EVALUATION OF GFRP

FRAMING CONNECTIONS

By

Karl W. Larson

Thesis submitted to the faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Civil Engineering

APPROVED:

Thomas M. Murray, Chairman

W. Samuel Easterling

Don A. Garst

May, 1994

Blacksburg, VA 24061

Evaluation of GFRP

Framing Connections

by

Karl W. Larson

Committee Chairman: Thomas M. Murray

(ABSTRACT)

The objective of this thesis is to verify the assumption of designing the connection as simply supported in a GFRP bonded-bolted framing angle configuration. To achieve this, nine framing angle connection tests were performed. The assumption was found to be valid for the 2 bolt bonded, the 2 bolt unbonded, and the 3 bolt unbonded framing angle connections tested, however, more tests are needed varying different parameters before final conclusions can be reached. Suggestions are made for different areas of possible research into GFRP.

ACKNOWLEDGMENTS

I would like to thank Dr. Thomas M. Murray for his guidance and support throughout my graduate studies and serving as my thesis committee chairman. Also, I would like to thank Dr. Samuel Easterling and Professor Don Garst for serving as thesis committee members.

I would like to thank all the other graduate students at the lab for their support and help with my research and accomplishing the writing of this thesis. A special thanks to the laboratory technicians, Dennis Huffman and Brett Farmer, for their help with my testing. Also I would like to thank Bob Simonds without whom I may have not been able to finish this thesis on time.

I would like to give thanks to my parents and family for supporting me throughout my many years in college. Also I would like to thank my girlfriend, Andrea Kellum, for helping me to keep my sanity throughout my graduate years.

Finally, I would like to acknowledge Morrison Molded Fiberglass Company for their contribution of the materials used in the tests.

TABLE OF CONTENTS

TABLE OF CONTENTS(CONT.)

Chapter | Page

TABLE OF CONTENTS(CONT.)

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES(CONT.)

Table Page

List of Nomenclature

A = Cross-sectional area

b = Length of section

b_f = Length of flange

d = Height of section

E = Modulus of elasticity

E_m = Measured modulus of elasticity

F_{tu}unotched = Tension failure stress of that particular unnotched laminate

f_u = Ultimate flexural stress

G_b = Beam shear modulus

h = Height of section

I_b = The second moment of inertia of the connected beam

K_b = Mean value of I_b/L_b for all beams at the top of the story

K_c = Mean value of I_b/L_b for all columns in the story

L_b = Length of the connected beam

L_c = Story height for a column

M_u = Ultimate moment

r = Radius of gyration

SBS = Short beam shear

List of Nomenclature(Cont.)

S_i = Secant rotational stiffness of the connection

S_x = Section modulus about the x-x axis

t_a = Thickness of angle

t_f = Thickness of flange

TFF = Tension failure factor

t_w = Thickness of web

V_n = Nominal strength of the connection angle

ε = Time dependent creep strain

$\sigma_{\theta 90}$ = Circumferential laminate stress at the edge of the hole 90° from the actual load

Chapter I

INTRODUCTION

1.1 INTRODUCTION

One of the more interesting structural concepts that is currently under development is the use of structural plastics instead of steel or concrete as building materials in construction. Since around the 1960's, there has been a great interest in plastic and its potential use in civil engineering. This interest has motivated many research projects focusing on the use of this material in various civil engineering applications.

For example, one application is the rehabilitation of buildings or bridges after an earthquake. Due to the lightweight nature of structural plastics, the use of a large capacity crane would not be needed. Instead, the structural elements could be carried into the building or attached to the bridge by a low capacity lifting device. This simplification of the construction process makes the installation and erection process much easier to accomplish. However, in the final cost analysis the fact that structural plastics cost more than steel must be taken into account, thus the savings derived from their use may not be very great.

There are several types of plastics available to the engineer with inherently different properties, both material and physical. Due to this nature, the scope of this report will be limited to the GFRP with the tradename of EXTERN produced by Morrison Molded Fiberglass Company (MMFG) in Bristol, VA. This type of plastic consists of glass fibers in a resin matrix and is produced using a process called pultrusion. In this report, this material is called GFRP which stands for Glass Fiber Reinforced Plastic.

1.2 BACKGROUND

In the structural GFRP industry, it is a common practice to recommend the use of an adhesive with a bolted connection to provide the joint with the benefits of both connections. The bolted connection provides the clamping force for the curing of the adhesive and reduces the effects of peel and tension in eccentric joints. In addition, the adhesive connection reduces the stress concentrations in the joint and increases the joint stiffness.(Structural Plastics Design Manual, 1984) However, this increase in stiffness provided by the adhesive may create a connection that is stiff which must be taken into consideration in classifying the type of connection designed.

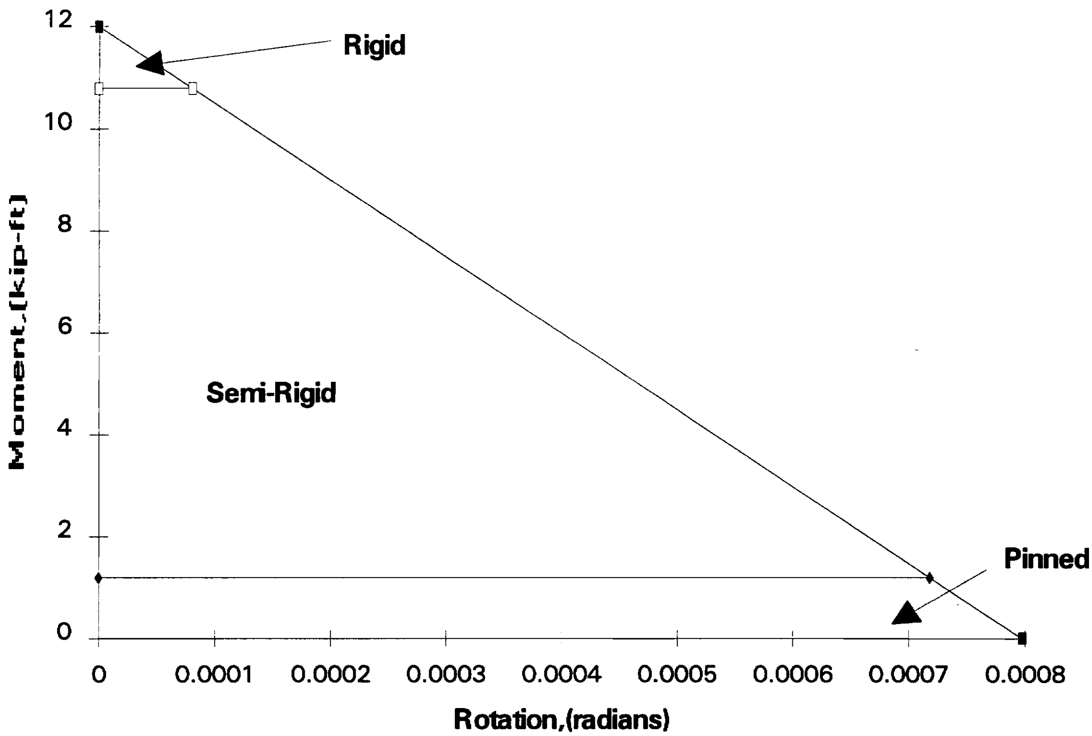
1.3 CONNECTION DESIGN

There are several different methods that have been proposed to classify connections. The three methods that this section will discuss are the method used in the Allowable Stress Design Specification (ASD) (Allowable Stress Design Specification for Structural Steel Buildings, 1989) , the method used in the Load Resistance and Factor Design Specification (LRFD) (Load And Resistance Factor Design Specification for Structural Steel Buildings, 1986), and the method used in the Eurocode3 (Eurocode3, 1992).

In ASD, there are three types of connections, namely rigid (Type I), pinned (Type II), and semi-rigid (Type III). A rigid connection is assumed to have sufficient rigidity to have the angles remain unchanged between connecting members. Pinned connections assume that as far as gravity load is concerned the ends of the beams or girders are connected for shear only and are free to rotate under gravity load. Finally, a semi-rigid connection is assumed to posses a moment capacity between that of a rigid connection and a simple connection.

On the other hand, LRFD has only two types of connections, namely fully restrained(FR) and partially restrained(PR). The pinned connection is not considered to be a classification type in the LRFD specification. A type FR connection is assumed to have sufficient rigidity to maintain the angles between the intersecting angles of the connecting members. A type PR connection is assumed to have insufficient rigidity to maintain the angles between intersecting members.

In both the ASD and the LRFD methods, the type of connection depends on the rotation of the connection given some applied loading and the span of the section. One method of determining the type of connection is to form beam lines for the loading and span being considered comparing the moment applied vs. the rotation at the beam end(Murray, 1993 and Salmon and Johnson, 1990). For example, a W16x26 A36 beam with a distributed loading of 1kip/ft and a length of 12 ft. would have the beam line as shown in Fig. 1.1. In Fig 1.1, the beam line goes from the fixed end moment (12 kip-ft) to the simple rotation (0.0008 radians). Horizontal lines to determine the breaks for the different type of connections are then placed at 0.1 M_f and 0.9 M_f. Using the beam line, the type of connection designed can be determined by examining where the moment vs. rotation curve of the connection lies in relation to the beam line. However, it must be noted that it can not be said that a certain type of connection will only exhibit one classification because the beam line is a function of loading and span.



MF= Fixed end moment

Figure 1.1 Beam Line

The Eurocode3 approaches the classification of connections using a different method of analysis. It starts out relatively the same as the other methods classifying the connections into three different types, specifically, rigid, semi-rigid, and flexible. However, it diverges from there and takes a slightly different approach to the classification of connections. First, the connection can be classified as a simple or nominally pinned connection if its rotational stiffness based on its actual anticipated behavior satisfies the condition in Eqn.1.1.

$$S_i \leq 0.5EI_b / L_b \qquad (1.1)$$

where

S_i = secant rotational stiffness of the connection

I_b = the second moment of area of the connected beam

L_b = length of the connected beam

In a rigid and semi-rigid connections, it must first be decided if the type of connection that is being designed is in an unbraced frame or a braced frame. if Eqn.1.2 is satisfied for every story in the frame, the connection is in an unbraced frame, otherwise it is in a braced frame.

$$K_b / K_c \geq 0.1 \qquad (1.2)$$

where

K_b = mean value of I_b/L_b for all beams at the top of the story

K_c = mean value of I_c/L_c for all columns in the story

I_b = second moment of inertia of a beam

I_c = second moment of inertia of a column

L_b = span of a beam (center-to-center of columns)

L_c = story height for a column

Depending on the type of frame, the moment rotation characteristic curve is then compared to either the braced or unbraced line shown in Fig. 1.2.

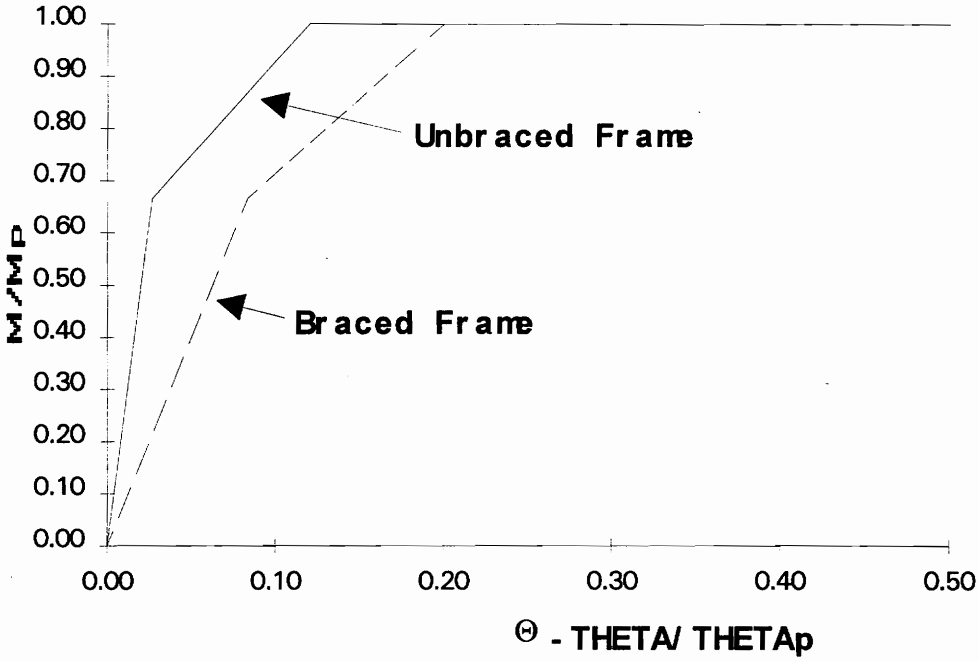


Figure 1.2

Recommended Classification Boundaries For Eurocode 3

Taken from Eurocode3 (Eurocode 3, 1992)

1.4 SCOPE OF RESEARCH

This research involved the use of nine full-scale beam tests to analyze the differences and the behavior of a bolted connection and an adhesive-bolted connection. The type of connection analyzed was a double-angle framing connection with a varying number of stainless steel bolts. The adhesive was an epoxy resin with an aliphatic amine curing agent that has a tradename of Magnobond 24. The capacity, stiffness, and general behavior of each connection tested will be analyzed.

1.5 Overview of Research

In Chapter 2, a literature review is reported on connections in GFRP. The sections cover the two kinds of connections tested, namely bolted connections and adhesive-bolted connections, along with a review of the literature on adhesive connections. Also a review is presented of literature covering the basics of connection design in GFRP.

In Chapter 3, the background on the chemistry and physical characteristics of GFRP is reviewed. Also the material properties of GFRP that must be considered in designing a GFRP connection are reviewed.

In Chapter 4, details of the experimental program are given. The different setups are defined along with the instrumentation and equipment used in each test.

In Chapter 5, the results of the nine tests are given. The failure mode and failure load are analyzed for each test. Also the results are given for the tensile coupon test performed on the material. The effects of the adhesive and the number of bolts are analyzed.

In Chapter 7, a summary of the research conducted as well as recommendations for further research that could be conducted are given.

Chapter II

LITERATURE REVIEW

2.1 Introduction

There are several different types of connections available in GFRP including mechanical connections, adhesive connections, welded connections, and combination connections. Each type of connection has advantages and disadvantages of which an engineer should be aware of in design. This review will only deal with literature about three of these types of connections: mechanical, adhesive, and adhesive-mechanical. The review will begin with some resources that cover the basics of connection design in GFRP and then get more specific literature about the three types of connection mentioned.

2.2 Structural Plastic Connection Basics

A major reference for the general topic of connections in GFRP structural members is "A Report on Current Practice in Structural Plastic Connection: Phase One-Literature Search"(1992) by Robert Austin. This report was prepared for review by the ASCE Materials Committee Structural Plastics Subcommittee and is an excellent beginning resource for an engineer interested in designing GFRP connections. It provides an overview of research done on plastic connections and the recommendations reached by the researchers. However, there are no specific methods given for the determination of the design strength of GFRP connections.

The next significant reference is *Joining Fibre-Reinforced Plastics* (1987) which was edited by F. Matthews. This reference goes into more detail on the design of the two major types of connections used in GFRP, namely, mechanical and adhesive connections. The text provides some methods for determining the design strength of the two types of connections. However, it must be acknowledged that each manufacturer has their own lay-up for the glass fibers in GFRP, so no design formulae are presented. Therefore, each final design is specific for the manufacturer, however the procedures presented are good for preliminary design. The text also provides some procedures for looking at the stresses exhibited in the two different types of connections in GFRP.

Another general reference is the *Structural Plastic Design Manual* (1984) edited by F. Herger. This manual explains the basics for the three most common types of connections employed in structural plastic design, specifically, mechanical connections, adhesive bonding, and plastic welding. However, it does not provide any formulae for determining the design strength of a connection, but instead states that a designer must rely on "joining criteria developed from test and rule of thumb derived from experience."

Next, the manual entitled the *Plastics Engineer Handbook* (1976) provides some of the basics on connection design in GFRP. This reference primarily elaborates in more detail on the basics of the formation of the three major types of connections in GFRP. Again, it does not provide any means of determining the design strength of GFRP connections.

Finally, there is the *Handbook of Fiberglass and Advanced Plastics Composites* (1969). Again, this book provides the basic concepts behind the design of GFRP connections, but does not provide any means of determining the design strength of GFRP connections.

2.3 Mechanical Connections

The first reference on mechanical connections is the journal article "Performance of Pultruded PFRP Connections Under Static and Dynamic Load Conditions"(1993) by Mosallam, Abdelhamid, and Conway. This paper reviews a series of static and dynamic tests made in the development of a universal connector for GFRP. The universal connector consists of a framing angle connection in which both ends of the angles have been stiffened using triangular shaped stiffeners. The researchers tested the universal connector in both the bonded and unbonded configurations. The researchers comes to the conclusion that the universal connector was a success in increasing the strength and stiffness of GFRP connections.

A paper entitled "Design of Glass-Fibre-Reinforced Plastic Bolted Connections"(1993) by Erki, Rosner, and Dutta reviews the material properties of plastics and their influence on the behavior of GFRP connections. The paper presents the results of a computer model to predict the short-term load-displacements of a bolted GFRP connection. However, this model does not account for fatigue, creep, and other time dependent effects that may affect both the strength and stiffness of the connection. Therefore, further investigation of these factors would be required before a final analysis could be reached for GFRP connections.

"Stress and Strength Analysis of Composite Joints Using Direct Boundary Element Method"(1993) by Lin and Lin presents an analysis of the stress distribution and strength of an orthotropic composite plate with a circular hole under uniform loading. The researchers found that stress concentrations increase when the ratio of edge distance to hole diameter increases, and the maximum strength decreases when the ratio of edge distance to hole diameter decreases. The researchers reached the conclusion that for a safe design the ratio of the edge distance to the diameter of the hole should be greater than two in GFRP connections.

"Design and Performance of Connections for Pultruded Frame Structures"(1992) by Bank, Mosallam, and McCoy reviews the experimental and analytical investigation of several beam-to-column connections. The researchers recommend the use of semi-rigid frame analysis in the designing of GFRP connections when the designer has data on the connection rotational stiffness. In the absence of this data, pultruded frames should be designed as hinged frames and not rigid frames.

A paper "Strain-Relief Inserts for Composite Fasteners-An Experimental Study" (1992) by Herrera-Franco and Cloud studies the possibility of relieving the stress at holes in composites through the use of isotropic material inserts. Several tests were performed and reductions in stress were observed for both an epoxy insert and an aluminum insert.

A paper "Simplified Procedures for Designing Composite Bolted Joints"(1990) by Chamis presents procedures for examining several of the limit states involved in GFRP connections. However, these procedures are preliminary and must be accompanied by finite element analysis and testing in order to reach the final design of the connection.

A paper "Beam-To-Column Connections for Pultruded FRP Structures"(1990) by Bank, Mosallam, and Gonsior examines several beam-to column connection tests and investigates the stiffness and strength of each GFRP connection. The moment-rotation curves are given and elastic stiffness coefficients are tabulated for each test. However, no method for determining the design strength of GFRP connections is given.

"Composite Bolted Joint Analysis Programs"(1990) by Snyder, Burns, and Venkayya examines the following composite bolted joint analysis programs available to the designer: A4EJ, BJSFM, SASCJ, SAMCJ, SCAN, and JOINT. This paper primarily was examining these programs from the point of view of aircraft design and not for use in civil engineering structures. It was found that for all the programs studied the user must check the input data against the problem statement and the output data to see if it holds any meaning for the design of the connection. Also in most cases the analysis codes tended to be conservative and in some cases gave over conservative results for the design of connections.

A paper "The Study of the Behavior of a Composite Multi-Bolt Joint"(1989) by Yang and Ye examines a method to compute the bolt forces in a multi-hole composite GFRP joint. The results of the theoretical analysis coincide fairly well with the experimental program. However, more experimentation is required before this model is completely validated.

A paper "Strength of Composite Laminate with Reinforced Hole"(1989) by Lee and Mall examines using reinforcements on circular holes in composites. It was found that, in general, the composite with a reinforced hole showed significant improvement over the strength of a laminate with an open hole. An aluminum insert performed as the best reinforcement. However, this improvement depended on the size of reinforcement with the largest size reinforcement showing the most improvement.

"Observations on Bolted Connections in Composite Structures"(1989) by Marshall, Wood,and Mousley examines a three-dimensional finite element analysis of pin-loaded and bolted holes in composite laminates. The effects of the clamping ratio, stacking sequence, and clamping type were shown to have an influence on the magnitude of the interlaminar normal stress local to the bolt hole. It was observed that the introduction of a clamping load improves the stress state of the joint. However, using an increased clamping load causes an increase in the interlaminar shear stresses at the washer edge. Also it is observed that friction is beneficial in reducing the bearing stresses in pinned joints.

A paper "Modeling Clamp-Up Effects in Composite Bolted Joints"(1987) by Smith, Ashby, and Pascoe proposes a simple three-dimensional approach for predicting bearing stresses at failure in a composite bolted joint. This approach takes into account the load carried as a result of friction between the washers and laminate. The model predicts a strength increase due to initial bolt tightening caused by the confining pressure. It suggests that the initial failure mechanism is a function of clamp up. Next, a parametric study was conducted to evaluate the effects on joint performance of the friction between washers and laminates, washer size, and the properties of laps in joints. It was found that by increasing the friction or the washer size, at a given clamp-up pressure, increases the bearing stress at failure of the composite.

"Elasto-Plastic Failure Analysis of Composite Bolted Joints"(1986) by Tsujimoto and Wilson examines a finite element analysis that was carried out for determining the stresses around a hole in a composite laminate. On the basis of the results of this analysis, a failure criterion was proposed for each of the basic failure modes: bearing, shearout, and net-tension. The results of the failure criteria are then compared to two different 2-D elastic criteria. It is found that the Tsai-Hill elastic 2-D analytical models and the elasto-plastic methods reasonably predict accurate strengths as compared to experimental data. On the other hand, the Tsai-Wu 2-D model was found to be conservative for the bearing and shearout test geometry's, but was accurate for the net tension geometry.

"Pin Bearing Strength of Fiber Reinforced Composites Laminates" (1985) by Mallick and Little examines the results of several pin bearing tests. It was found that the failure mode of the pin in bearing depends on the type of material, ratio of edge distance to hole diameter, and fiber orientation angle. It was also noticed that bolt bearing stresses could be improved if the clamping force of the bolt is increased, but this improvement will level off at high clamping forces.

"The Strength of Bolted Joints in Glass Fibre/Epoxy Laminates"(1985) by Kretsis and Matthews examines several tests performed on single-hole joints in both glass and carbon fiber plastics. It was found that the effects of width, edge distance, hole size, bolt clamping pressure, and stacking sequence were similar for both types of plastics. It was also found that the micromechanism of failure of bolted joints was heavily dependent on the lay-up of the plastic.

A paper "Failure of Composite Laminates Containing Pin Loaded Holes-Method of Solution"(1984) by Chang and Scott presents a method for predicting the failure strength and failure mode of fiber reinforced composites containing one or two pin loaded holes. First, the stress distribution is calculated using the finite element method. Second, the failure load and mode are predicted by means of a proposed failure criterion. The results of this method were then compared to experimental results. It was found that the results of the experimental and theoretical coincided fairly well. However, the method does not account for bolt clamping forces that some studies have said will effect the strength of a joint.

"Comparison of Single and Multi-Hole Bolted Joints in Glass Fibre Reinforced Plastic"(1982) by Pyner and Matthews examines several tests performed on single and multi-hole composite laminates. It is observed that the joint strength decreases as the joint geometry becomes more complex. Also strength data from single-bolt tests should be employed with caution to multi-bolt joints. As the joint becomes more complex the application of single-bolt tests becomes less relevant. It appears that the determination of the strength of multi-hole joints by testing is essential to the design of multi-hole joints.

"Strength of Multi-Bolt Joints in GRP"(1982) by Godwin, Matthews, and Kilty presents the results of an experimental study of multi-hole joints in GFRP under tensile loading. It is found that pitch significantly affects the strength in bolted joints and that a column of bolts is found to be weaker then a row of bolts. The author suggests that the optimum joint geometry is a single row of bolts at a pitch of 2.5 diameters and an end distance of 5 diameters. With this geometry, joint strength is roughly one half gross panel strength and failure is in tension. Increased safety can be obtained by increasing the pitch from 5 to 6 diameters. At this pitch, the failure is in the bearing mode and net joint strength is roughly one-third gross panel strength.

"Single- and Multiple-Bolted Joints in Orthotropic Materials"(1982) by Rowlands, Rahman, Wilkinson, and Chiang evaluates the effect of variations in friction, material properties, load distribution among the bolts, end distance, bolt clearance, and bolt spacing experimentally and numerically for wood and composite bolted joint. It was found that most previous analysises have ignored friction to simplify the analysis. However, this simplification can frequently lead to incorrect results. Nevertheless, the changes in friction only have minimal influence in stiff composites such as fiber glass. In terms of bolt spacing, joint performance is not greatly affected for end distances greater then 4D or bolt spacing greater then 4D. However, the response for bolt spacing greater then 4D should be the subject of further investigation. It was found that a substantial change can occur in joint strength depending on the load distribution between the bolts. For bolt clearance, a large increase in contact radial stresses is observed due to increased bolt tolerances. It is noted that well-fitting pins in reamed holes are needed for good load distribution in composites.

"Analysis of the Net Tension Failure Mode in Composite Bolted Joints"(1982) by York, Wilson, and Pipes presents a semi-empirical strength analysis to predict the net tension strength in composite bolted joints. The method uses a plane-stress finite element analysis to predict the stress state along the net tension plane of the composite. This theoretical model showed good correlation to the experimental data for both pin loading and out-of-plane constraint loading for a range of w/D (width of specimen/hole diameter) ratios. However, this method does require testing to characterize material properties and to determine the functional relationship between the notch sensitivity parameters and the fastener hole radius.

"Stress Distribution Around a Single Bolt in Fibre-Reinforced Plastic"(1982) by Matthews, Wong, and Chryssafitis examines the results of a three-dimensional finite element analysis that show that the stress distributions around a hole depend on whether the load is applied with a bolt or a pin. It is found that significant differences in the stress distribution exist around a hole depending on the type of fastener used in the joint.

A paper "Strength of Mechanically Fastened Composite Joints"(1982) by Chang, Scott, and Springer proposes a method for predicting the failure strength and failure load of mechanically fastened fiber laminates. This method uses Yamada's failure criterion along with a proposed failure hypothesis to predict the failure strength and failure mode. The results generated compared readably well with the experimental testing. Also parametric studies were performed to evaluate the effects of joint geometry and ply orientation on the failure strength and mode.

"Photoelastic Investigation of Bolted Joints in Composites"(1982) by Prabhakaran examines the use of a transmission photoelastic method to study pin-loaded composite models that simulate bolted joints in composites. It was found that the influence of end distance was appreciable for the shortest end distance employed and the effect of material anisotropy was clearly evident by the isochromatic fringe patterns. However, further study needs to be undertaken to obtain the complete stress analysis of the composite hole and to study the effect of different material and erection parameters on composite joints.

"A Finite Element Analysis of Single and Two-Hole Bolted Joints in Fibre Reinforced Plastic"(1981) by Wong and Matthews presents the results of a two-dimensional finite element analysis of bolted joints in fiber reinforced plastics. The effect on the bearing strength due to the width and end distance of a single-hole joint was examined. However, this method must be expanded to include through-thickness stresses and appropriate failure criteria in order to be useful in predicting joint strength.

"Failure of Composite Joints Under Combined Tension and Bolt Loads"(1981) by S. Tang examines the results of an experimental program testing the static strength of composite laminates under combined loading is given. The researcher proposes a tension failure factor (Eqn.2.1) to determine the failure modes of composite laminates subjected to combined tension and bolt load.

$$TFF = \sigma_{\theta 90} / F_{tu} unnotched \qquad (2.1)$$

where

TFF = Tension failure factor

$\sigma_{\theta 90}$ = Circumferential laminate stress at the edge of the hole 90° from the axial load

F_{tu} unnotched = Tension failure stress of that particular unnotched laminate

For the tests done, the theoretical results were validated by the experimental results. However, more testing is needed before this concept will be completely validated.

A paper "Determination of Safety Factors for use when Designing Bolted Joints in GRP"(1979) by Johnson and Matthews examines several tests conducted on single-hole bolted joint specimens to determine a reasonable number for the safety factor. If the limit load is taken as the load that concedes to the development of visible cracking, than the corresponding ultimate factor of safety to predict the maximum load that the joint can sustain is 2.0. It should be noted that in a previously discussed reference, Pyner has discussed the fact the failure loads of single-hole joints cannot always be used to predict the behavior of multi-hole joints. However, the general results of this study using single hole-joints should be applicable to the multi-hole situation.

"Mechanical Connections for Structural Plastics"(1977) by Meyers is a compilation of references and data from several sources on GFRP connections. However, at the time of the paper, little research had been done in civil engineering for the use of plastics. Instead, research into GFRP connections had been focused in the military and aerospace industry.

"The Effect of Clamping Pressure on Bolt Bearing in Glass Fibre-Reinforced Plastics."(1976) by Stockdale and Matthews examines several tests conducted examining the bolt bearing failure modes in composite bolted joints. It was found that by increasing the bolt clamping load the hole bearing failure load was increased. This increase was attributed to the combined effects of restraint provided by the washers and the frictional resistance to slip. It is also noted that the washers should have a reamed hole to match the bolt diameter; however, a reason for doing this is not given.

2.4 Adhesive Connections

The first reference on this topic is a book *Adhesives in Civil Engineering* (1992) by Mays and Hutchinson. This book covers the general topic of the use of adhesives in civil engineering. It discusses the topics of adhesive classification and properties, adhesion and surface pretreatment, behavior of adhesive joints, testing adhesive joints, connections between plastics, and many others. It provides a good basic understanding for the design and performance of adhesive joints in GFRP.

"Simplified Procedures for Designing Adhesively Bonded Composite Joints"(1991) by Chamis and Murthy presents some preliminary design procedures for adhesive joints in GFRP. However, the design must be verified through finite element analysis and testing before final design is reached.

A book *Adhesion and Bonding in Composites* (1990) by Yosomiya, Morimotom, Nakajima, Ikada, and Suzuki provides a good basis for the understanding of the behavior of adhesives in composite joints. It covers such topics as interfacial characteristics, wettability and adhesion, interface analysis of composite materials, and interfacial strength of composite materials.

A paper "Adhesive Bonding of Polymer Composites"(1989) by Vinson presents a review of the literature dealing with adhesive bonding of polymer matrix composites. The paper ends with a few simple design criteria for adhesive joints. The criteria include:

1. Maximum shear stresses and normal stresses in the adhesive can be reduced by making the flexural stiffness and the extensional stiffness as large as possible

2. There is a maximum bond line length beyond which no additional load carrying capacity is possible because the peak shear and peel stresses do not diminish once the ineffective bond length is reached.

3. As the adhesive bond length increases, the failure or yielding of the adherend becomes more likely.

"The Mechanical Testing and Computer Modeling of Composite Bonded Joints"(1985) by Curtis and Ainsworth examines single and double overlap bonded joints without defects. The researchers performed a finite element analysis and found correlation between experimental and theoretical results for the joint configurations considered.

The book *Structural Adhesive Joints in Engineering* (1984) by Adams and Wake covers such topics as the nature and magnitude of stresses in adhesive joints, standard mechanical test procedures, factors influencing the choice of adhesive, surface preparation, and service life.

A paper "A Review of the Strength of Joints in Fibre-Reinforced Plastics: Part 2 Adhesively Bonded Joints"(1982) by Matthews, Kilty, and Godwin reviews the work published to date on the subject of adhesive bonds. It covers the general principles of adhesive bonding and gives some general guidelines for the design of adhesive connections.

"The Science of Adhesion: Part 2 Mechanics and Mechanisms of failure"(1982) by Kinloch reviews the different failure modes for adhesive joints and presents some methods for the design of several connection configurations. However, the paper does point out that before attempting the design of an adhesive joint, the mechanical properties of the adhesive and the GFRP must be clearly known.

A paper "Adhesive Bonding of GRP"(1982) by Bodwitch and Stannard evaluates several acrylic adhesives used to bond GFRP. The influence of glue-line thickness and shear strain rate on the joint strength were investigated as well as the effects of various environmental conditions.

"Adhesive Joints Involving Composites and Laminates. Measurement of Stresses Caused by Resin Swelling"(1981) by Sargent and Ashbee examines the geometry of swelling associated with water intake in composite adhesive joints using an optical interference method. By generating Moiré fringes from the images of the interference patterns and applying the thin plate elasticity theory to the measured deformation of the cove slip, it is possible to determine the swelling stresses that would be encountered in a real joint.

"Stresses in Adhesievly Bonded Joints: A Closed-Form Solution"(1981) by Delale, Erdogan, and Aydinoglu reviews the formulation of a plate theory for looking at adhesive bonded connections. The authors come to the conclusion that for adhesive connections with small adhesive thicknesses a plate theory that properly accounts for the transverse shear effects may be used with some degree of confidence.

2.5 Adhesive-Mechanical Connections

The first reference on adhesive-mechanical connections is a paper "Performance of Pultruded PFRP Connections Under Static and Dynamic Loads"(1993) by Mosallam, Abdelhamid, and Conway. This paper examines the response of a new fiberglass universal connector under static and dynamic loading. The universal connector consists of a framing angle connection in which triangular shaped stiffeners have been added at both ends. For the universal connector, it was observed that under static loads the addition of the adhesive increased the stiffness and the strength of the connection. A rigid assumption was achieved up to a moment of 5 kips-inch , 20% of the ultimate moment capacity. If a rigid assumption is used, it is recommended that a safety factor of 4 or more is used for the connection moment capacity. If the full range of the flexural capacity is desired(F.S.=1.0), a semi-rigid analysis is recommended to achieve a more cost effective structure.

"MMFG Test for Epoxied vs. Non-Epoxied Structural Connections"(1992) presents the results of several short-beam tests on adhesive connections, mechanical connections, and adhesive-mechanical connections. The researchers reach the conclusion that the rigidity of the joint is increased by the inclusion of an adhesive and that the design of the joint is dependent on the understanding of the failure mode of the joint.

A paper "Bonded-Bolted Composite Joints"(1985) by Hart-Smith was prepared for use in the airplane industry so it's application to civil engineering structures is limited. Also, it should be noted that testing was conducted using carbon fiber composites, therefore the application to glass fiber composites is unknown. The researchers examined the use of a simple lap-joint configuration with a bonded-bolted composite joint for use in aircraft. For the use of aircraft, the researchers conclude that a well-designed adhesive joint is just as good as an adhesive-mechanical connection. However, using bolts provides the advantage in heavily loaded structures of impeding any initial damage that would cause failure if the bolts were not used.

Chapter III

Material Characteristics and Properties of GFRP Used in Tests

3.1 Physical Chemistry of GFRP

During this century, organic chemists have developed many new substances with a wide range of possible uses. One such substance that was developed is the super polymers or more commonly called "plastics"(Holmes and Just, 1983).

Plastics are split into two main categories: thermoplastics and thermosets. Thermoplastics are produced using a process called "addition polymerization" which is a chemical process by which a repeating unit is added to the molecular structure. This process makes the thermoplastic have a chain-like nature in its molecular structure. Because of this chain-like nature, the thermoplastic will become hard when cooled and soften when heated. Obviously, this property would not be very beneficial in civil engineering, therefore this type of plastic is not commonly used for civil engineering applications(Holmes and Just, 1983) However, there has recently been the development of some thermoplastics that have a greater tolerance for temperature. Instead of softening at 100°C, this material has the ability to maintain integrity until temperatures as high as

280°C (Hollaway, 1987). Thermosets, however, undergo a further chemical reaction in their formation. This process, called "condensation polymerization," allows the chains of units to be linked together producing a more rigid composition. Due to this cross-linked molecular composition, the thermosets set hard, and cannot be reformed by heating. This property of thermosets makes it a more likely candidate for use in structural applications(Holmes and Just, 1983)).

GFRP is a thermoset and consists of several basic components(MMFG Design Manual, 1989). First, there are two types of glass in GFRP, mat and rovings. The rovings contain 800-4000 fiber filaments and provide the strength along the longitudinal (pultruded) direction of the section. The mat consists of long glass fibers intertwined and bound with a small amount of resin called binder. Because of this intertwined nature, the mat provides the multi-directional strength properties of the GFRP section. Second, there is the resin that binds the reinforcing glass fibers together. A typical resin for GFRP is an isophthalic polyester. This is a general purpose resin and provides good corrosion resistance in various corrosive environments. Also another available resin is a premium grade vinyl ester resin which provides a higher strength and has better corrosion resistance properties. Finally, there is a surfacing veil of a polyester non-woven fabric that encases the glass reinforcement and adds a layer of resin to the surface. This veil protects against "Fiber Blooming" which is the occurrence of glass fibers on the surface of the GFRP.

There are several manufacturing processes that can be used in the manufacture of composites. These include: Cold-Press Molding Techniques, Hot-Press Molding Techniques, Pultrusion, and Resin Injection(Hollaway 1987). The scope of this report will be limited to the materials produced using the manufacturing process called pultrusion(Figure 3.1). The pultrusion process produces continuous lengths of GFRP sections for use in structural and other applications(MMFG Design Manual, 1989). Pultrusion involves pulling the rovings and mats through a resin bath that saturates the glass fibers. The surfacing material is then added to the mix and the material is pulled through a preformer that gradually shapes the material into the desired configuration. These materials are then pulled through a heated steel forming die which activates the bonding process between the resin and the glass. The materials then harden into the shape desired for the section. Finally, the section is cut to the length desired. This process is fairly efficient and can produce a great number of plastic section in a short period of time. In fact, most of the time is spent is setting up the machine and the materials for the section that is needed.

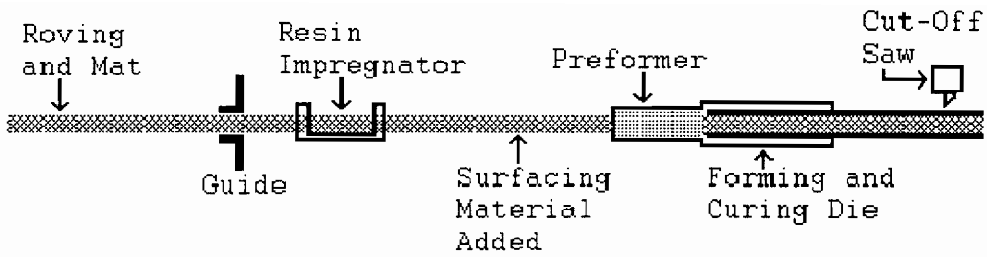


Figure 3.1 The Pultrusion Process

Taken from MMFG Design Manual(MMFG Design Manual,1989)

3.2 Physical Characteristics of GFRP

There are several material characteristics of GFRP that are important to a structural engineer and differentiate it from other materials. They include:

- High Strength
- Lightweight
- Corrosion Resistant
- Non-Conductive
- Electro-Magnetic Transparency
- Dimensional Stability
- Fire Resistance
- Damping Capabilities
- Ultraviolet Radiation Effects

3.2.1 High Strength

GFRP exhibits higher strength when compared to steel on an amount of strength provided per pound of material required basis. This characteristic is due mostly to the lower density of plastics as compared to steel (see Sect. 3.2.2). This strength is primarily obtained from the glass fibers and depends on the type, orientation, quantity, and location of the glass fibers in the section.(MMFG Design Manual, 1989) However in terms of cost, GFRP costs two to three times more per pound than steel. Therefore, at present, if the building can be accomplished using steel, GFRP is not economical. The use of GFRP is limited only to structures that require some of the special material characteristics that GFRP exhibits.

3.2.2 Lightweight

In terms of weight, GFRP is 80% lighter than steel and 30% lighter than aluminum(Table 3.1).(MMFG Design Manual, 1989) This low weight eliminates the need for high lifting capacity cranes in construction. Depending on the size of section needed, they can even sometimes be moved easier by hand. However, the GFRP sections are more susceptible to damage during transportation and handling then steel sections.

Table 3.1
GFRP vs. Traditional Materials w.r.t. Density

Type of Material	Density,(lbs/in^3)
Extern 500/525/625(GFRP)	0.062-0.07
Steel	0.284
Aluminum	0.092
Ponderosa Pine	0.19

Data taken from MMFG Design Manual(MMFG Design Manual,1989)

3.2.3 Corrosion Resistance

Corrosion resistance is one of the primary reasons for shifting from steel or wood to GFRP. This material will not rot and is impervious to a broad range of corrosive environments(Table 3.2).(MMFG Design Manual, 1989)

3.2.4 Non-Conductive and Electro-Magnetic Transparency

GFRP will not conduct electricity. This makes GFRP an excellent insulator for electrical power lines. The possible use of GFRP as the building material for transmission and electrical power towers is presently being studied. Also the possibility exists for using GFRP as a cover for the third rail in subways.(Mosallam, 1993)

Electro-magnetic transparency is another reason to move to GFRP from steel. Essentially, the material allows radio waves, microwaves, and other electro-magnetic frequencies to pass through it.(MMFG Design Manual, 1989) This makes the material an excellent cover for protecting sensitive receiving/transmitting equipment from harmful environmental effects. One of first uses that GFRP saw in its lifetime was use as radomes for covers for radar equipment on ships during World War II(Hollaway, 1990).

Table 3.2
Corrosion Resistance of EXTERN(GFRP) to Selected Chemicals and Products

	Series 500-525		Series 625	
Chemical	R.T.	160°F	R.T.	160°F
Acetone	NR	NR	NR	NR
Diesel Fuel	R	NR	R	R
Fuel Oil	R	NR	R	R
Gas, Natural	R	NR	R	R
Gasoline, Auto	R	NR	R	R
Gasoline, Aviation	R	NR	R	R
Kerosene	R	NR	R	R
Nitric Acid 20%	NR	NR	R	120°
Sulfuric Acid 0-30%	R	R	R	R
Sulfuric Acid 30-50%	NR	NR	R	R
Sulfuric Acid 50-70%	NR	NR	R	120°

R.T.= Room Temperature
R= Resistant
NR= Not Resistant
Data taken from MMFG Design Manual(MMFG Design Manual, 1989)

3.2.5 Thermal Expansion

The coefficient of thermal expansion of GFRP is slightly less than steel and significantly less than aluminum(Table 3.3)(MMFG Design Manual, 1989). This means that under higher temperatures the material will not deform into a different shape. However under high temperatures, there will be a change in the physical properties of GFRP(See 3.4 Temperature Effects).

Table 3.3
Comparison of Coefficient of Linear Expansion for Common Building Materials

Material	Coefficient of Linear Expansion (10^{-6}in./in/°F)
Extern 500/525/625 (GFRP)	5.2
Steel	6-8
Aluminum	13.5
Ponderosa Pine	1.7

Data taken from MMFG Design Manual (MMFG Design Manual, 1989)

3.2.6 Fire Protection

Due to a flame retardent additive, some types of GFRP are resistant to fire. Table 3.4 shows the results of several flammability tests that have been run by MMFG on Extern series 525 and 625 sections.(MMFG Design Manual, 1989) However, if no flame retardent is present, Series 500, this material will easily burn and produce noxious fumes. Therefore, the degree of fire protection needed will determine the type of material to be used on a project.

Table 3.4
Results of Flammability Tests Conducted on Series 525 and 625

	Test	Value
Flammability Classification (1/16")	UL94	VO
Tunnel Test	ASTM E84	25 Max
NBS Smoke Chamber	ASTM E662	650-700(Typical)
Flame Resistance (Ignition/Burn Seconds)	FTMS 406-2023	55/30
Flammability	ASTM D635	Self Extinguishing
UL Thermal Index	(Generic)	130°C

Data taken from MMFG Manual (MMFG Design Manual, 1989)

3.2.7 Damping Capabilities

GFRP has an inherently high loss factor for vibrations unlike steel which has a low loss factor. Several researchers have investigated the damping characteristics of composite materials.

