ATLSS

LEHIGH
University

FINAL REPORT
TO THE
NATIONAL SCIENCE FOUNDATION

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Director
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on Advanced Technology for Large Structural Systems

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ABSTRACT

The Center for Advanced Technology for Large Structural Systems (**ATLSS**) at Lehigh University was established in May, 1986, as one of the national Engineering Research Centers (ERCs) created by the National Science Foundation (NSF). NSF sponsorship of the Center continued through December 1997. This report reviews the achievements attained by ATLSS in its cross-disciplinary research, education, and industry collaboration programs; programs aimed at benefitting constituents of the bridge, building, offshore structure, and ship structure industries.

Major achievements towards high-performance materials, structural design and performance, and structural serviceability criteria are highlighted, as are six new ATLSS technologies that are moving to commercial practice. Also highlighted are the specific successes that occurred in the education program and the major collaborations that were developed with industry and government, and the Center's impact on Lehigh University. A brief description of the ATLSS Multidirectional Experimental Laboratory is included, because this renowned facility is the physical cornerstone of the ATLSS Center and the heart of its research on large structural systems.

The report concludes with a look forward and description of how ATLSS is implementing its strategy to be a self-sustaining Center and how the continuing ATLSS may differ from an NSF ERC. Lessons learned are also cited.

EXECUTIVE SUMMARY

The Center for Advanced Technology for Large Structural Systems (**ATLSS**) at Lehigh University was established in May, 1986, as one of the national Engineering Research Centers (ERCs) created by the National Science Foundation (NSF). NSF sponsorship of the Center continued through December 1997. ATLSS met all major goals of its original proposal and, throughout its operation, successfully focused resources, research energies, and cross-disciplinary educational efforts towards developing new knowledge, methodologies, and products for the constituents of the large-structures industry: designers, producers, fabricators, inspectors, and owners of bridges, buildings, ships, and offshore structures. ATLSS research achieved new higher levels of technology in high performance materials, structural design and performance and structural serviceability criteria.

Working with steel producers, we developed the compositions and the heat treatments needed to produce high-performance steels in this country, and we developed parameters that enable these steels to be fabricated economically without or with minimal pre- and post-heating and with undermatching as well as matching-strength weld metal. Working with designers and users, we developed innovative designs for structures that enable full utilization of the high-performance characteristics of these materials. Working with other producers and users, we demonstrated the suitability of advanced, high-performance fiber composite materials both as strength enhancing materials when used with concrete and steel, and when used independently in structures.

ATLSS expanded the knowledge on models and methodologies for structural connections, both in steel and precast concrete. The Center developed and patented a new ATLSS Connector design, which facilitates field erection of steel frames, had prototypes installed in industrial buildings at two sites nationally, and sold prototypes to industry in Australia. We conducted an international workshop on structural connections. In the aftermath of the 1994 Northridge earthquake, the Center became the national focal point for the evaluation of new and retrofit designs of beam-to-column connections for welded steel moment-resisting frames (SMRF) and for the evaluation of welding procedures for SMRF. Our study of high-performance materials has carried over into the evaluation of new connections for SMRF where a steel tubular column is filled with high-strength high-performance concrete. Another study led to a design for a bolted retrofit design that ATLSS licenses to industry.

We completed the fundamental research into replacing the conventional surface ship-hull design with an innovative unidirectional double-hull design. Double hulls can provide greater survivability and affordability for surface combatants, and greater protection against penetration and spills for commercial tankers. We affirmed this new concept through extensive theoretical and experimental studies into double-hull design, materials, fabrication and manufacturing systems, and serviceability, and presented the outcomes at an ATLSS-coordinated, national technical symposium on advanced double-hulls. Double hull construction should be standard by year 2010.

Our studies of structural serviceability criteria resulted in new design guidelines, new software tools for bridge inspection, new monitoring systems, and potential new repair procedures. We developed new fatigue design guidelines for welded aluminum beams, and riveted and welded steel girders. We developed a new intelligent fatigue-cycle counting chip that combines fatigue data collection and analysis into one simple, interrogatable unit for laboratory and field use. We developed and patented a "Smart Paint" for fatigue crack detection. We developed a software system for bridge engineers to use in inspecting for fatigue and produced it in multimedia to facilitate training. We developed and patented a corrosion monitor to track in-situ the corrosion of bridges and other structures or to measure the corrosivity of a site, which aids in material selection. We have worked with industry to develop repair procedures for deteriorated offshore platform members.

Our industry and government collaborations were strong. General partners, project partners, and project advisors numbered about 70, with an additional approximately 200 commercial clients. Our partners included several trade associations, whose member companies represent additional participants. Through collaborations with the Civil Engineering Research Foundation (CERF) and the Construction Industry Institute (CII), we interacted with many other companies. Our collaborations with government agencies included FHWA and Coast Guard (in DoT), MMS (in DoI), NIST (in DoC), Navy and Corps of Engineers (in DoD) and the Ship Structures Committee. Technology transfer to practicing engineers was a key element in our collaborative efforts. We conducted four national symposia and workshops; developed 21 short courses which were presented at industry sites, by satellite, and at Lehigh; and hosted numerous meetings of national and international technical and professional groups. The impact of our collaborations is demonstrated by the fact that as ATLSS' annual revenues from NSF rose from a startup level of $1.4M to a high of $2.8, the Center's annual revenues from all sources rose from a startup level of $1.85M to a high of $7.0M — a strong positive indication that NSF revenues were well leveraged.

In our educational program, we supported 195 graduate students, including 29 women, who have received 39 PhD and 115 MS degrees. Thirty-one students are progressing towards a degree. In addition, 224 undergraduate students participated in ATLSS research through REU and other programs, with 130 women included. Eleven percent of all the students have been African-American and Hispanic students. Fourteen academic disciplines were represented. Educational outreach through REU and minority-institution programs included 25 other colleges and universities. Fifty percent of our graduate students found employment in firms representing the structures and materials industries. Lehigh contributed strongly to our mission. It hired eight new faculty to conduct and guide research in ATLSS. It provided 70 graduate fellowships and 48 tuition scholarships to support cross-disciplinary students. It provided facilities and infrastructure for ATLSS valued at about $18M. A total of forty-five Lehigh faculty participated in ATLSS. In return, these faculty contributed by developing new and modified academic courses which introduce ATLSS research findings, by developing new collaborations, and by scholarly papers and presentations.

The ATLSS Center is continuing. With the Commonwealth of Pennsylvania and Carnegie-Mellon University, we formed a Pennsylvania Infrastructure Technology Alliance (PITA) in 1997 to address the state's infrastructure research needs. With its industry advisory board, the alliance is a true commonwealth-university-industry partnership. We have a Memorandum of Understanding with the U.S. Navy to be a primary university for research for ship structures. We are part of two university consortia addressing the technology needs of the Pennsylvania Department of Transportation. And, we are pro-actively seeking to become a national Center for Advanced Bridge Systems.

The ATLSS Center has become an outstanding representative of the industry it serves. Its facilities for experimentation and the expertise of its researchers are known nationally and internationally. Its faculty and staff provide counsel influencing the research agenda of the major U.S. construction and civil engineering research councils, and of major trade organizations. ATLSS is a critical component of Lehigh University, whose highest research priority - Materials and Structures - underlies the Center's research emphasis and strength. ATLSS is now a premier university partner with industry and government in addressing the research needs of the large structures industries.

