FHWA Study Tour for Advanced Composites in Bridges in Europe and Japan

INTERNATIONAL
TECHNOLOGY

FHWA's Scanning Program

U.S. Department of Transportation
Federal Highway Administration

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NOTICES

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FHWA Study Tour for

Advanced Composites in Bridges in Europe and Japan

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FHWA International Technology Exchange Programs

The FHWA's international programs focus on meeting the growing demands of its partners at the Federal, State, and local levels for access to information on state-of-the-art technology and the best practices used worldwide. While the FHWA is considered a world leader in highway transportation, the domestic highway community is very interested in the advanced technologies being developed by other countries as well as innovative organizational and financing techniques used by the FHWA's international counterparts.

International Technology Scanning Program

The International Technology Scanning Program accesses and evaluates foreign technologies and innovations which could significantly benefit U.S. highway transportation systems. This approach allows for advanced technology to be adapted and put into practice much more efficiently without spending scarce research funds to recreate advances already developed by other countries.

Access to foreign innovations is strengthened by U.S. participation in the technical committees of international highway organizations and through bilateral technical exchange agreements with selected nations. The program is undertaken cooperatively with the American Association of State Highway Transportation Officials and its Select Committee on International Activities, and the Transportation Research Board's National Highway Research Cooperative Program (Panel 20-36), the private sector, and academia.

Priority topic areas are jointly determined by FHWA and its partners. Teams of specialists in the specific areas of expertise being investigated are formed and sent to countries where significant advances and innovations have been made in technology, management practices, organizational structure, program delivery and financing. Teams usually comprise Federal and State highway officials, private sector and industry association representatives as well as the academic community.

The FHWA has undertaken over 20 of these reviews and disseminated results nationwide. Topics have covered pavements, bridge construction and maintenance, contracting, intermodal transport, organizational management, winter road maintenance, safety, intelligent transportation systems, planning, and policy. Findings are recommended for follow-up with further research and pilot or demonstration projects to verify adaptability to the United States. Information about the scan findings, and results of pilot programs are then disseminated throughout the country to State and local highway transportation officials and the private sector for implementation.

This program has resulted in significant improvements and savings in road program technologies and practices throughout the United States, particularly in the areas of structures, pavements, safety, and winter road maintenance. Joint research and technology-sharing projects have also been launched with international counterparts, further conserving resources and advancing the state-of-the-art.

For a complete list of International Technology Scanning topics and to order free copies of the reports, please see the inside back cover of this publication.

Website: www.international.fhwa.dot.gov **E-Mail: international@fhwa.dot.gov**

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EXECUTIVE SUMMARY

Under the Federal Highway Administration's (FHWA) International Technology Scanning Program, a team of 13 U.S. bridge engineers and advanced composite experts from Federal and State transportation agencies, academia, and industry conducted a 2-week scanning tour of Europe and Japan. The purpose of the tour was to assess the state of technology in the use of advanced composite materials, known as fiber-reinforced polymers (FRPs) or polymer matrix composites (PMCs), in bridge design and construction.

The scanning team visited the United Kingdom, Germany, Switzerland, and Japan from 14 to 28 October 1996. The tour included 23 project sites, 1 manufacturing site, and 5 workshops that provided an overview of the developments and applications of PMCs in bridge engineering.

The study had five primary objectives, which were to:

1. Evaluate the performance of PMCs in the civil engineering environment for new bridges and for the rehabilitation of existing structures

2. Gain an understanding of all issues involved in selecting and applying PMCs to bridges, ranging from technical specification to proof testing and performance monitoring

3. Learn about project implementations in the areas of design, construction, and project management

4. Summarize the findings in a comprehensive report for the benefit of the U.S. bridge engineering community

5. Assist in accelerating the acceptance and implementation of PMCs in the U.S. bridge industry.

The results of the first four objectives are documented in this report in the form of ten topical review summaries on issues related to PMCs in bridges. These summaries are organized as follows:

- New Bridge Structures
- Strengthening of Existing Bridges
- Seismic Retrofit
- Design
- Connection and Detailing
- Instrumentation and Monitoring
- Durability
- Research
- Construction
- Management.

The fifth objective was achieved by all scanning team members through an increased awareness and understanding of the state of PMC bridge technology outside the United States. This objective will continue to be met with the dissemination of this report.

The technical findings of the scanning tour can be summarized under three categories: new construction, strengthening of existing structures, and seismic retrofit. Although all the countries visited had built new structures using PMCs, the structures were all in one-of-a-kind demonstration projects to showcase the technology and were supported by significant subsidies from the public and private sectors. The most promise for the use of PMCs in bridge design and construction was found in structural rehabilitation, both for strengthening of existing deficient bridge structures and for seismic retrofit. In both areas, several commercial systems have been developed in the countries visited, including materials, design and application specifications, application methods, and quality assurance procedures. The technologies encountered are of potential interest for the rehabilitation of U.S. bridges, concurrent developments in the United States have resulted in equivalent technologies. The technologies observed by the scanning team can, however, provide additional rehabilitation tools and concepts for broader applications of PMCs in the United States, as long as the fairly high costs quoted for these technologies abroad can be made competitive for the U.S. market.

The scanning team encountered some developments related to connections and detailing of PMCs in bridge engineering, but the general lack of innovative and simple connection concepts seems to slow the implementation of advanced composite structural systems worldwide. All countries visited had similar concerns about durability and long-term performance. Aside from reports on a few accelerated material test programs and long-term exposure tests, however, no systematic and permanent monitoring programs and procedures are in place to assist in developing verified long-term performance and life-cycle cost data.

The focus of research differs from country to country and, in most cases, is product or industry driven. In the United States, the focus of research is more generic, which is partially the result of the funding sources and mechanisms used in this country. Most research in the United States is funded by the Government and conducted at academic institutions. In Europe and Japan, industry in general and the construction industry in particular play more significant roles in PMC research and development for civil engineering applications.

Probably the most significant finding of the scanning team was the close collaboration among the construction industry, the composite materials and manufacturing industry, the civil engineering design community, the academic community, and government agencies. This collaboration has allowed the countries visited to effectively coordinate product development and implementation in a large number of high-visibility demonstration projects to showcase the technology. These demonstration projects are paralleled by comprehensive education and training programs for design professionals and the construction industry. Although similar efforts have been attempted in the United States, they must be characterized as sporadic and isolated.

This report on the use of advanced composite materials in bridges in Europe and Japan provides information on the scanning tour objectives, scope, format, and participants. This is followed by summaries of the findings in the topic areas outlined above. Project descriptions for each of the sites visited and the workshops are included for both Europe (projects E1 to E18) and Japan (projects J1 to J11). The project descriptions are followed by brief assessments of the technologies and their potential uses for bridge applications in the United States. Pertinent published references are listed at the end of this report.

1.0 SCANNING TOUR OBJECTIVES

In recent years, problems with the aging and rapidly deteriorating bridge infrastructure have prompted a resurgence in research and development of new and more durable materials for bridge infrastructure renewal. New materials may have applications in rehabilitation of existing bridges and complete structural replacement or new construction. Fiber-reinforced polymer matrix composite (PMC) materials were developed and used primarily in the aerospace and defense industries. In addition to outstanding strength/weight ratios, these materials also have a high degree of chemical inertness to most civil engineering or bridge environments, which strongly suggests their consideration for bridge infrastructure renewal. Over the past decade, numerous research projects into the characterization and development of PMCs in bridge design and construction have been ongoing in the United States. Even so, the United States seems to be falling behind countries in Europe and Japan, where there are a number of high-visibility demonstration projects and field applications.

To gauge the state of U.S. technology in this area, the FHWA organizaed a technology scanning tour to assess advanced composite bridge construction technology in selected European countries and Japan. In addition, the panel was to identify and recommend areas in which foreign technologies should be further investigated for possible transfer to the United States and pinpoint mechanisms and procedures through which U.S. advanced composite bridge technology could be enhanced and accelerated. The mission statement and goals in the following paragraphs guided the scanning team's investigation.

1.1 Mission Statement

In fulfilling the mandate of Section 6005 of the Intermodal Surface Transportation Efficiency Act (ISTEA), a scanning team was formed to observe, investigate, and document the application of fiber-reinforced polymer composite materials in highway bridge structures and the experiences of trans-portation agencies in Japan and selected European countries (the United Kingdom, Switzerland, and Germany) in using such applications.

1.2 Goals

The goals of the scanning team were to:

- Evaluate the performance and durability of bridges built with composite materials as they relate to the manufacturing process of the composite materials and the fabrication process of structural members for new construction, as well as for rehabilitation and/or strengthening of existing members

- Interview owners, designers, fabricators, and contractors of composite material bridges about technical issues involving selection, specification, design, manufacturing, fabrication, construction, inspection, proof testing, and performance monitoring, as well as research and development of bridge applications for composite materials

- Gather and review details and documentation on all aspects of the projects, including design methodology, specifications, standards, production processes, contracting methods, costs, and performance records

- Publish a comprehensive report summarizing the findings of the scanning team to share with engineers and researchers and to make presentations to the U.S. bridge engineering community on practical structural applications.

- Assist in accelerating the implementation of fiber-reinforced polymer composite materials in U.S. bridge engineering.

2.0 SCOPE OF STUDY AND PARTICIPANTS

2.1 Scope of the Study

This study of the state of advanced composites in bridge structures in Europe and Japan consisted of a review of published materials on advanced composite bridge projects; four organizational meetings before and during the scanning tour; the scanning tour itself, including visits to the United Kingdom, Germany, Switzerland, and Japan; a review of literature obtained during the scanning tour; and this assessment report. During the tour, the scanning team visited 23 projects and 1 manufacturing facility. Team members also participated in 5 workshops on advanced composite bridge technology, emphasizing development and applications in the particular country or region.

The study focused on the 10 topic areas listed in Table 1. The issues of the development and application of advanced composites in bridges for the topic areas are presented in Section 3.0 of this report. This section includes a summary of the scanning team's findings and their relevance to U.S. practice, an assessment of transferable technologies, and a discussion of research and development needs in the United States. Of particular interest were the applications of fiber-reinforced PMCs in the construction and rehabilitation of new and existing bridge structures.

For new bridge structures, technological advantages of these materials were investigated, together with their impact on construction, maintenance, durability, and cost. For structural rehabilitation of existing bridges, the application of PMCs was broken down into strengthening and seismic retrofit because of differences in design and performance objectives. Strengthening typically addressed issues of structural repair and increased live load. Seismic retrofit also requires consideration of structural ductility, in addition to strength and stiffness considerations.

Table 1. Study Tour Topic Areas

Topic Number	Topic Area
1	New Bridge Structures
2	Strengthening of Existing Bridges
3	Seismic Retrofitting
4	Design
5	Connections and Detailing
6	Instrumentation and Monitoring
7	Durability
8	Research
9	Construction
10	Management

In examining design, the scanning team explored the differences in design philosophies and approaches, as well as the availability of comprehensive design guidelines, criteria, and standards. Particular emphasis was placed on connections and detailing, because simplification in construction and long-term performance of connections are critical for broad application of advanced composites in civil engineering. The health and service life monitoring of bridge systems becomes increasingly important; this issue is addressed under the topic of instrumentation and monitoring.

Table 2. Scanning Tour Workshops and Projects

Country	Project	Project Description
United Kingdom	E1	Cambridge Workshop: development of aramid cables, Prof. C. Burgoyne
	E2	Aberfeldy Footbridge: all advanced-composite cable-stayed bridge, pultruded glass-reinforced polymer (GRP) box sections and aramid cable stays
	E3	Bonds Mill Bridge: bascule bridge made with pultruded GRP box sections
	E4	Second Severn Approach Enclosures: pultruded GRP enclosures for bridge approaches
Germany	E5	Düsseldorf Workshop: overview on post-tensioning of bridges with composite cables, Prof. F. Rostasy
	E6	Ulenbergstrasse Bridge, City of Düsseldorf: glass fiber prestressing tendons in two-span concrete slab bridge
	E7	Schiessbergstrasse Bridge: Bayer AG, Leverkusen, glass fiber prestressing tendons in three-span slab bridge with fiber optic sensors for crack detection and chemical sensors for corrosion monitoring
Switzerland	E8	EMPA Workshop, Dübendorf: presentation and lab visit, Prof. U. Meier
	E9	Storchenbrücke, Winterthur: cable-stayed bridge with two carbon-fiber-reinforced plastic (CFRP) cables
	E10	Co-op City, Winterthur: department store with carbon laminate strengthening of floor slabs around escalator cutouts
	E11	Oberriet Rhein Bridge: recently strengthened with 1 km of carbon laminates
	E12	Fürstenland Bridge: strengthening of box girder bridge with 8 km of carbon laminates applied to insides of webs
	E13	Koblenz/Waldshut Railway Bridge: strengthening of steel cross-girders with carbon laminates
	E14	Advanced Composite Manufacturing: manufacturing of carbon laminate sheets and filament winding
	E15	Haltingen Bridges: steel plate bonding project
	E16	Giezenen Bridge: ca.1912 arch bridge with corrosion damage to steel plate strengthening
	E17	Ibach Bridge: first carbon laminate strengthening of a prestressed concrete bridge
	E18	Sins Wooden Bridge: strengthening of cross-girders with carbon laminates
Japan	J1	Tsukuba City Workshop: Japanese perspective on FRP reinforcement and tendons, Public Works Research Institute (PWRI)
	J2	Osaka Worskhop: carbon fiber sheet strengthening
	J3	PWRI Composite Cable-Stayed Bridge: entirely composite cable-stayed pedestrian bridge, demonstration project, 20 m long
	J4	Sumitomo Bridges: external aramid cable prestressing tendons
	J5	Aramid Rod Anchor Blocks
	J6	Seismic Column Retrofitting
	J7	Akashi-Kaikyo Bridge: aramid pilot rope for world's longest span bridge (1,992-m mainspan)
	J8	Hanshin Expressway Bridge: deck strengthening, CFRP sheet strengthening
	J9	Rolling Traffic Load Test Simulator: reinforced-concrete slab strengthened with carbon fiber sheets, Prof. S. Matsui
	J10	Hiyoshigura Viaduct: CFRP sheeting, Tonen Corporation
	J11	Tokyo Rainbow Bridge: precast aramid tendon, prestressed walkway panels

The most important obstacles to the general acceptance of PMCs in civil engineering and construction are the uncertainties, claims, and speculations regarding the durability of these materials in the civil engineering environment. To overcome these obstacles, significant research is required into the long-term behavior of these materials, accelerated test methods and procedures, new shapes and forms, and design concepts, in conjunction with conventional structural materials and design standards. Finally, the impact of these new materials on actual construction, in terms of weight and handling, and on the management of projects involving PMCs was investigated.

2.2 Projects, Locations, and Schedules

A list of workshops and project sites visited is in Table 2, which is divided into sections on Europe (projects E1 to E18) and Japan (projects J1 to J11). Workshops in each country are listed first, followed by the projects and site visits.

Locations of the sites visited are indicated by project numbers on the maps of the United Kingdom, Germany, Switzerland, and Japan (Figures 1 through 4). Summaries of the individual projects in Europe are in Section 4.0, and the projects in Japan are summarized in Section 5.0.

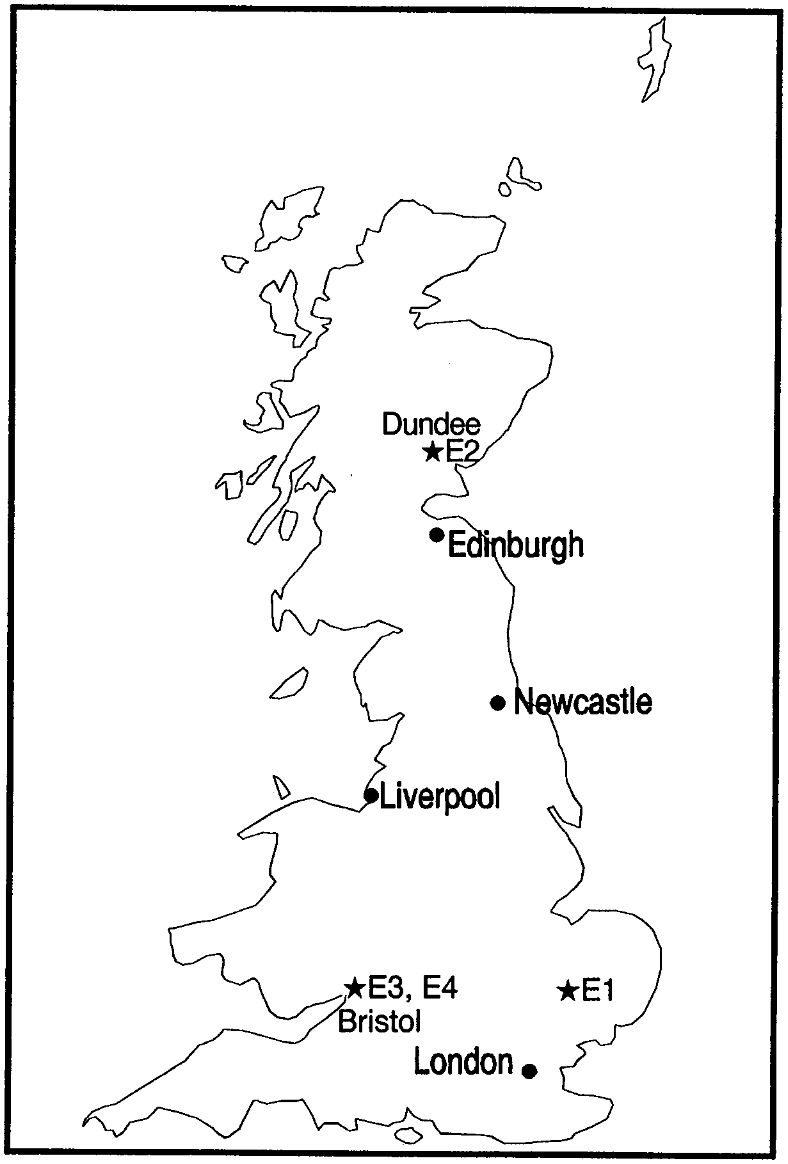

Figure 1. Map of England and Scotland

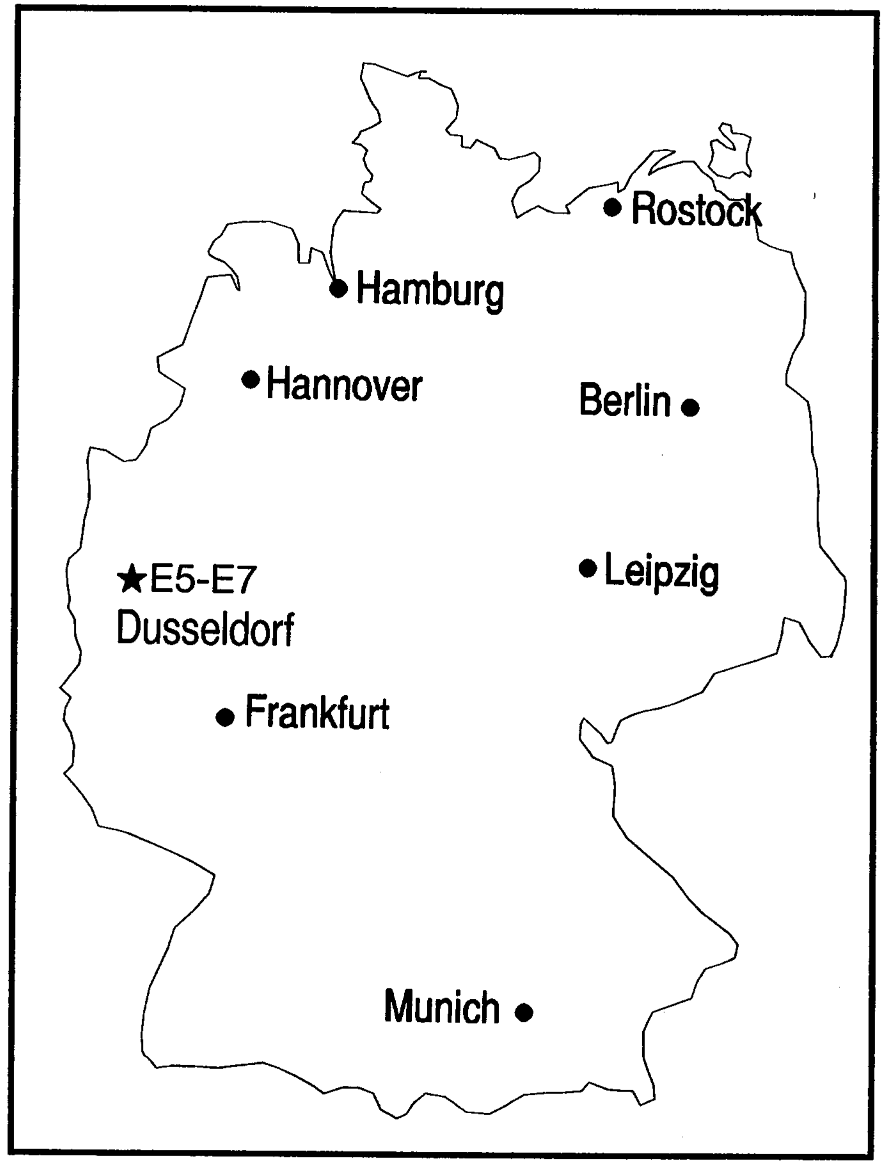

Figure 2. Map of Germany

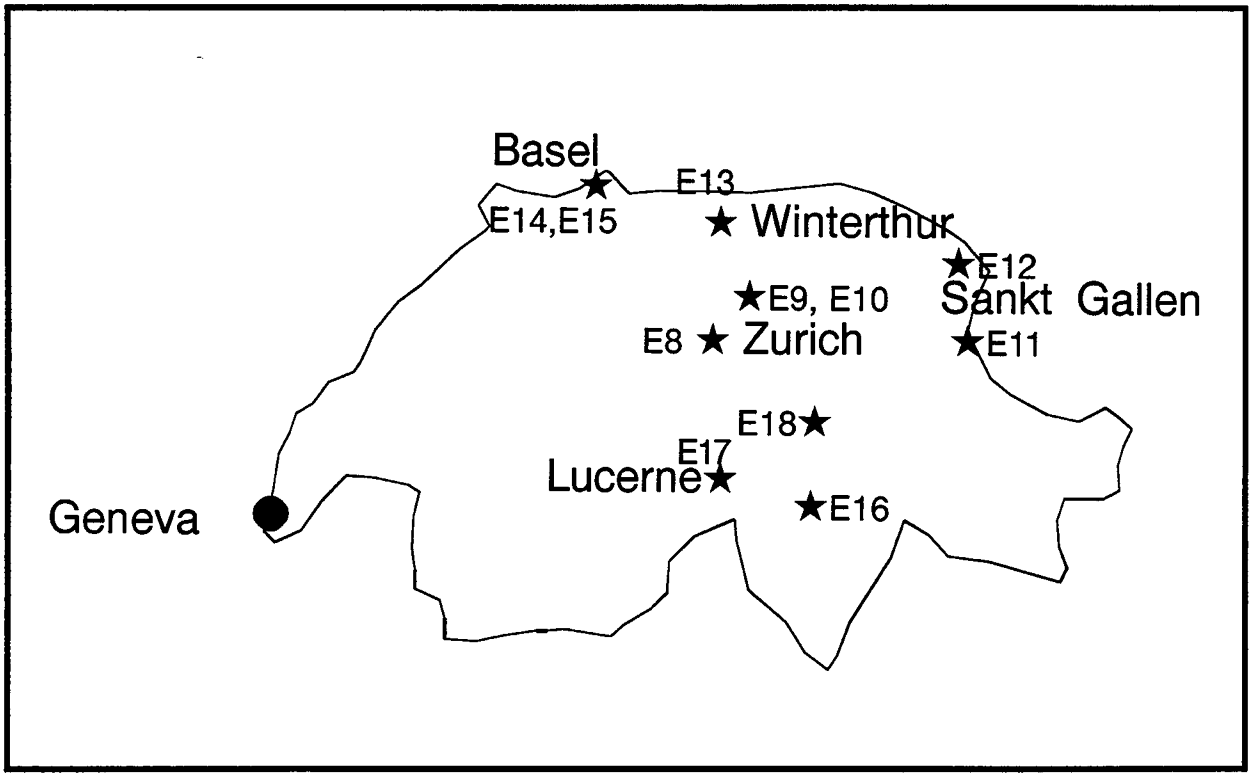

Figure 3. Map of Switzerland

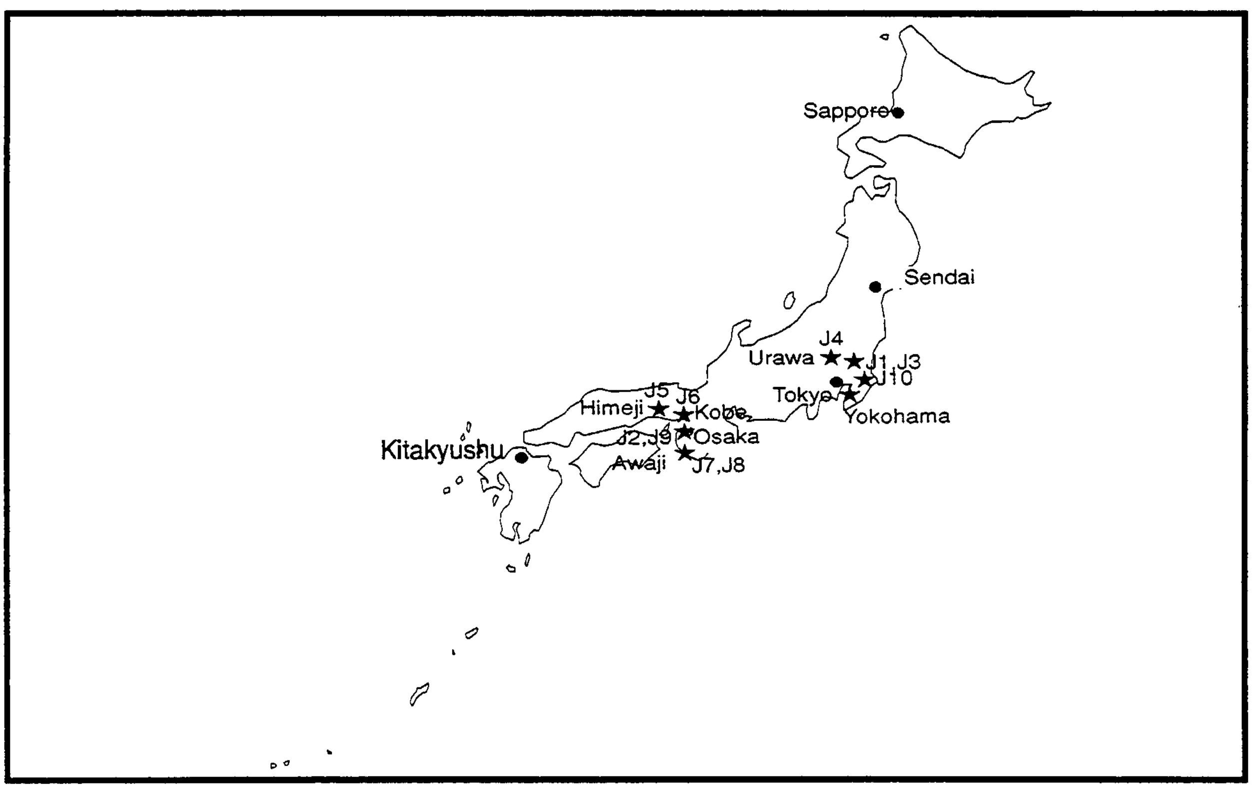

Figure 4. Map of Japan

2.3 Scanning Team Members and Foreign Contacts

The scanning team included a broad representation of professionals from the bridge design and composite manufacturing areas. The team consisted of four representatives from FHWA, four representatives from State Departments of Transportation (DOTs), two representatives from academia, and three from the advanced composite industry (see Table 3). The team members' diverse backgrounds and expertise in bridge design, research, project management, administration, composite manufacturing, and composite application provided balance and depth to the study and workshop discussions and to this report.