The paper "Characterization of the Vibration Damping Loss Factor of Glass and Graphite Fiber Composites"(1991) by Crane, R. and Gillespie, J. discusses the experimental results of the damping provided by glass and carbon-fiber composites. From testing, it was found that the amount of damping provided by the composite is effected by the fiber type, matrix mix, and fiber orientation.

Another paper "Damping Properties of Fiber Reinforced Composites"(1986) by J. Chottiner, Sanjana, and Kolek discusses several other aspects relevant to damping in composites. This includes such things as the use of additives, use of different resins, and the use of other materials besides glass. The researchers performed several tests on some composite sections that were made using the method of hand dipping.

3.2.8 Ultraviolet Radiation Effects

Ultraviolet light is an environmental attack on GFRP that is produced by sunlight. The surfacing veil is used to give the GFRP some protection from the effects of UV, namely "fiber blooming". Also Extern Series 525 and 625 contain a UV inhibitor to enhance the protection against UV light. The color of GFRP selected also effects the degree of fading from UV light. However, the structural integrity of the GFRP is not effected by fading of the color.(MMFG Design Manual, 1989)

3.3 Material Properties of GFRP

GFRP exhibits several material properties that must be taken into consideration when designing GFRP connections. They are:

- Modulus of Elasticity
- Shear Modulus
- Anisotroic Effects
- Temperature Effects
- Creep Effects
- Brittle Failure
- Manufacturing Effects

3.3.1 Modulus of Elasticity

The modulus of Elasticity of plastic is approximately one tenth that of steel (Table 3.5). Because of this low modulus of elasticity, the design of GFRP sections will normally be controlled by deflection instead of strength(MMFG Design Manual, 1989).

3.3.2 Shear Modulus

The shear modulus of GFRP is also low compared to metals.(G_{GFRP}=4.25*10^5 psi) Due to this low shear modulus, a designer should be aware that shear stresses add deflection to beams beyond the classic model and should be accounted for in the design of GFRP.(MMFG Design Manual, 1989)

Table 3.5
Comparison of Modulus of Elasticity of GFRP vs. Steel

Material	Modulus of Elasticity (10^6psi)
Series 500/525	2.6
Series 500/525 W and I shapes >4"	2.5
Series 625	2.8
Series 625 W and I Shapes >4"	2.5
Steel	29.0

Data taken from MMFG Design Manual and Steel Structures: Design and Behavior (MMFG Design Manual, 1989 and Salmon and Johnson, 1990)

Lawrence Bank proposes one method to account for shear stresses in the paper "Properties of Pultruded Fiber Reinforced Plastic Structural Members"(1989). The solution to the classic analysis for the deflection of composite beams takes the general form:

$$w(x) = f_1(x) / EI + f_2(x) / kAG \qquad (3.1)$$

The researchers propose to modify the equation for use with pultruded FRP beams to:

$$w(x) = f_1(x) / E_b I + f_2(x) / G_b A \qquad (3.2)$$

The term G_b replaces the term kG in the general equation and is not equal to G, the material shear modulus. Using testing to determine these parameters, the designer can then account for the effects of shear stresses on the response of the structure. The researchers found that the effects of shear deflection increase as the section anisotropy ratio(E_b/G_b) increases and as the slenderness ratio (L/r) decreases. It most be noted that in general the effects shear deflection are a function of the span to depth ratio in steel and not a function of the slenderness ratio. The effects of shear deflection are most severe for L/r ratios less than 60. Therefore, it is recommended that the contribution be included in deflection calculations for L/r ratios less than 60.

3.3.3 Anistropic Effects

Unlike steel, GFRP is not a homogeneous material. GFRP exhibits different material properties along its major axes and the designer should be aware of this effect in design (Table 3.6). For example in tension, the strong axis will be in the pultruded direction and the weak axis will be perpendicular to the strong axis.

3.3.4 Temperature Effects

In GFRP, the material properties are temperature dependent (Table 3.7). At low temperatures, there is no problem with a decrease in material properties. In fact, the beam will even experience an increase in material properties. However at high temperatures (above 150°F), the material will experience material property degradation and should account for this in design (MMFG Design Manual, 1989).

Table 3.6
Comparison of Selected Material Properties of Common Building Materials LW and CW

Property	Extern 500/525	Carbon Steel	Aluminum	Ponderosa Pine
Tensile Strength LW,(ksi)	30	60	45	0.42
Tensile Strength CW,(ksi)	7	60	45	-----
Flexure Strength LW,(ksi)	30	60	45	15.4
Flexure Strength CW,(ksi)	10	60	45	9.4

Data taken from MMFG Design Manual (MMFG Design Manual, 1989)
LW= Length Wise CW= Cross Wise

Table 3.7
Approximate Retention of Mechanical Properties of EXTERN at Elevated Temperatures

	Temperture (°F)	Series 500/525	Series 625
Ultimate Stress	100	85%	90%
	125	70%	80%
	150	50%	80%
	175	NR	75%
	200	NR	50%
Modulus of Elasticity	100	100%	100%
	125	90%	95%
	150	85%	90%
	175	NR	88%
	200	NR	85%

Data taken from MMFG Design Manual (MMFG Design Manual, 1989)

3.3.5 Creep Effects

In GFRP, the glass reinforcement is resistant to the effects of loading over a period of time. However, the resin is effected by the duration of loading. Therefore, the effect of creep in a beam is dependent on the quantity and type of glass reinforcement present in the beam. If the glass to resin ratio is increased, the effect of creep in the beam is decreased.(Homes and Just, 1983)

A method to account for creep is proposed by Bank and Mossallam in the paper "Creep and Failure of a Full-Size Fiber Reinforced Plastic Pultruded Frame"(1990). It is proposed to use Findley's power law of creep to account for creep in GFRP sections (Eqn.3.3).

$$\varepsilon = \varepsilon_o + \varepsilon_m (t / t_o)^n \qquad (3.3)$$

where

ε =time dependent creep strain   t=time

ε_o and ε_m = functions of stress t_o=constant taken as unity

n = independent of stress

t = time

This general form of Finley's power law of creep can then be used to derive a viscoelastic modulus for the material using a procedure described in the Structural Plastics Design Manual(Structural Plastics Design Manual, 1984). The stress dependence of ε_o and ε_m can be represented by hyperbolic functions and the equation takes the following form (Eqn.3.4).

$$\varepsilon = \varepsilon'_o \sinh(\sigma / \sigma_o) + \varepsilon_t (t / t_o) \sinh(\sigma / \sigma_t) \qquad (3.4)$$

This form of the equation can be rewritten to obtain relationships for a viscoelastic modulus (Eqn.3.5).

$$E_v = \frac{E_o E_t}{E_t + E_o t^n} \qquad (3.5)$$

where

$E_t = \sigma_t / \varepsilon_t = \sigma / m$

$Eo = \sigma_o / \varepsilon_t'$

This model for creep has been validated over a period of 26 years by Findley,"26-Year Creep and Recovery of Poly(Vinyl Chloride) and Polyethylene" by William Nichols Findley, and is the method recommended by the ASCE Structural Plastics Design Manual to account for creep in plastics.

3.3.6 Brittle Failure

Structural plastics tend to have a very brittle failure mechanism. Unlike a steel connection, GFRP is unable to redistribute localized stresses within a bolt group. Therefore, GFRP tends to have almost no yielding plateau as compared to steel which has a large yielding plateau (Austin, 1992).

3.3.7 Manufacturing Effects

The manufacturing processes used to make the composite effects the internal structure of the composite. Composites which have been formed under pressure generally will have a higher fiber volume fraction than those which have been manufactured by hand. Also the method of manufacture will effect the degree of impregnation of the fiber into the resin matrix (Hollaway, 1990)

Chapter IV

EXPERIMENTAL PROGRAM

4.1 EXPERIMENTAL TEST PROGRAM

An experimental test program was developed to test the validity of using a simply supported design assumption for the design of GFRP bonded-bolted double framing angle connections. The program consisted of nine tests of two different connection configurations. The tests were divided into three series, differing by the number of bolts used in a row of the connection and the span. The first series used a double angle framing connection with two bolts in a row and a 10 ft. span in both the bonded and unbonded configuration. The second series used a double angle framing connection with three bolts in a row and a 10 ft. span in both the bonded and unbonded configuration. The third series used a double framing angle connection with two bolts in a row and an 8 ft. span in the unbonded configuration.

Table 4.1 is the test matrix. Each test is identified as follows:

- The first number denotes the test series: I, II, or III
- The next number denotes the number of bolts in a row: 2 or 3
- The next letter denotes either or bonded or an unbonded connection: B or U
- The next number denotes the test number in the series: 1 or 2
- The next letter, s, denotes a span of 8 ft. instead of 10 ft.

Test data and results are found in Appendices A through D. For simplicity in further discussions, The Tests will be refered to sequentially by the numbers 1 through 9.

Table 4.1

Test Identification Table

Test No.	Test Id.	Series	Bolts in a Row	Hole Size (in.)	Span (ft.)	Bonded/ Unbonded
1	I-2bU1	I	2	3/8	10	U
2	I-2bU2	I	2	3/8	10	U
3	I-2bB1	I	2	3/8	10	B
4	II-3bU1	II	3	3/8	10	U
5	II-3bU2	II	3	3/8	10	U
6	I-2bB2	I	2	3/8	10	B
7	III-2bU1s	III	2	3/8	8	U
8	III-2bU2s	III	2	3/8	8	U
9	II-3bB1	II	3	3/8	10	B

4.2 Components of Test Assemblies

Beams and Angles. A W 8x8x3/8 beam and a ∠3x3x3/8 angle were used for all tests. The cross-section dimensions of the beam and angle were fairly uniform for all nine tests. Cross-section dimensions and section properties of the beams and angles are given in Appendices A though C.

Column. A W 6x6x1/4 beam section was used as the column in all tests. Cross section dimensions are given in the appendices

Bolts and Washers. For each test, 3/8" ∅ x 2" 304SS bolts with hex nuts and 2 washers were used.

4.3 Test Set-Up

4.3.1 Test Setup: Test 1 and Test 2

In Tests 1 and 2, the test set-up consisted of the following. The test beam apparatus was assembled as seen in Fig. 4.1. In bonded connections, the connection surfaces were sanded to remove the surfacing material in order to provide a better bonding surface. Two short angle sections were attached to the bottom of the test set-up beam at the free end and at the column to provide lateral support using eyehooks, cables, and turnbuckles. This setup was then placed in a Satech 300 kips capacity Universal testing machine. The loading was distributed from the loading head of the Satech using a spreader beam and two rollers as shown in Fig. 4.1. The loading rate was controlled using a computer control connected to the Satech loading machine. The only difference between Test 1 and Test 2 was in the instrumentation as will be explained in Section 4.4.

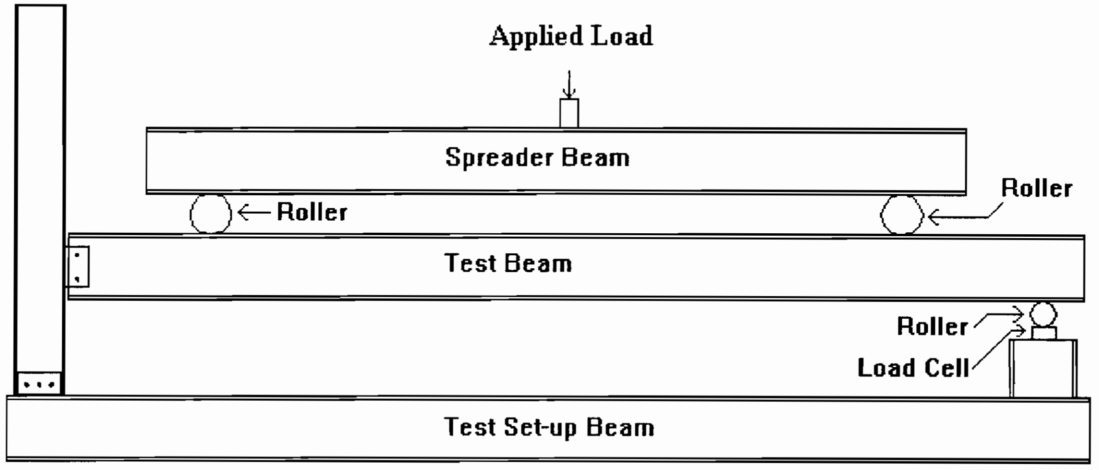


Fig. 4.1 Test Assembly

4.3.2 Test Set up: Test 3 through Test 9

During Test 3, it was noticed that some problems with torsion were occurring with the testing assembly. The Test Set-Up Beam was twisting and sliding out of the Universal Testing machine. In order to stiffen the assembly, it was necessary to move the assembly from the Universal Testing machine to the laboratory reaction floor. The test assembly was then laterally supported at both ends and at the center. Also stiffeners were added to the test assembly and the spreader beam at load points to help prevent further problems. The loading was than applied using a hydraulic ram and pump system. This was controlled using a thumb trigger, so the rate of loading was not as accurate as with the Universal Testing machine.

4.4 Test Instrumentation

In Test 1, the following instrumentation was used. The computer control for the Satech gave the applied load for the test. A load cell placed at the free end, measured the reaction resulting in only two unknowns: reaction and moment at the column. Two displacement transducers were placed at the midspan to measure deflection. Finally, four potentiometers were placed horizontally at the connection in an attempt to measure rotation(see Fig. 4.2). Because a potentiometer malfunctioned in Test 1, this assembly was changed to having two potentiometers measure the vertical slip at the connection for Test 2 and all future tests(see Fig. 4.3). In all other tests, the only addition to the instrumentation was a load cell to measure the applied load by the hydraulic system.

4.5 Load Program

In tests 1 and 2, the load was applied at a loading rate of 500 lbs/min by the computer control until failure or the test was halted. In tests 3 through 9, the load was applied gradually in 2 kips increments by a thumb trigger until failure or the test was halted.

4.6 Test Failure Determination

The following criteria were used to determine the failure of a connection in all tests. If parts of the connection or beam cracked, failure was determined to have occured and the loading was stopped. Next, if the test assembly was about to fail then loading was stopped. If loading was stopped due to an impending test set-up failure, it was then determined if the connection assembly had been damaged by the loading. If damage had occured, it was then determined if re-testing the connection would provide any beneficial results.

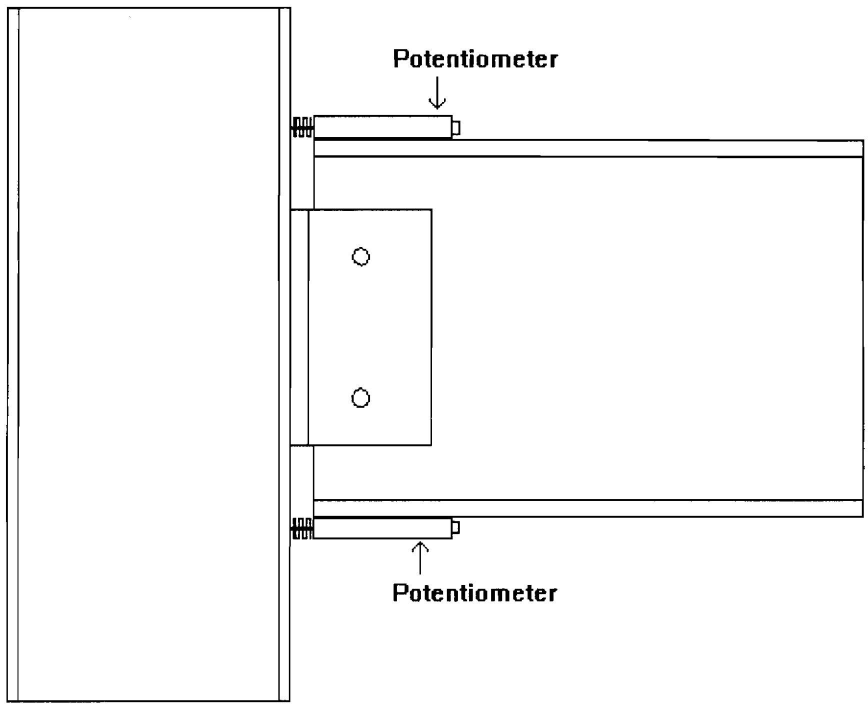


Fig 4.2 Test Instumentation Test 1

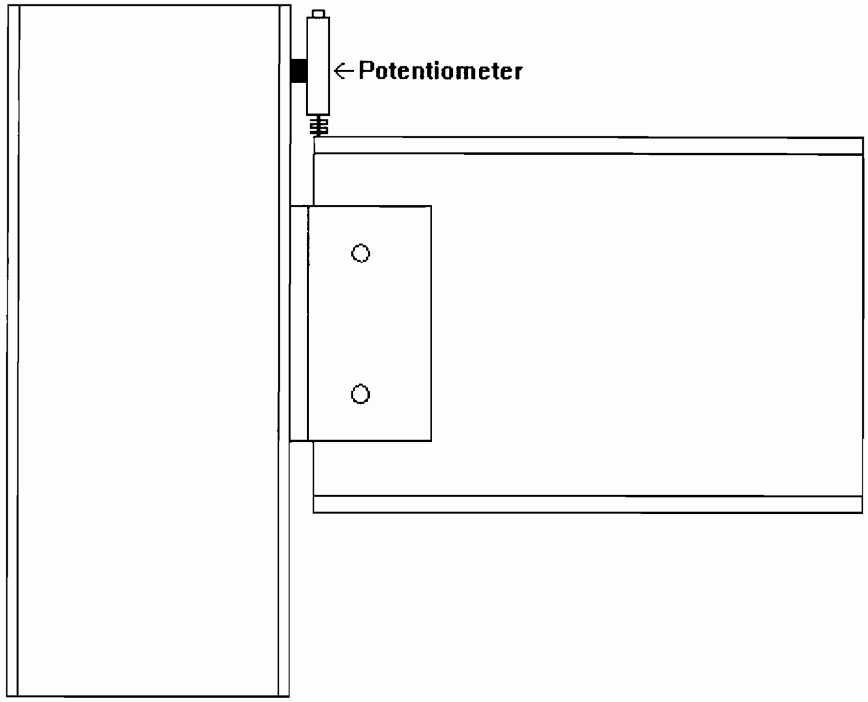


Fig. 4.3 Test Instrumentation Test 2 through Test 9

Chapter V

EVALUATION OF TEST RESULTS

5.1 Introduction

Complete results for Test 1 through 9 are found in Appendices A through C, respectively. Each set of test results contains a test summary sheet, plots of applied load versus deflection(see Fig. A1), plot of applied load vs. deflection on each side of the test beam(see Fig. A2), plots of load vs. slip at the column(see Fig. A3), plots of load vs. reaction at the free end(see Fig A4), and plots of applied load vs. moment at the column, (see Fig A5). The theoretical deflections were calculated assuming elastic material properties, full section properties, the measured modulus of elasticity for each beam (see Sect. 5.1), and neglecting shear deformation. The moment at the column was calculated by taking the sum of the moments equal to zero at the column. The shear at the column was calculated by summing the vertical forces except at failure where an assumption of one-half the applied load was used. This assumption was used due to the fact that the instrumentation used did not continuously read the shear at the free end. Therefore, this point was missed in data recording. However, beacuse throughout all tests the reaction at the free end was close to one-half the applied load, an assumption of one-half the applied load was used.

5.1 Tensile Coupon Test Results

Coupons were taken from the three beams used in the tests and material property tests were conducted. For beam 1, the tests were conducted by the laboratory at Morrison Molded Fiberglass Company. For beams 2 and 3, the tests were conducted at Virginia Tech. The coupons were machined, and tests were performed according to ASTM standard specifications. Table 5.4 shows the measured modulus of elasticity, ultimate load, and ultimate stress for each coupon tested. A summary of all coupon test results and the test summaries of each coupon test done at Virginia Tech are given in Appendix D.

Table 5.1

Tensile Coupon Test Results

Beam	Measured Modulus of Elasticity (ksi)	Ultimate Load (kips)	Ultimate Stress (ksi)
1	2.866	10.59	36.77
2	3.328	12.22	42.14
3	2.898	12.61	43.48

5.2 Predicted Failure Loads

The failure load of the test beam is needed to ensure that the connection will fail before the beam. In predicting the failure load of the beam the following equation was used:

$$M_u = f_u \text{ x } S_x \qquad (5.1)$$

where

M_u = Ultimate moment

f_u = Ultimate flexural stress, (psi)

S_x = Section modulus about the x-x axis, (in.^{3})

Nominal ultimate flexural stress, 16,685 psi, and section modulus, 24.80 in.^{3} were obtained from the MMFG Design Manual (MMFG Design Manual, 1989). It should be noted, That nominal ultimate flexural stess was obtained by MMFG by performing full scale beam tests to the test the flexural capacity of the beam and not from tensile coupon tests. This means that for a W8x8x3/8 beam the ultimate moment would be:

$$M_U = 12{,}685 \text{ psi x } 24.80 \text{ in.}^3$$
$$= 26.2 \text{ kip-ft.}$$

This means that assuming a simply supported connection the beam with a= 1 ft. 5 3/4 in., distance from the column and free end to the point of application of the load, would fail at a shear load at the coumn of 17.7 kips which is greater then the predicted failure load of the connection of 16.88 kips (see below). Therefore, the connection should fail before the test beam in series I and II. In series III, assuming simply supported and a= 2.33 ft. means that the beam would fail at the connection at a load of 11.24 kips which is less than the predicted load of the connection of 16.88 kips. However, because none of the connections tested except for the bonded three bolt connection comes even close to the predicted failure load for the beam the connection should still fail before the beam.

To accurately determine the failure load of a double framing angle connection the following limit states must be analyzed.

- Beam Gross Shear
- Block Shear (Beam Side)
- Bearing/Tearout (Beam Side)
- Bolt Shear (Beam Side)
- Net Shear of the Angle (Beam Side)
- Block Shear of the Angle (Beam Side)
- Bearing/Tearout of the Angle (Beam Side)
- Gross Shear of the Angle at the Heel
- Flexure Rupture of the Angle
- Net Shear of the Angle (Column Side)
- Block Shear of the Angle (Column Side)
- Bearing/Tearout of Angle (Column Side)
- Bolt Shear (Column Side)
- Bearing at the Column Flange
- Tear Out of the Column Flange From the Column Web

At present, there is no accurate method for determining the failure loads for many of these limit states in composite connections. The only material properties for which standard tests are associated are tensile strength, flexural strength, compresive strength, bearing strength, compresive shear strength, modulus of elasticity, and short beam shear strength. These properties are determined using ASTM standard material property tests.

The main material properties of interest in this research are the modulus of elasticity of the beam and the short beam shear strength of the angle. The modulus of elasticity is needed to calculate a theoretical applied load vs. deflection plot. The short beam shear strength as this is the industry standard for designing framing angle connections (MMFG Design Manual, 1989). To calculate the strength of a framing angle connection the following equation is used(MMFG Design Manual, 1989):

$$V_n = SBS \times (h \times t_a \times 2) \qquad (5.2)$$

where

V_n = Nominal strength of the connection angle

SBS = Short beam shear value determined using ASTM D2344

h = the height of the angle

t_a = thickness of the angle

The value for the short beam shear was taken as the the nominal value of 4500 psi (MMFG Manual, 1990) because no other data was available. The equipment necessary to perform short beam shear tests were not available as part of this project.

Several assumptions are made in the application of Equation 5.2 to the design of this connection. First, the short beam shear test predicts the shear strength by loading the coupon perpendicular to the direction of the fiber layers. However, the angle is loaded parallel to the direction of the fiber layers in the test setup. Second, The test is perfomed on a 1 3/4 inch square coupon of the composite. The application to a 10 ft. span beam with a framing angle connection from this small coupon is highly debatable. Obviously, there would be different loading and diferent interaction among the fibers in a framing angle connection with a long beam span.

5.3 Test Results Series I

Four tests were conducted in Series I. A series 500 Extern W8x8x3/8 with a double angle framing connection using a 3x3x3/8 angle and connected to a W6x6x1/4 column were used. Test 1 and 2 were unbonded, while Tests 3 and 6 were bonded. The span length for all tests was 10 ft.

The failure mode for Tests 1 and 2 was fairly similar consisting of net shear along the bolt line in one angle and gross shear in the corner of the other angle(See Fig. 5.1). However, the angle in which net shear occurred switched sides between Test 1 and Test 2. Also in both Tests 1 and 2 there were bearing failures at the bolt holes in both the column flange and the web of the beam. The failure mode for Test 3 was a shear crack forming in the web of the test beam starting at the bottom bolt(See Fig. 5.2). In Test 4, the connection was not taken to failure to ensure that the beam could be used for Series II

Test 3. The maximum load applied at the connection was 6 kips. A summary of the test results for Series I is found in Table 5.2.

Fig. 5.1 Typical Angle Failure

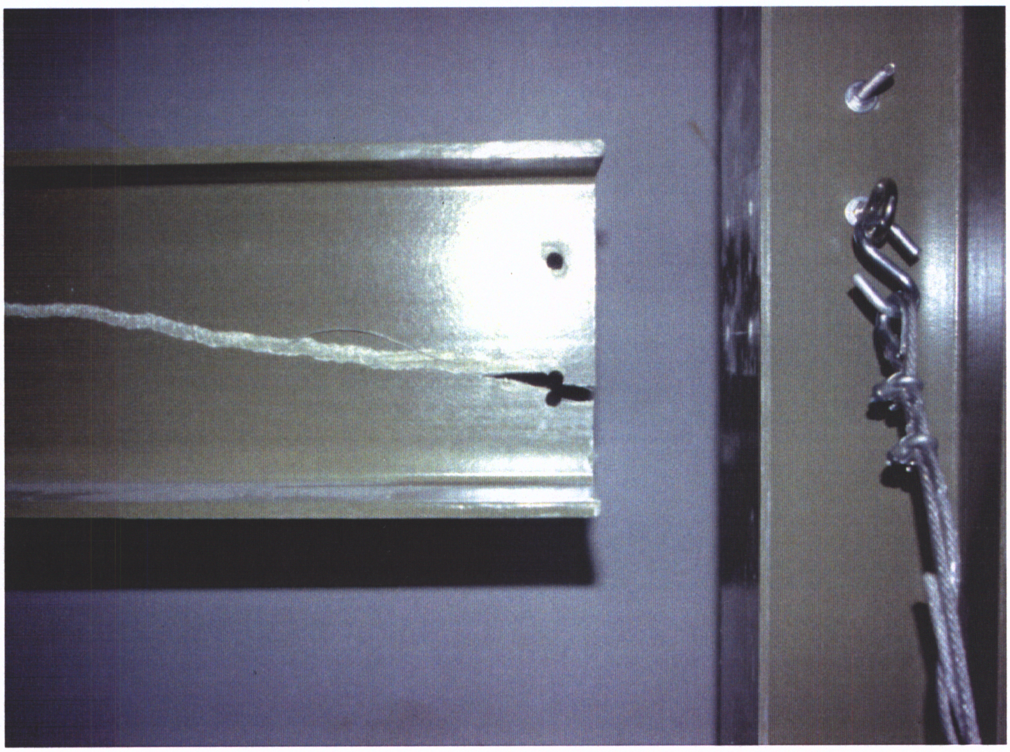


Fig. 5.2 Typical Beam Failure

In comparing the predicted failure load (Equation 5.1) to the actual failure load, it was found that the actual Factor of Safety was 1.5 for the unbonded connections and 2 for the bonded connections in this series. This is a substantail reduction when compared to the factor of saftey of 4.0 which is used in the design of these connections (MMFG Design Manual, 1989).

In looking at the moment at the column, it was found that the actual moment was 2.6 % of the ultimate moment of the beam in the unbonded connection and was 10.3 % of the ultimate moment of the beam in the bonded connection.

Table 5.2

Series I Test Results

Test No.	Test Id.	E_m (ksi)	Failure Mode	Predicted Failure Mode	Failure Load (kips)	Predicted Failure Load (kips)	Failure/ Predicted x100%
1	I-2bU1	2.866	NS&GS	GS	6.50	16.88	38.5
2	I-2bU2	2.866	NS&GS	GS	6.58	16.88	39.0
3	I-2bB1	2.866	SC	GS	9.20	16.88	54.5
6	I-2bB2	2.898	N/A	GS	6.00*	16.88	N/A

E_m= Measured Modulus of Elasticity

NS = Net Shear of Angle

GS = Gross Shear of Angle

SC = Shear Crack Formed in Web of Beam

N/A= Not taken to failure

* Max Load at connection before testing was stopped

Predicted Failure Load = 4500psi x 2 x 0.375 in. x 5 in. / 1000 lbs/kips

= 16.88 kips

5.4 Series II Test Results

Series II consisted of three tests. A series 500 Extern W8x8x3/8 with a double angle framing connection using a 3x3x3/8 angle and connected to a W6x6x1/4 column were used for Tests 4 and 5. In Test 9, the connection was bonded and a series 525 Extern beam was used instead of a series 500 beam. The span length for all tests was 10 feet.

The failure mode for Test 4 was gross shear in the corner of one angle(see Fig. 5.1). In Test 5, the failure mode was a shear crack forming in the web of the beam(See fig. 5.2). In both Tests 4 and 5, there were bearing failures at the bolt holes in the flange of the column and the web of the beam. In Test 9, the test was halted due to an imminent failure of the test set-up. The maxium applied load at the connection was 14 kips. Summary of the test results for Series II is found in Table 5.2.

In comparing the predicted failure load vs. the actual failure load, it was found that in Test 1 and Test 2 the average factor of safety was closer to 2.25. In the bonded configuration, it was found that the actual factor of safety was 3.3. This is a substantail reduction in the unbonded case when compared to the factor of saftey of 4.0 which is used in the design of these connections (MMFG Design Manual, 1989).

In comparing the moment at the column, it was found that the maximum moment was 9.2% of the ultimate moment of the beam in the unbonded case and 10.6% of the ultiimate moment of the beam in the bonded case.

In Test 9, the distance from the column and free end to the point of application of the load was varied from a = 4 ft. to 1 ft. 5 3/4 in. The behavior of the beam was fairly similiar for all values of "a" tested. The average moment at the column for all tests was 7.5% of the ultimate moment.

Table 5.3

Series II Test Results

Test No.	Test Id.	E_m (ksi)	Failure Mode	Predicted Failure Mode	Failure Load	Predicted Failure Load	Failure/ Predicted x100%
4	II-3bU1	3.328	GS	GS	8.15	16.88	48.3
5	II-3bU2	3.328	SC	GS	10.65	16.88	63.1
9A	II-3bB1	2.898	N/A	GS	2.5	16.88	N/A
9B	II-3bB1	2.898	N/A	GS	3.0	16.88	N/A
9C	II-3bB1	2.898	N/A	GS	4.0	16.88	N/A
9D	II-3bB1	2.898	N/A	GS	14.00*	16.88	N/A

E_m= Measured Modulus of Elasticity

NS = Net Shear of Angle

GS = Gross Shear of Angle

SC = Shear Crack Formed in Web of Beam

N/A= Not Taken to Failure

* Max load reached before testing was stopped

Predicted Failure Load = 4500psi x 2 x 0.375 in. x 5 in. / 1000 lbs/kips

= 16.88 kips

5.5 Series III Test Results

Series II consisted of two tests. A series 500 Extern W8x8x3/8 with a double angle unbonded framing connection using a 3x3x3/8 angle and connected to a W6x6x1/4 column were used. The span length for all tests was 8 ft.

The failure mode for Test 7 was net shear along the bolt one in one angle and gross shear in the corner of the other angle(see fig. 5.8). The failure mode for Test 8 was the formation of a shear crack in the web of the beam(See fig.5.9). In both Tests 7 and 8, there were bearing failures at the bolt holes in the flange of the column and the web of the beam. The test results for Series III are shown in Table 5.3.

In comparing the predicted failure load vs. the actual failure load, it was found that the average actual factor of safety was 2.25 instead of 4.0. This is a substantail reduction when compared to the factor of saftey of 4.0 which is used in the design of these connections (MMFG Design Manual, 1989).

In comparing moments, it was found that the moment at the column was 7.3% of the ultimate moment.

Table 5.4

Series III Test Results

Test No.	Test Id.	E_m (ksi)	Failure Mode	Predicted Failure Mode	Failure Load	Predicted Failure Load	Failure/ Predicted x100%
7	III-2bU1s	3.328	NS&GS	GS	8.05	16.88	47.7
8	III-2bU2s	3.328	SC	GS	9.05	16.88	53.6

E_m= Measured Modulus of Elasticity

NS = Net Shear of Angle

GS = Gross Shear of Angle

SC = Shear Crack Formed in Web of Beam

N/A= Not Taken to Failure

Predicted Failure Load = 4500psi x 2 x 0.375 in. x 5 in. / 1000 lbs/kips

= 16.88 kips

5. 6 Effect of Test Parameters On System

5.6.1 Effect of Number of Bolts

The addition of one bolt in the unbonded configuration in Series II increased the strength by about 30% when compared to Series I. In the bonded configuration , a strength increase of 34% was seen between Series I and Series II.

There was only a significant increase seen in the unbonded configuration and only a slight increase seen in the unbonded configuration between Series I and Series II. In looking at Series I and Series III, it is interesting to note the difference in the amount of moment at the column. In the unbonded connection, there is a 28% increase between series I and II and a 36% increase seen between Series I and Series III. The difference between Series I and II is hard to expain unless one notes the fact that this was the point that the test set-up experienced a major change. There was a change in the rate of loading because in Tests 1 and 2, the universal testing machine controlled the rate at which the beam was loaded, while in other tests the rate of loading was controlled by a thumb trigger. This slower rate of loading in Tests 1 and 2 means that the system had more time to distribute the forces being applied to the connection. This time dependent property of behaving differently under different loading rates is an important property of composite (see section 3.3.5 Creep Effects). Another point to make is that in terms of stiffness all of the unbonded connections were under 10% of the ultimate moment of the beam. This means that the design of these connections using a simply supported assumption would be acceptable.

5.6.2 Effect of Adhesive

The addition of the adhesive caused an increase in strength of about 30% in the strength of the two bolt connection. In the three bolt connection, there was only a 12% increase in strength seen between the bonded and unbonded connection.

In terms of stiffness, a slight change was noticed between the bonded and unbonded connection. The load deflection plots for the bonded connections fairly closely resemble the load deflection plots for the unbonded connections. However, there was a slight increase in the amount of moment at the column of the connection. In the bonded configuration, the 2 bolt bonded connection and the 3 bolt bonded connection were both over 10% of the ulitmate moment of the beam. This means that it would be acceptable to design the 2 bolt bonded connection and the 3 bolt bonded connection as partially restrained.

CHAPTER VI

SUMMARY, OBSERVATIONS, AND RECOMMENDATIONS

6.1 Summary

The primary objective of this research was to determine the effects of the use of an adhesive in a GFRP connection. The effects of the number of bolts and use of an adhesive were evaluated in this study. The results from three series of tests were used to determine the effects of these parameters.

When data from the tests is compared, it was noticed that the results from all series were fairly close in terms of stiffness except for Tests 1 and 2 (see Sect. 5.7.1). However, an increase in strength is found between Series one, 2 bolt confiuration, and Series two, 3 bolt configuration, and between Series one, two bolt configuration long span, and Series three, two bolt configuration short span. This causes the conclusion to be reached that the inclusion of a third bolt in a double framing angle connection increases the strength, but does not greatly increase the stiffness. In terms of the use of an adhesive, it was found that the adhesive effected the strength and the stiffness of the connection. Both the 3 bolt and 2 bolt bonded connection had a moment greater than 10 % of the ultimate moment of the beam, thus forcing a partially restrained assumption to be used in the design of these connections.

6.2 Observations

At present, there is no standard fiber placement for GFRP materials. Each company has trademarked the design and placement of the glass fibers in their structural shapes. This creates a problem that no research at present can be taken to be valid for a different company's material without investigating the placement of the fibers. This is due to the face that the number and placement of the glass fibers effects the strength and response of the structural shapes. Therefore, some type of standard cross-sections with given fiber placement should be implemented.

Another observation is noticed when the failure loads and failure modes are examined for all tests. There seems to be some scatter in the limit states and which will control the ultimate load of the connection. For example in Tests 5 and 6, the same connection failed in both shear of the angles and a shear crack forming in the web of the beam.

Finally, this is a very soft material and this property makes for some interesting problems concerning highway bridges and walkways. The potential for vandalism is great on these type of structures. Unlike steel, the vandals could easily damage the load carrying capacity of the structure. To make repairs would be impossible because there is no means to rejoin glass fibers.

6.3 Recommendations

1. In terms of material testing at present, a short beam shear test is done to investigate shear in the beam. The use of the results of this test being used in large scale tests is not acceptable. Therefore, some type of shear test should be developed that can account for the effects of a longer span lengths and connection complexity.

2. The use of a simply supported assumption for design is acceptable for the connection configurations tested for the 2 and 3 bolt case. However, the use of the adhesive in both 2 and 3 bolt case must be designed using a partially restrained assumption. However, further research varying different parameters of the connection configuration should be taken before general conclusions can be reached.

3. Material tests and design calculations should be developed to address all limit states in GFRP bolted and adhesive-bolted connections.

References

Chapter I

1. *Manual of Steel Construction Allowable Stress Design*, American Institute of Steel Construction, Washington D.C, 1989.

2. *Manual of Steel Construction Load and Resistance Factor Design*, American Institute of Steel Construction, Washington D.C, 1986.

3. "Eurocode 3: Design of Steel Structures European Committee for Standardisation", European Comunity, Brussels, Belgium, 1993.

4. Murray, Thomas, "Class Notes of CE6434 Advances Topics in Steel Design", Virginia Tech, Blacksburg, VA, Fall 1993.

5. Salmon, Charles and Johnson, John, *Steel Structures Design and Behavior*, Harper & Row Publishers, New York, 1990.

6. *Structural Plastics Design Manual*, American Society of Civil Engineers, New York, 1984.

Chapter II

Section 2.2

1. Austin, Robert, "A Report on Current Practices in Structural Plastic Connections: Phase One-Literature Search", Report Prepared for Review by the ASCE Material Committee Structural Plastics Subcommittee, June 1992.

2. Frados, J., ed., *Plastics Engineering Handbook of the Society of the Plastics Industry, Inc.*, Van-Nostrand-Reinhold, New York, 1976.

3. Lubin, George, ed., *Handbook of Fiberglass and Advanced Plastics Composites*, Robert E. Krieger Publishing Company, New York, 1969.

4. Mattews, F.L., ed., *Joining Fibre-Reinforced Plastics*, Elsevier Applied Science, London, 1987.

5. *Structural Plastics Design Manual*, American Society of Civil Engineers, New York, 1984.

Section 2.3

1. Bank, L.C., Mossllam, S.M., and Gonsior, H.E., "Beam-to-Column Connections for Pultruded FRP Structures", *Proceedings of the First Materials engineering Congress*, New York, August 1990, pp.804-813.

2. Bank, Lawerence, Mossallam, Ayman, and McCoy, Greg, "Design and Performance of Connection for Pultruded Frame Structures", *Proceeding, The 48th Annual Conference, Composite Institute*, The Society of Plastic Industry, Ohio, Feb 1993, pp.1-8.

3. Chang, Fu-Kuo, and Scott, Richard, "Failure of Composite Laminates Containing Pin Loaded Holes: Method of Solution", *Journal of Composite Materials,* Technomic Publishing Co., Vol. 18, May 1984, pp.225-278.

4. Chang, Fu-Kuo, Scott, Richard, and Springer, Richard, "Strength of Mechanically Fastened Composite Joints", *Journal of Composite Materails*, Technomic Publishing Co., Vol. 16, Nov 1982, pp.470-494.

5. Chamis, Christos, "Simplified Procedures for Designing Composite Bolted Joints", *Journal of Reinforced Platics and Composites*, Technomic Publishing Co., Vol. 9, 1990, pp.614-626.

6. Erki, M.A., Rosner, C.N., and Dutta, A., "Design of Glass-Fibre-Renforced Plastic Bolted Connections", *Microcumputers in Civil engineering*, Elsevier Science Publishing Ltd., 1993, pp.367-376.

7. Godwin, E.W., Mattews, F.L., and Kilty, P.F., "Strength of Multi-Bolt Joints in GRP", *Composites*, Vol. 13, 1982, pp.268-272.

8. Herrera-Franco, Pedro and Cloud, Gary, "Strain-Relief Inserts for Composite Fasteners: An Experimental Study", *Journal of Composite Materials*, Vol. 26, May 1992, pp.751-777.

9. Johnson, M. and Mattews, F.L., "Determination of Saftey Factors for use when Designing Bolted Joints in GRP", *Composites*, IPC Business Press, Vol. 10, No.2, April 1979, pp.73-76.

10. Kretis, G. and Mattews, F.L., "The Strength of Bolted Joints in Glass Fibre/Epoxy Laminates", *Composites*, Butterworth & Co. Ltd., Vol.16, April 1985, pp.92-102.

11. Lee, J.H. and Mall, S., "Strength of Composite Laminate with Reinforced Hole", *Journal of Composite Materials*, Technomic Publishing Co., Inc., Vol.23, No.3, March 1989, pp.337-347.

12. Lin, Chien-Chang and Lin, Chuen-Horng, "Stress and Strength Analysis of Composite Joints Using Direct Boundary Element Method", *Composite Structures*, Elsevier Applied Science, Vol. 25, 1993, pp.209-215.

13. Mallick, P.K. and Little, R.E., "Pin Bearing Strength of Fiber Reinforced Composite Laminates", *Advanced Composites: Conference Proceedings*, ASM, 1985, pp. 39-47.

14. Marshall, I.H., Arnold, W.S., Wood, J., and Mousley, R.F., "Observations on Bolted Connections in Composite Structures", *Composite Structures*, Vol. 13, No. 2, 1989, pp.133-151.

15. Matthews, F.L., Wong, C.M., and Chyssafitis, S., "Stress Distrubution Around a Single Bolt in Fibre-Reinforced Plastic", *Composites*, Vol. 13, 1982, pp.316-322.

16. Meyers, Vernon, "Mechanical Connections for Structural Plastics", *Journal of the Technical Councils of ASCE*, Dec 1977, pp.93-103.

17. Mosslam, Ayman, Abdelhamid, Mohamed, and Conway, Jerroled, "Performance of Pultruded PFRP Connections Under Static and Dynamic Loads", *Proceeding, The 48th Annual Conference, Composite Institute*, The Society of Plastic Industry, Ohio, Feb 1993, pp.1-9.

18. Prabhakaran, R., "Photoelastic Investigation of Bolted Joints in Composites", *Composites*, Vol. 13, No. 3, July 1982, pp.253-256.

19. Pyner, G.R. and Mattews, F.L., "Comparison of Single and Multi-Hole Bolted Joints in Glass Fibre Reinforced Plastic", *Glass Reinforced Epoxy Systems Part II*, Technomic Publishing Company, CT., 1982, pp.24-31.

20. Rowlands, R.E., Rahman, M.U., Wilkinson, T.L., and Chiang, Y.I., "Single- and Multi-Bolted Joints in Orthotropic Materials", *Composites*, Butterworth & Co., Inc., Vol. 13, July 1982, pp.273-279.

21. Smith, P.A., Ashby, M.F., and Pascoe, K.J., "Modeling Clamp-Up Effects in Composite Bolted Joints", *Journal of Composite Materials*, Technomic Publishing Co., Inc., Vol. 21, No. 10, Oct 1987, pp.878-897.