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I. INTRODUCTION

In this final report to the National Science Foundation (NSF) by the Center for Advanced Technology for Large Structural Systems (ATLSS) at Lehigh University, a review of the Center's achievements from 1986 through 1997 is presented in *Sections II through X,* followed by a look to the future *Section XI* and a list of lessons learned, *Section XII.* In the review, the Center's perspectives relative to the state-of-the-art of large structural systems are presented; along with ATLSS' major research accomplishments, new technologies, and infrastructure; its impact on large-structures engineering; its accomplishments in education; its successes with industry and other government agencies; and its impact on Lehigh University. The look ahead describes how the continuing vision for the ATLSS Center is being implemented.

The ATLSS Center was established on May 1, 1986 by a grant from the prestigious NSF Engineering Research Centers (ERC) program . Funding from NSF was sustained annually [at levels varying from $1.4M (initial year) to $2.7M (years 7, 8, and 9)] for eleven years through April 30, 1997. NSF continued its sponsorship of the Center through December 31, 1997, but without additional funding.

II. PERSPECTIVES: 1986 THROUGH 1997

In Technology

> "Structures of highly efficient design will be fabricated of modular components made of composites of steel, concrete and many other materials. Design considerations will include ease of fabrication and construction. Provisions for monitoring and inspection will be built into a new structure. Automation and robotics will speed up many labor intensive processes. Life cycle cost, not first cost, will govern material selection. Computer design and control will be pervasive. Knowledge-based expert systems will assist in the design of both structures and details. Computers will facilitate rapid redesign, guide materials selection and fabrication, schedule erection sequences, and route the flow of resources used in fabrication and construction."

In its 1986 vision, ATLSS foresaw the above scenario for technology relative to 21st century construction. This scenario is nearing reality, and all elements of it are or could be standard by or soon after the start of the 21st century. ATLSS has been a significant enabler in much of the development. Building upon developments that had occurred in structural research and practice, and in laboratory experimentation, since 1986, as well as on structural needs that surfaced after natural and man-made disasters such as earthquakes and structural failures, ATLSS redefined its goals in 1995:

> "To improve the life-cycle performance of large structural systems comprising the civil and marine infrastructure, through technological innovations and a systems-oriented research program which lead to enhancements in materials, design, construction methods, service performance, and renewal methods for large structures."

The newer focus on more sustainable development for the infrastructure, was predicated on the view, that to complete the development of the 1986 scenario, new efforts are required. New innovative structural systems must be conceived and implemented to fully and properly exploit the newer materials that are possible today. Better information systems, including condition monitoring and assessment systems, are essential to implementing life-cycle engineering and must be developed. New systems and methodologies must be proven for renewing existing structures and for enabling future renewal of new structures.

Inherent with ATLSS has been the need to study large scale structures as multi-axis structural systems, and one goal in our 1986 plans was to construct a new stiff reaction-wall, strong-floor laboratory providing the capability to do multiaxis experimentation on full-scale structures. The fruition of this goal was the ATLSS Multidirectional Experimental Laboratory, which has a reaction wall wrapping around an end and one side of a 40-foot-wide by 100-foot-long strong floor (12m x 30m). The wall is 50 feet (15m) tall at the end and, along the side, incrementally steps down to 20-feet (6m) tall. Opened in 1989, it allows experimentation on full-scale assemblies up to five stories tall using a broad complement of computer-controlled hydraulic actuators to impose static, fatigue, and dynamic multi-axis loads. This laboratory, which is world renowned, is the physical cornerstone of the ATLSS Center, the heart of its research on large structural systems, and the testbed for other developments and innovations arising from ATLSS research.

In Education

> Students will graduate with superior strength in a specific discipline and sufficient cross-disciplinary strength to contribute to systems oriented teams. "Substantially more than 10% of the total [graduate engineering] enrollment" of Lehigh will be involved in Center programs. New Center-coordinated graduate educational activities will be conducted, with industry participation and cross-disciplinary sharing: new courses related to large structures, multi-disciplinary case-study teams, and computer-simulated construction projects. Moreover "undergraduate students will join in the work of this Center," and there will be interinstitutional cooperation with area colleges and universities.

ATLSS retained the above 1986 education vision throughout its NSF tenure, with substantial success. The Center achieved, on average, over fifty graduate students annually conducting research, as either a Center Scholar or as a research affiliate. This figure represents about 7 percent of the graduate engineering students at Lehigh, which was a significant achievement. About twenty new or modified academic courses were introduced with several being team taught by a cross-disciplinary faculty team. Multi-disciplinary teams occurred on nearly 80 percent of ATLSS research projects and about half of all projects had active industry participation. The education program kept pace with newer developing educational approaches. For example, as new multimedia information systems and agility concepts emerged and grew, ATLSS' educational approaches changed to include preparing students to function with these media.

The Center also engaged, on average, about 20 undergraduates annually in its research program, about half of whom participated in the ATLSS Research Experience for Undergraduates (REU) program. Finally, the Center had solid interinstitutional involvement, not only from the REU programs, but also from faculty participation, particularly nearby Lafayette College in Easton, PA.

In Industry Collaboration

> "Information will be disseminated through a variety of computerized techniques, such as transferable expert systems for desk-top computers." A "National Information Center, as part of the Center, will develop a database on design, materials, fabrication and corrosion control." Further, "an industrial liaison program, available to companies for an annual membership fee, will be important in the reeducation of practicing engineers, in developing case studies, in identifying pertinent problems, and in extending the activities of the Center to many companies." Industry participation will occur to set long-range policy, to identify problems at the program level and, finally, to allow close interaction at the project level.

This 1986 vision foresaw that technology transfer and collaboration with industry would be integral components in ATLSS' programs. In fact, our industry programs exceeded these original forecasts. ATLSS was the first ERC to recruit and hire a full-time industry liaison officer. The Center established a successful partnership program with an annual fee based on company size, and established industry-led councils, panels, and task groups to advise on strategic planning, major funding, programs, and individual projects. Two transferable expert systems, Bridge Fatigue Investigator and Designer Fabricator Interface, were achieved and one, the (BFI), designed for use by bridge engineers and inspectors, was also extended into a hypermedia training system (HBFI) for education and training. ATLSS established a national information center, called TICSS (Technical Information Center for Steel Structures), developed the software systems for it, and then turned it over to the American Institute for Steel Construction (AISC). ATLSS conducted over 30 short-courses for industry and government engineers, many at the firm or agency site, including a two-day satellite course to nine sites across the country. Multi-day new-technology symposia for industry were conducted on large-scale testing technology, on connection technology, and on advanced double-hull ship-design technology. Industry partners and affiliates assisted strongly in the development of the new technologies resulting from our research: ATLSS Connectors, Corrosion Coulometer, High-Performance Cu-Ni Steels, Fatigue Monitoring System, Bolted Connections for Seismic Retrofit of Steel Frames, and Smart Paint.

III. ADVANCES IN RESEARCH FACILITIES

The capability to do advanced research on large structures depends strongly on the availability of facilities to do realistic large-scale experimentation, advanced high-capacity computer modeling, and substantial materials testing. Therefore, the achievements that ATLSS has had in developing its research facilities are vital.

ATLSS' Principals for Facilities			
John Fisher	**Frank Stokes**	**Bob Dales**	**John Wilson**
Alan Pense	**Eric Kaufmann**	**Charles (Bud) Hittinger**	**Peter Bryan**
Roger Slutter	**Stephen Pessiki**	**John Hoffner**	**Ed Tomlinson**
Peter Mueller	**Jack Bower**	**David Schnalzer**	

Although research on large structures began in the 1920s, its focus for several decades was on single members of structures. In the 1950s, prompted by the availability of new, larger, more capable structural testing laboratories at both academia and industry, including the Fritz Engineering Laboratory at Lehigh University, research on structural assemblies began to be the norm. It was the 1970s, however, before researchers realized that the three-dimensional behavior of structures was significantly more complex than could be learned from two-dimensional studies, and before new experimental facilities capable of multi-axis testing of structures began to be conceived and constructed. The trend continued through the late 1970s and 1980's, and took a new turn as combinations of strong laboratory floors and stiff reaction walls were designed to accommodate a broader range of structures than earlier more specialized, multi-axis units.