In each of the countries visited, the scanning team was privileged to meet some of the leading experts in the fields of advanced composite bridge research and development. A partial list of the principal contributors to the information exchange during this technology scanning tour is in Table 4.

In addition to the key people listed in Table 4, who helped greatly in organizing the study in their respective countries, other participants and experts in individual projects and workshops are listed with each project report. Their contributions to the discussions and assistance with providing project information are greatly appreciated.

Table 3. Scanning Team Members and Affiliations

Name	Affiliation
John Hooks	FHWA, Washington, DC (Co-Chair)
James Siebels	Colorado DOT, Denver, CO (Co-Chair)
Frieder Seible	University of California, San Diego, CA
John Busel	Composites Institute, New York, NY
Milo Cress	FHWA, Lincoln, NB
Chao H. Hu	Delaware DOT, Dover, DE
Fred Isley	Hexcel, Pleasanton, CA
Gloria Ma	Xxsys Technologies, San Diego, CA
Eric Munley	FHWA, McLean, VA
Jerry Potter	Florida DOT, Tallahassee, FL
James Roberts	California DOT, Sacramento, CA
Benjamin Tang	FHWA, Washington, DC
Abdul-Hamid Zureick	Georgia Institute of Technology, Atlanta, GA

Table 4. Foreign Contacts and Experts

Country	Name	Title	Affiliation
United Kingdom	Mr. A.E. Churchman	Managing Director	Maunsell Structural Plastics, Ltd.
	Dr. Chris J. Burgoyne	Lecturer	University of Cambridge
Germany	Dr.-Ing. Ferdinand Rostasy	Professor	Technical University, Braunschweig
	Dr.-Ing. Rainer Voigt	Technnical Program Director	Federal Department of Transportation
Switzerland	Prof. Urs Meier	Director	Federal Laboratory for Materials Testing and Research (EMPA)
	Dr. Marie Anne Erki	Professor and Head	Dept. of Civil Engineering, Royal Military College of Canada
Japan	Mr. K. Nishikawa	Head, Bridge Division	PWRI, Ministry of Construction
	Mr. M. Kanda	Chief Research Engineer, Bridge Div.	PWRI, Ministry of Construction
	Mr. M. Uemara	General Manager	Tonen Corporation

3.0	TOPICAL SUMMARIES

To assess the state of advanced composite technology in selected European countries and Japan and to put this state of technology in perspective with developments in the United States, findings from the review are discussed in the contexts of the topics shown in Table 1. Each topical review summarizes the findings relevant to the topic with direct reference to projects E1 through E18 and J1 through J11. Following the summary of findings, the relevance to U.S. practice is established, and transferable technologies are identified. Finally, research and development activities necessary to advance the use of PMCs in U.S. bridge engineering and construction are discussed for each of the topic areas.

3.1	NEW BRIDGE STRUCTURES (TOPIC 1)

Summary of Findings

Advanced composite materials have been used on a wide variety of new bridge projects both in Europe and Japan. The observed application of advanced composite materials in new bridge construction can be classified into three categories: bridge structures made entirely of advanced composite materials (Figures 5, 6, and 7); concrete bridges with nonmetallic reinforcement, prestressing components, or external cable stays; and protective or secondary structural systems (Figure 8).

The scanning team visited three bridges made entirely of advanced composite materials: the Aberfeldy Footbridge (E2), the Bonds Mill Bridge (E3), and the Public Works Research Insitute (PWRI) Composite Cable Stayed Demonstration Bridge (J3).

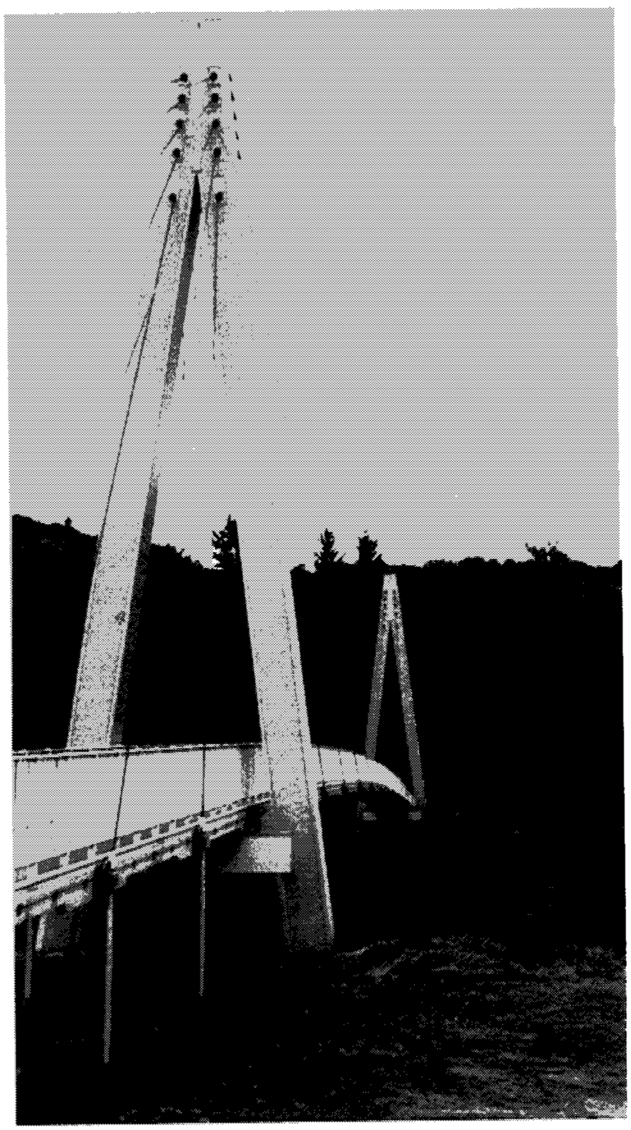

Figure 5. Aberfeldy Footbridge (E2)

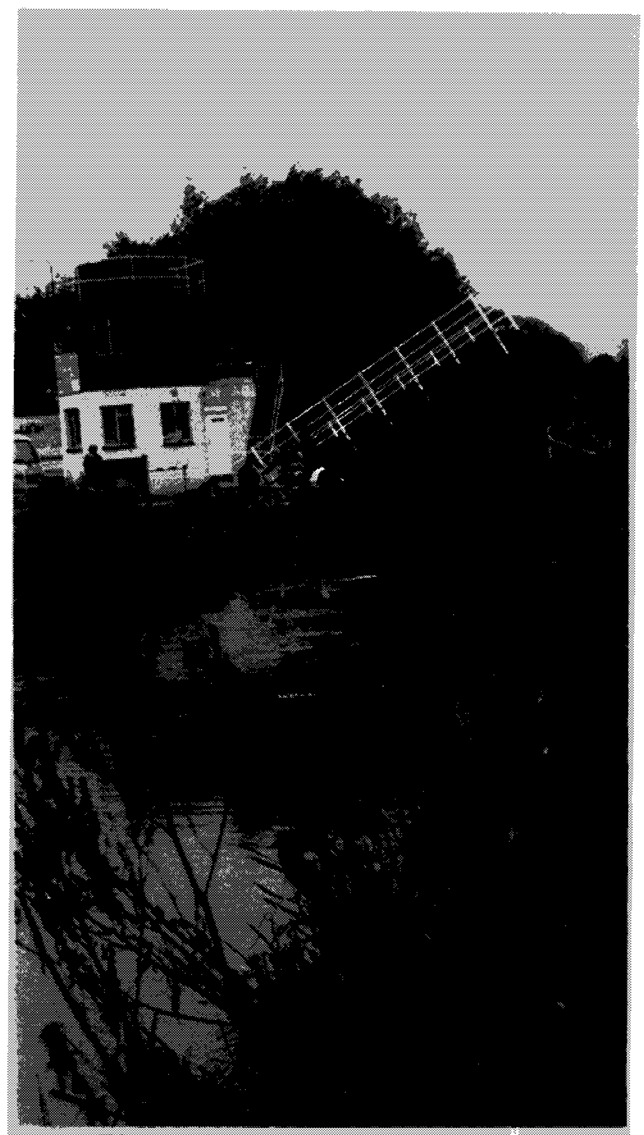

Figure 6. Bonds Mill Bridge (E3)

These projects clearly show the feasibility and potential for advanced composite bridges and constitute the pioneering work in this field. All three bridges, however, are "one-of-a-kind" or demonstration projects; broad-based acceptance in the civil engineering community and commercialization have not yet occurred. Although significant advantages for construction can be derived from the light weight and high strength/weight ratio of these new bridge materials, durability and long-term

Figure 7. PWRI Demonstration Bridge (J3)

Figure 8. Maunsell's Bridge Enclosure System

performance issues still require further research and data development. Initial cost also seems to be a major obstacle when material and labor donations to the projects are discounted. Long-term life-cycle cost models do not yet exist, but need to be developed before broader applications can be implemented.

For advanced composite bridge systems to be successful, components should be modular, and assembly should be simple and have reliable connections. The Aberfeldy and Bonds Mill Bridges rely on chemical bonding with an epoxy adhesive and a mechanical toggle system. The PWRI demonstration bridge uses only mechanical fasteners in the form of glass-fiber-reinforced plastic (GFRP) bolts with assembly and connection concepts derived from steel structures. The long-term performance of these connection details must be monitored.

Currently, complete FRP bridge systems are limited primarily to pedestrian bridges. For all-advanced-composite vehicular bridges, developments in guard or barrier rails and their connections to the decks are still needed.

Significant developments and advances were observed both in Europe and Japan in the use of fiber-reinforced plastic reinforcing and prestressing elements and stay cables for structural concrete. Tendon and rebar systems based on carbon (CFRP), aramid (AFRP), and GFRP exist. Cable/tendon types of all fiber materials have been developed in Europe. Examples of these developments include:

- In the United Kingdom, the dry parallel aramid fiber Parafil® system developed by Linear Composites
- In Germany, the GFRP Polystal® system developed by Bayer AG and Strabag AG
- In Switzerland, the CFRP carbon fiber cables and anchorages developed by BBR and the Federal Laboratory for Materials Testing and Research (EMPA).

All three systems have been used as internal or external post-tensioning systems or as cable stays in numerous demonstration projects (E2, E6, E7, and E9).

Again, however, cost differences in using these developments compared with continuously improving conventional steel tendon technology limit commercial applications. The least expensive tendon system of those mentioned, the German GFRP (E5) post-tensioning system Polystal,® was discontinued for economic reasons after the system development and demonstration projects. Problems with durability of conventional steel tendon systems were at one time the driving force behind FRP tendon development. Now, improved corrosion protection systems for steel tendons lessen the need for new nonmetallic materials, except for applications in very corrosive environments. Thus, applications of FRP tendons are expected to be limited. The best opportunities are in ground anchors, external tendons, and guy systems. Some special applications can benefit from the lower modulus in FRP tendons, which results in reduced prestress losses in case of tendon shortening.

In Japan, in addition to aramid and carbon prestressing tendon systems, unstressed FRP reinforcing bars and grids have been developed (J1). The most common brand names of aramid reinforcement are Technora,® Arapree,® and Fibra,® and of carbon elements, Leadline,® CFCC,® and NACC.® Glass fibers are used in the reinforcement grid system known as Nefmac.® Actual usage of FRP reinforcement or prestressing of concrete bridges has declined in Japan since the early 1990's for simple economic reasons. However, close to 100 demonstration projects of new concrete structures with FRP reinforcement have been executed in Japan (J15) and elsewhere (Figure 9).

Finally, the use of FRPs in the form of enclosure systems for new steel girder bridges was demonstrated in England by Maunsell (E4). Such systems provide a protective enclosure that reduces corrosion by 95 percent, provides access and a platform during construction of the bridge concrete deck, and allows continued inspection and maintenance without traffic interruptions. Maunsell developed this bridge enclosure system from the pultruded glass-fiber-composite (GFC) modules of its advanced composite construction system (ACCS), with the addition of special connectors, seals, and edge members. Although the concept is very attractive from a technical point of view, the high cost associated with the enclosure system (about US$44/ft^2 of enclosure area) may make commercialization outside the United Kingdom difficult.

Relevance to U.S. Practice

The FRP tendon systems developed in Europe and Japan are of interest, because only limited U.S. developments are in progress in this area. In particular, the applications as ground anchors and external tendons should be investigated. Also, short prestressing units, where anchor set, creep, and relaxation can greatly diminish actual prestressing force levels, should be reevaluated for use of FRP tendon technology.

Transferable Technologies

In addition to the acquisition of complete tendon systems for specific applications, the Swiss anchorage technology for carbon tendons seems very promising. This technology includes gradated stiffness in the anchorage housing filler material by means of aluminum oxide pellet additions to the epoxy matrix (E8, E9).

Research and Development

For further research and development of FRPs in new bridge systems, primary emphasis must be placed on low-cost manufacturing, simple and reliable connection details, and complete characterization of issues related to durability. Furthermore, design guidelines and standards should be developed, and training of engineering and design professionals in these new technologies should be facilitated.

Figure 9. Beadington Trail Bridge, Calgary, Alberta Post-Tensioned With Leadline CFCC® Tendons (J1)

3.2	STRENGTHENING OF EXISTING BRIDGES (TOPIC 2)

Summary of Findings

Strengthening of existing bridge systems with FRPs has been widely observed both in Switzerland and Japan. In all strengthening projects, the composite material was carbon-fiber based, because carbon fibers offer the best strength, stiffness, and durability characteristics. The strengthening philosophies and approaches in Switzerland and Japan vary, however, based on differences in the perceived problems and rehabilitation philosophies.

The primary area of application of CFRP bridge-strengthening measures is in deck strengthening, mainly for conventional-composite reinforced-concrete decks on steel girders. In Switzerland, the main objective in deck strengthening is the transverse positive moment capacity between longitudinal girders. In Japan, the deficiency is primarily the deck punching shear capacity. In both cases, increased live-load capacities (increased legal truck loads) are the main reasons for strengthening the deck soffit.

The Swiss concept of additional live-load capacity in the transverse direction between steel girders (E11) relies on discretely spaced and epoxy-bonded pultruded carbon laminates that are 1 to 2.5 mm (0.04 to 0.1 in) thick and 25 to 120 mm (1 to 5 in) wide. These act as concen-trated strips of additional soffit reinforcement, spaced as much as 0.75 m (2.5 ft) apart (see Figure 10). This spacing clearly does not affect or improve the potential deck punching shear problems under traveling wheel loads, but is used to increase the factor of safety in terms of flexural deck capacity. CFRP laminate strengthening is not used where the factor of safety is less than 1 or where the concrete quality of the deck soffit is deteriorated. The pultruded carbon laminates are manufactured by Stesalit AG, and the strengthening system is marketed by Sika Corporation as Sika Carbodur.®

The Japanese concept for strengthening the deck slab soffit is driven by two design considerations: supplementation of very

Figure 10. CFRP Laminate Strengthening (E11)

little, nominally provided longitudinal deck reinforcement and the wheel load punching shear failure mode for higher legal loads and illegal overloads. Thus, both the soffit area between longitudinal girders and the bridge deck cantilever soffit regions are strengthened (J8). Because punching shear failure under wheel loads can occur anywhere in the bridge deck, distributed strengthening in the form of carbon sheet wet layup strips covering the entire soffit area are used (J2, J9, J10) (see Figure 11). Three main manufacturers and products exist on the Japanese market: Replark® from Mitsubishi, Towsheet® from Tonen, and Torayca Cloth® from Toray.

Figure 11. CFRP Sheet Strengthening (J2)

In addition to differences in design philosophies, the Swiss and Japanese systems also differ in ease of application and quality control. The Swiss system requires minimal surface preparations (only grinding in the strip area) and provides a high degree of quality control as a result of due to the use of premanufactured and certified laminates. Japanese systems require onsite field mixing of the epoxy matrix, as well as sandblasting and priming of the entire bridge deck soffit area. Both systems use direct tension pullout tests of cored discs to validate tensile bond characteristics between the carbon overlay and the concrete substrate. During these tests, the failure surface has to be located in the concrete substrate for a successful application.

In addition to deck slab strengthening, both systems have been applied to concrete column and girder strengthening (E9, J17, J18). Tests and applications in Switzerland (E8, E12) have also demonstrated CFRP laminate strengthening on the sides of beam or girder webs for temporary or permanent strengthening measures.

The costs for the various strengthening techniques vary from project to project. For current U.S. market conditions, costs were estimated to be approximately US$30/ft of installed CFRP strip and approximately US$15 to $25/ft^2 per layer of wet layup carbon sheet. Note that these estimates can change considerably, based on material costs and production volumes.

Relevance to U.S. Practices

Bridge-strengthening systems do have considerable relevance to the U.S. market because of the large number of deficient bridges in the U.S. inventory. However, deck punching failures under wheel loads, encountered in Japan, do not seem to be a problem in most U.S. bridges. Furthermore, carbon sheet strengthening has also been developed and applied in the United States. No additional relevance exists, other than the need to apply this technology consistently.

Transferable Technologies

The Sika Carbodur® system is currently being evaluated in the United States as part of the Civil Engineering Research

Foundation Hitec Program. This system, together with two of the Japanese systems, could have numerous applications in U.S. bridge strengthening where flexural deck deficiencies exist.

Research and Development Needs

Research and further developments should focus on a philosophy that is consistent with U.S. design practice. Research and development should also focus on design guidelines and criteria that will allow general applications, not just in regions where safety factors need to be slightly increased. In particular, anchorage and CFRP termination guidelines should be established, as well as design criteria that would ensure full participation of the concrete substrate, through strain limits and quantifiable crack width control.

3.3	SEISMIC RETROFIT (TOPIC 3)

Summary of Findings

Rehabilitation for seismic strength and/or ductility enhancement of bridge structures with FRP was observed only in Japan. The study tour did not visit regions of high seismicity in Europe. Seismic retrofit with FRPs in Japan was limited to square and rectangular bridge columns, using either aramid or carbon sheet overlays in a manual wet layup process (J2, J6) (Figure 12).

In Japan, the seismic retrofit philosophy for bridge columns is somewhat different from the U.S. approach. The primary emphasis is on rehabilitation in the form of strength enhancement, not in increased deformation capacity or ductility. Most single-bent bridge columns in Japan have cutoffs (dropoffs) of the main column reinforcement at one or more locations along the column height. These are strictly based on linear elastic demands of first mode or cantilever response, without tension shift considerations for flexurally cracked zones. Past earthquakes in Japan, in particular the Kobe earthquake of 1995, have shown the vulnerability of these single column bents with the formation of flexural hinges at the bar cutoff location, when elastic design levels are exceeded. Seismic retrofit in Japan addresses this longitudinal flexural strength deficiency by addition of longitudinal column reinforcement in the form of FRP sheet overlays of predominantly vertical fibers. Even small amounts of FRP sheets with horizontal fiber orientation can also significantly increase column shear strength, which was another deficiency encountered in large rectangular single column bents during the 1995 Kobe earthquake. Both aramid and carbon sheet (or tape) retrofit applications have been developed and applied in Japan. To date, an estimated 200 bridge columns have been retrofitted with CFRP sheet overlays, and another 800 or more retrofits are in the planning and construction phases (J2, J6).

The three primary manufacturers for CFRP sheets are Mitsubishi with the Replark® system, Tonen with the Towsheet,® and Toray with the Torayca Cloth.® All systems are applied using similar processes: sand-blasting of the column surface, sealing or priming with epoxy primer, application of the CFRP sheets in vertical and horizontal layers, and epoxy saturation of each layer. Various application processes that ensure proper field mixing of multicomponent epoxies by distinct color schemes for the components and the mixed adhesive, such as

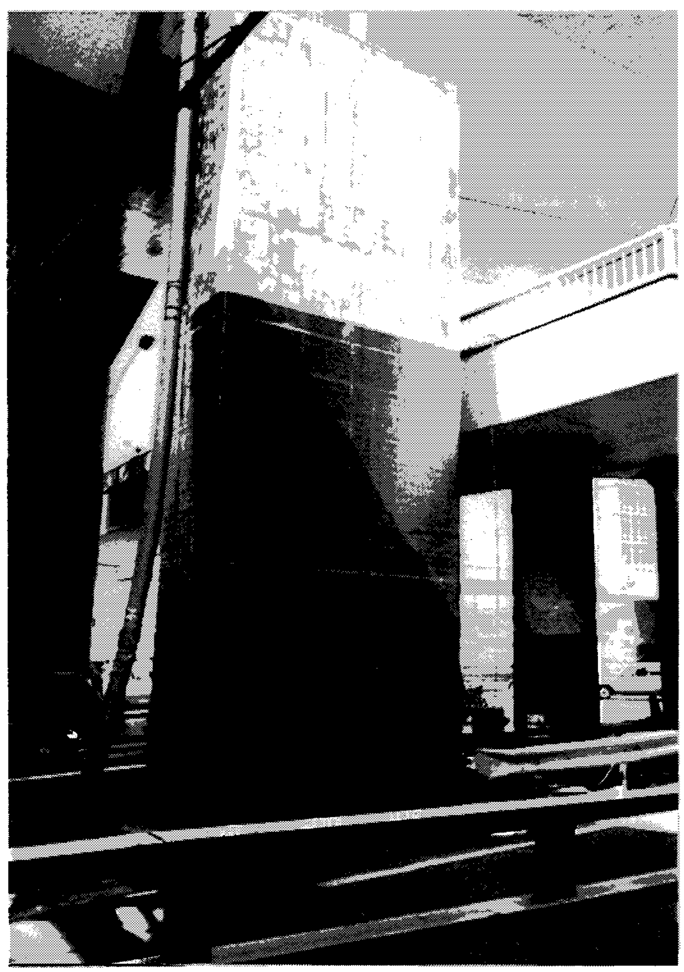

Figure 12. Seismic Retrofit of Bridge Columns With CFRP Sheets

the Sho-bond system, are used to provide a high level of quality assurance. The dimensions of the single column bents currently retrofitted with CFRP sheets do not allow significant ductility enhancement in the potential plastic hinge region at the column base with the CFRP sheets applied directly onto the rectangular column geometry. Significant transverse or out-of-plane stiffness would be required from the jacket retrofits to stabilize the longitudinal column bars against buckling. However, the same is true for thin steel plating of rectangular columns. Although some tests on small-scale rectangular or square columns at Sumitomo Construction Company (J6) showed ductility enhancements by a factor of about 2, the same enhancement cannot be expected in full-scale columns with side dimensions of up to 2 to 3 m (6.6 to 9.8 ft).

In addition to the FRP sheet bridge column retrofit, Mitsubishi and Obayashi have also developed an automated carbon tow, wet-winding system that has been used primarily for chimney retrofits, not bridge columns.

Relevance to U.S. Practice
The seismic column retrofit technology with FRP sheet overlays is clearly relevant to general U.S. seismic retrofit practices, but it is not unique. It is already practiced widely in the United States, although with different design philosophies, guidelines, and criteria.

Transferable Technologies
The Japanese CFRP sheet systems should be considered for application to seismic column retrofit in the United States. Application should, however, be subsequent to full validation testing to meet U.S. design criteria.

Research and Development Needs
Significant strength enhancement both for flexure and shear can be expected with CFRP sheet overlays, even on large rectangular concrete columns. Considerable research is required, however, both in the United States and Japan, to establish design and behavior models for large concrete sections in which only the perimeter is reinforced and the core is made up of effectively unreinforced concrete.

3.4 DESIGN (TOPIC 4)

Summary of Findings
The lack of comprehensive design guidelines for the use and application of FRP materials in bridge design and construction seems to be one of the key reasons that FRPs have so far been applied only in one-of-a-kind demonstration projects. Clearly, each of the projects observed was guided by specific design requirements and criteria, but few attempts have been made to formulate comprehensive national and international standards. Design guidelines range from proprietary-limit state design packages, such as the one developed for new structures by Maunsell for the ACCS (E1 to E4) to system-specific guidelines developed in Switzerland by EMPA and Sika for CFRP laminate strengthening. Only in Japan do efforts seem to be underway to develop more generic design guidelines for groups of applications, such as cable systems and CFRP sheet strengthening.

With the possible exception of the Maunsell system, which was described in very general terms as a complete-limit state design package independently and specifically developed for the ACCS, all other applications were developed in conjunction with conventional concrete technology. These applications require direct reference of the design to conventional national design procedures and codes. It is difficult to assess all the aspects and implications of the specific design approaches encountered, but the following list highlights some general impressions of the state of design using advanced composite materials in civil engineering and bridge applications.

