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Structural Engineering and Materials

EXPERIMENTAL INVESTIGATION OF THE MULTIPLE ROW EXTENDED 1/2 END-PLATE MOMENT CONNECTION

by

Emmett A. Sumner, P.E.
2001 MBMA Graduate Fellow

and

Thomas M. Murray, Ph.D., P.E.
Principal Investigator

Submitted to

Metal Building Manufacturers Association
1300 Sumenr Ave.
Cleveland, Ohio 44115-2851

Report No. CE/VPI-ST 01/14

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Research Report

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EXECUTIVE SUMMARY

End-plate moment connections are widely used by the low-rise metal building industry to provide the rigid connections necessary in gable frames. There are numerous end-plate moment connection configurations. The multiple row extended 1/2 (MRE 1/2) end-plate moment connection configuration is the focus of this investigation. The MRE 1/2 end-plate moment connection has three rows of bolts at the tension flange, one row located outside the beam flange and two rows located inside the beam flange.

Six MRE 1/2 end-plate moment connection tests were conducted at the Virginia Tech Structures and Materials Laboratory. The purpose of the tests was to investigate the moment strength of the connections and to validate the current design procedures. Details of the connection design, test set-up, testing procedure, and test results are presented within this report.

It is concluded that the current design procedures, presented in the forthcoming *AISC Steel Design Guide 16, Flush and Extended Multiple Row Moment End-Plate Connections* (Murray and Shoemaker, 2002), conservatively predict the strength of MRE 1/2 end-plate moment connections. The strength predictions are adequate for MRE 1/2 end-plate connections utilizing A325 or A490 bolts with a standard or a large inner pitch distance.

ACKNOWLEDGEMENTS

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EXPERIMENTAL INVESTIGATION OF THE MULTIPLE ROW EXTENDED 1/2 END-PLATE MOMENT CONNECTION

1. INTRODUCTION

End-plate moment connections are widely used by the low-rise metal building industry to provide the rigid connections necessary in gable frames. They are used to connect the columns to the rafters and to splice rafter segments together. An end-plate moment connection consists of a steel plate that is shop-welded to the end of a beam section that is then field-bolted to the connecting member using rows of high-strength bolts. There are numerous end-plate moment connection configurations. The multiple row extended 1/2 end-plate moment connection configuration was the focus of this investigation.

The multiple row extended 1/2 (MRE 1/2) end-plate moment connection has three rows of bolts at the tension flange. One row is positioned outside the flange of the beam section on an extended portion of the end-plate, and the other two rows are positioned inside the beam flange. A typical MRE 1/2 connection is shown in Figure 1.1.

Six MRE 1/2 end-plate moment connection tests were conducted at the Virginia Tech Structures and Materials Laboratory. The purpose of the tests was to investigate the moment strength of the connections and to validate the current design procedures. Details of the connection design, test set-up, testing procedure, and test results are presented within this report. Discussion of the results and recommendations are also provided.

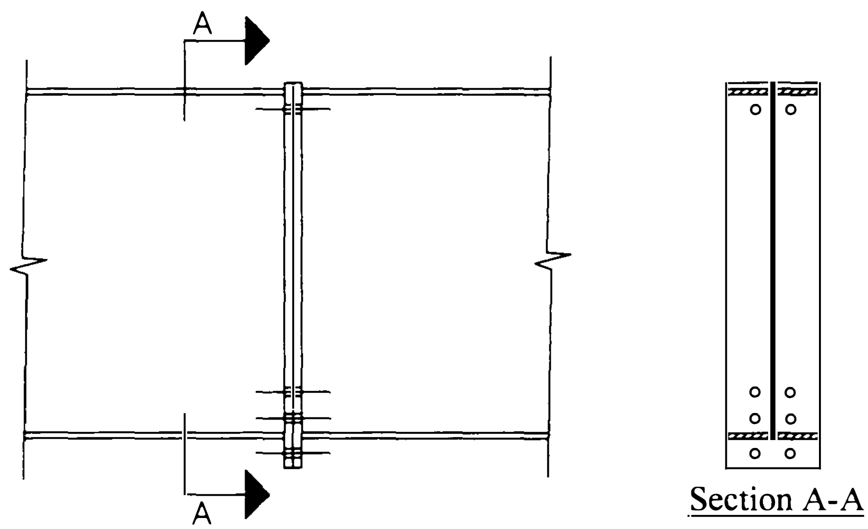


FIGURE 1.1: TYPICAL MRE 1/2 END-PLATE MOMENT CONNECTION

2. TEST SPECIMENS

2.1. OVERVIEW

Each of the six connection test specimens consisted of two built-up beam sections spliced together at midspan using a multiple row extended 1/2 end-plate moment connection. Each test beam was fabricated with an end-plate on both ends so that it could be utilized for two tests. The built-up beam sections were 30 in. deep with 1/2 in. by 8 in. flanges and a 3/8 in. web thickness. The end-plate thickness, bolt grade, and distance of the inner bolts from the tension flange were varied to investigate their affect on the connection strength. A constant bolt diameter of 3/4 in. and a gage of 3 in. were used for all of the test connections.

The test matrix is shown in Table 2.1. The connection geometric parameters shown in the test matrix are defined in Figure 2.1. The test connection naming convention is a combination of the connection type, bolt diameter, end-plate thickness, and the nominal beam depth. A test designation of MRE 1/2-3/4-3/8-30 indicates a multiple row extended end-plate connection with one row of bolts outside the flange and two rows inside the flange. The designated connection has 3/4 in. diameter bolts, a 3/8 in. thick end-plate, and a nominal beam depth of 30 in.

2.2. DESIGN

The test specimen connections were designed using methods developed at the University of Oklahoma and Virginia Tech. The methods for the design of nine different end-plate connection configurations have been unified and are presented in the forthcoming *AISC Steel Design Guide 16, Flush and Extended Multiple Row Moment End-Plate Connections* (Murray and Shoemaker, 2002). The design guide utilizes yield-line theory to determine the end-plate thickness for a given end-plate geometry, and it provides a procedure to determine the bolt forces including prying forces. A summary of the procedure and the equations used to design the test specimen connections are shown in Appendix A. Figure A-1 is a flowchart outlining the analysis procedure. Table A-1 is a summary of the end-plate and bolt force equations for the MRE 1/2 connection. Table A-2 is a summary of the bolt force equations.

Two different connection design options are presented in the AISC Design Guide (Murray and Shoemaker, 2002); thick plate design or thin plate design. The thick plate design option designs an end-plate thick enough to avoid the development of significant bolt prying forces. The prying forces are assumed to be zero and the design results in the smallest diameter bolts possible and a thick end-plate. The thin plate design option assumes maximum bolt prying forces are present. This results in the thinnest end-plate possible and larger diameter bolts.

The test specimen connections were designed to investigate both the thick plate and thin plate design options. This resulted in the design of two connections for each bolt layout pattern. Two different bolt layout patterns were used, one with a standard inner pitch distance and one with a large inner pitch distance. The inner pitch distance is the distance from the inside face of the tension flange to the centerline of the first inside row of bolts (dimension p_{fi} in Figure 2.1). A large inner pitch distance is necessary when an end-plate connection is used in a diagonal knee connection that connects a column to a rafter.

A constant bolt diameter of 3/4 in. was used. ASTM A325 bolts were used for both the thick and thin plate connection tests. To investigate the behavior of ASTM A490 bolts, two thick plate tests were performed using A490 bolts. The connection bolts were assumed to be "snug-tight." In accordance with the AISC Design Guide (Murray and Shoemaker, 2002), the "snug-tight" condition for 3/4 in. diameter bolts provides a pretension level equal to 50 percent of the LRFD (AISC, 1999) minimum specified pretension force.

2.3. MATERIALS AND FABRICATION

The steel used for the end-plate and built-up beam section was ASTM A572 Grade 50 with a nominal yield strength of 50 ksi. The ASTM A325 and A490 bolts were used along with ASTM A563 nuts. No washers were used. The welding of the specimens was performed in accordance with all current American Welding Society specifications. Detailed fabrication drawings can be found in Appendix H.

TABLE 2.1: Test Matrix

Test Identification	Bolt Diameter (in.)	Bolt Grade	End-Plate Thickness (in.)	Inner Pitch, p_{fi} (in.)	Outer Pitch, p_{fo} (in.)	Gage g (in.)	Beam Depth, h (in.)	End-Plate Width, b_p (in.)
Test A - MRE 1/2-3/4-3/8-30	3/4	A325	3/8	1 1/4	1 1/4	3	30	8
Test B - MRE 1/2-3/4-3/4-30	3/4	A325	3/4	1 1/4	1 1/4	3	30	8
Test B1 - MRE 1/2-3/4-3/4-30	3/4	A490	3/4	1 1/4	1 1/4	3	30	8
Test C - MRE 1/2-3/4-1/2-30	3/4	A325	1/2	5	1 1/4	3	30	8
Test D - MRE 1/2-3/4-3/4-30	3/4	A325	3/4	5	1 1/4	3	30	8
Test D1 - MRE 1/2-3/4-3/4-30	3/4	A490	3/4	5	1 1/4	3	30	8

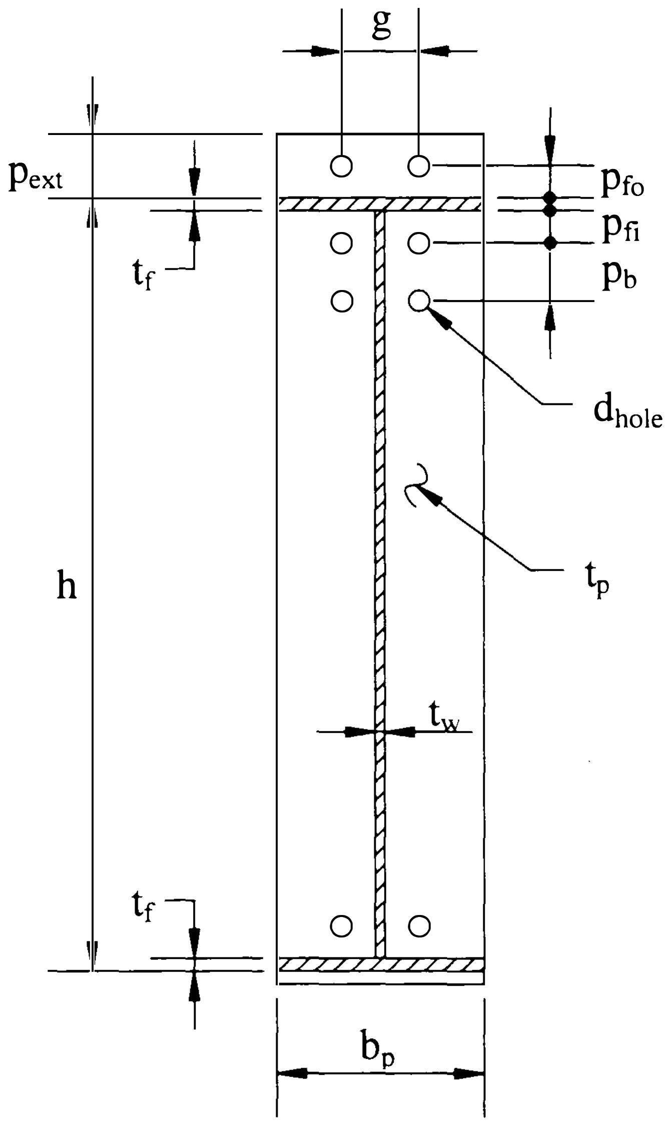


FIGURE 2.1: END-PLATE GEOMETRY NOTATION

3. EXPERIMENTAL TESTING

3.1. TEST SETUP

The connections were tested as a splice connection loaded under pure moment. The test specimen was simply supported with rollers at each end. The ends were supported by stiffened support beams connected directly to the reaction floor. Symmetrical loading was applied using two hydraulic rams connected in parallel to a single hydraulic pump. The hydraulic rams were supported by vertical load frames bolted to the reaction floor. The specimen was braced laterally using "come-alongs" at the supports and lateral brace mechanisms placed on the top and bottom flanges as close as possible at the load points and at midspan. The lateral brace mechanisms were connected to the vertical load frames which were bolted to the reaction floor. A typical test setup is shown in Figure 3.1 and Figure 3.2.

3.2. INSTRUMENTATION

The six connection test specimens were instrumented to measure the applied load, specimen deflection, end-plate separation, and bolt forces. The instrumentation layout is shown in Figure 3.3. The applied load was measured using two load cells, one placed between each hydraulic ram and the supporting frame. Displacement transducers were used to measure the vertical deflection of the specimen at the load points and at midspan. The separation of the end-plates was measured using instrumented calipers placed as close to the web as possible on both sides of the tension flange. The bolt forces were measured using instrumented bolts. Half of the bolts for each connection were instrumented using 120 ohm strain gages to measure the bolt strains. The strain gages were inserted into a 2mm hole, drilled into the unthreaded portion of the bolt, and then secured with an epoxy adhesive. The bolts are then calibrated in a universal testing machine to determine the elastic load-strain relationship. Using this relationship, the bolt tension load was monitored throughout the testing sequence. All of the instrumentation was calibrated prior to use and connected to a PC-based data acquisition system.

3.3. TESTING PROCEDURE

Once the test specimen was erected in the reaction frame, the instrumented connection bolts were installed. The test bolts were connected to the PC-based data acquisition system and the system zeroed. The bolts were then tightened to the specified "snug tight" level as indicated by the bolt strain readings. The non-instrumented bolts were tightened to the same torque by "feel" with reference to the torque applied to the instrumented bolts. The tightening sequence was repeated until all bolts had achieved the same pretension level.

The displacement transducers and calipers were setup and connected to the data acquisition system. The calibration of each transducer was then verified and recalibration performed as necessary. The instrumentation was then zeroed and a preload cycle of approximately 20 percent of the predicted failure load was applied. The initial stiffness of the specimen was compared to the theoretical elastic stiffness and the behavior of the instrumentation closely observed. Any necessary adjustments to the instrumentation were made and the data acquisition system zeroed.

An initial zero reading was recorded and the test was begun. The loading was applied in increments of approximately 10 percent of the predicted failure load. The specimen was allowed to settle at each load step. Data points were recorded and real-time plots of the test data monitored at each load step. As the specimen began to soften, indicated by flattening of the load-deflection plot, the load steps were applied based on a target deflection instead of a target load. The load steps were continued until failure of the connection.

3.4. TENSILE COUPON TESTS

Tensile coupon tests were conducted on the end-plate material used in the testing program. The standard tensile coupon specimens were prepared, measured and tested in accordance with ASTM A370 "*Standard Test Methods and Definitions for Mechanical Testing of Steel Products*". The yield strength was determined using a 0.2 percent offset of the recorded stress-strain relationship. The ultimate tensile strength and the total elongation were also determined. A summary of the tensile test results is shown in Table 3.1.

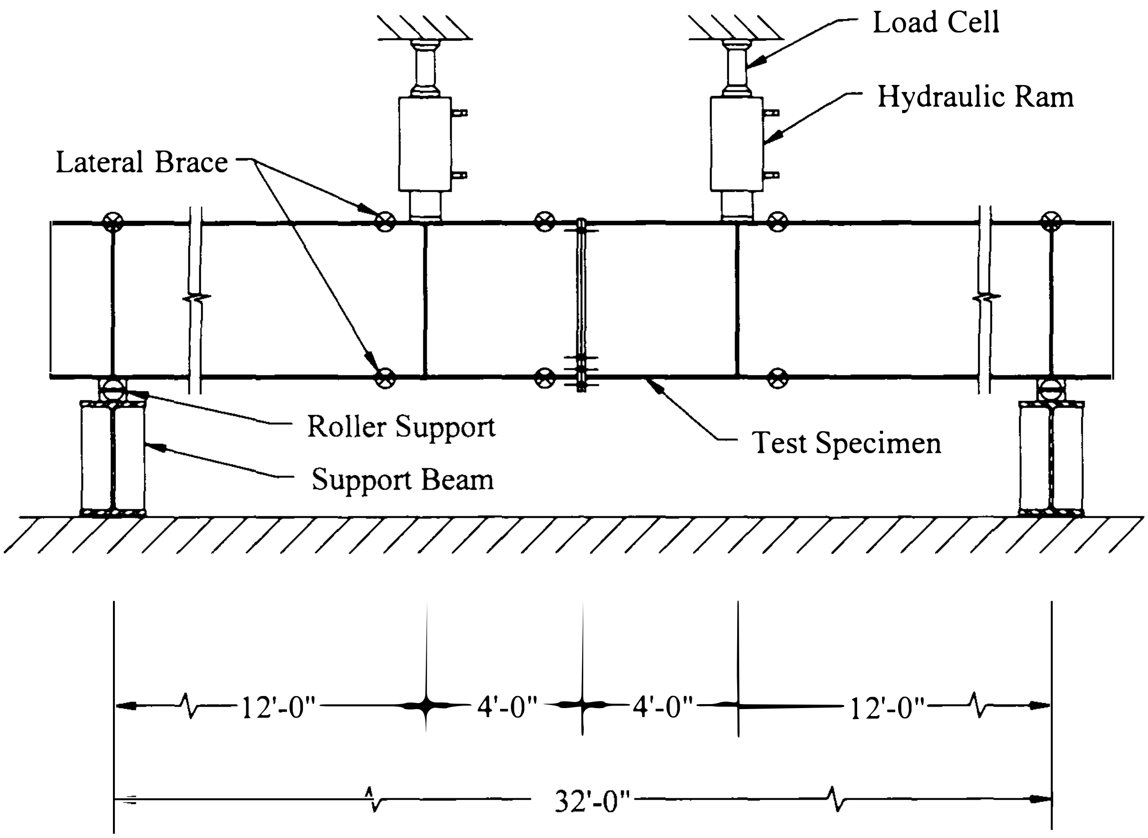


FIGURE 3.1: TEST SETUP

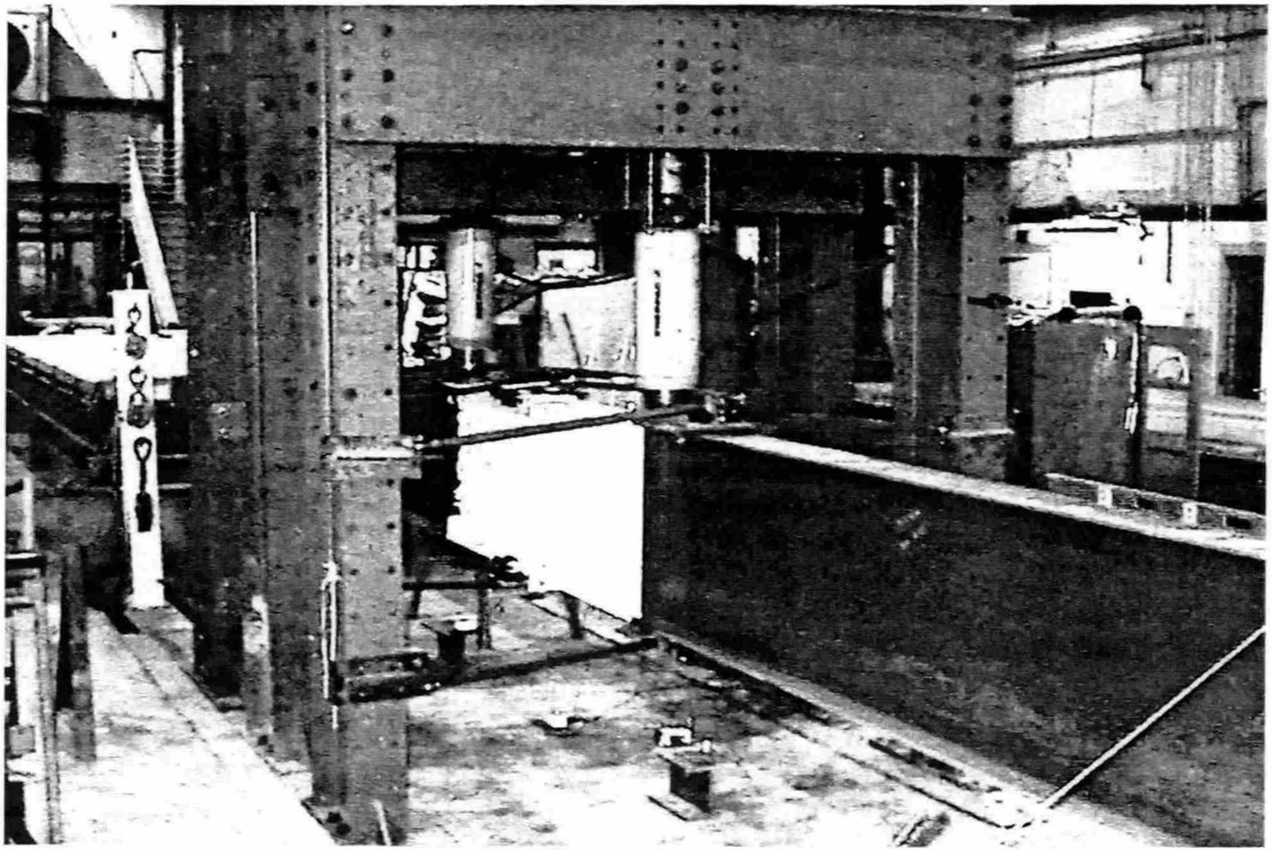


FIGURE 3.2: PHOTOGRAPH OF TEST SETUP

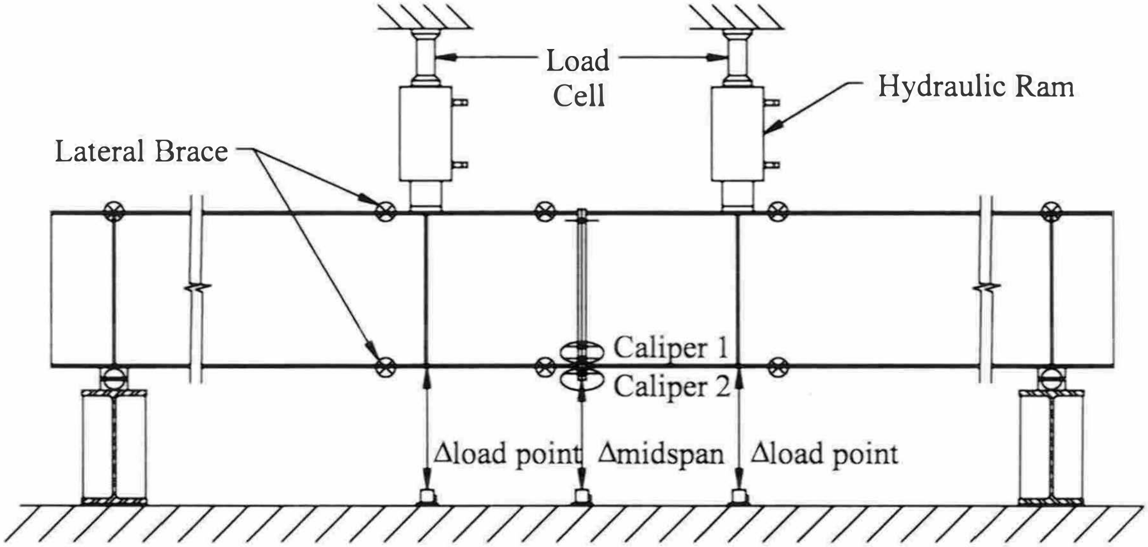


FIGURE 3.3: TEST INSTRUMENTATION

TABLE 3.1: Summary of Tensile Coupon Tests

Specimen	Coupon Number	Thickness (in.)	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation 8 in. Gage (%)	Average Yield Str. (ksi)
End-Plate A	1	0.378	61.7	86.2	23	62.0
	2	0.378	61.7	86.3	23	
	3	0.382	62.7	85.9	22	
End-Plate B	1	0.748	61.5	87.2	24	62.3
	2	0.753	63.0	87.1	26	
End-Plate C	1	0.496	61.3	85.2	25	60.7
	2	0.494	60.1	85.2	23	
End-Plate D	1	0.749	61.4	87.2	24	61.3
	2	0.749	61.2	87.2	22	

4. EXPERIMENTAL RESULTS

4.1. OVERVIEW

Detailed results for each test are included in Appendices B through G. Each appendix includes a test summary sheet, analysis calculation sheet, test plots, and photographs of the specimens before and after failure. The test summary sheet includes the measured specimen dimensions, calculated strengths, and experimental results. The calculation sheet shows detailed calculations using the design methods included in Appendix A.

The first plot included in the appendices shows the applied midspan moment versus midspan vertical deflection. The small additional moment induced by the weight of the testing apparatus is included in data shown on the plots. However, the moment due to self-weight of the specimen is not included. The theoretical elastic stiffness is plotted along with the experimental data. The theoretical stiffness was calculated using the following:

$$\Delta_{Theoretical} = \frac{Pa}{24EI}\left(3L^2 - 4a^2\right)$$

Where P is the applied hydraulic ram load, a is the distance from the applied load to the end support, L is the span of the test beam, E is the modulus of elasticity (29,000 ksi), and I is the moment of inertia of the test specimen.

The second plot included in the appendices shows the applied midspan moment versus end-plate separation. The end-plate separation measured by each of the calipers is shown. A bilinear curve fit of the end-plate separation data is also shown. The first line represents the initial elastic stiffness of the plates and the second line represents the yield plateau. The intersection of the two lines is considered the yield moment. In a thin plate test, where the connection strength is controlled by the end-plate strength, the yield moment should correlate closely with the calculated moment strength of the end-plate, M_{pl}. In a thick plate test, where the strength is controlled by bolt tension rupture with no prying, the yield moment indicates the onset of bolt yielding.

The third plot included in the appendices shows the bolt forces versus the applied midspan moment (not included for tests B1 and D1). Data points for the instrumented bolts used in each test are included on the same plot to allow easy comparison. The initial bolt force value is the "snug-tight" pretension value recorded prior to the application of load. The bolt forces shown are based on the bolt strain reading multiplied by an elastic load calibration coefficient. Once the bolts reach their yield strength (the proportional limit), the bolt force readings are no longer valid. The LRFD (AISC, 1999) specified bolt proof load, $P_t = A_{bolt} F_{y\ bolt}$, is shown on each of the plots. Once the bolt forces exceed this value, they have yielded and the bolt forces shown indicate the relative amount of bolt strain but not the correct bolt tension force.

Photographs of the test specimen are also included in the appendices. The first photograph in each appendix is the specimen before testing. The subsequent photographs are the specimen at maximum load or after failure.

4.2. CONNECTION PERFORMANCE

A summary of the test results is shown in Table 4.1. The predicted strength based on measured data and the observed experimental strengths are shown. In addition, ratios of the observed strengths to the predicted strengths are shown. A controlling strength ratio greater than one indicates a conservative prediction, and a controlling strength ratio less than one indicates an unconservative prediction.

4.2.1. THIN PLATE TESTS

The results from the two thin plate tests (Test A–MRE 1/2-3/4-3/8-30 and Test C–MRE 1/2-3/4-1/2-30) show that the thin plate design procedures for the end-plate and bolt strength are conservative. Thin plate tests have two failure modes. One is end-plate failure which is identified by yielding of the end-plate and non-linear (inelastic) end-plate separation. The other failure mode is bolt tension rupture due to a combination of direct bolt tension and prying forces.