The first notable reaction wall was constructed in the Large Size Structure Laboratory at the Building Research Institute of the Japanese Ministry of Construction. The 25m-tall, 20m-wide wall was built near mid-length of a 50m-long laboratory strong floor enabling test structures to be constructed on both sides of the wall and tested with horizontal loads reacted by the wall. At US institutions, the first reaction-wall, strong-floor combinations were constructed at the University of Texas at Austin (1978) and the University of Michigan (1985), the latter being modeled after the Texas wall. These 20-ft (6m) tall walls were the first to continue around a corner to enable horizontal loads in two directions. In May 1986, a large structures laboratory opened at the University of California at San Diego (UCSD) featuring a 50-ft tall, 29.5-ft (9m) wide reaction wall at one end of 120-ft long, 52-ft wide strong floor (37m x 16m), and found rapid acceptance from designers of civil structures on the seismically active west coast.

Upon Lehigh's acquisition of the Homer Research Laboratories of Bethlehem Steel Corporation late in 1986 and renaming of the site as Lehigh's Mountaintop Campus, one building was allocated to ATLSS for constructing a new world-class research facility. Construction of the new Multidirectional Experimental

Laboratory began in April 1987 and culminated in its dedication in June 1989. With its size and scope, it provided a new and unique capability to do multiaxis experimentation on full-scale structures up to five stories tall. The current operational equipment for experimentation includes 22 computer-controlled actuators and a hydraulic capacity of 600 gpm (0.038 m^3/s) at 3000 psi (20.7 Pa), to provide a unique multiaxis dynamic load capability. Computer systems, offices, and conference room facilities are included along with Materials Evaluation Laboratories for Mechanical Testing, Welding and Joining, Metallography and Electron Microscopy.

ATLSS now has a total research area (offices and laboratories) of about 50,000 sq. ft (4645 sq m) in the Imbt Laboratories building. The total cost of constructing, equipping and purchasing these facilities has been about $18M. Additional has been invested in upgrading the structural facilities in Fritz Engineering Laboratory which are managed by ATLSS. Of this, about $1.8M was allocated from the ERC grant. The remaining 90 percent was contributed by Lehigh University (about $9M), the Commonwealth of Pennsylvania ($2M), and industry (about $5M).

With its research facilities, ATLSS is superbly equipped to perform the experimentation and analyses needed to conduct research on large-scale structures and on structural materials. A full-scale 60 x 20 ft (18 x 6 m) prototype segment of a cantilevered replacement deck for the Williamsburg (NYC) Bridge, and a full-scale three-story building frame with experimental viscoelastic bracing for seismic-damping are completed experimentation examples that nationally distinguish the ATLSS Multidirectional Experimental Laboratory.

IV. ACHIEVEMENTS IN RESEARCH AND TECHNOLOGY

IV.1 High-Performance Materials

Research in high-performance materials, and particularly steel, has a history of excellence at Lehigh. ATLSS continued this research towards high strength, high value materials, emphasizing a strong component directed toward both the development and the application of high-performance steel and steel weldments, and also including vigorous components directed towards the applications of advanced composite materials and high-performance concrete.

ATLSS' Principals for High Performance Materials			
Robert Dexter	Kaz Kasai	Stephen Pessiki	Bob Stout
John Fisher	Le-Wu Lu	Jim Ricles	Dave Thomas
John Gross	Alan Pense	Richard Sause	

High-Performance Steels. The initial high-performance steel research projects in ATLSS were conducted mainly for pressure vessel applications and concerned the weldability of new alloy steels and the development of welding procedures to optimize weldment properties, particularly notch toughness. Microalloys such as columbium and vanadium were shown to be deleterious to weld metal fracture toughness especially after postweld heat treatment. Later, ATLSS began to investigate these steels, such as the copper-bearing precipitation-hardened A710 steel, for civil-engineering structures, especially as part of beam-to-column connections to achieve improved ductility and moment rotation capacity.

After the Japanese found that steel performance was enhanced by special controlled rolling and heat treatment called thermal-mechanical-controlled processing (TMCP), a practice that requires substantial new investment by most steel producers, ATLSS began evaluating TMCP high-performance steels as replacements for the Navy's HY-series of high-strength quenched and tempered steels. We determined that: 1) lowering the alloy and carbon content would eliminate the need for auxiliary heat treatment; and 2) some concomitant loss in strength and hardenability could be offset by TMCP procedures. ATLSS has since continued development work on high-performance steels to optimize the composition and properties for 70- and 100-ksi (482 and 689 MPa) minimum yield strength steel for applications to bridges and other large structures. Our results suggest that a less costly controlled-rolling processing provides a combination of properties equivalent or superior to conventional TMCP processing, does not require the installation of new steel processing equipment and, thus, is a competitive new process for high-performance steels.

To effectively exploit the properties of high-performance steels, ATLSS is studying new and innovative designs for structural components and forms, particularly for innovative bridge designs but also for civil infrastructure in general as well as innovative weld joint designs, such as the use of undermatching weld metals, and welding processes. We are also developing ductile fracture models so that the extraordinary fracture resistance of high-performance steels can be demonstrated and reliably predicted. Our studies have led to follow-on projects involving advanced weld procedures such as electrogas and laser welds. Also on the basis of our studies, the Navy has begun to allow undermatched welds in destroyers being fabricated with HSLA-100 steel. ATLSS' work in HPS was acknowledged in the 1997 Pankow Innovation Award to the American Iron and Steel Institute.

High Performance Composites. ATLSS' research into applications of advanced composites for large structures was effective both in demonstrating their feasibility as primary members in certain structures and in evaluating their potential as retrofit and repair materials; and it has provided new information on the properties of advanced fiber composites.

With E.T. Techtonics, a small business in Philadelphia, ATLSS conducted long-term material-property and load-test experiments on full-scale pedestrian bridges that were totally advanced composites (kevlar and other), except for some fasteners. We studied full-scale reinforced concrete beams bonded in the positive moment region with (kevlar, E-glass, and other) composite sheets to define the effectiveness of the composites in delaying cracking of the concrete and increasing the beams' load-carrying capacity. We studied small concrete columns reinforced internally and externally with composites to demonstrate the increase in column strength afforded by the composites. These studies were conducted both at Lehigh and at California State University at Northridge (CSUN). We have also studied full-scale 16-inch-wide (41 cm) reinforced concrete columns additionally reinforced externally with various fiber-reinforced composites to examine the strengthening effect of the composites. ATLSS also worked with the University of Delaware on an NCHRP-IDEA project, "Rehabilitation of Steel Bridges through the Application of Advanced Composites Materials," by providing proof-of-concept with full-scale experimentation.

IV.2 Structural Connections

A key initial issue for ATLSS was that "connection technology is one of the most labor intensive and costly aspects of fabrication and construction and the cause for the greatest uncertainty in design." Moreover, because connections are a frequent source of failures, research towards improved design concepts and fabrication and construction considerations for connection systems was an important continuing component of the ATLSS program. Our accomplishments in connections research led to: more rational methodologies for designing steel and precast concrete connections, new connections for greater construction-site productivity, welded connections with improved seismic resistance, and retrofit designs for distressed connections.

