Automation and Robotics in Construction X
G.H. Watson, R.L. Tucker and J.K. Walters (Editors)

AUTOMATED CONSTRUCTION IN THE ATLSS INTEGRATED BUILDING SYSTEMS

B. Vincent Viscomi, Research Professor
William D. Michalerya, Manager of Industry Liaison and Technology Transfer
Le-Wu Lu, Professor of Civil Engineering

NSF Center for Advanced Technology for Large Structural Systems (ATLSS)
Lehigh University, Bethlehem, PA 18015 USA

ABSTRACT

The AIBS (ATLSS Integrated Building Systems) program was developed to coordinate ongoing research projects in automated construction and connections systems. 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. A family of structural systems, called ATLSS connections, are being developed with enhanced fabrication and erection characteristics. These ATLSS connections possess the capability of being erected by automated construction techniques. This feature minimizes human assistance during construction and will result in quicker, less expensive erection procedures in which workers are less susceptible to injury or fatalities. The technology for automated construction is heavily dependent on the use of Stewart platform cranes which are controlled by a system of six cables to allow precise movement in six directions. A scale-model Stewart platform crane has been constructed in the ATLSS laboratory to test the feasibility and limitations of automated construction with these connections.

INTRODUCTION

A comprehensive research program in automated construction is underway at the National Science Foundation-sponsored Center for Advanced Technology for Large Structural Systems (ATLSS) at Lehigh University. The broad objective of the "ATLSS Integrated Building Systems (AIBS)" project is to develop connections and structural systems that are economical in terms of overall construction costs, easier to erect, are effective in resisting gravity and lateral loads together with the development of automated systems (see Figure 1) [1].

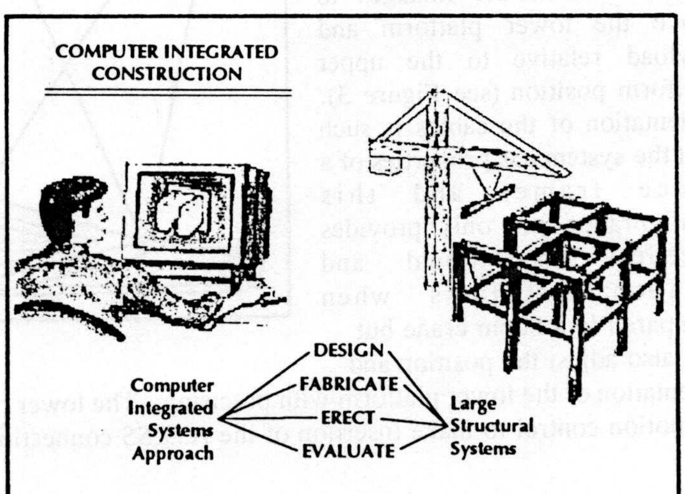

Figure 1

Connections are an expensive part of structural systems and are typically the location of potential structural distress and failure. A series of new beam-to-column connections, known as ATLSS connections, 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 should result in quicker, safer and less expensive erection procedures. The concept is based on using a tapered solid "tenon" piece on the beam which slips into a three-dimensional "mortice" guide mounted on the column (see Figure 2). The analytical analysis of this connection is being performed using finite element procedures. Experimentation, conducted concurrently with the theoretical work, has been performed by isolating the various loadings the connection would experience. This connection concept can cover a large range of structural needs, including shear, partial- and full-moment connections.

