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**ENERGY DISSIPATION IN STEEL COUPLING BEAMS USING
LOCALIZED ENERGY DISSIPATING DEVICE
(WITHOUT AND WITH THE USE OF ELASTOMERIC PADS)**

By

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ABSTRACT

The energy dissipating mechanism in coupled shear walls is generally through the formation of plastic hinges at the connection of coupling beam to the wall and at the base of each wall. Since the yield damage is not confined to the beam, the repairs are expensive. This can be avoided by shifting the yielding to another location by splicing a fuse beam at the mid-span of the coupling beam with a slip critical bolted connection. The fuse beam is made of a lower yield strength and more ductile steel material, so that the fuse beam yields in shear before the coupling beam stresses reach the elastic limit. This allows the fuse beam to be replaced and the coupling beam can be reused. This concept can be considered an effective rehabilitation strategy for seismic design.

An experimental pilot study was conducted to explore the above concept. Two fuse beams each, with two web stiffeners and three web stiffeners were tested. In an effort to increase energy dissipation, one each of the above type of fuse beam was tested by adding elastomeric pads, under the web and flange splice plates, due to their excellent energy absorption and damping capabilities. Details of the experimental program and the results obtained from these pilot tests are presented.

Calibrated analytical models of the test setup with fuse beam and shear wall were developed which duplicated the results obtained from the experimental tests conducted in this study and test data available for shear wall. These models were used to model a four storey coupled shear wall systems without and with fuse beams, and without and with elastomeric pads. A comparison of the performance results obtained for each case is presented to demonstrate the performance capabilities of the fuse beam.

It was concluded that fuse beams had the potential to dissipate energy and delay the yielding of other coupled shear wall components. Addition of stiffeners in the fuse beam prevented local buckling of the web of the fuse beam. Elastomeric pads did not contribute much towards enhancing energy dissipating characteristics.

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LIST OF SYMBOLS

A	=	original cross sectional area of the specimen
A_w	=	area of web
a	=	distance between transverse stiffeners
d	=	overall depth
E	=	modulus of elasticity of the material
E_{sh}	=	elastic modulus at the onset of hardening
f'_c	=	compressive strength of concrete
f'_t	=	tensile strength of concrete
F_y	=	yield stress of steel
H	=	clear distance between flanges
I_x	=	moment of inertia about major axis
k_v	=	stiffener spacing factor
L	=	original length of the specimen
ΔL	=	change in length
L_b	=	un-braced length
L_p	=	limiting un-braced length
P	=	applied load
t_w	=	thickness of web
V_n	=	nominal shear strength
σ	=	normal stress
ε	=	normal strain
ε'_c	=	concrete compressive strain

CHAPTER 1

INTRODUCTION

1.1 General

Earthquakes typically subject building structures to large magnitude lateral loads. The resulting destruction by these loads has placed damage control strategies at the forefront of the design of building structures in seismic areas. Non-invasive and low-cost rehabilitation strategies after the earthquake have received great attention. In order to capitalize on both of these fronts, it is proposed that a localized energy dissipating device be strategically placed in a coupled wall system commonly used in building structures to dissipate the energy of the earthquake forces. This device is used for splicing coupling beams at a location which is subjected to least or no bending moment and constant shear force, and that can be easily accessed for replacement with very little destruction of the surrounding structure. This device behaves like a shear link in an eccentrically braced frame. The aforementioned localized device of the structure will be referred to as a “fuse beam” in this study. This research explores the feasibility of the concept of using fuse beams in coupled shear wall systems. Four tests to determine the capacity and energy dissipating characteristics of the fuse beam are carried out. Two tests are done without using elastomeric pads and two tests are done with using elastomeric pads. Due to their excellent energy dissipating characteristics, elastomeric pads were used to study if they could increase the performance of the coupled wall system with fuse beams further. The findings of this experimental testing are presented in this study.

1.2 Coupled Wall System

Individual wall piers (shear walls) are coupled together using coupling beams to resist large lateral loads. They provide the lateral stiffness and strength. Under individual action they would tend to transfer the loads through flexure. Connecting the walls to each other by coupling beams change the load transfer characteristics in the walls to an axial tension-compression couple. Coupling beams can be reinforced concrete beams, structural steel beams, or hybrid beams. Structural steel coupling beams provide a viable alternative in cases where height is a restriction and use of deep concrete beams is not possible or a concrete beam cannot achieve the required stiffness or strength economically. Coupling beams must be sufficiently strong and stiff, must yield before the wall piers, behave in a ductile manner, and exhibit significant energy absorbing characteristics. Coupling beams are usually designed to dissipate energy through the formation of plastic hinges at the connection between the beam and the wall and at the base of each wall. A few examples of the coupled wall systems are shown in Figs. 1.1(a) and 1.1(b). Achieving the desired behavior of coupled walls depends primarily upon ensuring that the coupling beams provide adequate strength and stiffness. The coupling beams must yield before the shear walls, behave in a ductile manner, and also exhibit significant energy absorbing characteristics. In this study the behavior of structural steel coupling beams is investigated.

1.3 Eccentrically Braced Frames

Eccentrically Braced Frames (EBF's) are used most extensively in regions of high seismic activity. EBF's are hybrid lateral force-resisting systems that dissipate energy

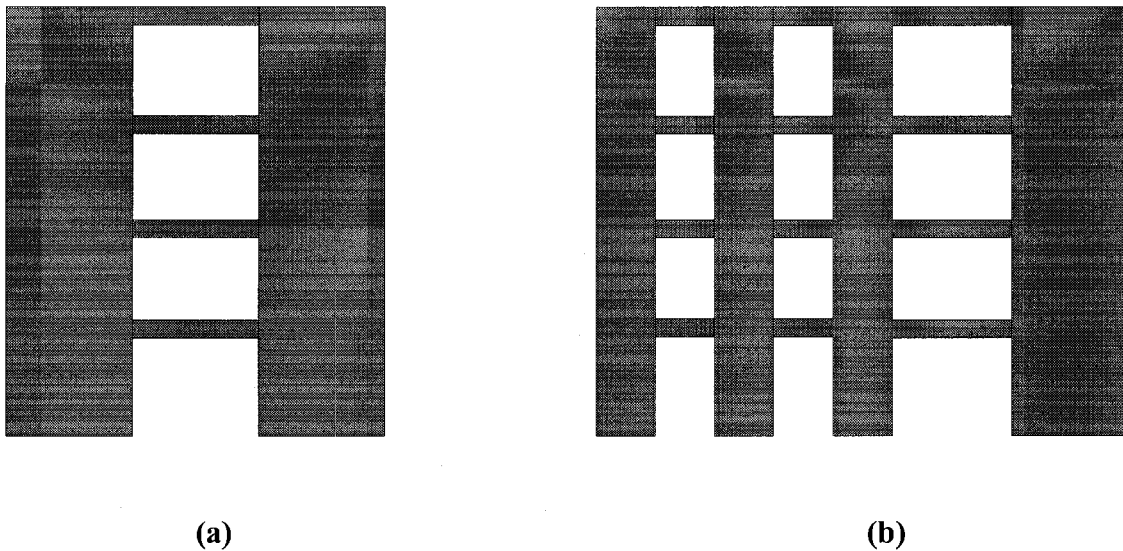


Figure 1.1 Coupled Wall Systems: (a) Two Shear Walls, and (b) Multi Shear Walls

in shear or moment links, and thus protect the remainder of the frame from inelastic action. EBF's combine stiffening effects due to diagonal braces with yielding in the link beams. Typical hysteresis curves for EBFs are stable and well-rounded, hence indicative of the ability to dissipate large amounts of energy. Designed with shear links incorporated to dissipate energy introduced by lateral loads, a variety of designs have been developed for EBF's, such as the D-braced EBF, K-Braced EBF, and the V-Braced EBF, all of which incorporate a small shear link in the beams. An example of K and V-Braced EBF's are shown in Figs. 1.2(a) and 1.2(b), respectively. Earlier research has shown that K-braced EBF are most effective in reducing the development of plastic moments near the column faces.

1.4 Energy Dissipation

Hysteretic energy is the work done in the plastic range, and is a non-recoverable dissipated energy. A sample hysteresis graph of load (P) versus deformation (δ) is shown in Figure 1.3. The area under each loop represents the energy dissipated. This energy is dissipated during yielding under various states of loading; axial, bending, and

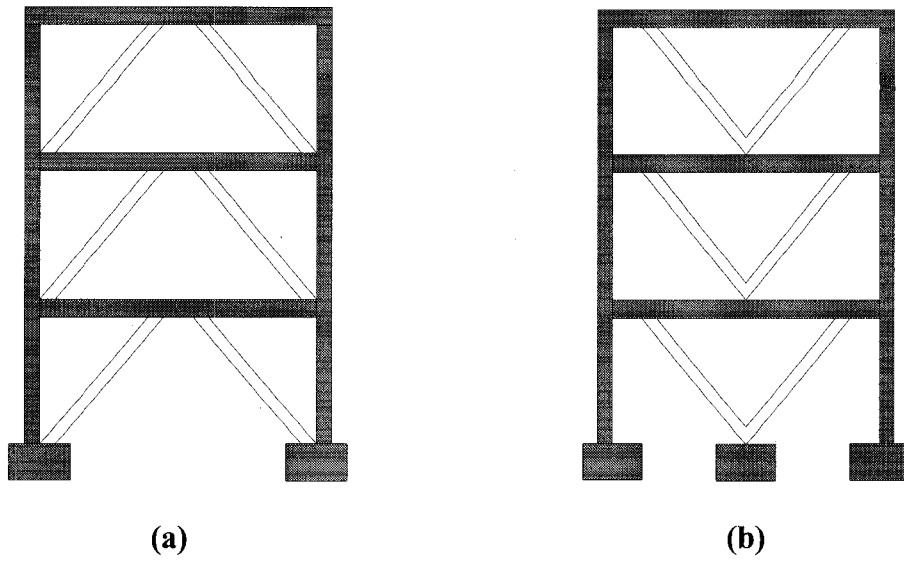


Figure 1.2 Eccentrically Braced Frames: (a) Type K, and (b) Type V

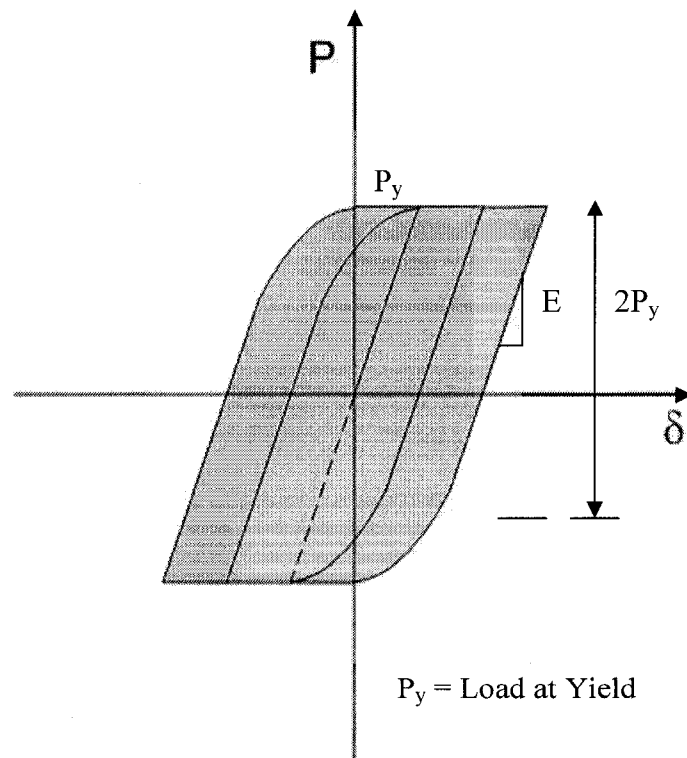


Figure 1.3 Sample Hysteresis Graph

shear. The Bauschinger effect is found at the onset of stress reversal in steel. This is where stiffness softening occurs gradually with yielding. This is a natural property of steel and results in the rounding of the corners of the hysteresis graph. Behavior of this kind is significant because it shows less than ideal hysteretic energy for the system. Experiments have shown that due to the Bauschinger effect unloading occurs elastically up to two times the yield stress of the material, as shown in Fig. 1.3, and then plastic deformations get initiated and continue until the cyclic load is again reversed.

1.5 Splice Joints

Splices are often required when the lengths of members are limited by fabrication, transportation and handling or by construction processes. Splicing involves the joining of two beams or girders of similar or dissimilar cross sections without altering their strength and load carrying properties. A sample splice joint is shown in Figure 1.4. A beam splice must transfer the shear, moment, and axial load of one beam to the other at the location of the splice in order to be effective (Sheikh-Ibrahim and Frank, 1998). Different design procedures are available for splicing: bolted or welded or mixed. In this experiment only the bolted splice is used. There are three different guidelines that specify the design procedures for bolted beam splices. The three guidelines are: LRFD (Load and Resistance Factored Design) Manual of Steel Construction (2001), published by the AISC (American Institute of Steel Construction), AASHTO's (American Association of State Highway and Transportation Officials) Standard Specifications for Highway Bridges (1996), and The Guide to Design Criteria for Bolted and Riveted Joints (1987). Each of these guides gives differing bolt configurations (Sheikh-Ibrahim and Frank, 1998). Typically in moment splices the shear is transferred through the web

connection and the moment is resolved into tension-compression couple acting as forces on the flanges.

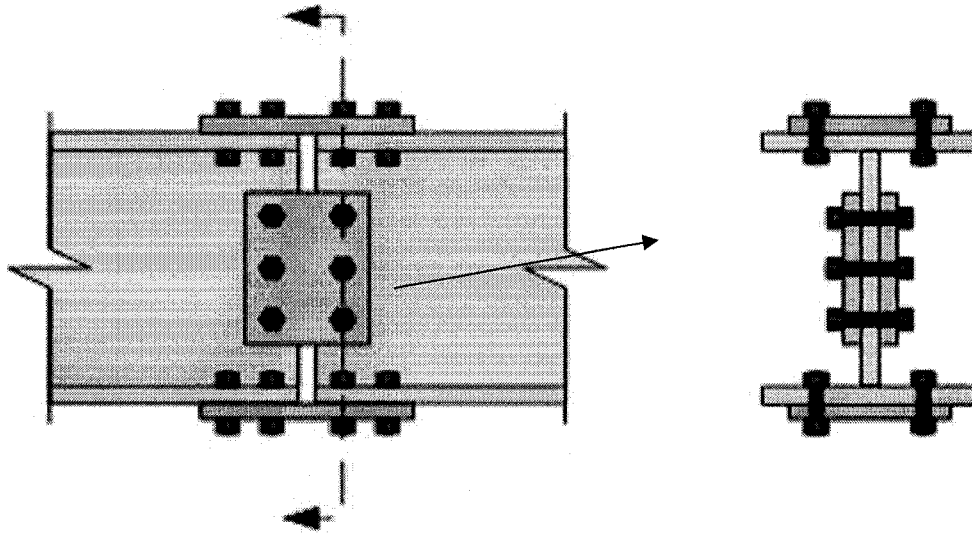


Figure 1.4 Splice Joint

1.6 Elastomers and Elastomeric Bearings

An elastomer is defined as a substance that can be subjected to substantial amounts of force or deformations and upon release returns to its approximate original dimensions. Natural rubber, obtained from the rubber tree in Asia, was the first known elastomer. It was used exclusively until the 1920's when the technology to produce synthetic materials was introduced. Currently, the most extensively used elastomers are neoprene, silicone and the urethane family.

Elastomers are used in a variety of situations because of their unique characteristics. Their characteristics include, but not limited to, the following:

- (i) Good inherent flame resistance,
- (ii) Performs well even during contact with oil and many chemicals,
- (iii) Adheres well to a variety of metals and fabrics,
- (iv) Resistant to weather, aging, and ozone, and

- (v) Can withstand damaging forces such as flexing and twisting.

Because of these unique characteristics of elastomers, they have been used in a wide variety of civil engineering applications, including

- (i) Bridge bearings,
- (ii) Waterproofing systems for bridge decks,
- (iii) Anti-vibration mounts for buildings and other structures,
- (iv) Anti-vibration mounts for rail tracks,
- (v) Joint seals in concrete structures, including water stops,
- (vi) Dock fenders and other shock absorbers, and
- (vii) Base isolation of buildings for earthquake protection.

However, elastomers have yet to be extensively used in structural steel connections. With the unique properties of elastomers, a pad can be used in beam splice connections subjected to cyclic loads. Use of elastomeric pads in spliced connections could help reduce the loss of pre-tension forces in the bolts during cyclic loading and also increase energy dissipating characteristics of the connection.

The use of rubber as a bearing dates back to 1889. Elastomeric bearings are found to be more reliable and longer lasting than the metallic and knuckle bearings, which have been used in the past. Different types of elastomeric bearings include the following:

- (i) Plain elastomeric bearings, and
- (ii) Laminated elastomeric bearings.

Plain elastomeric bearings are homogeneous and not reinforced. These are used where low loads and small movements are expected. These are the simplest type of bearing

available and can be installed easily. Laminated elastomeric bearings contain alternate layers of rubber and steel that are strongly bonded together. The metal plates are then covered by rubber on all sides. These bearings have high vertical stiffness and very low horizontal stiffness relative to the plane of the plates. In the tests conducted plain elastomeric bearings are used.

1.7 Fuse Beam

In coupled beam-wall systems, the yield damage is always not just confined to the beam-end, but also to the shear wall it is connected to. The replacement and the repairs in these cases are usually expensive. To avoid these locations of yielding in the coupling beam, the yielding can be shifted to the center of the beam by introducing a localized energy dissipating device called the 'fuse beam' at mid-span. The fuse beam could be used to behave like the deformable shear link in eccentrically braced structural frames. The fuse is connected to the coupling beam by using a bolted spliced connection at both its ends. Ideally, a standard 'I' beam can be used for the fuse. However, the fuse can be built-up from steel plates. By reducing the cross-sectional area of the fuse, the yield strength of the steel, or both, the point at which the fuse yields in shear can be reduced in comparison to the rest of the coupling beam. This is imperative so that the coupling beam is not damaged in any way. The mid-span point of the coupling beam is the location of constant shear and zero bending moment. Adding a fuse at the mid-span of the coupling beam will allow the fuse to bear the damage due to shear force and dissipate energy. The fuse will subsequently yield earlier rather than the coupling beam. The fuse is easily replaceable due to it being bolted to the coupling beam. Provided the wall piers do not undergo excessive rotations, the use of the fuse can be considered as an effective

rehabilitation strategy in future structures to minimize seismic damage costs. Figure 1.5 shows a fuse beam connected to a coupling beam.

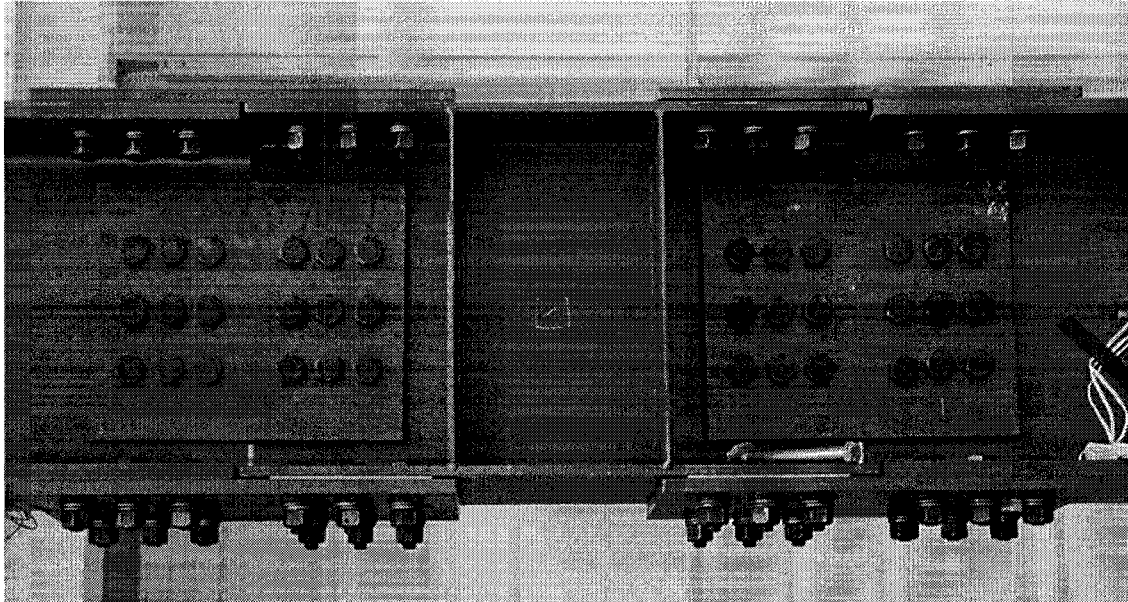


Figure 1.5 Fuse Beam

1.8 Application of Fuse Beams

The fuse beam is designed to react to lateral loads in much the same way as the K and V-Braced frames are designed. In an earthquake the coupled shear wall has to dissipate energy. This can be achieved by the formation of plastic hinges at the connection of the beam to the wall and then the base of the wall. In these coupled shear walls, the rehabilitation is cost prohibitive because the concrete in the shear wall must be removed and re-poured in order to replace the coupling beam. However, in an attempt to facilitate cost efficient rehabilitation, a fuse beam can be incorporated into the coupling beam. The fuse beam is placed at a point of constant shear and zero moment, which will be ideally at the mid-span of the coupling beam. The fuse beam is specifically designed to yield before plastic hinges form in the coupling beam. Thus, the ability for a fuse to

yield is a method of energy dissipation that replaces occurrences of plastic hinges forming in the coupling beam or/and the shear wall.

The new San-Francisco-Oakland Bay Bridge's design introduces the concept of a coupling beam designed to yield under high shear. Scheduled for completion in 2007, the tower of the bridge consists of four steel shafts interconnected in the transverse and longitudinal directions by replaceable bolted shear links (McDaniel et al., 2003). The shear links are built from wide flange sections that are designed to yield in shear where the middle of the beam is the deformable area. The tower shafts are designed to remain elastic under the Safety Evaluation Earthquake (SEE) with a return period of 1,500 years, while the links are allowed to deform in-elastically to protect the tower from permanent damage (McDaniel et al., 2003).

1.9 Goal and Objectives

The goal of the project is to evaluate the feasibility of the concept of using fuse beams in coupled shear wall systems to increase their energy dissipating characteristics, and also to allow for cost effective rehabilitation of building structures after earthquakes due to the ease in replacing the fuse beams. The goal is also to evaluate whether elastomeric pads, if added in the spliced connection of the fuse beam to the coupling beam, increase the energy dissipating characteristics of the coupled shear wall further. The project consists of two interconnected studies. One is an experimental study and the other an analytical study. The goals of the experimental study are

1. To design the coupling beam and fuse beam specimen, and to design the test setup.

2. To test the specimens for two cases, namely, without elastomeric pads and with elastomeric pads, and analyze the data collected.

The objective is to use this data to model the fuse beam analytically for both cases and use it in a coupled wall system analysis.

The goals of the analytical study are

1. Analytically model the fuse beam to match the experimental test behavior.
2. Model and analyze a coupled shear wall system under cyclic loading without fuse beams and then re-analyze the same system placing fuse beams in the coupling beams.
3. Model and analyze with cases without elastomeric pads and with elastomeric pads.

The primary objective of the study is to determine if fuse beams can be installed in coupling beams of coupled shear wall systems in such a manner that the system still behaves in the same manner when fuse beams were not installed and simultaneously dissipate more energy. In doing so, the coupling beam should remain elastic, and the shear yielding must be concentrated to the fuse beam only. Thus, the damage from the fixed ends of the coupling beam will now move to the mid-span of the coupling beam. If found to be true, then, fuse beams can be proposed to be installed in coupling beams to reduce rehabilitation costs due to seismic damage and to increase the energy dissipating capability of the coupling beam. The objective of using elastomers in this study is to see if the elastomers can delay the yielding of the fuse beam and thus increase the energy dissipating capabilities.

1.10 Scope

If the fuse beam is specifically designed to yield before the coupling beams develop plastic hinges at the junctions with the shear wall, then only the fuse beam will need to be replaced, as opposed to the reconstruction of the entire connection of the coupling beam with the shear wall system. The tests performed are scaled down tests, meaning the coupling beam sizes used for testing are smaller than the regular coupling beam sizes. The limits of actuator capacity available in the laboratory for testing were considered while designing the coupling beam such that the fuse beam failed in shear before the actuator capacity was reached.

In an effort to increase the energy dissipation characteristics and/or delay the yielding of the fuse beams, elastomeric pads are added. These pads are placed between the splice plates and the beam, both on the web and the flanges. The elastomeric pads used in this test will be plain elastomeric pads. The objective of using elastomers in this study is to see if the elastomers can delay the yielding of the fuse beam and thus increase the load carrying capacity. The elastic properties of the pads should enable the web of the fuse to absorb more energy when yielding. The motivation for using elastomeric pads is their excellent energy absorption and damping capabilities. These properties may help to increase the efficiency of the fuse beam in the shear wall system, which will be explored. However, the material of the pad is not varied in the study.

The scope of this project will have two broad aspects. One is the experimental testing, which will include design of test specimens and the test setup, physical testing of specimens, and analysis of test results. The other is analytical analysis based on finite element method using OpenSees (Open System for Earthquake Engineering Simulation,

The Regents of the University of California, 1999, 2000), a research oriented software developed at the University of California, Berkeley. The scopes of experimental testing and analytical analysis are discussed in detail below.

Experimental Testing (Test Design, Test Setup, Testing and Analysis of Results):

Test Design

The following tasks are identified for this part of the study:

1. Design and select a coupling beam specimen keeping in mind that the actuator capacity available in laboratory is 30 kips.
2. Design and select the fuse beam specimen keeping in mind that the fuse beam must yield in shear before the coupling beam, splice joint or bolts yield.
3. Design of the splice joint and bolts so that they behave as a slip critical joint to avoid bearing of bolts on the coupling beam or fuse.

Test Setup and Testing

The following tasks are identified for this part of study:

1. Design the coupled-beam test system in which the fuse beam is located at the mid-span of the coupling beam and is subjected to cyclic shear load.
2. Use a pair of actuators and beam spans which produce the desired cyclic loads under which shear failure will occur in the fuse beam.
3. Brace the beam at required locations to avoid out-of-plane movement or buckling.
4. Strain gauge the coupling beam and the fuse beam at appropriate locations to monitor the material behavior under cyclic loads.

5. Conduct four fuse beam tests: Two tests without elastomeric pads and two tests using elastomeric pads at the Large Scale Testing Facility of University of Cincinnati at Center Hill.
6. Conduct tension coupon tests on the steel material of the fuse beam web at the High Bay Laboratory of University of Cincinnati on main campus.

Analysis of Results

The test results obtained will be analyzed to obtain the following:

1. Hysteretic response behavior in terms of load versus tip deflection for the fuse beams.
2. Strain versus load plots for both the coupling beam and the fuse beam to confirm that the coupling beam remains in the elastic state when the fuse beam yields, and also to access energy dissipated by the fuse beam.

The aforementioned scope will apply to both cases, namely fuse beams without elastomeric pads and fuse beams with elastomeric pads. A comparison of the above results obtained for the two cases will be done.

Analytical Study: (Modeling, Calibration and Validation, Application)

Modeling

The following tasks are identified for this part of the study:

1. Using the properties and strain versus load characteristics of the fuse beam obtained from experimental testing and analysis, develop a 2-D finite element model of the experimental test setup using the element library and analysis procedures available in the software package OpenSees.

2. In the above model use the shear link element or a suitable element available in the software to model the fuse beam behavior, and use elastic beam elements to model the coupling beam behavior.
3. Similarly for the shear walls of the coupled walls, model a pre-designed and pre-analyzed shear wall using the fiber based elements available in the software package OpenSees.

Validation:

The following tasks are identified for this part of the study:

1. Calibrate the experimental test setup model based on the model available in the OpenSees software (e.g. bi-linear or tri-linear model) to idealize the behavior of the shear link. The points selected on the graphs for idealization will be adjusted so that the model predicts the behavior of the shear link as close as possible to that obtained from the experiments.
2. Calibrate the shear wall element and check if it predicts results of the previously tested shear wall.

Application:

The following tasks are identified for this part of the study:

1. Use the calibrated models of walls and coupling beams in a coupled shear wall system.
2. Analyze the coupled shear wall system first without the fuse beam as a part of the coupling beams. Investigate the effects on force versus sway of the shear wall, vertical force at the base of shear wall versus number of load cycles and moment at the base of the shear wall versus number of load cycles.

3. Analyze the coupled shear wall system, with the fuse beam as a part of the coupling beams. Investigate the effects on force versus sway of the shear wall, vertical force at the base of shear wall versus number of load cycles and moment at the base of the shear wall versus number of load cycles.
4. Compare the results of the above two analyses and investigate if the fuse beam contributed as desired in affecting the system behavior.
5. Repeat the analysis for the cases of fuse beam with elastomeric pads.
6. Discuss the advantages, if any, of using elastomeric pads.

CHAPTER 2

EXPERIMENTAL STUDY

2.1 General

Shear walls are individually designed to carry lateral loads through flexural resistance. When coupling beams are added between the shear walls, the load transfer becomes more similar to the behavior of a frame. Depending on the degree of coupling, the wall piers will be subjected to axial forces as well as moments. Normally coupling beams are designed to dissipate energy through the formation of plastic hinges at the connection between the beam and the wall and at the base of each wall (Harries et al., in review). This makes rehabilitation of the structure expensive and time consuming due to the yielding mechanism developing at these points. Incorporating a fuse beam at the mid-span of the coupling beam allows for the concentration of the damage due to the shear forces to be located on this relatively small fuse beam. The fuse beam is connected to the coupling beam using bolted spliced connections (slip-critical connection), which is capable of developing the full moment strength of the main beam. The fuse beam can then be replaced easily if damaged during an earthquake. Although in theory this seems a reasonable assumption, only proper testing and analysis will be able to show whether or not a fuse beam behaves the way described above.

2.2 Experimental Testing

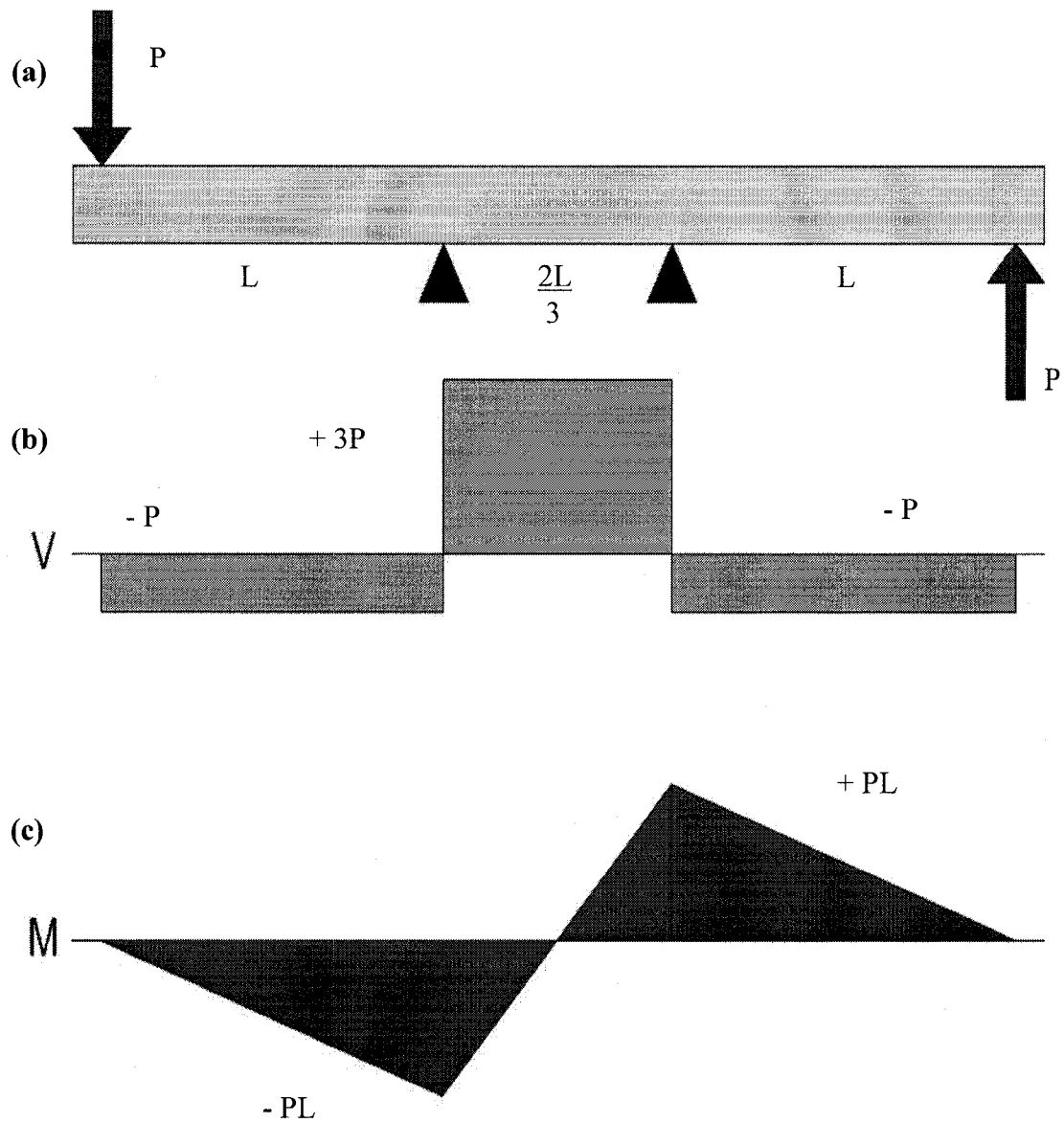
2.2.1 Description of Test Setup

The design of the test setup was based on certain limitations and design philosophies particular to this test. One of the limitations was the maximum actuator capacity of 30 kips (134 KN) available for testing at the laboratory. Since this is a very

small force to cause shear failure in a W-section beam, the test setup was designed in such a manner that 90 Kips (400 KN) shear force could be achieved in the coupling beam between the supports using two 30 Kips (134 KN) actuators.

The setup was a double overhanging beam which was continuous over two pinned supports. The length of the overhangs on each side of the support was one and half times the length of the beam between the supports. The lengths of the overhangs were 12 ft (3.66 m) on one side of each support. With two equal and opposite loads of 30 Kips (134 KN) acting on the free ends of the beam, from mechanics, this arrangement gives a shear force of magnitude equal to three times the magnitude of load, which equals 90 Kips (400 KN), applied at the free ends. This arrangement produces a constant shear force in the supported portion of the beam and zero bending moment at the center of the beam. The loading, support condition, shear force and bending moment diagrams produced in the coupling beam are shown in Fig. 2.1.

Sketches of the plan and elevation of the test setup are shown in Figs. 2.2 and 2.3. A photographic view of the test setup is shown in Fig. 2.4. The coupling beam was a W14 x 61 section made of A-992 steel. The reasons for selecting this section are presented in Section 2.2.2, which describes the design of the test setup. The beam was supported at two locations equidistant from the center with a total supported span of 8 ft (2.44 m). As shown in Figs. 2.2 and 2.3, centered at 3 ft (0.914 m) from the end of the fuse beam, on one side of the flange, is the bracket attachment for the pin used to simply support the beam at this location. The placement of the pin was designed to simulate a frictionless surface on which the beam can rotate. Rods passing through a bracket on the bottom flange of the beam were used as contact surfaces to give the pins support and



$$L = 12 \text{ ft (3.66 m)}$$

Figure 2.1 Test Beam: (a) Loading and Support Conditions; (b) Shear Force Variation; and (c) Moment Variation

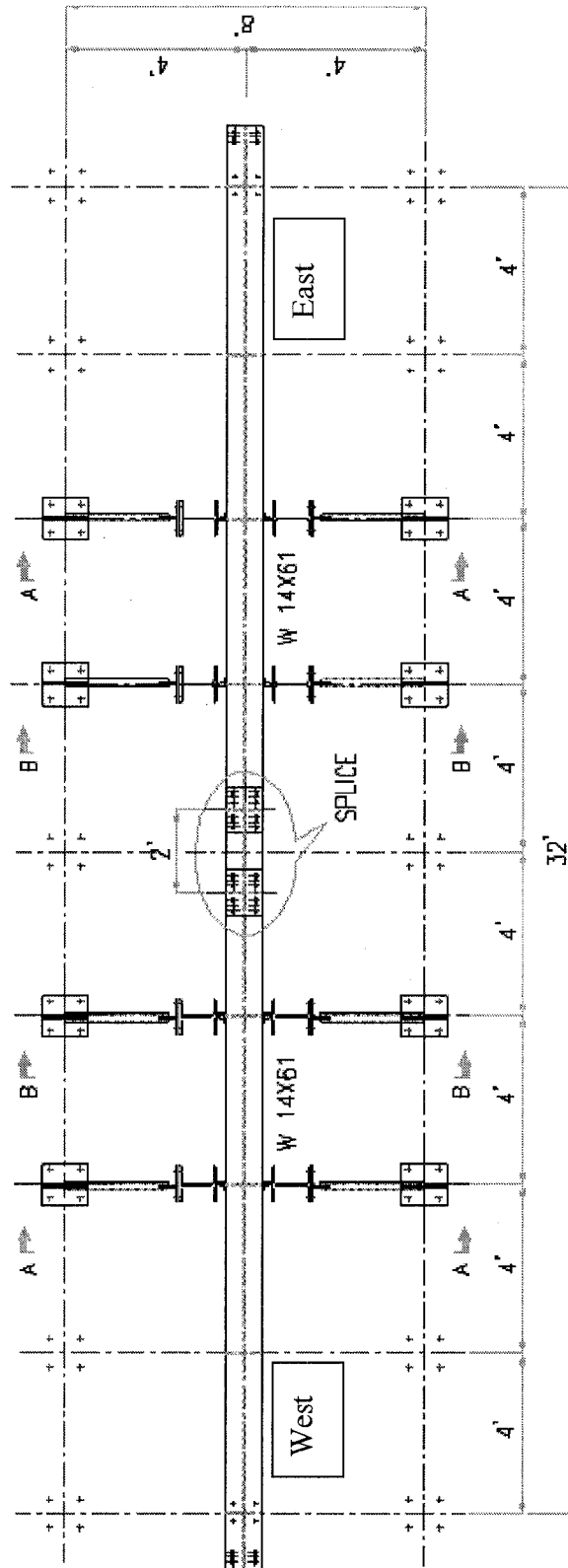


Figure 2.2 Plan of Test Setup

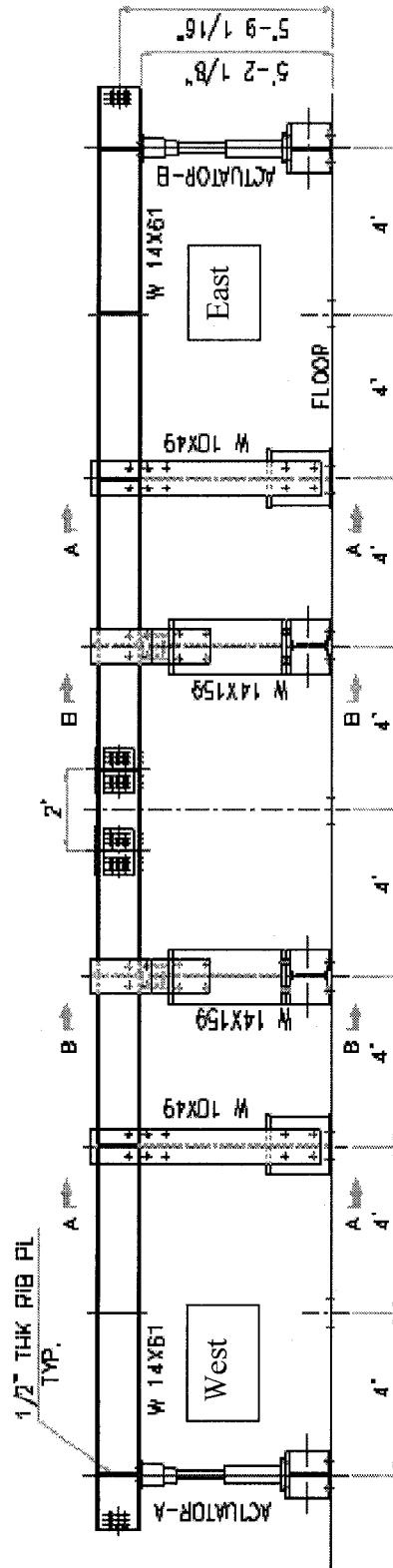


Figure 2.3 Elevation of Test Setup

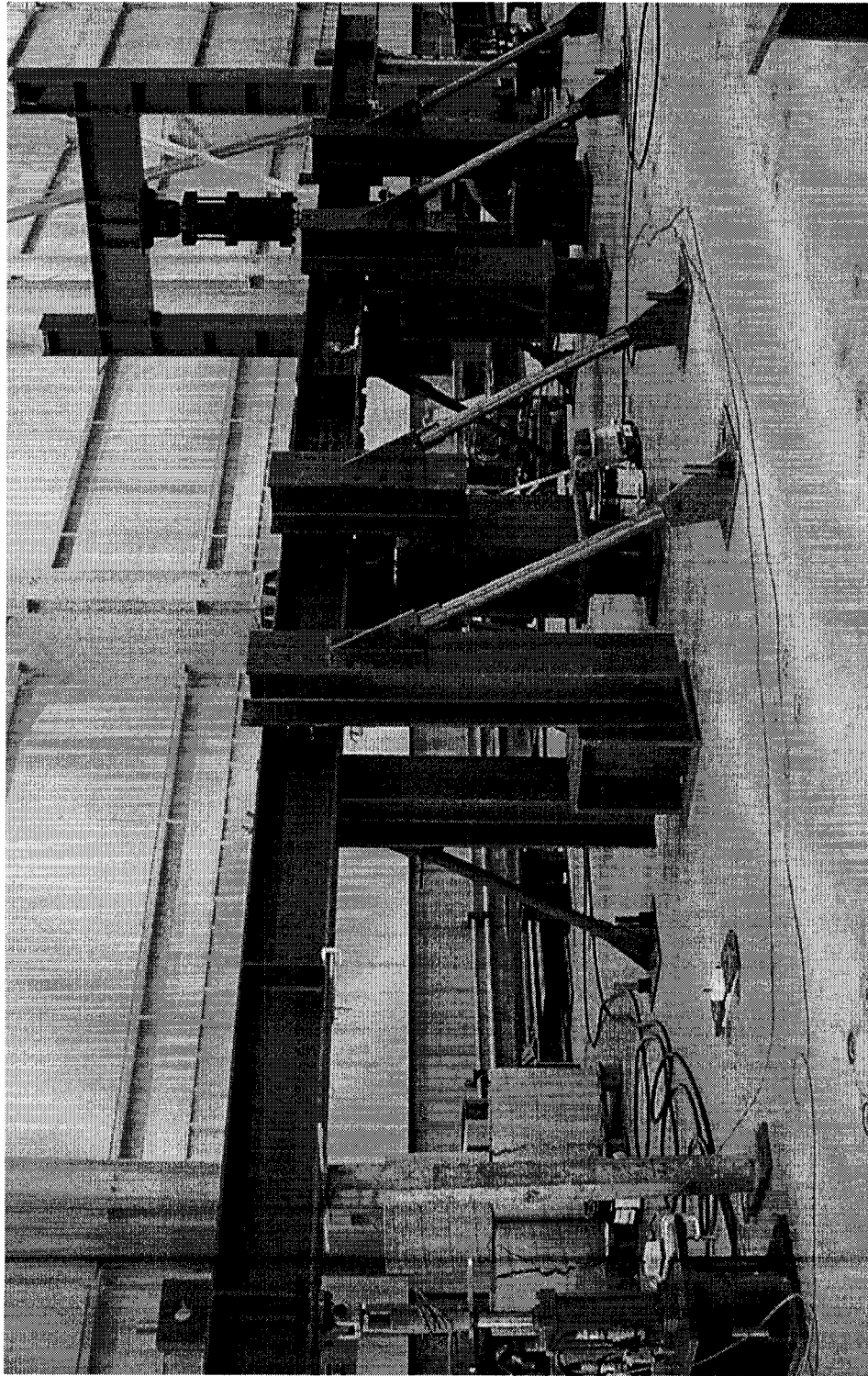


Figure 2.4 Photographic View of Actual Test Setup

freedom of movement. The rods were milled and greased to minimize friction between the beam bracket and the supports. The supports were mounted on an adjustable frame that allows for fabrication tolerances and gives an exact bearing at the supports.

The beams were also braced at four locations, as shown in Figs. 2.2 and 2.3. Two bracings were at the location of the supports. Two other braces were placed 4 ft (1.22 m) outward from each support. These braces prevented the coupling beam from experiencing any out of plane movement. In order to adjust for the tolerances experienced during fabrication, few shims made from scrap steel were clamped onto the braces.

Two actuators were placed at the free ends to induce loads, as shown in Figs. 2.2 and 2.3. They were programmed to oscillate in opposite directions creating the necessary cyclic shear forces at the center of the connection where the fuse beam was placed.

The fuse beam, 2 ft (0.61 m) long, was placed at the center of the supported portion of the beam where the shear force is constant and the moment is zero. The fuse beam was connected to the coupling beam using slip critical bolted connections. Splice plates were used on the webs and flanges. Slip critical connections were used to avoid slippage of bolts and hence bearing on the coupling beam flanges and webs. DTI (Direct Tension Indicators) washers were used to indicate pretension forces while bolt tightening, and thus ensuring slip critical condition for the connectors of the splice joint.

Plain elastomeric pads were only used in two tests. The elastomeric pads used were $\frac{1}{4}$ in. (6 mm) thick, and were installed between the splice plates and the web of the beam on both sides of the web and in between the flange plates and the flanges of the beam on both flanges. The size of the elastomeric pads was the same as the splice plates.

The whole setup had to be instrumented to electronically collect all the required test data as the test was conducted. For each test several measurements were taken to characterize the behavior of cyclic loading acting on the coupled beam with a fuse beam bolted at the center. A wire potentiometer was mounted to the side of each actuator, which measured the displacement of the actuator as it applied the load to the coupling beam ends. The wire potentiometers were connected using clamps to the base of the actuator and the other end was wired to the center of the coupling beams bottom flange. Also mounted to each actuator was a load cell that measured the amount of force applied on the coupling beams. Located 48 in. (1,220 mm) towards the fuse from each actuator, another wire potentiometer was installed. These potentiometers were used to measure the displacement of the beam to make sure the coupled beams behaved linearly between the pinned support and the actuator. Four strain gauges were placed along the top centerline of the top flange of the beam. Two of these strain gauges were attached at each pinned support, and the other two strain gauges were attached 12 in. (305 mm) from the edge of the coupling beam where the fuse beam was connected. These strain gauges were placed to record the coupling beam flange strains and ascertain after testing that they remained in the elastic region throughout the cyclic loading. A 45-degree strain rosette was attached at the central axes of the web of the fuse beam. Another 45-degree strain rosette was attached on one side of the fuse beam along the centerline of the web, and at 12 in. (305 mm) from the edge of the coupling beam where the fuse is connected. These rosettes were placed to record the coupling beam web strains and ascertain after testing that they remained elastic and whereas the fuse beam assumed plasticity. A schematic sketch of the location of the various strain gauges is shown in Fig. 2.5.

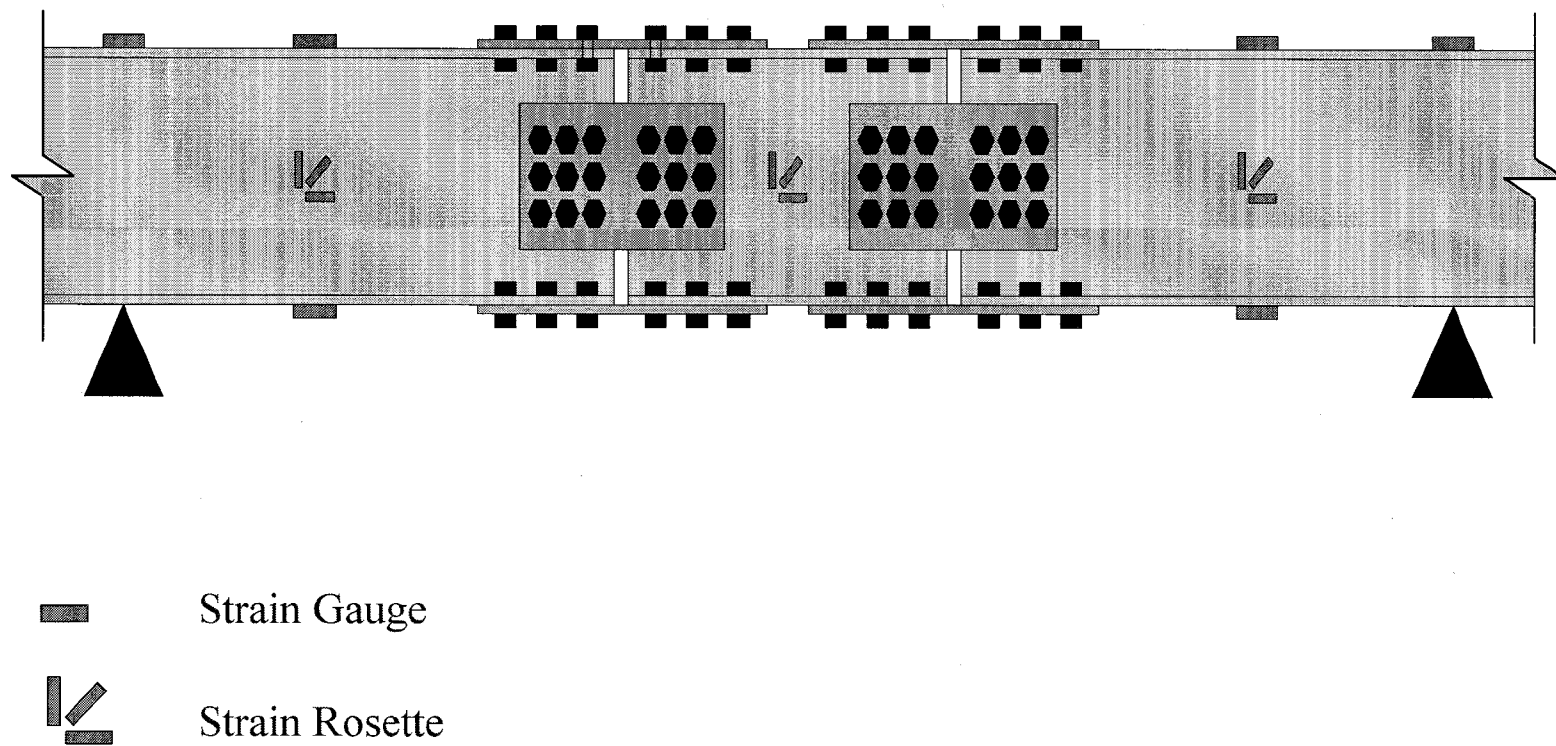


Figure 2.5 Instrumentation of the Test Setup

2.2.2 Design of Test Setup

A shear force of 90 Kips (400 KN) is very small compared to the shear forces experienced by shear walls in real structures. Hence the size of the coupling beam chosen for the test had to be a scaled version of a prototype beam normally used in practice for a coupling beam.

A W14 x 61 beam section of A-992 grade steel was selected for the coupling beam. The beam was selected keeping two important points in mind. One, the fuse beam had to be designed to possess the same depth as the coupling beam, and with a shear capacity just lower than the coupling beam. The other point being, the fuse beam should yield before the 90 Kips (400 KN) shear force could be reached, whereas the coupling beam still remained elastic under this shear. This coupling beam was checked to safely carry a shear force of 90 Kips (400 KN) and remain elastic. The design calculations for the capacity of the beam are shown in Section A.2 of Appendix A.

As stated earlier, the fuse beam was designed to yield before the shear force reached 90 Kips (400 KN). The fuse beam is a built-up section consisting of two flange plates, 3/8 in. (10 mm) thick, and a web plate, 1/8 in. (3.15 mm) thick, welded together. The depth of the fuse beam is same as that of the main coupling beam (W14 x 61). A36 steel was used to fabricate the fuse beam instead of A992 steel, which was used for the coupling beam. The tensile capacity of the material used was ascertained by conducting a tension test on a coupon cutout from the fuse beam web material prior to fabrication. The design check of the fuse beam is shown in Section A.3 of Appendix A.

The splice plates were designed to have at least the same or more shear and moment than the coupling beams (W14 x 61). The splice plates include two web plates,

3/8 in. (10 mm) thick, one for each side of the beam web, and two flange plates, one for each beam flange that are 1/2 in. (12.5 mm) thick. They were bolted together by 12-Nos. of 5/8 in. (16 mm) diameter A-325 bolts on the flanges, with 6 bolts on either side of the fuse beam, and 18-Nos. of 5/8 in. (16 mm) diameter A-325 bolts on the webs, with 9 bolts on either side of the fuse beam. The bolts were designed for slip critical connection, and were pre-tensioned using DTIs. The prescribed pretension force for these bolts is 19 Kips (85 KN). Slip critical connections were designed to eliminate possible shear failure of the bolts or bearing failure of the bolts on the web or flange plates of the connecting beams. The design calculations of the splice and bolt connection are shown in Section A.4 of Appendix A.

Two kinds of fuse beams were selected; two fuse beams with two web stiffeners, and two fuse beams with three web stiffeners. One of each kind was tested with elastomeric pads.

2.2.3 Tension Coupon Test on Fuse Beam Material

The fuse has been specifically designed to yield before the main coupling beam. In order to make sure the fuse beam yields before the coupling beam, tensile tests of the steel used for the web of the fuse beam was conducted. The coupling beam has a nominal yield limit of 50 ksi (350 MPa). The fuse has been designed to yield at a stress lower than the main coupling beam.

The specimens were fabricated as per the ASTM specifications (A370-02) for tension coupon testing. Prior to testing, the cross-sectional area of the specimen was determined. During the test, the load and strain were measured. Using the resulting stress versus strain relationship, the yield stress, ultimate stress, and the modulus of

elasticity of the steel were determined. The yield stress is the point at which the stress/strain relationship becomes nonlinear. This can be easily seen when graphed. The ultimate stress of the steel is the highest point on the y-axis of the resulting graph. The mechanical specifications for steel products are noted in ASTM A370-02 and the standards for testing steel products are noted in ASTM E8-96a. Proper gripping pressure, loading rate, data collection and stress/strain interpretations are also specified for the purposes of standardizing the tests. In the test, all appropriate standards were followed. The sketch of specimen is shown in Fig. 2.6. The calculations are presented in Section A.5 of Appendix A and photographs are presented in Appendix B.

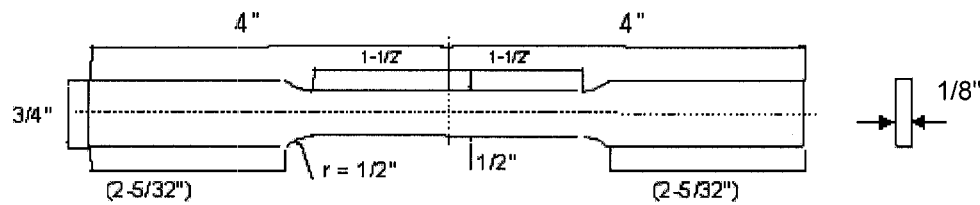


Figure 2.6 ASTM E8 Sheet-Type Coupon Dimensions

In order to simulate a pure tension test, the coupons were axially loaded by the grips. To facilitate this process there are guide-lines on the inside of wedges that are used to assure that the specimen is aligned perfectly along the vertical axis. The coupons were subjected to a monotonic load. The program was set to displacement control to allow for yielding to be measured. The initial load rate was 0.000249 in./sec (0.00632 mm/sec) and was continued until yielding occurred. Thereafter the load rate was increased tenfold to 0.00249 in./sec (0.0632 mm/sec). Around the time when the ultimate load was

about to be reached, the extensometer was removed in order to prevent it from being snapped-out when the coupon broke.

2.2.4 Fuse Beam and Coupling Beam Test

The two actuators were programmed to oscillate in opposite directions for each cycle and were controlled manually. The actuators were set for displacement control so the beams do not experience any unnecessary forces. The displacements were calculated from the rotation of the coupling beam supports. The rotation was increased incrementally as per the AISC cyclic test guidelines given in AISC Seismic code, 2002. The 0.025, 0.05 and 0.01 radians cycles were repeated three times and the cycles from 0.02 radians were repeated only twice till the test was stopped. The rotation, displacement and the number of cycles for all the tests are shown in Table 2.1. A sample of the displacements of both

Table 2.1 Rotation at Support, Tip Deflection and Number of Cycles for Each Step

Rotation at Support (Radians)	Tip Deflection (in.)	Number of Test Cycles	Rotation at Support (Radians)	Tip Deflection (in.)	Number of Test Cycles
0.0025	0.02	3	0.18	1.44	2
0.005	0.04	3	0.2	1.6	2
0.01	0.08	3	0.22	1.76	2
0.02	0.16	2	0.24	1.92	2
0.03	0.24	2	0.26	2.08	2
0.04	0.32	2	0.28	2.24	2
0.05	0.4	2	0.3	2.4	2
0.06	0.48	2	0.32	2.56	2
0.07	0.56	2	0.34	2.72	2
0.08	0.64	2	0.36	2.88	2
0.09	0.72	2	0.38	3.04	2
0.1	0.8	2	0.4	3.2	2
0.12	0.96	2	0.42	3.36	2
0.14	1.12	2	0.44	3.52	2
0.16	1.28	2	0.46	3.68	2

the west and east actuator during the whole test is shown in Fig. 2.7. It can be inferred from the graph shown in Fig. 2.7 that the two actuators oscillated in opposite directions to almost similar amplitudes.