The initial failure of Test A occurred in the end-plate. The ratio of the yield moment to the end-plate strength is 1.29, which indicates a conservative strength prediction. Subsequent to the end-plate failure, the specimen was loaded until the bolts failed in tension rupture. The ratio of the maximum applied moment to the bolt strength with maximum prying, M_q, is 1.61, indicating a conservative strength prediction.

The performance of Test C was similar to Test A. The initial failure occurred in the end-plate, resulting in a yield moment to end-plate strength ratio of 1.15. Loading of the specimen was continued until the bolts failed in tension rupture. This resulted in a ratio of the maximum applied moment to bolt strength with maximum prying, M_q, of 1.52. The predicted failure mode of Test C was bolt rupture with maximum prying, but the experimental results show that the end-end-plate failed prior to the bolts. This occurred because the bolt force design procedure is more conservative than the end-plate design procedure.

4.2.2. THICK PLATE TESTS

The results from the four thick plate tests (Test B-MRE 1/2-3/4-3/4-30, Test B1-MRE 1/2-3/4-3/4-30, Test D-MRE 1/2-3/4-3/4-30, and Test D1-MRE 1/2-3/4-3/4-30) show that the thick plate design procedures for the end-plate and bolt strength are conservative. The thick plate tests have only one failure mode, bolt tension rupture with no prying forces. For the thick plate tests, the experimental yield moment only indicates the onset of yielding in the bolts and not end-plate failure. The yield moment to end-plate strength ratios indicate the separation between initial bolt yielding and the predicted end-plate strength. These ratios should always be lower than one and do not indicate an unconservative prediction.

The four thick plate tests resulted in bolt tension rupture. No yielding of the end-plates was observed. The ratios of the maximum applied moment to predicted bolt strength with no prying ranged from 0.97 (only slightly unconservative) to 1.13. The slightly unconservative result from Test D1 (0.97) is considered acceptable because the AISC LRFD resistance factor, ϕ, for bolt tension is 0.75. The 0.75 strength reduction will reduce the strength considerably below the level of the observed 3 percent overstress.

Thick plate connection specimens utilizing both A325 and A490 bolts were tested. The observed to predicted strength ratios for the two A325 tests (Test B-MRE 1/2-3/4-3/4-30, Test D-MRE 1/2-3/4-3/4-30) are 1.13 and 1.09. The strength ratios for the two A490 tests (Test B1-MRE 1/2-3/4-3/4-30, Test D1-MRE 1/2-3/4-3/4-30) are 1.06 and 0.97. A comparison of the applied moment versus end-plate separation plots shows that the A325 connections exhibited larger plate separations prior to failure. The higher strength ratios and the higher plate separations indicate the A325 connections exhibited slightly more ductility than the A490 connections.

The four thick plate tests investigated, along with other parameters, the effect of a large the inner pitch distance. Two tests (Test B-MRE 1/2-3/4-3/4-30, Test B1-MRE 1/2-3/4-3/4-30) were conducted with a standard inner pitch distance and two tests (Test D-MRE 1/2-3/4-3/4-30, Test

D1-MRE 1/2-3/4-3/4-30) were conducted with a large inner pitch distance. The observed to predicted strength ratios for the specimens with the standard inner pitch distance were 1.13 and 1.06. The strength ratios for the specimens with the large inner pitch distance were 1.09 and 0.97. This indicates a 4 percent decrease in strength was observed for the large inner pitch connections utilizing A325 bolts. The large inner pitch distance connections utilizing A490 bolts have a decrease in the strength of 9 percent. This indicates that the decrease in strength of the connections with a large inner pitch distance is a function of the bolt grade, and therefore the bolt ductility.

TABLE 4.1: Summary of Test Results

Test Identification	Predicted			Experimental			Strength Ratios	
	M_{pl} (k-ft)	M_n (k-ft)	Failure Mode	M_y (k-ft)	M_{max} (k-ft)	Failure Mode	M_y / M_{pl}	M_{max} / M_n
Test A - MRE 1/2-3/4-3/8-30	256.6	256.6	EP Yielding	330.0	462.1	EP Yielding / Bolt Rupture	**1.29**	1.61 *
Test B - MRE 1/2-3/4-3/4-30	994.7	561.9	Bolt Rupture	540.0	633.3	Bolt Tension Rupture	0.54	**1.13**
Test B1 - MRE 1/2-3/4-3/4-30	994.7	705.5	Bolt Rupture	640.0	749.9	Bolt Tension Rupture	0.64	**1.06**
Test C - MRE 1/2-3/4-1/2-30	353.0	316.2	Bolt Rupture w/Prying	405.0	482.0	EP Yielding / Bolt Rupture	1.15	**1.52**
Test D - MRE 1/2-3/4-3/4-30	825.3	513.0	Bolt Rupture	500.0	558.7	Bolt Tension Rupture	0.61	**1.09**
Test D1 - MRE 1/2-3/4-3/4-30	825.3	644.1	Bolt Rupture	450.0	622.8	Bolt Tension Rupture	0.55	**0.97**

Notes: 1. The **bold type** strength ratios are the ***predicted*** controlling ratios

2. The shaded strength ratios are the ***observed*** controlling ratios

3. * indicates that the ratio shown is M_{max} / M_q instead of M_{max} / M_n

5. SUMMARY AND CONCLUSIONS

Six multiple row extended end-plate moment connection tests were conducted to investigate the moment strength of the connections and to validate the current design procedures presented in the AISC Design Guide (Murray and Shoemaker, 2002). The end-plate thickness, inner pitch distance. and bolt material (grade) were varied to determine the effects on the connection strength.

Based on the analysis of the test results, the following conclusions are presented:

- The design procedures presented in the AISC Design Guide (Murray and Shoemaker, 2002) conservatively predict the strength of MRE 1/2 end-plate moment connections. The strength predictions are adequate for MRE 1/2 end-plate connections utilizing A325 or A490 bolts with a standard or a large inner pitch distance.
- MRE 1/2 end-plate connections utilizing A325 bolts are slightly more ductile than the same connections utilizing A490 bolts.
- A large inner pitch distance slightly decreases the strength ratio of thick plate MRE 1/2 end-plate connections.
- The decrease in the strength ratio of thick plate MRE 1/2 end-plate connections with a large inner pitch distance is dependant on the type of bolt used, A325 or A490. The less ductile A490 bolts provide a lower strength ratio.

6. REFERENCES

AISC, (1999). *Load and Resistance Factor Design Specification for Structural Steel Buildings*, American Institute of Steel Construction, Chicago, IL.

Murray, T. M., and Shoemaker, W. L. (2002). *Flush and Extended Multiple Row Moment End-Plate Connections*, Design Guide Series 16, American Institute of Steel Construction, Chicago, IL (in press).

APPENDIX A

MRE 1/2 END-PLATE MOMENT CONNECTION

DESIGN PROCEDURE

FIGURE A-1: END-PLATE ANALYSIS PROCEDURE FLOWCHART

BOLTED END-PLATE CONNECTION ANALYSIS

Given: End-plate thickness, Bolt diameter, End-plate and beam geometry, Material properties
Find: Connection Moment Strength

Start

For extended connection: $\gamma_r = 1.00$
Calculate Y from Table A-1

Connection Strength - End-Plate Yielding

$M_{pl} = F_{py} t_p^2 Y$

where: F_{py} = end-plate material yield stress
t_p = end-plate thickness

Connection Strength – Bolt Rupture (No Prying Action)

$M_{np} = [\, 2 P_t (\Sigma d_n)]$

where: $P_t = A_b F_t = (\pi d_b^2 /4) F_t$
F_t = nominal tensile strength of bolts
d_b = nominal bolt diameter
d_n = distance from centerline of compression flange to the n^th^ bolt row

$M_{np} < 0.9 M_{pl}$

Yes:

Thick Plate Behavior
Controlled by Bolt Rupture
(no prying action)

$$\phi M_n = \min \begin{vmatrix} \phi M_{np} \\ \phi_b M_{pl} / \gamma_r \end{vmatrix}$$

where: $\phi = 0.75$, $\phi_b = 0.9$

End of procedure

No:

Thin Plate Behavior
(w/prying action)

Go to Page 2

BOLTED END-PLATE CONNECTION ANALYSIS (cont'd)

From Page 1

Thin Plate Behavior (w/prying action)

Bolt Prying Force for Inside Bolts

$$Q_{max,i} = \frac{w' t_p^2}{4 a_i} \sqrt{F_{py}^2 - 3\left(\frac{F_i'}{w' t_p}\right)^2}$$

where: $w' = b_p/2 - (d_b + 1/16)$
d_b = diameter of bolt
t_p = end-plate thickness
$a_i = 3.682\,(t_p / d_b)^3 - 0.085$
F_{py} = end-plate material yield stress
$F_i' = [t_p^2\, F_{py}\, (0.85\, b_p / 2 + 0.80\, w') + \pi\, d_b^3\, F_t / 8] / (4\, p_{f,i})$
F_t = nominal tensile strength of bolts

Bolt Prying Force for Outer Bolts

$$Q_{max,o} = \frac{w' t_p^2}{4 a_o} \sqrt{F_{py}^2 - 3\left(\frac{F_o'}{w' t_p}\right)^2}$$

where: $w' = b_p/2 - (d_b + 1/16)$
d_b = diameter of bolt
t_p = end-plate thickness
$a_o = \min \left| \begin{array}{l} 3.682\,(t_p / d_b)^3 - 0.085 \\ p_{ext} - p_{f,o} \end{array} \right.$
F_{py} = end-plate material yield stress
$F'_o = [t_p^2\, F_{py}\, (0.85\, b_p / 2 + 0.80\, w') + \pi\, d_b^3\, F_t / 8] / (4\, p_{f,o})$
F_t = nominal tensile strength of bolts

Go to Page 3

BOLTED END-PLATE CONNECTION ANALYSIS (cont'd)

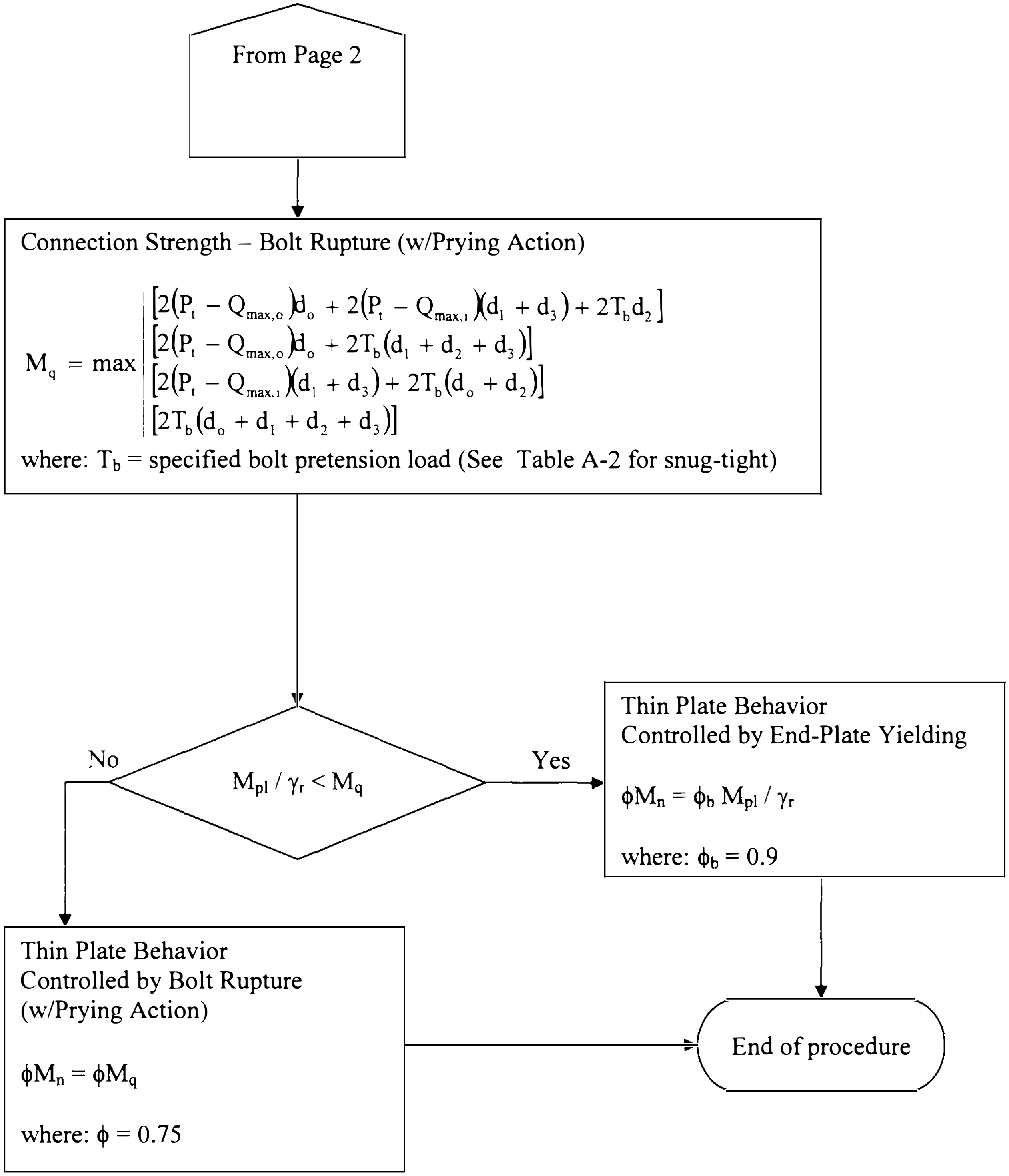
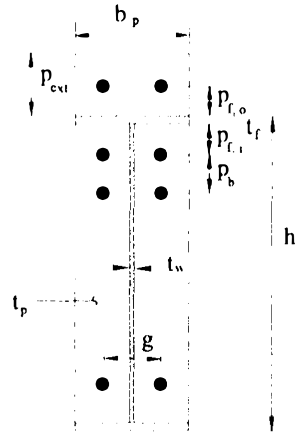
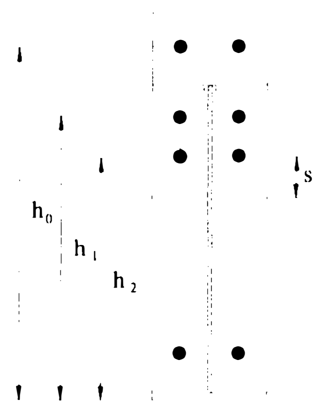
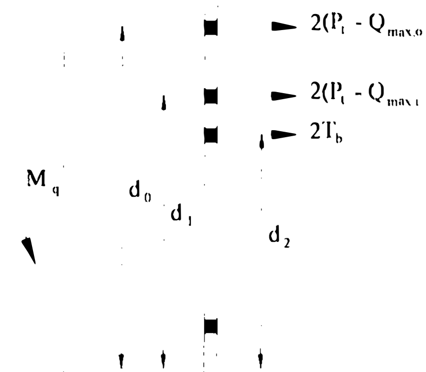


TABLE A-1 SUMMARY OF MULTIPLE ROW EXTENDED 1/2 MOMENT END-PLATE ANALYSIS

Geometry	Yield-Line Mechanism	Bolt Force Model
		

End-Plate Yield	$\phi M_n = \phi_b M_{pl} = \phi_b F_{py} t_p^2 Y$ $Y = \frac{b_p}{2}\left[h_1\left(\frac{1}{p_{f,i}}\right) + h_2\left(\frac{1}{s}\right) + h_0\left(\frac{1}{p_{f,o}}\right) - \frac{1}{2}\right] + \frac{2}{g}\left[h_1\left(p_{f,i} + 0.75p_b\right) + h_2\left(s + 0.25p_b\right)\right] + \frac{g}{2}$ $s = \frac{1}{2}\sqrt{b_p g}$ $\phi_b = 0.90$ Note: Use $p_{f,i} = s$, if $p_{f,i} > s$
Bolt Rupture w/Prying Action	$\phi M_n = \phi M_q = \max \begin{vmatrix} \phi[2(P_t - Q_{max,o})d_0 + 2(P_t - Q_{max,i})d_1 + 2(T_b)d_2] \\ \phi[2(P_t - Q_{max,o})d_0 + 2(T_b)(d_1 + d_2)] \\ \phi[2(P_t - Q_{max,i})d_1 + 2(T_b)(d_0 + d_2)] \\ \phi[2(T_b)(d_0 + d_1 + d_2)] \end{vmatrix}$ $\phi = 0.75$
Bolt Rupture No Prying Action	$\phi M_n = \phi M_{np} = \phi[2(P_t)(d_0 + d_1 + d_2)]$ $\phi = 0.75$

TABLE A-2: SUMMARY OF BOLT FORCE PREDICTION EQUATIONS

<table>
<tr><td>Bolt Proof Load</td><td colspan="2">$$P_t = A_b F_t = \frac{\pi d_b^2}{4}(F_t)$$
F_t = nominal tensile strength of bolts = 90 ksi for A325 and 113 ksi for A490 bolts, as specified in Table J3.2, AISC LRFD Specification.</td></tr>
<tr><td>Bolt Pretension</td><td colspan="2">T_b = specified force in Table J3.1, AISC LRFD Specification for fully tightened bolts
For snug-tightened bolts, T_b is taken as the following percentage of the AISC specified pretension force:
$d_b \le 5/8$ in., 75% of Table J3.1, AISC LRFD
$d_b = 3/4$ in., 50% of Table J3.1, AISC LRFD
$d_b = 7/8$ in., 37.5% of Table J3.1, AISC LRFD
$d_b \ge 1$ in., 25% of Table J3.1, AISC LRFD</td></tr>
<tr><td rowspan="2">Maximum Prying Force[1]</td><td>Inside Bolt Rows</td><td>Outside Bolt Rows</td></tr>
<tr><td>$$Q_{max.i} = \frac{w' t_p^2}{4a_i}\sqrt{F_{py}^2 - 3\left(\frac{F_i'}{w' t_p}\right)^2}$$
$$a_i = 3.682\left(\frac{t_p}{d_b}\right)^3 - 0.085$$
$w' = b_p/2 - (d_b + 1/16)$
$$F_i' = \frac{t_p^2 F_{py}\left(0.85\frac{b_p}{2} + 0.80w'\right) + \frac{\pi d_b^3 F_t}{8}}{4p_{f.i}}$$</td><td>$$Q_{max.o} = \frac{w' t_p^2}{4a_o}\sqrt{F_{py}^2 - 3\left(\frac{F_o'}{w' t_p}\right)^2}$$
$$a_o = \min\left\{ 3.682\left(\frac{t_p}{d_b}\right)^3 - 0.085,\; p_{ext} - p_{f.o} \right\}$$
$w' = b_p/2 - (d_b + 1/16)$
$$F_o' = \frac{t_p^2 F_{py}\left(0.85\frac{b_p}{2} + 0.80w'\right) + \frac{\pi d_b^3 F_t}{8}}{4p_{f.o}}$$</td></tr>
</table>

[1] If the radical in the expression for $Q_{max.i}$ or $Q_{max,o}$ is negative, combined flexural and shear yielding of the end-plate is the controlling limit state and the end-plate is not adequate for the specified moment.

APPENDIX B

TEST A – MRE 1/2-3/4-3/8-30

RESULTS

TEST SUMMARY

TEST NAME: Test A - MRE 1/2-3/4-3/8-30
TEST DATE: June 4, 2001

CONNECTION DESCRIPTION

TYPE:	Multiple Row Extended 1/2 (MRE 1/2)
NUMBER OF TENSION BOLTS:	6 (2 outside, 4 inside)
NUMBER OF COMPRESSION BOLTS:	2

BEAM DATA

SECTION TYPE:	Built-Up
DEPTH, h:	30.0 in.
FLANGE WIDTH, b_f:	8.0 in.
FLANGE THICKNESS, t_f:	0.496 in.
WEB THICKNESS, t_w:	0.375 in.
MOMENT OF INERTIA, I:	2500 in^4
NOMINAL YIELD STRESS, F_y:	50 ksi

END-PLATE DATA

END PLATE THICKNESS, t_p:	0.381 in.
END PLATE WIDTH, b_p:	8.0 in
END PLATE LENGTH, L_p:	33.0 in.
END-PLATE EXTENSION OUTSIDE FLANGE, p_{ext}:	2.56 in.
OUTER PITCH, BOLT TO FLANGE, p_{fo}:	1.29 in.
INNER PITCH, BOLT TO FLANGE, p_{fi}:	1.17 in.
INNER PITCH, BOLT TO BOLT, p_b:	2.24 in.
GAGE, g:	3.00 in
MEASURED YIELD STRESS, F_{yp}:	62.0 ksi

BOLT DATA

BOLT DIAMETER, d_b:	3/4 in.
BOLT LENGTH, L_b:	2.0 in.
BOLT TYPE:	ASTM A325
BOLT PRETENSION, T_b:	Snug Tight (Average: 14.6 kips/bolt)
NOMINAL BOLT YIELD STRENGTH, F_{yb}:	90.0 ksi

EXPERIMENTAL RESULTS

MAXIMUM APPLIED MOMENT, M_{max}:	462.1 k-ft
YIELD MOMENT (Based on plate separation), M_y:	330.0 k-ft
FAILURE MODE:	End-Plate Yielding / Bolt Tension Rupture

PREDICTED STRENGTHS

END-PLATE STRENGTH, M_{PL}:	256.6 k-ft
BOLT TENSION RUPTURE (w/o Prying), M_{NP}:	563.1 k-ft
BOLT TENSION RUPTURE (w/Prying), M_Q:	286.4 k-ft
CONTROLLING STRENGTH, M_n:	256.6 k-ft

Multiple Row Extended Unstiffened 1/2 End-Plate Connection Analysis

By: EAS
Date: 6/26/2001

Project Name: **MBMA**
Connection ID: **Test A - MRE1/2-3/4-3/8-30**

Plate Data

tp =	0.381	in.
Fyp =	62	ksi
bp =	8	in.
g =	3	in.
pfi =	1.17	in.
pfo =	1.29	in.
pext =	2.56	in.
pb =	2.24	in.

Member Data

Section: Build-up Section

h =	30	in.
bf =	8	in.
tf =	0.496	in.

Bolt Data

Material:	A325	
dia. =	0.75	in.
Ft =	90	ksi
Tb =	14.6	kips
(Tb @ 0.7xPt =	27.8	kips)

End-Plate Yielding (Mpl)

ϕ =	0.90					
γr =	1.00					
ho =	31.29	in.				
h1 =	28.33	in.				
h2 =	26.09					
s =	2.45	in.		c =	1.17	in.
Y =	234.50 +	106.19 +	1.50	=	342.2	
Mpl =	256.6	k-ft				
ϕMpl =	231.0	k-ft				

Bolt Rupture w/ Prying Action (Mq)

ϕ =	0.75								
Pt =	39.8	kips							
ai =	0.398	in.	ao = min(	0.398	1.270	) in. =		0.398	in.
wi' =	3.188	in.	wo' =	3.188	in.				
Fi' =	14.63	kips	Fo' =	13.27	kips				
Qimax =	16.98	kips	Qomax =	17.17	kips				
d1 =	28.09	in.	do =	31.04	in.		d2 =	25.85	in.
Mq =	max (	3436.6	2977.1	2940.7	2481.2	) in-kips =		286.4	k-ft
ϕMq =	214.8	k-ft							

Bolt Rupture w/o Prying Action (Mnp)

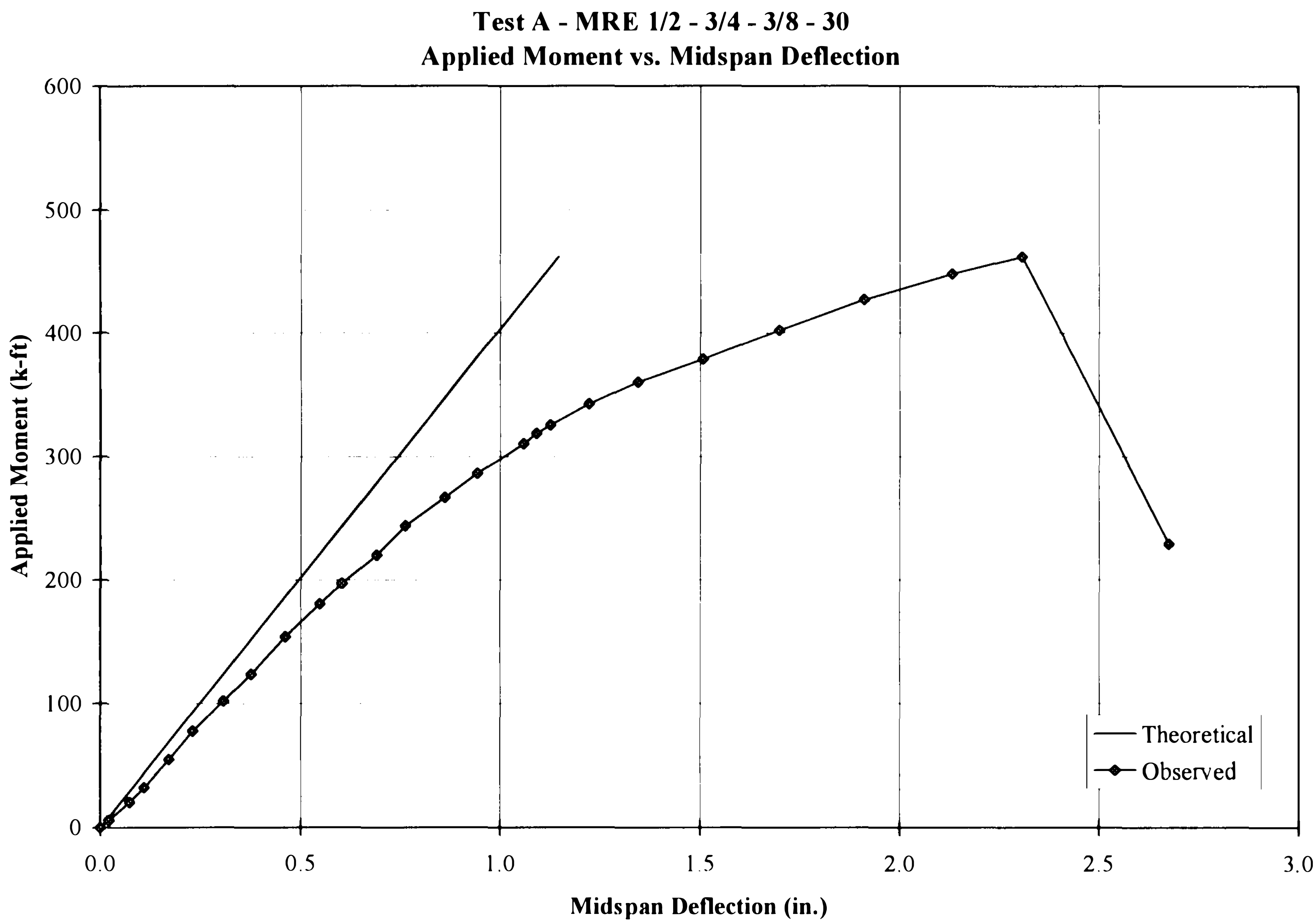
ϕ =	0.75	
Pt =	39.8	kips
do =	31.04	in.
d1 =	28.09	in.
d2 =	25.85	in.
Mnp =	563.1	k-ft
ϕMnp =	422.3	k-ft