- The high strength and relatively low modulus of affordable advanced composites often result in designs that are stiffness driven and do not use the strength capacities.
- Thin FRP laminates, overlays, or members need to be checked and designed for local stability (e.g., GFRP webs in the Bonds Mill Bridge [E3]) and may require stabilization with structural foam cores or stiffeners.
- To provide effective interaction with existing concrete members, the crack widths in the concrete need to be limited to levels that still ensure full aggregate interlock. Strain limits in the existing reinforcement (E10 to E12) and strain limits in the exsiting FRP overlay should play a greater role in design criteria and guidelines.
- Design of FRP strengthening measures for existing concrete structures must address FRP reinforcement termination and spacing requirements to provide safety and serviceability performance levels consistent with conventional concrete design practice.
- Loss of strength or aging of certain FRPs under sustained loads, referred to as "stress corrosion," seems to be a potential problem (E5, E8) with GFRP, in particular, and should be addressed as part of the design process.
- Cyclic load and fatigue characteristics of FRPs seem to exceed those of other materials, as long as the stress range and the mean stress do not facilitate stress corrosion.
- High temperature and fire response characteristics can be controlled by resin

additives and coatings and can be comparable to or better than those for conventional materials, such as steel.

- Durability of advanced composite materials under the typical civil engineering environments still requires a broader data base, both from accelerated tests and long-term exposure tests, before durability can be used as a dominant design parameter.

- Because of the multitude of fibers and fiber architecture, resins and resin formulations, and manufacturing processes for advanced composite materials, strict performance specifications—not material or process specifications—are needed to ensure safety and serviceability.

- In the design process, more emphasis should be placed on the light weight of FRPs and simplifications that can be derived from this characteristic in the construction process.

- Detailed cost/benefit models, including maintenance and life-cycle data, should be developed, both for advanced composite materials and conventional materials to provide rational bases for choices of materials.

Relevance to U.S. Practice
Although some of the design criteria and guidelines developed in other countries deal with similar performance issues, they have indirect relevance to U.S. design practices. Some behavior characteristics that were observed and documented could, however, form the basis for research and development in the United States.

Transferable Technologies
Because design philosophies, procedures, criteria, and codes need to be accepted by the U.S. civil engineering community, direct transfer of design technologies is only applicable in a limited form. Direct correlation to U.S. design practice must be established.

Research and Development Needs
Design guidelines for the United States need to be developed and based on well-defined performance criteria, rather than on material or process specifications. These guidelines must address the impact of uncertainties in short- and long-term mechanical characteristics in the form of partial safety factors.

3.5 CONNECTIONS AND DETAILING (TOPIC 5)

Summary of Findings
The directional and highly anisotropic nature of advanced composites, and of the fibers themselves, make connections and detailing of local force transfer regions paramount design considerations.

For new advanced composite structural systems, success depends largely on the connections. Specifically, the ease and speed with which individual components can be assembled and the performance of these connections, over time, in typically highly stressed regions will determine the viability of these systems. Different connection systems were encountered in Europe and Japan. In the Aberfeldy (E2) and Bonds Mill Bridges (E3), Maunsell used adhesive bonding and special pultruded connector elements with a mechanical toggle system (Figure 13). In Japan (J3), a more traditional steel construction approach was employed, using bolted connections, in which the bolts are manufactured from GFRP (Figure 14). In all three new bridge demonstration projects, the connections are significantly overdesigned and exposed to low permanent stress levels. Maunsell also developed a special suspender, or bracket, system for its bridge enclosure concept (E4).

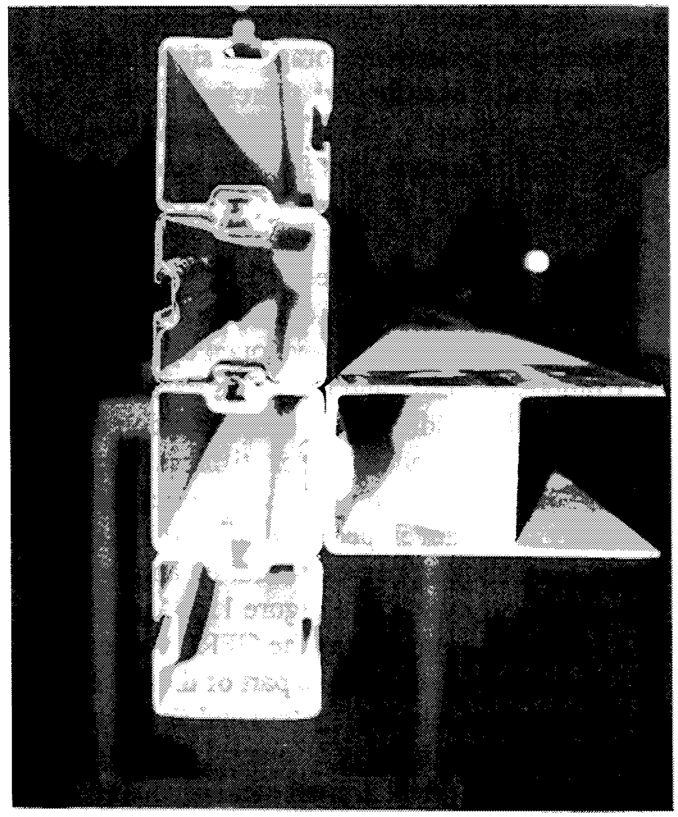

Figure 13. Toggle Connection for Pultruded GFRP Panels

Both in Europe (E5, E9) and in Japan (J1, J3), reinforcement and cable systems mimic conventional reinforcement and tendon anchorage details, in the form of bonds with deformed bars or twisted strands and in metallic anchorage housings for prestressing tendons. In Japan, nonmetallic cable anchorages of GFRP were installed in one of the demonstration projects (J4). To eliminate tendon failures in the anchorage, new types of filler materials in the anchor cones need to be developed to ensure a gradual force transfer with constant shear

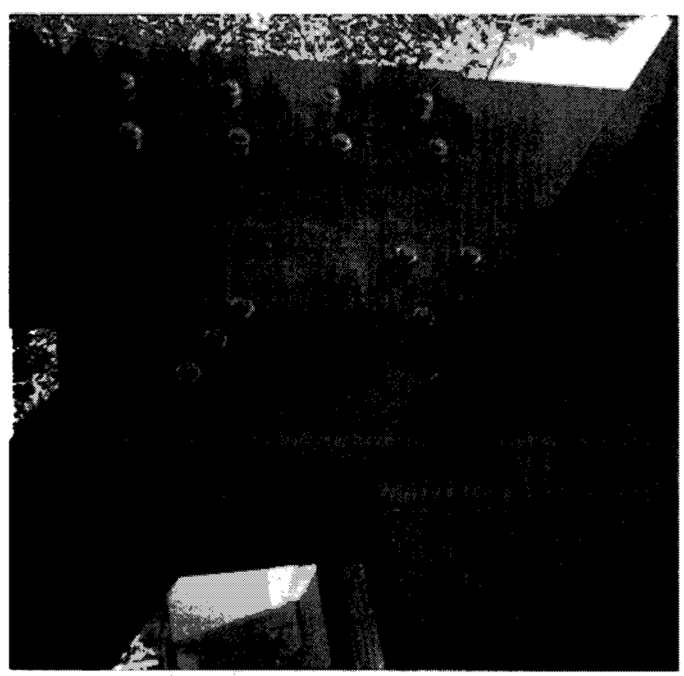

Figure 14. GFRP Bolted Connection

stress distribution between the composite tendons and the anchor block housing. This force transfer is accomplished through the use of resin fillers of various stiffnesses inside the conical anchorage. A significantly larger force transfer and, therefore, total anchorage length, is required for advanced composite tendons than for steel tendons. Tendon anchorage systems that are based on significant research and development and show promise for future applications include the anchor cone and spike for the dry parallel aramid fiber cable, developed by Linear Composites, Ltd., and known as Parafil® (E1, E2). In addition, the carbon tendon anchorage with gradated filler stiffness through the addition of aluminum oxide pellets in the epoxy filler, developed by BBR and EMPA (E8, E9) shows promise for future applications (see concept in Figure 15). Another promising technology is the GFRP anchorage housing developed as part of the Technora® post-tensioning system and applied in one of the Sumitomo demonstration bridge projects (J4). Very limited data on actual failure loads and locations of tendon and anchorage systems and on manufacturing and installation costs were made available to the team.

Finally, the connections between FRP laminate or sheet-strengthening measures and the existing concrete structures are typically controlled by the tensile (horizontal shear) strength of the existing concrete substrate. Because of the low substrate tensile characteristics and the high tensile capacity in the adhesive/resin system, generally no special design or detailing requirements arise. Other considerations include prestress CFRP laminates or applications where high forces can develop in discrete laminate strip systems and additional anchorage requirements into the concrete core or to the compression zone of the member.

Relevance to U.S. Practice
Although the connections and details observed by the scanning team seemed functional and well developed, they also represent fairly complicated systems that will be difficult to transfer to the U.S. market because of cost implications. The advantages of the manufacturing and assembly phases of the connections and details observed may be limited and do not seem to justify replacement of conventional construction technology in the United States.

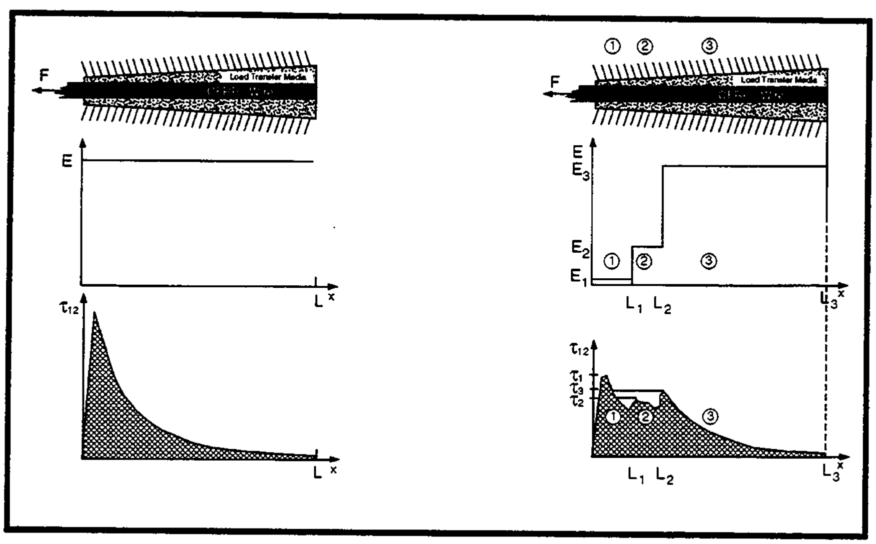

Figure 15. Carbon Rod Anchorage Model
Reproduced with permission from EMPA.

Transferable Technologies

Specific technologies related to connections and details that deserve further investigation for transfer to the U.S. market are the CFRP cable anchorage system in Switzerland, the glass-fiber-reinforced composite (GFRC) nonmetallic anchorage developed in Japan, and the connection details of Maunsell's ACCS.

Research and Development Needs

For complete composite bridge structures, no connections of guard or barrier rails to the composite bridge deck have been developed. All connection systems need to be exposed and evaluated for durability under the typical civil engineering environment. This evaluation would include short-term accelerated tests and permanent instrumentation and monitoring of demonstration projects.

3.6 INSTRUMENTATION AND MONITORING (TOPIC 6)

Summary of Findings

One of the surprising findings of the team was that, despite the many questions and concerns raised about the durability characteristics of FRPs in the civil engineering environment, no long-term field instrumentation and monitoring plans for prototype projects have been developed or implemented.

The only permanent monitoring system was encountered at the Schiessbergstrasse Bridge (E7) in Leverkusen, Germany, where the Polystal® tendon system has effectively been discontinued in production. The emphasis of this monitoring system was more on the demonstration of the instruments, data gathering, and transmission than on the continued performance monitoring of the bridge.

Short-term testing and monitoring over and above simple service load tests and one-time, in situ proof load tests are performed systematically both in Germany and Switzerland. In England, limited tests were primarily conducted to support academic studies. Most short-term monitoring programs were discontinued after a few years, because the bridge response had stabilized and no changes were recorded. No permanent or semipermanent instrumentation on the prototype structures visited in Japan was encountered.

All countries visited conduct laboratory or demonstration field tests as part of their FRP system development and in situ service load tests. Conventional strain and deflection measurements seem to be routinely conducted following the FRP installations. However, no specific plans or schedules exist to repeat service load or proof load tests at regular intervals to determine changes in response characteristics.

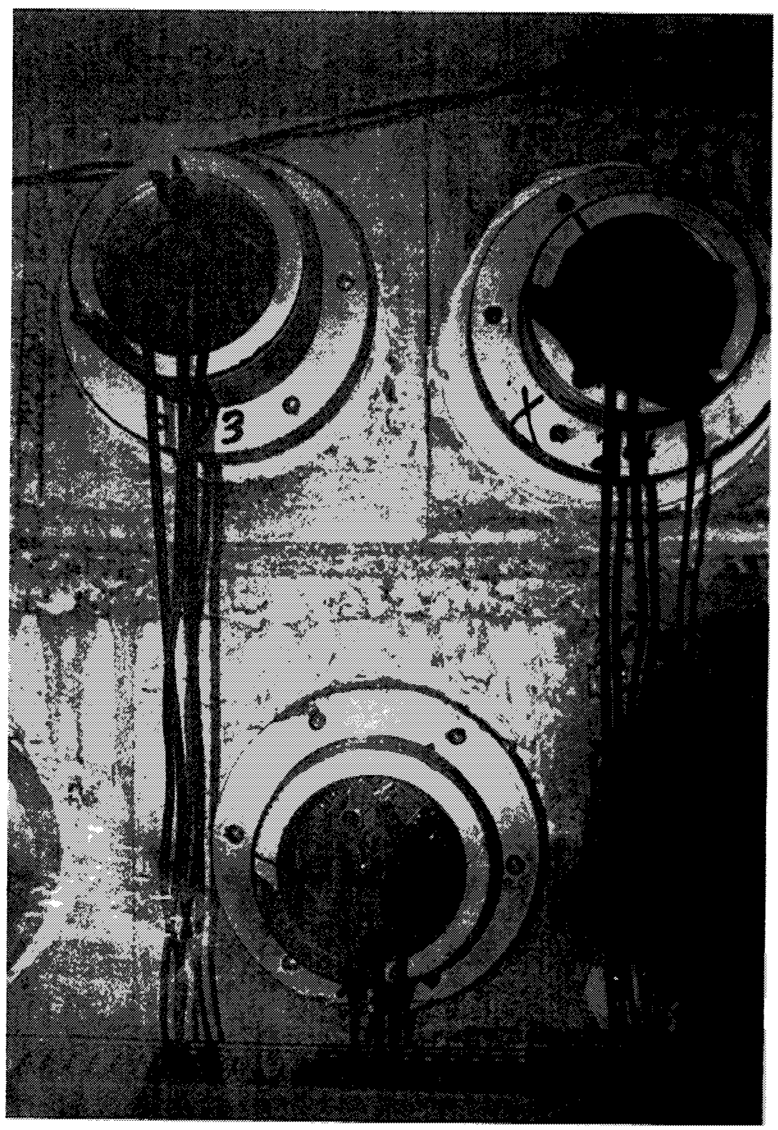

Figure 16. GFRP Rods Instrumented With Fiber Optics and Copper Wire

In terms of instrumentation technology, embedded fiber optic sensors in composite cable systems (i.e., Bragg sensors) (E5, E7, E8, E9) provide convenient strain measurements. In addition, the fiber optic and copper wire sensors embedded in the individual GFRP rods during the manufacturing of Polystal® (Figure 16) show the vision to produce smart materials (E5) that simplify continued health monitoring. Complete bridge monitoring systems with remote real-time data transmission and online data checks with predicted performance models and builtin warning systems were presented by Deha Com in Germany (E5, E7). These sensors consisted of fiber optic and copper wire strain sensors, chemical corrosion gauges, and crack location and crack width instrumentation.

Relevance to U.S. Practice

The most significant finding related to U.S. practice was not so much what was encountered abroad in terms of monitoring and instrumentation systems, but rather in what does not seem to be done anywhere in the world. The team did not observe a comprehensive development and implementation plan for long-term monitoring and data generation in direct support of durability, general structural health, and life-cycle cost data development.

Transferable Technologies

Individual instrumentation and sensor technology is not new to the United States, and most of the technology encountered by the scanning team has actually been developed in the United States. For example, fiber optic Bragg sensors were developed by the U.S. Navy. The concept of smart materials that have sensors installed during the manufacturing process, such as Polystal® (E5), should be pursued.

Research and Development Needs

Instrumentation and measurement systems need to be developed, and a comprehensive, long-term monitoring plan should be established and implemented on a series of prototype demonstration projects. Questions and concerns still exist about the durability of FRPs in the civil engineering environment, under such conditions as the following:

- Stress corrosion, in the form of strength degradation, under sustained loads
- Relaxation and creep
- Chemical stability of the resin and fiber system
- Water absorption.

3.7 DURABILITY (TOPIC 7)

Summary of Findings

Durability, or the capacity to maintain visual and structural integrity with time in typical civil engineering environments, seems to be the most controversial aspect of advanced composite materials worldwide. The durability of FRPs is often cited as their strongest selling point, particularly when problems with a rapidly aging and deteriorating bridge infrastructure are being addressed. On the other hand, questions concerning uncertainties with the long-term performance of FRPs in terms of ultraviolet resistance, creep, relaxation, stress corrosion, chemical resistance, and fire exposure are raised around the world and must be answered before general acceptance by the civil engineering and construction community.

The difficulty with determining long-term structural integrity of FRPs arises from the multitude of fiber, resin, and manufacturing systems and their widely different performance characteristics under exposure to permanent loads and various environmental conditions. Frequently, the limited shortcomings of one material's system are generalized to all other FRPs or demands are placed on FRPs, such as fire exposure and resistance requirements, that are not placed on any other bridge construction material.

To provide answers to questions of durability, accelerated tests and long-term exposure tests are conducted around the world. Typically, however, these tests are focused on one specific system and application, making extrapolations to other systems and environments difficult. Furthermore, the scientific community is still divided on the issues of merit and the meaning of accelerated tests and their correlation to actual exposures in the everyday environment. A good example is the potential problem of alkaline reaction with glass. Rapid degradation rates of glass can be shown in elevated pH environments, but contact with aged concrete may not be represented by these tests. Another example concerns aramids, which, when submerged in water, show very high water absorption rates that may not occur in AFRPs in typical bridge applications.

Most of the FRP applications in bridge projects observed during the scanning tour were based on CFRPs. This was largely attributed to the high degree of chemical inertness of carbon fibers and the resulting durability benefits. Glass fibers were found in only limited applications, namely in the bridge systems made entirely of advanced composites (E2, E3, E4, and J3), as well as for reinforcing elements in the form of a post-tensioning system (E6, E7, E8) and a reinforcement grid (J1). The use of aramids was observed in the form of a dry parallel fiber cable system (E1, E2), as reinforcement and prestressing systems (J1, J4, J5, and J11), and as a seismic retrofit concept (J6). All other applications used CFRPs, largely because of durability considerations, but also based on the mechanical properties of the carbon fibers, in particular their modulus.

Each country or region visited focuses on different material systems and, to a certain degree, justifies the choice with durability. Bridge applications in the United Kingdom focused on glass and aramids; in Germany, on glass; in Switzerland, on carbon; and, in Japan, on carbon and aramids. Although these choices are mostly driven by the countries' predominant types of applications, justifications are largely sought in the expected long-term performance (see Table 5 from reference [8]).

All discussions on durability seem to point in one direction, which is: For specific applications, clear long-term performance specifications must be established, and the advanced composite industry must meet and ensure performance goals. In addition to well-defined short-term and accelerated test protocols, carefully planned and monitored field demonstration projects must be conducted to correlate some of the accelerated test data and to develop durability and service life prediction models.

Relevance to U.S. Practice
The durability issues of advanced composite materials in the civil engineering environment are the same around the world, and all established research data are clearly relevant to U.S. practice. Durability research in the United States does not seem to lag behind, however, and can be characterized as more generic and less system specific.

Transferable Technologies
One important aspect of durability observed during the scanning tour was the determination of structural integrity of CFRP laminates under elevated temperatures and fire exposure. Testing protocols, procedures, and data of these fire tests are relevant to U.S. applications.

Research and Development Needs
Systematic definition of performance characteristics, short-term validation tests, accelerated exposure tests, and long-term monitoring are required to provide a generic data base for FRP durability in civil engineering environments.

Table 5. Quantitative Rating of Fiber Types [8]

Criterion	Weighting Factor	Weighted Rating for Laminates With Fibers of:		
Range of Weighting Factor	1–3	Carbon	Aramid	E-Glass
Tensile Strength	3	9	9	9
Compressive Strength	2	6	0	4
Young's Modulus	3	9	6	3
Long-Term Behavior	3	9	6	3
Fatigue Behavior	2	6	4	2
Bulk Density	2	4	6	2
Alkaline Resistance	2	6	4	0
Cost	3	6	6	9
Total Points		55	41	32
Ranking		1	2	3

Ratings: 3=very good, 2=good, 1=adequate, 0=inadequate

3.8 RESEARCH (TOPIC 8)

Summary of Findings

The introduction of new materials to the civil engineering and construction environments requires significant research and development. This was obvious at all stages of the technology scanning tour. Of interest, however, is the way in which research and development are conducted in the various countries visited.

In the United Kingdom, industry seems to take the lead with ideas and product development, which are then supported by application-specific university testing. In addition, universities engage in smaller scale generic research to characterize FRP performance. Furthermore, large demonstration projects are implemented (E2, E3) following, or sometimes in parallel with, a few large-scale laboratory validation tests.

In Germany, the developments of the GFRP Polystal® post-tensioning system were led by industry and supported by government with systematic university research and validation testing.

In Switzerland, the main thrust of research comes from EMPA, which has close ties to industry. Because EMPA is affiliated with the Swiss Federal Technical University (ETH), academic research is part of the development program. Key factors in the research at EMPA are the federally funded laboratories and research staff. The research is very systematic, but also very project and product specific.

Finally, in Japan, most of the research and development is initiated, funded, and conducted in the industry sector. Government research laboratories, such as PWRI of the Japan Ministry of Construction, are charged with coordination and writing of specifications and standards. Most notable in Japan are the close alliance between the construction industry and the advanced composite manufacturing industry and the organization of industrial participants in national interest groups, such as the Advanced Composite Cable (ACC) Club. Such organizations promote their products and train the engineering community in the use of new technologies. Research in Japan is based on a significant amount of large-scale experimental testing of specific ideas and principles, followed by a large number of immediate prototype demonstration projects. There is less emphasis on generic and theoretically supported research data. Demonstration projects are subsidized through the participating companies to showcase product development.

Relevance to U.S. Practice

Research abroad differs from U.S. research practice in that most research in the United States is conducted by universities, with limited industry support. More fundamental and applied research seems to be conducted in the United States before large-scale prototype demonstration projects are implemented, and the U.S. Government seems to provide larger portions of funding for research and development.

Transferable Technologies

Although no specific technologies can be transferred in the research sector, incentives for industry to participate more actively in research and development efforts should be investigated. Japanese companies, for example, derive significant tax advantages when they can show a certain amount of expenditures directed toward research and development of new technologies.

Research and Development Needs
In many cases, research in the United States seems to be fragmented and isolated and should be better coordinated and focused to derive more and immediate benefits.

Large prototype demonstration projects seem to find faster and easier application and implementation abroad. U.S. industry needs to participate much more directly and actively in the research process.

3.9 CONSTRUCTION (TOPIC 9)

Summary of Findings

One of the key advantages of advanced composite materials is their high strength-to-weight ratio, which typically results in significant structural weight savings. Direct benefits for construction are:

- Reduction of shipping costs
- Erection and placement, either by hand or with light lifting equipment, eliminating the need for heavy machinery
- Prefabrication of components and subassemblages, which are only controlled by size and shape, not by weight.

Possible disadvantages include the damage potential during handling and erection. To date, these characteristics are exploited to only a limited degree in the overall cost/benefit assessment, as compared to conventional structural materials and construction procedures.

Applications in which these advantages have been used include: the bridge systems made entirely of advanced composite materials, promoted by Maunsell in the United Kingdom (E2, E3, E4), the CFRP laminate strengthening system developed by Sika and EMPA in Switzerland (E8, E10, E11, E12), and the CFRP sheet strengthening of bridge deck soffit regions in Japan (J2, J8, and J10).

Additional training of construction personnel is required in:

- Field mixing of adhesives
- Surface preparations and handling of materials before application
- Environmental influences of temperature, humidity, and dust on the application
- Protective gear during application
- Disposal of excess or waste materials.

All of these areas require specially trained and experienced field labor and professionals, as well as onsite quality control and inspection procedures.

Other construction considerations are connected to the use of advanced composite post-tensioning cable systems, which typically require larger and heavier tendon anchorages (E5, E8, J1) than conventional steel tendons. Because of the reduced material modulus, significantly larger stressing distances requiring resetting of jacks and/or larger stressing durations for typical power supplies are needed.

To date, the number of commercial projects implemented is very small, allowing a realistic assessment of the construction impact of advanced composite materials. Most projects observed by the scanning team were one-of-a-kind demonstration projects, specifically designed to showcase new technologies and constructed or erected with significant volunteer labor and government or industry subsidies. Only when advanced composite bridge projects are competitively bid and executed can the true impact of these new materials on the construction market be assessed.

Relevance to U.S. Practice

Because most of the projects observed were not competitively bid, it is difficult to assess any relevance from the construction processes for the U.S. bridge industry.

Transferable Technologies

Of interest in the United States are the government and industry consortia assembled to implement large-scale demonstration projects to showcase the technology.

Research and Development Needs

Complete and detailed documentation of all construction-related aspects of advanced composite materials must be provided to use the information in competitive market situations.

3.10 MANAGEMENT (TOPIC 10)

Summary of Findings
Management implications of projects involving advanced composite materials are difficult to assess, because very few truly commercial projects based on competitive bidding were observed. The nature of project management generally follows the character of the project, namely that of a demonstration project.

Management of these demonstration projects, however, shows clear differences from U.S. practice. For example, in most countries, demonstration projects seem easier to award by the sole source arrangement than in the United States. Additionally, in all countries visited, the construction industry participates in projects as a full partner and, in many cases, as the leading partner. Industry participates significantly in financing demonstration projects, in addition to government funding, which facilitates these projects to a large degree.