22. Snyder, Bruce, Burns, Joe, and Venkayya, Vipperla, "Composite Bolted Joints Analysis Program", *Journal of Composites Technology and Research*, Vol. 12, No. 1, 1990, pp.41-51.

23. Stockdale, J.H. and Mattews, F.L., "The Effect of Clamping Pressure on Bolt Bearing Loads in Glass Fibre-Reinforced Plastics", *Composites*, Vol. 7, No. 1, Jan 1976, pp.34-38.

24. Tang, S., "Failure of Composite Joints Under Combined Tension and Bolt Loads", *Journal of Composite Materials*, Technomic Publishing Co., Inc., Vol. 15, July 1981, pp. 329-335.

25. Tsujimoto, Yoshifumi and Wilson, Dale, "Elasto-Plastic Failure Analysis of Composite Bolted Joints", *Journal of Composite Materials*, Vol. 20, No. 3, May 1986, pp.236-252.

26. Wong, C.M.S. and Mattews, F.L., "A Finite element Analysis of Single and Two-Hole Bolted Joints in Fibre Reinforced Plastic", *Journal of Composite Materials*, Technomic Publishing Co., Inc., Vol. 15, Sept 1981, pp.481-491.

27. Yang, L. and Ye, L.Y., "The Study of the Behavior of a Composite Multi-Bolt Joint", *Composite Structures 5*, The 5th International Conference on Composite Structures, Elsevior Applied Science, London, 1989, pp.579-590.

28. York, J.L., Wilson, D.W., and Pipes, R.B., "Analysis of the Net Tension Failure Mode in Composite Bolted Joints", *Journal of Reinforced Plastics and Composites*, Vol.1, 1982, pp.141-153.

Section 2.4

1. Adams, Robert and Wake, William, *Structural Adhesive Joints in Engineering*", Elsevier Applied Science Publishers, London, 1984.

2. Bodwitch, M.R. and Stannard, K.J., "Adhesive Bonding of GRP", *Composites*, Vol. 13, No. 3, July 1982, pp.298-304.

3. Chamis, C.C. and Murthy, P.L.N., "Simplified Procedures for Designing Adhesively Bonded Composite Joints", *Journal of Reinforced Plastics and Composites*, Technomic Publishing Co., Inc., Vol. 10, Jan 1991, pp.29-41.

4. Curtis, A.R. and Ainsworth, P.D., "The Mechanical Testing and Computer Modeling of Composite Bonded Joints", *Composite Structures 3*, Proceedings of the 3rd International Conference on Composite Structures, Elsevier Applied Science, London, 1985, pp.562-574.

5. Delale, F., Erdogan, F., and Aydinogulu, M., "Stresses in Adhesively Bonded Joints: A Closed-Form Solution", *Journal of Composite Materials*, Vol.15, May 1981, pp.249-271.

6. Kinlock, A.J., "Review of Science of Adhesion: Part 2 Mechanics and Mechanisms of Failure", *Journal of Material Science*, Vol. 17, 1982, pp.617-651.

7. Mattews, F.L., Kilty, P.F., and Godwin, E.W., "A Review of the Strength of Joints in Fibre-Reinforced Plastics: Part 2 Adhesively Bonded Joints", Butterworth & Co. Ltd., Vol. 13, Jan 1982, pp.29-37.

8. Mays, G.C. and Hutchinson, A.R., *Adhesives in Civil Engineering*, Cambridge University Press, New York, 1992.

9. Sargent, J.P. and Ashbee, K.H.G., "Adhesive Joints Involving Composite and Laminates. Measurement of Stress Caused by Resin Swelling", *Journal of Composite Materials*, Vol.15, Nov 1981, pp.492-501.

10. Vinson, Jack, "Adhesive Bonding of Polymer Composites", *Polymer Engineering and Science*, Society of Plastic Engineers, Vol. 29, No. 19, Mid-October 1989, pp.1325-1331.

11. Yosomiya, Ryutoko, Morimoto, Kiyotake, Nakajima, Akio, Ikada, Yoshito, and Suzuki, Toshio, *Adhesion and Bonding in Composites*, Marcel Dekker, Inc., New York, 1990.

Section 2.5

1. Hart-Smith, L.J., "Bonded-Bolted Composite Joints", *Journal of Aircraft*, AIAA/ASME/ASCE/AHS 25th Structures, Structural Dynamics, and Materials Congress, CA, Vol. 22, Nov 1985, pp.993-1000.

2. "MMFG Test for Epoxied vs. Non-Epoxied Strucutural Connections", MMFG, VA, 1992.

3. Mossllam, Ayman, Abdelhamid, Mohamed, and Conway, Jerroled, "Performance of Pultruded PFRP Connections Under Static and Dynamic Loads", *Proceeding, The 48th Annual Conference, Composite Institute*, The Society of Plastic Industry, Ohio, Feb 1993, pp.1-9.

Chapter III

1. Austin, Robert, "A Report on Current Practices in Structural Plastic Connections: Phase One- Literature Search", Report Prepared for Review by the ASCE Material Committee Structural Plastics Subcomittee, June 1992

2. Bank, Lawerence C., "Properties of Pultruded Fiber Reinforced Plastic Structural Members", *Transportation Research Record 1223*, Transportation Research Board, Washington D.C., 1989, pp.117-124.

3. Bank, L.C., and Mosallam, A.S., "Creep and Failure of a Full-Size Reinforced Plastic Pultruded Frame", *Composite Material Technology 1990*, American Society of Mechanical Engineers, New York, ASME PD-Vol. 32, 1990, pp.49-56.

4. Chottiner, J., Sanjana, Z.N., and Kolek, R.L., "Damping Properties of Fiber Reinforced Composites", The Society of Plastics Industry, 41st Annual Conference, Jan 1986, Session 25-C, pp.1-6.

5. Crane, Roger and Gillespie, John, "Characterization of the Vibration Damping Loss Factor of Glass and Graphite Fiber Composite", *Composites Science and Technology*, Vol. 40, No. 4, 1991, pp.355-375.

6. Findley, William, "26-Year Creep and Recovery of Poly(Vinyl Chloride) and Polyehylene", *Polymer Engineering and Science*, Vol. 27, No. 8, April 1987, pp.582-585.

7. Hollaway, L.C., ed., *Polymer and Polymer Composites in Construction*, Thomas Telford Ltd., London, 1990.

8. Holmes, M. and Just, D.J., *GRP in Structural Engineering*, Applied Science Publishers, London, 1983.

9. *MMFG Design Manual*, Morrison Molded Finer Glass Company, VA, 1989.

10. Mossallam, Ayman, "Pultruded Composites: Materials for the 21st Century", *Plastic Composites for 21st Century Construction*, American Society of Civil Engineers, New York, 1993.

11. Salmon, Charles and Johnson, John, *Steel Structures Design and Behavior*, Harper & Row Publishers, New York, 1990.

12. *Structural Plastics Design Manual*, American Society of Civil Engineers, New York, 1984.

Chapter V

1. *MMFG Design Manual*, Morrison Molded Finer Glass Company, VA, 1989.

APPENDIX A

SERIES I TEST RESULTS

TEST SUMMARY

TEST#1

TEST DESIGNATION: I-2bU1

TEST DATE: July 28, 1993

PURPOSE: Double angle two-bolt unbonded connection test

SPAN: 10 ft.

PARAMETERS:
- 2 point loading at 1ft. 5 3/4 in. from each end
- Double angle 2-bolt unbonded connection
- Full length stiffeners provided on both sides at load points and reactions
- Bolt diameter, 3/8 in.

FAILURE LOAD: 12.99 kips (maximum applied load)
6.50 kips at connection

FAILURE MODE: Net shear in one angle along the bolt line and gross shear in the heel of the other angle

PREDICTED FAILURE LOADS:
Gross Shear of Connection Angles: 16.88 kips

DISCUSSION:
- Load deflection curve was essentially linear
- Linear transducer malfuctioned testing
- Unable to determine which limit state occured first in the angles
- Brittle Failure
- CW moments assumed to be positive

TEST#1

MEASURED DIMENSIONS:

Beam:	b_f = 8 in.
	$t_{f,top}$ = 0.374 in.
	$t_{f,bottom}$ = 0.375 in.
	d = 8 in.
	t_w = 0.378 in.
Angle:	t = 0.375
	b = 3 in.
	d = 5 in.
Column:	b_f = 6 in.
	t_f = 0.246 in.
	d = 6 in.
	t_w = 0.247 in.

$I_x = 99.53\ in.^4$

Test Set-up
Test#1

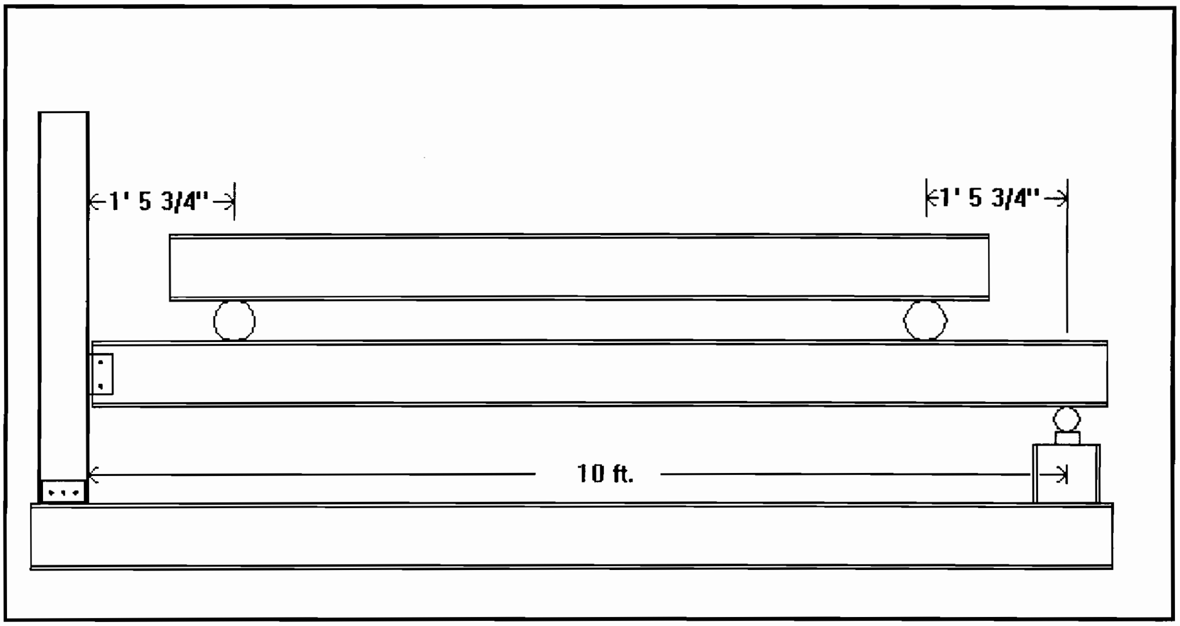


Fig.1 Test Set-up

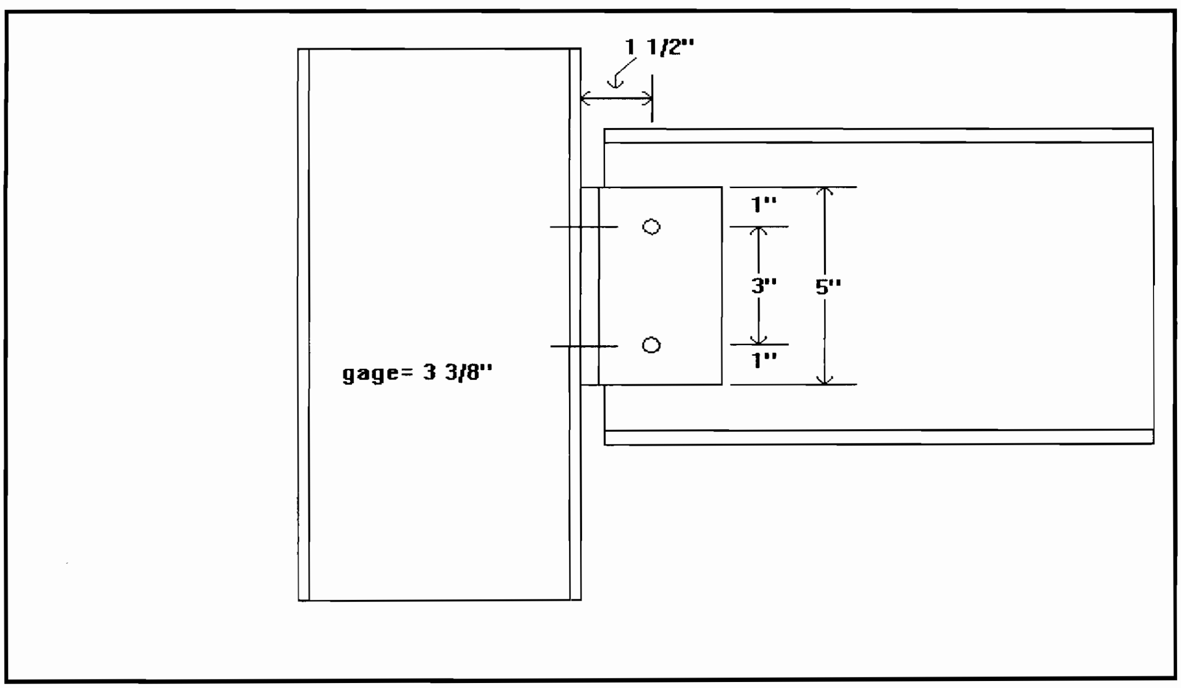
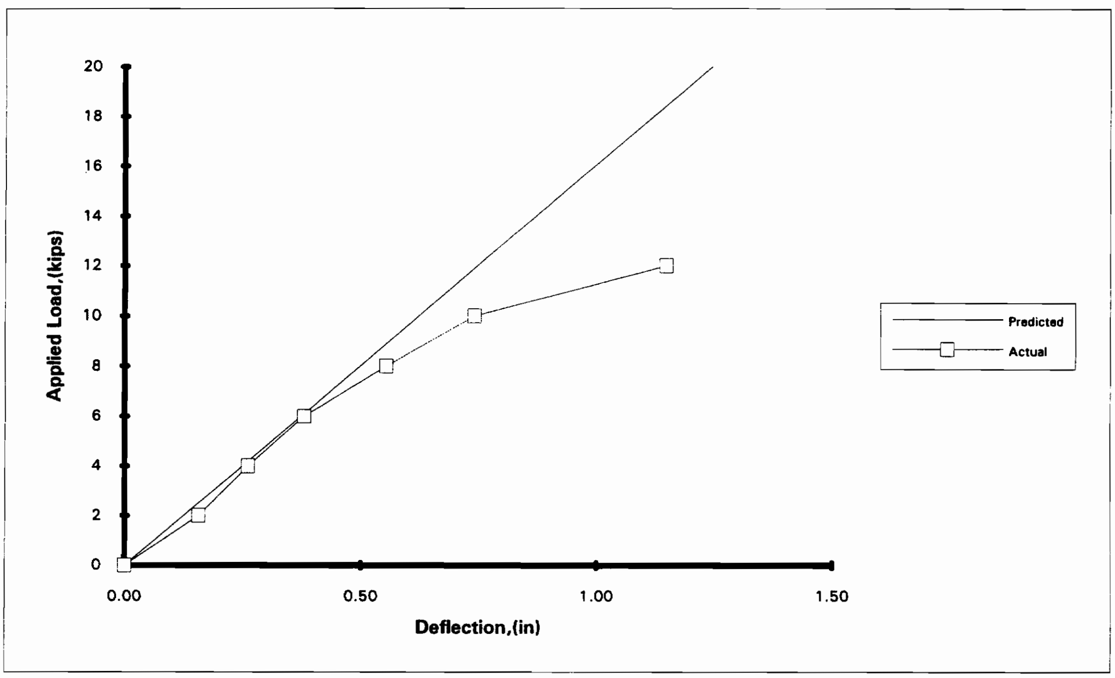
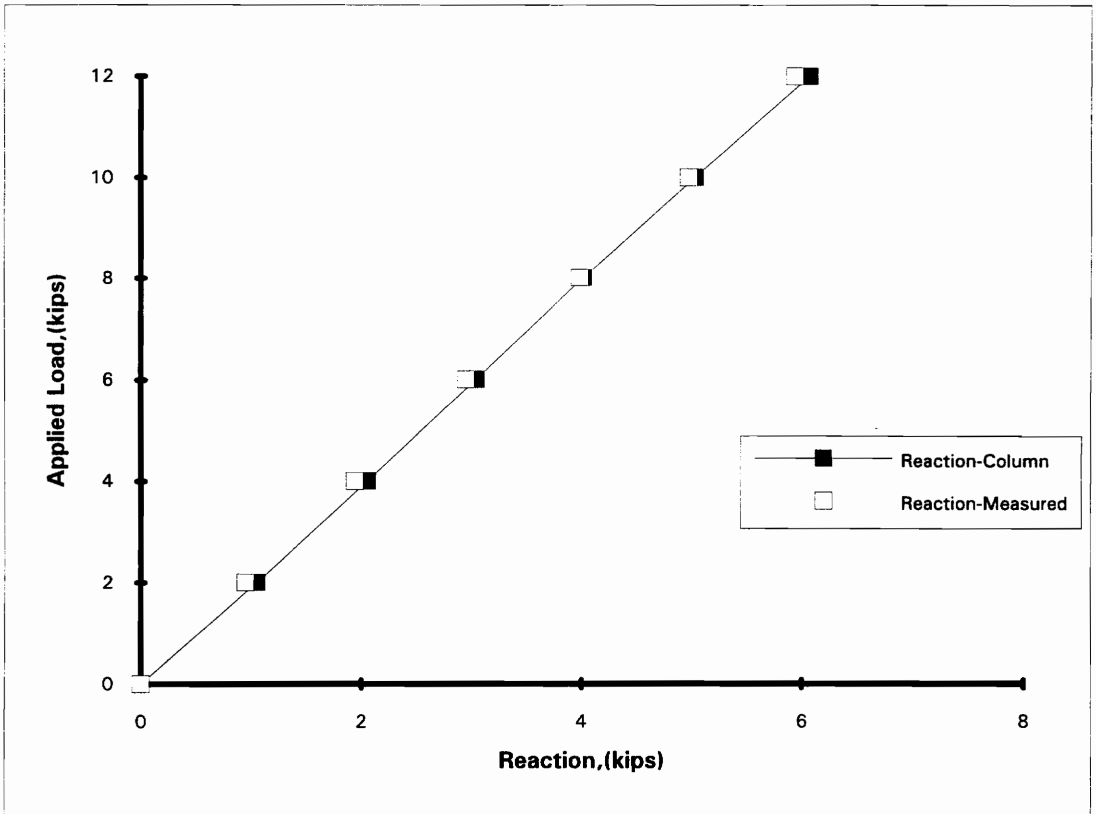


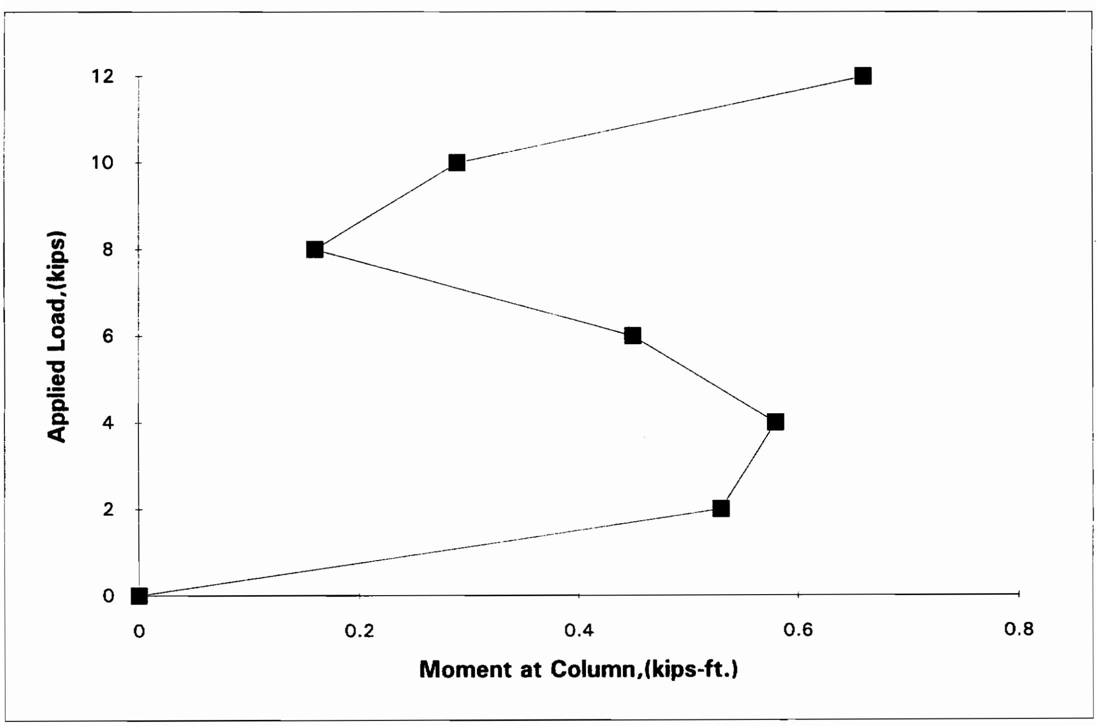
Fig. 2 Connection Detail



Applied Load vs. Deflection



Applied Load vs. Reaction



Applied Load vs. Moment at Column

TEST SUMMARY

TEST#2

TEST DESIGNATION: I-2bU2

TEST DATE: August 4, 1993

PURPOSE: Double angle two-bolt unbonded connection test

SPAN: 10 ft.

PARAMETERS:
- 2 point loading at 1ft. 5 3/4 in. from each end
- Double angle 2-bolt unbonded connection
- Full length stiffeners provided on both sides at load points and reactions
- Bolt diameter, 3/8 in.

FAILURE LOAD: 13.15 kips (Maximum Applied Load)
6.58 kips at connection

FAILURE MODE: Net shear in one angle along the bolt line and gross shear in the heel of the other angle

PREDICTED FAILURE LOADS:
Gross Shear of Connection Angles: 16.88 kips

DISCUSSION:
- Load deflection curve was essentially linear
- Unable to determine which limit state occured first in the angles
- Brittle Failure
- CCW moments assumed to be positive

TEST SUMMARY(Cont.)

TEST#2

MEASURED DIMENSIONS:

Beam:	b_f = 8 in.
	$t_{f,top}$ = 0.374 in.
	$t_{f,bottom}$ = 0.375 in.
	d = 8 in.
	t_w = 0.379 in.
Angle:	t = 0.373 in.
	b = 3 in.
	d = 5 in.
Column:	b_f = 6 in.
	t_f = 0.246 in.
	d = 6 in.
	t_w = 0.247 in.

I_x = 99.53 in.^{4}

Test Set-up
Test#2

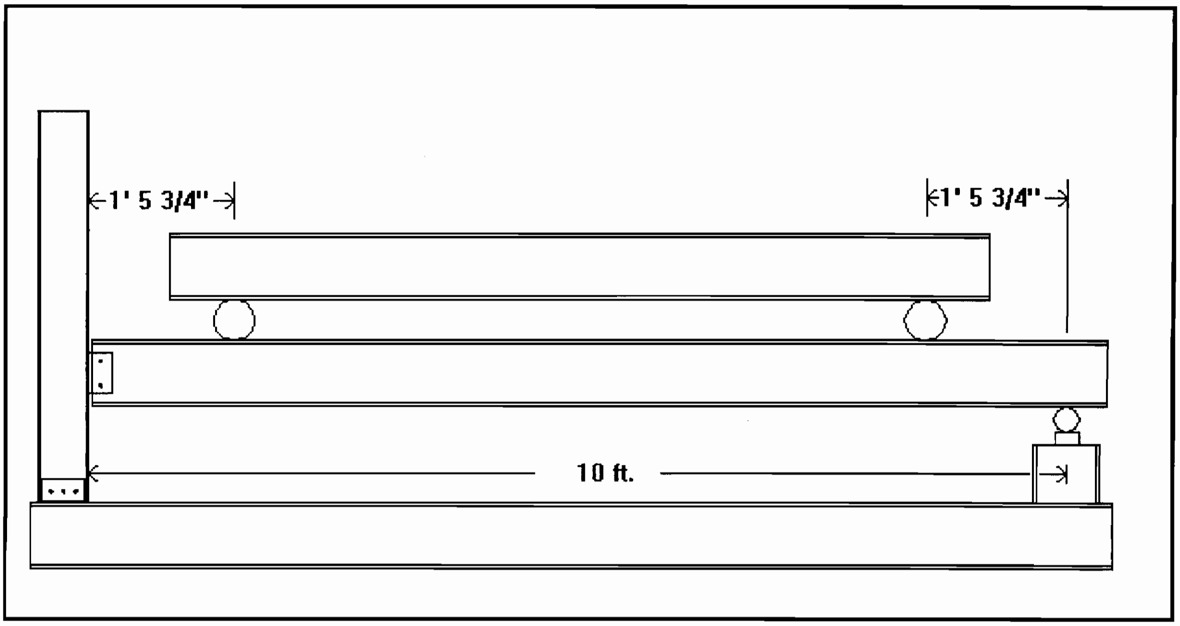


Fig.1 Test Set-up

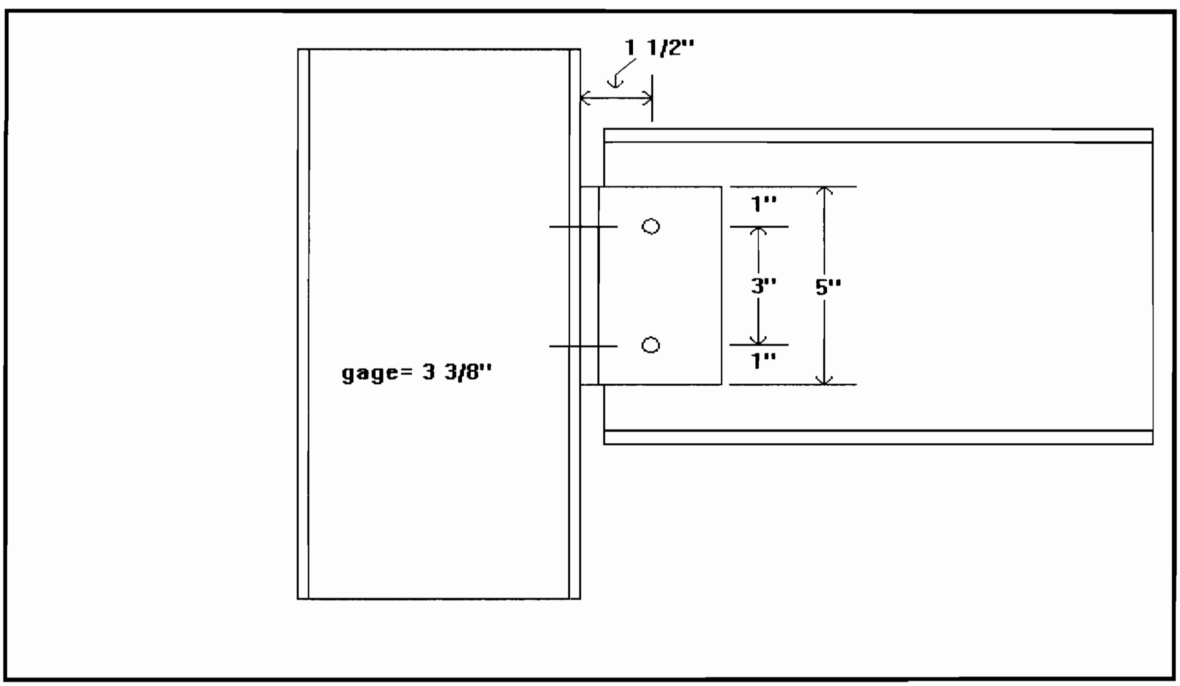


Fig. 2 Connection Detail

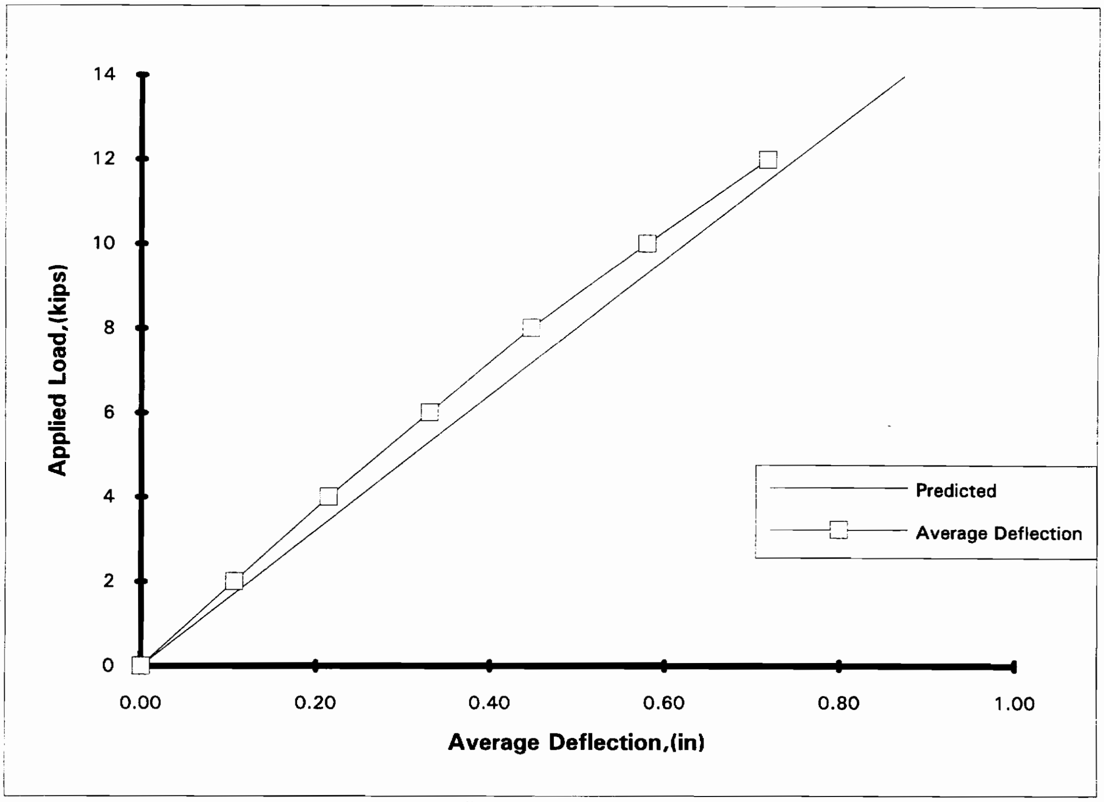


Figure A1 Applied Load vs. Average Deflection

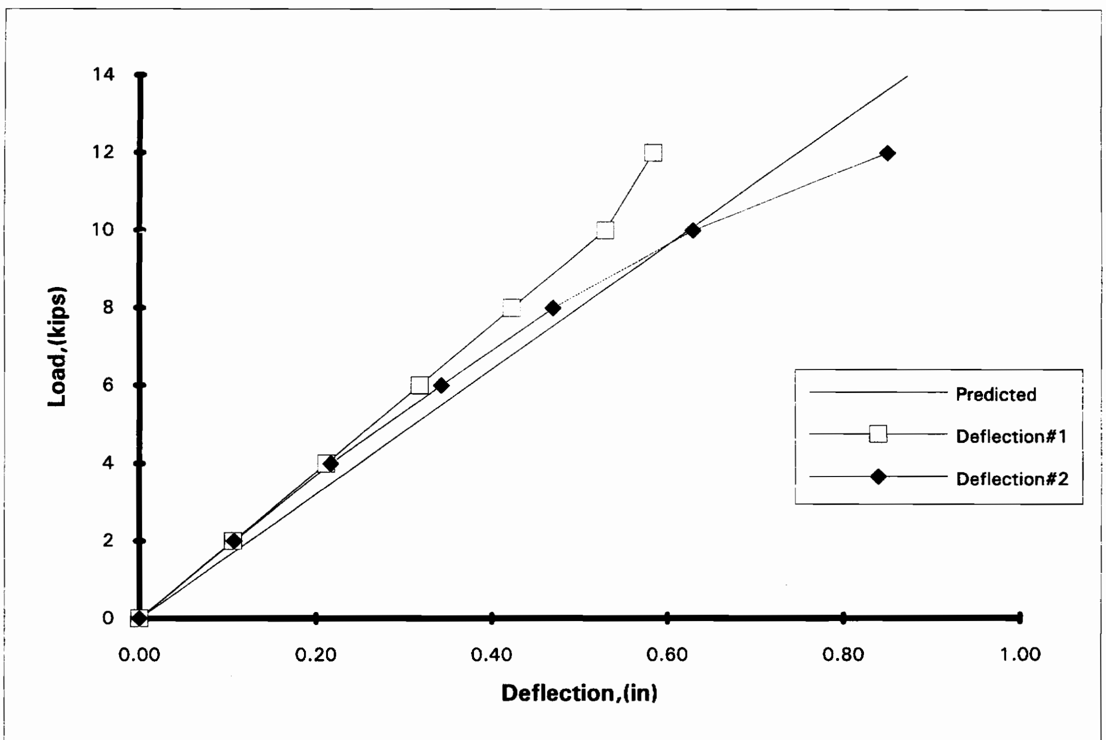


Figure A2 Applied Load vs. Deflection

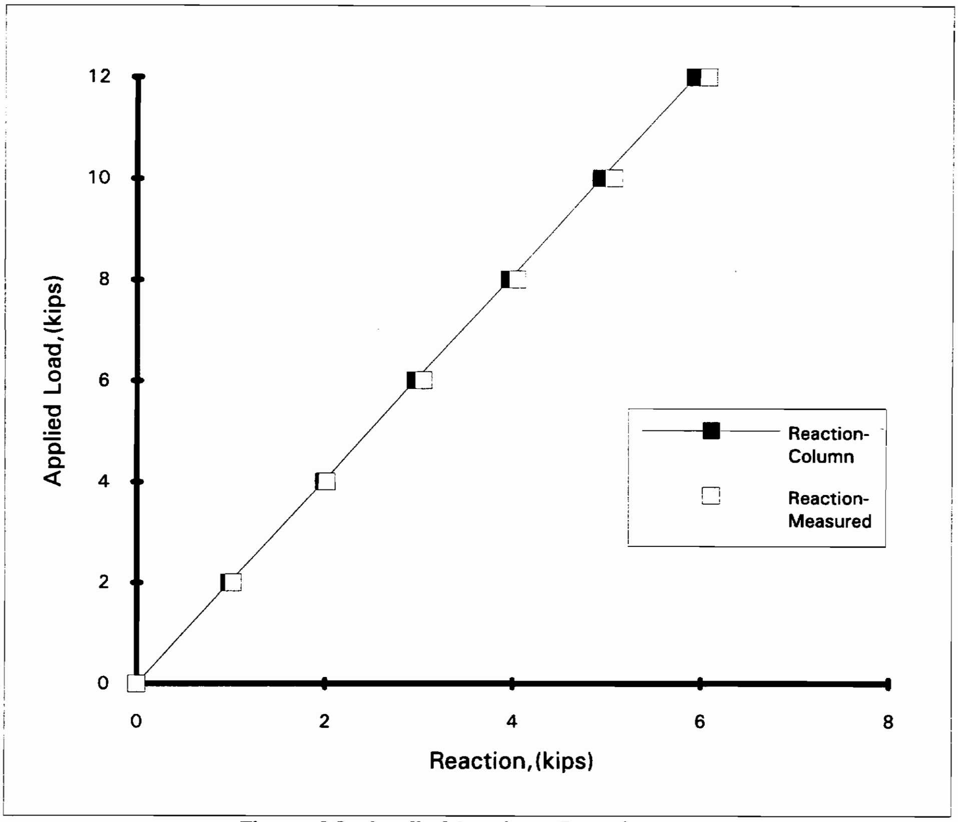


Figure A3 Applied Load vs. Reaction

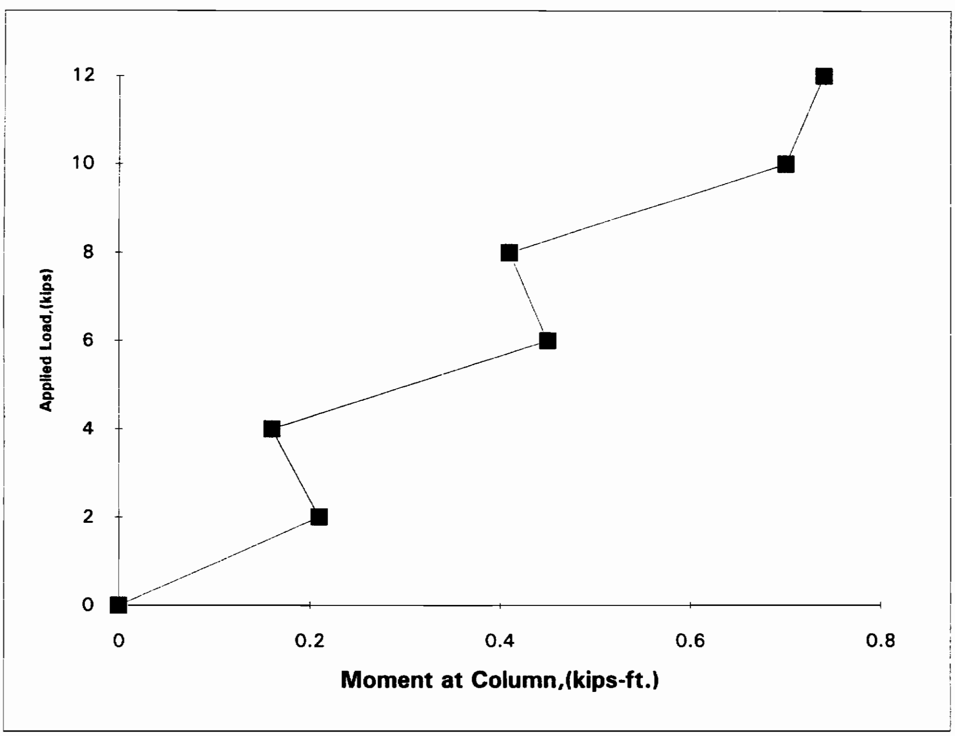


Figure A4 Applied Load vs. Moment at the Column

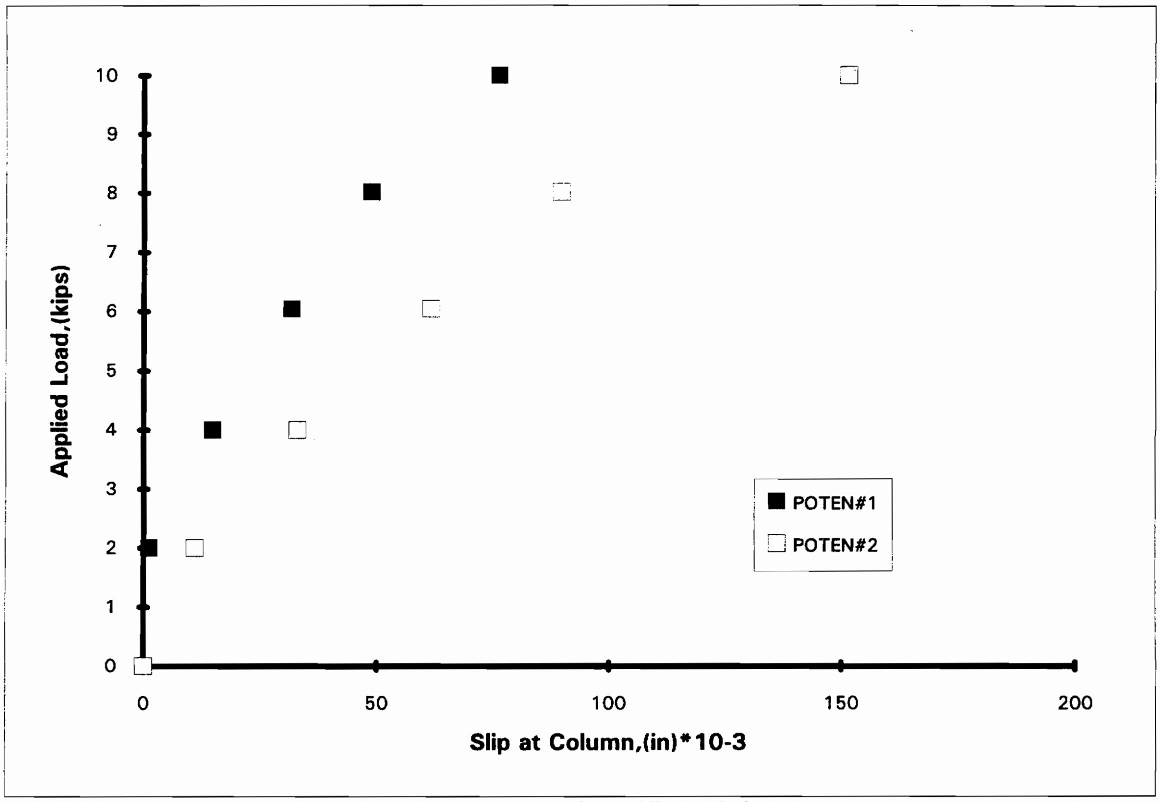


Figure A5 Applied Load vs. Slip at Column

TEST SUMMARY

TEST#3

TEST DESIGNATION: I-2bB1

TEST DATE: September 10, 1993

PURPOSE: Double angle two-bolt bonded connection test

SPAN: 10 ft.

PARAMETERS:
- 2 point loading at 1ft. 5 3/4 in. from each end
- Double angle 2-bolt bonded connection
- Full length stiffeners provided on both sides at load points and reactions
- Bolt diameter, 3/8 in.

FAILURE LOAD: 18.4 kips (Maximum Applied Load)
9.2 kips at connection

FAILURE MODE: Shear crack formed in the web of the beam.

PREDICTED FAILURE LOADS:
Gross Shear of Connection Angles: 16.88 kips

DISCUSSION:
- Load deflection curve was essentially linear
- Due to a lateral instability problem with the test set-up Beam and/or connection may have been damaged during testing, therefore test may be invalid
- Brittle Failure
- CW moments assumed to be positive

TEST SUMMARY(Cont.)

TEST#3

MEASURED DIMENSIONS:

Beam:	$b_f =$ 8 in.
	$t_{f,top} =$ 0.374 in.
	$t_{f,bottom} =$ 0.375 in.
	$d =$ 8 in.
	$t_w =$ 0.378 in.
Angle:	$t =$ 0.373 in.
	$b =$ 3 in.
	$d =$ 5. in.
Column:	$b_f =$ 6 in.
	$t_f =$ 0.25 in.
	$d =$ 6 in.
	$t_w =$ 0.247 in.