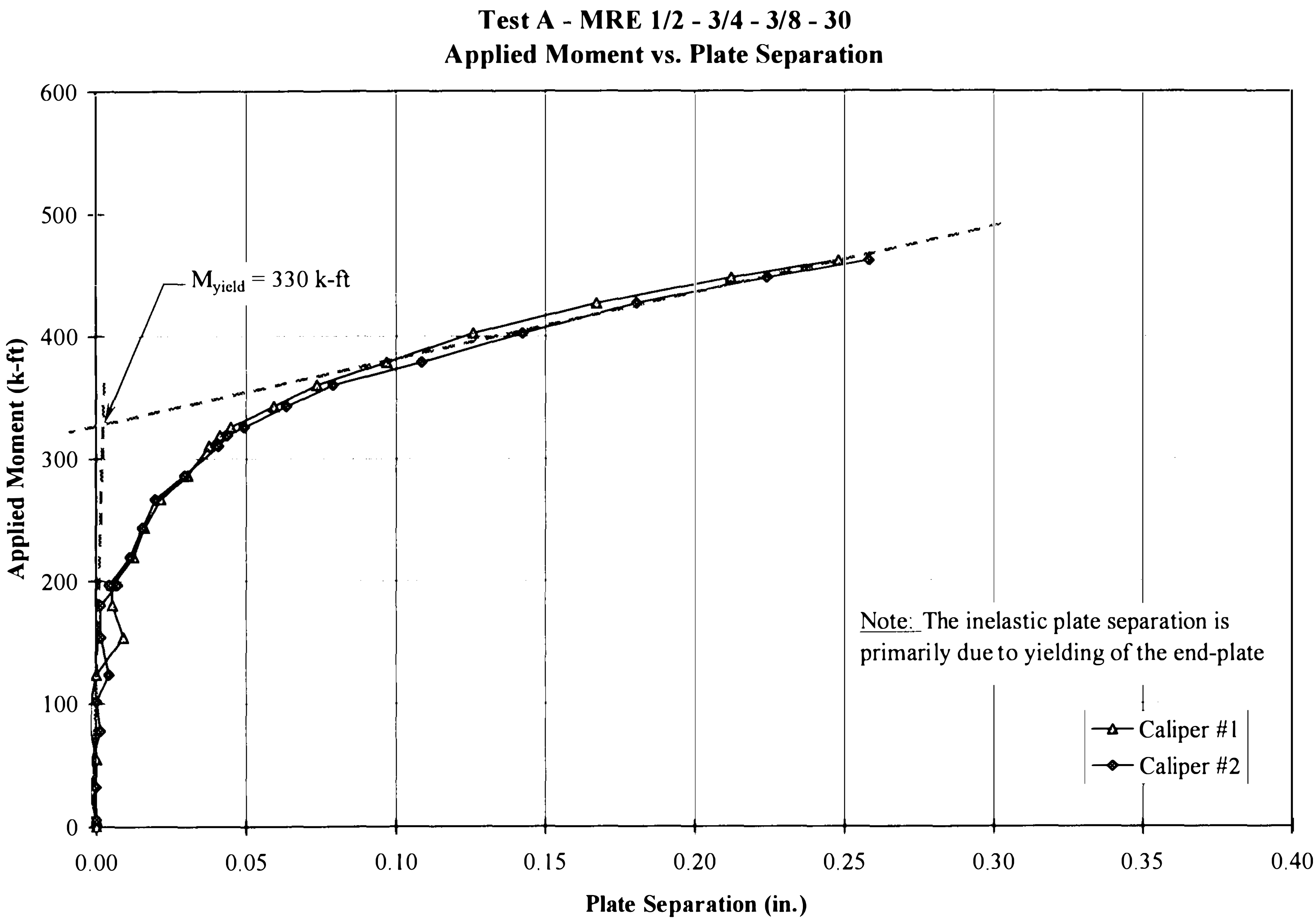
Summary

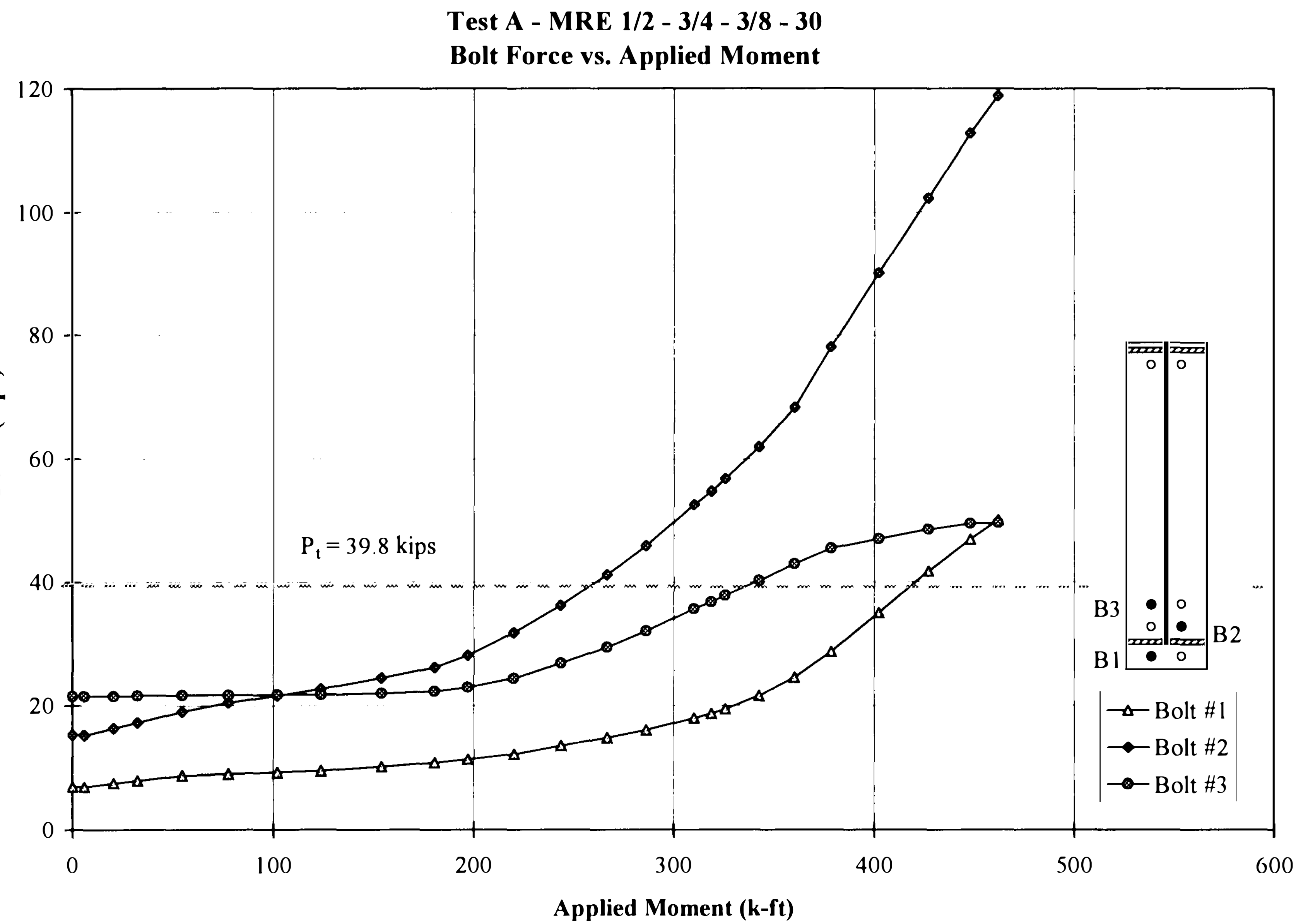
Mpl =	256.6	k-ft	< Mq ==> Mn = Mpl
0.9 Mpl =	231.0	k-ft	
Mq =	286.4	k-ft	
Mnp =	563.1	k-ft	

Mn =	**256.6**	**k-ft**
ϕMn =	**231.0**	**k-ft**

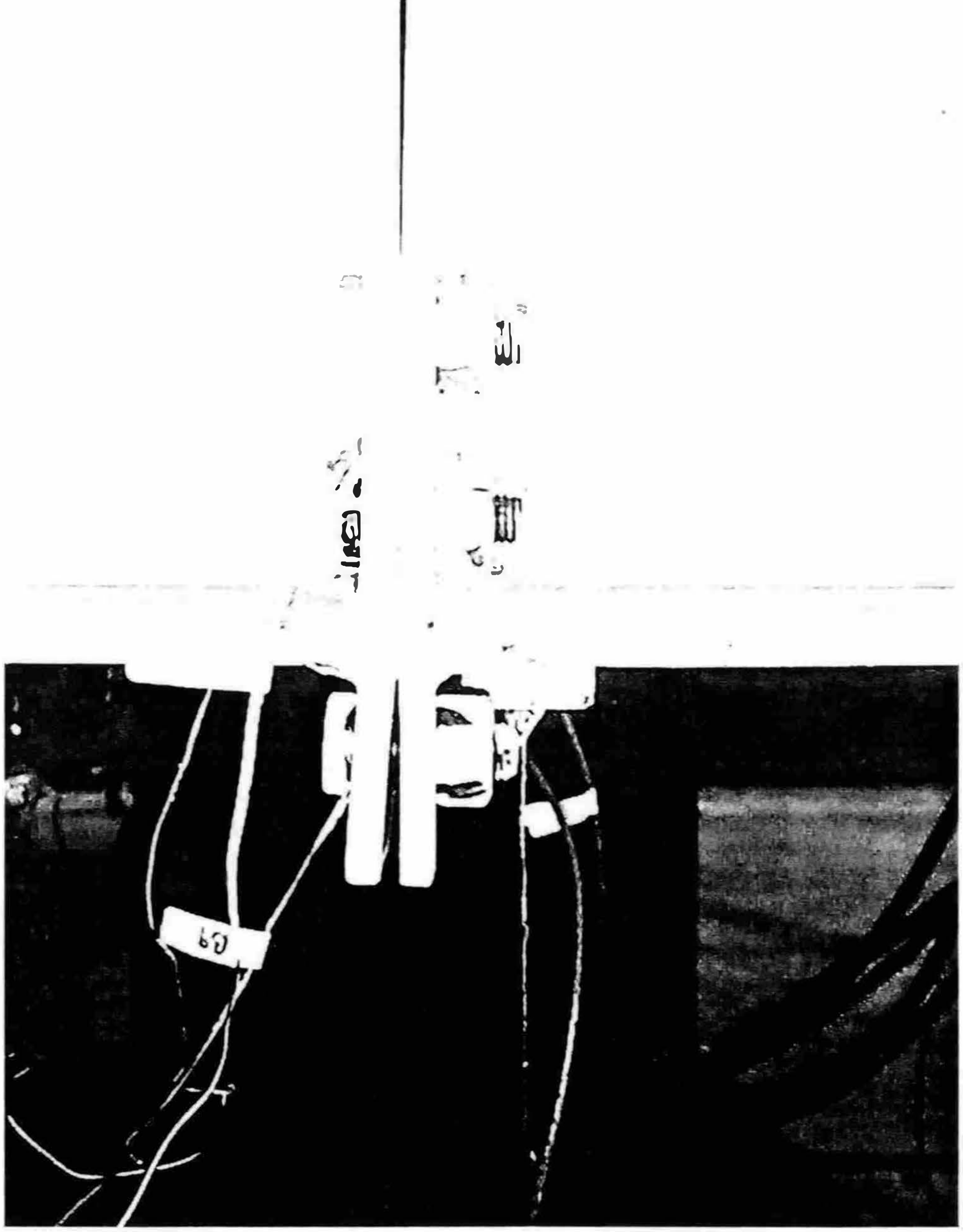
Plate Yielding Controls, Mpl

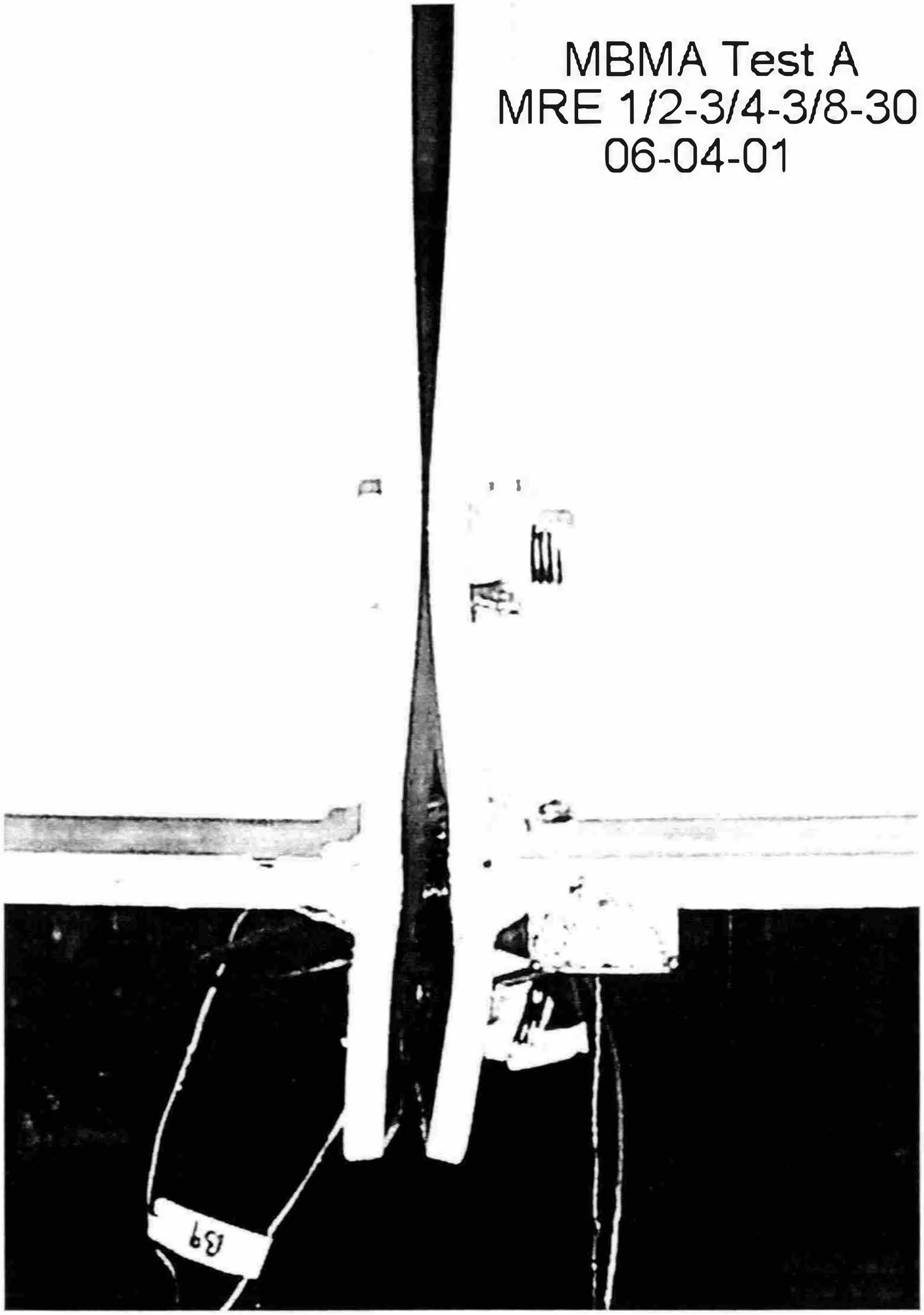

Test A - MRE 1/2 - 3/4 - 3/8 - 30
Applied Moment vs. Midspan Deflection
Applied Moment (k-ft)
Midspan Deflection (in.)
0
100
200
300
400
500
600
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Theoretical
Observed

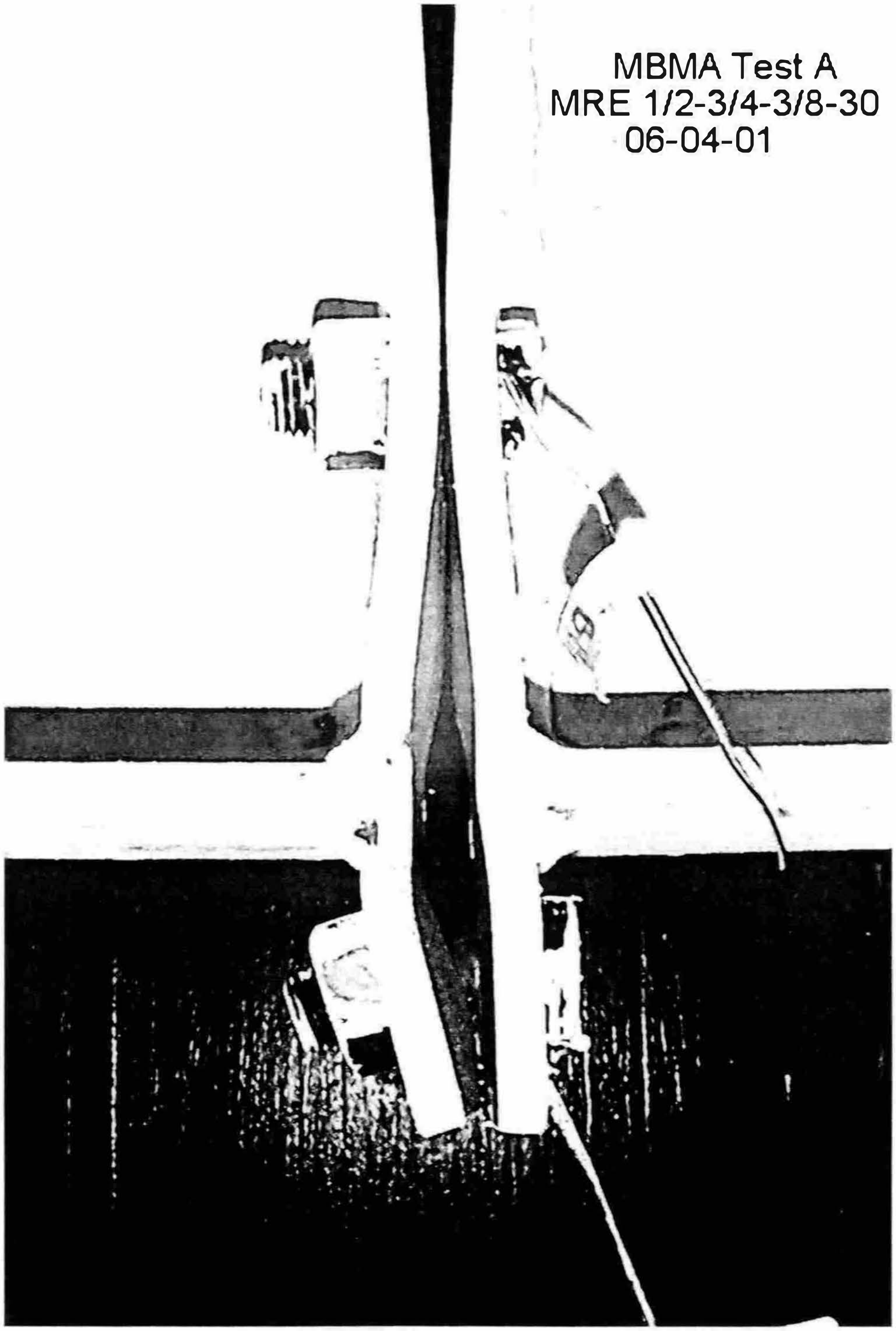

Test A - MRE 1/2 - 3/4 - 3/8 - 30
Applied Moment vs. Plate Separation
Applied Moment (k-ft)
Plate Separation (in.)
M_{yield} = 330 k-ft
Note: The inelastic plate separation is primarily due to yielding of the end-plate
Caliper #1
Caliper #2
600
500
400
300
200
100
0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40

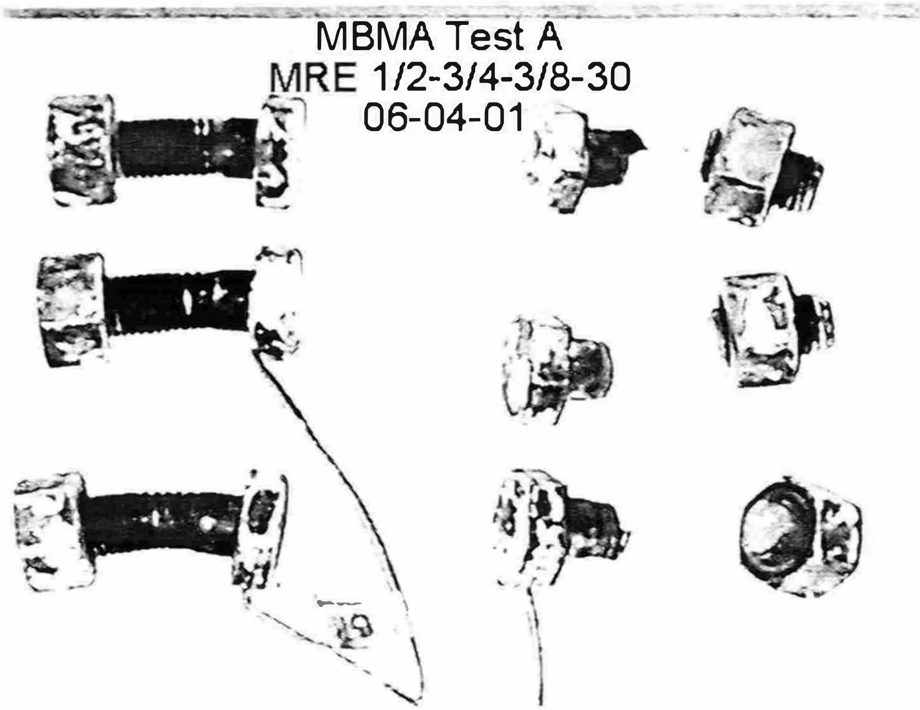

Test A - MRE 1/2 - 3/4 - 3/8 - 30
Bolt Force vs. Applied Moment
Bolt Force (kips)
Applied Moment (k-ft)
P_t = 39.8 kips
B3
B2
B1
Bolt #1
Bolt #2
Bolt #3
0
20
40
60
80
100
120
0
100
200
300
400
500
600

MBMA Test A
MRE 1/2-3/4-3/8-30
06-04-01




MBMA Test A
MRE 1/2-3/4-3/8-30
06-04-01


MBMA Test A
MRE 1/2-3/4-3/8-30
06-04-01


MBMA Test A
MRE 1/2-3/4-3/8-30
06-04-01

APPENDIX C

TEST B – MRE 1/2-3/4-3/4-30

RESULTS

TEST SUMMARY

TEST NAME: Test B - MRE 1/2-3/4-3/4-30
TEST DATE: June 5, 2001

CONNECTION DESCRIPTION

TYPE:	Multiple Row Extended 1/2 (MRE 1/2)
NUMBER OF TENSION BOLTS:	6 (2 outside, 4 inside)
NUMBER OF COMPRESSION BOLTS:	2

BEAM DATA

SECTION TYPE:	Built-Up
DEPTH, h:	30.0 in.
FLANGE WIDTH, b_f:	8.0 in.
FLANGE THICKNESS, t_f:	0.496 in.
WEB THICKNESS, t_w:	0.375 in.
MOMENT OF INERTIA, I:	2500 in^4
NOMINAL YIELD STRESS, F_y:	50 ksi

END-PLATE DATA

END PLATE THICKNESS, t_p:	0.751 in.
END PLATE WIDTH, b_p:	8.0 in.
END PLATE LENGTH, L_p:	33.0 in.
END-PLATE EXTENSION OUTSIDE FLANGE, p_{ext}:	2.56 in.
OUTER PITCH, BOLT TO FLANGE, p_{fo}:	1.25 in.
INNER PITCH, BOLT TO FLANGE, p_{fi}:	1.24 in.
INNER PITCH, BOLT TO BOLT, p_b:	2.24 in.
GAGE, g:	3.02 in.
MEASURED YIELD STRESS, F_{yp}:	62.3 ksi

BOLT DATA

BOLT DIAMETER, d_b:	3/4 in.
BOLT LENGTH, L_b:	2.5 in.
BOLT TYPE:	ASTM A325
BOLT PRETENSION, T_b:	Snug Tight (Average: 16.1 kips/bolt)
NOMINAL BOLT YIELD STRENGTH, F_{yb}:	90.0 ksi

EXPERIMENTAL RESULTS

MAXIMUM APPLIED MOMENT, M_{max}:	633.3 k-ft
YIELD MOMENT (Based on plate separation), M_y:	540.0 k-ft
FAILURE MODE:	Bolt Tension Rupture

PREDICTED STRENGTHS

END-PLATE STRENGTH, M_{PL}:	994.7 k-ft
BOLT TENSION RUPTURE (w/o Prying), M_{NP}:	561.9 k-ft
BOLT TENSION RUPTURE (w/Prying), M_Q:	335.1 k-ft
CONTROLLING STRENGTH, M_n:	561.9 k-ft

Multiple Row Extended Unstiffened 1/2 End-Plate Connection Analysis

By: EAS
Date: 6/26/2001

Project Name: MBMA
Connection ID: Test B - MRE1/2-3/4-3/4-30

Plate Data

tp =	0.751	in.
Fyp =	62.3	ksi
bp =	8	in.
g =	3.02	in.
pfi =	1.24	in.
pfo =	1.25	in.
pext =	2.56	in.
pb =	2.24	in.

Member Data

Section: Build-up Section

h =	30	in.
bf =	8	in.
tf =	0.496	in.

Bolt Data

Material:	A325	
dia. =	0.75	in.
Ft =	90	ksi
Tb =	16.1	kips
(Tb @ 0.7xPt =	27.8	kips)

End-Plate Yielding (Mpl)

ϕ =	0.90					
γr =	1.00					
ho =	31.25	in.				
h1 =	28.26	in.				
h2 =	26.02					
s =	2.46	in.		c =	1.24	in.
Y =	231.53 +	106.66 +	1.51	=	339.7	

Mpl =	994.7	k-ft
ϕMpl =	895.2	k-ft

Bolt Rupture w/ Prying Action (Mq)

ϕ =	0.75								
Pt =	39.8	kips							
ai =	3.612	in.	ao = min(	3.612	1.310	) in. =	1.310	in.	
wi' =	3.188	in.	wo' =	3.188	in.				
Fi' =	45.16	kips	Fo' =	44.80	kips				
Qimax =	6.60	kips	Qomax =	18.25	kips				
d1 =	28.02	in.	do =	31.00	in.		d2 =	25.78	in.