ATLSS' Principals for Structural Connections		
George Driscoll	Eric Kaufmann	Bill Michalerya
John Fisher	Le-Wu Lu	Jim Ricles
Kaz Kasai	Peter Mueller	Vince Viscomi

Steel Connections. For years, designers had been treating connections for steel frameworks as either simple (no bending moment capacity) or rigid (full moment capability), and the practice was known to be economically inefficient. ATLSS' initial research in this area, therefore, was focused, with counsel from industry advisors, on the efficiency of using nonlinear semi-rigid (or partially restrained) bolted connections between beams and columns. Large-scale beams (up to 27-inch-deep (68 cm)) beams) were evaluated under static reversed loading and theoretical computer analyses. These completed studies satisfied a strategic goal to increase the knowledge base about nonlinear connection behavior, enabled engineers to accurately determine the percentage of moment capacity that can be developed with certain connection details, and provided a basis for new design procedures.

Another team of ATLSS researchers searched for other innovations in connection design. Motivated by possibilities for cost-effective, high-strength connections that decrease the construction-site time and reduce risk to the construction worker involved in making beam-to-column connections, this team invented the now patented ATLSS Connector. The design concept for this connector is based on using a tapered solid "tenon" piece on the beam which slips into a three-dimensional "mortise" guide mounted on the column. The tenon is shop-bolted to the beam web by means of web-framing plates that extend from the back of the tenon, while the mortise may be welded or bolted to the column flange or web at the construction site (with the column on the ground) or in the shop. The ATLSS Connector design that evolved is a high-performance connector satisfactory for beam-to-column connections; and manufacturable from high strength steel castings, (cast HSLA 80 low-carbon, high-strength low-alloy steel). An initial demonstration installation was in use for 24-months at a low-rise industrial plant building (a DuPont Polymers plant) in Clinton, IA; and a second demonstration installation has been in use at a DuPont facility in New Johnsonville, TN, since December 1994. Although a business plan was developed to commercialize the connector and connectors were sold to an Australian firm, the anticipated market has not developed.

ATLSS research on steel connections intensified following the 1994 earthquake in Northridge, CA, when numerous welded steel moment frames fractured at the beam-to-column connections. ATLSS became a key participant in analyzing the failures (many fractured connections were sent to ATLSS for analysis), and in designing and experimentally evaluating full-scale assemblies that represented or were potentially (a) improved, next-generation connections or (b) connections suitable for retrofitting the failed connections. Concrete-filled-steel tube columns with various wide-flange beam connections were a major new-design study and involved both traditional strength steel and concrete and high performance steel and concrete. Bolted retrofit connections represented other design studies, which were often done in conjunction with private industry and which resulted in one invention co-owned by ATLSS and an engineering firm, and exclusively licensed to the firm. The ATLSS research results from these studies are a critical component of a strong industry effort to ensure that superior seismic performance is attained in welded steel moment frames.

Precast Concrete Connections. Another ATLSS research team worked to develop improved precast concrete connections and joints. The research focused on: developing a consistent design methodology as a basis for new design codes, developing and experimentally verifying rational models which unify the analysis and design of many types of connections, and extending the ATLSS connection concept to precast concrete.

In the first two areas, we developed analytical "truss" or strut-and-tie models, where the joints are conceptualized as a collection of uniaxially loaded bars configured as a truss to convey the load through the joint. We focused on commonly used connections and demonstrated with experimental results that truss models are a unifying model, which can be extended to more generalized joint designs. New design provisions based on truss models are being considered for the ACI Standard Building Code.

In research to extend the ATLSS Connection concept to precast concrete frames, we developed joint designs in which precast beams are interlaced with precast columns through passages in the columns, and conducted experiments on prototype design assemblies, and demonstrated that two designs would be satisfactory for parking garage applications even in seismic zones.

Connections Workshop. To draw attention to the research needs in structural connections and to highlight the role of ATLSS in connection research, ATLSS organized and hosted an international Workshop on "Connections for Building Structures in the 21st Century," in November, 1991, and published its Proceedings.

IV.3 Double-Hull Ship Technology

In February 1991, ATLSS initiated research on another class of large structural systems – ship structures, beginning a multi-phase, research and development program called the Fleet of the Future Program (FFP). The program's principal objective was to assist the U.S. Navy with new and better designs, materials, and manufacturing technologies and large-scale proof-of-principle testing for the Navy's future surface fleet. FFP projects involved design, joining, and manufacturing issues for an advanced unidirectional double-hull combatant ship. The unidirectional double-hull ship is made of a series of longitudinal box structures creating an inherently stiffer and stronger ship than the conventional "plates with ribs and longitudinals" design. But issues about the stability, fatigue strength, and fracture resistance of the fabricated modules of the hull needed resolution through research.

ATLSS' Principals for Double-Hull Technology			
Robert Dexter	**Bill Jahn**	**Jim Ricles**	**Bob Stout**
John Fisher	**Eric Kaufmann**	**Richard Roberts**	**Emory Zimmers**
John Gross	**Le-Wu Lu**	**Bruce Somers**	

Working closely with the Naval Surface Warfare Center Carderock Division and with Ingalls Shipbuilding, ATLSS' FFP team developed an integrated research program. After a full-scale prototype double-hull section was fabricated by Ingalls Shipbuilding, seven experimental test specimens were extracted from the prototype and sent to ATLSS where they formed the basis of both a manufacturing phase and an experimental phase of the program. The **manufacturing team** evaluated welding details and fabrication concepts for double-hulls. The **stability team** utilized predictions to develop an experimental plan for testing the various modules, which ranged in size from moderate 3x3x10 feet (0.9x0.9x3m) to large 9x3x35 feet (2.7x0.9x10.7m). Test results validated stability analyses and design tools for multi-cell hull structures as well as recommendations for the width and thickness of hull plates. The **fatigue and fracture** team evaluated producible high-quality weld details for the double-hull. Using standard shipyard practices, various weld details were fabricated from Navy standard high strength steel, HSLA-80, and tested in fatigue. This study provided data that justifies using existing fatigue-resistance design rules, such as those published by the American Association of Highway and Transportation Officials (AASHTO), for ship design. Crack propagation in large multicell structures fabricated from high-strength steel was also studied, revealing a remarkable ability of cellular structures made from high strength steel to maintain structural integrity even with cracks traversing one-half the structure's cross section.

The successful technological developments from the two-year double-hull program included: Strength prediction methods for double-hull cells; Buckling resistance, fatigue cracking, and fracture resistance data for double hull structures; Fatigue distribution curves for reliability-based design; and Guidelines for weld detail design, inspection and repair.

Technology Transfer. The double-hull program began an ongoing ATLSS relationship with the Office of Naval Research, the U.S. Coast Guard and the shipbuilding industry. ATLSS research teams have been awarded a number of additional maritime research projects, including a major on-going program to experimentally evaluate half-scale prototype single-hull sections made entirely of fiber reinforced polymers.

ATLSS also served as the testing facility for an advanced double-hull welding program for both commercial and combatant ships which involved four companies, three universities, two government laboratories, and five new welding technologies. In addition, ATLSS coordinated a national Advanced Double Hull Technical Symposium, sponsored by the Maritime Administration and the Office of Naval Research and held in October 1994 at NIST.

IV.4 Structural Serviceability Systems

The serviceability of large structures depends upon their resistance to deterioration. Two primary modes of deterioration limiting serviceability are corrosion and fatigue. Methods for rapidly and efficiently locating deterioration, assuring reliability, repairing or retrofitting, and predicting remaining service life are critically important for large structural systems. For this reason, ATLSS conducted research to study the bases for corrosion and fatigue and to develop new technologies for corrosion and fatigue sensing systems, which alert inspectors and owners to deterioration. ATLSS also studied the life-long deterioration of steel bridges, and the residual strength and repair of deteriorated and damaged offshore platform members.