Projects that can be viewed as "commercial" were encountered in the United Kingdom with Maunsell's bridge enclosure system at the Second Severn Approach Bridges (E4), in Switzerland with the CFRP laminate strengthening of bridge decks and girders (E11 and E1), and in Japan with the seismic bridge column retrofit using CFRP sheets (J6). Because no alternative products have been tested and approved in the United Kingdom for advanced composite bridge enclosure systems, or in Switzerland for FRP strengthening, it is difficult to judge the potential application of these projects in the United States. This is particularly true, because quoted costs seem to be high from a U.S. bridge construction point of view. In Japan, it was not clear how seismic CFRP sheet retrofit contracts are obtained by the construction companies.

Adjacent bridge columns include a variety of retrofits, such as steel-plate jacketing or reinforced-concrete jacketing, which seems to imply that the 200 bridge column installations were still more demonstration than commercial projects.

Finally, one management aspect that was noticeable in all countries was the willingness by industry to organize and participate in the training of designers, engineers, and construction professionals. Industry also played a leadership role in developing design guidelines and standards, cooperating very closely with the appropriate government agencies.

Relevance to U.S. Practice
Of direct relevance to U.S. practice are the close partnerships among industry, government, and the research community to educate the civil engineering profession in the new technologies and implement high-visibility demonstration projects. Another key factor is the direct participation of the civil engineering and construction industries in the projects and product development.

Transferable Technologies
Flexibility in the contracting of projects involving new materials and technologies, as well as government incentives to industry to participate in new technology development and demonstration projects, should be further addressed in the United States.

Research and Development Needs
Technology transfer workshops and seminars should be developed. In addition, cost/benefit models for new technologies should be generated and evaluated for all life-cycle cost predictions. Finally, special legislation could be enacted to facilitate implementation of these new technologies.

4.0 ADVANCED COMPOSITES IN BRIDGES IN EUROPE

Over the past two decades, advanced composite materials have been used in civil engineering applications in many European countries. Three countries, the United Kingdom, Germany, and Switzerland, were selected by the scanning team as representative of recent developments and applications in the use of advanced composites in bridge engineering. In each country visited, the type of advanced composite materials and systems, as well as the bridge applications, differ depending on specific requirements, national needs, and/or industry participation.

In the United Kingdom, the developments observed were driven primarily by industry with the introduction of a new fiberglass construction system and a lightweight aramid cable system. Problems with continued maintenance of steel girder bridges have led to an innovative GFRP enclosure concept, which will significantly reduce the corrosion rate and subsequent maintenance.

In Germany, corrosion problems with older post-tensioned concrete structures prompted the Government to initiate a research and development program on nonmetallic tendons to eventually replace steel prestressing elements. The resulting new prestressing system, the HLV Polystal,® was systematically developed, tested, installed in demonstration projects, and monitored. However, significant improvements in the durability and corrosion protection of conventional steel prestressing tendons have made the more costly Polystal® tendons virtually obsolete.

In Switzerland, the rehabilitation and strengthening of existing concrete bridge decks and structural concrete slabs has led to research and development of the CFRP laminate strengthening system. Furthermore, the Swiss tradition in post-tensioning and cable-stay concepts and systems (e.g., VSL, BBR, Suspa) has been extended to the area of advanced composites. Of interest are the development of pultruded parallel wire carbon cable stays and, in particular, the Swiss anchorage technology.

Workshops were held to provide overviews of activities in the United Kingdom, Germany, and Switzerland. These took place in Cambridge, England (E1); Düsseldorf, Germany (E5); and Dübendorf, Switzerland (E8). Summaries of the workshop discussions, as well as project summaries for each of the project sites that the team visited, are provided in this section.

4.1 CAMBRIDGE WORKSHOP (PROJECT E1)

Workshop Objective

The objective of this workshop was to provide an overview of advanced composite research and applications in the United Kingdom. The workshop was organized by Prof. Chris J. Burgoyne at the University of Cambridge.

Workshop Contacts and Meeting Participants

Dr. Chris J. Burgoyne, Professor, University of Cambridge; Mr. John R. Cunninghame, Bridge Division, Transport Research Laboratory (TRL); Mr. Sibdas Chakrabati, Principal Engineer, Highways Agency (HA); Dr. Martin Pick and Mr. Brian Wilson, Marketing Managers, Linear Composites, Ltd.

Workshop Description

Dr. Burgoyne, shown in Figure 17, presented research developments [1] on aramid cables, reinforced-concrete beams with bonded and unbonded aramid tendons [2], and concrete shear reinforcement with aramid hoops or spirals. The key advantages of using external aramid cables are their strength, very high strength-to-weight ratio, and durability. For these applications, parallel lay (parafil) ropes have been developed. For bonded or partially bonded pretensioning tendons, braided or pultruded aramid-reinforced polymers (ARP) rods are used, which typically feature a reduced modulus with increased failure strain capacities. Research focused on the

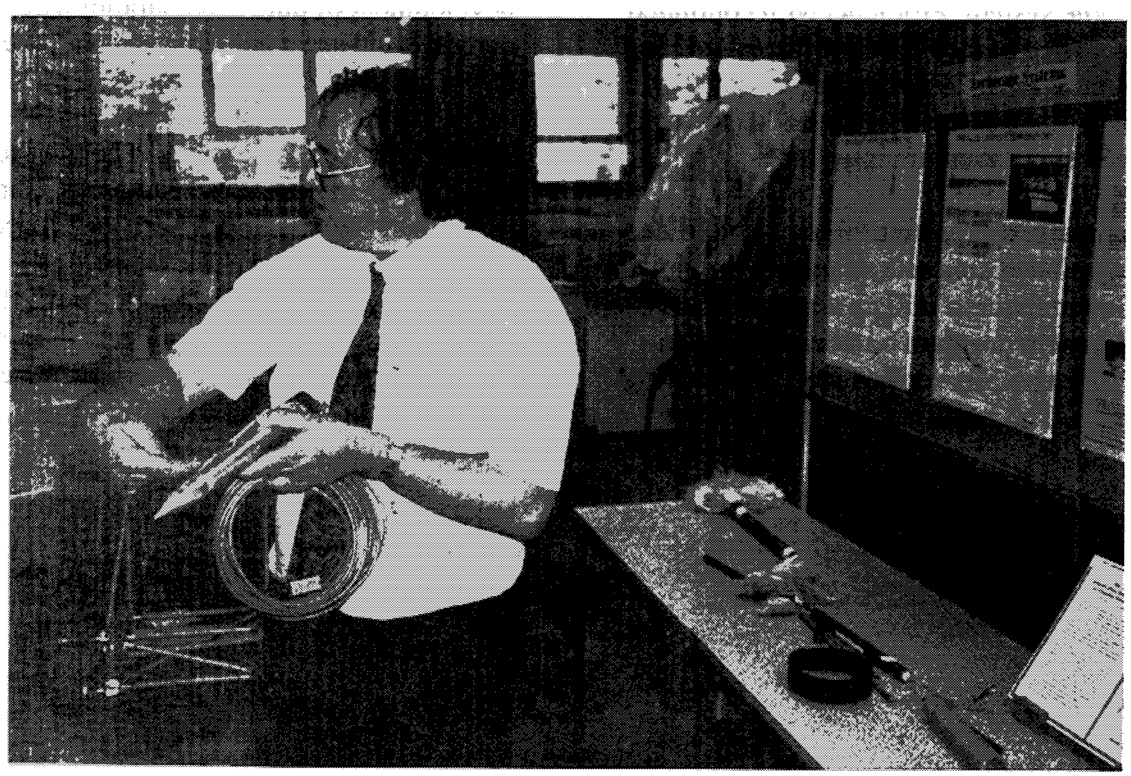

Figure 17. Professor Burgoyne at the Cambridge Workshop

development of anchorage systems for the dry parallel lay "parafil" ropes using a friction cone concept (Figures 18 and 19) and on the use of aramid reinforcement with concrete beams (Figures 20 and 21).

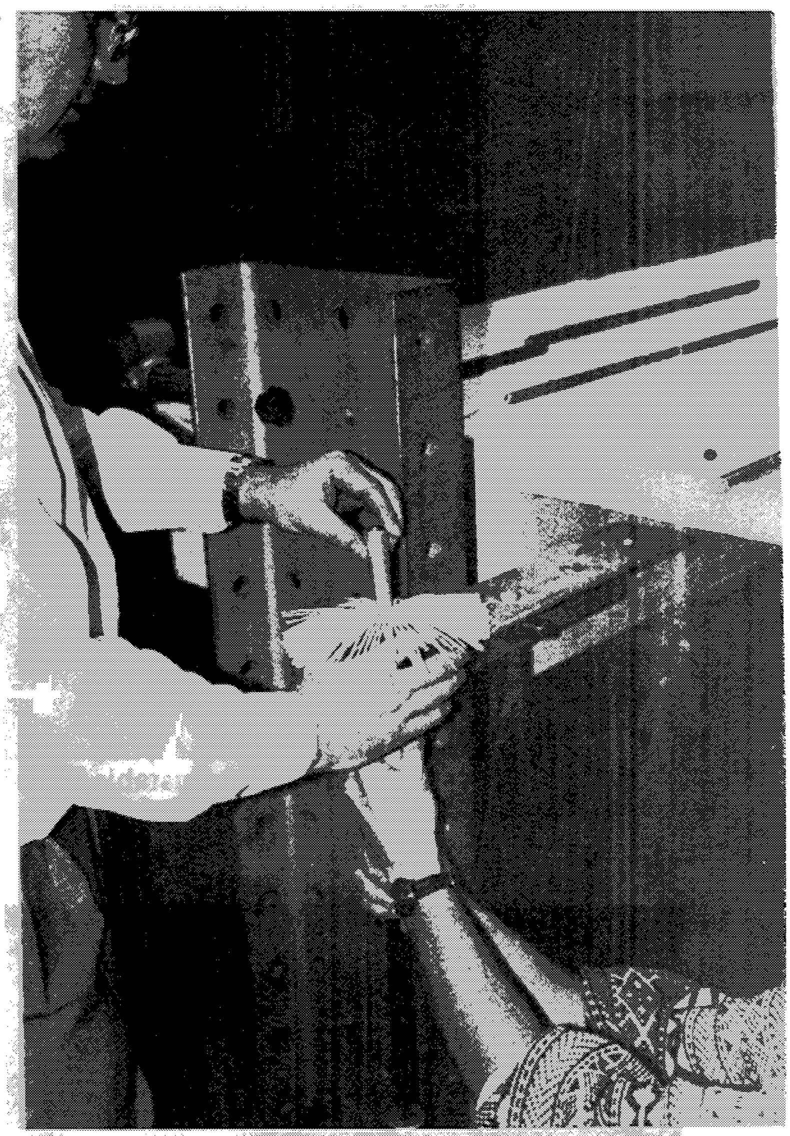

Figure 18. Demonstration of Parafil Anchor Technique

Bonded tendons show high load-carrying capacities at reduced deformation capacities. Unbonded tendons allow large deformations in prestressed concrete beams at reduced load-carrying capacities. A concept of partial unbonding of aramid tendons can increase both deformation and load-carrying capacities.

Parafil rope applications were presented by Linear Composites, Ltd. These applications consisted of repair of a vertically cracked cooling tower; cable stays for bridges, antennas, and roof systems; and support of urban train and trolley bus overhead conductors. Related pro-ducts and applications are in the form of webbed flat materials (para-web) for earth anchors, embankment stabilization, windbreaks, and sun-screens, as well as support slings. The reduced modulus of aramid tendons in comparison to steel ten-dons allows the tendon to maintain prestress load levels when creep and shrinkage in the main member result in member shortening. This property was used advantageously in the transverse pre-stressing of a log-decked bridge in Ontario, Canada, in 1995.

The HA in the United Kingdom [3] is working on a program to assess the use of nonmetallic reinforcement and prestressing materials in concrete bridges and is planning a demonstration project of an experimental concrete bridge using nonmetallic materi-als. In conjunction with the planning studies for this demonstration project, TRL is con-ducting tests to validate safety of design methods and assess durability.

Figure 19. Adjustable Parafil Anchorage

Figure 20. Crack Patterns and Failure Modes in Prestressed Concrete Beams With (top to bottom) Steel, Bonded Aramid, and Partially Bonded Aramid Tendons

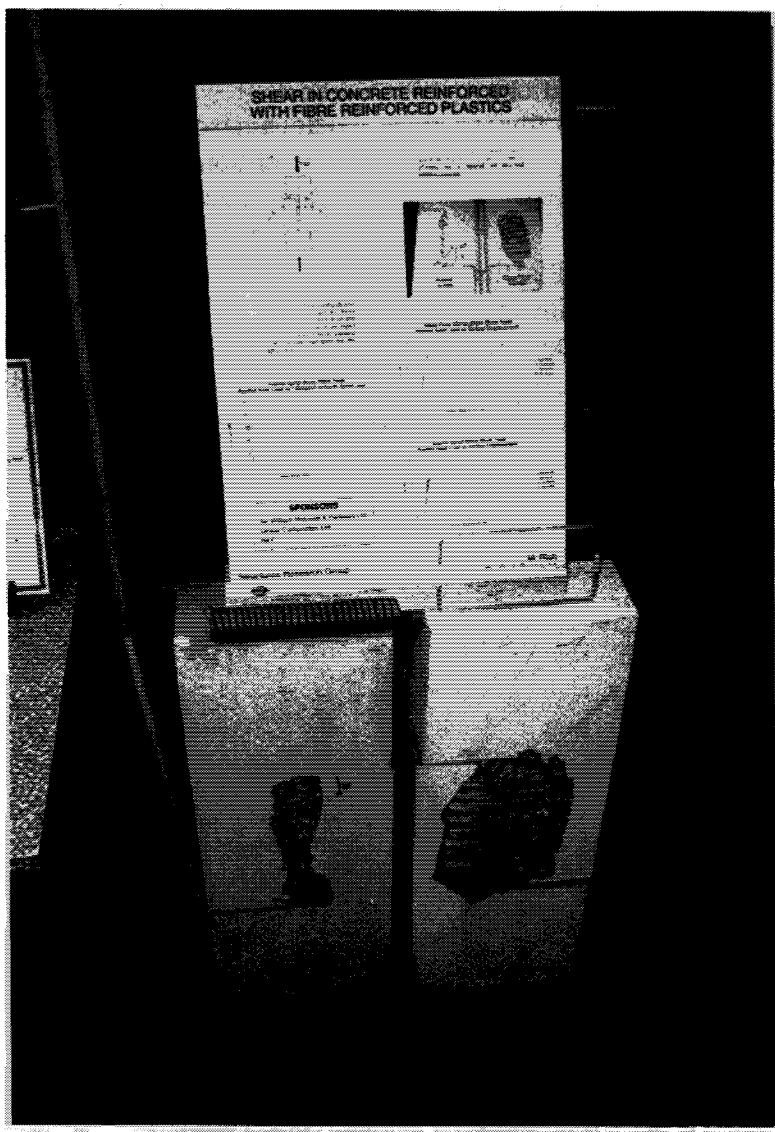

Figure 21. Shear Specimens Reinforced With Aramid Stirrups

4.2 ABERFELDY FOOTBRIDGE (PROJECT E2)

Project Summary
World's first cable-stayed footbridge made entirely of advanced composite materials (Figure 22). The bridge is 113 m long with a 63-m mainspan. Superstructure/deck and pylons are made from pultruded E-glass (a type of fiberglass), and polyester sections and cables, from dry parallel aramid fibers in polyethylene sheathing.

Project Data

Designer:	Maunsell Structural Plastics
Contractor:	O'Rourke Civil Engineering, Ltd.; University of Dundee; GEC Reinforced Plastics; Linear Composites, Ltd.
Owner:	Aberfeldy Golf Club
Designed:	1991
Completed:	June 1992
Cost:	£120,000* (US$200,000)

** Plus donated labor*

Project Objective
Extend Aberfeldy Golf Course from 9 holes to 18 holes on the other side of the River Tay with a footbridge that is maintenance free for at least 20 years. Demonstrate application of Maunsell's ACCS.

Alternative Concepts
Conventional timber, concrete, or steel cable-stayed bridges or steel truss bridges at more than twice the project cost.

Design Considerations
Construction access, lightweight (no heavy lifting equipment), durability, no scheduled maintenance for 20 years.

Figure 22. Aberfeldy Footbridge, Overview

Project Contacts
Allan E. Churchman, Managing Director, Maunsell Structural Plastics, Ltd.; George Innis, President, Aberfeldy Golf Club.

Composite Material	Deck/Pylons	Cable Stays
Fiber	E-Glass	Kevlar 49
Matrix	Isophthalic Polyester Resin	None
Manufacturing	Pultrusion	Parallel Sheathing
Assembly	Toggle & Epoxy Bonding	-------
Adhesive	Epoxy	-------
Tensile Modulus	22 GPa (3.2 x 10^6 psi)	127 GPa (18.4 x 10^6 psi)
Tensile Strength	300 MPa (4.3 ksi)	1.9 GPa (276 ksi)
Ultimate Strain	1.4%	1.6%

Project Description
The footbridge is 2.2 m wide (7.2 ft) and 113 m long (370 ft), with a mainspan of 63 m (206 ft), between two A-frame pylons (Figure 23). The pylons are 17.2 m tall and support the mainspan with fan-type cable. The mainspan is a vertical circular arc linked to the side spans with continuous transition slopes. A-frame pylon dimensions were determined by the width of the bridge by a 30° slope of the uppermost cable stay [4].

All structural components of the bridge (except cable anchorages, cable connector moldings and ties, pylon foundations, and abutments) are made of advanced composite materials. The bridge deck, A-frame pylons, and handrails are made of GFRP (Figures 25 and 26), and the cable stays are made of dry parallel aramid fibers (Kevlar) in polyethylene sheaths. The design concept was based on Maunsell's ACCS and Linear Composites' parafil ropes. The ACCS consists of modular cellular pultruded GFRP sections that can be assembled into larger structural sections by mechanical toggle and adhesive bonding (Figure 24).

Construction/Installation
The GFRP elements were pultruded by GEC Reinforced Plastics and transported to the site for assembly. Tower legs were assembled at the factory with cable anchorage provisions and were delivered to the site following excavation and foundation work. Legs were assembled into the A-frames and bonded together, and anchorages were added. Towers were winched into a vertical position using temporary ropes, and the mainspan was assembled on land and winched over the crossbeams by hand using temporary ropes. Cable stays were anchored and handrails and approach spans added. Ballast was added to the mainspan deck.

Instrumentation, Monitoring, Testing
Initial testing of ACCS was performed at the University of Surrey. Two 3-cell box beams (2 m wide, 0.76 m deep, 18 m long) were assembled using the standard ACCS components, then proof-load tested under full design load in four-point bonding for 7 months. Subsequently, one of the beams was load tested to failure. Parallel accelerated weathering tests were carried out on laminates and bonded joints. Construction assembly tests were performed at the University of Dundee, which also monitored the bridge during and after construction. Static load tests with sandbags were performed.

Special Issues
Few problems were observed. The primary problem was associated with the light weight of the structure. Without added ballast, the bridge is somewhat underdamped in windy conditions and very lively under pedestrian traffic. During construction, the placement or driving of the toggles between long plank sections required special lubricants and toggle-driving equipment. Slight sagging of the bridge after 4 years of service can be attributed to the low cable modulus and creep in the parafil cables.

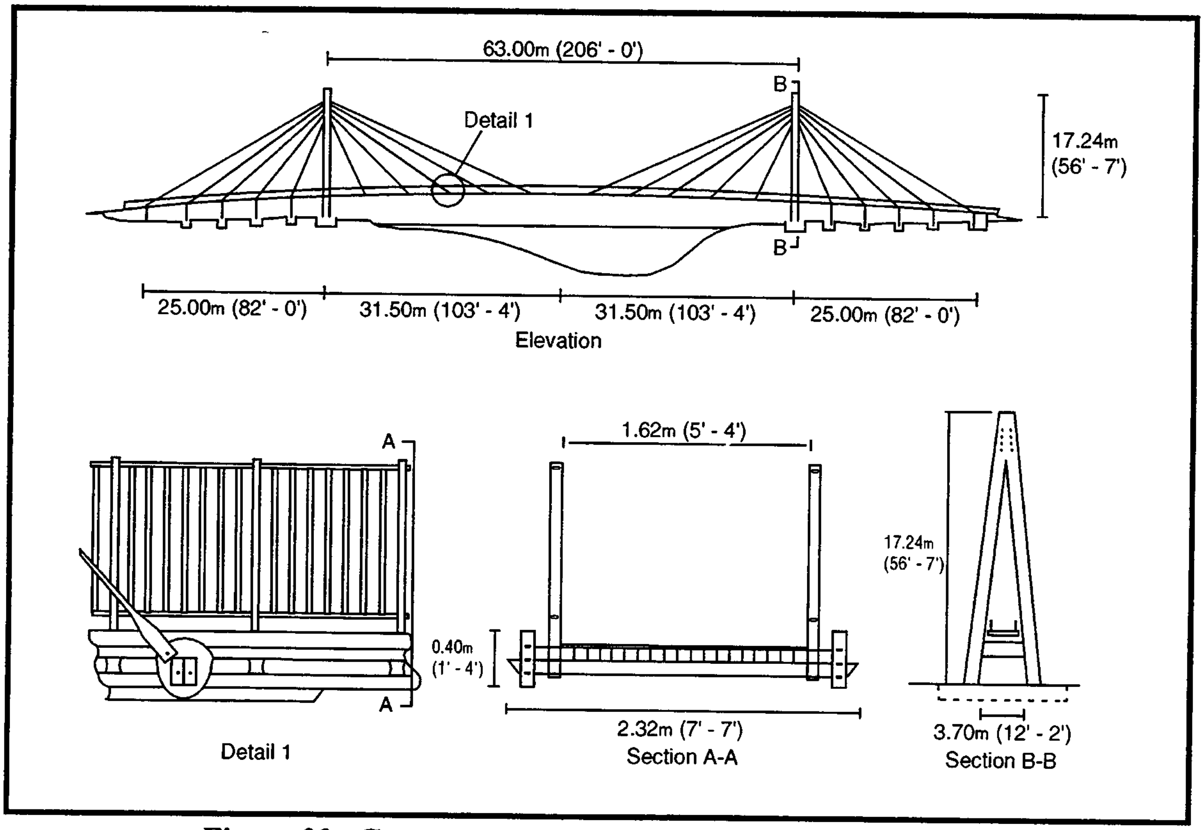

Figure 23. Geometry and Details of Aberfeldy Footbridge

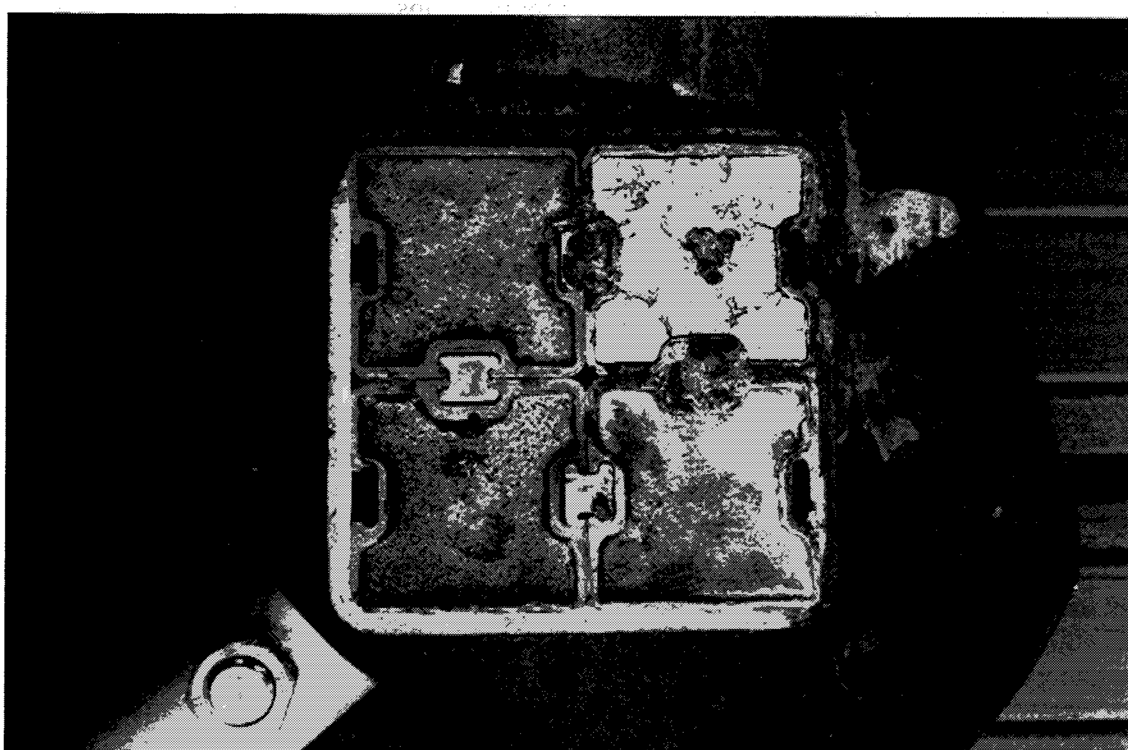

Figure 24. Toggle-Connected Crossbeam and Stay Cable Anchorage Connection

⇑ **Figure 25. Prefab GFP Handrail System and Conveyor Belt Wear Surface**

⇐ **Figure 26. A-Frame Pylon and Cable Stay Anchorages**

4.3 BONDS MILL BRIDGE (PROJECT E3)

Project Summary
Entirely advanced composite bascule bridge with 8.2-m span for two-lane traffic (Figure 27).

Project Data

Designer:	Designer Composites Technology, Ltd.
Owner:	Cotswold Canals Trust
Completed:	1994
Cost:	£65,000* (US$110,000) **Plus volunteer labor*

Project Objective
The project objective was to design and build a bascule bridge with minimal weight and long-term durability.

Alternative Concepts
Steel girder bascule bridge with orthotropic deck or open grating.

Design Considerations
Light weight, 40-ton-truck loading.

Project Contact
Allan E. Churchman, Managing Director, Manusell Structural Plastics, Ltd.