Mq =	max (	4021.5	3065.6	3686.3	2730.4	) in-kips =	335.1	k-ft
ϕMq =	251.3	k-ft						

Bolt Rupture w/o Prying Action (Mnp)

ϕ =	0.75	
Pt =	39.8	kips
do =	31.00	in.
d1 =	28.02	in.
d2 =	25.78	in.
Mnp =	561.9	k-ft
ϕMnp =	421.4	k-ft

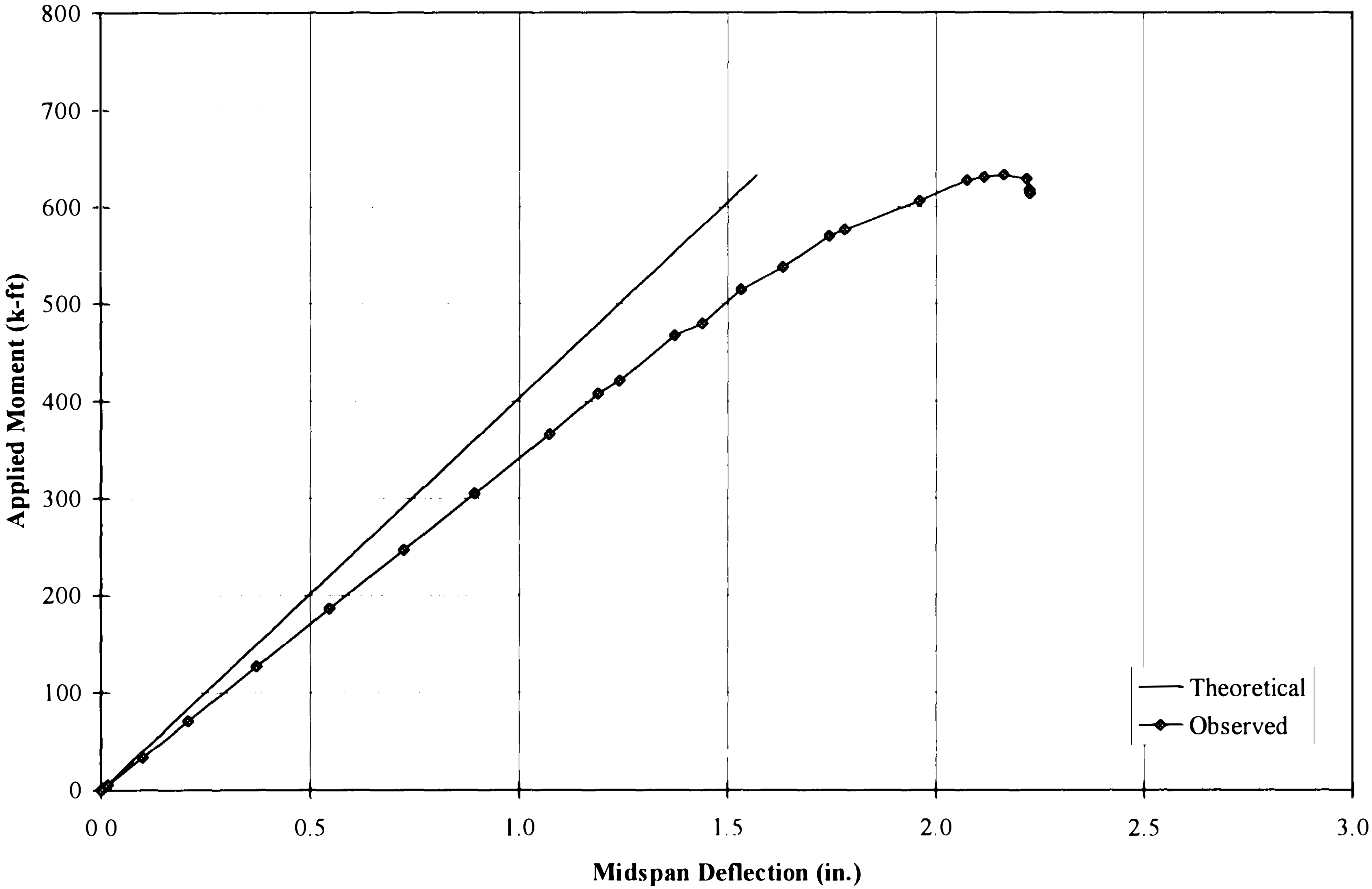
Summary

Mpl =	994.7	k-ft	
0.9 Mpl =	895.2	k-ft	
Mq =	335.1	k-ft	
Mnp =	561.9	k-ft	< 0.9 Mpl ==> Mn = Mnp

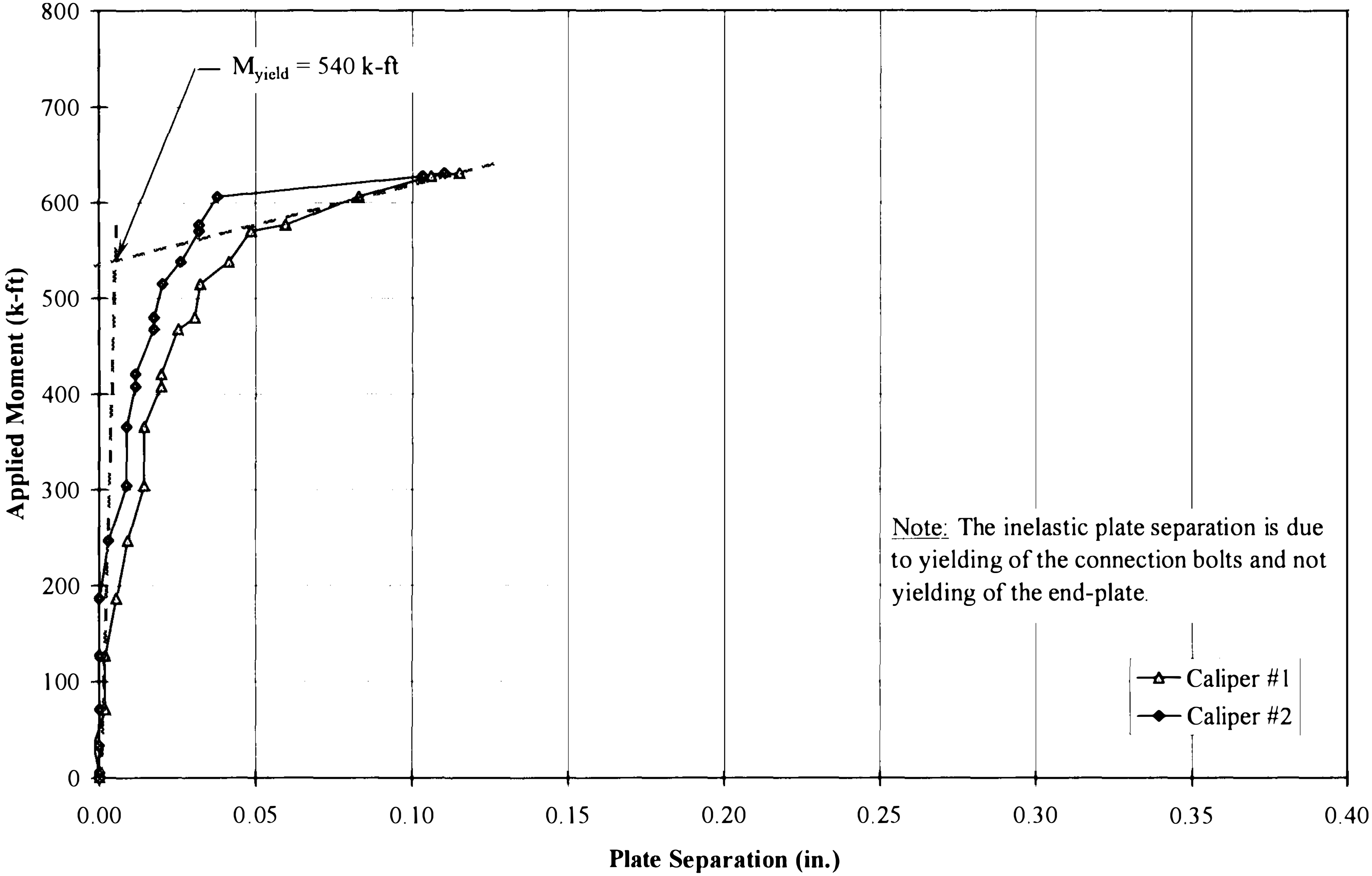
Mn =	**561.9**	**k-ft**
ϕMn =	**421.4**	**k-ft**

Bolt Tension Rupture w/o Prying Controls, Mnp

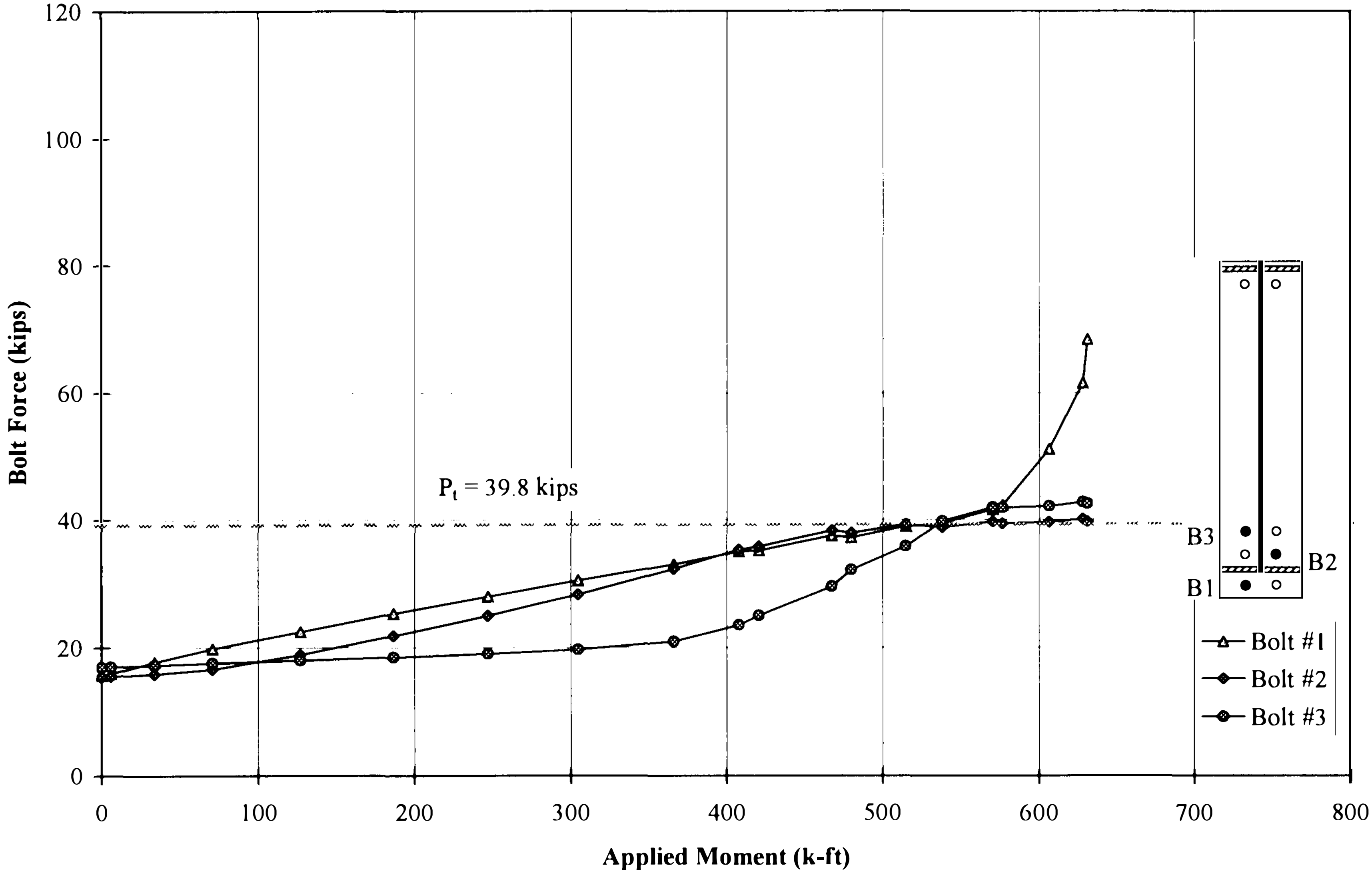
Test B - MRE 1/2 - 3/4 - 3/4 - 30
Applied Moment vs. Midspan Deflection



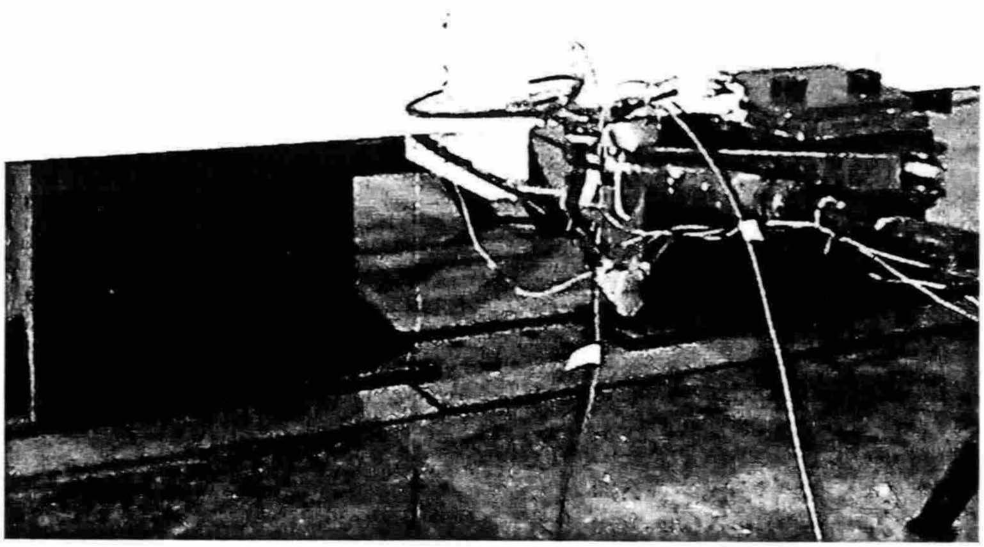
Test B - MRE 1/2 - 3/4 - 3/4 - 30
Applied Moment vs. Plate Separation



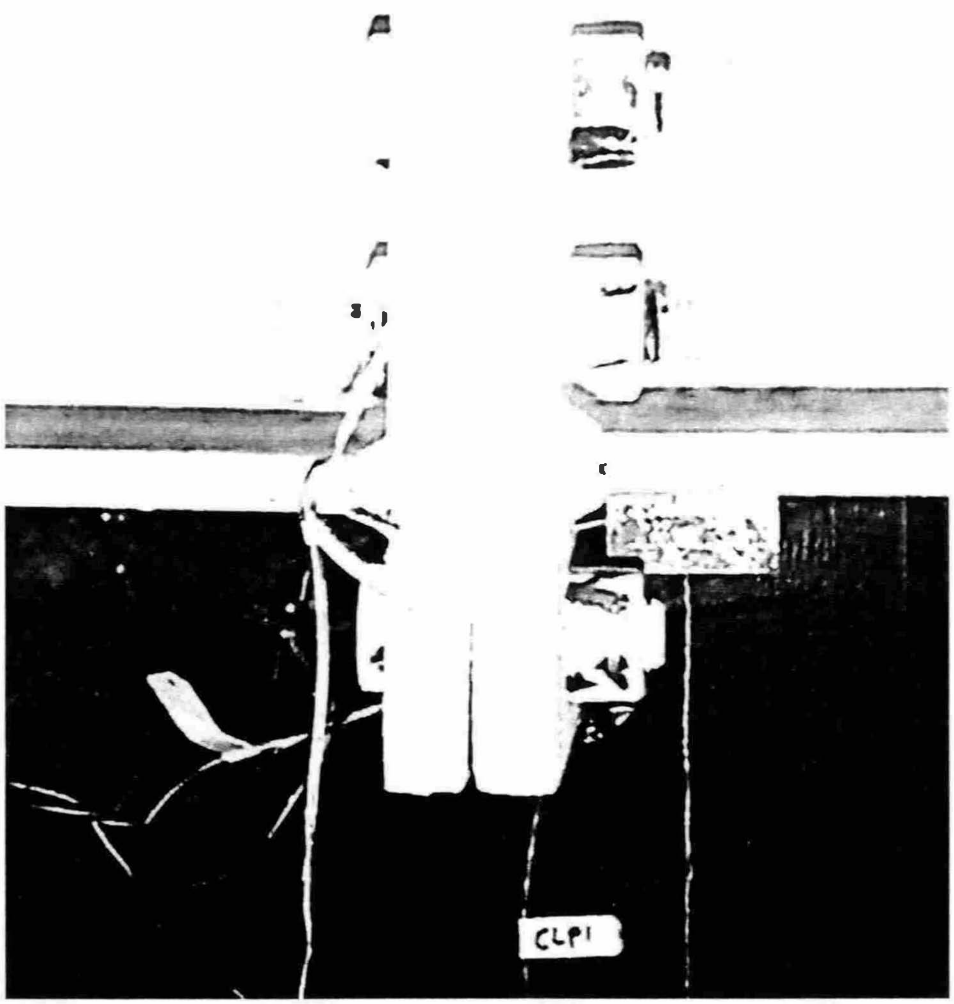
Test B - MRE 1/2 - 3/4 - 3/4 - 30
Bolt Force vs. Applied Moment

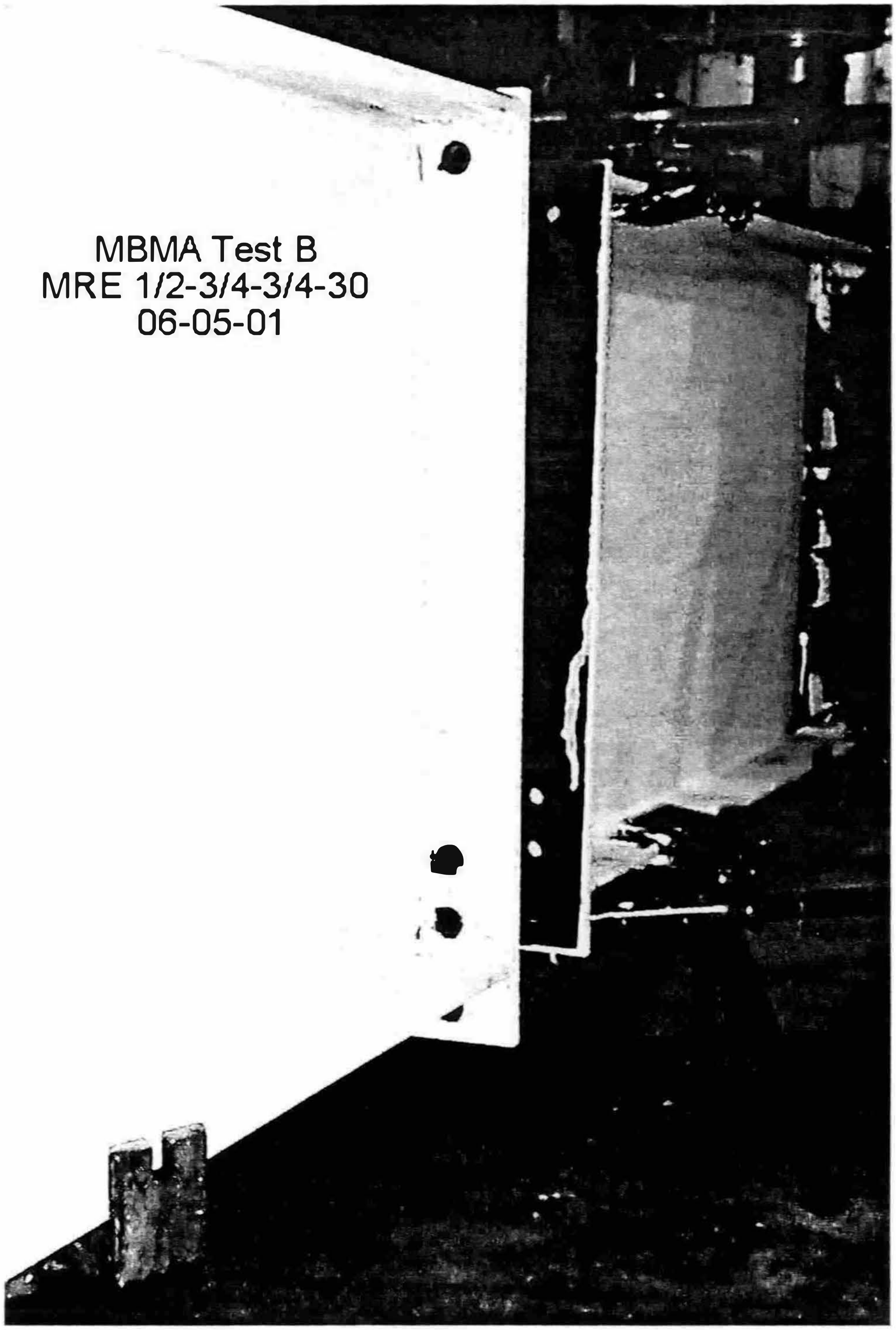


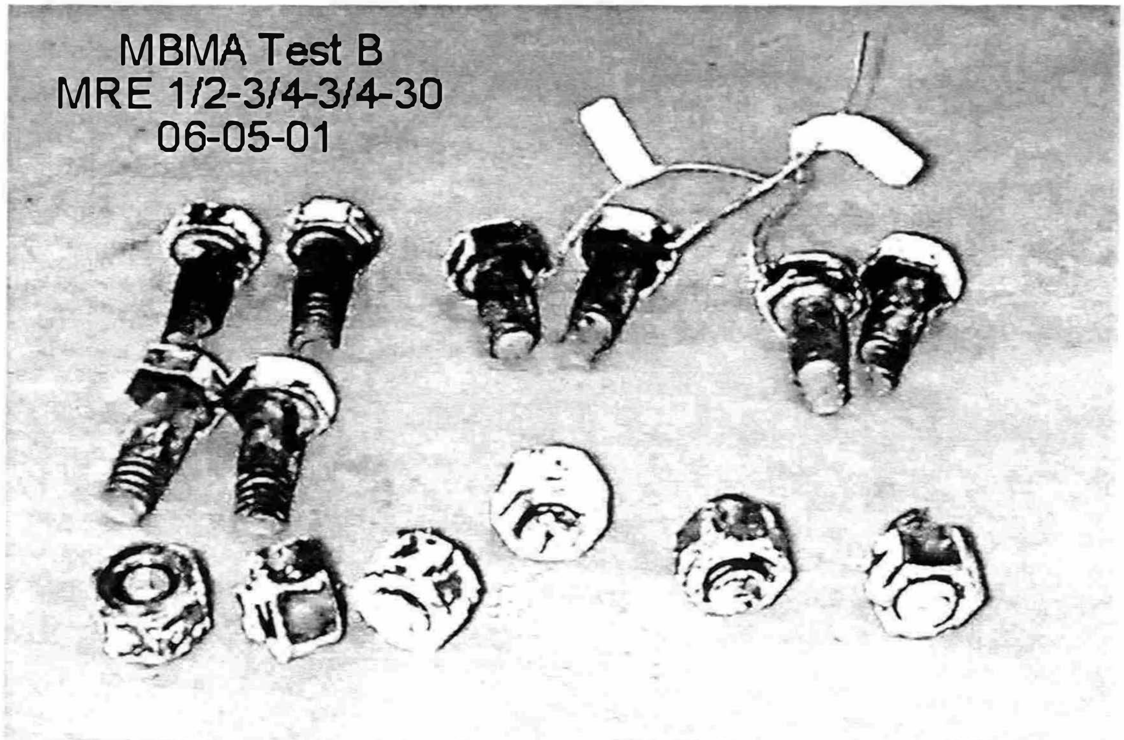
MBMA Test B
MRE 1/2-3/4-3/4-30
06-05-01



MBMA Test B
MRE 1/2-3/4-3/4-30
06-05-01




MBMA Test B
MRE 1/2-3/4-3/4-30
06-05-01


MBMA Test B
MRE 1/2-3/4-3/4-30
06-05-01

APPENDIX D

TEST B1 – MRE 1/2-3/4-3/4-30

RESULTS

TEST SUMMARY

TEST NAME: Test B1 - MRE 1/2-3/4-3/4-30
TEST DATE: June 6, 2001

CONNECTION DESCRIPTION

TYPE:	Multiple Row Extended 1/2 (MRE 1/2)
NUMBER OF TENSION BOLTS:	6 (2 outside, 4 inside)
NUMBER OF COMPRESSION BOLTS:	2

BEAM DATA

SECTION TYPE:	Built-Up
DEPTH, h:	30.0 in.
FLANGE WIDTH, b_f:	8.0 in.
FLANGE THICKNESS, t_f:	0.496 in.
WEB THICKNESS, t_w:	0.375 in.
MOMENT OF INERTIA, I:	2500 in.^{4}
NOMINAL YIELD STRESS, F_y:	50 ksi

END-PLATE DATA

END PLATE THICKNESS, t_p:	0.751 in.
END PLATE WIDTH, b_p:	8.0 in.
END PLATE LENGTH, L_p:	33.0 in.
END-PLATE EXTENSION OUTSIDE FLANGE, p_{ext}:	2.56 in.
OUTER PITCH, BOLT TO FLANGE, p_{fo}:	1.25 in.
INNER PITCH, BOLT TO FLANGE, p_{fi}:	1.24 in.
INNER PITCH, BOLT TO BOLT, p_b:	2.24 in.
GAGE, g:	3.02 in.
MEASURED YIELD STRESS, F_{yp}:	62.3 ksi

BOLT DATA

BOLT DIAMETER, d_b:	3/4 in.
BOLT LENGTH, L_b:	2.5 in.
BOLT TYPE:	ASTM A490
BOLT PRETENSION, T_b:	Snug Tight
NOMINAL BOLT YIELD STRENGTH, F_{yb}:	113.0 ksi

EXPERIMENTAL RESULTS

MAXIMUM APPLIED MOMENT, M_{max}:	749.9 k-ft
YIELD MOMENT (Based on plate separation), M_y:	640.0 k-ft
FAILURE MODE:	Bolt Tension Rupture

PREDICTED STRENGTHS

END-PLATE STRENGTH, M_{PL}:	994.7 k-ft
BOLT TENSION RUPTURE (w/o Prying), M_{NP}:	705.5 k-ft
BOLT TENSION RUPTURE (w/Prying), M_Q:	441.9 k-ft
CONTROLLING STRENGTH, M_n:	705.5 k-ft

Multiple Row Extended Unstiffened 1/2 End-Plate Connection Analysis

By: EAS
Date: 6/26/2001

Project Name: MBMA
Connection ID: Test B1 - MRE1/2-3/4-3/4-30 (A490 bolts)

Plate Data

tp =	0.751	in.
Fyp =	62.3	ksi
bp =	8	in.
g =	3.02	in.
pfi =	1.24	in.
pfo =	1.25	in.
pext =	2.56	in.
pb =	2.24	in.

