Advanced Composites for Bridge Infrastructure Renewal

Frieder Seible, Gilbert A. Hegemier, and Vistasp Karbhari, *University of California, San Diego*

Applications of advanced composite materials such as glass fibers, aramids, or carbon fibers in polymer matrices are important in extending the life of our nation's bridge infrastructure into the 21st century. The increasing number of deficient bridge structures necessitates the rapid development of new rehabilitation technologies in the form of new materials and applications, with proven structural effectiveness, quality control, durability, and affordability. Advanced composite materials offer unique mechanical and durability characteristics that can affect bridge infrastructure renewal. Recent developments in automated manufacturing and application processes of advanced composite structural components indicate that not only structurally, but also economically, these new materials are becoming very competitive in civil engineering applications. Research at the University of California, San Diego (UCSD), by the Advanced Composites Technology Transfer Consortium (ACTT), shows that, for example, seismically deficient bridge columns can be wrapped with carbon fibers in an automated fashion, reducing current time requirements for equivalent steel jacket installations, and advanced composite replacement bridge decks can be built in one-step manufacturing processes at weight savings by a factor of 10 or more over conventional concrete decks.

Problems with the existing bridge inventory range from wear and environmental deterioration of structural components to increased traffic load demands, and from insufficient detailing at the time of the original design to inadequate maintenance and rehabilitation measures. An estimated 40 percent of all bridges are believed structurally deficient or obsolete, requiring repair, strengthening, widening, or replacement. In addition to increasing or changing traffic demands, common deficiencies include:

1. Deck deterioration due to wear, de-icing salts, temperature and freeze/thaw cycles, chain beating, etc.,
2. Scour at bridge substructures in riverbeds,
3. Corrosion of structural steel members,
4. Corrosion of reinforcement in structural concrete, both mild and post-tensioned,
5. Dynamic response problems under extreme wind or earthquake loads, and
6. Aging of materials.

With the majority of the U.S. bridge inventory built in the fifties and sixties, many bridges are at an age where environmental deterioration, wear, and changing demands require rehabilitation and upgrading measures. Repair, strengthening, and/or retrofitting technologies are still at a state where most applications are empirical, based on experience and trial and error rather than on a sound scientific basis, without the benefits of large-scale experimental verification or adequate analytical predictive and diagnostic modeling.

The art of rehabilitation needs to be quickly developed into a broad-based science to provide the required technical database for the proper assessment of existing structural condition, materials and application processes, combined structural behavior of existing and added components, durability, and environmental impact. The large volume of rehabilitation work requires the development of new technologies based on new materials, new manufacturing processes and, to the civil construction area, new industries, in order to extend the bridge inventory at current service levels into the 21st century.

Advanced composite materials, primarily developed and used in the defense and aerospace industries, offer unique mechanical and chemical characteristics in terms of strength, stiffness, durability, and adhesion to conventional structural materials, with great potential for a wide variety of infrastructure rehabilitation applications. While past attempts to introduce advanced composite materials such as glass, aramid, or carbon fiber polymer matrix composites to the civil construction area have proven uneconomical, recent advances can make advanced composite materials affordable to a degree, where, in combination with strength, weight, and ease of installation benefits, very competitive rehabilitation systems can be developed.

An Advanced Research Project Agency (ARPA) Technology Reinvestment Project (TRP) program conducted by the Advanced Composites Technology Transfer Consortium (ACTT) at the University of California, San Diego (UCSD), addresses the development and application of advanced composites for bridge infrastructure renewal in the form of automated polymer matrix composite (PMC) manufacturing and retrofit technology development for deficient steel and concrete bridges, concrete deck replacement by all PMC bridge decks, and new all advanced composite bridge systems.

Opportunities for Advanced Composites in Bridge Infrastructure Renewal

Advanced composites are materials created through the combination of several material phases, one or more serving as the reinforcement and the other as the matrix. The idea of an advanced composite is analogous to that of reinforced concrete. However, advanced composites present immense opportunities for the tailoring of the material to fit the specific requirements of structural elements. Special mechanical and chemical characteristics of advanced composites, as well as their durability in the civil environment, make them attractive for use in infrastructure rehabilitation. Some of the generic advantages that motivate the investigation for use of advanced composites in bridge repair and renewal are:

1. High strength-to-weight ratio,
2. High stiffness-to-weight ratio,
3. Resistance to chemical attack,
4. Corrosion resistance,
5. Good fatigue resistance,
6. Controllable thermal expansion characteristics, and
7. Unique and controllable damping characteristics.

These advantages, combined with the potential to tailor materials for enhanced performance (such as crash resistance, damping, etc.), have led to increased research into the use of composites in civil infrastructure related applications. For the successful implementation of advanced composites in all of these applications, however, it is essential to understand that design cannot be done following the metals paradigm. Design decisions for composites are coupled to such an extreme degree that decisions made regarding materials, configuration, and processes have intricate connections and interrelations (Figure 1).