ATLSS' Principals for Structural Serviceability			
Carl Beidleman	Rich Granata	Alex Ostapenko	Malcolm White
D. Christodoulides	Mark Kaczinski	Jim Ricles	Marvin White
Robert Dexter	Henry Leidheiser	Greg Tonkay	John Wood
John Fisher	Wei-Ping Li	David Veshosky	Ben Yen

ATLSS research into **corrosion science** included studies of crevice corrosion, a major mode of corrosion in riveted and bolted metallic structural assemblies, and of the application of electrochemical impedance spectroscopy (EIS) for monitoring corrosion of steel reinforcing bars in concrete. In a study that culminated in a new patent, a **corrosion monitor**, based on electrical coulometric principles, was developed and proven in several field studies involving different applications. The monitor's key features are that: It provides a measure of the corrosion rate; it is small and suitable for in-situ use; it accounts for the accumulation of dirt and debris on the corroding surface; it accounts for the general nature of the environment; it can be used unattended; it can be sited in hard-to-access locations; and it is adaptable to remote interrogation. In September 1991, U.S. Patent No. 5,045,775 was issued for the coulometer. The coulometer has had field trials on bridges in Michigan, New Jersey, and Pennsylvania; was evaluated at Kure Beach, NC; and was used in Maine and Hawaii to measure the ambient corrosion rate for existing and proposed structures. The Corrosion Coulometer is moving to commercial practice through Competitive Technologies, Inc.

Fatigue Science and Sensors. Extensive pre-ATLSS studies by ATLSS Director John Fisher and other personnel at Lehigh established a fundamental basis for fatigue assessment and monitoring of large structural systems and led to many design guidelines. ATLSS continued fundamental studies of fatigue in four areas:

ATLSS studied full-size **riveted bridge girders** to generate the experimental and analytical information needed for the determination of the fatigue strength of riveted structural members in bending, particularly members with long service life. Girders were removed from railroad bridges and tested in fatigue under practical, variable load magnitudes, and this testing provided the necessary information for the generation of an appropriate S-N curve for riveted bridge girders. These studies were used to develop provisions for fatigue rating older railroad bridges. Our fatigue results for riveted bridge girders have been applied by the U.S. Army Corps of Engineers to the large riveted hydraulic gates in operation at their locks and dams.

Long-life welded steel details were studied under long-life (exceeding 100 million cycles) variable amplitude fatigue tests. Full-size (W36x260) A588 weathering-steel bridge girders with different categories of welded details (web attachments, cover-plated flanges, transverse stiffeners, and diaphragm connections). The results provided design suggestions on using constant-amplitude fatigue curves for these details.

A full-scale fatigue-test data base for **welded aluminum beams** with several butt-weld and fillet-weld details was developed, to examine behavior differences between the full-scale beams and small axial test specimens. This cooperative project between ATLSS and the Alcoa Technical Center furnished new information on the behavior of welded aluminum, and suggested adjustments for the next generation of fatigue design guidelines.

Research was conducted into new **fatigue sensing systems** that facilitate both inspecting for fatigue cracks and collecting fatigue data. The research led to the development of **Smart Paint** which facilitates routine visual inspection for fatigue cracks. It is a paint containing microencapsulated dyes. When a fatigue crack develops or grows in a structure coated with Smart Paint, the microcapsules rupture releasing a high-contrast, visible dye along the crack; enabling an inspector to more readily observe the crack. ATLSS developed specifications for the microcapsules and developed the use of the paint for detecting cracks by applying it to beams and girders being fatigue tested in our other research programs. U.S. Patent No. 5,534,289 was issued in July 1996 for Smart Paint as a fatigue crack detector. Smart Paint technology is being commercialized through Competitive Technologies, Inc. Another system, the **Fatigue Monitoring System**, is an electronic data processing chip that, in real time, collects conditioned strain gage signals from a structure being monitored, does a rainflow count of the stress cycles for different stress ranges, computes the corresponding single equivalent stress range and cycle count, and stores this data for engineering analysis. The system has been field tested and a patent application has been filed.

IV.5 Computer Integration

The construction industry comprises diverse, detached participants frequently acting with minimal transfer of information, which potentially limits their effectiveness and the cost-effectiveness and quality of constructed facilities. Computer integration makes it possible to reduce interface limits between industry participants. The ATLSS research in the area of computer integration had accomplishments in methodologies and prototype systems.

ATLSS' Principals for Computer Integration		
Peter Bryan	**Donald Hillman**	**Stephanie Wagaman**
Frank Harvey	**Richard Sause**	**John Wilson**

As one example of our **methodology**, integrated models of design/construction activities - "process" models - and of design/construction information - "product" models - were developed as part of a "Framework for Integrated Design." The models were developed in parallel and then integrated. They combine concepts and terminology from the field of structural engineering with modeling concepts and conventions from the field of computer science, and provide a theoretical foundation for future computer-aided engineering systems. A prototype for steel frame design was developed.

ATLSS researchers also developed and implemented **prototypes** of new multimedia and knowledge-based systems, and produced a framework for future intelligent diagnostic systems. One intelligent prototype system addresses the major infrastructural problem of the fatigue evaluation of steel I-girder bridges. The Bridge Fatigue Investigator (BFI) system aids the evaluation and enhances the effectiveness of bridge inspection. It has undergone field testing by consultants and transportation agencies. It is available in a training version with hypermedia (HBFI). Another intelligent prototype system fosters communication between designers and fabricators for the preliminary design of steel beam-to-column connections, thus alleviating the mismatch between the intentions of designers and the capabilities of fabricators. A third prototype system "Technical Information Center for Steel Structures" uses knowledge-based system technology; a pilot system with bibliographic and other reference material was delivered to AISC and other industry partners.

Technology Transfer. In 1987, ATLSS led an international NSF workshop on "Construction Automation: Computer Integrated Construction" which gathered a strategic view of how to integrate computer technology better into the construction process. In 1991, for the Civil Engineering Research Foundation (CERF) Forum, "Setting a National Agenda for the Civil Engineering Profession," ATLSS researchers helped develop two high priority areas emphasizing the need for integrating computer systems in construction for competitiveness and performance. In 1992, we presented a keynote address to The National Academy of Engineering on "Computing: The Transformation of Engineering." We collaborated, too, with other institutions including Carnegie Mellon University, Cornell University and Pennsylvania State University involved with computer-aided engineering for the construction industry. Also, working with the Construction Industry Institute (CII), we helped to provide nationally disseminated methods and guidelines for the identification, justification, and implementation of 3-D modeling for cost-effective design and construction.

IV.6 Construction Automation

From two early surveys conducted by ATLSS, one in 1987 of robotics technology in domestic and overseas construction and the second in 1993 of the then-current and emerging automated construction technologies, a trend that emerged was that future attention should be directed towards improvements in technology which enable construction site enhancements, such as providing new assembly forms such as modularization or providing the craftsman with automated process control for operations involving lifting and moving. These surveys pointed the way to ATLSS research focusing on changes in crane operations and developments in prefabricated connectors that facilitate a more rapid assembly of building frames.

ATLSS' Principals for Construction Automation			
John Egbers	Le-Wu Lu	Bill Michalerya	Sarah Slaughter
Mike Groover		Duke Perreira	Vince Viscomi

Our studies to facilitate more rapid building assemblies by developing prefabricated connectors resulted in the development of the ATLSS Connectors described earlier. Parallel with this we proceeded with studies to effect changes in crane operation. It was conceived that, when using ATLSS Connectors, cranes fitted with sensors or with a supplemental platform having sensors could manipulate structural members to engage the tenon and mortise parts of the connectors. One form of a patented device known as a Stewart Platform (after one of the inventors) was studied because it could be adapted to existing cranes and it had the requisite degrees of motion control. A pilot scale-model computer-controlled platform was designed, fabricated, fitted with electronics, and installed on elevated rails and successfully used in the ATLSS Multidirectional Experimental Laboratory to assemble beam-to-column units and frame-to-column units equipped with ATLSS Connectors.