For each cycle the data was read into a text file and saved as the test progressed. The data recorded for each rotation was input into a MS Excel file. This was done so that the load versus displacement graphs can be reviewed to make sure the tests are progressing satisfactorily in the intended manner. The maximum strain value read by the different strain gauges was also noted for each cycle to ensure that all the components are in elastic strain range. The tests were continued, increasing the displacements of the actuators, even after the strain gauge in the fuse beam web crossed the elastic strain, but

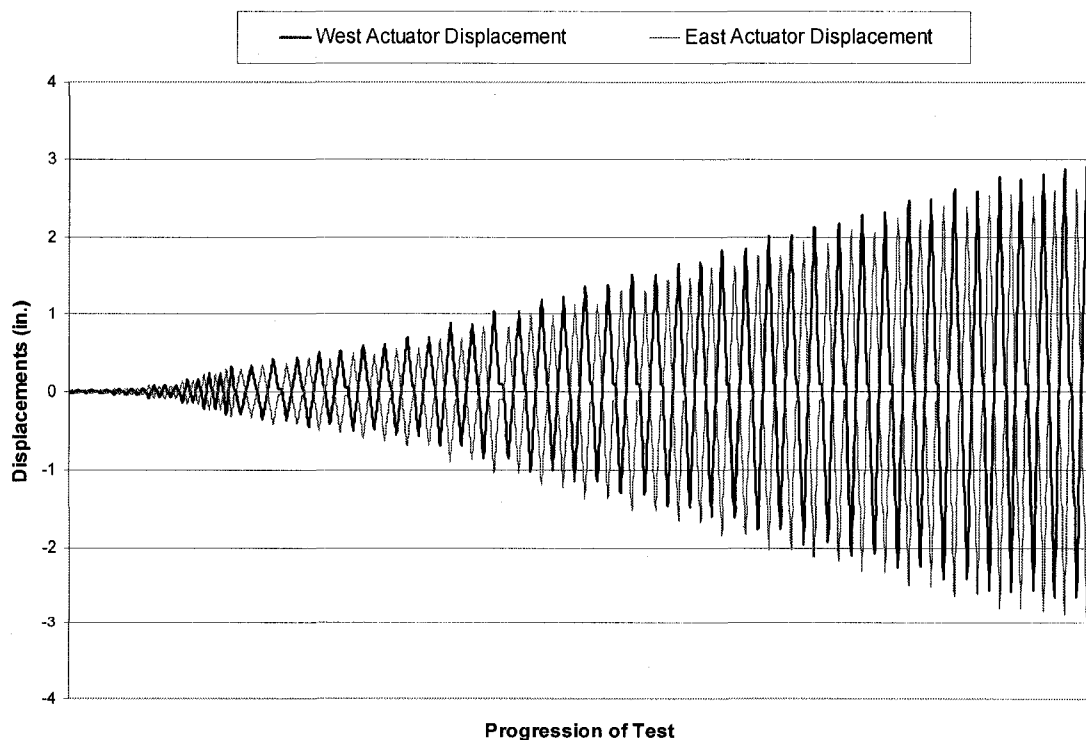


Figure 2.7 West and East Actuator Displacements During a Test

all the strain gauges in the coupling beam remained elastic. This process was continued until it was noticeable from the load versus displacement graphs that the beam was still picking up load despite the fuse beam strain crossed the elastic limit. The tests were stopped once it was noticed that the beam was not picking up any more load with increased displacement of the actuator. At all cycles after the fuse beam strain crossed the elastic limit, the strain gauges on the coupling beams were checked to confirm that they still remained in the elastic limit.

2.3 Test Results

2.3.1 Tension Coupon Test

One fuse coupon was tested by the 2003 NSF Research Experience for Undergraduates (REU) students. The calculated yielding occurred at 38.0 Ksi (266 MPa). This stress is lower than the yield stress material of the coupling beam, thus ensuring yielding of the fuse beam before the coupling beam. The test results and details are taken from the NSF 2003 REU students report. The stress versus strain relationship recorded is shown in Fig. 2.8 and photographs of the test are shown in Appendix B.

2.3.2 Test # 1 – Fuse Beam Having Two Stiffeners and Without Elastomers

In this test, the fuse beam buckled at a rotation of 0.28 radians. The test was continued so the behavior of the fuse afterwards could be observed. The test was stopped at 0.32 radians, at which point the fuse had gone well into the plastic range. The fuse developed fatigue points at the locations of the buckling. The web of the fuse yielded in shear, as expected. The bolt holes on the beam and the fuse beam showed no visual signs of bearing or other damage (as was noticed after testing), indicating that the slip critical

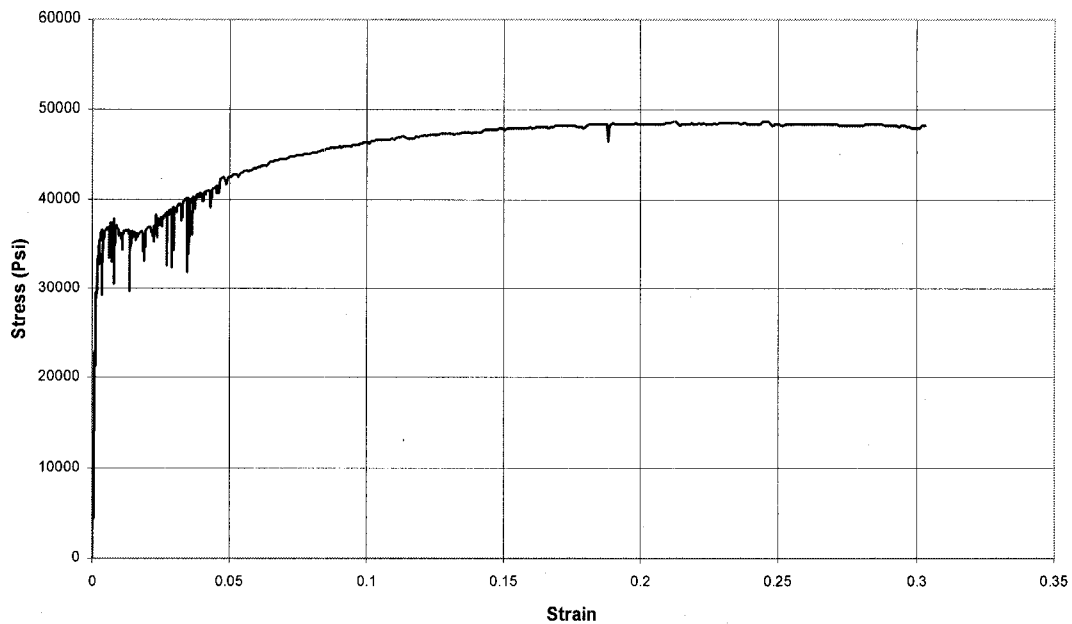


Figure 2.8 Stress Versus Strain Relationship of Fuse Coupon

connections performed as expected. Analysis and graphs of the test results are presented in Section 2.4.1. Photographs of the test are shown in Appendix D.

2.3.3 Test # 2 – Fuse Beam Having Two Stiffeners and With Elastomers.

This test was stopped at a rotation of 0.40 radians. The fuse did not buckle but the strain readings reflected that it had yielded and the strains were well into the plastic range. The test was continued beyond yielding of the fuse beam material, because the actuator was still picking up load. The test was stopped when it was noted that the actuator was not picking considerable load with increased actuator displacements and the strains in the coupling beam were approaching the elastic limit. The elastomeric pads delayed the yielding, and the bolts did begin to make popping noises as the cycles neared the zero points of loading. This noise sounded like the bolts were slipping, but the load versus displacement graphs did not show any signs of slippage and the bolt holes suffered

no damage (as was observed after the completion of the test). The elastomeric pads got wedged in the gaps between the fuse and the coupling beam causing them to be shredded as the test progressed. Analysis and graphs of the test results are presented in Section 2.4.2. Photographs of the test are shown in Appendix D.

2.3.4 Test #3 – Fuse Beam Having Three Stiffeners and Without Elastomers

In this test, the fuse beam yielded at a rotation of 0.28 radians. The test was continued to see if the fuse beam buckled like it had buckled in Test # 1. The test was stopped at 0.36 radians, at which point the fuse had gone well into the plastic range but the coupling beam was still elastic. The bolt holes on the beam and the fuse showed no signs of bearing or other major damage (as was observed after the test was completed), so the slip critical connections functioned well. Analysis and graphs of the test results are presented in Section 2.4.3. Photographs of the test are shown in Appendix D.

2.3.5 Test # 4 – Fuse Beam Having Three Stiffeners and With Elastomers

This test was stopped at a rotation of 0.46 radians. at the point that the coupling beam neared its elastic limits. The fuse beam crossed its elastic yield limit at 0.36 radians cycle. The fuse beam did not buckle but the strain readings reflected that it had yielded and was well into the plastic zone, though the actuator was still picking up load. The test was stopped when the actuators reached their stroke limit. The elastomeric pads delayed the yielding, but the bolts made a lot of popping noise near the zero points of loading as the cycles progressed. This noise sounded like the bolts were slipping, but the load versus displacement graphs did not show any signs of slipping and the bolt holes suffered no damage (as was observed after the test was completed). The elastomeric pads got wedged in the gaps between the fuse and the coupling beam causing them to be shredded

as the test progressed. Analysis and graphs of the test results are presented in Section 2.4.4. Photographs of the test are shown in Appendix D.

In all the four tests there was no physical damage observed in the web and flange splice plates, the bolts and the bolt holes. The bolt holes showed no sign of bearing failure of the bolts confirming that the connections behaved as slip critical. The coupling beam strain gauge readings never crossed the elastic strain limit of the coupling beam steel material. General photographs of test setup, apparatus and instruments used in testing are shown in Appendix C.

2.4 Analysis of Test Results

The test data for each test collected during experimentation were converted into MS Excel files. The data for each cycle zeroed down. Zeroing meant the data be corrected to make sure they started from zero reading. Zeroing of data is to add a correction factor to numerically ascertain that each cycle started with a zero reading. All the zeroed data for each cycle were put together to form the total data for the test for all cycles combined. In doing so, the last data readings of a particular cycle are added to all the readings of the zeroed data of the next cycle. This process ascertained that each cycle takes off from exactly the position where the previous cycle ended. The experimental data included east and west wire potentiometer readings, which were the tip deflections of the ends of the beam overhangs where the actuator is attached, the load cell recordings, which were the load developed or transmitted at the tips of the beam, and the strain readings of all the strain gauges in the setup. The average tip deflection versus average load, the shear stress versus shear strain along with the elastic slope and hardening slope trend lines, and the strains versus loading graphs for the coupling beam and fuse beam

have been plotted, analyzed and discussed. The average tip deflection is the average of the readings of the east and west wire potentiometers. (The east and west location is shown in Figs. 2.2 and 2.3). The average load is the average of the loads recorded by the east and west load cells attached to the actuators. Graphs for average tip deflection versus average load were also plotted. Also, from the available data the shear stress and shear strain in the web of the fuse beam was calculated, and graph for shear stress versus shear strain were plotted. The shear strain is calculated from the strain recorded by the strain rosettes mounted on the fuse. The shear stress is calculated using standard mechanics formulae using the shear force created from the induced loads. The shear force is calculated from the shear force diagram for the beam shown in Fig. 2.1 for each load level. The elastic slope trend line is drawn using the elastic range data of the strain gauges mounted on the web of the fuse beam, and the trend line for the hardening slope is drawn using the peak values of the same data in the plastic range. Equations of the elastic slope line and hardening slope line are presented in the respective graphs. The above graphs are analyzed individually for each test in subsequent sub-sections.

2.4.1 Test #1 – Fuse Beam Having Two Stiffeners and Without Elastomers

Figure 2.9 shows the graph between the average load and the average deflection. It can be seen that the maximum average load reached during forward loading is around 18 kips (80 KN) at an average tip deflection of around 2 in. (50 mm), and the maximum average load reached during reverse loading is around -20.5 kips (-91 KN) (negative sign indicates reverse loading) at an average tip deflection of -2.5 in. (-63 mm) (negative sign indicates downward deflection from zero position). In the forward loading it can also be noticed that after reaching 18 kips (80 KN), the load begins to drop even with an increase

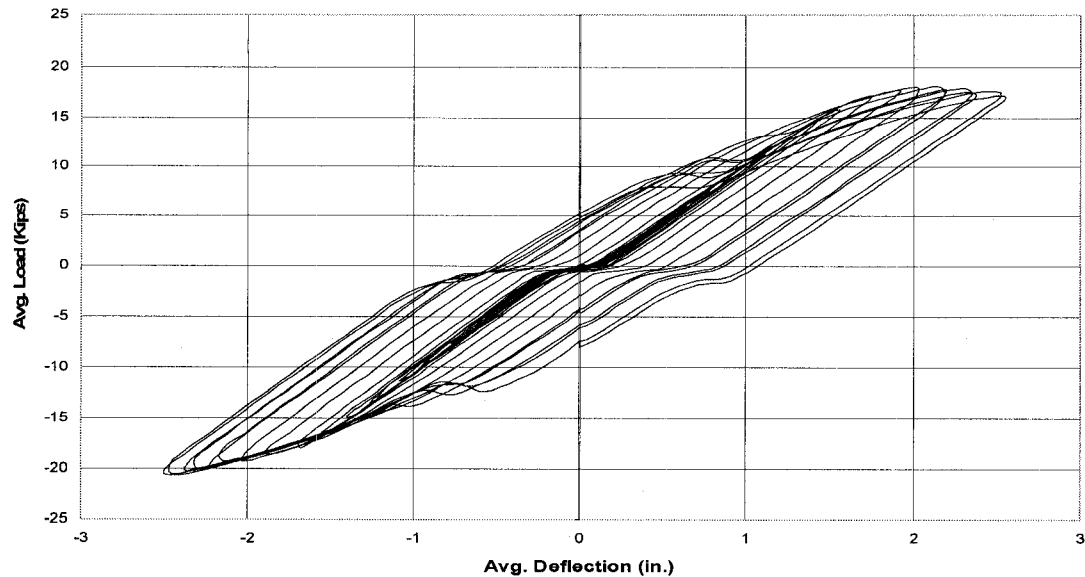


Figure 2.9 Test # 1 Average Load Versus Average Deflection

in the average tip deflection during the last three cycle sets. This indicated that the fuse beam had yielded to an extent that it was unable to pick up anymore load, and hence the test was stopped. The small amount of pinching observed in the hysteretic loops at the start of load cycles may have resulted due to the erection tolerance between the hinge rod and the hole of the hinge support. During this period the actuator does not pick up any load till the actuator displacements are more than the tolerance and the rod bears on to the hole edges of the hinge support. Figure 2.10 shows the graph of shear stress versus shear strain of the web of the fuse beam. The hysteresis curves are near about symmetrical about the x and y axes. The maximum shear stress is about 38 Ksi (267 Mpa) and the maximum shear strain is about 21,500 micro strains. The shear stress versus the shear strain is linear for most part of the testing and the loops begin to widen towards the end cycles, when the steel in the fuse beam crosses the elastic range and begins to undergo plastic deformations. The elastic slope is found to be 15,100 Ksi (104,111 MPa) which is 35% larger than the nominal shear modulus of steel and the hardening slope is 300 Ksi

(2,068 MPa). The coupling beam strains and fuse beam strains versus loading plots are shown in Fig. 2.11. It can be inferred from the graph that the coupling beam remained elastic throughout the loading cycle, whereas the fuse beam crossed its elastic limit.

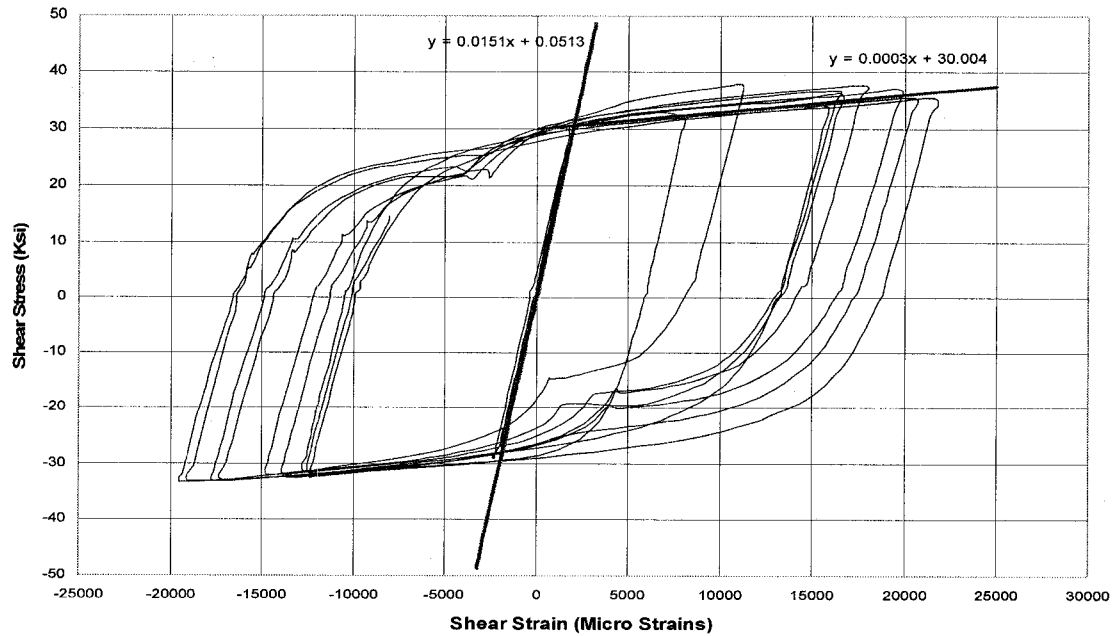


Figure 2.10 Test # 1 Shear Stress Versus Shear Strain in Fuse Beam Web

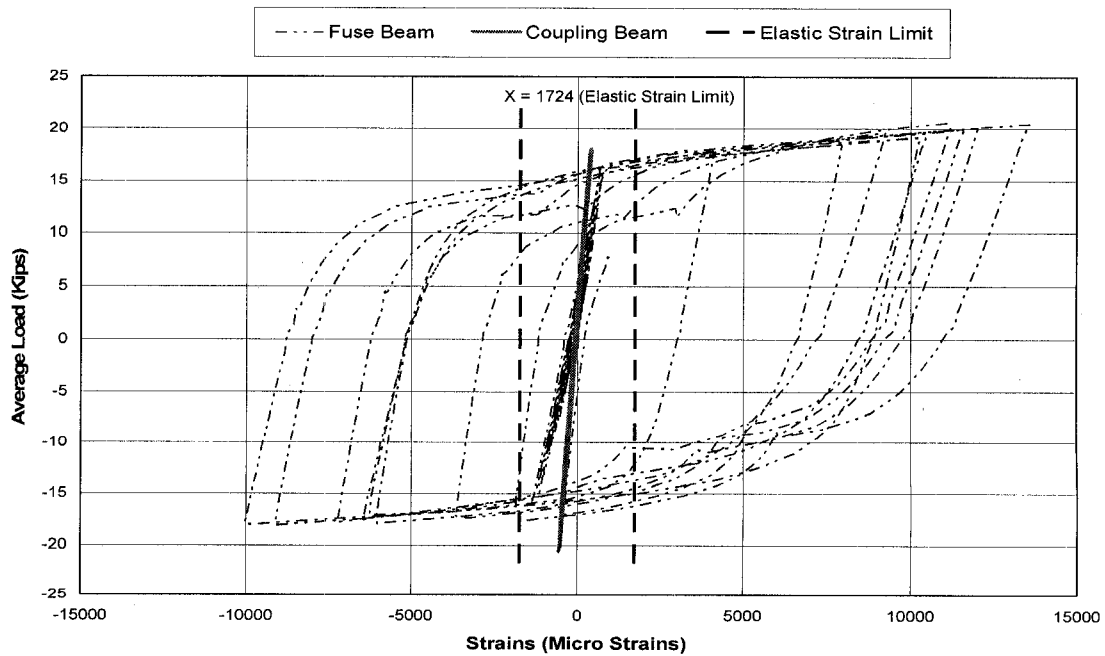


Figure 2.11 Test # 1 Coupling Beam and Fuse Beam Strains Versus Average Load

2.4.2 Test #2 – Fuse Beam Having Two Stiffeners and With Elastomers

Figure 2.12 shows the graph between the average load and the average deflection. It can be seen that the maximum average load reached during forward loading is around 12 Kips (53 KN) at an average tip deflection of around 3 in. (76 mm) and the maximum average load reached during reverse loading is around -21.5 kips (-96 KN) (negative sign indicates reverse loading) at an average tip deflection of -3 in. (-76 mm) (negative sign indicates downward deflection from zero position). In the forward loading it can also be noticed that after reaching 12 Kips (53 KN), the load begins to drop even with an increase in the average tip deflection during the last three or four cycle sets. This indicated that the fuse beam had yielded to an extent that it was unable to pick up anymore load, and hence the test was stopped. It also indicated that the actuator load was less with elastomeric pads for the same amount of tip deflection. It can be noticed from the graph that the first quadrant is wider than the third quadrant of the hysteretic loops. This is because the fuse beam yielded in the first quadrant before the third quadrant, thus creating a weak zone in the fuse beam. This concentrated the further damage at that location and the fuse beam material continued to go non-linear in that direction, whereas it remained elastic in the other direction. The behavior of the curve in the negative quadrant appears to be unusual, where the stiffness does not reduce as expected during strain hardening. This behavior needs to be explored to find a reason as to why such a behavior is occurring. Figure 2.13 shows the graph of shear stress versus shear strain of the web of the fuse beam. The hysteresis curves are near about symmetrical about the x and y axes until the last three rotation cycles. The curve becomes unsymmetrical towards the last three sets of rotation cycle because, the fuse beam yielded in one direction of

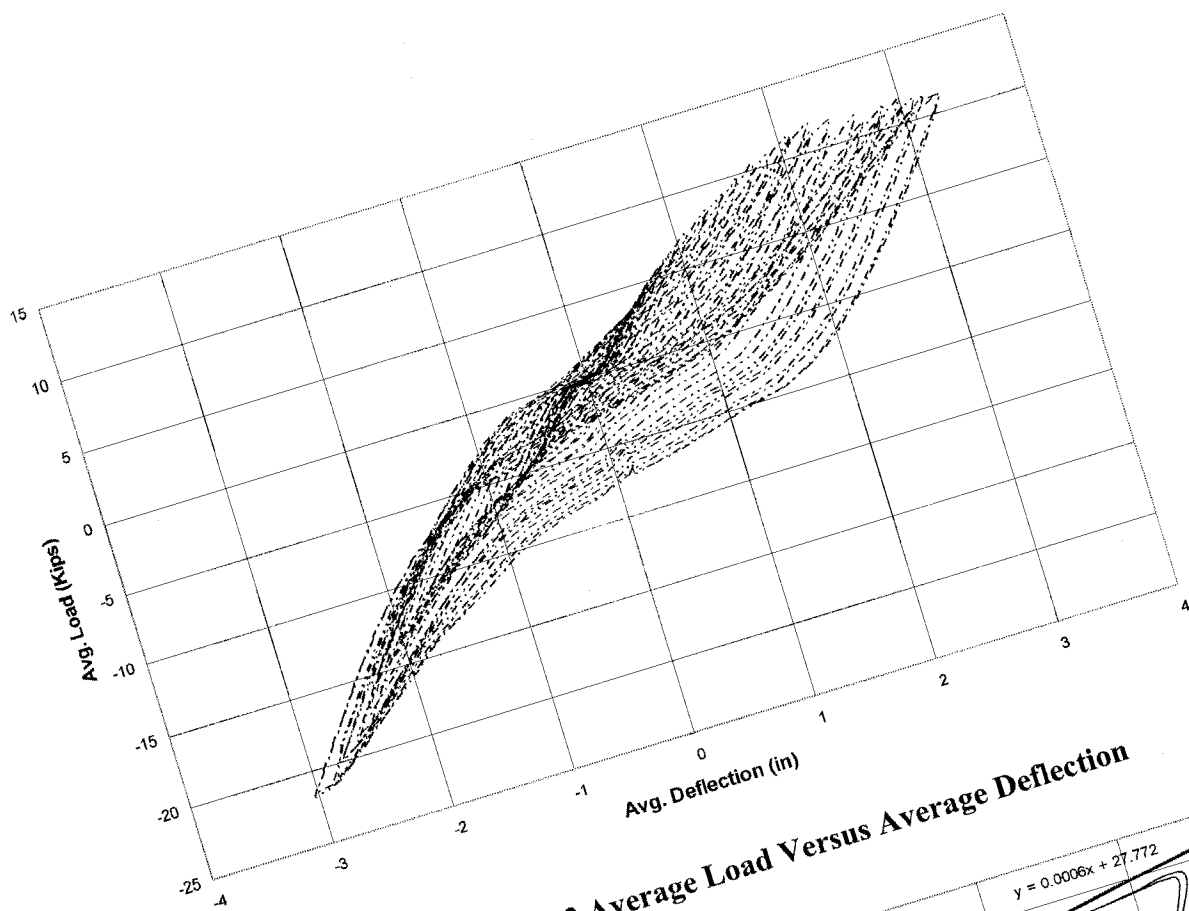


Figure 2.12 Test # 2 Average Load Versus Average Deflection

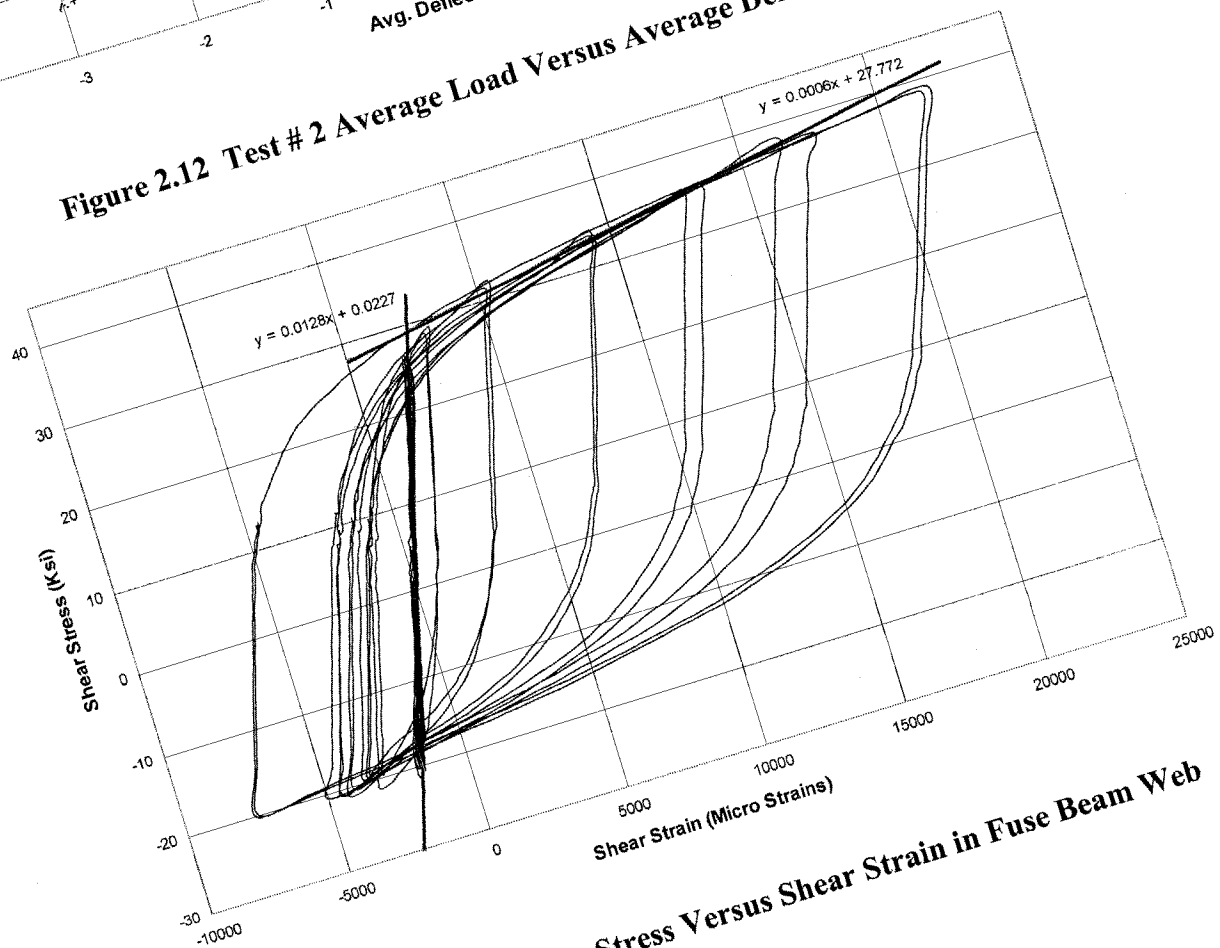


Figure 2.13 Test # 2 Shear Stress Versus Shear Strain in Fuse Beam Web

loading at that point, which created a yield point. This caused the strain to increase rapidly in the direction of loading for higher loads. The maximum shear stress reached was 39 Ksi (274 Mpa) and the maximum shear strain was 22,000 micro strains. The shear stress versus the shear strains linear for most part of the testing and the loops begin to widen towards the end cycles when the fuse beam steel material crosses the elastic range and begins to undergo plastic deformations. The elastic slope was found to be 12,800 Ksi (88,253 MPa) which is 15% lesser than shear modulus obtained for fuse beam in Test # 1 and it is 15% higher than the nominal shear modulus of steel, and the hardening slope was 600 Ksi (4,137 MPa). The coupling beam strains and fuse beam strains versus loading plots are shown in Fig. 2.14. It can be inferred from the graph that the coupling beam stayed elastic throughout the loading cycle, whereas the fuse beam crossed its elastic limit.

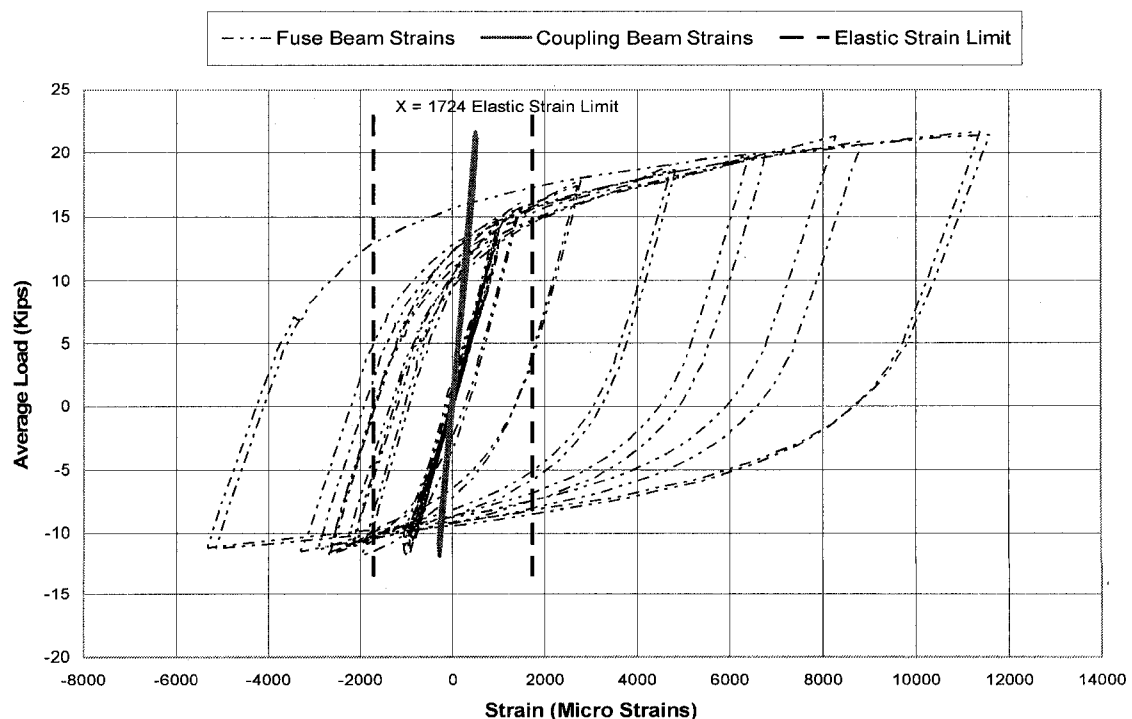


Figure 2.14 Test # 2 Coupling Beam and Fuse Beam Strains Versus Average Load

2.4.3 Test #3 – Fuse Beam Having Three Stiffeners and Without Elastomers

Figure 2.15 shows the graph between the average load and the average deflection. It can be seen that the maximum average load reached during forward loading is around 16 Kips (71 KN) at an average tip deflection of around 2.25 in. (57 mm) and the maximum average load reached during reverse loading is around -26.5 Kips (-118 KN) (negative sign indicates reverse loading) at an average tip deflection of -2.6 in. (-66 mm) (negative sign indicates downward deflection from zero position). In the forward loading cycle it can also be noticed that after reaching 16 Kips (71 KN), the load begins to drop even with an increase in the average tip deflection during the last four to five rotation cycle sets. This indicated that the fuse has yielded to an extent that it was unable to pick up anymore load, and hence the test was stopped. The initial pinching observed in the hysteretic loops at the start of load cycles is due to the erection tolerance gap between the hinge rod and the hole of the hinge support. During this period the actuator does not pick up any load till the actuator displacements are more than the tolerance and the rod bears on to the hole edges of the hinge support. Figure 2.16 shows the graph of shear stress versus shear strain of the web of the fuse beam. The maximum shear stress was about 50 Ksi (351 MPa) and the maximum shear strain is about 30,000 micro strains. The three stiffeners increased the aspect ratio of the fuse beam web and were helpful in avoiding buckling of the fuse beam web, as was noticed in Test # 1. The shear stress versus the shear strain is linear for most part of the testing but the loops begin to widen towards the end cycles when the fuse beam steel material crosses the elastic range and begins to undergo plastic deformations. The elastic slope was found to be 15,400 Ksi (106,180 MPa) which is 38% greater than the nominal shear modulus of steel and the

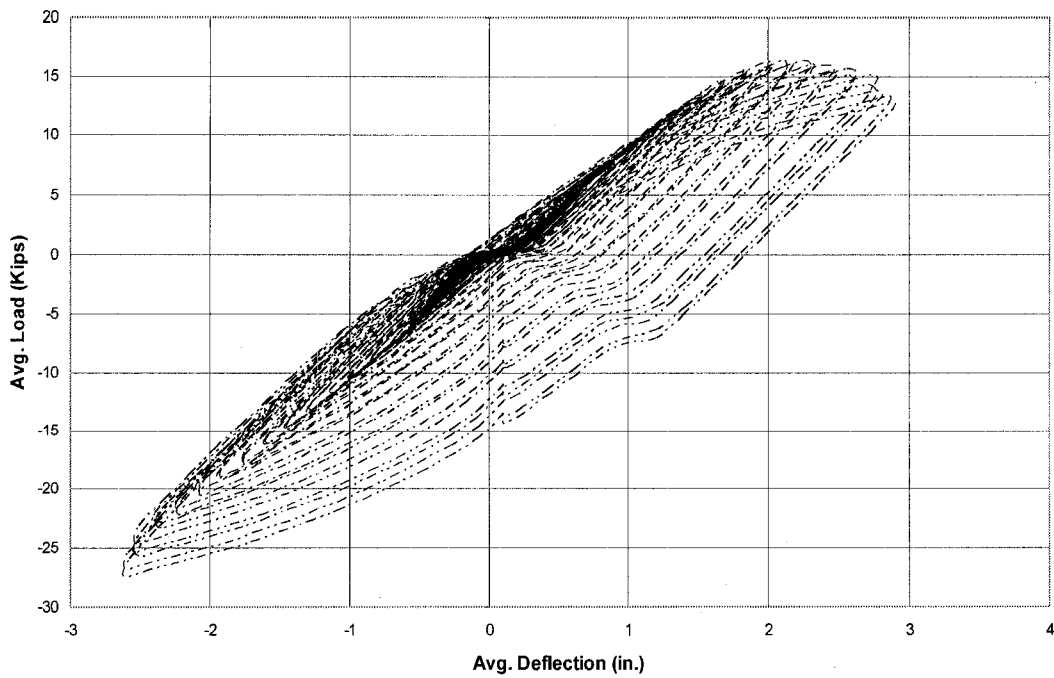


Figure 2.15 Test # 3 Average Load Versus Average Deflection

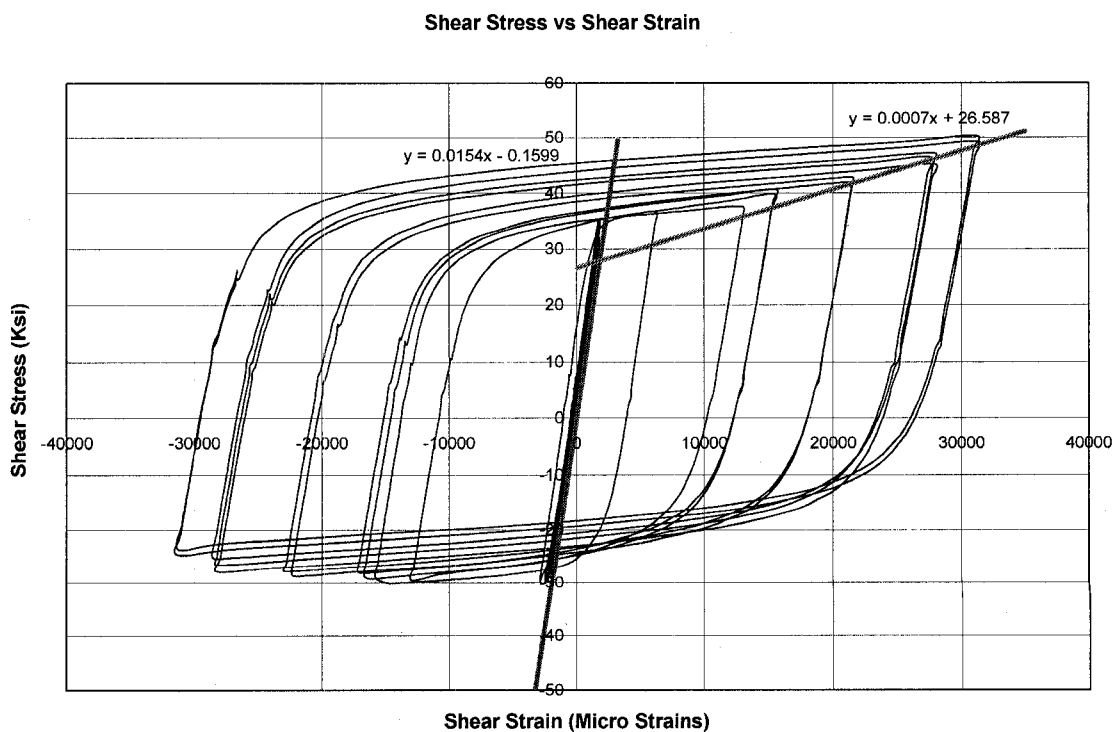


Figure 2.16 Test # 3 Shear Stress Versus Shear Strain in Fuse Beam Web

hardening slope was 700 Ksi (4,826 MPa). The coupling beam strains and fuse beam strains versus loading plots are shown in Fig. 2.17. It can be inferred from the graph that the coupling beam stayed elastic throughout the loading cycle, whereas the fuse beam crossed its elastic limit.

2.4.4 Test #4 – Fuse Beam Having Three Stiffeners and With Elastomers

Figure 2.18 shows the graph between the average load and the average deflection. It can be seen that the maximum average load reached during forward loading is around 13.4 Kips (60 KN) at an average tip deflection of around 3.9 in. (99 mm) and the maximum average load reached during reverse loading is around -19.5 Kips (-87 KN) (negative sign indicates reverse loading) and an average tip deflection of -3.2 in. (-81 mm) (negative sign indicates downward deflection from zero position). In the forward loading it can also be noticed that after reaching 13.4 Kips (60 KN), the load begins to drop even with an increase in the average tip deflection during the last two to three rotation cycle sets. This indicated that the fuse beam had yielded to an extent that it was unable to pick up anymore load, and hence the test was stopped. It also indicated that the actuator load was less in the presence of elastomeric pads than without elastomeric pads for the same amount of tip deflection. It can also be noticed from the graph that the first quadrant widens more than the third quadrant of the hysteretic loops. This is because the fuse beam yielded in the first quadrant before the third quadrant, thus creating a weak spot in the fuse beam. It concentrated the further damage at that location and the fuse beam material continued to become non-linear in that direction, whereas remain elastic in the other direction. The behavior of the curve in the negative quadrant appears to be unusual, where the stiffness does not reduce as expected during strain hardening. This needs to be

explored as to why such a behavior is occurring. Figure 2.19 shows the graph of shear stress versus shear strain of the web of the fuse beam. The curve was unsymmetrical towards the last three sets of rotation cycle, because the fuse beam yielded in one direction of loading at that point, which created a yield point. This caused the strain to increase rapidly in the direction of loading for higher loads. The maximum shear stress was 36 Ksi (252 MPa) and maximum shear strain was 24,000 micro strains. The shear stress versus the shear strain is linear for most part of the testing and the loops begin to widen towards the end cycles when the fuse beam steel material crosses the elastic range and begins to undergo plastic deformations. The elastic slope is found to be 14,000 Ksi (96,526 MPa) which is 25% higher than the nominal shear modulus of steel and 10% lower than the shear modulus of fuse beam in Test # 3, and the hardening slope is 300 Ksi (2,068 MPa). The coupling beam strains and fuse beam strains versus loading plots

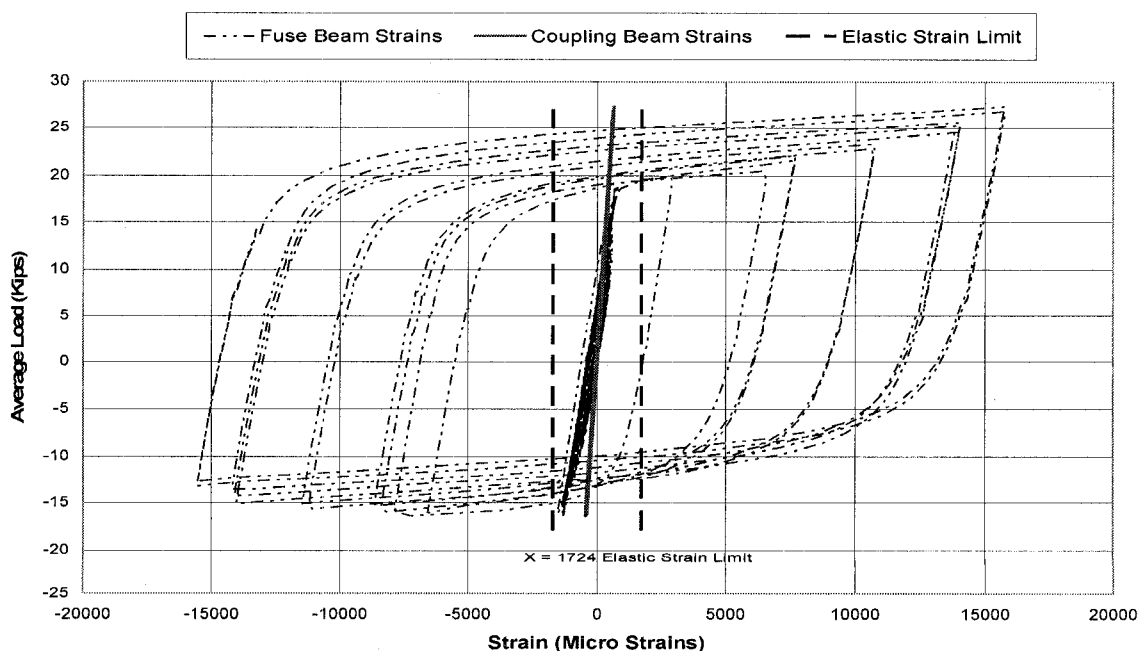


Figure 2.17 Test # 3 Coupling Beam and Fuse Beam Strains Versus Average Load

are shown in Fig. 2.20. It can be inferred from the graph that the coupling beam stayed elastic throughout the loading cycle, whereas the fuse beam crossed its elastic limit.

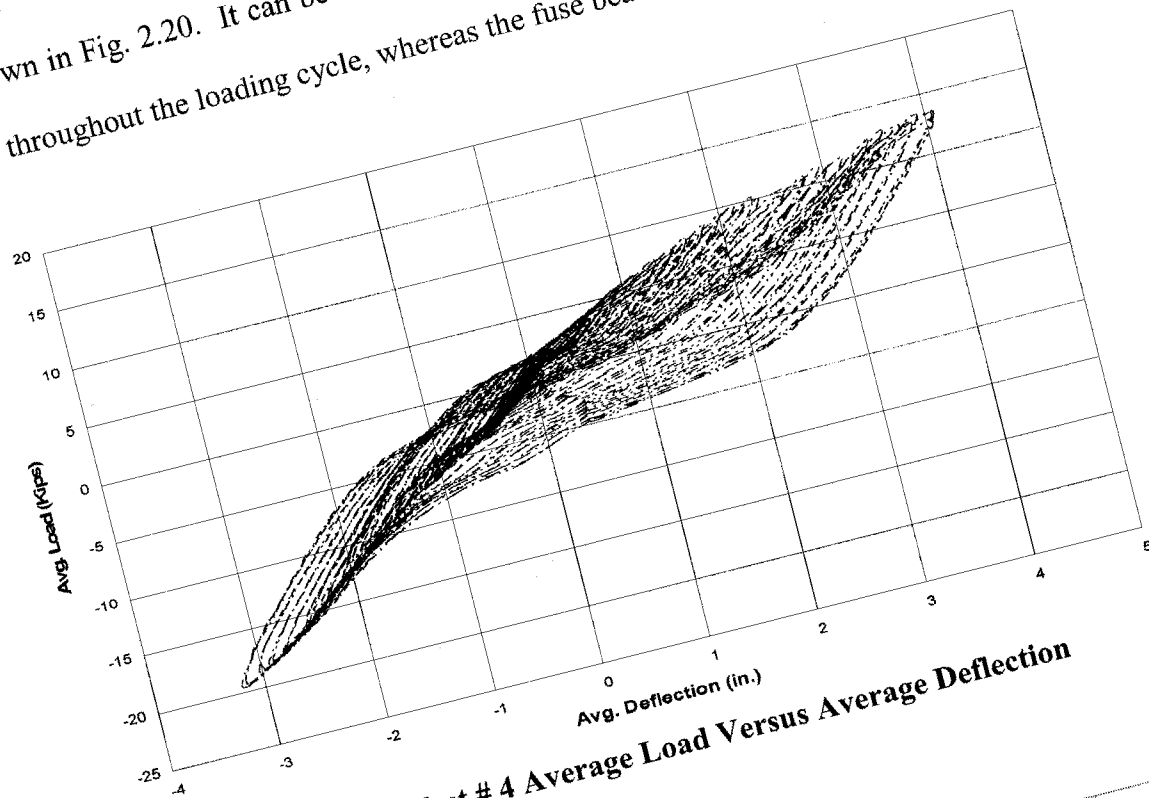


Figure 2.18 Test # 4 Average Load Versus Average Deflection

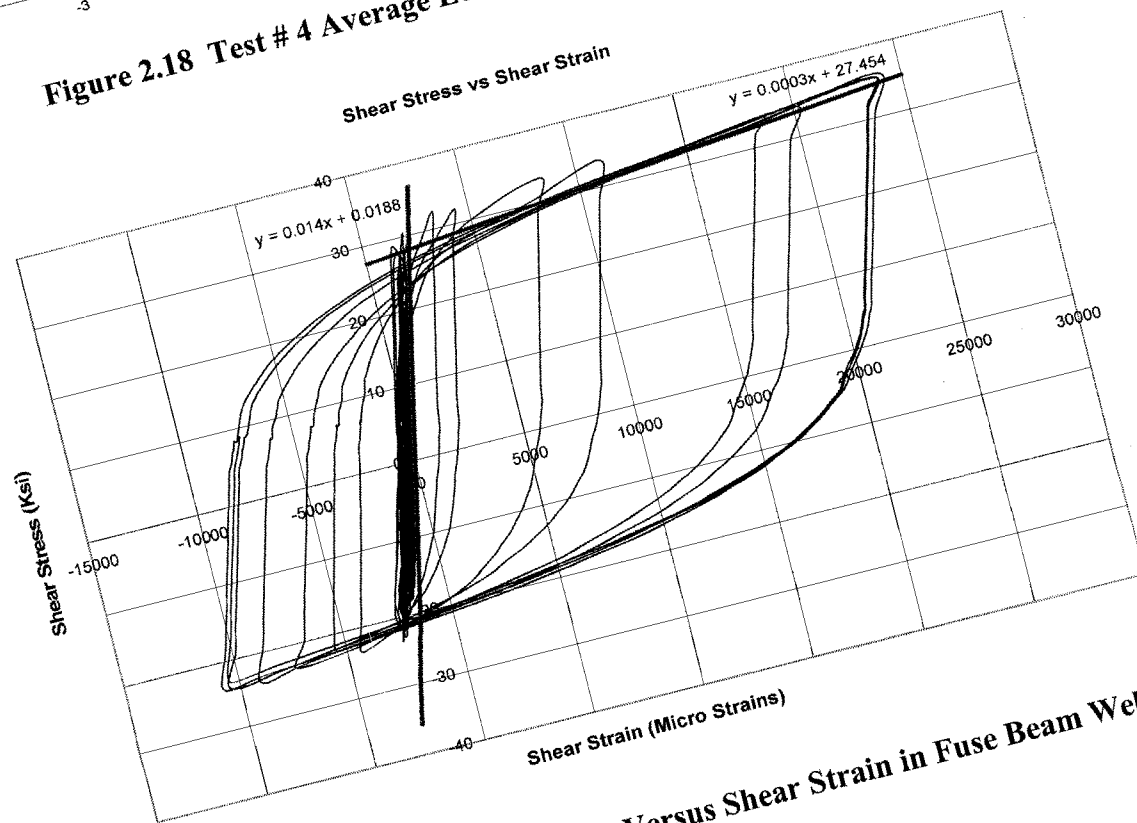


Figure 2.19 Test # 4 Shear Stress Versus Shear Strain in Fuse Beam Web

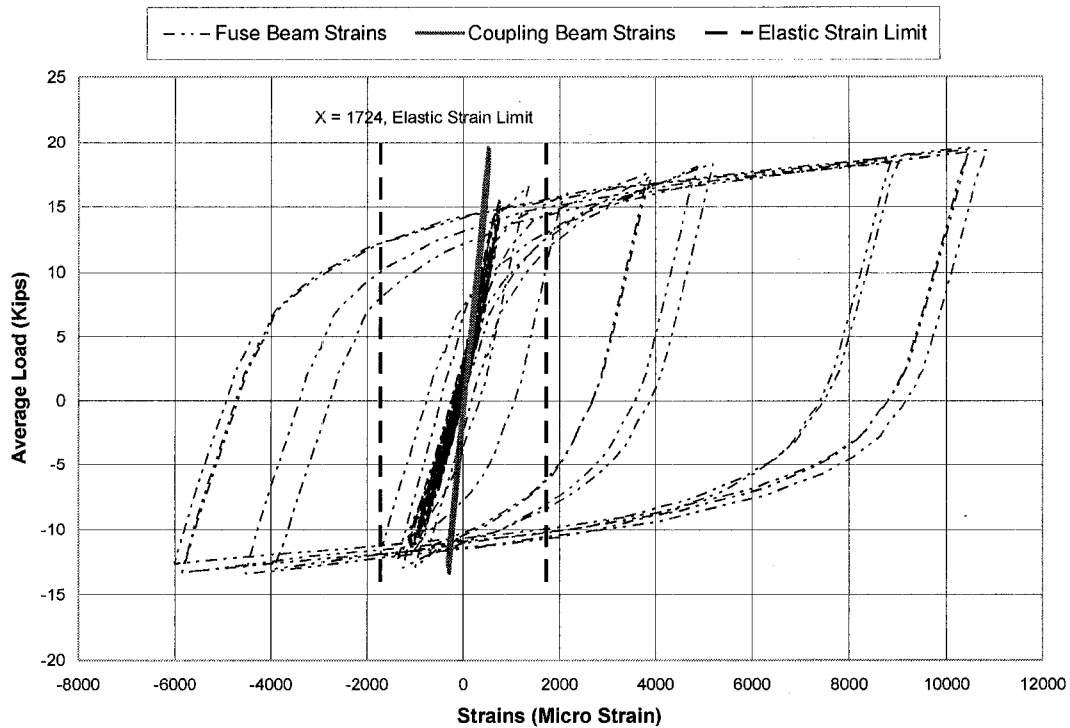


Figure 2.20 Test # 4 Coupling Beam and Fuse Beam Strains Versus Average Load

Table 2.2 shows the maximum strains in the coupling beam top and bottom flange for tests 1 through 4. It can be seen that all the strains recorded are lower than the elastic strain limit of the coupling beam (1724 microns). The strain gauge for the west coupling beam bottom flange of Test # 1 malfunctioned and so recordings were not available.

Table 2.2 Coupling Beam Flange Strains Recorded During Testing

Strain Gauge Location	Test # 1 (microns)	Test # 2 (microns)	Test # 3 (microns)	Test # 4 (microns)
West Coupling Beam Top Flange	468	605	641	473
West Coupling Beam Bottom Flange	-	582	623	526
East Coupling Beam Top Flange	486	617	739	463
East Coupling Beam Bottom Flange	524	631	726	450

CHAPTER 3

ANALYTICAL STUDY

3.1 General

In this chapter the analytical study undertaken in an attempt to analyze and generalize the experimental test results is described. The analytical study is composed of three phases, namely, modeling phase, calibration and validation phase, and application phase.

The modeling phase consists of generating a two-dimensional finite element model of the experimental test setup and analyzing it using OpenSees (Open System for Earthquake Engineering Simulation), a research oriented software developed at the University of California, Berkeley (The Regents of the University of California, 1999, 2000). The model incorporates the exact dimensions of the fuse beam and coupling beam used in the experimental testing and analysis. The model uses suitable elements available in the OpenSees software library (e.g., elastic, elastic perfectly plastic, hardening, steel 01, steel 02 and hysteretic material) for the fuse beam and the coupling beam elements of the test setup. In addition to the simulation of the experimental test, an isolated cantilever shear wall, whose results are available, is modeled using a fiber wall element of the software.

The calibration phase consists of calibrating the elements of the analytical model with experimental test setup model by adjusting the properties of material models available in the software (e.g. elastic, elastic-perfectly plastic, hardening, steel 01, steel 02 and hysteretic material). The validation phase consists of analyzing the analytical model and matching the analysis results with the actual test results. The modeled shear

wall element is also calibrated and analyzed to match with the results of a previously tested shear wall.

The application phase involves using the above generated analytical model in a coupled wall system of known geometry, and loading data, and analyzing it without and with fuse beams. The analysis results examined are the force versus sway, and vertical force and moment at the base of shear wall versus number of load cycle variations. The results from both the analyses are compared. This is repeated with the fuse beam cases with elastomeric pads inserted.

3.2 Modeling

Use of OpenSees is comprised of following steps: developing the finite element model using the library elements available, choosing an appropriate iterative analysis procedure for the nonlinear problem, selecting the quantities of interest to be monitored during the analysis, and declaring the output format for the results computed so that the interpretations can be made. The model builder, part of OpenSees, is responsible for building various objects in the finite element model such as nodes, elements, constraints, material properties, and material loading pattern and adding them to the solution domain. For the coupled beam with fuse beam, the procedure used to formulate the finite element model is described in this section. The same procedure was used for all the four tests conducted.

3.2.1 Experimental Test Setup

The basic dimensions of the model are defined at the start using the “basic model builder” command. A two-dimensional model definition was selected, and in OpenSees this automatically defaults to an element library with three degrees of freedom at each

node. For the coupling beam, as explained later, a standard beam-column element was selected. The “node” command was used to define the nodal coordinates of the nodes in the model. In this model, the free ends of the coupling beam, the pinned supports, and the connection points of the coupling beam and fuse beam are taken as nodes to define the elements. The fuse beam model is formulated using nodes representing the four corners of the fuse beam. Beam-column elements are used to represent the two vertical sides, truss elements are used to represent the top and bottom of the fuse beam, and a diagonal truss element is used to represent the shear strain-deformation behavior of the web, as shown in Fig. 3.1. The arrangement of nodes and elements of the experimental test setup coupling beam with fuse beam is also shown in Fig. 3.1. The circled numbers in the figure represent the elements and the non-circled numbers represent the nodes. The “constraints” command is used to define the constraint boundary conditions of the model. The nodes which represent the pinned support of the experiment are defined as pinned joints in the analytical model by releasing their rotational degrees of freedom and constraining the other two translational degrees of freedom. Since the model was generated using the global coordinate system, no transformation was required; hence, the “geometric transformation” command is put to “linear”. The “uniaxial material” command is used to define the material properties of various elements in the model. The coupling beam material was chosen to be an “elastic” material, the frame elements of the fuse beam was chosen to be “elastic” material, and the diagonal truss element of the fuse beam was chose to be “hysteretic” material (refer to Fig. E.3 of Appendix E showing the hysteretic curve for the material). The elastic material defines the element to have elastic properties, based on the elastic modulus value defined. The “hysteretic” material

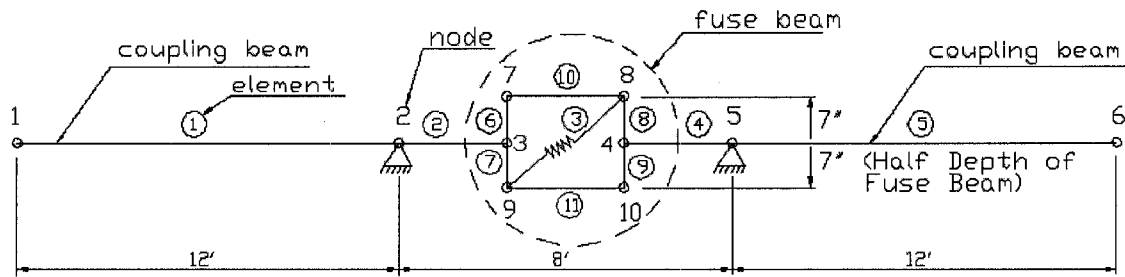


Figure 3.1 Nodes and Elements of the Analytical Model of the Test Setup

allows to construct an uniaxial bilinear hysteretic material with degrading unloading stiffness and also with pinching and damage due to ductility and energy. The “element” command is used to define the elements connecting the nodes. The coupling beams were defined as “elastic beam-column” elements and the fuse beam was composed of “elastic beam-column” elements for the two vertical sides, and “truss” elements for the top, bottom and diagonal elements. The side elements of the fuse beam were selected as “elastic beam-column” elements to facilitate the connectivity of the coupling beam to the fuse beam. The top elements of the fuse beam were selected as “truss” elements, and were modeled as very stiff axial bars that undergo only linear deformation. The diagonal shear spring element of the fuse beam is represented by the “truss” element and is defined by the hysteretic behavior obtained from load-deformation plots of the experimental test. The model builder phase of the program ends here.

The next phase is the definition of analysis data and analysis commands to input the cyclic loading history and to choose the appropriate analysis algorithms to solve the system equations. The “pattern” command is used to input load data for the model. In the model “plain pattern” was used with “series” pattern tag to represent the loading history for cyclic load analysis. The loads can be input in terms of forces or displacements, depending whether load control or displacement control was used to apply

the cyclic load. In the model here, displacements of the actuator are input as a series of load pattern. The cyclic displacements of each actuator applied at the respective nodes are put in a data file and this file is linked to run with the pattern command of the program. The program automatically extracts one value at a time from the data file and analyses the system for this load value. The “analysis” commands are a series of commands, through which we can define the solution strategy used to solve the resulting system nonlinear equations by applying the loads incrementally. In the model “static” analysis command was used to define that static load analysis will be performed for the model. The “constraints” command is used to enforce a relationship between element degrees of freedom and system global degrees of freedom. This command determines how the element forces will be computed for elements in which the element coordinate axes are not parallel to the global coordinate axes (which is true for the diagonal truss element and the vertical beam-column elements of the fuse beam) in the analysis. In the model “constraints transformation” were used. The “integrator” command is used to construct the integrator object. In the model “load control integrator” was used to determine: the predictive step for time ($t + dt$), to specify the tangent matrix at this time step, to compute the residual vector for any iteration cycle, and determine the correction needed based on the displacement increment computed. The “algorithm” command is used to choose a solution algorithm used to solve the resulting system nonlinear equations. In this model “Newton algorithm” was used, which uses the Newton-Raphson method to march along the nonlinear hysteretic behavior of the fuse beam diagonal shear spring. The “test” command is used to construct a convergence test object which defines the convergence criteria to be followed for each load increment. The solution algorithm

requires a convergence test object to determine if convergence has been achieved at the end of an iteration step. The test command performs these checks. In the model “norm unbalance” test was used to check convergence to an order of 1×10^{-6} in 25 iterations. The “numberer” command is used to construct the degree of freedom numberer object which determines the mapping between equation numbers and degrees of freedom. In the model “RCM (Reverse Cuthill Mckee)” numberer was used to number the degrees of freedom. The “system” command is used to construct the linear solver objects to store and solve the resulting system of equations. In the model “sparse general” system command was used to construct a general sparse system of equations object which factors and solves the equations during the analysis. The “analyze” command was used with the number of analysis steps specified to run the analysis of the model after all input was complete. The number of analysis steps depends on the number of incremental steps the prescribed displacements in the “series” data file will be applied, the time increment for each step in the series definition of the load data input, and the fraction increment used in the load control step. 14,100, 15,900, 14,700 and 17,700 analysis steps were specified for Tests # 1, 2, 3 and 4 respectively. The program is now ready to run and execute with the above inputs implemented.