$I_x = 99.53$ in.^{4}

Test Set-up
Test#3

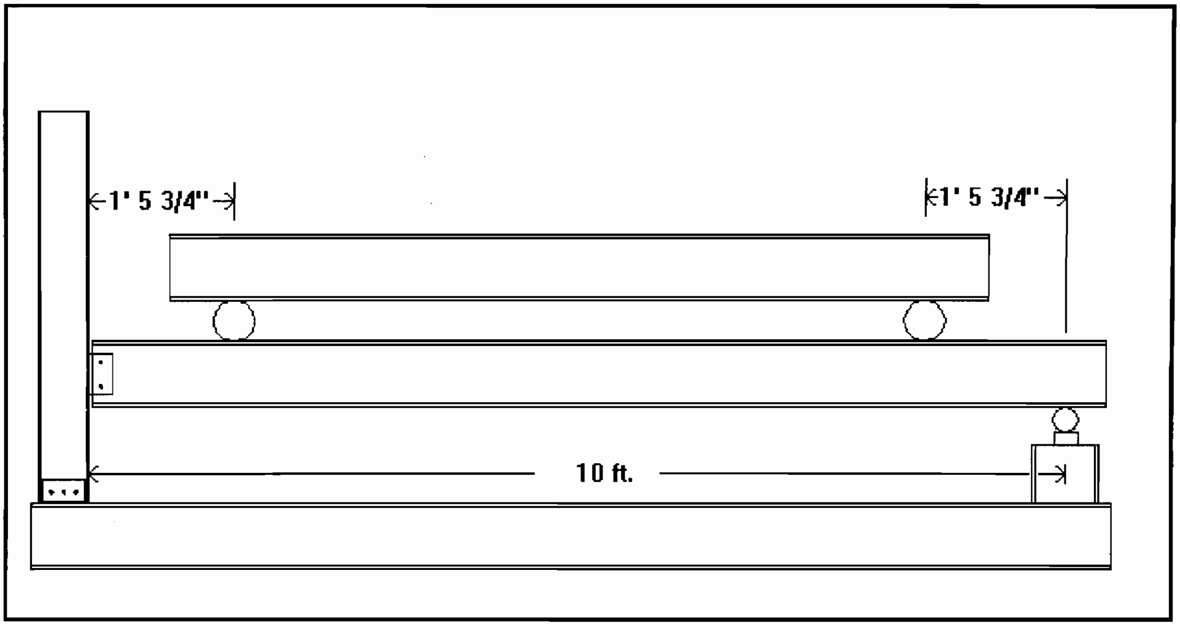


Fig.1 Test Set-up

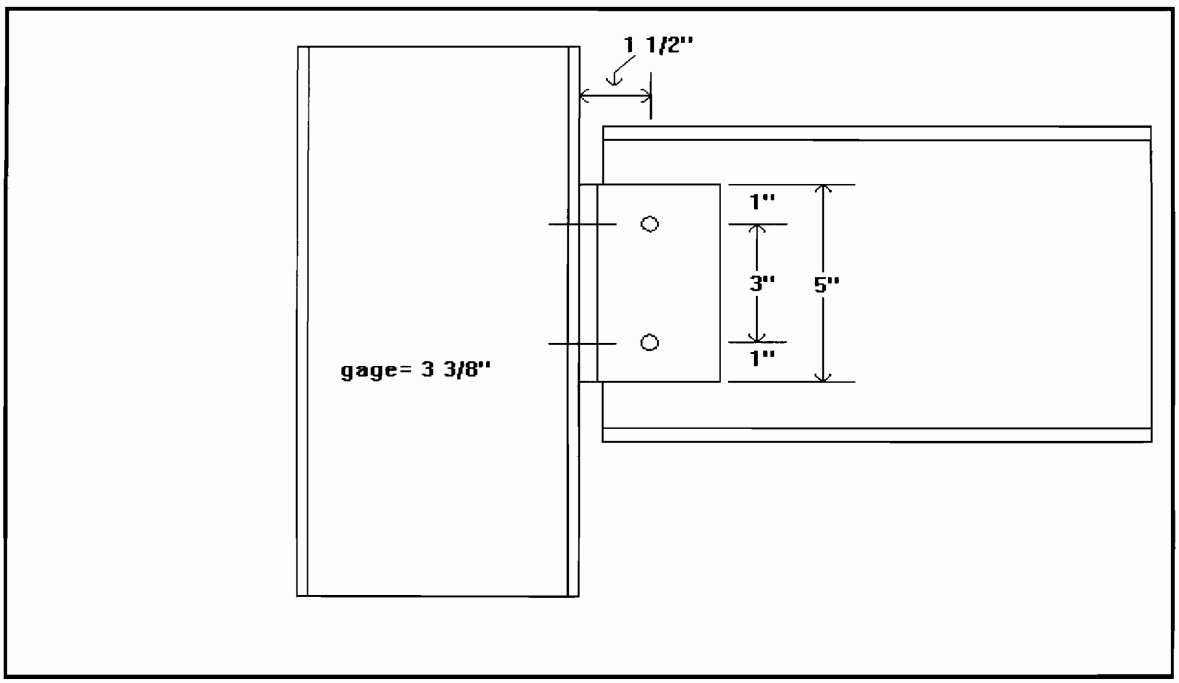
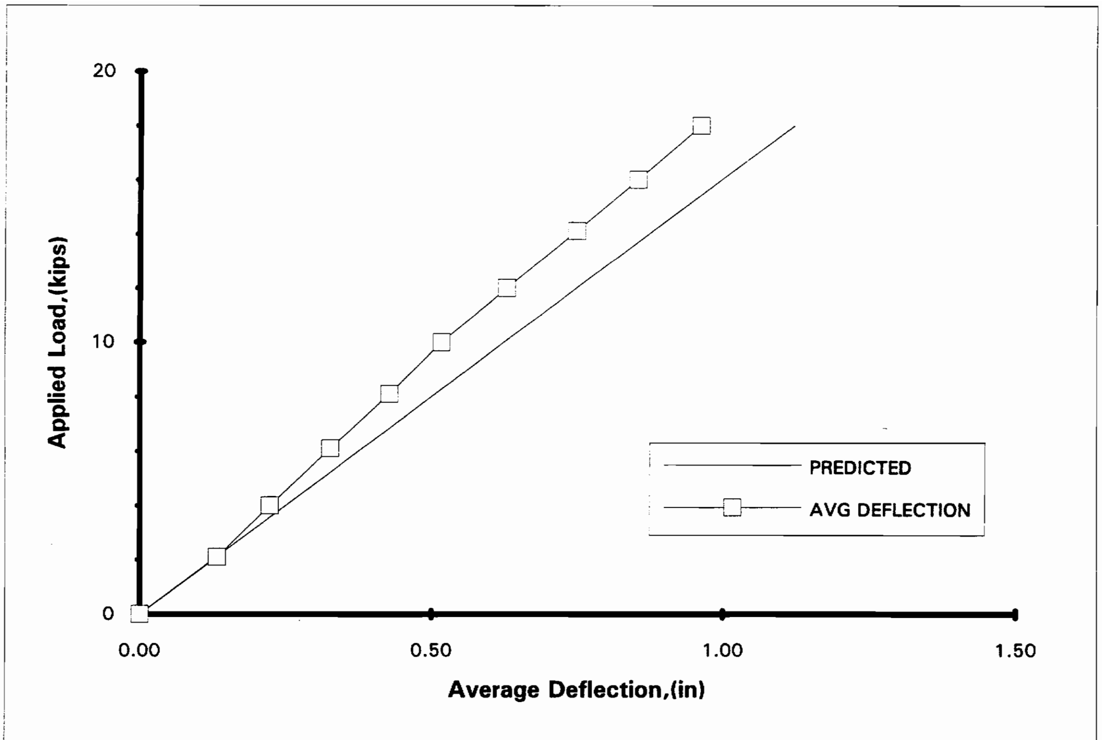
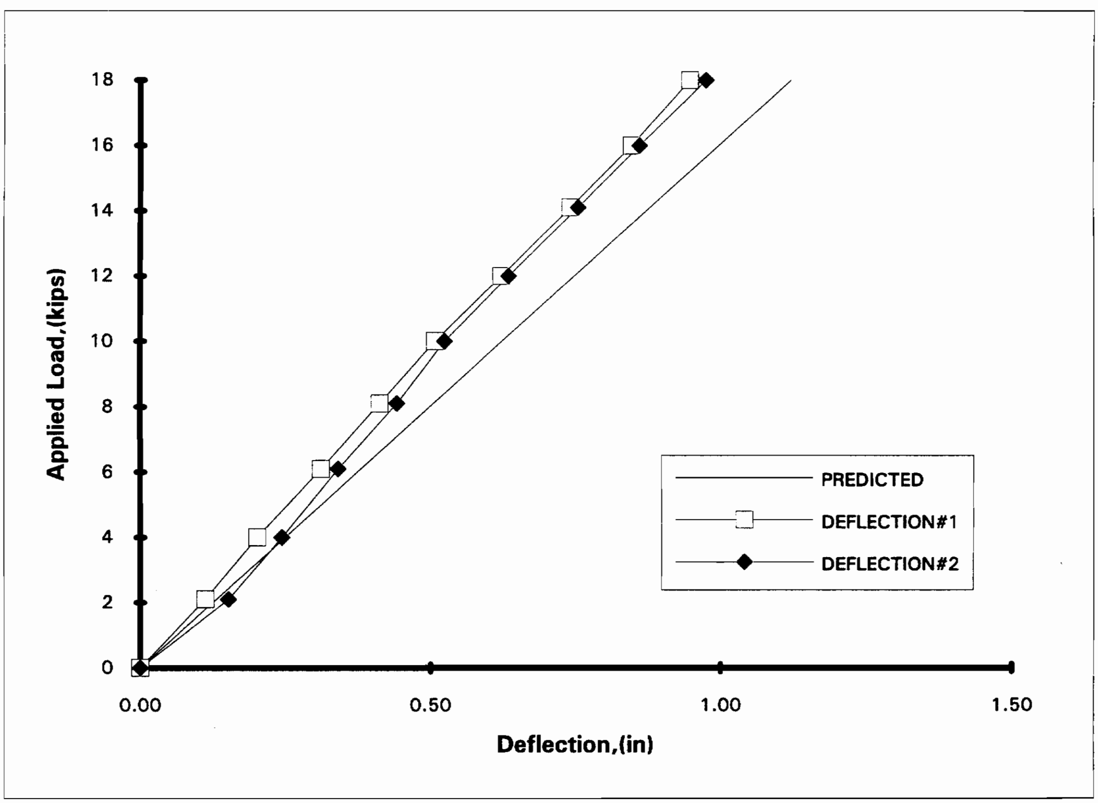


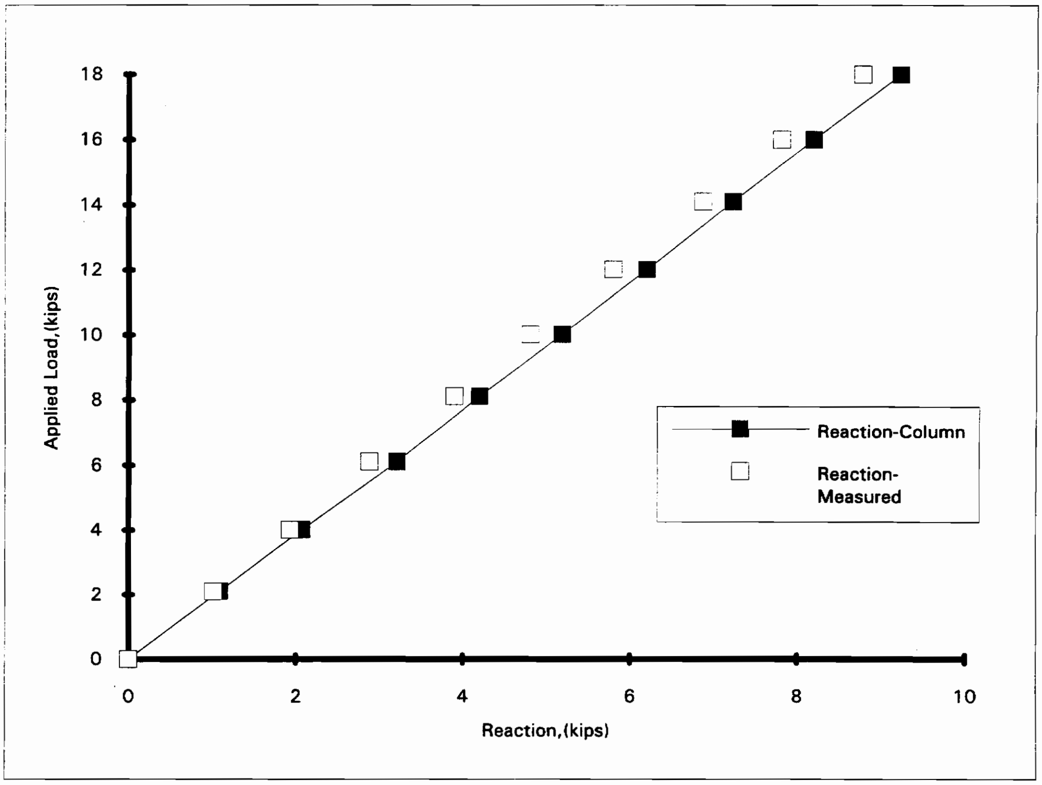
Fig. 2 Connection Detail



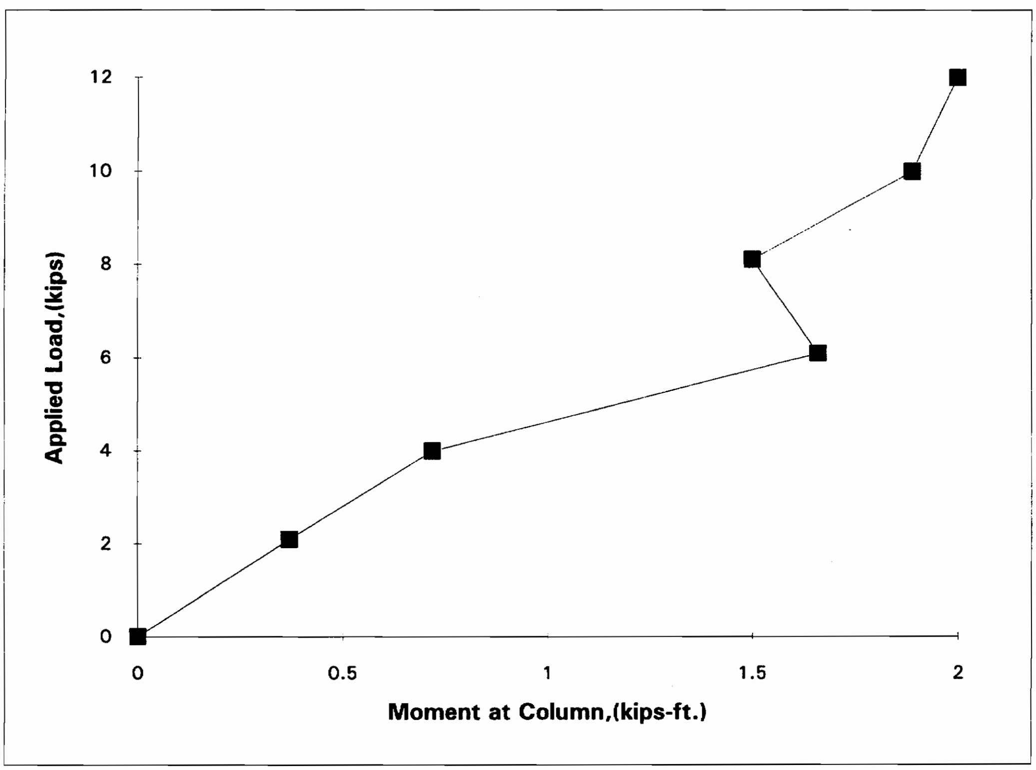
Applied Load vs. Average Deflection



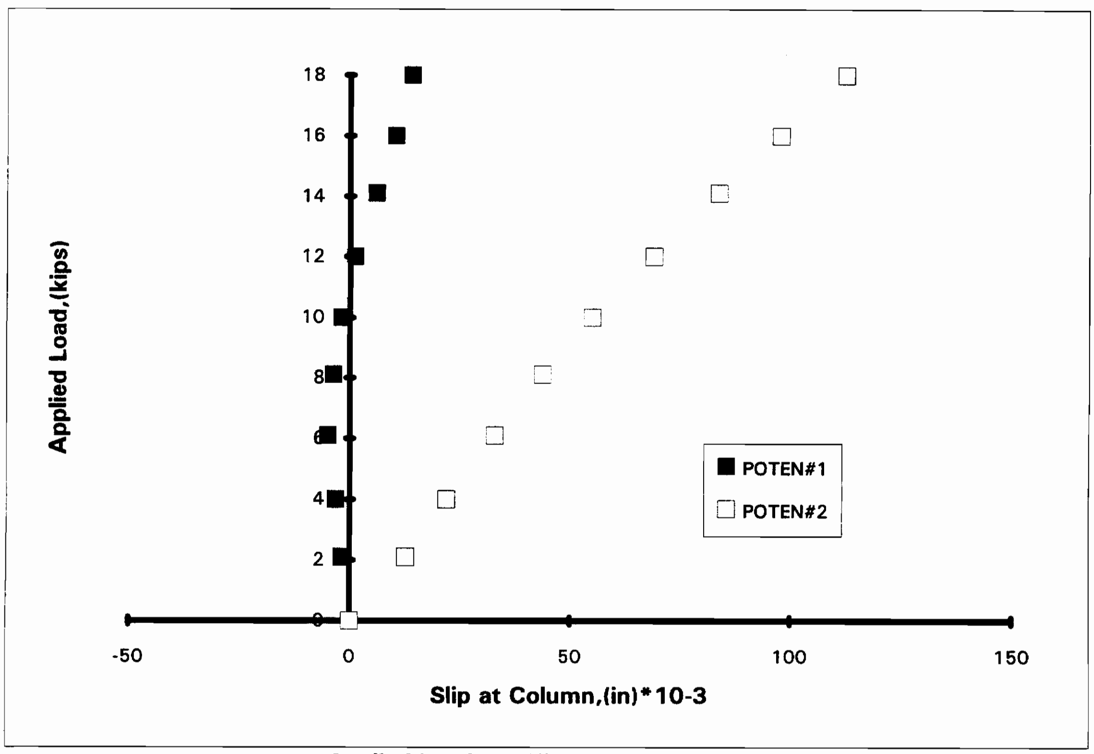
Applied Load vs. Deflection



Applied Load vs. Reaction



Applied Load vs. Moment at the Column



Applied Load vs. Slip at the Column

TEST SUMMARY

TEST#6

TEST DESIGNATION: I-2bB2

TEST DATE: 10/23/93

PURPOSE: Double angle two-bolt bonded connection test

SPAN: 10 ft.

PARAMETERS:
- 2 point loading at 1ft. 5 3/4 in. from each end
- Double angle 2-bolt bonded connection
- Full length stiffeners provided on both sides at load points and reactions
- Bolt diameter, 3/8 in.

FAILURE LOAD: 12.0 kips (Maximum Applied Load)
6.0 kips at connection

FAILURE MODE: Not Taken to Failure

PREDICTED FAILURE LOADS:
Gross Shear of Connection Angles: 16.88 kips

DISCUSSION:
- Load deflection curve was essentially linear
- Beam not taken to failure in order to prevent damage to test beam
- CW moments assumed to be positive

TEST SUMMARY(Cont.)

TEST#6

MEASURED DIMENSIONS:

Beam:	b_f = 8 in.
	$t_{f,top}$ = 0.375 in.
	$t_{f,bottom}$ = 0.378 in.
	d = 8 in.
	t_w = 0.380 in.
Angle:	t = 0.373 in.
	b = 3 in.
	d = 5 in.
Column:	b_f = 6 in.
	t_f = 0.249 in.
	d = 6 in.
	t_w = 0.246 in.

$I_x = 99.55\ \text{in.}^4$

Test Set-up
Test#6

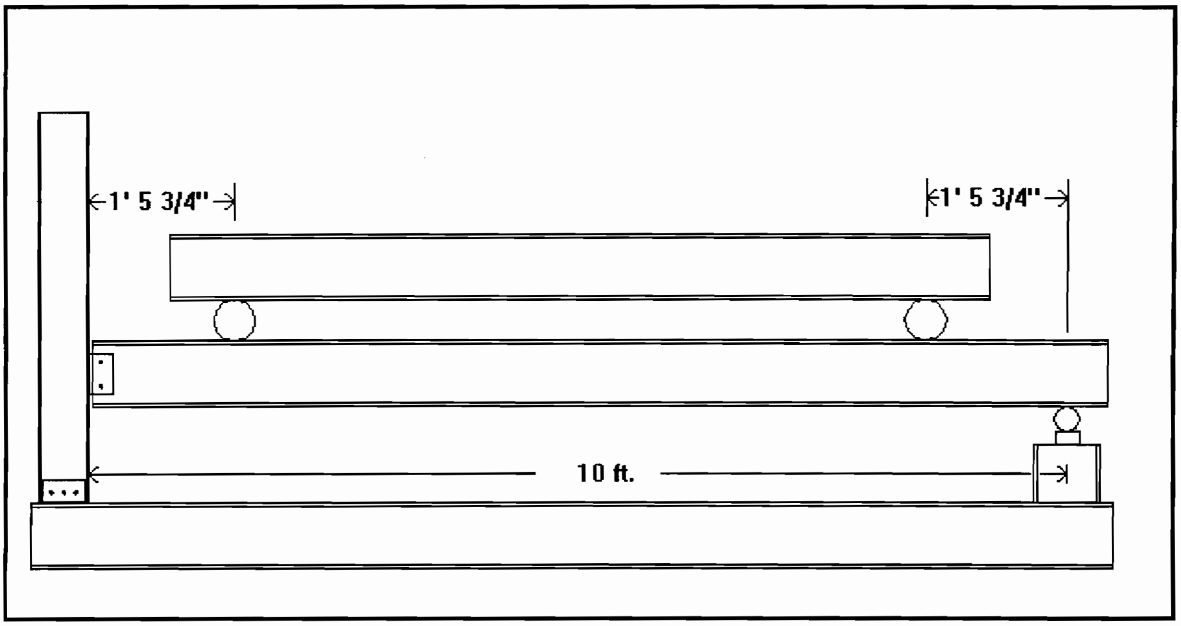


Fig.1 Test Set-up

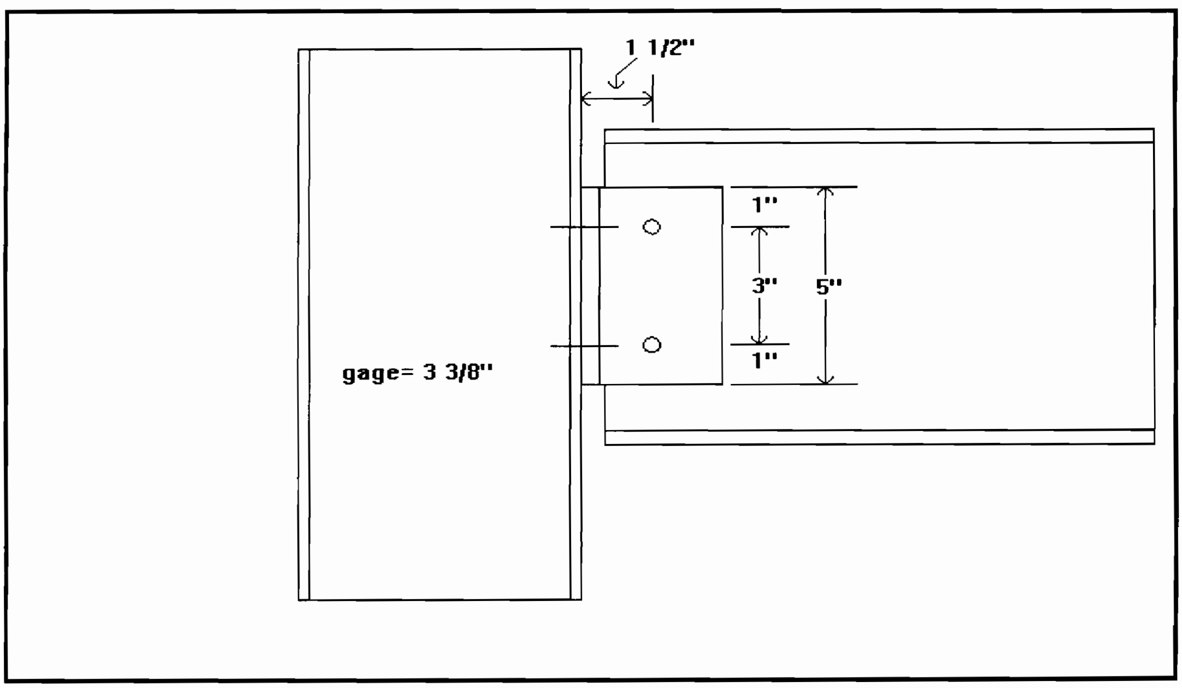
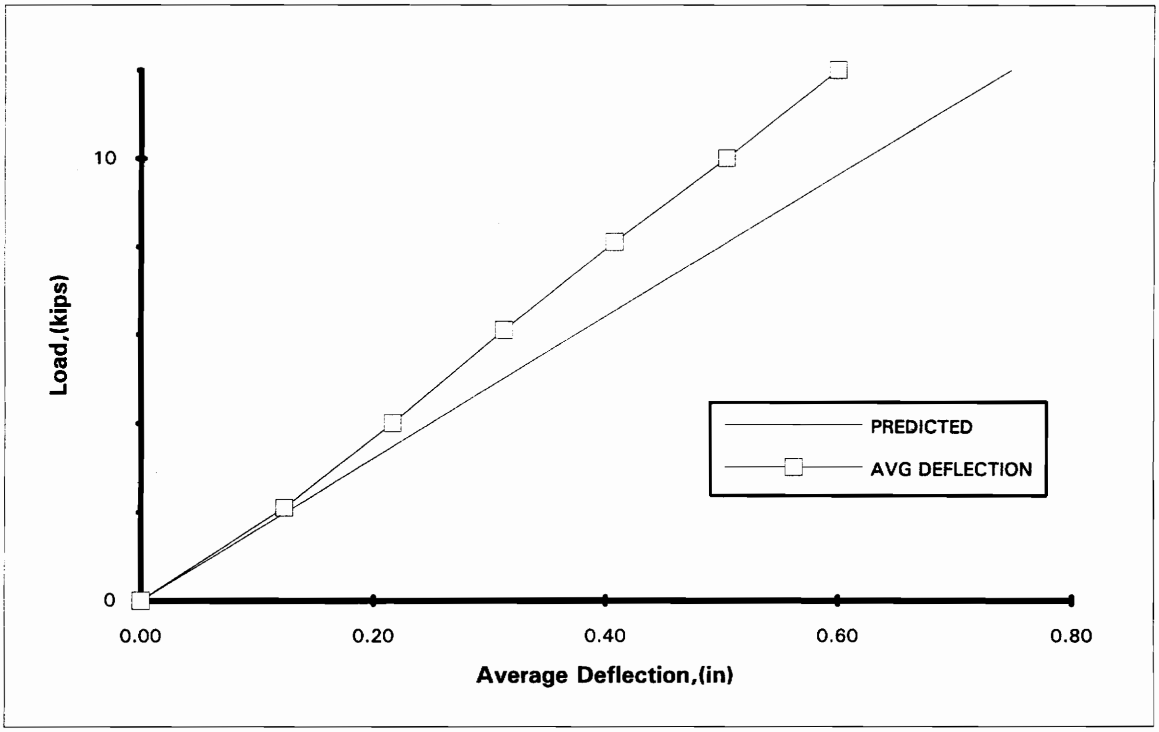
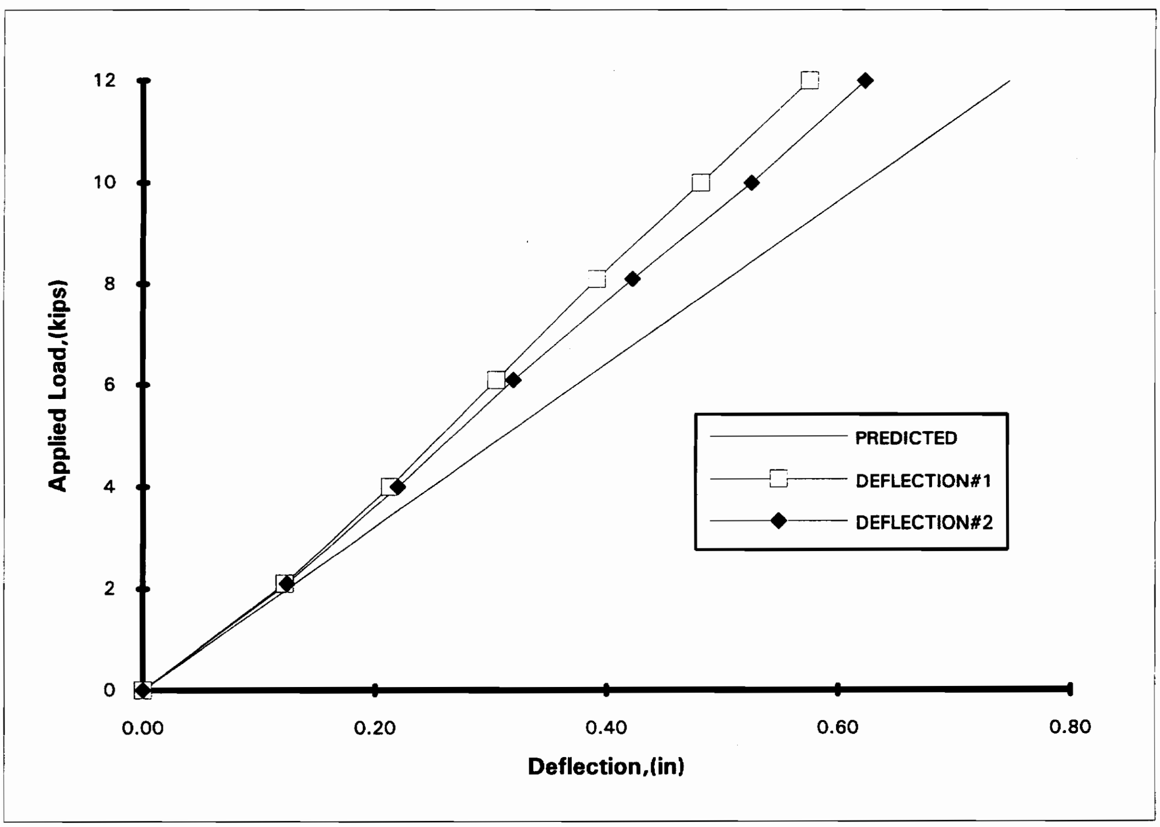


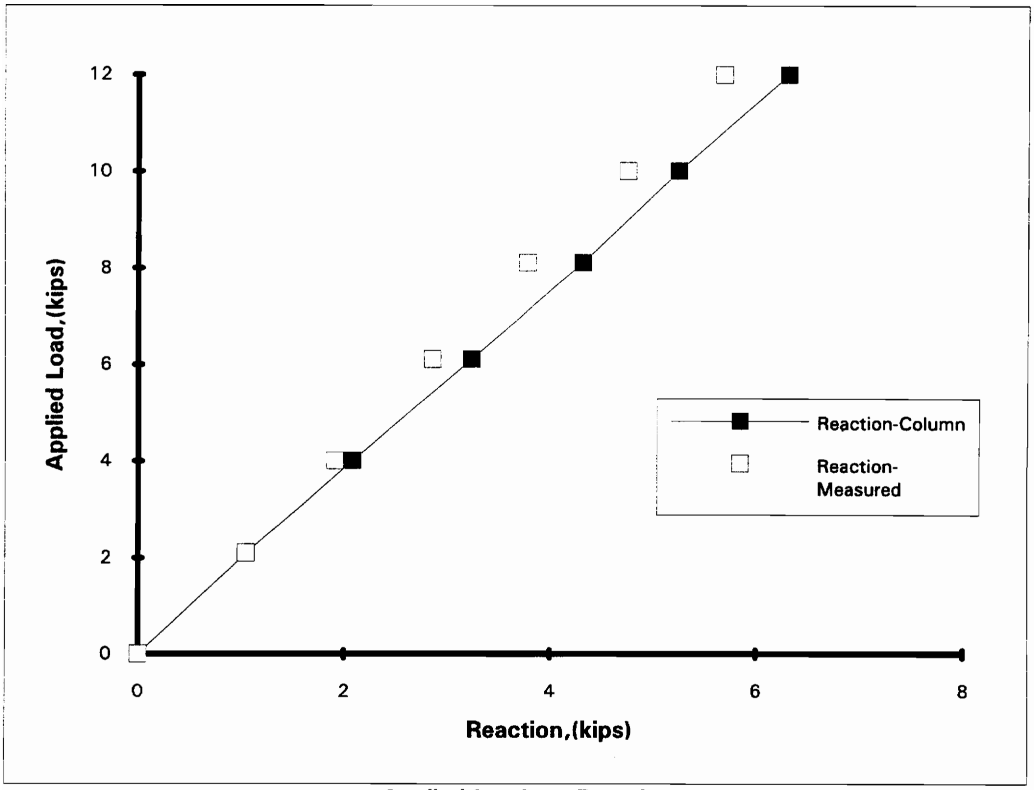
Fig. 2 Connection Detail



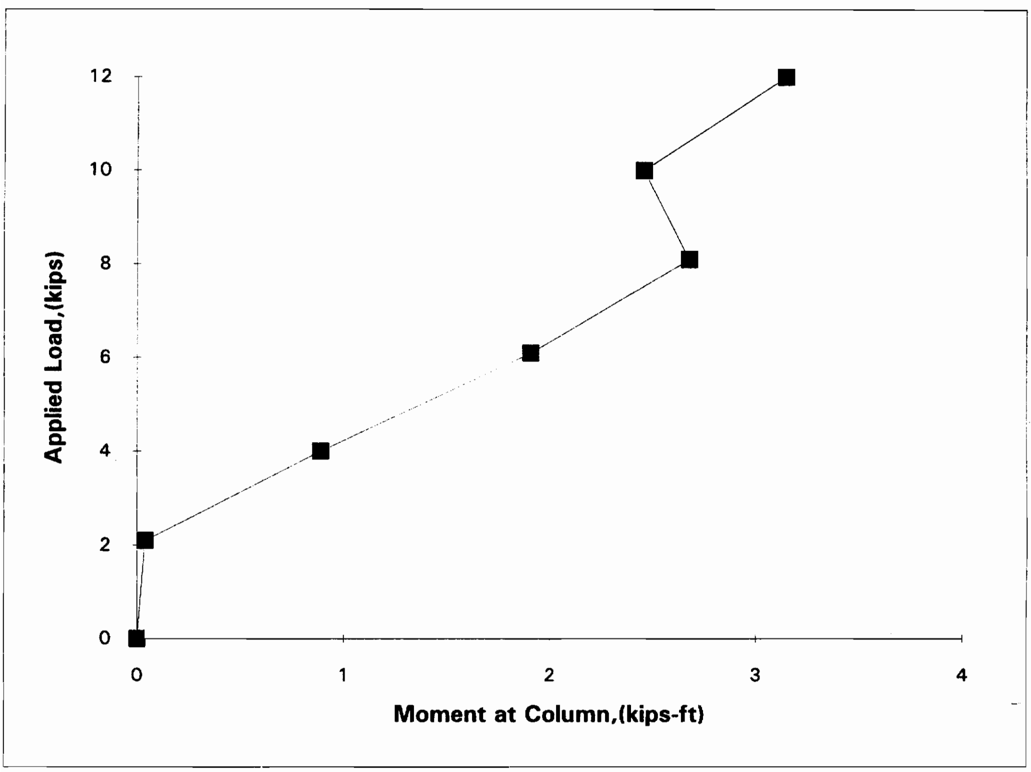
Applied Load vs. Average Deflection



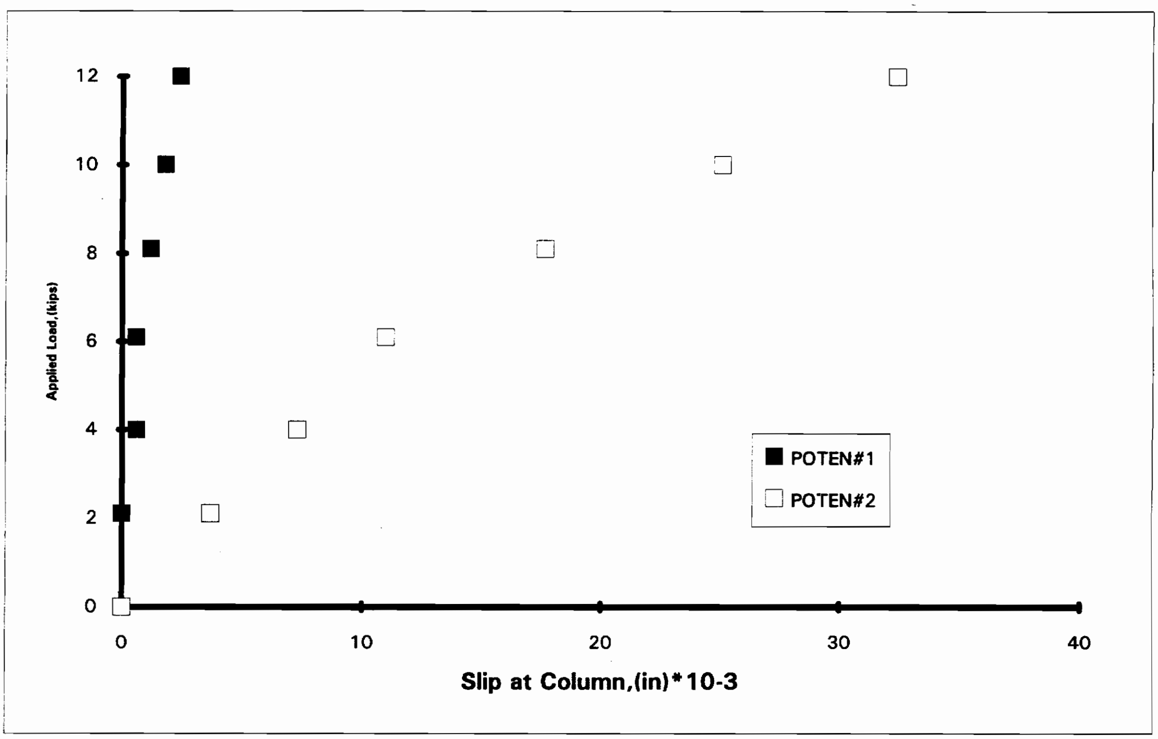
Applied Load vs. Deflection



Applied Load vs. Reaction



Applied Load vs. Moment at the Column



Applied Load vs. Slip at the Column

APPENDIX B

SERIES II TEST RESULTS

TEST SUMMARY

TEST#4

TEST DESIGNATION: II-3bU1

TEST DATE: September 23, 1993

PURPOSE: Double angle three-bolt unbonded connection test

SPAN: 10 ft.

PARAMETERS:
- 2 point loading at 1ft. 5 3/4 in. from each end
- Double angle 3-bolt unbonded connection
- Full length stiffeners provided on both sides at load points and reactions
- Bolt diameter, 3/8 in.

FAILURE LOAD: 16.3 kips (Maximum Applied Load)
8.15 kips at connection

FAILURE MODE: Gross shear in the heel of one angle

PREDICTED FAILURE LOADS:
Gross Shear of Connections Angles: 16.88 kips

DISCUSSION:
- Load deflection curve was essentially linear
- Brittle Failure
- CCW moments assumed to be positive

TEST SUMMARY(Cont.)

TEST#4

MEASURED DIMENSIONS:

Beam:	b_f = 8 in.
	$t_{f,top}$ = 0.375 in.
	$t_{f,bottom}$ = 0.375 in.
	d = 8 in.
	t_w = 0.380 in.
Angle:	t = 0.368 in.
	b = 3 in.
	d = 5 in.
Column:	b_f = 6 in.
	t_f = 0.249 in.
	d = 6 in.
	t_w = 0.250 in.