Concurrent with our studies, the Robot Systems Division at the National Institute of Standards and Technology (NIST) was developing its ROBOCRANE, which is also based on a Stewart Platform. Therefore, ATLSS and NIST initiated a collaboration that began with a joint exhibit of the ROBOCRANE with ATLSS Connectors at the 1992 Construction Exposition (CONEXPO), and led in August 1994 to a Cooperative R&D Agreement (CRADA) to "foster industrial participation in the development, evaluation, and utilization of cable driven Stewart platform cranes in conjunction with ATLSS connections in various large scale assembly applications." The CRADA resulted in joint demonstrations and new industry collaborations.

V. DISSEMINATION OF RESEARCH RESULTS

ATLSS researchers have actively transferred their research results to practicing engineers and to other researchers through journal publications, conference and other presentations, and conference proceedings. Many of these papers have been co-authored and presented by students; some have been co-authored with industry personnel. Because members of the large-structure industries are practitioners, many of the papers have been presented both at practitioner-oriented conferences and in scholarly refereed journals.

The researchers have also disseminated their research results through academic courses. Thirteen new or modified graduate courses evolved from ATLSS studies and involved six departments. At the undergraduate level, six new or significantly modified courses evolved.

VI. INDUSTRY/GOVERNMENT PARTNERSHIPS

ATLSS developed a comprehensive scope of industry interactions that significantly contributed to our overall programs and to the ERC goal of establishing a partnership among industry, academia and government.

Collaborations and Alliances. We have had 22 general partners, 36 project partners, and 40 project advisors, comprising 68 different companies, trade associations, and government agencies. Added to these are over 200 firms for whom ATLSS has done commercial testing. Another 20 companies and agencies served as Education Collaborators or participants in our educational program, by conducting seminars for us, hosting field trips, or lecturing in our short courses. This was a remarkable achievement in an industry as fragmented as the U.S. construction industry. Moreover, several collaborations established during our NSF tenure are having major post-NSF benefits, see *Section X.*

A significant development was the formation of consortia to support larger projects. Studies involving the residual strength of and repair methods for deteriorating assemblies in offshore structures had project consortia involving up to seven partners co-sponsoring the planning and cost of the study. Similar consortia have sponsored our studies on high-performance steel.

ATLSS developed strong, specific alliances with other influential agencies in order to extend our national outreach. We were members of the National Council of Civil Engineering Research established by the Civil Engineering Research Foundation (CERF), and of the Research Centers' Council and Research Committee established by the Construction Industry Institute (CII). Through these alliances, ATLSS was able to influence national research agenda and best direct our agenda.

Evolution of Technology Transfer. From 1988 to 1993, ATLSS had a full-time Manager of Industry Liaison. The role of industry liaison evolved considerably in that time. An early change involved our joining the function of technology transfer to that of industry liaison, to reflect the need not only to recruit industry participation but to transfer research results to industry. We worked with the Lehigh University Office of Research on intellectual property issues. In 1990, Lehigh moved these issues to a new non-profit subsidiary company, Competitive Technologies, Inc. (CTI). In 1993, CTI became a for-profit company with Lehigh becoming a 20-percent owner, and our Manager becoming its chief operating officer. ATLSS then formed a partnership with CTI to continue developing our industry liaison and technology transfer activities. CTI became responsible for our intellectual property items; economic assessments of technologies that we developed; and moving ATLSS technology to practice. The ATLSS technologies that CTI is moving to commercialize are shown on the included sheets titled *ATLSS Technology Items.*

ATLSS made a continuing effort to transfer technology to industry and government engineers through project panel meetings, semi-annual advisory council meetings, and short courses. Each advisory council meeting had part devoted to project discussion, often through a poster session or presentation by principal investigator or student. While most short courses were conducted at Lehigh, some were conducted at industry sites and one was conducted live by satellite to nine government-agency sites across the country. ATLSS also organized and conducted major, technical symposia or workshops on: large structures experimentation (1989), structural connections (1991), large structures technology (1994) and the advanced double-hull program (1994).

ATLSS Technology Items

Licensable Items

Property Number: 998049

Patent and Issue Date: 5045775 on 9/3/91

Title: Corrosion Monitor

Technology Summary: A system for monitoring and measuring environmental corrosion. The system includes a sample corrosion element of substantially the same material as the structure to be monitored, a galvanic cell for generating an electric signal indicative of the corrosion on the corrosion element, and a monitor for receiving and storing the generated signal. The system is designed to incorporate corrosion products and environmental contaminants in order to simulate actual, localized conditions on a particular area of a structure.

Property Number: 998053

Patent and Issue Date: 5244300 on 9/14/93

Title: ATLSS Connector

Technology Summary: A structural connector used to interconnect two members. Commonly a beam to a column. The connector includes a tapered insertable part attached to the first member and a receiving part attached to the second member and adapted to receive the insertable part. Upon insertion of the tapered part into the receiving part, the members are structurally interconnected.

Property Number: LU92-007

Patent and Issue Date: 5534289 on 7/9/96

Title: Smart Paint

Technology Summary: A paint for monitoring a structure for the formation of cracks and for providing protection of the structure from the environment. Its application includes the following steps: applying to the structure a first coating comprising microcapsules of some color, applying over the first coating, a second coating having a second color, and identifying cracks which form in the structure by observing changes in the color of the second coating resulting from eruption of microcapsules in the first coating.

Property Number: LU92-008

Patent and Issue Date: Proprietary Technology

Title: Bridge Fatigue Investigator (BFI); with Hypermedia (HBFI)

Technology Summary: A computer-based hypermedia bridge fatigue analysis tool designed to support the training of and technology transfer to bridge inspectors and engineers for steel I-girder bridges. This tool includes an on-line reference section, a random access video disk, a multimedia database, computer morphing, and 3D graphics and renderings.

Property Number: LU92-010

Patent and Issue Date: Application filed

Title: Fatigue Data Processor

Technology Summary: A real-time processor of strain gauge data for fatigue life assessment of large structures (e.g., bridges, ships, airplanes, etc.). The entire system consists of sensors and processing modules distributed on a large structure and battery powered, a radio repeater near the structure being monitored, and a computer at a central facility. The sensors and processor modules collect and process data on site in real time. Processed data is transmitted to the radio repeater, which transmits multiplexed data from the processor modules to the central facility for display. The system performs continuous monitoring, event triggered processing, or remote controlled data collection. The algorithm used for estimating fatigue damages includes rainflow counting, stress histogram generation, and equivalent stress range calculations.

Property Number: LU95-022

Patent and Issue Date: Application filed

Title: Bolted Frame Connection

Technology Summary: An innovative cost-effective repair method developed jointly by Lehigh University and ICF Kaiser Engineers, Inc. It uses specially fabricated brackets with high-strength bolts for repairing damaged welds in steel moment frame buildings, such as seismically damaged building frames. These innovative brackets provide advantage over traditional weld repairing techniques in safety, cost, and ease of installation. ICF Kaiser is the exclusive licensee.

VII. A NEW GENERATION OF ENGINEERING GRADUATES

The educational mission of ATLSS was to develop a new generation of engineering graduates more effective in engineering practice. We provided research opportunities for students to acquire the knowledge, skills, and motivation to function effectively on the structures- and materials-related technological challenges that they will face in the future. We involved our students in teams of faculty, research staff, other graduate and undergraduate students, and industry representatives so they could gain a systems perspective of research and engineering challenges.