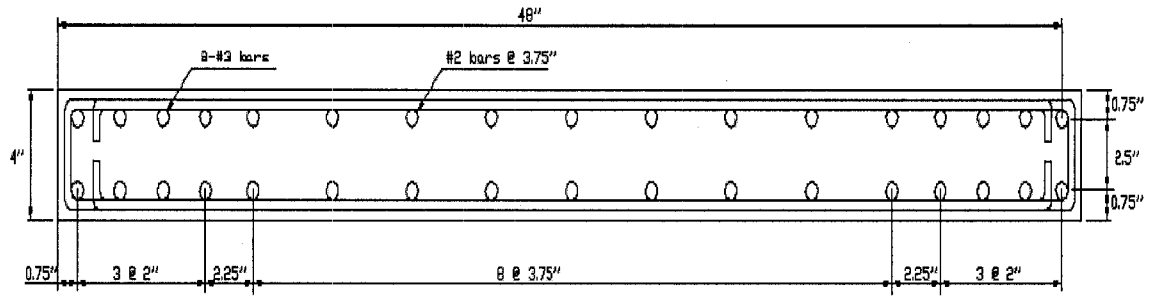
The next phase is the definition of output commands required from the analysis. The “recorder” command is used to record and monitor the analysis results of interest to the analyst. In the model “node” recorder and “element” recorder were used. The results of interest in the analysis were the displacements of the end nodes where the actuator was attached and the element forces of the overhang portion of the coupling beam. These results could be compared to the results recorded from the experimental tests. The nodal

displacements of the nodes forming the fuse beam were also of interest to verify that the fuse beam deforms elastically as a whole and the flanges rotate as a rigid body, which was done by specifying a very high cross-sectional area for the fuse beam flange elements. The input programs for fuse beam tests 1, 2, 3 and 4 are presented in Sections E.2, E.3, E.4 and E.5, respectively, of Appendix E. The results obtained for the displacements of the fuse beam nodes, which shows that the flanges behaved rigidly as the web deformed, are explained and presented in Section E.6 of Appendix E.

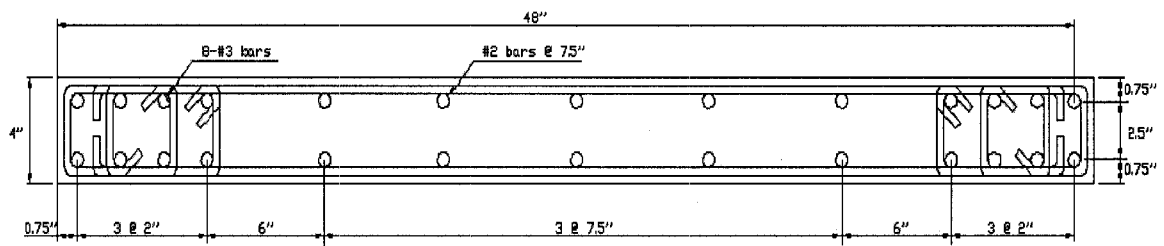
3.2.2 Shear Wall

The shear wall selected for analysis was a pre-designed cantilever shear wall, the test results for which were available (Thomsen and Wallace, 1995) to calibrate and validate the model. The shear wall was a four storey reduced scale (1/4 scale) model, the dimensions and cross-sections of which are presented in Fig. 3.2(a) and 3.2(b). The concrete compressive strength (f'_c) used was 6.33 Ksi (44 MPa) and the maximum concrete compressive strain (ϵ'_c) was 0.0063 (Thomsen and Wallace, 1995). The yield strength (F_y) of reinforcement bars used were 75 Ksi (517 MPa). The elastic modulus (E) of the reinforcement bar used was 29,000 Ksi (200,000 MPa) and the tangent modulus (E_{sh}) at the onset of strain hardening was 1,500 Ksi (10,342 MPa). The analytical model of the shear wall is presented in Fig. 3.2(c). The basic dimensions of the model are defined at the start using the “basic model builder” command of OpenSees. A two-dimensional model definition was selected in OpenSees, which automatically defaults to defining three degrees of freedom at each node. The “node” command was used to define the nodal coordinates of the nodes in the model. A node was taken at each of the four floor levels of the shear wall and at the base, as shown in Fig. 3.2(c). The circled

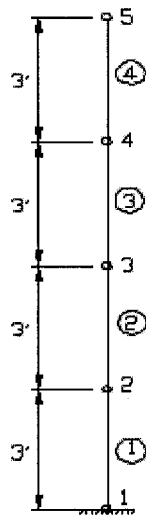
numbers in the figure represent the elements and the non-circled numbers represent the nodes. The “constraints” command is used to define the constraint boundary conditions of the model. The node which represents the base of the shear wall was defined as a fixed support in the analytical model. The wall being a cantilever model, the top of the transformation was required; the “geometric transformation” command was put to linear. The “uniaxial material command” is used to define the material properties of various elements in the model. The core concrete of the shear wall was taken as “concrete 02” material (Fig. E.5 of Appendix E), which allows for tensile strength of concrete other than its compressive strength to be considered in the analysis. The cover of concrete was taken as “concrete 01” material (Fig. E.4 of Appendix E), which allows for degraded linear unloading behavior and considers no tensile strength. The reinforcement bars were taken as uni-axial “steel 01” material (Fig. E.6 of Appendix E), which is used to construct bi-linear steel objects with kinematic hardening. The “section” command is used to construct a section force-deformation object for a beam-column element, which defines the force versus deformation response of a cross-section of the beam-column element. The types of section available are elastic, uni-axial, fiber, plate fiber, elastic membrane plate and bi-directional sections. The core concrete and cover wall was left free. Since the model was generated using global coordinate system, no concrete were defined using “fiber” section, with rectangular fibers across the cross-section. A fiber section has a general geometric configuration formed by sub-regions of simpler regular shapes, called patches. The sub-command “patch” was used to define the discretization of the section into fibers. The reinforcement bars were defined using straight layer fibers of bars through the section. Two different sections were defined along the total length of the



(a)



(b)



(c)

Figure 3.2 Shear Wall Details: (a) Cross-Sectional View of the Shear Wall at Top Three Levels, (b) Cross Sectional View of the Shear Wall at the Bottom Level, and (c) Analytical Model of the Shear Wall

shear wall due to different reinforcement distribution along the height of the shear wall. The “element” command is used to define the elements connecting the nodes. All the shear wall elements were defined as “nonlinear beam-column” elements which consider the spread of plasticity along the length of the element and require a pre-defined fiber section type to define its behavior. The model builder phase for the shear wall ends here.

The next phase is the definition of analysis data and analysis commands. The “pattern” command is used to input load data for a model. In the model “plain pattern” was used with “series” pattern tag to represent the series of loads for a cyclic analysis. The loads can be input in terms of forces or displacements. In this study, displacements of the actuator are input as the series load pattern. The cyclic displacements of the actuator applied at the top of the wall are input in a data file, and this file is linked to run with the pattern command of the program. The program automatically extracts one value at a time from the data file and analyses for each value. The analysis commands are a series of commands through which the solution strategies are defined. The “analysis” command is used to define what analysis type will be used. In the model “static” analysis command was used to define static analysis of the model. The “constraints” command is used to enforce a relationship between element degrees of freedom and system global degrees of freedom. This command determines how the element forces will be computed for elements in which the element coordinate axes are not parallel to the global coordinate axes (which is true for the vertical non-linear beam-column elements of the shear wall) in the analysis. In the model “constraints transformation” were used. The “integrator” command is used to construct the integrator object. It is used to determine: the predictive step for time $(t + dt)$, to specify the tangent matrix at this time step,

compute the residual vector for any iteration, determine the correction needed based on the displacement increment computed. In the model “integrator” command used was “load control”. The “algorithm” command is used to construct the solution algorithm, which determines the sequence of steps taken to solve the resulting system nonlinear equations. In this model “Newton algorithm” was used, which uses the Newton-Raphson method to march along the nonlinear hysteretic behavior of the shear wall. The “test” command is used to construct a convergence test object. The solution algorithm requires a convergence test object to determine if convergence has been achieved at the end of an iteration step. The test command performs these checks. In the model “normal unbalance” test was used to check convergence to an order of 1×10^{-6} in 30 iterations. The “numberer” command is used to construct the degree of freedom numberer object. This object determines the mapping between equation numbers and degrees of freedom numbers. In the model “RCM (Reverse Cuthill Mckee)” numberer was used to number the degrees of freedom. The “system” command is used to construct the linear solver objects to store and solve the resulting system of equations. In the model “sparse general” system command was used to construct a general sparse system of equations object which factors and solves the equations during the analysis. The “analyze” command was used with the number of analysis steps specified to run the analysis of the model after all input was complete. The number of analysis steps depends on the number of displacements in the “series” data file, the time increment in the series definition of the load data input, and the fraction used in the load control step. 33,000 analysis steps were specified for this analysis. The program now is ready to run and execute with the above inputs implemented.

The next and final phase is the definition of output commands required from the analysis. The “recorder” command is used to record and monitor the analysis results of interest to the analyst. In the model “node” recorder and “element” recorder were used. The displacements of the top node of the shear wall, and the forces on the topmost member of the shear wall were recorded to plot the force versus sway for the shear wall. The input program of the shear wall is presented in Section E.7 of Appendix E.

3.3 Calibration and Validation

3.3.1 Experimental Test Setup

In the calibration phase the physical properties, including stresses or forces and strains or deformation, of the fuse beam elements of the analytical model are adjusted to match the hysteretic analysis results obtained with the actual experimental test results recorded. The experimental test results of interest are the load versus deflection of the ends of the coupling beam where the actuator displacements are applied. The properties of the fuse beam element in the analytical model were selected primarily from the load versus deflection graphs obtained from experimental testing. The definition of hysteretic element model in OpenSees requires three values of stress or force, and respective strain or deformation, to be specified for the positive and negative directions. The stress/force and strain/deformation values for the hysteretic model are selected from the points where the graph changes the elastic slope considerably, and these values are multiplied by a factor obtained by trial and error on a case to case basis. The selection process was based on judgement, and was done by fitting trend lines on the existing graphs. Trend line for the elastic portion was drawn along the cluster of elastic slope in the graph. The trend lines for the hardening portions were drawn connecting peaks of the test cycles in the

post elastic range. An example is demonstrated in Fig. 3.3. The validation of the analytical model is complete when the analytical results are almost identical to the experimental test results. The physical properties of the fuse beam elements of the analytical model were adjusted, by changing the diagonal spring element properties, to match with reasonable accuracy the load versus deflection predicted by the analytical model with those obtained from the experimental tests. This ensured that the fuse beam in the model had properties that made the model predict results close to the experimental test, or in other words the mathematical model of the fuse beam, as shown in Fig. 3.1, behaves similar to the fuse beam in the experimental test. The calibration values which validate the analytical model with the experimental model for the four different fuses are given below.

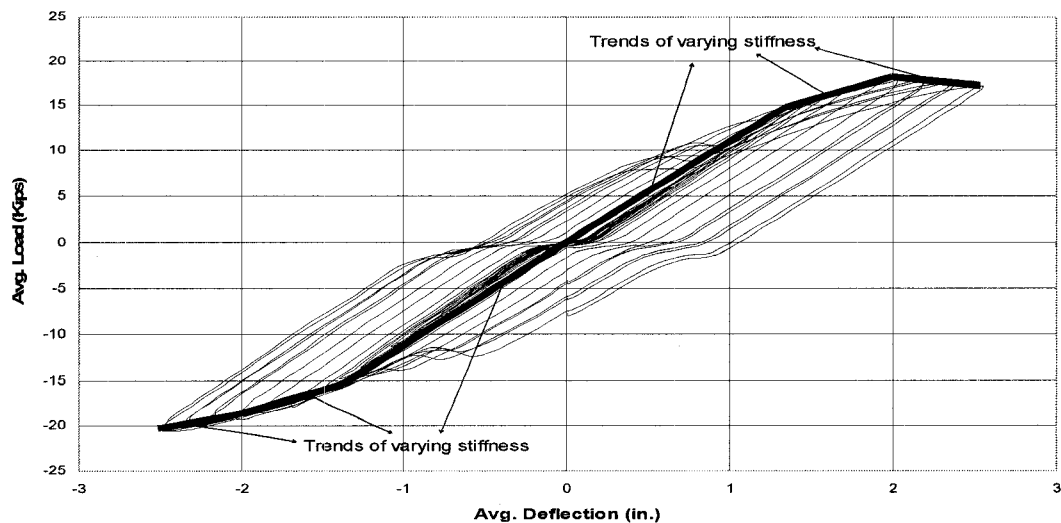


Figure 3.3 Trends of Varying Stiffness in an Experimental Test Result

Test #1 (Fuse Beam Having Two Stiffeners and Without Elastomers): The stress/force and strain/deformation values for the diagonal hysteretic element of the fuse

beam in the analytical model that produced nearly similar behavior, in terms of force versus displacement curves at the tip of the coupling beam, to that obtained from experimental testing were as follows: (i) a force of 90 Kips (400 KN) and strain of 0.0045 for first point on the graph, a force of 108 Kips (480 KN) and strain of 0.0085 for second point on the graph, and a force of 104 Kips (462.5 KN) and strain of 0.0158 for the third point on the graph in the first positive quadrant; and (ii) a force of 95 Kips (422.5 KN) and a strain of 0.00475 for the first point on the graph, a force of 114 Kips (507 KN) and strain of 0.009 for the second point on the graph, and a force of 125 Kips (556 KN) and strain of 0.015 for the third point on the graph in the third negative quadrant. These properties for the diagonal spring element of the fuse beam in the analytical model (refer to Fig. 3.1) produced a load versus deflection graph as shown in Fig. 3.4. The comparison of the analytical model and the experimental results are shown in Fig. 3.5. It can be seen from the two overlaid graphs, shown in Fig. 3.5, the analytical model reproduces reasonably well the behavior of the experimental coupled beam system.

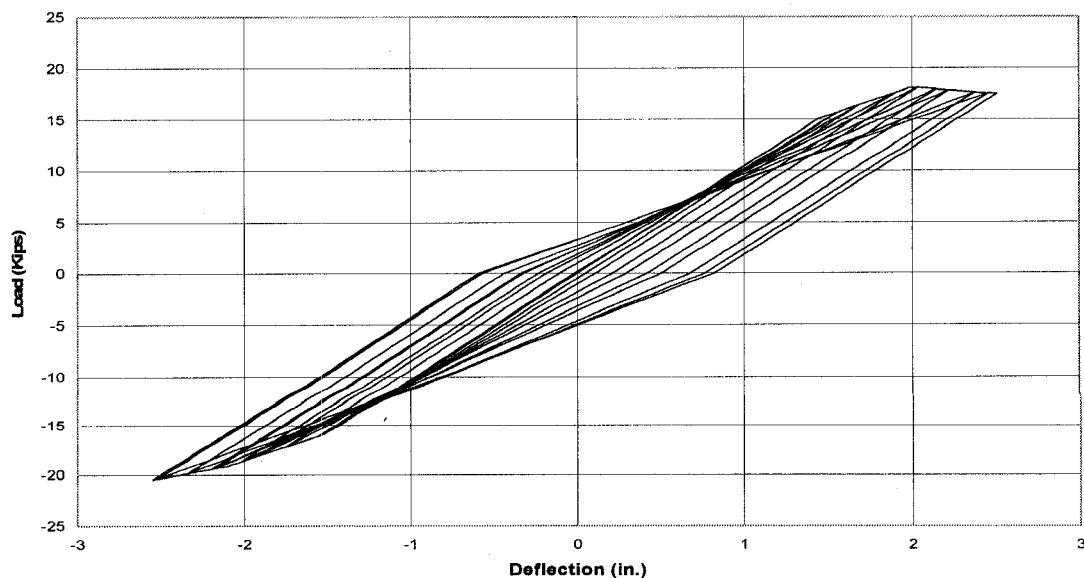


Figure 3.4 Analytical Result of Load Versus Deflection of Test # 1

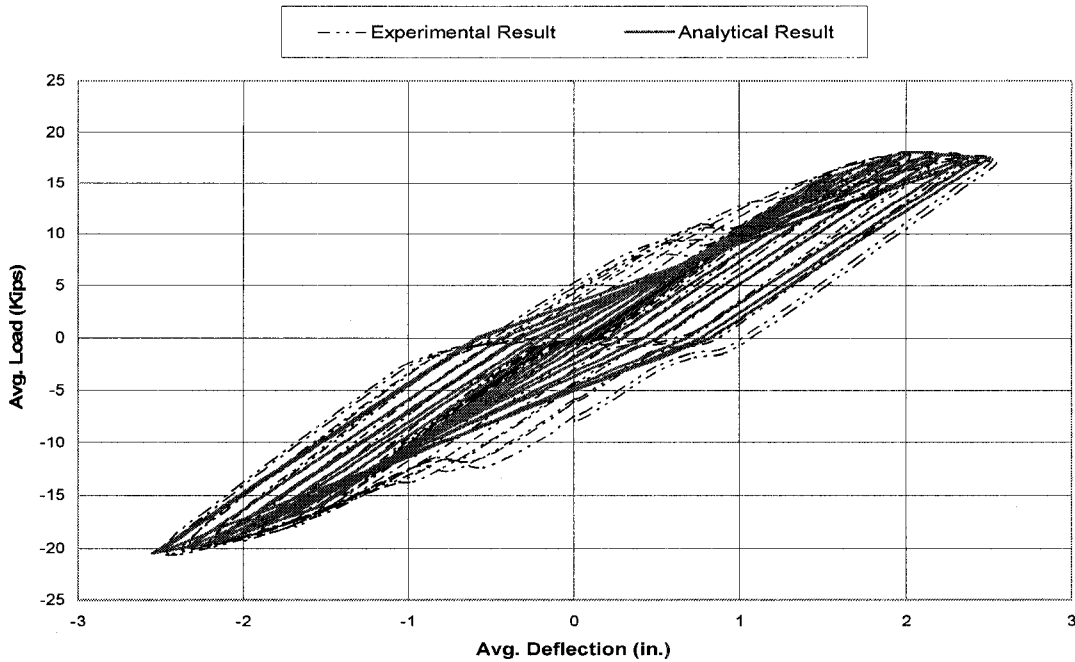


Figure 3.5 Comparison of Experimental and Analytical Results of Test # 1

Test #2 (Fuse Beam Having Two Stiffeners and With Elastomers): The stress/force and strain/deformation values for the diagonal hysteretic element of the fuse beam in the analytical model that produced nearly similar behavior, in terms of force versus displacement curves at the tip of the coupling beam, to that obtained from experimental testing were as follows: (i) a force of 30 Kips (133.5 KN) and strain of 0.003 for first point on the graph, a force of 120 Kips (534 KN) and strain of 0.0185 for second point on the graph, and a force of 129 Kips (574 KN) and strain of 0.021 for the third point on the graph in the third negative quadrant; and (ii) a force of 42 Kips (187 KN) and a strain of 0.007 for the first point on the graph, a force of 71 Kips (316 KN) and strain of 0.016 for the second point on the graph, and a force of 66 Kips (293.5 KN) and strain of 0.03 for the third point in the first positive quadrant. These properties of the diagonal spring element of the fuse beam in the analytical model (refer to Fig. 3.1)

produced a load versus deflection graph as shown in Fig. 3.6. The comparison of the analytical model and the experimental results are shown in Fig. 3.7. It can be seen from the two overlaid graphs, shown in Fig. 3.7, the analytical model simulates with reasonable accuracy the behavior of the experimental coupled beam system.

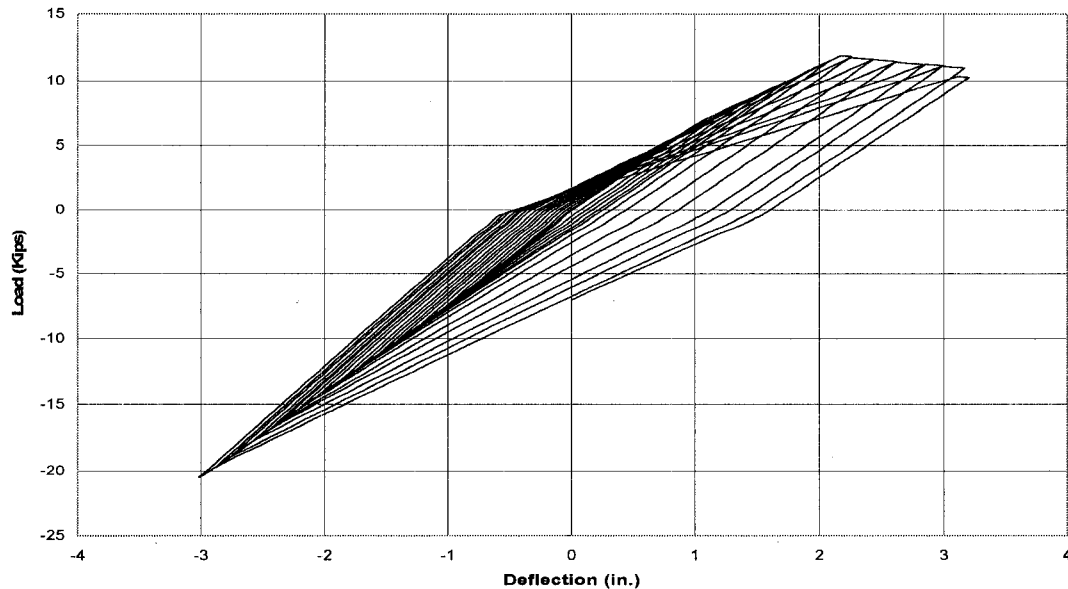


Figure 3.6 Analytical Result of Load Versus Deflection of Test # 2

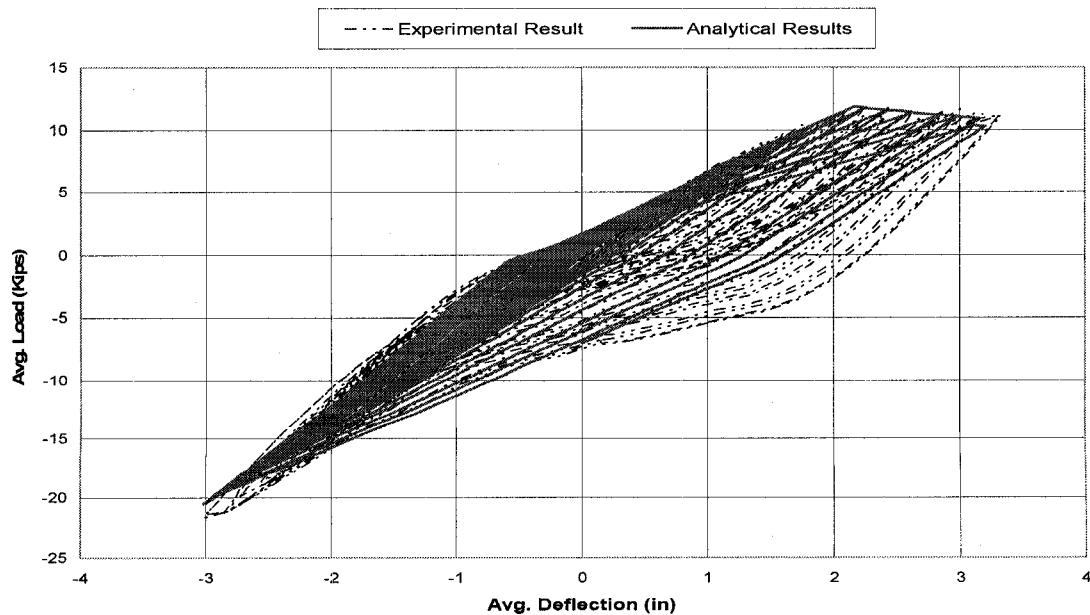


Figure 3.7 Comparison of Experimental and Analytical results of Test # 2

Test #3 (Fuse Beam Having Three Stiffeners and Without Elastomers): The stress/force and strain/deformation values for the diagonal hysteretic element of the fuse beam in the analytical model that produced nearly similar behavior, in terms of force versus displacement curves at the tip of the coupling beam, to that obtained from experimental testing were as follows: (i) a force of 90 Kips (400 KN) and strain of 0.0047 for first point on the graph, a force of 120 Kips (534 KN) and strain of 0.0078 for second point on the graph, and a force of 144 Kips (640.5 KN) and strain of 0.01 for the third point on the graph in the third negative quadrant; and (ii) a force of 87 Kips (387 KN) and a strain of 0.007 for the first point on the graph, a force of 99 Kips (440.5 KN) and strain of 0.0115 for the second point on the graph, and a force of 77 Kips (342.5 KN) and strain of 0.024 for the third point on the graph in the first positive quadrant. These properties of the diagonal spring element of the fuse beam (refer to Fig. 3.1) in the analytical model produced a load versus deflection graph as shown in Fig. 3.8. The comparison of the analytical model and the experimental results are shown in Fig. 3.9. It

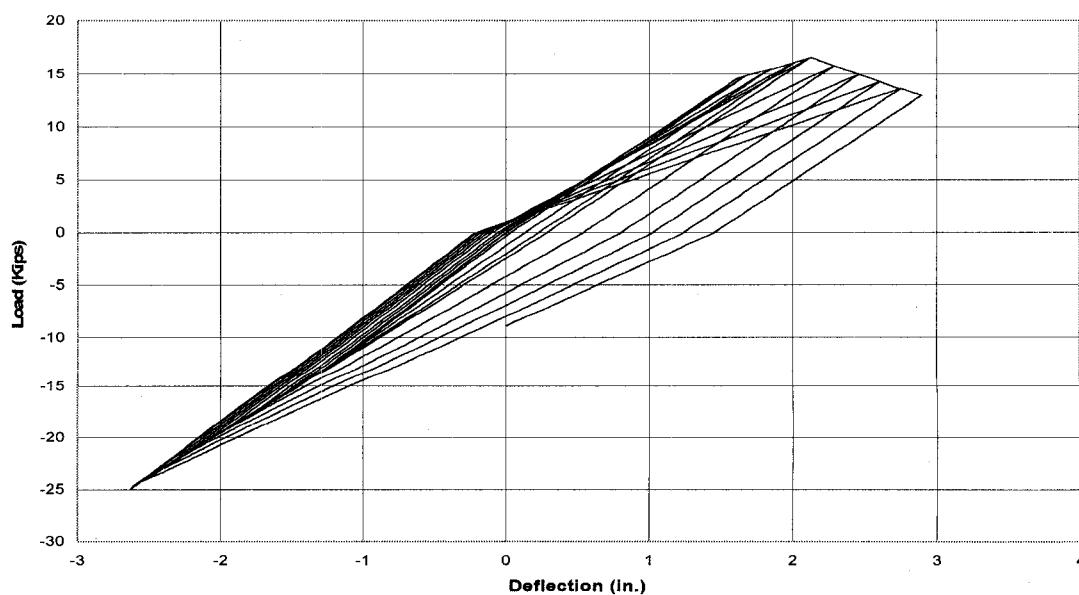


Figure 3.8 Analytical Result of Load Versus Deflection of Test # 3

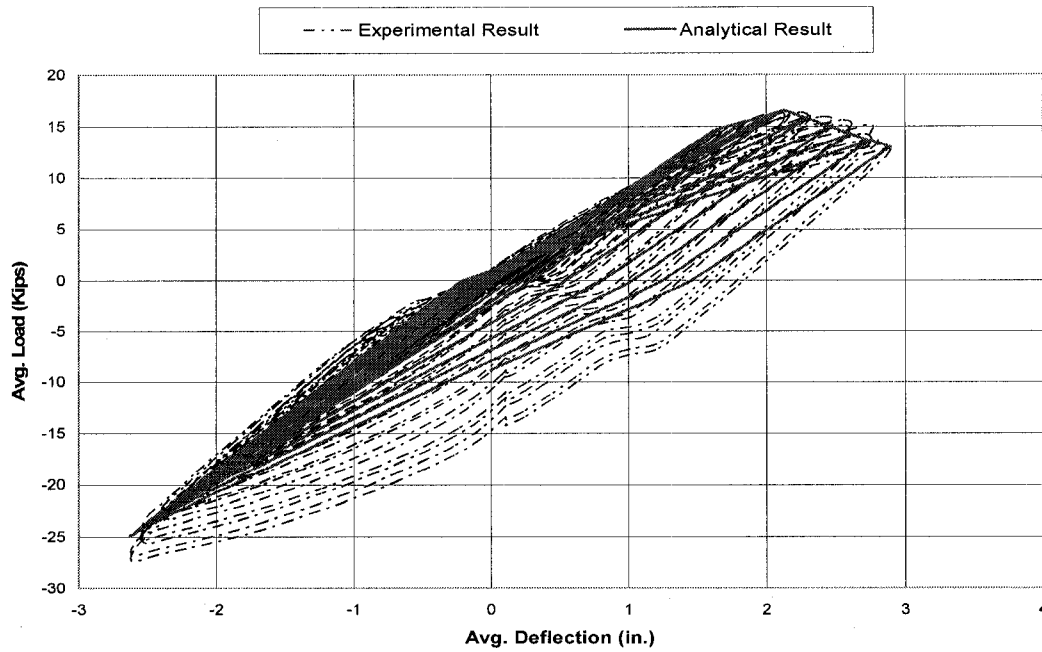


Figure 3.9 Comparison of Experimental and Analytical results of Test # 3

can be seen from the two overlaid graphs, shown in Fig. 3.9, the analytical model simulates reasonably well the behavior of the experimental coupled beam system.

Test #4 (Fuse Beam Having Three Stiffeners and With Elastomers): The stress/force and strain/deformation values for the diagonal hysteretic element of the fuse beam in the analytical model that produced nearly similar behavior, in terms of force versus displacement curves at the tip of the coupling beam, to that obtained from experimental testing were as follows; (i) a force of 15 Kips (67 KN) and strain of 0.0015 for first point on the graph, a force of 65 Kips (289 KN) and strain of 0.01 for second point on the graph, and a force of 92 Kips (409 KN) and strain of 0.0175 for the third point on the graph in the third negative quadrant; and (ii) a force of 15 Kips (67 KN) and a strain of 0.0015 for the first point on the graph, a force of 50 Kips (222.5 KN) and strain of 0.013 for the second point on the graph, and a force of 70 Kips (311.5 KN) and strain of 0.029 for the third point on the graph in the first positive quadrant. These

properties of the diagonal spring element of the fuse beam in the analytical model (refer to Fig. 3.1) produced a load versus deflection graph as shown in Fig. 3.10. The comparison of the analytical model and the experimental results are shown in Fig. 3.11.

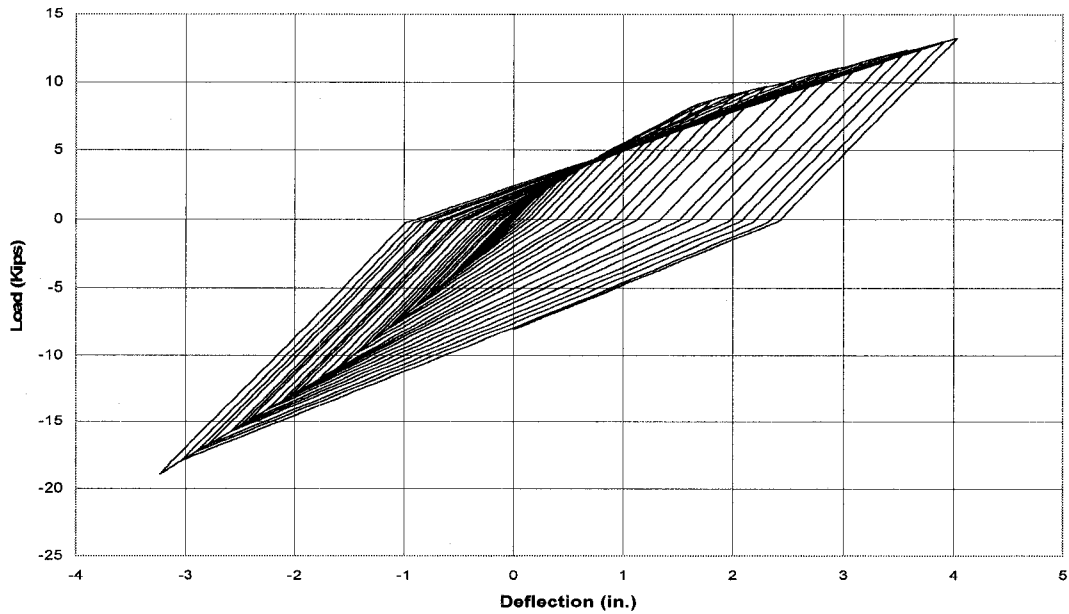


Figure 3.10 Analytical Result of Load Versus Deflection of Test #4

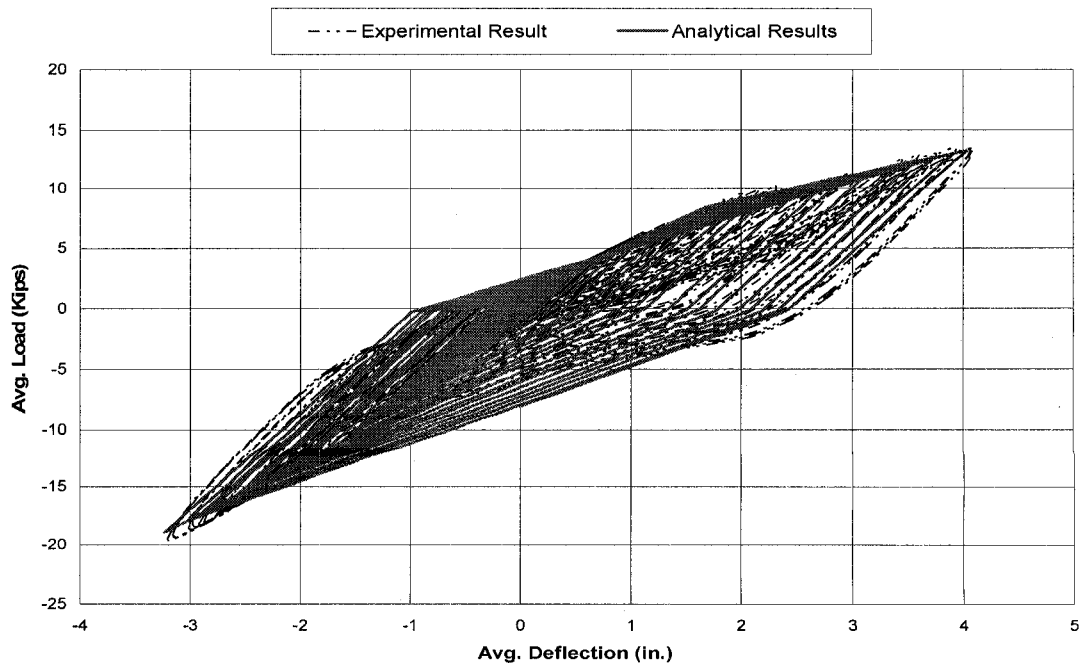


Figure 3.11 Comparison of Experimental and Analytical results of Test #4

It can be seen from the two overlaid graphs, shown in the Fig. 3.11, the analytical model simulates reasonably well the behavior of the experimental coupled beam system.

3.3.2 Shear Wall

In the calibration phase, the physical properties including: (i) compressive strength, compressive strain, crushing strength, maximum strain, and tensile strength of the concrete; and (ii) yield strength, elastic modulus, and hardening slope of the reinforcement bars of the wall elements of the analytical model are adjusted so that the force versus sway of the top of the shear wall obtained from the analytical model matched reasonably well with the available actual experimental test results. The properties of the concrete and reinforcement of the wall element in the analytical model were selected primarily from the calculations of the prototype scaled (1/4) wall designed by Thomsen and Wallace (1995). The force versus sway of the above shear wall, as reported by Thomsen and Wallace (1995), and is shown in Fig. 3.12. The definition of “concrete 02” material in OpenSees requires the following to be specified: the initial values of compressive strength of concrete (f'_c) = 6.33 Ksi (44 MPa), initial compressive strain of concrete (ϵ'_c) = 0.0063, yield stress of reinforcing bars (F_y) = 60 Ksi (414 MPa), elastic modulus (E) of reinforcing bars = 29,000 Ksi (200,000 MPa), and tangent modulus of reinforcing bars at onset of hardening (E_{sh}) = 1,500 Ksi (10,344 MPa) were taken from the test data. The values for crushing strength, crushing strain, ratio of unloading slope and initial slope, tensile strength and slope of tensile softening branch of concrete and yield strength of reinforcement bars were based on judgment and adjustment to match the analytical results with the experimental shear wall. The validation of the analytical model is complete if the analytical results obtained by using these values in

OpenSees simulate the behavior reasonably well of the experimental shear wall. The physical properties of the wall elements of the analytical model were adjusted to simulate

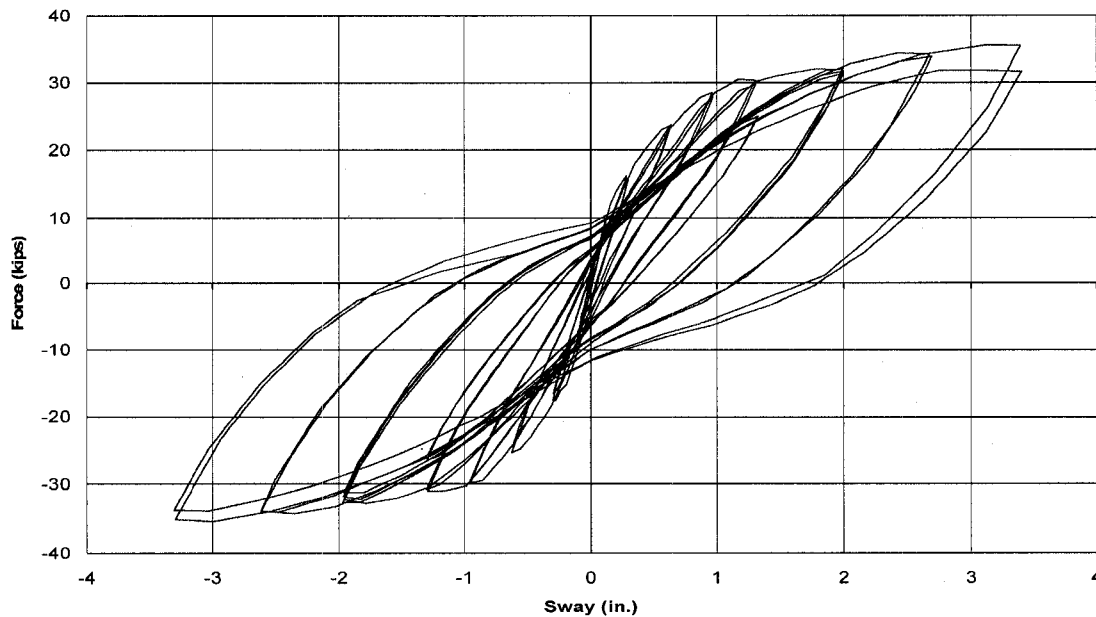


Figure 3.12 Experimental Result of Force Versus Sway of the Shear Wall

reasonably well the force versus sway results predicted by the analytical model with those reported for the experimental tests. This ensured that the shear wall in the model had properties that would allow the model to mimic the behavior of the experimental shear wall. The values of the concrete and reinforcement parameters in the analytical model which predicted a close behavior to the experimental behavior are as follows: (i) for concrete the compressive strength was chosen as $f'_c = 6.33$ Ksi (44 MPa), compressive strain of $\epsilon'_c = 0.00603$, crushing strength was chosen as $f_{cu} = 1$ Ksi (21 MPa), crushing strain was chosen as $\epsilon'_{cu} = 0.016$, the ratio between loading and initial slope was chosen as 'ratio' = 0.2, the tensile strength was chosen as $f_t = 0.63$ Ksi (4.4 MPa), and the slope of the linear tension softening was chosen as $E_t = 400$; and (ii) for

the reinforcement the yield strength was chosen as $F_y = 75$ Ksi (517 MPa), the elastic modulus was chosen as $E = 29,000$ Ksi (200,000 MPa) and the hardening slope was chosen as $b = 0.05$. The above values were obtained by a trial and error procedure. The graph of force versus sway obtained from the analytical analysis using these values is shown in Fig. 3.13. A comparison of the analytical and experimental results is shown in Fig 3.14, which shows that the results obtained match reasonably well. The unloading stiffness of the shear wall could not be exactly duplicated. This could be due to not using the shear fiber elements to represent the shear forces in the wall and that captures the shear behavior of the wall. To study the effect of fuse beams in the coupling beams, shear forces in the walls were not necessary to be compared. The OpenSees file used for the shear wall analysis is presented in Section E.7 of Appendix E.

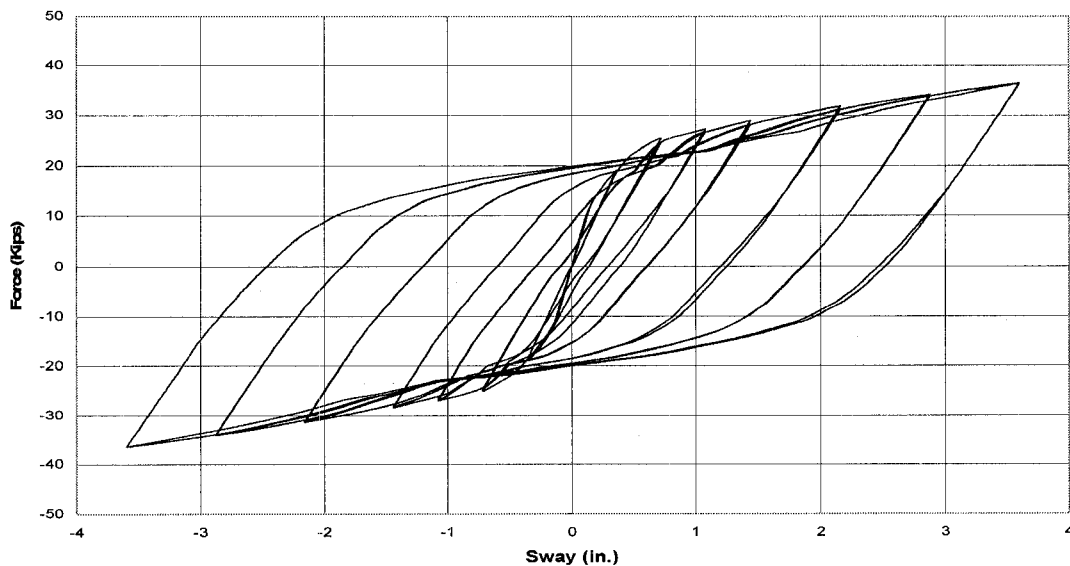


Figure 3.13 Analytical Result of Force Versus Sway of the Shear Wall

3.4 Application

The application phase involved combining the previously generated analytical models for the experimental test coupled beam system and the shear wall into a coupled

shear wall system with known geometry. The loading data of the cantilever shear wall previously modeled (see Fig. 3.2c) was used to perform analysis. The analysis results that are examined are the force versus sway, and vertical force and moment at the base of

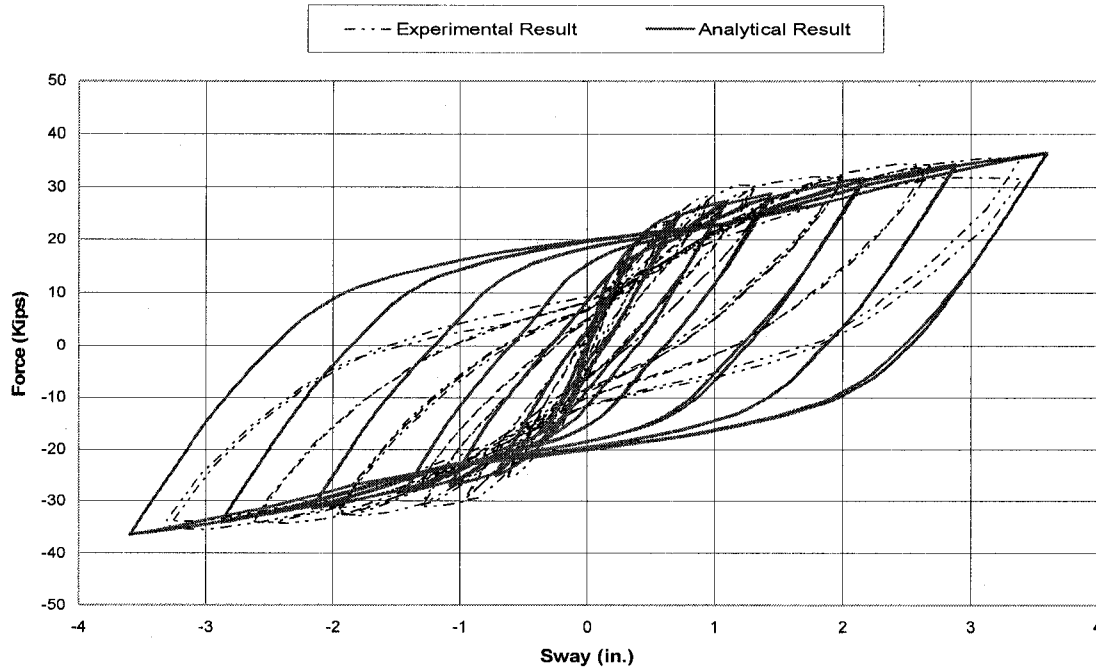


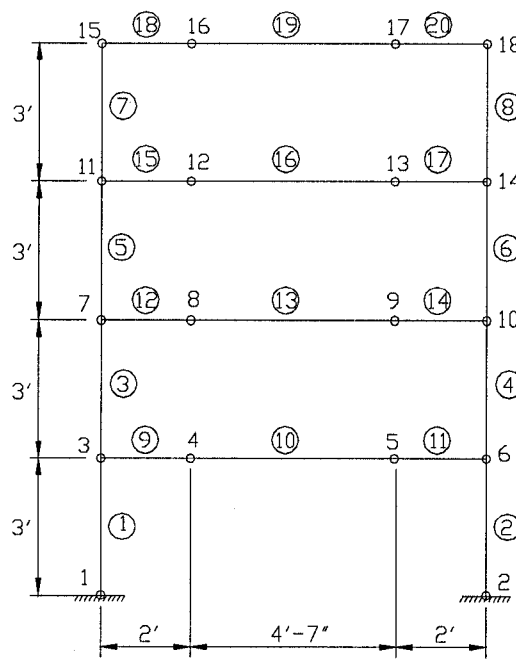
Figure 3.14 Comparison of Force Versus Sway-Experimental and Analytical Results

the shear wall versus number of cycles. The coupled shear wall system is first modeled and analyzed without the fuse beams, and the same system is re-analyzed by inserting one fuse beam in each of the coupling beams. The results from both the analyses are compared. This is repeated for the fuse beam cases with elastomeric pads inserted.

3.4.1 Coupled Shear Wall System Without Fuse Beams

The coupled shear wall system consists of two similar shear walls, which were previously analyzed, coupled together with steel coupling beams. The shear wall has the same geometry and physical properties of the calibrated and validated shear wall. The coupling beams are elastic beams connected to the shear walls through rigid joints. The

center to center distance between the shear walls is 103 in. (262 cm) corresponding to the coupling beam test setup. The clear distance between the faces of the shear walls are 55 in. (140 cm), which is also the length of the coupling beam. The depth, 48 in. (122 cm), of the shear wall is taken care of by introducing rigid beam elements of 24 in. (0.61 m) length connecting the centerline of the shear wall to the ends of the coupling beams. The analytical model of the four-storey coupled shear wall frame system is shown in Fig. 3.15. The circled numbers represent the elements and the non-circled numbers represent



Note: Elements 9, 11, 12, 14, 15, 17, 18 and 20 are rigid elements

Figure 3.15 Analytical Model of Coupled Wall (Without Fuse Beam)

the nodes. The modeling part of the OpenSees program contains all the portions of the shear wall input data with added elements and properties for the coupling beams. The coupling beams are modeled as “elastic beam-column” elements with elastic modulus of 29,000 Ksi (200,000 MPa), cross-sectional area equal to 17.9 in.² (115.5 cm²), and moment of inertia about the major axis equal to 640 in.⁴ (26,640 cm⁴), which is

similar to the properties of a W14 x 61 section used for the coupling beam section in the four fuse beam tests conducted as part of the experimental test program reported in Chapter 2. For rigid links shown in Fig.3.15, a very large cross-sectional area of 5,000 in.² (32,258 cm²), and moment of inertia of 50,000 in.⁴ (2,081,157 cm⁴) is used. The displacements are applied to both the shear walls, at the top storey of each wall. Only the dead loads due to self weight of the shear walls were applied at the nodes of each storey level. The “recorder” statement in the program is used to record the top sway of both the shear walls, the member forces in the top elements of the shear walls, the vertical force and moment variation at the base of the shear wall, force and deformation of the diagonal element of the fuse beam, and the member forces of the coupling beam ends.

The horizontal force versus sway predicted by analyzing the model shown in Fig. 3.15 using OpenSees for both the left and right shear wall is shown in Fig. 3.16. It can be seen from this figure that both the left and right shear wall of the coupled shear wall

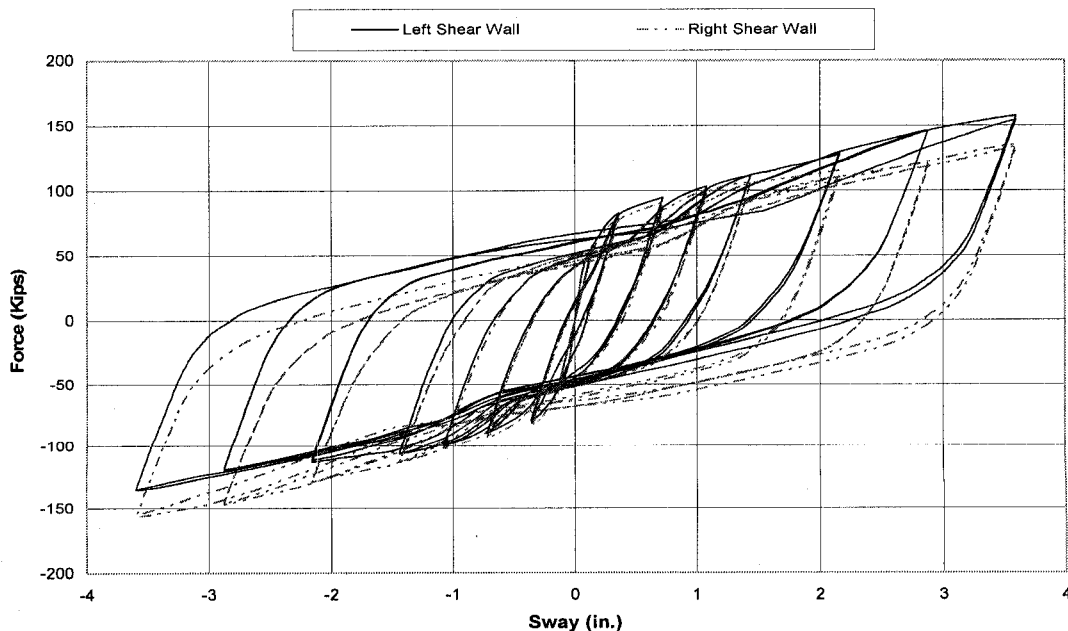


Figure 3.16 Force Versus Sway for Left and Right Shear Walls

system develop about 155 Kips (689 KN) force with a sway of 3.6 in. (91 mm) when in tension, and 135 Kips (600 KN) force with the same sway when in compression. It can also be seen that both the walls develop nearly the same load with corresponding sway in both tension and compression in every cycle of the test (the difference is only the self weight of the walls). It can be inferred from the graph that the coupled shear wall system transfers forces from one shear wall to another, thus behaving like a conventional coupled shear wall. The vertical force at the base versus number of cycles for the left and right shear wall bases is shown in Figs. 3.17 and 3.18, respectively. From these figures it can be seen that in both the shear walls the vertical forces gradually increase with every load cycle, and eventually reach a maximum vertical force of around 300 Kips (1,335 KN) in both tension and compression in the last cycle i.e., 32nd load cycle. The moment at the base versus number of cycles for the left and right shear walls is shown in Fig. 3.19 and Fig. 3.20, respectively. From these figures it can be seen that the moment at the base of

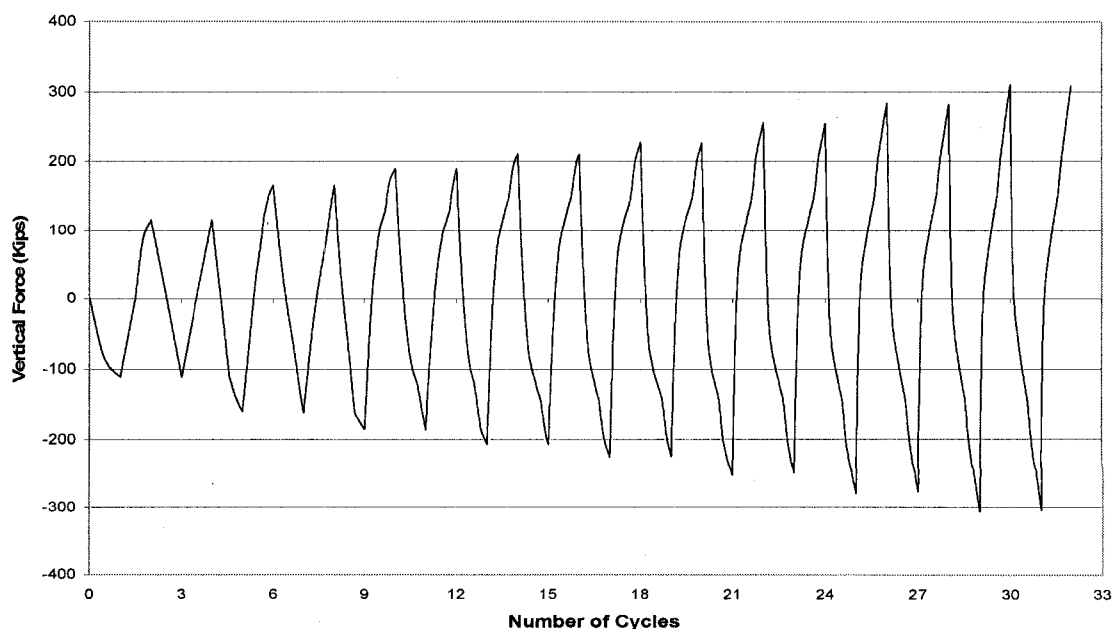


Figure 3.17 Vertical Force Versus Number of Cycles - Base of Left Shear Wall

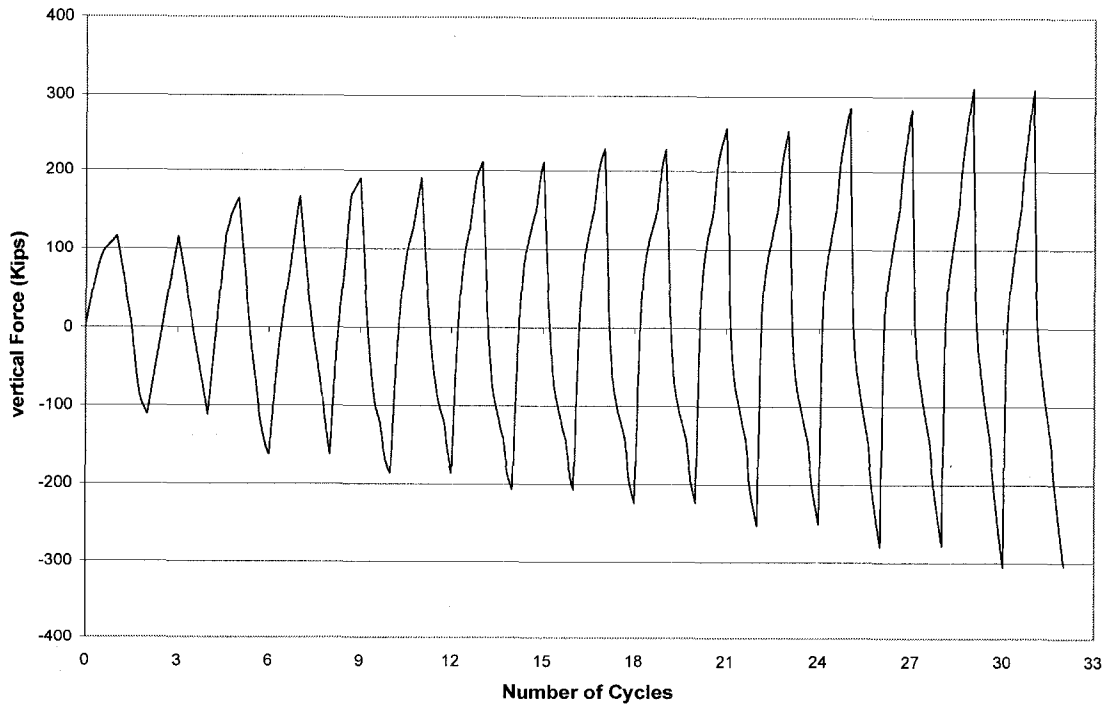


Figure 3.18 Vertical Force Versus Number of Cycles - Base of Right Shear Wall

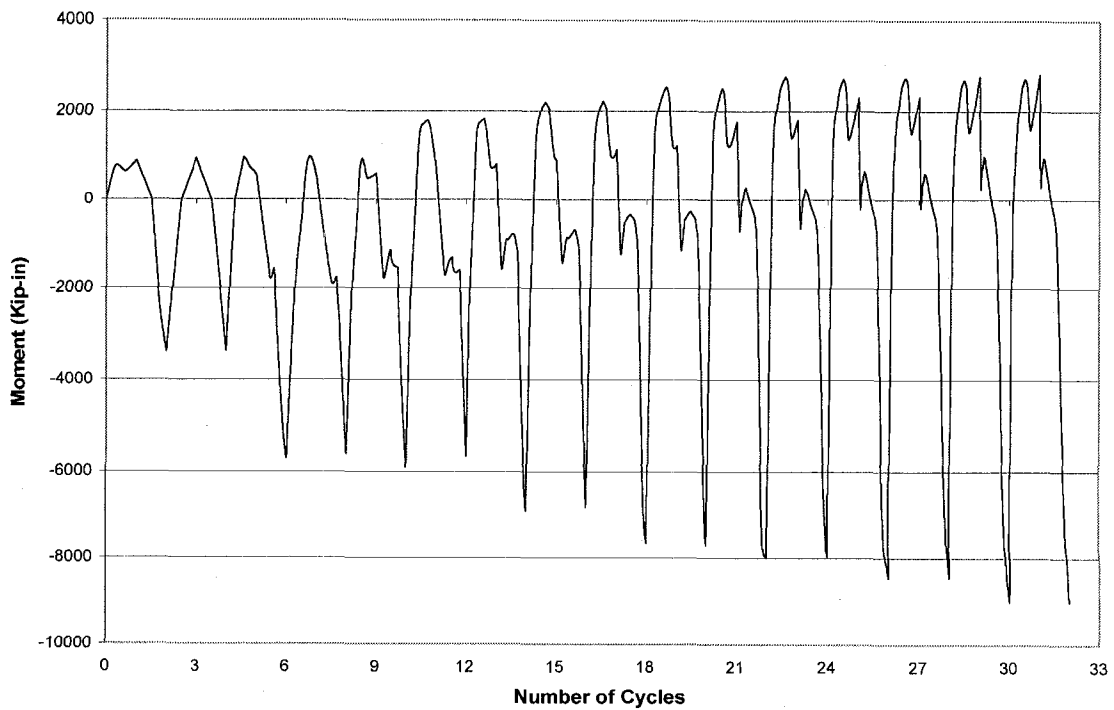


Figure 3.19 Moment Versus Number of Cycles - Base of Left Shear Wall

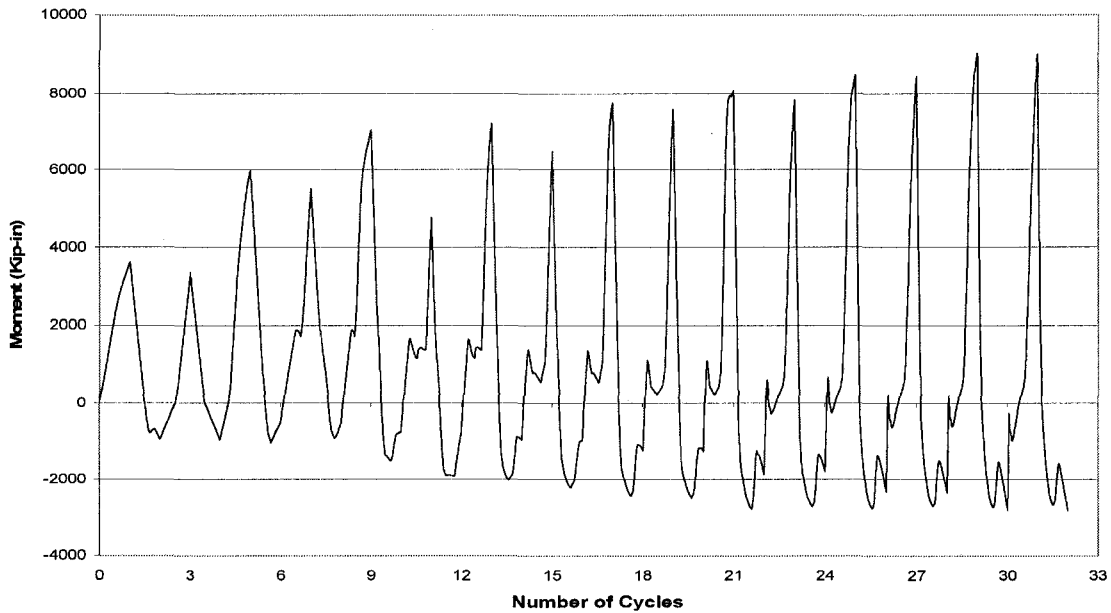
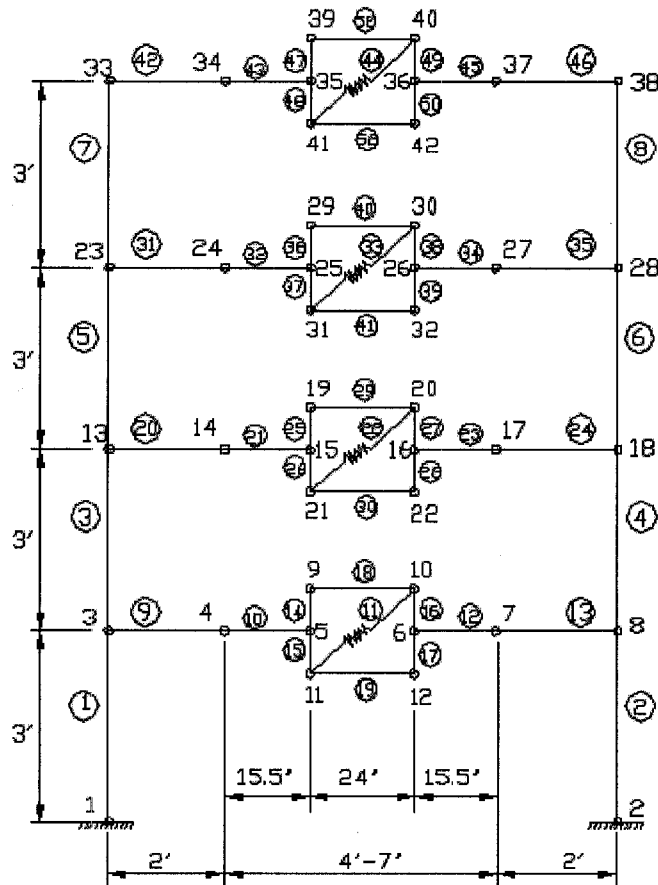


Figure 3.20 Moment Versus Number of Cycles – Base of Right Shear Wall

both the shear wall increases gradually with every load cycle, and eventually reaches a maximum moment of around 9,000 Kip-in. (1017 KN.m) in the last cycle i.e., 32nd load cycle. Both the vertical force and moment results indicate coupling action between the shear walls of the coupled shear wall system analyzed. The OpenSees input file for the coupled shear wall without fuse beams is presented in Section E.8 of Appendix E.