Project Description
The bascule bridge [4] is 8.2 m (27 ft) long and 4.3 m (14 ft) wide for two lanes of regular BS 5400 traffic loads (40-ton trucks). The structural depth is 0.86 m (2.8 ft), and the superstructure comprises a six-cell box girder built with the Maunsell ACCS. The overall bridge cross-section geometry is depicted in Figure 28. The cells of the ACCS pultruded planks are filled with structural epoxy foam that has a density of 100 kg/m^3 (6.2 lb/ft^3) to provide support to the thin

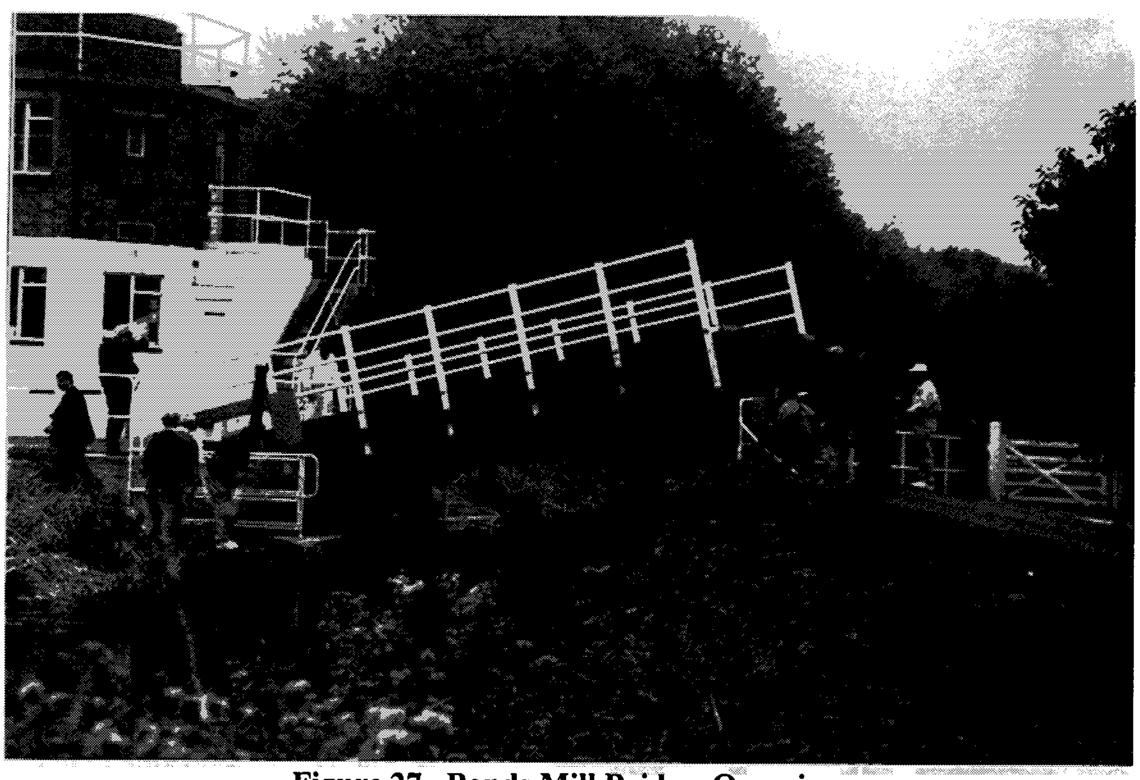

Figure 27. Bonds Mill Bridge, Overview

webs under high wheel loads. The superstructure is stiffened transversely with ACCS diaphragms.

The deck consists of a "double ply" of ACCS planks with cells running in perpendicular directions. Wear, impact, and skid resistance are provided by replaceable epoxy-sealed and coated marine plywood with sand grit. The total weight of the superstructure and wear surface is 4.5 tonnes (10 kip) for 35 m^2 (375 ft^2) of bridge deck area.

Composite Materials	
Fiber	E-glass
Matrix	Isophthalic polyester resin
Manufacturing	Pultrusion
Assembly	Mechanical Toggle & Epoxy Bonding
Adhesive	Epoxy
Tensile Modulus	22 GPa (3.2 x 10^6 psi)
Tensile Strength	300 MPa (43.5 ksi)
Ultimate Strain	1.4%

1MPa = 145 psi

Construction/Installation

The superstructure was built in two halves in the fabrication shop and delivered to the site, where the sections were bonded together. The second layer, or transverse deck planks, was bonded in place. The pultruded handrails were fitted to the bridge, and the complete bridge, with yoke, was lifted into place. The replaceable wear surface was added in situ. Site construction took 3 months, using a volunteer labor force.

Instrumentation, Monitoring, Testing

Static load, long-term creep, and durability tests were performed at the University of Surrey. Design of the bridge was based on Maunsell's limit state design for ACCS, considering deflection limits, maximum strain levels of 25 percent of first-ply failure in the laminates, and buckling limit states based on relevant test results.

Special Issues

No problems with the construction or service performance have been reported.

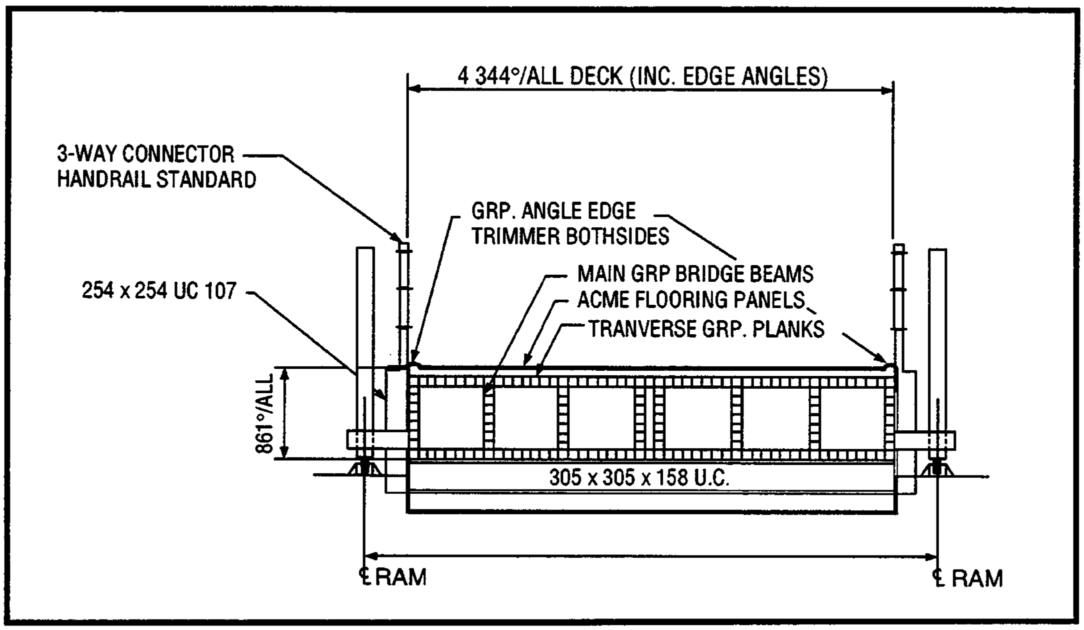

Figure 28. Cross-Section Geometry and Dimensions

Reproduced with permission from Maunsell Structural Plastics, Ltd.

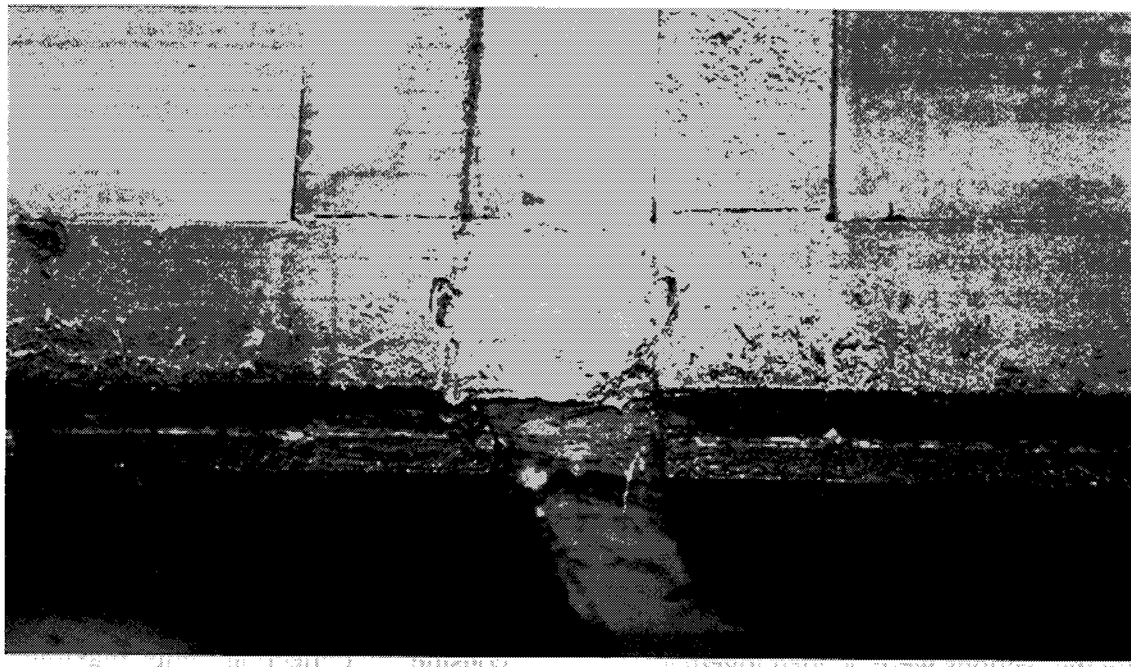

Figure 29. Connection Details

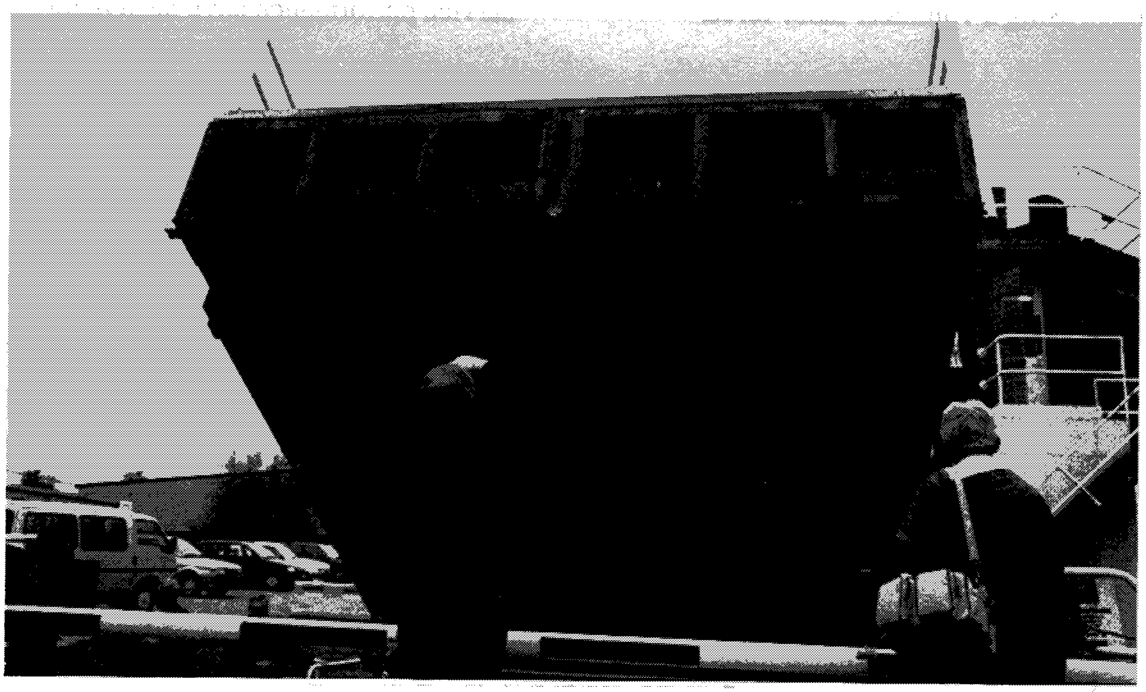

Figure 30. Bascule Bridge in Open Position

4.4	SECOND SEVERN APPROACH ENCLOSURES (PROJECT E4)

Project Summary
GFRP bridge bottom soffit enclosure system suspended with hangers from the steel superstructure (Figure 31).

Project Data

Designer:	Maunsell Structural Plastics
Contractor:	Balfour Beatty Civil Engineering, Ltd.
Construction:	Started March 1993
Cost:	£282/m^2 (US$44/ft^2)

Project Objective
The objective is to provide access to the steel girder superstructure for inspection and maintenance without traffic interruption. The enclosures also significantly reduce corrosion rates (up to 95 percent).

Alternative Concepts
None.

Design Considerations
Full access for inspection and maintenance. Also, capable of supporting construction loads during deck construction. Design load 1.9 kN/m^2 (40 psf). Deflection limit under design load of L/120; that is, span length divided by 120.

Project Contacts
Allan E. Churchman, Managing Director, Maunsell Structural Plastics, Ltd.; Peter Head, Managing Director, Maunsell & Partners, Ltd.

Project Description
The Maunsell GRP bridge enclosure system [4] was conceived in the early 1980's and first applied on the Tees Viaduct in 1987–89. The system consists of pultruded multicell E-glass panels in polyester matrix, connected with special GRP connector elements, which allow attachment of GRP hangers (Figure 32). Separate enclosure sections are connected by neoprene joint seals. Specially molded curved side panels with foam core and triangular GRP facia edge moldings provide the enclosure system with

Figure 31. Bridge Structure Crossing One of the Second Severn Approaches, Overview

aesthetically and visually pleasing characteristics. The enclosure system (Figures 33 and 34) allows for limited corrosion protection of the steel beams, because the corrosion potential in the enclosed system is reduced to less than 5 percent of the unenclosed level. Enclosures can also be used to support formwork during deck construction. The expected maintenance-free service life is 30 years.

Construction/Installation
The lightweight enclosure components and the specially designed and developed hanger system can be erected by two or three workers from hydraulic hoists or platforms. After enclosure installation, no further interruption of the roadways below is required.

Instrumentation, Monitoring, Testing
Load testing was conducted to verify service-load deflection limit states. No other testing or long-term monitoring of the enclosure system is in progress. Fire testing of the system was performed at the Warrington Fire Research Center.

Composite Material	
Fiber	E-Glass
Matrix	Polyester
Manufacturing	Pultrusion
Assembly	Toggle Connection
Tensile Modulus	22 GPa (3.2 x 10^6 psi)
Tensile Strength	300 MPa (43.5 ksi)
Ultimate Strain	1.4%

1MPa = 145 psi

Special Issues
Potential problems include drainage, if water penetrates the enclosure, and handling during construction. Costs are high at £282/m^2 (US$44/$ft^2$) per enclosure area, but reported cost studies on the project have shown benefits when traffic management, traffic delays, access equipment, and reduced maintenance costs are taken into account in a life-cycle evaluation.

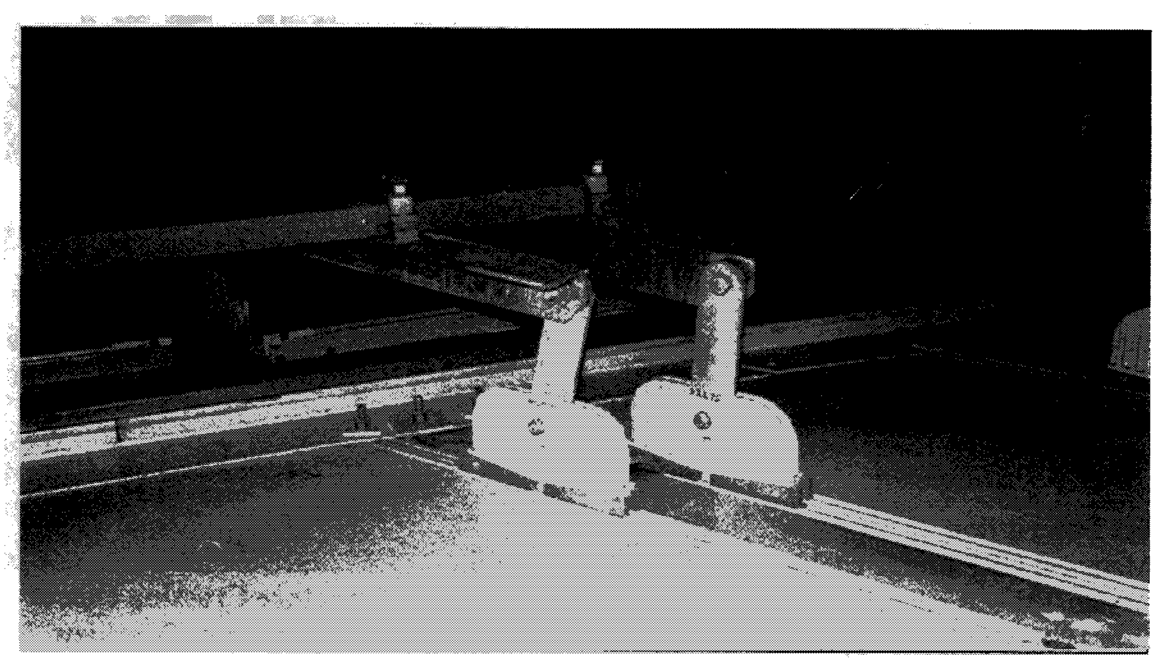

Figure 32. Hanger System

Figure 33. Enclosure System and GRP Flares

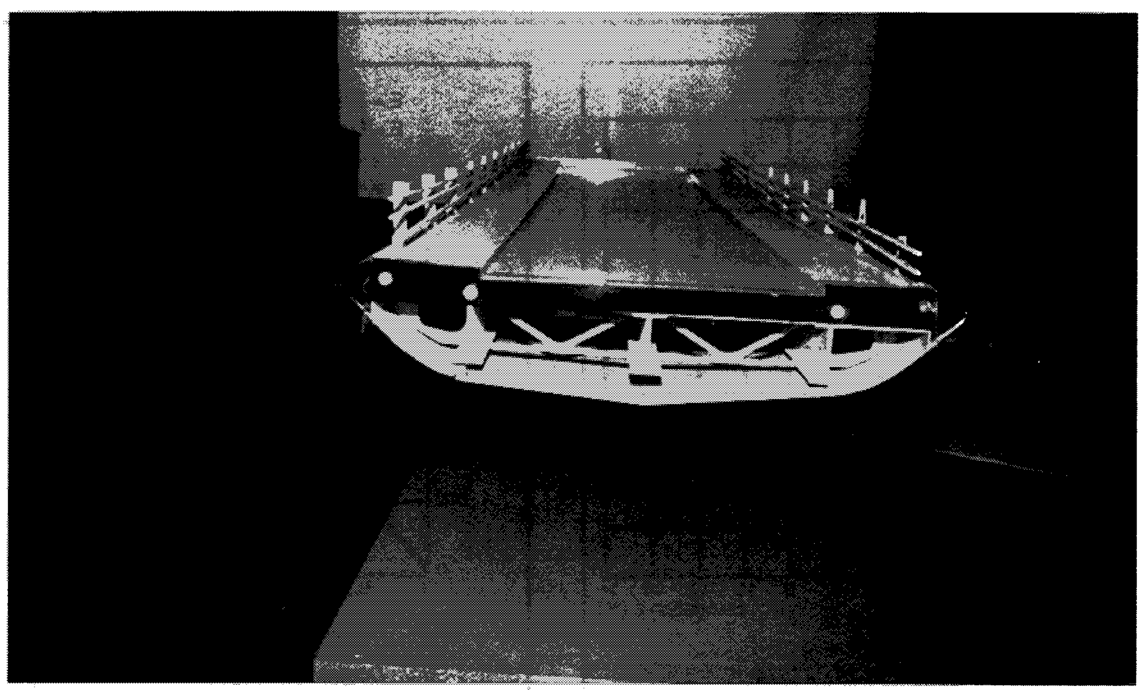

Figure 34. Model of Bridge Enclosure System

Workshop Description

An overview of advanced composite developments and applications in Germany was provided by Prof. Dr. Ing. Ferdinand Rostasy from the Technical University of Braunschweig. Dr. Rostasy has been active in advanced composite research for the past 13 years. In 1985, the German Federal Government provided a research grant to an industry consortium consisting of Bayer AG, a chemical company, and Strabag Bau AG, a contractor, to develop a nonmetallic post-tensioning system. The system, called HLV-Polystal® [6], consists of pultruded glass fiber bars in online coated polyaramid sheaths with a tensile strength of >1,520 N/mm^2 (220 ksi), a modulus of elasticity of 41 kN/mm^2 (7.4×10^6 psi), and a strain to failure of 3.3 percent (see Figure 35). In addition to the industry participants, three of the leading German technical universities participated in research and development on HLV-Polystal® system: the University of Stuttgart (Prof. Rehm) on materials, the University of Darmstadt (Prof. König) on design, and the University of Braunschweig (Prof. Rostasy) on anchorage systems. In addition to the mechanical characteristics mentioned above, other key advantages of HLV-Polystal® are its low specific weight of 2 g/cm^3 (125 pcf) and high durability in typical civil engineering applications. Disadvantages are sensitivity to stress corrosion and manufacturing costs, which are two to three times those of steel strands and tendons. Long-term strength was established experimentally at 70 percent of the short-term strength, and tolerable stress ranges were established at >50 N/mm^2 (7.3 ksi) at 2 million cycles. Durability tests showed extensive resistance of load-bearing glass fibers to temperature loads and

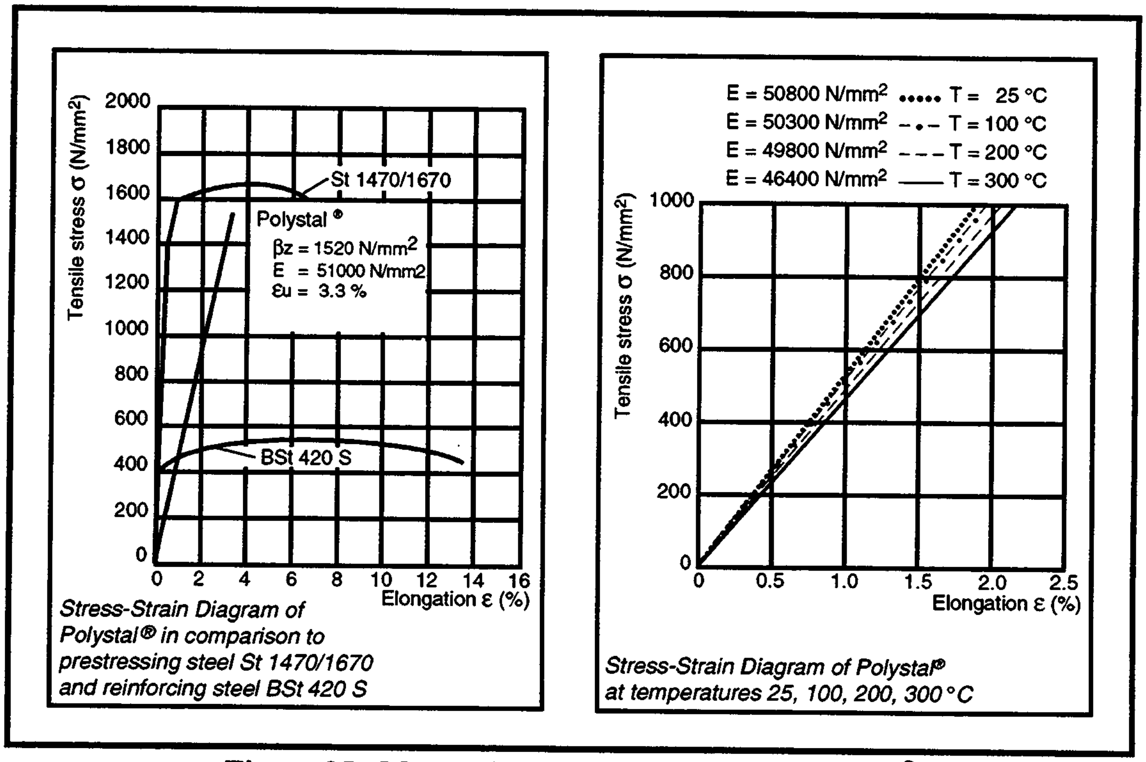

Figure 35. Mechanical Characteristics of Polystal®

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electromagnetic neutrality. HLV-Polystal® has been applied in several demonstration bridge projects in Germany (1980, Lünensche Gassel, Düsseldorf; 1986, Uhlenbergstrasse Bridge, Düsseldorf; Marientelde Pedestrian Bridge, Berlin) as regular or external tendons. However, improved durability and reduced costs of conventional prestressing tendons and the high manufacturing costs of Polystal® have led to discontinuation of its production. Based on the German experience, special applications for Polystal® can be found in temporary or permanent ground anchors in corrosive soils, for guy wires and cable stays, and for external post-tensioning in corrosive environments. However, limited applications in conventional prestressed concrete are envisioned.

Composite Materials	
Fiber	E-Glass
Matrix	Unsaturated Polyester Resin
Manufacturing	Pultrusion
Assembly	Post-Tensioning Tendons
Tensile Modulus	51 kN/mm^2 (7.4 x 10^6 psi)
Tensile Strength	1,570 N/mm^2 (220 ksi)
Ultimate Strain	3.3%

1 MPa = 145 psi

Instrumentation, Monitoring, Testing
Another key element in the development of HLV-Polystal® was the concurrent development of embedded health-monitoring systems and sensors. Copper wire and fiber optic sensors were embedded into the glass bar during manufacturing. In addition to the internal tendon health monitoring, extensive fiber optic and chemical sensor applications have been developed [7] and used in Germany to detect concrete cracking, crack width, and corrosion potential. Polystal® was also used in the repair of a subway station tunnel in Paris, France (Figure 36), where 19 HLV-Polystal® ties and 38 aramid fiber strands were placed as tension ties between newly strengthened butress walls. As expected, the aramid ties showed more than double the relaxation of the Polystal® ties.

In November 1991, a followup BRITE/EURAM Program, No. 4142, "Fiber Composite Elements and Techniques as Non-Metallic Reinforcement of Concrete," was started. Its objectives were to: (1) characterize materials and manufacturing processes suitable for applications in civil engineering structures, (2) determine load-carrying characteristics of concrete members reinforced or prestressed with FRP, (3) develop reinforcing elements, anchorages and application techniques, and (4) develop criteria for design, detailing, and execution. Partners in this program are the University of Braunschweig, Germany, and the University of Ghent, Belgium, as well as Sicom, AK70, HBG, Suspa, Cousin, DSI, and NDI.

Workshop Contact
Dr. Ing. Ferdinand Rostasy, Professor, Technical University, Braunschweig.

