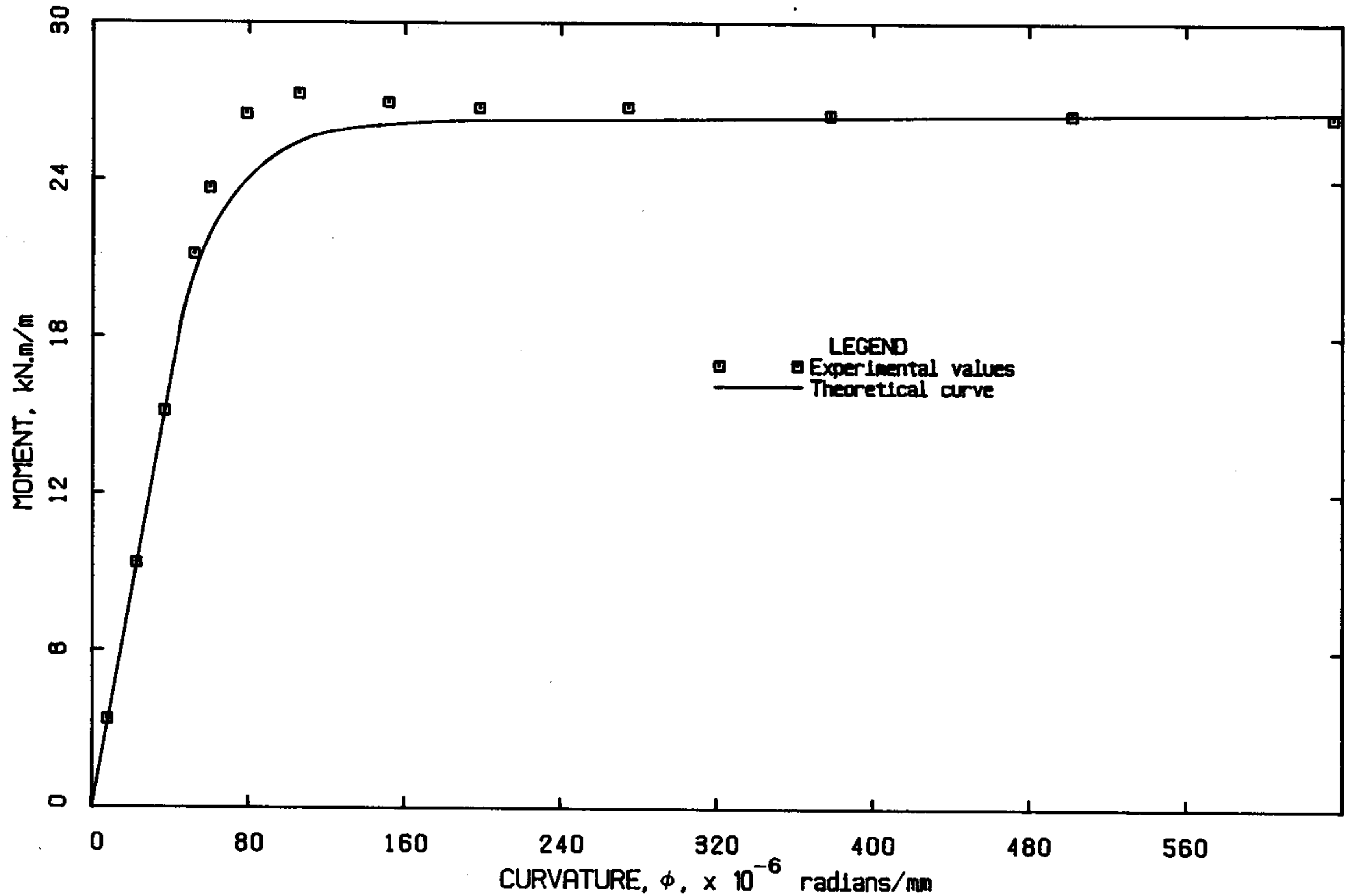


Figure 3.4 Moment Curvature Diagram for 5 mm Corrugated Plate

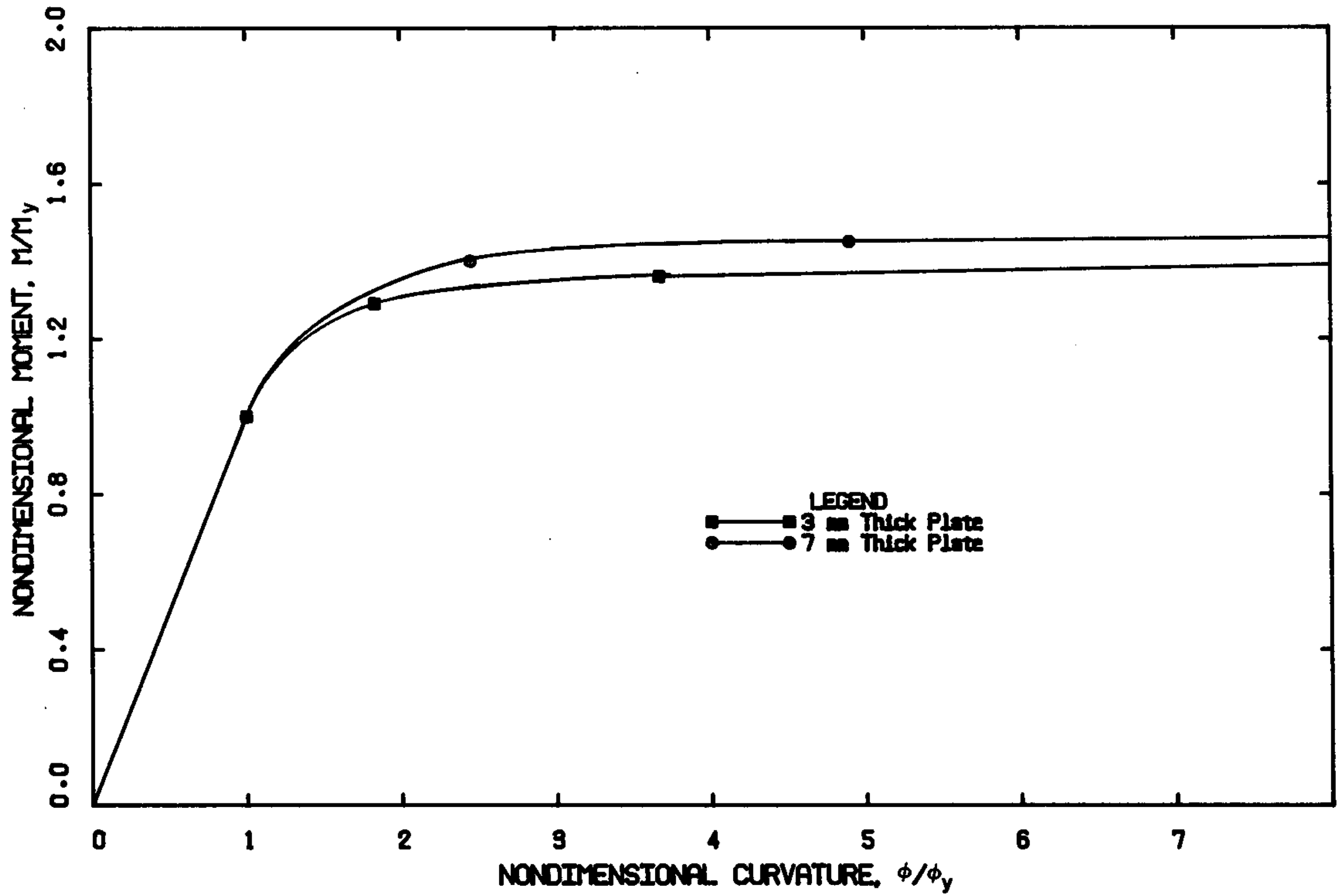


Figure 3.5 Moment Curvature Diagrams for 3 and 7 mm Corrugated Plates

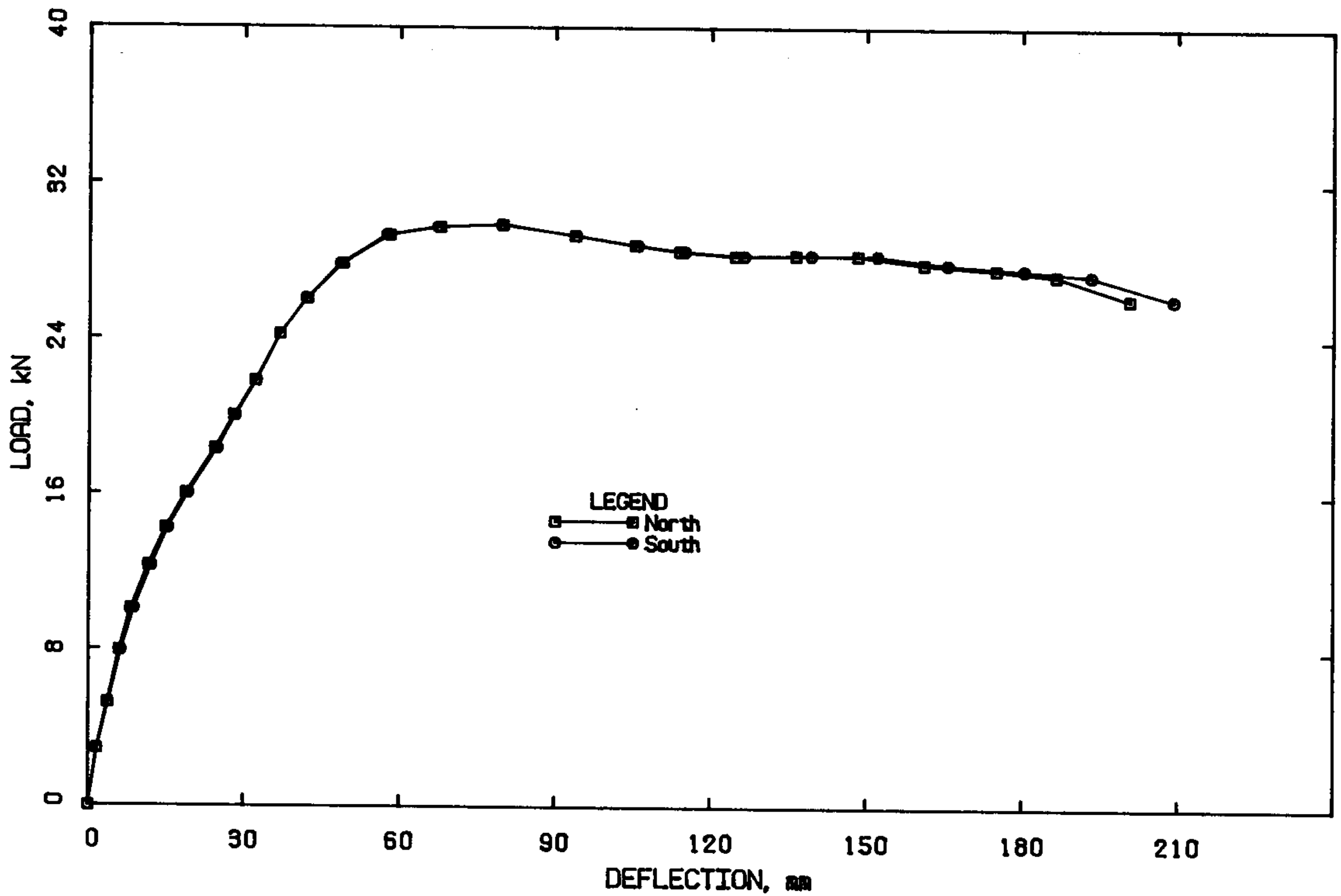


Figure 3.6 Load Deflection Curves for Specimen 5C2L

