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ADVANCED TECHNOLOGY FOR LARGE STRUCTURAL SYSTEMS

Lehigh University

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AUTOMATED CONSTRUCTION AND ATLSS CONNECTIONS

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ABSTRACT

In this paper we present a means for improving the constructability of structural systems through an integration of crane technologies and automated assembly/erection methodologies with structural connection design. We discuss some aspects of the current erection process and cranes. We also present a design methodology that has lead to a new connection geometry which has features to allow ease of erection and show how equipment repeatability, part tolerances and dimension, are related to successful assembly. An automated crane erection system which can be used to build structural systems is then described.

INTRODUCTION

The Engineering Research Center for Advanced Technology for Large Structural Systems (ATLSS) was created at Lehigh University in 1986 by a grant from the United States National Science Foundation. The primary mission of the ATLSS Center is to serve as a focal point for research and education that will lead to technological developments which increase the competitiveness of the U.S. construction industry. To meet this challenge, the ATLSS Integrated Building Systems (AIBS) program was developed to coordinate ongoing research efforts in automated construction and connection systems. As illustrated in Figure 1, the objective of this program is to design, fabricate, erect and evaluate cost-effective building systems with a focus on providing a computer integrated approach to these activities to increase safety, productivity, and quality of the construction process at the job site. Figure 2 illustrates the activities within the AIBS program; other projects supporting this program are shown in the four corners.

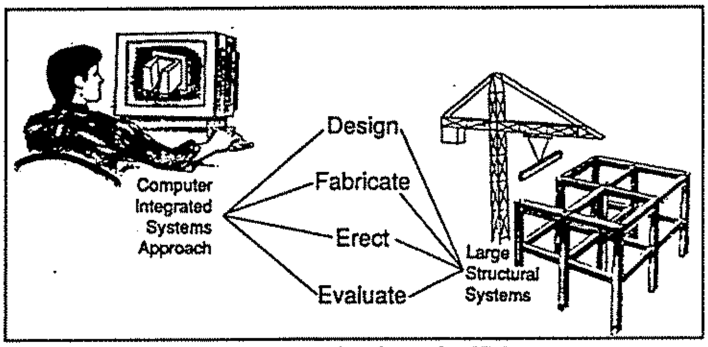

Figure 1 Objective of AIBS

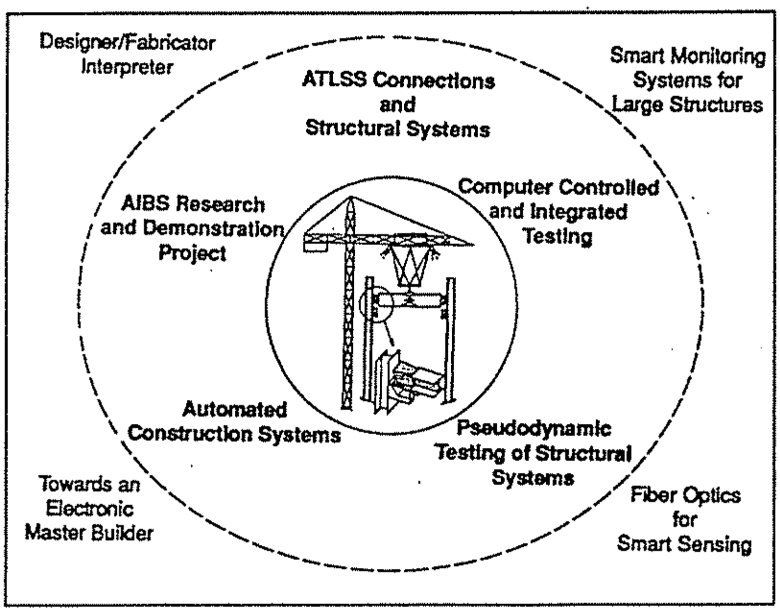

Figure 2 AIBS Activities and Projects

As part of the effort a series of new beam-to-column connections known as ATLSS connections are being developed with an emphasis on cost-efficient fabrication as well as geometric configurations which provide an automatic self-guided erection feature to greatly

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facilitate initial placement. This feature will minimize human assistance during construction and will result in quicker, less expensive erection procedures where workers are less susceptible to injury or fatalities. ATLSS connections, in both concrete and steel, possess the capability of being erected by automated construction techniques.

ACES, an Automated Crane Erection System, is an on-site material handling system designed for use in construction processes where material handling is crucial to efficient delivery of the finished structure. The range of application is from the framing process to the placing of facade. ACES consists of: 1) a moving platform base, cable-driven, Stewart Platform used in locating, acquiring, moving, placing and securing structural and non-structural elements at the construction site; 2) construction elements incorporating ATLSS connections; 3) motion and sensor control software for movement within cluttered work sites subject to environmental disturbances such as wind gusts; and 4) the design and as built database. ACES is being used to demonstrate the application and use of the ATLSS connection in computer assisted erection of steel and concrete frames; the acquisition of site data and realization of an as built data base; and the planning, scheduling and delivery of material components to specific on-site locations at the appropriate time.

Justification

Construction, a $300 billion dollar industry, comprises approximately 8% of the United States Gross National Product and employs approximately four million people annually, nearly 6% of the American work force. Throughout the 1980's the total volume of construction awards throughout the world has been steadily declining. Moreover the U.S. share of the limited market has shown a significant decrease.

Construction productivity, defined as Gross Product originating per man-hour in the construction industry, has shown an average annual net decrease of near 1.7% since 1969. The average of all industries for the same period has been increasing at an net annual rate of 0.9&, while the manufacturing sector has posted an increase of 1.7%

The use of structural steel accounts for the largest portion of labor costs in buildings. For office buildings it accounts for 10.7% of the labor cost while for manufacturing buildings it accounts for 17.8 percent.

Incidents of occupational injury and illness reported for construction workers comprise over 10% of all cases reported. On the average, 14% of American construction workers report work-related injuries or illnesses annually, and half of those reporting miss nearly nine work days per injury. Workmens compensation insurance for steel workers is 19.3 percent, the highest of all construction workers. In Japan, construction work hazards have caused a shortage of construction laborers and have forced the implementation of automated technologies in many hazardous jobs.

INTEGRATED BUILDING SYSTEMS DEMONSTRATION EFFORT

Construction Process

The current practice within the design, fabrication and erection fields of the construction industry is to perform the tasks independently either by a group of subcontractors or, on a much smaller extent, by various divisions of a single company. Because of this independence, it is possible and in fact common place to design a structurally sound system which is extremely difficult and costly to fabricate and/or erect. On site rework and plumbing, difficult to fabricate connections, and labor intensive processes are common. Thus, what on the surface may look like a cost effective approach may in fact be more costly than if the tasks were both planned and performed in a more integrated fashion.

It is recognized that structural weight reduction is not the only means of saving costs as shop and erection costs also depend on the machine and labor costs. The fact that careful selection of connections can significantly reduce the fabrication and erection costs has been documented [1]. Total cost reduction involves reducing the net cost of material, labor and time.

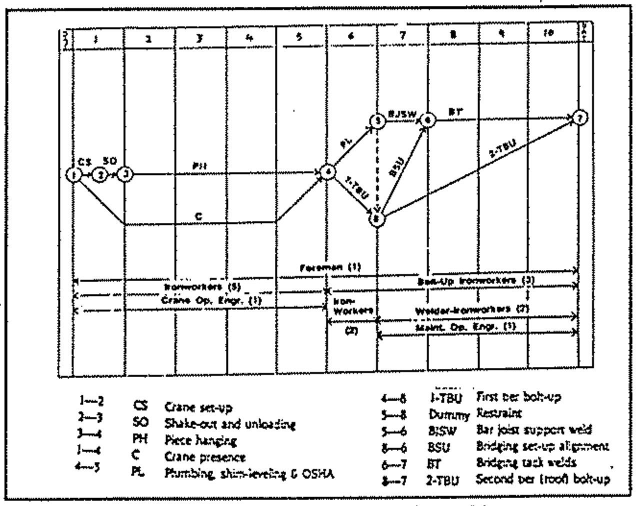

Figure 3 Steel Erection Flow Chart

A typical steel erection flow chart with functional work distribution is given in Figure 3. To consider the productivity issue we examine the "piece-hanging" process, step 3-4, represented by the Petri Net of Figure 4. The Net includes three loops associated with the "hookers-on", the "raising gang" and the "crane crew". These three groups of people each have a significant yet different function in the erection process. The hookers-on first select a member, then dress-it-up in preparation of the hooking step which is done with the crane crew. The crane crew then lifts the element and in cooperation with the raising gang allows the piece to be temporarily fastened. The crane crew then proceeds to lower the crane back down to the hooking area. The raising gang, upon completing the temporary fastening, acquires additional connectors and moves to the site where the next assembly is to occur.

Of these three gangs, the crane crew is the slowest. The crane cycle time is typically two to ten times as long as the actual working time of either the hookers on or the raising gang. Not only is the crane the bottle neck operation within the piece-hanging process, it is the bottleneck in all processes that require material to be delivered on floors above ground level and in many cases the ground level itself.

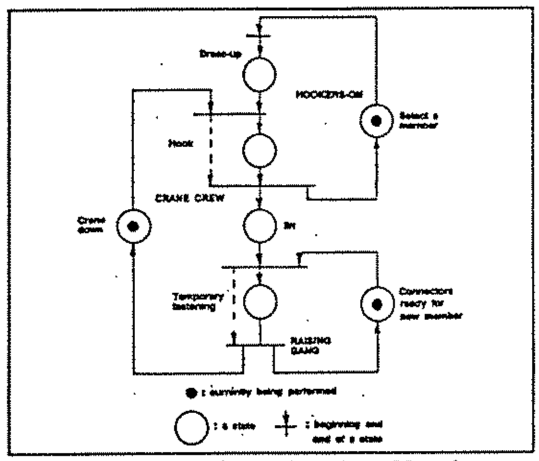

Figure 4 Petri Net for Piece Hanging

The productivity of the site is further reduced by the times where the crane can actually function or be utilized. Although it is common practice to have cranes operate on a twenty four hour work schedule when possible, light winds may make it impractical to be used for approximately ten to forty percent of the time. These time losses directly drive the completion date.

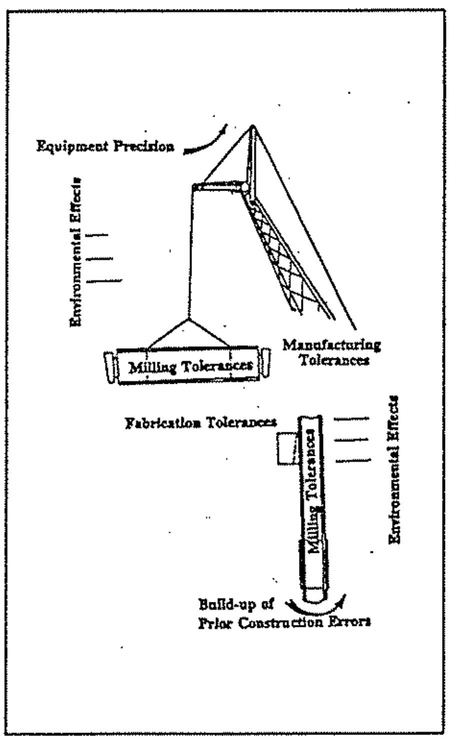

Figure 6 Tolerance and Precision

Figures 5 and 6 exemplify the types of materials and holding systems found in piece hanging. We see that spreaders, lashings, shackles or

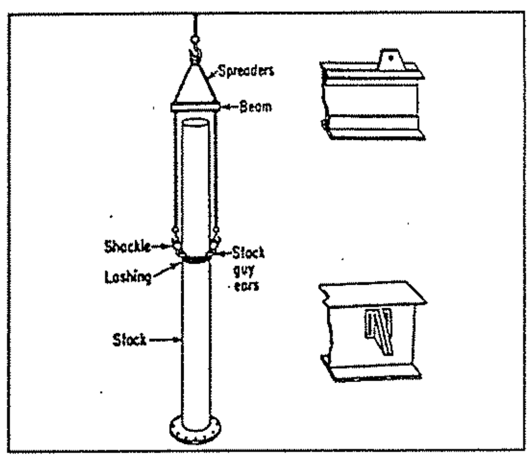

Figure 5 Handling and Holding

extraneous features are added onto the pieces so that they can be held. The parts are then hung from imprecise, non-dexterous equipment and are subjected to environmental effects such as wind. Using these types of equipment, and aided by the raising gang, the pieces are moved through a tortious path so that they may be properly positioned and aligned for preliminary connecting. Should the columns, which are subject to tolerance stacking, be improperly aligned then the use of various methods of persuasion are employed so that preliminary connections can be made.

Shimizu has well realized this problem when they designed the "Mighty Jack", shown in Figure 7 [2]. The system is first carried into position by a large crane. The power unit holds two grippers which attach to and then move the tops of columns so as to properly align the beam connections with their seat. This and other automated equipment, such as the Kajima "Bolting Robot", the Ohbayashi Gumi "Auto Clamp", a wireless remote device designed for placing steel columns in high places and the Takenaka Komuten "Robot Tower Crane" represent significant steps toward automation of the framing process. The chief drawback of these approaches is a lack of integration between the structural element, node design, task planning and the various classes of automation equipment. As an alternative, we have decided to redesign the connections for ease of assembly and, given the easier assembly process, to use a more robust crane geometry We believe that this integration is possible only with the development and use of a framing knowledge base which will include essential geometric and structural properties of the nodes and elements, element to node assembly and connection securing rules.

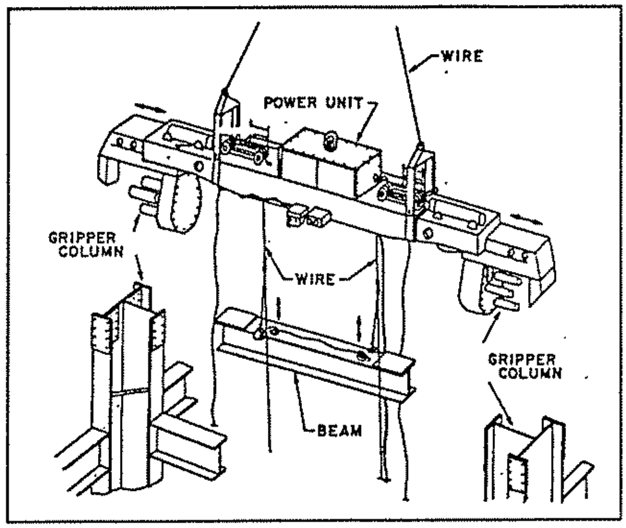

Figure 7 Shimizu Mighty Jack

During the last fifty years, in most manufacturing arenas, we have seen changes in how things are produced. These changes were driven first by capacity and speed limitations as we moved from manual to hard automation and then by product variation and batch sizes as we moved more toward flexible manufacturing methods. Construction on the other hand has never made the large shift from manual to hard automation and as a consequence has found it difficult to shift toward the use of flexible manufacturing methods. Hard automation was driven by the need to produce a particular geometry rapidly and in quantity. It was able to perform by keeping product variation to a minimum. Construction has a great deal of part variety and size variation within a part type; tolerances further increase the variation. Currently, the large tolerances typical in construction tend to build up resulting in the need of on-site fixes such as plumbing of building floors and shimming of connections. To control the range of variety and size variation, classes or groups of construction elements must be designed and manufactured for the assembly/construction task. To control the effect of tolerances, smart or intelligent construction automation tools, the analog of flexible manufacturing at the construction site, should be utilized. The rational approach to good construction practices is to develop and use connections which are less labor intensive, of higher quality, matched to the precision of the construction equipment, [3,4], and provide other relative benefits such as improved safety at the job site.

Current Connection Methods and Their Disadvantages

The utilization of structural frames within the construction industry requires inputs from at least five groups of people or specializations. Architects determine the general form of the structure; steel mills produce structural members such as beams and plates with various nominal sizes; structural design engineers determine and select the nominal sizes of the structural members and the class of connections required to make the frames which will allow the architectural form to sustain the loads and deflections which will occur; fabricators detail the connection selected by the designer, cut the structural members to the correct size, make or obtain the other components of the connections, and assemble the connections onto the structural members typically away from the construction site;

erectors take the fabricated elements and assemble them into a structural frame at the construction site. The assembly requires pre-positioning, aligning, temporarily securing the connections, plumbing the building, and causing permanent connections to be made..

Although the design of a structural unit may need both architectural and code requirements, the typical design process does not consider the resulting fabrication nor erection requirements. These designs are "thrown over the wall" to the fabricator who must then redesign the structural connections during the detailing phase so that they can be cost effectively fabricated. The results are again "thrown over the wall" to the erector who must then attempt to create the structural assemblies desired by moving and placing inaccurate components using imprecise equipment in a hazardous environment, Figure 8. The results of such actions lead to less than ideal results, Figure 9.

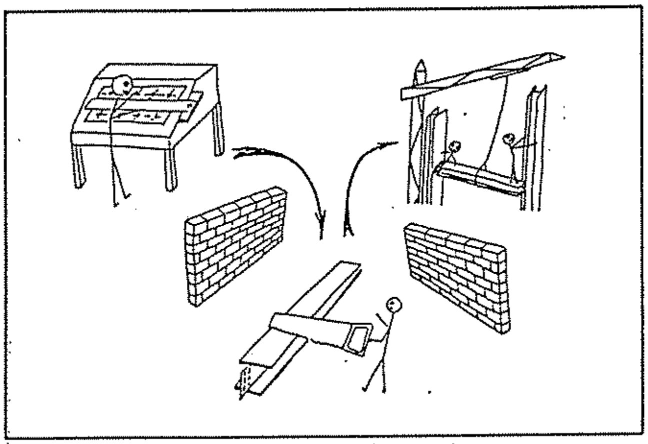

Figure 8 Integration Today

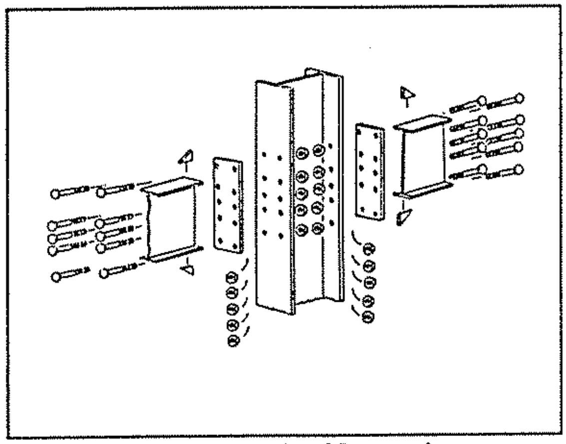

Figure 9 Result of Integration

Typically a connection consists of a number of parts which must be attached to the structural members that will eventually makeup the structure. At the fabricator shop, usually away from the actual construction site, portions of a connection are attached to one structural member while other portions of the same connection are attached to a second structural member. At the construction site the erector will secure these two portions of the connection to each other by means of welding and/or bolting. The erector may have to perform some modification to the fabricated structural elements, usually on-site, if the members do not fit together properly. This modifications are due to tolerance buildup within the structure, improperly fabricated members and/or improperly erected portions of the structure.