I_x = 99.38 in.^{4}

Test Set-up
Test#4

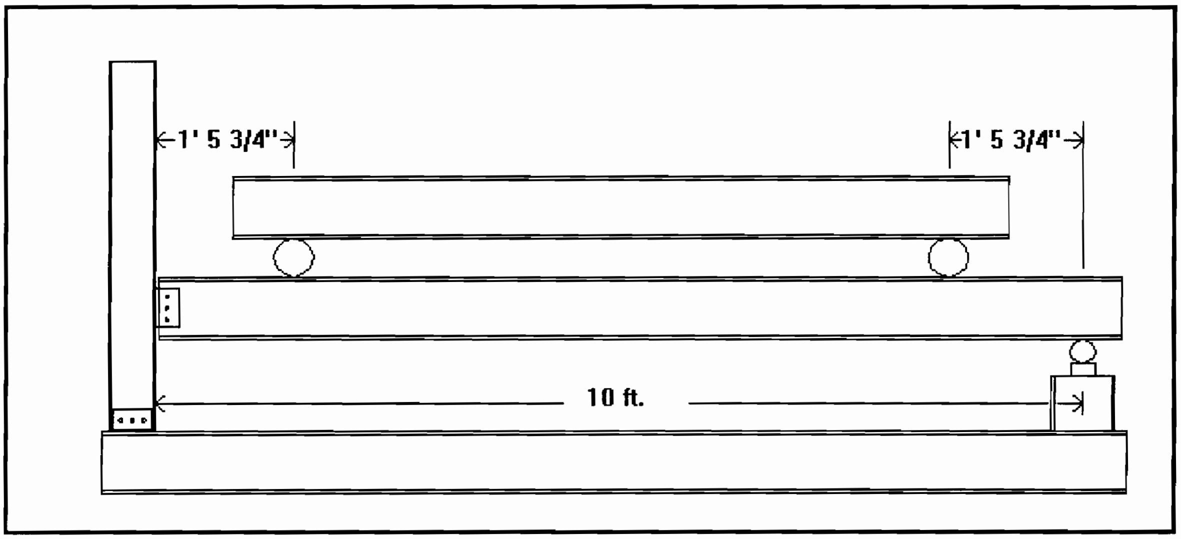


Fig 1 Test Detail

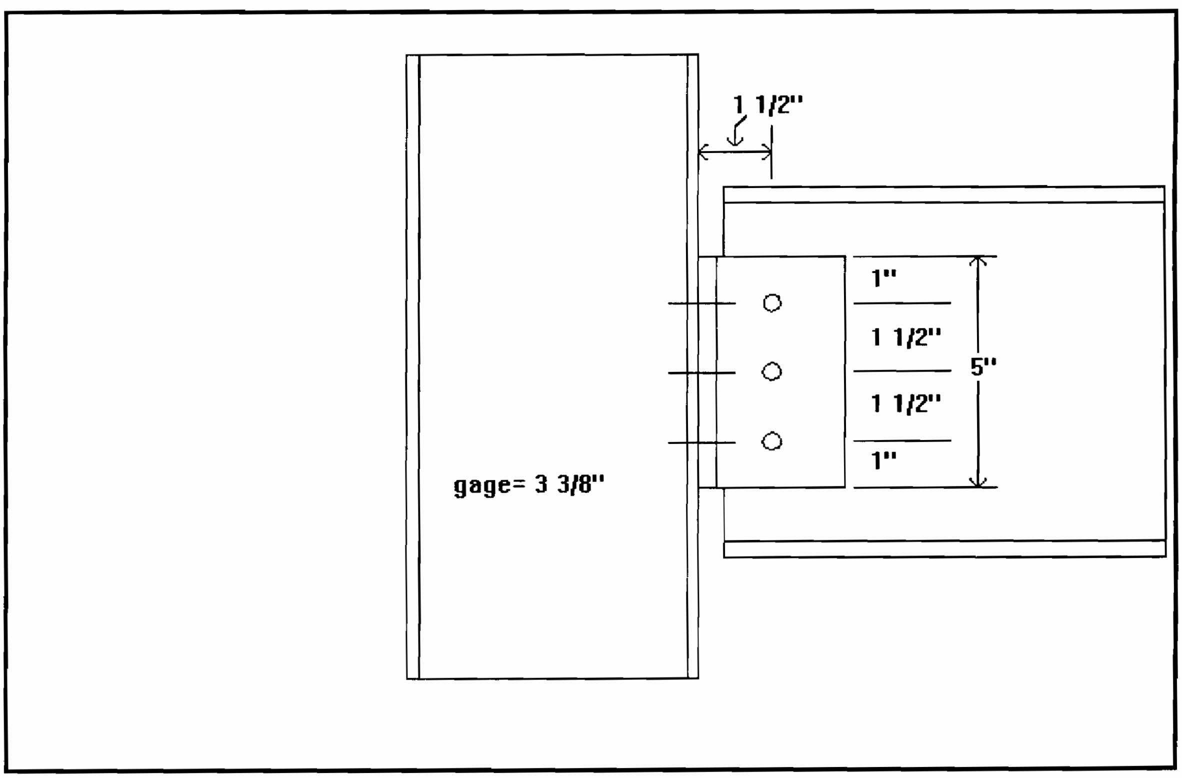
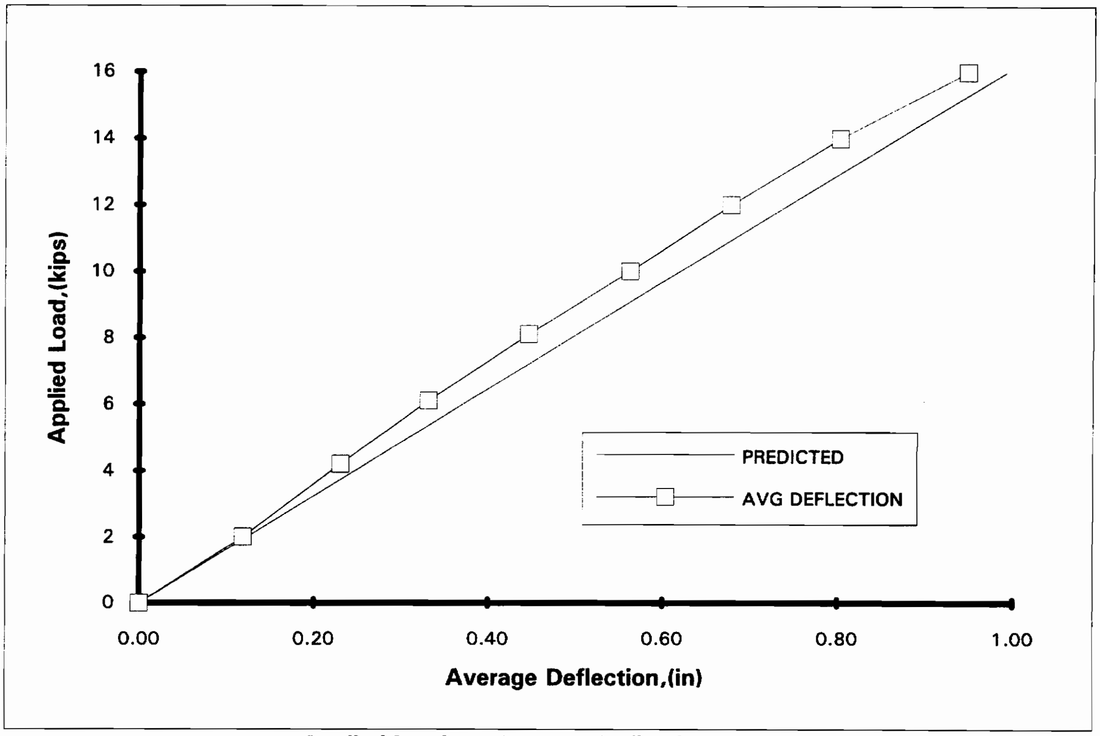
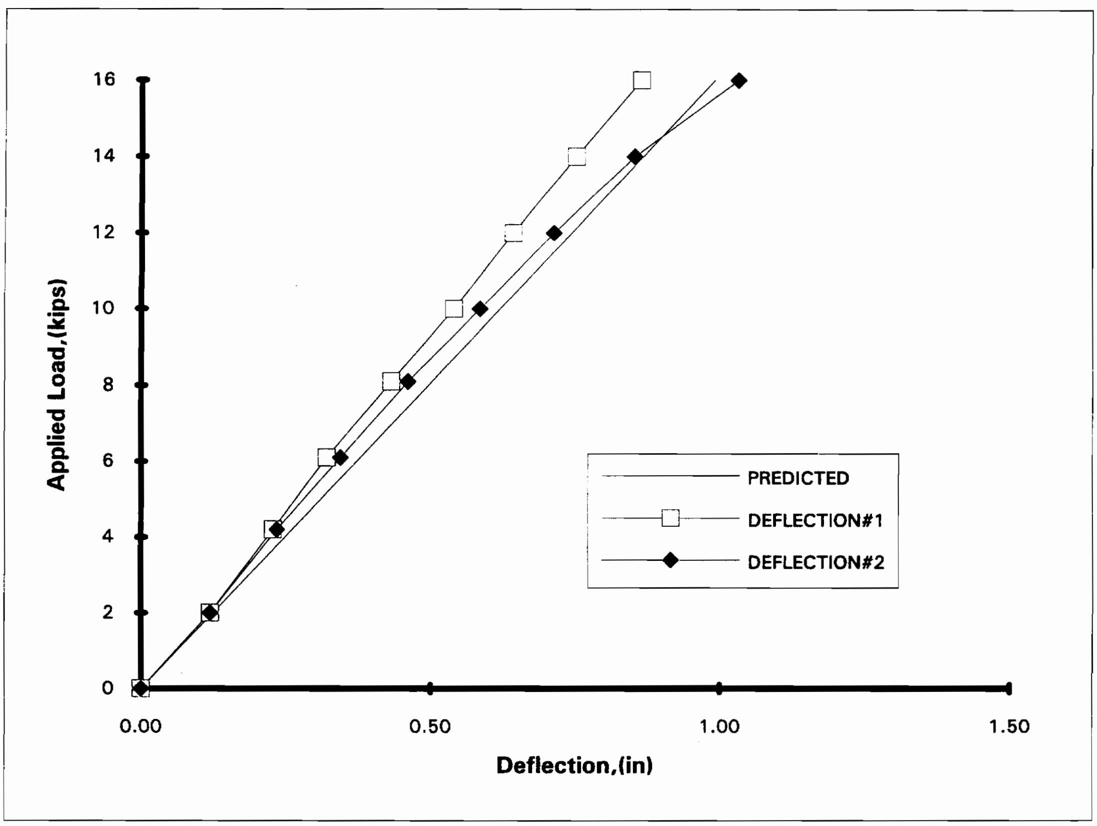


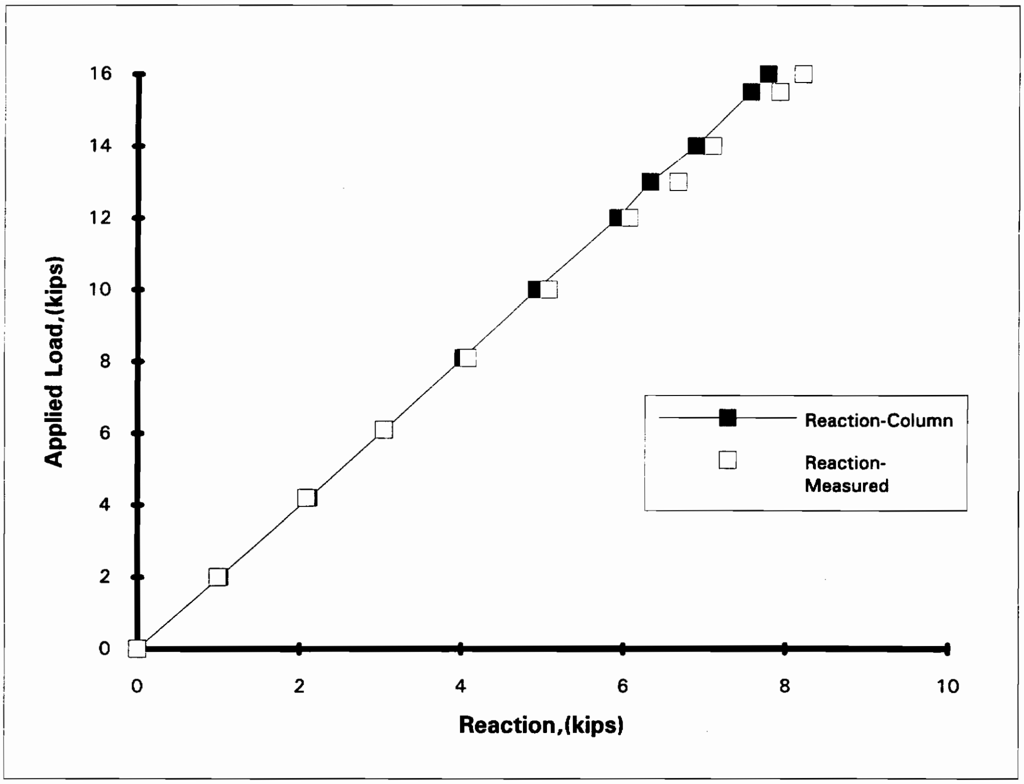
Fig 2 Connection Detail



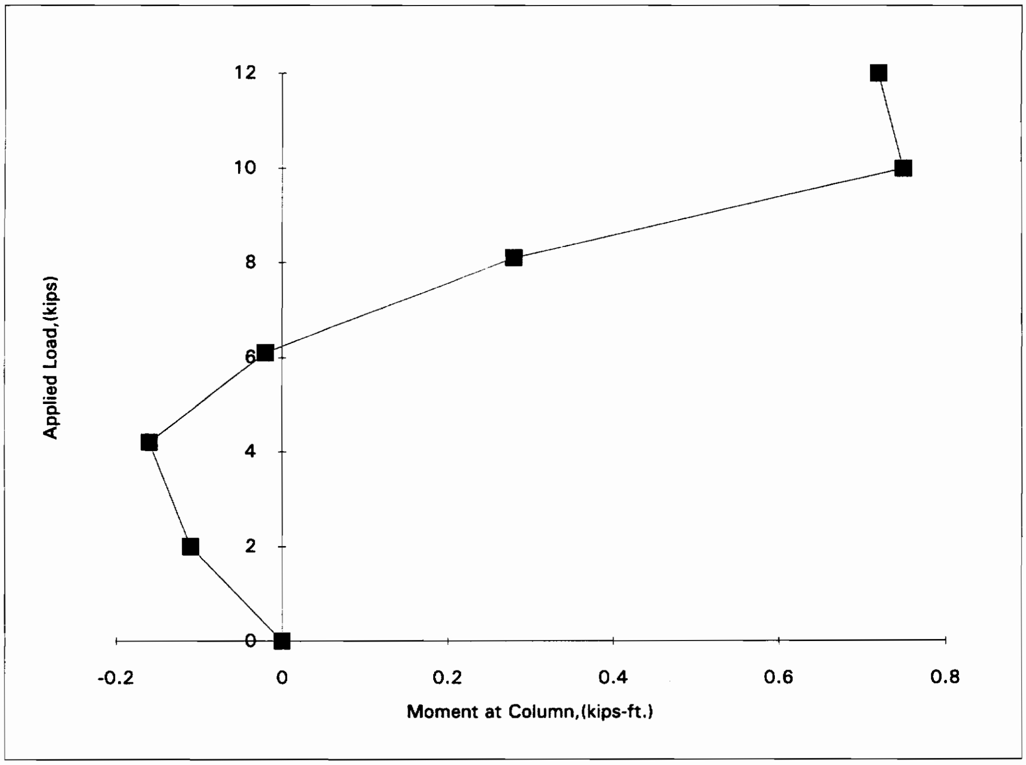
Applied Load vs. Average Deflection



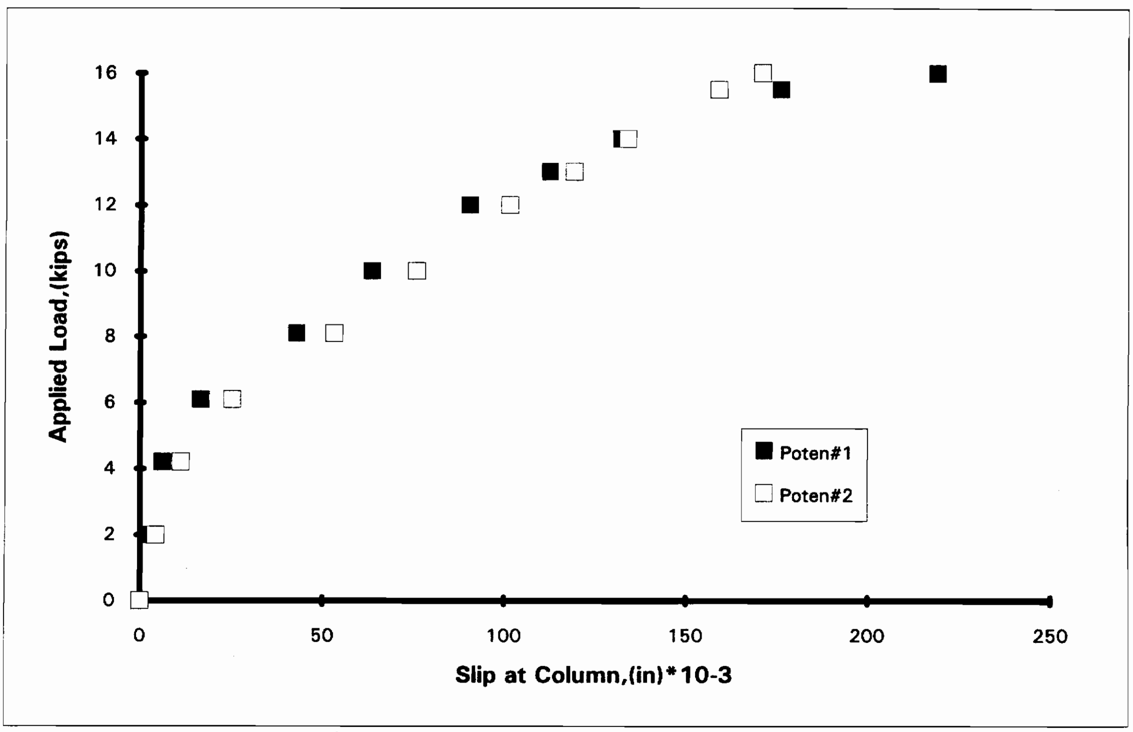
Applied Load vs. Deflection



Applied Load vs. Reaction



Applied Load vs. Moment at the Column



Applied Load vs. Slip at the Column

TEST SUMMARY

TEST#5

TEST DESIGNATION: II-3bU2

TEST DATE: September 30, 1993

PURPOSE: Double angle three-bolt unbonded connection test

SPAN: 10 ft.

PARAMETERS:
- 2 point loading at 1ft. 5 3/4 in. from each end
- Double angle 3-bolt unbonded connection
- Full length stiffeners provided on both sides at load points and reactions
- Bolt diameter, 3/8 in.

FAILURE LOAD: 21.3 kips (Maximum Applied Load)
10.65 kips at connection

FAILURE MODE: Shear crack formed in web of beam.

PREDICTED FAILURE LOADS:
Gross Shear of Connection Angles: 16.88 kips

DISCUSSION:
- Load deflection curve was essentially linear
- Brittle Failure
- CCW moments assumed to be positive

TEST SUMMARY(Cont.)

TEST#5

MEASURED DIMENSIONS:

Beam: b_f = 8 in.
$t_{f,top}$ = 0.375 in.
$t_{f,bottom}$ = 0.375 in.
d = 8 in.
t_w= 0.380 in.

Angle: t = 0.370 in.
b = 3 in.
d = 5 in.

Column: b_f= 6 in.
t_f= 0.249 in.
d = 6 in.
t_w= 0.250 in.

$I_x = 99.38$ in.^{4}

Test Set-up
Test#5

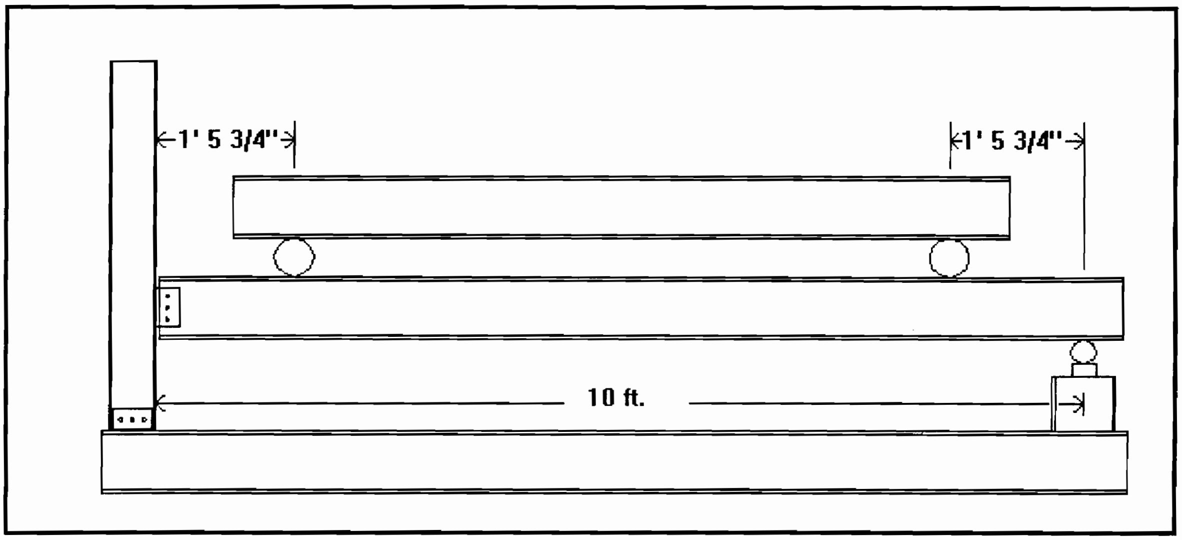


Fig 1 Test Detail

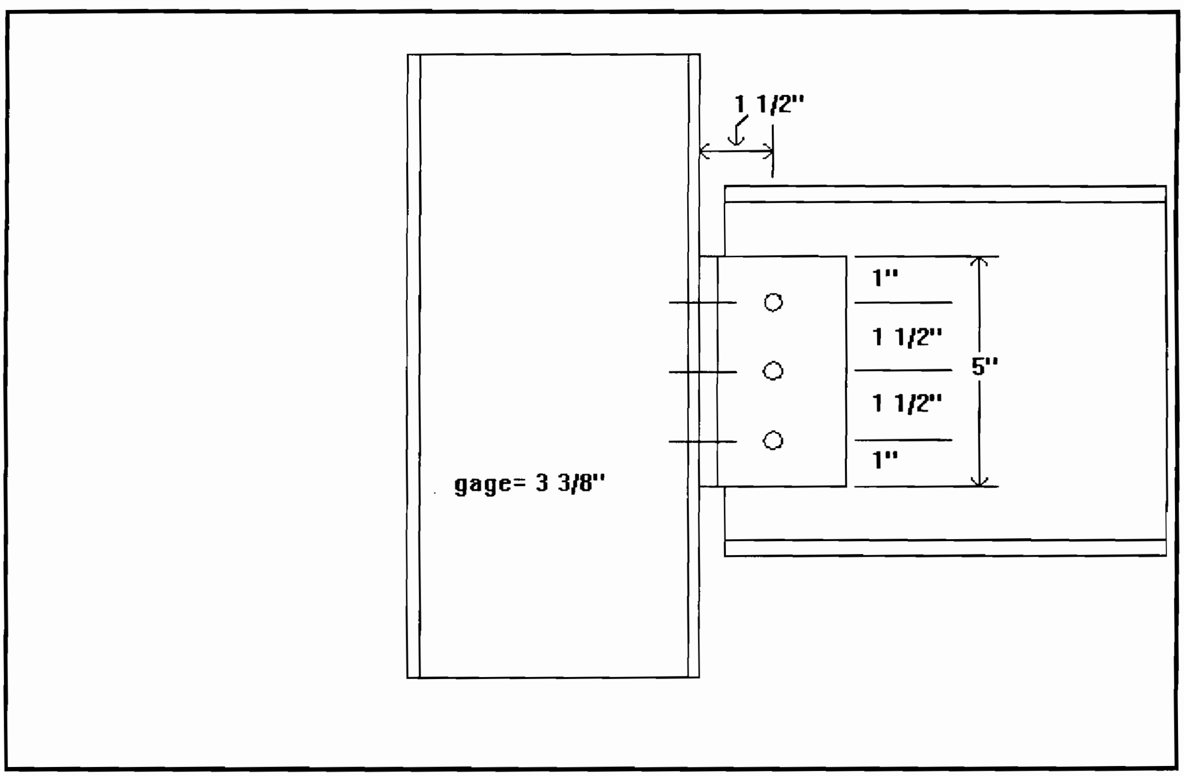
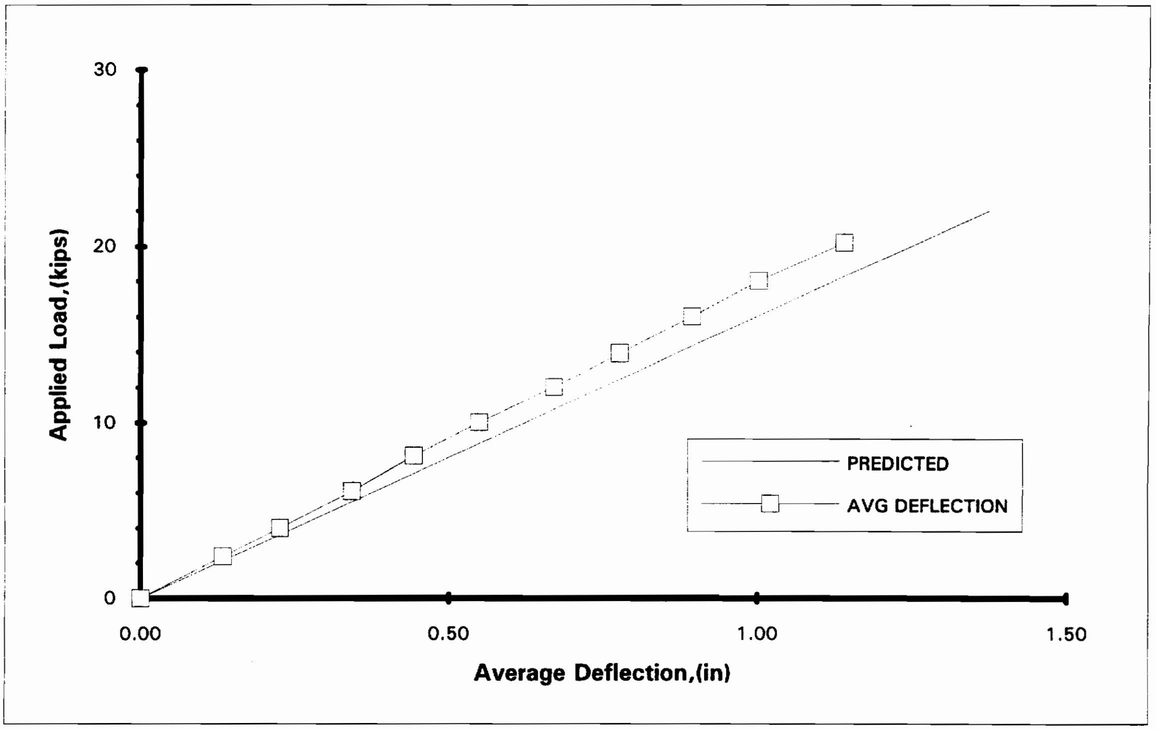
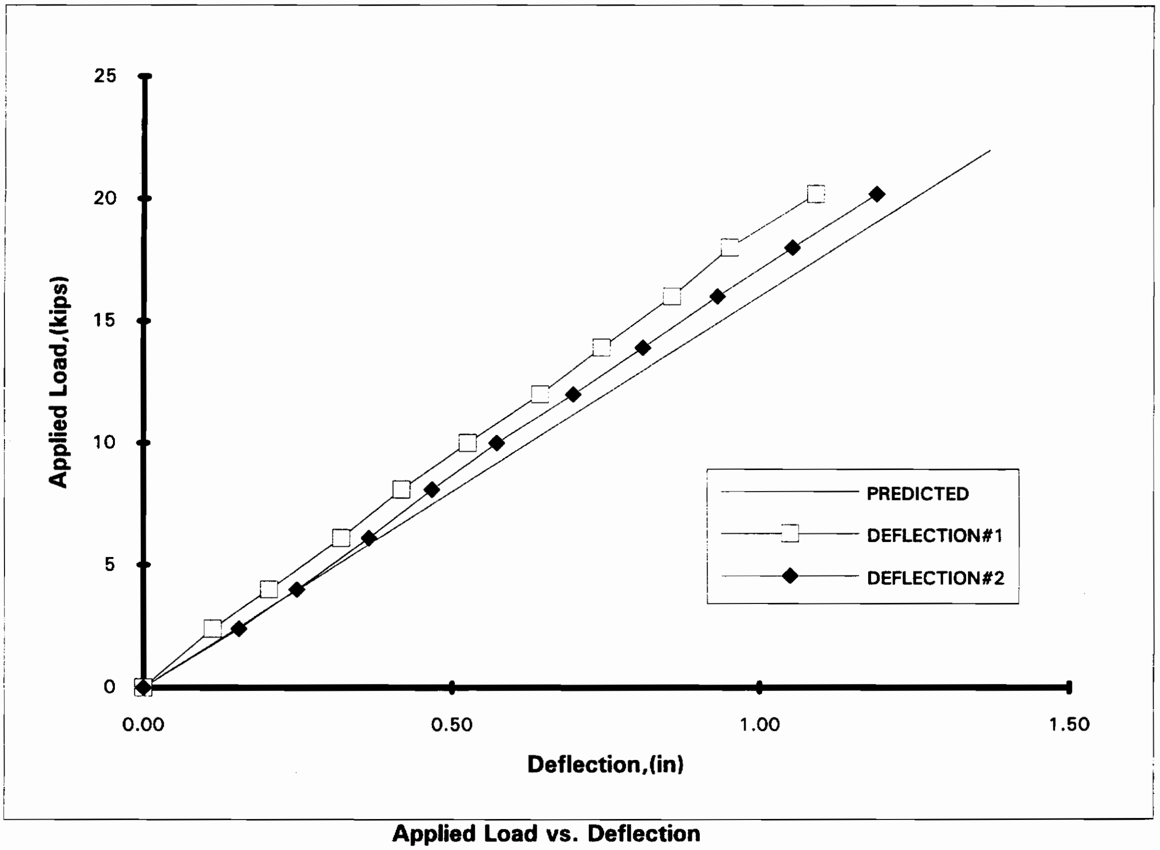


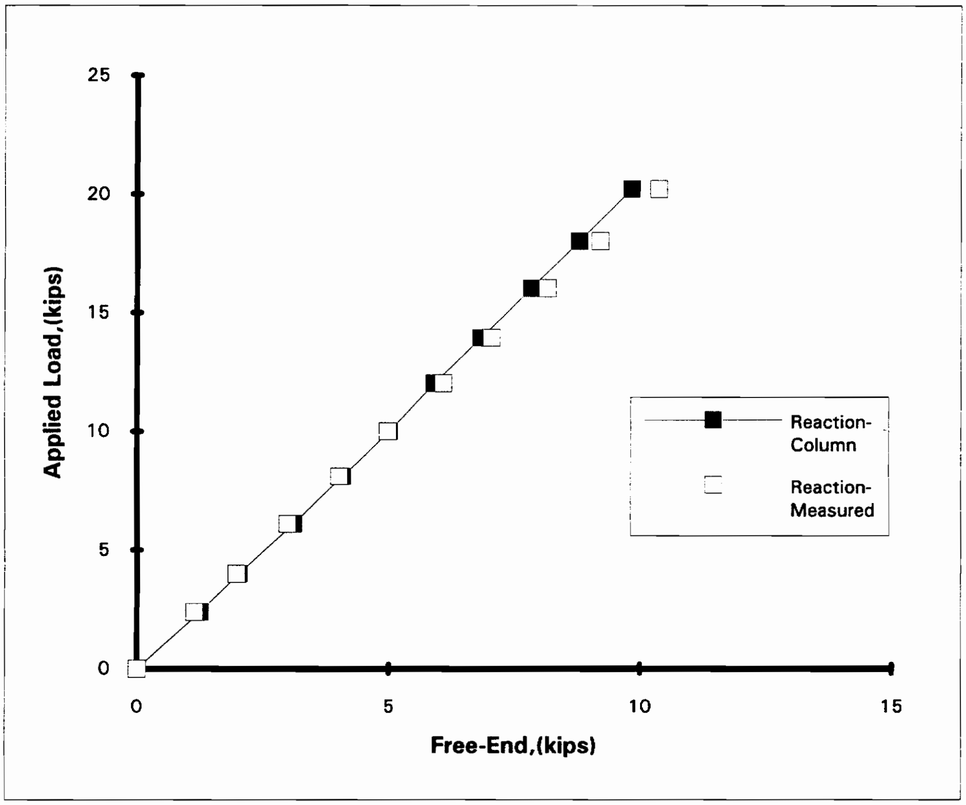
Fig 2 Connection Detail



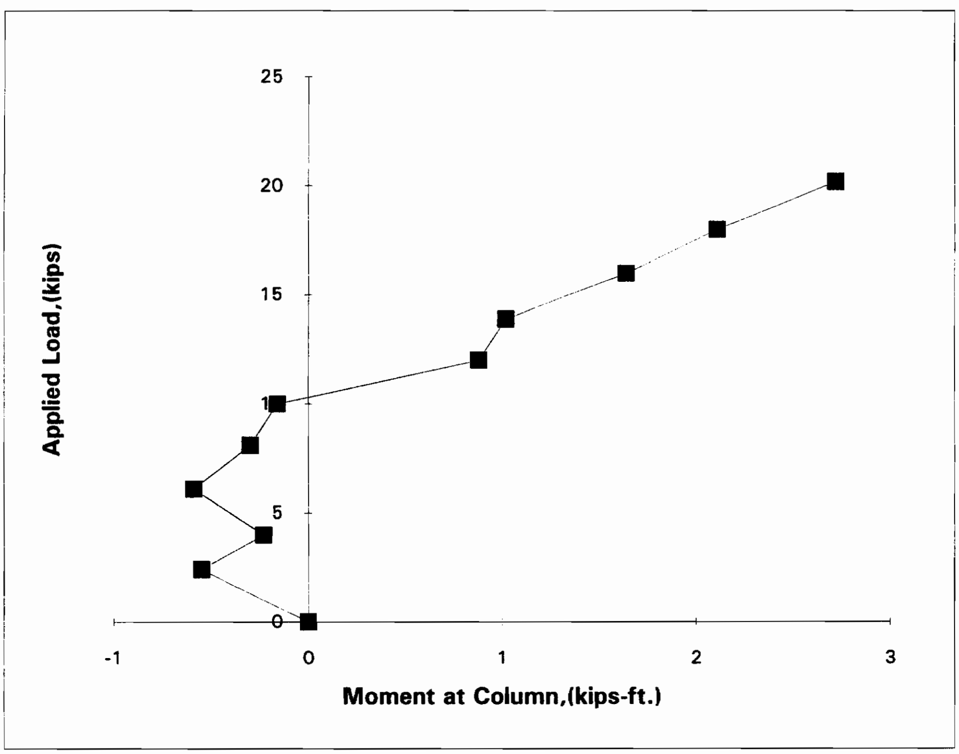
Applied Load vs. Average Deflection



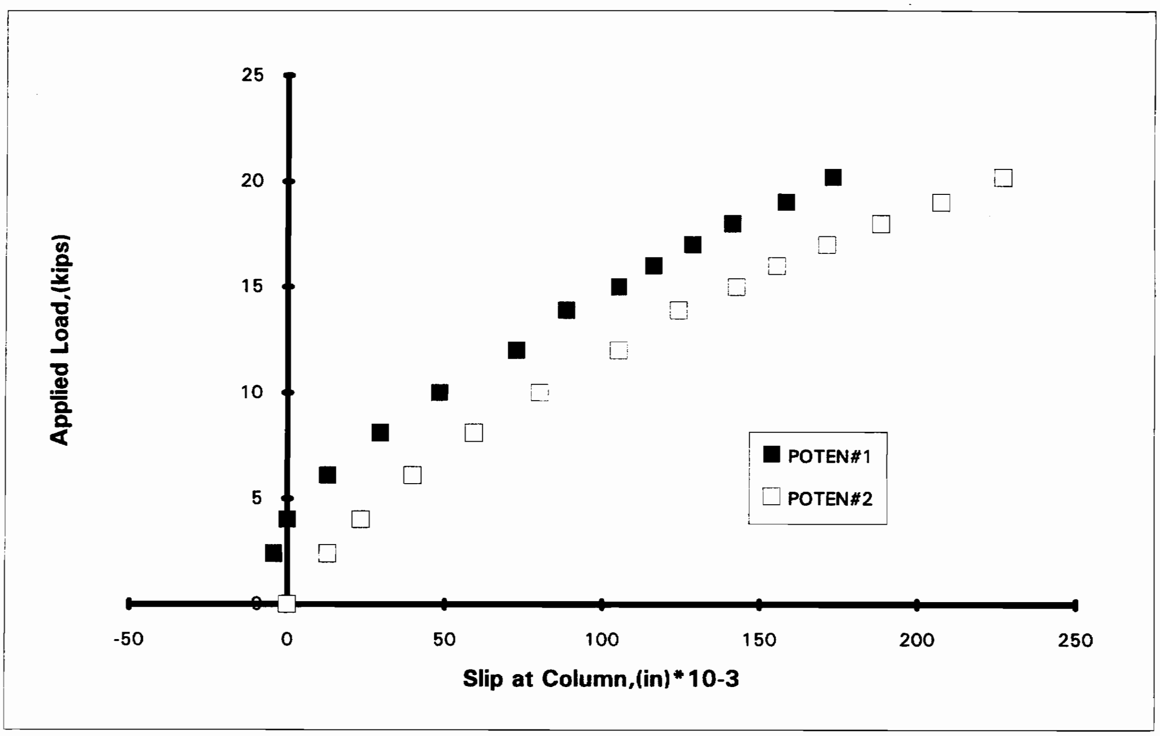
Applied Load vs. Deflection



Applied Load vs. Reaction



Applied Load vs. Moment at the Column



Applied Load vs. Slip at the Column

TEST SUMMARY

TEST#9

TEST DESIGNATION: II-3bB1

TEST DATE: 11/20/93

PURPOSE: Double angle three-bolt bonded connection test

SPAN: 10 ft.

PARAMETERS:
- 2 point loading at 4 ft. from each end(9A)
- 2 point loading at 3 ft. from each end(9B)
- 2 point loading at 2 ft. from each end(9C)
- 2 point loading at 1 ft. 5 3/4 in. from each end(9D)
- Double angle 2-bolt bonded connection
- Full length stiffeners provided on both sides at load points and reactions
- Bolt diameter, 3/8 in.

FAILURE LOAD: 28.0 kips (Maximum Applied Load)
14.0 kips at connection

FAILURE MODE: Not taken to failure

PREDICTED FAILURE LOADS:
Gross Shear of Connection Angles: 16.88 kips

DISCUSSION:
- Load deflection curve was essentially linear
- Stress showing in angle corners on both sides and at the intersection of the web and the flange in the column
- Loading stopped due to imminent failure of test set-up
- CW moments assummed to be positive, 9A through 9C
- CCW moments assumed to be postive, 9D

Test Summary(Cont.)

Test#9

MEASURED DIMENSIONS:

Beam: b_f = 8 in.
$t_{f,top}$ = 0.377 in.
$t_{f,bottom}$ = 0.378 in.
d = 8 in.
t_w = 0.379 in.

Angle: t = 0.370 in.
b = 3 in.
d = 5. in.

Column: b_f = 6 in.
t_f = 0.253 in.
d = 6 in.
t_w = 0.248 in.

$I_x = 99.55\ in.^4$

Test Set-up
Test#9

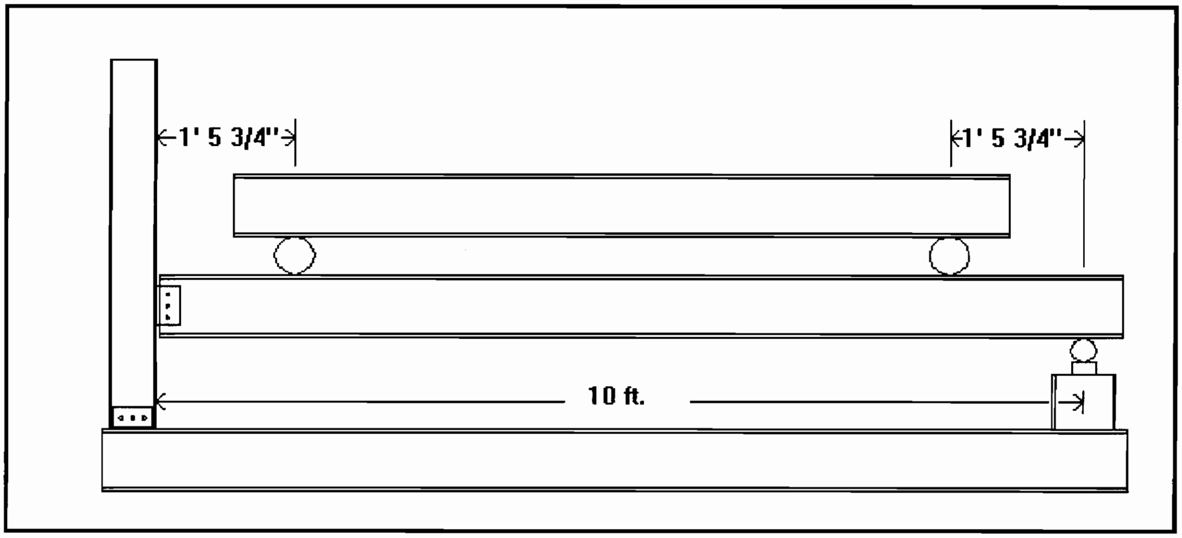


Fig 1 Test Detail

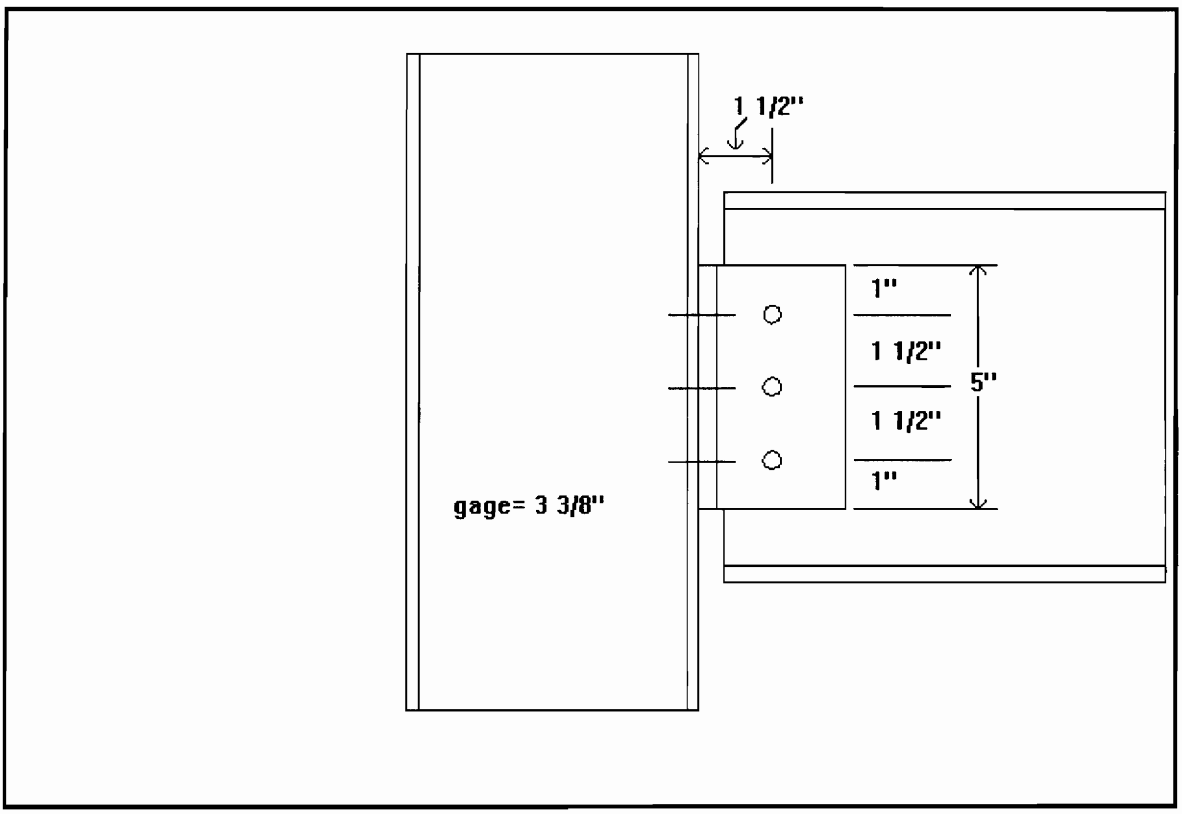
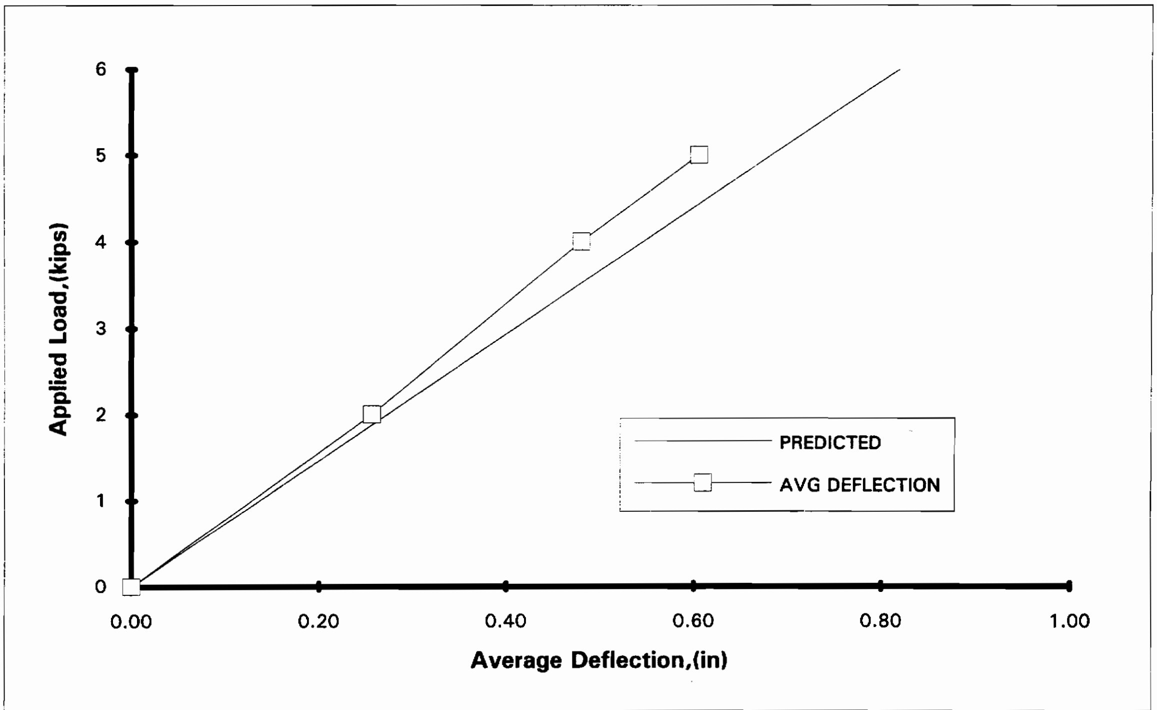
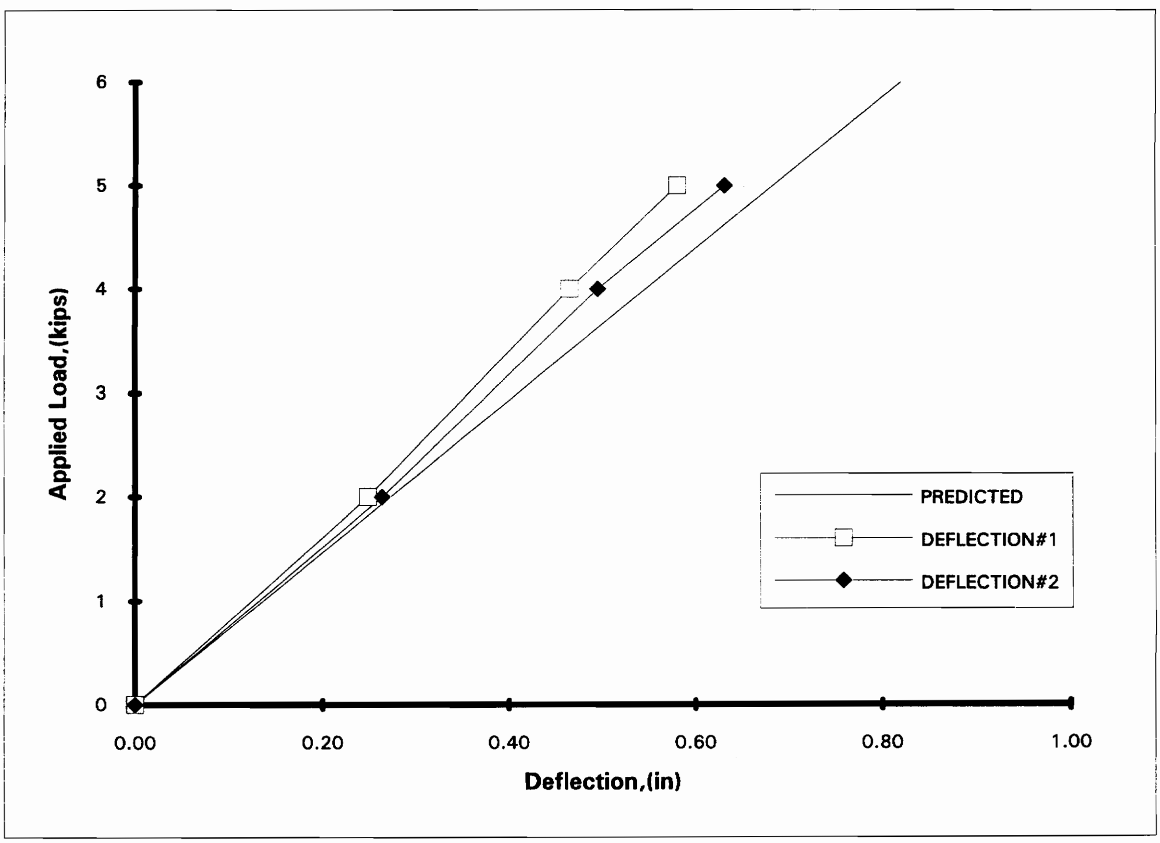