A decision made with regard to any one of these has ramifications on the others. For example, if pultrusion were selected as the manufacturing process, fabrication is restricted to constant cross-section products with a large percentage of reinforcement in the axial direction. Similarly, the choice of 3D woven architectures in near-net shape would almost automatically result in the selection of resin transfer molding (RTM) as the manufacturing process. This choice in turn would result in the deselection of matrix material choices to the thermoset family, based on viscosity requirements. The need for cylindrical structural elements presents the opportunity to use a number of fabrication technologies, but the final choice will be determined not only on the basis of shape, but also on the orientation needed. A need for continuous fiber in the hoop direction almost always predicates the selection of a winding type of operation over others because of the intrinsic capability to lay down continuous fibers in tension. In the case of advanced composities, the design process can be thought of as the management of the product realization process (PRP) in the concurrent fashion. A generic materials transformation process for composites is depicted in Figure 2. Within each step, the designer (or design team) faces a number of alternatives (including the possibility of skipping the step). Given the many alternate routes and the implications of early decisions on product competitiveness, the successful completion of the conceptual stage of the PRP, which includes the design of the materials transformation process, is of utmost importance.

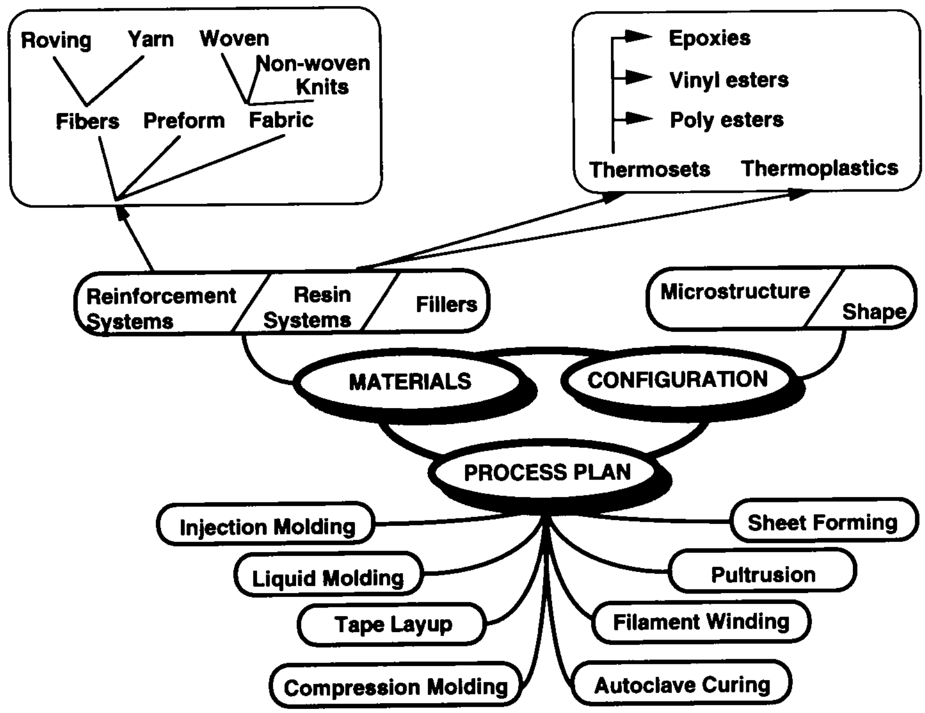

FIGURE 1 Advanced composite materials and manufacturing interactions.

In advanced composites design, the material and structure are very often realized at the same time, thereby complicating the design process. In the case of RTM thermoset systems, the composite material is actually formed at the same time as the structure itself. This important aspect presents both a designer's dream and nightmare at the same time. If armed with the appropriate tools of design and analysis, the designer is able to select the appropriate fabric types the fiber types for each part of a large structure and combine them into one manufacturing operation, such that the structure is tailored to respond appropriately at different points. Advanced composites design, then, is not just the design of an element or structure but essentially the design of the material from which the element is to be fabricated and the design of the fabrication process.

Materials and processes have to be chosen appropriately—glass would be the preferred reinforcement material based on economics, with carbon being used selectively in critical areas. Manufacturing processes such as pultrusion—estimated to give completed profiles and shapes in the $2 to $3/lb range, with raw material costs being as high as 80 percent of the overall costs—are obviously preferably to others such as fiber placement, where costs can be hundreds of dollars per pound, with material costs being in the 10 to 30 percent range. Costs dictate that such processes must be used only for very specific applications and are typically not competitive in the civil construction industry. Table 1 shows some representative property ranges of advanced composites for possible civil construction applications.

For any load-carrying structure, shape is often forgotten. For the application of composites to civil engineering, a one-to-one replacement will not be successful. In fact, a major criticism of pultruded sections applied to date has been that the I-beams buckle or fail in overload. The use of such shapes is probably not appropriate for the loading and materials used, and considerable attention needs to be paid to this factor. The concept of the shape factor was introduced as a dimensionless number characterizing the efficiency of a

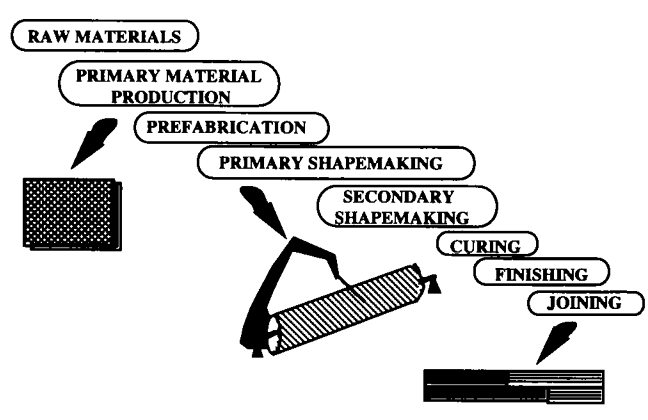

FIGURE 2 Materials transformation process.

