3-1-1990

ATLSS Connections -- Concept, Development and Experimental Investigation

Robert B. Fleischman

B. Vincent Viscomi

Le-Wu Lu

Recommended Citation

Fleischman, Robert B.; Viscomi, B. Vincent; and Lu, Le-Wu, "ATLSS Connections -- Concept, Development and Experimental Investigation" (1990). ATLSS Reports. ATLSS report number 91-02:.
http://preserve.lehigh.edu/engr-civil-environmental-atlss-reports/165

ADVANCED TECHNOLOGY FOR
LARGE
STRUCTURAL SYSTEMS

Lehigh University

ATLSS Connections - Concept, Development and Experimental Investigation

by

Robert B. Fleischman
B. Vincent Viscomi
Le-Wu Lu

ATLSS Report No. 91 - 02

March, 1991

An NSF Sponsored Engineering Research Center

ADVANCED TECHNOLOGY FOR
LARGE
STRUCTURAL SYSTEMS

Lehigh University

ATLSS Connections - Concept, Development and Experimental Investigation

by

Robert B. Fleischman
Research Assistant

B. Vincent Viscomi
Visiting Research Professor

Le-Wu Lu
Professor of Civil Engineering

ATLSS Report No. 91 - 02

March, 1991

ATLSS Engineering Research Center
Lehigh University
117 ATLSS Dr., Imbt Laboratories
Bethlehem, PA 18015-4729
(215) 758-3535

An NSF Sponsored Engineering Research Center

Table of Contents

ABSTRACT

A series of new beam-to-column connections known as ATLSS connections are currently under development. The emphasis in these new designs is on ease of fabrication and erection. The fundamental principle behind these connections is a self-guided erection feature. The object of this feature is to allow the initial placement of building members with reduced human assistance. This results in quicker, less expensive erection and less susceptibility of workers to injury or fatalities.

Many different connection types are being developed to cover the range of structural needs and erection options. These include an erection-aid type, with a traditional connection to follow; a shear connection; a partial-moment connection; the shear component of a fully rigid connection; and an attachment to a traditional connection.

A test has been conducted on a shear-type steel ATLSS connection. This particular connection was comprised of a dove-tailed double web-angle attached to the beam web, which slipped into self-aligning brackets attached to the column flange. The connection was analyzed and designed as a shear connection. Except for a crane operator, it was erected without human assistance, after which it was tested to failure. The connection behaved as a simple connection and reached over 90% of the end shear required to form a plastic moment at midspan.

Currently, finite element analyses are being performed on models of these connections and both reduced- and full-scale connection experiments are being designed. These will be followed by the utilization of the ATLSS connections in a full-scale, three-dimensional test structure.

1. INTRODUCTION

The ATLSS Connection refers to any new connection developed by the ATLSS Center[1] with an emphasis on ease of constructibility. Each of these connections contains a self-guided erection feature. This feature allows the initial placement of members with reduced human assistance. Furthermore, a self-supporting feature eliminates the need for a worker to manuever and secure the beam while in a precarious situation. These features should result in quicker, safer, and less expensive erection of structures. The ATLSS connection concept is part of an effort to integrate building construction (See Sec. 1.1).

1.1 AIBS

ATLSS Integrated Building Systems (AIBS) is a project at the ATLSS Center. The objective of this initiative is to provide the means to design, fabricate, erect and evaluate cost-effective building systems with a focus on providing a computer-integrated systems approach. The project involves researchers in connections, new materials, integrated design and construction, automated construction, and structural monitoring. The long-term intent of this program is to lead to a family of structural systems with enhanced fabrication and erection characteristics, an automated construction system incorporating power tools capable of transporting, positioning, and/or connecting construction materials at the job site, and sensor systems which gather and process information for the successful conclusion of the construction process as well as the monitoring of building life cycle performance (ATLSS, 1990).

Some of the advantageous features of the ATLSS connection depend on or would be improved with an advanced erection system. These possibilities are being explored in the AIBS project and by others (Dagalakis et al, 1989). A six-cable suspension system called the Stewart Platform is being evaluated for erection purposes at NIST[2]. It consists of an equilateral trianglular platform suspended by six wireropes, two at each vertex. The six-degree-of-freedom capabilities enable the platform to have a significant stiffness superiority over conventional cranes. Futhermore, the stiffness is adjustable, and the crane can exert a substantial horizontal force. The objective of the NIST's work is to develop dynamically stabilized cranes capable of lifting, moving and positioning heavy loads, and possibly performing some erection fastening tasks (Dagalakis et al, 1989). Among its possible uses, the Stewart Platform can be used in conjunction with the ATLSS connections.

The design of building connections is often relegated to the fabricator. In some cases, the intent of the designer is unclear. In other cases, the intent is clear, but the fabricator's options are limited by the design. A knowledge-based system (KBS), the Designer-Fabricator Interpreter, is being developed to provide a means to overcome these inefficiencies. The primary goal of this project is to provide a problem-solving common ground which can alleviate the mismatches which can occur. The system can evaluate a connection's design and suggest alternatives based on other participants involved. It also transforms knowledge so participants can understand each other's viewpoints more adequately (ATLSS, 1990).

---

[1] Center for the Advanced Technology for Large Structural Systems, Lehigh University, Bethlehem, PA 18015.

[2] National Institute of Standards and Technology, formerly the National Bureau of Standards.

1.2 ATLSS Connections

While the concepts associated with the ATLSS connection can be applied to all types of building connections (column splices, bracing, beam-to-girder, etc.) and materials, the scope of this paper is limited to steel beam-to-column connections. The general idea is to have a female guide on the column face which will accept a male piece attached to the end of the beam.

The beam-to-column connection is a key component of steel building construction. The cutting, drilling and shop fastening comprise a large portion of the fabrication effort; the placement and field fastening control the speed and cost of erection; and, the connection itself is a critical structural component. Current fabrication processes involve the cutting of detail material into shapes for the connection pieces. Holes for bolts are drilled in both the detail material and the main members. Depending on the erection scheme, these pieces are either shop welded or bolted to the main members or shipped loose to the field. The erection of beams in a building involves suspending the beam from a crane and manuvering it into position. An ironworker must guide the beam to the proper location and fit erection or permanent bolts until the beam is stable. Later, the remainder of the bolts are placed and the structure is aligned and plumbed. This may involve the use of slotted holes, shimming, or mechanical force. If moment capacity is desired, field welding of the flanges may take place.

To accomplish its intended purpose, the ATLSS beam-to-column connection must contain the following features :

- **Self-alignment** -- The connection must be able to guide the beam toward the proper location once the male and female pieces make contact. Futhermore, the male piece cannot jam or catch (Whitney, 1982) on the female guide, nor can it pull out horizontally once it engages.
- **Tolerances** -- The connection has no chance of succeeding if the male piece cannot enter the female guide. The connection must therefore have tolerances which allow for misalignment or out-of-plumbness.
- **Adjustment** -- Because of the tolerances which must be built in, it is unlikely that the connection will be precisely in its correct position after erection. Therefore, the connection must have the ability to be adjusted easily.
- **Strength and Stability** -- The connection must be strong enough to carry the erection loads, and it must also be stable to allow erection of the structure to continue until the final fastening. If the connection is also intended as a structural component, it must be able to carry the design loads as well.
- **Modularity** -- The ultimate goal of this concept is to have a limited assortment of mass-produced connections with a standard shop fitting operation and quick, automatic erection capabilities.

2. THEORY AND CONSIDERATIONS

The theoretical study of the ATLSS connection is a two part process. Before the customary investigations into the connection's structural behavior are undertaken, the connection itself must be defined, checked, and assessed for its practicality in fabrication and its performance in erection. This chapter examines the latter process.

2.1 Coupling Device

Most of the ATLSS connections make use of a tapered *male piece* on the beam which slips into a *female guide* mounted on the column. This will be referred to as the *keystone* coupling. The vertical distance that the female guide occupies is referred to as the *runway length.* The sloped planes on the female guide that interface with the male piece are referred to as the *contact surfaces* (See Fig. 1). The keystone coupling has been designed as a three-dimensional or two-dimensional piece.

The three-dimensional keystone was the subject of a study on robotic erection of structures (Nguyen and Perreira, 1988). Within this study it was found that the optimum configuration for the self-guiding connection was a chamfered piece with three slopes : in the vertical direction on the front at the column face; in the vertical direction on the sides; and in the horizontal direction on the sides (See Fig. 2). The reasons for this chamfer are to proportion the insertion forces and torques so that the male part slides easily into the female; and, to provide a means for valid alignment during the pre-insertion phase. This connection piece would have to be a solid or a hollow three-dimensional piece. The obvious higher costs could be partially defrayed by casting or mass-producing this piece. This 3-D connection would be more accurate and easier in placement than its 2-D counterpart.

The two-dimensional keystone uses plates or angles to form a contact *plane* parallel to, and slightly out from the column face. The planar configuration allows the connection to be fabricated from plate or angles. Four geometric considerations are considered when detailing the couplings :

- **Slope of the fitting** -- For bearing considerations, the slope should be as flat as possible. For practical considerations (clearance width, runway length), the slope should be as steep as possible (See Fig. 3).
- **Opening width** -- Once the male piece slips into the female guide, it is desired that the male piece should not be able to pull out horizontally. This geometric constraint restricts the bottom horizontal dimension of the male piece (lower width) b_1 to be larger than the upper inside dimension (mouth) b_2 of the female guide (See Fig. 3).
- **Development length** -- The vertical length of the keystone depends on the loads it is intended to carry. The length is required to spread out the contact forces and it must be sufficient to fit the required bolts on the beam web. A lower bound on the vertical length is provided by the need for a sufficient runway for automatic erection. It may be necessary to limit the beam bolt's vertical location to within the horizontal projection of the female guide in order to fully utilize the bolts. The efficiency of the bolts at different locations is under investigation.
- **Weld pattern and length** -- The strength of the female guide is dependent on the weld that attaches it to the column face. The outer perimeter of the female piece defines the weld pattern, and hence the moment of inertia of the weld. This property is of importance because of the large lateral forces created as a result of the steep contact surfaces (See Sec. 2.4). From this standpoint, it would be beneficial to make the female guide one piece (See Fig. 4-a,b).