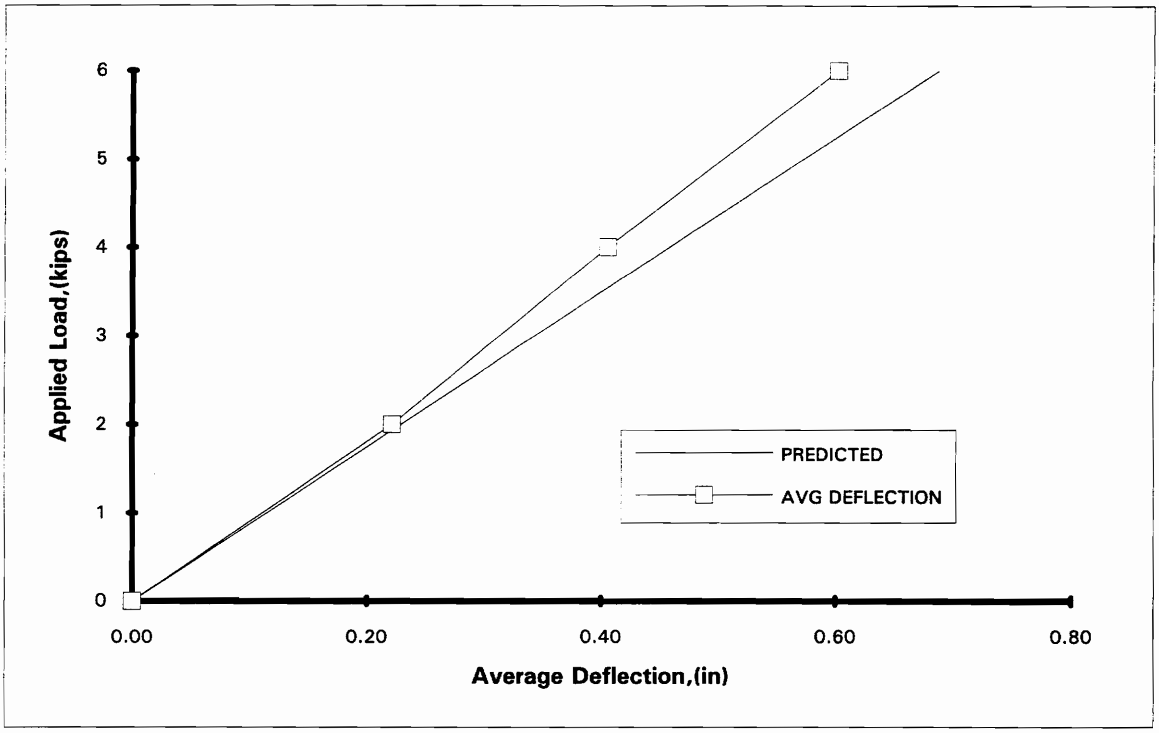
Fig 2 Connection Detail



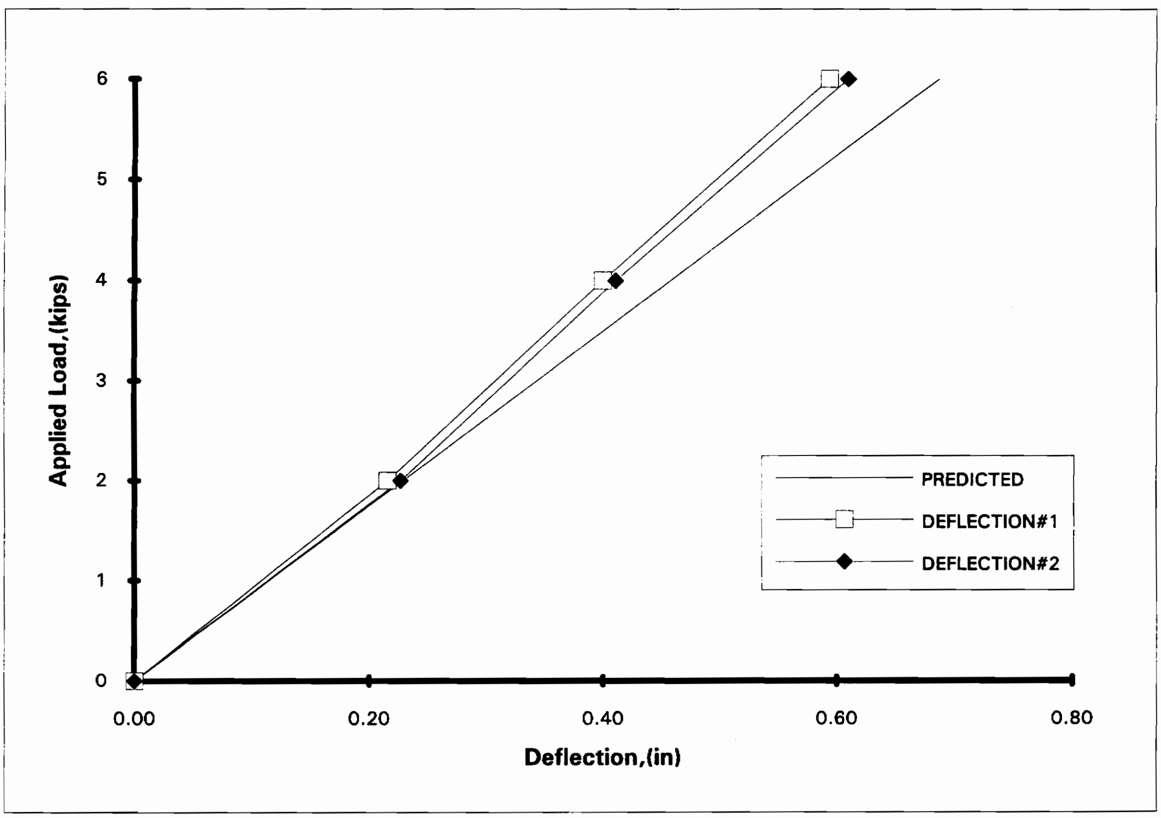
Applied Load vs. Average Deflection (9A)



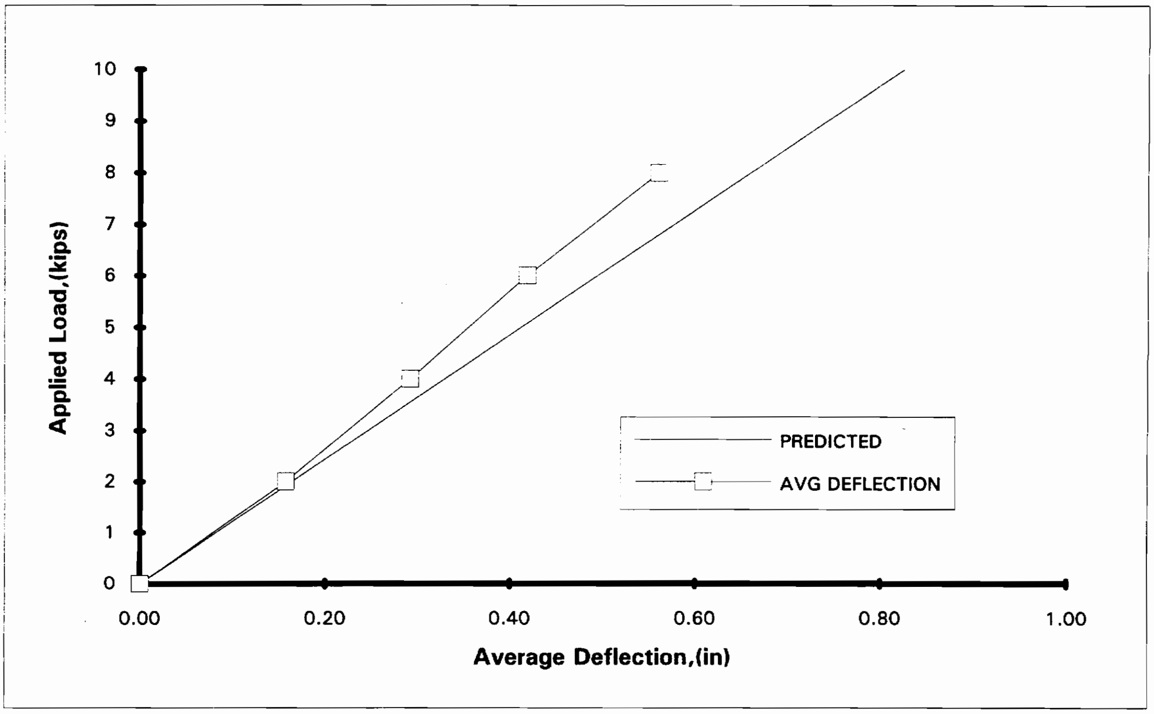
Applied Load vs. Deflection (9A)



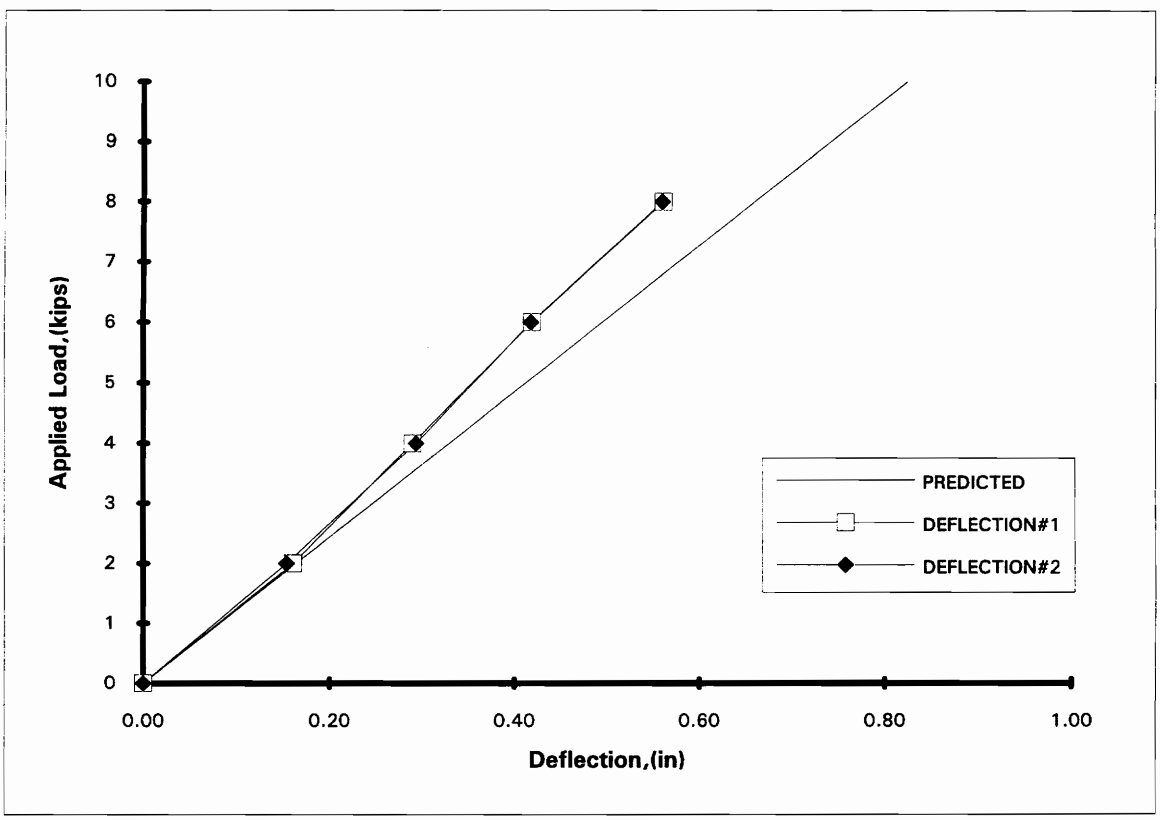
Applied Load vs. Average Deflection (9B)



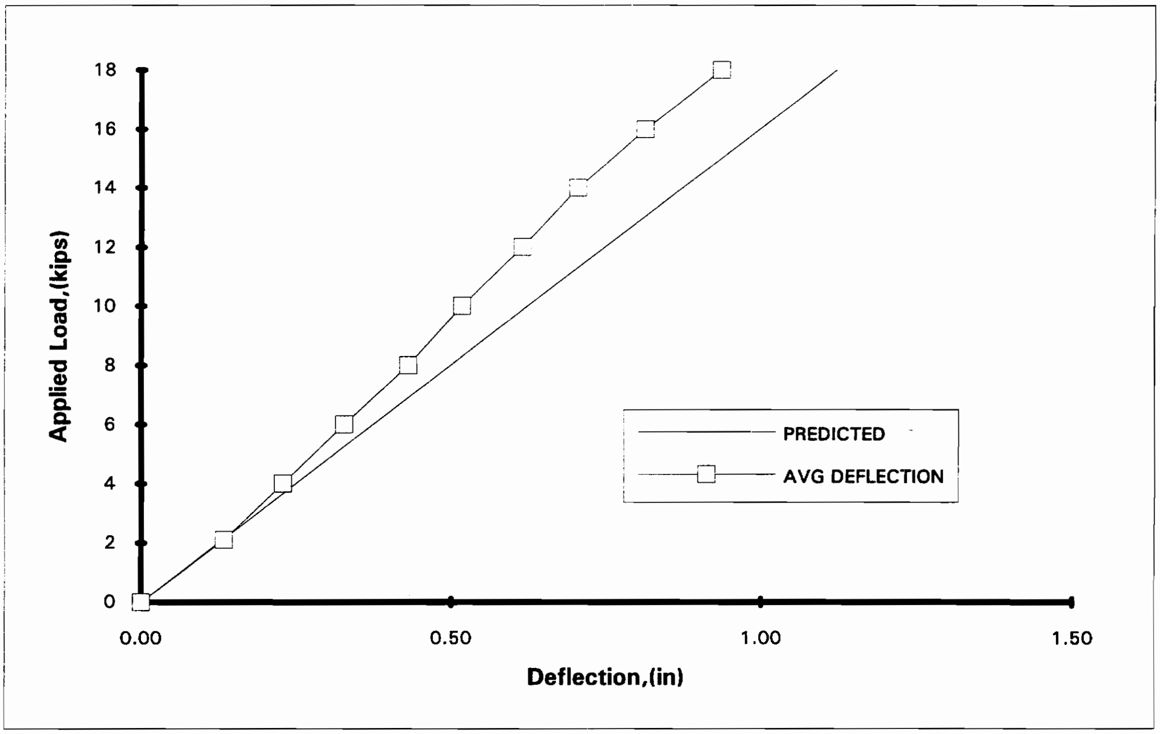
Applied Load vs. Deflection (9B)



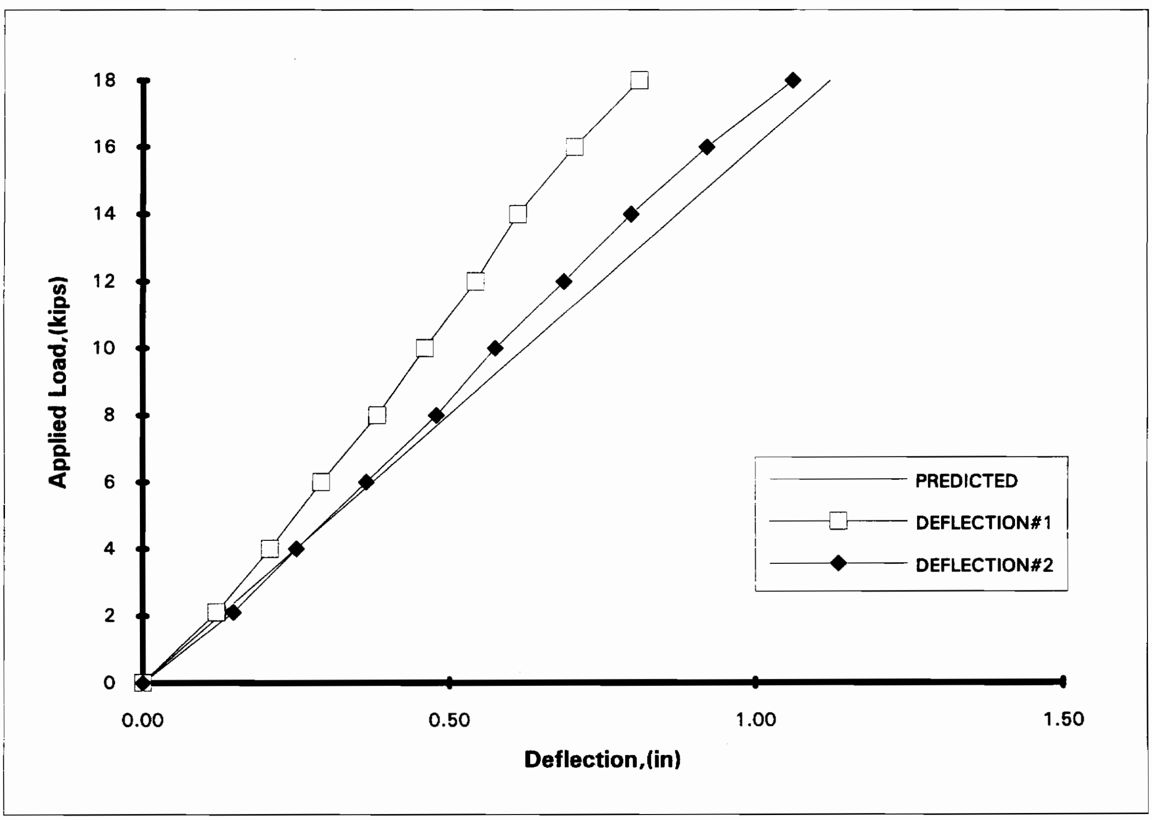
Applied Load vs. Average Deflection (9C)



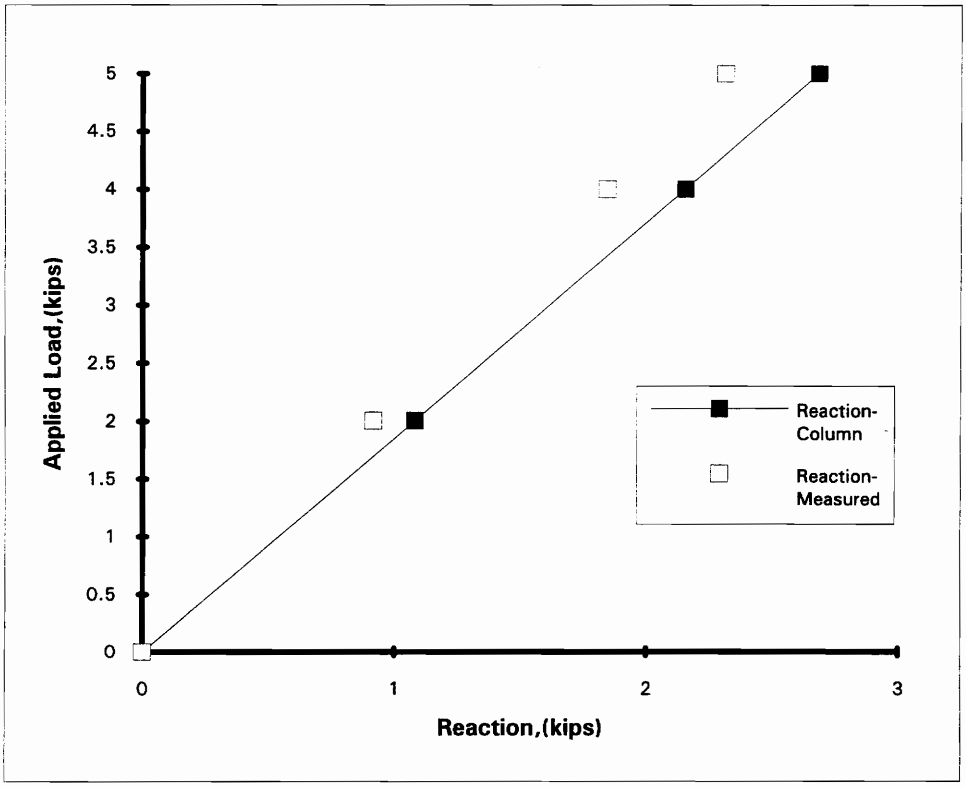
Applied Load vs. Deflection (9C)



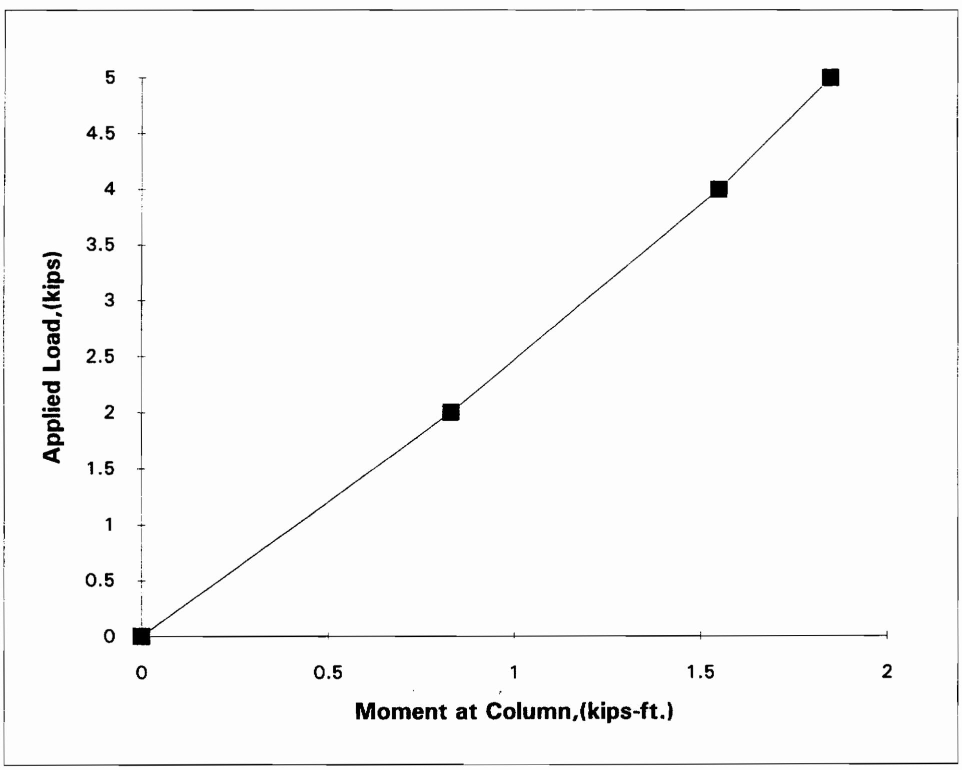
Applied Load vs. Average Deflection (9D)



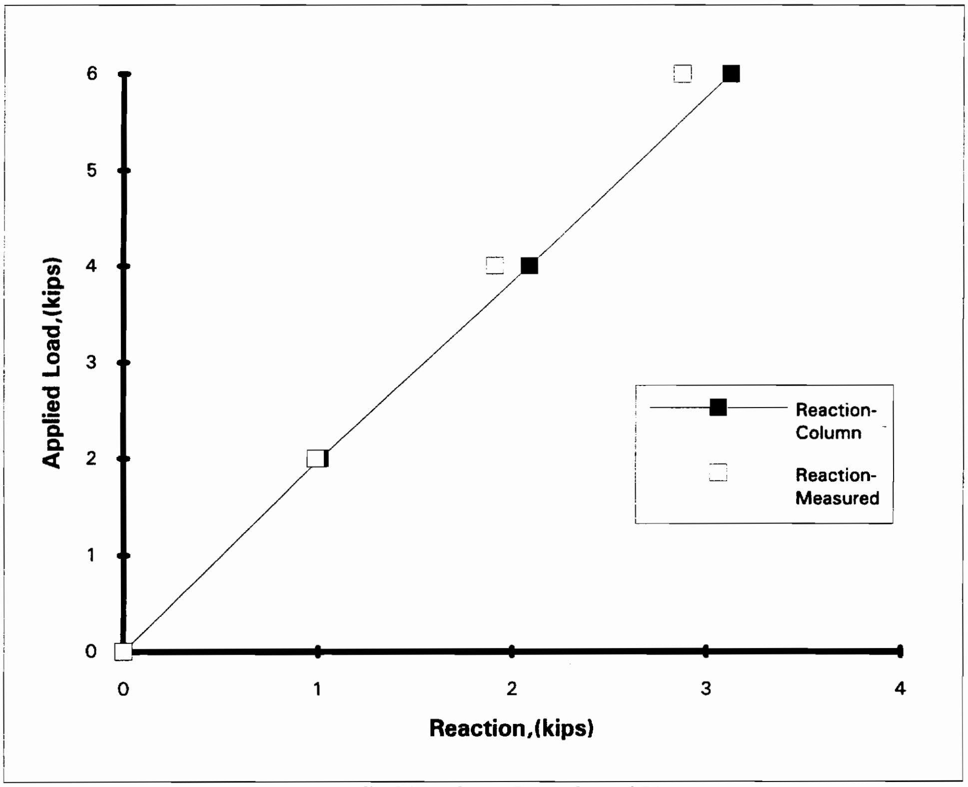
Applied Load vs. Deflection (9D)



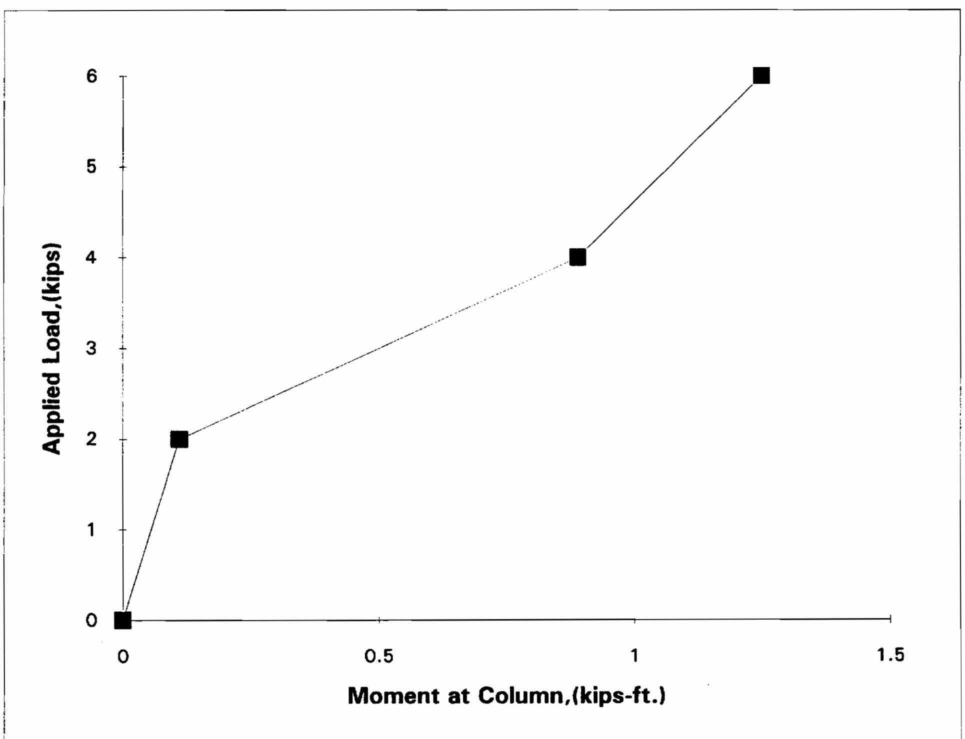
Applied Load vs. Reaction (9A)



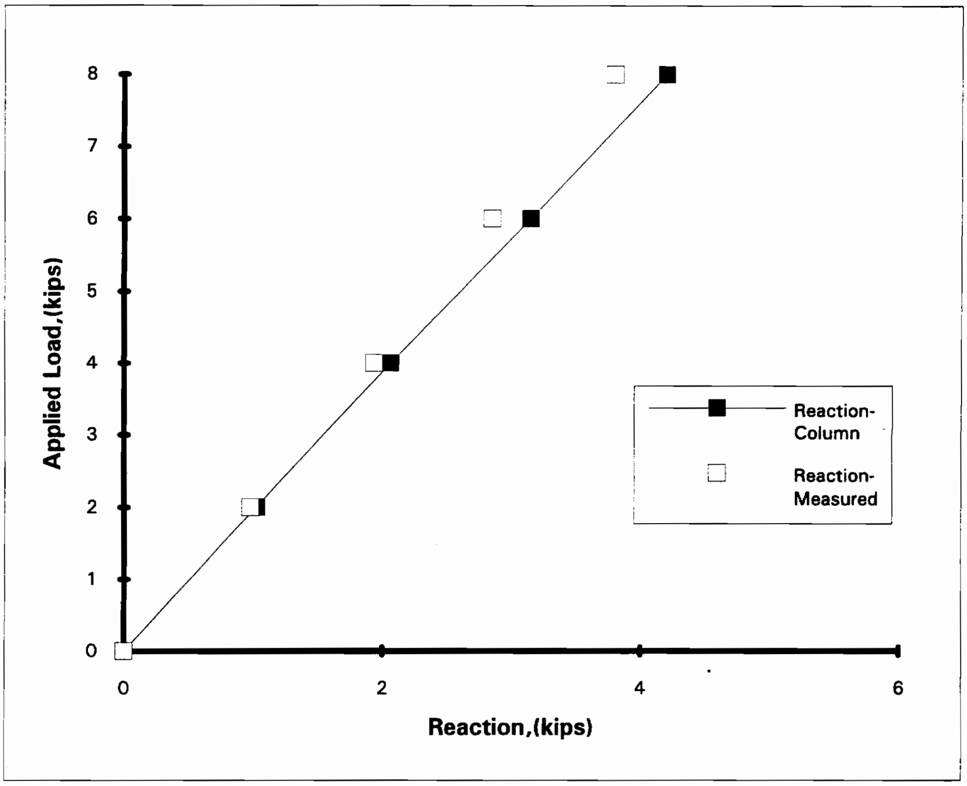
Applied Load vs. Moment at the Column (9A)



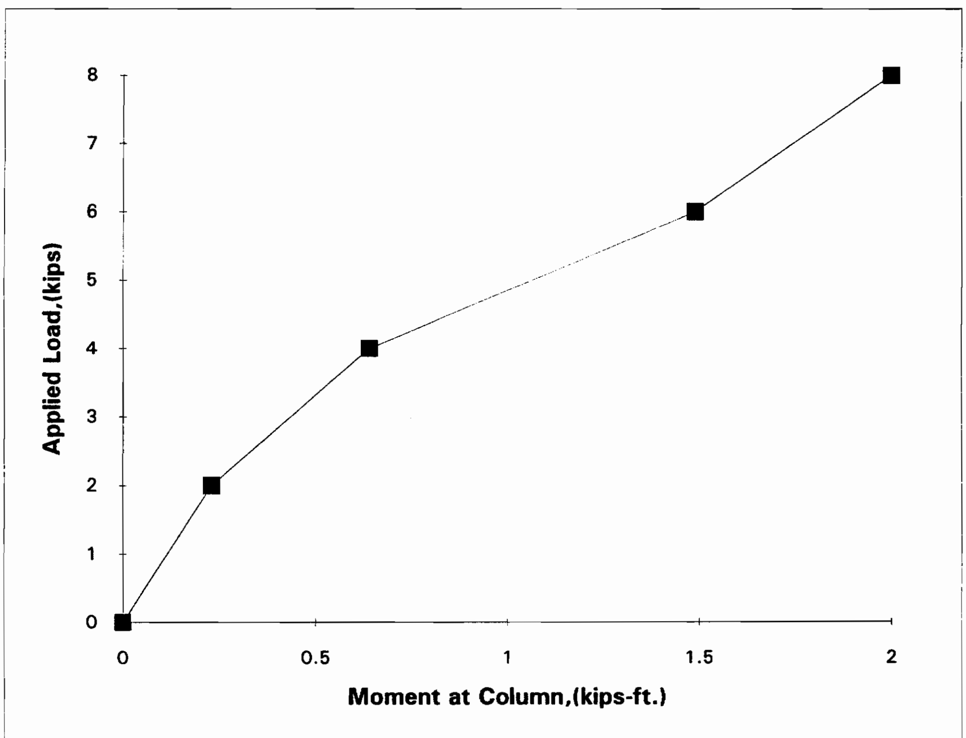
Applied Load vs. Reaction (9B)



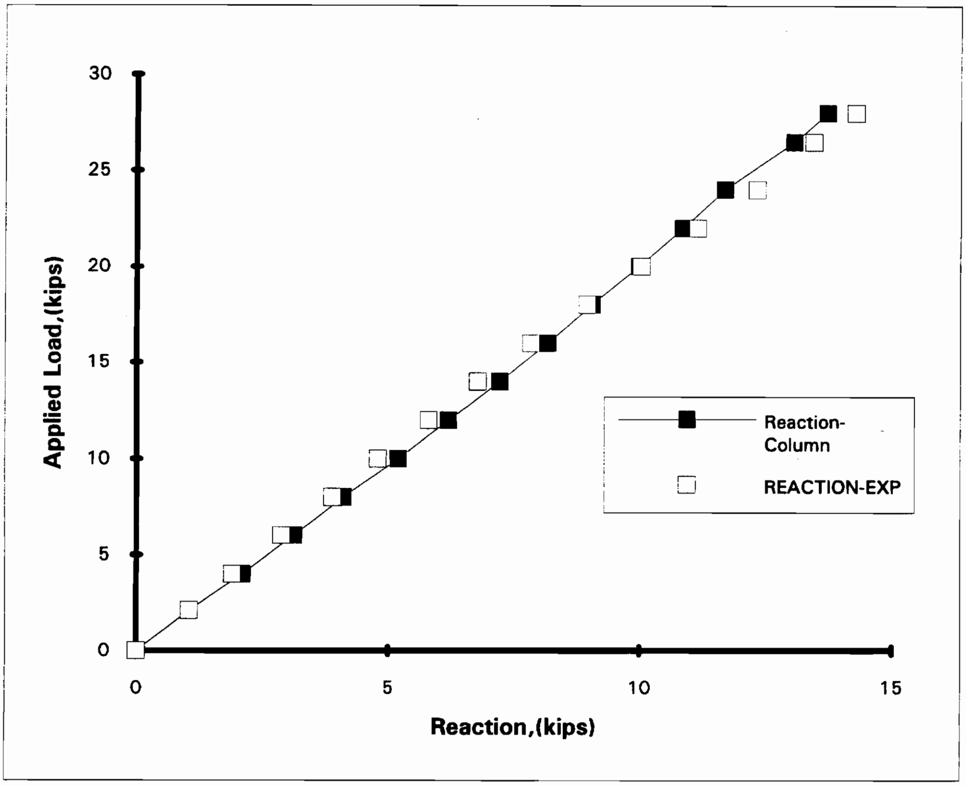
Applied Load vs. Moment at the Column (9B)



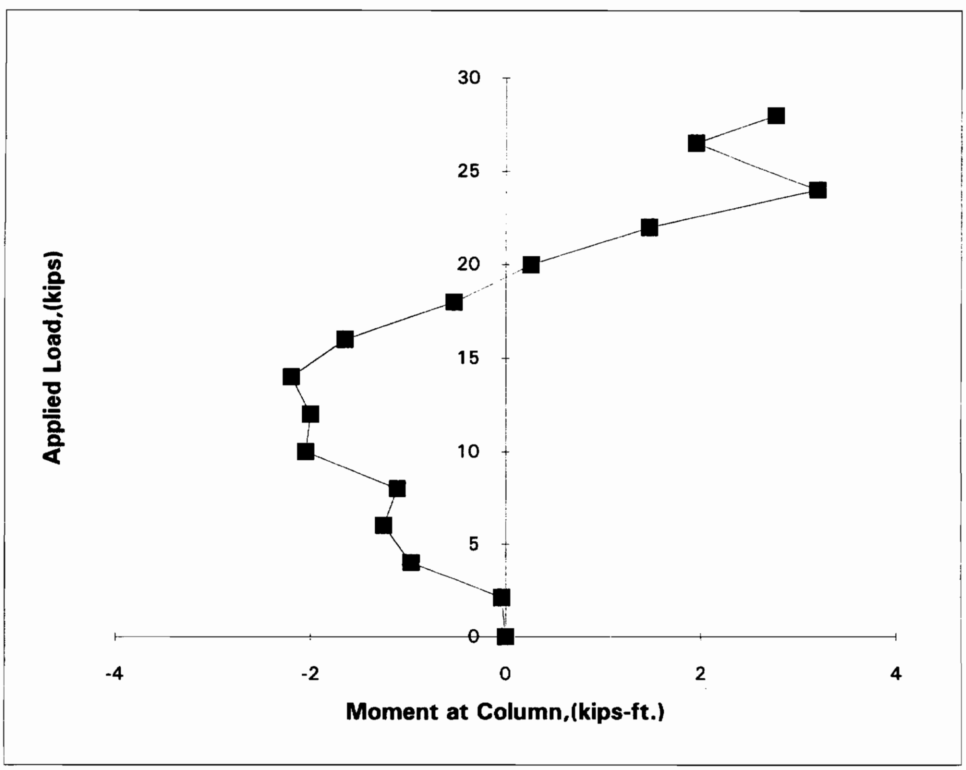
Applied Load vs. Reaction (9C)



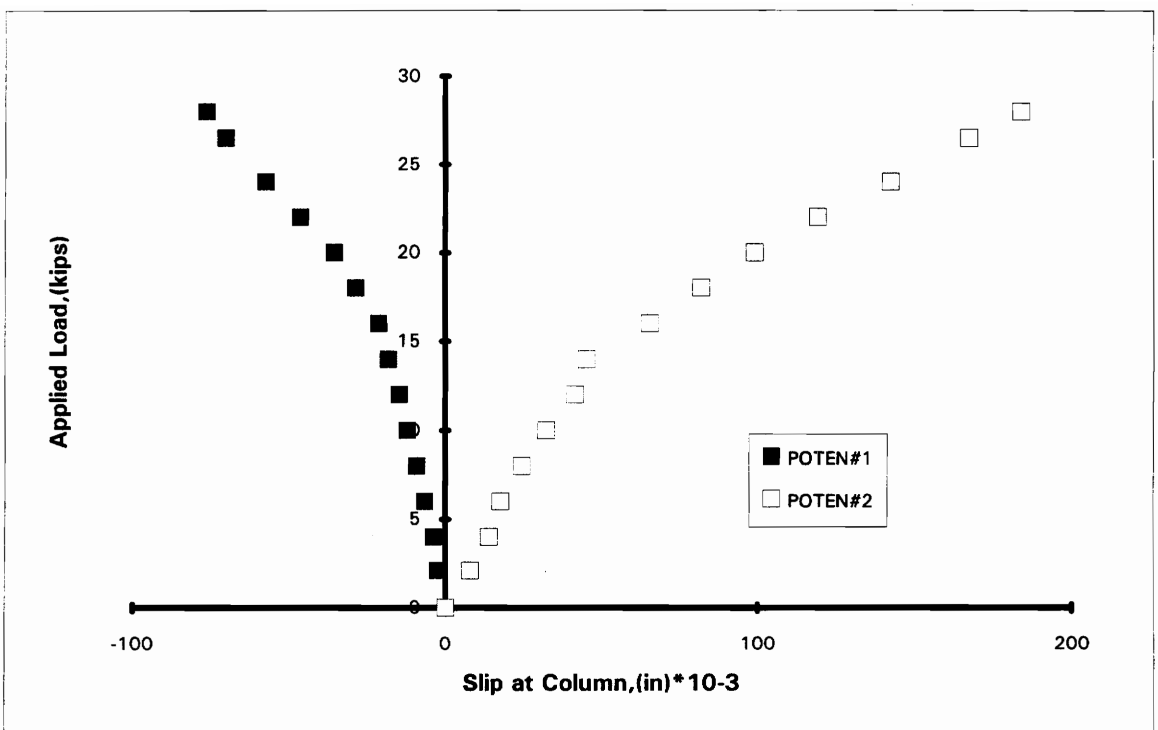
Applied Load vs. Moment at the Column (9C)



Applied Load vs. Reaction (9D)



Applied Load vs. Moment at the Column (9D)



Applied Load vs. Slip at the Column (9D)

APPENDIX C

SERIES III TEST RESULTS

TEST SUMMARY

TEST#7

TEST DESIGNATION: III-2bU1s

TEST DATE: 11/3/93

PURPOSE: Double angle two-bolt unbonded connection test

SPAN: 8 ft.