3.4.2 Coupled Shear Wall System With Fuse Beams and Without Elastomeric Pads

The coupled shear wall system considered is same as the model presented in Section 3.4.1, except that the two shear walls are coupled together with steel beams having fuse beams incorporated in them. This coupling beam is similar to the one used in the experimental test setup, that was validated earlier for Fuse # 1 and Fuse # 3 of Test # 1 and # 3, respectively. The analytical model of the four-storey coupled wall frame system is shown in Fig. 3.21, which is similar to the one described in Section 3.4.1 and shown in Fig. 3.15, with the exception of the fuse beam being inserted at the mid-span of



Note: Elements 9, 13, 20, 24, 31, 35, 42 and 46 are rigid links

Figure 3.21 Analytical Model of Coupled Wall With Fuse Beam

each coupling beam. The modeling details for the shear walls, coupling beams, and the rigid links are same as presented in Section 3.4.1, and so are the loading details. The fuse beam properties of the validated analytical model of Test # 1 (refer to Section 3.3.1) were used for the fuse beams in all the coupling beams of the analytical shown in Fig. 3.21.

The horizontal force versus sway predicted by analyzing the model shown in Fig. 3.21 using OpenSees for both the left and right shear wall is shown in Fig. 3.22. It can be seen from this figure that the left shear wall of the coupled shear wall system develops a maximum force of about 120 Kips (534 KN) at a sway of 2.16 in. (55 mm) when in

tension, and remains nearly constant for the last four loading cycles. The same is the case with the right shear wall in compression. This is due to the fact that the fuse beam yields at this load cycle, and henceforth the shear wall is unable to resist any further force (the fuse beam force does not increase with increase in deformation; refer to Fig 3.40). The left shear wall develops a force of about 120 Kips (534 KN) in compression, and the right shear wall develops a force of about 135 Kips (600 KN) in tension for the maximum sway of 3.6 in. (91 mm). It can be inferred from above that transfer of forces occurs from one shear wall to the other in the coupled shear wall system, thus behaving like a conventional coupled shear wall system. The vertical force versus number of cycles for the left and right shear wall base is shown in Figs. 3.23 and 3.24, respectively. From these figures it can be seen that the maximum vertical force for the left shear wall is about 260 Kips (1,156 KN) in compression and 210 Kips (934 KN) in tension, and for the right shear wall is about 210 Kips (934 KN) in compression and about 260 Kips (1,156 KN) in tension. The tensile force in the left shear wall and the compressive force in the right shear wall reach their maximum in the 21st load cycle and stabilize at this value for the later cycles. This is due to the fact that the fuse beam yields at this load cycle. The moment at the base versus number of cycles for the left and right shear walls is shown in Fig. 3.25 and Fig. 3.26, respectively. From these figures it can be seen that the maximum moment in two shear walls varies between 7,900 Kip-in. (893 KN.m) and 7,400 Kip-in. (836 KN.m). It can be also seen from the graphs that the moment does not noticeably increase after the 18th load cycle. This is also due to the fact that the fuse beam yields at this load cycle. Both the vertical force and moment results indicate that coupling action

occurs between the shear walls of the coupled shear wall system. The OpenSees input file is presented in Section E.9 of Appendix E.

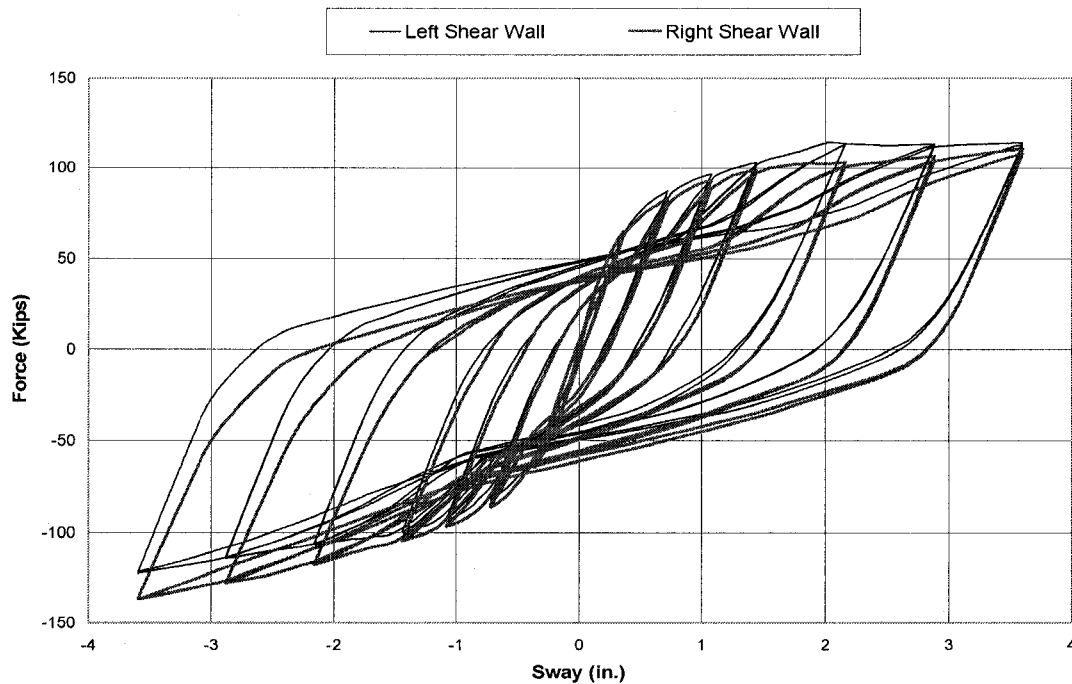


Figure 3.22 Force Versus Sway for Left and Right Shear Walls

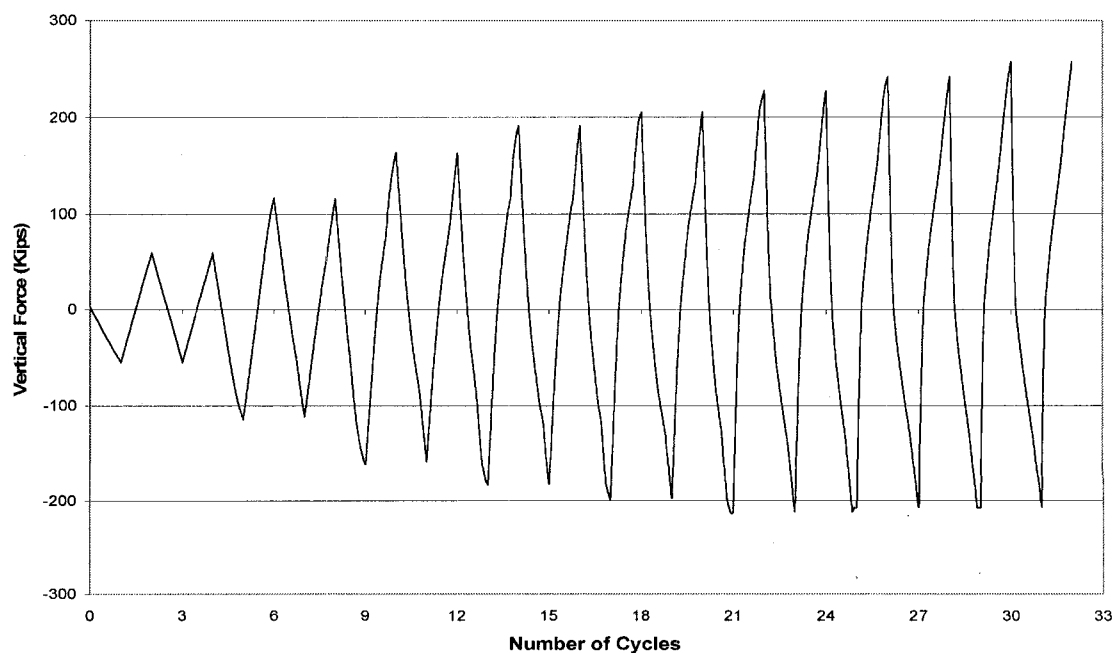


Figure 3.23 Vertical Force Versus Number of Cycles – Base of Left Shear Wall

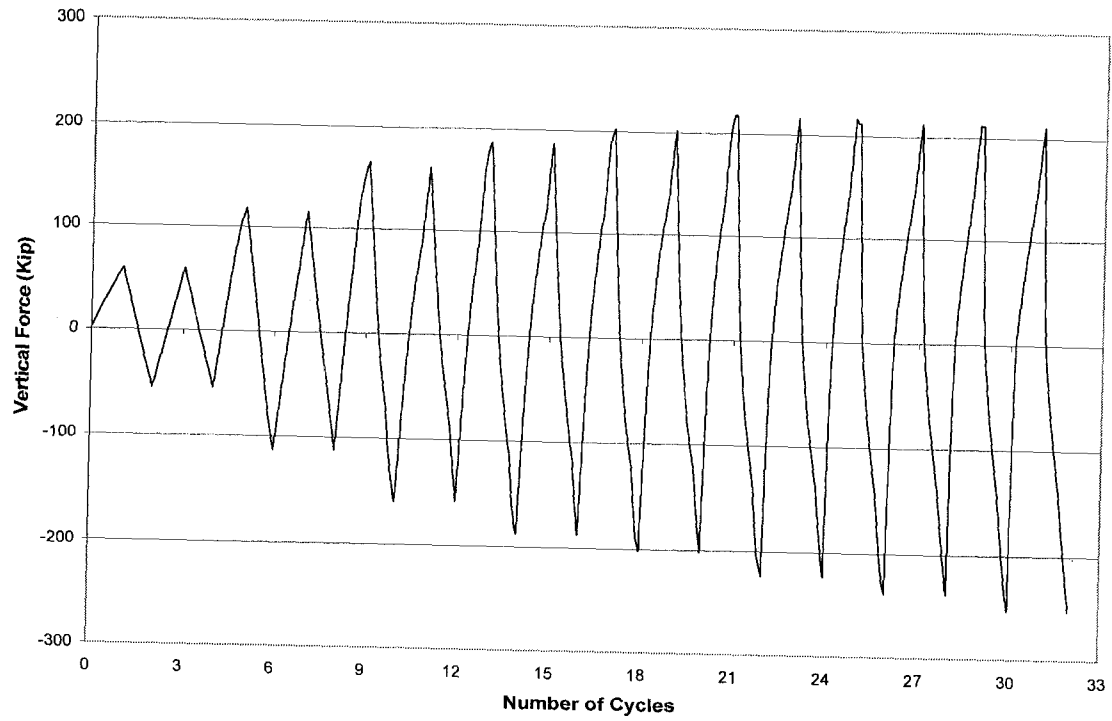


Figure 3.24 Vertical Force Versus Number of Cycles – Base of Right Shear Wall

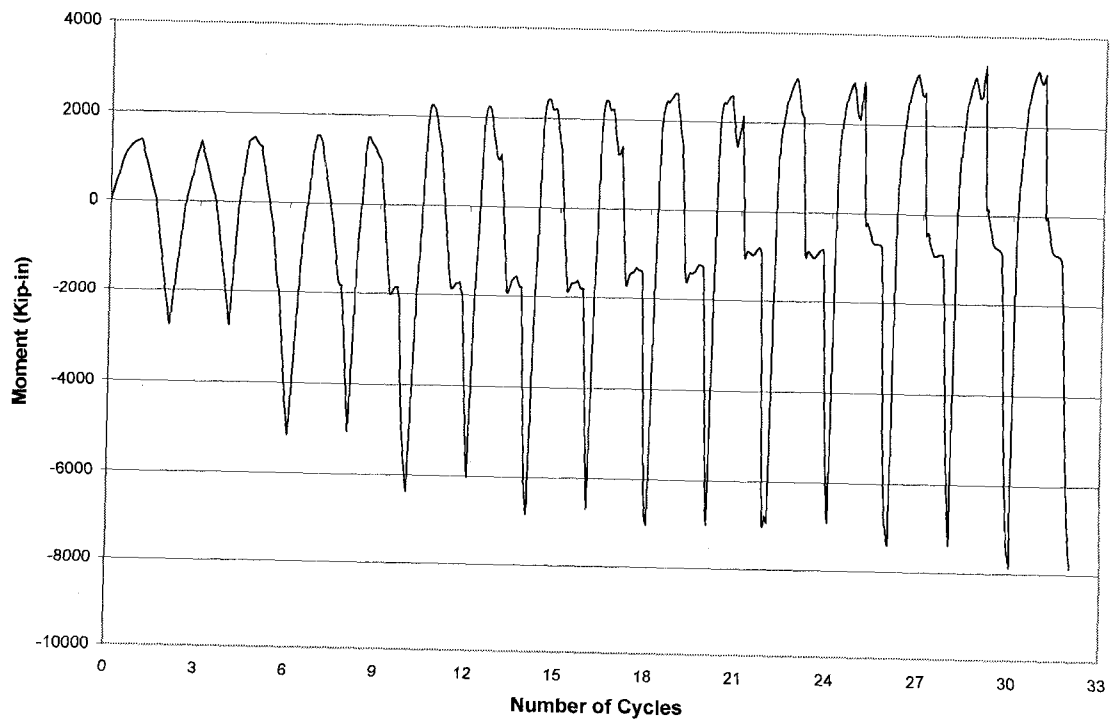


Figure 3.25 Moment Versus Number of Cycles – Base of Left Shear Wall

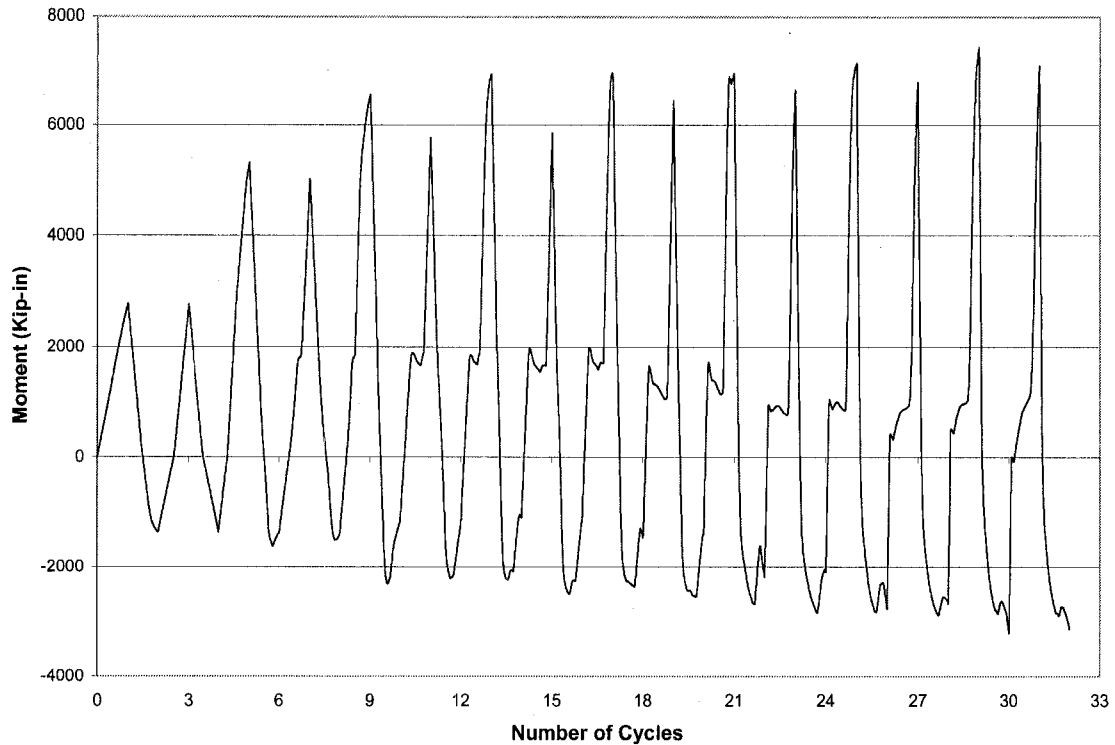


Figure 3.26 Moment Versus Number of Cycles – Base of Right Shear Wall

3.4.3 Coupled Wall System (With Fuse Beams and With Elastomeric Pads)

The coupled shear wall system is the same as described in Section 3.4.2, except that the coupling beams with fuse beam also have elastomeric pads installed. This coupling beam is similar to the one used in the experimental test setup that was validated earlier for Fuse # 2 and Fuse # 4 of Tests # 2 and # 4, respectively. The finite element model is similar to that shown in Fig. 3.21, with the exception that now the properties used for the fuse beam are the one's with elastomeric pads included. The horizontal force versus sway predicted by analyzing this model using OpenSees for both the left and right shear wall is shown in Fig, 3.27. It can be seen from the figure that the left shear wall develops a force of about 125 Kips (556 KN) in tension and 100 Kips (445 KN) in compression and the right shear wall develops the 125 Kips (556 KN) in compression and

100 Kips (445 KN) in tension with a sway of 3.6 in. (91 mm). The above results indicated that transfer of forces occurs from one shear wall to the other in the coupled shear wall system, thus behaving like a conventional coupled shear wall system. The variation of vertical force versus number of cycles for the left and the right shear wall base is shown in Fig. 3.28 and 3.29, respectively. From these figures it can be seen that the maximum vertical force for the left shear wall is about 140 Kips (623 KN) in compression and 240 Kips (1,068 KN) in tension, and for the right shear wall is about 240 Kips (1,068 KN) in compression and 140 Kips (623 KN) in tension. The compressive force in the left shear wall and the tensile force in the right shear wall reach their maximum in the 18th load cycle and stabilize at these values for the later cycles. This is due to the fact that the fuse beam yields at this load cycle and hence the shear wall is unable to resist any force further (the fuse beam force does not increase with increase in deformation; refer to Fig 3.41). The variation of moment at base versus the number of cycles for the left and right shear wall is shown in Fig. 3.30 and Fig. 3.31, respectively. From these figures it can be seen that the maximum moment of the left shear wall and the right shear wall is around 6,900 Kip-in. (780 KN.m) and 8,200 Kip-in. (926 KN.m), respectively. It is also seen that the moment does not noticeably increase after the 18th load cycle in the left wall. This is also due to the fact that the fuse beam yields at this load cycle. Both the vertical force and moment results indicated that coupling action occurs between the shear walls of the coupled shear wall system. The OpenSees input file is presented in Section E.9 of Appendix E.

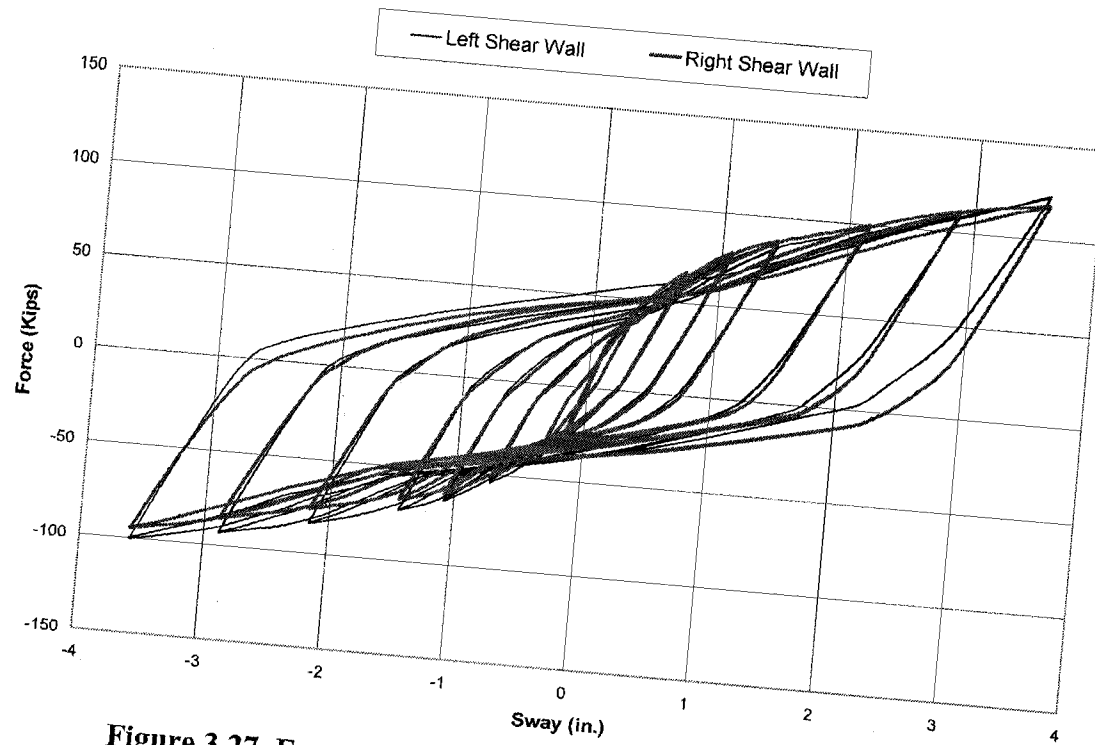


Figure 3.27 Force Versus Sway for Left and Right Shear Walls

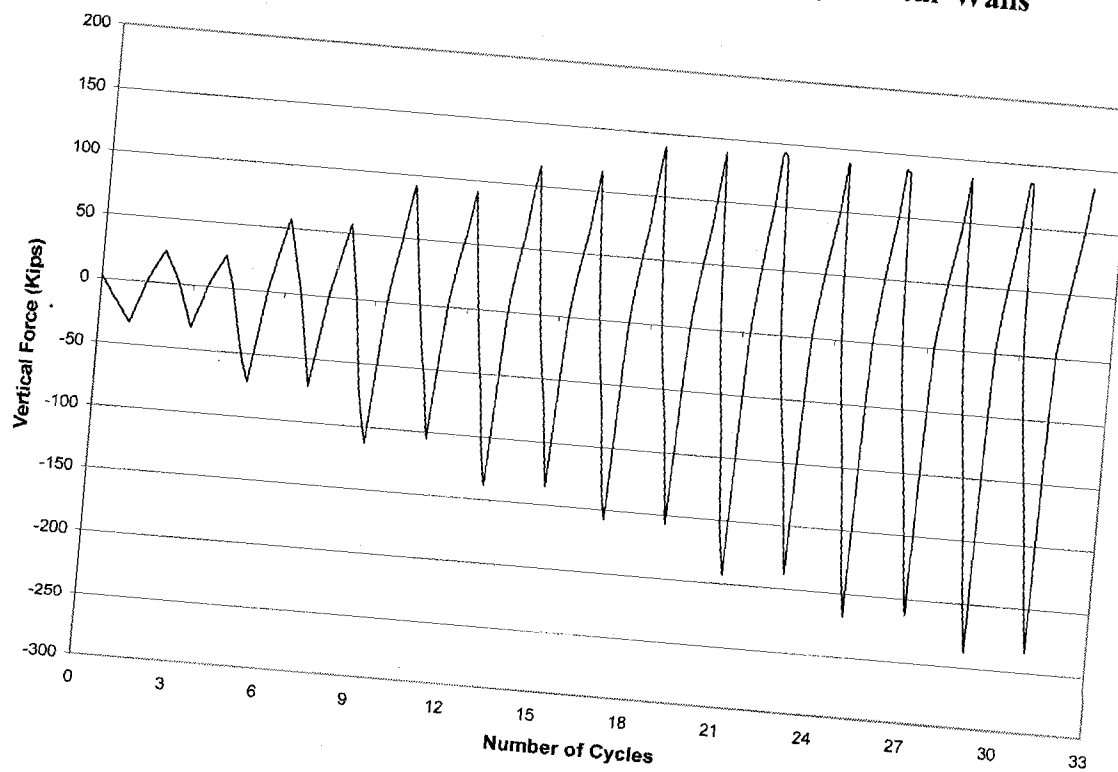


Figure 3.28 Vertical Force Versus Number of Cycles – Base of Left Shear Wall

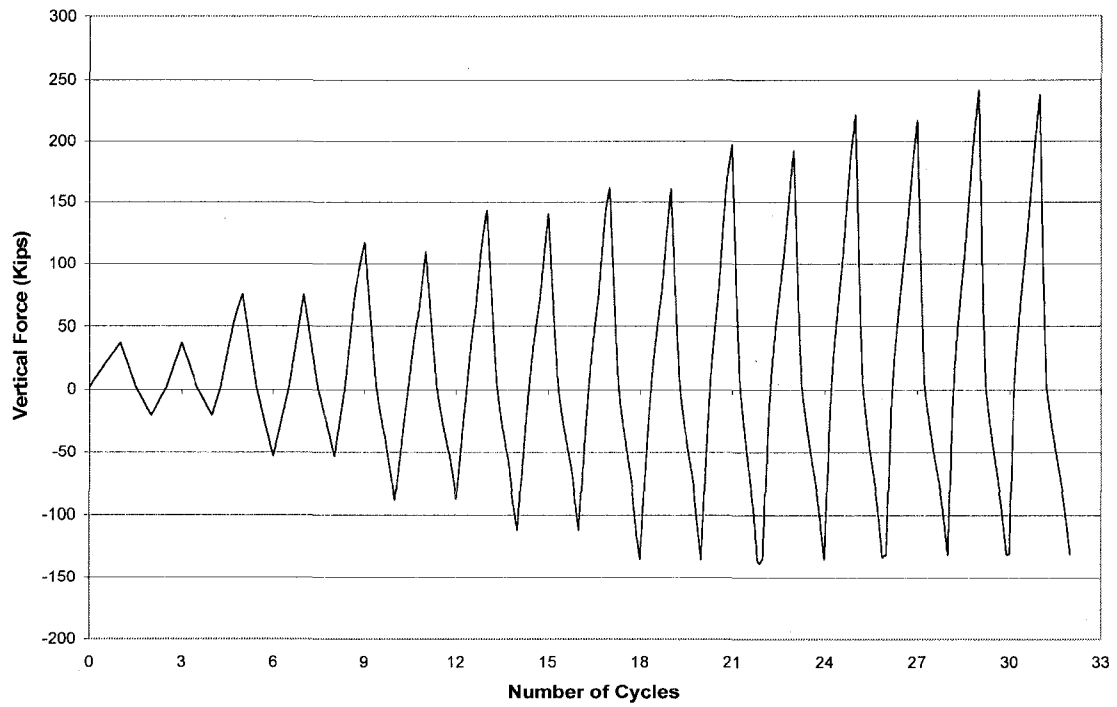


Figure 3.29 Vertical Force Versus Number of Cycles – Base of Right Shear Wall

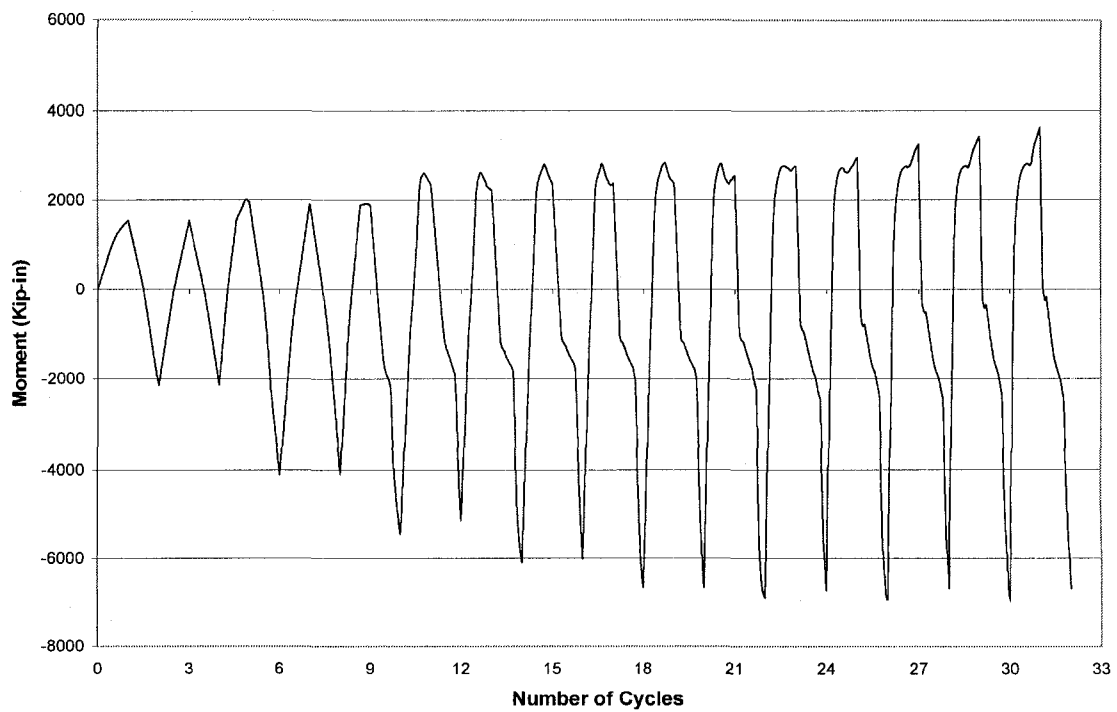


Figure 3.30 Moment Versus Number of Cycles – Base of Left Shear Wall

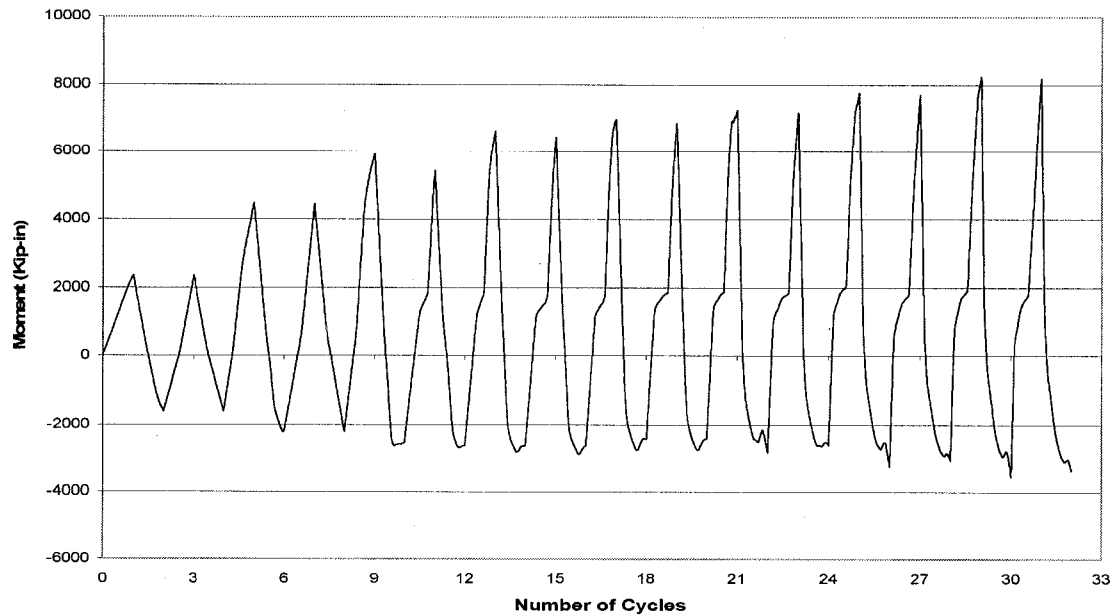


Figure 3.31 Strain Versus Number of Cycles for the Right Shear Wall

3.5 Comparison of Results

3.5.1 Comparison Between Coupled Shear Wall System Without and With Fuse Beams

From Figs. 3.16, 3.22 and 3.27, which show the variation of force versus sway for left and right shear walls, it can be seen that in all the three cases analyzed, namely, coupled shear wall system without fuse beams, coupled shear wall system with fuse beams but without elastomeric pads, and coupled wall system with fuse beams and elastomeric pads, the left and the right shear walls in the coupled shear wall system are able to transfer safely the forces from one shear wall to the other as in the case of conventional coupled shear wall systems. It can be thus inferred that with the presence of fuse beams the coupled shear wall system behaved as a conventional coupled shear wall system. From Fig. 3.16 (coupled shear wall without fuse beams), the maximum force in the left and right shear walls is about 155 Kips (689 KN) for a 3.6 in. (91 mm) sway. From Fig. 3.22 (coupled shear wall with fuse beams and without elastomeric pads), the

maximum force in the left and right shear walls is about 120 Kips (534 KN) and 135 Kips (600 KN), respectively, for a 3.6 in. (91 mm) sway. From the above magnitudes of forces created in the shear walls it can be inferred that the coupled shear wall with conventional coupling beams (without fuse beams) dissipated more energy than the coupled shear wall with fuse beams of lesser capacity than the conventional coupling beams. In order for the coupled shear walls with fuse beams to dissipate equal or more energy than the coupled shear walls with conventional coupling beams, the fuse beams must have equal or more capacity of the conventional coupling beams and the coupling beams in that coupled shear wall should have higher capacity than the fuse beam.

Figure 3.32 shows the superposition of the vertical force versus the number of cycles at the base of the left shear wall of the coupled wall system without fuse beams and with fuse beams and without elastomeric pads. It can be seen from the graphs overlaid in Fig. 3.32 that for both cases the maximum vertical force at the base of the left shear walls gradually increases with load cycle until load cycle 21 is reached. After this load cycle the vertical force in tension does not change appreciably in the left shear wall of the coupled shear wall system with fuse beams, whereas it gradually keeps on increasing for the case without fuse beams. A similar behavior is observed for the vertical force in compression in the right shear wall, as can be seen from Fig. 3.33. The 21st load cycle is at which the fuse beam yielded, reducing the coupling action between the walls, and thus reducing the forces in the walls. The fuse beam being the weakest link in the coupled shear wall system bears most of the damage and yields. The coupling action (tension-compression force transfer between the shear walls) in the coupled shear wall system starts to decrease at the point when the fuse beam yields, and thereafter the

vertical force transferred to the shear walls decrease by about 15% to 30% (during load cycles 21 to 32) as compared to the coupled shear wall system without fuse beam.

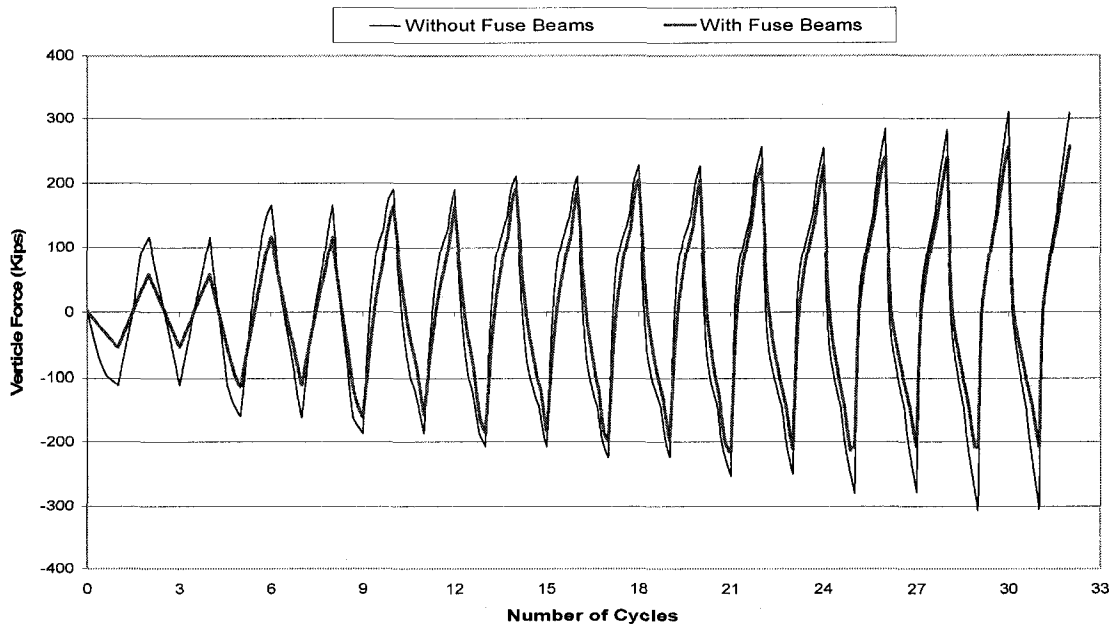


Figure 3.32 Comparison of Vertical Force Versus Number of Cycles at the Base of Left Shear Wall for Coupled Wall Without and With Fuse Beams (Without Elastomeric Pads)

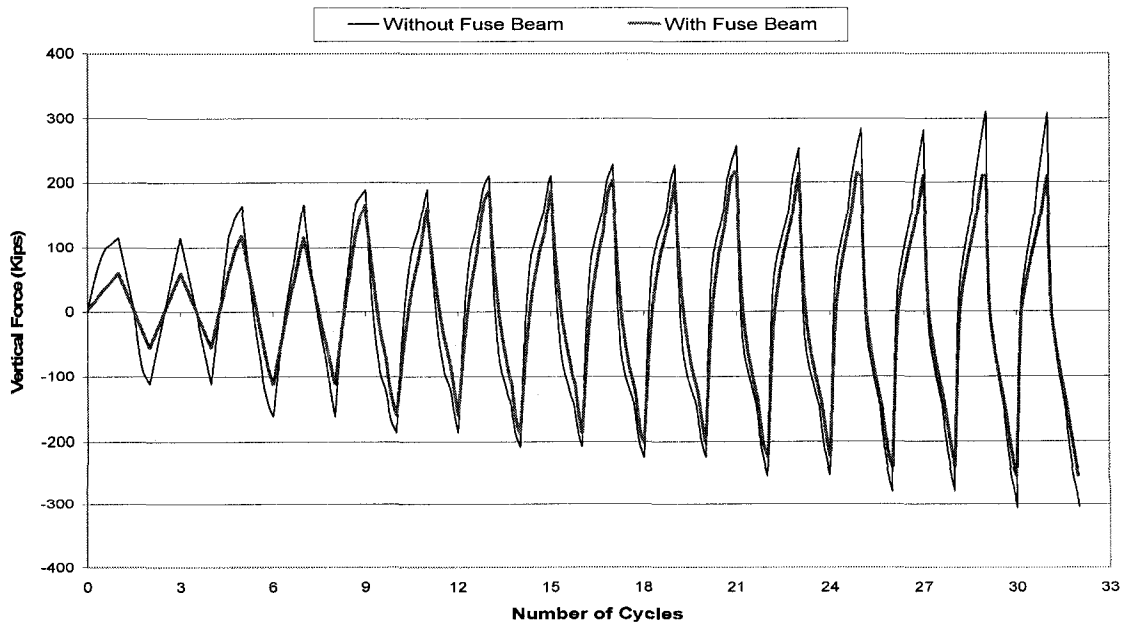


Figure 3.33 Comparison of Vertical Force Versus Number of Cycles at the base of Right Shear Wall for Coupled Wall Without and With Fuse Beams (Without Elastomeric Pads)

Figures 3.34 and 3.35 show the superposition of the moments at the base of the shear walls versus the number of cycles for the left and right shear walls, respectively, without and with fuse beams. It can be seen from the graphs overlaid in these figures that the moment build-up at the base of the two shear walls beyond load cycle 21 is not appreciable for coupled shear wall system with fuse beams, whereas the moments in the coupled shear wall without fuse beams gradually keeps on increasing. This happened because the fuse beam yielded at load cycle 21. Though there is a drop in vertical load transferred to the shear wall, there is a decrease of about 12% in the base moment when the left shear wall is in compression and the right shear wall is in tension in the coupled shear wall system with fuse beam compared to the one without fuse beam. Similarly, there is an increase of about 10% in the base moment when the left shear wall is in tension and the right shear wall is in compression. This indicates that coupling action

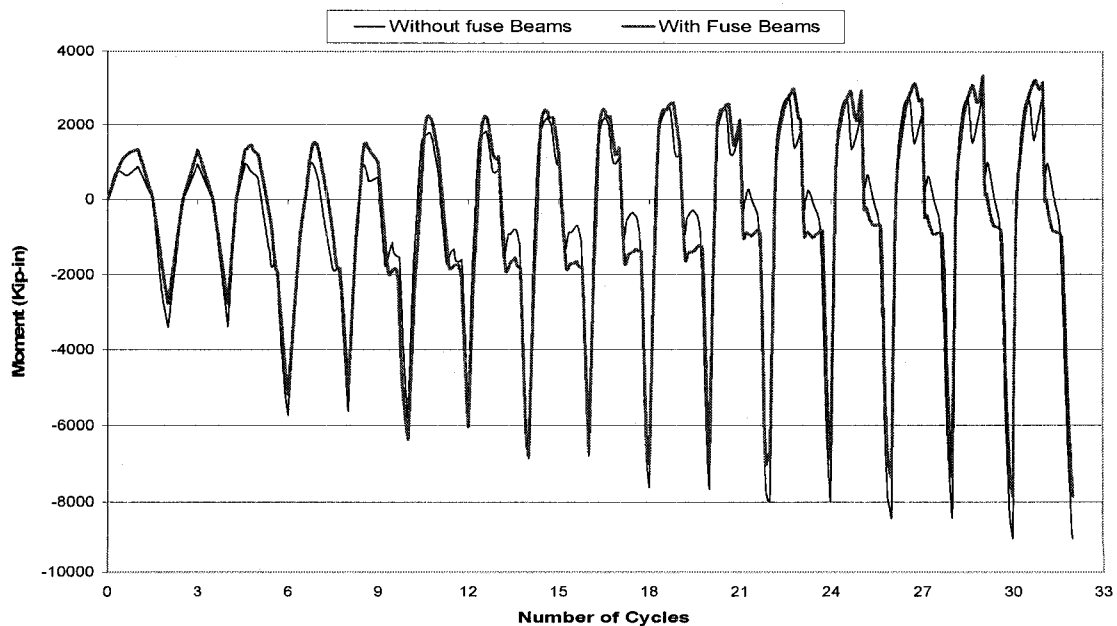


Figure 3.34 Comparison of Moment Versus Number of Cycles at the Base of Left Shear Wall for Coupled Wall Without and With Fuse Beams (Without Elastomeric Pads)

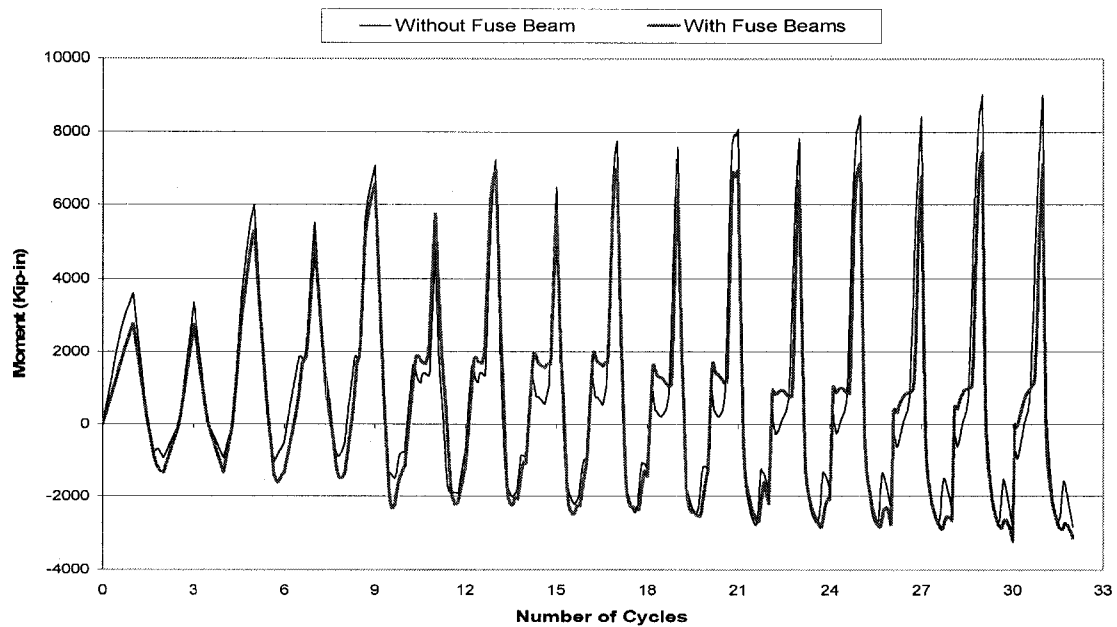


Figure 3.35 Comparison of Moment Versus Number of Cycles at the base of Right Shear Wall for Coupled Wall Without and With Fuse Beams (Without Elastomeric Pads)

still occurs in the coupled wall system. This difference in the moments at the base of the shear wall indicates that lower stresses at the base of the shear wall are created. It can be thus inferred that the yielding at the base of the shear wall of the coupled shear wall can possibly be delayed or reduced by introducing a fuse beam at the mid-span of the coupling beam and the fuse beam will yield and dissipate the energy.

3.5.2 Comparison Between Coupled Wall System With Fuse Beams and Without and With Elastomeric Pads.

From Fig. 3.22 (coupled shear wall with fuse beams and without elastomeric pads) it can be seen that the maximum force in the left and right shear walls is about 120 Kips (534 KN) and 135 Kips (600 KN), respectively, for a 3.6 in. (91 mm) sway. From Fig. 3.27 (coupled shear wall with fuse beams and with elastomeric pads) it can be seen that the maximum force in the left and right shear walls is 125 Kips (566 KN) and 100 Kips (449 KN), respectively. The force versus sway hysteresis curves for the coupled

shear wall system without elastomeric pads are wider than the hysteresis curves for the coupled shear wall system with elastomeric pads. From the above magnitudes of forces created in the shear walls and the width of the hysteresis curves, it can be inferred that the coupled shear wall with fuse beams and without elastomeric pads dissipated more energy than the coupled shear wall with fuse beams and with elastomeric pads.

Figures 3.36 and 3.37 show the superposition of the vertical force versus the number of cycles at the base of the left shear wall and right shear wall, respectively, of the coupled wall system with fuse beams and without elastomeric pads and with elastomeric pads. It can be seen that the tensile vertical force in the left shear wall and the compressive force in the right shear wall do not change appreciably in the coupled shear wall system without elastomeric pads after load cycle 21. Similarly, it can be seen that the compressive force in the left shear wall and the tensile force in the right shear wall do not change appreciably in the coupled wall system with elastomeric pads after load cycle 18. This is because the respective fuse beams yielded at the indicated load cycles, reducing the coupling action between the two shear walls, and thus reducing axial forces transferred to the walls. This is also attributed to the fact that the stiffness of the fuse beams reduced with elastomeric pads (as was obtained from experimental results). Because of reduced stiffness, horizontal displacements produced lower horizontal forces and thus, lower vertical forces and moments. The fuse beam in coupled shear wall systems with elastomeric pads yielded three cycles ahead of that without elastomeric pads. When yielding occurs in (load cycle 21 or 18 as mentioned above) in the fuse beam, the decrease in vertical force transferred to the shear wall ranged from 35% to 50% (difference in the vertical forces for the two cases with respect to the vertical force in

coupled shear wall system without elastomeric pads) in coupled shear wall system with elastomeric pads as compared to without elastomeric pads.

Figures 3.38 and 3.39 show the superposition of moment versus number of cycles at the base of the left and right shear wall, respectively, for the coupled shear walls without and with elastomeric pads. From these figures it is seen that there is a drop of about 12% in the moment when the left shear wall is in compression and an increase of about 10% when the left shear wall is in tension in the coupled shear wall system with elastomeric pads compared to the one without elastomeric pads. The right shear wall had an increase in moment, both in tension and compression, of about 21%. It can be deduced that the coupling action between the coupled shear walls reduced by the addition of elastomeric pads. Also, the lateral loading was displacement based, and for higher displacements the force developed was lower in case with elastomeric pads. This is due to lower fuse beam stiffness in case with elastomeric pads than without elastomeric pads

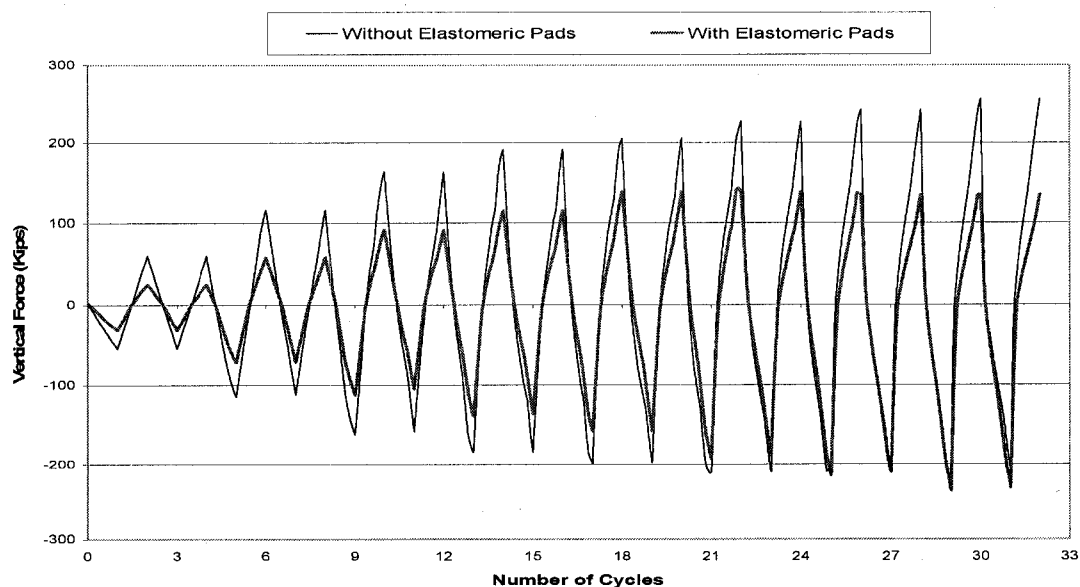


Figure 3.36 Comparison of Vertical Force Versus Number of Cycles at the Base of Left Shear Wall for Coupled Wall With Fuse Beams and Without and With Elastomeric Pads

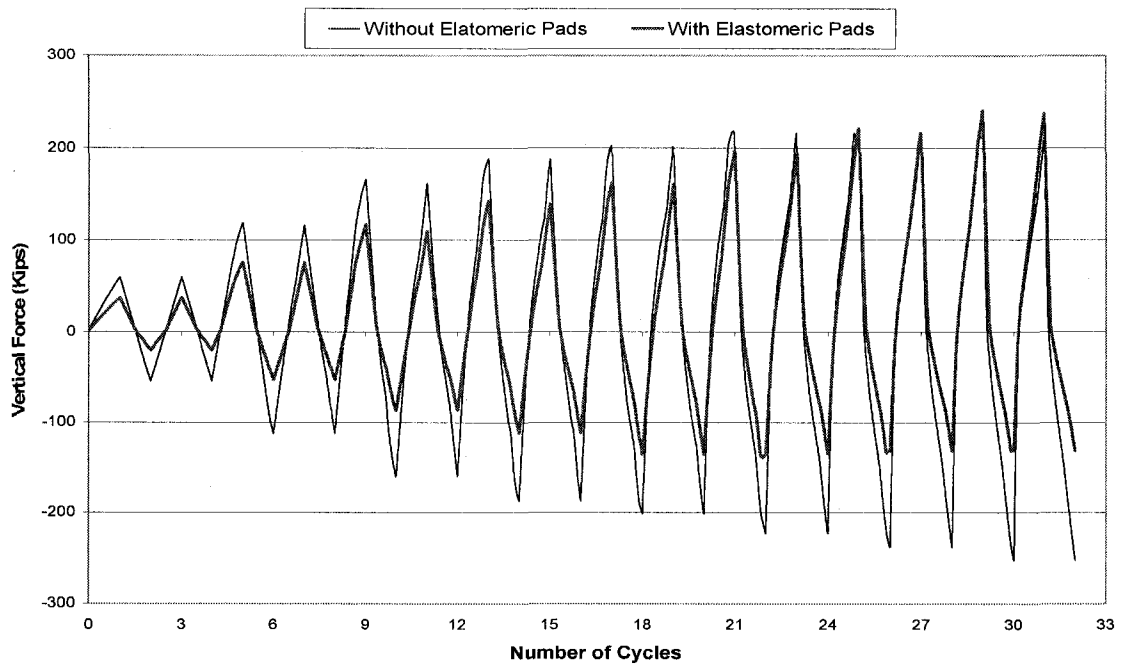


Figure 3.37 Comparison of Vertical Force Versus Number of Cycles at the Base of Right Shear Wall for Coupled Wall With Fuse Beams and Without and With Elastomeric Pads

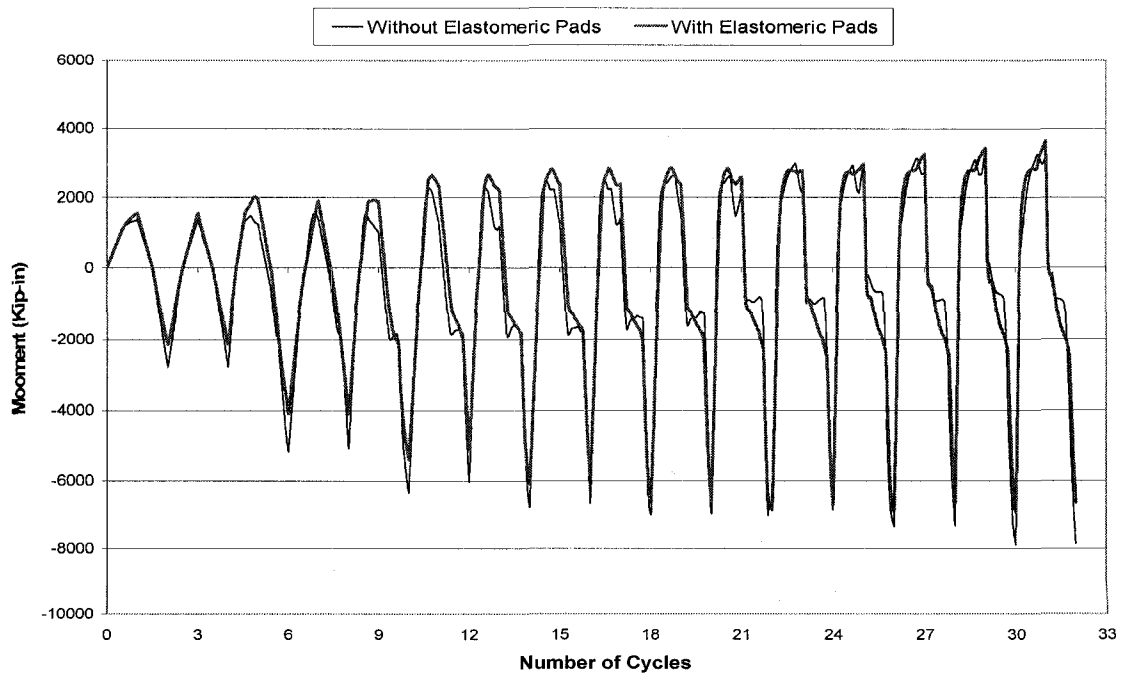


Figure 3.38 Comparison of Moment Versus Number of Cycles at the Base of Left Shear Wall for Coupled Wall With Fuse Beams and Without and With Elastomeric Pads

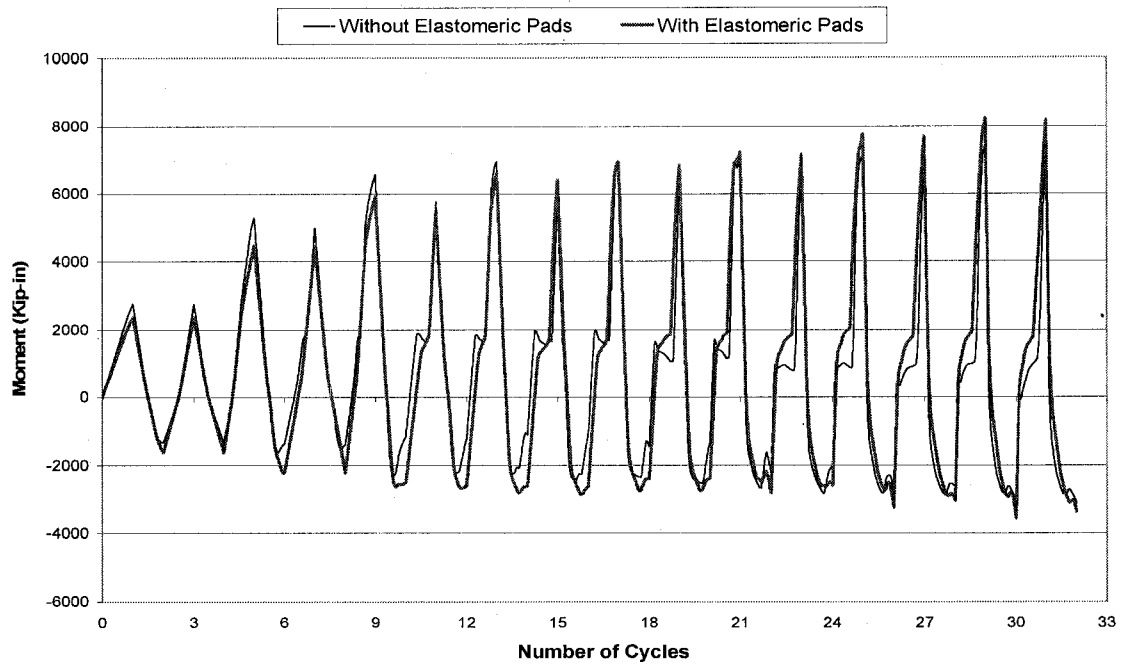


Figure 3.39 Comparison of Moment Versus Number of Cycles at the base of Right Shear Wall for Coupled Wall With Fuse Beams and Without and With Elastomeric Pads

as was obtained from the experimental test. From the above it is inferred that the presence of elastomeric pads does not delay or reduce the yielding in the coupled shear wall components, and hence does not enhance the performance of coupled shear walls.