TABLE 1 Advanced Composite Material Properties

High Performance Fibers (High Modulus)				
Type	E GPa (Msi)	f_u GPa (ksi)	ε_u (%)	$/lbs
Carbon	320 - 725 (46 - 110)	1.7 - 5.5 (250 - 800)	1.7 - 2.2	40 - 700
Aramid (Kevlar 49,149)	117 - 186 (17 - 27)	3.4 - 4.1 (500 - 600)	2.0 - 2.8	10 - 25
Glass (S)	89 (12.9)	4.6 (665)	5.4 - 5.7	3 - 5

Low-Medium Performance Fibers (Low-Med Modulus)				
Type	E GPa (Msi)	f_u GPa (ksi)	ε_u (%)	$/lbs
Carbon	170 - 310 (25 - 45)	1.4 - 6.8 (200 - 1000)	1.3 - 2.0	12 - 40
Aramid (Kevlar 29)	62 - 83 (9 - 12)	2.8 (400)	3.6 - 4.0	8 - 12
Glass	55 - 81 (8 - 12)	2.8 - 4.1 (400 - 600)	3 - 4.8	1 - 3
Polyethylene (Spectra 900)	117 (17)	2.6 (380)	3.5	40

Resin				
Type	E GPa (Msi)	f_u GPA (ksi)	ε_u (%)	$/lbs
Epoxy	2.0 - 4.5 (0.3 - 0.65)	27.6 - 62.0 (4 - 9)	4.0 - 14.0	1.20 - 3
Vinylester	3.6 (0.49)	80 (12)	4.0	1 - 1.5

specific shape (cylinder, square, I-beam, etc.) for a given mode of loading. Following that approach, it is clear that under tension the best performance (axial load-carrying capacity at the lowest self weight) is given by the combination that results in the highest value of E/ρ, where E is the Young's modulus and ρ is the density. Similarly, in flexure, the higher factor, $E^{1/2}/\rho$, indicates the best materials system for flexural shapes. Table 2 gives the results for a number of materials systems based on these two measures and clearly shows the mechanical advantages that can be derived from advanced composite structural elements and systems.

Seismic Retrofitting of Bridge Columns

Recent earthquakes in California, such as Whittier 1987, Loma Prieta 1989, and Northridge 1994, have

TABLE 2 Comparison of Axial and Flexural Efficiencies for Different Material Systems

Materials System	Youngs Modulus (GPa) E	Density (g/cm³) ς	Axial Efficiency		Flexural Efficiency	
			E/ρ	Ranking	$E^{1/2}/\rho$	Ranking
Mild Steel	200	7.8	25.6	4	1.8	5
Carbon-PEEK	134	1.6	83.8	2	7.2	2
HS Carbon-epoxy	181	1.6	113.1	1	8.4	1
E-glass-epoxy	38.6	1.8	21.4	5	3.5	4
Kevlar-epoxy	76	1.46	52.1	3	6.0	3

shown the vulnerability of bridge columns built before the 1971 San Fernando earthquake.

For example, six of the seven bridge collapses during the recent Northridge earthquake could have been prevented if existing steel jacket column retrofit technology were implemented. Tests on 0.4 scale bridge columns at UCSD (*1*) have shown that carbon fiber jacket retrofits in a flexural lap-spliced plastic column hinge zone, and for full height shear retrofit, can be just as effective as comparable steel jacket retrofits (*2*).

The carbon jackets were installed using an automated winding machine that places six toes of prepreg carbon (12k, AS4) at up to 40 rpm on the column. Advantages of the automated carbon jacket installation are the speed of application, including controlled curing, at approximately one-quarter of the time of installation for comparable steel jackets, and the tailoring of the jacket thickness and fiber orientation, which allow use of the carbon fiber material to the fullest extent.

As an example, the dimensions and reinforcement layout of a shear column test specimen are depicted in Figure 3 together with the variable thickness carbon jacket design. A jacket thickness of only 0.4 mm (0.015 in.) of carbon was required over the shear critical center region of the column to prevent brittle shear failure. The schematic shear test setup is depicted in Figure 4 and experimental load-deflection hysteresis loops for the carbon fiber retrofitted shear column are shown in Figure 5. Completely stable hysteresis loops up to a displacement ductility level of $\mu\Delta = 10.5$ were achieved, at which point the test was terminated due to test setup limitations.

Comparative load-deflection curve envelopes for the unretrofitted or "as-built" shear column, a steel jacket retrofitted column with 5 mm (3/16 in.) jacket thickness, and the carbon fiber retrofitted column are depicted in Figure 6, with a clear improvement of deformation capacity in both steel and carbon retrofitted cases over the "as-built" case, which failed in brittle shear at a displacement ductility of $\mu\Delta = 2.0$.