Member Data

Section: Build-up Section

h =	30	in.
bf =	8	in.
tf =	0.496	in.

Bolt Data

Material:	A490	
dia. =	0.75	in.
Ft =	113	ksi
Tb =	17.5	kips
(Tb @ 0.7xPt =	34.9	kips)

End-Plate Yielding (Mpl)

ϕ =	0.90					
γr =	1.00					
ho =	31.25	in.				
h1 =	28.26	in.				
h2 =	26.02					
s =	2.46	in.		c =	1.24	in.
Y =	231.53 +	106.66 +	1.51	=	339.7	
Mpl =	994.7	k-ft				
ϕMpl =	895.2	k-ft				

Bolt Rupture w/ Prying Action (Mq)

ϕ =	0.75							
Pt =	49.9	kips						
ai =	3.612	in.	ao = min(	3.612	1.310	) in. =	1.310	in.
wi' =	3.188	in.	wo' =	3.188	in.			
Fi' =	45.92	kips	Fo' =	45.56	kips			
Qimax =	6.56	kips	Qomax =	18.14	kips			
d1 =	28.02	in.	do =	31.00	in.	d2 =	25.78	in.

Mq =	max (	5302.7	3853.5	4417.0	2967.8	) in-kips =	441.9	k-ft
ϕMq =	331.4	k-ft						

Bolt Rupture w/o Prying Action (Mnp)

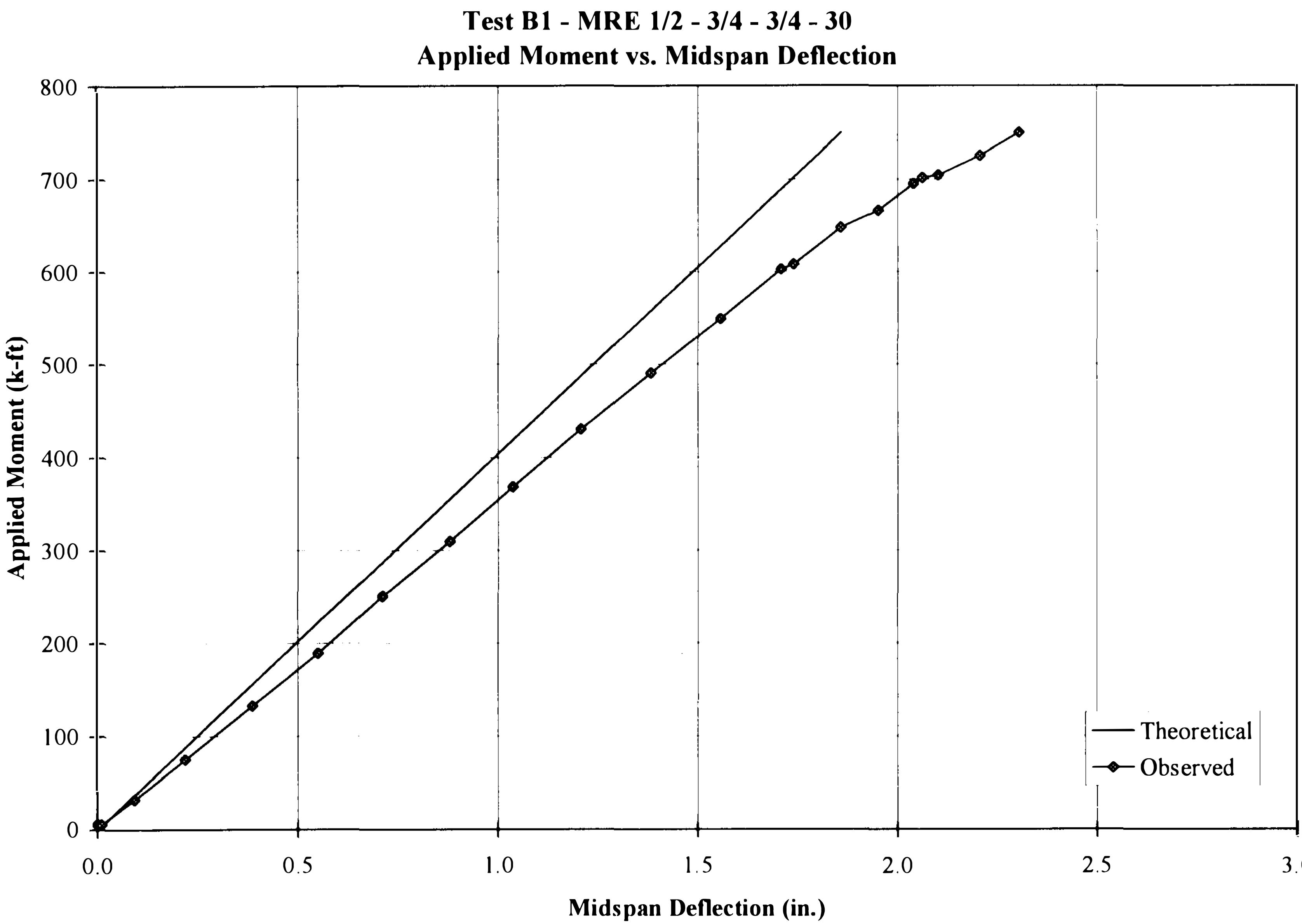
ϕ =	0.75	
Pt =	49.9	kips
do =	31.00	in.
d1 =	28.02	in.
d2 =	25.78	in.
Mnp =	705.5	k-ft
ϕMnp =	529.1	k-ft

Summary

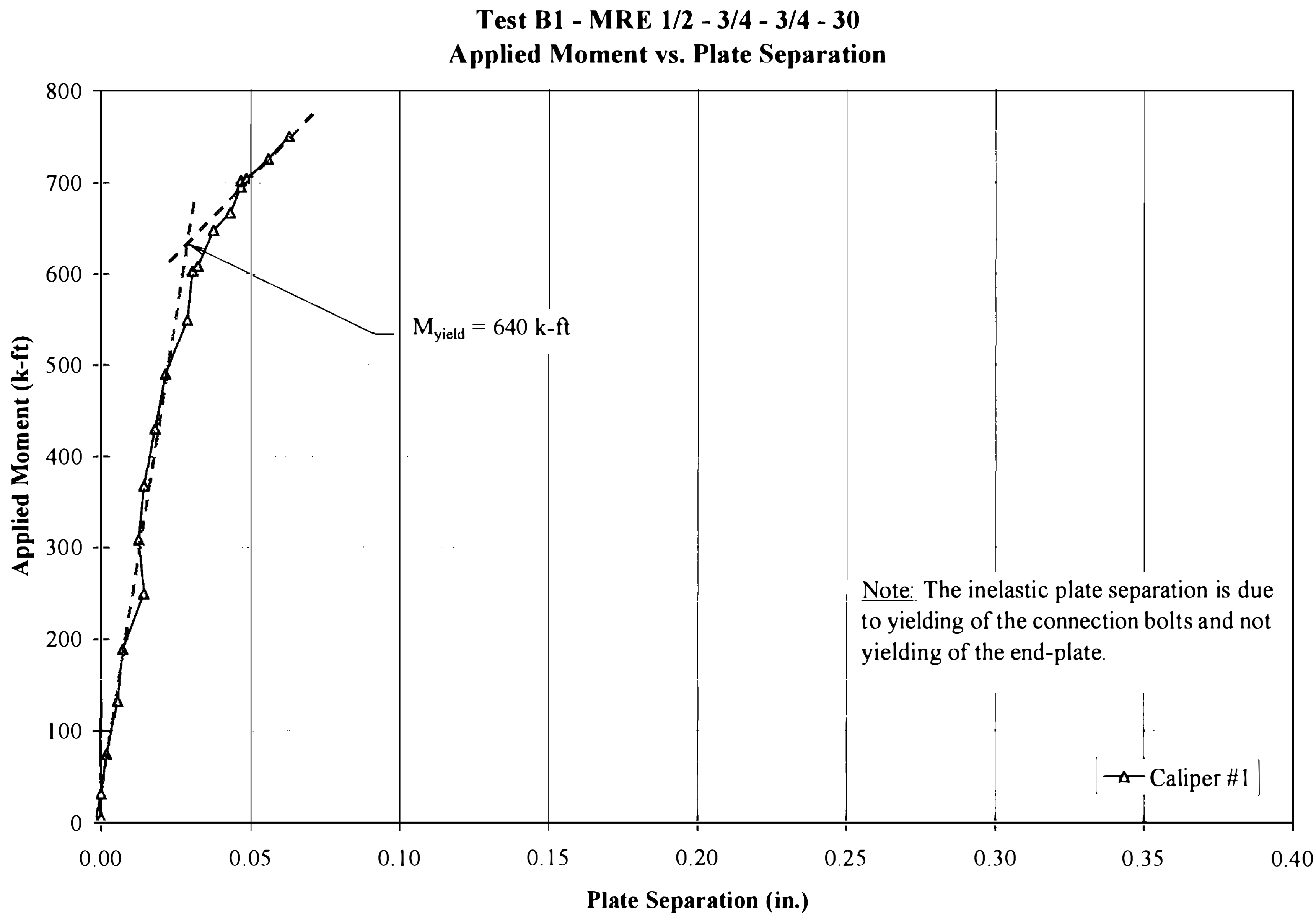
Mpl =	994.7	k-ft	
0.9 Mpl =	895.2	k-ft	
Mq =	441.9	k-ft	
Mnp =	705.5	k-ft	< 0.9 Mpl ==> Mn = Mnp

Mn =	**705.5**	**k-ft**
ϕMn =	**529.1**	**k-ft**

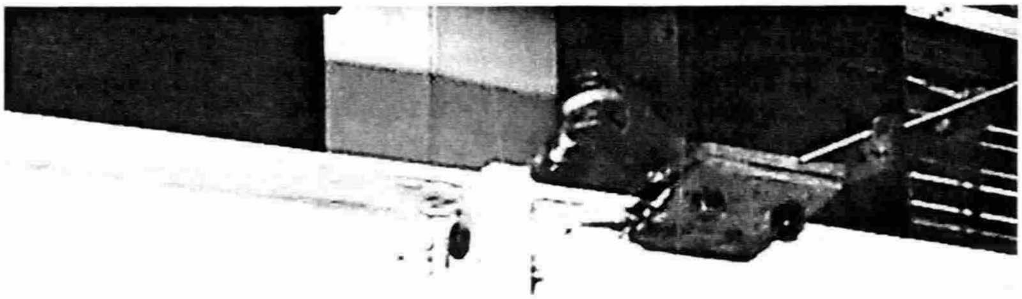
Bolt Tension Rupture w/o Prying Controls, Mnp



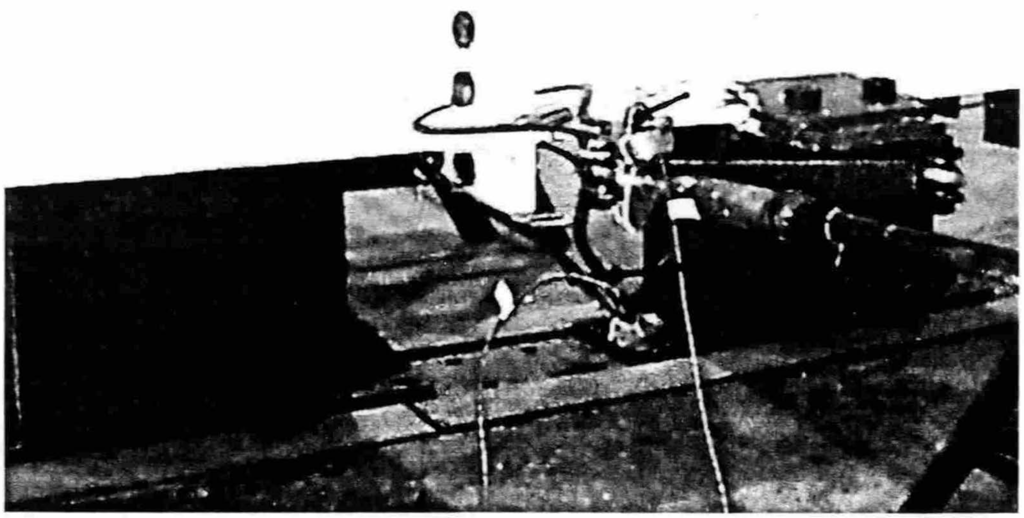
Test B1 - MRE 1/2 - 3/4 - 3/4 - 30
Applied Moment vs. Midspan Deflection
Applied Moment (k-ft)
Midspan Deflection (in.)
0
100
200
300
400
500
600
700
800
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Theoretical
Observed

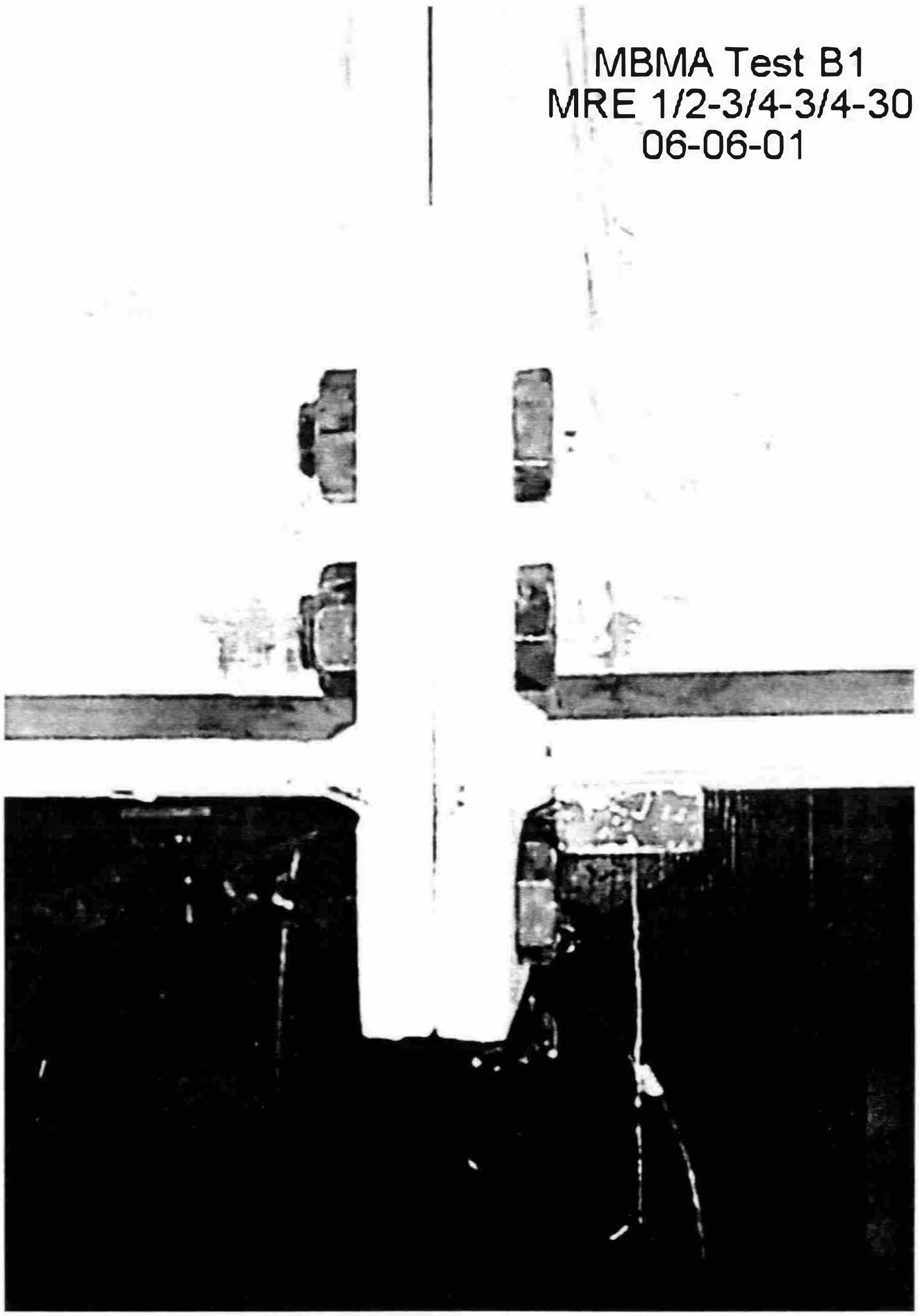


Test B1 - MRE 1/2 - 3/4 - 3/4 - 30
Applied Moment vs. Plate Separation
Applied Moment (k-ft)
800
700
600
500
400
300
200
100
0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Plate Separation (in.)
M yield = 640 k-ft
Note: The inelastic plate separation is due to yielding of the connection bolts and not yielding of the end-plate.
Caliper #1



MBMA Test B1
MRE 1/2-3/4-3/4-30
06-06-01




MBMA Test B1
MRE 1/2-3/4-3/4-30
06-06-01

APPENDIX E

TEST C – MRE 1/2-3/4-1/2-30

RESULTS

TEST SUMMARY

TEST NAME:	Test C - MRE 1/2-3/4-1/2-30 (Large inner pitch distance)
TEST DATE:	June 7, 2001

CONNECTION DESCRIPTION

TYPE:	Multiple Row Extended 1/2 (MRE 1/2)
NUMBER OF TENSION BOLTS:	6 (2 outside, 4 inside)
NUMBER OF COMPRESSION BOLTS:	2

BEAM DATA

SECTION TYPE:	Built-Up
DEPTH, h:	30.0 in.
FLANGE WIDTH, b_f:	8.0 in.
FLANGE THICKNESS, t_f:	0.497 in.
WEB THICKNESS, t_w:	0.375 in
MOMENT OF INERTIA, I:	2500 in^4
NOMINAL YIELD STRESS, F_y:	50 ksi

END-PLATE DATA

END PLATE THICKNESS, t_p:	0.498 in.
END PLATE WIDTH, b_p:	8.0 in
END PLATE LENGTH, L_p:	33.0 in.
END-PLATE EXTENSION OUTSIDE FLANGE, p_{ext}:	2.59 in.
OUTER PITCH. BOLT TO FLANGE, p_{fo}:	1.35 in.
INNER PITCH. BOLT TO FLANGE, p_{fi}:	4.88 in.
INNER PITCH. BOLT TO BOLT, p_b:	2.23 in.
GAGE, g:	3.01 in.
MEASURED YIELD STRESS, F_{yp}:	60.7 ksi

BOLT DATA

BOLT DIAMETER, d_b:	3/4 in.
BOLT LENGTH, L_b:	2.0 in.
BOLT TYPE:	ASTM A325
BOLT PRETENSION, T_b:	Snug Tight (Average: 15.2 kips/bolt)
NOMINAL BOLT YIELD STRENGTH, F_{yb}:	90.0 ksi

EXPERIMENTAL RESULTS

MAXIMUM APPLIED MOMENT, M_{max}:	482.0 k-ft
YIELD MOMENT (Based on plate separation), M_y:	405.0 k-ft
FAILURE MODE:	End-Plate Yielding / Bolt Tension Rupture

PREDICTED STRENGTHS

END-PLATE STRENGTH, M_{PL}:	353.0 k-ft
BOLT TENSION RUPTURE (w/o Prying), M_{NP}:	514.4 k-ft
BOLT TENSION RUPTURE (w/Prying), M_Q:	316.2 k-ft
CONTROLLING STRENGTH, M_n:	316.2 k-ft

Multiple Row Extended Unstiffened 1/2 End-Plate Connection Analysis

By: EAS
Date: 6/26/2001

Project Name: MBMA
Connection ID: Test C - MRE1/2-3/4-1/2-30 (Large inner pitch)

Plate Data

tp =	0.498	in.
Fyp =	60.7	ksi
bp =	8	in.
g =	3.01	in.
pfi =	4.88	in.
pfo =	1.35	in.
pext =	2.59	in.
pb =	2.23	in.

Member Data

Section:	Build-up Section	
h =	30	in.
bf =	8	in.
tf =	0.497	in.

Bolt Data

Material:	A325	
dia. =	0.75	in.
Ft =	90	ksi
Tb =	15.2	kips
(Tb @ 0.7xPt =	27.8	kips)

End-Plate Yielding (Mpl)

φ =	0.90					
γr =	1.00					
ho =	31.35	in.				
h1 =	24.62	in.				
h2 =	22.39					
s =	2.45	in.		c =	2.45	in.
Y =	167.54 +	112.31 +	1.51	=	281.4	

Mpl =	353.0	k-ft
φMpl =	317.7	k-ft

Bolt Rupture w/ Prying Action (Mq)

φ =	0.75								
Pt =	39.8	kips							
ai =	0.993	in.	ao = min(	0.993	1.240	) in. =		0.993	in.
wi' =	3.188	in.	wo' =	3.188	in.				
Fi' =	5.35	kips	Fo' =	19.35	kips				
Qimax =	12.03	kips	Qomax =	11.33	kips				
d1 =	24.37	in.	do =	31.10	in.		d2 =	22.14	in.

Mq =	max (	3793.9	3182.8	2970.7	2359.7	) in-kips =	316.2	k-ft
φMq =	237.1	k-ft						

Bolt Rupture w/o Prying Action (Mnp)

φ =	0.75	
Pt =	39.8	kips
do =	31.10	in.
d1 =	24.37	in.
d2 =	22.14	in.
Mnp =	514.4	k-ft
φMnp =	385.8	k-ft

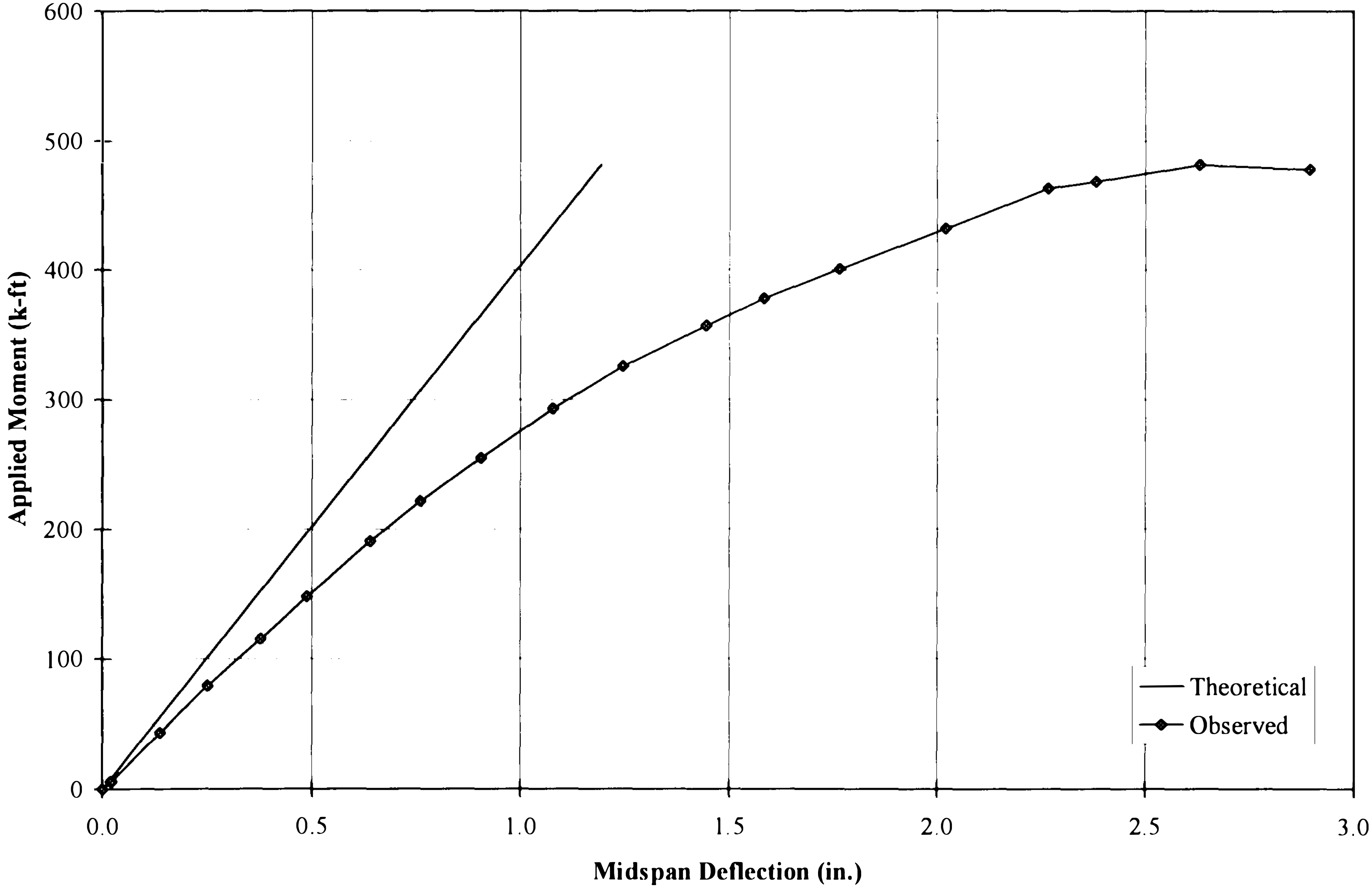
Summary

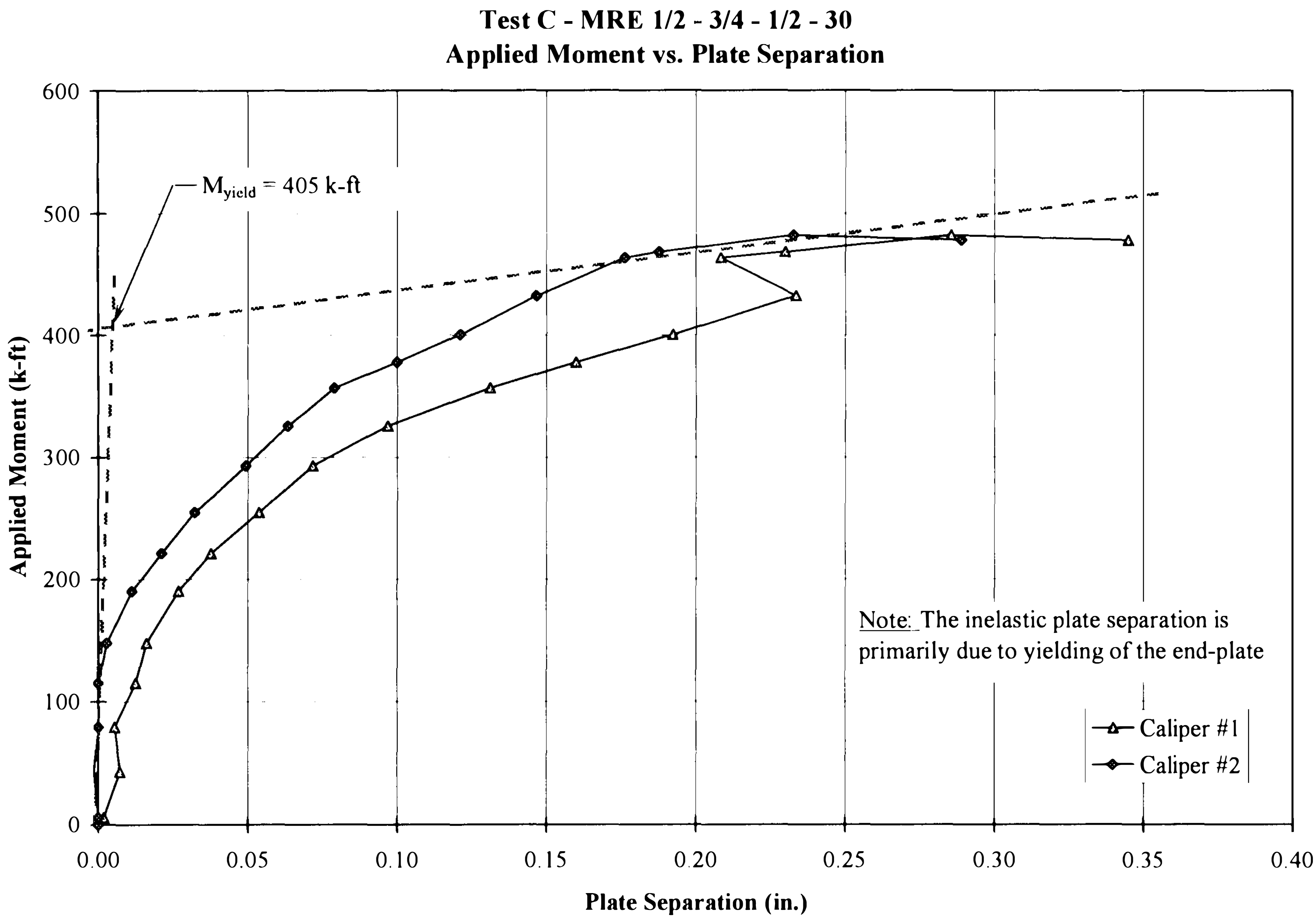
Mpl =	353.0	k-ft	
0.9 Mpl =	317.7	k-ft	< Mnp ==> Mn = Mq
Mq =	316.2	k-ft	< Mpl ==> Mn = Mq
Mnp =	514.4	k-ft	