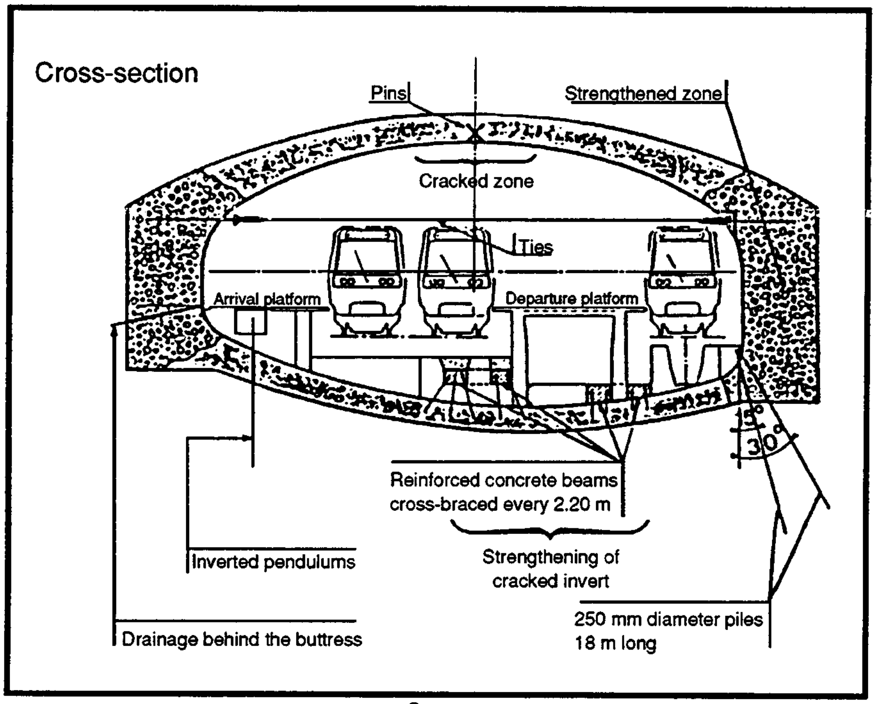

Figure 36. Polystal® Repair to Paris Metro

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4.6 ULENBERGSTRASSE BRIDGE (PROJECT E6)

Project Summary
A Federal demonstration project by the German Ministry of Economy, Medium-sized Enterprises, Technology and Transport of Northrhine-Westphalica, Düsseldorf, to test HLV-Polystal® tendon bridge construction.

Project Data

Designer:	Strabag Bau AG & König u. Heunisch
Contractor:	Strabag Bau AG/Bayer AG
Owner:	City of Düsseldorf
Designed:	1985
Construction:	1986

Project Objective
Internal post-tensioning and monitoring of a two-span, continuous slab bridge using 59 HLV (60-ton) tendons with nineteen 7.5-mm-diameter Polystal® rods each.

Alternative Concepts
Conventional high-strength steel post-tensioning tendons.

Design Considerations
Conventional (DIN 1072) Bridge Design Guidelines for 60/30-ton loading.

Project Contacts
Dr. Ing. R. Voigt, Technical Program Manager, Federal Department of Transportation; Dr. Ing. F. Rostasy, Professor, Technical University, Braunschweig.

Project Description
The Ulenbergstrasse two-lane road bridge (plus oversized pedestrian walkways) in Düsseldorf is a 46.9-m-long (154-ft) and 15-m-wide (49-ft) slab and cantilever bridge continuous over two spans (see Figures 37 to 39). The depth of the superstructure is

Figure 37. Ulenbergstrasse Bridge, Overview

1.52 m (5 ft), and the bridge is post-tensioned with 59 bonded HLV-Polystal® parabolic tendons [6] at a working load of 60 tons each. Each tendon was made of 19 HLV-Polystal® rods that are 7.5 mm in diameter (0.3 in) and stressed to 50 percent of their short-term strength. All 59 tendons were monitored for 8 years with embedded copper wire and fiber optic sensors [7] to validate design assumptions. Monitoring was terminated after all readings stabilized.

Composite Materials	
Fiber	E-Glass
Matrix	Unsaturated Polyester Resin
Manufacturing	Pultrusion
Assembly	Bonded Post-Tensioning Tendons
Adhesive	Grouted
Tensile Modulus	51 kN/mm^2 (7.4 x 10^6 psi)
Tensile Strength	1,520 N/mm^2 (220 ksi)
Ultimate Strain	3.3%

1 MPa = 145 psi

Construction/Installation

Construction of the bridge followed conventional construction procedures for cast-in-place prestressed concrete built on falsework with parabolic draped corrugated sheet metal ducts.

Instrumentation, Monitoring, Testing

Each tendon of the 19 HLV-Polystal® rods included 3 rods with embedded copper wire and fiber optic sensors for multiplexed strain monitoring along the tendon profile. The bridge was load tested after completion with static and rolling-truck loading. The actual measured deflection under the test loading was 0.9 mm compared with the predicted expected deflection of 1.2 mm.

Special Issues

Special anchorage systems needed to be developed by SICOM AG for anchorage of the Polystal® glass fiber rods. The anchorage consists of a machined profiled steel housing filled with a synthetic resin molded around the fanned-out Polystal® rods.

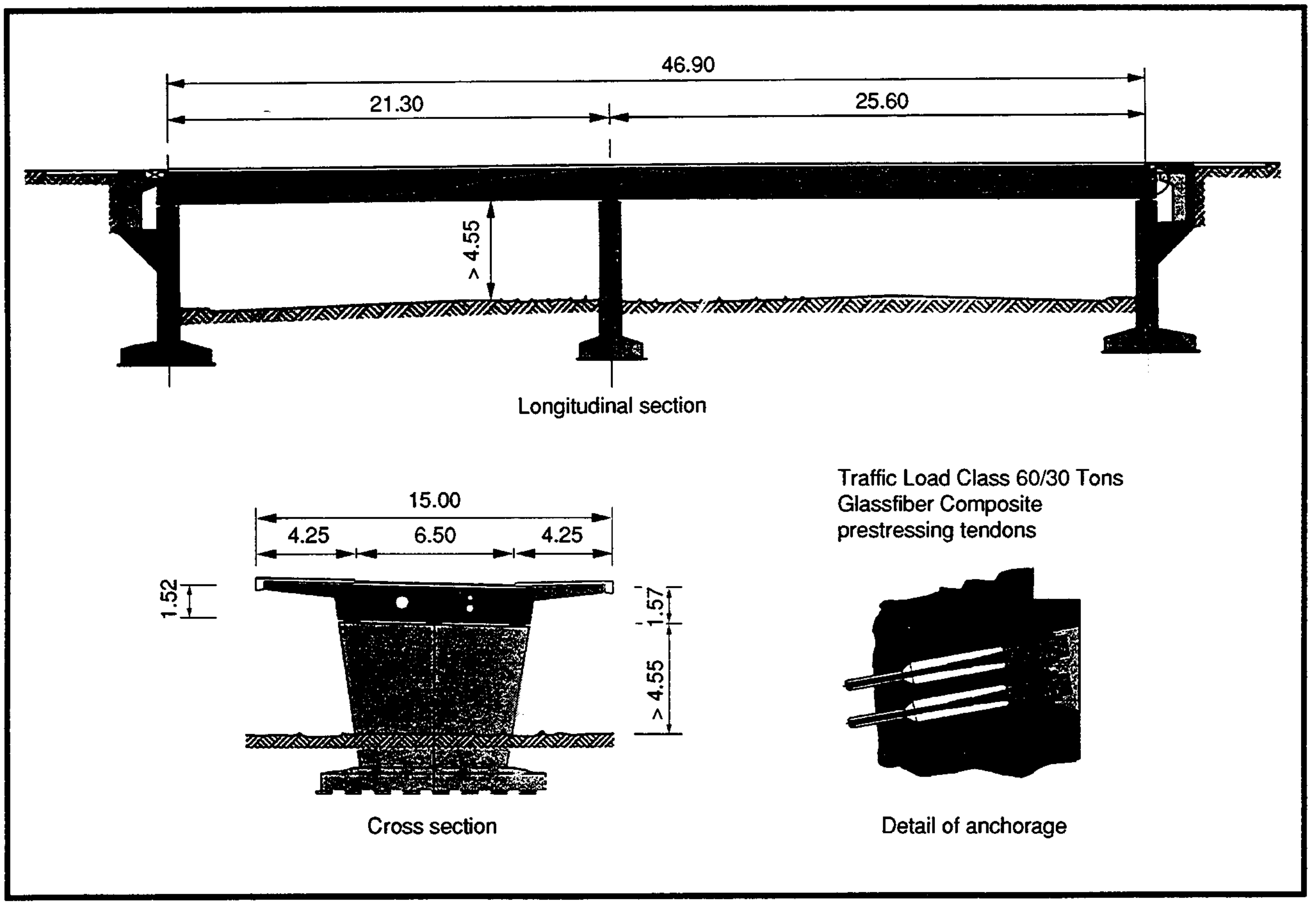

Figure 38. Geometric Dimensions

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Figure 39. Two-Lane Road Bridge With Large Pedestrian Cantilever Overhangs

4.7 SCHIESSBERGSTRASSE BRIDGE (PROJECT E7)

Project Summary
A 53-m (174-ft), three-span, two-lane road bridge on the premises of Bayer AG to provide access to a future planned parking structure.

Project Data
Designer: Obermayer
Owner: Bayer AG
Designed: 1989
Completed: 1991

Project Objective
Demonstrate applicability of HLV-Polystal® post-tensioning system and instrument and monitor the structure under traffic loads.

Alternative Concepts
Conventional high-strength steel post-tensioning tendons.

Design Considerations
The specific weight of Polystal® is 25 percent of steel tendons and the E-modulus is about 25 percent of steel. Allowable working stress level in Polystal® is 50 percent of ultimate, and it is electro-magnetically neutral.

Project Contacts
Dipl. Ing. H. Jonas, Department Head, Obermayer, Cologne; Dr. Ing. R. Voigt, Techn. Angest., Federal Department of Transportation.

Project Description
The three-span continuous slab bridge with cantilevers has a total length of 53 m (174 ft) and a width of 9.7 m (32 ft) (see Figures 40 and 41). The depth of the superstructure is

Figure 40. Schiessbergstrasse Bridge, Overview

1.12 m (3.7 ft), and it is designed for DIN 1072 live load (60/30-ton trucks). The bridge is post-tensioned with 27 continuous parabolic HLV-Polystal® tendons [6] comprised of 19 E-glass rods that are 7.5 mm (3 in) wide and have a nominal prestressing working load of 60 tons each.

Composite Materials	
Fiber	E-Glass
Matrix	Unsaturated Polyester Resin
Manufacturing	Pultrusion
Assembly	Post-Tension Tendons
Adhesive	Grouted
Tensile Modulus	51 kN/mm2 (7.4 x 10^6 psi)
Tensile Strength	1,520 N/mm^2 (220 ksi)
Ultimate Strain	3.3%

1 MPa =145 psi

Construction/Installation

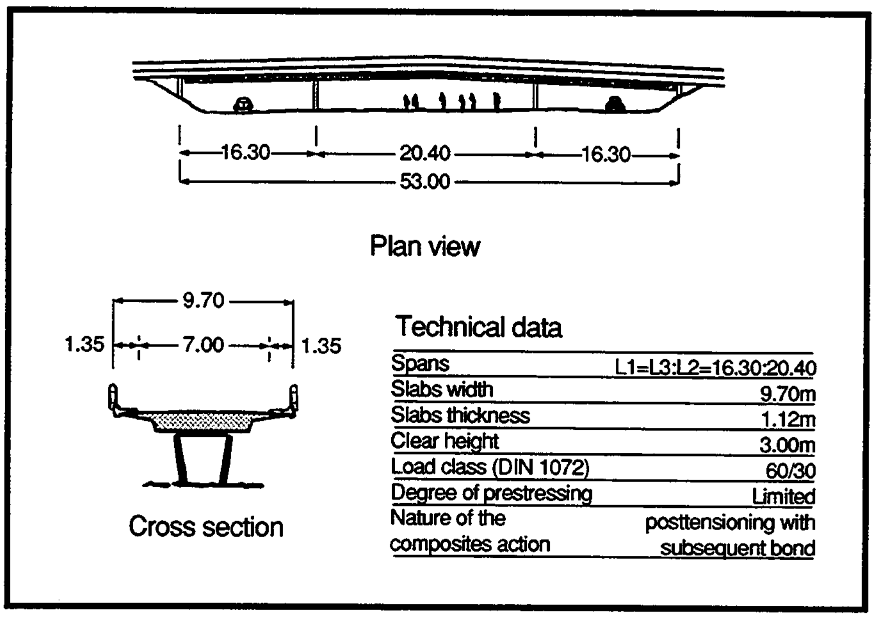
Construction of Schiessbergstrasse Bridge followed conventional cast-in-place prestressed concrete construction on falsework. Post-tensioning ducts in the form of corrugated sheathing were provided for 27 HLV Type III Polystal® tendons, as well as 12 Type 5-lb VSL steel tendons, in case an alternative post-tensioning system is needed at a later date.

Instrumentation, Monitoring, Testing

The Schiessbergstrasse Bridge is fully instrumented for traffic load and durability monitoring, as shown in Figures 43 and 44. Each of the 27 HLV-Polystal® tendons contains 3 glass rods with embedded optical fiber sensors [7] to monitor tendon strains. Crack-monitoring fiber optic sensors were attached along four lines at the deck and bottom soffit (Figure 42) to detect concrete cracks and monitor crack width. Chemical sensors are placed in the deck and soffit concrete to monitor the corrosion potential. A program is in place to monitor the bridge every year for 5 years and, subsequently, every 5 years.

Special Issues

The bridge was monitored for the 12-month period from 1 January to 31 December 1994. All readings are computer controlled, transmitted through telephone lines directly to the engineering office, and automatically checked against predicted and allowable performance tolerances.



Spans	L1=L3:L2=16.30:20.40
Slabs width	9.70m
Slabs thickness	1.12m
Clear height	3.00m
Load class (DIN 1072)	60/30
Degree of prestressing	Limited
Nature of the composites action	posttensioning with subsequent bond

Figure 41. Technical Bridge Data

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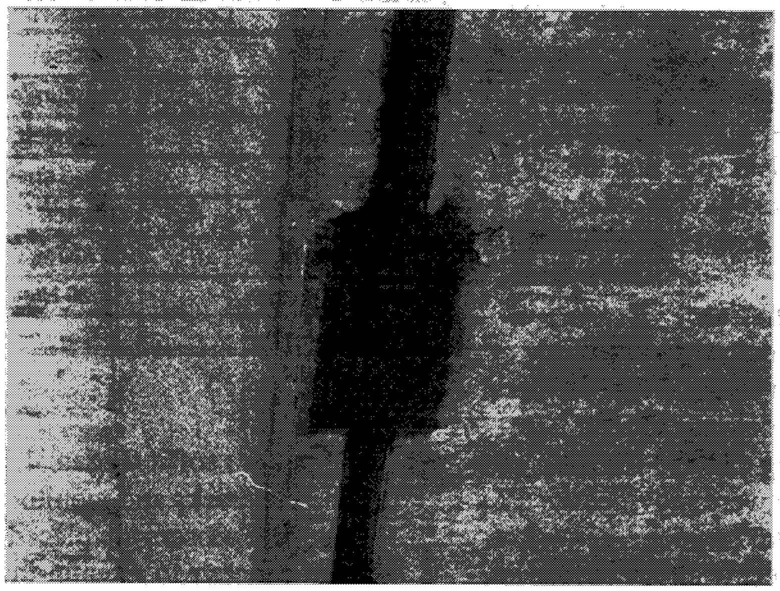

Figure 42. Soffit Groove for
Optical Fiber Sensors

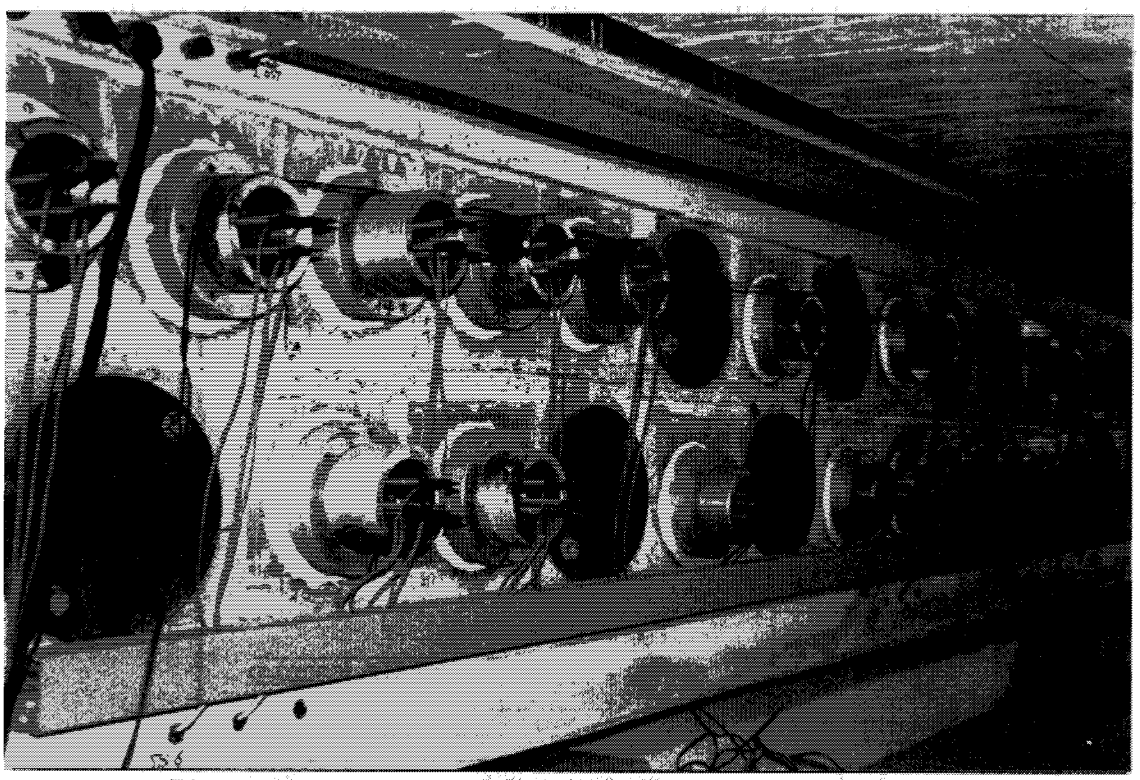

Figure 43. Tendon Anchorage in Abutment Control Room

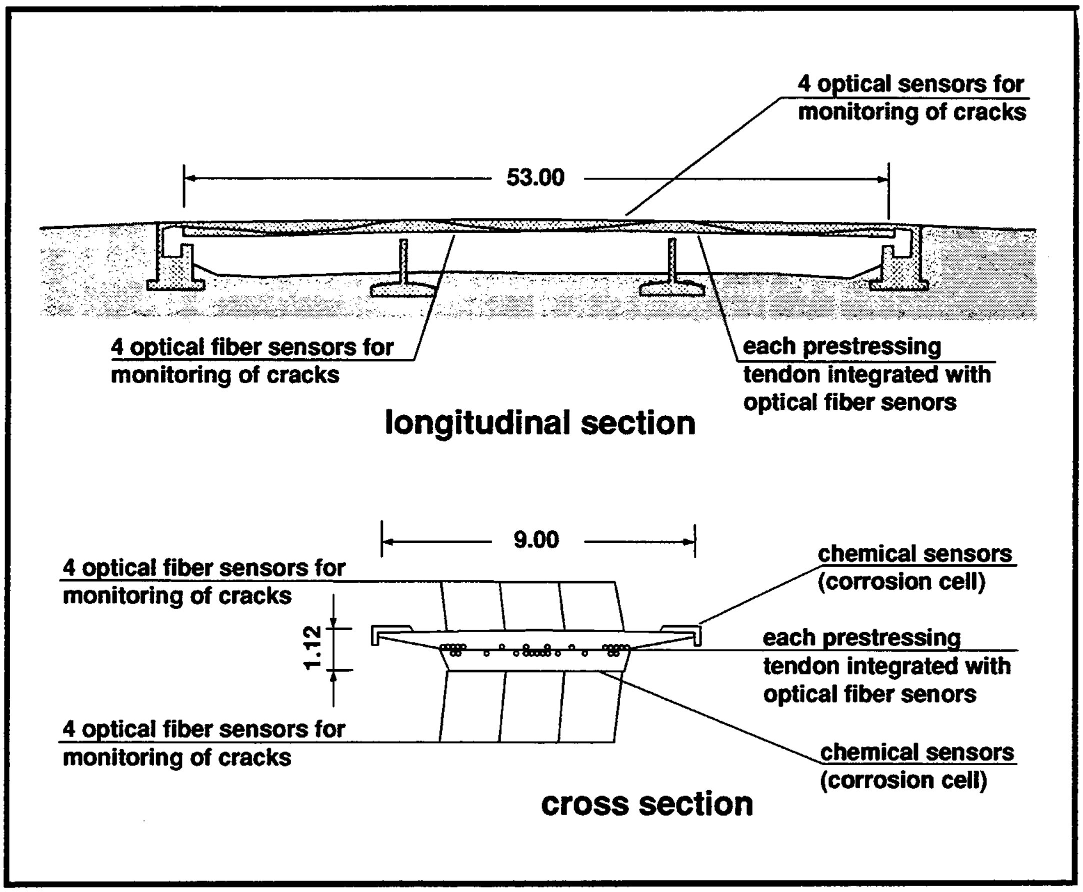

Figure 44. Arrangement of the Optical Fiber Sensors and Chemical Sensors

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4.8 EMPA WORKSHOP (PROJECT E8)

Workshop Objective
The workshop objective was to provide an overview of advanced composite research and applications in civil engineering structures in Switzerland [8]. The workshop was organized by Prof. Urs Meier from the Swiss Federal Laboratories for Materials Testing and Research (EMPA) in Dübendorf, Switzerland.

Workshop Contacts and Meeting Participants
Prof. Urs Meier, Director, EMPA; Dr. Marie-Anne Erki, Professor and Head, Department of Civil Engineering, Royal Military College at Canada; Werner Steiner, Technical Manager, Sika AG; and the technical staff of EMPA.

Workshop Description
The EMPA workshop was hosted by Prof. Erki of the Royal Military College of Canada, in the absence of Prof. Meier, who had made all the arrangements and set the agenda. The workshop was also attended by Mr. Steiner from Sika AG, as well as eight members of the EMPA administrative and research staff.

The main focus of the workshop was on structural rehabilitation using CFRP laminates [8, 9] post-bonded to existing structural members and systems to increase load-carrying capacities (Figure 45). The CFRP laminates are pultruded strips of 50-mm width (2 in) and 1.2-mm thickness (0.05 in) made from 12k rowings of Torey T700 carbon. For member strengthening, these CFRP laminate strips are bonded to the substrate with a two-component epoxy. To date, members and structures successfully strengthened with CFRP laminates include reinforced and prestressed concrete beams, timber, and steel crossbeams in bridges, as well as reinforced concrete columns and masonry walls for seismic retrofitting. Also, strengthening of aluminum box sections for automotive applications is being developed.

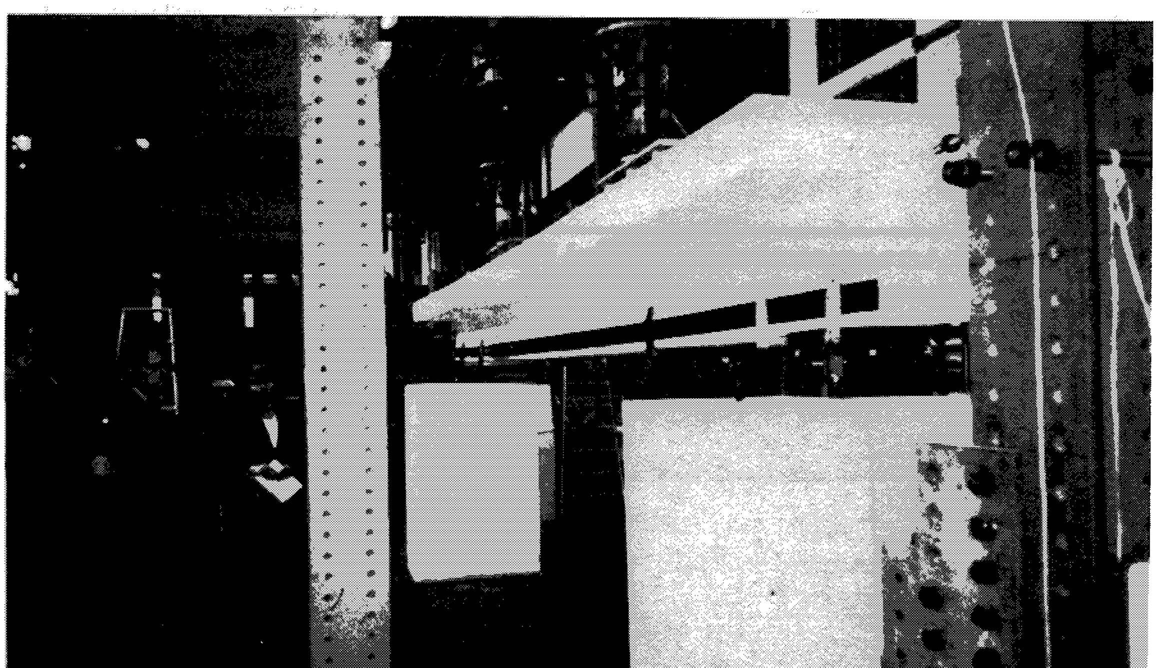

Figure 45. External CFRP Laminate Strengthening on T-Girder Web

Advantages of CFRP strengthening are the light weight and strength of the CFRP laminates, their ease of handling and installation without heavy equipment, and their simple application in overhead installations where the viscosity of the epoxy adhesive is sufficient to support the self-weight of the CFRP strip during curing. Installation can occur in sections that are 15 to 20 m (50 to 65 ft) long, can be performed in tight and congested areas and above suspended utility lines, and can cross other CFRP laminate strips with adjustments in the thickness of the epoxy adhesive layer. Cost of the CFRP strips is SFR55 to SFR80/m (US$14 to $20/ft) for materials or SFR100 to SFR120/m (US$25 to $30/ft), including surface preparation and installation.