The steel jacket retrofitted column exhibited a slightly higher initial stiffness and a slight increase in lateral load carrying capacity, with increasing displacement levels due to the isotropic nature of the steel

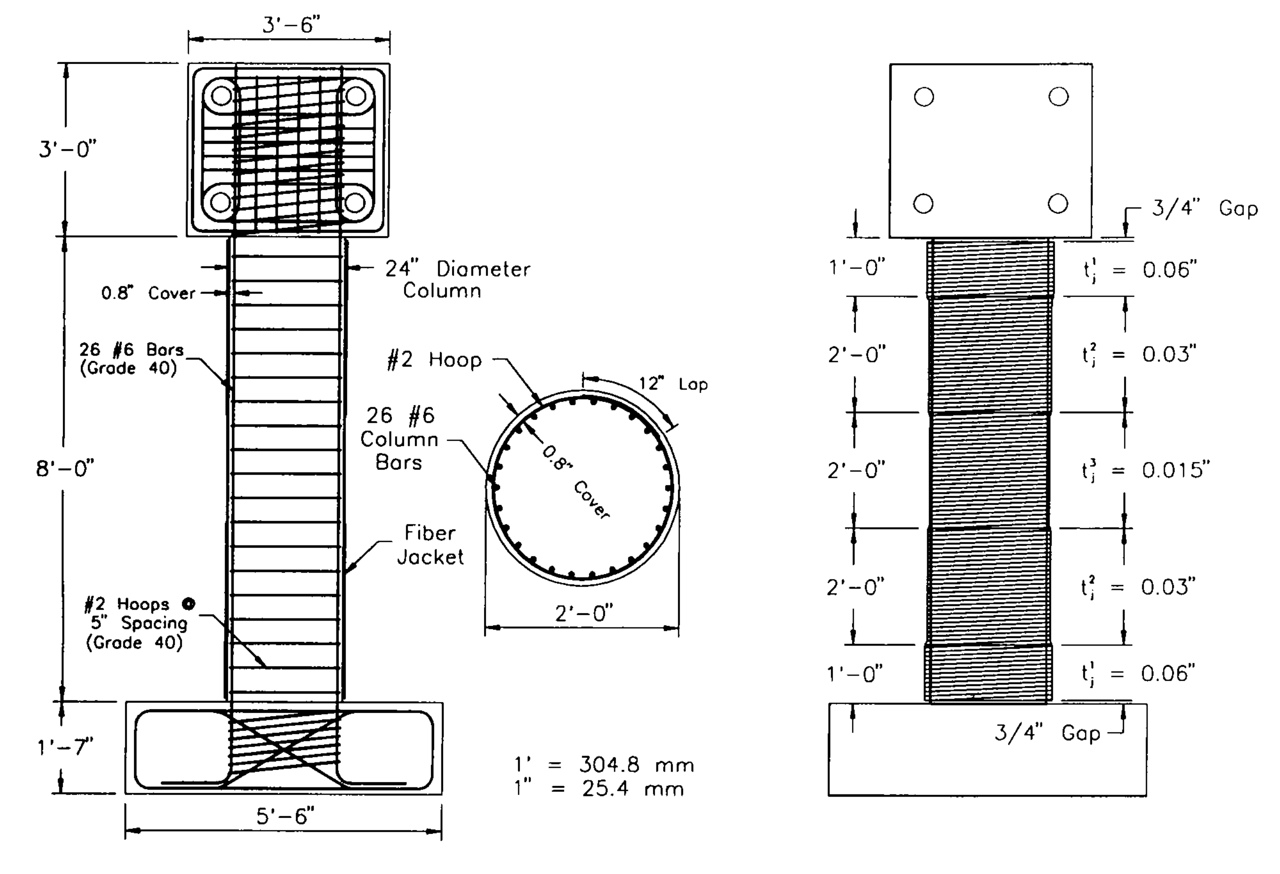

FIGURE 3 **Carbon fiber jacket shear column test specimen details: (*a*) specimen dimensions and reinforcement, (*b*) jacket retrofit design.**