Figures 3.40 and 3.41, respectively, show the plots of axial force versus axial deformation of the diagonal spring member of the fuse beam in the coupled shear wall system without and with elastomeric pads. From the figures it can be seen that the fuse beam material in both the cases yielded and underwent significant plastic deformations. This can be inferred, since the force in the diagonal truss element did not increase after experiencing a deformation of about 0.22 in. and 0.4 in., respectively, for cases without and with elastomeric pads. Figures 3.42 and 3.43 show the plots of the coupling beam shear force versus number of cycles for the coupled shear walls without and with

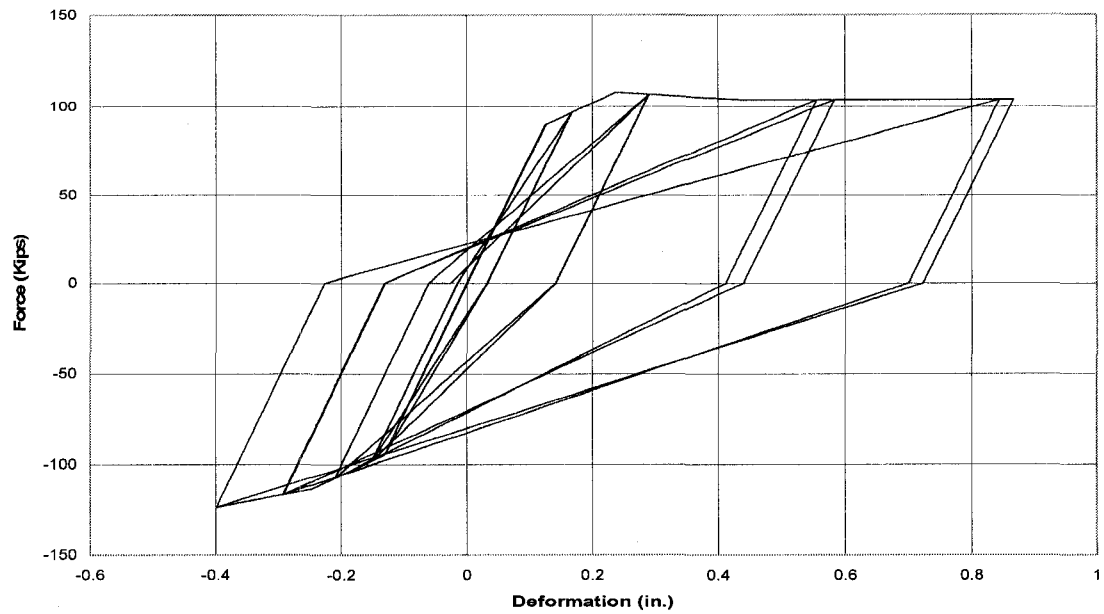


Figure 3.40 Force Versus Deformation of Fuse Beam in Coupled Shear Wall With Fuse Beam and Without Elastomeric Pads

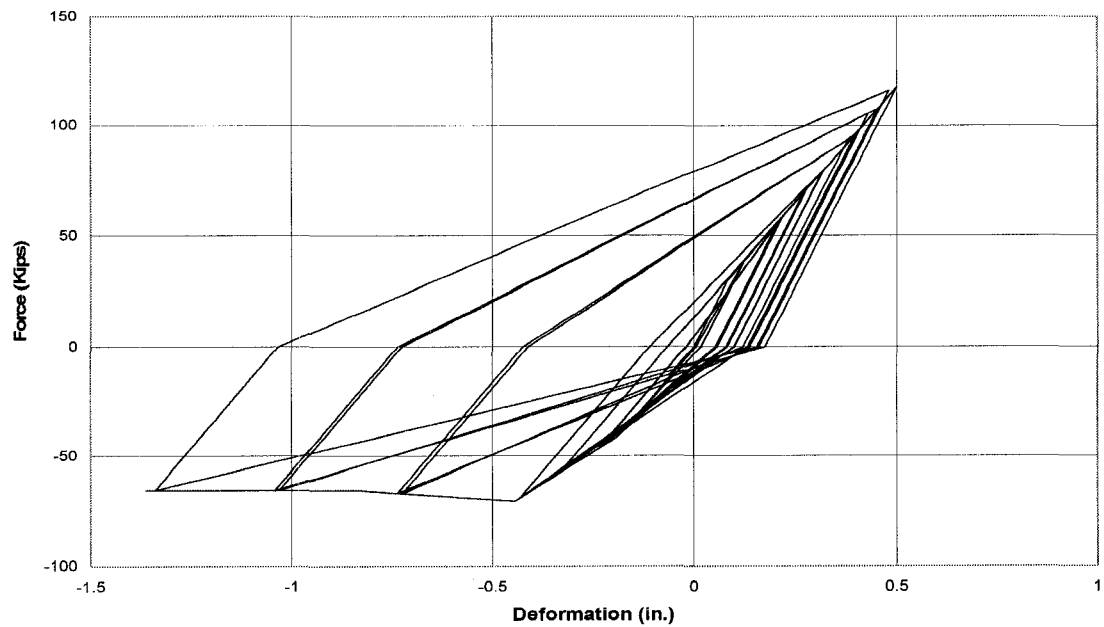


Figure 3.41 Force Versus Deformation of Fuse Beam in Coupled Shear Wall With Fuse Beam and With Elastomeric Pads

elastomeric pads, respectively. From these plots it can be seen that the maximum shear force in the coupling beam is about 62 Kips (276 kN) for the coupled shear wall without elastomeric pads and 58 Kips (258 kN) for coupled shear wall with elastomeric pads.

Both these shear forces are less than the design capacity of 141 Kips (627 KN) for the W14 x 61 (A-992 steel) coupling beam, which indicates that the coupling beam remains elastic in both the cases.

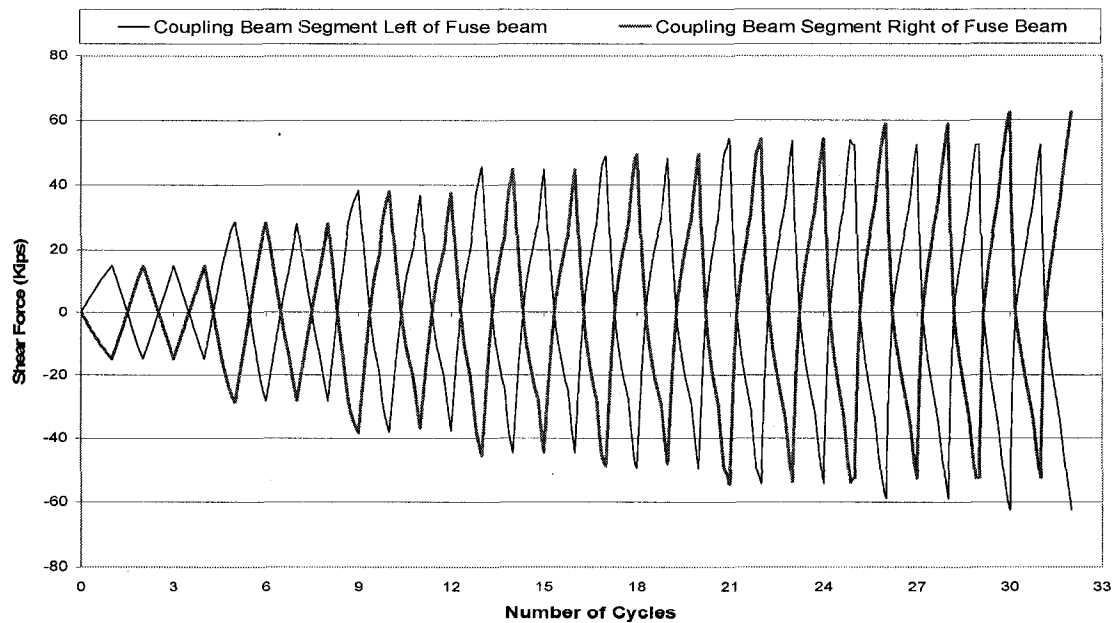


Figure 3.42 Shear Force Versus Number of Cycles of Coupling Beam in Coupled Shear Wall With Fuse Beam and Without Elastomeric Pads

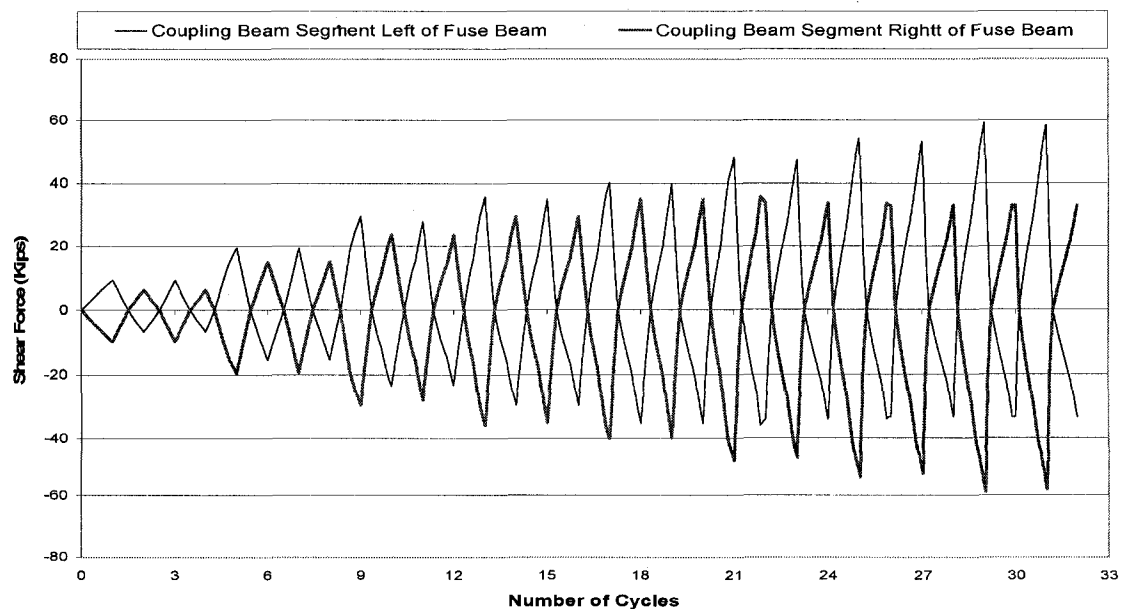


Figure 3.43 Shear Force Versus Number of Cycles of Coupling Beam in Coupled Shear Wall With Fuse Beam and With Elastomeric Pads

Figures 3.44 and 3.45 show the plots of the end moments of the coupling beam versus number of cycles for the coupled shear walls without and with elastomeric pads. From these plots it can be seen that the maximum moment on the coupling beam is about 170 Kip-ft (231 KN.m) for the coupled shear wall without elastomeric pads, and 155 Kip-ft (211 KN.m). Both these moments are less than the design capacity of 383 Kip-ft (520 KN.m), of the W14 x 61 (A-992 steel) coupling beam, indicating that the coupling beam is within the elastic limit. The calculation of the coupling beam capacity of the coupling beam is presented in Section A.2 of Appendix A. It can be deducted from the above checks, that the coupling beam remains elastic throughout the analysis and the fuse beam yields both the cases of analysis.

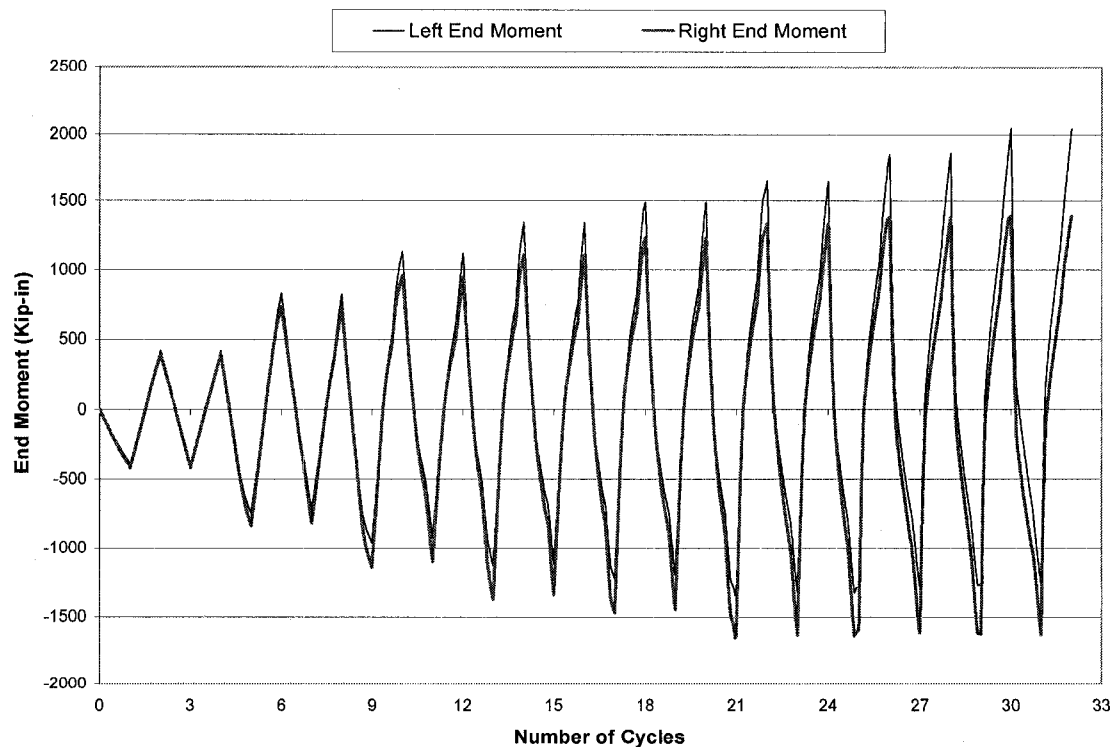


Figure 3.44 End Moment Versus Number of Cycles of Coupling Beam in Coupled Shear Wall With Fuse Beam and Without Elastomeric Pads

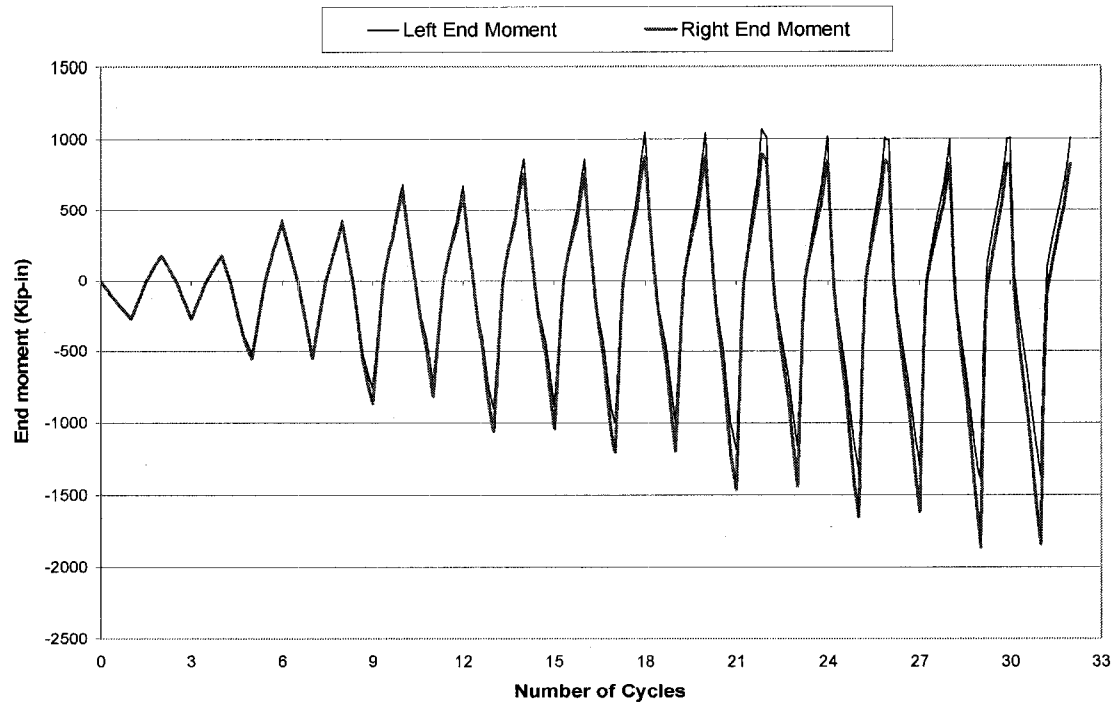


Figure 3.45 End Moment Versus Number of Cycles of Coupling Beam in Coupled Shear Wall With Fuse Beam and With Elastomeric Pads

The degree of coupling (DOC) for a coupled shear wall system is defined as

$$\text{DOC} = \frac{Td}{M_L + M_R + Td} \quad (3.1)$$

where

T = axial force at the base of the shear wall,

d = center to center distance between shear walls,

M_L = Moment at the base of the left wall,

M_R = Moment at the base of the right wall.

Figure 3.46 shows the degree of coupling for the three coupled shear wall systems analyzed in Sections 3.41, 3.42 and 3.43. For these three cases the following interpretations can be made from Fig. 3.46:

1. Coupling beam without fuse beams: DOC of 74% is achieved and remains more or less constant throughout the test.
2. Coupling beam with fuse beam and without elastomeric pads: DOC starts at 59% and reaches a peak of 72% in the 20th cycle, and then drops after 21st load cycle when the fuse yields. It reaches a minimum value of 69% towards the end of test.
3. Coupling beams with fuse beams and elastomeric pads: DOC starts at 43% and reaches a peak of 64% in the 19th cycle, and then drops to 62% towards the end of test.

From the above it is inferred that lower degree of coupling occurs in a coupled wall system with fuse beams and without elastomeric pads, but the reduction is not significant. It is further observed that this reduction in the degree of coupling is much more in case with elastomeric pads and hence less preferable.

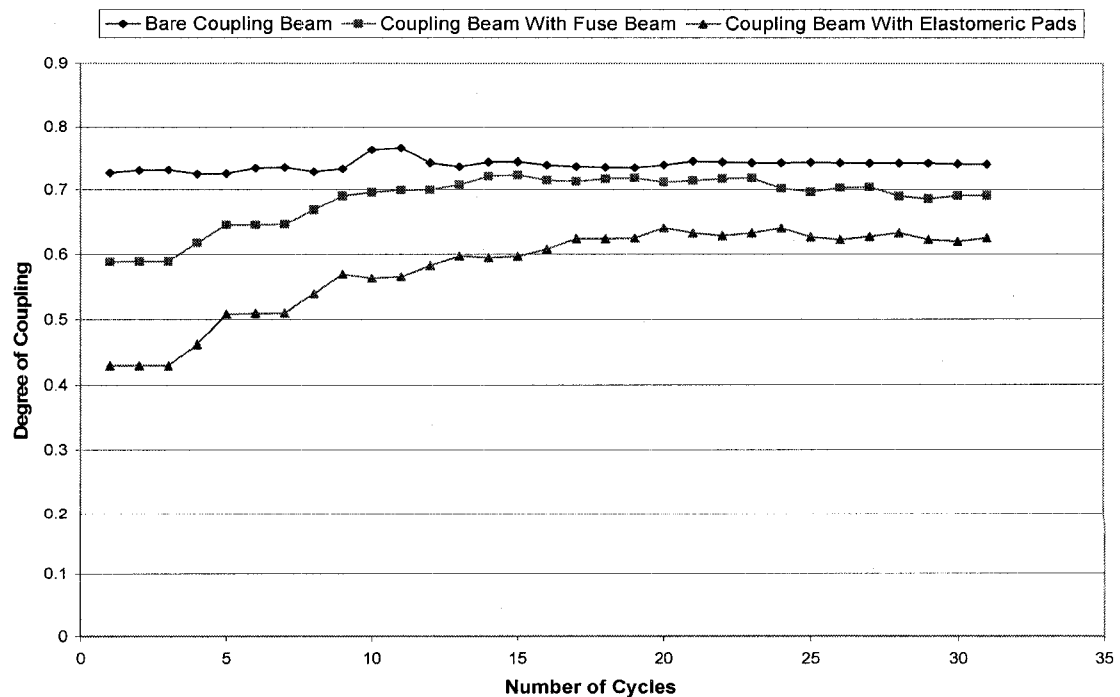


Figure 3.46 Degree of Coupling Versus Number of Cycles

CHAPTER 4

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

4.1 General

The summary of Chapter 1 through Chapter 3 is presented here briefly explaining: the goal, objective, and scope of work; the experimental test design, test setup, testing procedure, results obtained, and analysis of results; and the analytical modeling, calibration, validation, application, analysis of results, and comparison of results. The conclusions from the experimental tests and the analytical study are also presented in this chapter. Finally, based on experimental and analytical study results, recommendations for future research are suggested.

4.2 Summary

This section presents a summary of the research reported. In Chapter 1, first the behavior of structural components and basic concepts used, such as the coupled shear wall system, eccentrically braced frames, energy dissipation, splice joints, elastomers and elastomeric bearings, and fuse beam application, are explained in the context of the research undertaken. A brief literature review of recent work, more of which is still in progress, on coupled shear walls is presented. The goal, objective, and scope of the present research are then presented. The goal of the research is to evaluate the feasibility of using fuse beams to increase energy dissipation capabilities of coupled shear walls. The goal of the research includes the task of designing a test setup to evaluate performance of a coupled beam without and with fuse beams, and to perform four fuse beam tests: two fuse beam tests without elastomeric pads, and two fuse beam tests with elastomeric pads. The test results are used to develop a calibrated analytical model of the

experimental test setup. Also, a calibrated analytical model of a pre-designed shear wall, for which experimental data was available, is developed. The above two models are then used to analyze a coupled shear wall system without and with fuse beams. For the case with fuse beams, two cases are considered: without elastomeric pads and with elastomeric pads. The overall objective of the research is to determine if a fuse beam could be installed in a coupling beam of a coupled shear wall system in such a way that its addition concentrates the yield damage to the fuse beam only, thus moving the damage from the other areas of the coupled shear wall system, if no fuse beam was installed. In doing so, the total coupled shear wall system should be so designed that the coupling beam remains elastic throughout the test and the total system still transfers safely the forces from one shear wall to the other as in a conventional shear wall system. In addition to moving the yield location and still behaving like conventional shear wall system, the objective was to see if fuse beams can increase the energy dissipating capabilities of a coupled shear wall system. If found to be true, fuse beams could be proposed to be installed in coupling beams in locations where they could be easily replaced after the earthquake, thus reducing rehabilitation costs due to seismic damage. The scope of the research conducted had two broad aspects. One was the experimental study, which included the design of test setup, testing of four fuse beam specimens, and analysis of the test results. The other objective was the analytical study which included developing a finite element model of the test setup and a pre-designed shear wall using OpenSees, calibrating and validating the models, applying them to analyze a coupled shear wall system, and from the results obtained draw conclusions on the impact of the fuse beams on system behavior.

In Chapter 2 the experimental study undertaken in this research is described. This part of the research consisted of tension coupon test of the fuse beam web material, designing the coupling beam test setup, setting up the test setup, and performing the four tests. The tension coupon test was carried out at the High Bay Laboratory at the University of Cincinnati main campus. The coupon preparation and testing was conducted as per ASTM specifications for tension coupon testing. The yield stress was found to be 38 Ksi (266 MPa). This stress was below the yield stress of the coupling beam steel material, which was of A-992 grade steel with a yield stress of 50 Ksi (350 MPa). The coupling beam test setup was designed keeping in mind the capacity of the actuators available in the laboratory. A coupling beam which would not yield in shear or bending within the available actuator capacity was selected. The fuse beam was designed to yield in shear before the coupling beam, splice joint or bolts. The splice joint was designed as a bolted connection with slip critical bolts. The fuse beam was placed at the mid-span of the coupling beam. The coupling beam was braced at four different locations to avoid out of plane movement. The actuators were placed on the two ends of the coupling beam and they oscillated in equal and opposite directions in a cyclic pattern. The test was carried out as per AISC cyclic test guidelines. The testing was done at the Large Scale Testing Facility of University of Cincinnati at Center Hill. Four fuse beam tests were conducted. Two of the fuse beams had two vertical web stiffeners and two fuse beams had three vertical web stiffeners leading to different aspect ratios for the web panels. One type of each fuse beam was tested without elastomeric pads, and one type of each fuse beam was tested with elastomeric pads placed in the splice joint.

The test results and the analysis of results for the four fuse beam tests conducted are also described in Chapter 2. Test # 1 was stopped at 0.32 radians rotation cycle. The fuse beam buckled at 0.28 radians rotation. Test # 2 was stopped at 0.40 radians rotation cycle. The fuse beam did not buckle, but the strain gauge readings suggested that the fuse beam had yielded and undergone plastic deformations. Test # 3 was stopped at 0.36 radians rotation cycle. The fuse beam yielded at 0.28 radians rotation cycle, but test was continued until 0.36 radians cycle, keeping the coupling beam elastic to see if the actuator still picked up any load. The fuse beam did not buckle. Test # 4 was stopped at 0.46 radians rotation cycle. The fuse beam yielded at 0.36 radians cycle, but test was continued until 0.46 radians cycle. The fuse beam did not buckle. In all the four tests, the coupling beam strains remained in the elastic range throughout the test. The bolts, bolt holes, and splice plates experienced no damage. The elastomeric pads in Tests # 2 and # 4 were squeezed and sheared at the splice joint locations. The strain gauge and wire potentiometer readings from all the tests were recorded and converted to Excel spreadsheets. Diagrams of average load on actuator versus average tip deflection were plotted. Tests # 1 and # 3 had a distinct elastic slope and a hardening slope. Tests # 2 and # 4 did not pick up much load initially with increasing deflections, but gradually picked up loads with higher deflections. This was probably due to the shearing of elastomeric pads in the splice joints, thus allowing the fuse beam to rotate. Graphs showing the fuse beam strains and coupling beam strains versus average load were also plotted to show that the coupling beam always remained elastic even as the fuse beam strains crossed its elastic limit and experienced significant plastic deformations.

In Chapter 3 the analytical study part of the research is described. This part consists of three phases including: the modeling phase, calibration and validation phase, and application phase. OpenSees (Open System for Earthquake Engineering Simulation, 1999, 2000), a research oriented software developed at the University of California, Berkeley, was used to model and analyze the test setup and coupled shear wall systems. A 2-D finite element model of the experimental test setup was formulated and analyzed using OpenSees. The loading was similar to the experimental cyclic loading. The element load versus deformation characteristics/properties of the fuse beam in the program were taken from the experimental results plotted earlier. The properties of the fuse beam were calibrated within the OpenSees program so as to predict the same load versus deflection behavior as was obtained from the experimental tests. This ensured that the analytical model of the test setup mimicked the behavior recorded during experimental testing. Four such analytical models, one for each of the four experimental tests conducted, were prepared. A pre-designed four storied cantilever shear wall with known loading, and whose force versus sway result was available, was also modeled using OpenSees. The shear wall was subjected to a known horizontal cyclic loading at the top of the wall. The shear wall was analyzed and its modeling properties were calibrated within the OpenSees program so that the force versus sway predictions matched with the experimental results available. The above two analytical models were finally used to formulate the finite element model of a four storey coupled shear wall system with coupling beams, without and with fuse beams.

Three types of coupled shear wall systems were analyzed, namely, coupled shear wall system without fuse beams, coupled shear wall system with fuse beam and without

elastomeric pads, and coupled shear wall system with fuse beam and with elastomeric pads. The loading on each shear wall of the coupled wall was similar to the loading on the above modeled shear wall. The coupled shear wall system without fuse beam consisted of two shear walls similar to the shear walls modeled earlier, and with W14 x 61 (A-992) steel section coupling beams. The model was analyzed and force versus sway graphs for the top of the left and right shear walls were plotted. The vertical load and moment versus the number of cycles graphs were also plotted for the base of the left and right shear walls. The coupled wall system with fuse beams and without elastomeric pads also consisted of two shear walls similar to the shear walls modeled earlier. They were connected by a coupling beam with a fuse beam included in it. The fuse beam in the analytical model had the same properties of the fuse beam without elastomeric pads, as obtained from experimental tests which was modeled earlier. Graphs of the force versus sway for the top, and vertical force and moment versus number of load cycles for the base of the left and right shear wall were plotted. The coupled shear wall with fuse beam and with elastomeric pads, had the same model as the coupled walls with fuse beams and without elastomeric pads, but the fuse beam properties were changed. The fuse beams had the same properties of the fuse beams with elastomeric pads, as obtained from experimental tests. Graphs of the force versus sway for the top, and vertical force and moment versus number of load cycles for the base of the left and right shear wall were plotted. The results of the three coupled shear wall systems were compared for the shear wall base stresses and strains versus number of cycles and the force versus sway characteristics of the top of the shear wall.

4.3 Conclusions

To avoid yielding of the coupling beams in coupled shear wall systems, it is possible to shift the yielding to another location by adding a fuse beam at the mid-span of the coupling beam. The fuse beam has to be of lower shear capacity, i.e., it is made of steel which has lower yield stress than the steel used for the coupling beam and/or the area of web is smaller. By doing so, the fuse beam will bear the damage due to the shear force rather than the coupling beam. This would force the fuse beam to yield under extreme loading rather than the coupling beam. Adding elastomeric pads along with the fuse beam could possibly delay the yielding due to excellent damping capabilities of elastomeric pads. Experimental tests were carried out to verify if the above assumptions were true. Analytical study was also conducted to support the experimental results.

Four fuse beam tests were conducted. Two tests (Tests # 1 and # 3) were conducted without using elastomeric pads, and two tests (Tests # 2 and # 4) were conducted using elastomeric pads. The experimental test results of the two tests without elastomeric pads showed that the coupling beam with fuse beam had smooth and gradually widening loops of load versus deflection curves indicating large energy dissipation. The experimental test results of the two tests with elastomeric pads also showed that the coupling beam with fuse beam had smooth and gradually widening loops of load versus deflection curves thus indicating larger energy dissipation capacity. However the hysteresis loops obtained for the latter case indicated significant pinching in the early stages of the test, since the actuator was not picking up much additional load at higher deflections of the actuators. This could be due to the fact that the elastomeric pads sheared over their thickness, thus causing the fuse beam to rotate additionally and so not

resisting much additional force as the deformation increased. The results for strains in the flanges and web of the coupling beam in all the four tests confirmed that the coupling beam remained elastic throughout the test, even after the fuse beam had crossed its elastic yield limit. In the experimental tests without elastomeric pads (Tests # 1 and # 3), the fuse beam web stiffeners governed the buckling of the fuse beam web. In Test # 1 the fuse beam web buckled while yielding in shear, whereas the fuse beam web in Test # 3 did not buckle while yielding in shear. From the results obtained from the experimental study it was concluded that the fuse beam was able to dissipate energy and failed by shear yielding, whereas the coupling beam remained elastic. The results showed that only the fuse beam experienced all the plastic deformation damage, and could be replaced during rehabilitation, whereas the coupling beams remained elastic and can be reused. Comparing the result of Test # 3 (in which the fuse beam had three web stiffeners) with Test # 1 (in which the fuse beam had two web stiffeners), it was concluded that the addition of stiffener provided more fuse beam web rigidity and prevented the local buckling of the web of the fuse beam. There was no considerable change in the maximum load carrying capacity of the two fuse beams. The experimental test results were used successfully to generate an analytical model for each test that simulated the experimental results.

Three different coupled shear wall system models were developed in the analytical study, and results obtained were compared. Plots of vertical force and moment versus number of load cycles at the base of the shear walls were compared. Results showed that the coupled shear walls with fuse beams and without elastomeric pads provided sufficient coupling between the shear walls. Reduced vertical forces with low

difference in moments at the base of the coupled shear walls with fuse beams, indicated there was coupling between the wall and also the yielding of the base of the shear wall of the coupled shear wall could be delayed or reduced by introducing a fuse beam at the mid-span of a coupling beam. The fuse beam yields first and dissipates the energy. From the force versus sway diagrams of the three coupled shear wall systems, it is observed that the coupled shear wall without fuse beams developed higher forces than the coupled shear wall system with fuse beams and without and with elastomeric pads for the same induced horizontal displacements. This happened because the fuse beam was purposefully designed weaker than the coupling beam. In order for the coupled shear walls with fuse beams to dissipate equal or more energy than the coupled shear walls with conventional coupling beams, the fuse beams must have equal or more capacity of the conventional coupling beams and the coupling beams in that coupled shear wall should have higher capacity than the fuse beam.

From the analysis of coupling beam shear force and bending moments and fuse beam force-deformation results obtained, it is found that the coupling beam remained elastic throughout the analysis and the fuse beams yielded. From the analyses of coupled shear wall without and with elastomeric pads it was concluded that the coupling action of the coupled shear wall system reduced with the addition of elastomeric pads, and led to high percentage reduction of vertical forces and hence an increase in moment at the base of the walls. This could result in higher stresses and strains at the base of the shear walls. It can be concluded from above that the presence of elastomeric pads, does not necessarily delay or limit the yielding of the coupled shear wall components and hence does not help much for better performance of the coupled shear wall system.

It is also concluded from the comparison of the degree of coupling for the three cases of analysis, that fuse beams without elastomeric pads have more degree of coupling than with elastomeric pads. The degree of coupling for the case of coupling beams with fuse beams is not significantly less compared to bare coupling beams.

4.4 Recommendations

In this study experimental tests were conducted using a W14 x 61 size coupling beam, which is a scaled version (about 1:4) of an actual coupling beam used in the field. This beam was selected due to the limitations of the capacity of the actuator that was available in the laboratory. It is recommended to perform more fuse beam tests with realistic coupling beam sizes used in practice. In this study only two tests were conducted without elastomeric pads and two tests were conducted with elastomeric pads. More tests are recommended in order to ascertain the behavior of the fuse beam and to generalize the findings. Also, the elastomeric pads properties and thickness needs to be varied to truly assess the contributions made by them. It is also recommended that use of fuse beams as an energy dissipating device, which may locally fail under extreme loading conditions, needs to be explored for other structural applications, other than the coupled shear wall systems. An example would be their use in bridge tower connections in the transverse direction, as used in the San Francisco-Oakland bay Bridge design, which uses replaceable bolted shear links (Mc Daniel et al., 2003) as a strategy for rehabilitation.

The coupled shear wall system analyzed in this study was a four storey coupled shear wall system. Usually coupled shear walls are used when building height is taller than four stories. Due to lack of design and test data available, at the time of analysis, for shear walls with higher number of stories, the available four storey shear wall model was

only analyzed in this study. Though the results were very encouraging, cases involving for higher storey coupled shear wall systems need to be investigated

The use of elastomeric pads in this study has shown that their addition may not result in a gain in energy dissipating capabilities, as they substantially reduced the coupling action of the coupled walls, thus increasing the moments at the base of the shear walls. The pads used in the tests were 1/4 in. (6 mm) thick and experienced large shearing deformation across the thickness of the pads. It is recommended to test fuse beams with laminated elastomeric pads (with steel plates) or with elastomeric pads made of stiffer material.

Full-scale tests of coupled shear wall systems with steel coupling beams and with fuse beams need to be also conducted to finally verify the findings of the study.

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APPENDIX – A

DESIGN CALCULATIONS OF EXPERIMENTAL TEST SETUP

A.1 Introduction

The Design Calculations and checks for the experimental test setup are presented in this section. The coupling beam used in the test setup was a W 14 x 61 section, which was selected based on the actuator capacity of 30 Kips. The test setup was designed to produce a maximum shear of 90 Kips in the coupling beam as shown in Fig. 2.1 of Chapter 2. The maximum moment in the beam was 360 kip-ft. First the design checks performed for the coupling beam, fuse beam, and design of splice connection are presented in this Appendix.

A.2 Design Check of Coupling Beam

Beam size = W 14 x 61 , A-992 Steel.

F_y = yields stress = 50 ksi.

Maximum design shear = 90 kips

Maximum design moment = 30 Kips x 12 ft. = 360 kip-ft

From Table 5-3 (AISC, LRFD Manual, 3rd Edition, 2001):

Shear capacity of W 14 x 61 = 141 Kips > 90 Kips - Hence it has acceptable shear capacity per LRFD Manual.

The un-braced length ' L_b ' for the coupling beam = 8 ft. > L_p = 8.65 ft for W 14 x 61.

For $L_p <$ unbraced length ' L_b ' ,

Moment capacity of W 14 x 61 = 383 Kip-ft > 360 Kip-ft. - Hence it has acceptable bending capacity. (LRFD design)

Thus, the coupling beam is safe for the loads induced by the actuator during testing.

A.3 Design Check for Fuse Beam

The fuse beam was a built-up section designed so that it yielded before the actuator could reach its full capacity. The built-up section was made of flange plates of 10 in. width and 3/8 in. thickness and web plate of 1 ft - 1 1/8 in. depth and 1/8 in. thickness. The overall depth of the fuse beam was 1 ft - 1 7/8 in. which was same as the coupling beam. The built-up fuse beam section was checked to confirm that it reached shear yielding before 90 Kips. The fuse is placed in the center of the coupling beam where the moment is zero. The design check for the fuse beam is presented below.

Overall depth, ' d ' = 13.875 in.

Clear distance between flanges, ' h ' = 13.125 in.

Thickness of web, ' t_w ' = 0.125 in.

Web area for shear, ' A_w ' = 13.825 x 0.125 = 1.734 in².

Moment of inertia, ' I_x ' of the fuse beam section = 365.4 in².

$E = 29,000$ Ksi

$F_y = 38$ Ksi

$h / t_w = 105$

Distance between transverse stiffeners, ' a ' = 8 in.

$a / h = 0.7$

$k_v = 5 + 5 / (a / h)^2 = 15.2$

For

$$h / t_w \leq 1.10 \sqrt{k_v E / F_y}$$

$$V_n = 0.6 F_y A_w$$

$$1.10 \sqrt{k_v E / F_y} = 118.5 > h / t_w = 105$$

$V_n = 40$ Kips

To be on the conservative side and to assure that the fuse beam yields before 90 Kips, the 0.6 factor was removed from the V_n equation. This takes the maximum shear force possible in the fuse beam $= F_y A_w = 66 \text{ Kips} < 90 \text{ Kips}$, which is acceptable.

A.4 Design of Splice Connection

The splice joint connection had two web splice plates of 10 in. width and 3/8 in. thickness on either side of the web and two flange plates of 10 in. width and 1/2 in. thickness on either flange. The design calculation to check the shear strength of the splice plates and the shear capacity of the bolts is presented below.

Moment of Inertia of the splice plates about major axis, ' I_x ', (Ignoring self moment of inertia of the flange plates)

$$= 2 \times 3/8 \times 10^3 / 12 + 2 \times 1/2 \times 10 \times 7.2^3 = 581 \text{ in.}^4 > 365.4 \text{ (Fuse Beam 'I}_x\text{')}$$

$$< 640 \text{ (Coupling Beam 'I}_x\text{')}$$

$$\text{Total area} = 2 \times 10 \times 3/8 + 2 \times 1/2 \times 10 = 17.5 \text{ in.}^2$$

$$\text{Web plate area} = 7.5 \text{ in.}^2 > 5.21 \text{ in.}^2 \text{ (Web area 'A}_w\text{' of fuse beam and coupling beam)}$$

$$F_y = 50 \text{ Ksi}$$

Shear strength $= 0.6 \times 7.5 \times 50 = 225 \text{ Kips} > 90 \text{ Kips}$ (LRFD design). Hence it is acceptable.

Shear strength $= 0.4 \times 7.5 \times 50 = 150 \text{ Kips} > 90 \text{ Kips}$ (LRFD design). Hence it is acceptable.

The bolts used were A-325 (X-type) bolts of 5/8 in. diameter. The connection was designed as slip-critical connection. The bolt was subjected to double shear.

From Table 7-16 (AISC, LRFD Manual, 3rd Edition, 2001), design resistance to shear at service loads for bolts is as follows:

A325 bolt with 5/8 in. diameter and in double shear have a design resistance of 10.4 Kips.

There were 9 bolts in the web of the spliced connection in the experimental test setup.

Total capacity of 9 bolts = $10.4 \times 9 = 93.6$ Kips > 90 Kips shear. Hence the bolts have adequate shear capacity.

A.5 Tensile Coupon Test

In order to make sure the fuse beam is weaker than the coupling beam in shear, tensile tests of the steel used in the web of the fuse was conducted to determine its yield strength. Prior to testing, the cross-sectional area of the specimens must be determined. During the test, the load and strain were measured. Using the resulting stress verses strain relationship, it is possible to determine the yield stress, ultimate stress, and the modulus of elasticity of the steel used. The yield stress is the point at which the stress/strain relationship becomes non-linear. This can be easily seen when graphed. The ultimate stress of the steel is the highest point on the y-axis of the resulting graph.

For an applied load, 'P' the normal stress can be computed from the following equation:

$$\sigma = \frac{P}{A} \quad (A.1)$$

where

σ = normal stress,

P = applied load, and

A = original cross sectional area of the specimen.

The strain is equal to the change in length divided by the initial length, and is given by the following equation:

$$\varepsilon = \Delta L / L \quad (\text{A.2})$$

where

ε = normal strain,

ΔL = change in length, and

L = original length of the specimen.

Hooke's Law for an elastic material states that stress is equal to the product of strain and the modulus of elasticity of the material, which gives

$$\sigma = \varepsilon E \quad (\text{A.3})$$

where

E = modulus of elasticity of the material.

Since both stress and strain are known, this equation can be solved for the modulus, which gives

$$\sigma / \varepsilon = E \quad (\text{A.4})$$

The yield stress obtained from the experimental test was 38.0 Ksi., which was less than the coupling beam yield strength of 50 Ksi. The graph of stress versus strain relationship is presented in Fig. 2.8 of Chapter 2.