The common practice is to detail connections so that a temporary connection is required at the construction site. Usually the temporary connection requires the use of a drift pin. A temporary connection is used so that other members of the structure can be easily assembled. The members in the structure can be moved with sledge hammers, prying devices and/or guy lines during this phase of the erection to allow for the variation in element sizes due to milling and fabrication tolerances. In some cases the drift pin may be temporarily removed when connecting a third structural member to two members which have already been temporarily connected. This places the structure in an unstable or hazardous situation. In addition a member of the erection crew may be sitting on or suspended by one of the temporarily fastened elements.

The frame structure is usually put together a floor at a time. In some cases other grouping of elements may be used. The portion of the frame is erected by first making temporary connections between the major components of the frame. These components are usually the vertical columns and horizontal beams that interconnect the columns. Upon completing the temporary connections the building is made plumb, typically by a plumbing gang. Guy lines are usually employed. Shims are placed within the connections to raise or otherwise shift the positions of the beams and/or columns. When plumb to within a plumb tolerance, usually of the order of an inch per floor, the connections are permanently secured using either a number of bolts at each connection or by welding. Bolting is preferred by most erection companies as it is most easily performed at the job site. Welding is most typically done off-site at the fabrication shop. In some cases welding is used at the job site, in particular where rigid connections are desired.

To bolt the structure numerous bolt holes must be aligned at each of the connections; when alignment is not possible old holes are enlarged or new holes are made. The bolts are then placed through each set of the bolt holes and nuts are used to tighten the bolts. Care must be placed in tightening the bolts for too loose bolts will result in very loose connections and too tight bolts may be over stressed and eventually fail. In either case the connection will not be as secure as designed.

To weld a structure care must be taken to precondition the weld site, in particular preheating the connected elements is required when using many steels. Welding also requires highly trained labor and requires the moving of awkward equipment through a no-hospitable environment.

ATLSS Connection

A series of new beam-to-column connections known as ATLSS connections are currently under development at the ATLSS Center [5]. The emphasis of these new designs is on cost-efficient manufacture and fabrication as well as geometric configurations which provide an automatic self-guided erection feature to greatly facilitate initial placement. This feature will minimize human assistance during construction and will result in quicker, less expensive erection procedures in which workers are less susceptible to injury or fatalities. The connection is strong, can be scaled for various application, has a minimum number of parts and facilitates erection through top down placement. It is anticipated that the use of ATLSS Connections will greatly facilitate erection of floor and wall subsystems.

The ATLSS Connection design utilizes many of the concepts of automated assembly used in for mechanical and electrical system assembly. A compilation of these rules is given in Table I. Of these the most important are to minimize the number of parts and motions required for assembly.

Table I - Design Rules for Automated Assembly

- Minimize the number of parts
  - Cast parts together
- Minimize the number of different kinds of parts
- Minimize number of motions
  - Number of directions of action
  - Use layered assembly
- Minimize the use of fixtures
- Reduce number of adjustments, one-handed assembly
- Use modular design
  - Subassemblies
  - Use temporary parts for alignment, gripping
- Use easily orientated bodies
  - Very symmetrical parts
  - Very unsymmetrical parts
- Use of self alignment
  - Chamfers, clearances, reduce accuracy requirements
  - May increase material cost
  - Will decrease installation cost
  - Will increase quality
- Parts may need protrusions, flat surfaces for gripping
- Use external features to locate internal features
  - Lips and flanges, could be removable
- Make parts accessible during installation
- Use parts that do not tangle, wedge or jam in transit
- Use Suitable fasteners
  - Snaps, press preferred
  - Fewer elements
  - Adhesives
  - Minimize number of types
  - Easily located, picked up, inserted, secured
  - Self tapping and centering screws
- Preplace fasteners on elements
- Protect surfaces (screw threads) from scratches with flanges
- Watch out for tolerance buildup
- Encrypt part code on item for latter automatic determination

The geometric design of the ATLSS connection concept is based on fundamental principals of mechanics dealing with wedging, jamming, orientation preference and the geometric design of connection pair geometries subject to insertion forces and surface roughness [6]. A single connection is composed of a cone shaped protrusion, foot or tenon and a cone shaped basket, boot or mortise. Sizing for strength, ease of manufacture, tolerance for errors in fabrication are naturally inherent. Determining how to mount the cones, the size ratios of the actual cross sections, and detailed surface features will determine the practicality of the units. Three considerations, axial insertion, orientation preference and connection system symmetry are used as a basis for the initial connection designs.

The first consideration in determining the initial connection geometry are the potential problems associated with wedging, jamming and slip that occur along the primary insertion or cone axes. If we assume that a singular pair of right circular cone is used then these factors are controlled by the insertion force, apex angle, coefficient of friction and initial misalignment. Large apex angles require large insertion forces for proper seating because of poor slippage. Small apex angles and moderate misalignment result in turning moments which then result in wedging. Moderate apex angles, large coefficients of friction and small misalignments may result in jamming. When the apex angle is very small it is difficult to locate the top opening of the cavity with point of the cone. Larger angles increase the probability of finding the opening but decrease seating capability.

The use of right circular cones suffers from the loss of orientation preference about the cone axis. This is circumvented through the use of none circular cross-sections, for example the use of right elliptic cones. The beneficial orientation preference suggested by highly eccentric elliptic cross-sections, on the other hand, may tend to increase the insertion force required to overcome the frictional forces and allow the slippage required for proper seating.

When connecting a structural element to other structural elements or groups a number of connections are typically employed. The family of connections associated with a structural element forms a pattern. Not only is this pattern essential to developing the load carrying capabilities of the element, it determines the erection methods to be employed. We use it here to finalize the initial connection form concepts. Take for example the case where a beam is to have two end connections so that it can be placed horizontally between two vertical columns. A means of utilizing the cone shaped connections would be to simply imagine the beam to be along the major axis of an ellipse which forms the cross-section of a cone. Portions of the imaginary cone would be used to form the required connection geometry. Alternatively, one can imagine that a much smaller right elliptic cone is cut in half and each of the two halves are singularly mounted at each end of the beam. The mating cone or mortise is similarly split and the two halves are singularly applied to each of the two columns.

Although the halve cones provide a means of appendage to the beam and columns by use of their back surfaces they no longer provide the pin-hole encapsulation like effect. Thus, it is possible for one end of the beam to fall through. To eliminate this problem "three-quarter" cones are used. In addition the cones are made slightly oblique so as to work as if they were one.

The result of these simple ideas is referred to as the keystone coupling and they have been designed as two-dimensional or three dimensional units as illustrated in Figure 10. All three of the preferred geometries exhibit cone like behavior. In each case the cone shaped surfaces are replaced by inclined planes. Two, three or four sets are common. In the modified shear connector the inclined surfaces are primarily intended for alignment. This concept can be applied to many of the connections now commonly used in construction. In its most common form

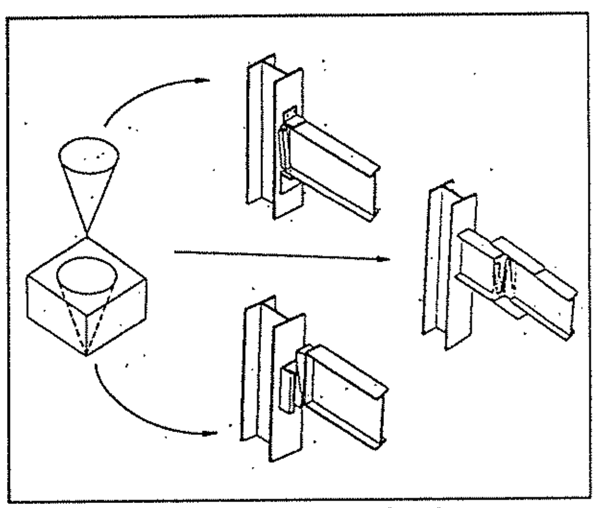

Figure 10 ATLSS Connection Concepts

only a single pair of inclined surfaces would be used. In the modified node implementation one pair of inclined surfaces is primarily intended for alignment only while the second pair of inclined surfaces is intended for both alignment and for load bearing. In its most common form two pairs of inclined surfaces would be used, one for alignment and one load bearing. In the keystone connection all surfaces are designed to be load bearing after being used for alignment.

In its purest form there exists no bolts, pins or weldments between the two mating cones. The units depend on gravity alone to form a load transferring contact surface between the male and female connection parts. It is capable of use in poor tolerance structures for shear and moment loads, with or without a means for locking into place. The connection is both self-centering and self-aligning.

The connections are designed for off-site fabrication and partial assembly. Only the placing of the foot into the shoe is required on site. Securing by way of a bolt or through welding is done on-site as a precautionary feature only. Off-site fabrication involves the manufacture of the connection pair and then fixing the foot and the shoe on the main structural members. The fixing can be done by either welding or bolting. The pair elements themselves are manufactured by welding of plates and angles or by casting and machining.

Refined Connection Geometry

Detailed kinematic, force, and stiffness analysis of the insertion process was used to further refine the connection geometry. First, using kinematic constraint equations and a given set of typical initial relative position and orientation errors between the desired and actual connection locations, required connection dimensions are determined. Secondly, using force and moment balance equations, the forces and moments acting on the beam during the process are determined. This information is used to refine the connection dimensions and may be used in the design and selection of the equipment used to handle the beam. Thirdly, the stiffness of the connection at different stages of the insertion process is obtained by combining the force equations with kinematic constraint equations.

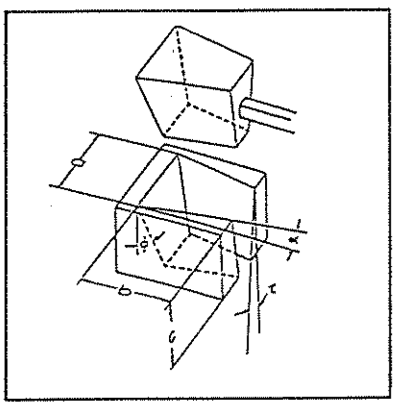

Figure 11 Connection Parameters

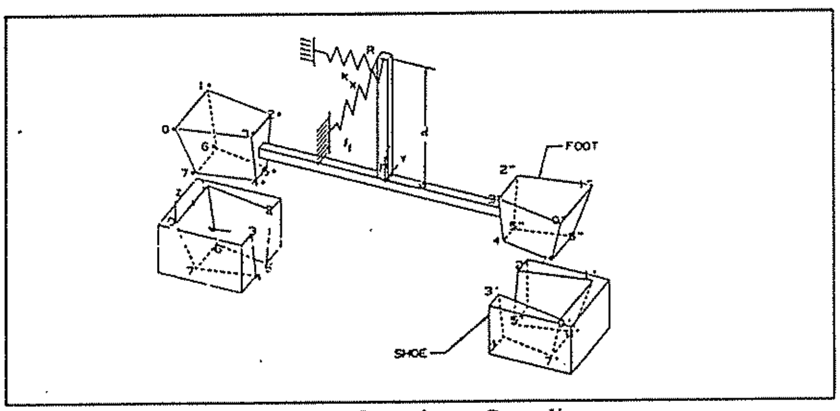

Figure 12 Insertion - Compliance

The connection consists of a "chamfered foot" and a "chamfered shoe" as shown in Figure 11. The foot is guided through the insertion process by the chamfers and is locked within the shoe at the end of the insertion by a wedging effect. The system being analyzed consists of two rigidly supported shoes a fixed distance apart and a beam and two feet as shown in Figure 12.

Beam-column insertions are composed of simple one sided insertion stages followed by the more complex two sided insertion stages where the simultaneous insertion of two feet into two shoes occurs. The analysis considered both types of insertion stages. Analysis of single sided insertion is similar to the analysis of the simple "peg and hole" problem [7] except that multiple types of contacts and insertion trajectories are possible. The type of contact that occurs depends on how the foot is initially located relatively to the shoe. The first contact made can belong to one of seven groups: one-point, two-point, three-point, line, line-(one-point), line-(two-point), or (two line)-(one-

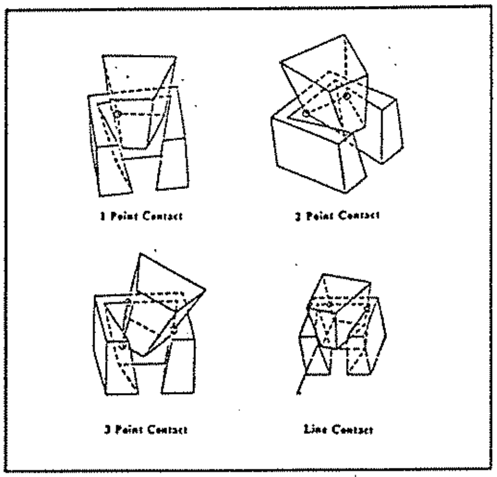

Figure 13 Insertion Contact Types

point) contact. Example contacts are given in Figure 13. There are thirty nine different contact types for single sided insertion.

In two sided insertion, simultaneous interaction between both feet of the beam and their mating shoes attached to columns occurs. The misalignment between the beam and the column members dictates which side the beam will engage first and what type of contact will occur. In the most common assembly, single sided insertion will first occur. Further insertion of the beam will initiate a contact on the other side of the beam. As the insertion process continues, contact trajectories proceed at each end of the beam and misalignment of the system components is reduced. There are one thousand five hundred twenty one types of double sided insertion stages. The number of stages is much higher than for the single sided insertion because one contact type can occur on one side of the beam while a different type of contact occurs on the other side.

We concentrated our efforts on a specific move pattern, shown in Figure 14, which we believe to be representative of the beam to column insertion process. The move pattern starts with the beam above the column members. The beam has an initial angle error about the vertical axis of δz and horizontal position errors in the x and y directions of dx and dy. As the beam is inserted, it will first make a one-point contact, at its left end. This begins stage 1 of the insertion process. As the beam continues to be inserted, a second one-point contact occurs. This time on the right end of the beam. This begins stage 2 of the insertion process. The system maintains that mating fashion until a two-point contact is initiated on the left. This begins the third stage of the insertion process. The results of a typical force-trajectory analysis are shown in Figure 15.

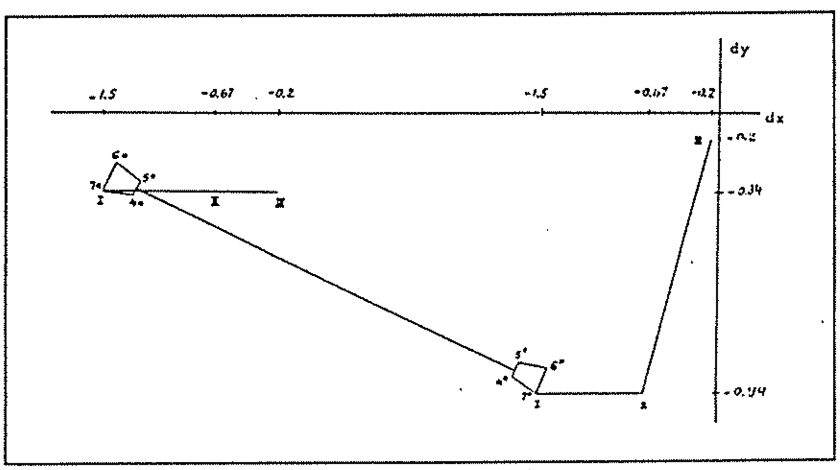

Figure 15 Resulting Trajectory

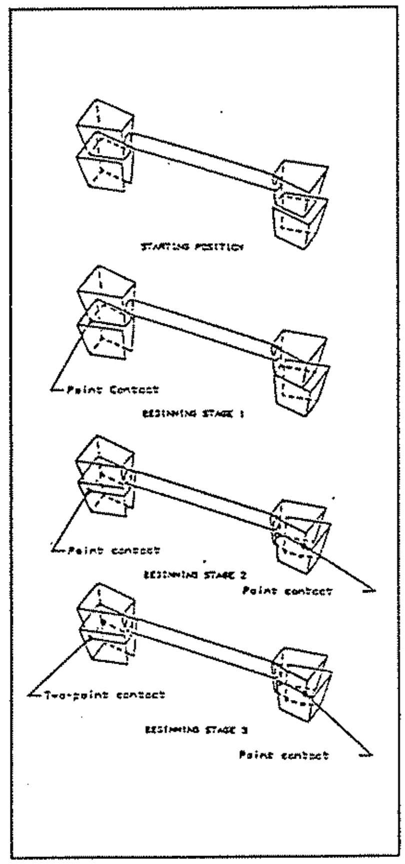

Figure 14 Insertion Stages

The beam is supported above its centroid at point R by a compliant interface between it and a rigid handling system as shown in Figure 14. The compliance is that of the actual handling system be it a tower crane, a robotic arm, RCC device or other. Both translation and rotation compliance are assumed. The translational compliance is supplied by two springs attached at point R with the spring constants K_x and K_y. The rotational compliance is provided by a torsional spring with the spring constant k_Θ also mounted at R but not shown in the figure. We assume that the handling system will not allow the beam to rotate around either the X_f axis or Y_f axis.