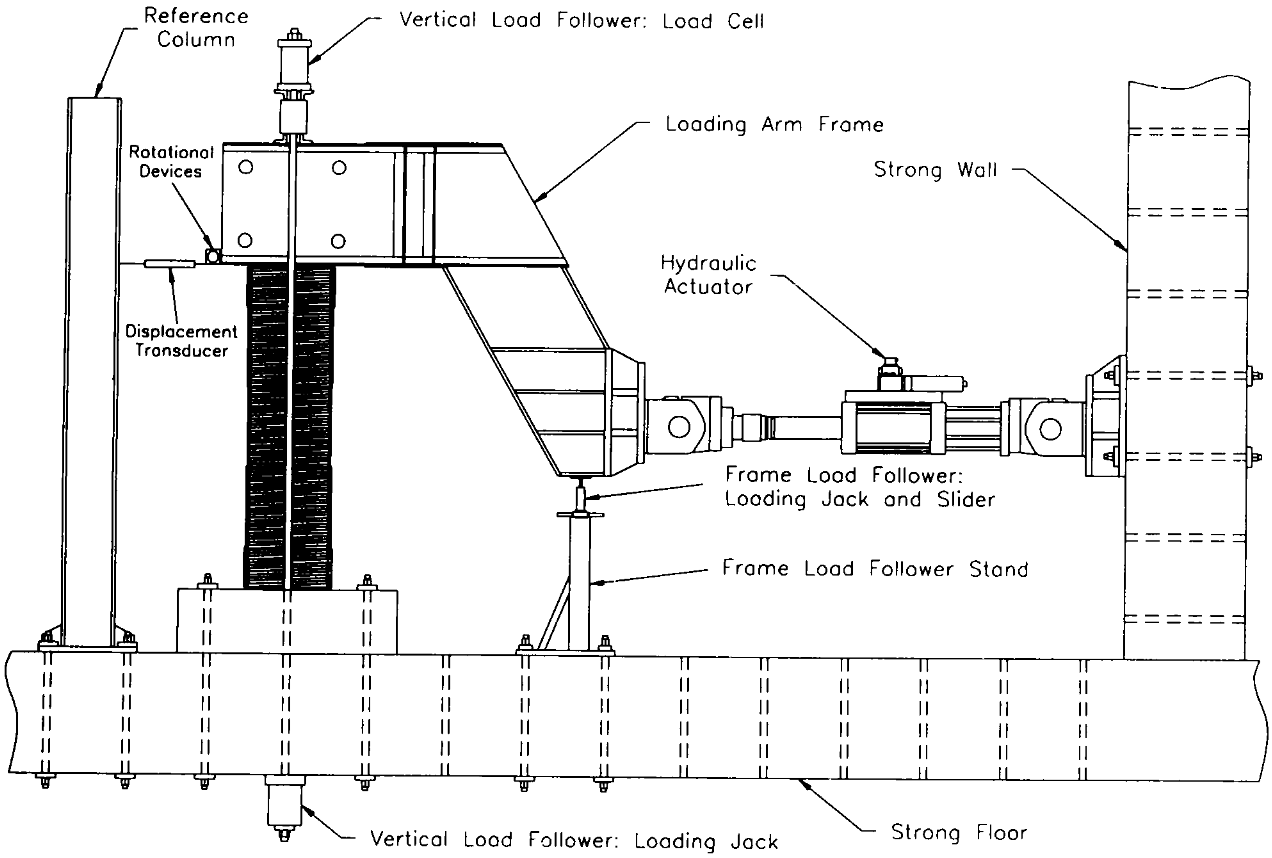

FIGURE 4 Schematic test setup.

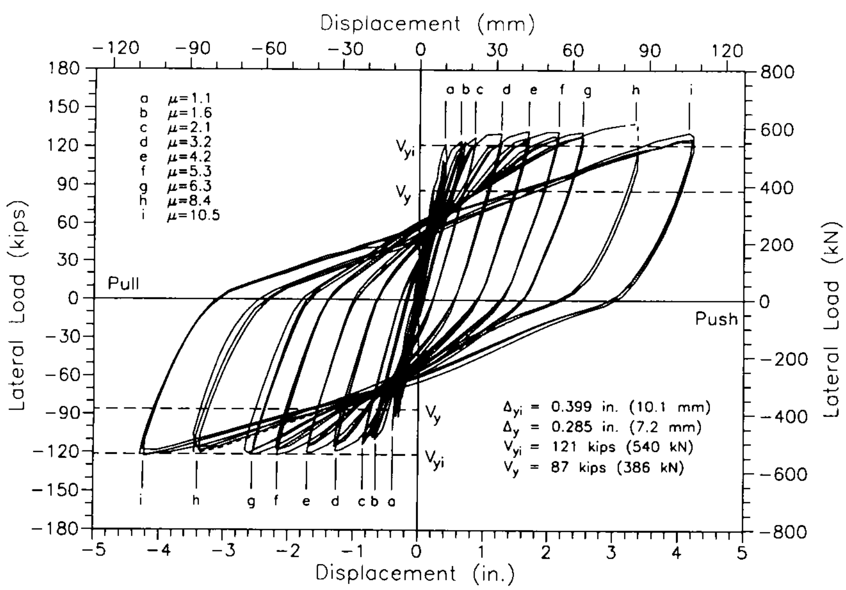

FIGURE 5 "Reduced" horizontal load-displacement curve for fiber retrofitted column.

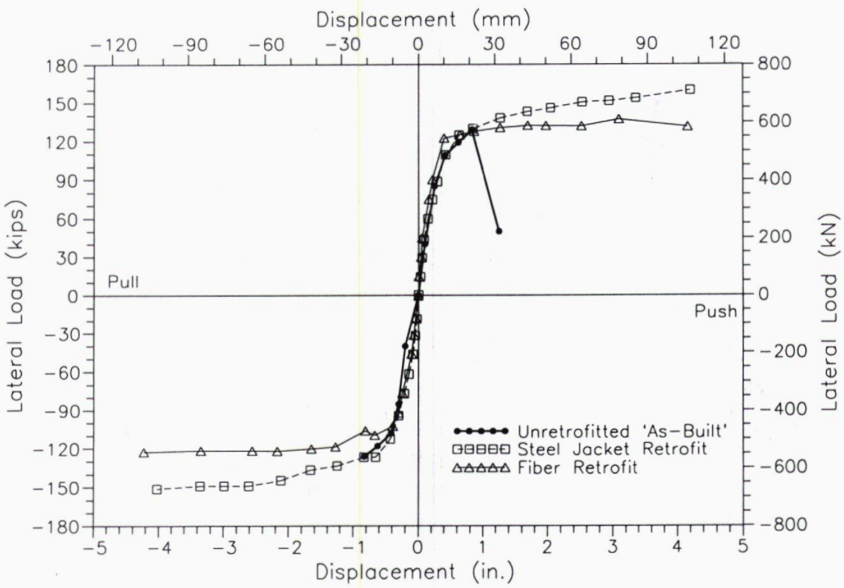

FIGURE 6 **Comparison of load-displacement envelopes for "as-built" steel jacket and carbon jacket retrofits.**