Consideration was given to where the coupling device should go in relation to the beam cross section. For the erection aids, the device must not interfere with the structural connection to follow. For the shear connections, the keystone is attached to the beam web. The preferred location is above the beam centroid because hanging a piece above its center of gravity is stable. On the other hand, configurations placing the keystone near the bottom of the web and using the composite action of the floor slab to gain partial moment resistance were considered.

To develop any substantial moment capacity, a connection must engage the beam flanges. There are various ways to accomplish this with ATLSS connections : 1) The ATLSS connection can be attached to the beam web and traditional flange connections can be shop attached to the beam and field connected to the column. 2) The ATLSS connection itself can make up one of the flange connections. 3) A full-depth, tight-fitting, three-dimensional keystone connection can be used.

2.2 Structural Role

The ATLSS connection concept can cover a large range of structural needs. These include the connection as an erection aid only, as a shear connection, as a partial-moment connection, and as a full-moment connection.

When used as an erection aid only, the ATLSS connection must be relatively inexpensive because it is an additional item. It also may not need to be very precise as the final aligning is done at the time of securing the actual connection. This ATLSS connection must carry the construction loads, and must slip into place easily and without jamming. The ATLSS connection, when used as a simple or shear connection, can be a more refined and larger version of the erection aid. There is a need for smoother contact surfaces to facilitate uniform transfer of shear. Securing bolts are required to keep the beam from sliding toward and away from the column. To minimize the effect of the beam's flexural forces, these would be located at the elevation of the beam's neutral axis.

As a partial-moment connection, the ATLSS connection can be connected to the flange, or the traditional web erection aid can be paired with flange tees, plates or angles. These connections may face obstacles to their acceptance into practice, since not only is their erection a new process, but semi-rigid design is not currently common practice. A full-moment connection must develop the full flexural force in both the flanges and the web. Therefore, a full-moment connection could be obtained by pairing an ATLSS shear connection with flange tees/plates. Another option would be enhancing an existing full-moment connection by adding a self-guiding feature.

2.3 Erection Techniques

There are two approaches to the manner in which the ATLSS connections could be erected. One is to leave the connection as loose as possible and make the opening as forgiving as possible. The object then would be to get the beam in the general position safely, but not in a fixed manner. Then, during plumbing, the beam could be brought to its exact location and the male piece tightened. This could be accomplished with oversize female guides and snug-tightened bolts in slotted holes. The second approach is to tighten the male piece initially and have it slip into a tight-fitting female guide. The latter is much less expensive from an erection standpoint because it does not require a follow up gang to adjust the beam. However, the fabrication costs associated with the high tolerances needed could outweigh the erection savings. It may be possible to combine these two approaches by placing the tight-fitting ATLSS connection on one end of the beam and allow the other end to have a compliant ATLSS connection. One connection fits tightly while the other is allowed to position itself within an oversized female guide. This eliminates internal stresses and the need to fit both ends at the same time. The male piece at the compliant end must be able to be properly fastened for a range of positions relative to the female piece.

Because the ATLSS connection uses gravity to its advantage, most designs involve dropping the beam in place. This is not feasible in situations where there are overhead obstructions such as column splice plates. Overhead flange obstruction presents a problem for full-moment connections and beam-to-girder connections. With this in mind, some ATLSS connections have been designed to slide, swing or twist into place from the horizontal. This technique can in some cases eliminate the need for coping the lower flange.

2.4 ATLSS Connection Design Considerations

The ATLSS connection has one feature that separates it from traditional connections. In its purest form, the ATLSS connection has no bolted or welded connection between its beam and column pieces. The ATLSS connection depends on gravity to form a load transfering contact surface between the male and female connection parts. Depending on the workmanship, the member camber, etc., the location of these surface forces can vary from a uniform distribution to a point load. This can subject the connection to biaxial bending and torsion (See Fig. 5).

For a shear connection subject to gravity load only, it could be possible to have only the contact surface as the load transfer mechanism. Because of the steep slope required for erection, the contact force contains a large horizontal component. These self-equilibrating, outward components tend to open the female connection and highly stress the column weld. Of course, for connections subjected to reversed loading or connections made to resist moment, a traditional fastening procedure is required. The more load the connection transfers with its contact surface, the less expensive it will be. If there is no physical connection (bolting, welding), it is possible to have a purely *pinned* connection. This is because the clearance required within the female guide for erection is much larger than that required to restrict the simple beam rotations.

Tolerances are allowed for each piece involved in the construction process. This is due to the natural deformations involved in the creation of each piece, the degree of accuracy of the tools which cut and drill, and human error. With these tolerances come the unavoidable accumulation of errors in length and spacing. Therefore, forgiveness and adjustability must be built into the connection system.

2.5 Special Tools

The evolution of the ATLSS Connection is occuring in conjunction with that of other special techniques or use of new tools. Slip-in-place erection would require a highly accurate crane with multiple degrees of freedom at both ends. The crane would have to exert force at times to overcome frictional stoppages, and, at other times, become flexible so as to not impede the self-aligning features of the ATLSS connection. The Stewart Platform (See Sec. 1.1) has the potential to accomplish these tasks.

Most connections use slotted holes or shims to allow for adjustment. Special shims may have to be developed for the keystone connections. A new wedge-like tool is envisioned to assist in final adjustment. Research is being done elsewhere[3] on automatic welding machines that climb the columns. These machines would allow for greater flexibility in the design of the ATLSS connections.

---

[3] Lincoln Arc Welding Company

3. CONNECTIONS

This chapter contains descriptions of the steel connections that have been proposed for use as ATLSS connections. The connections deemed as having the greatest potential for good performance and cost savings will be explored through physical models, finite element analyses, and full-scale experimentation. The proposed connections cover the full range of beam-to-column steel connections. The connections all share some common features : all are configured and erected in such a way that costly beam copes are not required; All connections have some sort of adjustability, be it with shims, oversize guides, or slotted holes.

3.1 Erection Aids

There are four ATLSS connections that classify as erection aids only. The characteristic that is shared by these connections is that the erection aid is inexpensive. The first two are of the keystone variety, the other two are additional items added to existing connections.

Figure 6 shows the keystone erection aid. It is attached to the beam web. This connection could be used in conjunction with flange connections such as angles, tees or plates. The pieces that make up the connections can be mass-produced. The one-piece female guide allows for a superior weld pattern on the column face (See Sec. 2.1) and permits quick and accurate fabrication layout. Figure 7 shows a *containment type* erection aid. In this case, the seat provides the complete erection support while the female pieces are oversized and provide only stability to the beam. An erection pin can be inserted if neccessary. The connection has versatility because it can cover a wide range of structural needs. A clip angle can be attached at the top for a simple connection. The female guide can contain access holes to allow bolting of the web piece, creating a partial-moment connection. The seat angle can be replaced by a seat tee to form a rigid connection.

Figure 8 shows a top-and-seat-angle connection with a beam modified for automatic erection. The beam has tabs on its flange so it will have lateral stability when it rests on the angles. Erection pins give the beam longitudinal stability. It is anticipated that these undersized pins can be dropped in automatically. The erection process involves a horizontal movement, followed by a vertical movement as shown in Fig. 9. Figure 10 shows an erection aid for the extended end-plate connection. This is nothing more than the traditional end-plate connection with side wings that slip into slots. The end-plate connection as it currently exists is a potentially dangerous connection. This small modification would eliminate the dangers. Since the aid would be designed to carry the erection loads completely there is no need for erection bolts. The structural bolts could be placed at the erector's convenience in a much safer environment, and without having to worry about supporting the beam. Once the bolts are in, the erection aids can be burned or knocked off if they are posing an obstruction to other trades.

3.2 Shear Connections

Figure 11 shows the keystone shear connection. It is similar to the keystone erection aid. There are some key differences. The depth of the shear connection is much larger than that of the erection aid. This is because the connection contains more bolts along the beam web to carry the design shear. The contact surfaces between the male and female parts of the shear connection must be smoother and a better fit than the erection aid to limit torsional moments on the column face. Since the keystone is the complete connection, it requires anchoring bolts on the column face to keep the beam from sliding longitudinally. These will be placed at the same level as the beam's neutral axis to maintain the simple beam action.

A less expensive method of creating a shear connection is to use a lower flange keystone connection with a top clip (See Fig. 12). Since the shear is not being developed through the web, the large depth is not needed. The male piece need not be double angles, it can be a plate welded to the lower flange. The beam would come in from the side, and then drop down using a tab for lateral stability.

3.3 Partial-Moment Connections

The partial-moment ATLSS connections are made by placing a keystone on the upper flange and a traditional connection on the lower flange. The advantages of these connections are that they are fairly inexpensive and easy to erect, while providing some moment resistance. In spite of these advantages, these connections have not gained widespread acceptance. This is most likely due to the absence of an easy-to-use design procedure. This problem is exacerbated in situations where there is load reversal as the connection's hysteretic behavior may be very difficult to predict because of asymmetry about its neutral axis. However, with large advancements in computers, these difficulties will become less formidable.