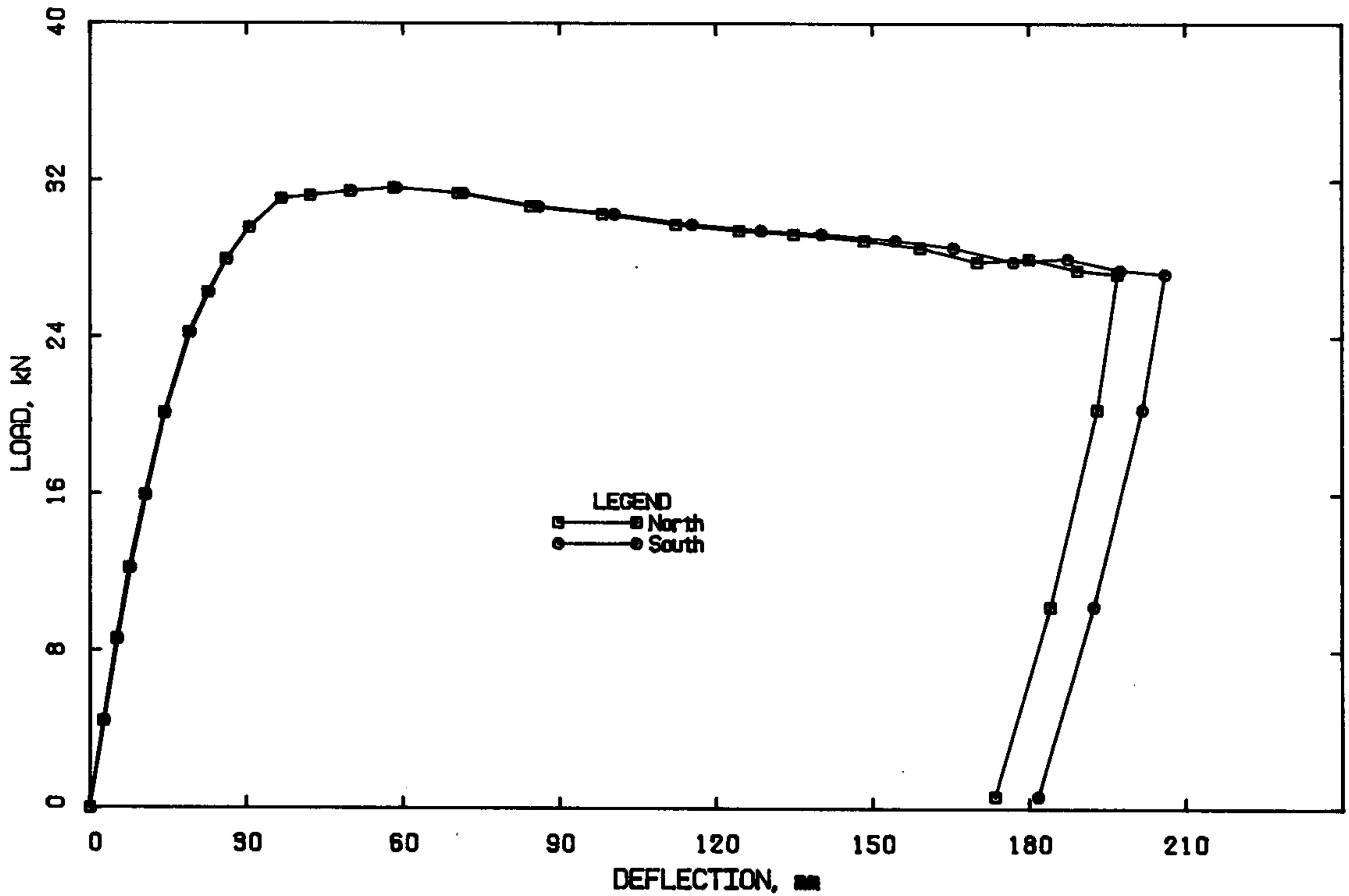


Figure 3.7 Load Deflection Curves for Specimen 5C2M

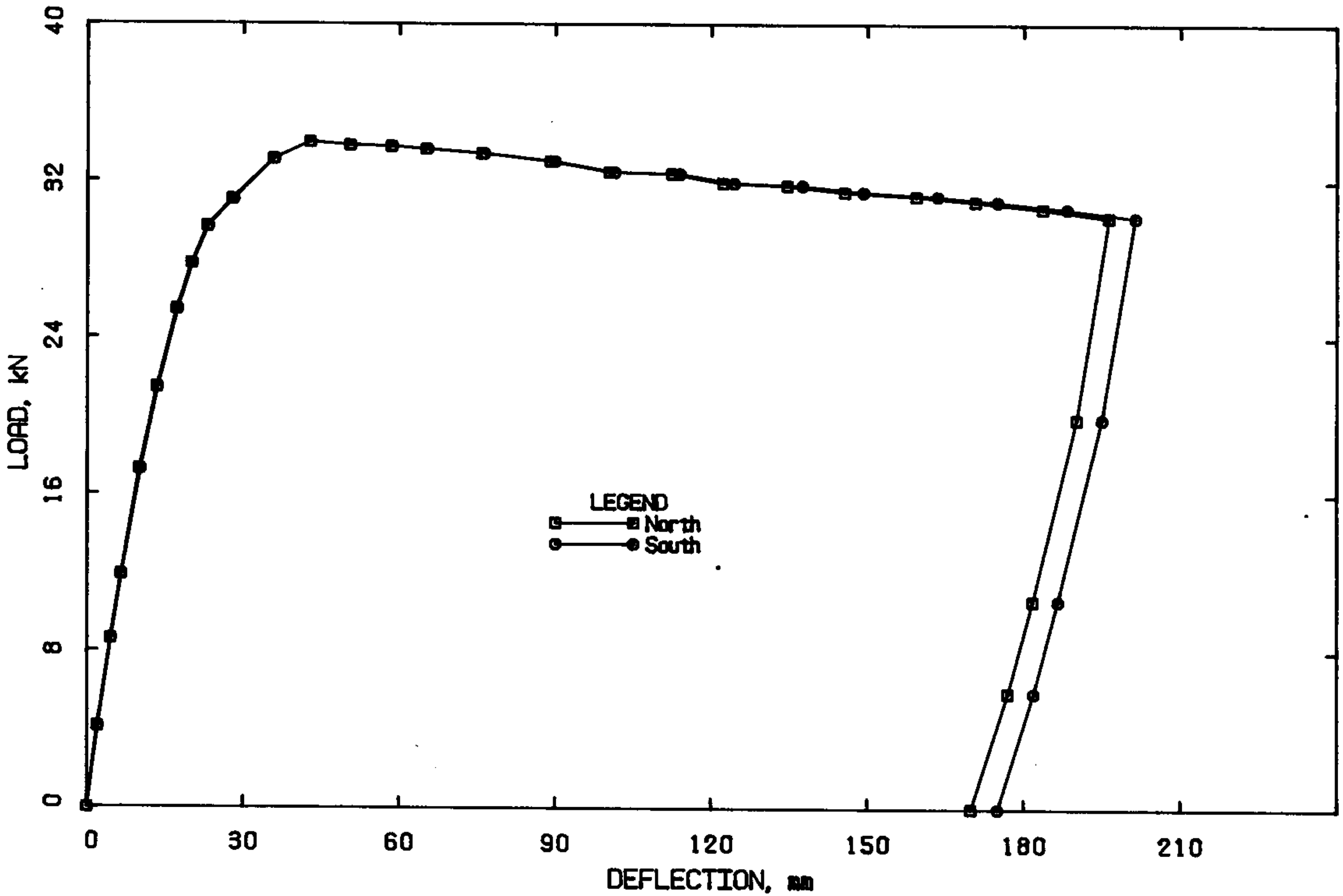


Figure 3.8 Load Deflection Curves for Specimen 5C2H

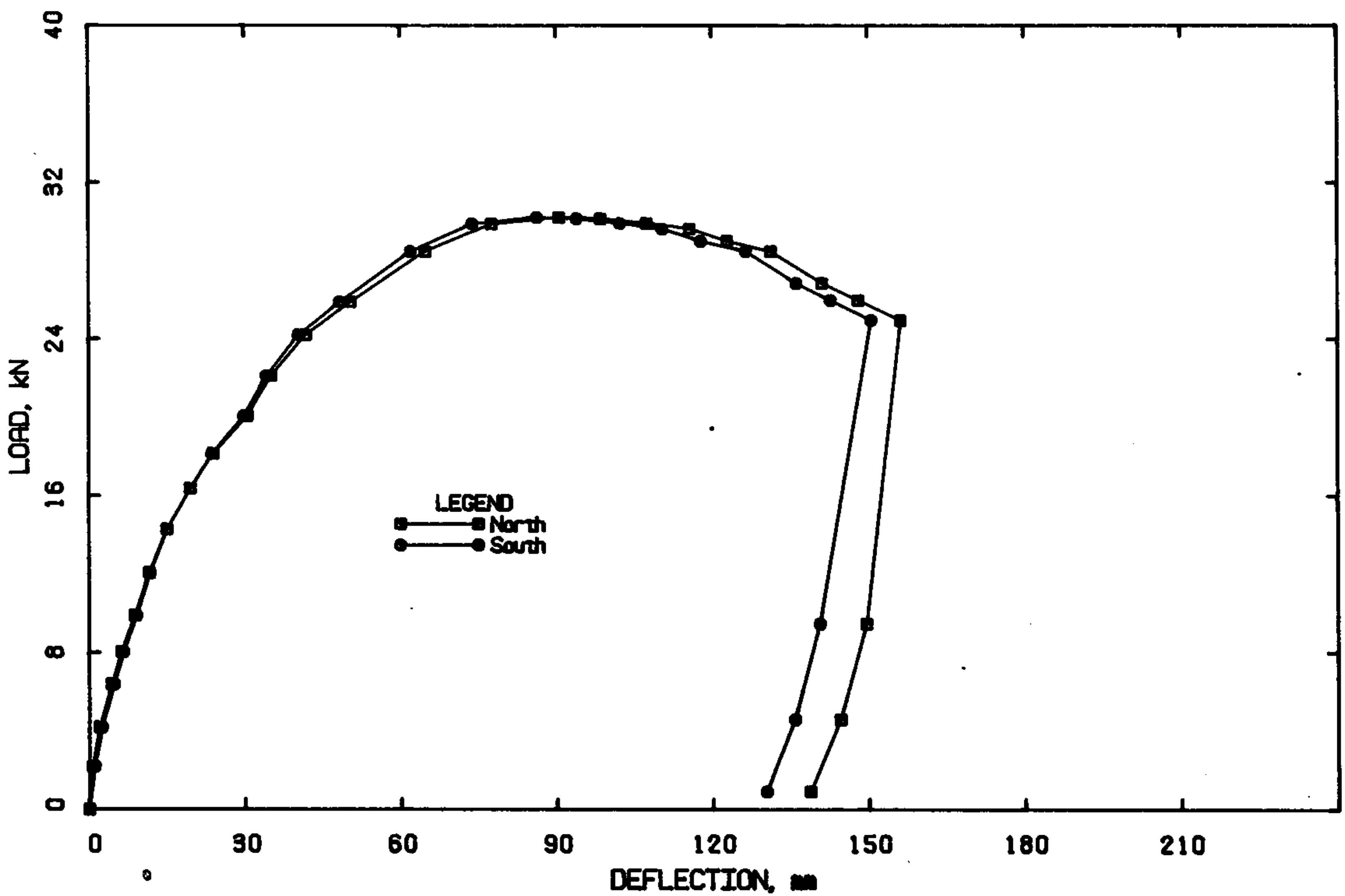


Figure 3.9 Load Deflection Curves for Specimen SI2L

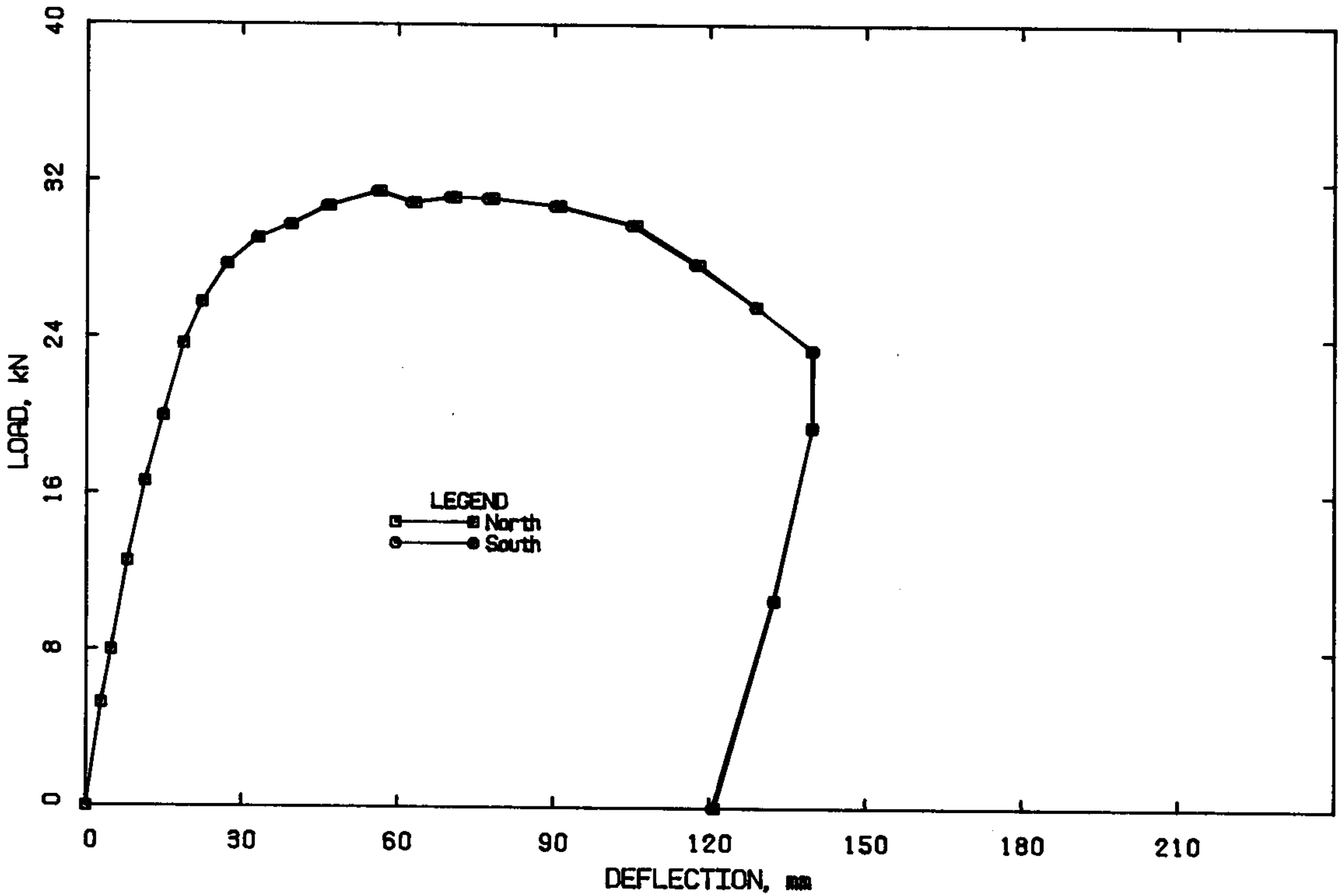