Mn =	**316.2**	**k-ft**
φMn =	**237.1**	**k-ft**

Bolt Tension Rupture w/ Prying Controls, Mq

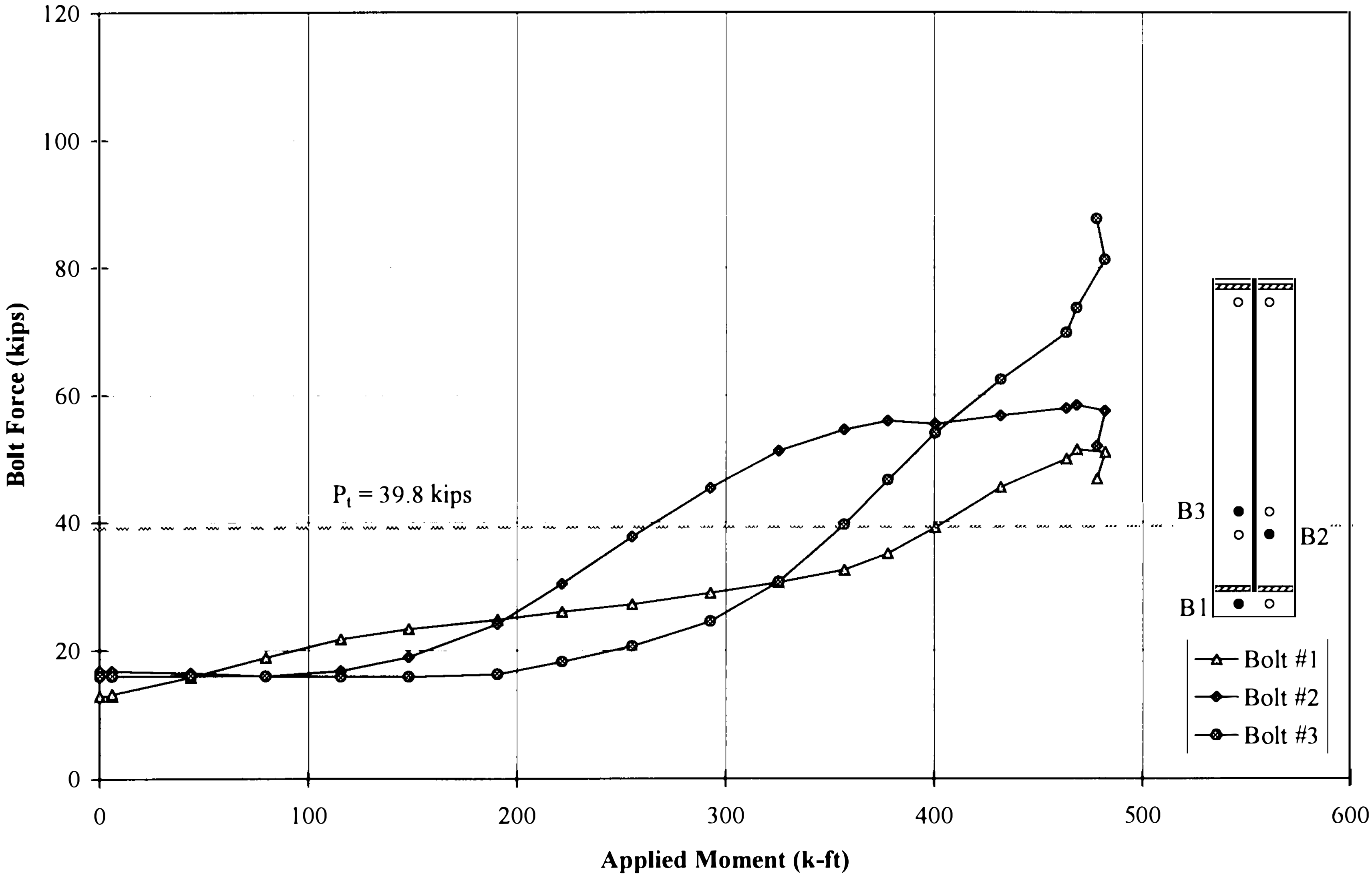
Test C - MRE 1/2 - 3/4 - 1/2 - 30
Applied Moment vs. Midspan Deflection



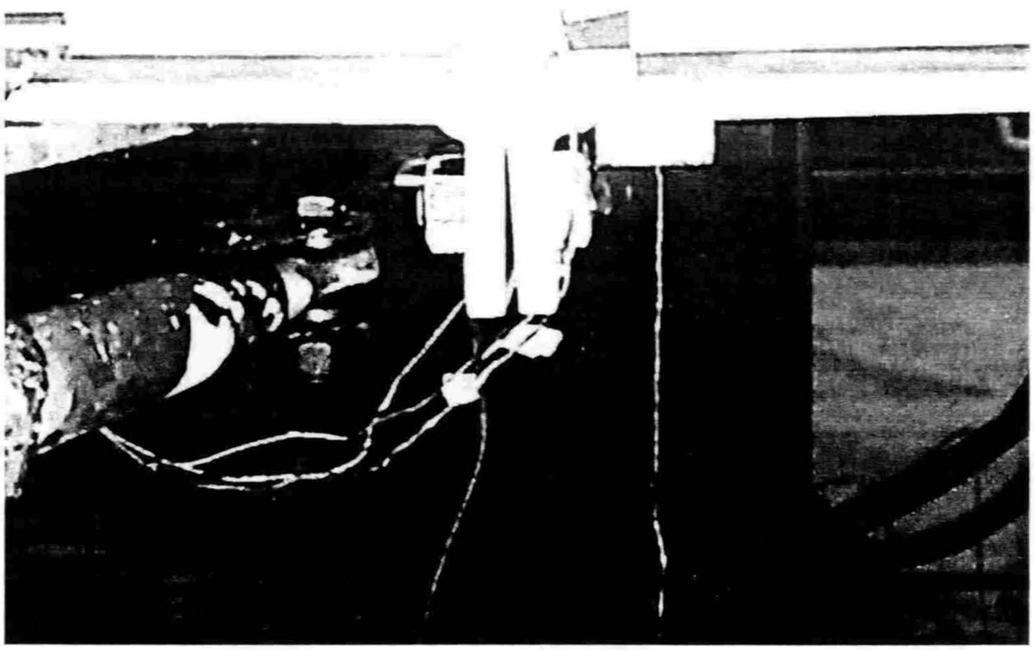


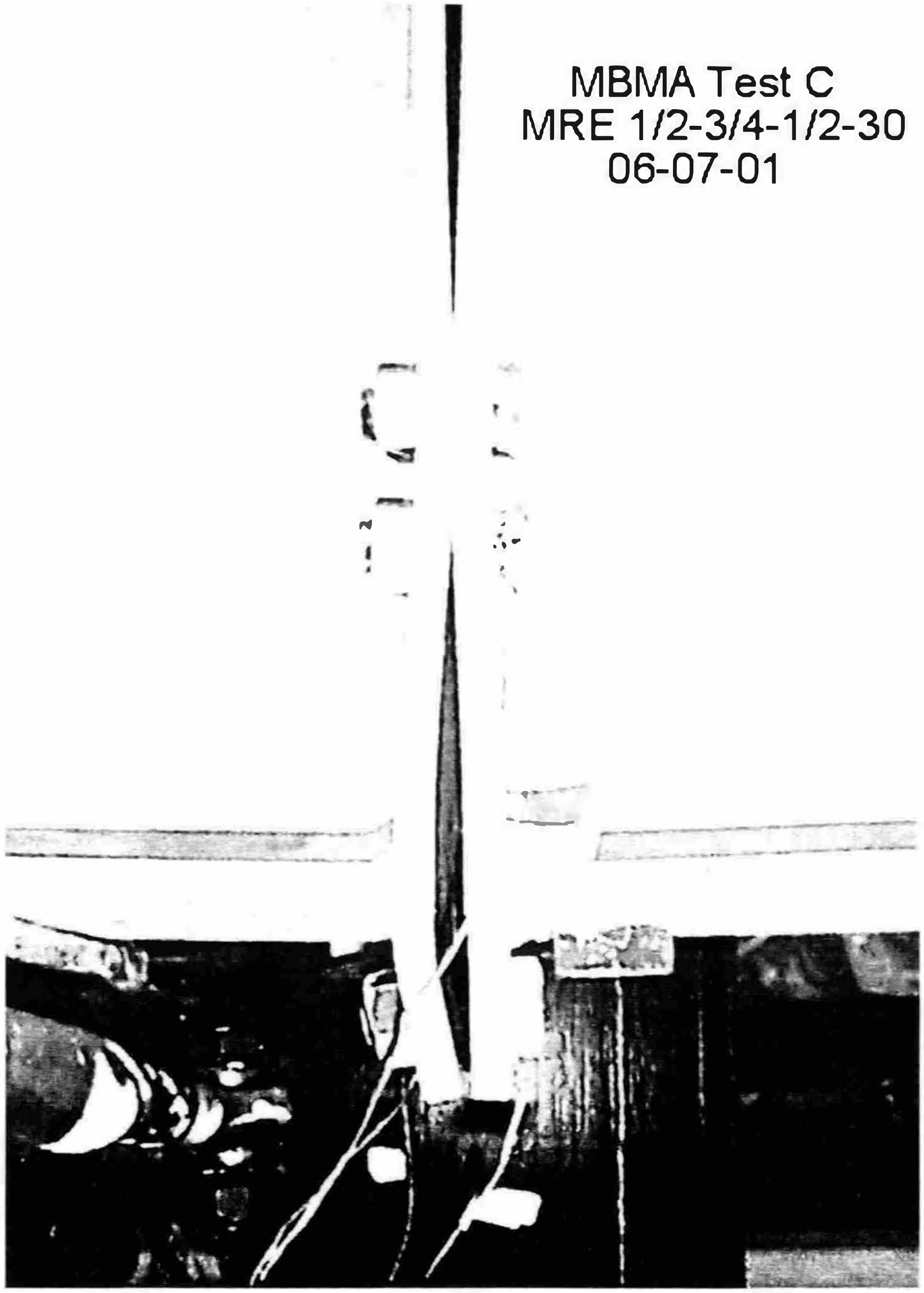
Test C - MRE 1/2 - 3/4 - 1/2 - 30
Applied Moment vs. Plate Separation
M_{yield} = 405 k-ft
Applied Moment (k-ft)
Plate Separation (in.)
600
500
400
300
200
100
0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Note: The inelastic plate separation is primarily due to yielding of the end-plate
Caliper #1
Caliper #2

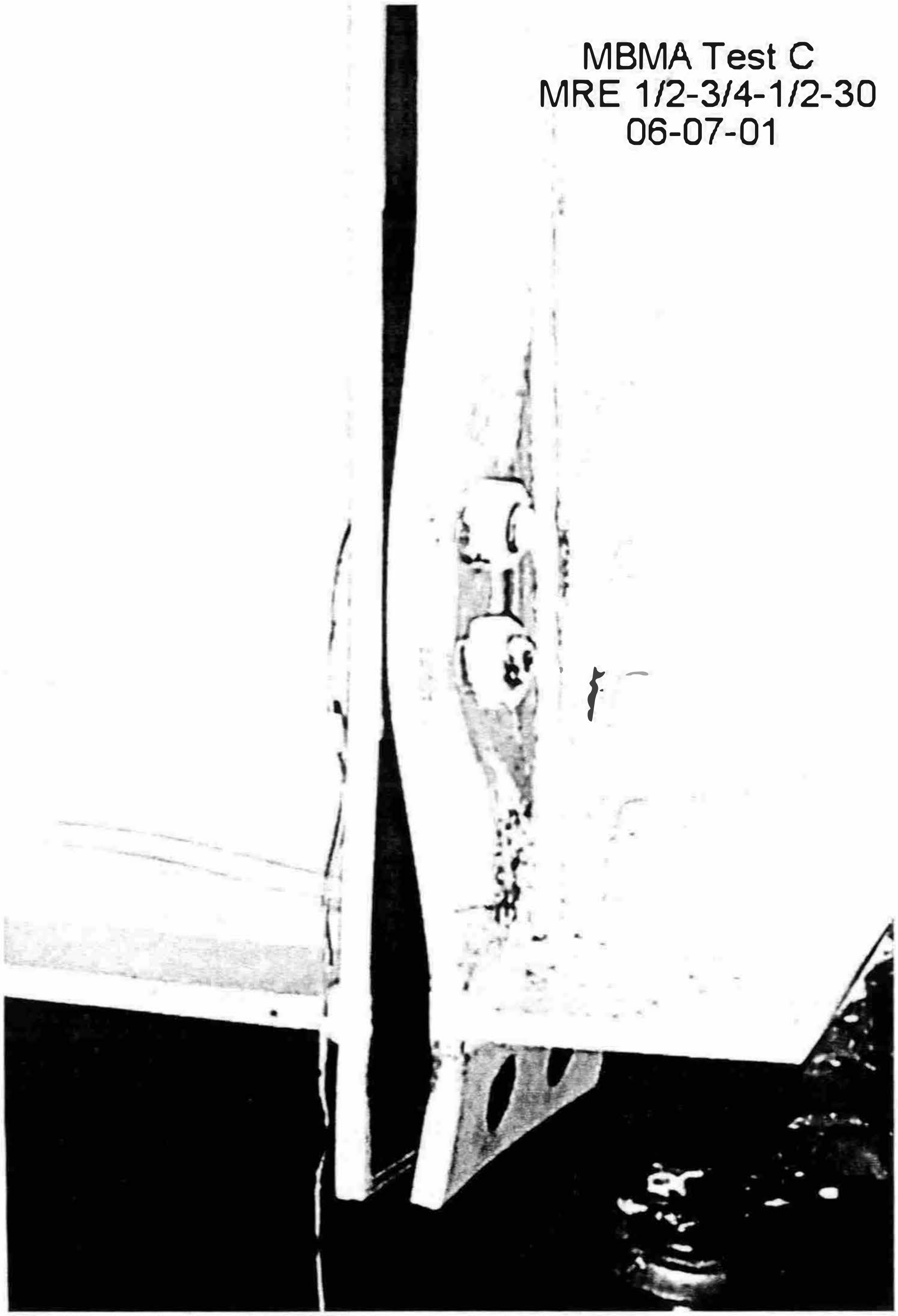
Test C - MRE 1/2 - 3/4 - 1/2 - 30
Bolt Force vs. Applied Moment



MBMA Test C
MRE 1/2-3/4-1/2-30
06-07-01




MBMA Test C
MRE 1/2-3/4-1/2-30
06-07-01


MBMA Test C
MRE 1/2-3/4-1/2-30
06-07-01

APPENDIX F

TEST D – MRE 1/2-3/4-3/4-30

RESULTS

TEST SUMMARY

TEST NAME: Test D - MRE 1/2-3/4-3/4-30 (Large inner pitch distance)
TEST DATE: June 8, 2001

CONNECTION DESCRIPTION

TYPE:	Multiple Row Extended 1/2 (MRE 1/2)
NUMBER OF TENSION BOLTS:	6 (2 outside, 4 inside)
NUMBER OF COMPRESSION BOLTS:	2

BEAM DATA

SECTION TYPE:	Built-Up
DEPTH, h:	30.0 in.
FLANGE WIDTH, b_f:	8.0 in.
FLANGE THICKNESS, t_f:	0.498 in.
WEB THICKNESS. t_w:	0.375 in.
MOMENT OF INERTIA. I:	2500 in^4
NOMINAL YIELD STRESS, F_y:	50 ksi

END-PLATE DATA

END PLATE THICKNESS, t_p:	0.751 in.
END PLATE WIDTH, b_p:	8.0 in.
END PLATE LENGTH, L_p:	33.0 in.
END-PLATE EXTENSION OUTSIDE FLANGE, p_{ext}:	2.56 in.
OUTER PITCH, BOLT TO FLANGE, p_{fo}:	1.27 in
INNER PITCH, BOLT TO FLANGE. p_{fi}:	4.94 in.
INNER PITCH, BOLT TO BOLT, p_b:	2.23 in.
GAGE, g:	3.01 in.
MEASURED YIELD STRESS, F_{yp}:	61.3 ksi

BOLT DATA

BOLT DIAMETER, d_b:	3/4 in.
BOLT LENGTH, L_b:	2.5 in.
BOLT TYPE:	ASTM A325
BOLT PRETENSION, T_b:	Snug Tight (Average: 17.5 kips/bolt)
NOMINAL BOLT YIELD STRENGTH, F_{yb}:	90.0 ksi

EXPERIMENTAL RESULTS

MAXIMUM APPLIED MOMENT, M_{max}:	558.7 k-ft
YIELD MOMENT (Based on plate separation), M_y:	500.0 k-ft
FAILURE MODE:	Bolt Tension Rupture

PREDICTED STRENGTHS

END-PLATE STRENGTH, M_{PL}:	825.3 k-ft
BOLT TENSION RUPTURE (w/o Prying), M_{NP}:	513.0 k-ft
BOLT TENSION RUPTURE (w/Prying), M_Q:	305.6 k-ft
CONTROLLING STRENGTH, M_n:	513.0 k-ft

Multiple Row Extended Unstiffened 1/2 End-Plate Connection Analysis

By: EAS
Date: 6/26/2001

Project Name: MBMA
Connection ID: Test D - MRE1/2-3/4-3/4-30 (Large inner pitch)

Plate Data

tp =	0.751	in.
Fyp =	61.3	ksi
bp =	8	in.
g =	3.01	in.
pfi =	4.94	in.
pfo =	1.27	in.
pext =	2.56	in.
pb =	2.23	in.

Member Data

Section: Build-up Section

h =	30	in.
bf =	8	in.
tf =	0.498	in.

Bolt Data

Material:	A325	
dia. =	0.75	in.
Ft =	90	ksi
Tb =	17.5	kips
(Tb @ 0.7xPt =	27.8	kips)

End-Plate Yielding (Mpl)

ϕ =	0.90					
γr =	1.00					
ho =	31.27	in.				
h1 =	24.56	in.				
h2 =	22.33					
s =	2.45	in.		c =	2.45	in.
Y =	172.94 +	112.02 +	1.51	=	286.5	
Mpl =	825.3	k-ft				
ϕMpl =	742.8	k-ft				

Bolt Rupture w/ Prying Action (Mq)

ϕ =	0.75								
Pt =	39.8	kips							
ai =	3.612	in.	ao = min(	3.612	1.290	) in. =		1.290	in.
wi' =	3.188	in.	wo' =	3.188	in.				
Fi' =	11.17	kips	Fo' =	43.43	kips				
Qimax =	7.56	kips	Qomax =	18.34	kips				
d1 =	24.31	in.	do =	31.02	in.		d2 =	22.08	in.
Mq =	max (	3667.8	2953.0	3424.4	2709.6	) in-kips =		305.6	k-ft
ϕMq =	229.2	k-ft							

Bolt Rupture w/o Prying Action (Mnp)

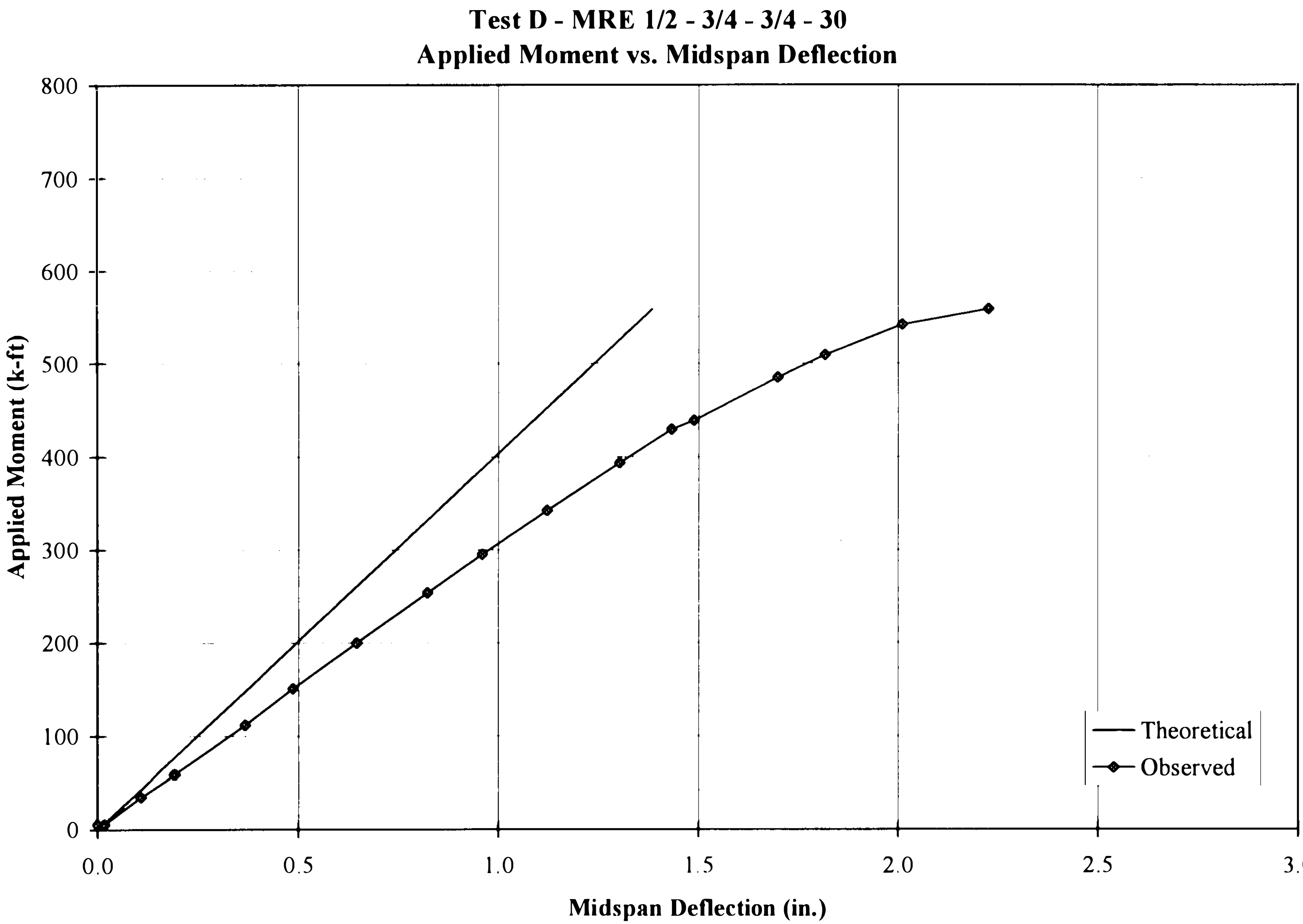
ϕ =	0.75	
Pt =	39.8	kips
do =	31.02	in.
d1 =	24.31	in.
d2 =	22.08	in.
Mnp =	513.0	k-ft
ϕMnp =	384.8	k-ft