The constraint equations describe the relationship between the connection geometry and allowable positions and orientations of the beam relative to the columns. It was found that the connection geometry parameters, a,b,c,α,τ,ϕ,L, greatly affect the maximum allowed amount of initial misalignment, dx, dy and δz between the beam and the column. The results of the analysis shows, for example, if the positioning equipment has an initial position and orientation error of δz=0.3°, dx=-1.5", dy=-0.3", then the two sets of geometrical constraint equations result in maximum values of a=8", b=4", c=12", L=20 ft., α=9°, τ=14°, ϕ=9° for the connections and the beam. These values only guarantee that it is possible to start an initial and geometrically stable insertion. The connection geometry affects the forces and moments acting on the beam and the handling systems, as well as the stiffness of the connection and the insertion trajectory. Acceptable combinations of parameters required for a successful sequence of movements were found. Thirdly, the compliance of the connection and the resulting trajectory of the beam were derived. It was found that the success of an insertion is highly dependent on the stiffness of the connection. The stiffness of the connection in the first stage of the insertion process is primarily controlled by the angle ϕ and the friction coefficient μ. A good connection design will produce a low initial stiffness so that minimal power is required to insert the beam. Finally, the trajectory of the beam during the insertion process was determined.

Two geometric requirements must be met to achieve a successful insertion. First the foot must be so aligned as to engage the chamfer of the shoe. The alignment is further restricted to a region where a stable insertion process can occur. The insertion will fail if any of the four bottom corners of the feet are outside of the mating portion of the shoes as shown in Figure 16. To avoid such a failure, combinations of acceptable geometrical parameters can be determined for any specific set of maximum initial beam placement errors.

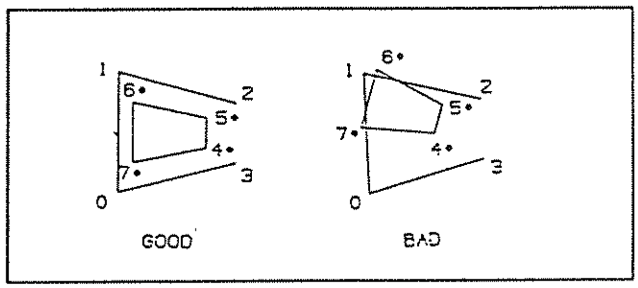

Figure 16 Starting Positions

A more restrictive condition occurs as the foot is placed within the shoe. The relative pose of these two parts in this case is shown in Figure 17. In both cases, the beam has been rotated clockwise relative to the shoes. In the first of the two cases, x_{7*f} has a positive value. Due to geometrical considers, attempts to insert the feet will result in further clockwise rotation. In the second case, x_{7*f} has a negative value. The relative orientation will be reduced as the insertion process proceeds. The second case is kinematically stable. Note that the longer the beam, the smaller the allowable initial angle.

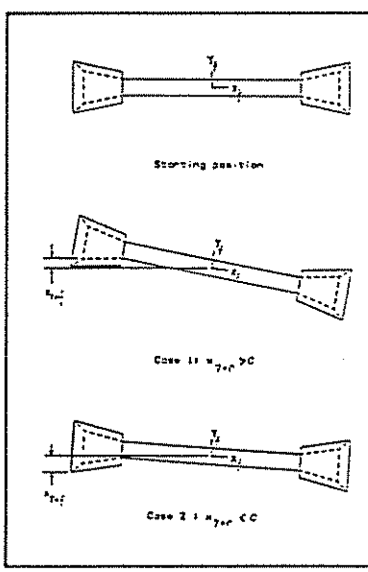

Figure 17 Kinematic Stability

In these earlier studies it was also found that the connection geometry parameters greatly influence the maximum permissible amount of initial misalignment between the structural members to be connected. The misalignments are caused by the positional and geometric tolerances of the structural components and the precision of the equipment used to fabricate the components and erect the structure.

Tolerances, Dimensions and Repeatability

We have also developed a general method to determine the interrelationship between part geometry, tolerances and precision applicable to most assembly tasks and have applied the technique to determine the relative sizes of the ATLSS connection components and required equipment precision so that it is sufficiently tolerant of system imprecision and the buildup of tolerance stacks [3,4].

Robust automated component insertion systems which consistently perform in a successful manner are a growing need in industry. Design for assembly techniques have addressed this problem area in a number of different ways. In the following method, part dimensions, tolerances, and equipment precision are related to the ability of the equipment to successfully perform the desired assembly. The result being tools that ensure the compatibility of a product design with the automated manufacturing/erection process being used. The method is cast in terms of a dimensionless part size ratio and the probability of successful assembly. The results of an experiment show when the size ratio is modified to include compliance, it can be used to accurately predict the ability to assemble/erect parts in a less than certain environment.

In any insertion operation alignment of the components is an important consideration. Active and passive strategies for adding compliance have been applied to the automated assembly process to improve the alignment and mating of components [8]. The use of spring loaded fixtures, grippers and Remote Center Compliance or RCC devices are common examples of the passive strategy.Active strategies require the assembly equipment to respond to feedback from sensory inputs. In many applications a force/torque sensor may be used to promote effective error recovery routines. The force/torque information is utilized in determining the resulting path of the robot, or logic branching is used to generate a series of move-and-bump cycles. Great care must be taken when applying active control strategies to ensure that the process does not become unstable.

Chamfers and clearances are also a means of supplying assembly compliance [9]. We have developed insertion models which incorporate clearances for numerous geometries, as shown in Figure 18, in an attempt to further increase the connection compliance. Closed form solutions have been found for 1-D and circle cases [3] and Monte-Carlo simulations are used for all other cases [4]. When a peg is inserted into a hole there are a number of parameters which can affect the success of the mating process. These parameters cause the center lines of the hole and peg to deviate laterally and angularly from each other. The misalignment results from imprecision of the device inserting the peg or the fixture which contains the part with the hole or from tolerancing generated in either the peg or hole. Typically, parts are designed to afford a certain amount of clearance during mating. The clearance is required to overcome any errors accrued by the milling/manufacturing/fabricating equipment along with the dimensional errors associated with each component as a result of tolerance stacking/erecting. When the variations of the components and the equipment do not meet a minimum level, a collision or jam will occur that reduces the productivity of the process.

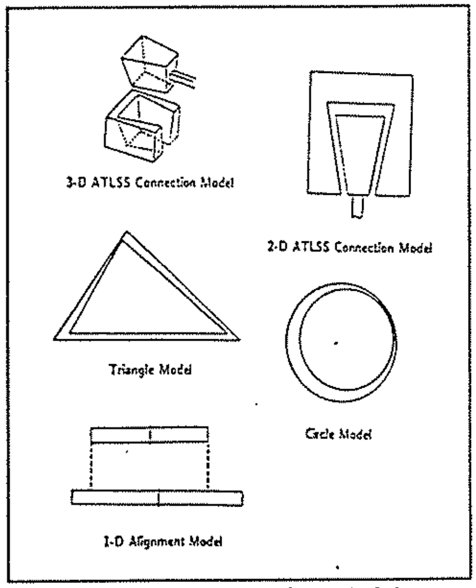

Figure 18 PSA Design Models

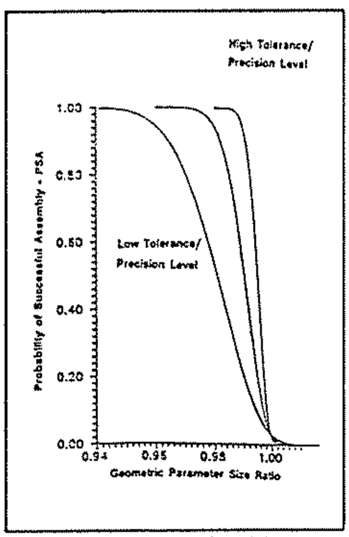

Figure 19 Derived PSA

The productivity of the assembly process can be expressed in terms of a Probability of Successful Assembly or PSA. The PSA gives the design/fabrication engineer the ability to determine the required clearance and tolerance specification of the mating parts to ensure a specified level of productivity, when the positioning errors of the assembly/fabrication/erection equipment is known. Various models have been developed which take into account the size ratio, part tolerancing and equipment precision factors for determining the PSA of an assembly/erection process [3,4]. This is a fundamental break from typical design where clearance selection is based on experience or empirical methods. The primary design variable in this method is the non-dimensional size ratio. In the case of a circular pin and hole the size rate SR = d_p/d_h where d_h is the mean diameter of the hole, and d_p is the mean diameter of the peg. For other geometries the ratio is associated with weighted averages of the characteristic sizes of the parts. Figure 19 shows a graph of the theoretical results for the PSA over size ratios ranging from .618 to .983. for a general pin-hole combination. It shows how part tolerances and equipment precision levels, measured in standard deviations, effect the PSA over various parameter size ratios.

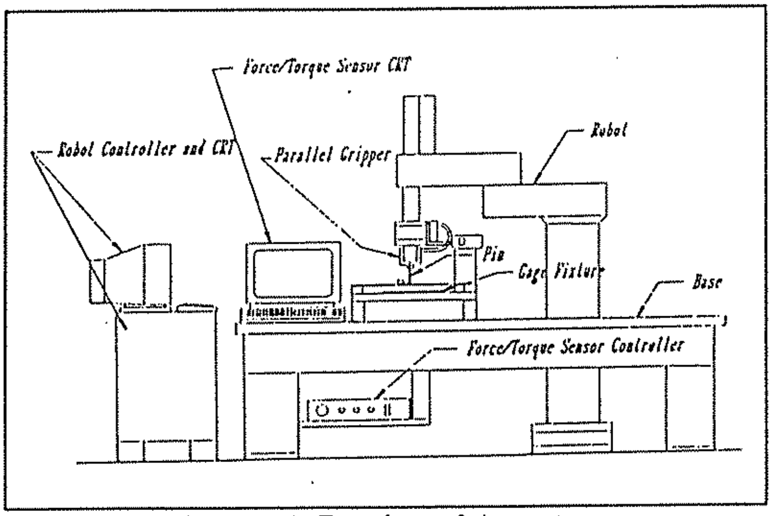

Figure 20 Experimental Apparatus

An experiment was performed to verify the appropriateness of the theoretical method [10]. The apparatus used in the experiment is shown in Figure 20. A Selective Compliance Automatic Robotic Arm, SCARA class robot was used. Fixed rigidly to the end of the arm is a force/torque sensor. The sensor is capable of recording forces and torques along and about the X, Y, and Z axes. The robot software is capable of generating desired pin placement. The robot is secured to the same precision machined base as the fixture which contained the hole. The machine base also provided space for the monitors used to capture force, position and insertion fault data.

In the experiment various pins and holes were selected. The size ratio was noted and the pin loaded into the gripper. The robot gripper is then jogged to a position where the pin centerline matched the hole centerline and the tip of the pin is exactly above the hole. A controlled placement error is then superposed to that of the original gripper position. The placement error represents the effect of the tolerance stack in the building and the precision of a robotic crane. The deviation to the exact insertion location was generated from a set of numbers having a normal distribution randomly generated by computer. The robot program was executed and a success or failure was determined and documented. This procedure was repeated 300 times for each pin-hole combination. Twenty pin-hole combinations were tested.

Weibull curve fits for both the experimental and theoretical PSA curves are shown in Figure 21. The plots appear to be parallel. For a given size ratio the experimental curve shows a significant increase in the PSA over that predicted in the theoretical curve. The curves suggest that a smaller size ratio can produce better insertion efficiency than expected from the rigid system theory. An effective size ratio, $SR_{eff.}$, the size ratio that would make the rigid insertion model PSA equal to the experimental PSA, is then determined.

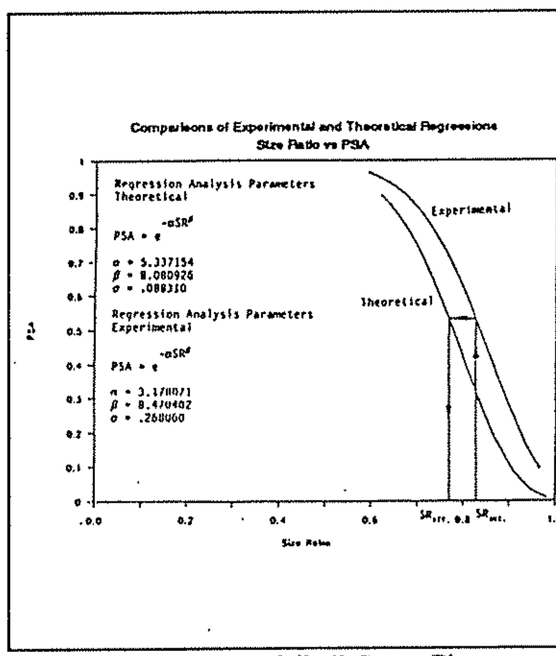

Figure 21 Weibull Curve Fits

Like the ATLSS Connection each pin-hole combination used in the experiment has an effective compliance. The rigid insertion model assumed that the compliance was null. As pointed out earlier, increased connection compliances increases the probability of insertion; this effectively increasing the size ratio. A relationship between actual size ratios, effective size ratios, connection geometry, handling system compliance and connection compliance can thus be found. This relationship shows that it is important to choose the ATLSS Connection parameters so that the connection compliance is high, the interior surfaces allow slippage and to use erection equipment with sufficient compliant to allow the desired resulting motions to occur during the insertion process while being accurate and thus stiff enough to allow the erection equipment to find the holes and start the insertion process.

ACES DEVELOPMENT

The Problem

Recently, one of the authors conducted a detailed review of construction robots being developed and characteristics common to these robots [2]. He observed common conditions of where these robots were applied and likely features of where other robot applications exist in construction. Four rules were formulated: 1) The work environment is often dangerous and hazardous for human construction workers; 2) The tasks are repetitive. Many tasks performed by the human construction worker are repeated over and over; 3) The work requires mobility or transportability. Construction work is performed at various locations around the work site; and 4) The work requires intelligent-like behavior. Sangrey [11] has suggested that the unstructured and non-repetitive nature of construction tasks requires new strategies and tools for sensing and control. Sensory perception, decision making and judgement are required to deal with variations in the work.

Today's cranes are gross motion systems which are swing sensitive to external loads such as wind, are not dexterous and are controlled manually with little or no external computer or sensory input. The payload is free to rotate and sway in all directions much like a pendulum under the slightest lateral pressure. Under these conditions it is very difficult for a crane to work with precision or support robotic operations. Although, automatic crane anti-sway control devices have been applied to control the pendulum effects in the horizontal directions they still fail to suppress unwanted rotations of the load [13]. Other systems have been developed which try to solve the sway problem by employing several auxiliary wires and winches. These systems add considerable complexity and cost to the load handling system and have not found acceptance in the industry. Shapiro [12] has suggested that most crane accidents are caused by overloads, equipment misuse, and errors in the planning stage, such as when the crane is positioned inaccurately or is inadequate for the job. Currently, payloads of construction cranes are stable only in the vertical direction. Other characteristics are:

- LOW PRECISION AND ACCURACY
  Large kinematic linkages and loads, such as weight, wind and thermal produce larger deflections and vibrations than obtained with industrial robots.
- POOR STABILITY AND CONTROLLABILITY
  Payload is hoisted with one cable (pendulum effect), therefore payload rotations are not controllable and positioning is underdamped.
- LARGE POSITIONING UNCERTAINTY
  Errors in measuring the relative position and orientation of linkage components are multiplied in large systems; there is an amplification effect on sensor errors and nonlinearities.
- LARGE WORK-SPACE VOLUME
  The large work-space volume makes requirements on external sensors, such as how many external sensors will be required, and where they should be located, extremely demanding. Current industrial robot technology will most likely render economically unfeasible solutions to these problems.
- HIGH SAFETY REQUIREMENTS
  The amount of power under control and the level of investment in equipment and product dictate that safety issues should be of great concern. It is common practice in industry to restrain people from the robot's work volume when it is in operation. This solution will not be practical for crane operations, thus generating a number of safety issues.
- NON-REPETITIVE TASKS
  While industrial robots work best at repetitive tasks, crane applications are typically non-repetitive.
- IMPRACTICALITY OF TEACHING LOCATIONS
  Positions and paths will have to be automatically generated and adjusted using database and sensor information. The practice of teaching locations either on-line or off-line will be impractical.

- LACK OF DESIGN FOR ASSEMBLY
  Design for assembly is used with industrial robots to reduce precision requirements and simplify operations.

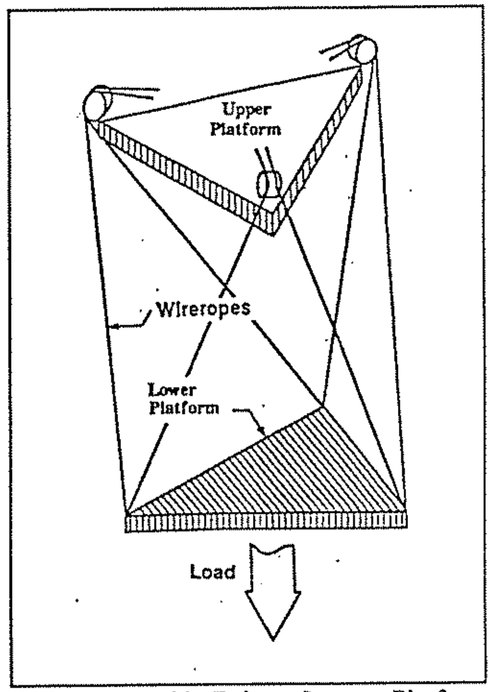

Figure 22 Cable Driven Stewart Platform

The ATLSS Solution

The desirable characteristics of tomorrow's cranes are systems with both large gross motion capability to move around the job site while being insensitive to wind gusts and having fine motion capability required for the final placement of the component. Systems which use externally obtained sensor and design data to assist or/and control the crane are also desirable. The system must have a self contained metrology system for location identification and precise measurement. Conventionally designed robots having a serial linkage arrangement have been suggested for construction. The low payload to manipulator arm weight ratio of these robots are an ineffective addition to the construction site [14].