Figure 3.10 Load Deflection Curves for Specimen 5I2M

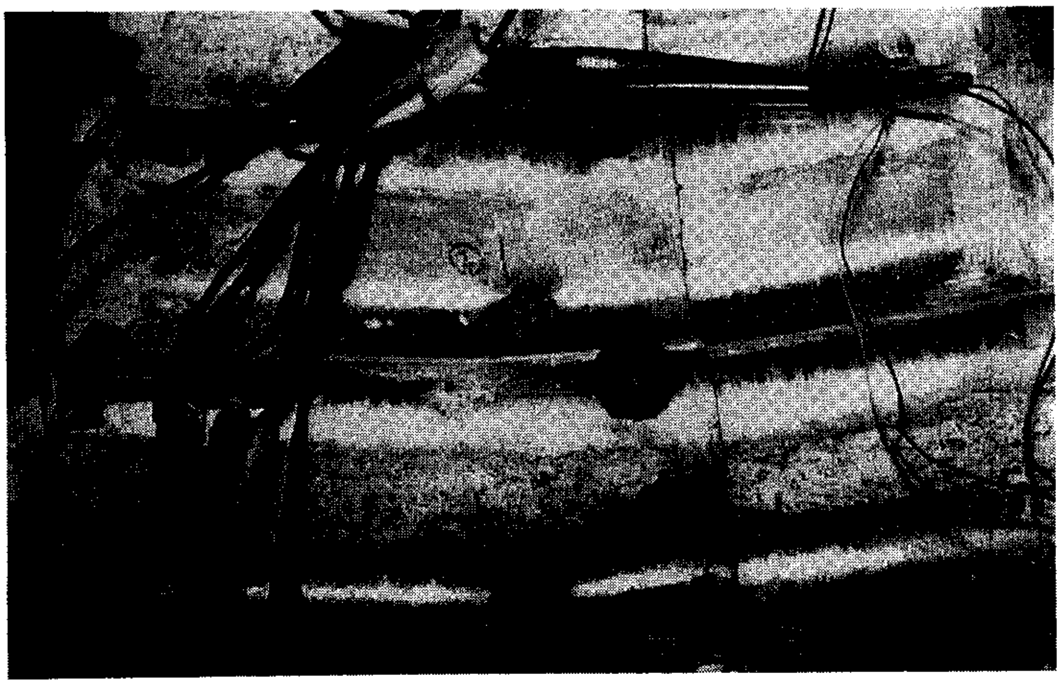


Figure 3.11 Tearing at Bolt Holes

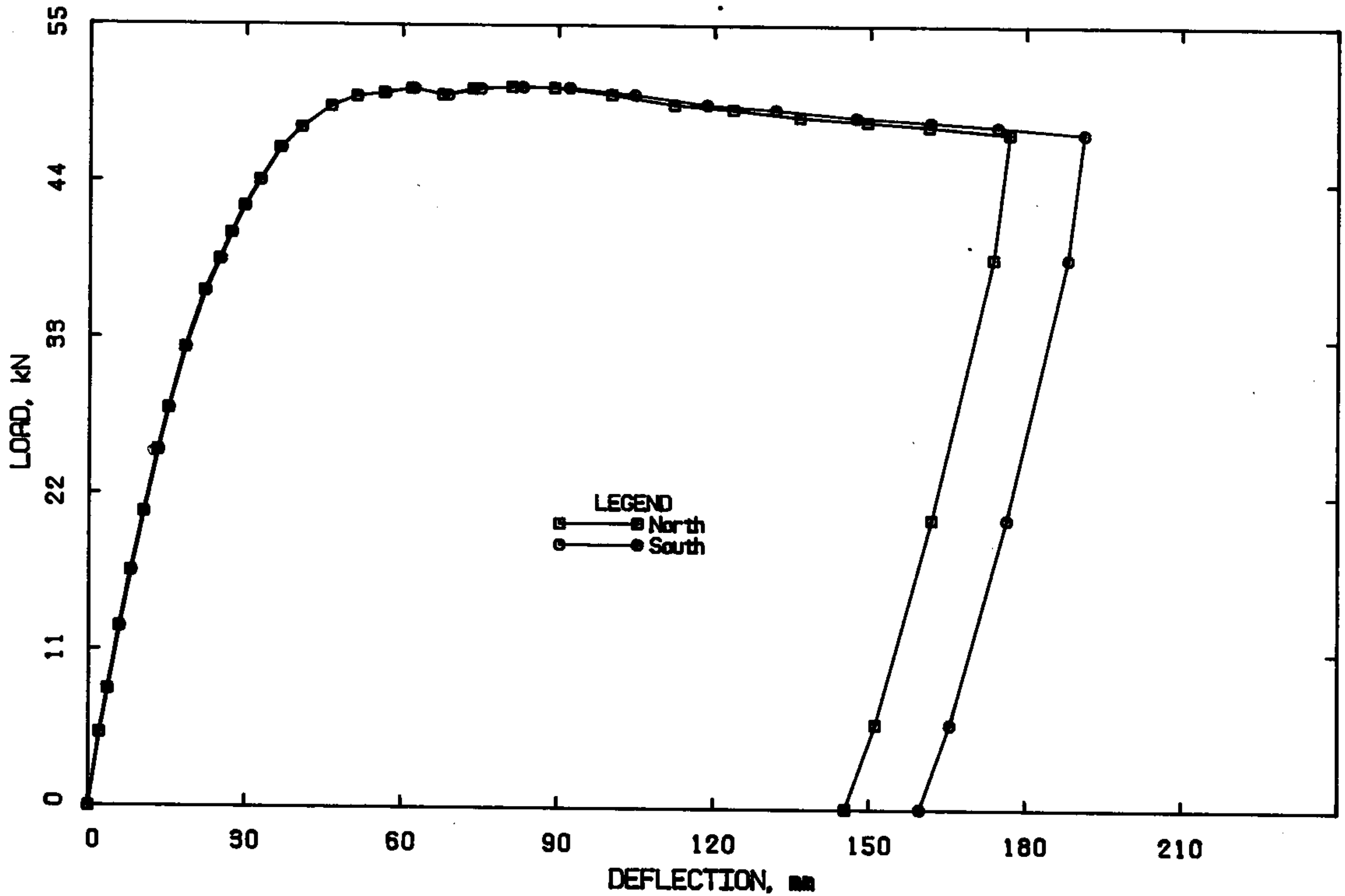


Figure 3.12 Load Deflection Curves for Specimen 7C2M

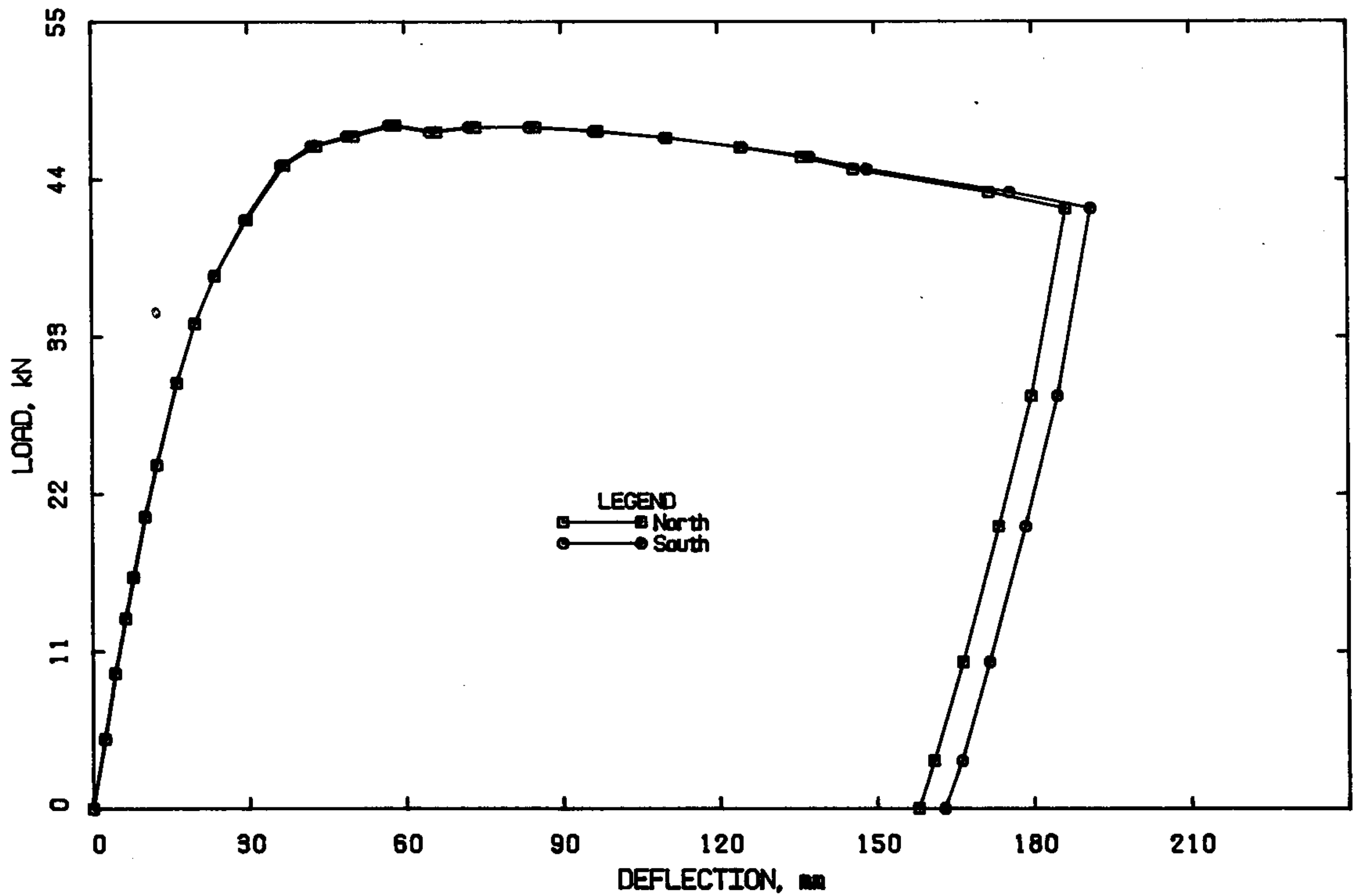


Figure 3.13 Load Deflection Curves for Specimen 7C3MC