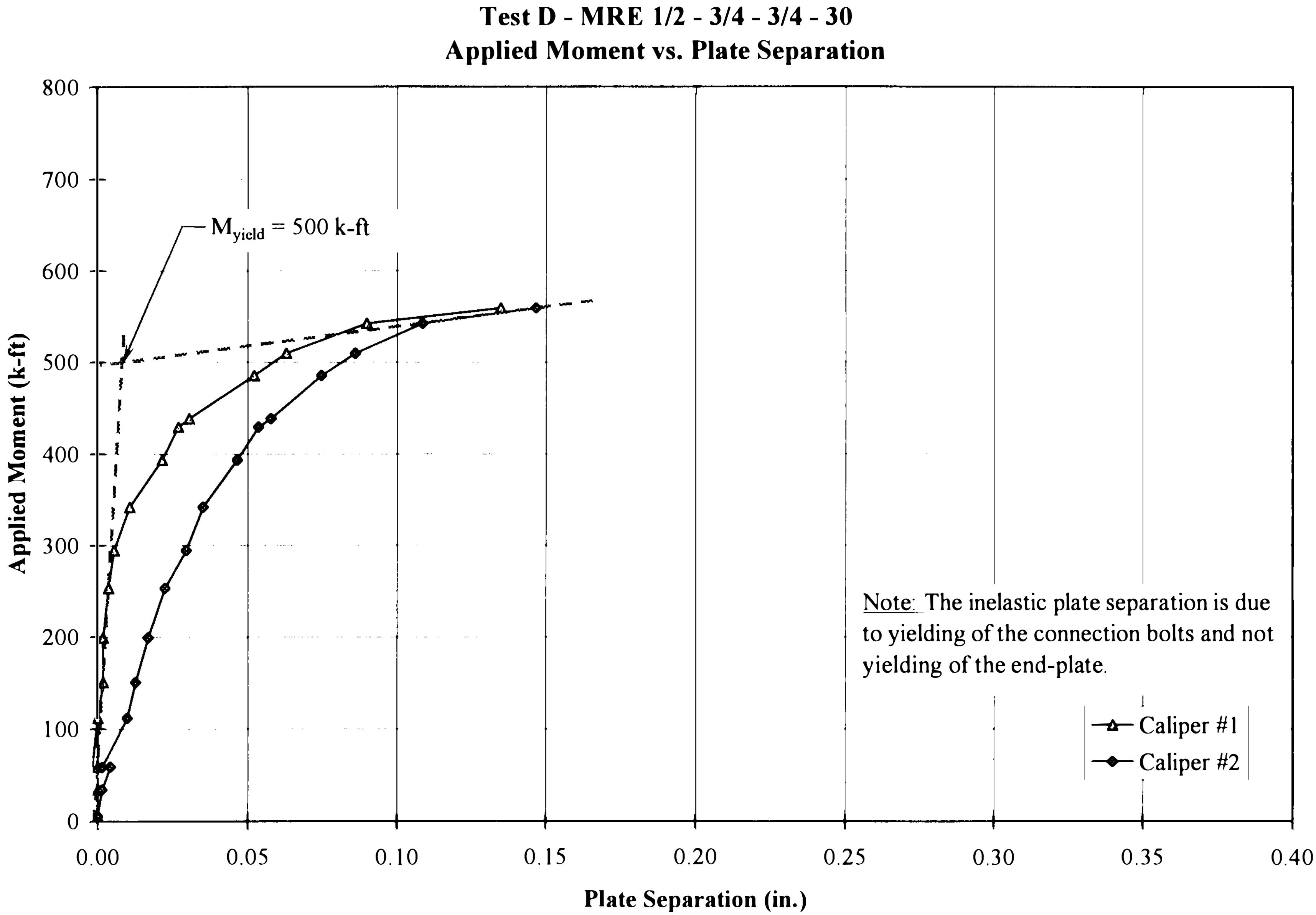
Summary

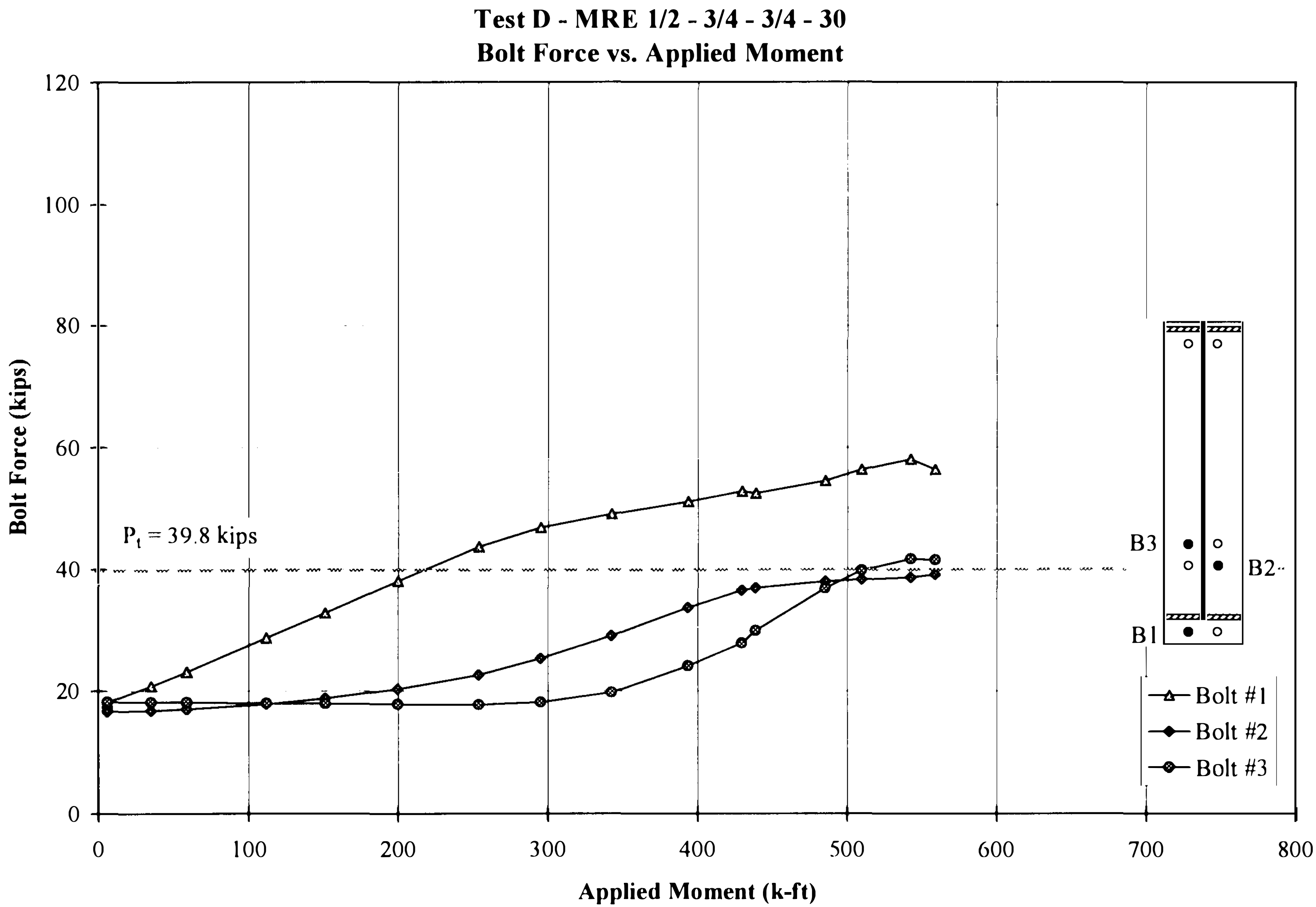
Mpl =	825.3	k-ft	
0.9 Mpl =	742.8	k-ft	
Mq =	305.6	k-ft	
Mnp =	513.0	k-ft	< 0.9 Mpl ==> Mn = Mnp

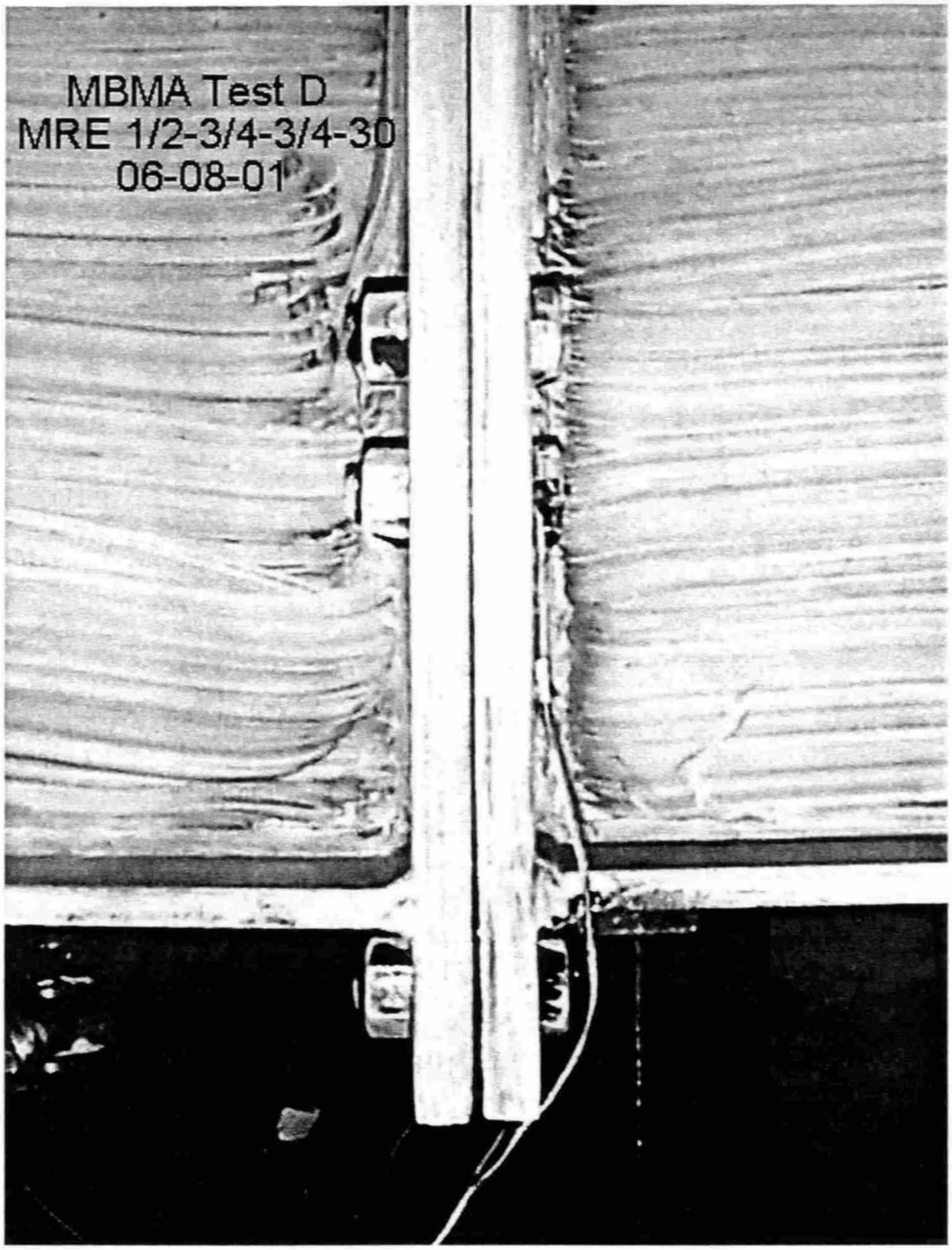
Mn =	**513.0**	**k-ft**
ϕMn =	**384.8**	**k-ft**

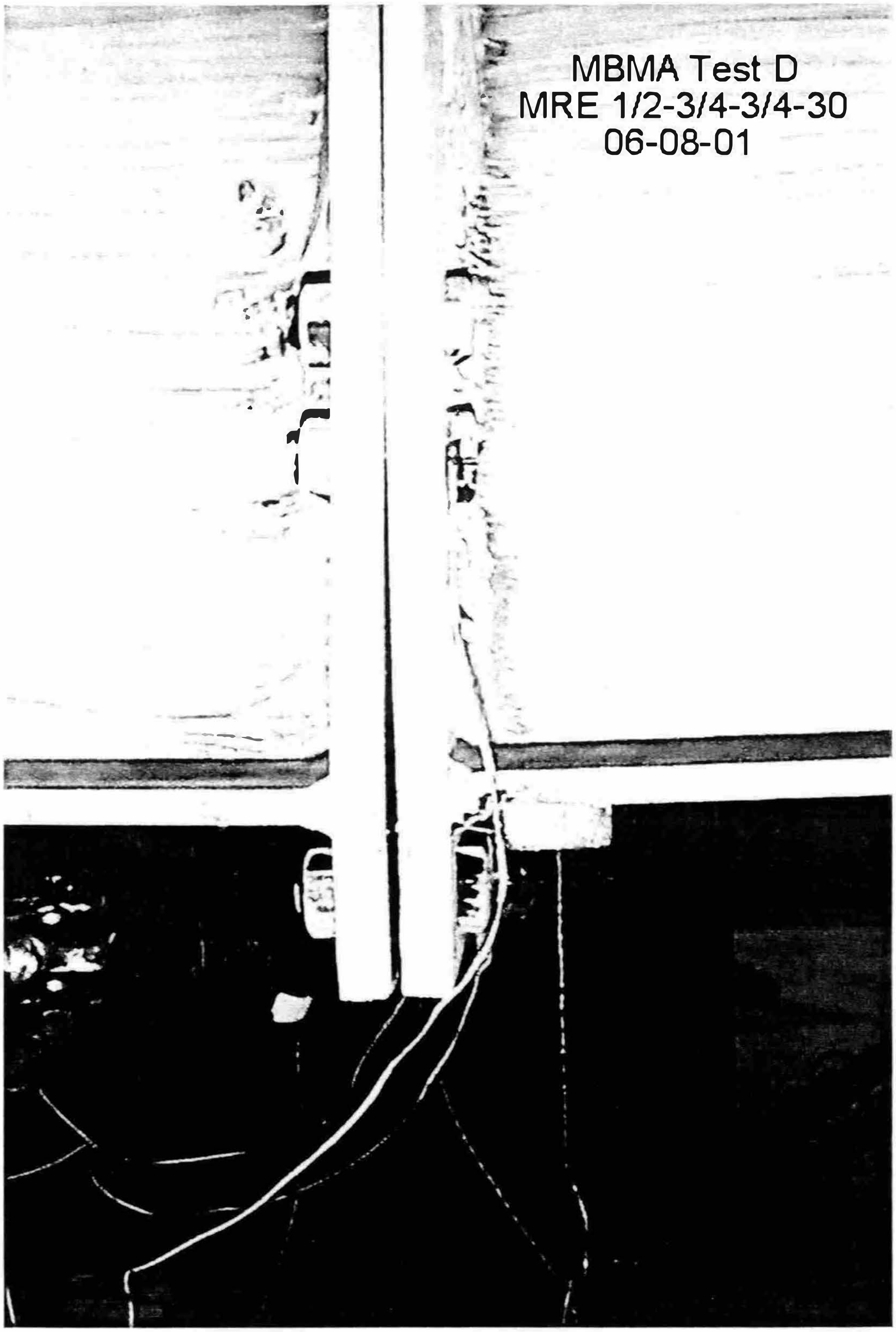
Bolt Tension Rupture w/o Prying Controls, Mnp


Test D - MRE 1/2 - 3/4 - 3/4 - 30
Applied Moment vs. Midspan Deflection
Applied Moment (k-ft)
Midspan Deflection (in.)
0
100
200
300
400
500
600
700
800
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Theoretical
Observed


Test D - MRE 1/2 - 3/4 - 3/4 - 30
Applied Moment vs. Plate Separation
Applied Moment (k-ft)
Plate Separation (in.)
M_{yield} = 500 k-ft
Note: The inelastic plate separation is due to yielding of the connection bolts and not yielding of the end-plate.
Caliper #1
Caliper #2
0
100
200
300
400
500
600
700
800
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40


Test D - MRE 1/2 - 3/4 - 3/4 - 30
Bolt Force vs. Applied Moment
Bolt Force (kips)
Applied Moment (k-ft)
P_t = 39.8 kips
B3
B2
B1
Bolt #1
Bolt #2
Bolt #3
0
20
40
60
80
100
120
0
100
200
300
400
500
600
700
800


MBMA Test D
MRE 1/2-3/4-3/4-30
06-08-01


MBMA Test D
MRE 1/2-3/4-3/4-30
06-08-01

APPENDIX G

TEST D1 – MRE 1/2-3/4-3/4-30

RESULTS

TEST SUMMARY

TEST NAME: Test D1 - MRE 1/2-3/4-3/4-30 (Large inner pitch distance)
TEST DATE: June 8, 2001

CONNECTION DESCRIPTION

TYPE:	Multiple Row Extended 1/2 (MRE 1/2)
NUMBER OF TENSION BOLTS:	6 (2 outside, 4 inside)
NUMBER OF COMPRESSION BOLTS:	2

BEAM DATA

SECTION TYPE:	Built-Up
DEPTH, h:	30.0 in.
FLANGE WIDTH, b_f:	8.0 in.
FLANGE THICKNESS, t_f:	0.498 in.
WEB THICKNESS, t_w:	0.375 in.
MOMENT OF INERTIA, I:	2500 $in.^4$
NOMINAL YIELD STRESS, F_y:	50 ksi

END-PLATE DATA

END PLATE THICKNESS, t_p:	0.751 in.
END PLATE WIDTH, b_p:	8.0 in.
END PLATE LENGTH, L_p:	33.0 in.
END-PLATE EXTENSION OUTSIDE FLANGE, p_{ext}:	2.56 in.
OUTER PITCH, BOLT TO FLANGE, p_{fo}:	1.27 in.
INNER PITCH, BOLT TO FLANGE, p_{fi}:	4.94 in.
INNER PITCH, BOLT TO BOLT, p_b:	2.23 in.
GAGE, g:	3.01 in.
MEASURED YIELD STRESS, F_{yp}:	31.3 ksi

BOLT DATA

BOLT DIAMETER, d_b:	3/4 in.
BOLT LENGTH, L_b:	2.5 in.
BOLT TYPE:	ASTM A490
BOLT PRETENSION, T_b:	Snug Tight
NOMINAL BOLT YIELD STRENGTH, F_{yb}:	113.0 ksi

EXPERIMENTAL RESULTS

MAXIMUM APPLIED MOMENT, M_{max}:	622.8 k-ft
YIELD MOMENT (Based on plate separation), M_y:	450.0 k-ft
FAILURE MODE:	Bolt Tension Rupture

PREDICTED STRENGTHS

END-PLATE STRENGTH, M_{PL}:	825.3 k-ft
BOLT TENSION RUPTURE (w/o Prying), M_{NP}:	644.1 k-ft
BOLT TENSION RUPTURE (w/Prying), M_Q:	400.0 k-ft
CONTROLLING STRENGTH, M_n:	644.1 k-ft

Multiple Row Extended Unstiffened 1/2 End-Plate Connection Analysis

By: EAS
Date: 6/26/2001

Project Name: MBMA
Connection ID: Test D1 - MRE1/2-3/4-3/4-30 (A490 bolts, Large inner pitch)

Plate Data			**Member Data**		
tp =	0.751	in.	Section:	Build-up Section	
Fyp =	61.3	ksi	h =	30	in.
bp =	8	in.	bf =	8	in.
g =	3.01	in.	tf =	0.498	in.
pfi =	4.94	in.	**Bolt Data**		
pfo =	1.27	in.	Material:	A490	
pext =	2.56	in.	dia. =	0.75	in.
pb =	2.23	in.	Ft =	113	ksi
			Tb =	17.5	kips
			(Tb @ 0.7xPt =	34.9	kips)

End-Plate Yielding (Mpl)

ϕ =	0.90				
γr =	1.00				
ho =	31.27	in.			
hl =	24.56	in.			
h2 =	22.33				
s =	2.45	in.	c =	2.45	in.
Y =	172.94 +	112.02 +	1.51	=	286.5

Mpl =	825.3	k-ft
ϕMpl =	742.8	k-ft

Bolt Rupture w/ Prying Action (Mq)

ϕ =	0.75							
Pt =	49.9	kips						
ai =	3.612	in.	ao = min(	3.612	1.290	) in. =	1.290	in.
wi' =	3.188	in.	wo' =	3.188	in.			
Fi' =	11.36	kips	Fo' =	44.18	kips			
Qimax =	7.56	kips	Qomax =	18.22	kips			
d1 =	24.31	in.	do =	31.02	in.	d2 =	22.08	in.

Mq =	max (	4799.5	3590.5	3918.6	2709.6	) in-kips =	400.0	k-ft
ϕMq =	300.0	k-ft						

Bolt Rupture w/o Prying Action (Mnp)

ϕ =	0.75	
Pt =	49.9	kips
do =	31.02	in.
d1 =	24.31	in.
d2 =	22.08	in.

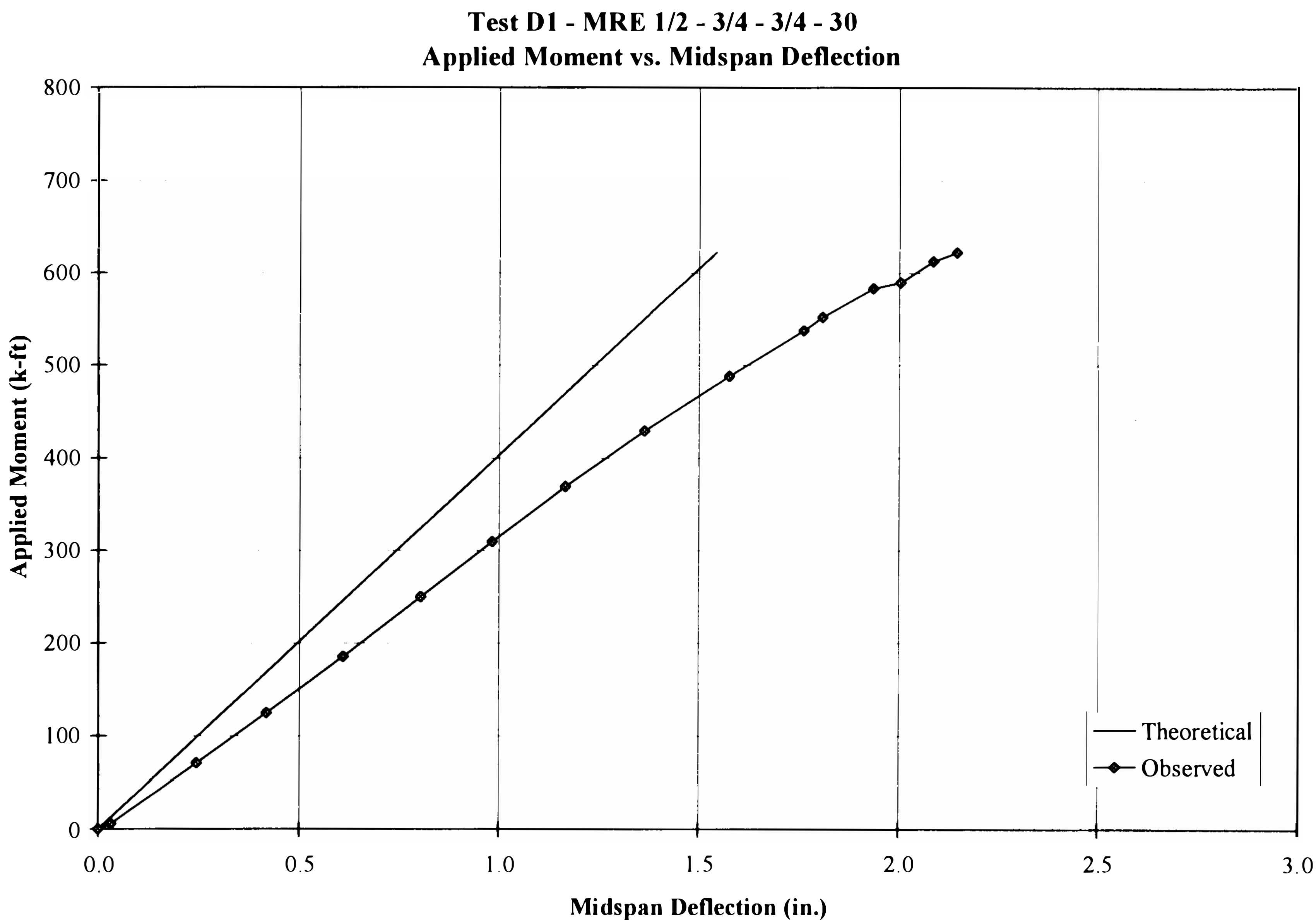
Mnp =	644.1	k-ft
ϕMnp =	483.1	k-ft

Summary

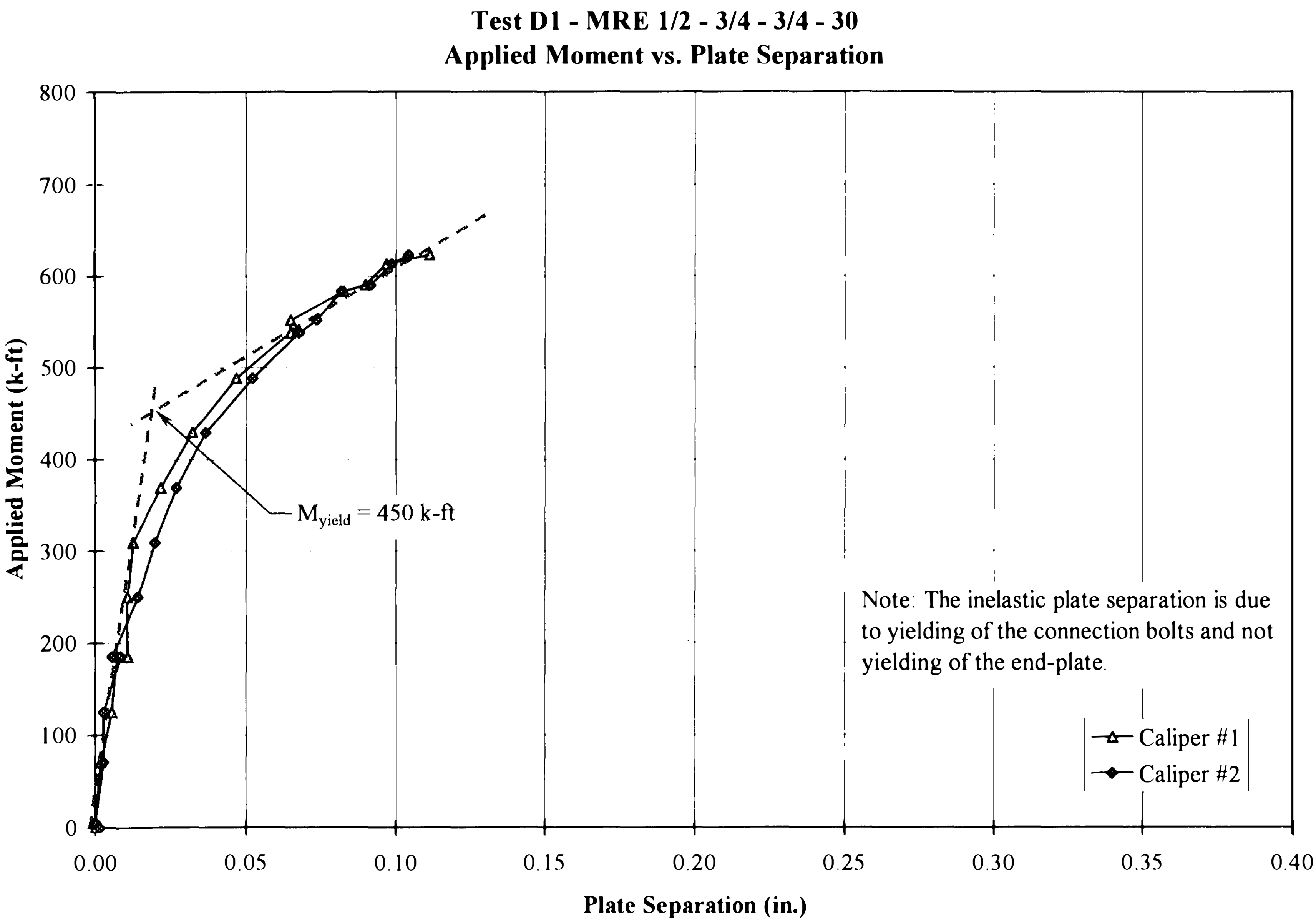
Mpl =	825.3	k-ft	
0.9 Mpl =	742.8	k-ft	
Mq =	400.0	k-ft	
Mnp =	644.1	k-ft	< 0.9 Mpl ==> Mn = Mnp