The automated construction of building components is currently possible because of recent advances in crane technology which are related to the development of the Stewart platform [15]. A Stewart platform is actually two platforms connected by a series of six individually controlled linkages. Typically, hydraulic actuators are used to link the platforms together for applications such as manipulator arms and aircraft flight simulators. A Stewart platform can also be assembled with six cables used as the linkages to move the lower platform and payload relative to the upper platform position as illustrated in Figure 22. Orientation of the cables is such that the system has properties of a space frame. The linkage arrangement not only provides excellent translational and rotational stiffness when compared to boom cranes but can also adjust the position and orientation of the lower platform with precision. The lower platform can move with six degrees-of-freedom to make insertion of ATLSS connections possible as shown in Figures 23 and 24.

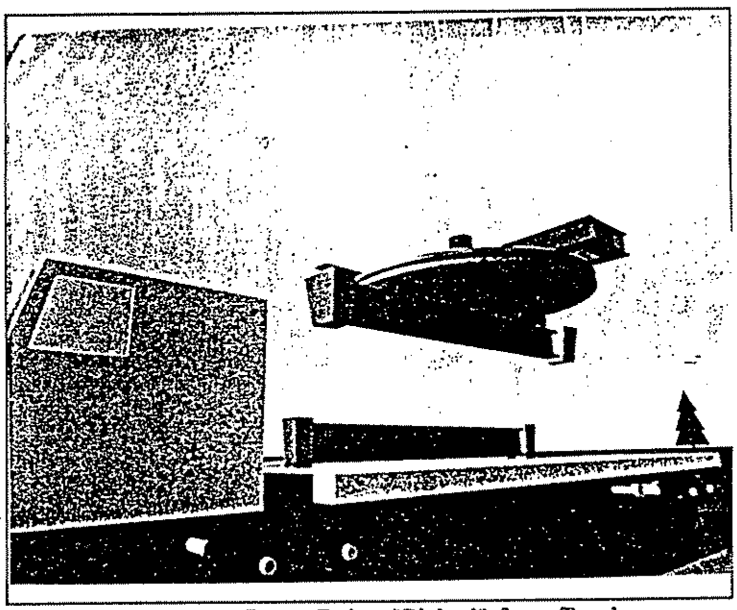

Figure 23 Beam Being "Picked" from Truck

Platforms can be designed and constructed with large work volumes and dexterity. We have written a simple graphics simulator than can be used to design and show how work volumes and dexterity vary with various sized platforms. Our current design allows a hung piece to be rotated around the vertical axis by +/- sixty degrees and about either horizontal axis +/- ninety degrees. Translational motion of the bottom platform relative to the top is such that the center of mass of the lower triangle must stay within a region slightly smaller than the upper triangle. Thus, if the upper platform is an equilateral triangle four meters on a side and the lower triangle is an equilateral triangle two meters on a side the horizontal translation is limited to approximately one meter in any direction. Vertical translations are limited only by the length of the cable at hand.

Stewart mechanisms are parallel link manipulators in that their moving links or cables appear to be somewhat parallel at all times. This is quite different from the more common serial links used in manufacturing where the links form a continuous chain. Parallel link manipulators are known for their high strength and stiffness to weight ratios. The actuators and parallel links do not bear moment loads and act in simple tension (or compression when cables are not used); allowing for large external force and moment carrying capacities. The apparent stiffness is generated by a combination of the space frame nature of the geometry, the strain in the cables and weight of the payload. The heavier the payload the more resistant the platform becomes in the horizontal direction. The unit is stiffest at the center of its range of motion. Near the limits of each range forces in one or more cables decrease. Along with this cable force decrease comes a decrease in strain, stiffness and stability. The stiffness of the platform is an important factor when considering flight speed and susceptibility to wind effects. Near the center of the work region the manipulator is highly dexterous.

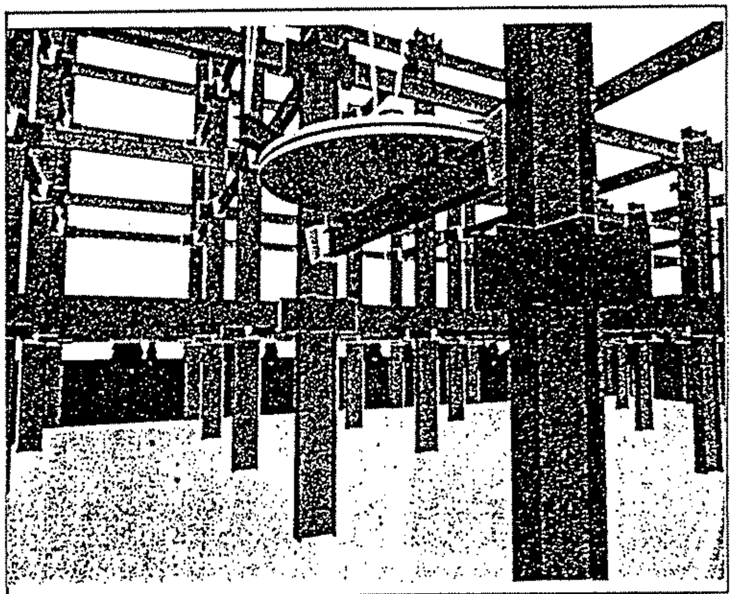

Figure 24 Beam Being "Placed in Structure

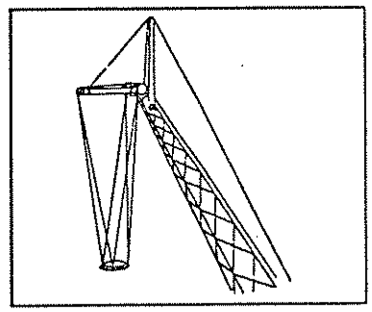

Figure 25 On Boom Crane

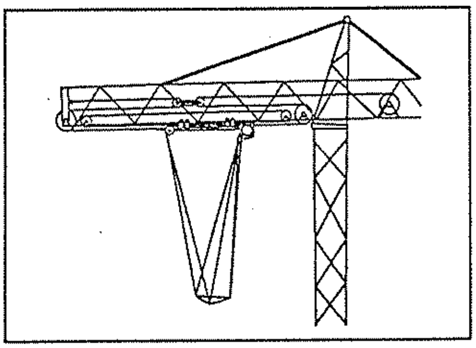

Figure 26 On Tower Crane

Stewart platforms can be placed on boom and tower cranes to greatly increase the platforms work volume [15], Figures 25 and 26. In these configurations the platform is subjected to large gyroscopic torques and centrifugal and Coriolis forces as it flies through it's trajectory. These forces and torques can be sensed and used within the controller to maximize the platform stability and flight speed thereby making efficient payload delivery possible.

A scale-model Stewart platform crane, shown in Figure 27, has been constructed to test the feasibility and limitations of automated construction with these connections. Six servo-electric (DC) motors are used to control the cable lengths and lift a design payload of 1.1 kN at 0.15 m/s. We plan to replace the motors during the next year increasing the payload to 8.8 kN and the speed to 0.3 m/s. Currently payloads of up to 2.2 kN can be lifted at reduced speeds. By attaching the upper platform of the Stewart platform to a motorized trolley, the work volume of the crane system includes a 4 m longitudinal run, a 4 m lift, and 1.2 m of transverse movement.

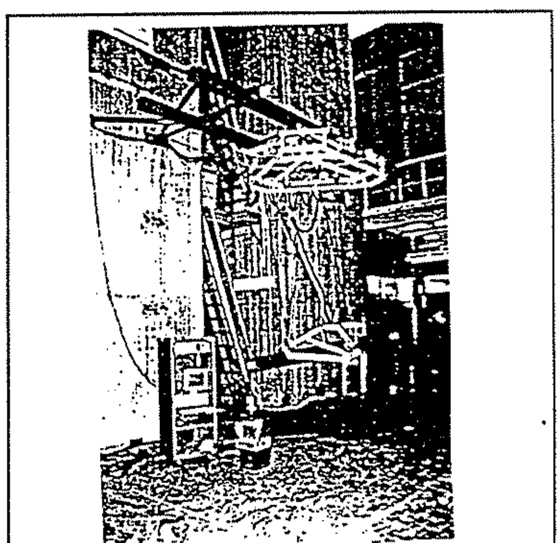

Figure 27 Scale Model Crane

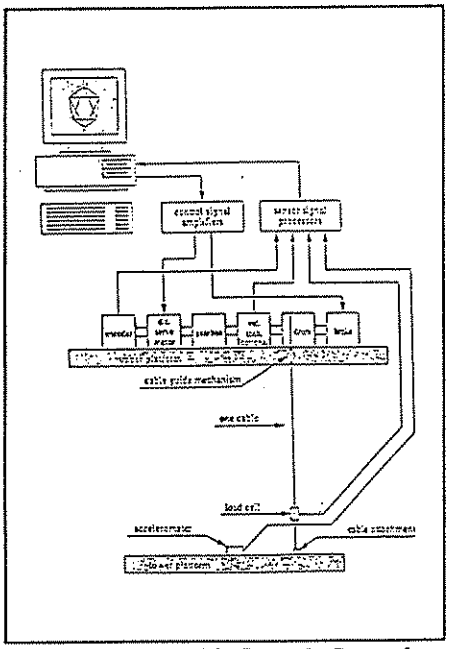

Figure 28 Cable Length Control

In our system cable length control is provided by a PC and DC servo amplifiers as shown in Figure 28. Force sensors within the platform cables are being used within cable slack and platform stability control algorithms which are intended to minimize flight time when the platform is in gross motion control mode and to minimize pose (position and orientation) errors when the platform is operating within a fine motion control mode. These same sensors will become part of the wind stabilization algorithm within the near future.

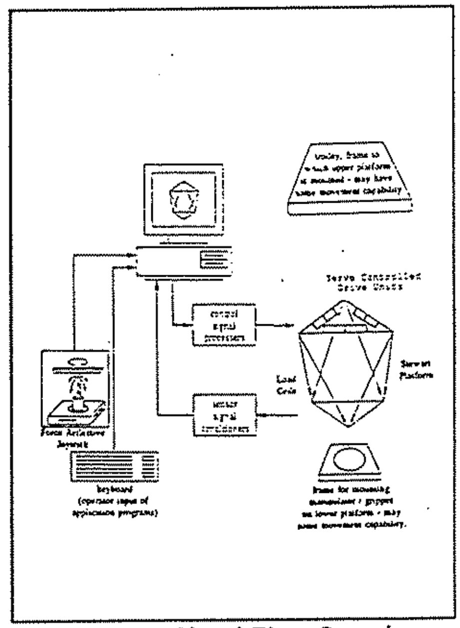

Figure 29 Signal Flow Overview

Manual control of the Stewart platform crane uses a specially designed six degree-of-freedom joystick. This joystick is actually a small scale Stewart platform which outputs the position and orientation or the joystick grip as the command signal for the control loop. Work is currently underway to develop force reflective and other control algorithms which will feedback the actual platform position and cable forces to the joystick operator for use as depicted in Figure 29.

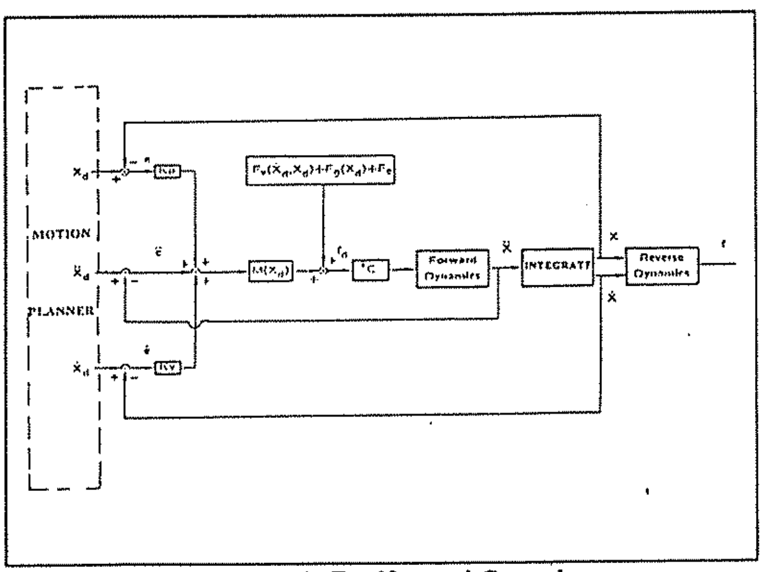

Figure 30 Feedforward Control

To insure both accuracy for component pre-insertion placement and compliance for ease of insertion an appropriate control scheme has to be applied. We believe and are currently implementing a hybrid force-position controller with task specific gain setting and feed-forward compensation. We have simulated the affects of the feed-forward compensator portion of the controller [16]. Both the controller and simulation required that we obtain a model for the kinematic relationship between the cable length and trolley position with that of the payload. This was found using simply transformation matrices. Differential kinematic equations were required to associated small changes in payload position and velocity with those of the cables. Similar expressions relate payload and wind forces to cable forces and cable forces to required motor torques. Application of Newton-Euler dynamic modeling equations result in expressions for forces and torques while the platform is moving and accelerating. Forward forms of these expressions were required in the simulations and reverse dynamic forms are required in the actual controller. A trapezoidal velocity motion planner was implemented in the simulation and various position and velocity gains were selected and tested. A block diagram of the controller is given in Figure 30.

In a typical simulation the upper platform or trolley is moved 15 meters in 30 seconds using a trapezoidal velocity profile while carrying a 5 m long W2 steel beam. The beam is taken to have a weight of 6670.8 N (1,500 lbf). Figure 31 shows how the cable forces vary and how the motion of the lower platform deviates from the ideal "rigid body" motion. The deviation is caused by the cable compliance resulting from the controller gains and variation in direction of the affective force of the payload onto each of the cables as it undergoes the controlled motion. Increasing the position control gain increases the placement accuracy of the payload while decreasing the compliance of the crane. Changing the velocity gains directly affects the settling time. We have yet to determine the optimal settings for a typical insertion.

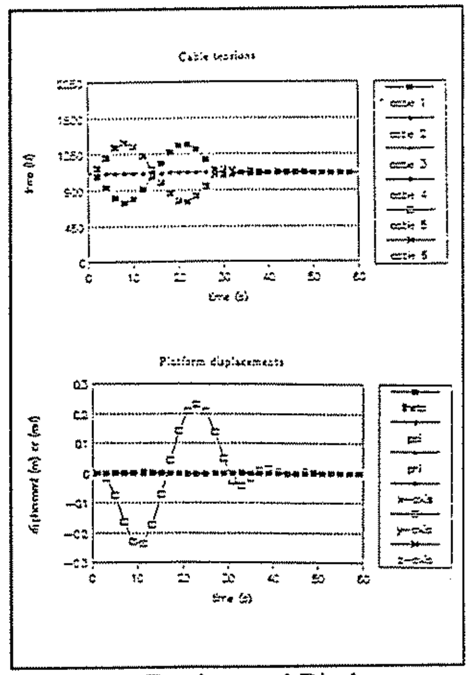

Figure 31 Tensions and Displacements

During the last year the primary focus of this ATLSS activity has been to develop, build and test the electrical, mechanical and low level control system of ACES. During the next two years the effort will be to increase the system capability by developing and implementing various control algorithms associated with locating, moving and placing material components at the construction site. The algorithms will be used in: the fusion and analysis of data obtained from multiple adaptive sensors; the application of kinetic, kinematic and dynamic gross and fine motion control algorithms; and the automated generation and decomposition of tasks required to define desirable trajectories. A program to obtain and process data required for generation of an as built data base and automated task scheduling will commence during the latter portion of that two year period. We expect to begin transferring the technologies developed within this research to other potential applications such as: warehousing, ship building and maritime use, decommissioning of nuclear facilities, mining, dredging and excavation, as well as others during this same time period.

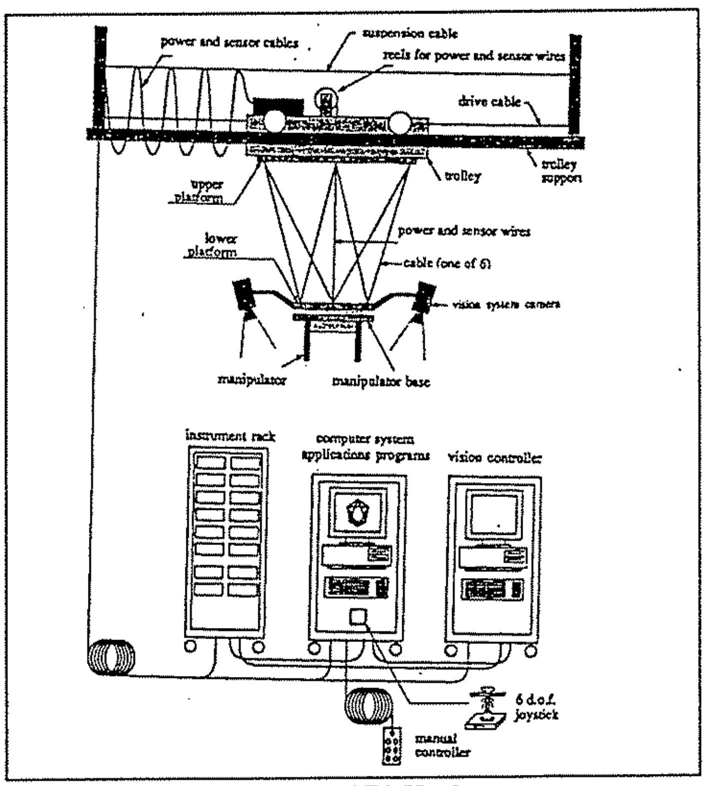

Figure 32 ACES Hardware

In addition to our efforts in machine dynamics we will also be conduct research in the sensor fusion area. The effort in sensor fusion will examine the use of control technologies, statistical and kinematic analysis techniques, to obtaining local and global estimates of the location of construction elements at the work site [17]. Our plans include the development of a vision system as illustrated in Figure 32. An active vision technique incorporating data from the two cameras as they look at the two ends of the beam would be combined using a Kalman filtering technique and Approximate Transforms to find and begin the simultaneous insertion to the pair of connections. Automatic operation thus becomes possible by integrating the vision system into the manual operation control loop. The installation of a vision system would also allow the development of an automated crane erection system which not only erects the building, but also assists with on-site material storage and inventory management. We have built and tested a preliminary version of the vision control algorithm which will allow the crane to sense the actual pose of the payload relative to the delivery site while being moved [16]. This involves the use of actively controlling the camera focal length and field of view under uncertainty conditions presented by the crane and those associated with the construction site.