Figures 13 through 15 show possible configurations for these connections. In Figure 13, one can see that the female guide at the top flange need be nothing more than a containment piece for stability. The support is provided by the seat. The bolts can be placed later at a safer time. The connection in Fig. 14 requires high tolerance to get the beam to the center of the column without beam web clearance problems. Note that it has a plate on the bottom also, so there is no field welding and the connection should have high moment capacity. The connection in Fig. 15 can be a twist-in-place connection if the tabs are placed catty-corner as shown, or a side-erection if the tabs are both on the same side. In the twist erection, the columns must be pulled back slightly to allow the beam to twist in. It is intended that the seat should be the means of support and the ATLSS plate as a guide.

3.4 Full-Moment Connections

A full-moment connection can be created by placing a keystone connection on the web, and plates or tees at the flanges. Because high accuracy is required for the welds, a three-dimensional keystone is envisioned (See Fig. 16). For clearance, the lower tee is shop attached to the column, while the top flange tee is shop attached to the beam. Backing bar emulators are built in to the tees. This connection can be a partial- to a full-moment connection depending on the size of the web attachment. Web buckling in the beam at the keystone must be investigated. Another way of achieving full-moment capacity is by using the extended end-plate. One such technique has been presented in the erection aid section (Refer to Fig. 10).

3.5 Futuristic Connections

The fundamental principle of the ATLSS Center is to perform research in the present by envisioning the future. Therefore, work on the ATLSS connection has not been limited by today's state-of-the-art in technology, materials, tools, or procedures. Along these lines, there have been some connections that have been proposed that are not meant for the current market. However, with technological advances in machinery and processes, they have a future. A mechanical approach is envisioned for connections of the future, using locks, latches, and movable parts.

One of these connections is shown in Fig. 17-a. The beam has a rod extending from its web at the centroid. The column has a piece of hardware that contains a spring-loaded locking device with two guidance bars extending upward and outward. Getting the rod to fall between these bars is fairly simple, and once this occurs, the beam can be brought down on its side and locked into the device. The device acts like a rotor, allowing the beam to spin. The weight of the shop attached seat angle causes the beam to spin the proper way. There is a stop for the top flange, and the seat can then be secured (See Fig. 17-b).

Another idea is to eliminate the column female piece completely. A portable device which can be attached to the crane could serve as an automatic aligner, support, and welder. The device would have sufficient degrees of freedom to manuver the beam to its proper location using a sensing system. Then, it would weld the beam or the beam's connection piece to the column, and continue to the next location.

4. EXPERIMENTATION

A test was conducted on a shear-type ATLSS connection. The connection was analyzed using a structural analysis computer program. After completing this analysis, it became apparent that the clearance provided for erection within the pocket was much larger than the horizontal component of the beam's end rotation (See Fig. 18). Therefore, the connection was predicted to behave as a purely *pinned* connection (no moment restraint).

4.1 Design for Strength

The connection was then designed for shear with the objective of carrying an end reaction sufficient to allow a plastic hinge under the load of the propped-cantilever testing frame (See Fig. 19). The bolts on the beam web were designed following AISC rules for double web angles. The angles themselves were designed to be the weak link in the connection to promote ductile failure. The bracket (column sleeve) weld was designed using a worst case reaction distribution for largest eccentric load. The welds had to resist biaxial bending, torsion and two components of shear (Refer to Fig. 5). The final configuration is shown in Figure 20. Some key dimensions are :

- 1/2 inch double web angles with short slotted holes.
- 3/4 inch column brackets.
- 1/2" inside clearance for erection.
- 13" depth of connection (lower half of the beam).
- 13:6 vertical slope.
- 27" deep beam

The constraints did produce one undesirable situation: because of the slope and pullout requirements, accessibility was limited, meaning a welder could only make a short return on the bracket inner face. In lieu of the forces to which the bracket would be subjected (See Sec. 2.4), this detail made it unclear whether the angle or the bracket weld would control.

4.2 Erection and Experimental Results

The ATLSS Connection was erected into a 19' propped-cantilever test frame (Refer to Figure 19). The beam, with the connection on one side only was lowered from an initial location which was out-of-line in the transverse, vertical and longitudinal direction. It was slipped into place by crane on the third attempt, without the aid of human alignment. The whole process[4] took approximately 5 minutes.

The experiment contained two separate tests. The initial test was the original ATLSS Connection. However, during testing the web angles slipped excessively *through* the column bracket. This is shown by the lower curve in Figure 21. It was observed that the web angle region beyond the beam web was being pushed closer together into the gap between the angles (See Fig. 22). The closure occured because the slope of the contact surface created a pair of self-equilibrating horizontal forces. The frame was unloaded, a steel plate was inserted in the gap, and the test was resumed. The vertical slip during the second (reinforced) phase is shown in the upper curve of Figure 21.

The ATLSS Connection behaved essentially like a purely *pinned* connection. Figure 23 shows the nearly perfect simple behavior of the beam. Figure 24 shows a magnification of the moment-rotation curve. The curve repeatedly reaches peaks and plummets to a valley. It is believed that this is due to slip of the bearing surface of the unfastened parts, or bolt slip at the beam web. Figure 25 shows the load-deflection relationship for the ATLSS Connection. The initial curve is nonlinear, not from inelasticity, but from vertical connection slip. Once the connection was reinforced it behaved linearly as expected. The connection developed a midspan load of 228.5 kips, or 93.6% of the load to cause a midspan plastic moment. The connection failed by gradual opening of the brackets as they rotated about the outside weldment. As mentioned previously, it was not possible to extend the inside weld return as far as required. The high connection shear was transformed into a horizontal component due to the bracket slope. Even though this component acts at a very small eccentricity, it is sufficient to overcome the resistance of the short weld return and rotates the bracket off the column.

4.3 Discussion

The connection was greatly strengthened by the insertion of the reinforcement plate. It is interesting to note that while the vertical connection slip lessened significantly from this addition (Refer to Fig. 21), the slip of the web angle on the beam acted conversely (See Fig. 26). Originally the weak angles deformed freely relieving the stresses on the bolted web connection. When the plate was added, the angles behaved more like a rigid body, and the deformation occured as slip in the bolted web connection with the slotted holes. The bolts had been tightened to the snug condition.

By using relative strains on various locations on the bracket, a plot of the vertical location of the end reaction centroid is shown in Figure 27. This indicates that the location of the beam end reaction is a load dependent value. The initial lowering of the centroid was due to the vertical connection slip. After the connection was reinforced, the average location was just below midpoint, but it *rose* dramatically near the end of the experiment. It is believed that this was a result of the lower weld opening up, causing a redistribution to the upper bracket.

---

[4] The erection process was captured on videotape.

5. PRESENT WORK AND FUTURE GOALS

With the exploratory work completed, theoretical and experimental work is now in progress. This work involves finite element analyses, small-scale erection models, and full-scale connection experiments. In the future, a three-dimensional frame will be built to examine the entire system performance of the ATLSS integrated building system.

5.1 Finite Element Analyses

Finite element meshes are being developed for the connections for three reasons. First, the force paths through connections which use sloped bearing surfaces are unknown. Second, the effect of out-of-fit can be more readily assessed. Finally, many of these connections are semi-rigid connections and their moment-rotation response is unknown. ANSYS[5], a self-contained general purpose finite element program, is being used.

A mesh using plate elements is being developed for the 2-D keystone ATLSS connection joining a beam and a column (See Fig. 28). The contact surfaces are being modelled by interface elements capable of bearing and sliding. The bolts have been modelled to include pre-tension and slip. The force path from these analyses will be used as the force boundary conditions for a substructure model of the connection only. This model will be made out of brick elements and will use the gap option of the interface elements in order to assess lack-of-fit effects. Analytical models are being developed for the three-dimensional keystone connection (See Fig. 29). Analyses will be performed to obtain the proper configuration and stiffness of the three-dimensional piece so as to carry the required forces while still having enough forgiveness to promote ductile behavior. Finite element analyses are being performed on the top-plate-and-seat-angle connections (See Fig. 30). These connections, while meeting the fabrication and erection requirements nicely, have unknown strength and stiffness. The analyses will quantify these values.

5.2 Connection Experimentation and Three-Dimensional Frame Tests

Full-scale experimentation will be used concurrently with the theoretical work. An experiment will be used to discover the various phenomena involved and to check the theoretical model before a full range of theoretical analyses are performed. The full-scale connection experimentation is especially useful with these connections because of the connection's dependence on a contact surface for force transfer. Unlike welds or bolts, which are defined by a fixed geometry, the contact surface can vary in location. This creates a challenging modelling situation for structural analyses.

Once the examination of the connections themselves is complete, the scope of the project will move to a systems level as the structure as a whole will be evaluated from planning, design, fabrication, erection, and monitoring. The testing will include the overall system and structural subsystems.

The structure will be a low-story, steel frame incorporating ATLSS full-moment and partial-moment connections in one direction and ATLSS shear and erection-aid connections in the other direction. The building will be automatically erected. After successful performance evaluations, it is anticipated that these connections will be field tested in actual structures.

---

[5] Swanson Analysis Systems, Inc, Houston, PA

References

ATLSS, 1990
FOURTH-YEAR ANNUAL REPORT TO NATIONAL SCIENCE FOUNDATION, VOLUME 1.
Bound Report, February 15, 1990.
Programs and Plans, Center for the Advanced Technology for Large Structural Systems, Bethlehem, Pennsylvania.

Dagalakis, N.G., Albus, J.S., Goodwin, K.R., Lee, J.D., Tsai, T.M., Abrishamian, H., Bostelman, R., Yancey, C. July, 1989
ROBOT CRANE TECHNOLOGY (FINAL REPORT). NIST Technical Note 1267, National Institute of Standards and Technology.

Nguyen, V. X., Perreira, N. D., June, 1988
A CHAMFERED CONNECTION FOR USE IN AUTOMATED FRAMING OF BUILDINGS. ATLSS Report 88-06, ATLSS Center, Lehigh University.