APPENDIX – B

TENSION COUPON TEST PHOTOGRAPHS

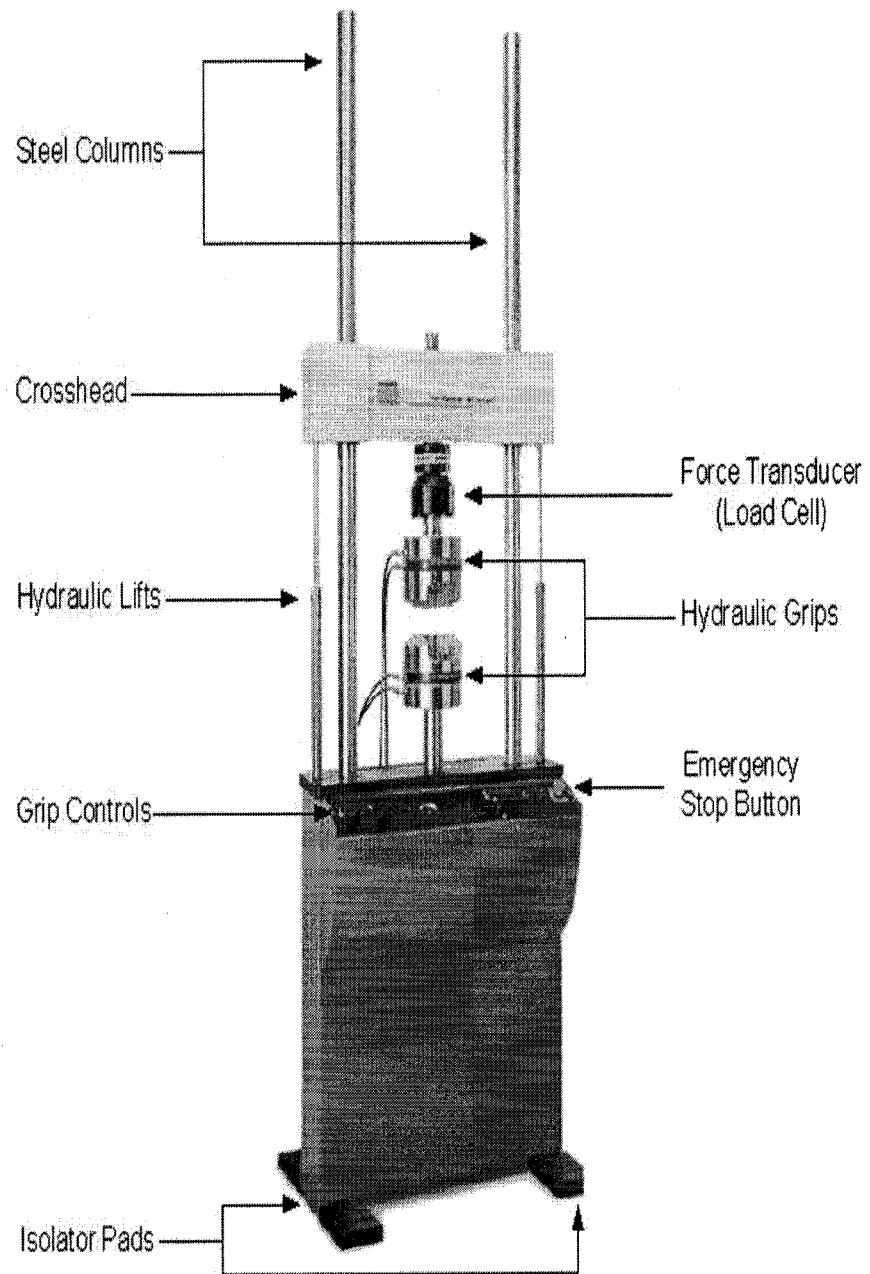


Figure B.1 MTS 312 Machine

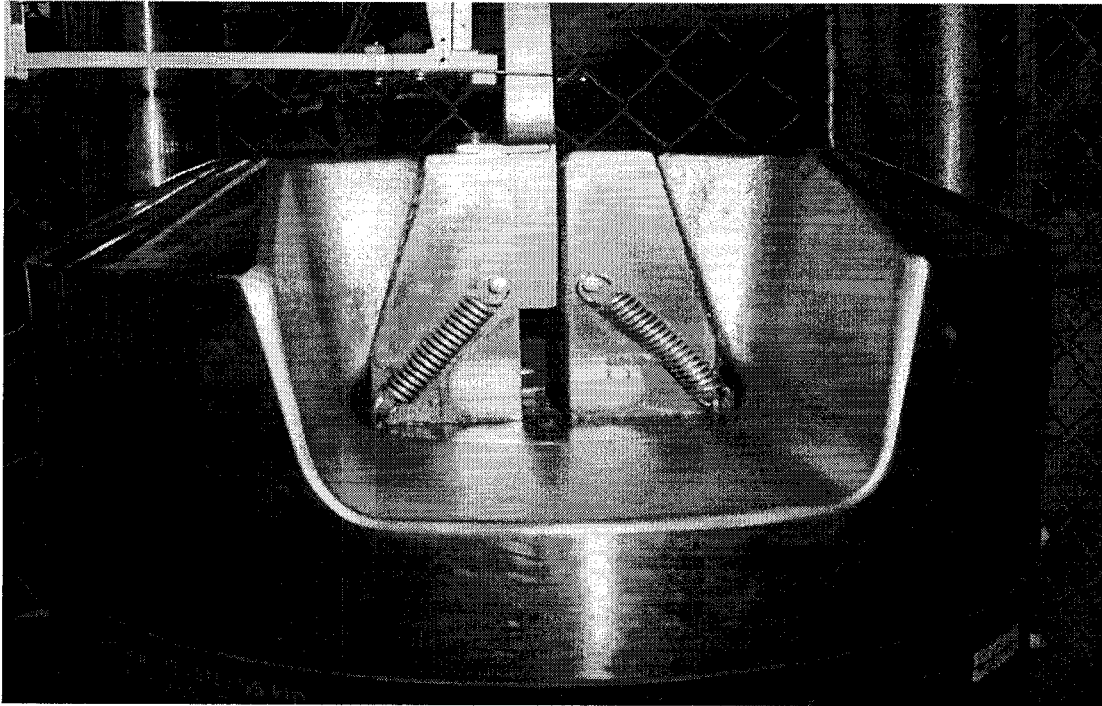


Figure B.2 MTS 647 Hydraulic Wedge Grips

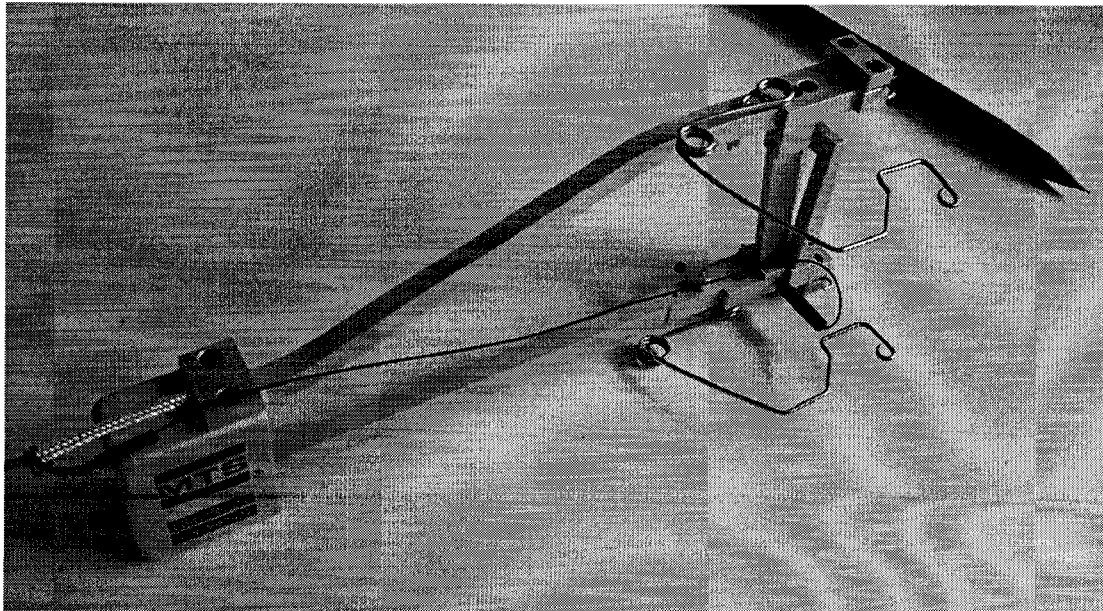


Figure B.3 MTS Strain-Extensometer



Figure B.4 Coupon Test Set-Up Between Grips

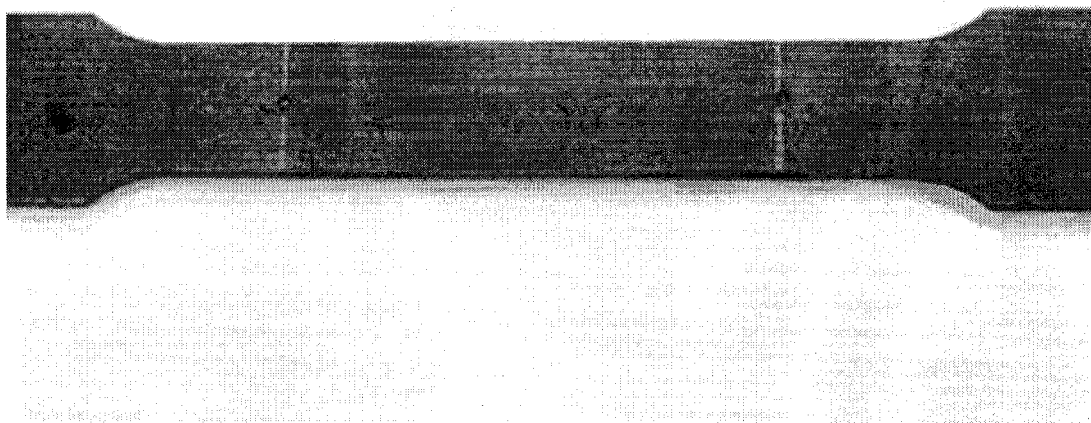


Figure B.5 Tension Test Coupon

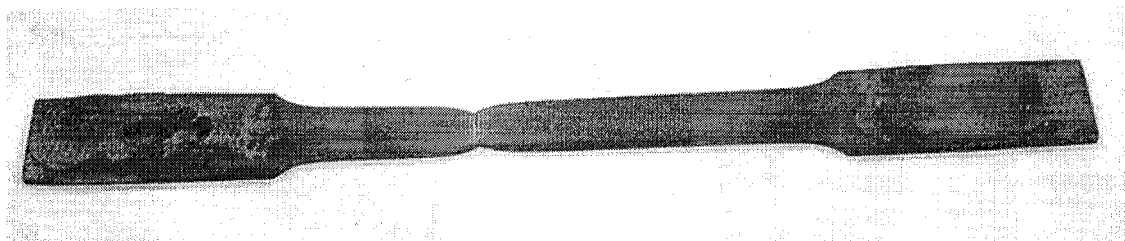


Figure B.6 Elongated Coupon

APPENDIX – C

TEST SETUP, APPARATUS AND INSTRUMENTS PHOTOGRAPHS

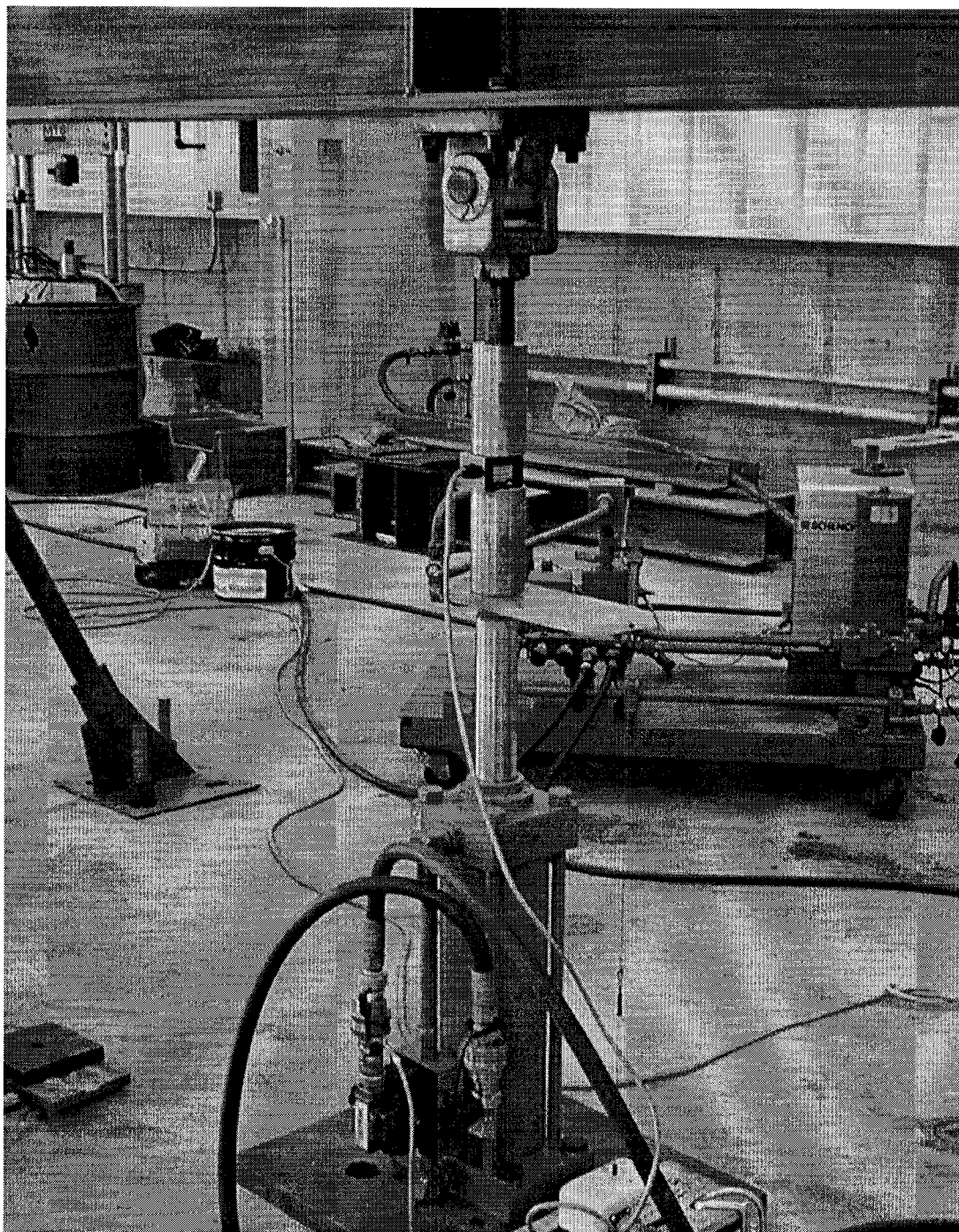


Figure C.1 Actuator and Load Cell

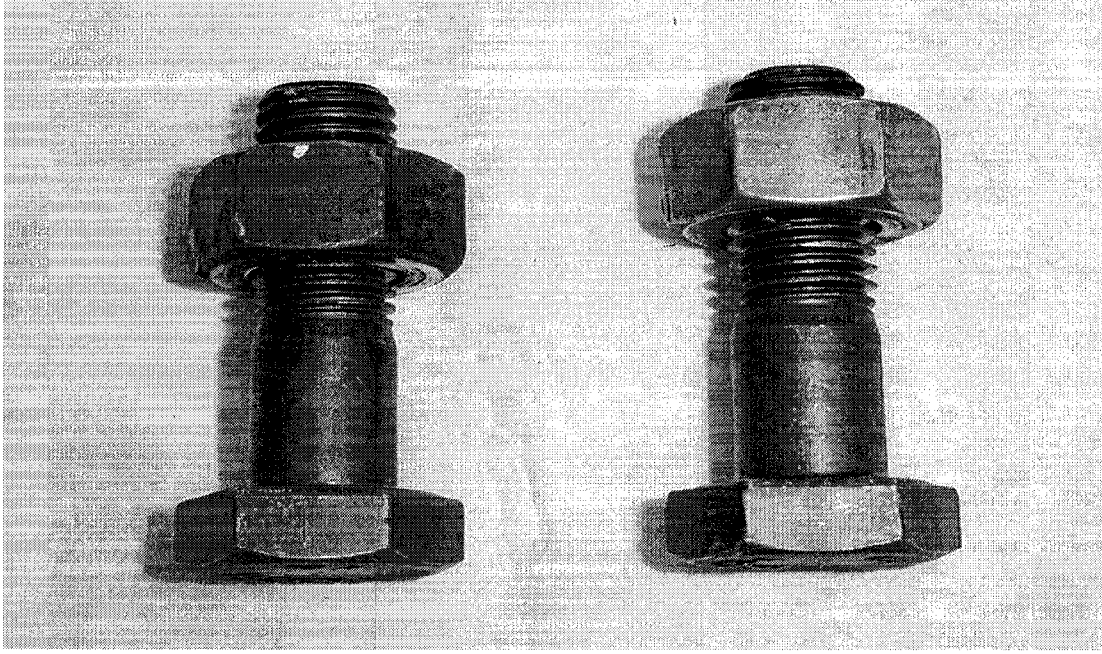


Figure C.2 A-325 Bolts



Figure C.3 Direct Tension Indicator (DTI) Washers

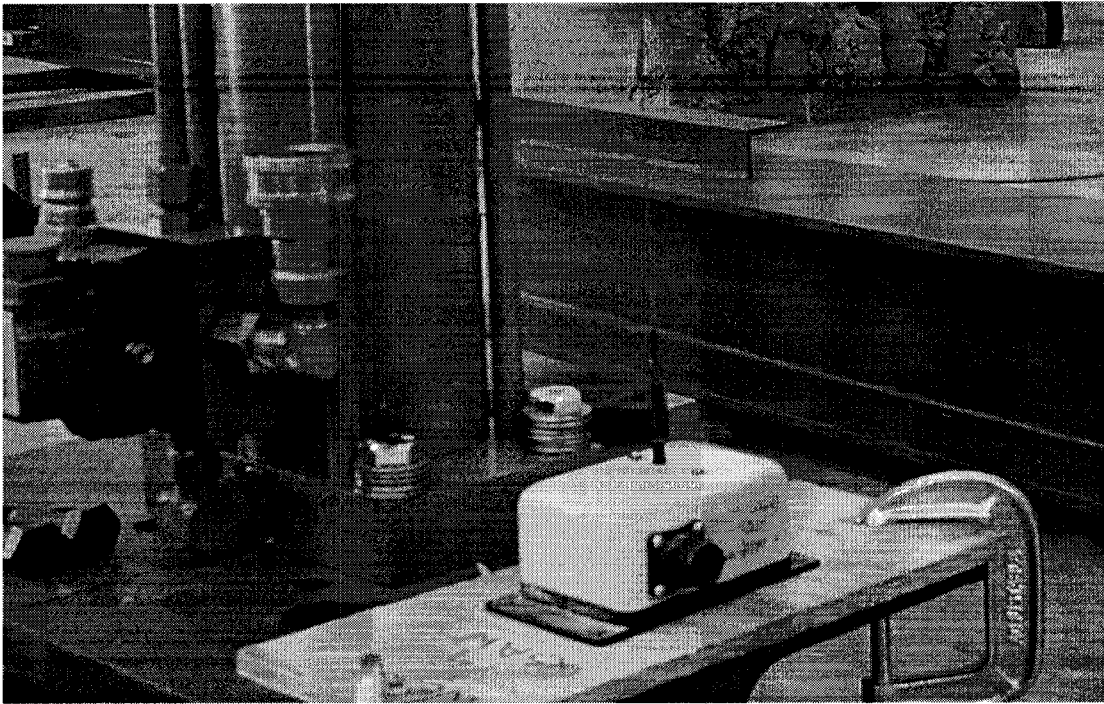


Figure C.4 Wire Potentiometer

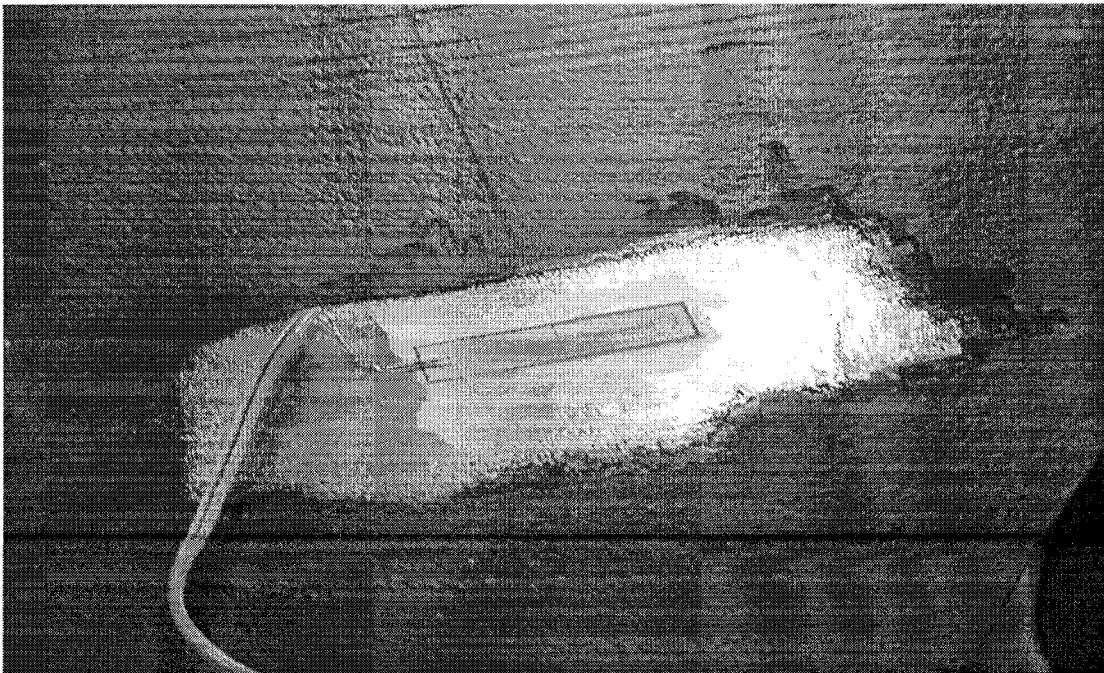


Figure C.5 Strain Gauge

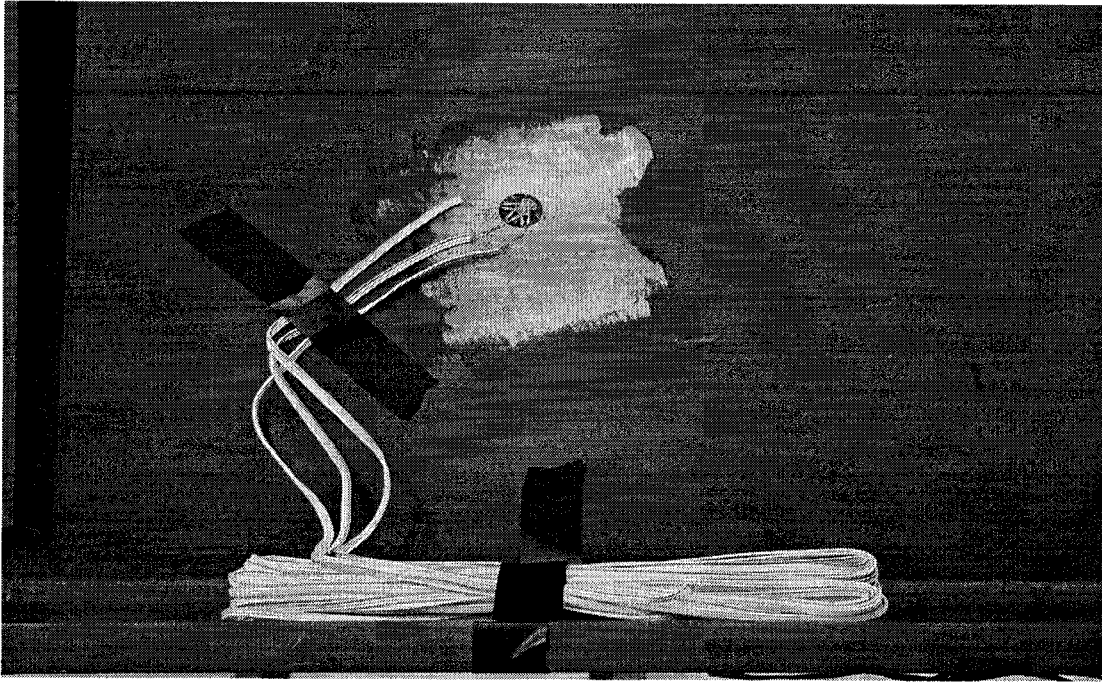


Figure C.6 Strain Rosette

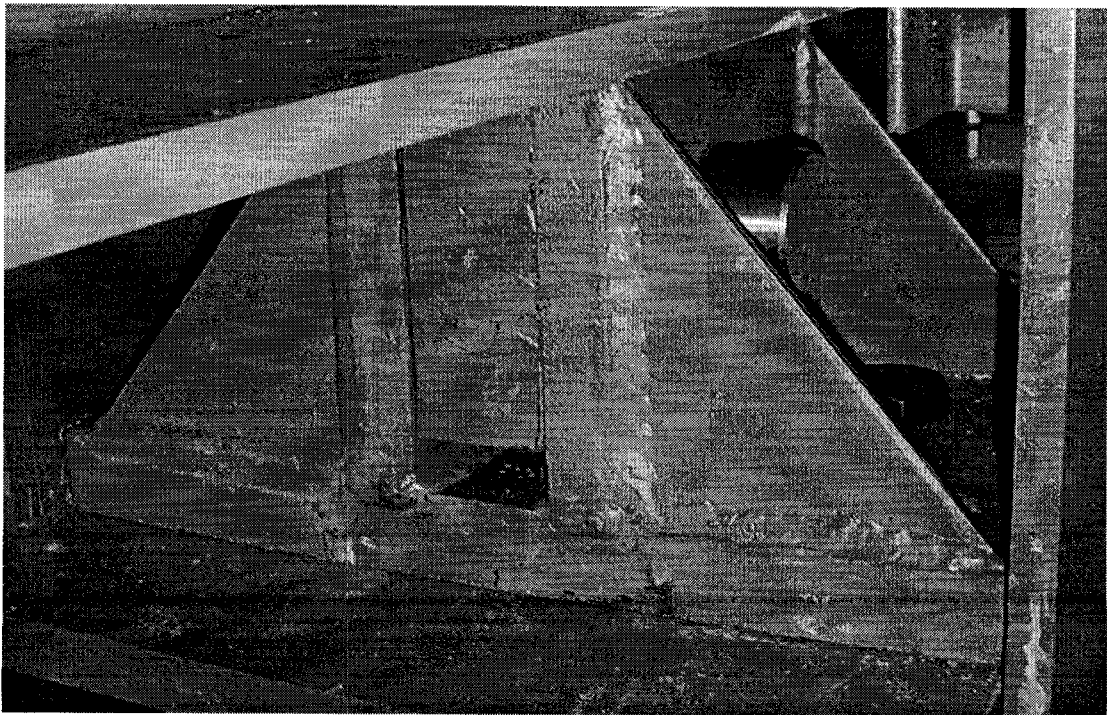


Figure C.7 Pinned Support

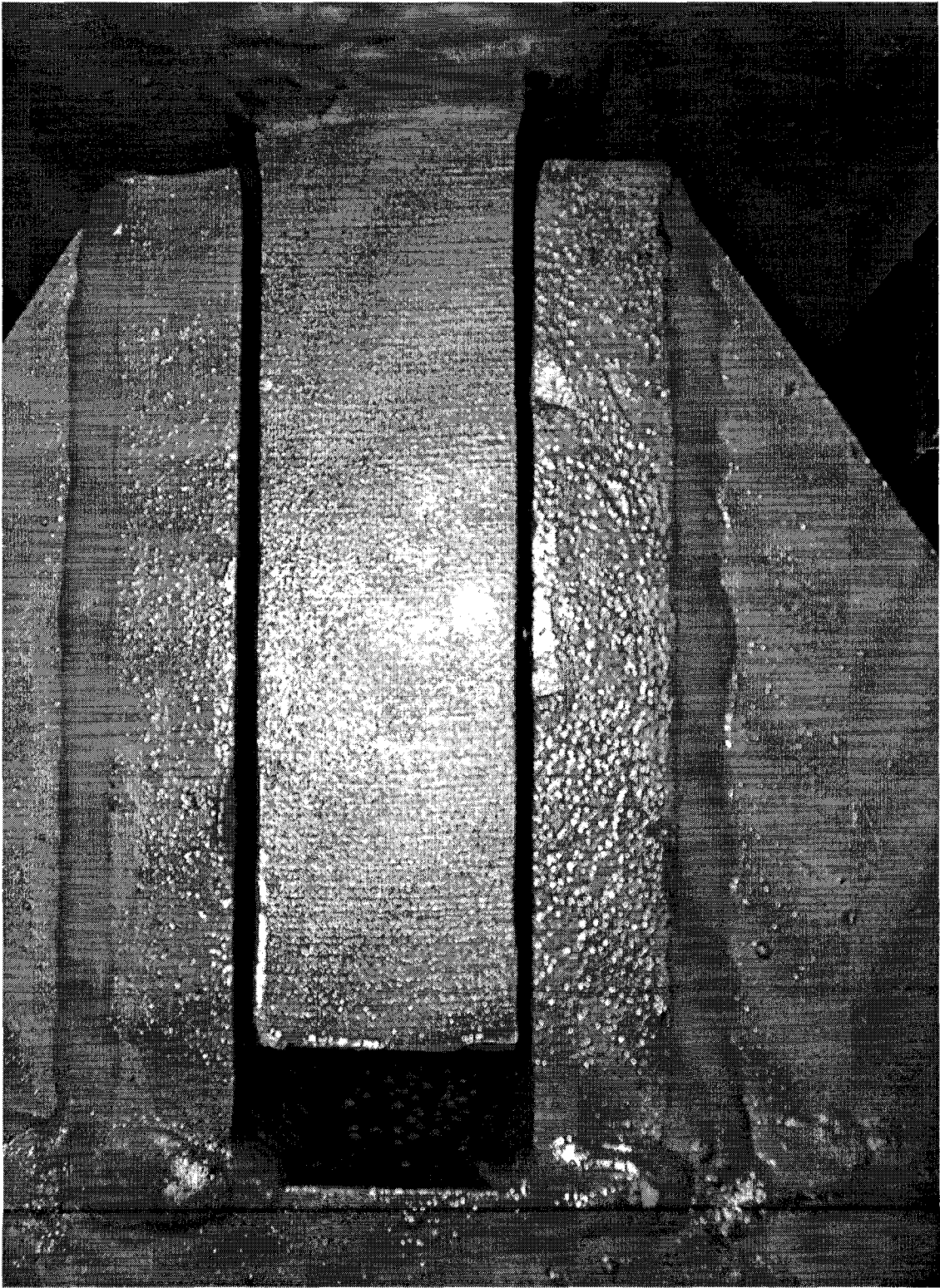


Figure C.8 Close Up of Pinned Support

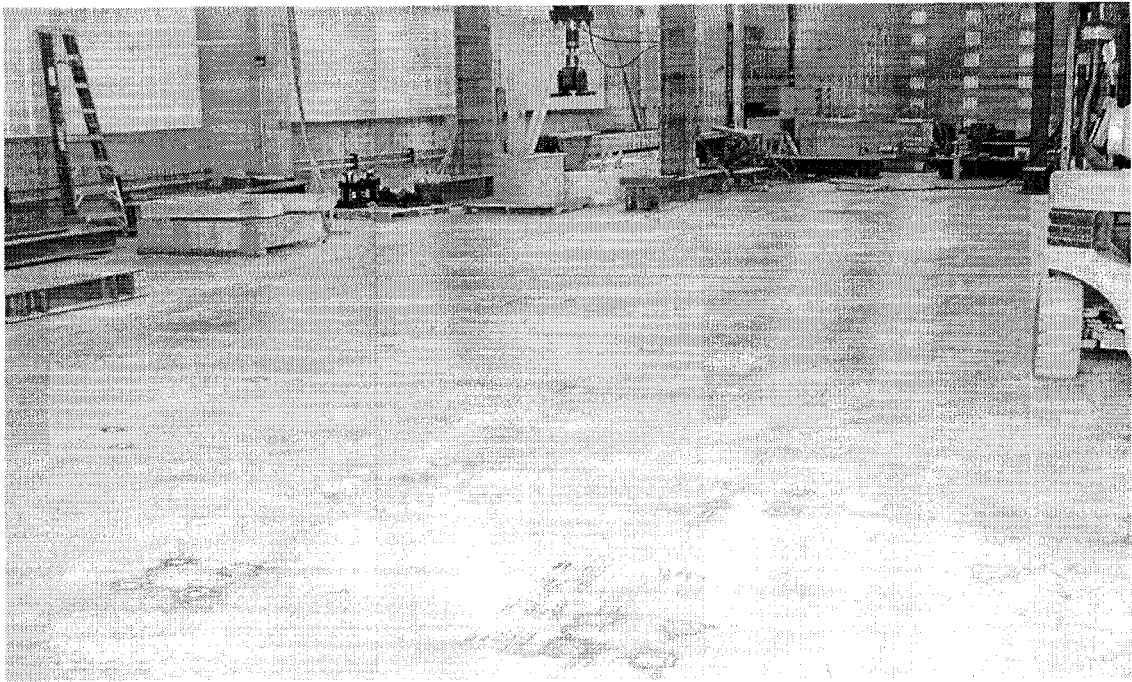


Figure C.9 Test Setup Area

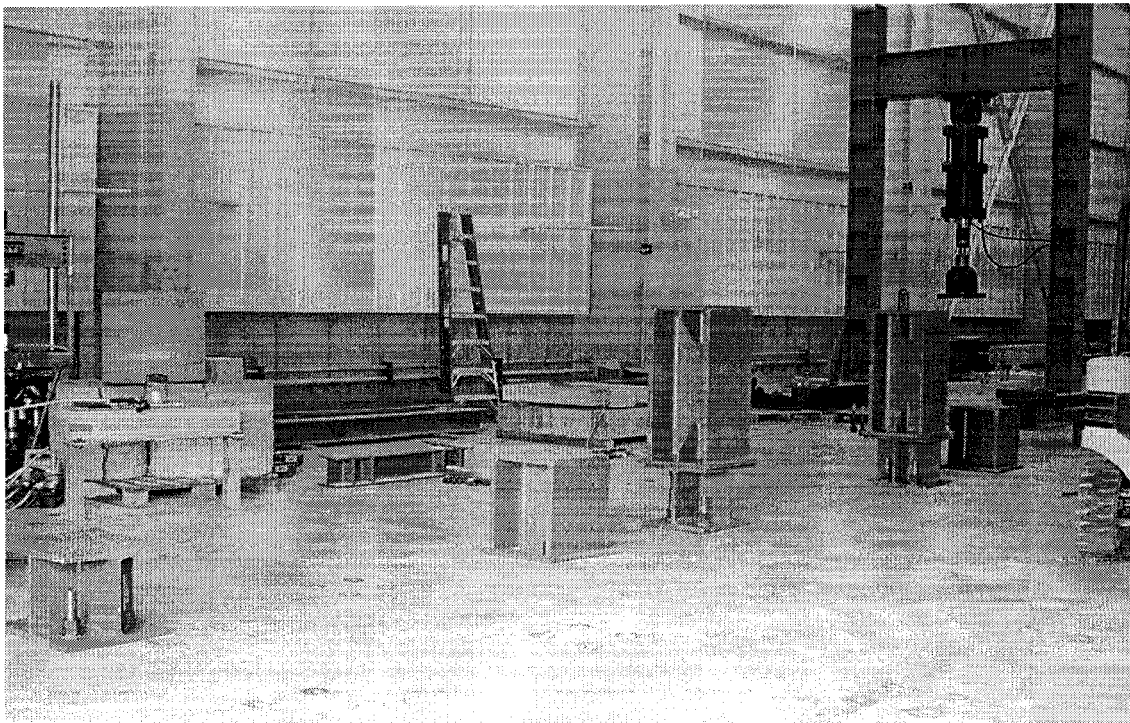


Figure C.10 Actuator and Coupling Beam Support Bases Placed in Position

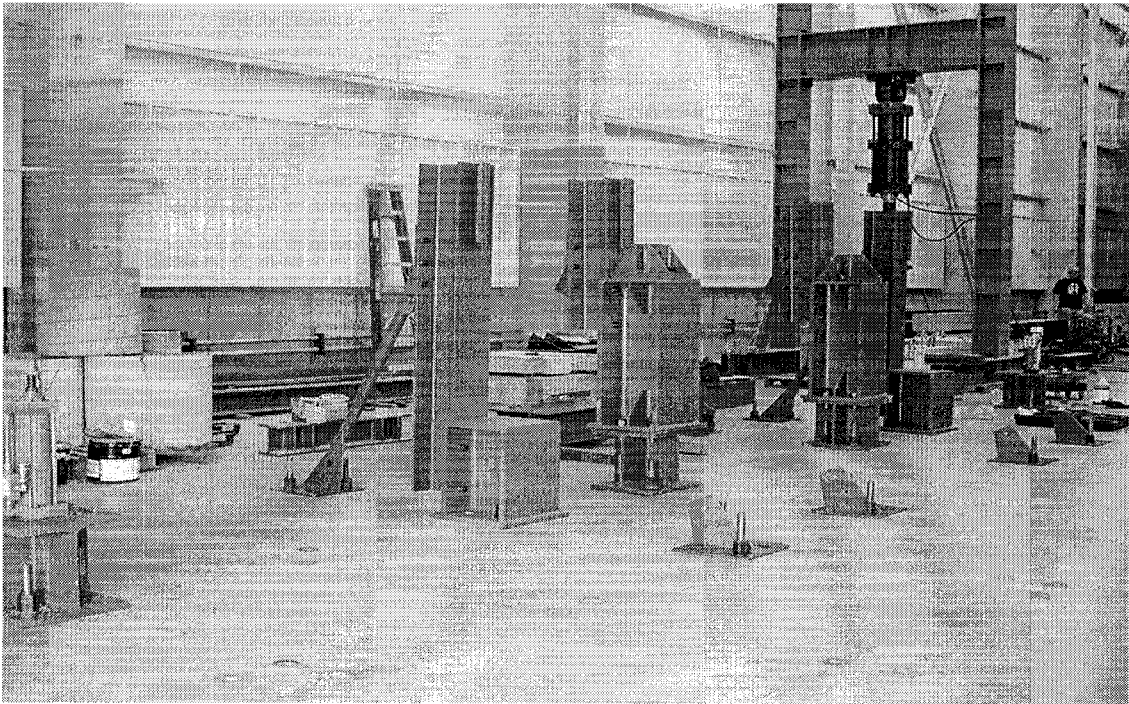


Figure C.11 Coupling Beam Supports and Braces on One Side Placed

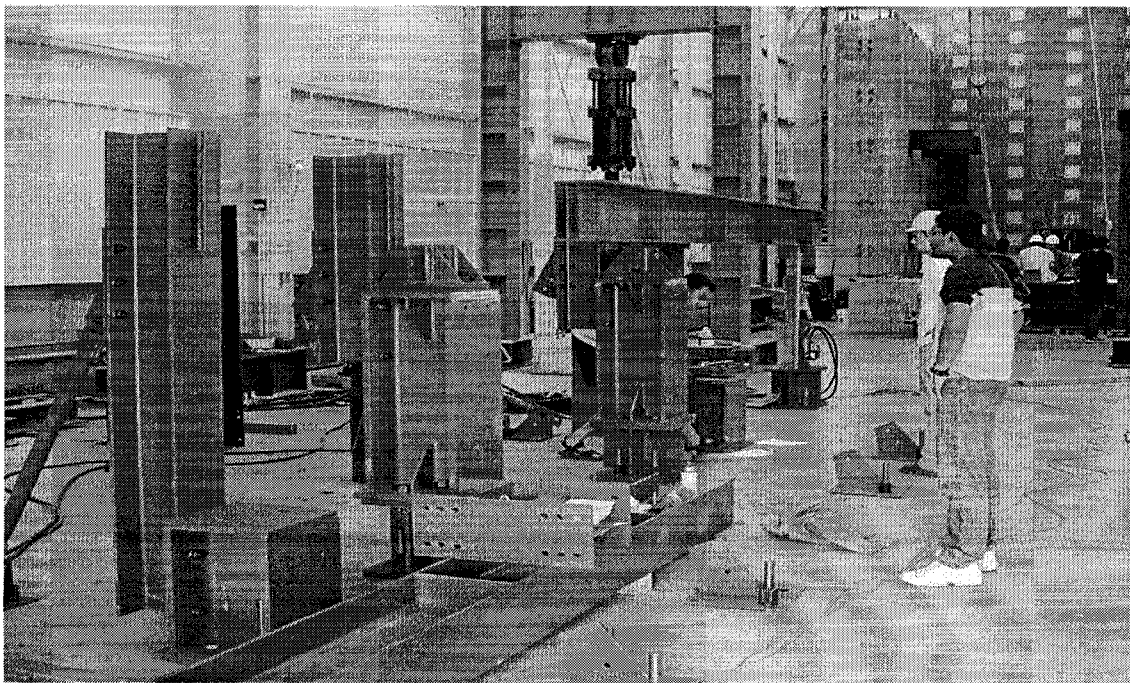


Figure C.12 East Side of the Coupling Beam Placed

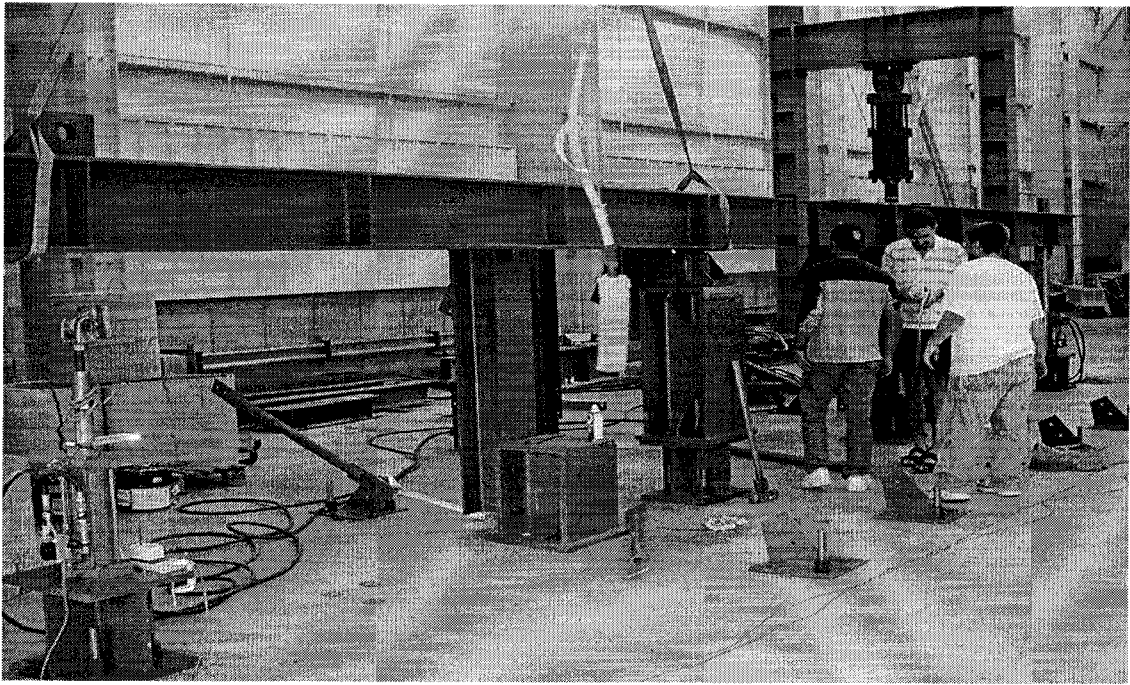


Figure C.13 West Side of the Coupling Beam Being Placed

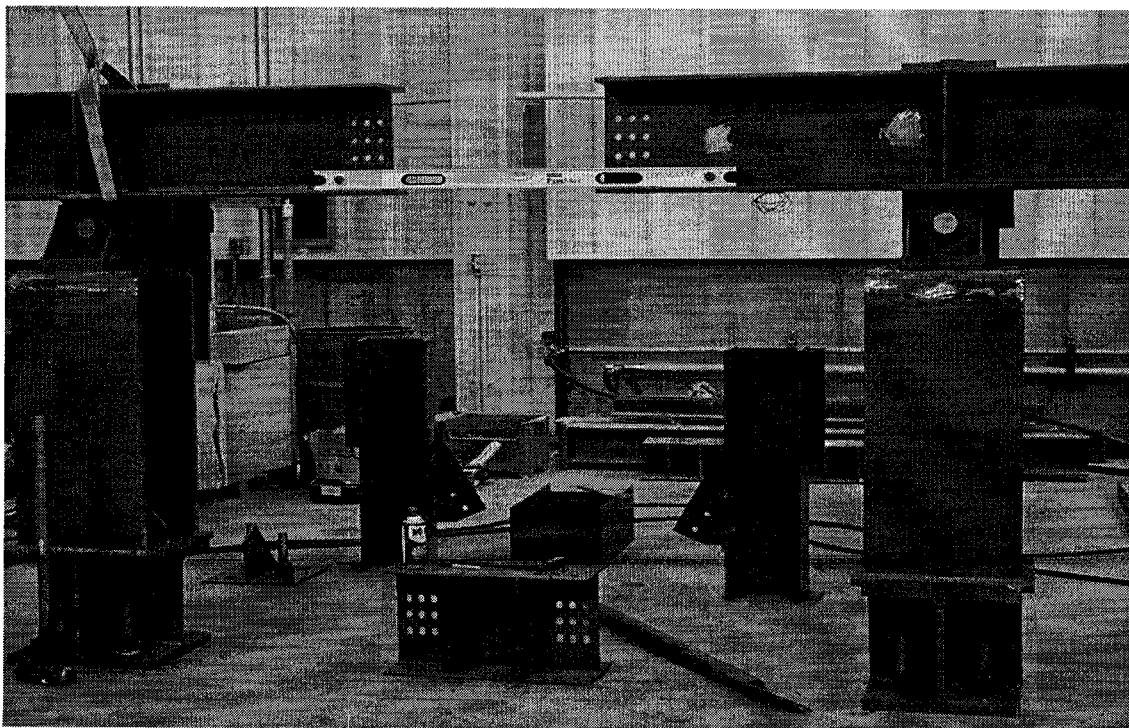


Figure C.14 Leveling of Coupling Beams

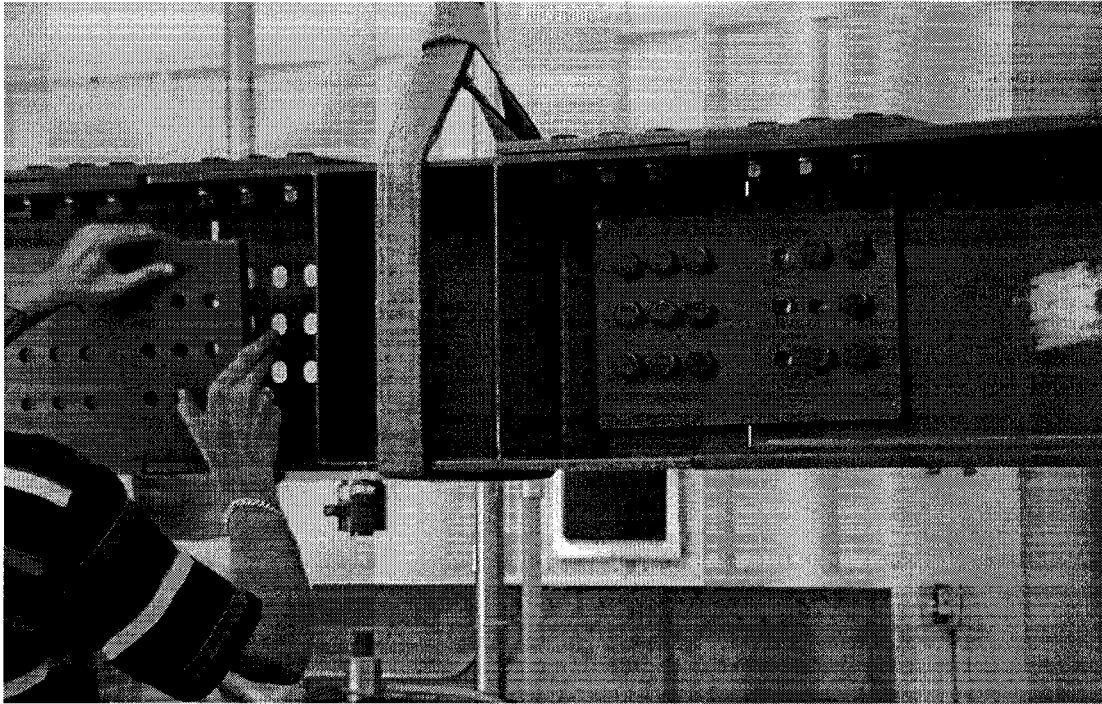


Figure C.15 Placing Fuse In Position

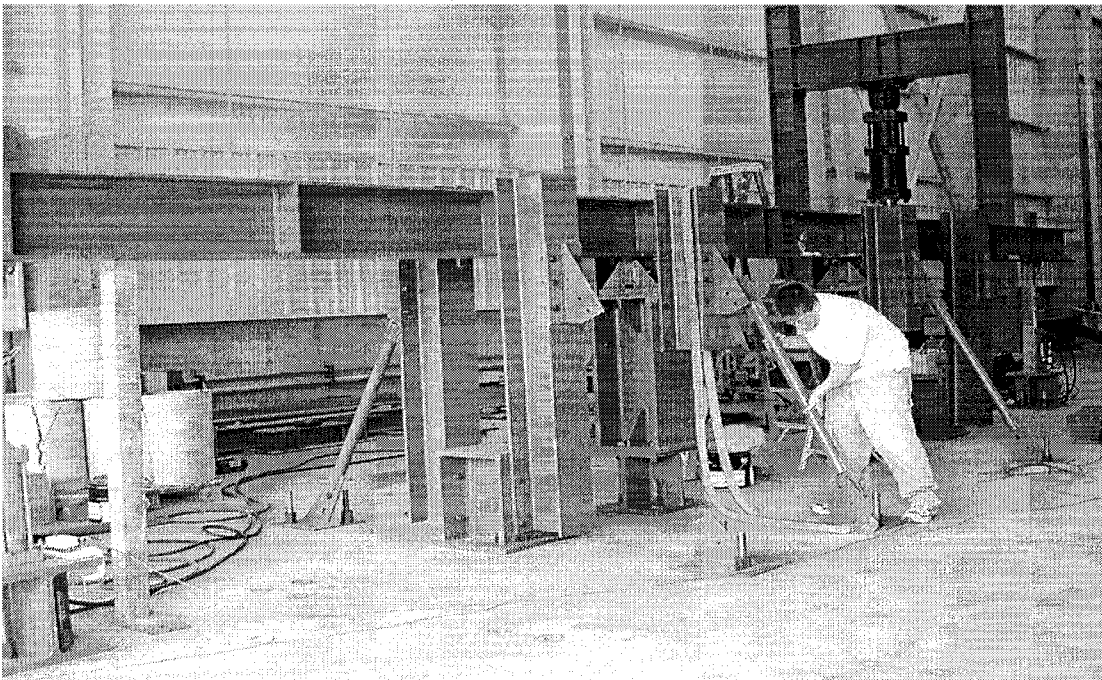


Figure C.16 Fixing Braces on Other Side

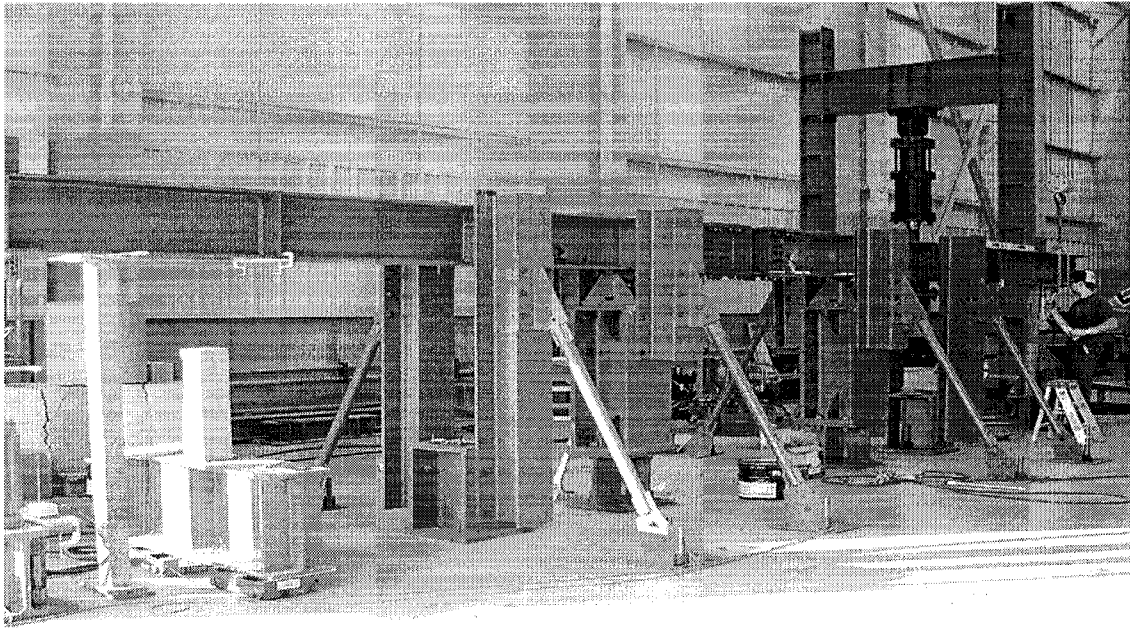


Figure C.17 Final Test Setup

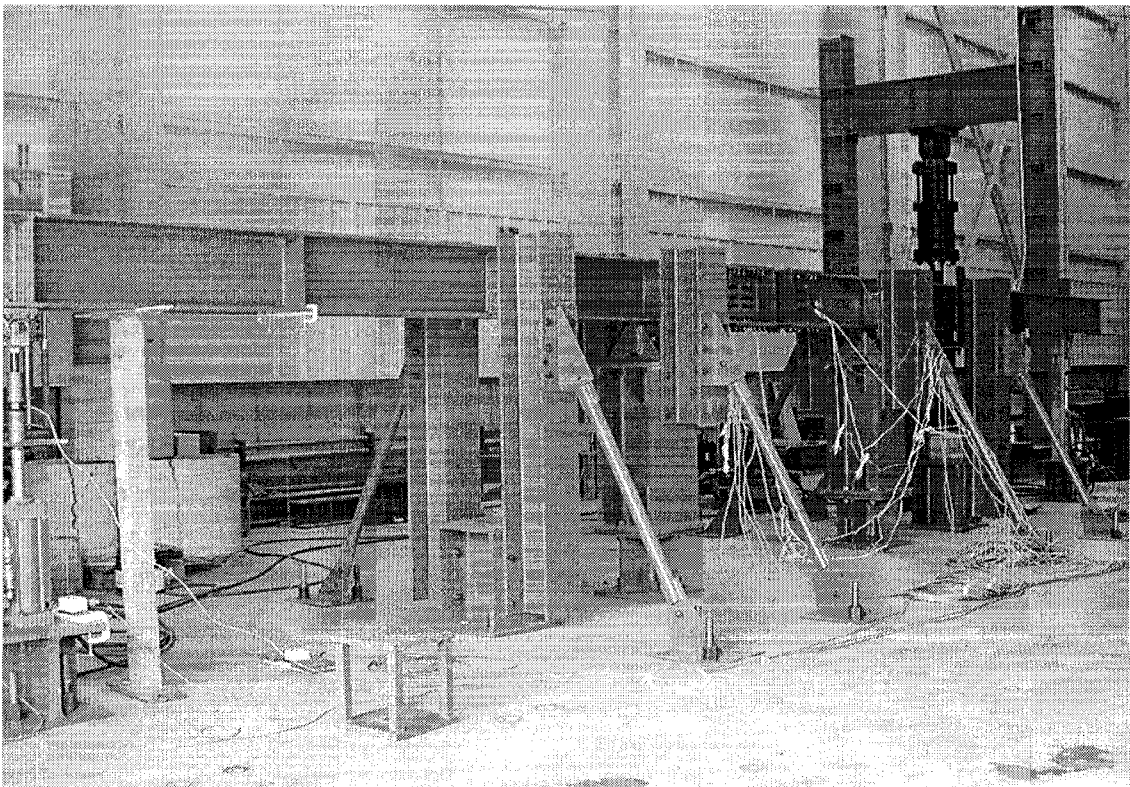


Figure C.18 Test Setup Instrumented, Wired and Ready for Testing

APPENDIX – D

FUSE BEAM TEST # 1, # 2, # 3 AND # 4 PHOTOGRAPHS

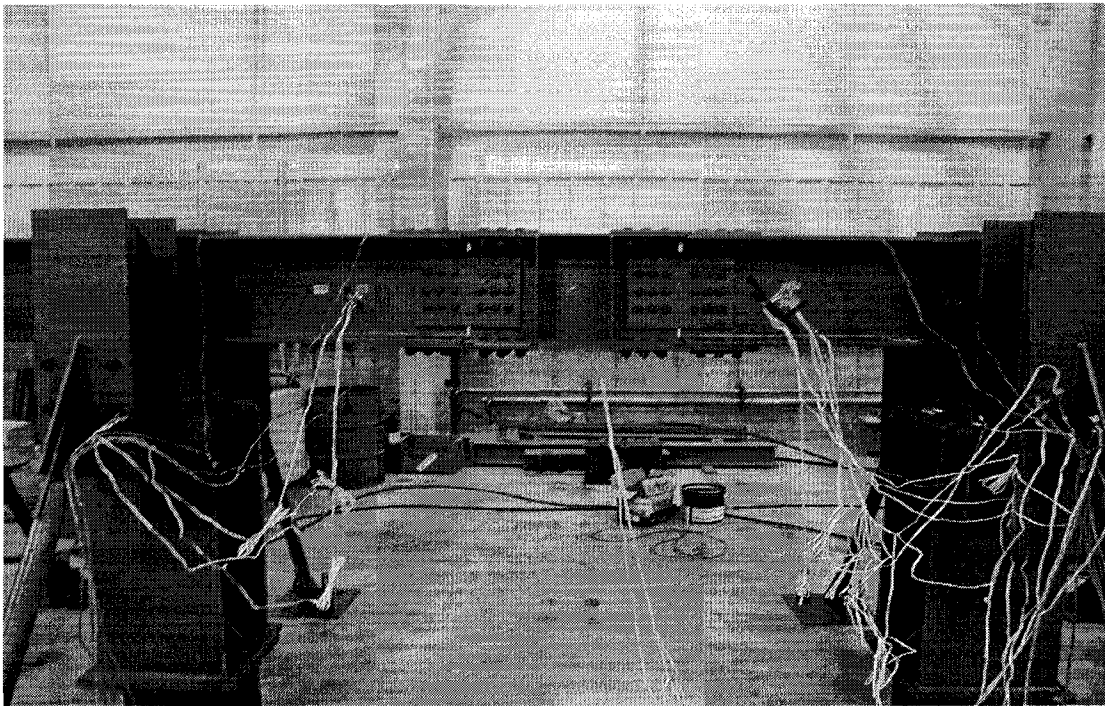


Figure D.1 Fuse Beam #1 Installed in Coupling Beam

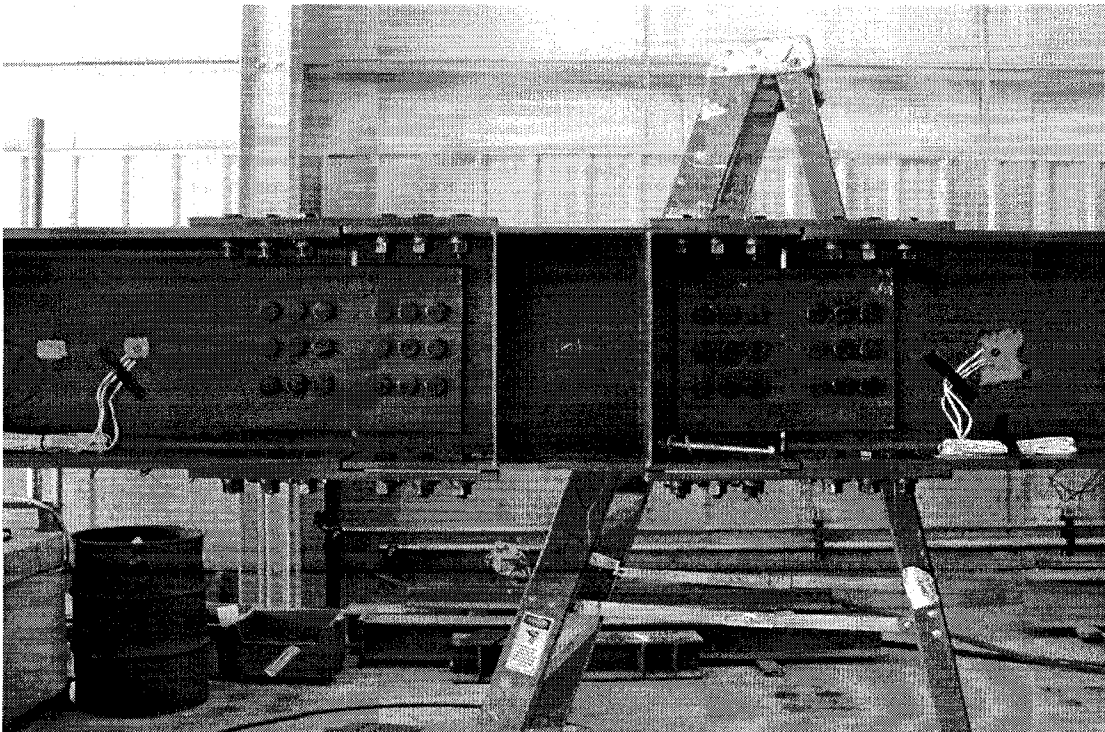


Figure D.2 Close Up of Fuse Beam # 1



Figure D.3 Full Test Setup During Testing

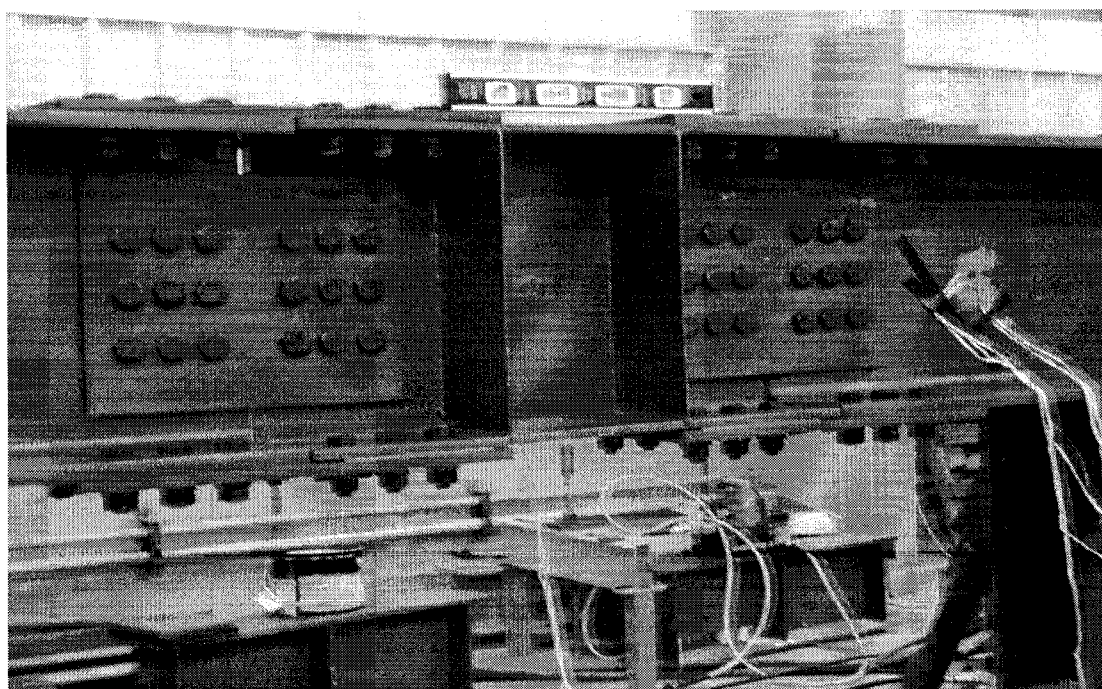


Figure D.4 Yield Pattern Developing During Test #1

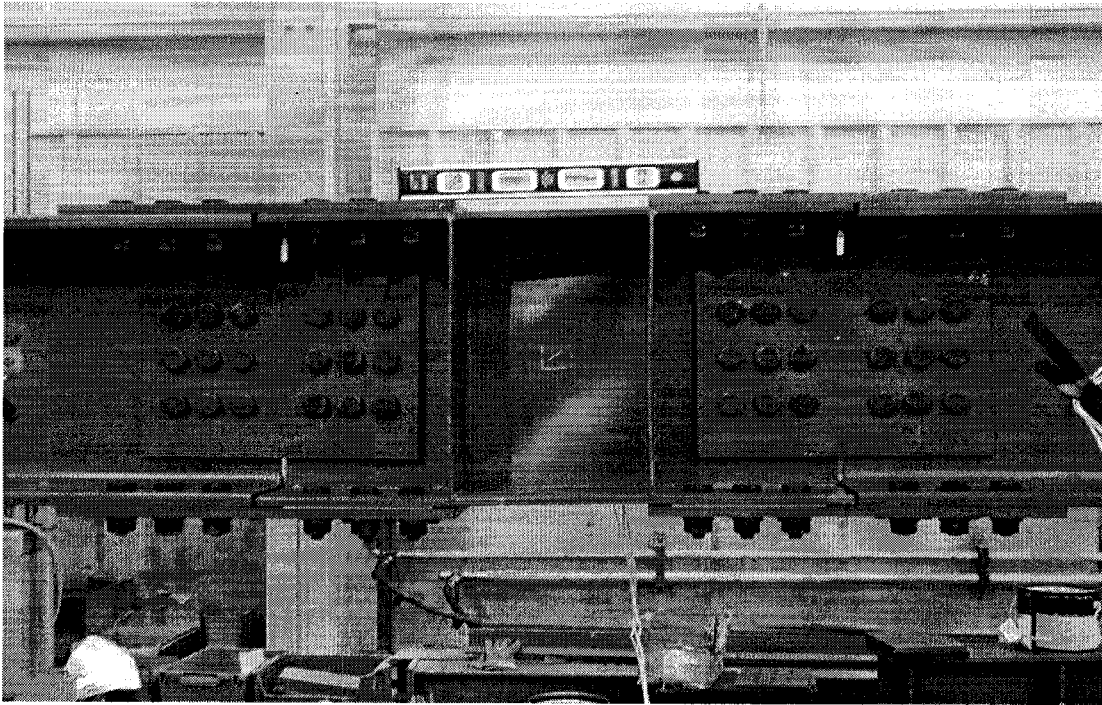


Figure D.5 Fuse Beam Web Buckling During Test #1

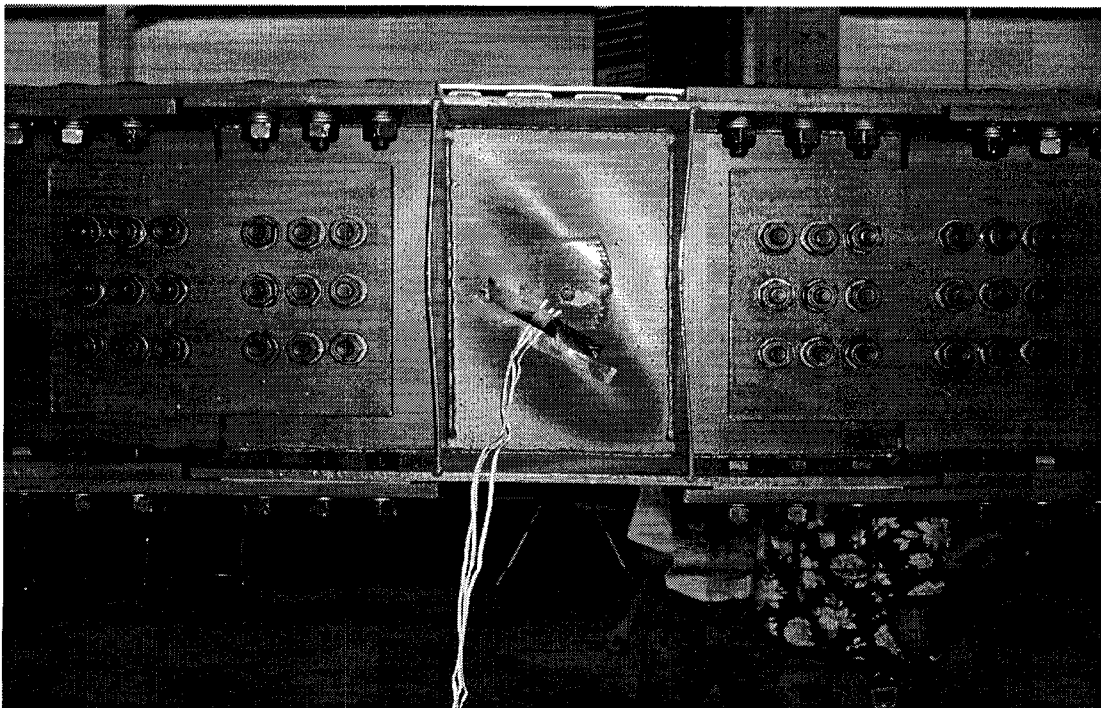


Figure D.6 Fuse Beam Buckling During Test #1 (Strain Gauge Side)