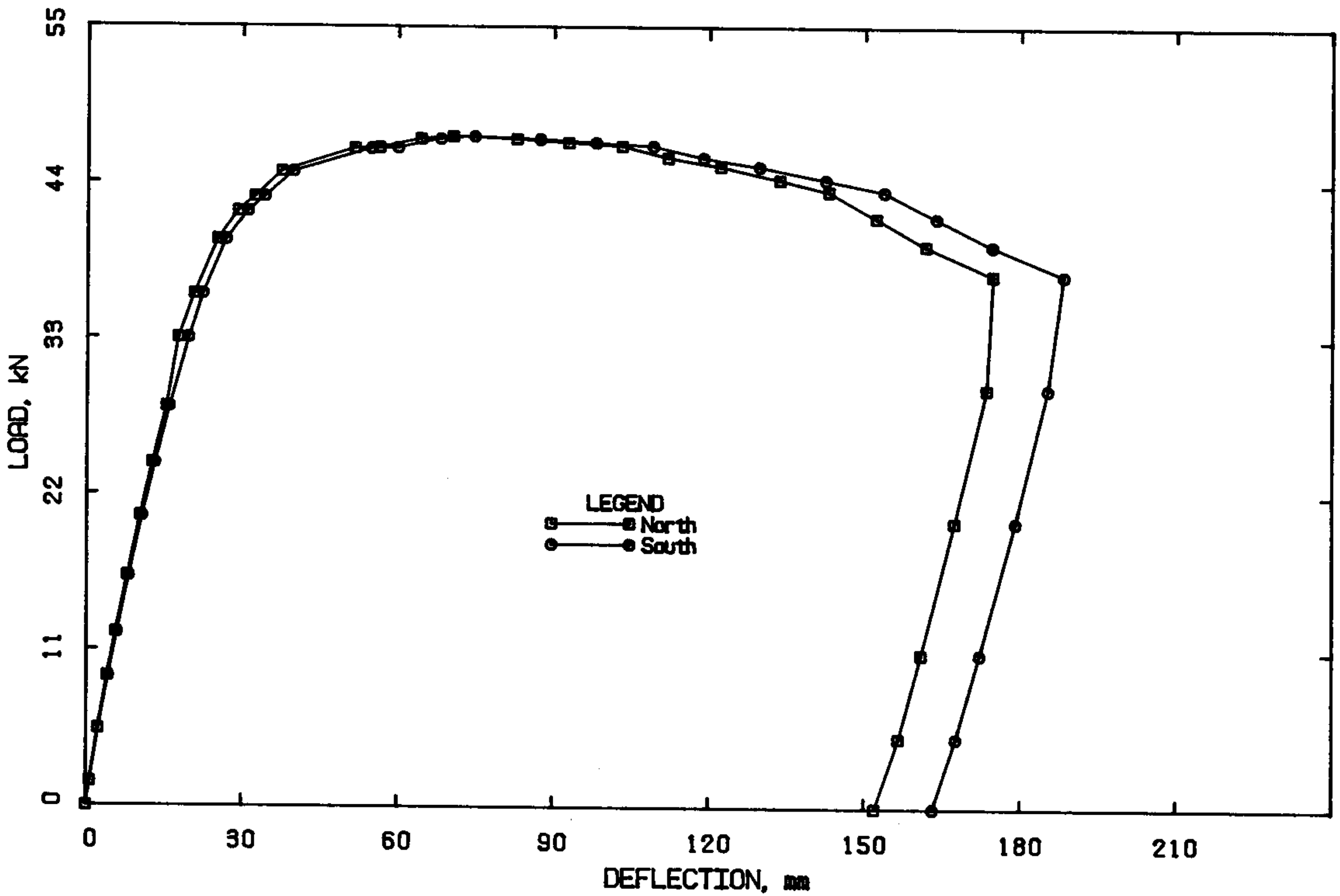


Figure 3.14 Load Deflection Curves for Specimen 7C3MV

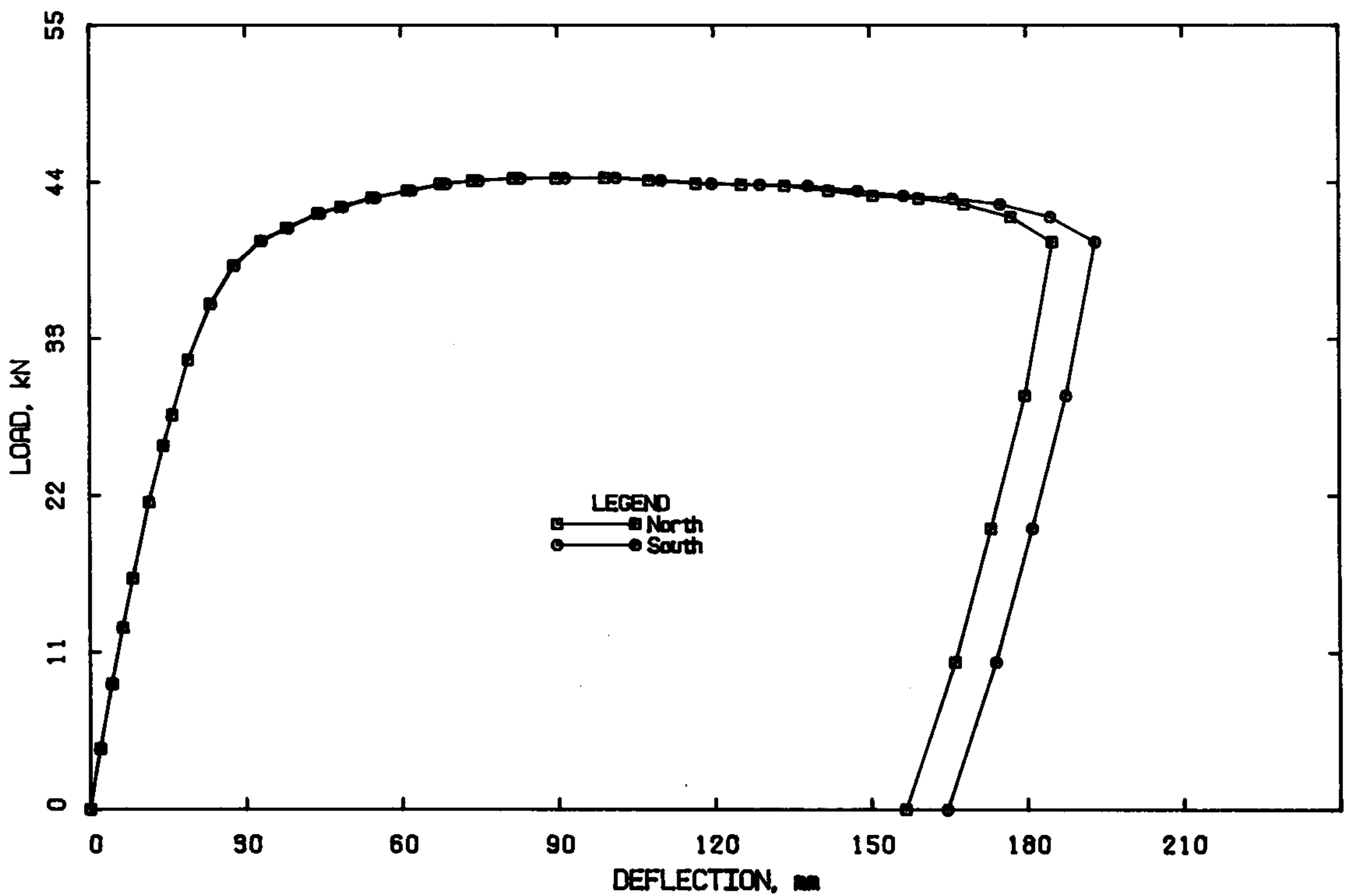


Figure 3.15 Load Deflection Curves for Specimen 7C3MVW

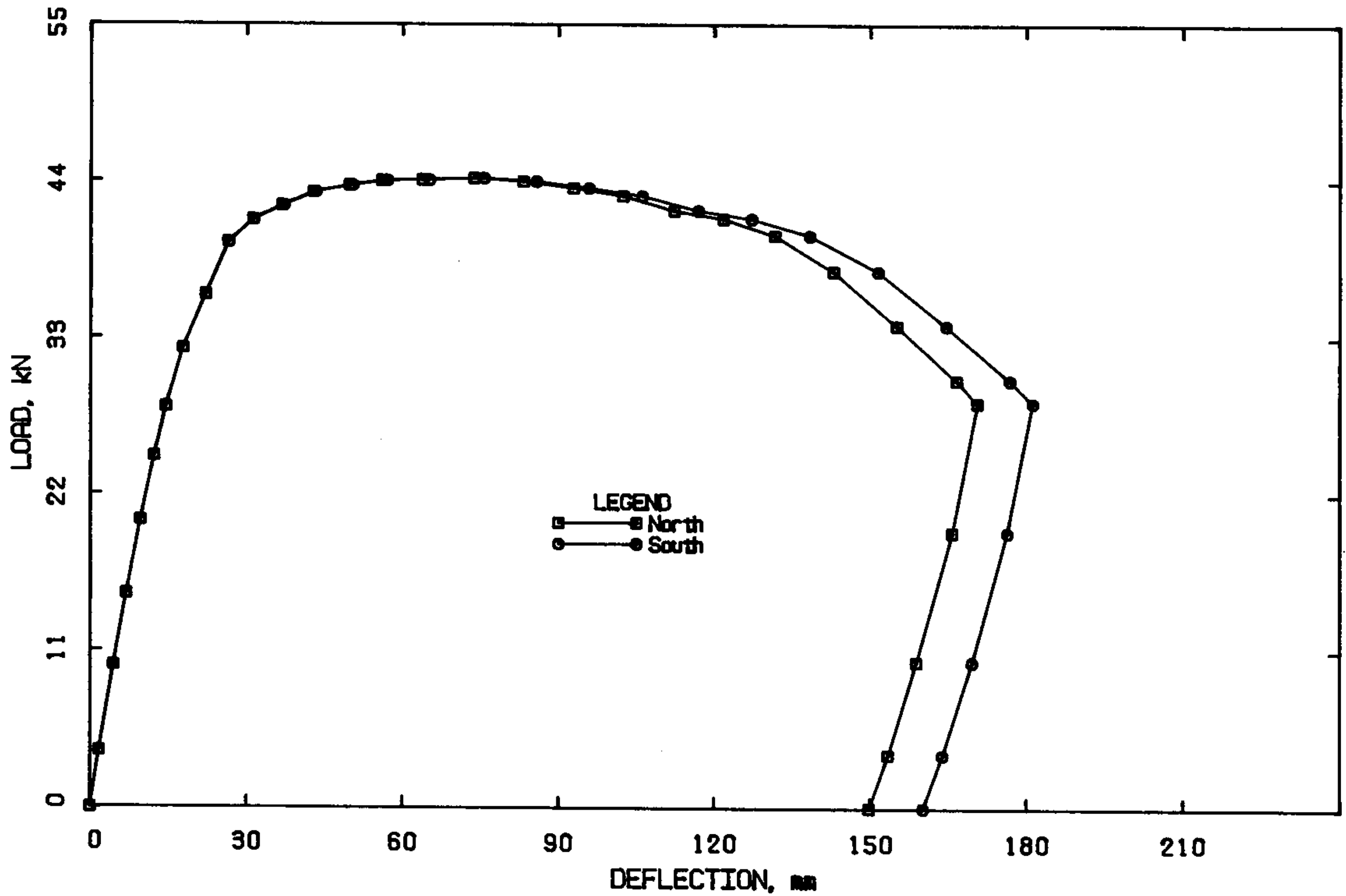


Figure 3.16 Load Deflection Curves for Specimen 7I3MC

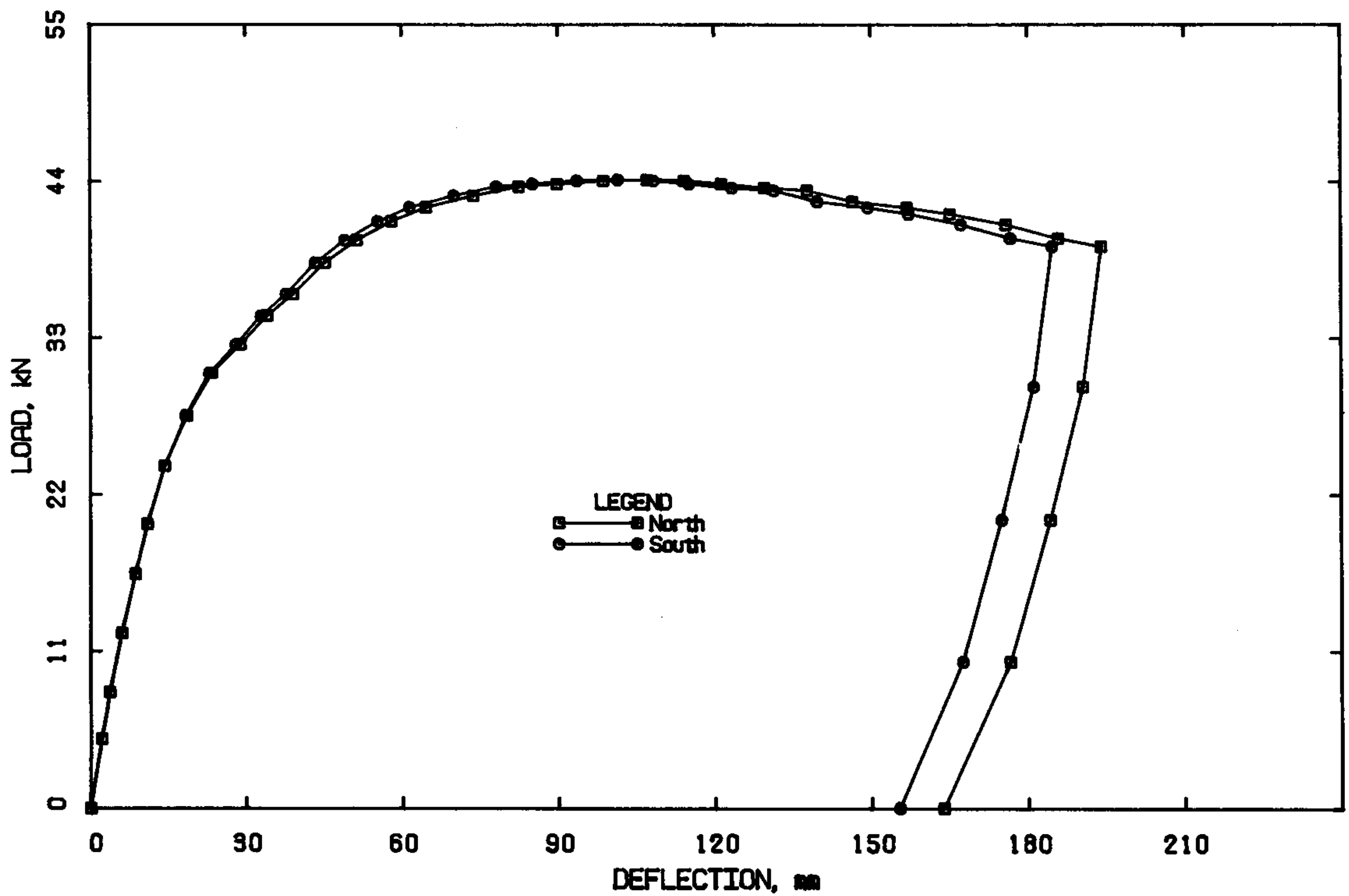