Whitney, D. E., March, 1982
QUASI-STATIC ASSEMBLY OF COMPLIANTLY SUPPORTED RIGID PARTS. Journal of Dynamic Systems, Measurement and Control 104:65-77.

List of Figures

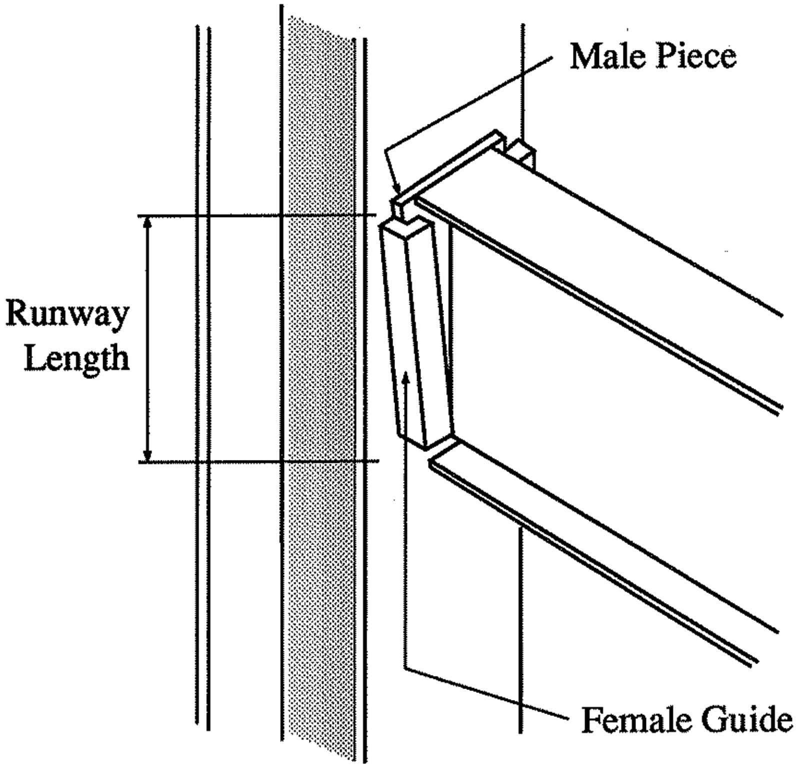

Figure 1: ATLSS Connection.

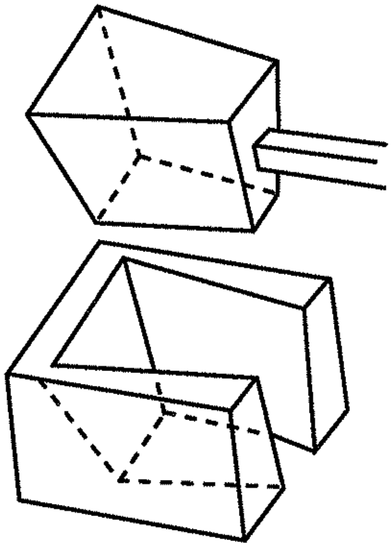

Figure 2: Chamfered Connection.

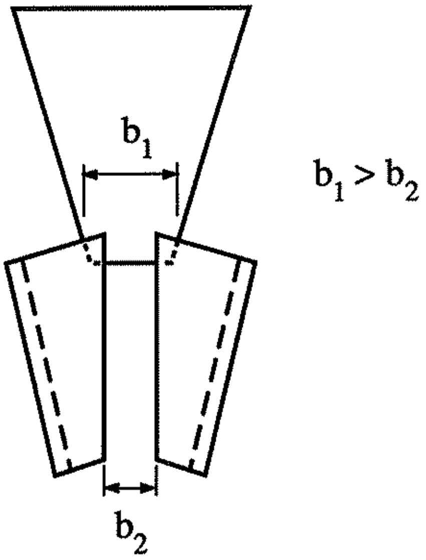

Figure 3: Geometric Considerations.

Figure 4: (a) Good Weld Pattern. (b) Poor Weld Pattern.

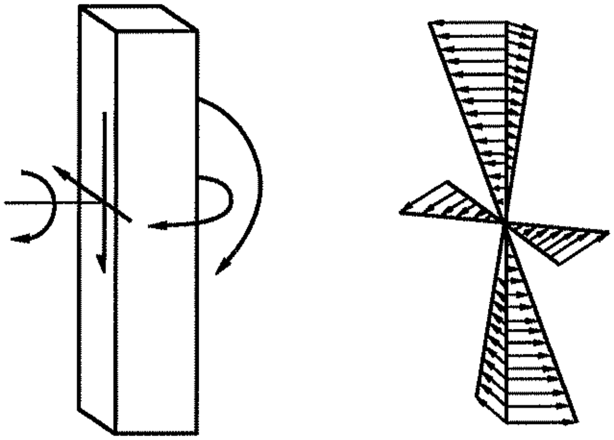

Figure 5: Force Distribution.

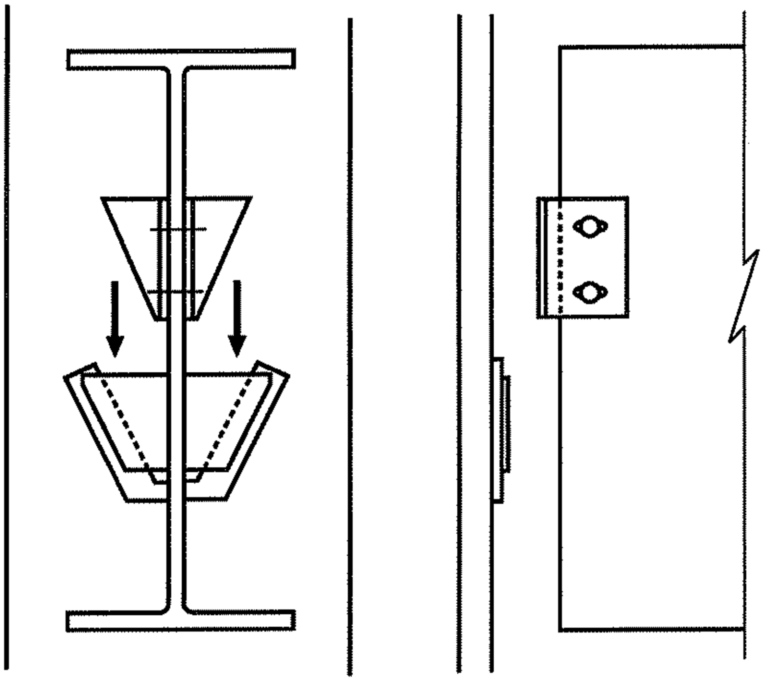
Figure 6: Keystone Erection Aid.

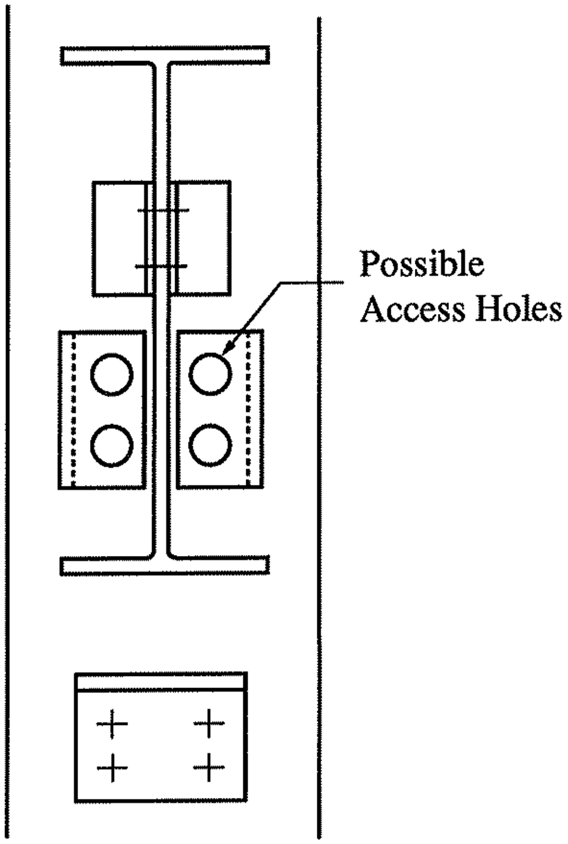

Figure 7: Web-Containment Erection Aid.

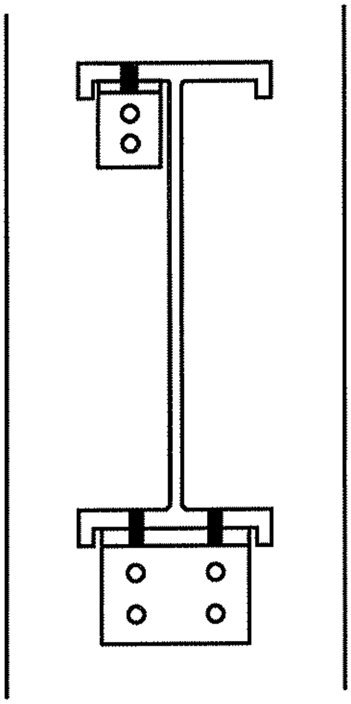

Figure 8: Beam Tabs.