Graduate Students. ATLSS supported 195 graduate students (corresponding to 211 degree candidates), including 29 (14.9 percent) females, seven (3.6 percent) African Americans, seven (3.6 percent) Hispanics, and 62 (31.8 percent) international students of whom 43 were Asians. Seventy degree candidates (33.2 percent) have been Ph.D. candidates. Through 1997 (including January 1998 commencement), the graduate students earned 154 academic degrees, 39 PhD and 115 MS. Thirteen disciplines were represented by the students, affirming the broad cross-disciplinary characteristic of ATLSS.

Industry and private practice have been the principal **post-graduate employers** for ATLSS graduate students after their ATLSS research, employing 97 (49.7 percent) of the students, including 21 at the PhD level. Another 15 students were employed in various levels of government, and 34 (17.4 percent) were employed by or continued in academia.

Academic awards were earned by two of our PhD graduates. Dr. Stuart Chen was named an NSF Presidential Young Investigator, as a new faculty member at the State University of New York at Buffalo. Also, Dr. Steven Wong received a Japanese Science and Technology Award (ICOT) for his work on communication theory in knowledge-based systems. **Awards for outstanding papers** were earned by six students. Ph.D. graduate Yi Zhou was a North American winner in the American Railway Engineering Association (AREA) Student Interest Award Program. In the annual Lincoln Arc Welding Foundation Program for the Advancement of Arc Welded Design, Engineering, and Fabrication, we had five winners: PhD graduate Christopher Higgins won a Gold Medal; MS graduate Michael Hebor won a Bronze Medal; PhD candidate Anil Jagiasi and MS graduates Arum Mayangarum and Ian Hodgson all won Merit Awards. Five students also won **major fellowship awards.** PhD graduates Dan Henkel and Javier Escobedo won NASA fellowships; PhD graduate Christopher Higgins won an NEHRP fellowship in Earthquake Hazard Reduction; MS graduate Cory Farschman held an NSF fellowship; and MS graduate Anthony Magee held an Oakridge National Laboratory Minority Program fellowship.

Undergraduate Students. Undergraduates were an integral component of our programs. Their initial involvement was principally through an REU program conducted each summer. However, we expanded as we could each year to offer more undergraduate opportunities during the academic year. At its peak in 1995 our undergraduate program included 16 REU students and 40 other undergraduate assistants, and we were sustaining a ratio of one undergraduate student to one graduate student. In 1997, we discontinued the REU program while we sought new funding from non-NSF sources.

Our REU programs had several goals: (1) Recruit non-Lehigh students in order to provide challenging research opportunities to students who might not otherwise have them and to inform other schools about ATLSS and Lehigh. One hundred twenty students from 25 colleges and universities and 14 different disciplines participated in the programs. (2) Recruit outstanding women and underrepresented minorities. Over 38 percent of the students were women, and over 20 percent were Black and Hispanic students. (3) Introduce the students to engineering practice through field trips and seminars by industry representatives. (4) Provide mentoring opportunities for our graduate students; and (5) Introduce the students to the challenges and opportunities of graduate school. Eleven of our REU students were later accepted to graduate school at Lehigh and became ATLSS graduate students. This group included three women, three African-Americans, and seven from outside colleges and universities.

Pre-College Outreach. A high-school chemistry teacher assisted, part-time for four years, on the research for Smart Paint, and is a co-inventor on the patent. Also, a middle school science teacher participated side-by-side in all activities with our REU students in Year 4. Moreover, numerous high school, middle school, and vocational school groups (including students, teachers, and parents) visited the ATLSS Multidirectional Experimental Laboratory for tours and presentations of ATLSS' activities and career opportunities.

Outreach to Minority Institutions. Through supplemental NSF grants, ATLSS established outreach programs with two minority institutions, California State University at Northridge (CSUN) and Wayne State University (WSU). Our research **with CSUN** was allied to ATLSS research on fatigue science, on applications of advanced composites, and on earthquake studies. Twelve CSUN undergraduate students and three CSUN professors participated in this research. Our study **with WSU** was allied to the development of software enhancing our capability to do pseudodynamic testing of structures in the ATLSS Multidirectional Experimental Laboratory. Two WSU female undergraduates and two graduate students participated in this research.

VIII. ATLSS WITHIN LEHIGH UNIVERSITY

ATLSS is the largest interdisciplinary research center (out of 20 centers/institutes/councils) at Lehigh University, in terms of both research personnel and research budget. It is significant that Lehigh's strategic plan identifies "Materials and Structures" as Lehigh's first-priority interdisciplinary area for research. This research area not only encircles the ATLSS research program, but its selection was influenced by ATLSS' presence and is reflective of our impact on the university's research culture. The Director of ATLSS is responsible to the Dean of the College of Engineering and Applied Science, and serves on the Dean's Council.

Commitment to Faculty. Lehigh originally committed to provide up to five new young engineering faculty members, who would be phased in as the research program developed and would conduct center-supported research. This commitment was exceeded with the hiring of seven outstanding younger faculty, including two with NSF Presidential Young Investigator (PYI) awards. These seven – who also represented seven disciplines or sub-disciplines – conducted significant ATLSS research and were quite successful in securing additional government and industry funds. Lehigh also hired a senior professor to bring the perspectives of a former senior industry executive to ATLSS' research and education in construction systems.

Forty-five Lehigh faculty participated in ATLSS, representing all four colleges of the university and seven disciplines of the College of Engineering and Applied Science. Seventeen visiting faculty also actively participated in our research; including three from Lafayette College, one from Villanova University, one from the University of Texas at Austin, one from the U.S. Naval Academy, one from the Naval Postgraduate School in Monterey, CA, two from universities in Europe, one from Nacional Politecnica in Ecuador, two from universities in Egypt, and six from Pacific Rim universities.

Commitment to Cross-Disciplinary Education. Lehigh originally committed two graduate fellowships to ATLSS each year until there were ten. These fellowships were to be used to support first-year graduate students for one academic year, after which these students would become ATLSS - supported research assistants. This commitment was met and the provision of ten fellowships continued uninterrupted from Year 5 through Year 11. In addition, Lehigh provided five additional graduate tuition scholarships each semester since the spring semester of Year 2. These scholarships were provided to research assistants receiving stipend support. ATLSS utilized its fellowship and scholarship awards to develop its cross-disciplinary base of graduate students over nine disciplines. Over 92 percent of the students awarded fellowships and scholarships have either completed their ATLSS research and earned their graduate degree or are actively pursuing their degree.

IX. ANNUAL REVENUES

ATLSS' annual revenues from NSF increased from a startup level of $1.40 M in Year 1 to about $2.8M in Years 7 and 8, before beginning a scheduled phase-down. Our total revenues also increased. From a startup level in Year 1 of $1.85M, the total revenues grew steadily, peaking in Years 6 and 7 at about $7.0M with the FFP program. Since that time, revenues have leveled near $5.5M. Our revenue, taking all sources into account, thus varied from a minimum 132 percent of NSF funding (Year 1) to a high of 272 percent (Year 6) and closed at 203 percent (Year 11). This is evidence that NSF revenues were effectively leveraged.

X. A LOOK TO THE FUTURE

The ATLSS Center is moving forward confidently into self-sufficiency, enabled by a number of new alliances. As this is occurring, organizational changes are also occurring; changes that deviate from the ERC organizational concept.

Developments Towards Self-Sufficiency

As ATLSS approached its start of phase-down funding from NSF, it began its self-study for a post-ERC operating mode. This study concluded that the Center's greatest strengths, interests, and recognition lay in large structures for the civil infrastructure and, to a lesser extent, for shipbuilding. A major option that ATLSS then unsuccessfully attempted was to earn a new grant as an ERC devoted to these topics.