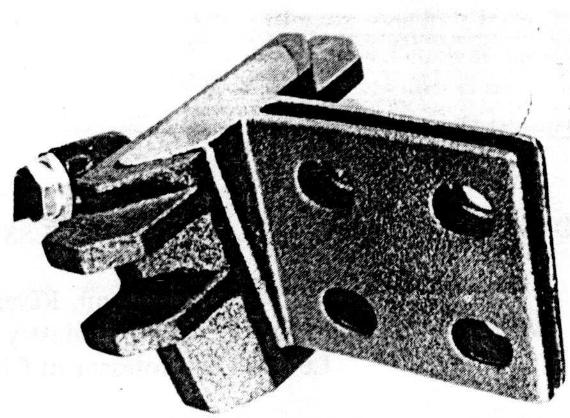

Figure 2

The technology for automated construction at the ATLSS Center is heavily dependent on the use of Stewart platform cranes. The Stewart Platform is actually two platforms connected by a series of six individually controlled linkages. At the ATLSS Center it has been designed and assembled with six cables used as the linkages to move the lower platform and payload relative to the upper platform position (see Figure 3). Orientation of the cables is such that the system has properties of a space frame, and this configuration not only provides excellent translational and rotational stiffness when compared to a boom crane but can also adjust the position and orientation of the lower platform with precision. The lower platform can move with six degrees-of-motion control to make insertion of the ATLSS connections possible.

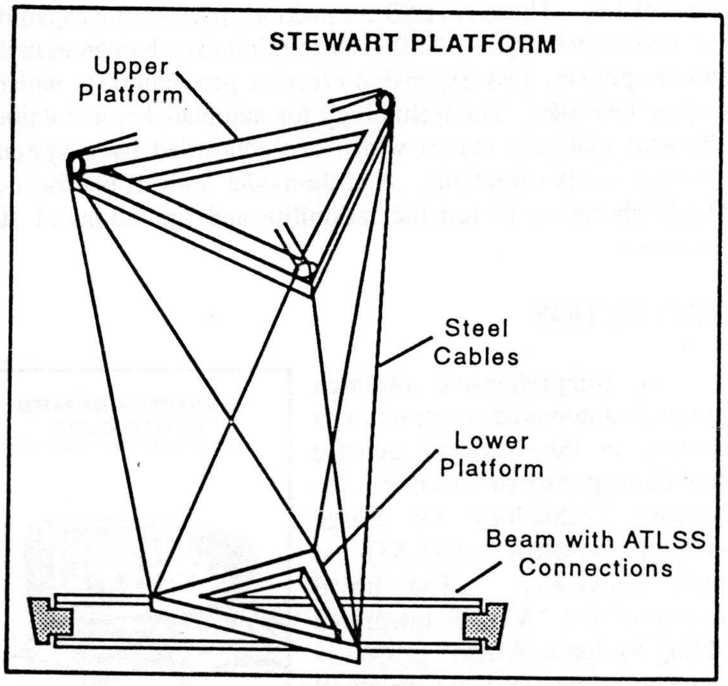

Figure 3

BUILDING CONSTRUCTION

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. In recent years, the total volume of construction awards has been declining. Moreover, the U.S. share of the market has shown a significant decrease. 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. Another goal of the AIBS team, by concentrating on the design of alternative connection methods, is to reduce construction costs to a minimum while maintaining or improving the quality of the constructed project.

The frames of steel structures are constructed in two basic steps: fabrication of structural steel members within the fabricating shop and erection of these members at the construction site. The fabrication of the structural members involves such operations as surface preparation, cutting, drilling, machining, assembly and painting. These operations are usually performed in an industrial shop environment by heavy equipment. The layout of the equipment is such as to facilitate the flow of material and information on the shop floor and will often incorporate up-to-date computerized operations. On the other hand, site erection requires the use of light equipment and labor which are constantly moved and repositioned in various parts of the structure, stipulating a product oriented layout.

In reality, the procedure for erecting building structures has changed very little over the past seventy five years. Field work requires workers to perform complicated and strenuous tasks in a highly dangerous environment. Workers are often required to position themselves at great heights, in difficult positions, and then must guide and secure structural members that typically weigh many times more than they do (see Figure 4). In most cases, a construction crane is involved and it is not unusual for the above described activities to take place out of the crane operator's sight.