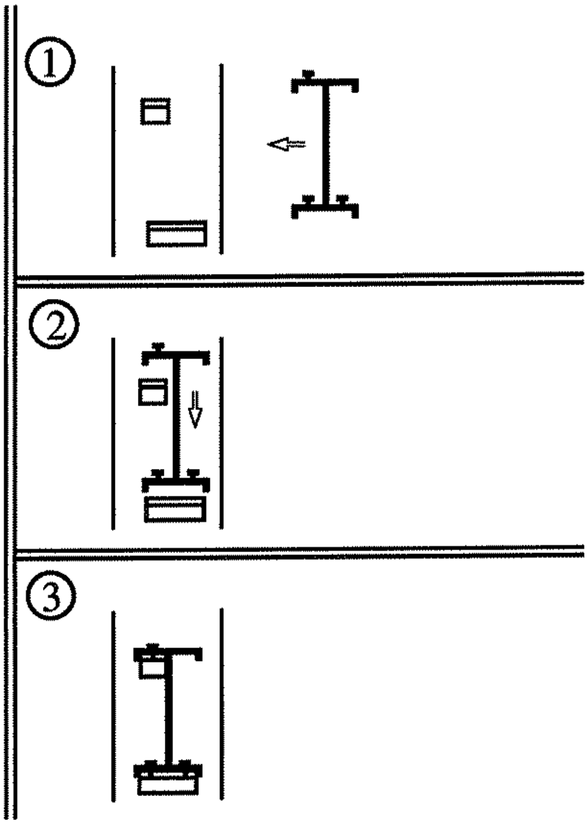

Figure 9: Erection Procedure for Beam with Tabs.

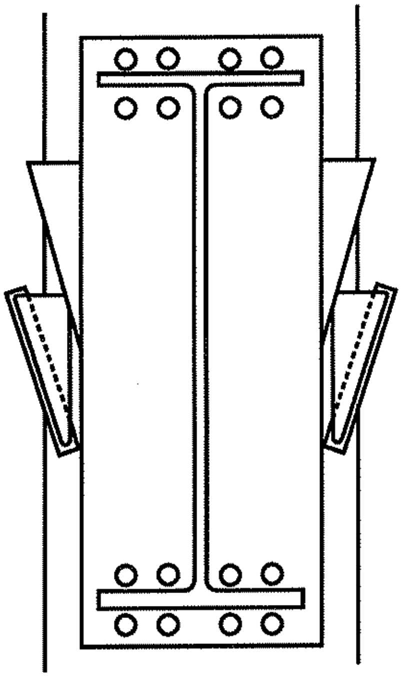

Figure 10: Extended End-Plate with Wing Tabs.

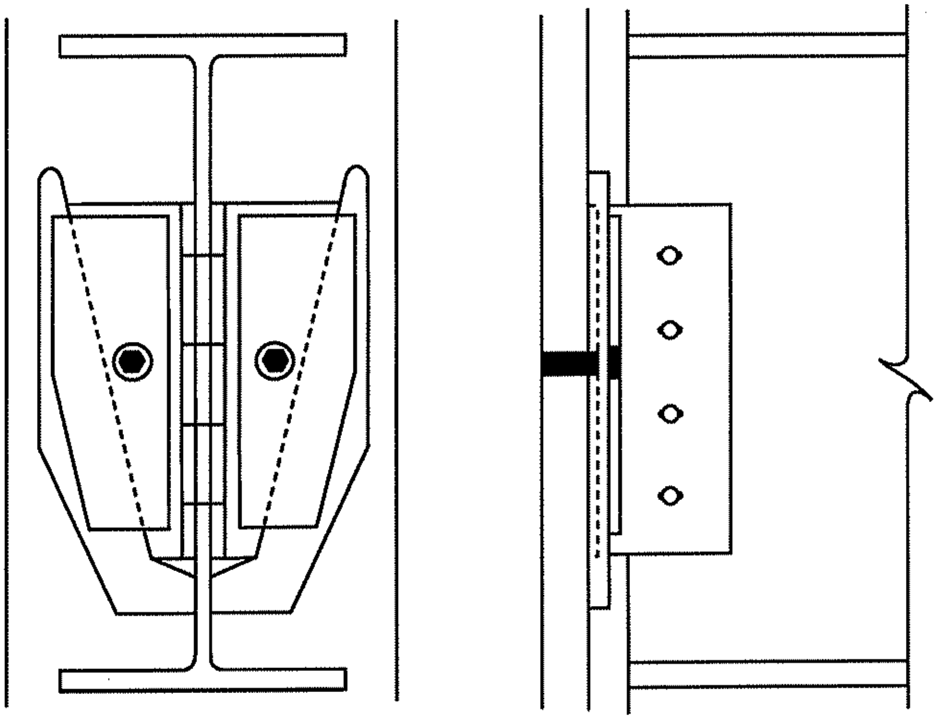

Figure 11: Keystone Shear Connection.

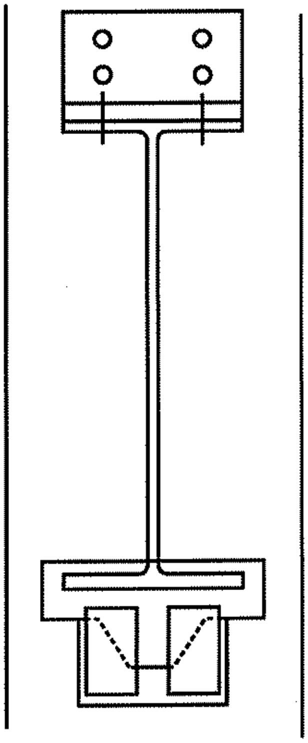

Figure 12: Lower Flange ATLSS Shear Connection.

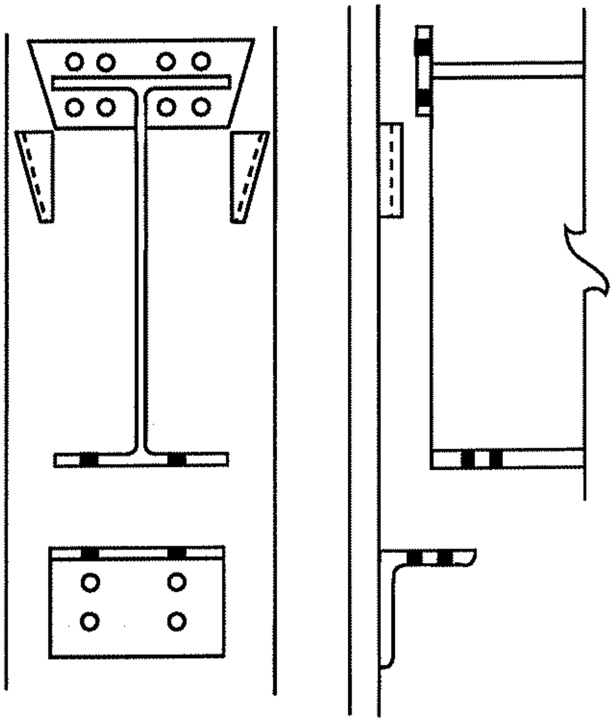

Figure 13: Seat-and-Plate Partial-Moment Connection.

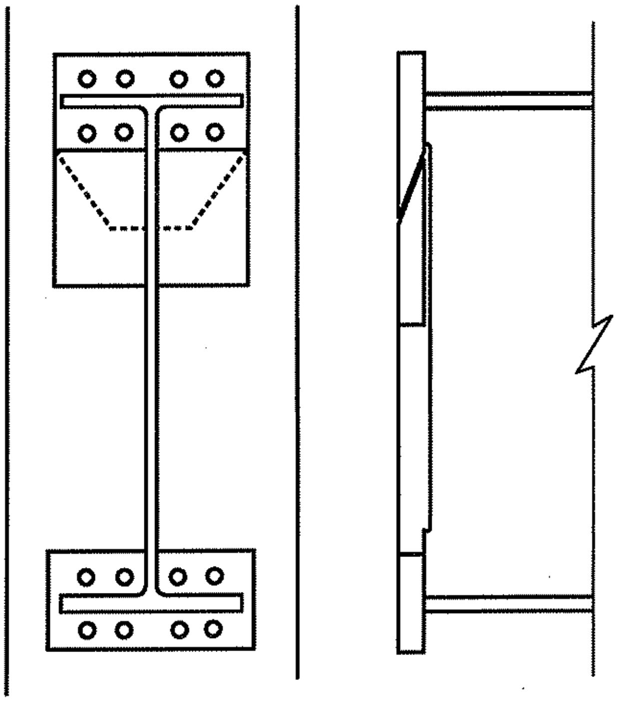

Figure 14: Double Flange-Plate Partial-Moment Connection.

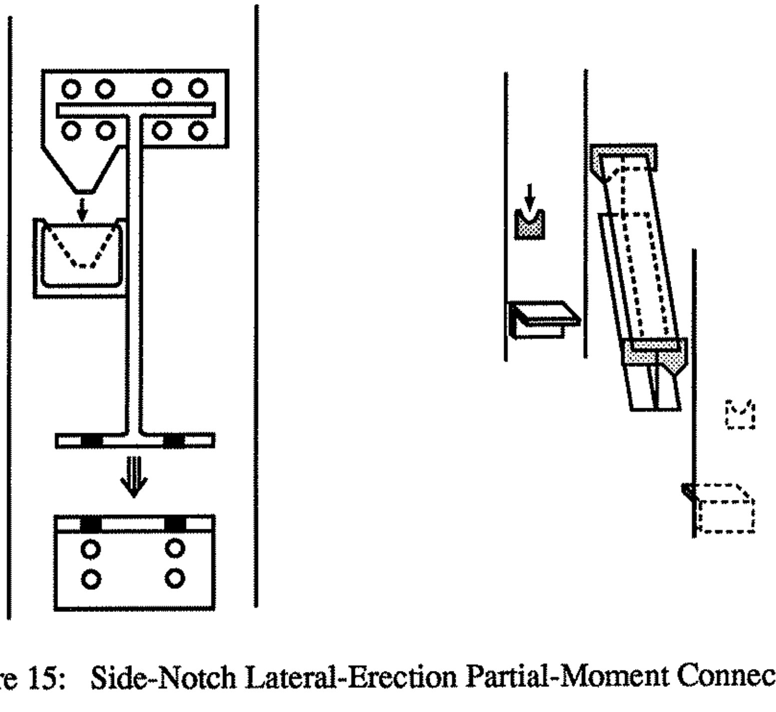

Figure 15: Side-Notch Lateral-Erection Partial-Moment Connection.