We believe that an automated framing system equipped with a vision system would be an important component in a program for the automated monitoring of construction quality control. Potential applications include quality control monitoring of connection placement, structural member alignment and actual dimensions. Most current quality control processes produce after-the-fact rejection with consequential delays, interruptions and expensive rework. Immediate feedback would enable remedial action to be taken while that construction activity is underway and thus minimize the consequences of defects

Knowledge Based System for Planning

In a related ATLSS project, information and knowledge of designers and fabricators is being utilized by a knowledge base system to aid in the automated design of cost-effective connections, Figure 33. In the near future that knowledge and data will be used to develop automated building erection scheduling and trajectory control plans. Vision and other sensing information will be used to create an as built data base which will then be used to automatically update interior designs for piping layouts as well as others as shown in Figure 34. Sensors linked to crane controllers could be used to monitor not only the load but also the wind, the position of the boom, etc. This information could be used to automatically and continuously set limits on position, velocity, acceleration and load in order to take some of the guess work from the operator, avoid stability problems, increase safety and productivity. Thus the sensing and knowledge base systems described here become the basis for the information gathering and processing system for successful conclusion of the construction process.

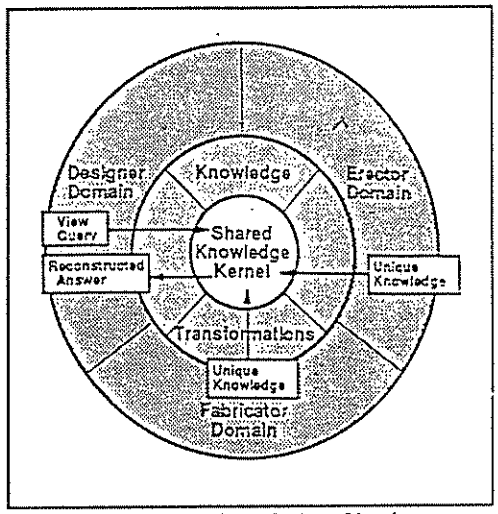

Figure 33 Knowledge Sharing

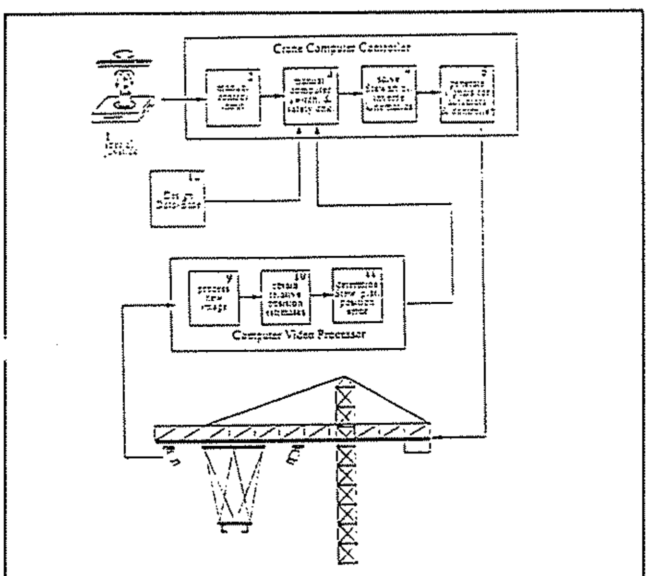

Figure 34 Data-Base Control

Framing of structures is a fairly complex task involving architecture and structural design, material selection and component fabrication, scheduling and delivery, and erection and inspection. The automated framing technology being developed will have a significant impact on each of these tasks. The technology will allow for automated erection sequencing and automated control of erection equipment; thus it will help transform the unobstructed erection site into an automated assembly system. Automating the framing process will save costs on site, because robotic devices can work more efficiently in a hazardous environment. Moreover, the knowledge base and planning simulation system which will be developed in the process will provide valuable information to structural engineers about the relative costs of design alternatives.

ANTICIPATED OUTCOMES AND ITS RELEVANCE TO PRACTICE

The end users of the ACES technology will be construction firms in charge of building the structure and the manufacturer of the automated construction system used for the erection of the structure. ACES is being designed to assist erection firms in locating, securing, moving and placing the structural elements. It is also being designed as the primary material handling system capable of locating, securing, moving and placing non-structural elements (such as windows, facade, and the like) throughout the construction site. The key technological barriers to automated construction being overcomey are: connection and structural design for constructability, implementation of mechanical/ control hardware for construction crane application, development of active sensing such as active vision and force reflective joysticks, and the development of the design and as built construction database.

The primary benefit of this effort is the reduction of process cycle time through reduction of idle time. Intrinsic to the material handling process is that it lays between two other processes. Both the prior and next process may not be capable of being performed while they are waiting for shipping and/or receiving to occur. The prior process upon completion will typically use a buffer to place completed work or have to wait for the completed work to be "shipped out" to the next process. A similar situation occurs at the next process. If no incoming buffer is available, the next process must wait to "receive" the work before it can start. Inefficient material handling can thus cause these processes to stall; as much as twenty to fifty percent of time may be wasted in this manner.

The construction industry has long realized the problem and compensates where it can through the use of on-site storage areas which in effect are attempts to create buffers between the processes. This is not completely effective if the storage buffer is located where travel time to/ from it is significant, requires the handling system to first move parts into the buffer and then back out, or if other storage costs are significant. On of the most immediate benefits of ACES is the reduction of the costly waiting time without the need of the storage/buffer.

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DEVELOPMENT, ANALYSIS, EXPERIMENTATION, AND IMPLEMENTATION OF ATLSS CONNECTIONS FOR AUTOMATED CONSTRUCTION

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ABSTRACT

A series of new beam-to-column connections known as ATLSS Connections (ACs) are currently under development. The emphasis of these new designs is on a self-guiding feature for use in automated construction. This feature will minimize human assistance during construction and will result in quicker, safer, and less expensive erection procedures. The AC concept is based on using a tapered solid tenon piece on the beam which slips into a three-dimensional mortise guide mounted on the column to form a shear connection. The analytical analysis of this connection is being performed using plane strain procedures. Experimentation, conducted concurrently with the theoretical work, has been performed by isolating the various loadings the connection would experience. Currently shear loading tests and tension loading tests have been completed, and rotation tests are underway. The AC concept can cover a large range of structural needs, including shear, partial-moment, and full-moment connections. Analysis and moment loading tests have been conducted on the moment-resistant versions of the connection. The current version of the AC will be optimized for structural performance. The AC has been successfully implemented to erect a portion of an actual building. In the future, it is envisioned that a complete 3-D building using shear and moment ACs will be erected and evaluated.

INTRODUCTION

During the past 3 years, a comprehensive research program in automated construction has been undertaken. The two main thrusts of the research, currently, are the development of a robotic crane capable of exact placement of members, and a self-guiding, self-locking connection to be used in conjunction with the crane. This paper is about the latter, an innovative steel building connection known as the ATLSS Connection (AC). The AC has evolved from a dovetailed double web angle used as an erection aid to a pair of three-dimensional steel connectors capable of carrying structural load. The concept has been extended to many building situations and connection types. The connection has recently been implemented in an actual structure. Currently, research is ongoing for the AC as a shear connection; as a partial- and full-moment connection; as a component of a composite connection; as a component of a tubular system; and as a means to erect a bay in one lift. The connection is capable of carrying gravity or lateral loads.

ATLSS Integrated Building Systems Program

The ACs are being developed at the Center for Advanced Technology for Large Structural Systems (ATLSS) at Lehigh University. The primary mission of the center, which was created in 1986 by a grant from the National Science Foundation (NSF), is to serve as a focal point for research and education that will lead to technological developments which increase the competitiveness of the U.S. Construction Industry. The ATLSS Center is driven by three main tenets: 1) Interdisciplinary research, exchange and education; 2) Industry advice and technology transfer; and 3) Innovation and long term goals. ATLSS has had success in these areas, in part by maintaining a consistent balance between short term needs and long term goals, a commitment to technology transfer, and a superb group of forward thinking industry advisors. The ATLSS Integrated Building Systems program (AIBS) is a good example of such a process, and it is our opinion that what separates our effort from unsuccessful attempts for automated construction in the past are the advantages afforded us by the ATLSS center's resources and philosophies.

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The AIBS program was developed to coordinate ongoing research projects in automated construction and connection systems. Its objective is to provide a means to design, fabricate, erect and evaluate cost-effective building systems with a focus on automation and computer integration [1]. The approach to automated construction at ATLSS incorporates recent advances in crane technology, which are related to the development of the Stewart Platform. The Stewart platform utilizes six individually controlled cables to move a lower platform containing the payload relative to an upper platform. This configuration not only provides excellent translational and rotational stiffness when compared to a boom crane, but it also provides six degree-of-freedom control [2]. The AC is a self-aligning, self-locking connection which can be used with the Stewart Platform system but does not necessarily require a robotic crane.

ATLSS Connections

The ATLSS Connection (AC) concept is based on using a tapered tenon piece on the beam which slips into a mortise guide mounted on the column [3] (See Fig. 1a). This is referred to as the keystone coupling and was originally designed as a two-dimensional unit, but because of superior erection features and a beneficial wedging action, a three-dimensional AC is being exclusively used in research, development and application (See Fig. 1b). To accomplish its intended purpose the AC must contain the following features: The AC must be able to guide the beam toward the proper location once the tenon and mortise pieces make contact; The tenon piece cannot jam or catch [4] on the mortise guide, nor can it pull out horizontally once it engages; Due to the tolerances involved in the construction process, the AC must allow for misalignment, and have the ability to be adjusted easily when the building is being plumbed; The AC must be stable during erection and carry the intended design loads during the life of the building. The ultimate goal of this effort is to have a limited assortment of mass-produced ACs with a standard shop-fitting operation and quick, automatic erection capabilities.

Studies on the erection characteristics of the three-dimensional or chamfered AC show that it is well suited for automatic erection due to its physical characteristics. An important characteristic is the sloping surfaces on the back face of the mortise, vertically; on the side faces of the mortise, vertically and, finally, on the side faces (arms) of the mortise, horizontally. The tenon has complimentary slopes. Studies performed at ATLSS [5] show that these chamfers proportion the insertion forces so that the tenon slides in easily, and these slopes also form a means for alignment during the insertion process.

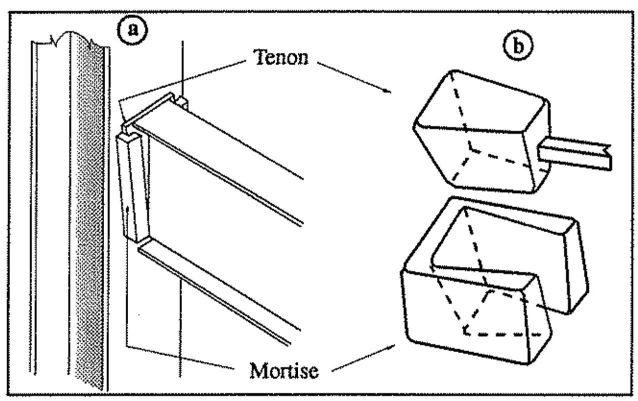

Figure 1. a) 2-D AC. b) 3-D AC.

DEVELOPMENT

The development of the AC involved the evaluation of a number of self-aligning, self-securing connection ideas. These ideas were conceived and evaluated by a team of ATLSS civil engineers and mechanical engineers, who exchanged ideas on structural performance and erection performance, respectively. These initial designs included the AC as an erection aid, a shear connection, and a partial- and full-moment connection [6]. The concepts, as they evolved, were critiqued by in-house experts and the highly qualified ATLSS industry panel. This panel, which included AISC representatives and designers, fabricators, and erectors from across the country responded with constructive comments and helpful insights. The overwhelming consensus was to concentrate on the shear connection, and expand it to moment connections later. It was concluded that the erection aid concept would not be cost effective due to the added material cost. The key concerns of the industry panel were the handling of fabrication and erection tolerances; the connection's ability to be adjusted during plumbing; and the elimination of as much field fastening as possible. Two of these recommendations, a) eliminating the erection aid idea, and b) eliminating field fastening, creates a situation in which the AC itself is the load transfer mechanism. This created the challenging structural engineering task of designing the slopes and sections of the connection, not only for positive erection qualities, but also for connection stiffness, serviceability and strength performance as will be discussed in the section on shear experiments.

It became clear that due to the tolerances involved, the 2-D, or knife-edge, connection (Refer to Fig. 1a) would not be acceptable. The three-dimensional keystone (3D AC), with its tapered sides, allows translational and rotational errors in initial placement, and as long as the small section of the bottom of the tenon is placed within the large opening at the top of the mortise, the self-correcting slopes and high stiffness of the three-dimensional mortise will cause the tenon to align the beam end properly. At this time, the ideas were narrowed to a few shear connection concepts using the 3-D AC. These connections were comprised of a mortise guide which mounts to the column, and a tenon connector with adjustment capabilities which attaches to the beam web.

Manufacturing options were considered next. It became clear at this time that machining or fabricating the 3-D piece was not cost-effective, and cast steel was the best choice, both from a material and economic standpoint. Even though this is the best option, it is realized that cast steel does not have universal industry acceptance and there will be continued attempts to improve the manufacture of the connection.

Phase I Prototype

The prototype connection developed into a tapered solid tenon with double web plates, and a similarly streamlined mortise with interior fillets replacing the re-entrant corners (See Fig. 2). The mortise was designed with stiffer and stronger sections toward the bottom of the connector. To handle the problem of adjustment, slotted holes were incorporated on the tenon framing plates. The Phase I AC was manufactured at a local foundry. The material was ASTM A27 cast steel, grade 70-36. The tensile coupons exhibited excellent properties: 76 ksi tensile strength, and 32% ultimate elongation. Radiographic analysis was used to examine material integrity. In early connections, a number of shrinkage gaps were found in the larger sections near the bottom of the mortise. An adjustment was made in the gating of the mortises, and these shrinkage gaps were controlled.

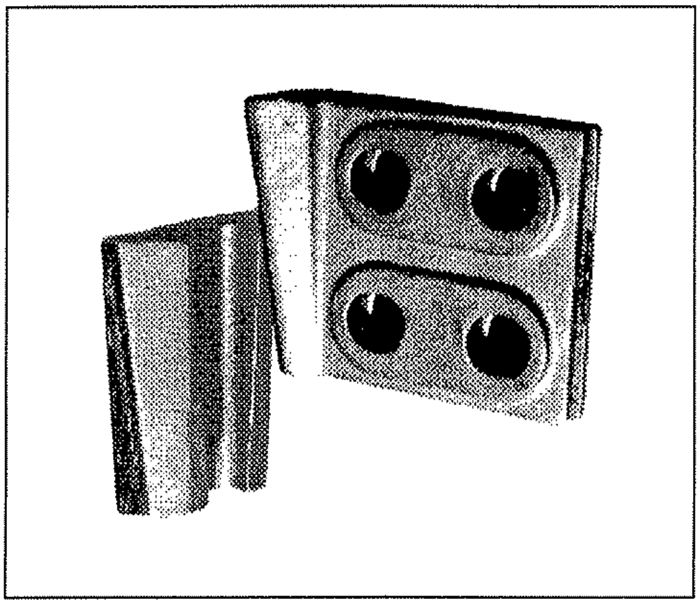

Figure 2. Phase I AC Prototype.

An experimental program was carried out to examine the Phase I prototype's shear loading response. This will be discussed in the next chapter. The effect of surface quality was also examined. This work was supplemented by some initial analytical work. The major deficiency of the Phase I prototype under shear loading was excessive vertical rigid body motion (RBM) of the tenon. These findings led to the development of a Phase II prototype.

Phase II Prototype

The Phase II prototype is a larger version of the Phase I prototype, with an elliptical rather that circular tenon cross-section (See Fig. 3). The reasons for the Phase II modifications are twofold: First of all, the Phase I prototype's performance characteristics pertaining to rigid-body motion of the tenon connector were deemed to be unacceptable. Secondly, from a research and model development standpoint, it was beneficial to have two data sets on behavior to verify our models. The changes due to performance enhancement include the addition of side stiffeners, or flutes, to the mortise; the addition of a seat at the bottom of the mortise; and, the addition of a seating screw that pulled the tenon and mortise parts into a tight fit. The changes due to parametric study were increased section size of the mortise cross-section; sharper return angle of the cross-section; softer slope of the taper; and different material properties. A comparison of the Phase I prototype and the Phase II prototype can be found in Table 1.

EXPERIMENTAL PROGRAM

The experimentation program studying the AC has been extensive. The AC's behavior is complex for several reasons: 1) The three-dimensional state of stress that exists in the connection; 2) The unusual geometry of the pieces; 3) The nonlinear material behavior in region of high stress; 4) The nonlinear geometric behavior due to the contact surfaces between the two connectors; 5) The second order nature of the problem due to RBM of the tenon connector. The complex nature of the connection dictates that the analytical models be verified experimentally.