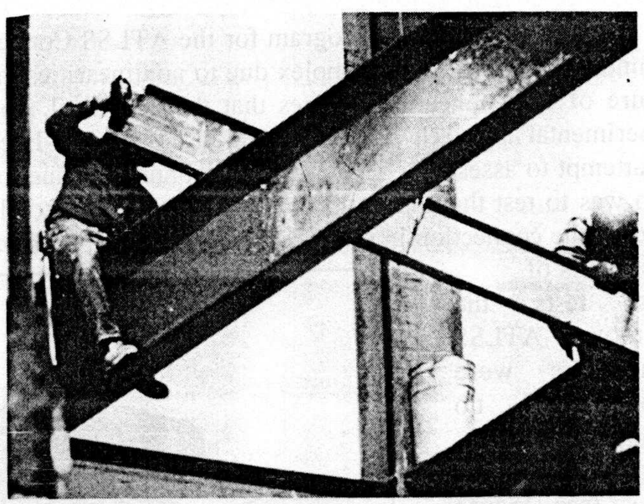

Figure 4

Thus, it is not surprising that, in the United States alone, between one and two thousand fatalities occur each year. During a five year period, the largest causes were due to falling from an elevation (33%) and from being struck by falling objects (22%). When the statistical pool is limited to building erection, the percentage of fatalities from falling climbs to 43%. It should be clear to the reader that a primary focus of the AIBS concept is to address this issue.

ATLSS CONNECTION

The ATLSS Connection concept is based on using an ATLSS Connector, comprised of a tapered tenon piece on the beam which slips into a mortise guide mounted on the column. The final ATLSS Connector configuration developed into a three-dimensional, conical solid tenon piece, and a three-dimensional mortise piece containing a conical cavity complementary to the tenon piece. To be useful for automated construction, both pieces must be attached to their respective members in the shop or on the ground at the site. The ultimate goal is to have a limited assortment of mass-produced connectors with a standard shop fitting operation and quick, automatic erection capabilities [2].

The development of the ATLSS Connection involved the evaluation of a number of self-aligning, self-securing connection ideas. These ideas were conceived and evaluated by a team of ATLSS engineers and an industry panel, who exchanged ideas on structural and erection performance. 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.

Manufacturing options were considered next. Some trial finite-element analyses were performed on a typical mortise to examine the possibility of fabricating the pieces out of steel plate. However, cast steel was determined as the cost-effective solution for this stage of development. It was realized that cast steel does not have universal industry acceptance and there would have to be continued attempts to improve the manufacture of the connection. Stamping and cold-forming have been acknowledged as possibilities.

The experimental program for the ATLSS Connection has been extensive. The ATLSS Connection's behavior is complex due to nonlinearities in geometry and material. The complex nature of the connection dictates that the analytical models be verified experimentally. The experimental approach 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 mode. From the results of these tests, the prototype ATLSS connectors were modified to included a seat, seating bolt, and flutes (see Figure 5). The seat and bolt were added to provide a physical connection between the tenon and mortise whereas the flutes were added for tension/flexural resistance.

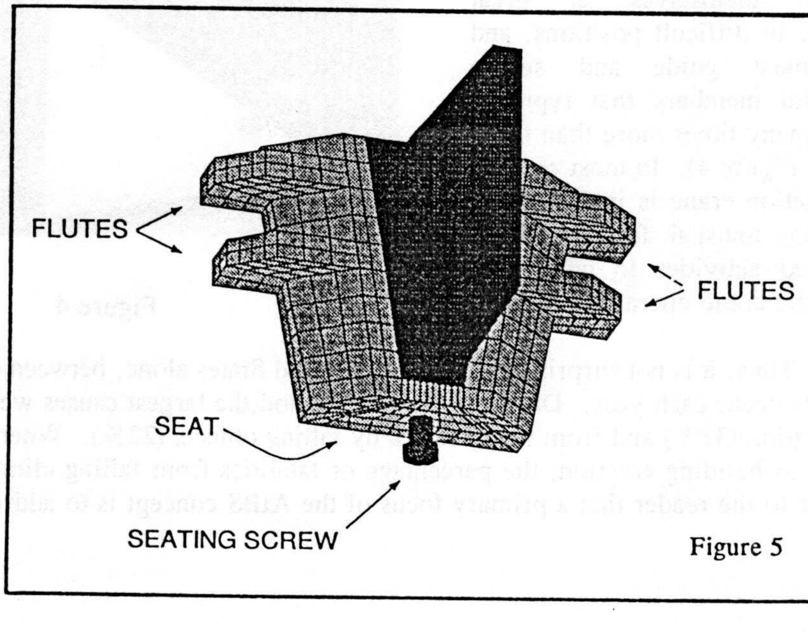

Figure 5

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. A representative analytical solution is shown in Figure 6.