Figure 3.17 Load Deflection Curves for Specimen 7I3MV

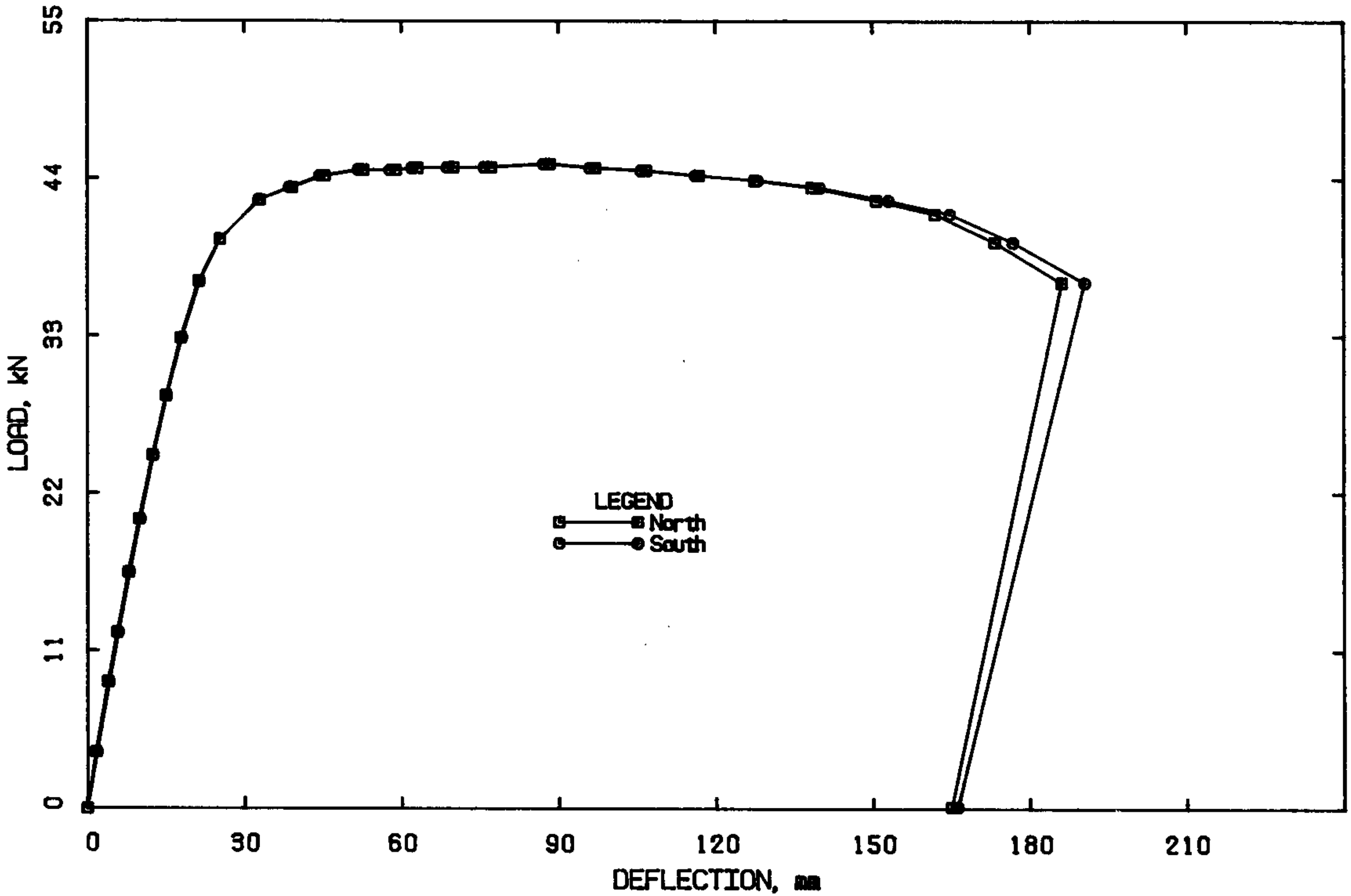


Figure 3.18 Load Deflection Curves for Specimen 7I4M

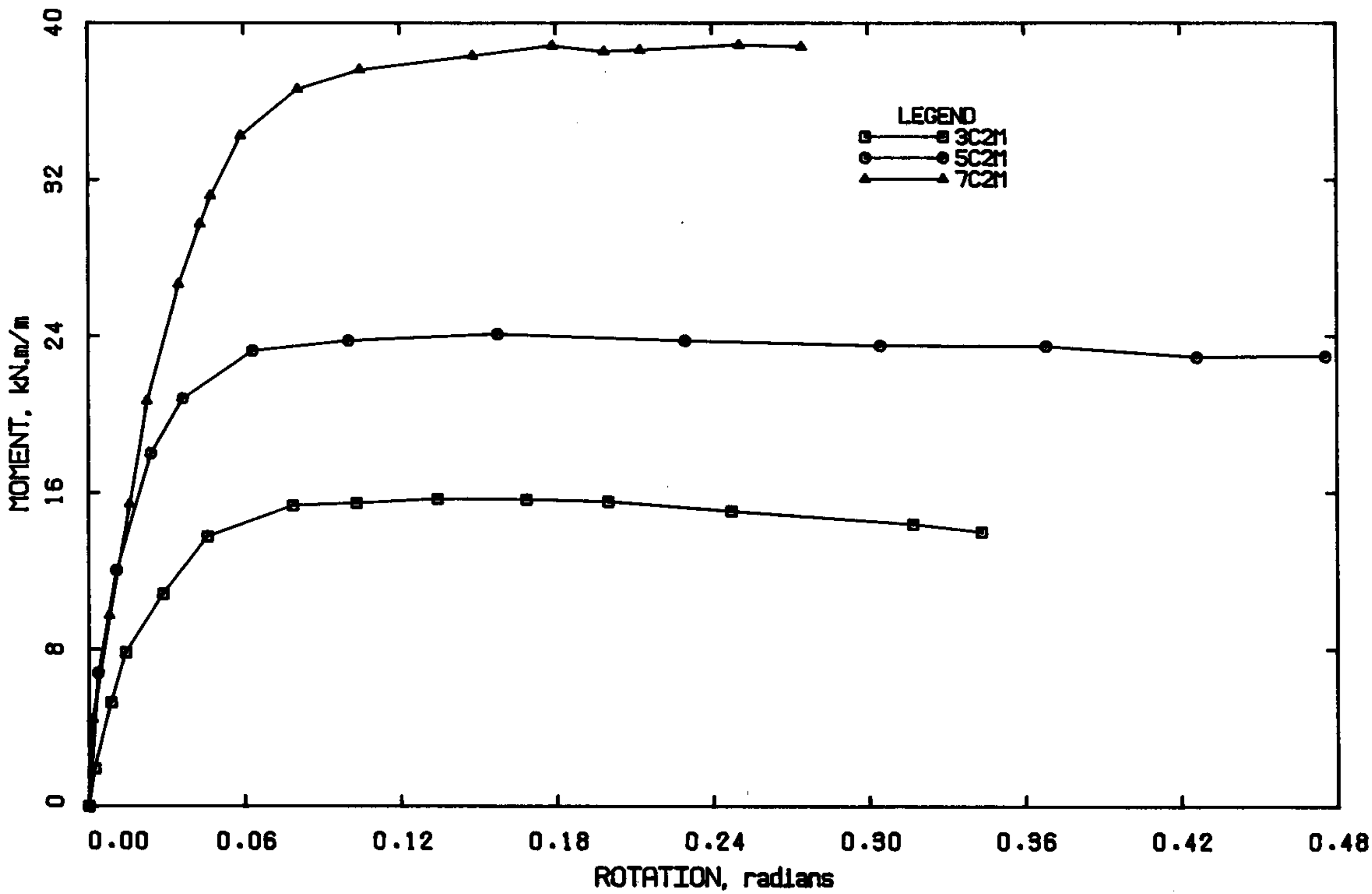


Figure 3.19 Moment Rotation Response for 3, 5 and 7 mm Specimens

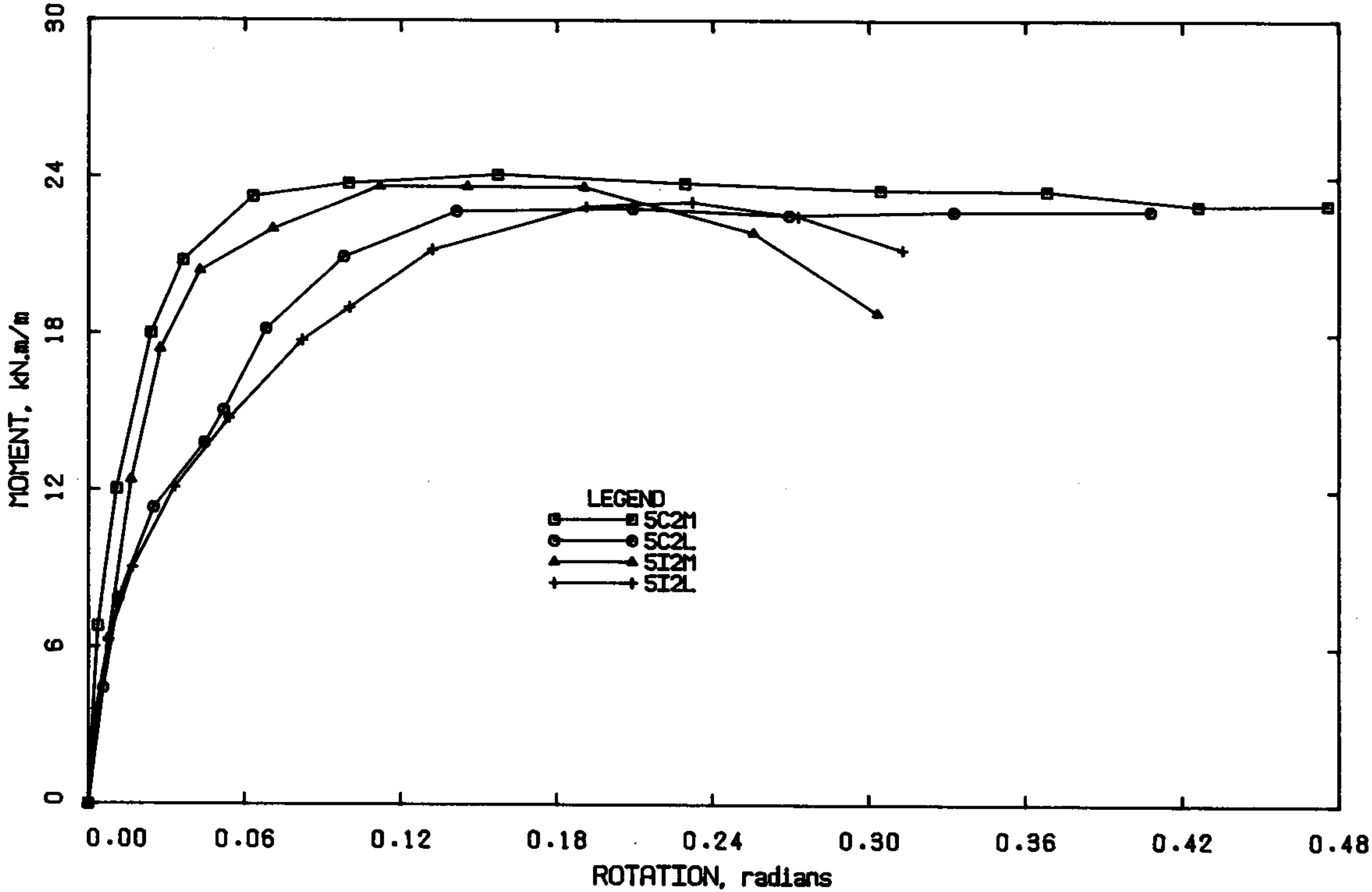