PARAMETERS:
- 2 point loading at 2.33 ft. from each end
- Double angle 2-bolt unbonded connection
- Full length stiffeners provided on both sides at load points and reactions
- Bolt diameter, 3/8 in.

FAILURE LOAD: 16.1 kips (Maximum Applied Load)
8.05 kips at connection

FAILURE MODE: One angle gross shear at the heel of the angle and the other angle in net shear along the bolt line

PREDICTED FAILURE LOADS:
Gross Shear of Connection Angles: 16.88 kips

DISCUSSION:
- Load deflection curve was essentially linear
- Brittle Failure
- CW moments assumed to be positive

TEST SUMMARY(Cont.)

TEST#7

MEASURED DIMENSIONS:

Beam: b_f = 8 in.
$t_{f,top}$ = 0.376 in.
$t_{f,bottom}$ = 0.376 in.
d = 8 in.
t_w = 0.378 in.

Angle: t = 0.367 in.
b = 3 in.
d = 5 in.

Column: b_f = 6 in.
t_f = 0.247 in.
d = 6 in.
t_w = 0.248 in.

$I_x = 99.45$ in.^{4}

Test Set-up
Test#7

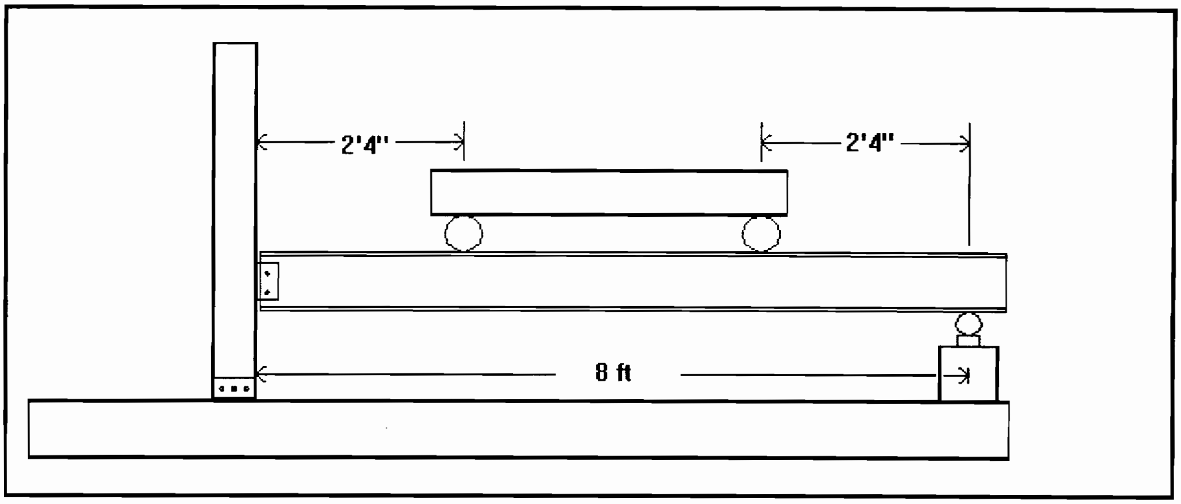


Fig 1 Test Detail

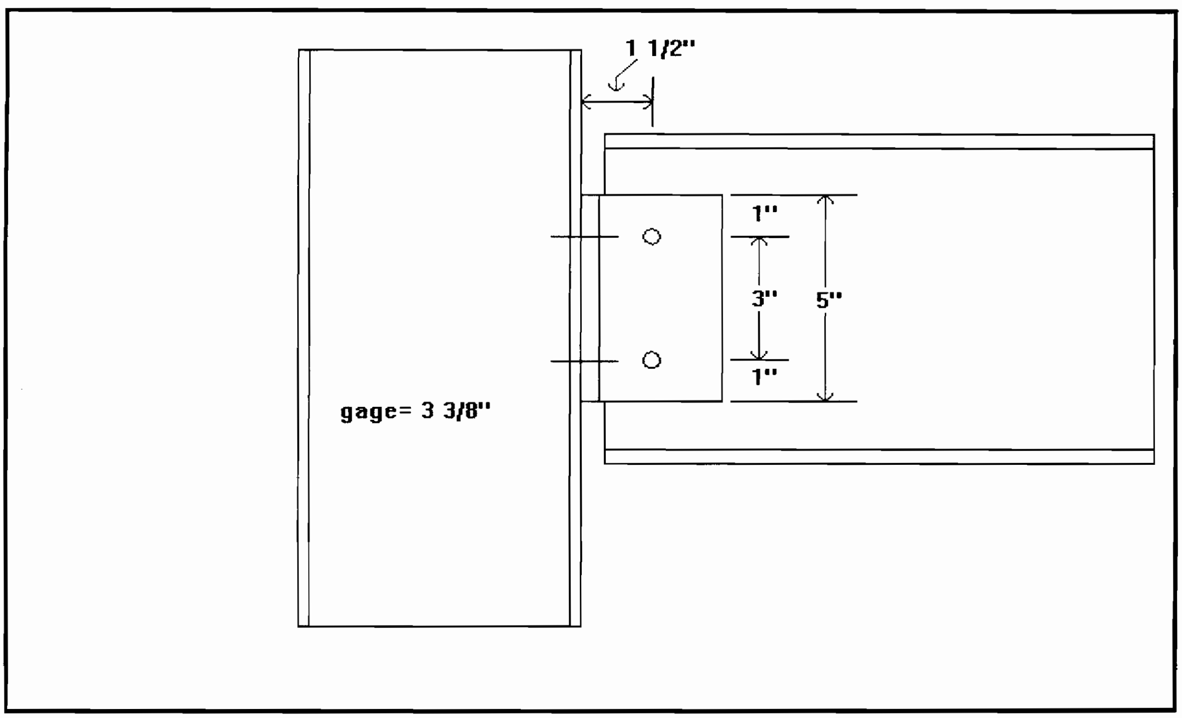
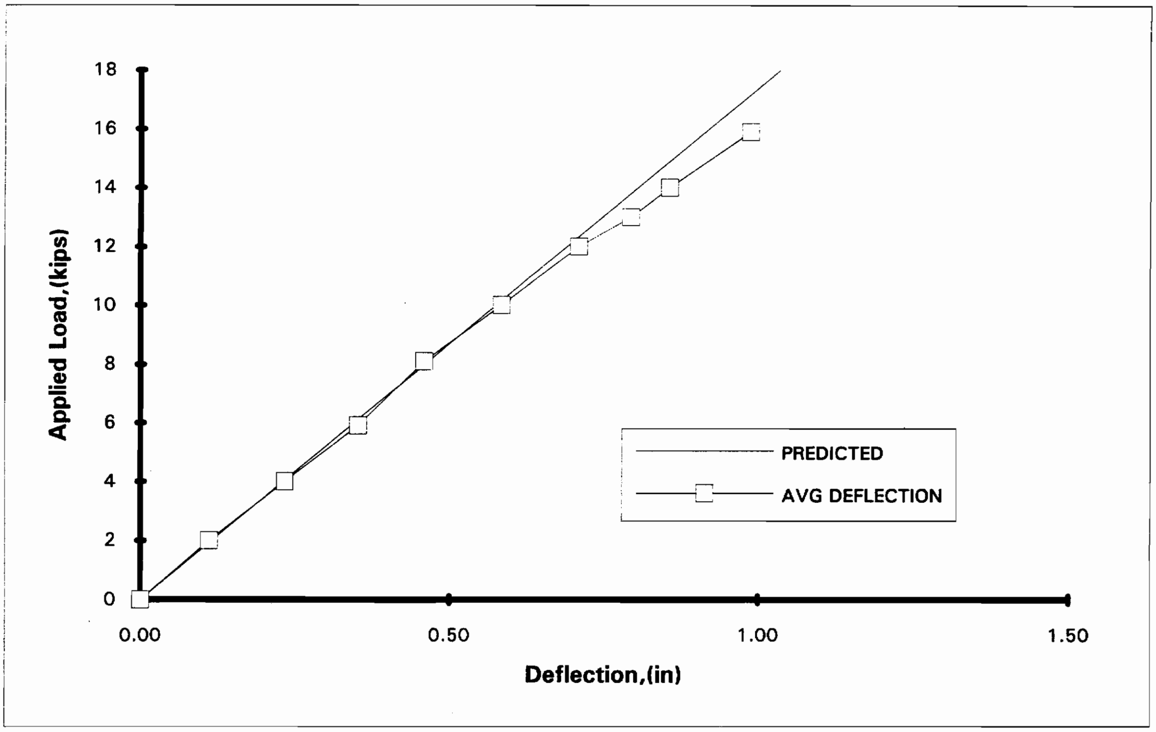
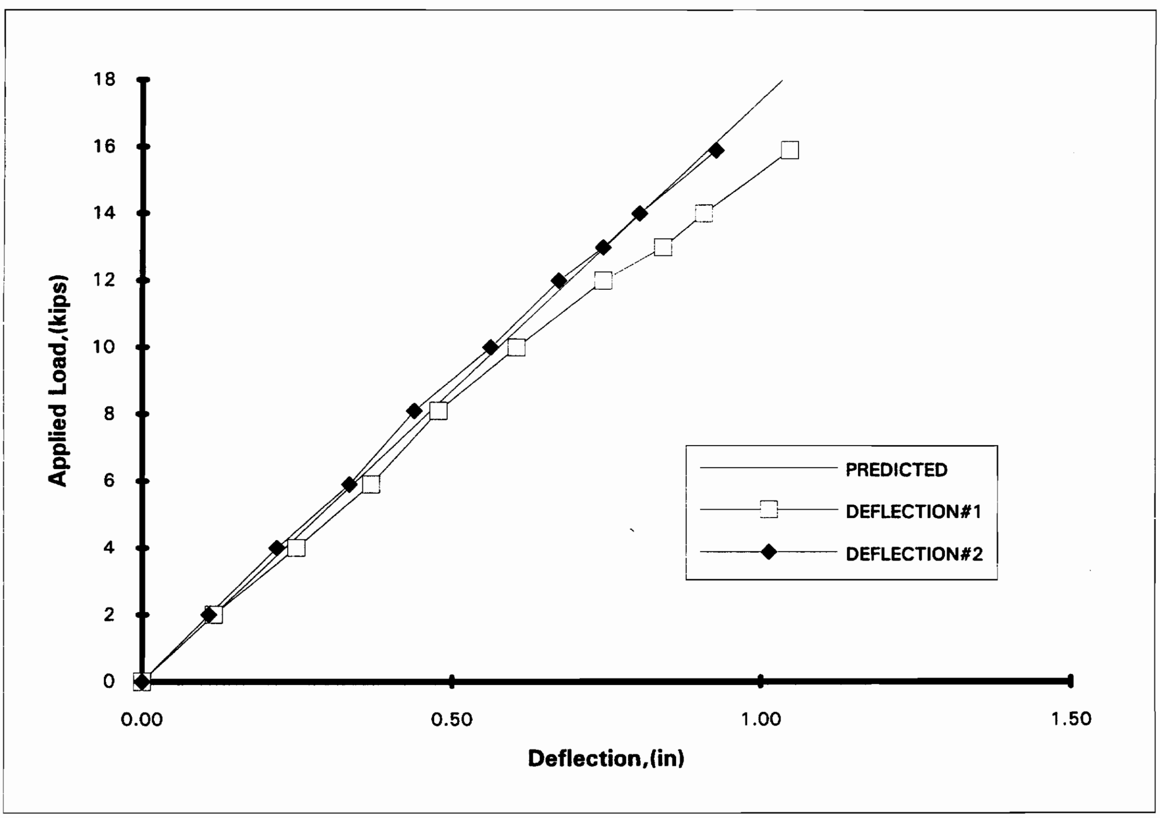


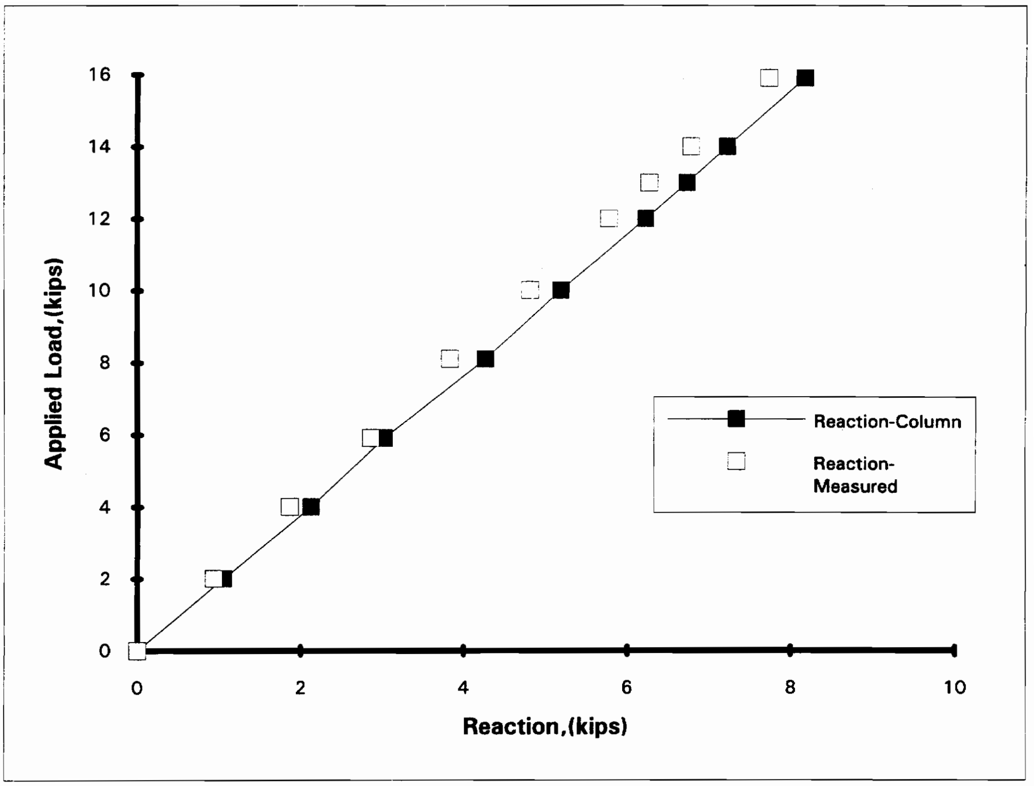
Fig 2 Connection Detail



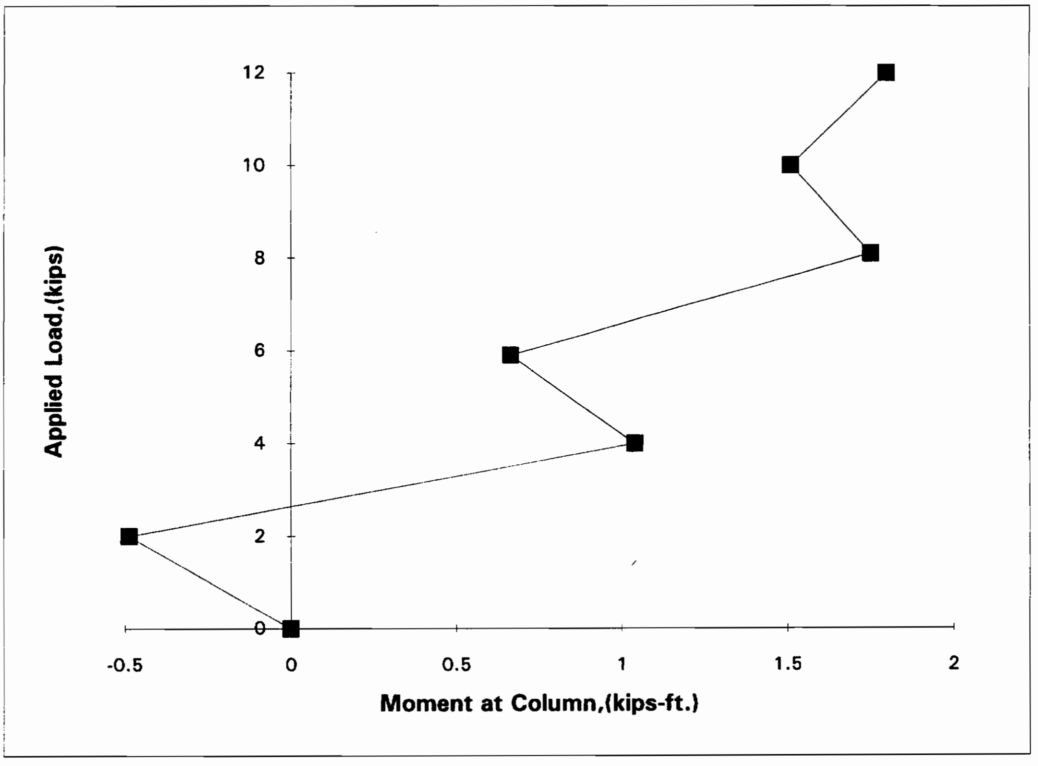
Applied Load vs. Average Deflection



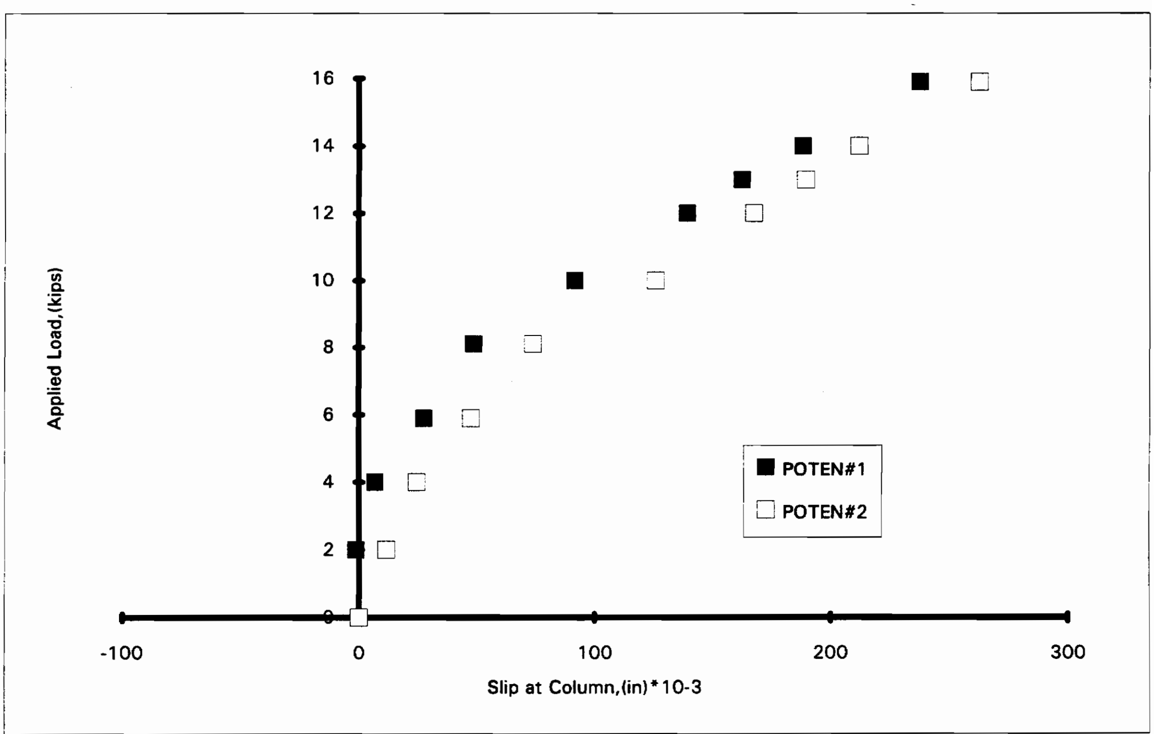
Applied Load vs.Deflection



Applied Load vs. Reaction



Applied Load vs. Moment at the Column



Applied Load vs. Slip at the Column

TEST SUMMARY

TEST#8

TEST DESIGNATION: III-2bU2s

TEST DATE: 11/4/93

PURPOSE: Double angle two-bolt unbonded connection test

SPAN: 8 ft.

PARAMETERS:
- 2 point loading at 2.33 ft. from each end
- Double angle 2-bolt unbonded connection
- Full length stiffeners provided on both sides at load points and reactions
- Bolt diameter, 3/8 in.

FAILURE LOAD: 18.1 kips (Maximum Applied Load)
9.05 kips at connection

FAILURE MODE: Shear crack in the web of the beam

PREDICTED FAILURE LOADS:
Gross Shear of Connection Angles: 16.88 kips

DISCUSSION:
- Load deflection curve was essentially linear
- Brittle Failure
- CCW moments assumed to be positive

TEST SUMMARY(Cont.)

TEST#8

MEASURED DIMENSIONS:

Beam:	$b_f =$ 8 in.
	$t_{f,top} =$ 0.376 in.
	$t_{f,bottom} =$ 0.376 in.
	$d =$ 8 in.
	$t_w =$ 0.378 in.
Angle:	$t =$ 0.367 in.
	$b =$ 3 in.
	$d =$ 5 in.
Column:	$b_f =$ 6 in.
	$t_f =$ 0.247 in.
	$d =$ 6 in.
	$t_w =$ 0.248 in.

$I_x = 99.45\ in.^4$

Test Set-up
Test#8

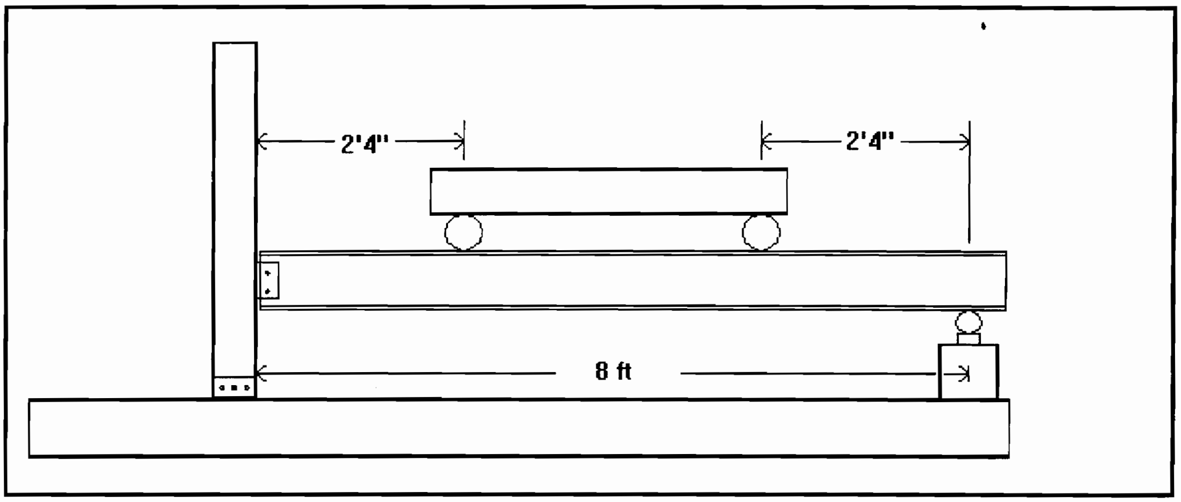


Fig 1 Test Detail

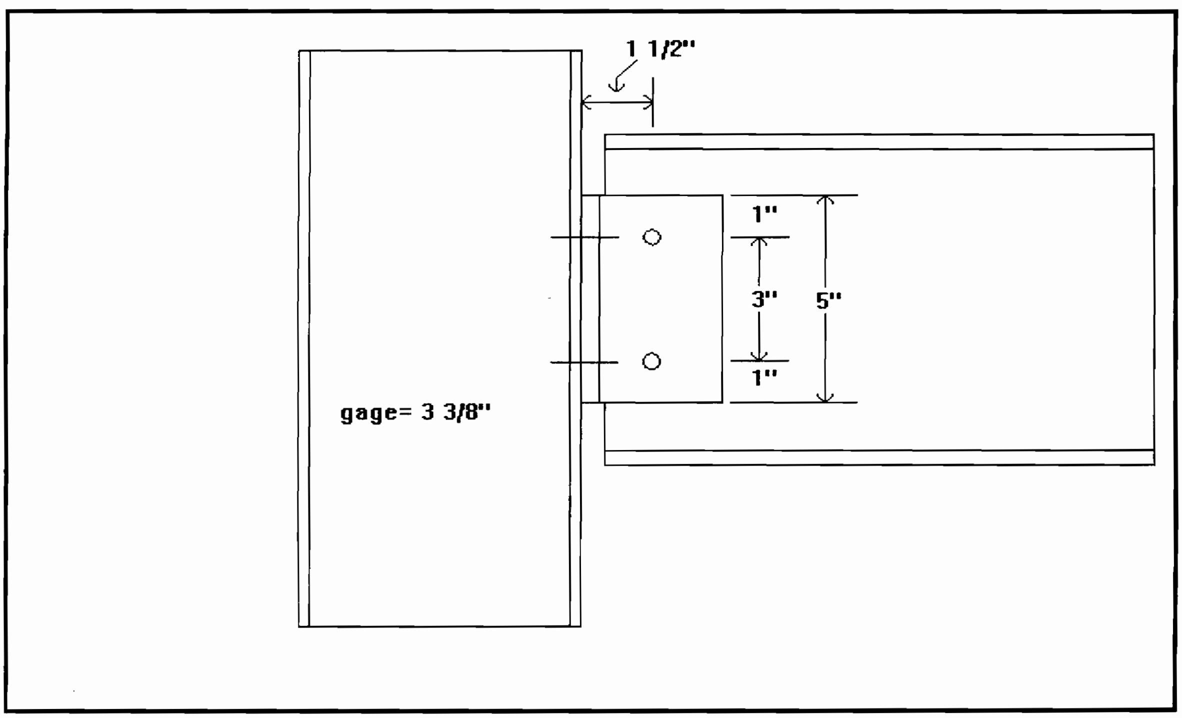
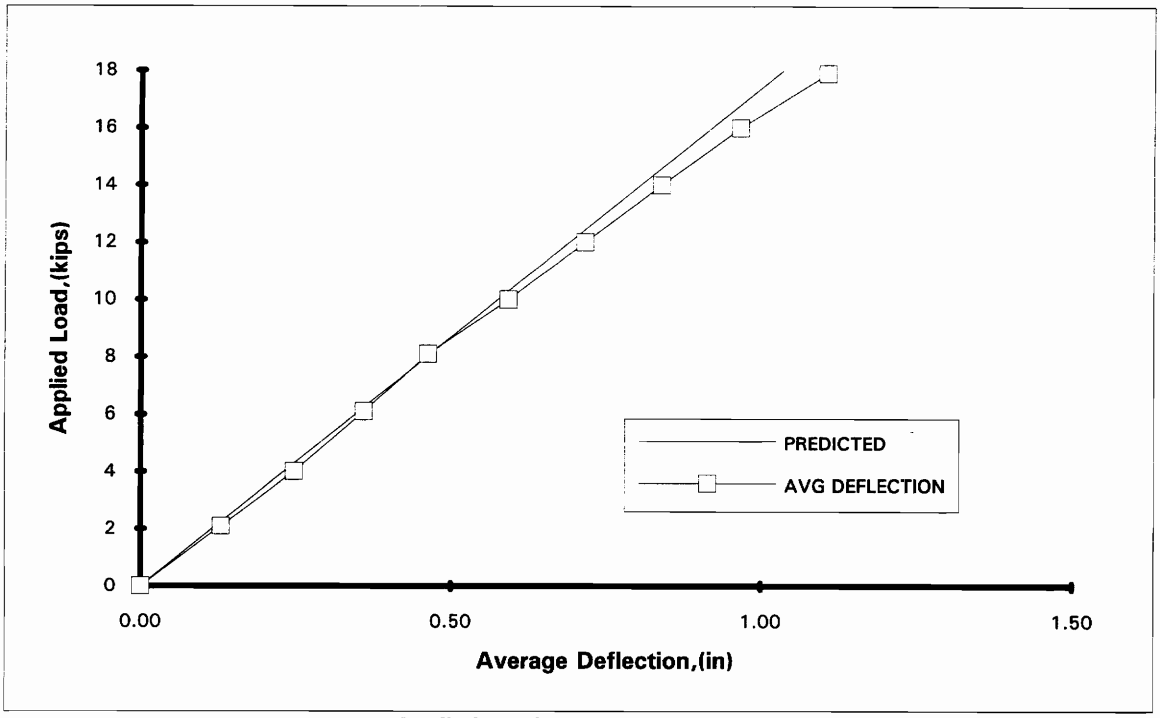
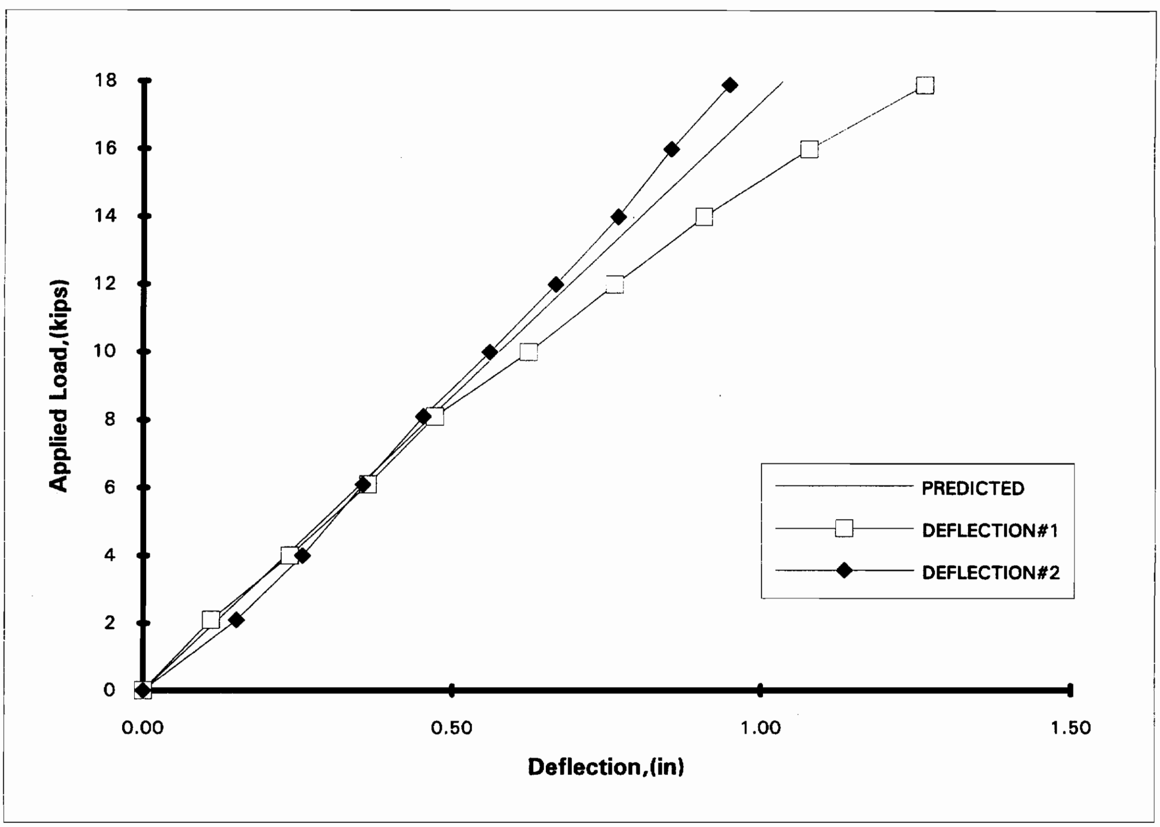


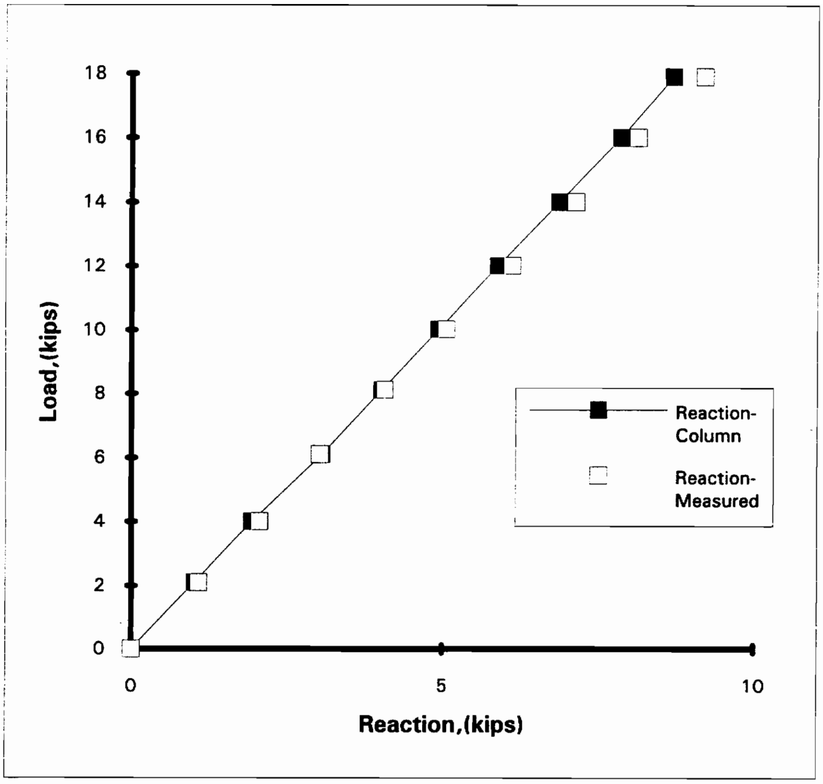
Fig 2 Connection Detail



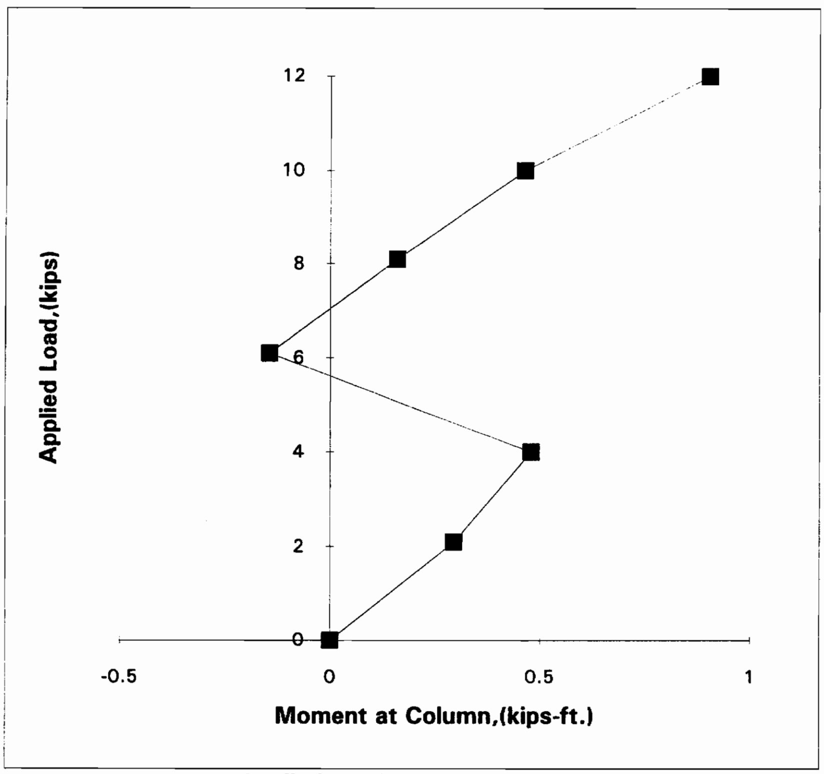
Applied Load vs. Average Deflection



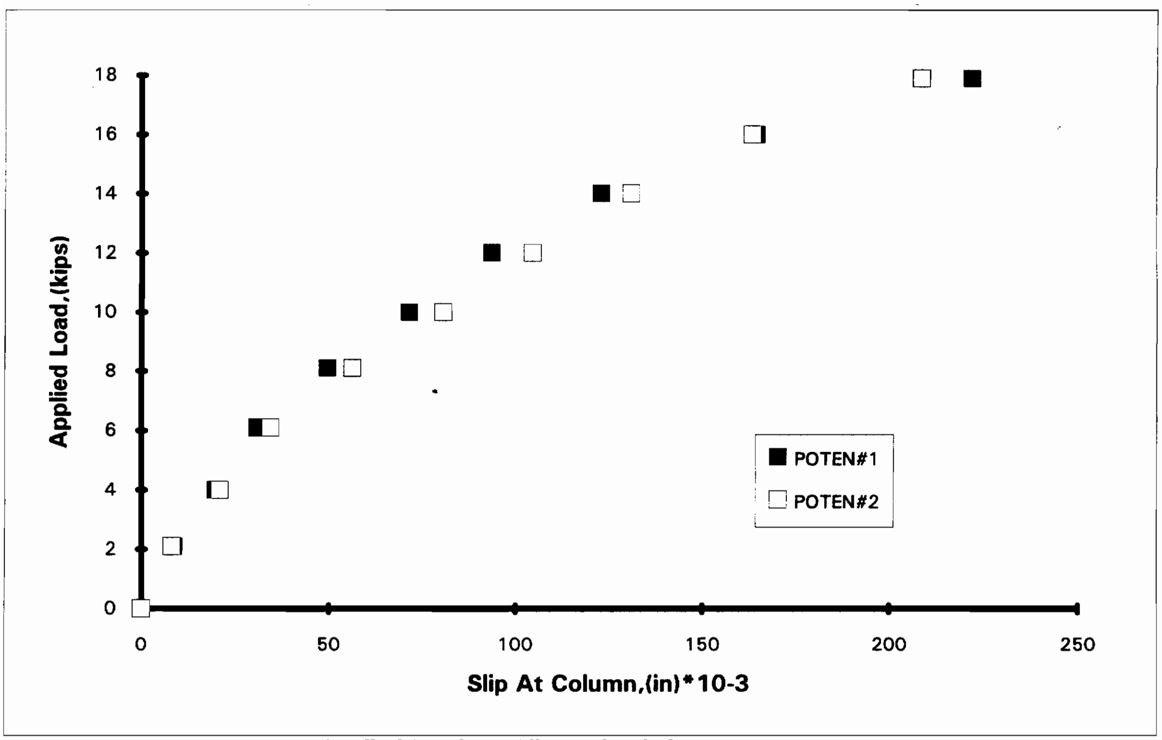
Applied Load vs. Deflection



Applied Load vs. Reaction



Applied Load vs. Moment at the Column



Applied Load vs. Slip at the Column

APPENDIX D

TENSILE TEST RESULTS

Results of GFRP Tensile Tests
Done at Virginia Tech

W 500 8x8x3/8

Test	E,ksi	Uload,k	Ustress,ksi
1, W01	3.63	12.85	44.2
2, W02	3.11	11.85	40.9
3, W03	3.98	13.3	45.2
4, W04	2.69	11.07	38.7
5, W05	3.23	12.03	41.7

Average 3.328 12.22 42.14

W525 8x8x3/8

Test	E,ksi	Uload,k	Ustress,ksi
1, W51	3.13	13.12	45.5
2, W52	3.05	11.76	40.2
3, W53	2.67	11.81	40.8
4, W54	2.97	12.61	43.7
5, W55	2.67	13.73	47.2

Average 2.898 12.606 43.48

A500 3x3x3/8

Test	E,ksi	Uload,k	Ustress,ksi
1, A1	3.49	10.7	38.4
2, A2	2.95	11.97	42.3
3, A3	3.54	11.26	39.5
4, A4	3.16	12.97	46

Average 3.285 11.725 41.55

Results of Mechanical Testing Done and Reported by MMFG

Tensile Testing

A500 3x3x3/8

Test	E,ksi	Uload,k	Ustress,ksi
1	2.72	10.09	35.5
2	2.55	10.5	37.6
3	2.98	9.96	34.8
4	2.86	10.23	36.4

Average 2.7775 10.195 36.075

W500 8x8x3/8

Test	E,ksi	Uload,k	Ustress,ksi
1	2.72	11.18	38.7
2	2.53	8.38	29.58
3	3.17	11.66	40.34
4	2.86	10.21	35.31
5	3.05	11.51	39.9

Average 2.866 10.588 36.766

Short Beam Shear Testing

A500 3x3x3/8

Sample	Uload,k	Ustress,ksi
1	0.921	5
2	0.959	5
3	0.989	5.3
4	0.955	4.8

Average 0.956 5.025

Short Beam Shear Test is Invalid due to failure of coupons in flexure.