Research at EMPA concentrated on applications under traffic load (vibrations); applications as prestressed laminates, with end-anchorage details; and structural integrity of the carbon fiber laminates under fire exposure. Overhead applications to bridge soffit slabs were of particular interest, because added reinforcement and shotcrete is sensitive to application under vibrations. Tests on different adhesives under different excitation frequencies are in progress. Fire tests on loaded beams strengthened with steel plates or CFRP laminates showed steel plates debond two to six times faster than uncoated carbon laminates. Fire tests also showed that protective coatings that delay heating of CFRP laminates can significantly extend the duration of structural integrity.

EMPA has also developed seismic strengthening methods for shear walls in buildings with diagonally applied CFRP laminate strips. Because of the concentrated force transfer in the carbon strips, anchorage at the ends of the carbon strips in footing and floor slabs should be addressed.

In most advanced composite projects at EMPA, preference seems to be given to carbon fiber composites over glass and aramids because of the high susceptibility of glass to stress corrosion and to various chemical environments. For aramids, the high degree of water absorption and the mismatch in coefficient of thermal expansion (negative for aramids) compared to conventional structural materials are deterrents in civil engineering applications.

Extensive cyclic loading and fatigue tests on fiberglass/epoxy beams (Figure 46) have demonstrated the outstanding fatigue characteristics of polymer matrix composite (PMC) structural members. Long-term creep tests on GFRP beams are also in progress at EMPA (see Figure 47).

Another area of emphasis at EMPA is anchorages for composite cables and tendons. Corrosion problems have been found with carbon tendons and zinc-filled conical steel housings due to the formation of a galvanic cell. On the other hand, epoxy fillers stiffened with aluminum oxide pellets and stiffness gradation along the conical anchorage length proved to be very effective at resisting corrosion. These newly developed carbon tendon anchorage systems have been extensively tested in short-term and fatigue-type environments [10].

Other research and development programs reported during the EMPA workshop addressed filament-wound carbon tubes for poles, pipes, and traffic signals; CFRP-reinforcement grids for nonmetallic concrete reinforcement; and CFRP-reinforced high-strength spun concrete. In most of these applications in new structural systems, the disadvantage of high cost outweighs the advantages derived in terms of durability and light weight. In the rehabilitation and strengthening of existing structures, cost effectiveness can be achieved.

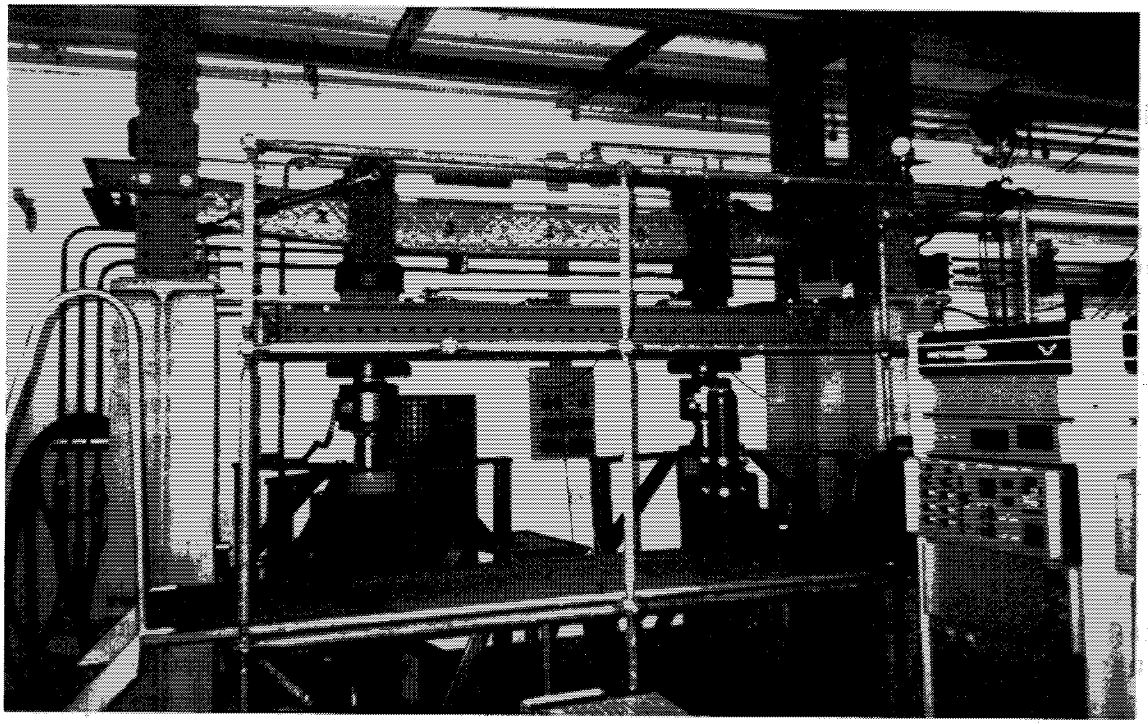
Figure 46. Cyclic Load Testing of CFRP Beams


Figure 47. Long-Term Creep Test on GFRP Beam

4.9 STORCHENBRÜCKE (Stork Bridge) (PROJECT E9)

Project Summary
First cable-stayed road bridge with 2 of 24 cable stays executed as CFRP cable stays, crossing a railroad station in Winterthur.

Project Data

Designer:	Höltschi & Schurter
Contractor:	BBR, Ltd. (Cables)
Owner:	City of Winterthur
Designed:	1994
Completed:	November 1996
Cost:	~ 3× cost of steel cable stay

Project Objective
Demonstrate the use and long-term behavior of carbon fiber composite stay cables in an actual road bridge application.

Alternative Concepts
Conventional high-strength steel cable stays.

Design Considerations
Special design considerations were necessary for the anchorage of the carbon fiber composite cables and the temperature loading of the bridge, because of differences in thermal coefficient between the carbon cables and adjacent steel cable stays.

Project Contacts
Professor Urs Meier, Director, EMPA, Dübendorf; Dipl. Ing. Heinz Meier, Research Engineer, EMPA, Dübendorf.

Project Description
A symmetric, single A-frame pylon cable-stayed bridge with 12 pairs of cable stays (see Figures 48 to 53). Total length is 124 m (406 ft), and the pylon heights are 38 m (125 ft), as shown in Figure 49. One of the 12 pairs of cable stays has been executed

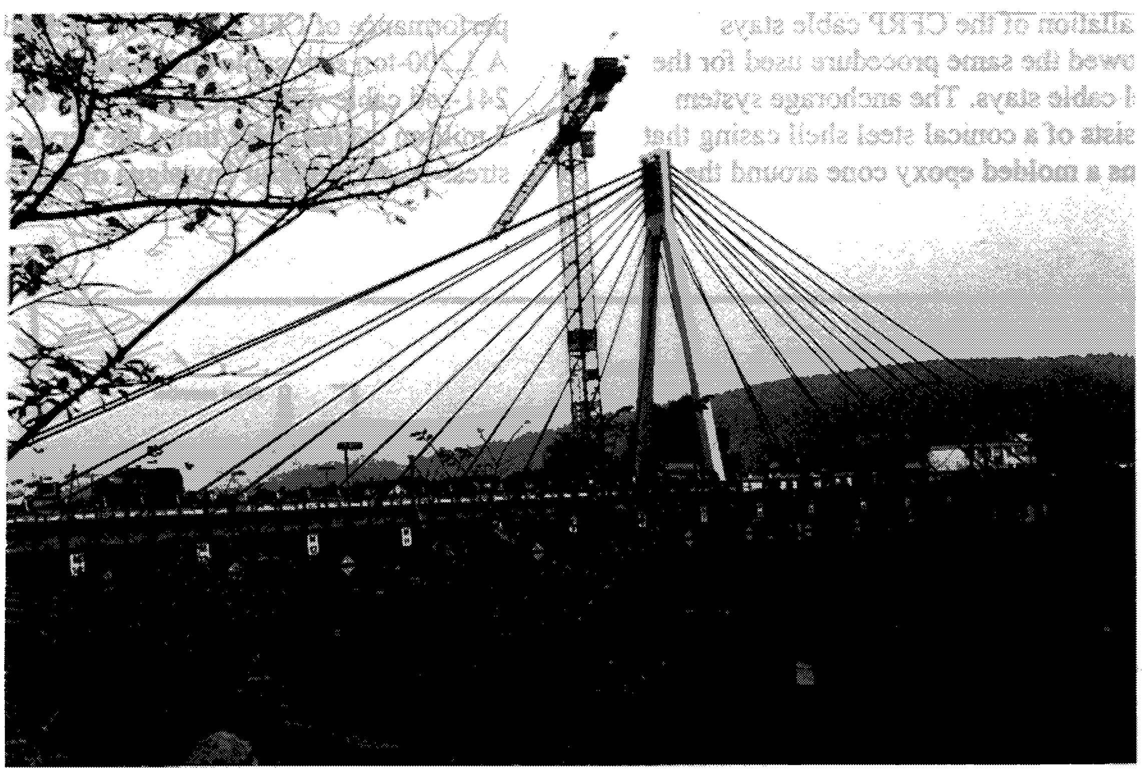

Figure 48. Storchenbrücke, Overview

as carbon cable for demonstration and long-term monitoring. The two carbon cable stays were installed in April 1996, and the bridge was scheduled to open for traffic in November 1996. The key advantages of the carbon cable stays are their light weight, which results in reduced sag under dead load; a more efficient equivalent cable modulus; and the expected durability, with significantly reduced maintenance and replacement requirements. Disadvantages of the carbon cable stays include the lower actual modulus, compared to steel cables, and the higher costs. Each carbon stay cable consists of 241 parallel pultruded CFRP rods of 5 to 6 mm (0.2 in) in diameter, with a 65- to 70-percent fiber volume fraction [10].

Composite Materials	CFRP Rods	Carbon Fibers
Fiber	Carbon	----------
Matrix	Epoxy Resin	----------
Manufacturing	Pultrusion of CFRP Rods	----------
Assembly	Parallel CFRP Rod Bundles	----------
Tensile Modulus	165 GPa (24 x 10^6 psi)	228 GPa (33 x 10^6 psi)
Tensile Strength	3,300 MPa (478 ksi)	4,800 MPa (700 ksi)
Ultimate Strain	2%	2.1%

Construction/ Installation

The CFRP cable stays were prefabricated with anchorages and shipped to the site. Installation of the CFRP cable stays followed the same procedure used for the steel cable stays. The anchorage system consists of a conical steel shell casing that forms a molded epoxy cone around the CFRP rods. The modulus of the epoxy cone anchorage is gradated from soft, at the cable, to stiff, at the anchor terminus, to provide uniform shear force transfer to the transverse pressure-sensitive CFRP rods. The stiffness gradation in the anchorage filler material is achieved by the addition of aluminum oxide pellets with varying thicknesses of epoxy coating [10].

Instrumentation, Monitoring, Testing

Bundles of 19 CFRP rods were tested at EMPA in static and fatigue loading. The static load-carrying capacity reached 92 percent of the sum of the single-wire capacity. Fatigue tests showed the superior performance of CFRP under cyclic loading. A 1,200-ton stay cable and anchorage of a 241-rod cable were tested at EMPA to over 8 million cycles at 3.2 times the service load stress levels, without any signs of damage.

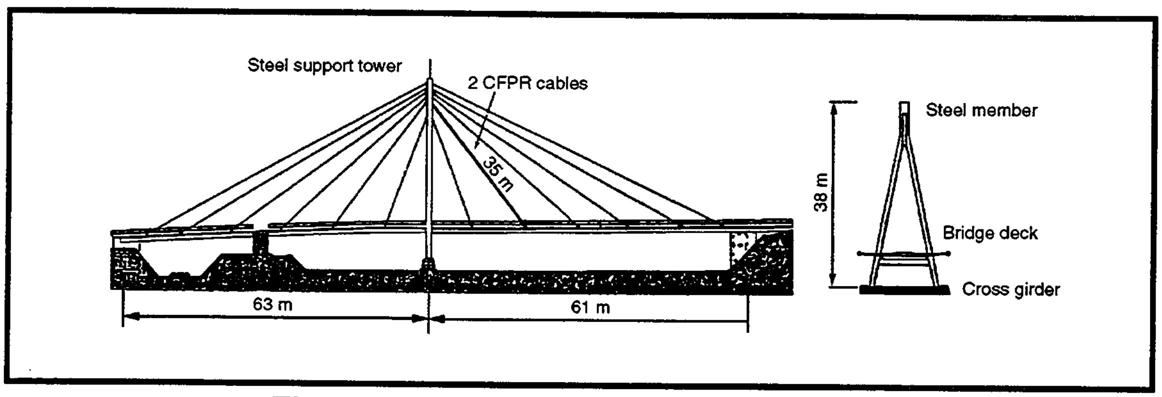

Figure 49. Bridge and Geometry Dimensions
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The installed 1,200-ton cable stays are instrumented with optical fiber Bragg gratings [11] and standard electrical resistance gauges for strain monitoring of the cable and anchorage, as well as tem-perature sensors, humidity sensors, and displacement transducers during the active monitoring time windows. Measured strains during construction, stressing, and anchoring were as expected and predicted.

Figure 50. Sealing (Waterproofing) of Bridge

Special Issues

One special issue relative to installation of two carbon cable stays between steel cable stays is the difference in cable stiff-ness and in the coefficient of thermal expansion. Carbon cable has a very small thermal co-efficient and will have a "stiffening" effect with decreasing temperature, because of the respective elongation and contraction of adjacent steel cable stays.

Figure 51. Waterproofing and Wear Surface Application

Figure 52. Top Cable-Stay-Stressing Anchorages

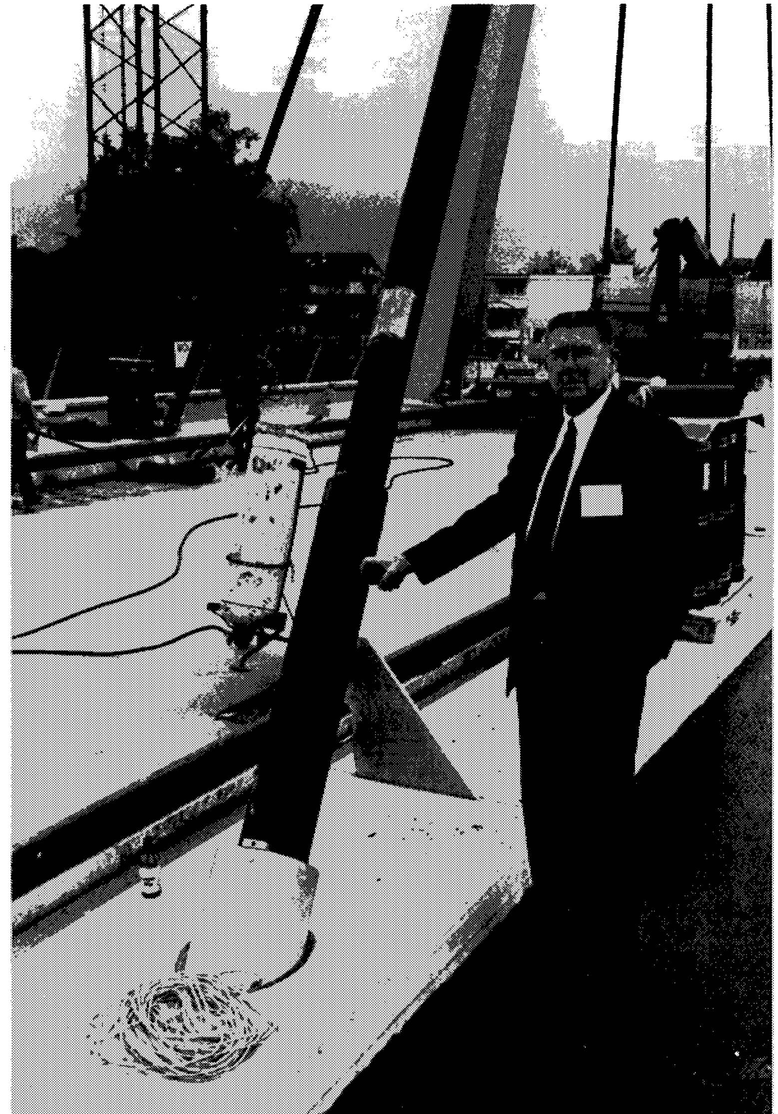

Figure 53. Bottom (Fixed) Anchorage of Carbon Cable and Instrumentation

4.10 CO-OP CITY DEPARTMENT STORE (PROJECT E10)

Project Summary
Strengthening of reinforced-concrete floor slabs with CFRP laminates to allow floor cutouts for elevator shafts and escalator openings (see Figure 54).

Project Data

Designer:	Deuring & Oehninger AG
Contractor:	Renesco AG
Owner:	Co-op City
Designed:	1995
Completed:	September 1996
Cost:	SFR120/m (US$31/ft)

Project Objective
To increase the factor of safety of floor slabs that have large cutouts by adding perimeter tension and distribution reinforcement to the bottom of the slab in the form of epoxy-bonded CFRP laminates.

Alternative Concepts
Steel plate bonding; however, problems exist with handling of the heavy steel plates onsite, pressure during epoxy curing, thickness of steel plates and crossing of strips, fire protection, and corrosion issues with steel plates.

Design Considerations
CFRP laminates are designed based on required strength and to keep the regular reinforcement in the elastic range under service loads to limit crack width. CFRP laminates are only applied in areas where the safety factor for the slab for the preexisting reinforcement is still ≥ 1.0. In all other cases, steel laminates are applied (Figure 55).

Project Contact
Werner Steiner, Techn. Manager, Sika AG.

Figure 54. New Escalator Opening in Existing Reinforced-Concrete Floor Slab

Project Description

The concrete flat slab structure of the Co-op City Shopping Center in Winterthur was erected 28 years ago. The multistory building had three underground floors, four above-ground levels, and an attic. Changes in use and the development of the attic space as a shopping area required the addition of an elevator and escalator extensions to below-ground floor and attic levels. The elevator cutout through five 350-mm (14-in) floor slabs had dimensions of 5 m × 3 m (16 ft × 10 ft), and the escalator openings had dimensions of 32 m × 17 m (105 ft × 56 ft). The strengthening around the openings required 3 km (1.9 mi) of CFRP laminates of 100-mm (4-in) width and 1.2-mm (0.05-in) thickness. CFRP laminate strips were up to 16 m (53 ft) long. In most cases, no suspended utility lines or service conduits needed to be removed for the CFRP installation (see Figure 57). More than 300 CFRP strip crossings were executed without problems (see Figure 56).

Composite Materials	
Fiber	Toray T700
Matrix	Sikadur-30
Manufacturing	CFRP Laminate Pultrusion
Assembly	Manual
Adhesive	Two-Component Epoxy
Curing	Ambient, 3 days, 90%
Tensile Modulus	150 kN/mm^2 (21.8 x 10^6 psi)
Tensile Strength	2,400 N/mm^2 (21.8 x 10^6 psi)
Ultimate Strain	1.4%

Construction/Installation

The reinforced concrete (RC) slab was sand-blasted to expose the concrete aggregate. The CFRP strips were cleaned, and a two-component epoxy paste was applied to both the RC slab and the CFRP or steel strip. The CFRP strips can be pressed on by hand (and

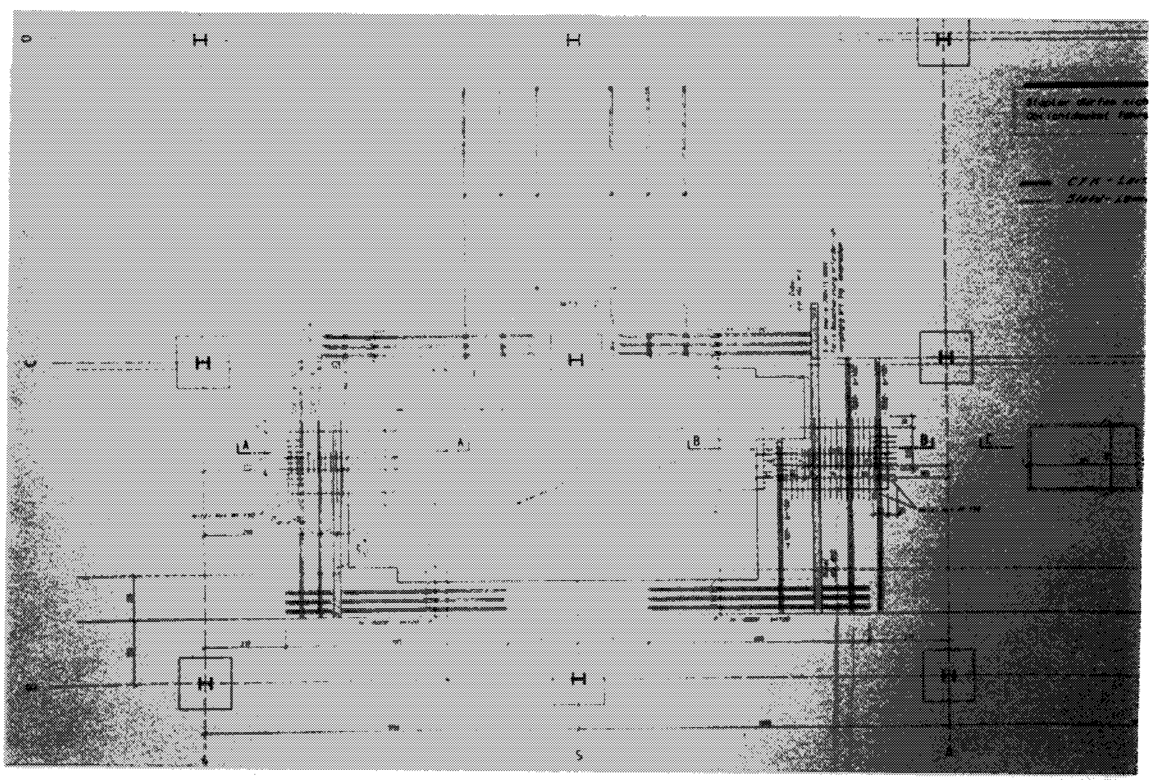

Figure 55. Strip Bonding Layout Around Escalator Opening, Showing CFRP Laminates (Red) and Steel Strips (Blue)

a hand roller) once; the weight of the steel strips requires constant pressure during curing. The light weight and flexibility of the CFRP laminates allowed installations of long strips in very congested areas and over suspended utility lines and conduits. Excess adhesive is removed.

Instrumentation, Monitoring, Testing
Tensile bond strength was tested by a direct tension test of a 50-mm-diameter (2-in) cored plug through the laminate. Failure should always occur in the substrate, not in the laminate or the epoxy adhesive joint. Also, the dew point is checked before installation by measuring air temperature, substrate temperature, and relative humidity.

Special Issues
Application of CFRP laminates in pre-stressed form as post-tensioning elements has been successfully tested at EMPA; however, no commercial installations have yet been executed.

Figure 56. Crossing of CFRP Laminates

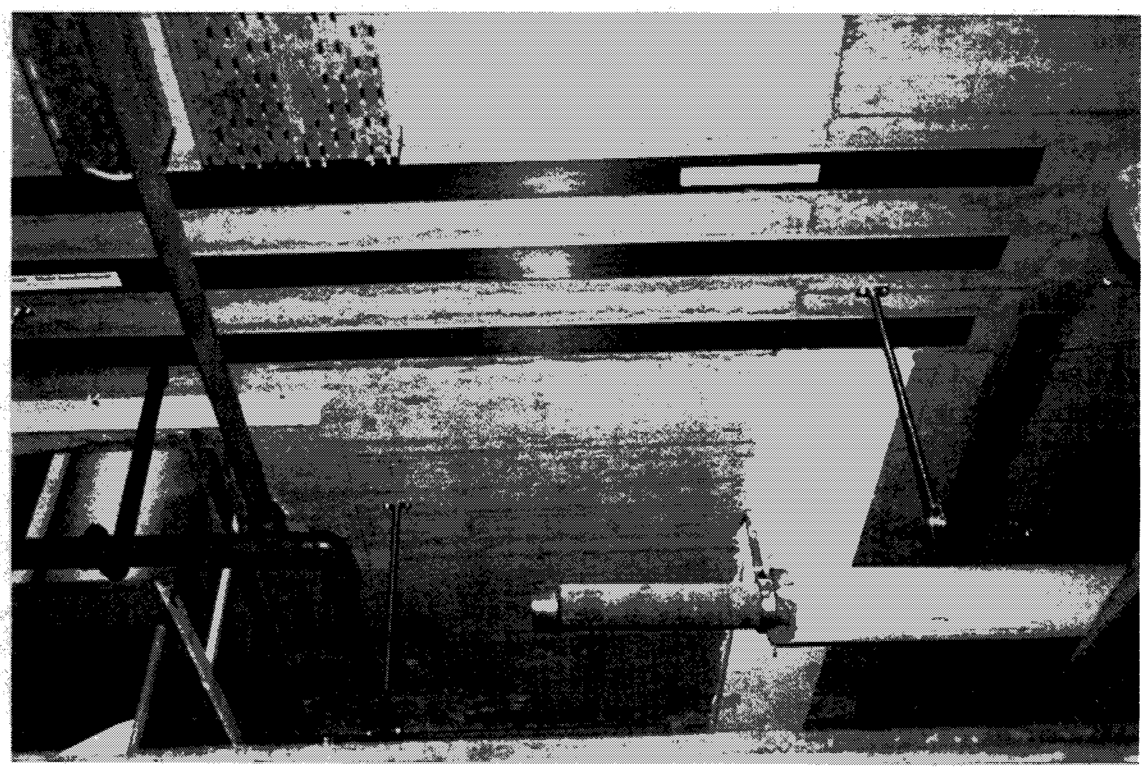

Figure 57. Installed CFRP Laminates and Steel Strip

4.11 OBERRIET RHEIN BRIDGE (PROJECT E11)

Project Summary
Complete rehabilitation and live-load-capacity upgrade required by increased traffic loads since bridge construction in 1963. Bottom soffit strengthening with transverse carbon laminates.

Project Data

Designer:	Albert Köppel, Consulting Engineer
Contractor:	Sika AG
Owners:	Kanton of St. Gallen and Austria
Designed:	1996
Completed:	October 11, 1996
Cost:	Total rehabilitation SFR2 million (US$1.67 million)

Project Objective
Rehabilitate entire bridge. Bring all elements up to current design standards. Increase factor of safety for transverse bending of deck slab to a factor of more than 1.5.