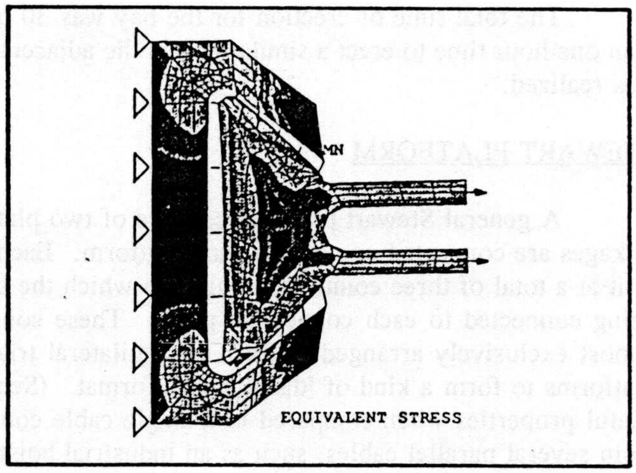

Figure 6

Given the objective of AIBS to provide cost-effective building systems, the ATLSS connector should be a modular connector, capable of multiple structural capabilities. Thus, the research program has been designed to examine the connector in a number of building situations: as a shear connection, as a composite partial-moment connection, as a full-moment connection and as a component in a tubular system. Research is ongoing in these areas and a future goal of AIBS is to design and test a three-dimensional structure using these connections in the ATLSS Center's multidirectional testing facility.

Recently, the ATLSS Connection was implemented in an actual building. The application was a low-elevation roof bay of a industrial plant. The dimensions of the bay were approximately 20' by 30'. The bay was designed to carry gravity load only. There were 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 ATLSS Connector on each corner.

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 4 minutes. Figure 7 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.

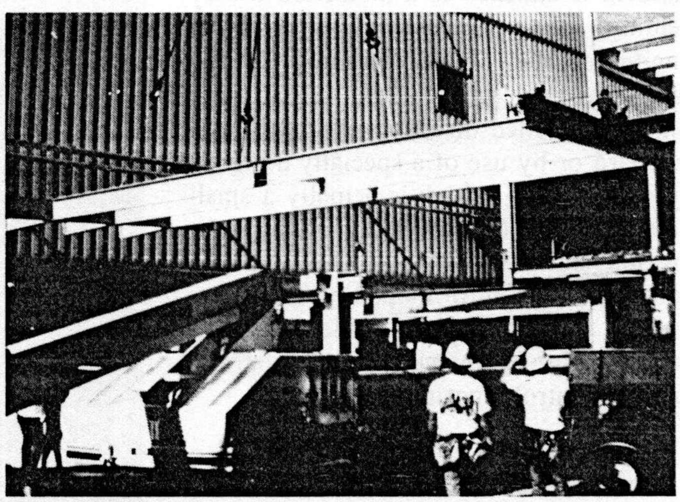
Figure 7

The total time of erection for the bay was 30 minutes. When compared with the more than one hour time to erect a similar bay in the adjacent span, a significant erection time savings was realized.

STEWART PLATFORM

A general Stewart platform consists of two platforms and six linkages. Each of the six linkages are connected one end to each platform. Each platform has the six linkages connected to it at a total of three connection points to which the six linkages are connected - two linkages being connected to each connection point. These connection points are non-colinear, and are almost exclusively arranged to form an equilateral triangle. The linkages are connected to the platforms to form a kind of 'daisy chain' format. (See Figure 3.) This arrangement has many useful properties when compared to a single cable construction site crane or a hook suspended from several parallel cables, such as an industrial hoist. These are:

a) lateral stability - allows the Stewart platform the ability to apply lateral force where required.
b) rotational stability - allows the Stewart platform to control the angle in the plane perpendicular to the direction of gravity of the lower platform - thus affording precise positioning and orientation abilities.
c) positioning capabilities - with control of the linkage lengths the Stewart platform is provided with limited positioning and orientationing capabilities of the lower platform with respect to the top platform. These limited capabilities are referred to as fine motion control and are useful as fine adjustments of the position and orientation of the lower platform.