Sample	Uload,k	Ustress,ksi
1	0.919	4.9
2	0.881	4.7
3	0.896	4.7
4	0.929	5

Average 0.9063 4.825

Test Designation:	Angle 500
Specimen Identification:	A1
Run Number:	1
Date:	3/31/94
Gage length (in.):	2
Total length (in.):	8
Length between shoulders (in.):	4
Thickness (in.):	0.368
Width (in.):	0.756

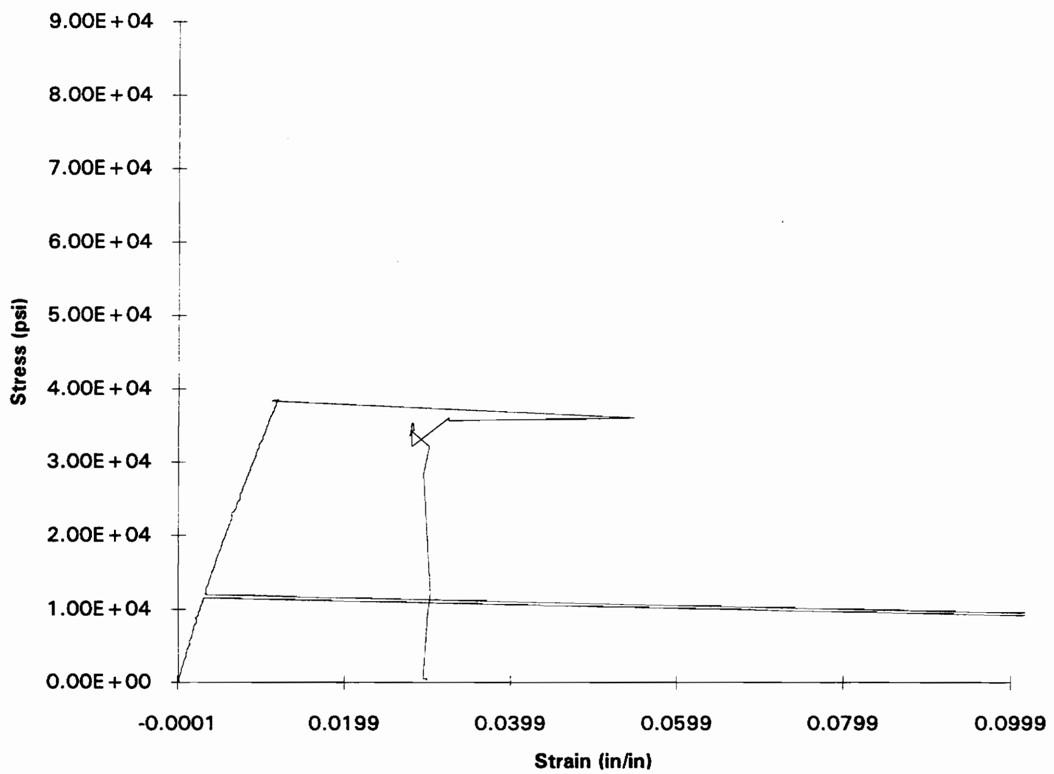
TENSION TEST OF MATERIALS

Test Setup:

Procedure: Tensile Test
LOAD RATE = 0.2 In/Min

Test Data:

.1% Offset Yield:	11584 psi
.2% Offset Yield:	**11584 psi**
.5 in/in Yield:	11584 psi
Ulimate Stress:	38568 psi
Modulus of elasticity:	3.46 ksi



Stress vs. Strain

Test Designation:	Angle 500
Specimen Identification:	A2
Run Number:	1
Date:	4/1/94
Gage length (in.):	2
Total length (in.):	8
Length between shoulders (in.):	4
Thickness (in.):	0.374
Width (in.):	0.757

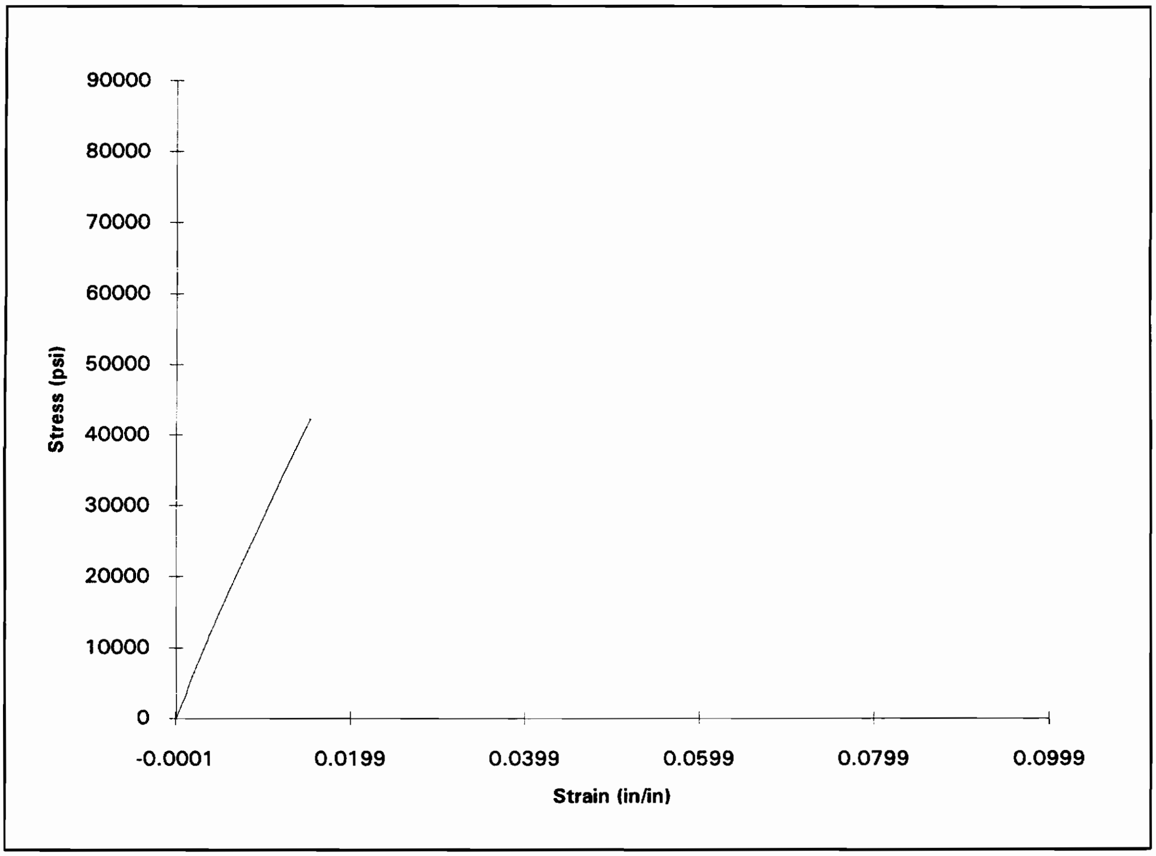
TENSION TEST OF MATERIALS

Test Setup:

Procedure: Tensile Test
LOAD RATE= 0.2 In/Min

Test Data:

.1% Offset Yield:	41237 psi
.2% Offset Yield:	**233 psi**
.5 in/in Yield:	15056 psi
Ulimate Stress:	42349 psi
Modulus of elasticity:	2.95 ksi



Stress vs. Strain

Test Designation:	Angle 500
Specimen Identification:	A3
Run Number:	1
Date:	4/1/94
Gage length (in.):	2
Total length (in.):	8
Length between shoulders (in.):	4
Thickness (in.):	0.374
Width (in.):	0.762

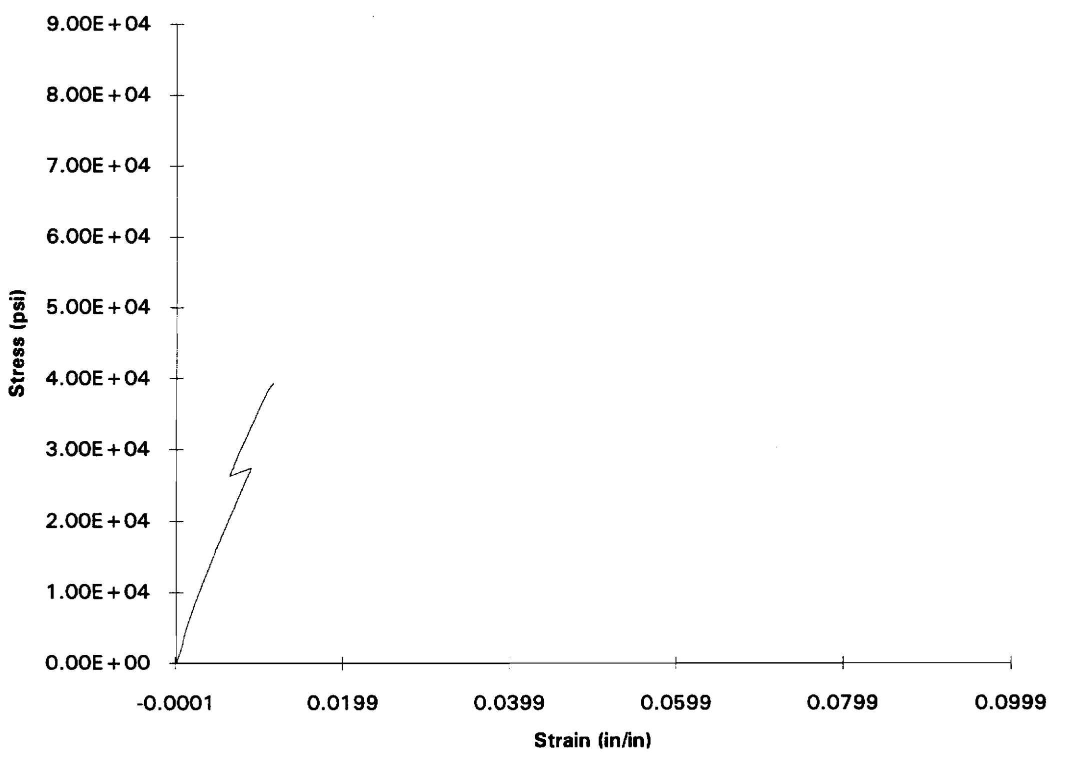
TENSION TEST OF MATERIALS

Test Setup:

Procedure:	Tensile Test
LOAD RATE=	0.2 In/Min

Test Data:

.1% Offset Yield:	24856 psi
.2% Offset Yield:	**0 psi**
.5 in/in Yield:	16511 psi
Ulimate Stress:	39739 psi
Modulus of elasticity:	3.54 ksi



Stress vs. Strain

Test Designation:	Angle 500
Specimen Identification:	A4
Run Number:	1
Date:	4/1/94
Gage length (in.):	2
Total length (in.):	8
Length between shoulders (in.):	4
Thickness (in.):	0.369
Width (in.):	0.764

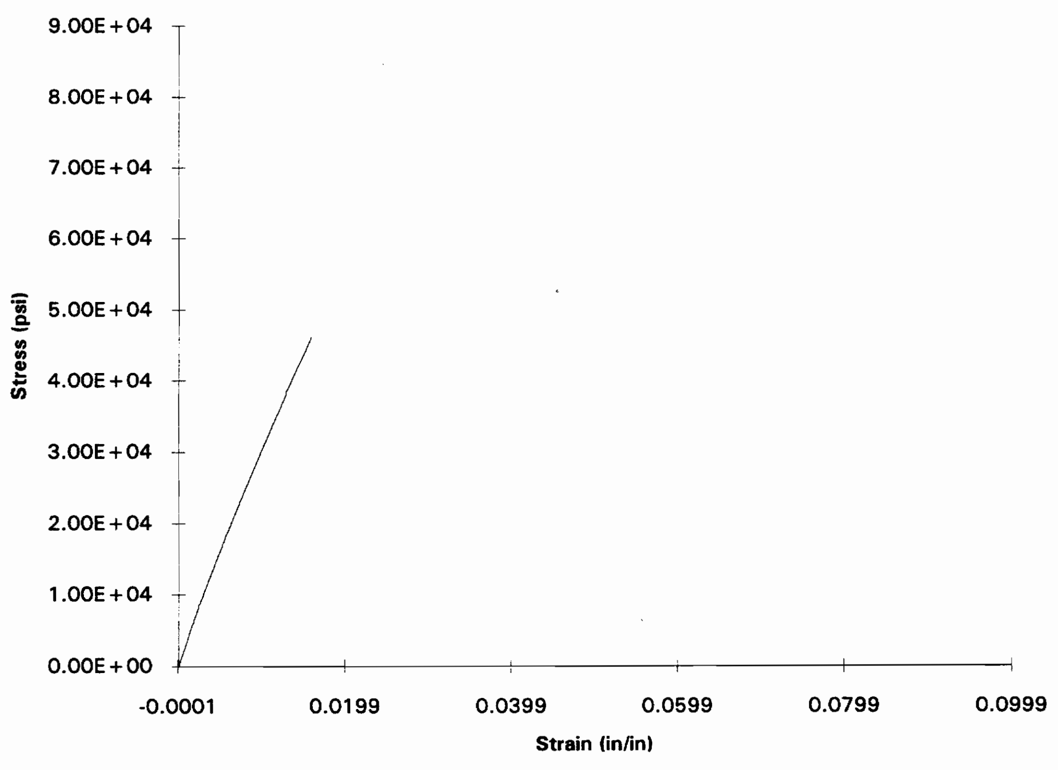
TENSION TEST OF MATERIALS

Test Setup:

Procedure:	Tensile Test
LOAD RATE =	0.2 In/Min

Test Data:

.1% Offset Yield:	41256 psi
.2% Offset Yield:	**38191 psi**
.5 in/in Yield:	16134 psi
Ulimate Stress:	46115 psi
Modulus of elasticity:	3.16 ksi



Stress vs. Strain

Test Designation:	Flange W-500
Specimen Identification:	W01
Run Number:	1
Date:	4/1/94
Gage length (in.):	2
Total length (in.):	8
Length between shoulders (in.):	4
Thickness (in.):	0.381
Width (in.):	0.763

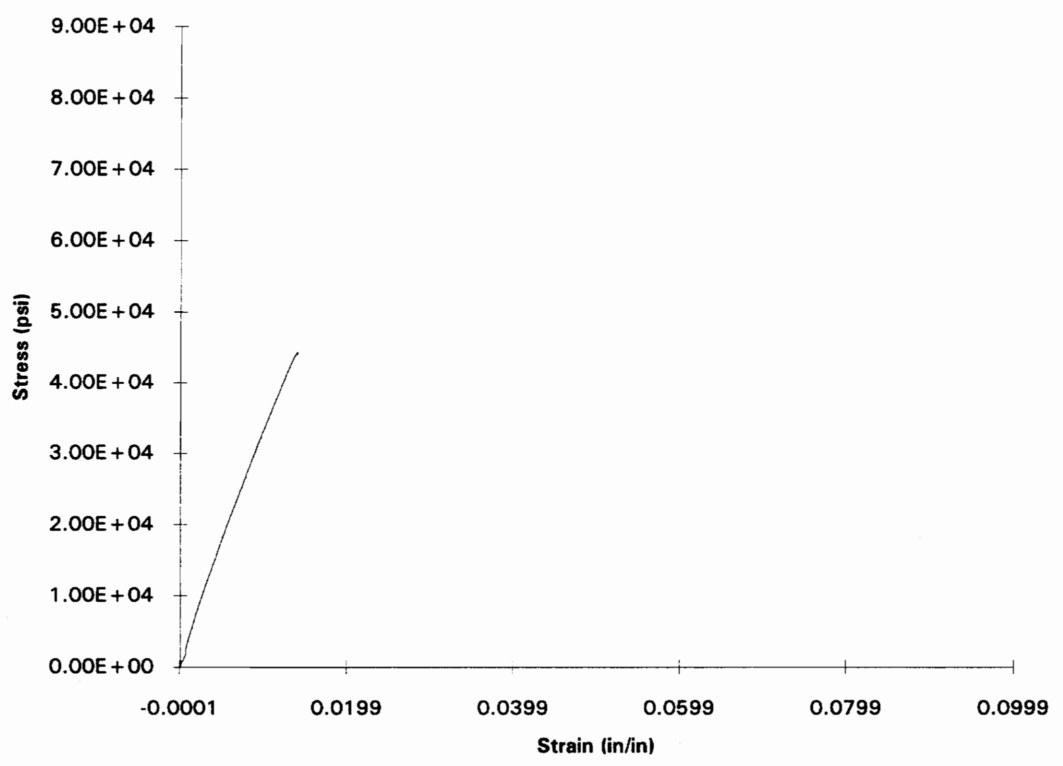
TENSION TEST OF MATERIALS

Test Setup:

Procedure:	Tensile Test
LOAD RATE=	0.2 In/Min

Test Data:

.1% Offset Yield:	35651 psi
.2% Offset Yield:	**0 psi**
.5 in/in Yield:	17712 psi
Ulimate Stress:	44293 psi
Modulus of elasticity:	3.63 ksi



Stress vs.Strain

Test Designation:	Flange W-500
Specimen Identification:	W02
Run Number:	1
Date:	4/1/94
Gage length (in.):	2
Total length (in.):	8
Length between shoulders (in.):	4
Thickness (in.):	0.380
Width (in.):	0.762

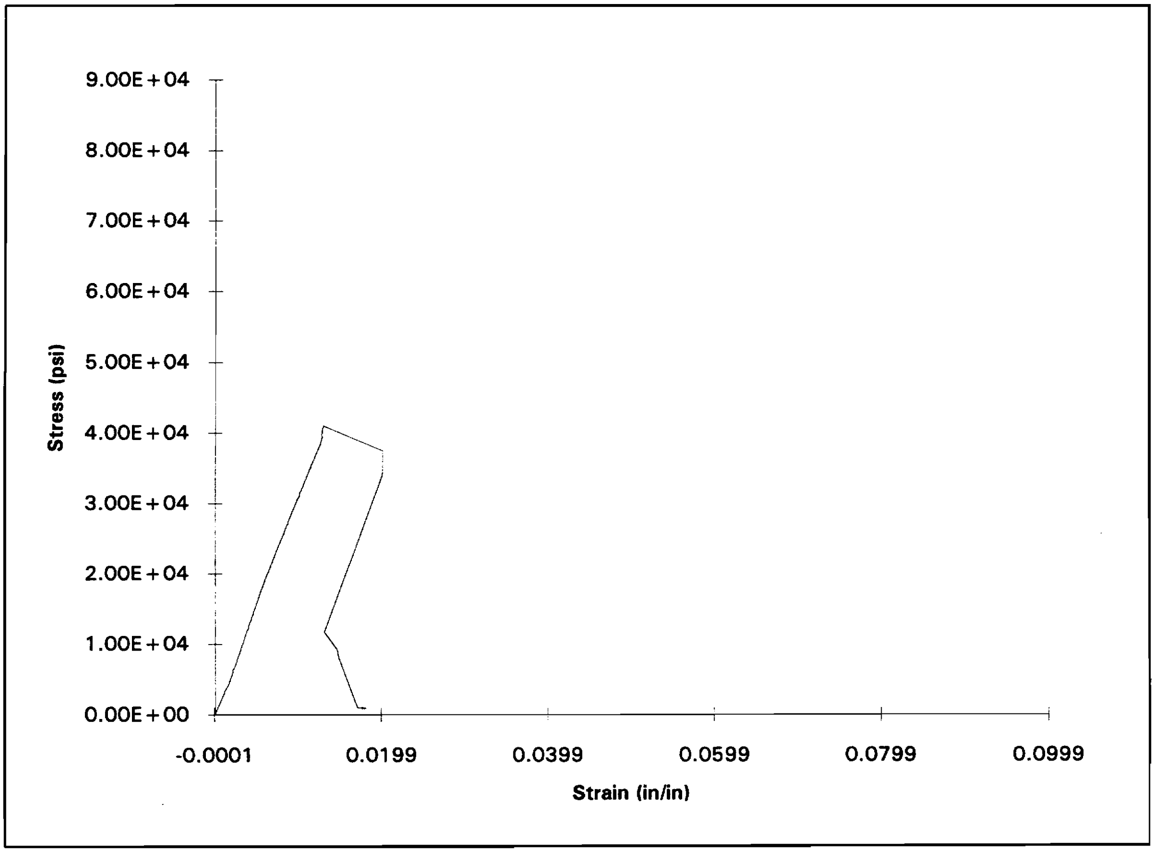
TENSION TEST OF MATERIALS

Test Setup:

Procedure:	Tensile Test
LOAD RATE=	0.2 In/Min

Test Data:

.1% Offset Yield:	41027 psi
.2% Offset Yield:	**41027 psi**
.5 in/in Yield:	15860 psi
Ulimate Stress:	41027 psi
Modulus of elasticity:	3.11 ksi



Stress vs. Strain

Test Designation:	Flange W-500
Specimen Identification:	W03
Run Number:	1
Date:	4/1/94
Gage length (in.):	2
Total length (in.):	8
Length between shoulders (in.):	4
Thickness (in.):	0.385
Width (in.):	0.764

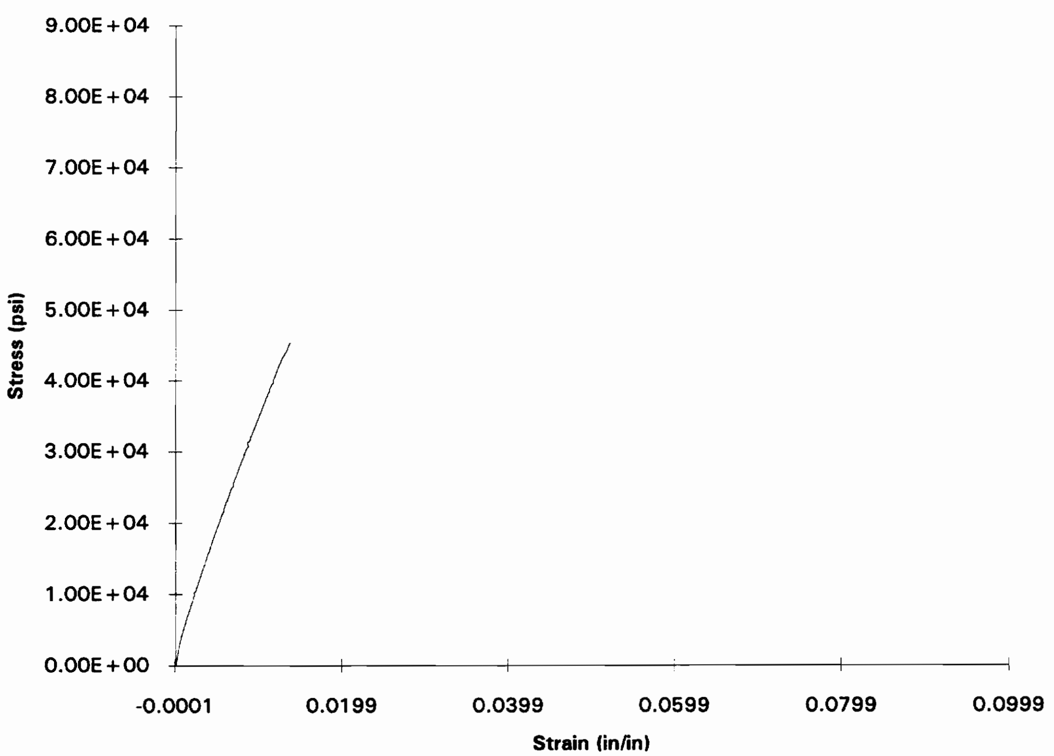
TENSION TEST OF MATERIALS

Test Setup:

Procedure:	Tensile Test
LOAD RATE =	0.2 In/Min

Test Data:

.1% Offset Yield:	30453 psi
.2% Offset Yield:	**43252 psi**
.5 in/in Yield:	19124 psi
Ulimate Stress:	45344 psi
Modulus of elasticity:	3.98 ksi



Stress vs. Strain

Test Designation:	Web W-500
Specimen Identification:	W04
Run Number:	1
Date:	4/1/94
Gage length (in.):	2
Total length (in.):	8
Length between shoulders (in.):	4
Thickness (in.):	0.376
Width (in.):	0.761

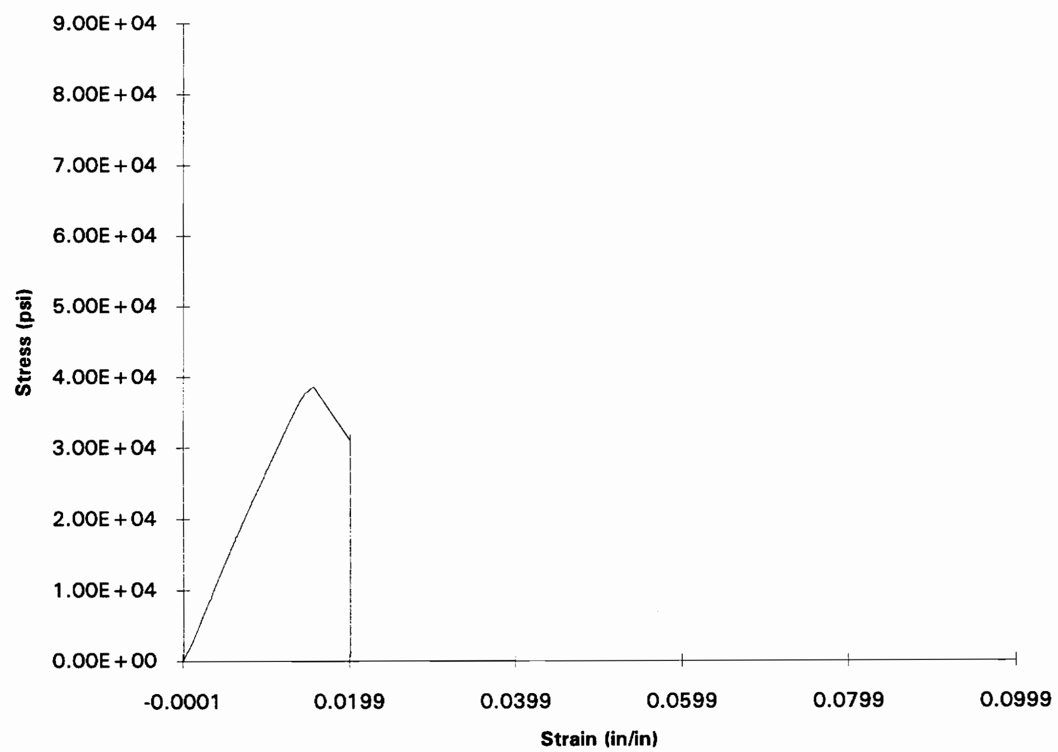
TENSION TEST OF MATERIALS

Test Setup:

Procedure:	Tensile Test
LOAD RATE =	0.2 In/Min

Test Data:

.1% Offset Yield:	38268 psi
.2% Offset Yield:	**38677 psi**
.5 in/in Yield:	13822 psi
Ulimate Stress:	38677 psi
Modulus of elasticity:	2.69 ksi



Stress vs. Strain

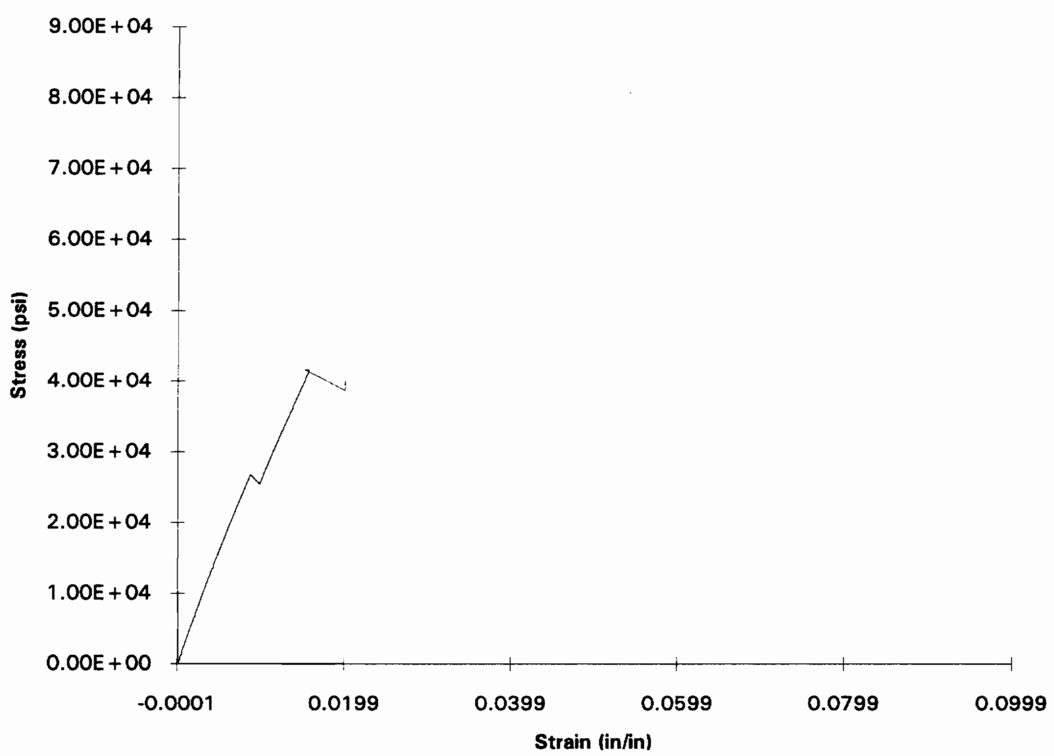
Test Designation: Flange W-500
Specimen Identification: W05
Run Number: 1
Date: 4/1/94
Gage length (in.): 2
Total length (in.): 8
Length between shoulders (in.): 4
Thickness (in.): 0.379
Width (in.): 0.762

TENSION TEST OF MATERIALS

Test Setup:
Procedure: Tensile Test
LOAD RATE = 0.2 In/Min

Test Data:
.1% Offset Yield: 26807 psi
.2% Offset Yield: 27567 psi
.5 in/in Yield: 15927 psi

Ulimate Stress: 41694 psi
Modulus of elasticity: 3.23 ksi



Stress vs. Strain

Test Designation:	Flange W-525
Specimen Identification:	W51
Run Number:	1
Date:	4/1/94
Gage length (in.):	2
Total length (in.):	8
Length between shoulders (in.):	4
Thickness (in.):	0.379
Width (in.):	0.761

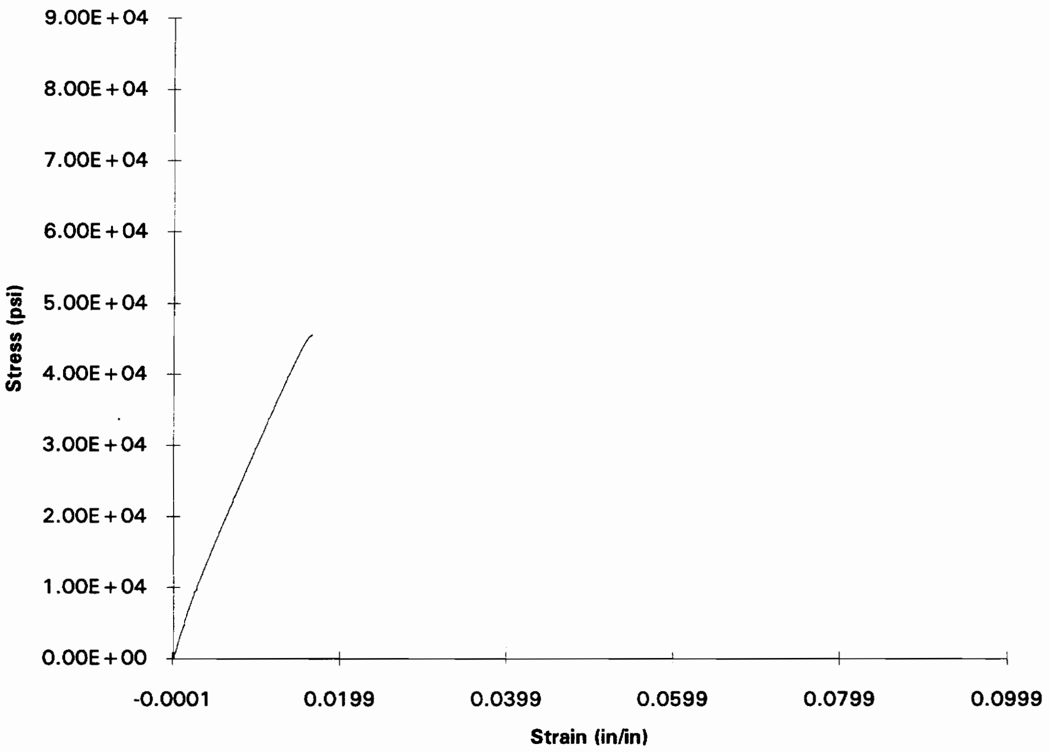
TENSION TEST OF MATERIALS

Test Setup:

Procedure: Tensile Test
LOAD RATE = 0.2 In/Min

Test Data:

.1% Offset Yield:	38142 psi
.2% Offset Yield:	**45405 psi**
.5 in/in Yield:	16227 psi
Ulimate Stress:	45558 psi
Modulus of elasticity:	3.13 ksi



Stress vs. Strain

Test Designation:	Flange W-525
Specimen Identification:	W52
Run Number:	1
Date:	4/1/94
Gage length (in.):	2
Total length (in.):	8
Length between shoulders (in.):	4
Thickness (in.):	0.383
Width (in.):	0.764

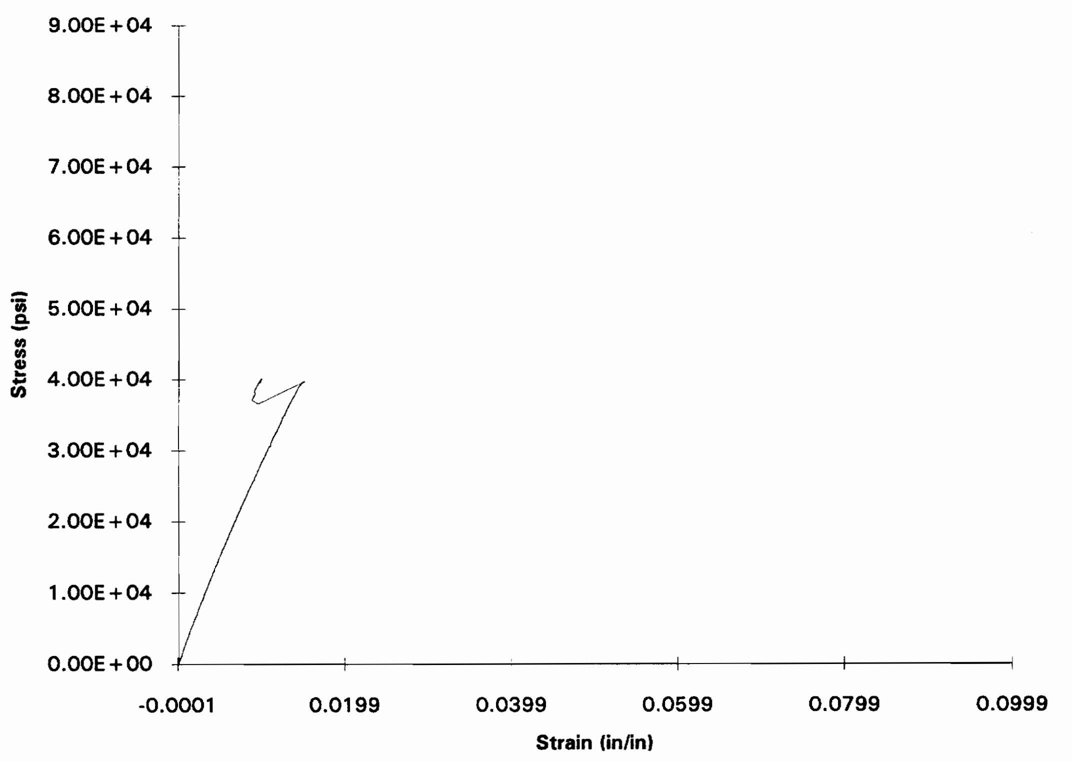
TENSION TEST OF MATERIALS

Test Setup:

Procedure:	Tensile Test
LOAD RATE=	0.2 In/Min

Test Data:

.1% Offset Yield:	32590 psi
.2% Offset Yield:	**39698 psi**
.5 in/in Yield:	15294 psi
Ulimate Stress:	40174 psi
Modulus of elasticity:	3.05 ksi



Stress vs. Strain

Test Designation:	Flange W-525
Specimen Identification:	W53
Run Number:	1
Date:	4/1/94
Gage length (in.):	2
Total length (in.):	8
Length between shoulders (in.):	4
Thickness (in.):	0.381
Width (in.):	0.760

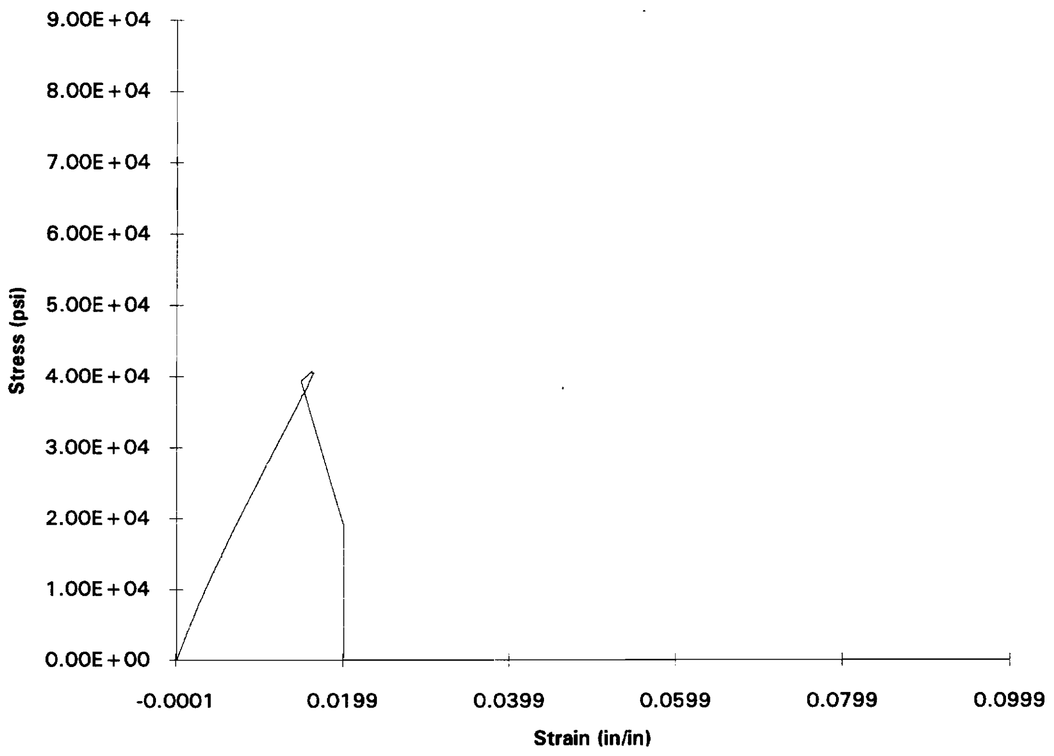
TENSION TEST OF MATERIALS

Test Setup:

Procedure:	Tensile Test
LOAD RATE =	0.2 In/Min

Test Data:

.1% Offset Yield:	34729 psi
.2% Offset Yield:	**39358 psi**
.5 in/in Yield:	13811 psi
Ulimate Stress:	40800 psi
Modulus of elasticity:	2.67 ksi



Stress vs. Strain

Test Designation:	Web W-525
Specimen Identification:	W54
Run Number:	1
Date:	4/1/94
Gage length (in.):	2
Total length (in.):	8
Length between shoulders (in.):	4
Thickness (in.):	0.378
Width (in.):	0.763

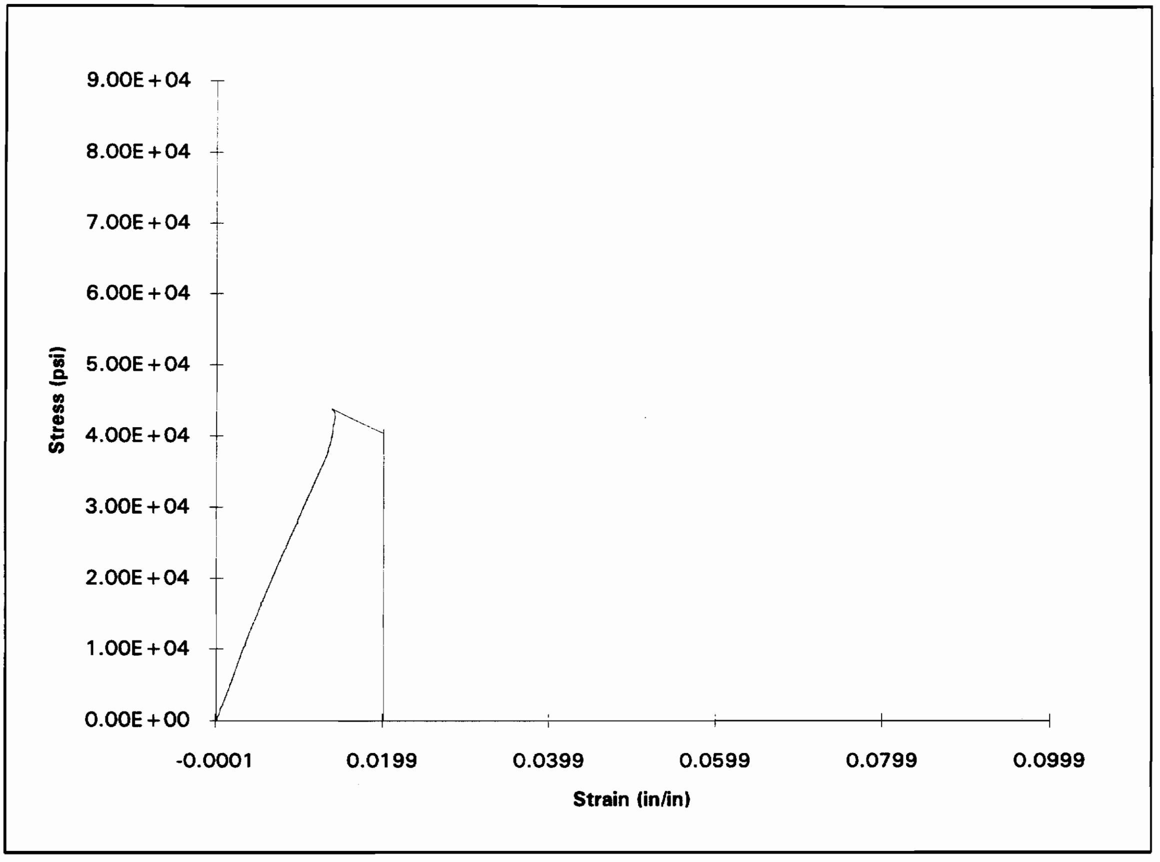
TENSION TEST OF MATERIALS

Test Setup:

Procedure: Tensile Test
LOAD RATE = 0.2 In/Min

Test Data:

.1% Offset Yield:	43806 psi
.2% Offset Yield:	**43806 psi**
.5 in/in Yield:	15262 psi
Ulimate Stress:	43806 psi
Modulus of elasticity:	2.97 ksi



Stress vs. Strain

Test Designation:	Flange W-525
Specimen Identification:	W55
Run Number:	1
Date:	4/1/94
Gage length (in.):	2
Total length (in.):	8
Length between shoulders (in.):	4
Thickness (in.):	0.381
Width (in.):	0.763

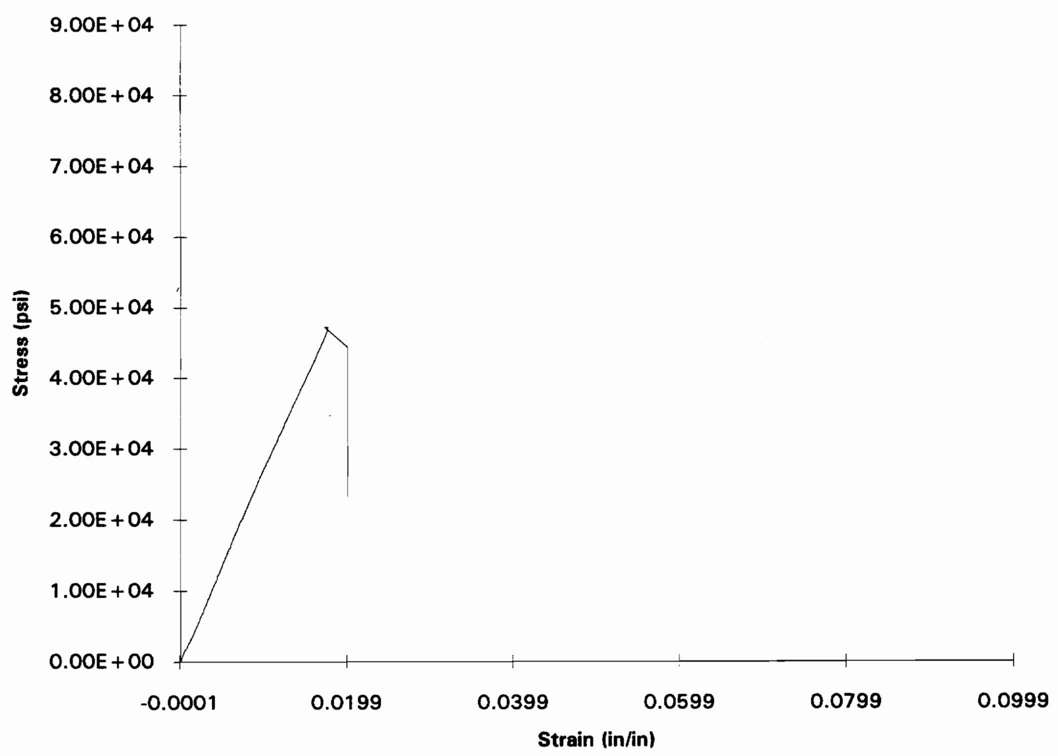
TENSION TEST OF MATERIALS

Test Setup:

Procedure:	Tensile Test
LOAD RATE=	0.2 In/Min

Test Data:

.1% Offset Yield:	47240 psi
.2% Offset Yield:	**47240 psi**
.5 in/in Yield:	13353 psi
Ulimate Stress:	47240 psi
Modulus of elasticity:	2.67 ksi



Stress vs. Strain

VITA

The author was born October 27, 1968 , in Washington D.C. He attended West Springfield High School and graduated in 1987. He received a Bachelor of Science Degree in Civil Engineering from Virginia Polytechnic Institute and State University in 1992.

The author began his graduate studies in January of 1992 at Virginia Polytechnic Institute and State University.