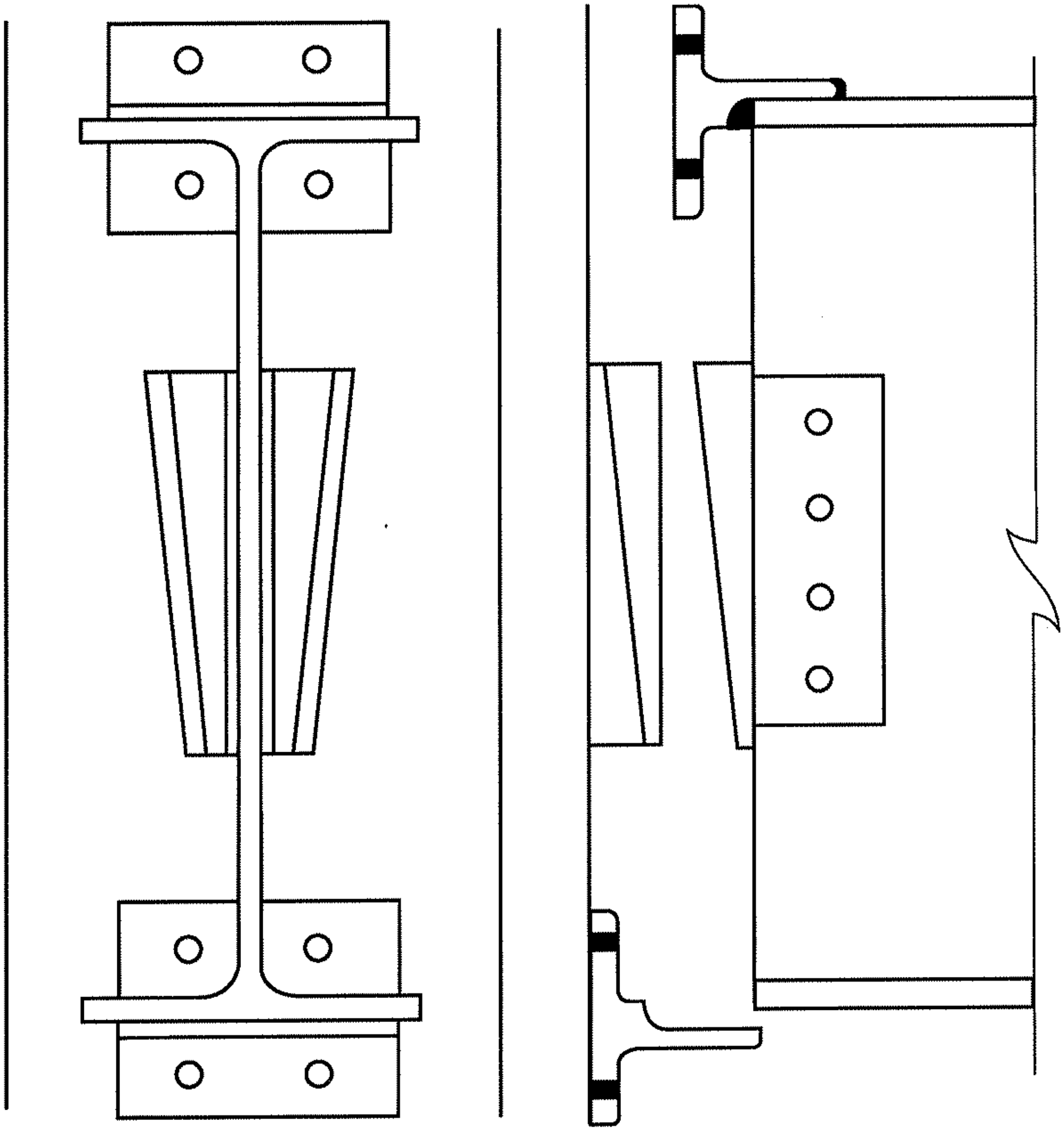

Figure 16: Three-Dimensional Keystone with Flange Tees.

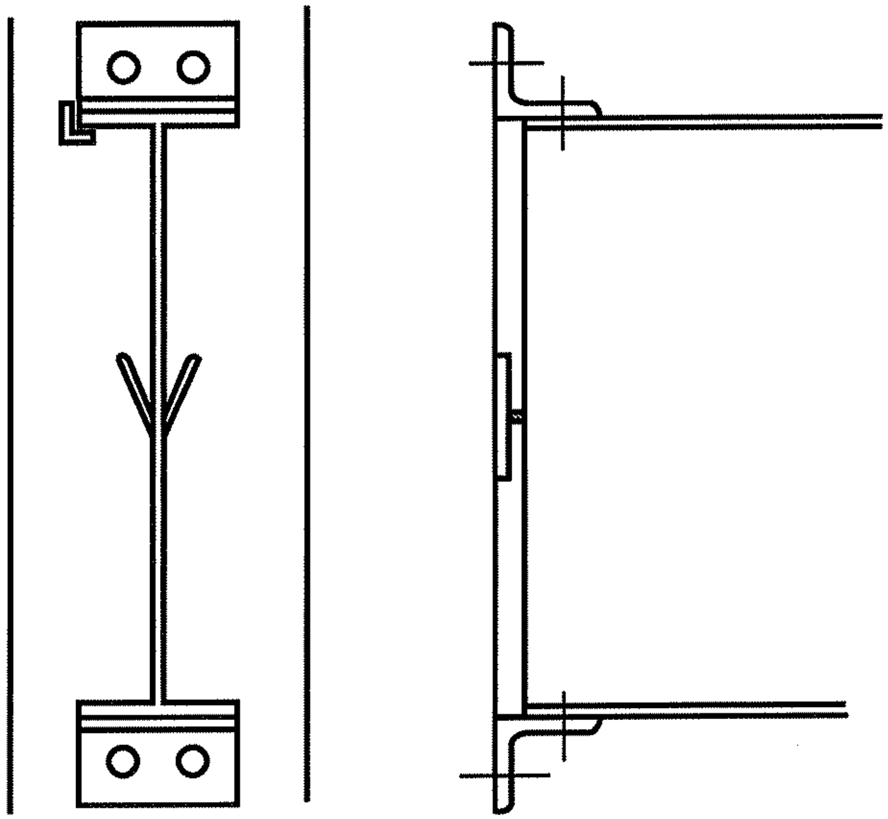

Figure 17a: Spin-in-Place ATLSS Connection.

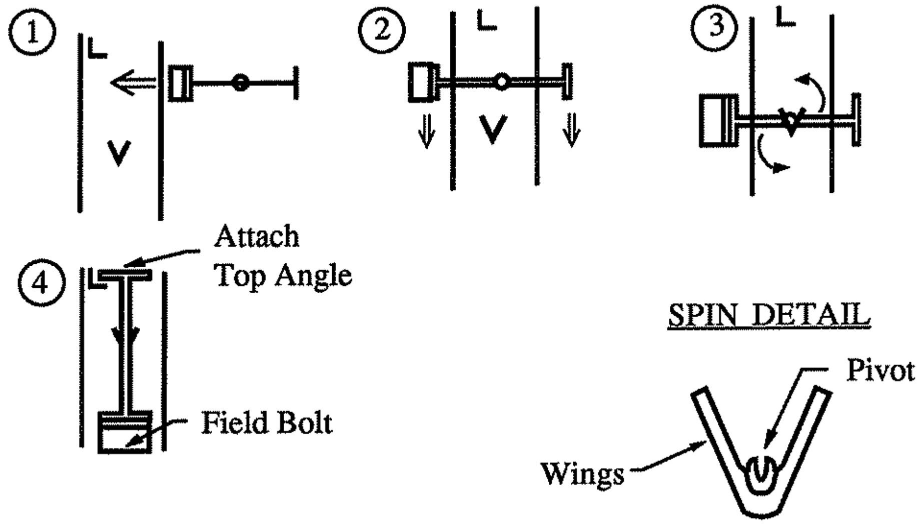

Figure 17b: Erection procedure.

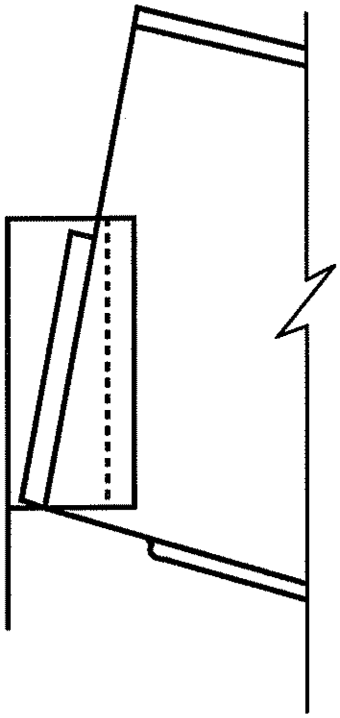

Figure 18: Freedom to Rotate.