A scale-model Stewart platform crane, shown in Figure 8, has been constructed at the ATLSS research facility [4]. Six servoelectric motors are used to control the cable lengths and to lift a design payload of up to 2 KN. The upper platform is attached to a motorized trolley yielding a work volume of a 4 m longitudinal run, a 4 m lift and a 1 -2 m of transverse movement. The ACES crane can be controlled directly at the computer keyboard or by use of a specially designed joystick. This joystick is actually a small scale Stewart platform which outputs the position and orientation as the command signal for the control loop. Force sensors, attached to each platform cable, are being used within cable slack and platform stability control algorithms.

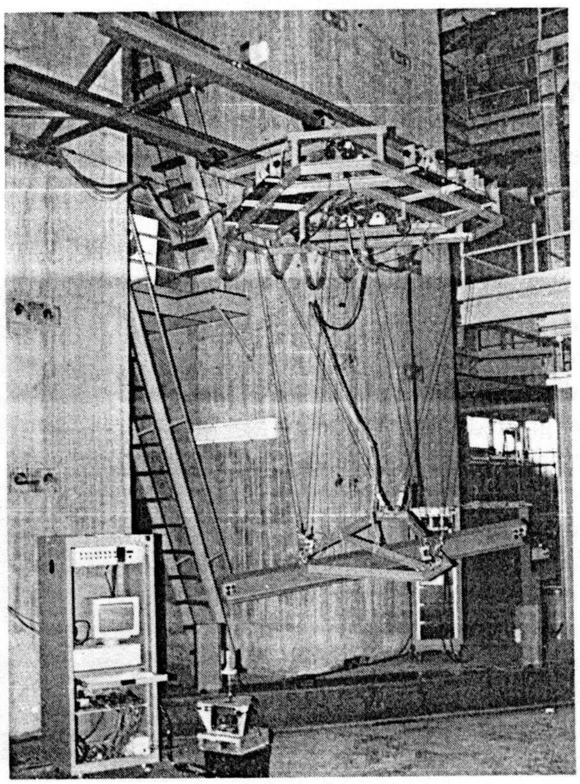

Figure 8

Planned future activities include research in the sensor fusion area and the development of a vision system as illustrated in Figure 9. Automatic operation then becomes possible by integrating the vision system into the manual operation control loop. The installation of a vision system will not also permit the development of an automated crane erection system but also will assist with on-site material storage and inventory management.

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.