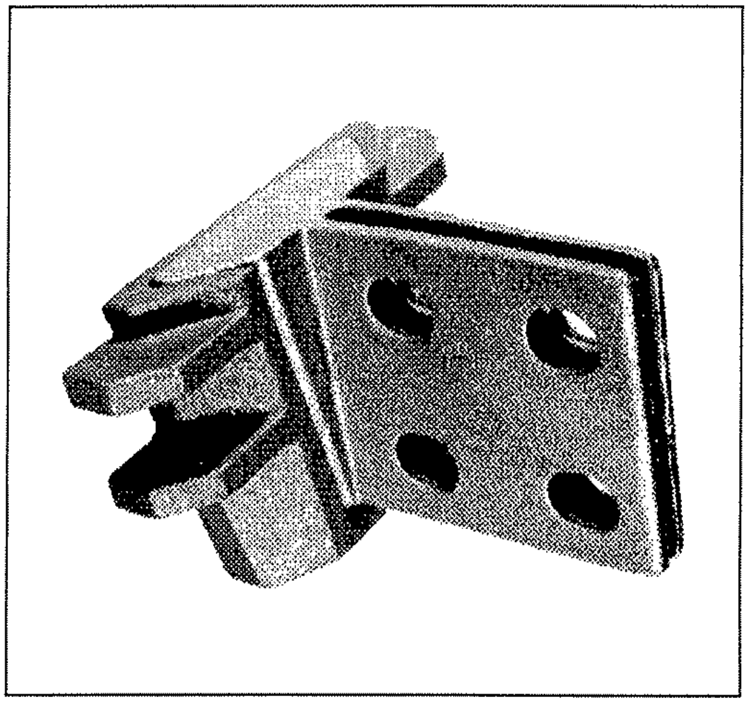

Figure 3. Phase II AC Prototype.

To overcome the complexity of the problem, the experimental philosophy was one of response isolation. Each step of the experimental program was an attempt to assess the behavior of the connection due to a single component of load. The first step was to test the connection by subjecting it to a total shear loading. This was followed by loading the connection in tension. Finally, the connection was loaded in a flexural manner. While both Phase I and Phase II connections have been tested in all three modes of loading, the shear tests were conducted predominantly with Phase I connections. The tension tests and rotation tests, completed recently, involve testing mostly Phase II connections.

Shear Experiments

The shear tests were performed using a W8x21 beam, 50ksi, on a 33" span, loaded at the third points (See Fig. 4). This caused the loading to be almost pure shear. The tenon was connected to the beam web using four 3/4" A325 bolts in 2 rows of 2. The mortise was welded to its fixture with a box weld comprising a 1/4" partial penetration with a 3/8" reinforcing fillet weld. Both the welds and the bolts were over-designed to force failure in the keystone itself. The tests were intended to be third-scale models of a typical building connection. See Table 2 for a list of the shear tests performed at the time of writing and selected results. Test names are constructed using AC followed by the test type, in this case SHR, and finally a abbreviation for the distinguishing parameter of the test.

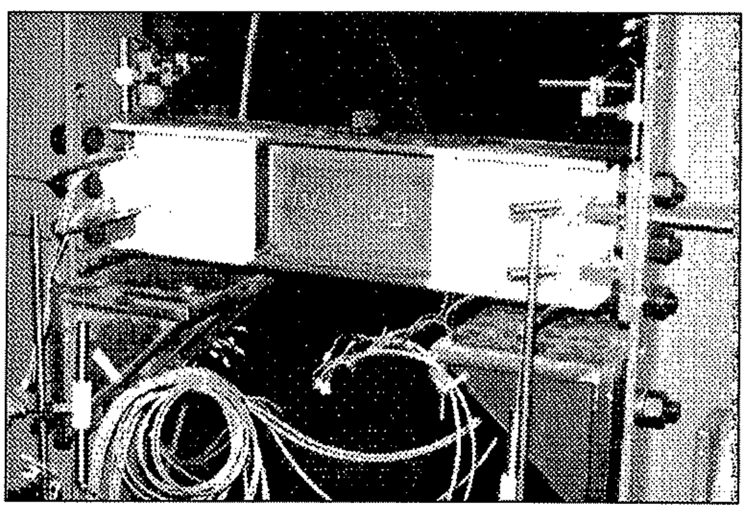

Figure 4. Shear Experiment Set Up.

The quantities of interest when testing a traditional building connection for gravity shear loads are strength and ductility. However, with the AC, there is one more pertinent quantity: rigid body motion (RBM) [7]. In the case of the first shear test, ACSHR, RBM was the overriding factor, and caused performance problems. Figure 5, a photograph of the tested specimen, shows the RBM as the tenon is pushed most of the way through the mortise. Figure 6 shows a plot of this vertical RBM versus connection shear. There are four important pieces of information in this plot. (1) The connection has excessive vertical RBM which is unacceptable. (2) The connection also has large initial RBM, 1/8", under a low load, approximately 5 k. This is termed seating and is also unacceptable. (3) On a positive note, the connection did achieve 70% of the beam's nominal ultimate shear, ΦV_n [8]. And, (4) The connection did not experience any RBM on its unload-load excursions.

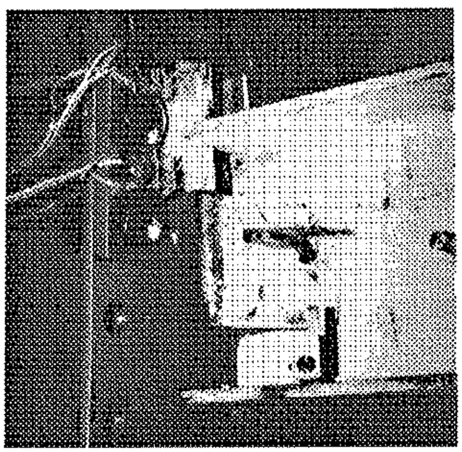

Figure 5. Tested Specimen, ACSHR.

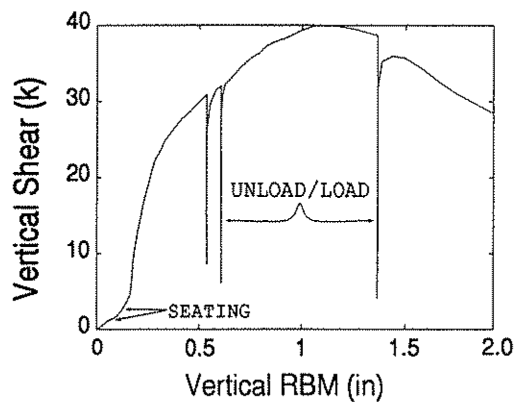

Figure 6. Test Results, ACSHR.

The latter characteristic occurs because of the wedging effect of the connection. This can be shown by using a simple 2D model. When the initial vertical load is applied, the tenon connector wedges itself in the mortise guide (See Fig. 7a). This causes equal and opposite normal forces to be generated. Since these are self equilibrating in the horizontal direction, they do not necessarily vanish if the load is removed. Following load removal, friction is required to maintain vertical equilibrium (See Fig. 7b). Note that when the load is removed the friction changes direction, possibly preventing the tenon connector from popping out. Calculating the critical value of the friction force, f, to keep the connection wedged results in $\mu > \tan\Theta$ where μ is the coefficient of friction and Θ is the slope of the taper. Clearly, from the wedging behavior exhibited in the experiment, this inequality is satisfied. For this case of Phase I geometry, this means $\mu > .085$, which is an expected result.

The final state of the mortise connector in test ACSHR was that the arms of the mortise had completely opened up to allow the tenon to push all the way through. At the bottom, where the mortise is very stiff, the arm was not able to accommodate the large rotations as the top sections had, and ductile failure occurred in the inner fillet of the bottom of the mortise. It was observed that the failure had gone through a large shrinkage gap, which tended to facilitate the failure. Radiographic analysis had shown the existence of these inclusions.

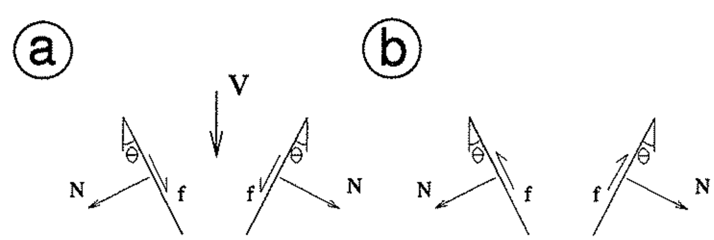

Figure 7. a) During Insertion. b) After Wedging.

In an attempt to address a limited number of issues at a time, the next modifications were made in an attempt to overcome the seating and the structural integrity problems only. The next test, ACSHRm, was performed on a connection that had been cast with improved gating. In addition, the contact surfaces were machined. The absence of the weak link of the inclusions allowed the connection to achieve ΦV_n (See Fig 8). The machined surfaces completely eliminated the initial seating (See Inset), in fact there was no RBM until well into the working range. The machining of the surfaces,σ while not an economic alternative, verified what had been suspected, that the seating was a tribological problem, i.e., surface roughness related. Surfaces in general are not smooth, instead they are made of peaks and valleys. These peaks are referred to as asperities, and when a normal load is applied to the surface, it is transferred only where peaks of one body meet peaks of the other body [9]. Assuming a perfectly plastic material, then, as the load increases, the contact area must also increase in order to keep from violating plasticity. Therefore, the asperities must flatten to both increase their cross-sectional area and to allow other asperities to aid in the load transfer. With the roughness of cast steel in the order of 2000-4000 μin. r.m.s., and the steep slope of the AC magnifying the effect of the mostly horizontal asperity flattening by 12:1 in the vertical direction,

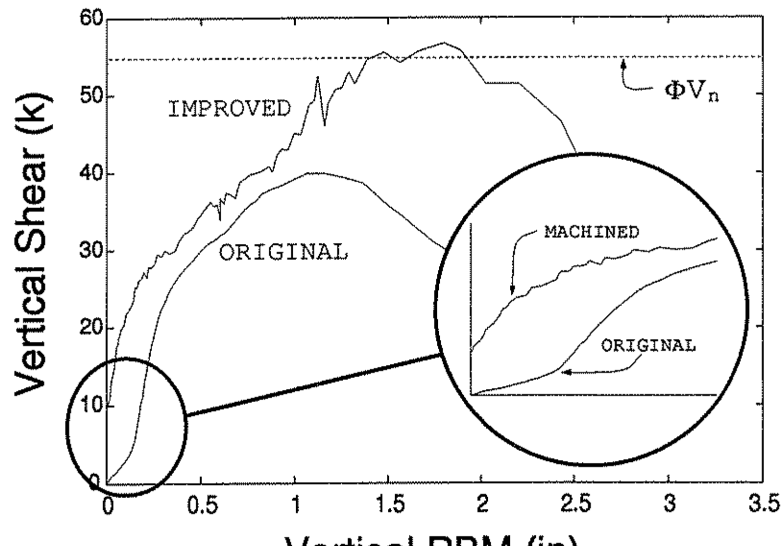

Figure 8. Test ACSHRm.

$$\Delta_{seating} = (surfaces) * R_{ave} * (slope) * (sides) = 2 * 3000x10^{-6} * \frac{12}{1} * 2 = 0.144 \ inches$$

it is easy to see how the first connection had 1/8" seating RBM under very low load. The load value at the end of seating gives an approximation to the amount of the contact surfaces actually in contact at the end of seating, as follows:

$$A_n = 3A_r = 3\frac{N}{\sigma_H} = 3\left(\frac{\frac{V}{\sin\theta + \mu\cos\theta}}{6k}\right) = \frac{V}{\sigma_y[\sin\theta + \mu\cos\theta]}$$

where A_n is the nominal area of contact, A_r is the real area of contact (A_r approaches one-third of the nominal area at its upper limit [9]), σ_H is the material hardness, k is the maximum shear stress, σ_y is the yield stress, and N ,V , μ, and θ are as in Figure 7. If the assumption of low or no friction component during asperity flattening is used, given the test results of ACSHR, the nominal area of contact for each arm of mortise is 0.83 sq. in. Assuming a uniform thickness of contact throughout the depth of the mortise results in a contact surface width of about 1/4 inch. This result was verified in the experiments by observing the wear marks on the contact surfaces. Since the average width of the mortise arm is about 3/4 in., obviously the full area of the mortise is not being utilized. This is because of the deflection/deformation interaction of the arms of the mortise. This will be discussed in the section on analysis of shear loading response.

Test ACSHRf attempted to eliminate the vertical RBM. Returning to the simplified planar equilibrium model from Fig 7a, it can be seen that the normal force and the frictional force can be resolved into horizontal and vertical components (See Fig. 9a). Since, as mentioned previously, the horizontal forces are self- equilibrating, they do not rely solely on the value of the vertical load. Instead, they are also heavily influenced by the slope of the taper and the coefficient of friction as expressed in the equation for the horizontal component

$$H = \frac{V}{2}\left[\frac{\cos\Theta - \mu \sin\Theta}{\mu \cos\Theta + \sin\Theta}\right]$$

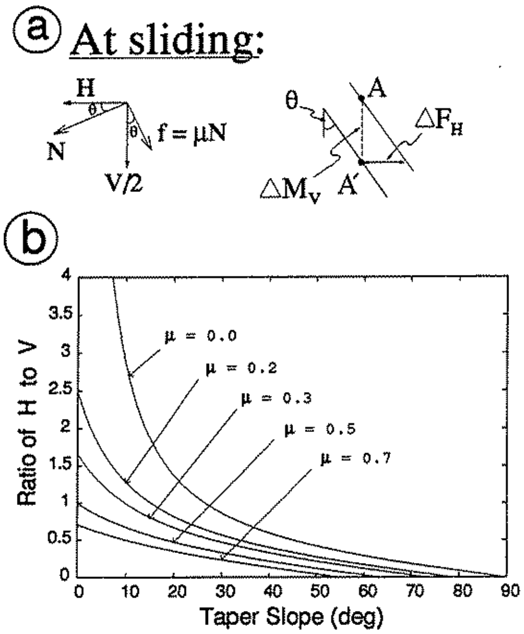

Figure 9. Outward Horizontal Force.

where Θ is the slope of the taper, μ is the coefficient of friction and V is the applied shear. See Figure 9b for values of the horizontal force, H, for different values of Θ and μ. It can be seen that these horizontal forces can become *larger than the applied load* for low friction or steep slope. This is one of the tradeoffs between structural performance and erection performance. A steep slope allows the connection to secure itself in a stable manner and wedge, but it also creates extremely large horizontal force components. The vertical RBM of the tenon is due largely to the opening of the mortise (Refer to Fig 7c). The opening of the mortise is a function of the horizontal force and the horizontal stiffness of the mortise. Hence, to reduce the vertical RBM, one can either lessen the horizontal force by making the slope less steep, or increase the mortise's horizontal stiffness. In Phase I, the latter was attempted by adding side stiffeners or flutes. This was the connection used in test ACSHRf. As shown in Figure 10, the flutes did arrest the vertical RBM, but only after a lesser but still unacceptable deflection. In test ACSHRfm, the flutes were similarly ineffective (See Fig. 11).

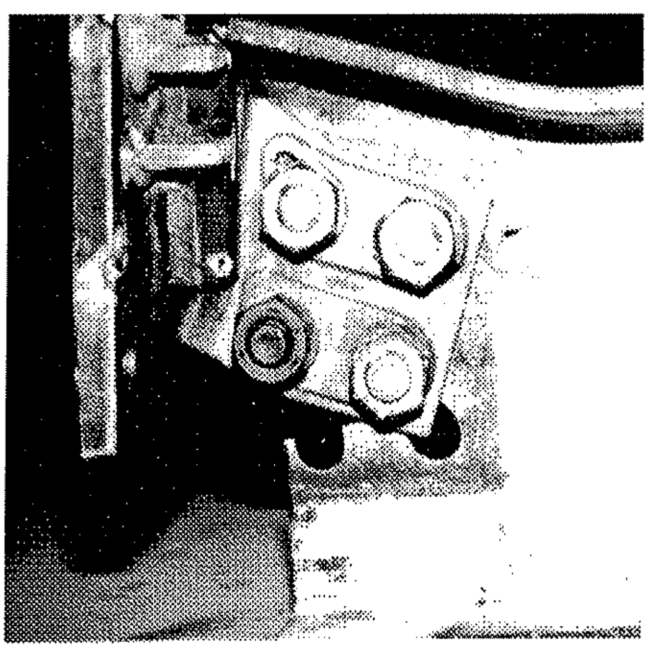
Figure 10. Tested Specimen, ACSHRf.

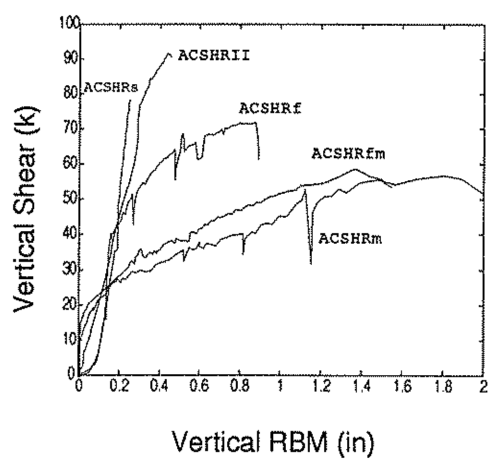

Figure 11. Comparison of Shear Tests.

The following test, ACSHRs, incorporated a seat at the bottom of the mortise. The seat provides a region of high stiffness near the bottom. Direct contact on the seat would cause a large percentage of the vertical shear to be transferred at the bottom, causing the lower bolts on the beam web to be overstressed, and it would also alleviate the beneficial wedging action. Therefore, a gap of between 1/16" and 3/16" was left between the bottom of a tight fitting tenon and the seat. This provides, as a last resort, a positive stop against vertical RBM. As can be seen in Fig. 11, the seat was successful in stopping the RBM, but it had little effect on the initial seating due to the asperities.

From the results of these tests, it was decided that the next prototype should have a seat with a 1/8" gap, *and flutes*. The flutes were added for tension/flexural resistance. As a solution to the asperity seating problem, a seating screw was added. This 1/2" screw would enter a tapped hole in the tenon through an access hole in the seat, and by bearing against the bottom of the seat, pull the tenon connector down into place. This accomplishes three things: 1) It eliminates the asperity seating problem by causing it to happen before actual load is applied (e.g., dead weight of the floor); 2) It pre-loads the connection with beneficial wedging forces; and 3) it provides a physical connection between the tenon and mortise. Figure 12 shows a sketch of this AC.