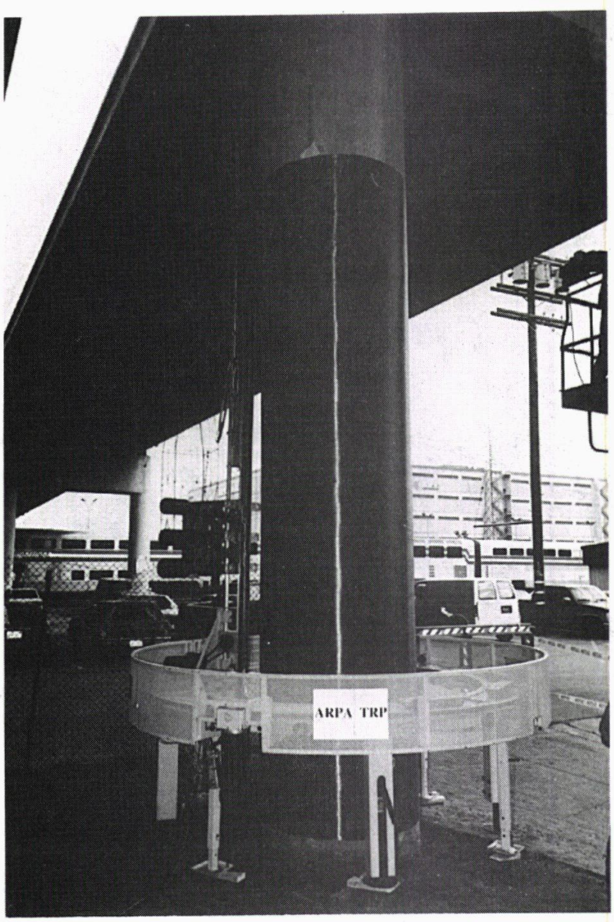

FIGURE 7 **Automated carbon jacket installation.**

jacket, resulting in a more concentrated plastic hinge and more strain hardening at the column ends. Stiffness and capacity increases are not sought for in bridge column retrofits, since typically higher seismic force levels are transmitted to adjacent structural elements. Thus, the carbon jacket with only horizontal or hoop directional strength and stiffness can accommodate the requirement for no stiffness or strength increase even better than a steel jacket, as in Figure 6. With the automated fiber lay-up, which can also be employed for rectangular columns (Figure 7), carbon fiber jackets can be competitive with steel jacket retrofits without even considering premiums for reduced lane closure requirement or early completion incentives.

In addition to automated carbon fiber jacketing systems, developments on in-situ applications of advanced composite hybrid jackets to columns using a resin infusion molding process are currently in progress at UCSD.

Bridge Deck Replacement

Due to their light weight, corrosion resistance, environmental durability, and high stiffness-to-weight and strength-to-weight ratios, advanced composites have potential for use in bridge decks. It should be remembered that a major factor leading to the deterioration of our infrastructure, including bridges, is the deterioration of steel by corrosion, due to both moisture ingress and the use of de-icing salts. The use of composites readily addresses this concern. Although lighter weight may not initially appear to be a major factor beyond reduced seismic demands, it does play an important role. Reduction in dead weight of bridge decks translates to increased live load capacity. In terms of rehabilitation, this could mean that if heavy decks were to be replaced (even partially) with lighter composite construction, the load rating could conceivably be increased. Lighter weight of sections also means a reduced need for specialized equipment such as huge cranes, resulting in lower overall project costs. Transportation costs are also reduced, enabling the designer to consider the use of large sections prefabricated under controlled factory conditions. However, the main impetus would be the significant reduction in life-cycle costs. Despite these advantages, the application of advanced composites to bridges, and in fact to all civil engineering structures, will depend on two major factors: the development of cost-competitive materials and technology, and the deployment of appropriate technology.

A number of manufacturing techniques lend themselves to the efficient fabrication of large structures such as bridge decks. The resin infusion molding process allows for the lay-up of fabric around cores and mandrels (which can later be removed, leaving gaps similar to those in hollow box girders) with specific tailoring of the reinforcement architecture for complex loading conditions. It does not require expensive tooling and, due to the ease of fabrication, can be conducted with relatively low capital expense. Figure 8 shows an example of a full-scale deck section fabricated in a single manufacturing step using the resin infusion molding process. The flexibility of the process lends itself to a true blending of form and function in the same element. The deck section in Figure 8, manufactured and tested by ACTT at UCSD, showed twice the capacity of a comparable concrete deck at one-tenth of the weight. Pultrusion is, as mentioned above, perhaps the most cost-efficient composites fabrication process. It is capable of fabricating large elements of constant cross-section that can then be combined using mechanical or adhesive means for joining. This enables the use of standard type elements so as to fabricate large structures using a building block approach. The Aberfeldy bridge (*3*) is one example of this technology. Perhaps the best option is a combination of pultrusion and VARTM, with the building blocks (in the form of triangular and/or trapezoidal sections) being fabricated using pultrusion and then being connected using the VARTM process. In this case, additional fabric would be used between the pultruded cores, with resin then infused into the fabric. This technology would depend on the formulation of suitable resin systems and control of cure mechanisms to allow good secondary bonds between the pultruded parts and the infusing resin system. Such a method could open new avenues for rapid bridge deck construction, with the last stages even being conducted on site.