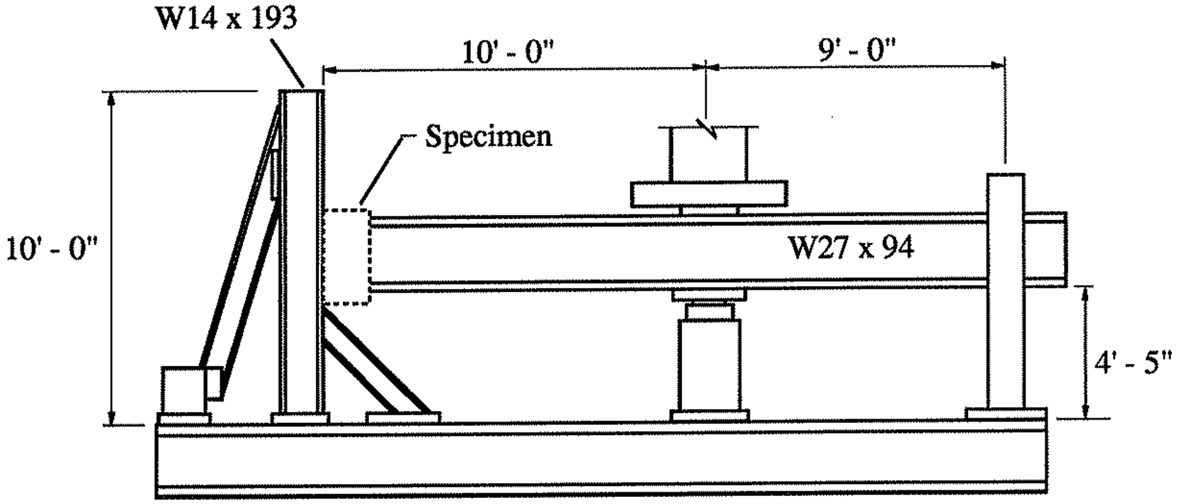

Figure 19: Experimental Frame.

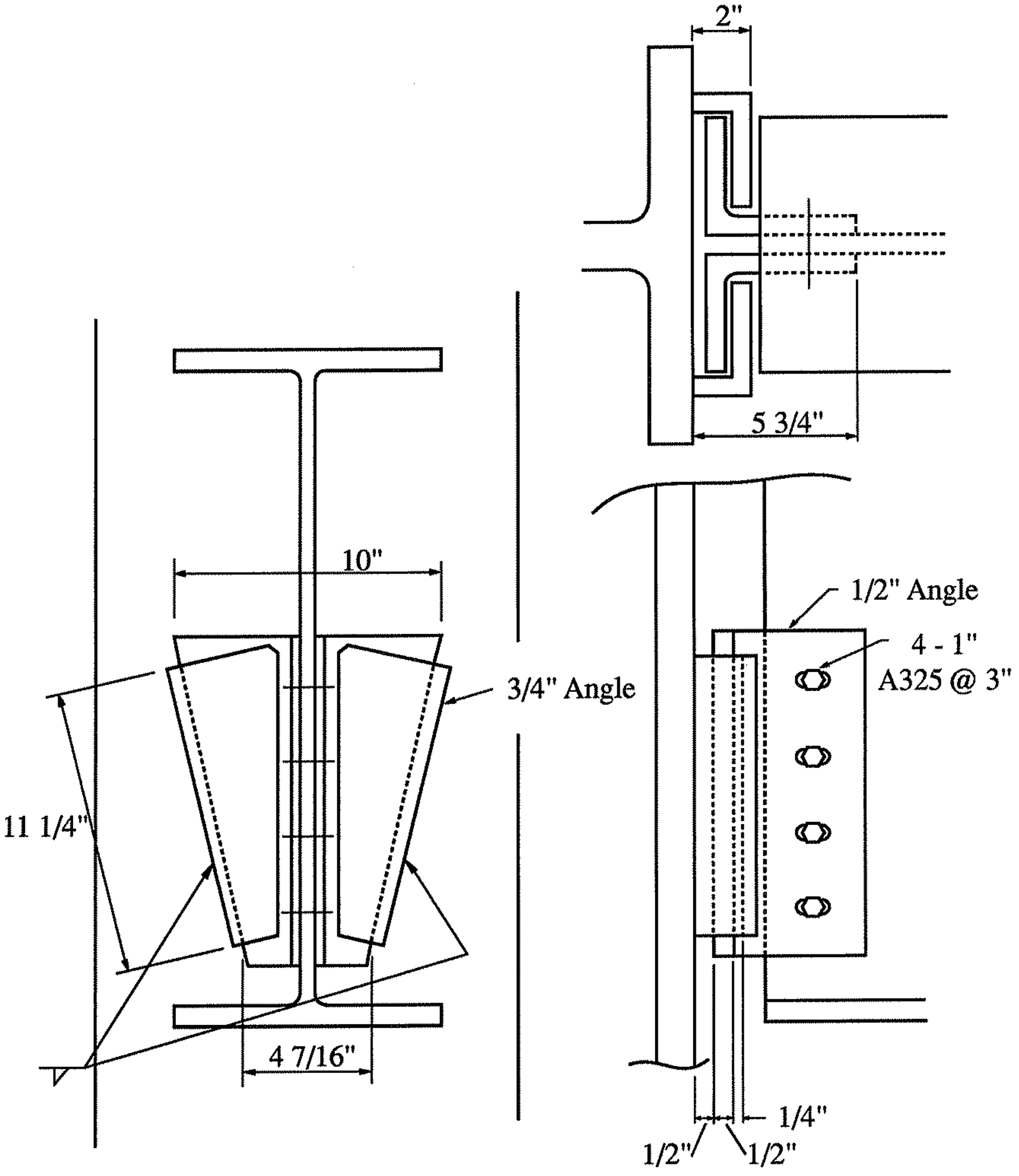

Figure 20: Final Connection Detail.

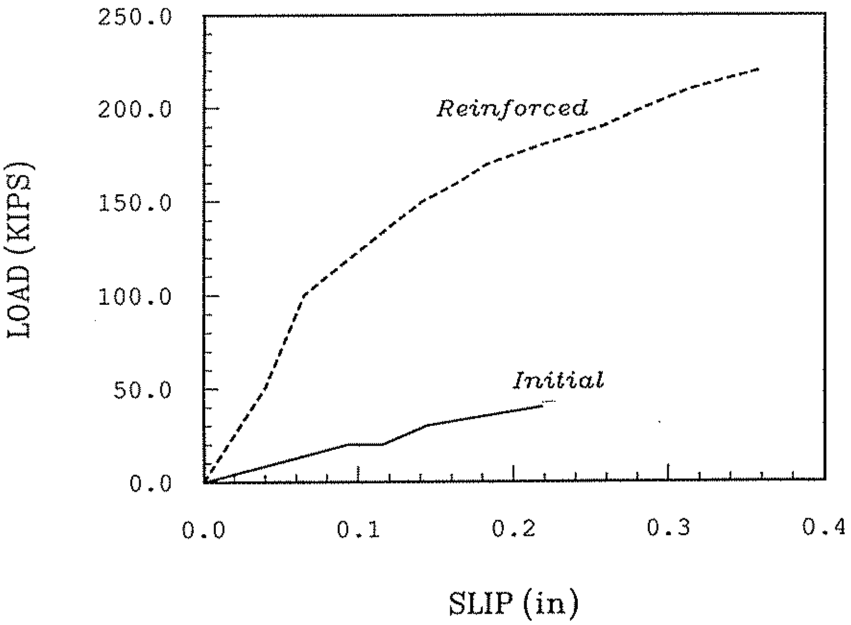

Figure 21: Vertical Joint Slip.

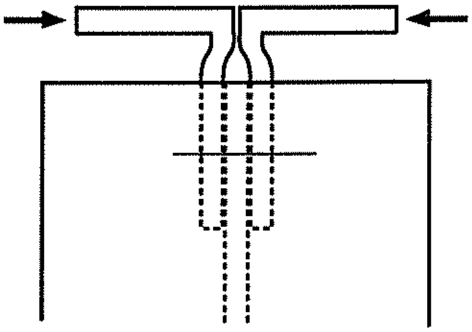

Figure 22 Web Angle Closure.

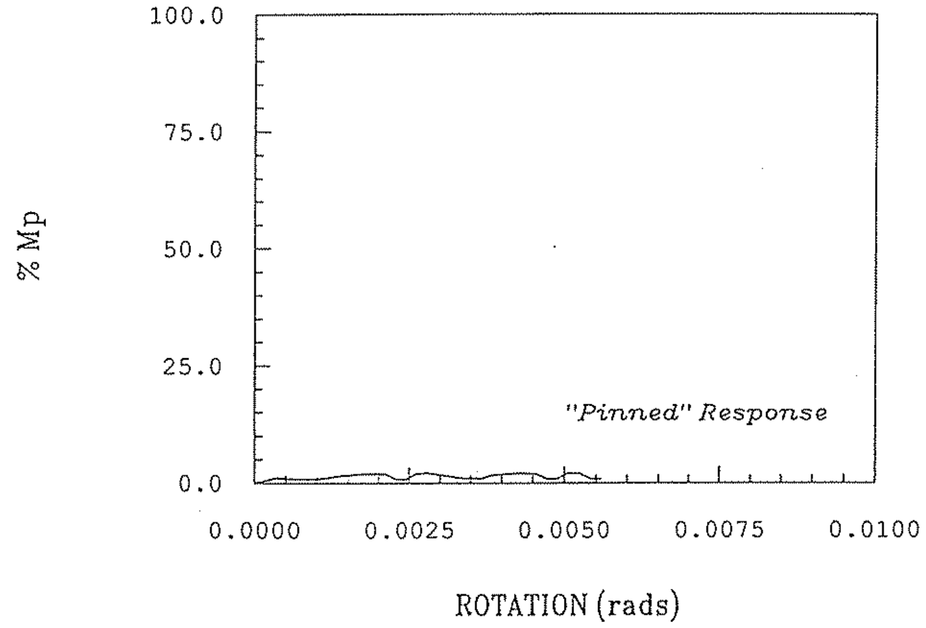

Figure 23 Connection Stiffness.