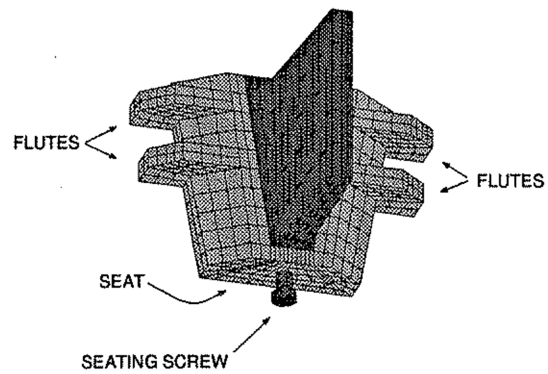

Figure 12. AC with All Features.

One shear test was performed with the Phase II connection, ACSHRII, to examine the effect of the slope of the taper on the RBM. For the purpose of verifying our simplest model, the flutes and the seat were cut off to observe the Phase II connection in its purest form. The connection, without its added features, lends itself to be compared with plane strain analyses of the typical cross-sections. As can be seen in Figure 11, the Phase II connection required neither flutes, seats or a seating screw to perform relatively successfully. This is due to the marked lessening of the taper slope, from 12:1 to 6:1.

Tension Experiments

To test the ACs in tension, a tee-jig was fabricated to which the mortise was mounted, and the tenon was bolted to a web plate. The tenon was inserted into the mortise, and then the tee stem and the web plate were gripped by opposite heads of a SATEC 600 kip Universal testing machine. Figure 13 shows the tee-jig gripped by the lower head with the AC mounted to it, just prior to the gripping of the tenon web plates by the upper head. Though the AC has not been earmarked as a tension connection, the tension tests are very valuable. First of all, they give the best direct planar comparison for the plane strain finite element analyses. Secondly, the results can be used to develop models for both shear and flexure, as similarities exist between these two situations and the tension situation. Finally, recent work in related projects is examining the AC as a couple transfer mechanism for composite connections. In this case, the couple component could either be tension or compression. Table 3 shows the list of tension tests and results.

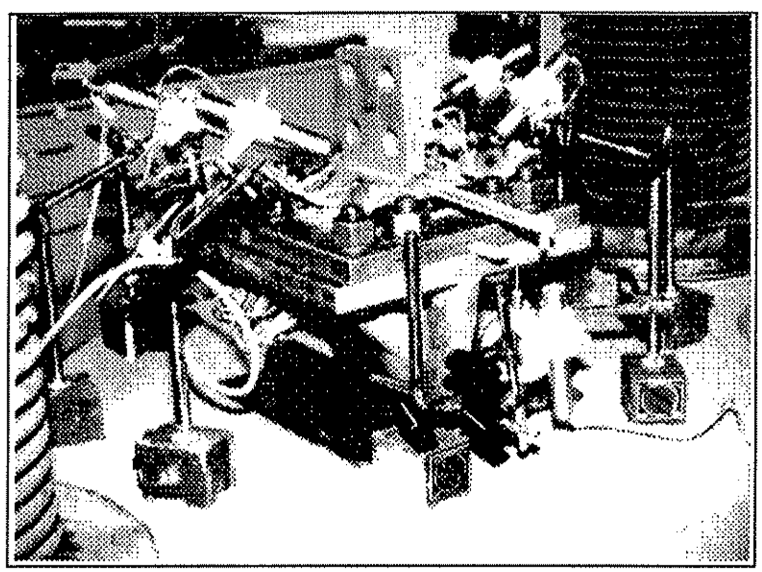

Figure 13. Tension Test Setup.

Tensile test ACTNS was performed with the Phase II Connection, without flutes and seat. The weld connecting the mortise to the test mounting plate was similar to the shear test welds: a box weld consisting of a 1/4" partial penetration covered by a 3/8" fillet. This test exhibited excellent stiffness until the weld failed suddenly (See Fig. 14). The reason for this sudden failure is the location of the box weld. As will be shown in the next chapter, this box weld is highly inefficient for use with the AC in tension.

For testing purposes, a slot weld was placed on the interior of connection ACTNSI, the Phase I connection. This weld was used to assist the box weld on the outer perimeter. In this case, due to the higher material ductility of the Phase I connection, the less sharp return angles, and the smaller cross-section, along with the retrofitted weld, the connection was tested through its complete behavior. The tenon was actually pulled all the way out of the mortise which exhibited a ductile mechanism in allowing the RBM to take place. As can be seen in Figure 14, the connection still maintained a reasonable stiffness in the working range despite being without flutes, a seat, and the seating screw.

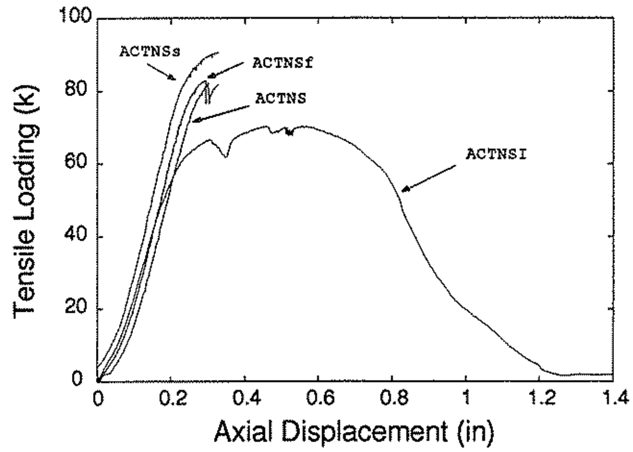

Figure 14. Tension Test Results.

Other tension tests have been attempted, ACTNSf, ACTNSs, tests with the flutes and the seats respectively. These exhibited behavior similar to ACTNS (See Fig. 14), except they obtained a higher load due to the improved weld. The connections were stiffer due to the added features, but only 5-10% more. There are two reasons for this reduced effect of the flutes or a seat in tension when compared to their marked effect on improving the shear response. The first reason pertains to the geometry of the AC. The equilibrium of the situation in tension can be obtained by referring back to Figure 7a, if one imagines the forces to be on a horizontal plane, and replaces V with T. For this simplified model, H is expressed in a similar expression for the horizontal force, the only difference is that the taper slope Θ is replaced by the return angle Φ. This return angle is an order of magnitude larger than the taper angle, so returning to Figure 9b, it can be seen that the horizontal force in tension is quite substantially smaller. This lessens the effects of the flutes. The second reason for the lessened effect is that a large portion of the connection's axial flexibility is due to the elongation of the slender web plates, and this is independent of the mortise's added features.

<u>Rotation Experiments</u>

The shear tests are not sufficient in determining the performance of a shear connection, because they only give the strength and serviceability performance. An investigation of the rotational ductility must be made. This was accomplished in two ways. First, a number of connections were tested on each end of long spans to get working range performance under a realistic moment to shear ratio. Then, cantilever experiments were performed to get an idea of the rotational ductility, even though the shear value is unrealistically low.

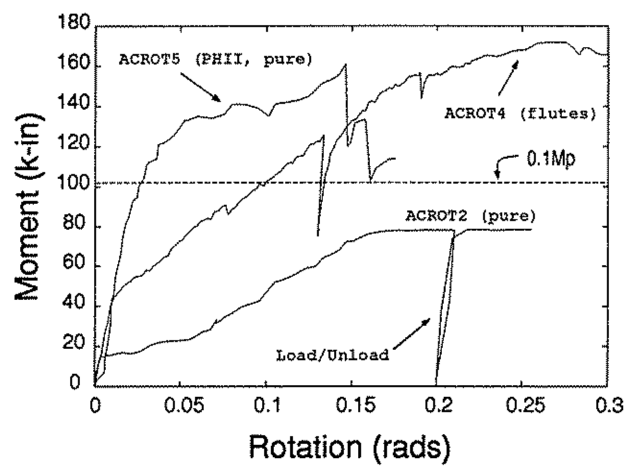

Figure 15. Rotation Test Results.

Figure 15 shows typical results from the tests. The connection can indeed be assumed to be simple as the maximum moment achieved is only about 10-15% Mp. The rotational ductility was excellent reaching values of up to 0.286 radian or 16 degrees. Table 4 shows a complete list of the rotation tests.

In the case of the Phase I cantilever tests, the tests had to be stopped because of test frame limitations. Further connection tests are planned as seen in Table 4. These will be both monotonic and cyclic to observe the behavior of the connection to lateral loads from wind or an earthquake. In the case of a shear connection where large rotations might be expected, it may be better to remove the flutes and allow the mortise itself some flexibility and yielding for energy dissipation and ductility.

One final observation was made during the rotation experiments. This was the verification of a phenomenon which we have labelled *flexure lock*. The vertical RBM of the tenon due to shear can be significantly lessened by the unavoidable rotation of the tenon due to beam flexure. Instead of pushing straight through, this rotation causes a couple to occur acting on the back face of the mortise near the bottom and on the arms of the mortise near the top (for negative bending). These normal forces create additional friction forces to be overcome to allow vertical RBM. As can be seen in Figure 16, the greater the moment to shear ratio, the less the RBM.

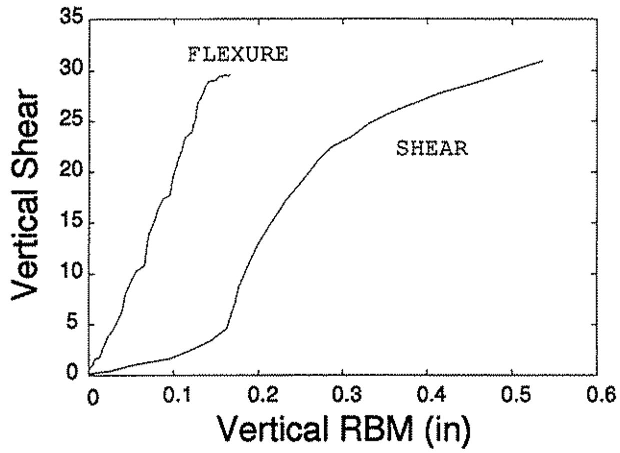

Figure 16. Flexure Lock.

ANALYSIS

The complexities of behavior mentioned at the beginning of the previous chapter which made experimentation essential also make analytical analyses involved and time-consuming. The approach taken in the analytical work has been consistent with the *response isolation* philosophy. The highly complex three-dimensional, compounded non-linear state of stress has been approximated as a 2-D planar problem by examining one loading situation at a time. Though the change is uniform and the shape remains the same, the cross-sections through the connection do vary in dimension. Also, the connection is not very deep with respect to its width, i.e. its aspect ratio is in the order of one. These two qualities make the choice between plane strain and plane stress analyses unclear. It has been the approach to use plane strain solutions of a typical interior cross section to assess the general behavior. Plane stress solutions of cross sections near the top and bottom are also examined in an attempt to bound the actual solution.

Finite Element Analyses

The finite element analyses were performed using ANSYS*, a general purpose finite element program. The analyses used elastic-plastic material properties, and non-linear contact surface elements. These elements are able to model two surfaces coming into and out of contact, and the normal and friction forces associated with the contact. The latest version of ANSYS, 5.0, has contact *surfaces* which allows the contact forces at a point in one body to move along the surface of the other body, modelling the second order nature of the contact problem. It is envisioned that this feature will greatly aid the analytical work in the near future.

Tension Analysis

While the experimentation program began with shear tests as an obvious starting point, there is a specific reason to start with tension in the planar analyses. The tension analyses involves a loading and response which occur in the plane. There are similarities between the planar tension analysis and the response in both shear and flexure. In the former case, a transformation from shear to horizontal force is required, in the latter varying levels of tension (including negative or compression) solution are stacked for behavior.

*Swanson Analysis Systems, Inc, Houston, PA.

The response of the tenon in tension is comprised of several components: elongation of the tenon web plates, shear deformation of the tenon body, and tenon horizontal RBM. This RBM in turn is comprised of several components: asperity flattening, cantilever beam deflection of the mortise arms, solid body contact deformation of the same, elongations of the same, and compressive straining of the tenon. A number of plane strain tension analyses have been performed to examine this behavior. Figure 17a shows the results using a slice from the lower region of the Phase II Connection geometry with no seat or flutes. As can be seen, a plastic hinge forms at the neck of the mortise arm due to the arm bending like a cantilever beam. In Figure 17b, the results are shown for a slice from the upper region, only this time with flute stiffeners added. In this case, the behavior is quite different. The flutes create a load carrying path to take the horizontal forces to the face of the column without resorting to cantilever bending stiffness. This causes the plastic deformation to occur as a shearing of the middle of the tenon slice. This creates a much stronger situation, although as explained previously, has little effect on stiffness (See Fig. 18).

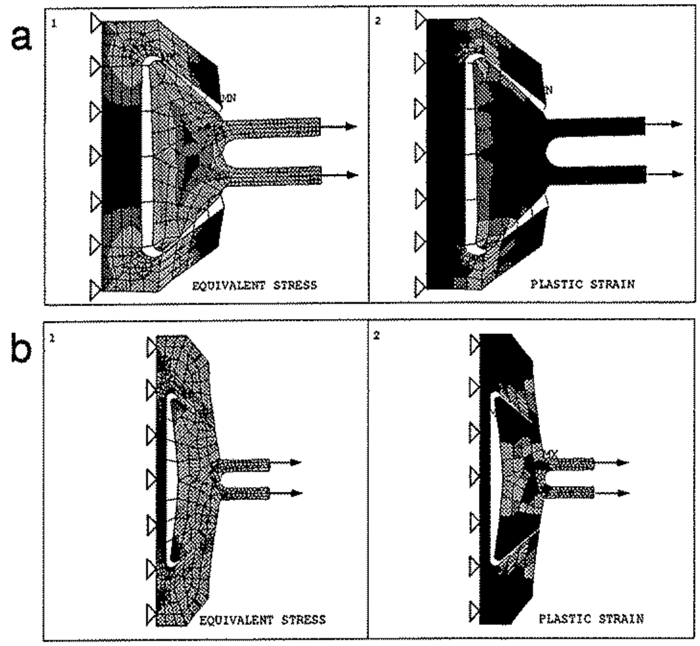

Figure 17. Plane Strain. a) Regular. b) Flutes.

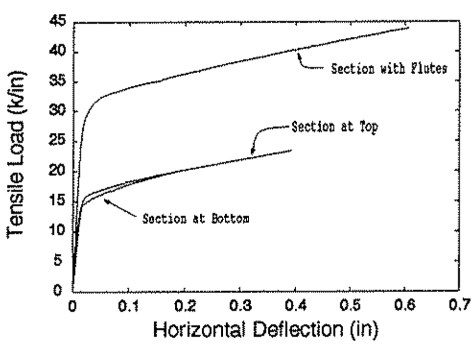

Figure 18. Tension Results, Analysis.

The effect of the weld location has a profound effect on the connection's response to tensile loading. In the previous figures, the plane strain analyses contained a boundary condition of a fully fixed back face. This is equivalent to the boundary conditions at the top and bottom face of the connection where the box weld wraps around the perimeter. More closer to the actual plane strain analysis of a typical inner cross-section is the case shown in Figure 19. As can be seen by the deformed shape, the back section of the mortise has the freedom to bend. Though an overall tension field exists, on each side tension-compression moment fields must be superimposed. The outer location of the box weld is in the high *compression* moment region. The high tension region is on the inside face of the mortise arm, and this is where a weld could be effective. Instead, the free deformations of the back section of the mortise tend to pry the weld off the surface.

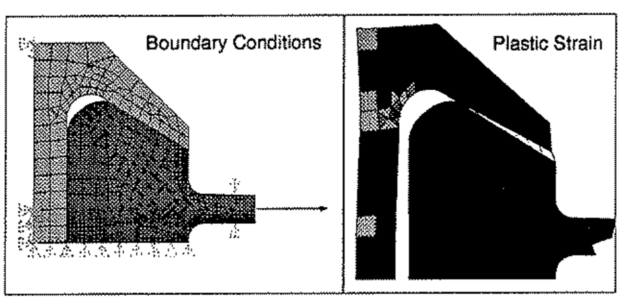

Figure 19. Analysis for Box Weld.

Shear Analyses

Answers to the shear behavior through planar analyses is not as straightforward as the tension analyses. However, both the tension and shear solutions involve high horizontal forces loading the arms of the mortise connector. The main difference is in the direction of the friction component, having a vertical component for shear loading.

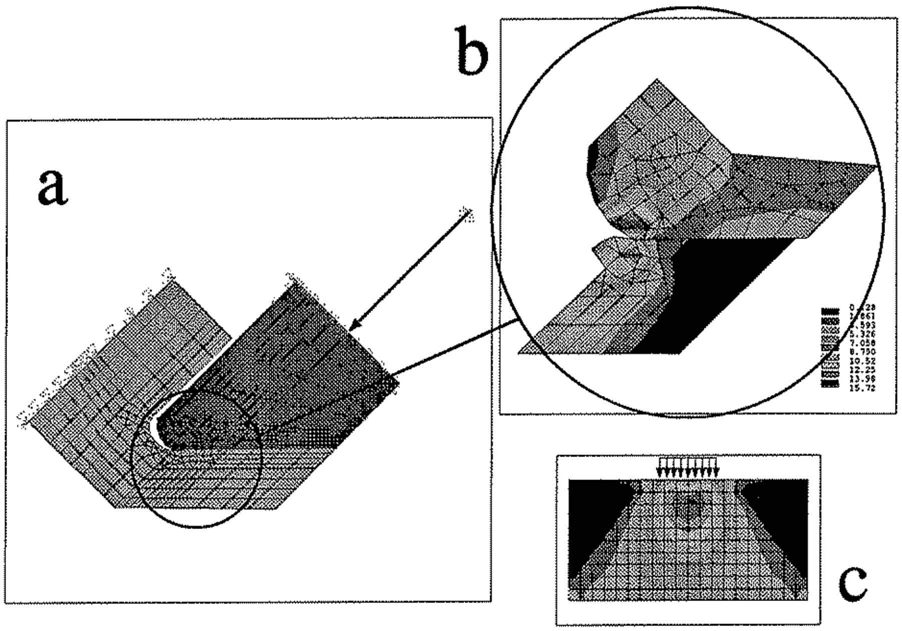

Figure 20. Plane Strain Shear Analysis. a) Model. b) Stress Intensity. c) Flamant Problem.