Figure 3.20 Moment Rotation Response for 5 mm Specimens

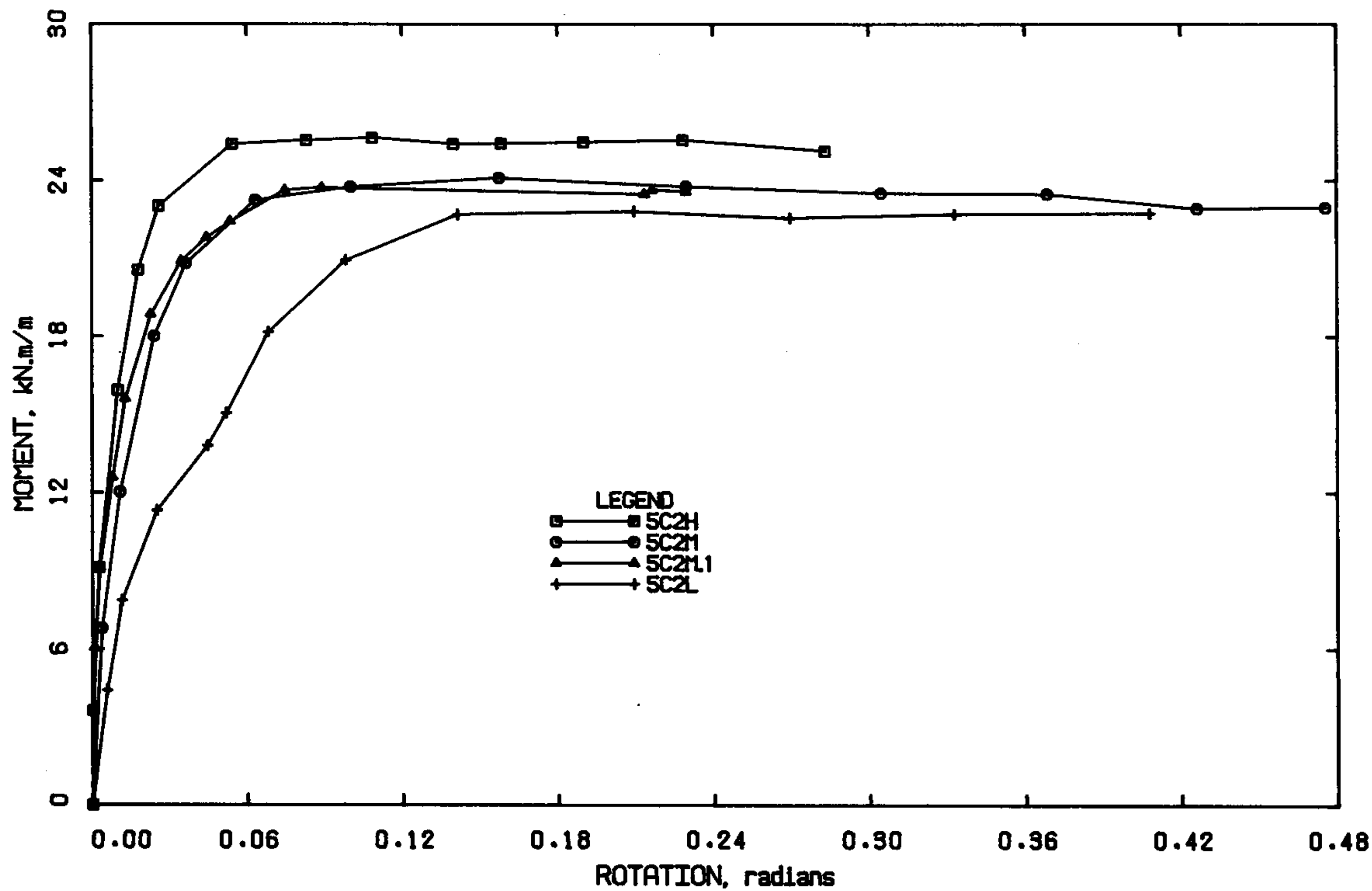


Figure 3.21 Moment Rotation Response for 5 mm Specimens, Correct Laps, High, Medium and Low Torques

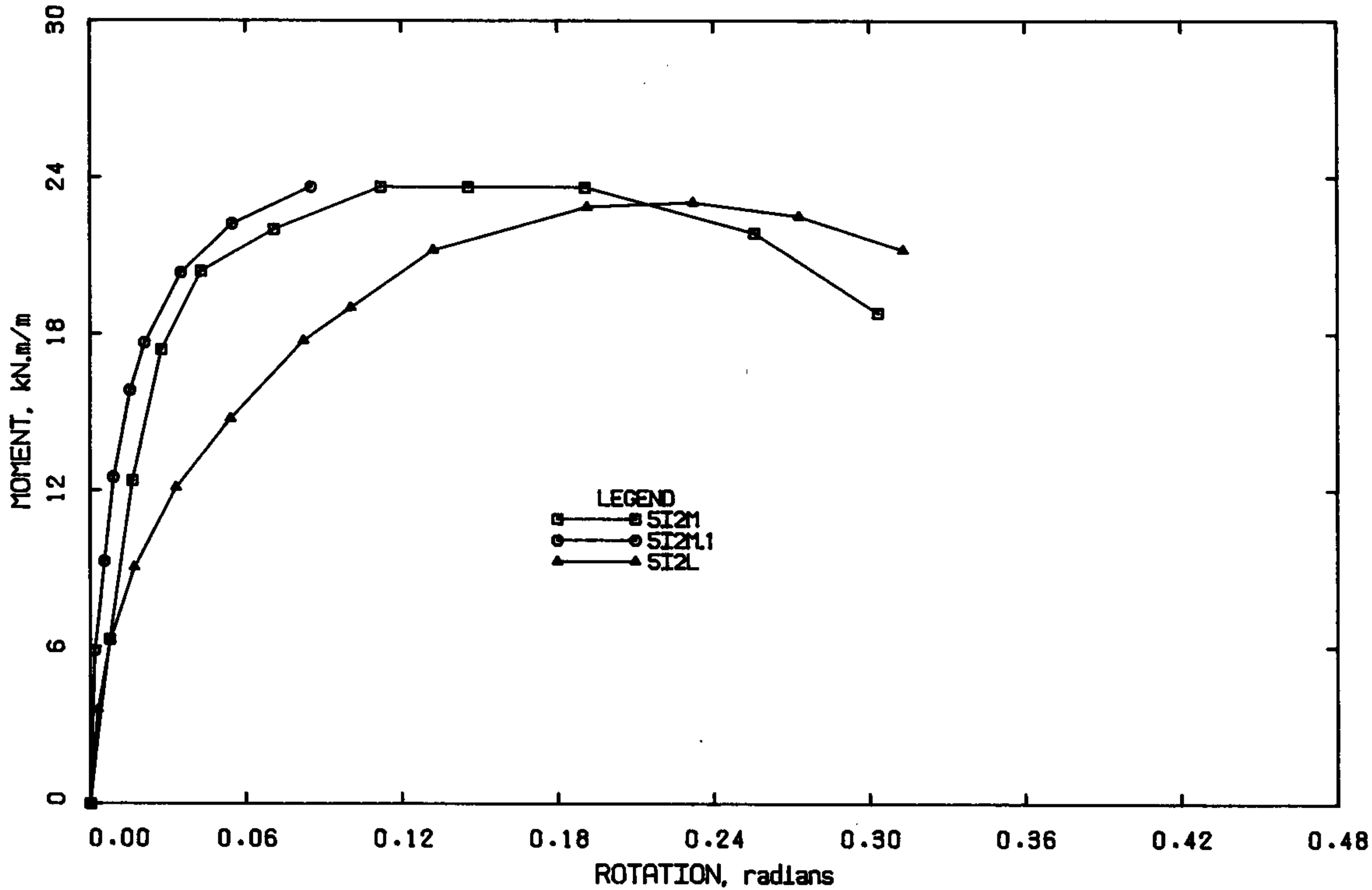


Figure 3.22 Moment Rotation Response for 5 mm Specimens, Incorrect Laps, Medium and Low Torques