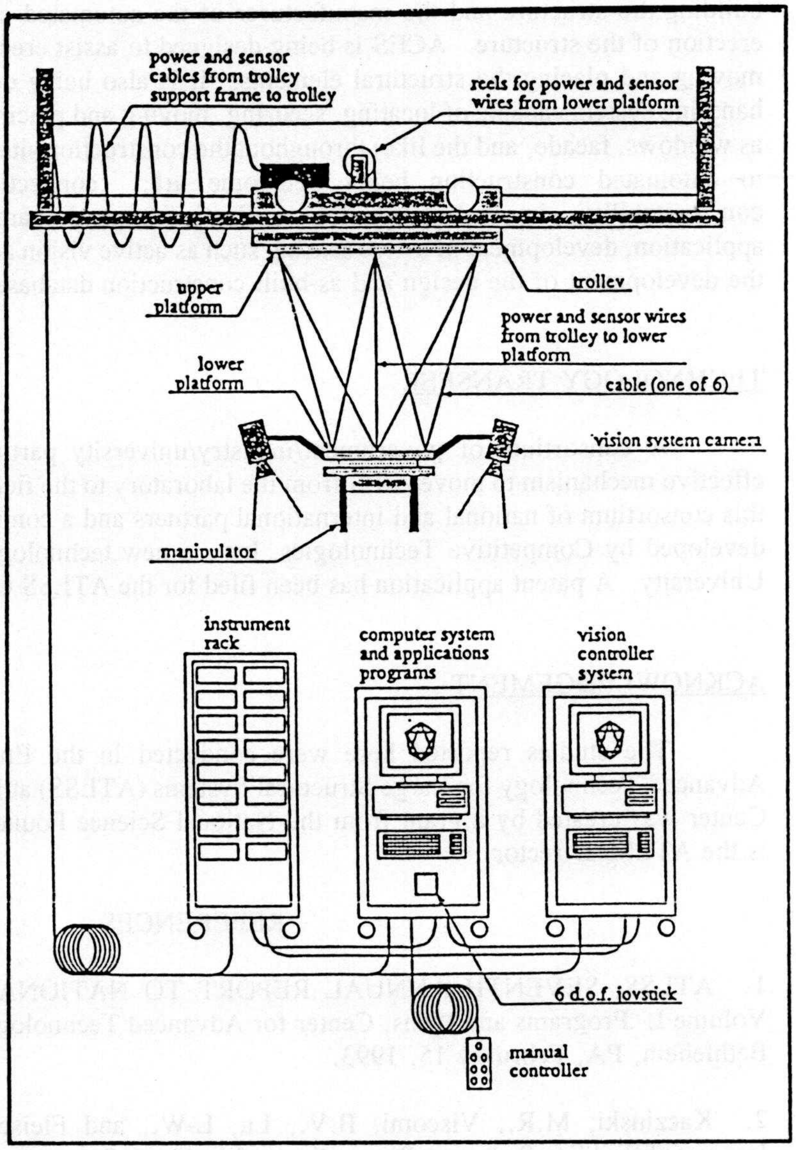

Figure 9

ATLSS is engaged in a collaborative research effort with the National Institute of Standards and Technology (NIST) combining the ATLSS Connection and Automated Crane Erection System (ACES) activities with the automated crane developments at the NIST Robot Systems Division. Both the ACES system and the NIST ROBOCRANE are based on the Stewart platform.

ANTICIPATED OUTCOMES

The end users of the AIBS technology will be design and 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 overcome 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.

TECHNOLOGY TRANSFER

A consortium of government/industry/university partners is envisioned as the most effective mechanism to move AIBS from the laboratory to the field. Currently ATLSS is forming this consortium of national and international partners and a commercialization strategy has been developed by Competitive Technologies, Inc., a new technology transfer subsidiary of Lehigh University. A patent application has been filed for the ATLSS Connection, and is nearing issue.

ACKNOWLEDGEMENT

The studies reported here were conducted in the Engineering Research Center for Advanced Technology for Large Structural Systems (ATLSS) at Lehigh University. The ATLSS Center was created by a grant from the National Science Foundation, and Dr. John W. Fisher is the ATLSS Director.

REFERENCES

1. ATLSS, SEVENTH ANNUAL REPORT TO NATIONAL SCIENCE FOUNDATION, Volume I: Programs and Plans, Center for Advanced Technology for Large Structural Systems, Bethlehem, PA, February 15, 1993.

2. Kaczinski, M.R., Viscomi, B.V., Lu, L-W., and Fleischman, R.B., An Approach to Integrated Building Systems. Proceedings of the Tenth Structures Congress, ASCE, San Antonio, TX, April 1992.

3. Fleischman, R.B., Viscomi, B.V., and Lu, L.W., Development, Analysis, Experimentation and Implementation of ATLSS Connection for Automated Construction, Proceedings of the National Steel Construction Conference, AISC, Orlando, FL, March, 1993.

4. Viscomi, B.V. and Perreira, N.D., An Automated Construction Erection System, Proceedings of the 9th International Symposium on Automation and Robotics in Construction, Tokyo, Japan, June 1992.