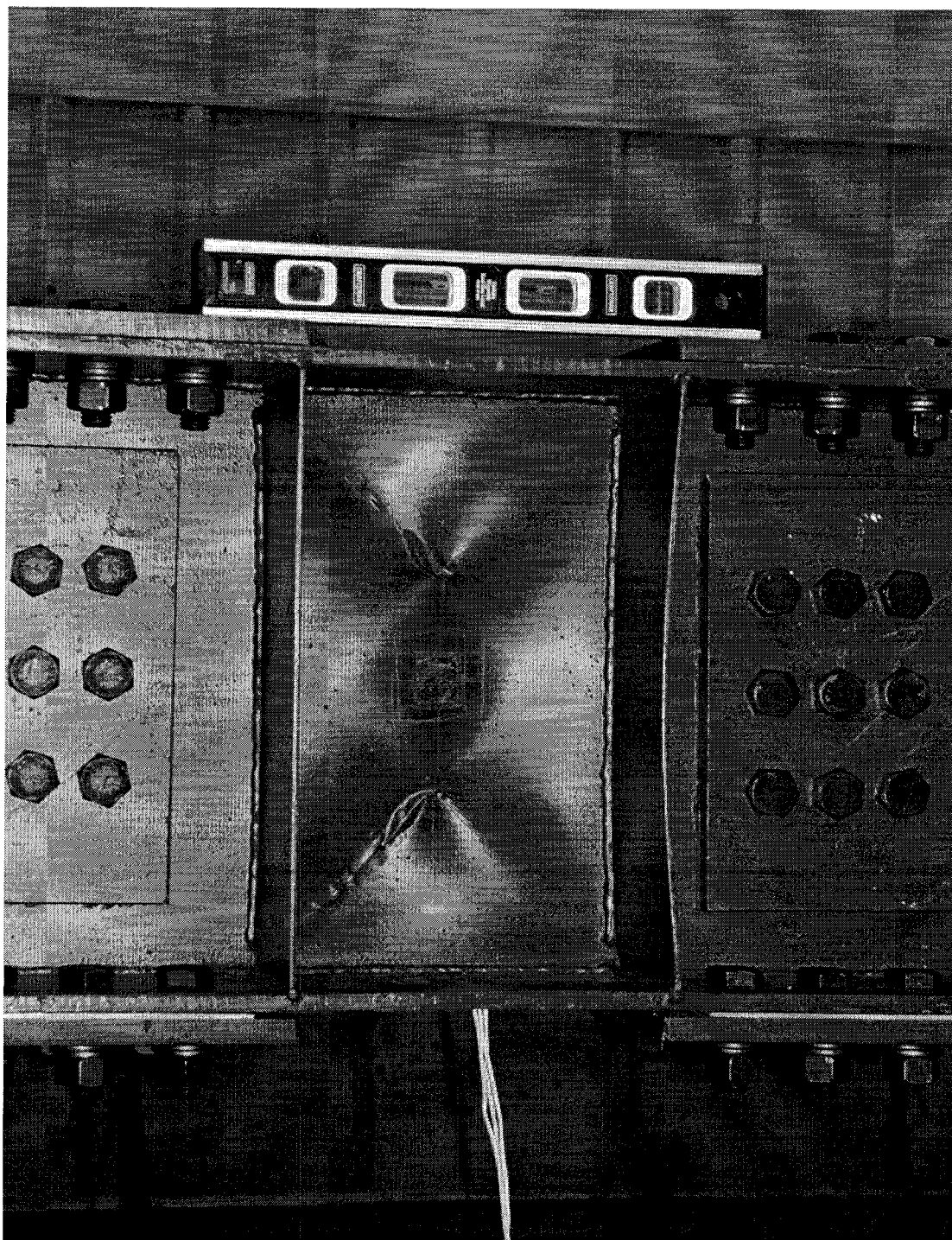


Figure D.7 Buckling Direction Changing During Cyclic Loading in Test #1

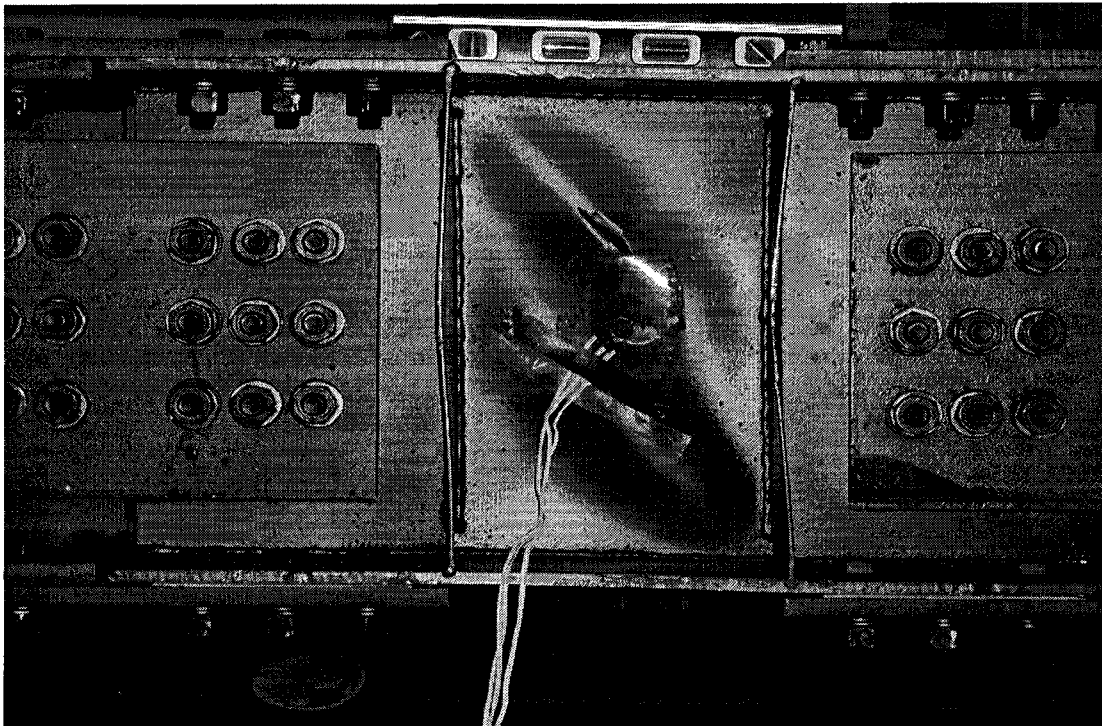


Figure D.8 Buckled Fuse After End of Test #1

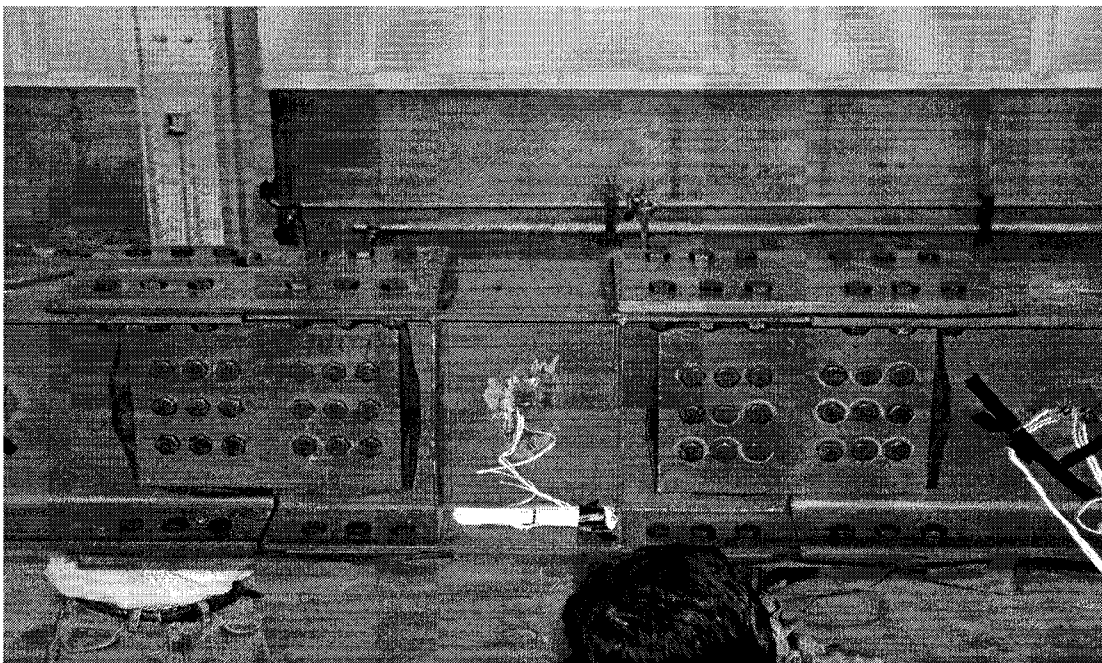


Figure D.9 Fuse Beam #2 Installed in Coupling Beam

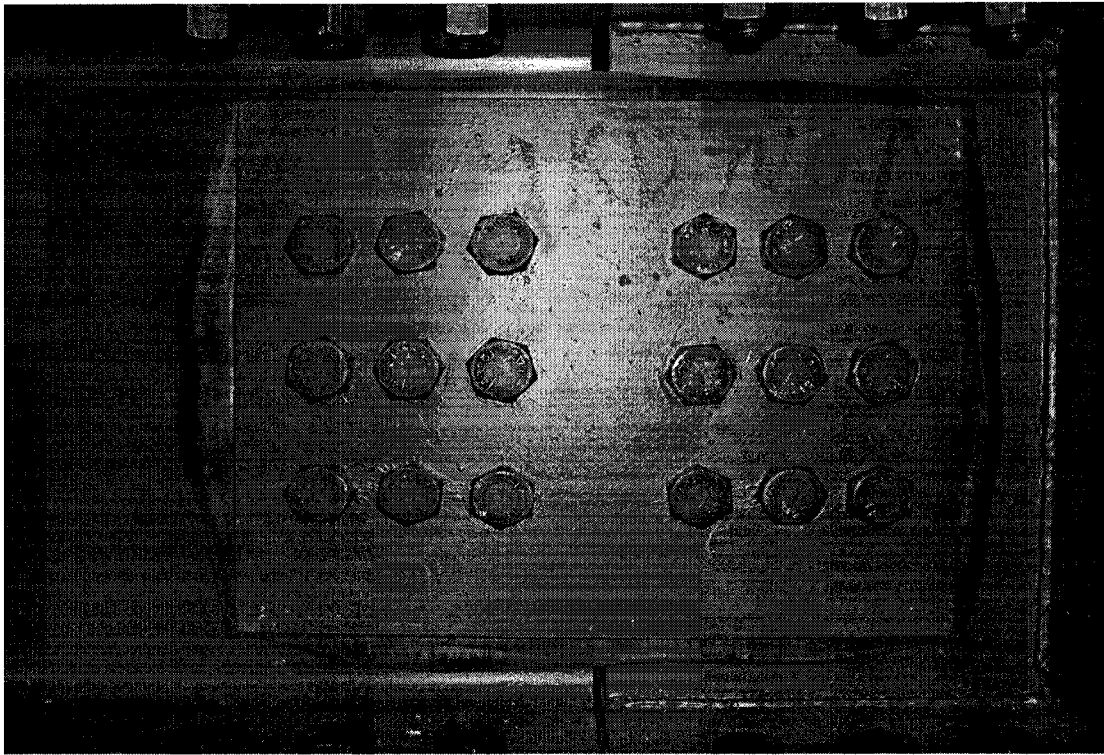


Figure D.10 Elastomeric Pads Squeezing Out Due to Pre-Tensioning of Bolts

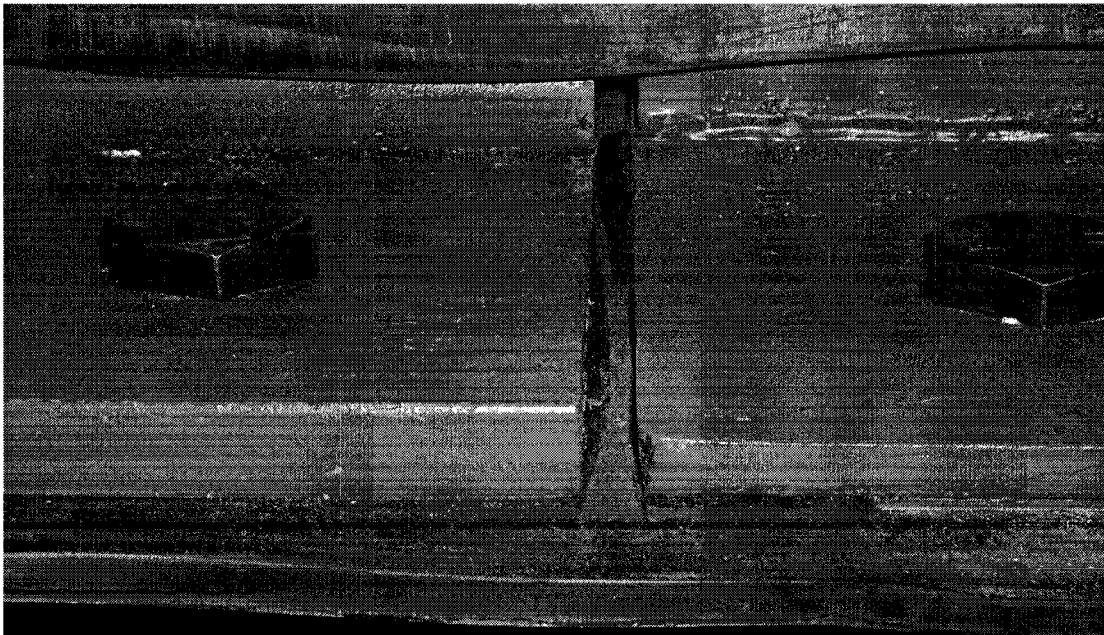


Figure D.11 Elastomeric Pads Beginning to Squeeze Between the Flange Splice Joint During Test #2

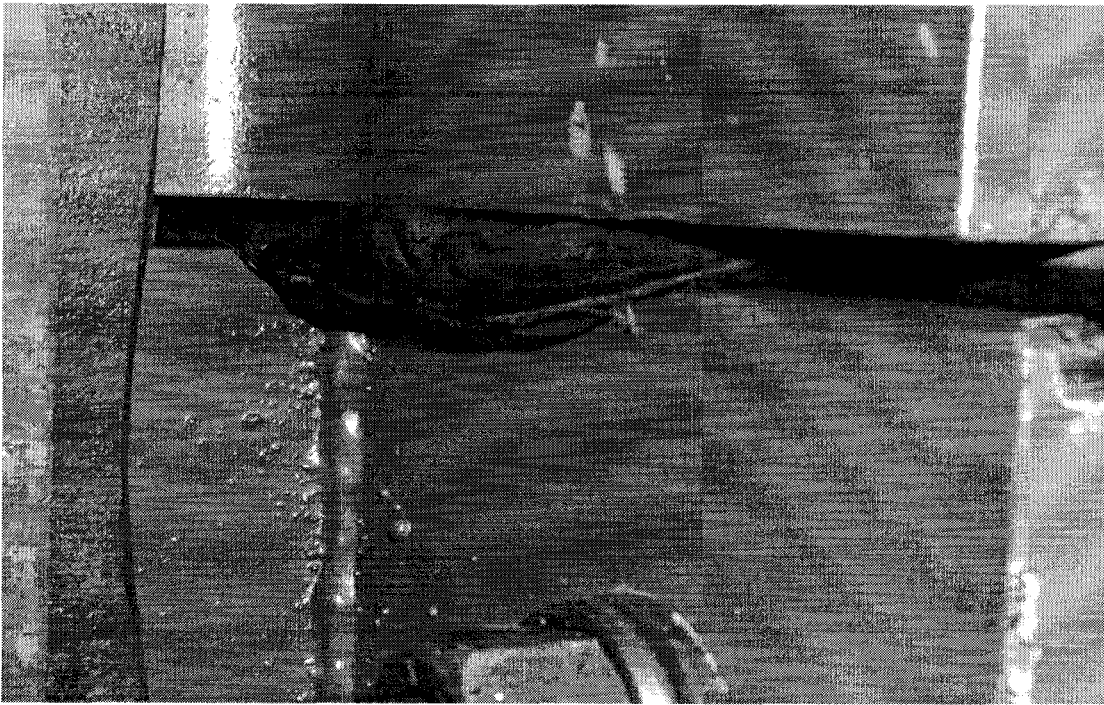


Figure D.12 Elastomeric Pads Squeezed and Sheared Between Flange Splice Joint During Test #2

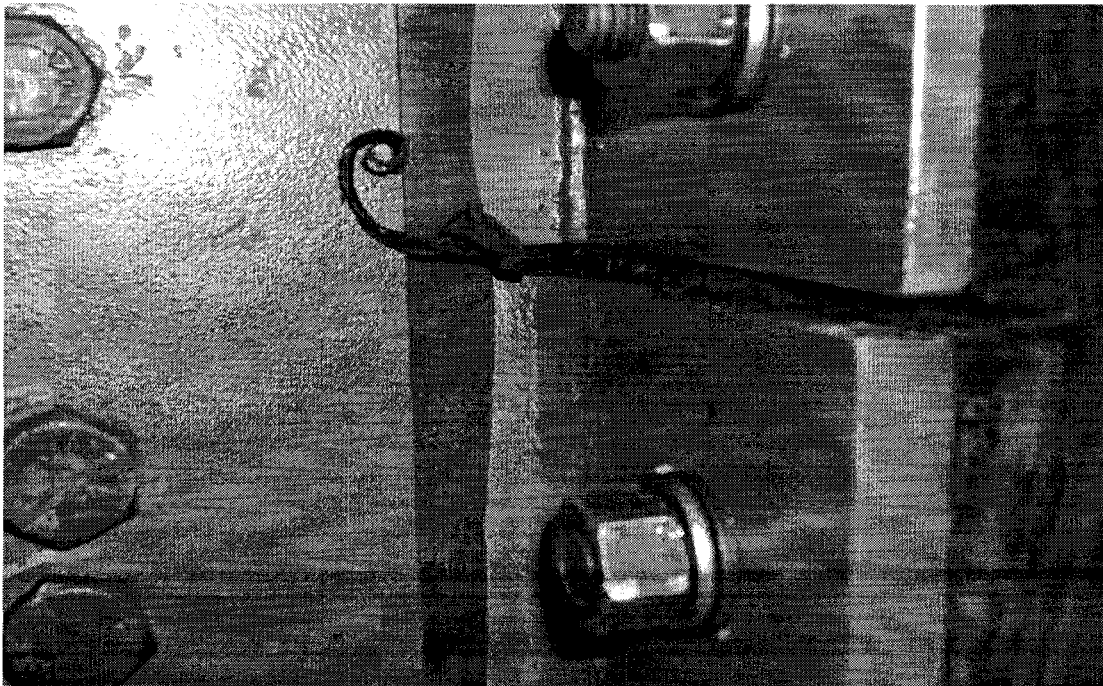


Figure D.13 Elastomeric Pads Squeezed and Torn Between Flange Splice Joint During Test #2

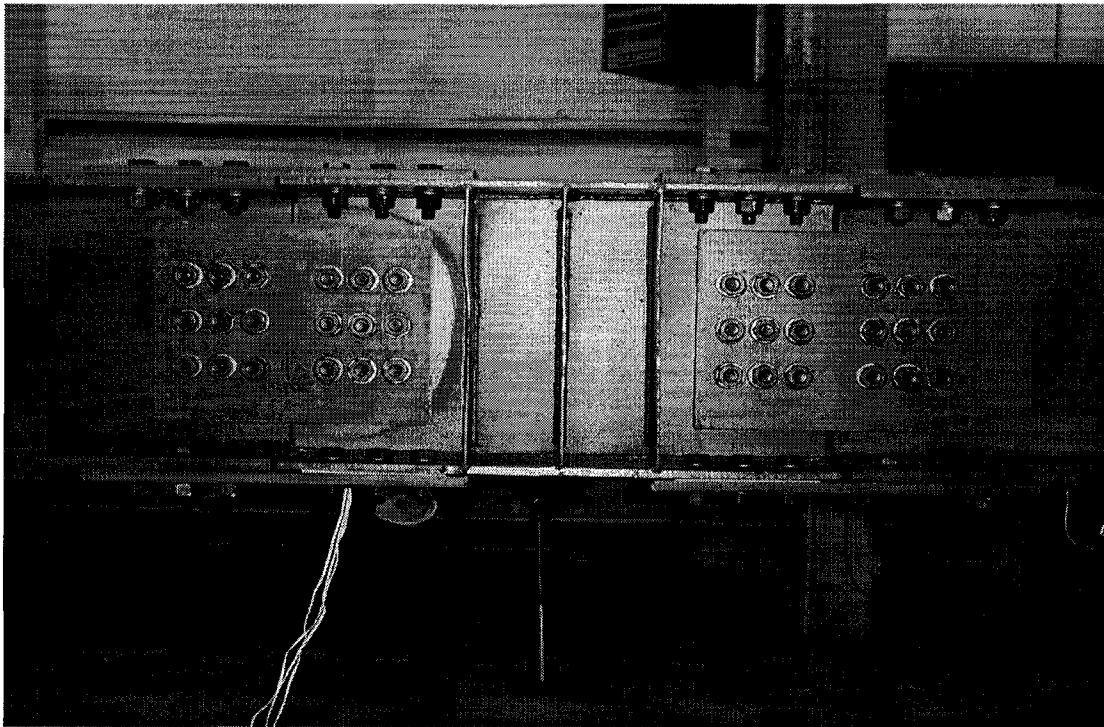


Figure D.14 Fuse Beam #3 Installed in Coupling Beam

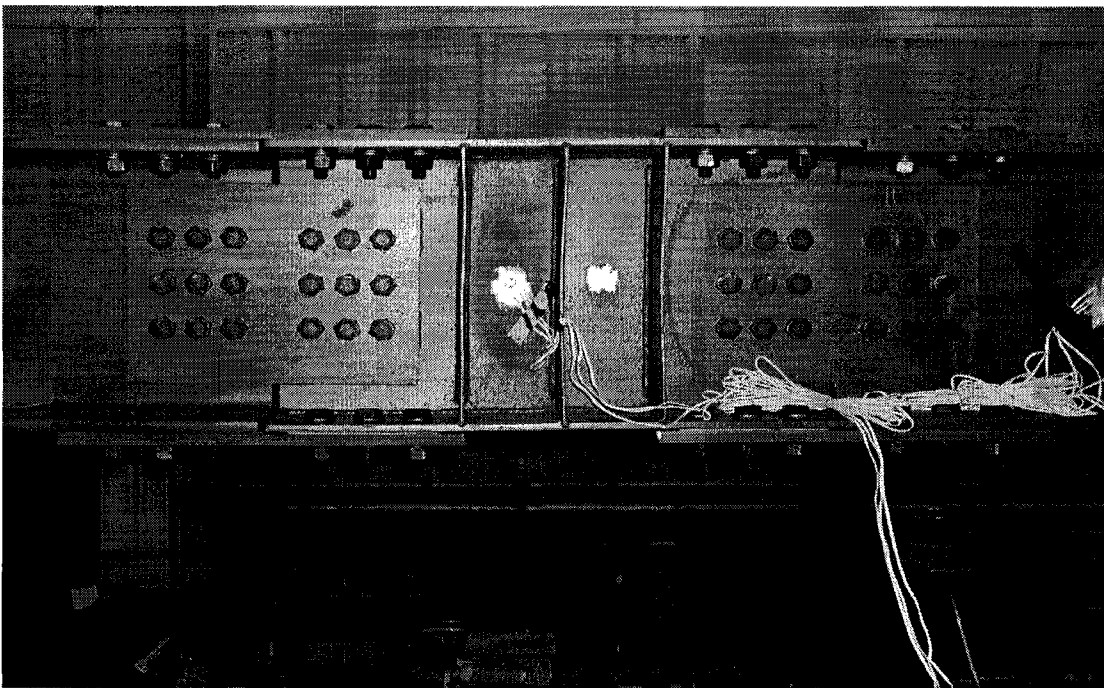


Figure D.15 Fuse Beam #3 During Testing

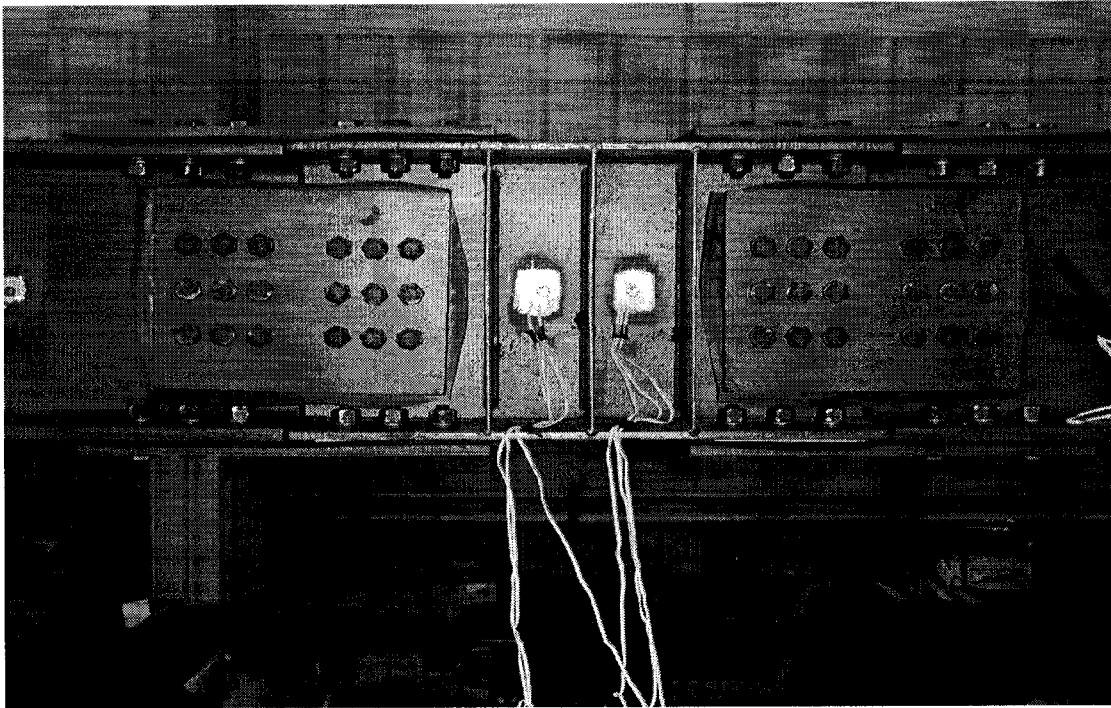


Figure D.16 Fuse Beam #4 Installed in Coupling Beam

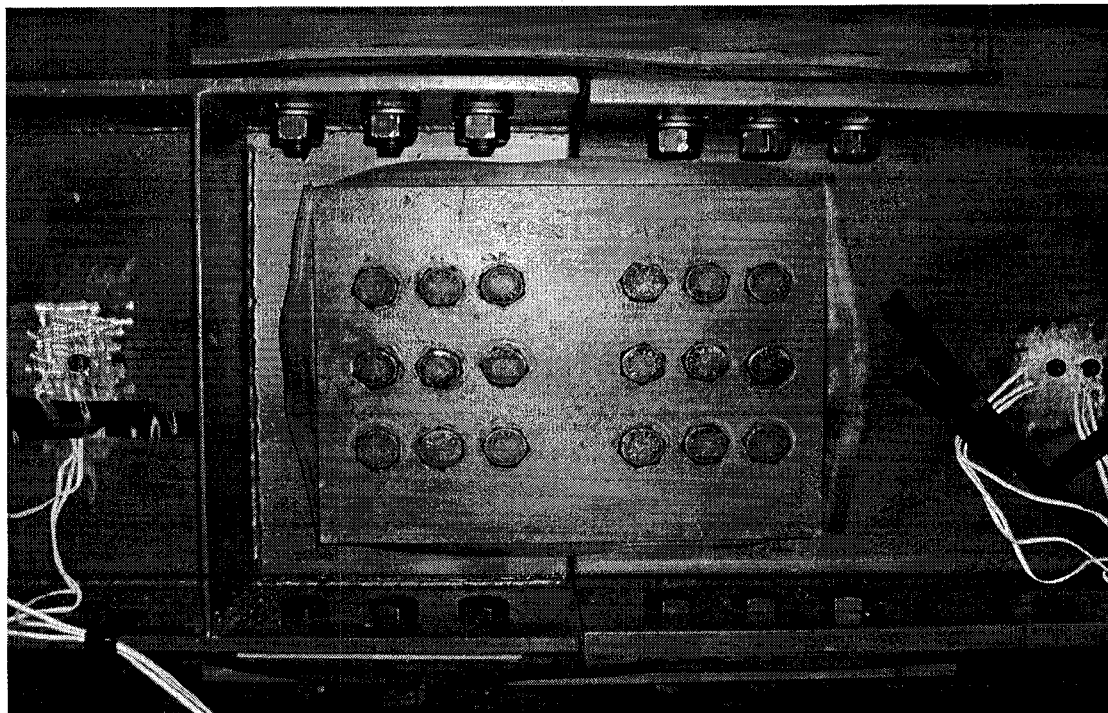
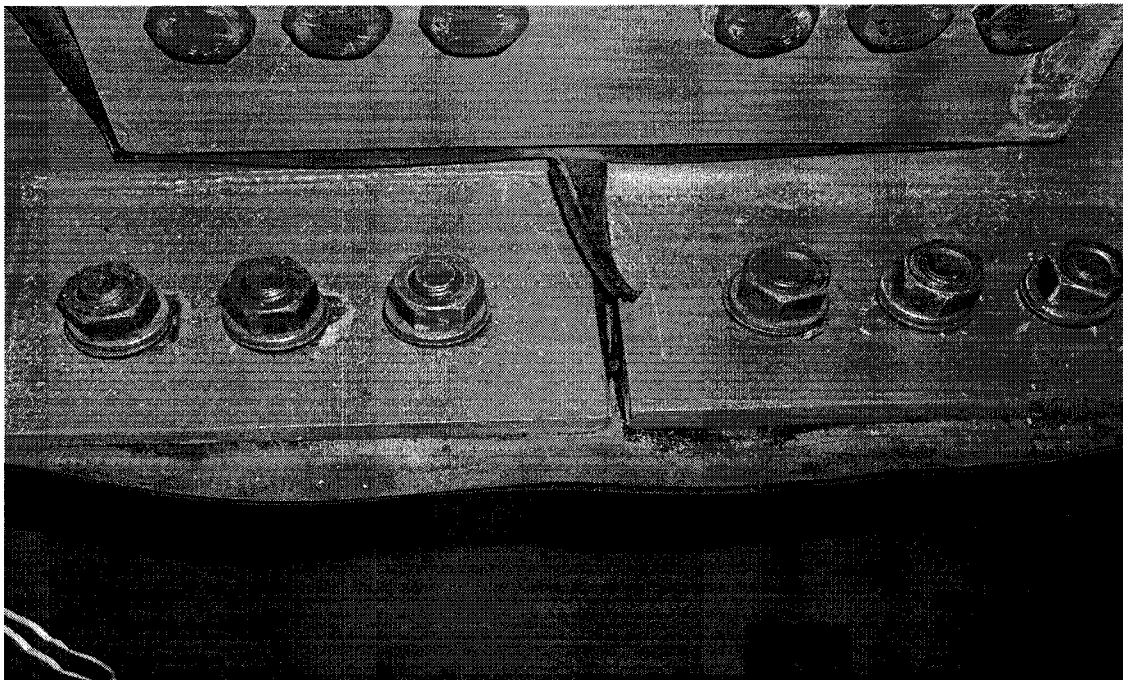
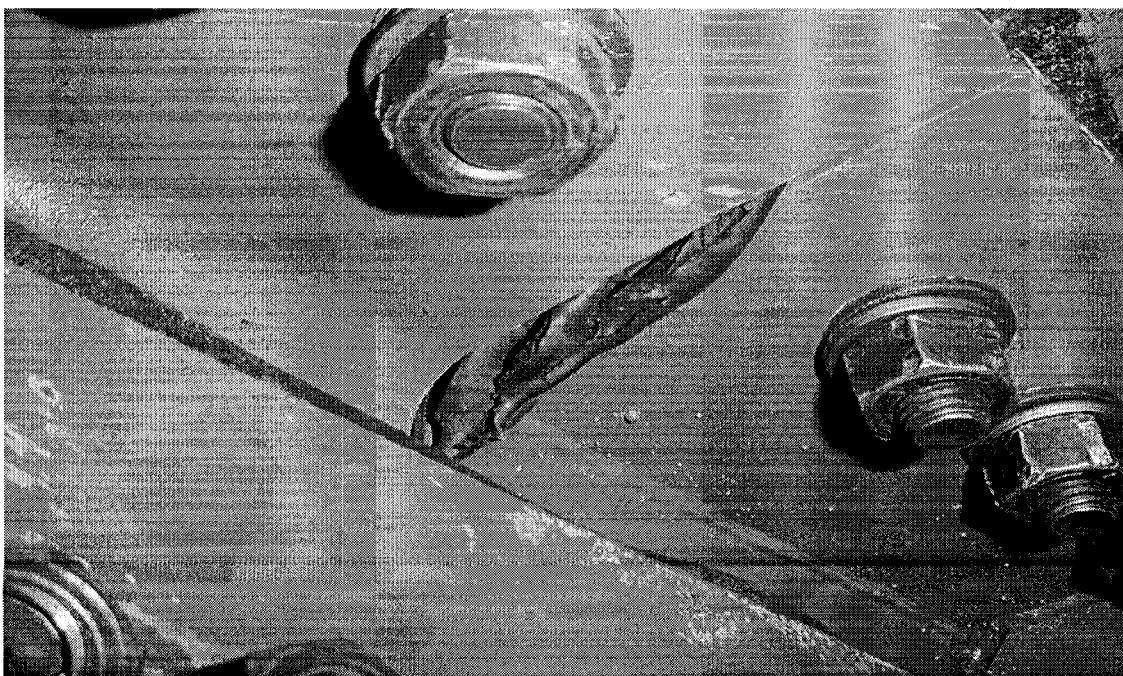


Figure D.17 Elastomeric Pads Squeezing Out Due to Pre-Tensioning of Bolts



**Figure D.18 Elastomeric Pads Squeezed and Sheared Between Flange Splice Joint
During Test #4**



**Figure D.19 Elastomeric Pads Squeezed and Torn Between Flange Splice Joint
During Test #2**

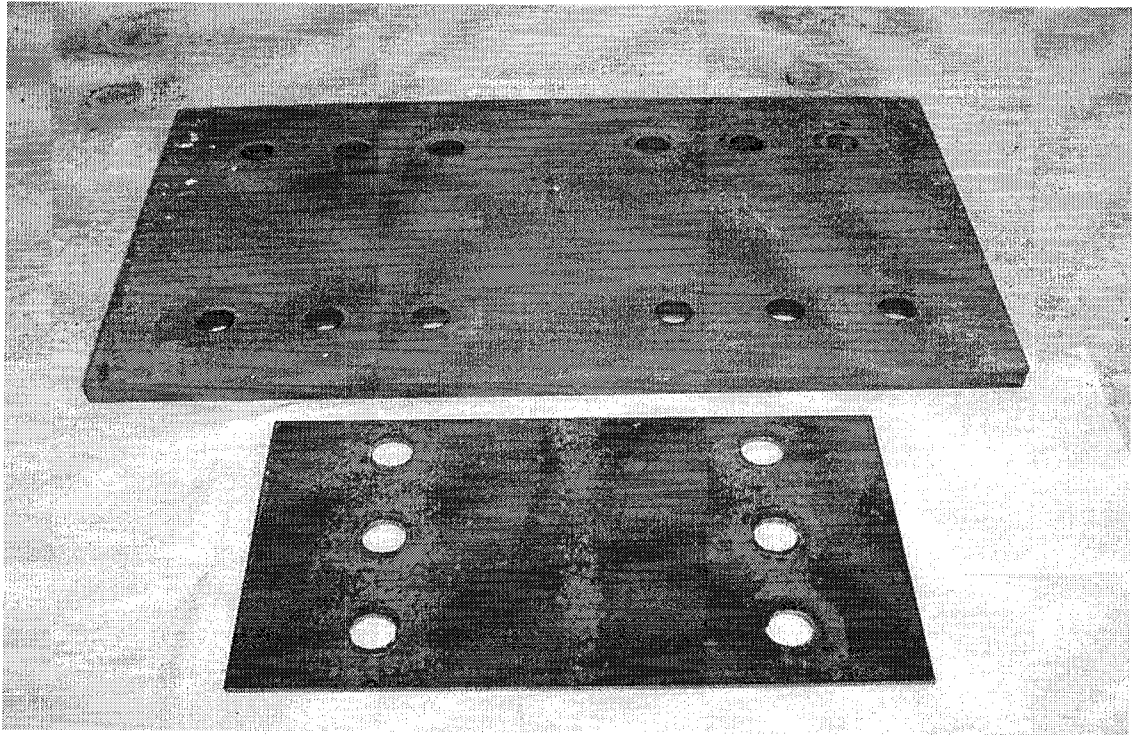


Figure D.20 Flange Splice Plates After Testing

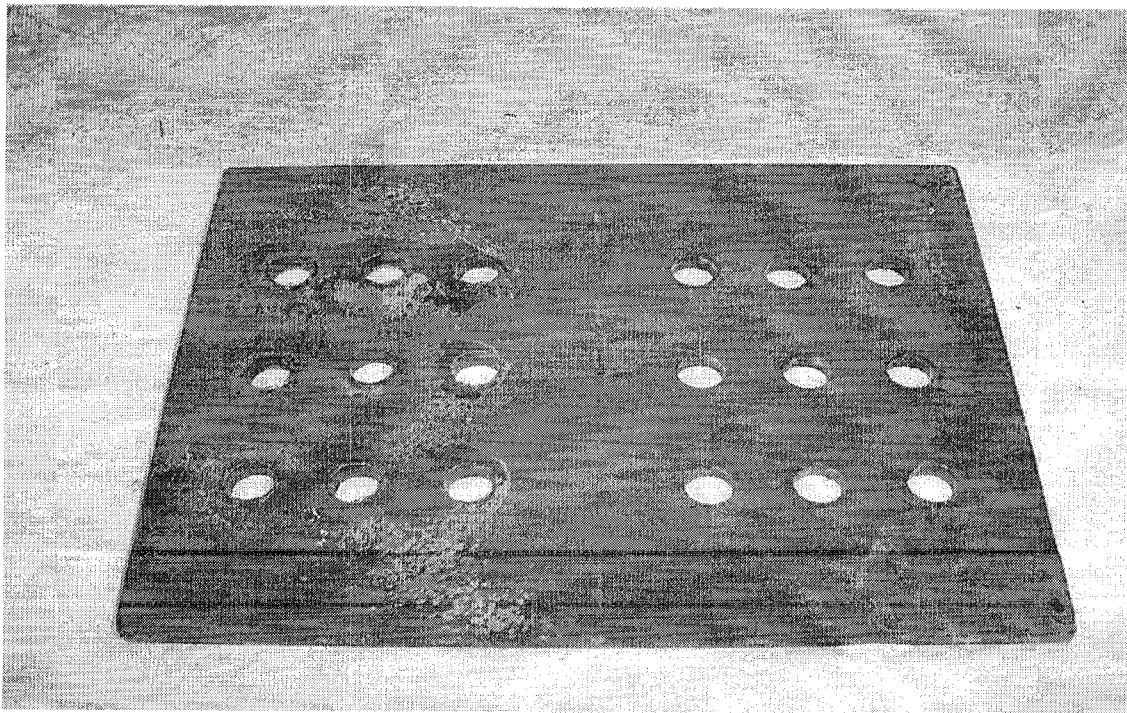


Figure D.21 Web Splice Plate After Testing

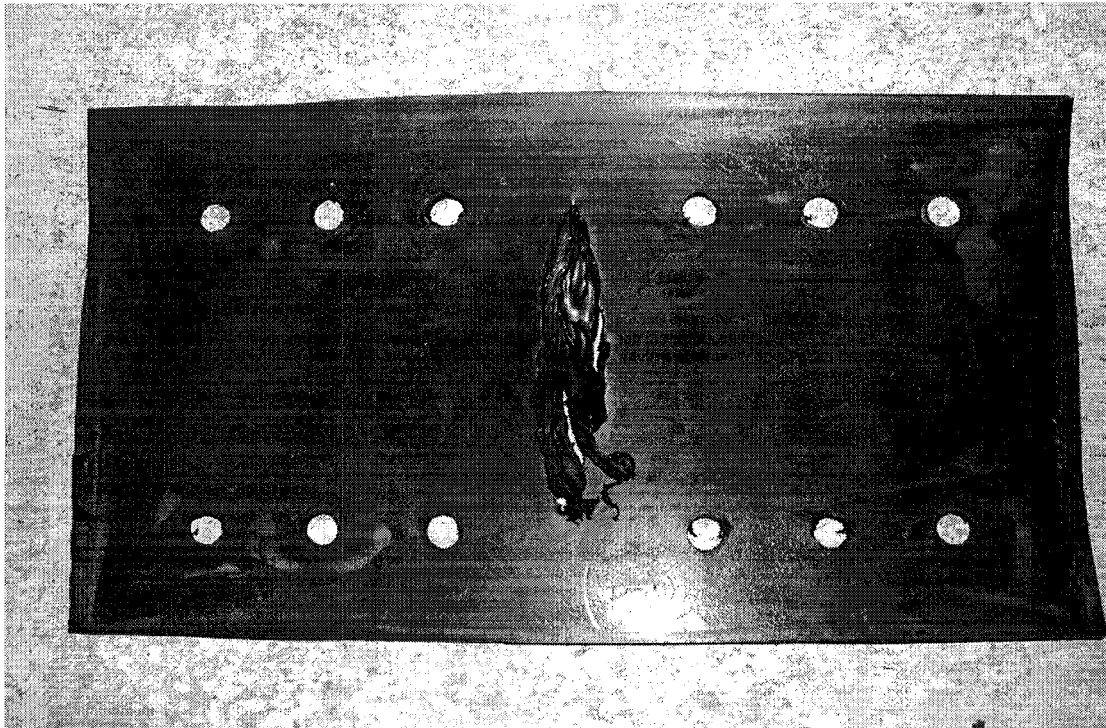


Figure D.22 Elatomer Pads After Testing

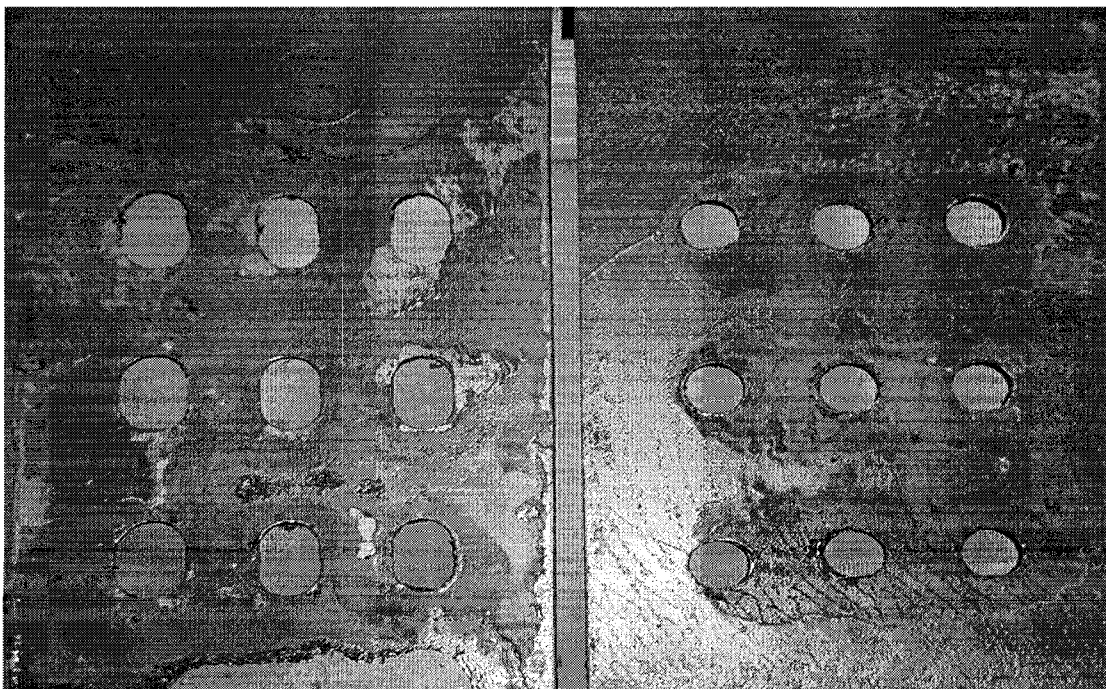


Figure D.23 Coupling Beam and Fuse Beam Web Bolt Holes After Testing

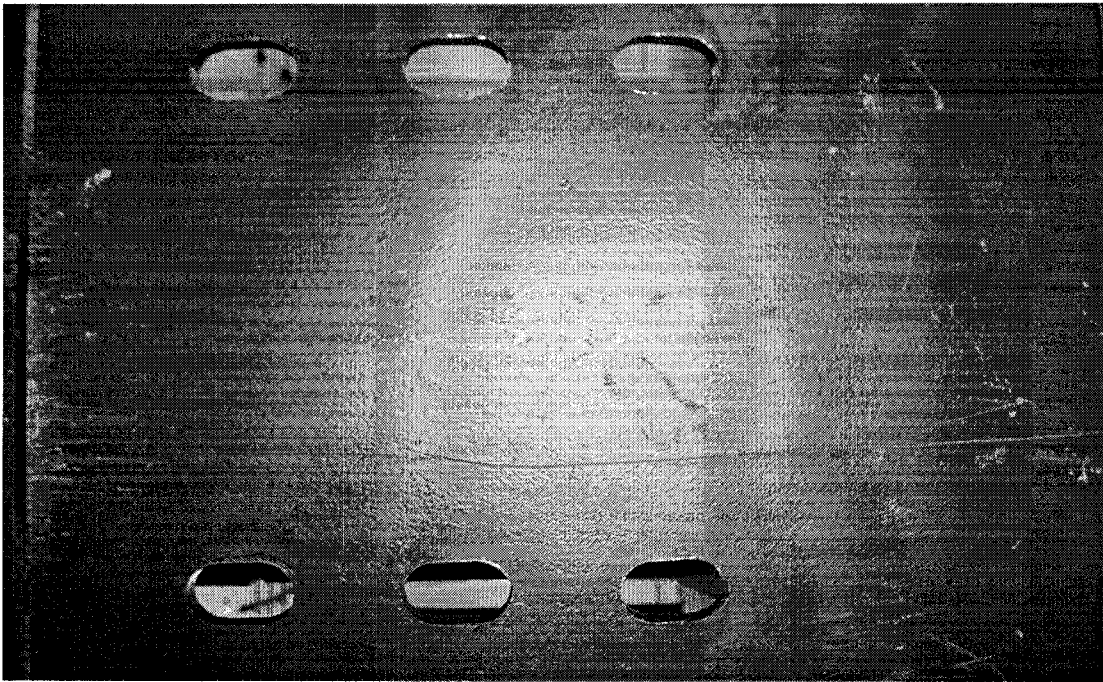


Figure D.24 Coupling Beam Flange Bolt Holes After Testing

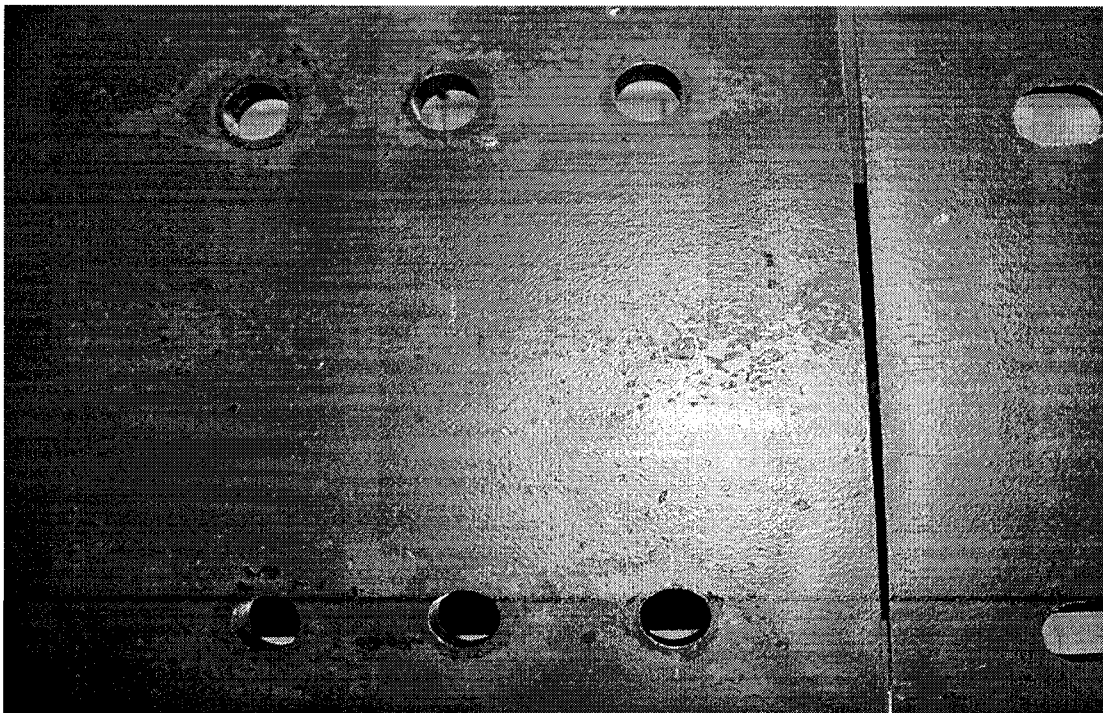


Figure D.25 Fuse Beam Flange Bolt Holes After Testing

APPENDIX – E

OPENSEES INPUT PROGRAM FILES AND ANALYTICAL RESULTS

E.1 Introduction

OpenSees input program files of the analytical study conducted are presented in this Appendix. Graphs indicating the rigidity of the fuse beam flanges in the analytical results are presented in this Appendix. The stress versus strain graphs of the right and left shear wall of the analyzed coupled walls are also presented in this Appendix.

E.2 Program File for the Fuse Beam Test # 1

```
# OpenSees Primer Fuse#1
# Units: kips, in, sec
# Start of model generation
# Create ModelBuilder (with 2-dimensions and 3 DOF/node)
model BasicBuilder -ndm 2 -ndf 3
# Create nodes
node 1 0.0 0.0
node 2 144.0 0.0
node 3 180.0 0.0
node 4 204.0 0.0
node 5 240.0 0.0
node 6 384.0 0.0
node 7 180.0 7.0
node 8 204.0 7.0
node 9 180.0 -7.0
node 10 204.0 -7.0
puts "Node definition successful"
# Set boundary conditions
fix 2 1 1 0
fix 5 1 1 0
geomTransf Linear 1
puts "Restraints definition successful"
# Defining materials
uniaxialMaterial Elastic 1 29000
uniaxialMaterial Hysteretic 2 90 0.0045 108 0.0085 104 0.0158 -95 -0.00475 -114 -0.009
-125 -0.015 0 0 0 0
puts "Material definition successful"
# Defining Elements
element elasticBeamColumn 1 1 2 17.9 29000 640 1
element elasticBeamColumn 2 2 3 17.9 29000 640 1
element truss 3 9 8 1 2
element elasticBeamColumn 4 4 5 17.9 29000 640 1
element elasticBeamColumn 5 5 6 17.9 29000 640 1
element elasticBeamColumn 6 3 7 10000 29000 100000 1
```

```

element elasticBeamColumn 7 3 9 10000 29000 100000 1
element elasticBeamColumn 8 4 8 10000 29000 100000 1
element elasticBeamColumn 9 4 10 10000 29000 100000 1
element truss 10 7 8 10000 1
element truss 11 9 10 10000 1
puts "Element definition successful"
# Analysis data
system SparseGeneral -piv
test NormUnbalance 1.0e-6 25
numberer RCM
constraints Transformation
algorithm Newton
integrator LoadControl 0.01
analysis Static
puts "Analysis definition successful"
# Output definition
recorder Node -file fuse1nodedisp.num -time -node 1 6 -dof 2 disp
recorder Node -file fuse1nodes.num -time -node 3 4 7 8 9 10 -dof 1 2 disp
recorder Element -file fuse1eleforce.num -time -ele 1 5 globalForce
recorder Element -file fuse1force.num -time -ele 3 force
recorder Element -file fuse1displ.num -time -ele 3 deformation
#recorder Element -file fuse1ssl.num -time -ele 3 material 2 stressStrain
puts "Output definition successful"
# Loading data
pattern Plain 1 "Series -dt 3.0 -filePath dispHist11.dat" {
  sp 1 2 1
}
pattern Plain 2 "Series -dt 3.0 -filePath dispHist16.dat" {
  sp 6 2 1
}
puts "Load definition successful"
analyze 14100

```

E.3 Program File for the Fuse Beam Test # 2

```

# OpenSees Primer Fuse#2
# Units: kips, in, sec
# Start of model generation
# Create ModelBuilder (with 2-dimensions and 3 DOF/node)
model BasicBuilder -ndm 2 -ndf 3
# Create nodes
node 1 0.0 0.0
node 2 144.0 0.0
node 3 180.0 0.0
node 4 204.0 0.0
node 5 240.0 0.0

```

```

node 6 384.0 0.0
node 7 180.0 7.0
node 8 204.0 7.0
node 9 180.0 -7.0
node 10 204.0 -7.0
puts "Node definition successful"
# Set boundary conditions
fix 2 1 1 0
fix 5 1 1 0
geomTransf Linear 1
puts "Restraints definition successful"
# Defining materials
uniaxialMaterial Elastic 1 29000
uniaxialMaterial Hysteretic 2 30 0.003 120 0.0185 129 0.021 -42 -0.007 -71 -0.016 -66 -
0.03 0 0 0 0
puts "Material definition successful"
# Defining Elements
element elasticBeamColumn 1 1 2 17.9 29000 640 1
element elasticBeamColumn 2 2 3 17.9 29000 640 1
element truss 3 9 8 1 2
element elasticBeamColumn 4 4 5 17.9 29000 640 1
element elasticBeamColumn 5 5 6 17.9 29000 640 1
element elasticBeamColumn 6 3 7 10000 29000 100000 1
element elasticBeamColumn 7 3 9 10000 29000 100000 1
element elasticBeamColumn 8 4 8 10000 29000 100000 1
element elasticBeamColumn 9 4 10 10000 29000 100000 1
element truss 10 7 8 10000 1
element truss 11 9 10 10000 1
puts "Element definition successful"
# Analysis data
system SparseGeneral -piv
test NormUnbalance 1.0e-6 40
numberer RCM
constraints Transformation
algorithm Newton
integrator LoadControl 0.01
analysis Static
puts "Analysis definition successful"
# Output definition
recorder Node -file fuse2nodedisp.num -time -node 1 6 -dof 2 disp
recorder Node -file fuse2nodes.num -time -node 3 4 7 8 9 10 -dof 1 2 disp
recorder Element -file fuse2eleforce.num -time -ele 1 5 globalForce
recorder Element -file fuse2force.num -time -ele 3 force
recorder Element -file fuse2displ.num -time -ele 3 deformation
#recorder Element -file fuse2ss1.num -time -ele 3 material 2 stressStrain
puts "Output definition successful"

```

```

# Loading data
pattern Plain 1 "Series -dt 3.0 -filePath dispHist21.dat" {
sp 1 2 1
}
pattern Plain 2 "Series -dt 3.0 -filePath dispHist26.dat" {
sp 6 2 1
}
puts "Load definition successful"
analyze 15900

```

E.4 Program File for the Fuse Beam Test # 3

```

# OpenSees Primer Fuse#3
# Units: kips, in, sec
# Start of model generation
# Create ModelBuilder (with 2-dimensions and 3 DOF/node)
model BasicBuilder -ndm 2 -ndf 3
# Create nodes
node 1 0.0 0.0
node 2 144.0 0.0
node 3 180.0 0.0
node 4 204.0 0.0
node 5 240.0 0.0
node 6 384.0 0.0
node 7 180.0 7.0
node 8 204.0 7.0
node 9 180.0 -7.0
node 10 204.0 -7.0
puts "Node definition successful"
# Set boundary conditions
fix 2 1 1 0
fix 5 1 1 0
geomTransf Linear 1
puts "Restraints definition successful"
# Defining materials
uniaxialMaterial Elastic 1 29000
uniaxialMaterial Hysteretic 2 90 0.0047 120 0.0078 144 0.010 -87 -0.007 -99 -0.0115 -77
-0.024 0 0 0 0
puts "Material definition successful"
# Defining Elements
element elasticBeamColumn 1 1 2 17.9 29000 640 1
element elasticBeamColumn 2 2 3 17.9 29000 640 1
element truss 3 9 8 1 2
element elasticBeamColumn 4 4 5 17.9 29000 640 1
element elasticBeamColumn 5 5 6 17.9 29000 640 1
element elasticBeamColumn 6 3 7 10000 29000 100000 1

```

```

element elasticBeamColumn 7 3 9 10000 29000 100000 1
element elasticBeamColumn 8 4 8 10000 29000 100000 1
element elasticBeamColumn 9 4 10 10000 29000 100000 1
element truss 10 7 8 10000 1
element truss 11 9 10 10000 1
puts "Element definition successful"
# Analysis data
system SparseGeneral -piv
test NormUnbalance 1.0e-6 25
numberer RCM
constraints Transformation
algorithm Newton
integrator LoadControl 0.01
analysis Static
puts "Analysis definition successful"
# Output definition
recorder Node -file fuse3nodedisp.num -time -node 1 6 -dof 2 disp
recorder Node -file fuse3nodes.num -time -node 3 4 7 8 9 10 -dof 1 2 disp
recorder Element -file fuse3eleforce.num -time -ele 1 5 globalForce
recorder Element -file fuse3force.num -time -ele 3 force
recorder Element -file fuse3displ.num -time -ele 3 deformation
puts "Output definition successful"
# Loading data
pattern Plain 1 "Series -dt 3.0 -filePath dispHist31.dat" {
  sp 1 2 1
}
pattern Plain 2 "Series -dt 3.0 -filePath dispHist36.dat" {
  sp 6 2 1
}
puts "Load definition successful"
analyze 14700

```

E.5 Program File for the Fuse Beam Test # 1

```

# OpenSees Primer Fuse#4
# Units: kips, in, sec
# Start of model generation
# Create ModelBuilder (with 2-dimensions and 3 DOF/node)
model BasicBuilder -ndm 2 -ndf 3
# Create nodes
node 1 0.0 0.0
node 2 144.0 0.0
node 3 180.0 0.0
node 4 204.0 0.0
node 5 240.0 0.0
node 6 384.0 0.0

```

```

node 7 180.0 7.0
node 8 204.0 7.0
node 9 180.0 -7.0
node 10 204.0 -7.0
puts "Node definition successful"
# Set boundary conditions
fix 2 1 1 0
fix 5 1 1 0
geomTransf Linear 1
puts "Restrains definition successful"
# Defining materials
uniaxialMaterial Elastic 1 29000
uniaxialMaterial Hysteretic 2 15 0.0015 65 0.01 92 0.0175 -15 -0.0015 -50 -0.013 -70 -
0.029 0 0 0 0
puts "Material definition successful"
# Defining Elements
element elasticBeamColumn 1 1 2 17.9 29000 640 1
element elasticBeamColumn 2 2 3 17.9 29000 640 1
element truss 3 9 8 1 2
element elasticBeamColumn 4 4 5 17.9 29000 640 1
element elasticBeamColumn 5 5 6 17.9 29000 640 1
element elasticBeamColumn 6 3 7 10000 29000 100000 1
element elasticBeamColumn 7 3 9 10000 29000 100000 1
element elasticBeamColumn 8 4 8 10000 29000 100000 1
element elasticBeamColumn 9 4 10 10000 29000 100000 1
element truss 10 7 8 10000 1
element truss 11 9 10 10000 1
puts "Element definition successful"
# Analysis data
system SparseGeneral -piv
test NormUnbalance 1.0e-6 25
numberer RCM
constraints Transformation
algorithm Newton
integrator LoadControl 0.01
analysis Static
puts "Analysis definition successful"
# Output definition
recorder Node -file fuse4nodedisp.num -time -node 1 6 -dof 2 disp
recorder Node -file fuse4nodes.num -time -node 3 4 7 8 9 10 -dof 1 2 disp
recorder Element -file fuse4eleforce.num -time -ele 1 5 globalForce
recorder Element -file fuse4force.num -time -ele 3 force
recorder Element -file fuse4displ.num -time -ele 3 deformation
puts "Output definition successful"
# Loading data
pattern Plain 1 "Series -dt 3.0 -filePath dispHist41.dat" {

```



```

sp 1 2 1
}
pattern Plain 2 "Series -dt 3.0 -filePath dispHist46.dat" {
sp 6 2 1
}
puts "Load definition successful"
analyze 17700

```

E.6 Horizontal Displacements of Fuse Beam Nodes

Fig. E.1 and Fig. E.2 shows the horizontal displacements of the fuse beam nodes versus the number of cycles. It can be seen from Fig. E.1 that nodes along the same vertical axis of the top and bottom flanges of the fuse beam have horizontal displacements of equal magnitude, but opposite direction. It can also be seen from Fig. E.2, that the nodes on the flange along the same horizontal axis have horizontal displacements of same magnitude and direction. From the above observations, we can infer that the flanges of the fuse beam behave as a rigid body.