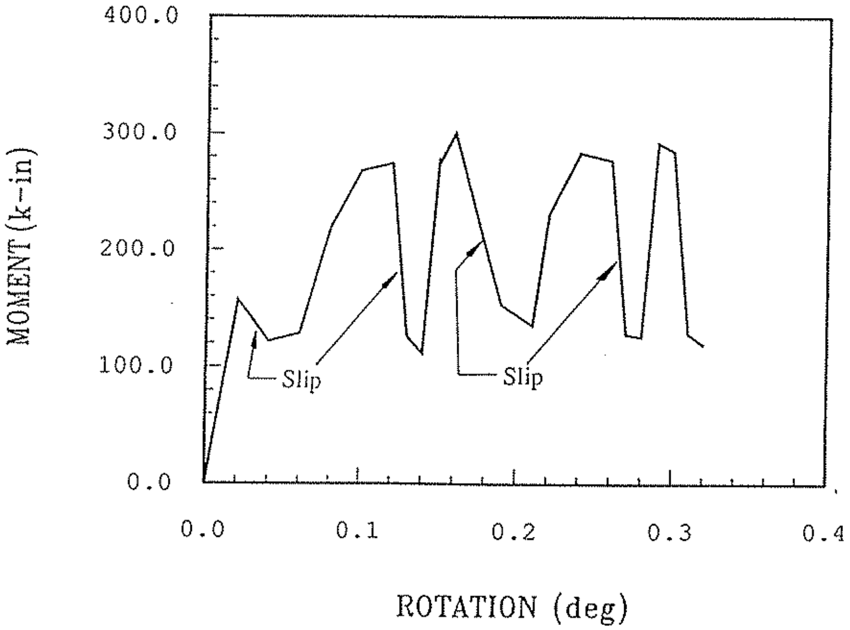

Figure 24 Moment-Rotation.

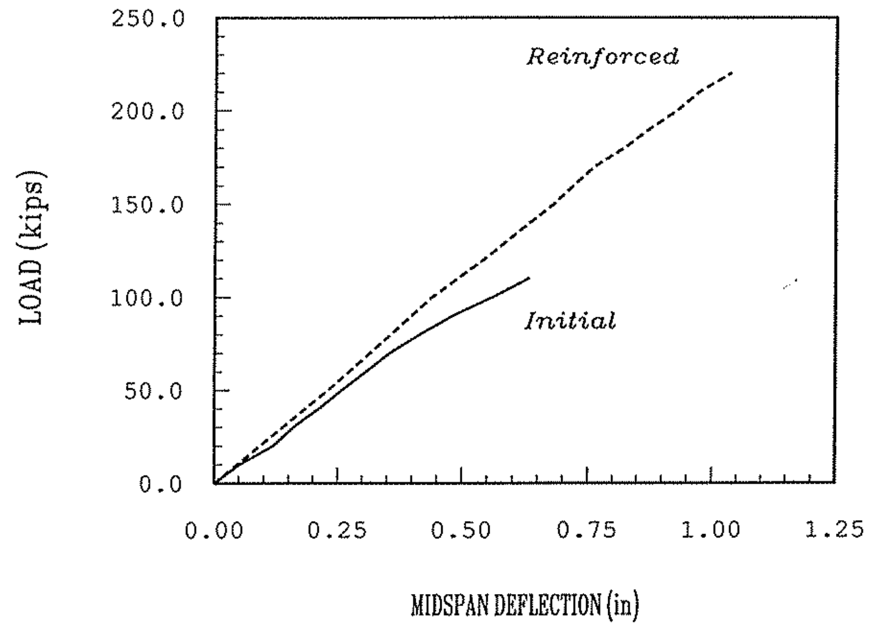

Figure 25 Load vs. Midspan Deflection.

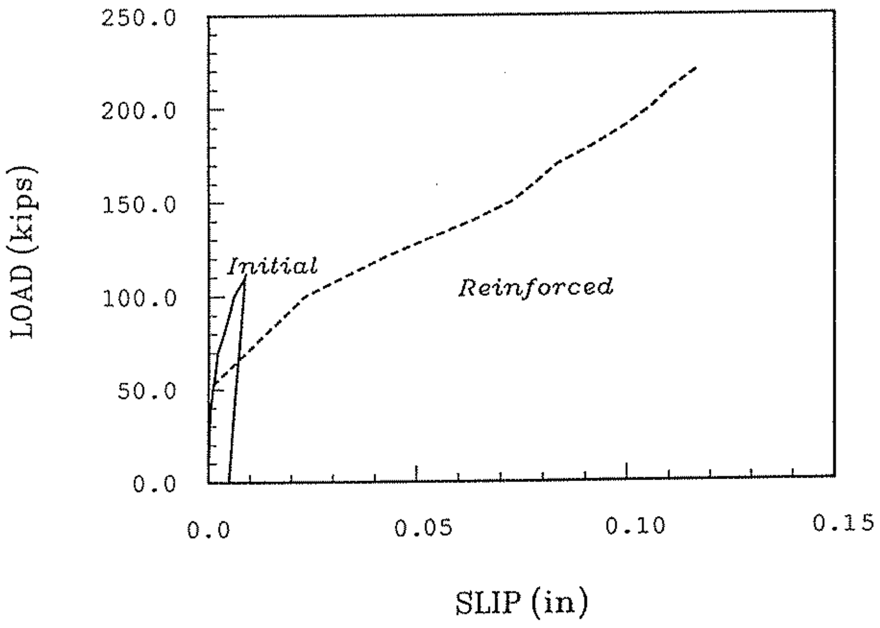

Figure 26 Web Angle Slip on Beam.

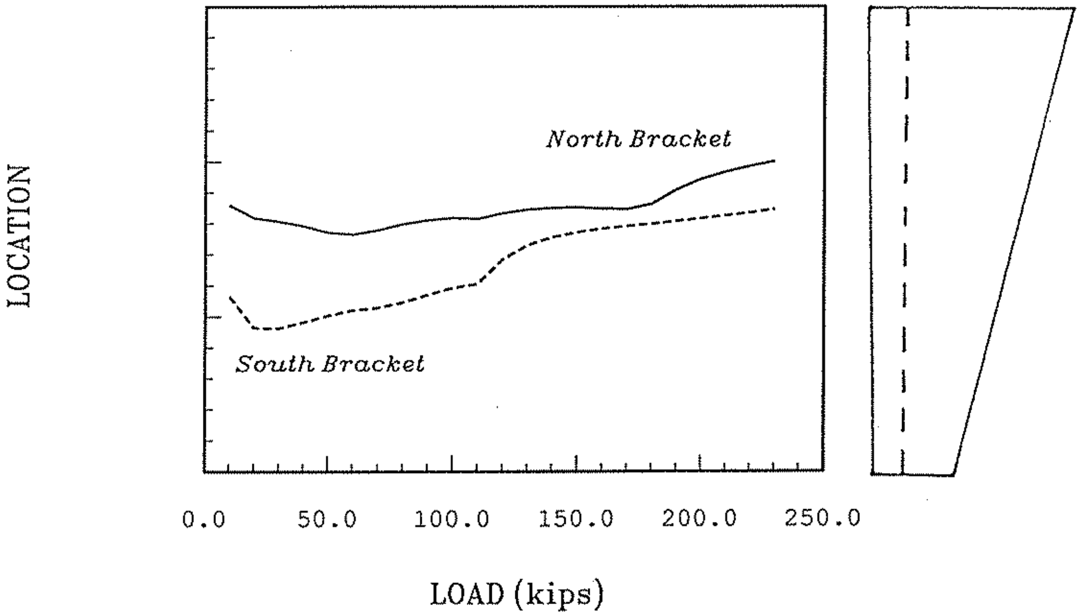

Figure 27   End Reaction Centroid Location.

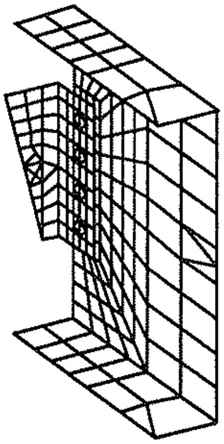

Figure 28: FE Mesh - Male 2-D.

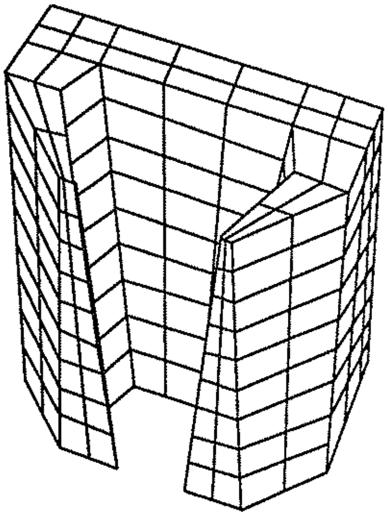

Figure 29: FE Mesh - Female 3-D.

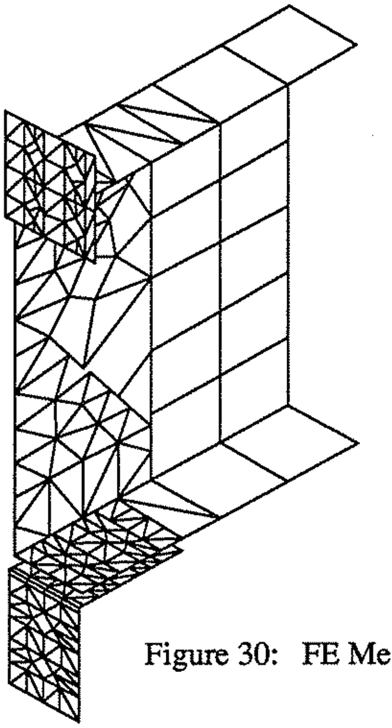

Figure 30: FE Mesh - Seat-Plate.