Mn =	**644.1**	**k-ft**
ϕMn =	**483.1**	**k-ft**

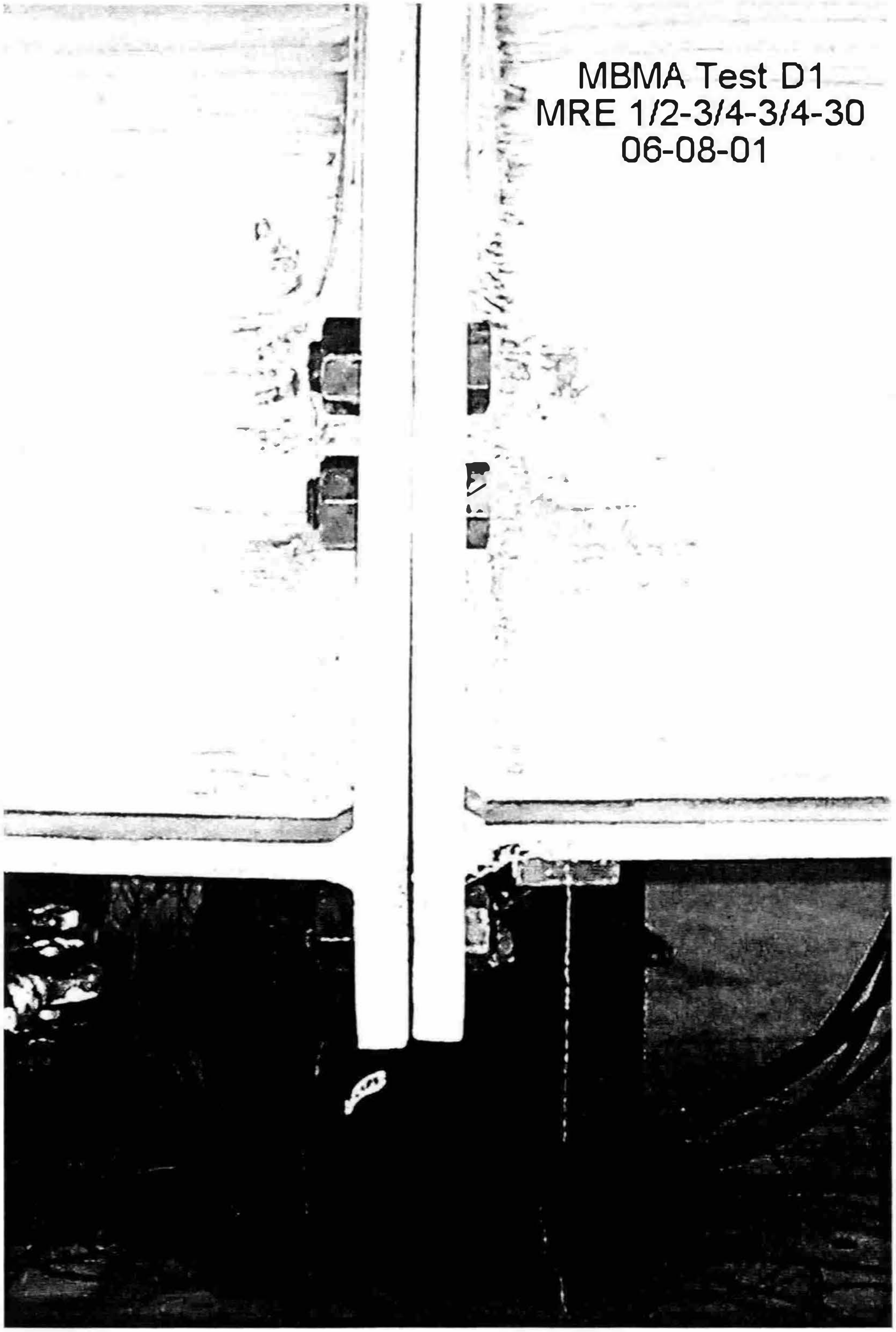
Bolt Tension Rupture w/o Prying Controls, Mnp

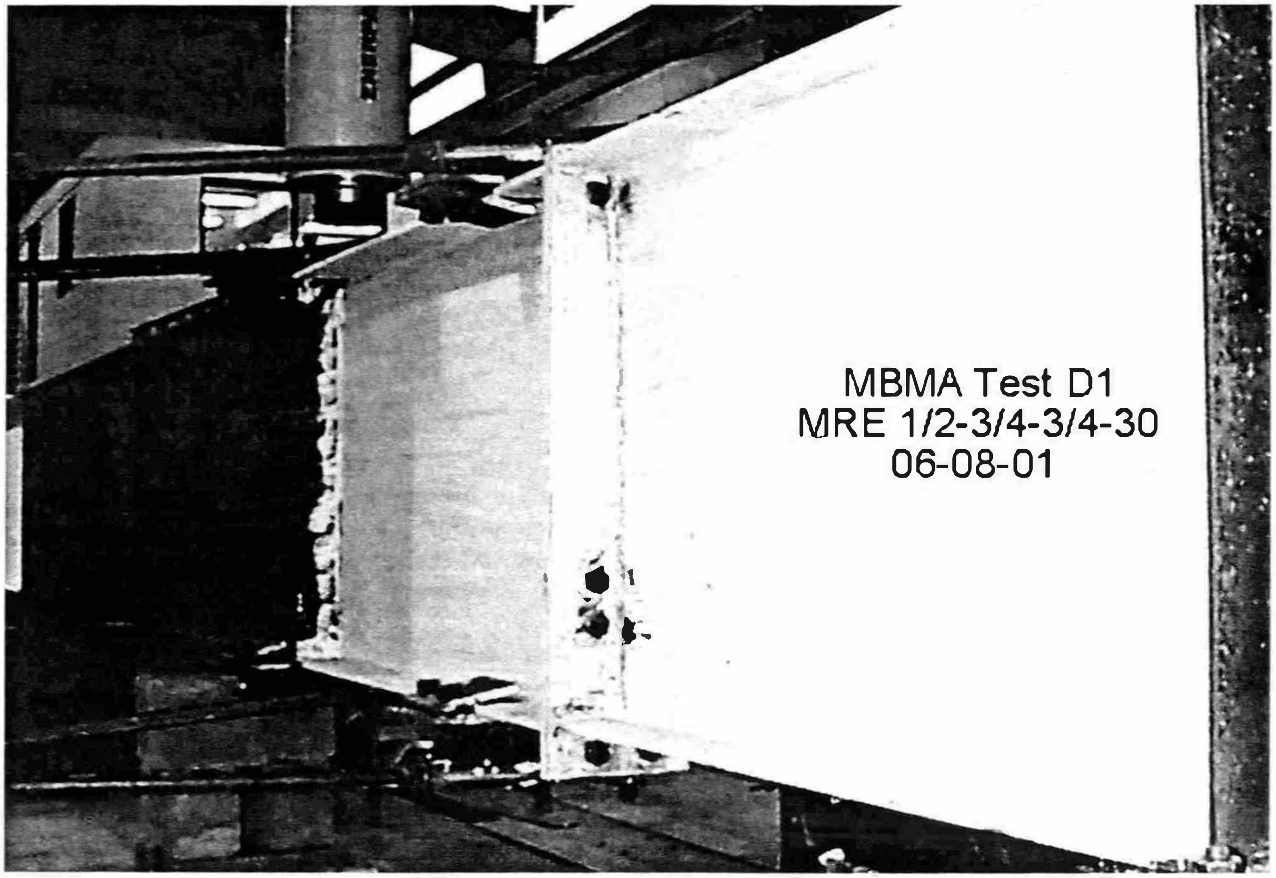


Test D1 - MRE 1/2 - 3/4 - 3/4 - 30
Applied Moment vs. Midspan Deflection
Applied Moment (k-ft)
800
700
600
500
400
300
200
100
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Midspan Deflection (in.)
Theoretical
Observed



Test D1 - MRE 1/2 - 3/4 - 3/4 - 30
Applied Moment vs. Plate Separation
Applied Moment (k-ft)
800
700
600
500
400
300
200
100
0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Plate Separation (in.)
M_{yield} = 450 k-ft
Note: The inelastic plate separation is due to yielding of the connection bolts and not yielding of the end-plate.
Caliper #1
Caliper #2


MBMA Test D1
MRE 1/2-3/4-3/4-30
06-08-01


MBMA Test D1
MRE 1/2-3/4-3/4-30
06-08-01

APPENDIX H

FABRICATION DRAWINGS

BEAM #1 & #2

Virginia Tech Department of Civil Engineering

Project: MBMA Moment End-Plate Testing

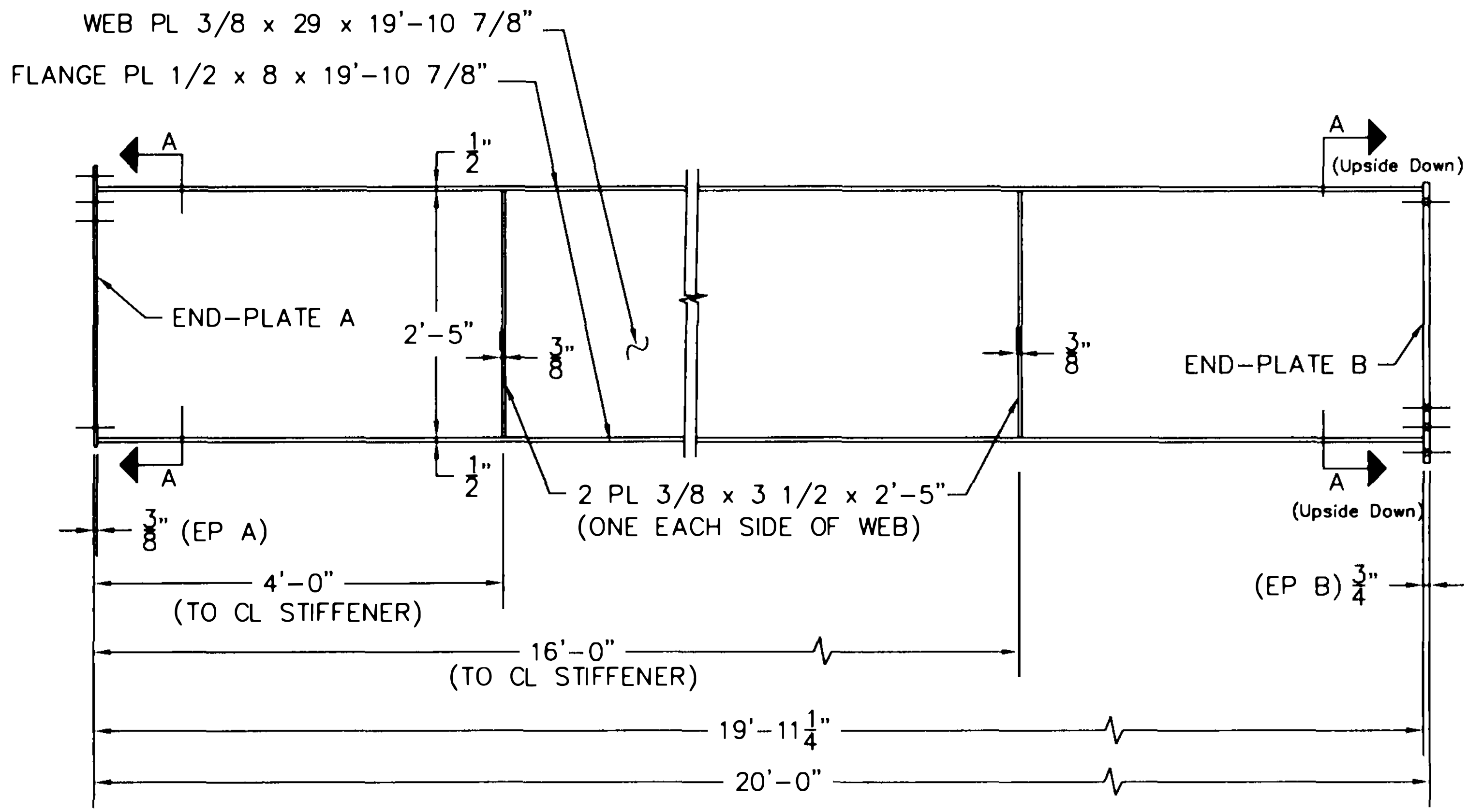
Date: 2/28/01

Scale: None

Drawn By: EAS

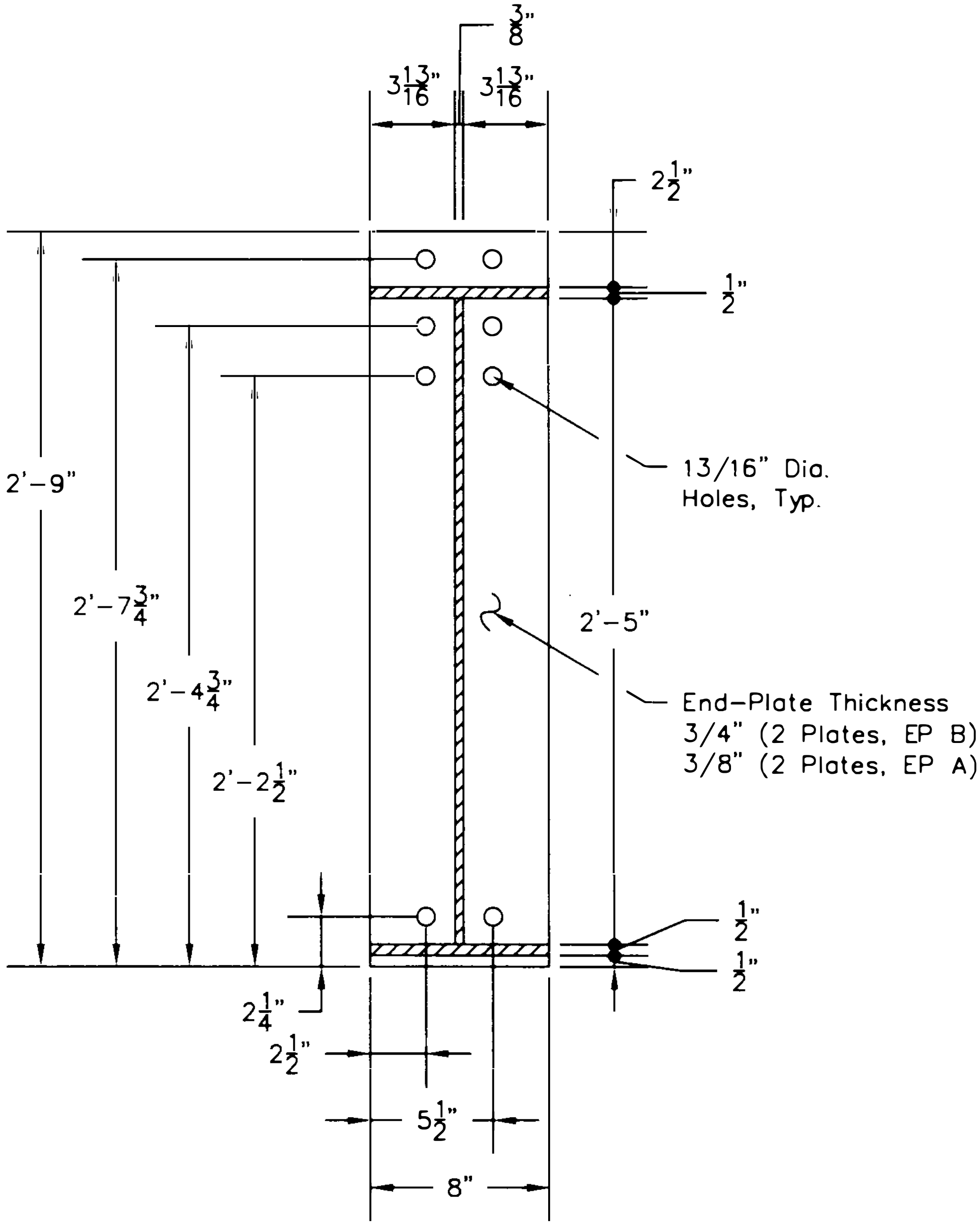
Page: 1 of 5

*NO PAINT



NOTE: A) PROVIDE 24" OF CONTINUOUS WELD AT EACH END
B) ALL STEEL SHALL HAVE A MINIMUM SPECIFIED YIELD STRESS OF 50 KSI.

BEAM LAYOUT (2 REQUIRED)



SECTION A-A: END-PLATE LAYOUT

(TYPICAL FOR END-PLATES A & B)

BEAM #1 & #2

*NO PAINT

Virginia Tech Department of Civil Engineering	Scale: 1 1/2" = 1'-0"
Project: MBMA Moment End-Plate Testing	Drawn By: EAS
Date: 2/28/01	Page: 2 of 5

BEAM #3 & #4

Virginia Tech Department of Civil Engineering

Project: MBMA Moment End-Plate Testing

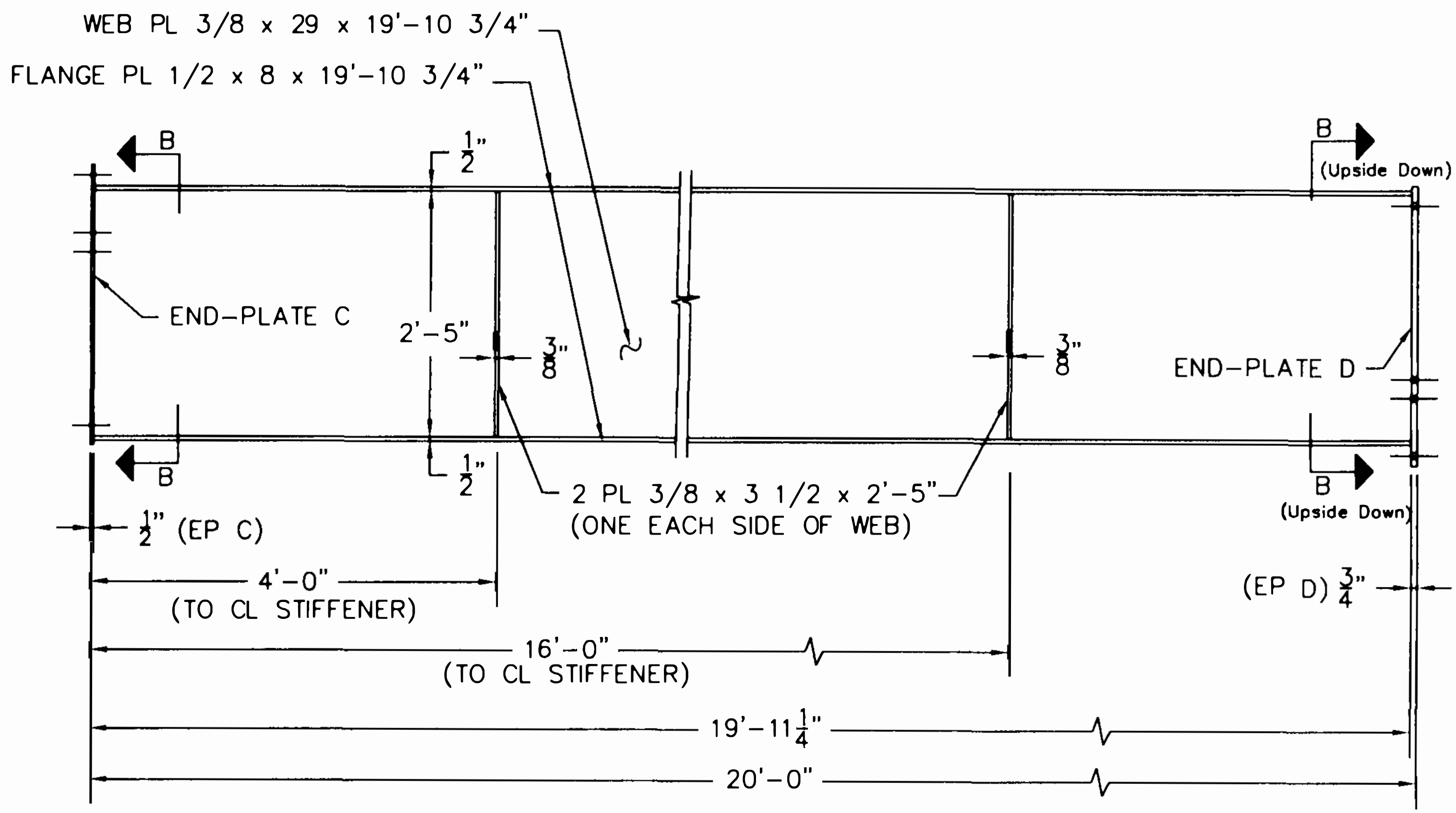
Date: 2/28/01

Scale: None

Drawn By: EAS

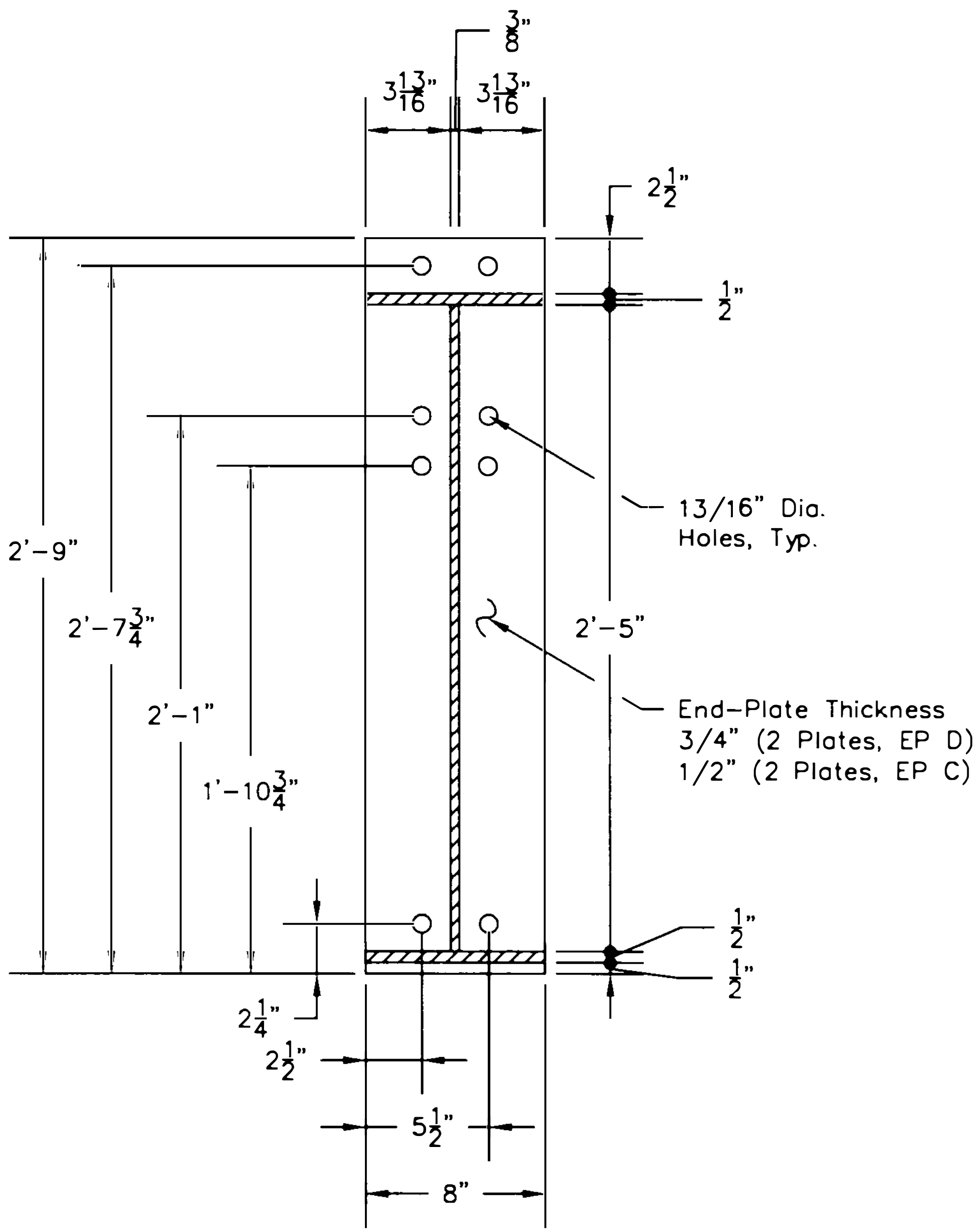
Page: 3 of 5

*NO PAINT



NOTE: A) PROVIDE 24" OF CONTINUOUS WELD AT EACH END
B) ALL STEEL SHALL HAVE A MINIMUM SPECIFIED YIELD STRESS OF 50 KSI.

BEAM LAYOUT (2 REQUIRED)



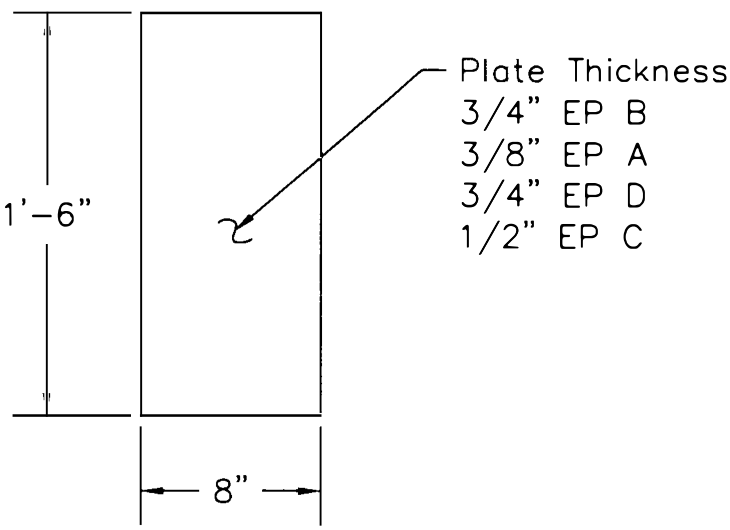
SECTION B-B: END-PLATE LAYOUT

(TYPICAL FOR END-PLATES C & D)

BEAM #3 & #4

*NO PAINT

Virginia Tech Department of Civil Engineering	Scale: 1 1/2" = 1'-0"
Project: MBMA Moment End-Plate Testing	Drawn By: EAS
Date: 2/28/01	Page: 4 of 5



NOTES: 1) PLATE SAMPLES SHALL BE CUT FROM THE SAME PIECE OF PLATE AS THE CORRESPONDING END-PLATE.
2) EACH PLATE SAMPLE SHALL BE MARKED TO IDENTIFY WHICH END-PLATE IT MATCHES.

END-PLATE TENSILE TEST SAMPLES

(ONE SAMPLE IS REQUIRED FOR EACH END-PLATE)

REQUIRED CONNECTION BOLTS

ALL BOLTS SHALL BE 3/4" DIAMETER A325 WITH A563 NUTS.

- END-PLATE CONNECTIONS B & D
  (24) 3/4" x 2 1/2" BOLTS

- END-PLATE CONNECTION A & C
  (24) 3/4" x 2" BOLTS

BEAM #1, #2, #3, & #4

*NO PAINT

Virginia Tech Department of Civil Engineering	Scale: 1 1/2" = 1'-0"
Project: MBMA Moment End-Plate Testing	Drawn By: EAS
Date: 2/28/01	Page: 5 of 5