ATLSS began a multi-pronged effort in both Harrisburg, PA, and Washington, DC, to seek new long-term funding. It was first in Harrisburg, however, where the values of past collaborations and of an ERC background were proven. Because, the Engineering Design Research Center (EDRC) at Carnegie-Mellon University, whose NSF funding like ATLSS' had come to an end, was also seeking self-sufficiency, ATLSS and EDRC jointly sought state funding through an innovative east-west Pennsylvania alliance that coupled two separate strengths (physical structures research and information and computer technology research) into a unit capable of addressing the state's physical and informational infrastructure. The Pennsylvania Infrastructure Technology Alliance (PITA) was legislatively approved for first-year funding effective July 1, 1997 at a level of $2.5M (split equally between Lehigh and CMU). Second-year funding has been approved at a level of $3M. Further continuation funding is anticipated. This funding has allowed ATLSS to maintain some core administrative staff and some core laboratory staff, while enabling it to initiate new projects and extensions of existing projects of value to Pennsylvania.

ATLSS continues to seek other major alliances. In March 1998, Lehigh signed a long-term Memorandum of Understanding (MOU) with the Naval Surface Warfare Center-Carderock Division stating that Lehigh will be a primary core university for naval research important to the Carderock Division. While the MOU is with Lehigh, ATLSS will be a primary unit because of its capability in large structures and materials testing. ATLSS is currently contracted with for over $1.0M to experimentally evaluate at least two half-scale prototype ship hulls fabricated entirely of advanced fiber composites (fiber reinforced plastics). We are also continuing to work towards being named and funded as a national Center for Advanced Bridge Systems, in which we would collaborate with the FHWA and with PennDOT.

In other lesser actions, we have joined with other Pennsylvania universities in two partnerships with the Pennsylvania Department of Transportation (PennDOT). We have signed three four-year agreements involving PennDOT, Penn State University, Drexel University, The University of Pittsburgh, and Howard University in Washington, DC. Further, we have joined with 13 universities in the state in another four-year cooperative agreement involving PennDOT. These partnerships ensure that ATLSS is part of the team that will improve Pennsylvania's transportation infrastructure for the 21st century.

ERC Organizational Concept

The ERC organizational concept calls for a strong cross-disciplinary research program, cross-disciplinary graduate and undergraduate student programs, an industry partnership program that is leveraged by NSF funding, and pro-active technology transfer programs. The NSF funding allowed a core administrative team for coordination and enabled faculty and students outside of the central discipline of the Center to participate in the Center's research.

Cross-Disciplinary Research. When ATLSS was with full NSF funding, its faculty, staff, and student researchers represented, on average, eleven disciplines from the four colleges of the university. Moreover, most projects had cross-disciplinary teams from three or more disciplines. In contrast, as ATLSS began the 1997-98 academic year, its researchers represented only five disciplines from three colleges of the university, and individual projects involved, at most, two disciplines. As new projects in new alliances have developed during the current academic year, a greater multi-disciplinary effort has occurred. However, the new projects mainly involve single disciplines. Thus, the broad cross-disciplinary characteristic of an ERC is not currently strong in the ATLSS Center. Further, it is questionable whether it will be significantly reinvigorated to expand beyond the traditional involvement of structures and materials.

Cross-Disciplinary Student Programs. A reduction in the level of cross-disciplinary research has led to a reduction in the number of disciplines represented by ATLSS students. At the start of the 1997-98 academic year, only two disciplines, structural engineering and materials science, were represented by ATLSS-supported students. With newer projects, there are three disciplines. However, only one project is truly cross-disciplinary.

In a broader sense, the ATLSS student program is significantly reduced from its ERC level, and is expected to remain so. As an ERC, ATLSS received, as cited earlier, ten fellowships and five tuition scholarships annually from Lehigh. In contrast, Lehigh is now providing six fellowships. From other revenues, ATLSS is supporting five additional students and, since January, there are four students supported by a new alliance. Of these 15 supported students, 14 are degree candidates in civil engineering. This is further evidence that the scope and cross-disciplinary nature of an ERC falters without ERC funding.

Industry/Government Partnerships. ATLSS will continue with a solid program of industry and government collaboration. However, our partnering plan with industry where General Partners contribute annual unrestricted monies to ATLSS is already waning, and our industry collaboration could trend towards a focused program requiring matching funds from industry.

Technology Transfer programs will continue, but at a scaled-back level of funding. Competitive Technologies, Inc., is continuing to move ATLSS technologies to market, but the frequency, size, and scope of ATLSS-sponsored short courses, seminars, and symposia will diminish.

Program Management. To oversee the cross-disciplinary ERC program at ATLSS, an administrative organization existed with a Director, an Associate Director for Research, an Associate Director for Education, a Deputy Director, a Manager of Industry Liaison and Technology Transfer, and a Business Manager. Beyond this Executive group, a Research Committee selected, prioritized, and reviewed research projects while an Education Committee performed the same function for students and student programs. Secondary committees, e.g. Computer Resources and Laboratory Operations, performed other niche functions. As the research scope has narrowed and the number of researchers has shrunk, the need for a committee structure has lessened. The Executive Committee is continuing, but will be restructured. The niche committees continue in order to respond to issues in their areas.

Director Position. The ATLSS Director since the Center's establishment, Professor John W. Fisher, has announced his phased retirement for 1999 and his wish for a new Director to begin with the academic year 1998-99. A national search for a senior professor to fill Dr. Fisher's position in the Civil Engineering Department is underway.

XI. LESSONS LEARNED

Among the lessons that ATLSS learned as an NSF ERC, the following are the most significant:

- The ERC goals are challenging for a university and its ERC team, especially in terms of cross-disciplinary research and industry partnering.
- ERC funding encourages exploratory research with continuity for students. This long-term characteristic is desirable.
- While the ERC program fosters cross-disciplinary research and teams, cross-discipline teams are difficult to sustain and work best on shorter-term projects. For applied research, the PI should be in the application discipline.
- Cross-disciplinary research is difficult to sustain without ERC funding. Replacement funding tends to be more discipline oriented.
- Industry partnering provides the most benefits when partners elect to be attentive to the research, beginning at any early stage, but requires monitoring to ensure that ERC goals and industry goals are both addressed without conflict. Periodic meetings with industry partners are essential.
- It is a difficult and lengthy process to transfer new technology to a heavily fragmented industry, unless the biggest players in that industry very publicly adopt it. The stage between completed research and commercial application and maintenance is a "gray" stage in which new funding is needed for development. Moreover, the authorship of the inventor can be threatened in this latter stage.
- Industry partners are highly unlikely to send employees to the ERC for extended research periods. They simply can't afford it. Conversely, faculty researchers are highly unlikely to send graduate students to industry for a summer or other similar research period. They simply can't do without the students for such a time.
- REU and undergraduate programs are desirable. They feed students into the graduate student program, they provide mentoring opportunities for the graduate students, and enhance an undergraduate's training. They also, however, impose heavy time demands on the core structure and on PIs.
- A strong administrative core structure is essential to coordinate the responsibilities of an ERC program. This core represents a substantial fiscal requirement for the ERC.
- University support, from department chairs whose faculty do ERC research, through the administration, to the President, is essential.
- The cessation of NSF funding at the conclusion of an ERC's term not only requires that the ERC plan for self-sufficiency, but may decrease the commitments that the university was providing the ERC, such as student fellowships and tuition waivers as the university allocates these to other initiatives.
- The ERC concept should be sustainable by NSF, provided that consistent adherence to goals and engineering relevance is maintained.

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