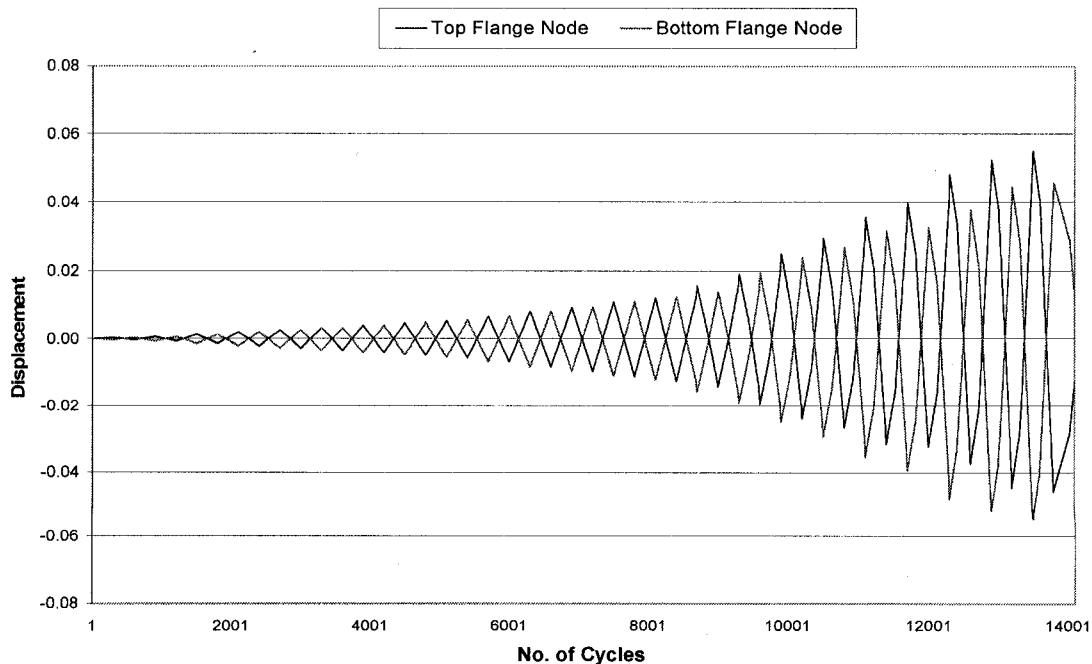


Figure E.1 Horizontal Displacements of Top and Bottom Fuse Flange Nodes

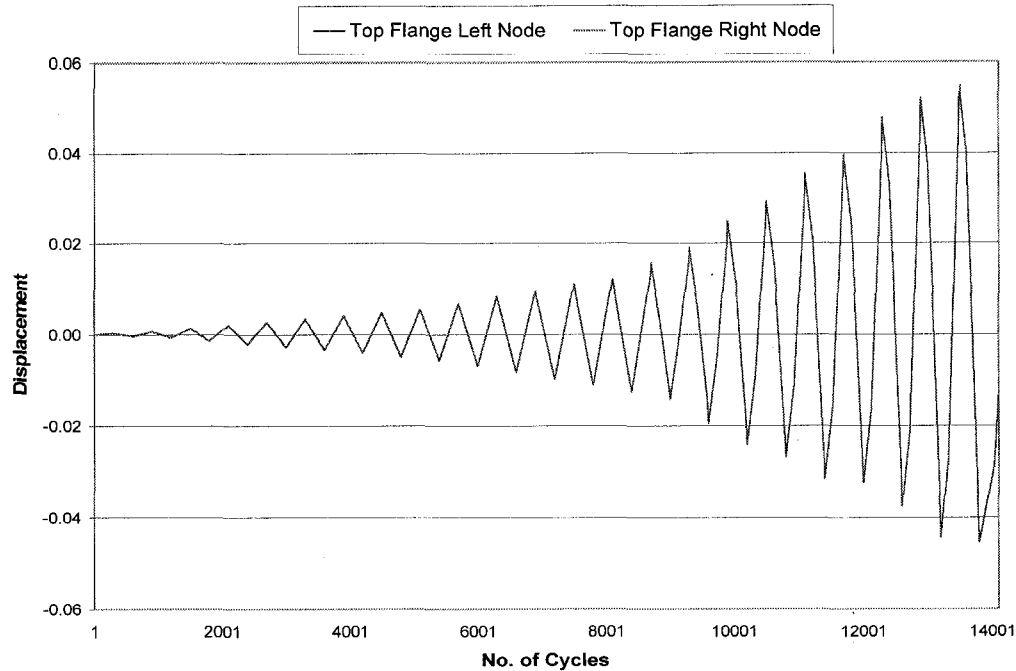


Figure E.2 Horizontal Displacements of Left and Right Nodes of Top Fuse Flange

E.7 Program File for the Shear Wall

```
# OpenSees Cyclic Reinforced Concrete Fiber Shear Wall
# Default Units: kips, in, s
# PARAMETERS DEFINITION
set nInt      3;          #number of integration points along length of element
set width     4; #width of cross-section
set depth     48; #depth of cross-section
set cover     0.75; #thickness of concrete cover
set fy        75; #Steel yielding stress
set Es        29000; #Steel Young's modulus
puts "parameters set successful";
model basic -ndm 2 -ndf 3
# NODE GENERATION
node 1 0.0 0.0
node 2 0.0 36.0
node 3 0.0 72.0
node 4 0.0 108.0
node 5 0.0 144.0
puts "nodes generation succesful"
fix 1 1 1 1
puts "restraint definition succesful"
# MATERIALS DEFINITION
# CONCRETE
```

```

# Core concrete
#          TYPE   TAG  fc  ec0  fcu  ecu  ratio  ft  Ets
uniaxialMaterial Concrete02 1 -6.33 -0.00603 -3.0 -0.016 0.2 0.63 400
# Cover concrete
#          TYPE   TAG  fc  ec0  fcu  ecu
uniaxialMaterial Concrete01 2 -4.0 -0.002 0.4 -0.006
# STEEL
# Rebars
#          TYPE   TAG  fy  E0  b
uniaxialMaterial Steel01 3 $fy $Es 0.05
puts "material definition successful"
#CROSS-SECTION DEFINITION
section Fiber 1 {
    # Concrete core fibers
    # patch rect $matTag $numSubdivIJ $numSubdivJK $yI $zI $yK $zK
    # note: z strong axis for bending
    patch rect 1 20 1 [expr -$depth/2+$cover] [expr -$width/2+$cover] [expr $depth/2-
$cover] [expr $width/2-$cover]; # -23.25 -1.25 23.25 1.25
    puts "defined core fibers";
    # Concrete cover fibers
    # Bottom
    patch rect 2 20 1 [expr -$depth/2] [expr -$width/2] [expr $depth/2] [expr -
$width/2+$cover]; # -24 -2 24 -1.25
    puts "defined bottom cover";
    # Top
    patch rect 2 20 1 [expr -$depth/2] [expr $width/2-$cover] [expr $depth/2] [expr
$width/2]; # -24 1.25 24 2
    puts "defined top cover";
    # Right
    patch rect 2 2 1 [expr $depth/2-$cover] [expr -$width/2+$cover] [expr $depth/2]
[expr $width/2-$cover]; # 23.25 -1.25 24 1.25
    puts "defined right cover";
    # Left
    patch rect 2 2 1 [expr -$depth/2] [expr -$width/2+$cover] [expr -$depth/2+$cover]
[expr $width/2-$cover]; # -24 -1.25 -23.25 1.25
    puts "defined left cover";
    # Rebar fibers
    # layer straight $matTag $numBars $areaBar $yStart $zStart $yEnd $zEnd
    layer straight 3 4 0.11 -23.25 1.25 -17.25 1.25
    layer straight 3 4 0.05 -11.25 1.25 11.25 1.25
    layer straight 3 4 0.11 17.25 1.25 23.25 1.25
    layer straight 3 4 0.11 -23.25 -1.25 -17.25 -1.25
    layer straight 3 4 0.05 -11.25 -1.25 11.25 -1.25
    layer straight 3 4 0.11 17.25 -1.25 23.25 -1.25
}
section Fiber 2 {

```

```

# Concrete core fibers
# patch rect $matTag $numSubdivIJ $numSubdivJK $yI $zI $yK $zK
# note: z strong axis for bending
patch rect 1 20 1 [expr -$depth/2+$cover] [expr -$width/2+$cover] [expr $depth/2-
$cover] [expr $width/2-$cover]; # -23.25 -1.25 23.25 1.25
puts "defined core fibers";
# Concrete cover fibers
# Bottom
patch rect 2 20 1 [expr -$depth/2] [expr -$width/2] [expr $depth/2] [expr -
$width/2+$cover]; #-24 -2 24 -1.25
puts "defined bottom cover";
# Top
patch rect 2 20 1 [expr -$depth/2] [expr $width/2-$cover] [expr $depth/2] [expr
$width/2]; #-24 1.25 24 2
puts "defined top cover";
# Right
patch rect 2 2 1 [expr $depth/2-$cover] [expr -$width/2+$cover] [expr $depth/2]
[expr $width/2-$cover]; #23.25 -1.25 24 1.25
puts "defined right cover";
# Left
patch rect 2 2 1 [expr -$depth/2] [expr -$width/2+$cover] [expr -$depth/2+$cover]
[expr $width/2-$cover]; #-24 -1.25 -23.25 1.25
puts "defined left cover";
# Rebar fibers
# layer straight $matTag $numBars $areaBar $yStart $zStart $yEnd $zEnd
layer straight 3 4 0.11 -23.25 1.25 -17.25 1.25
layer straight 3 4 0.05 -11.25 1.25 11.25 1.25
layer straight 3 4 0.11 17.25 1.25 23.25 1.25
layer straight 3 4 0.11 -23.25 -1.25 -17.25 -1.25
layer straight 3 4 0.05 -11.25 -1.25 11.25 -1.25
layer straight 3 4 0.11 17.25 -1.25 23.25 -1.25
}
section Fiber 3 {
# Concrete core fibers
# patch rect $matTag $numSubdivIJ $numSubdivJK $yI $zI $yK $zK
# note: z strong axis for bending
patch rect 1 20 1 [expr -$depth/2+$cover] [expr -$width/2+$cover] [expr $depth/2-
$cover] [expr $width/2-$cover]; # -23.25 -1.25 23.25 1.25
puts "defined core fibers";
# Concrete cover fibers
# Bottom
patch rect 2 20 1 [expr -$depth/2] [expr -$width/2] [expr $depth/2] [expr -
$width/2+$cover]; #-24 -2 24 -1.25
puts "defined bottom cover";
# Top

```

```

    patch rect 2 20 1 [expr -$depth/2] [expr $width/2-$cover] [expr $depth/2] [expr
$width/2]; #24 1.25 24 2
puts "defined top cover";
    # Right
    patch rect 2 2 1 [expr $depth/2-$cover] [expr -$width/2+$cover] [expr $depth/2]
[expr $width/2-$cover]; #23.25 -1.25 24 1.25
puts "defined right cover";
    # Left
    patch rect 2 2 1 [expr -$depth/2] [expr -$width/2+$cover] [expr -$depth/2+$cover]
[expr $width/2-$cover]; #24 -1.25 -23.25 1.25
puts "defined left cover";
    # Rebar fibers
    # layer straight $matTag $numBars $areaBar $yStart $zStart $yEnd $zEnd
    layer straight 3 4 0.11 -23.25 1.25 -17.25 1.25
    layer straight 3 9 0.05 -15 1.25 15 1.25
    layer straight 3 4 0.11 17.25 1.25 23.25 1.25
    layer straight 3 4 0.11 -23.25 -1.25 -17.25 -1.25
    layer straight 3 9 0.05 -15 -1.25 15 -1.25
    layer straight 3 4 0.11 17.25 -1.25 23.25 -1.25
}
puts "section definition successful"
# ELEMENT DEFINITION
# Definition of Geometric transformation (linear, P-delta, corotational)
geomTransf Linear 1
# Definition of element
#
    TYPE      TAG    ndI    ndJ    nsecs    secID    transfTag
element nonlinearBeamColumn 1    1    2    $nInt    1    1
element nonlinearBeamColumn 2    2    3    $nInt    2    1
element nonlinearBeamColumn 3    3    4    $nInt    2    1
element nonlinearBeamColumn 4    4    5    $nInt    3    1
puts "element definition successful"
# RECORDER GENERATION
recorder Node -file node5.num -time -node 5 -dof 1 disp
recorder Element -file eleforce4.num -time -ele 4 globalForce
# LOADS DEFINITION
pattern Plain 1 "Series -dt 1.0 -filePath dispHistSW.dat" {
sp 5 1 1
}
puts "loads definition successful"
# END OF MODEL GENERATION
# ANALYSIS GENERATION
#Type of system of equations: BandGeneral, BandSPD, ProfileSPD, SparseGeneral,
UmfPack, SparseSPD
system SparseGeneral -piv
#Type of constraint handler: Plain, Penalty, Lagrange, Transformation
constraints Transformation

```

```

#Type of DOF numberer: Plain, RCM
numberer RCM
#Type of convergence test: NormUnbalance, NormDispIncr, EnergyIncr
# test NormDispIncr $tolerance $maxNumIter <$printFlag> (1=no print, 1=print each
step, 2=print at convergence, etc.)
test NormUnbalance 1.0E-6 30 3
#Type of solution algorithm: Linear, Newton, NewtonLineSearch, ModifiedNewton,
KrylovNewton, BFGS, Broyden
algorithm Newton
integrator LoadControl 0.001
#Type of analysis object: Static, Transient, VariableTransient
analysis Static
initialize
puts "analysis definition successful"
analyze 33000

```

E.8 Program File for the Coupled Wall Without Fuse Beams

```

# OpenSees coupled wall without fuse beams
# Default Units: kips, in, s
# PARAMETERS DEFINITION
set nInt      3; #number of integration points along length of element
set width     4; #width of cross-section
set depth     48; #depth of cross-section
set cover     0.75; #thickness of concrete cover
set fy        75; #Steel yielding stress
set Es        29000; #Steel Young's modulus
puts "parameters set successful";
model basic -ndm 2 -ndf 3
# NODE GENERATION
node 1 0 0
node 2 103 0
node 3 0 36
node 4 24 36
node 5 79 36
node 6 103 36
node 7 0 72
node 8 24 72
node 9 79 72
node 10 103 72
node 11 0 108
node 12 24 108
node 13 79 108
node 14 103 108
node 15 0 144
node 16 24 144

```

```

node 17 79 144
node 18 103 144
puts "nodes generation succesful"
fix 1 1 1 1
fix 2 1 1 1
puts "restraint definition succesful"
# MATERIALS DEFINITION
# CONCRETE
# Core concrete
#
#      TYPE   TAG   fc   ec0   fcu   ecu   ratio   ft   Ets
uniaxialMaterial Concrete02 1 -6.33 -0.00603 -3.0 -0.016 0.2 0.63 400
# Cover concrete
#
#      TYPE   TAG   fc   ec0   fcu   ecu
uniaxialMaterial Concrete01 2 -4.0 -0.002 -0.4 -0.006
# STEEL
# Rebars
#
#      TYPE   TAG   fy   E0   b
uniaxialMaterial Steel01 3 $fy $Es 0.05
uniaxialMaterial Elastic 4 29000
puts "material definition successful"
#CROSS-SECTION DEFINITION
section Fiber 1 {
    # Concrete core fibers
    # patch rect $matTag $numSubdivIJ $numSubdivJK $yI $zI $yK $zK
    # note: z strong axis for bending
    patch rect 1 20 1 [expr -$depth/2+$cover] [expr -$width/2+$cover] [expr $depth/2-
$cover] [expr $width/2-$cover]; # -23.25 -1.25 23.25 1.25
puts "defined core fibers";
    # Concrete cover fibers
    # Bottom
    patch rect 2 20 1 [expr -$depth/2] [expr -$width/2] [expr $depth/2] [expr -
$width/2+$cover]; #-24 -2 24 -1.25
puts "defined top cover";
    # Top
    patch rect 2 20 1 [expr -$depth/2] [expr $width/2-$cover] [expr $depth/2] [expr
$width/2]; #-24 1.25 24 2
puts "defined bottom cover";
    # Right
    patch rect 2 2 1 [expr $depth/2-$cover] [expr -$width/2+$cover] [expr $depth/2]
[expr $width/2-$cover]; #23.25 -1.25 24 1.25
puts "defined left cover";
    # Left
    patch rect 2 2 1 [expr -$depth/2] [expr -$width/2+$cover] [expr -$depth/2+$cover]
[expr $width/2-$cover]; #-24 -1.25 -23.25 1.25
puts "defined right cover";
    # Rebar fibers

```

```

# layer straight $matTag $numBars $areaBar $yStart $zStart $yEnd $zEnd
layer straight 3 4 0.11 -23.25 1.25 -17.25 1.25
layer straight 3 4 0.05 -11.25 1.25 11.25 1.25
layer straight 3 4 0.11 17.25 1.25 23.25 1.25
layer straight 3 4 0.11 -23.25 -1.25 -17.25 -1.25
layer straight 3 4 0.05 -11.25 -1.25 11.25 -1.25
layer straight 3 4 0.11 17.25 -1.25 23.25 -1.25
}
section Fiber 2 {
# Concrete core fibers
# patch rect $matTag $numSubdivIJ $numSubdivJK $yI $zI $yK $zK
# note: z strong axis for bending
patch rect 1 20 1 [expr -$depth/2+$cover] [expr -$width/2+$cover] [expr $depth/2-
$cover] [expr $width/2-$cover]; # -23.25 -1.25 23.25 1.25
puts "defined core fibers";
# Concrete cover fibers
# Bottom
patch rect 2 20 1 [expr -$depth/2] [expr -$width/2] [expr $depth/2] [expr -
$width/2+$cover]; # -24 -2 24 -1.25
puts "defined top cover";
# Top
patch rect 2 20 1 [expr -$depth/2] [expr $width/2-$cover] [expr $depth/2] [expr
$width/2]; # -24 1.25 24 2
puts "defined bottom cover";
# Right
patch rect 2 2 1 [expr $depth/2-$cover] [expr -$width/2+$cover] [expr $depth/2]
[expr $width/2-$cover]; # 23.25 -1.25 24 1.25
puts "defined left cover";
# Left
patch rect 2 2 1 [expr -$depth/2] [expr -$width/2+$cover] [expr -$depth/2+$cover]
[expr $width/2-$cover]; # -24 -1.25 -23.25 1.25
puts "defined right cover";
# Rebar fibers
# layer straight $matTag $numBars $areaBar $yStart $zStart $yEnd $zEnd
layer straight 3 4 0.11 -23.25 1.25 -17.25 1.25
layer straight 3 4 0.05 -11.25 1.25 11.25 1.25
layer straight 3 4 0.11 17.25 1.25 23.25 1.25
layer straight 3 4 0.11 -23.25 -1.25 -17.25 -1.25
layer straight 3 4 0.05 -11.25 -1.25 11.25 -1.25
layer straight 3 4 0.11 17.25 -1.25 23.25 -1.25
}
section Fiber 3 {
# Concrete core fibers
# patch rect $matTag $numSubdivIJ $numSubdivJK $yI $zI $yK $zK
# note: z strong axis for bending

```



```

    patch rect 1 20 1 [expr -$depth/2+$cover] [expr -$width/2+$cover] [expr $depth/2-
$cover] [expr $width/2-$cover]; # -23.25 -1.25 23.25 1.25
puts "defined core fibers";
    # Concrete cover fibers
    # Bottom
    patch rect 2 20 1 [expr -$depth/2] [expr -$width/2] [expr $depth/2] [expr -
$width/2+$cover]; # -24 -2 24 -1.25
puts "defined top cover";
    # Top
    patch rect 2 20 1 [expr -$depth/2] [expr $width/2-$cover] [expr $depth/2] [expr -
$width/2]; # -24 1.25 24 2
puts "defined bottom cover";
    # Right
    patch rect 2 2 1 [expr $depth/2-$cover] [expr -$width/2+$cover] [expr $depth/2]
[expr $width/2-$cover]; # 23.25 -1.25 24 1.25
puts "defined left cover";
    # Left
    patch rect 2 2 1 [expr -$depth/2] [expr -$width/2+$cover] [expr -$depth/2+$cover]
[expr $width/2-$cover]; # -24 -1.25 -23.25 1.25
puts "defined right cover";
    # Rebar fibers
    # layer straight $matTag $numBars $areaBar $yStart $zStart $yEnd $zEnd
    layer straight 3 4 0.11 -23.25 1.25 -17.25 1.25
    layer straight 3 9 0.05 -15 1.25 15 1.25
    layer straight 3 4 0.11 17.25 1.25 23.25 1.25
    layer straight 3 4 0.11 -23.25 -1.25 -17.25 -1.25
    layer straight 3 9 0.05 -15 -1.25 15 -1.25
    layer straight 3 4 0.11 17.25 -1.25 23.25 -1.25
}
puts "section definition successful"
# ELEMENT DEFINITION
# Definition of Geometric transformation (linear, P-delta, corotational)
geomTransf Linear 1
# Definition of element
#
    TYPE      TAG  ndI  ndJ  nsecs  secID  transfTag
element nonlinearBeamColumn 1 1 3 3 1 1
element nonlinearBeamColumn 2 2 6 3 1 1
element nonlinearBeamColumn 3 3 7 3 2 1
element nonlinearBeamColumn 4 6 10 3 2 1
element nonlinearBeamColumn 5 7 11 3 2 1
element nonlinearBeamColumn 6 10 14 3 2 1
element nonlinearBeamColumn 7 11 15 3 3 1
element nonlinearBeamColumn 8 14 18 3 3 1
element elasticBeamColumn 9 3 4 5000 29000 50000 1
element elasticBeamColumn 10 4 5 17.9 29000 640 1
element elasticBeamColumn 11 5 6 5000 29000 50000 1

```

```

element elasticBeamColumn      12      7      8 5000 29000 50000 1
element elasticBeamColumn      13      8      9 17.9 29000 640 1
element elasticBeamColumn      14      9     10 5000 29000 50000 1
element elasticBeamColumn      15     11     12 5000 29000 50000 1
element elasticBeamColumn      16     12     13 17.9 29000 640 1
element elasticBeamColumn      17     13     14 5000 29000 50000 1
element elasticBeamColumn      18     15     16 5000 29000 50000 1
element elasticBeamColumn      19     16     17 17.9 29000 640 1
element elasticBeamColumn      20     17     18 5000 29000 50000 1
puts "element definition successful"
# LOADS DEFINITION
pattern Plain 1 "Series -dt 1.0 -filePath dispHistSW1.dat" {
sp 15 1 1
}
pattern Plain 2 "Series -dt 1.0 -filePath dispHistSW2.dat" {
sp 18 1 1
}
pattern Plain 3 Constant {
load 1 0 -0.3 0
load 2 0 -0.3 0
load 3 0 -0.6 0
load 6 0 -0.6 0
load 7 0 -0.6 0
load 10 0 -0.6 0
load 11 0 -0.6 0
load 14 0 -0.6 0
load 15 0 -0.3 0
load 18 0 -0.3 0
}
puts "loads definition successful"
# END OF MODEL GENERATION
# ANALYSIS GENERATION
#Type of system of equations: BandGeneral, BandSPD, ProfileSPD, SparseGeneral,
UmfPack, SparseSPD
system SparseGeneral -piv
#Type of constraint handler: Plain, Penalty, Lagrange, Transformation
constraints Transformation
#Type of DOF numberer: Plain, RCM
numberer RCM
#Type of convergence test: NormUnbalance, NormDispIncr, EnergyIncr
# test NormDispIncr $tolerance $maxNumIter <$printFlag> (1=no print, 1=print each
step, 2=print at convergence, etc.)
test NormUnbalance 1.0E-6 30 1
#Type of solution algorithm: Linear, Newton, NewtonLineSearch, ModifiedNewton,
KrylovNewton, BFGS, Broyden
algorithm Newton

```

```

integrator LoadControl 0.001
#Type of analysis object: Static, Transient, VariableTransient
analysis Static
initialize
puts "analysis definition successful"
# RECORDER GENERATION
recorder Node -file node15.num -time -node 15 -dof 1 disp
recorder Node -file node18.num -time -node 18 -dof 1 disp
recorder Element -file eleforce78.num -time -ele 7 8 globalForce
recorder Element -file eleforce1.num -time -ele 19 globalForce
recorder Element -file eleforce2.num -time -ele 1 globalForce
recorder Element -file eleforce19.num -time -ele 2 globalForce
recorder Element -file wallbase11.num -time -ele 1 section 1 fiber 0 0 stressStrain
recorder Element -file wallbase21.num -time -ele 2 section 1 fiber 0 0 stressStrain
recorder Element -file wallbase51.num -time -ele 1 section 1 fiber 0 21 stressStrain
recorder Element -file wallbase61.num -time -ele 2 section 1 fiber 0 21 stressStrain
recorder Element -file wallbase71.num -time -ele 1 section 1 fiber 0 -21 stressStrain
recorder Element -file wallbase81.num -time -ele 2 section 1 fiber 0 -21 stressStrain
analyze 33000

```

E.9 Program File for the Coupled Wall With Fuse Beams and Without Elastomeric Pads

```

# OpenSees coupled wall (with fuse beam and without elastomeric pads)
# Default Units: kips, in, s
# PARAMETERS DEFINITION
set nInt      3; #number of integration points along length of element
set width     4; #width of cross-section
set depth     48; #depth of cross-section
set cover     0.75; #thickness of concrete cover
set fy        75; #Steel yielding stress
set Es        29000; #Steel Young's modulus
puts "parameters set successful";
model basic -ndm 2 -ndf 3
# NODE GENERATION
node 1 0 0
node 2 103 0
node 3 0 36
node 4 24 36
node 5 39.5 36
node 6 63.5 36
node 7 79 36
node 8 103 36
node 9 39.5 43
node 10 63.5 43
node 11 39.5 29

```

```

node 12 63.5 29
node 13 0 72
node 14 24 72
node 15 39.5 72
node 16 63.5 72
node 17 79 72
node 18 103 72
node 19 39.5 79
node 20 63.5 79
node 21 39.5 65
node 22 63.5 65
node 23 0 108
node 24 24 108
node 25 39.5 108
node 26 63.5 108
node 27 79 108
node 28 103 108
node 29 39.5 115
node 30 63.5 115
node 31 39.5 101
node 32 63.5 101
node 33 0 144
node 34 24 144
node 35 39.5 144
node 36 63.5 144
node 37 79 144
node 38 103 144
node 39 39.5 151
node 40 63.5 151
node 41 39.5 137
node 42 63.5 137
puts "nodes generation succesful"
fix 1 1 1 1
fix 2 1 1 1
puts "restraint definition succesful"
# MATERIALS DEFINITION
# CONCRETE
# Core concrete
#          TYPE   TAG  fc  ec0  fcu  ecu  ratio  ft  Ets
uniaxialMaterial Concrete02 1 -6.33 -0.00603 -3.0 -0.016 0.2 0.63 400
# Cover concrete
#          TYPE   TAG  fc  ec0  fcu  ecu
uniaxialMaterial Concrete01 2 -4.0 -0.002 -0.4 -0.006
# STEEL
# Rebars
#          TYPE   TAG  fy  E0  b

```

```

uniaxialMaterial Steel01 3 $fy $Es 0.05
uniaxialMaterial Elastic 4 29000
uniaxialMaterial Hysteretic 5 90 0.0045 108 0.0085 104 0.0158 -95 -0.00475 -114 -0.009
-125 -0.015 0 0 0 0
puts "material definition successful"
#CROSS-SECTION DEFINITION
section Fiber 1 {
    # Concrete core fibers
    # patch rect $matTag $numSubdivIJ $numSubdivJK $yI $zI $yK $zK
    # note: z strong axis for bending
    patch rect 1 20 1 [expr -$depth/2+$cover] [expr -$width/2+$cover] [expr $depth/2-
$cover] [expr $width/2-$cover]; # -23.25 -1.25 23.25 1.25
    puts "defined core fibers";
    # Concrete cover fibers
    # Bottom
    patch rect 2 20 1 [expr -$depth/2] [expr -$width/2] [expr $depth/2] [expr -
$width/2+$cover]; #-24 -2 24 -1.25
    puts "defined top cover";
    # Top
    patch rect 2 20 1 [expr -$depth/2] [expr $width/2-$cover] [expr $depth/2] [expr
$width/2]; #-24 1.25 24 2
    puts "defined bottom cover";
    # Right
    patch rect 2 2 1 [expr $depth/2-$cover] [expr -$width/2+$cover] [expr $depth/2]
[expr $width/2-$cover]; #23.25 -1.25 24 1.25
    puts "defined left cover";
    # Left
    patch rect 2 2 1 [expr -$depth/2] [expr -$width/2+$cover] [expr -$depth/2+$cover]
[expr $width/2-$cover]; #-24 -1.25 -23.25 1.25
    puts "defined right cover";
    # Rebar fibers
    # layer straight $matTag $numBars $areaBar $yStart $zStart $yEnd $zEnd
    layer straight 3 4 0.11 -23.25 1.25 -17.25 1.25
    layer straight 3 4 0.05 -11.25 1.25 11.25 1.25
    layer straight 3 4 0.11 17.25 1.25 23.25 1.25
    layer straight 3 4 0.11 -23.25 -1.25 -17.25 -1.25
    layer straight 3 4 0.05 -11.25 -1.25 11.25 -1.25
    layer straight 3 4 0.11 17.25 -1.25 23.25 -1.25
}
section Fiber 2 {
    # Concrete core fibers
    # patch rect $matTag $numSubdivIJ $numSubdivJK $yI $zI $yK $zK
    # note: z strong axis for bending
    patch rect 1 20 1 [expr -$depth/2+$cover] [expr -$width/2+$cover] [expr $depth/2-
$cover] [expr $width/2-$cover]; # -23.25 -1.25 23.25 1.25
    puts "defined core fibers";

```

```

# Concrete cover fibers
# Bottom
patch rect 2 20 1 [expr -$depth/2] [expr -$width/2] [expr $depth/2] [expr -
$width/2+$cover]; #-24 -2 24 -1.25
puts "defined top cover";
# Top
patch rect 2 20 1 [expr -$depth/2] [expr $width/2-$cover] [expr $depth/2] [expr
$width/2]; #-24 1.25 24 2
puts "defined bottom cover";
# Right
patch rect 2 2 1 [expr $depth/2-$cover] [expr -$width/2+$cover] [expr $depth/2]
[expr $width/2-$cover]; #23.25 -1.25 24 1.25
puts "defined left cover";
# Left
patch rect 2 2 1 [expr -$depth/2] [expr -$width/2+$cover] [expr -$depth/2+$cover]
[expr $width/2-$cover]; #-24 -1.25 -23.25 1.25
puts "defined right cover";
# Rebar fibers
# layer straight $matTag $numBars $areaBar $yStart $zStart $yEnd $zEnd
layer straight 3 4 0.11 -23.25 1.25 -17.25 1.25
layer straight 3 4 0.05 -11.25 1.25 11.25 1.25
layer straight 3 4 0.11 17.25 1.25 23.25 1.25
layer straight 3 4 0.11 -23.25 -1.25 -17.25 -1.25
layer straight 3 4 0.05 -11.25 -1.25 11.25 -1.25
layer straight 3 4 0.11 17.25 -1.25 23.25 -1.25
}
section Fiber 3 {
# Concrete core fibers
# patch rect $matTag $numSubdivIJ $numSubdivJK $yI $zI $yK $zK
# note: z strong axis for bending
patch rect 1 20 1 [expr -$depth/2+$cover] [expr -$width/2+$cover] [expr $depth/2-
$cover] [expr $width/2-$cover]; # -23.25 -1.25 23.25 1.25
puts "defined core fibers";
# Concrete cover fibers
# Bottom
patch rect 2 20 1 [expr -$depth/2] [expr -$width/2] [expr $depth/2] [expr -
$width/2+$cover]; #-24 -2 24 -1.25
puts "defined top cover";
# Top
patch rect 2 20 1 [expr -$depth/2] [expr $width/2-$cover] [expr $depth/2] [expr
$width/2]; #-24 1.25 24 2
puts "defined bottom cover";
# Right
patch rect 2 2 1 [expr $depth/2-$cover] [expr -$width/2+$cover] [expr $depth/2]
[expr $width/2-$cover]; #23.25 -1.25 24 1.25
puts "defined left cover";

```

```

# Left
patch rect 2 2 1 [expr -$depth/2] [expr -$width/2+$cover] [expr -$depth/2+$cover]
[expr $width/2-$cover]; #-24 -1.25 -23.25 1.25
puts "defined right cover";
# Rebar fibers
# layer straight $matTag $numBars $areaBar $yStart $zStart $yEnd $zEnd
layer straight 3 4 0.11 -23.25 1.25 -17.25 1.25
layer straight 3 9 0.05 -15 1.25 15 1.25
layer straight 3 4 0.11 17.25 1.25 23.25 1.25
layer straight 3 4 0.11 -23.25 -1.25 -17.25 -1.25
layer straight 3 9 0.05 -15 -1.25 15 -1.25
layer straight 3 4 0.11 17.25 -1.25 23.25 -1.25
}
puts "section definition successful"
# ELEMENT DEFINITION
# Definition of Geometric transformation (linear, P-delta, corotational)
geomTransf Linear 1
# Definition of element
#
# TYPE TAG ndI ndJ nsecs secID transfTag
element nonlinearBeamColumn 1 1 3 3 1 1
element nonlinearBeamColumn 2 2 8 3 1 1
element nonlinearBeamColumn 3 3 13 3 2 1
element nonlinearBeamColumn 4 8 18 3 2 1
element nonlinearBeamColumn 5 13 23 3 2 1
element nonlinearBeamColumn 6 18 28 3 2 1
element nonlinearBeamColumn 7 23 33 3 3 1
element nonlinearBeamColumn 8 28 38 3 3 1
element elasticBeamColumn 9 3 4 5000 29000 50000 1
element elasticBeamColumn 10 4 5 17.9 29000 640 1
element truss 11 11 10 1 5
element elasticBeamColumn 12 6 7 17.9 29000 640 1
element elasticBeamColumn 13 7 8 5000 29000 50000 1
element elasticBeamColumn 14 5 9 5000 29000 50000 1
element elasticBeamColumn 15 5 11 5000 29000 50000 1
element elasticBeamColumn 16 6 10 5000 29000 50000 1
element elasticBeamColumn 17 6 12 5000 29000 50000 1
element truss 18 9 10 10000 4
element truss 19 11 12 10000 4
element elasticBeamColumn 20 13 14 5000 29000 50000 1
element elasticBeamColumn 21 14 15 17.9 29000 640 1
element truss 22 21 20 1 5
element elasticBeamColumn 23 16 17 17.9 29000 640 1
element elasticBeamColumn 24 17 18 5000 29000 50000 1
element elasticBeamColumn 25 15 19 5000 29000 50000 1
element elasticBeamColumn 26 15 21 5000 29000 50000 1
element elasticBeamColumn 27 16 20 5000 29000 50000 1

```

```

element elasticBeamColumn 28 16 22 5000 29000 50000 1
element truss 29 19 20 10000 4
element truss 30 21 22 10000 4
element elasticBeamColumn 31 23 24 5000 29000 50000 1
element elasticBeamColumn 32 24 25 17.9 29000 640 1
element truss 33 31 30 1 5
element elasticBeamColumn 34 26 27 17.9 29000 640 1
element elasticBeamColumn 35 27 28 5000 29000 50000 1
element elasticBeamColumn 36 25 29 5000 29000 50000 1
element elasticBeamColumn 37 25 31 5000 29000 50000 1
element elasticBeamColumn 38 26 30 5000 29000 50000 1
element elasticBeamColumn 39 26 32 5000 29000 50000 1
element truss 40 29 30 10000 4
element truss 41 31 32 10000 4
element elasticBeamColumn 42 33 34 5000 29000 50000 1
element elasticBeamColumn 43 34 35 17.9 29000 640 1
element truss 44 41 40 1 5
element elasticBeamColumn 45 36 37 17.9 29000 640 1
element elasticBeamColumn 46 37 38 5000 29000 50000 1
element elasticBeamColumn 47 35 39 5000 29000 50000 1
element elasticBeamColumn 48 35 41 5000 29000 50000 1
element elasticBeamColumn 49 36 40 5000 29000 50000 1
element elasticBeamColumn 50 36 42 5000 29000 50000 1
element truss 51 39 40 10000 4
element truss 52 41 42 10000 4
puts "element definition successful"
# LOADS DEFINITION
pattern Plain 1 "Series -dt 1.0 -filePath dispHistSW1.dat" {
sp 33 1 1
}
pattern Plain 2 "Series -dt 1.0 -filePath dispHistSW2.dat" {
sp 38 1 1
}
pattern Plain 3 Constant {
load 1 0 -0.3 0
load 2 0 -0.3 0
load 3 0 -0.6 0
load 8 0 -0.6 0
load 13 0 -0.6 0
load 18 0 -0.6 0
load 23 0 -0.6 0
load 28 0 -0.6 0
load 33 0 -0.3 0
load 38 0 -0.3 0
}
puts "loads definition successful"

```



```

# END OF MODEL GENERATION
# ANALYSIS GENERATION
#Type of system of equations: BandGeneral, BandSPD, ProfileSPD, SparseGeneral,
UmfPack, SparseSPD
system SparseGeneral -piv
#Type of constraint handler: Plain, Penalty, Lagrange, Transformation
constraints Transformation
#Type of DOF numberer: Plain, RCM
numberer RCM
#Type of convergence test: NormUnbalance, NormDispIncr, EnergyIncr
# test NormDispIncr $tolerance $maxNumIter <$printFlag> (1=no print, 1=print each
step, 2=print at convergence, etc.)
test NormUnbalance 1.0E-6 30 1
#Type of solution algorithm: Linear, Newton, NewtonLineSearch, ModifiedNewton,
KrylovNewton, BFGS, Broyden
algorithm Newton
integrator LoadControl 0.001
#Type of analysis object: Static, Transient, VariableTransient
analysis Static
initialize
puts "analysis definition successful"
# RECORDER GENERATION
recorder Node -file node33.num -time -node 33 -dof 1 disp
recorder Node -file node38.num -time -node 38 -dof 1 disp
recorder Element -file eleforce4345.num -time -ele 43 45 globalForce
recorder Element -file eleforce78mf.num -time -ele 7 8 globalForce
recorder Element -file eleforcebase1.num -time -ele 1 globalForce
recorder Element -file eleforcebase2.num -time -ele 2 globalForce
recorder Element -file fuseforce.num -time -ele 11 22 33 44 force
recorder Element -file fusedeform.num -time -ele 11 22 33 44 deformation
recorder Element -file wallbase1.num -time -ele 1 section 1 fiber 0 0 stressStrain
recorder Element -file wallbase2.num -time -ele 2 section 1 fiber 0 0 stressStrain
recorder Element -file wallbase5.num -time -ele 1 section 1 fiber 0 21 stressStrain
recorder Element -file wallbase6.num -time -ele 2 section 1 fiber 0 21 stressStrain
recorder Element -file wallbase7.num -time -ele 1 section 1 fiber 0 -21 stressStrain
recorder Element -file wallbase8.num -time -ele 2 section 1 fiber 0 -21 stressStrain
analyze 33000

```

E.10 Program File for the Coupled Wall With Fuse Beams and With Elastomeric Pads

```

# OpenSees coupled wall (with fuse beam and with elastomeric pads)
# Default Units: kips, in, s
# PARAMETERS DEFINITION
set nInt      3;  #number of integration points along length of element
set width     4;  #width of cross-section

```

```

set depth    48; #depth of cross-section
set cover    0.75; #thickness of concrete cover
set fy       75; #Steel yielding stress
set Es       29000; #Steel Young's modulus
puts "parameters set successful";
model basic -ndm 2 -ndf 3
# NODE GENERATION
node 1 0 0
node 2 103 0
node 3 0 36
node 4 24 36
node 5 39.5 36
node 6 63.5 36
node 7 79 36
node 8 103 36
node 9 39.5 43
node 10 63.5 43
node 11 39.5 29
node 12 63.5 29
node 13 0 72
node 14 24 72
node 15 39.5 72
node 16 63.5 72
node 17 79 72
node 18 103 72
node 19 39.5 79
node 20 63.5 79
node 21 39.5 65
node 22 63.5 65
node 23 0 108
node 24 24 108
node 25 39.5 108
node 26 63.5 108
node 27 79 108
node 28 103 108
node 29 39.5 115
node 30 63.5 115
node 31 39.5 101
node 32 63.5 101
node 33 0 144
node 34 24 144
node 35 39.5 144
node 36 63.5 144
node 37 79 144
node 38 103 144
node 39 39.5 151

```

```

node 40 63.5 151
node 41 39.5 137
node 42 63.5 137
puts "nodes generation succesful"
fix 1 1 1 1
fix 2 1 1 1
puts "restraint definition succesful"
# MATERIALS DEFINITION
# CONCRETE
# Core concrete
#
#      TYPE   TAG   fc   ec0   fcu   ecu   ratio   ft   Ets
uniaxialMaterial Concrete02 1 -6.33 -0.00603 -3.0 -0.016 0.2 0.63 400
# Cover concrete
#
#      TYPE   TAG   fc   ec0   fcu   ecu
uniaxialMaterial Concrete01 2 -4.0 -0.002 -0.4 -0.006
# STEEL
# Rebars
#
#      TYPE   TAG   fy   E0   b
uniaxialMaterial Steel01 3 $fy $Es 0.05
uniaxialMaterial Elastic 4 29000
#uniaxialMaterial Hysteretic 5 15 0.0015 65 0.01 92 0.0175 -15 -0.0015 -50 -0.013 -70 -
0.029 0 0 0 0
uniaxialMaterial Hysteretic 5 30 0.003 120 0.0185 129 0.021 -42 -0.007 -71 -0.016 -66 -
0.03 0 0 0 0
puts "material definition successful"
#CROSS-SECTION DEFINITION
section Fiber 1 {
    # Concrete core fibers
    # patch rect $matTag $numSubdivIJ $numSubdivJK $yI $zI $yK $zK
    # note: z strong axis for bending
    patch rect 1 20 1 [expr -$depth/2+$cover] [expr -$width/2+$cover] [expr $depth/2-
$cover] [expr $width/2-$cover]; # -23.25 -1.25 23.25 1.25
puts "defined core fibers";
    # Concrete cover fibers
    # Bottom
    patch rect 2 20 1 [expr -$depth/2] [expr -$width/2] [expr $depth/2] [expr -
$width/2+$cover]; #-24 -2 24 -1.25
puts "defined top cover";
    # Top
    patch rect 2 20 1 [expr -$depth/2] [expr $width/2-$cover] [expr $depth/2] [expr
$width/2]; #-24 1.25 24 2
puts "defined bottom cover";
    # Right
    patch rect 2 2 1 [expr $depth/2-$cover] [expr -$width/2+$cover] [expr $depth/2]
[expr $width/2-$cover]; #23.25 -1.25 24 1.25
puts "defined left cover";

```

```

# Left
patch rect 2 2 1 [expr -$depth/2] [expr -$width/2+$cover] [expr -$depth/2+$cover]
[expr $width/2-$cover]; #-24 -1.25 -23.25 1.25
puts "defined right cover";
# Rebar fibers
# layer straight $matTag $numBars $areaBar $yStart $zStart $yEnd $zEnd
layer straight 3 4 0.11 -23.25 1.25 -17.25 1.25
layer straight 3 4 0.05 -11.25 1.25 11.25 1.25
layer straight 3 4 0.11 17.25 1.25 23.25 1.25
    layer straight 3 4 0.11 -23.25 -1.25 -17.25 -1.25
layer straight 3 4 0.05 -11.25 -1.25 11.25 -1.25
layer straight 3 4 0.11 17.25 -1.25 23.25 -1.25
}
section Fiber 2 {
# Concrete core fibers
# patch rect $matTag $numSubdivIJ $numSubdivJK $yI $zI $yK $zK
# note: z strong axis for bending
patch rect 1 20 1 [expr -$depth/2+$cover] [expr -$width/2+$cover] [expr $depth/2-
$cover] [expr $width/2-$cover]; #-23.25 -1.25 23.25 1.25
puts "defined core fibers";
# Concrete cover fibers
# Bottom
patch rect 2 20 1 [expr -$depth/2] [expr -$width/2] [expr $depth/2] [expr -
$width/2+$cover]; #-24 -2 24 -1.25
puts "defined top cover";
# Top
patch rect 2 20 1 [expr -$depth/2] [expr $width/2-$cover] [expr $depth/2] [expr
$width/2]; #-24 1.25 24 2
puts "defined bottom cover";
# Right
patch rect 2 2 1 [expr $depth/2-$cover] [expr -$width/2+$cover] [expr $depth/2]
[expr $width/2-$cover]; #23.25 -1.25 24 1.25
puts "defined left cover";
# Left
patch rect 2 2 1 [expr -$depth/2] [expr -$width/2+$cover] [expr -$depth/2+$cover]
[expr $width/2-$cover]; #-24 -1.25 -23.25 1.25
puts "defined right cover";
# Rebar fibers
# layer straight $matTag $numBars $areaBar $yStart $zStart $yEnd $zEnd
layer straight 3 4 0.11 -23.25 1.25 -17.25 1.25
layer straight 3 4 0.05 -11.25 1.25 11.25 1.25
layer straight 3 4 0.11 17.25 1.25 23.25 1.25
    layer straight 3 4 0.11 -23.25 -1.25 -17.25 -1.25
layer straight 3 4 0.05 -11.25 -1.25 11.25 -1.25
layer straight 3 4 0.11 17.25 -1.25 23.25 -1.25
}

```

```

section Fiber 3 {
    # Concrete core fibers
    # patch rect $matTag $numSubdivIJ $numSubdivJK $yI $zI $yK $zK
    # note: z strong axis for bending
    patch rect 1 20 1 [expr -$depth/2+$cover] [expr -$width/2+$cover] [expr $depth/2-
$cover] [expr $width/2-$cover]; # -23.25 -1.25 23.25 1.25
puts "defined core fibers";
    # Concrete cover fibers
    # Bottom
    patch rect 2 20 1 [expr -$depth/2] [expr -$width/2] [expr $depth/2] [expr -
$width/2+$cover]; #-24 -2 24 -1.25
puts "defined top cover";
    # Top
    patch rect 2 20 1 [expr -$depth/2] [expr $width/2-$cover] [expr $depth/2] [expr
$width/2]; #-24 1.25 24 2
puts "defined bottom cover";
    # Right
    patch rect 2 2 1 [expr $depth/2-$cover] [expr -$width/2+$cover] [expr $depth/2]
[expr $width/2-$cover]; #23.25 -1.25 24 1.25
puts "defined left cover";
    # Left
    patch rect 2 2 1 [expr -$depth/2] [expr -$width/2+$cover] [expr -$depth/2+$cover]
[expr $width/2-$cover]; #-24 -1.25 -23.25 1.25
puts "defined right cover";
    # Rebar fibers
    # layer straight $matTag $numBars $areaBar $yStart $zStart $yEnd $zEnd
    layer straight 3 4 0.11 -23.25 1.25 -17.25 1.25
    layer straight 3 9 0.05 -15 1.25 15 1.25
    layer straight 3 4 0.11 17.25 1.25 23.25 1.25
    layer straight 3 4 0.11 -23.25 -1.25 -17.25 -1.25
    layer straight 3 9 0.05 -15 -1.25 15 -1.25
    layer straight 3 4 0.11 17.25 -1.25 23.25 -1.25
}
puts "section definition successful"
# ELEMENT DEFINITION
# Definition of Geometric transformation (linear, P-delta, corotational)
geomTransf Linear 1
# Definition of element
#      TYPE      TAG  ndI  ndJ  nsecs  secID  transfTag
element nonlinearBeamColumn 1    1    3    3    1    1
element nonlinearBeamColumn 2    2    8    3    1    1
element nonlinearBeamColumn 3    3    13   3    2    1
element nonlinearBeamColumn 4    8    18   3    2    1
element nonlinearBeamColumn 5    13   23   3    2    1
element nonlinearBeamColumn 6    18   28   3    2    1
element nonlinearBeamColumn 7    23   33   3    3    1

```

element	nonlinearBeamColumn	8	28	38	3	3	1
element	elasticBeamColumn	9		3	4	5000	29000 50000 1
element	elasticBeamColumn	10		4	5	17.9	29000 640 1
element	truss	11	11	10	1	5	
element	elasticBeamColumn	12		6	7	17.9	29000 640 1
element	elasticBeamColumn	13		7	8	5000	29000 50000 1
element	elasticBeamColumn	14		5	9	5000	29000 50000 1
element	elasticBeamColumn	15		5	11	5000	29000 50000 1
element	elasticBeamColumn	16		6	10	5000	29000 50000 1
element	elasticBeamColumn	17		6	12	5000	29000 50000 1
element	truss	18	9	10	10000	4	
element	truss	19	11	12	10000	4	
element	elasticBeamColumn	20		13	14	5000	29000 50000 1
element	elasticBeamColumn	21		14	15	17.9	29000 640 1
element	truss	22	21	20	1	5	
element	elasticBeamColumn	23		16	17	17.9	29000 640 1
element	elasticBeamColumn	24		17	18	5000	29000 50000 1
element	elasticBeamColumn	25		15	19	5000	29000 50000 1
element	elasticBeamColumn	26		15	21	5000	29000 50000 1
element	elasticBeamColumn	27		16	20	5000	29000 50000 1
element	elasticBeamColumn	28		16	22	5000	29000 50000 1
element	truss	29	19	20	10000	4	
element	truss	30	21	22	10000	4	
element	elasticBeamColumn	31		23	24	5000	29000 50000 1
element	elasticBeamColumn	32		24	25	17.9	29000 640 1
element	truss	33	31	30	1	5	
element	elasticBeamColumn	34	26	27	17.9	29000 640 1	
element	elasticBeamColumn	35		27	28	5000	29000 50000 1
element	elasticBeamColumn	36		25	29	5000	29000 50000 1
element	elasticBeamColumn	37		25	31	5000	29000 50000 1
element	elasticBeamColumn	38		26	30	5000	29000 50000 1
element	elasticBeamColumn	39		26	32	5000	29000 50000 1
element	truss	40	29	30	10000	4	
element	truss	41	31	32	10000	4	
element	elasticBeamColumn	42		33	34	5000	29000 50000 1
element	elasticBeamColumn	43		34	35	17.9	29000 640 1
element	truss	44	41	40	1	5	
element	elasticBeamColumn	45		36	37	17.9	29000 640 1
element	elasticBeamColumn	46	37	38	5000	29000 50000 1	
element	elasticBeamColumn	47		35	39	5000	29000 50000 1
element	elasticBeamColumn	48		35	41	5000	29000 50000 1
element	elasticBeamColumn	49		36	40	5000	29000 50000 1
element	elasticBeamColumn	50		36	42	5000	29000 50000 1
element	truss	51	39	40	10000	4	
element	truss	52	41	42	10000	4	

puts "element definition successful"

```

# LOADS DEFINITION
pattern Plain 1 "Series -dt 1.0 -filePath dispHistSW1.dat" {
sp 33 1 1
}
pattern Plain 2 "Series -dt 1.0 -filePath dispHistSW2.dat" {
sp 38 1 1
}
pattern Plain 3 Constant {
load 1 0 -0.3 0
load 2 0 -0.3 0
load 3 0 -0.6 0
load 8 0 -0.6 0
load 13 0 -0.6 0
load 18 0 -0.6 0
load 23 0 -0.6 0
load 28 0 -0.6 0
load 33 0 -0.3 0
load 38 0 -0.3 0
}
puts "loads definition successful"
# END OF MODEL GENERATION
# ANALYSIS GENERATION
#Type of system of equations: BandGeneral, BandSPD, ProfileSPD, SparseGeneral,
UmfPack, SparseSPD
system SparseGeneral -piv
#Type of constraint handler: Plain, Penalty, Lagrange, Transformation
constraints Transformation
#Type of DOF numberer: Plain, RCM
numberer RCM
#Type of convergence test: NormUnbalance, NormDispIncr, EnergyIncr
# test NormDispIncr $tolerance $maxNumIter <$printFlag> (1=no print, 1=print each
step, 2=print at convergence, etc.)
test NormUnbalance 1.0E-6 30 1
#Type of solution algorithm: Linear, Newton, NewtonLineSearch, ModifiedNewton,
KrylovNewton, BFGS, Broyden
algorithm Newton
integrator LoadControl 0.001
#Type of analysis object: Static, Transient, VariableTransient
analysis Static
initialize
puts "analysis definition successful"
# RECORDER GENERATION
recorder Node -file node33mf2.num -time -node 33 -dof 1 disp
recorder Node -file node38mf2.num -time -node 38 -dof 1 disp
recorder Element -file eleforce4345mf2.num -time -ele 43 45 globalForce
recorder Element -file eleforce78mf2.num -time -ele 7 8 globalForce

```

```

recorder Element -file eleforcebase21.num -time -ele 1 globalForce
recorder Element -file eleforcebase22.num -time -ele 2 globalForce
recorder Element -file fuseforcecmf2.num -time -ele 11 22 33 44 force
recorder Element -file fusedeformmf2.num -time -ele 11 22 33 44 deformation
analyze 33000

```

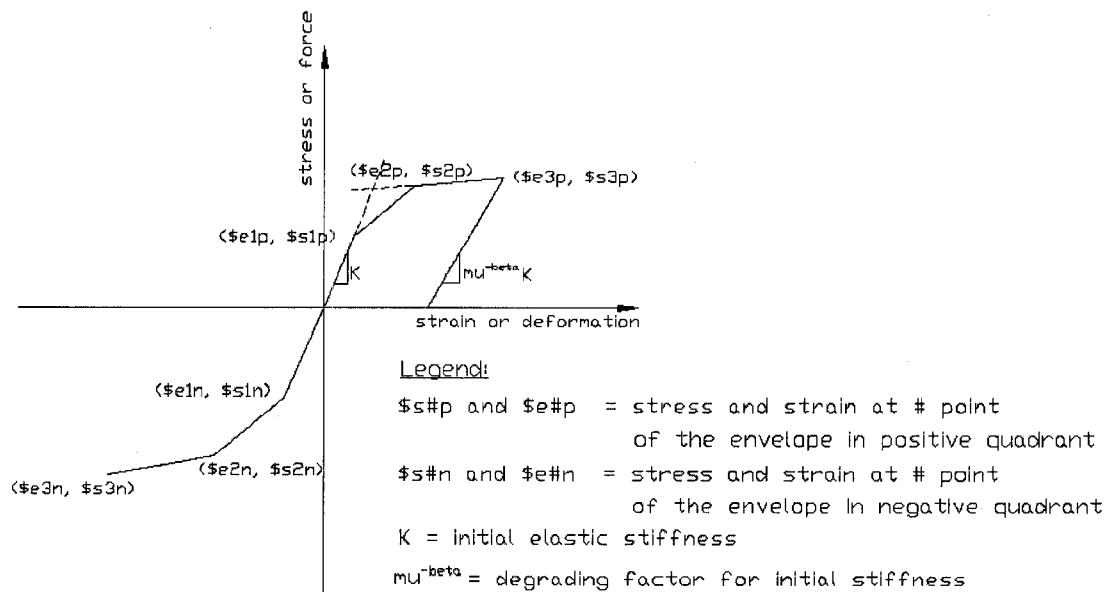


Figure E.3 Definition of Hysteretic Material in OpenSees

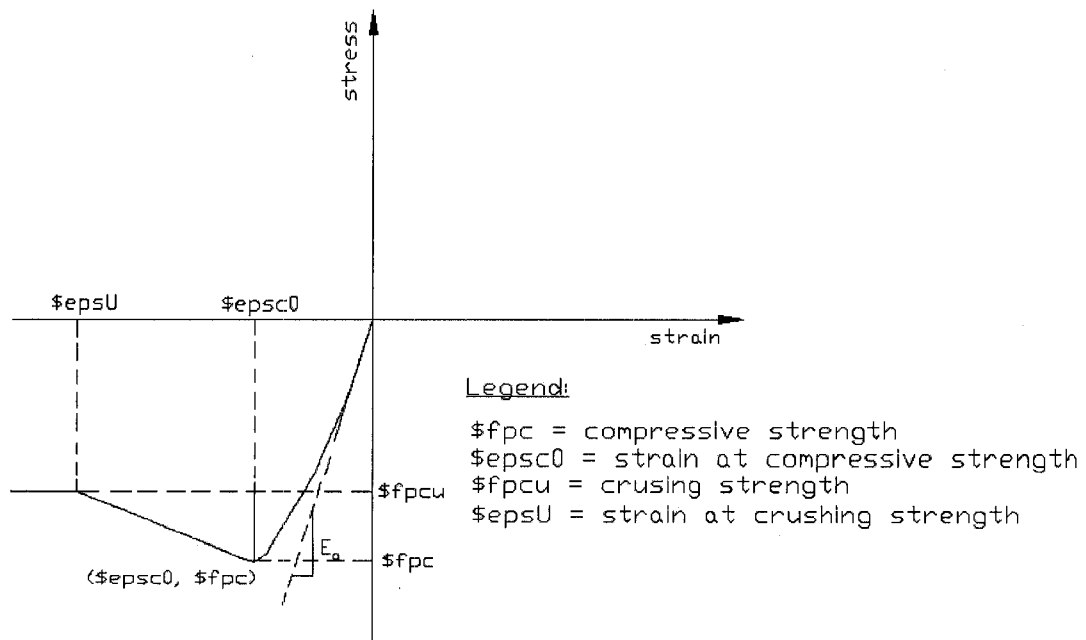


Figure E4 Definition of Concrete01 Material in OpenSees

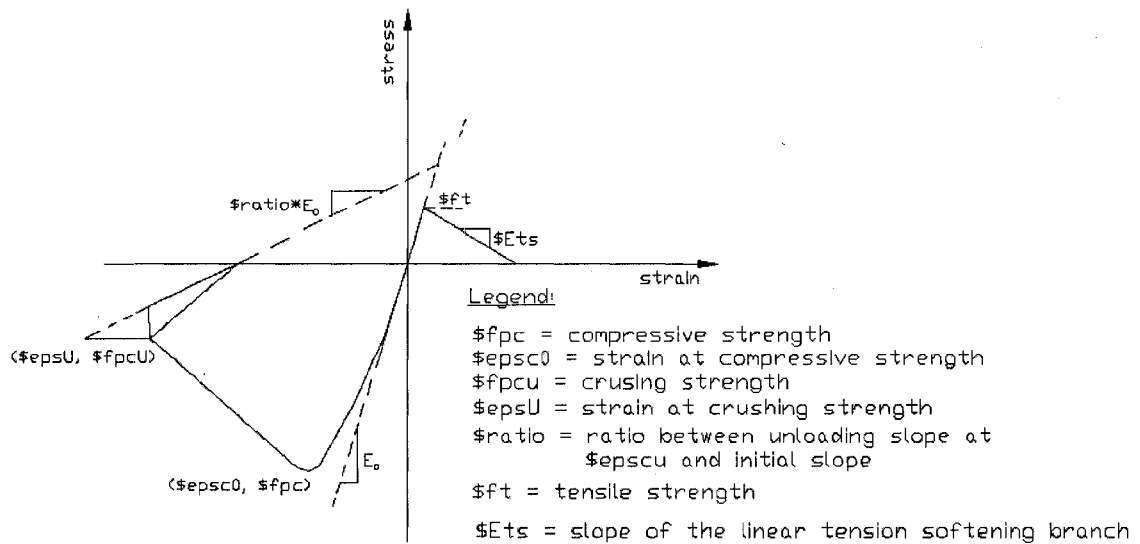


Figure E.5 Definition of Concrete02 Material in OpenSees

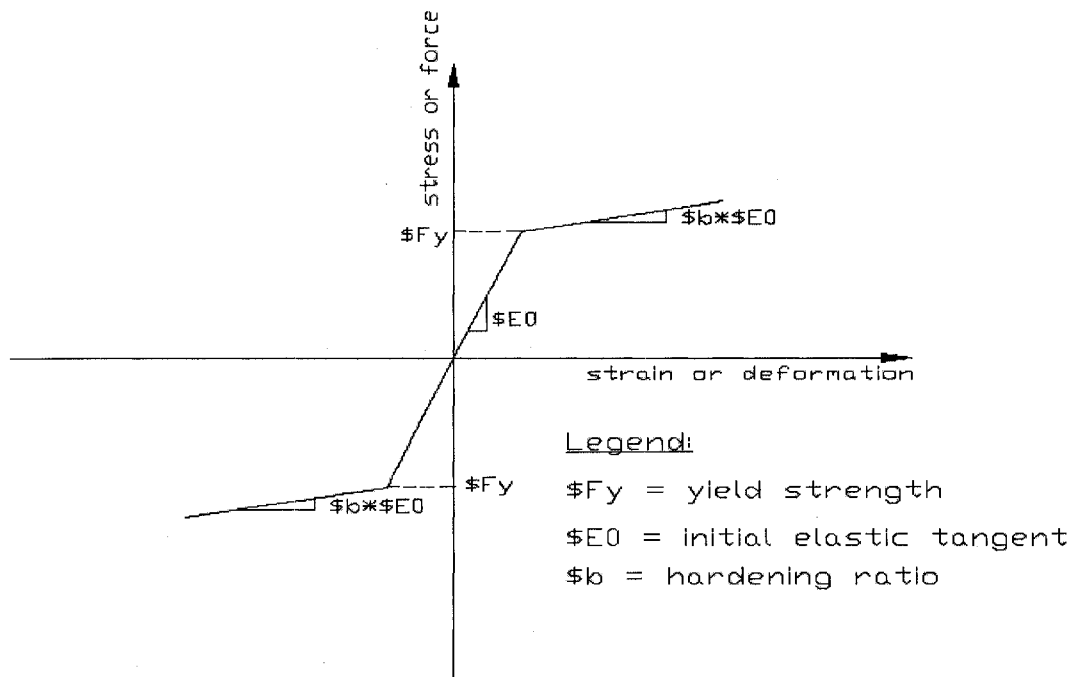


Figure E.6 Definition of Steel01 Material in OpenSees