Cost-effectiveness of the manufacturing process will be a major factor in the selection and use of a fabrication process. Costs are not only related to those of the constituent materials (resin and fiber) but also to the tooling (molds and dies), quality control, and processing steps. Methods that are automated and use prefabricated elements will obviously have a higher degree of robustness and hence efficiency. It is feasible that in the near future composite components will be available, analogous to prefabricated and precast concrete or steel girders. Concurrent cost modeling with advanced composite replacement decks to date shows that even on a first cost basis, advanced composite decks can be competitive with conventional reinforced concrete or orthotropic steel bridge decks.

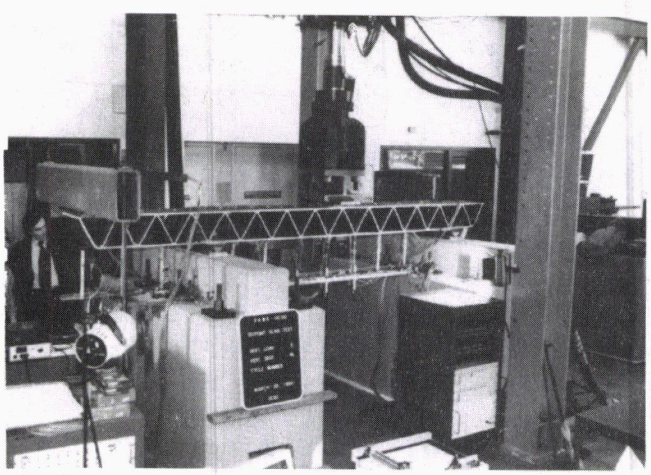

FIGURE 8 Advanced composite bridge deck test.

New Bridge Systems

Developments at UCSD through ACTT and in cooperation with Caltrans and the Federal Highway Administration are demonstrating both the technical and economical feasibility of using advanced composite materials for complete new bridge systems (*4*).

One demonstration project is focusing on a cable-stayed traffic bridge at Gilman Drive across Interstate 5 in La Jolla, where all components, including deck, superstructure, pylon, and cables (Figure 9), are manufactured using advanced composite materials and automated manufacturing technology.

Overall geometry and dimensions are depicted in Figure 10, which shows a cable-stayed bridge solution using conventional materials such as reinforced concrete for the superstructure and steel for pylon and cables. Direct

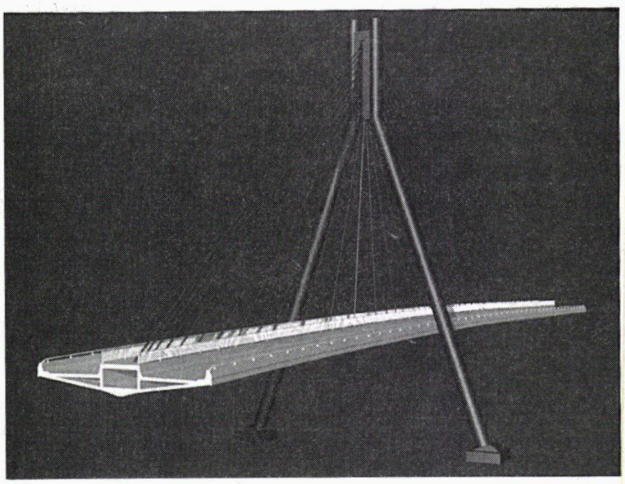

FIGURE 9 **Schematic of Gilman/I-5 cable-stayed bridge.**

cost comparisons are made by means of detailed cost modeling, even during the preliminary design phase, to ensure the development of an affordable and competitive product. The design development to date focuses on two alternate composite bridge types in which design alternative A is considering mass-manufactured, erector set-type composite components assembled by adhesive joining in the field with predominantly longitudinal construction joints. Design alternative B is examining segmental construction with transverse joints or continuous in-situ resin transfer molding technology.

In terms of materials and manufacturing processes, alternative A is investigating the use of standardized pultruded fiberglass sections, which are preassembled to modular deck or soffit panel units prior to field assemblage. On the other hand, alternative B is studying the Resin Infusion Molding process, currently used primarily in the ship industry.

In addition to the Gilman/I-5 cable-stayed bridge demonstration project, these new materials seem to be especially advantageous for the construction and erection of smaller modular bridge systems in regions where heavy lifting equipment is not available or access is restricted. Studies for single span vehicular bridges or pedestrian bridges similar to applications in China (*5*) and Europe (*3*) are currently under way at several research organizations throughout the United States. A major impact on bridge renewal with advanced composite bridge systems can be expected.

Conclusions

Aging and deteriorarion of the U.S. bridge inventory require the rapid development of new rehabilitation technologies. The large volume of bridge infrastructure renewal work necessitates exploration of materials and