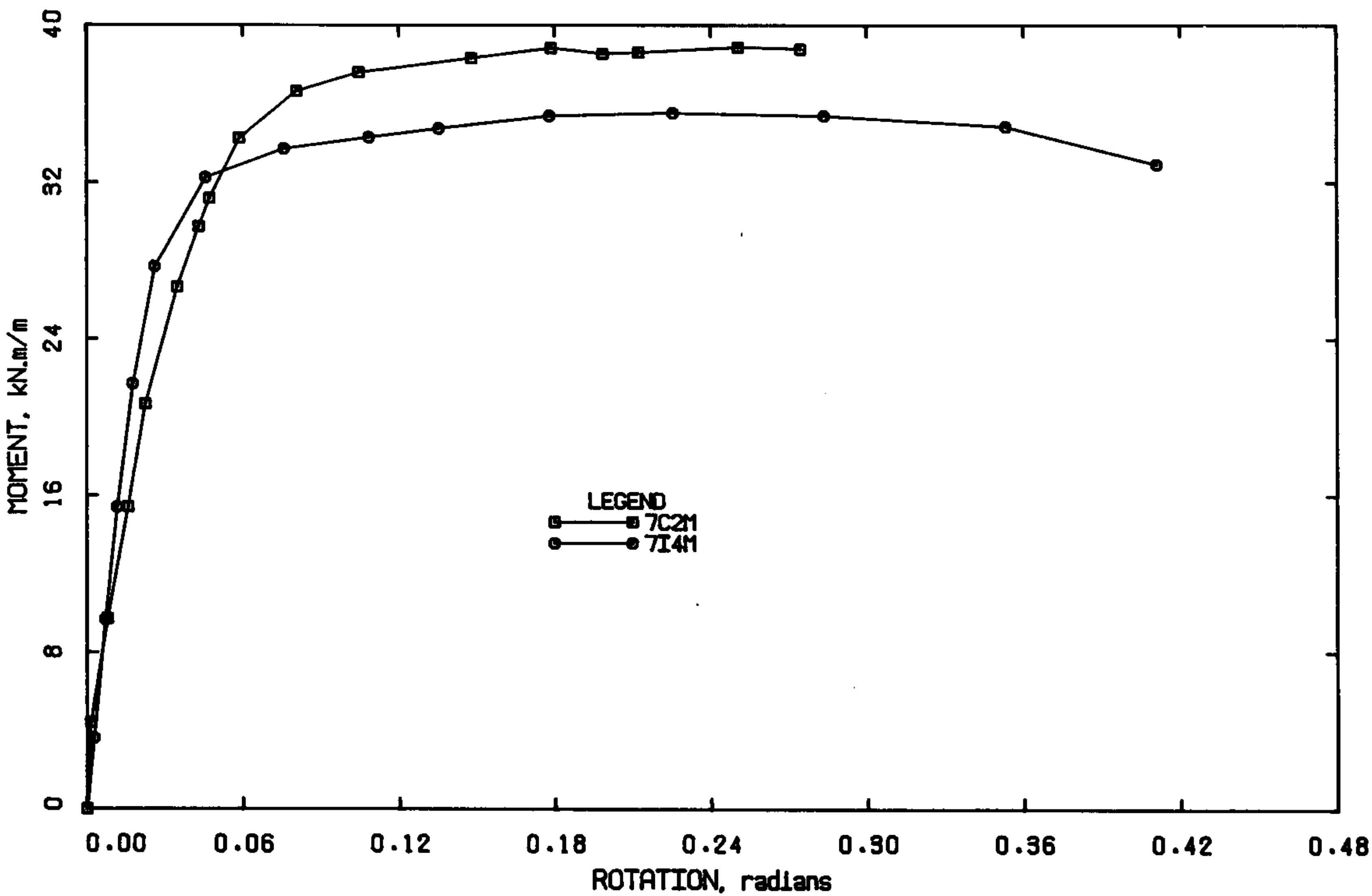


Figure 3.23 Moment Rotation Response for 7 mm Specimens, 2 and 4 Bolts

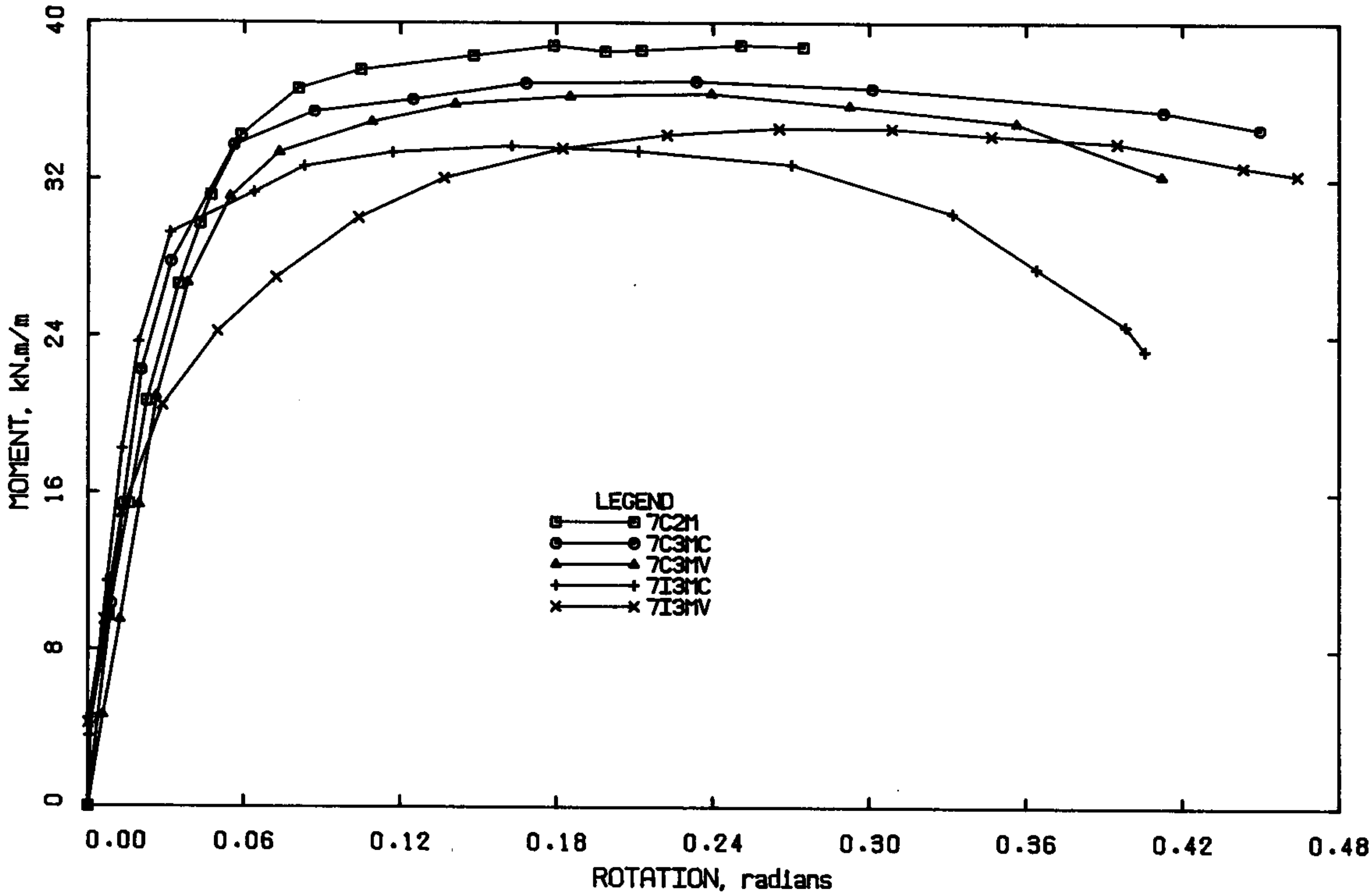


Figure 3.24 Moment Rotation Response for 7 mm Specimens, 2 and 3 Bolts

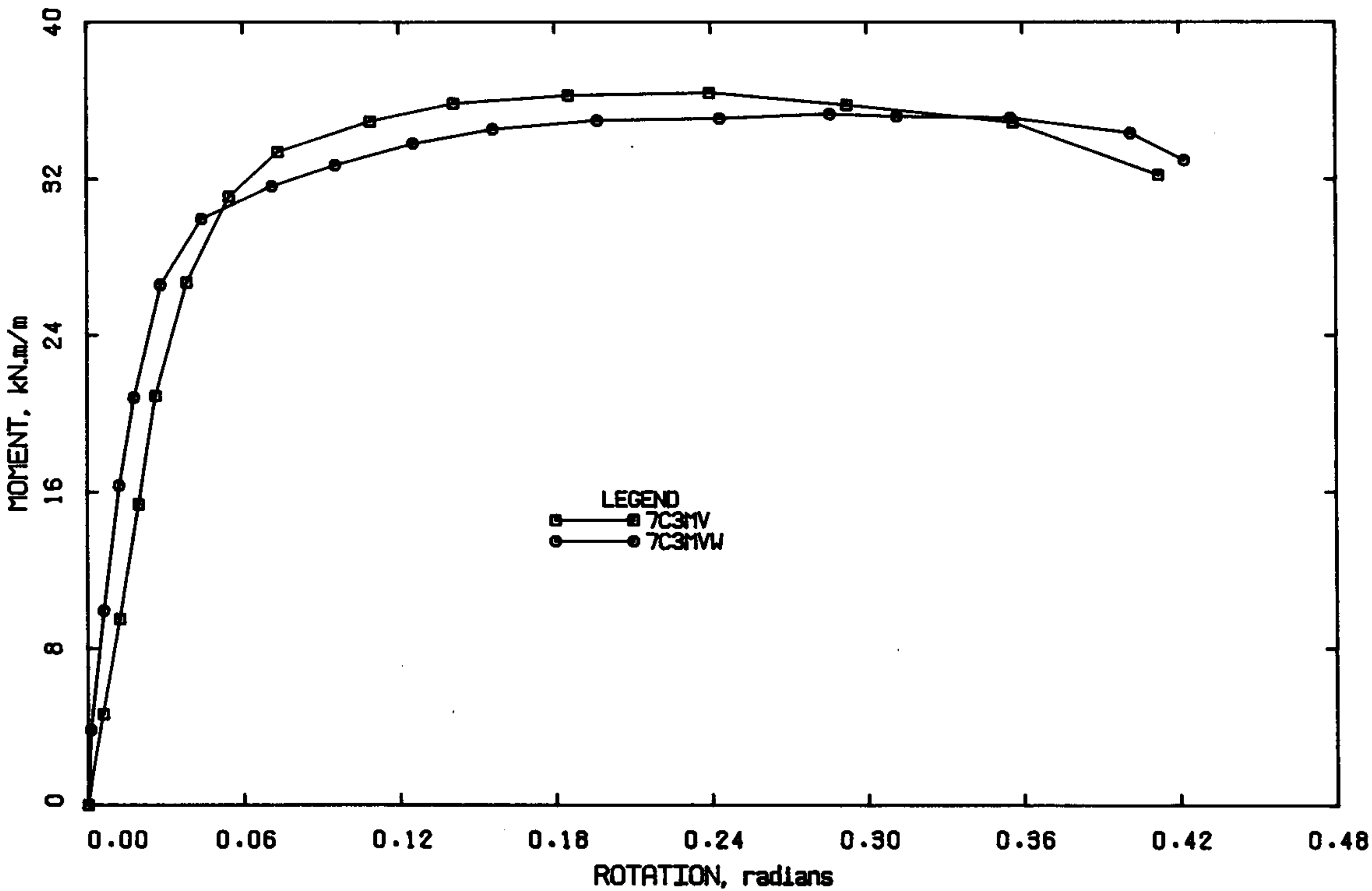


Figure 3.25 Moment Rotation Response for 7 mm Specimens

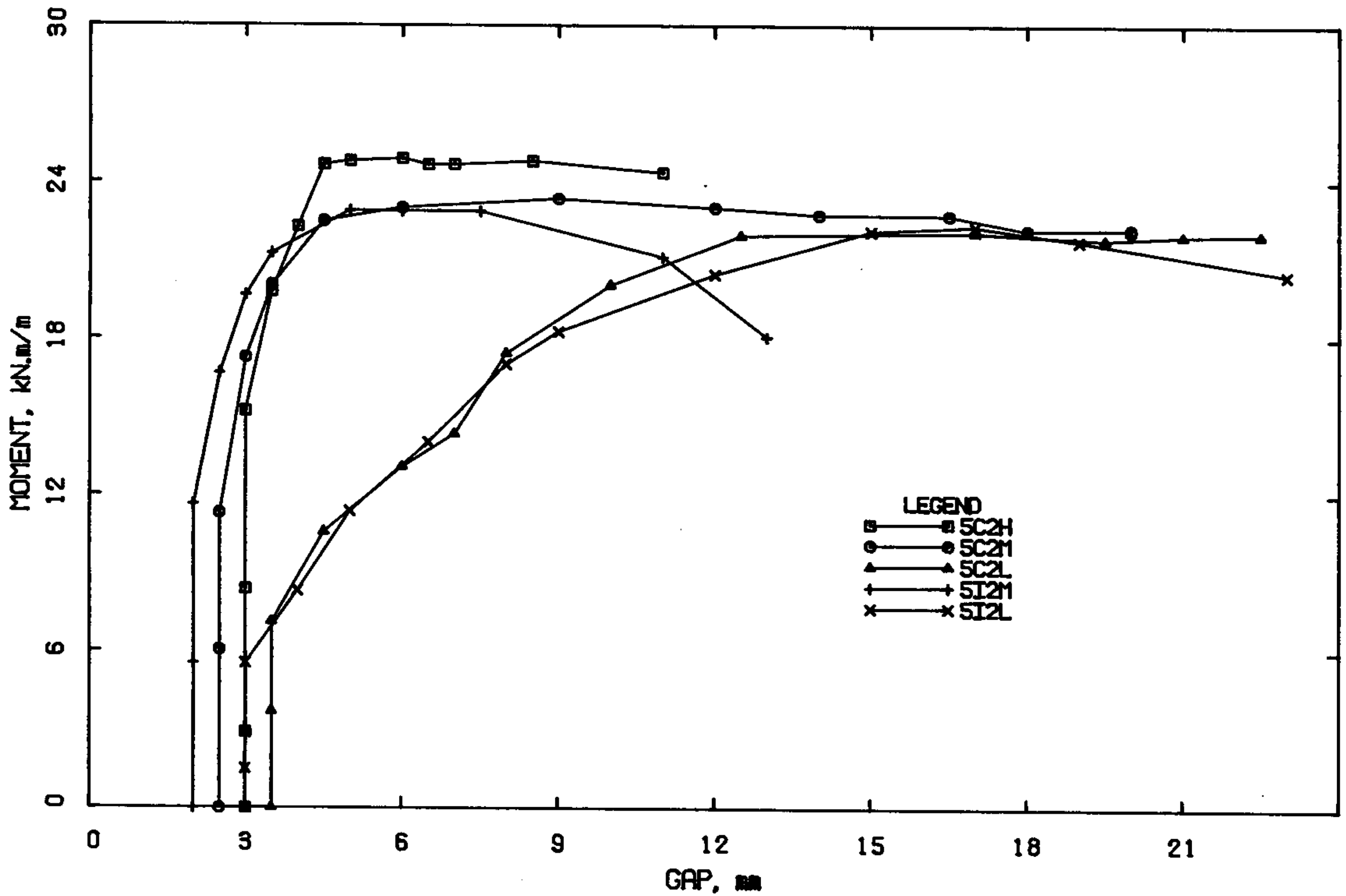


Figure 3.26 Moment versus Gap Opening for 5 mm Specimens

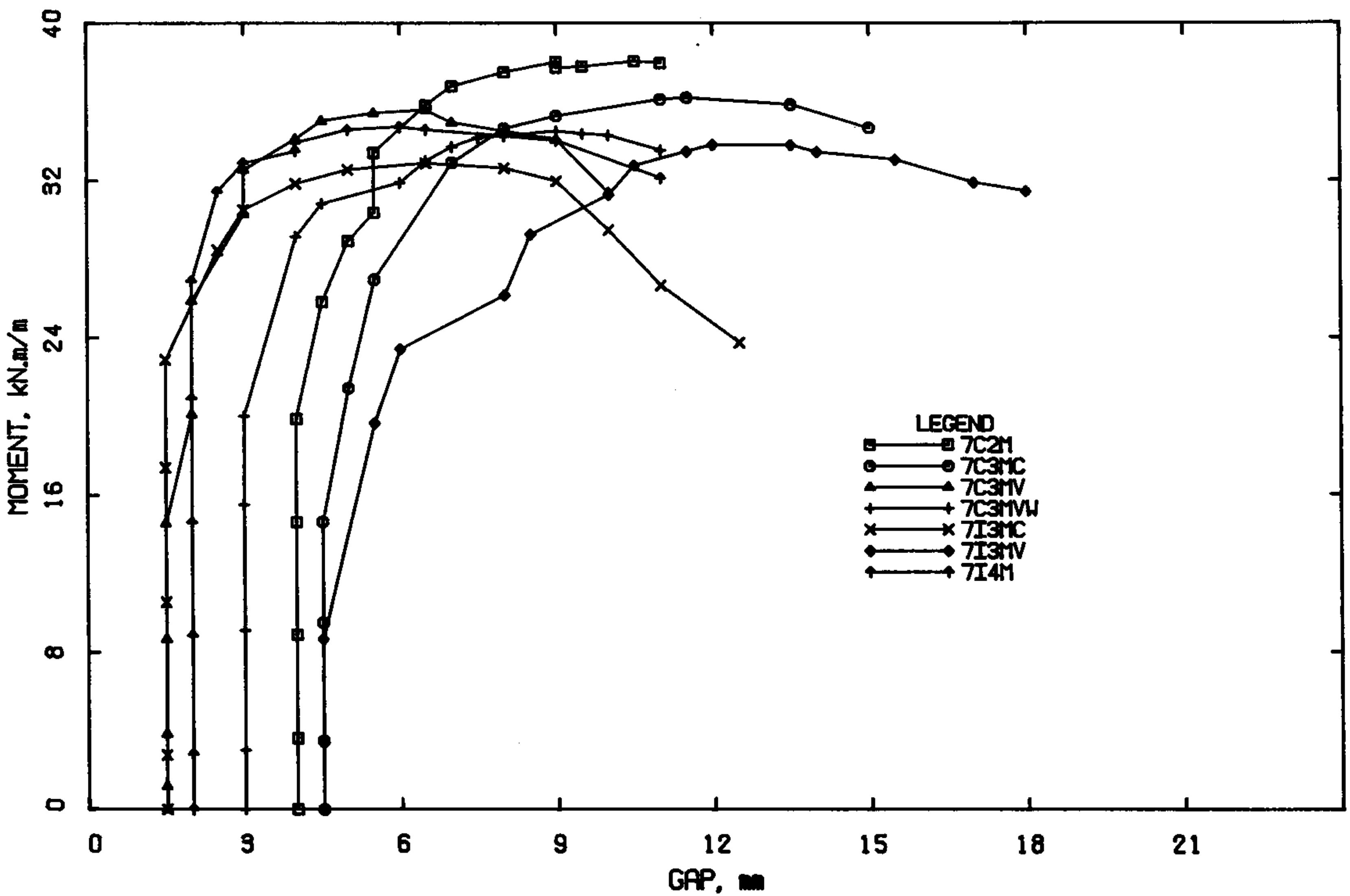


Figure 3.27 Moment versus Gap Opening for 7 mm Specimens

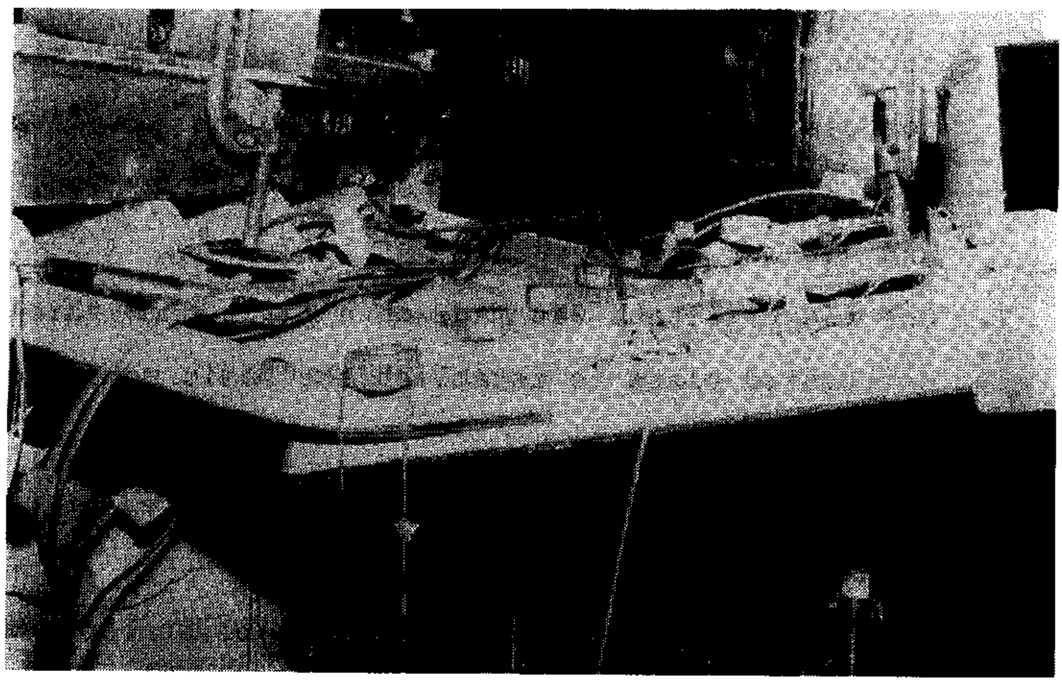


Figure 3.28 Gap Opening for Specimen under Load

4. Summary, Conclusions and Recommendations

4.1 Summary

1. Fifteen tests of lap joints of corrugated steel plates were conducted under uniform moment conditions. Three thicknesses of plates - 3, 5 and 7 mm - were tested with correct and incorrect laps. Low, medium and high torques were used to tighten the bolts. Laps were made with 2, 3 and 4 bolts per complete corrugation, and with and without sloped washers.
2. One flexural test was made on a plain 5 mm thick corrugated plate to establish the basic moment-curvature relationship.
3. The geometric properties of the corrugated plates were calculated from measured dimensions.
4. Tension coupons were tested to establish basic material properties.
5. The flexural test data of the lap joint tests were analysed to obtain the moment-rotation response of the different joints and to study the behaviour of these joints.

4.2 Conclusions and Recommendations

1. Within the limits of the test program, the moment-rotation diagrams that have been established for the lap joints can be used in the analysis of members made from corrugated plates.

2. The theoretical moment-curvature diagrams, as substantiated by tests for the 5 mm thick plate, can be used for the analysis of members made from corrugated plates.
3. The tests prove conclusively that there are correct and incorrect lap joints.
4. Correct lap joints are those in which no bolt exists on the tension side of the lap at the location where prying occurs. (See Fig. 1.1). These laps are correct for either direction of bending.
5. Incorrect lap joints are those in which a bolt exists on the tension side of the lap at the location where prying occurs. (See Fig. 1.2). These laps are incorrect for either direction of bending.
6. Correct laps exhibit very considerable ductility. In the tests, joint rotations exceeding 0.4 radians were obtained without any appreciable loss of moment capacity.
7. Incorrect lap joints, though not significantly weaker than correct lap joints, have reduced ductility. Shortly after the maximum moment is reached, tearing occurs transverse to the span from the edge of the bolt holes located on the tension side where prying occurs. The moment capacity then reduces.
8. The maximum moment obtained for both correct and incorrect lap joints appears to be at least 90% of the fully plastic moment capacity of the plain corrugated

plate provided that at least medium torque is used to tighten the bolts (250 N.m on a 20 mm diameter bolt).

9. It is recommended that all laps be made in the correct configuration with no bolts in the critical locations - B or T - as shown in Figure 1.1. The size of the bolts and length of the lap should be established to provide a joint with bending resistance more or less equal to that of the plain plate.

10. When a reduced torque is used to tighten the bolts, the lap joint has reduced initial stiffness with the gap opening up more rapidly. The joint has a somewhat reduced strength. It is therefore recommended that bolts be torqued as highly as practicable but to not less than 250 N.m. for a 20 mm diameter bolt. It is also recommended that the threads be lubricated to achieve the maximum bolt tension for a given torque.