The method in which the shear loading could be modelled in a horizontal plane has been approached in a number of manners. Simply using the simple 2-D model and transforming the shear into horizontal contact forces, which can be applied directly to the mortise slice has been attempted. In another analysis, a temperature differential between the tenon slice and mortise slice was applied to expand the tenon and model the larger cross-sections of the tenon fitting into the smaller cross-sections of the mortise. The most successful analysis so far has been to use displacement control of the tenon in an outward direction, and allow it to come into contact with the mortise arms. Then the contact forces are obtained, and the corresponding applied vertical shear can be back-calculated. Figures 20a,b show results from such an analysis. Figure 20c shows the maximum stress results for a classical Hertz or Flamant problem [10] which pertain to loading(s) or contact of a body on semi-infinite elastic regions. In both bodies, the region of contact contains results similar to the classical solutions. This effect of solid body contact can be substantial depending on load, the mortise arm's section geometry, and the plastic strain state.

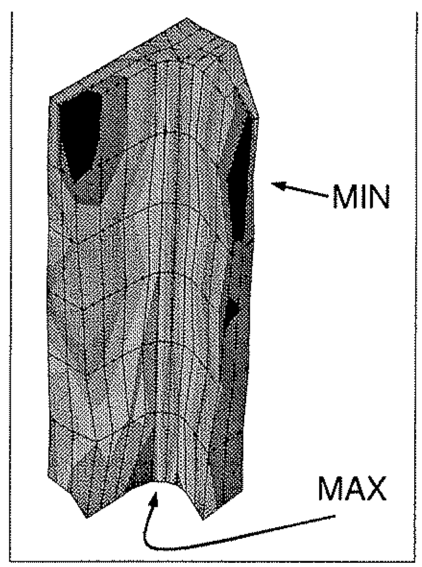

Figure 21. Full-depth Half-Symmetry.

A limited number of three-dimensional analyses have been performed on symmetry models of the connection. These analyses are very time intensive, but they are essential to provide a link between the extensive planar analyses and the actual 3-D experimentation. Also, in the experimentation, it is very difficult to make measurement at and around the contact surfaces, and this can be accomplished by the 3-D analyses. Figure 21 shows the maximum stress results from one of these analyses. The maximum stress locations for a slice are the same as in the planar analyses, but an idea of the vertical distribution is now obtained.

IMPLEMENTATION

Recently the AC was implemented in an actual building. The location was a low-elevation roof bay of a chemical plant. The dimensions of the bay were approximately 20' by 30'. The bay was designed to carry gravity load only. There are plans to possibly extend the bay upward, so removable connections would be advantageous. Since there were a large number of individual members in each bay, it was decided that the bay be pre-assembled on the ground using traditional connections, and then erected using an AC on each corner. Figure 22 shows a tenon connector at the end of a beam and a mortise guide mounted on a girder.

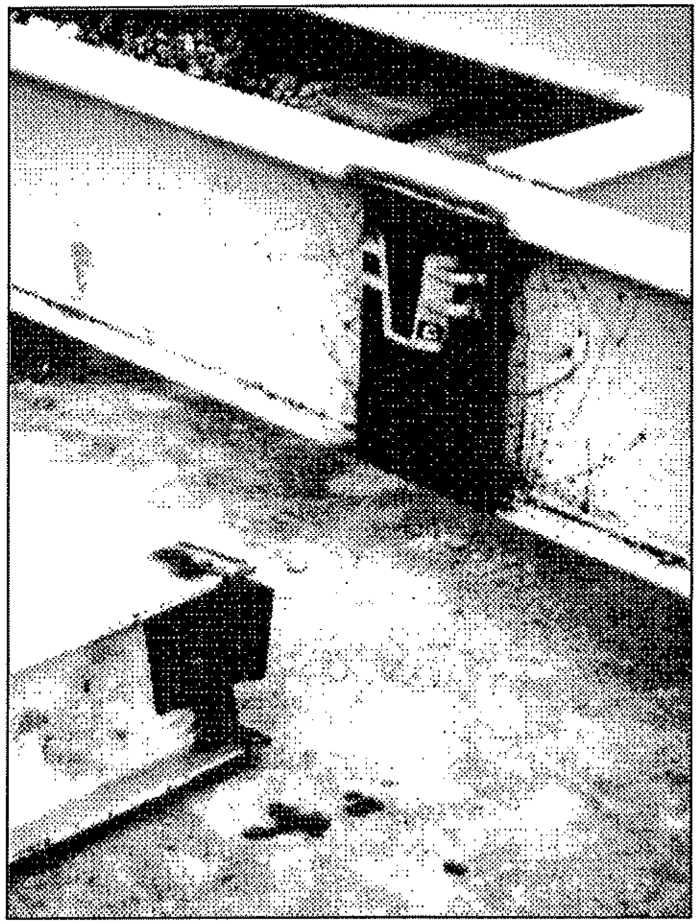

Figure 22. Members Prior to Erection.

The entire bay was hoisted and installed with a boom crane, two iron workers with guy wires , and a foreman. The assembly on the ground took 20 minutes, the attachment of the tenons to the corners of the bay took 5 minutes, and the lift took less than 2 minutes. Figure 23 shows a photograph of the large bay section being installed. After the large piece was placed, a three-point end piece was installed. This piece took approximately 1 minute to erect. Following successful erection, it took the iron workers 7 minutes to install the securing bolts.

The total time of erection for the bay was then 30 minutes. When compared with the more than one hour time to erect a similar bay in the adjacent span, a tremendous erection time savings was realized. This obviously has to be balanced with the extra fabrication costs, but it still is an overwhelming savings. Further implementation ventures are being sought.

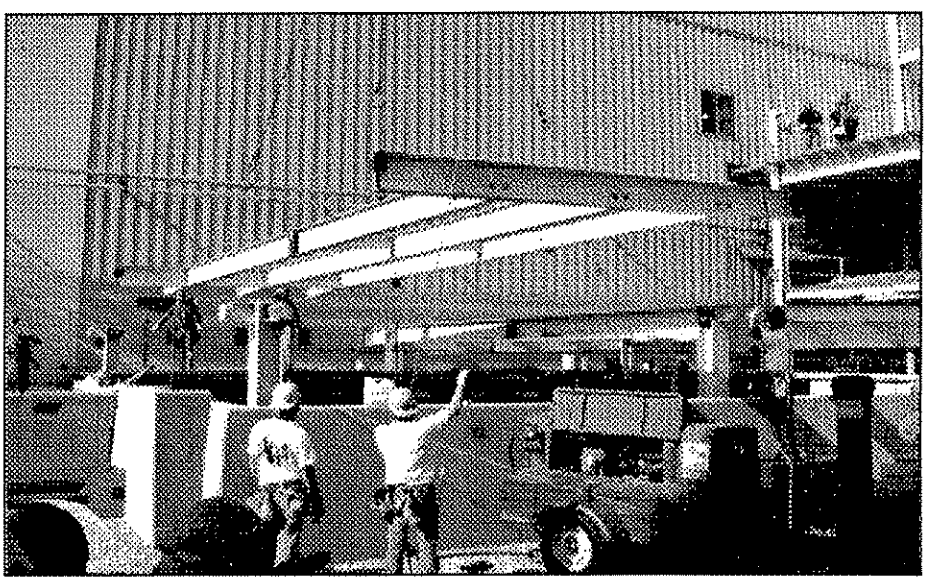

Figure 23. Bay During Erection.

CONTINUING AND FUTURE WORK

Currently there is an effort underway to examine the 3-D AC in a number of building situations: as a moment connection, as a composite partial-moment connection, and as a component in a tubular system.

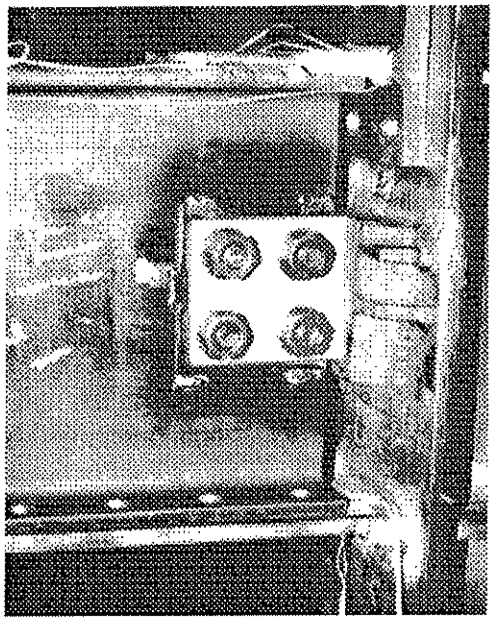

Figure 24. ATLSS Full Moment Connection.

The work on the full moment connection involves an emphasis on shop welded-field bolted construction. The connection is a tenon shop-attached to the beam web, along with a tee shop-attached to the top flange. The mortise and a bottom flange plate are shop-attached to the column (See Fig. 24). Finite element models of the configuration were developed. The experimental program consisted of setting the individual tolerances to allow fit-up, alignment and final tightening. Loading parameters were both monotonic and cyclic. The joints displayed increased stiffness and moment capacity over conventional counterparts [11]

An innovative use of the keystone is to incorporate it in a relatively new type of construction, semi-rigid composite. This design technique utilizes a concrete floor slab and its reinforcing to transfer gravity and wind moments to the supporting columns. By lowering the position of the AC along the beam web to a point near the lower flange, a semi-rigid composite joint is created (See Figure 25). Research on this connection is also ongoing at the ATLSS Center. Linear finite element analyses have been performed, along with three pilot tests. These tests used a top steel plate to simulate the composite action, thus providing a simple and quick way to determine the efficiency of moment transfer on the beam web, as opposed to the customary lower flange location. Results indicate that this type of joint can provide adequate resistance to lateral loads on unbraced frames in low seismic regions for low-rise structures. Actual composite cruciform tests will be underway in early 1993 [12].

Finally, research will also extend into the use of tubular members, which may be better suited for use with the AC. Tubular columns have proven to be cost-efficient and practical in the past. Tubular sections have the unique geometric advantage that allows the AC to be welded directly without much prior preparation. The tubes also eliminate the vertical clearance problem posed in beam-to-girder ACs and multi-tier weak axis beam-to-column AC.

In the future, an ATLSS end plate connection is slated for development (See Fig. 26), the AC will undergo at least one more prototype phase, and frame test will commence. It is the further goal of the project to design, erect and test a three-dimensional structure using an assortment of ACs in the ATLSS Center's multi-directional testing facility.

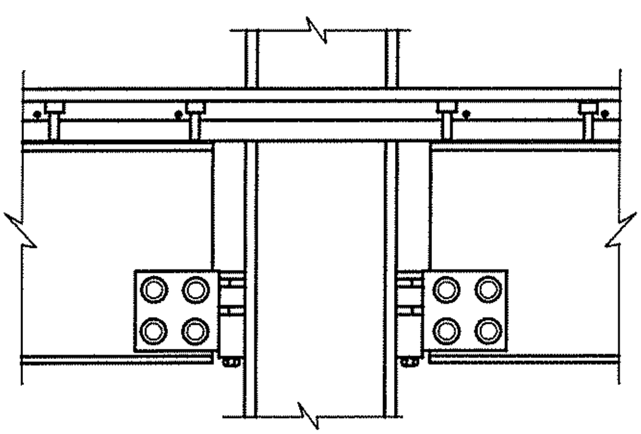

Figure 25. ATLSS Partial-Moment Connection

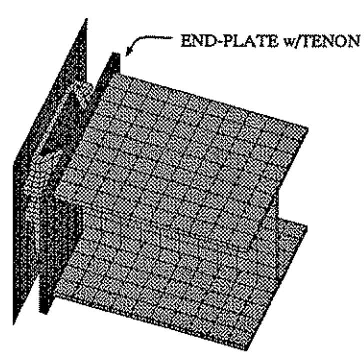

Figure 26. ATLSS End-Plate Connection.

ACKNOWLEDGEMENTS

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Table 1. Comparison of Phase I and Phase II Prototypes

ATTRIBUTE	PHASE I	PHASE II
Vertical Taper Slope, cot θ	12:1	6:1
Return Angle, Φ (deg)	30	45
Maximum width, w (in)	3.33	5.38
Maximum Thickness, t (in)	1.27	1.38
Tenon Depth, d (in)	4	4.25
Web Plate Thickness, t_p (in)	.25 tapering to .125	.22
Tenon Aspect Ratio (b/a)	2	3
Yield Strength, σ_y (ksi)	39.4	64.6
Ultimate Elongation, e_u (%)	32.3	22.4
Flute Stiffeners	Added Later	2 per arm, near top
Mortise Seat	Added Later	3/8" thick, 3/16" gap
Seating Screw	None	1/2" A325

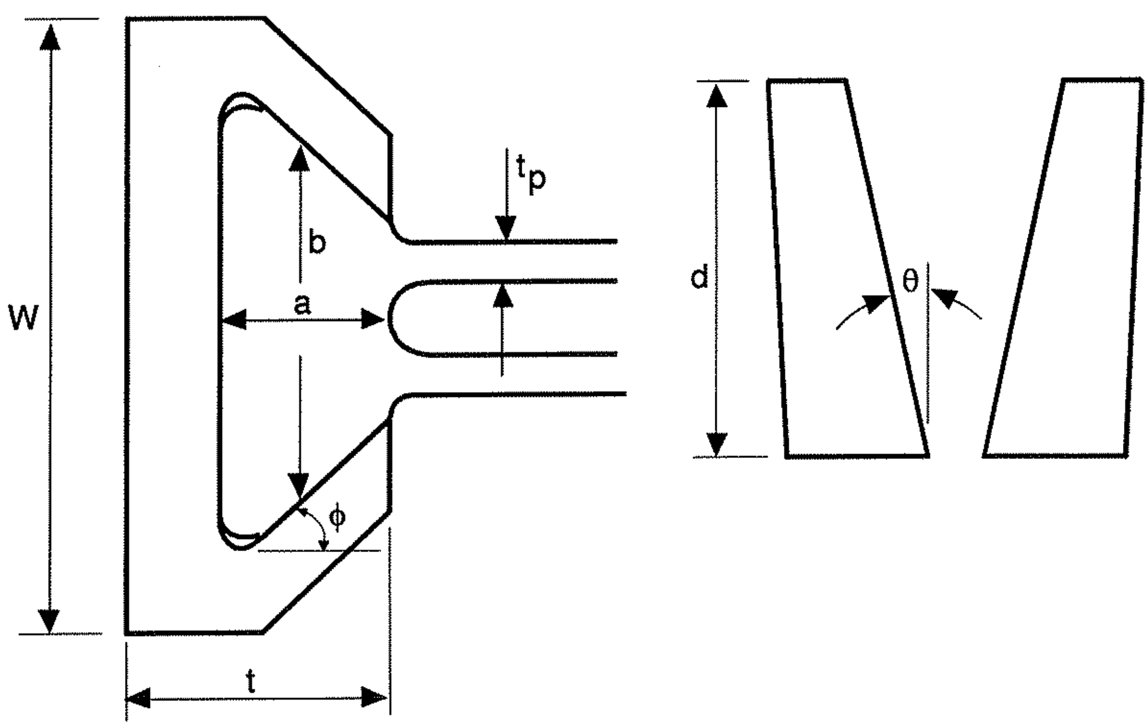

Table 2. ATLSS Connection Shear Experiments

TEST	Despcription	V_u (k)	$\Delta_{seating}$ (in)	K_{RBM} (k/in)	Δ_{RBM} (in)	Failure Mode
ACSHR	Phase I, pure	40.0	0.145	115.4	2.16	Push Through
ACSHRm	PhI, machine surfaces	56.7	0	110.0	1.80	Push Through
ACSHRf	PhI, flute stiffeners	71.6	0.125	714.3	0.88	Beam Web e.d. tear
ACSHRfm	PhI, flutes, machined	58.4	0	100.0	1.37	Push Through
ACSHRs	PhI, mortise seat	78.1	0.175	555.6	0.26	Bm Web Net Section
ACSHRsf	PhI, seat, flutes	73.5	0.105	931.0	0.22	Bm Web Net Section
ACSHRII	Phase II, pure	91.5	0.010	282.6	0.45	Web Plate Net Sect.

V_u = maximum shear; $\Delta_{seating}$ = seating RBM deflection; K_{RBM} = Working Range Stiffness.
Under test names: m = machined surfaces; f = flute stiffeners; s = seat, II = Phase 2.

Table 3. ATLSS Connection Tension Experiments

TEST	Description	T_u (k)	K_{AX} (k/in)	Failure Mode
ACTNS	Phase II, pure - retrofit with slot weld	37.0 82.2	- 393	Box Weld Failure Crack in top weld spread across arm section
ACTNSf	PhII, flute stiffeners	56.7	405	Crack in top weld spread around perimiter
ACTNSs	PhII, mortise seat	71.6	427	Crack in top weld spread along inner radius
ACTNSI	Phase I, pure	58.4	352	Pull Through
ACTNSss	Ph II, seat, screw	-	-	To be tested 1/93
ACTNSa	Ph II, flute, seat, screw	-	-	To be tested 1/93

T_u = maximum tension; K_{AX} = Working Range Stiffness.
Under test names: f = flute stiffeners; s = seat, ss = seat & screw; a = all features; I = Phase 1.

Table 4. ATLSS Connection Rotation Experiments

TEST	Description	Load Info.	$\%M_p$	Φ_U (rad)	Failure Mode
ACROT1	Phase I, pure	Frame, Mono.	11.7	0.031	Plastic Hinge, Mid-Span
ACROT2	Phase I, pure	Cant., Mono.	7.7	0.257	Actuator Stroke Limit
ACROT3	Phase I, pure	Cant., Mono.	8.4	0.245	Actuator Stroke Limit
ACROT4	Phase I, flutes	Cant., Mono.	15.3	0.286	Net Section, Web Plates
ACROT5	Phase II, pure	Cant., Mono.	15.8	0.197	Net Section, Web Plates
ACROT6	PhII, seat, screw	Cant., Cyclic	-	-	To be tested, 2/93
ACROT7	PhII, fl., seat, screw	Cant., Cyclic	-	-	To be tested 2/93
ACROT8	PhII, flutes, seat	Cant., Cyclic	-	-	To be tested 3/93