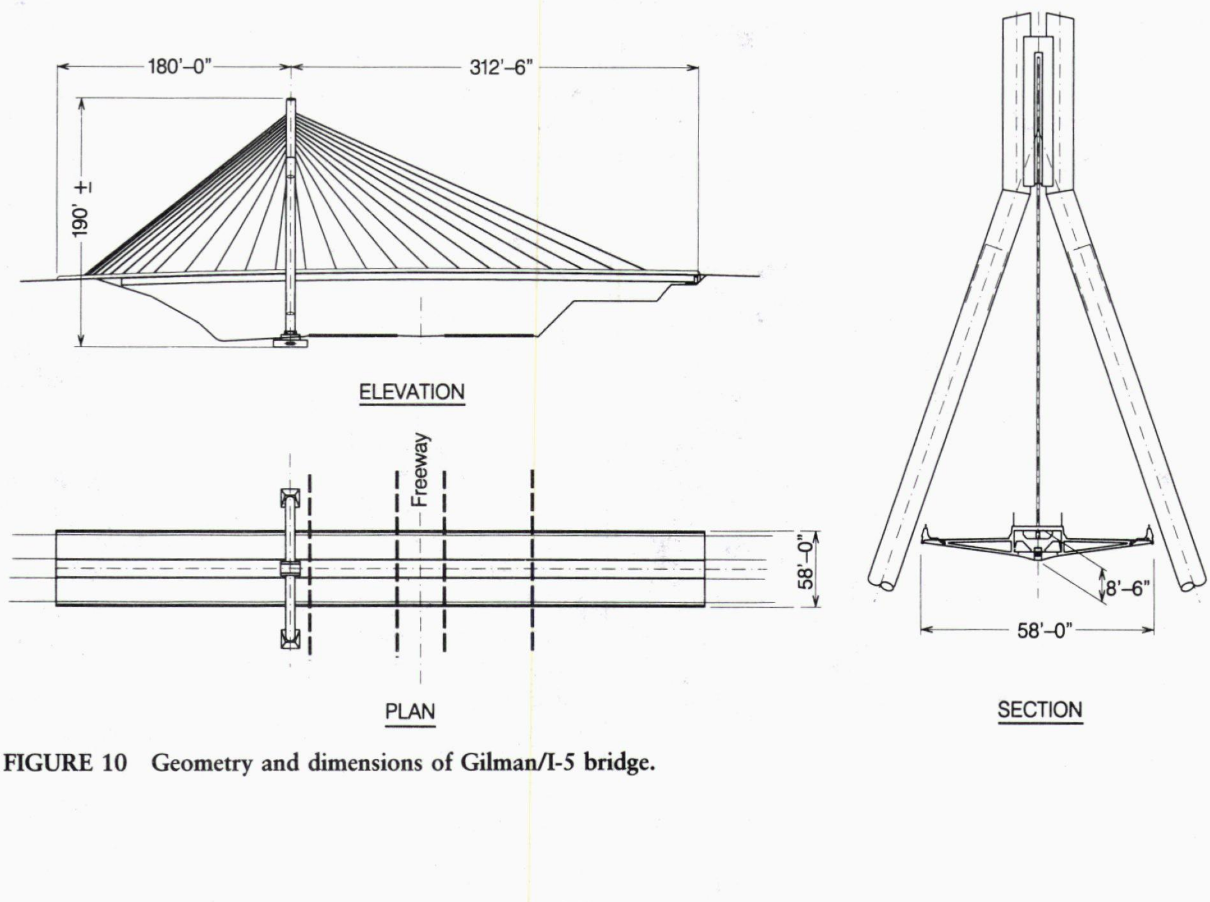

FIGURE 10 **Geometry and dimensions of Gilman/I-5 bridge.**

manufacturing processes that are new to the civil construction industry.

Promising infrastructure renewal technologies based on polymer matrix composites, primarily developed and used in the defense industry, are under development by ACTT. Specific developments and applications to date consist of advanced composite carbon jackets for the seismic retrofit of bridge columns, bridge decks for the complete replacement of existing concrete decks, and design developments for new all-advanced-composite bridge systems.

Research indicates that advanced composite jackets for the seismic retrofit of bridge columns can be just as effective structurally as the current steel jacketing technology. Advanced composite bridge decks, without corrosion or spalling problems, developed and tested show weight and savings over conventional concrete decks by factors of 5 to 10. Furthermore, developments with advanced composites for bridge infrastructure renewal have shown that as soon as automated manufacturing and installation processes can be developed, advanced composite rehabilitation and renewal components can be deployed at full cost-competitiveness with conventional construction materials, even at relatively high current costs for the advanced fibers and resin systems. Combined with excellent mechanical and durability characteristics, even complete advanced composite bridge systems are likely to play a major role in the nation's bridge infrastructure renewal program.

REFERENCES

1. Seible, F. S., G. Hegemier, M. J. N. Priestley, D. Innamorato, J. Weeks, and F. Policelli. *Carbon Fiber Jacket Retrofit of Circular Shear Bridge Column, CRC-2.* Advanced Composites Technology Transfer Consortium, Report No. ACTT-94/02, Structural Engineering, University of California, San Diego, La Jolla, September 1994, 54 pp.
2. Priestley, M. J. N., F. Seible, and Y. H. Chai. *Design Guidelines for Assessment Retrofit and Repair of Bridges for Seismic Performance.* Structural Systems Research Project Report No. SSRP-92/01, University of California, San Diego, August 1992, 266 pp.
3. Seible, R., G. A. Hegemier, and G. Nagy. *The Aberfeldy Glass Fiber Composite Pedestrian Bridge.* Advanced Composites Technology Transfer Consortium, Report No. ACTT-94/01, Structural Engineering, University of California, San Diego, La Jolla, January 1994, 52 pp.
4. Seible, F., and R. Burgueño. *Advanced Composites in Cable-Stayed Bridges.* Seminar on Cable-Stayed Bridges, Miami, Florida, October 1994.
5. Seible, F., S. Zunling, and G. Ma. *Glass Fiber Composite Bridges in China.* Advanced Composites Technology Transfer Consortium, Report No. ACTT-93/01, Structural Engineering, University of California, San Diego, La Jolla, April 1993, 36 pp.