11. On a statistical basis, lap joints with 3 bolts per corrugation will be loaded incorrectly 75% of the time. Lap joints with 4 bolts per corrugation will inevitably be loaded incorrectly.

12. Lap joints with 3 or 4 bolts, when loaded incorrectly, have reduced strengths as compared to correctly lapped joints. They exhibit limited ductility and develop tears underneath the bolt head in the critical location. The use of 3 or 4 bolts per corrugation is not recommended.

13. Sloped washers do not appear, on the basis of these

tests, to provide superior behaviour. Their use is therefore not recommended.

4.3 Further Work

1. While the tests cover a broad spectrum of configurations of lap joints, more tests are required to establish the behaviour of lap joints on a sound statistical basis.
2. The moment-curvature relationships for various plate thicknesses, as calculated from measured cross-sectional properties and yield strengths, should be verified with plain plate tests.

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Appendix A

Sample Calculation of Cross-sectional

Properties for 5 mm Plate

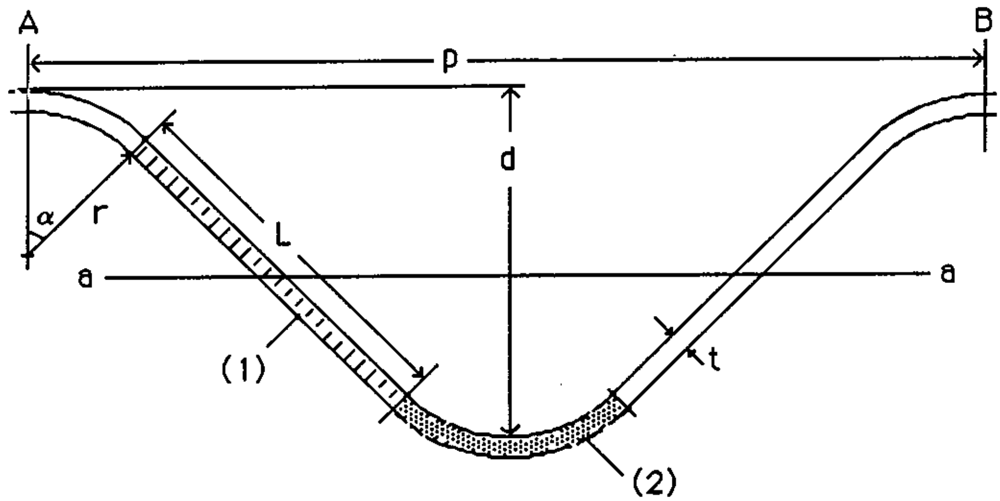

Fig. A.1

From Fig. A.1

[1] $L \cos \alpha + 2(r + t/2) \sin \alpha = p/2$

[2] $L \sin \alpha + 2[(r + t/2) - (r + t/2) \cos \alpha] = d$

For 5 mm plate, with

$t = 5.28$ mm

$d = 50.53$ mm

$p = 155.50$ mm

$\alpha = 45.3°$

[1] and [2] give $r = 30.54$ mm and $L = 43.43$ mm.

The cross-sectional area from A to B (see Fig. A.1) is equal to twice the area of section (1) plus twice the area of section (2), and the moment of inertia for the section from A to B is equal to twice the moment of inertia of section (1) plus twice the moment of inertia of section (2) about the netural axis a-a.

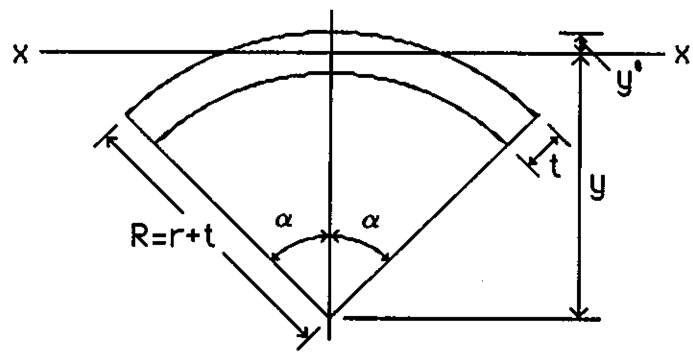

Fig. A.2

For section (2) in Fig. A.2

[3] Area, $A_2 = \pi\alpha t(2R - t)/180$

[4] $y = 180\ (\sin\alpha)(R - t/2)/\pi\alpha$

[5] $I_2' = \left[(\pi\alpha/180) + (\sin\alpha)(\cos\alpha) - (360\sin^2\alpha/\pi\alpha)\right]$
$(R - t/2)^3 t$

From [3] for the 5 mm plate

$$A_2 = \pi(45.3)(5.28)(2 \times 35.82 - 5.28)/180$$

$$A_2 = 276.90$$

From [4] for the 5 mm plate

$$y = 180(\sin 45.3)(35.82 - 5.28/2)/(45.3\pi)$$

$$y = 29.83$$

From [5] for the 5 mm plate

$$I_2' = \left[(\pi 45.3/180) + (\sin 45.3)(\cos 45.3) - (360\ \sin^2 45.3/\pi 45.3)\right]\ (35.82 - 5.28/2)^3(5.28)$$

$$I_2' = 2416.67$$

$y' = R - y = 35.82 - 29.83 = 5.99$

Moment of inertia of section (2) about neutral axis a-a is

$I_2 = I_2' + A_2\ [(d+t)/2 - y']^2$

$I_2 = 2416.67 + 276.90(27.91 - 5.99)^2$

$I_2 = 135426.94\ mm^4$

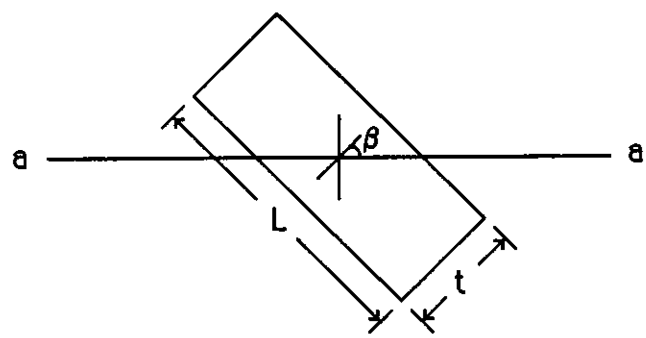

Fig. A.3

For section (1) in Fig. A.3

[6] $A_1 = (t)(L)$

[7] $I_1 = tL(t^2\sin^2\beta + L^2\cos^2\beta)/12$

with $\beta = 90° - \alpha = 90 - 45.3 = 44.7°$

From [6] for the 5 mm plate

$A_1 = 5.28 \times 43.43 = 229.31$

From [7] for the 5 mm plate

$I_1 = (5.28)(43.43)(5.28^2\sin^2 44.7 + 43.43^2\cos^2 44.7)/12$

$I_1 = 18465.17$

For section A to B (p = 155.50) in Fig. A.1

Total area $A = 2A_2 + 2A_1$

$A = 2(276.90) + 2(229.31) = 1012.42\ mm^2$

or $A = 1012.42 \times 1000/155.50 = 6.51 \times 10^3\ mm^2/m$

Moment of inertia $I = 2I_2 + 2I_1$

$I = 2(135426.94) + 2(18465.17) = 307784.22\ mm^4$

or $I = 307784.22 \times 1000/155.50 = 1.979 \times 10^6\ mm^4/m$

with $S = 2I/(d+t) = 1.979 \times 10^6/27.91$

or $S = 70.93 \times 10^3\ mm^3/m$

For section (2), moment of area about neutral axis a-a is

$$M_2 = (A_2)\ [(d+t)/2 - y']$$
$$= 276.90(27.91 - 5.99)$$
$$= 6068.82\ mm^3$$

For the area of section (1) above the neutral axis a-a, moment of area about neutral axis a-a is

$$M_1 = t(L/2)(L\sin \alpha/4)$$
$$= (5.28)(43.43/2)(43.43)(\sin 45.3/4)$$
$$= 884.64$$

Therefore, total plastic section modulus for section A-B is

$$Z = 2(M_2) + 4(M_1)$$
$$= 2(6068.82) + 4(884.64)$$
$$= 15676.20\ mm^3$$

or $Z = 15676.20 \times 1000/155.50 = 100.81 \times 10^3\ mm^3/m$

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