Alternative Concepts
Complete deck replacement or steel plate bonding to bottom soffit. Entire bridge replacement estimates were SFR4.5 million (US$3.75 million).

Design Considerations
Deck deterioration was not extensive, and only an 80-mm (3.1-in) concrete overlay was required. This kept the stress levels in the steel girders within the design range. CFRP strips were bonded to the deck soffit to increase the positive moment capacity. Negative moment region capacity was enhanced with additional steel embedded in the overlay concrete.

Project Contacts
Daniel Pfister, Bridge Engineer, Kanton of St. Gallen; Albert Köppel, Consultant, Bänzinger, Köppel & Partners.

Project Description
The Oberreit Bridge connects Switzerland and Austria across the Rhein River (Figure 58). The bridge is a three-span steel girder and concrete deck composite structure with spans of 35-45-35 m (114-148-114 ft). The

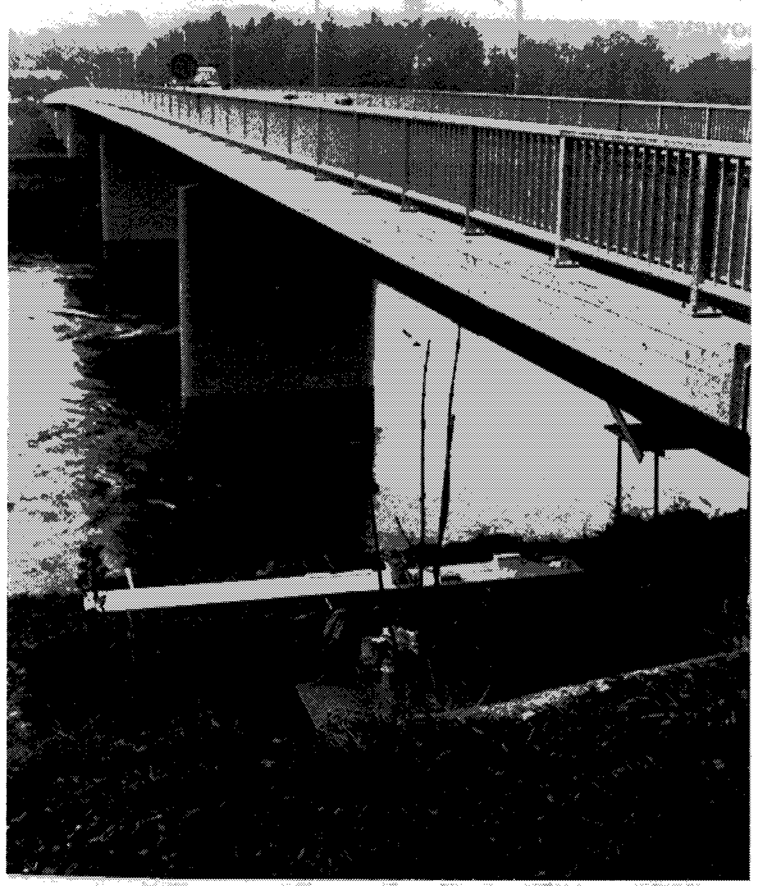

Figure 58. Oberriet Bridge, Overview

cross-section and dimensions are shown in Figure 59. A total of 670 m (~2200 ft) of 80-mm-wide (3.1 in) and 1.2-mm-thick (0.05 in) CFRP laminate strips was used to strengthen the positive moment region of the bridge deck in the transverse direction between the two steel main girders. The cost of the CFRP strengthening, including surface preparation and materials, was about SFR100,000 (US$83,000), compared to the deck replacement cost of about four times as much. The cost per unit length of installed carbon laminates was SFR149/m (US$38/ft).

Composite Materials	
Fiber	Toray T700 Carbon
Matrix	Epoxy Resin
Manufacturing	Pultrusion, 70% Fiber Volume
Assembly	Overhead, Manual
Adhesive	Sikadur-30, Epoxy
Curing	Ambient
Tensile Modulus	150 GPa (21.8 x 10^6 psi)
Tensile Strength	2,400 MPa (348 ksi)
Ultimate Strain	1.4%

Construction/Installation
The existing deteriorated concrete on top of the deck was removed with hydrojets, which also removed the 10 mm (0.4 in) of chloride contamination. The 80- to 100-mm (3.1- to 4.0-in) concrete overlay was used to increase the flexural capacity by adding additional reinforcement in the negative moment regions. The CFRP strips on the slab soffit were applied by hand after grinding and cleaning of the surface (Figures 60 and 61). CFRP strips were applied from a scaffold and spaced every 0.75 m (2.5 ft).

Instrumentation, Monitoring, Testing
Application begins only when the dew point on the concrete surface is not reached. This is determined for surface temperature and humidity measurements. After CFRP application, visual inspection, tapping for voids, and tension bond tests on cured carbon strips are conducted. Tension bond core tests (Figure 62) must show the failure plane in the concrete substrate, not in the epoxy joint. Electrical resistance and Demec strain (Figure 63) measurements were taken under proof load (wheel load) tests. Continued or permanent monitoring is planned.

Special Issues
Sika set up a training course in 1993-94 to familiarize engineers with the new CFRP technology. Design seems to be driven largely by strength with some considerations to crack width control.

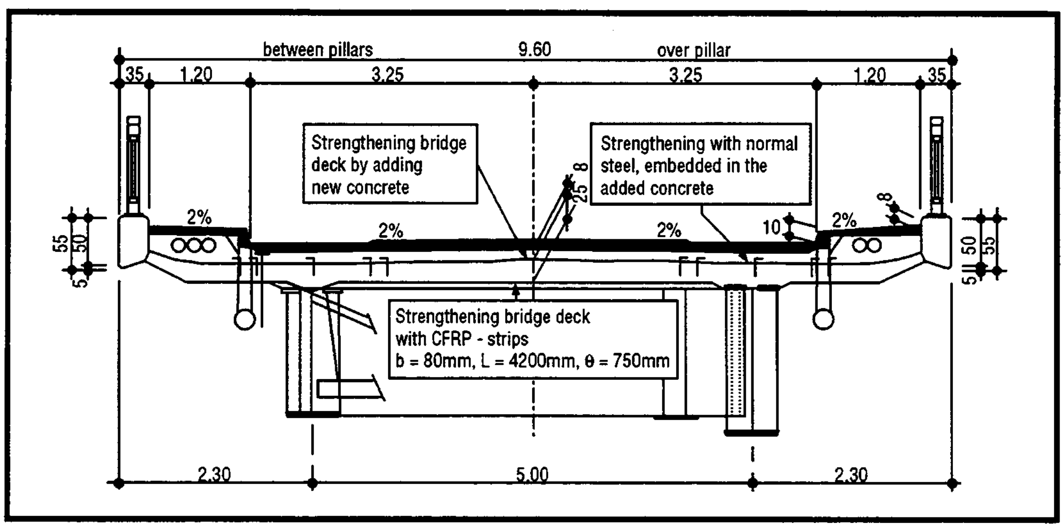

Figure 59. Cross-Section and Dimensions
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Figure 60. Application of Epoxy Adhesive to Carbon Laminate

Figure 61. Application of Carbon Laminate to Bridge Soffit

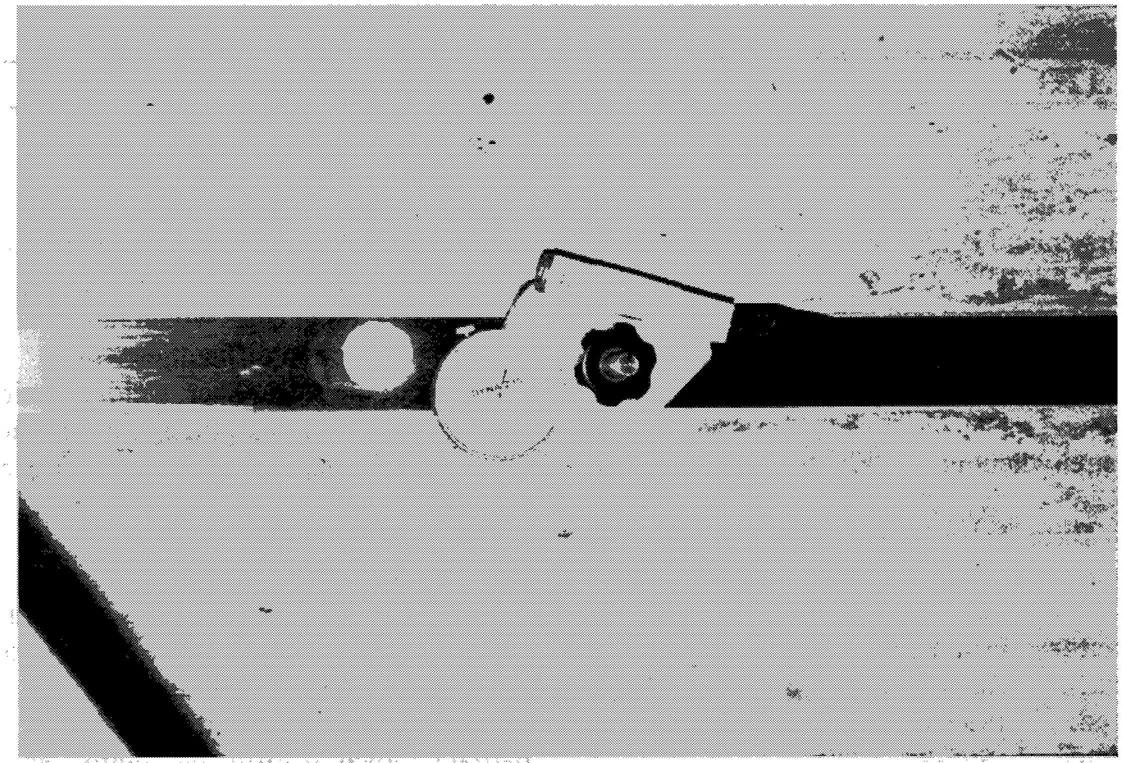

Figure 62. Tensile Bond Testing on Cored Carbon Laminates and Glued Steel Disks

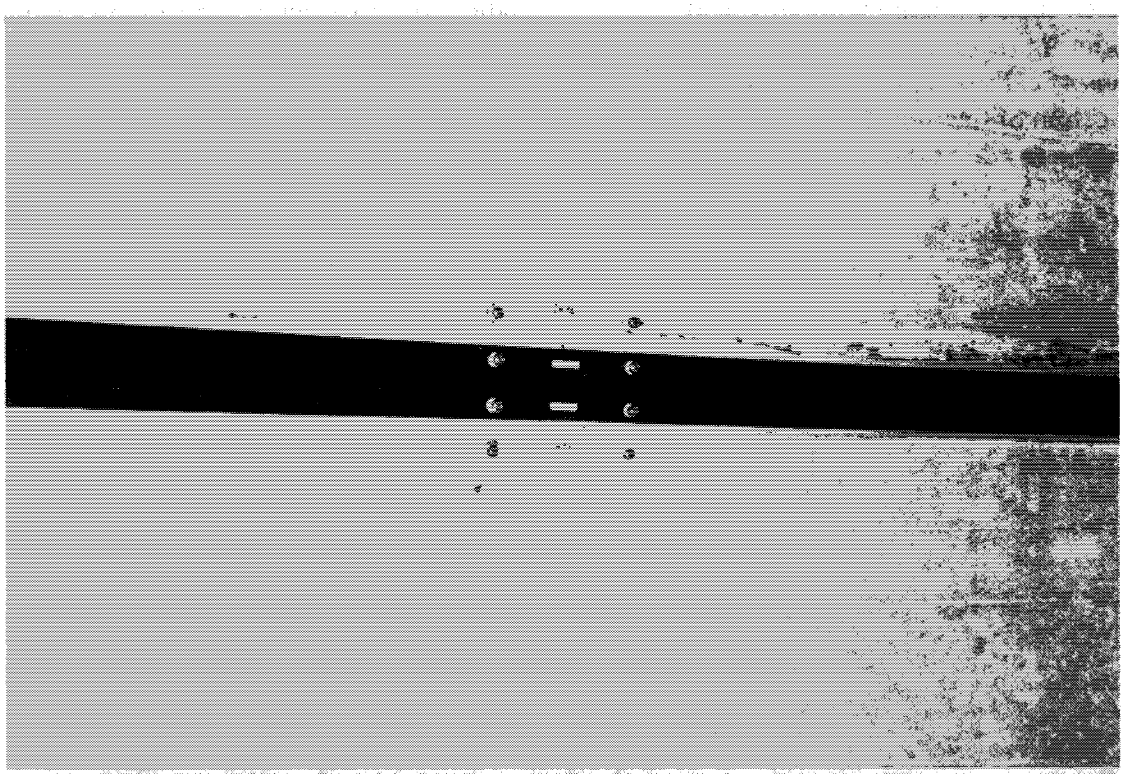

Figure 63. Demec Points for Absolute and Relative Strain Measurements

4.12 FÜRSTENLAND BRIDGE (PROJECT E12)

Project Summary
The Fürstenland Bridge (Figure 64) was constructed in 1941 and has extensive reinforcement corrosion and corrosion potential due to high chloride contents in the superstructure soffit slab. Partial soffit slab removal and repair required temporary girder strengthening.

Project Data

Designer:	Bänzinger + Köppel + Partners
Contractor:	Fritz Bruderer AG
Owner:	Kanton of St. Gallen
Designed:	1995
Completed:	1996-97
Cost:	Total SFR10 million (US$8.3 million)

Project Objective
Strengthen superstructure without visual impact during reconstruction of soffit slab by means of carbon laminates bonded to the lower portion of the multicell box girder webs on the inside of the superstructure.

Alternative Concepts
Steel plate bonding at the same locations where carbon laminates are applied. Although material costs would have been lower, construction difficulties with handling of the steel plates, welding inside the superstructure box girder, and continued maintenance, i.e., corrosion protection, led to the selection of the CFRP system.

Design Considerations
Repairs needed to be completed under full traffic conditions. An increase in the factor of safety was required for longitudinal flexural service-load-limit states during partial removal of soffit slab reinforcement and for permanent operation.

Project Contacts
Nuot Letta, Bridge Engineer, Kanton of St. Gallen; Albert Köppel, Consulting Engineer, Bänzinger + Köppel + Partners; Werner Kast, Consulting Engineer, Bänzinger + Köppel + Partners; Matthias Züst, Contractor, Fritz Bruderer AG.

Figure 64. Fürstenland Bridge, Overview

Project Description

Composite Materials	
Fiber	Toray T700 Carbon
Matrix	Epoxy
Manufacturing	Pultrusion
Assembly	External Bonding
Adhesive	Sikadur-30, Epoxy
Curing	Ambient Field Curing
Tensile Modulus	150 GPa (21.8 x 10^6 psi)
Tensile Strength	2,400 MPa (348 ksi)
Ultimate Strain	1.4%

The Fürstenland Bridge was constructed in 1941 as a reinforced concrete structure with a total length of 489 m (1,605 ft). The mainspan consists of a 135-m- (443-ft-) long and 60-m- (197-ft-) high open dual spandrel arch structure. Spandrel frames on the arch and approach frames are spaced approximately 22 m (72 ft) apart (Figure 65). The superstructure consists of a three-cell box girder with constant structural depth of 1.9 m (6.2 ft). Fifteen years ago, faulty deck drains were installed which allowed deck runoff water containing deicing salt to flow and accumulate inside the box girders. Measurements with electrical corrosion gauges indicated corrosion of the reinforcement. The decision was made to replace large portions of the soffit slab. With the removal of all or part of the soffit slab, the torsional and transverse load-carrying

Figure 65. Three-Cell Box Girder Superstructure on Spandrel Frames and Arches (489-m Length)

characteristics of the three-cell box girder superstructure will be significantly reduced, requiring individual girders to carry larger portions of the traffic load. Because the bridge has historical value, only internal strengthening measures were allowed. Individual girders were strengthened with the addition of CFRP laminates (Figure 66) to the bottom section of the girder webs.

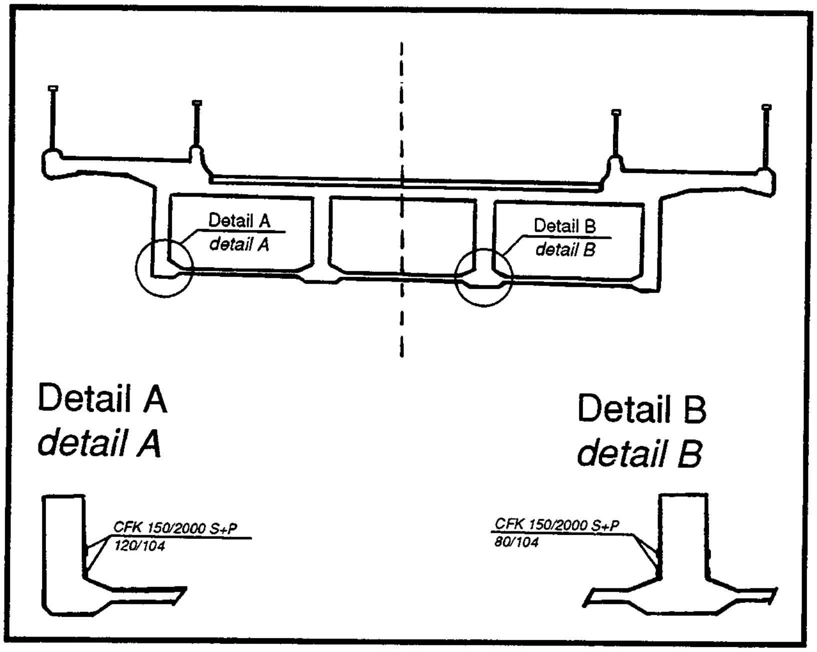

Figure 66. Cross-Section and Strengthening Locations
Reproduced with permission from Bänziger + Köppel + Partners.

Construction/Installation
As a first stage, the bridge deck was repaired and sealed to eliminate water penetration into the box sections. With electrical corrosion gauges (chloride content measurements), areas of high chloride contamination were identified. Carbon laminates, 80 mm (3.1 in) and 120 mm (4.7 in) wide and 1.2 mm (0.05 in) thick, were bonded to the lower web portions (Figure 67), and the bottom soffit slab was partially removed (Figure 68) and rebuilt (Figure 69). Estimated costs for the CFRP Strengthening are SFR100 to SFR120/m (US$25 to $31/ft) of installed CFRP laminate.

Instrumentation, Monitoring, Testing
Large-scale laboratory validation testing was conducted at EMPA. One of the beams was tested during the panel's visit and showed CFRP laminate failure to be about 5 percent below the design target load.

Figure 67. Application of CFRP Strips

Figure 68. Deteriorated Bottom Soffit Panel

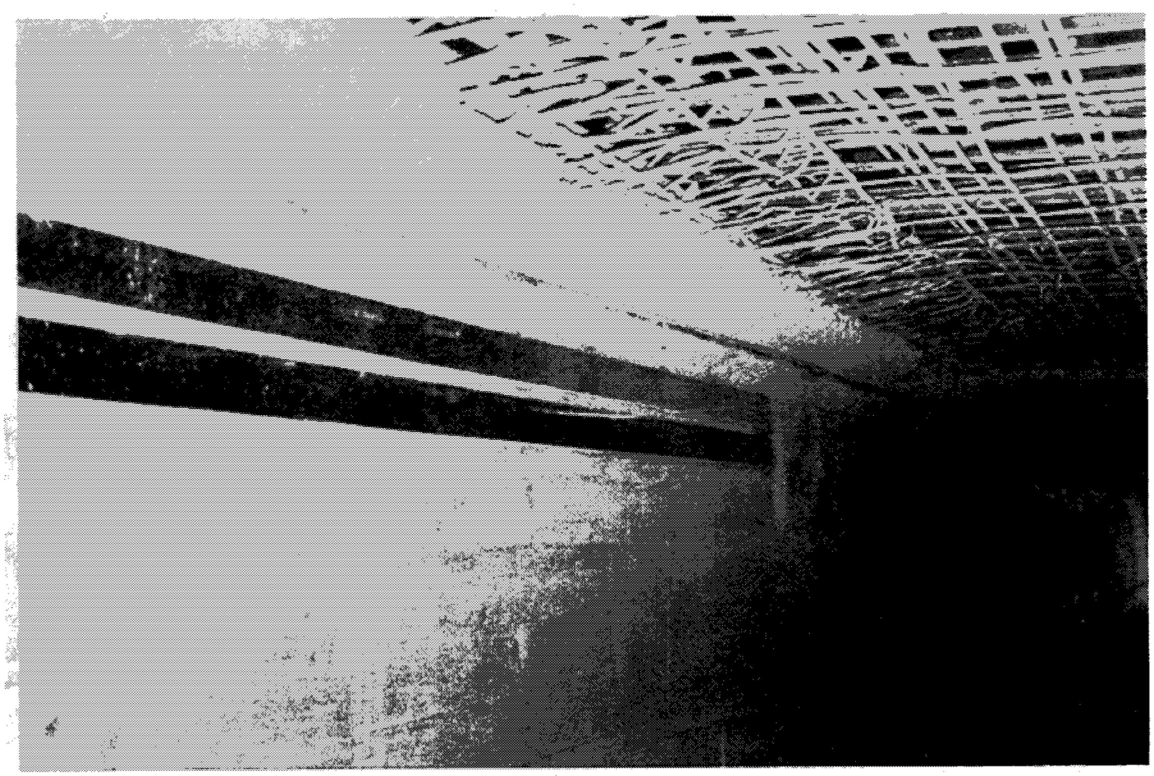

Figure 69. Temporary Construction Strengthening
With CFRP Strips During Bottom Soffit Repair

4.13 KOBLENZ/WALDSHUT BRIDGE (PROJECT E13)

Project Summary
This historic railroad wrought iron bridge (shown in Figure 70) is an excellent candidate for upgrading of the load rating by CFRP laminate bonding to the cross-girders.

Project Data

Owners: Shared by Swiss and German Federal Railway Systems
Designed: 1857
Completed: 1859

Project Objective
The project objective is to increase capacity for train speed, currently limited to 45 km/h (28 mph), and train weight, to permit double-deck commuter trains between Koblenz, Switzerland, and Waldshut, Germany.

Alternative Concepts
Steel plate bonding to the cross girders is one alternative, although it would increase the dead load of the structure. Historic preservation of this bridge does not allow additional members or other external strengthening measures.

Design Considerations
The Koblenz/Waldshut railway bridge is the oldest wrought iron bridge in continental Europe. Fracture analyses conducted by Prof. Brühwiler at the Federal Institute of Technology (ETH) in Lausanne determined crack growth rates and service life predictions. CFRP strengthening would possibly increase capacity and service life.

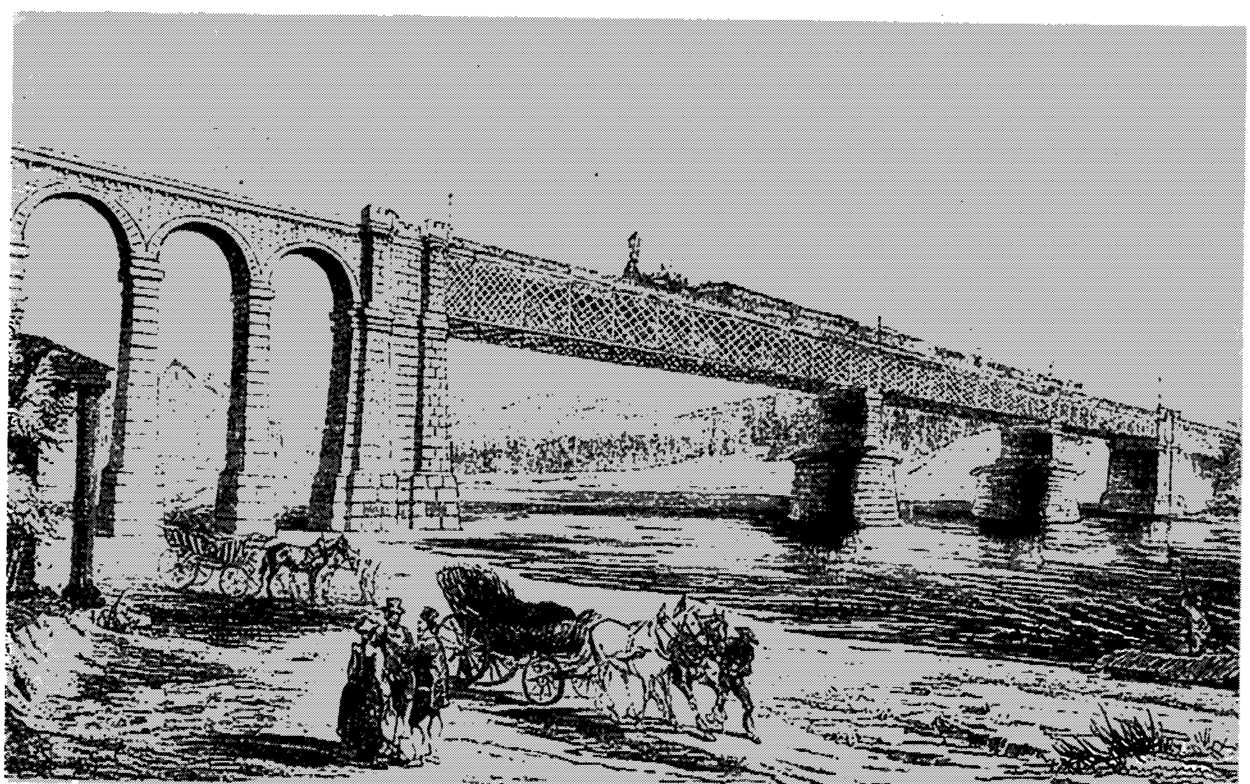

Figure 70. The Historic Koblenz/Waldshut Wrought Iron Bridge, ca. 1859
Reproduced with permission from EMPA.

Project Description

The Koblenz/Waldshut wrought iron bridge was completely rehabilitated in 1992 (Figure 71) at a cost of SFR900,000 (US$750,000). The rehabilitation work included new corrosion protection, painting of all steel members, and replacement of steel roller bearings. Some corroded rivets were replaced with high-strength bolts, however, the bridge was not strengthened at the time. A desire for double-deck commuter train traffic and higher speeds led to investigation of strengthening measures. The strengthening of the cross-girders with CFRP laminates would be similar to a project for a railroad bridge at Ossingen (upriver from the bridge), which was scheduled for strengthening in late 1996 and early 1997.

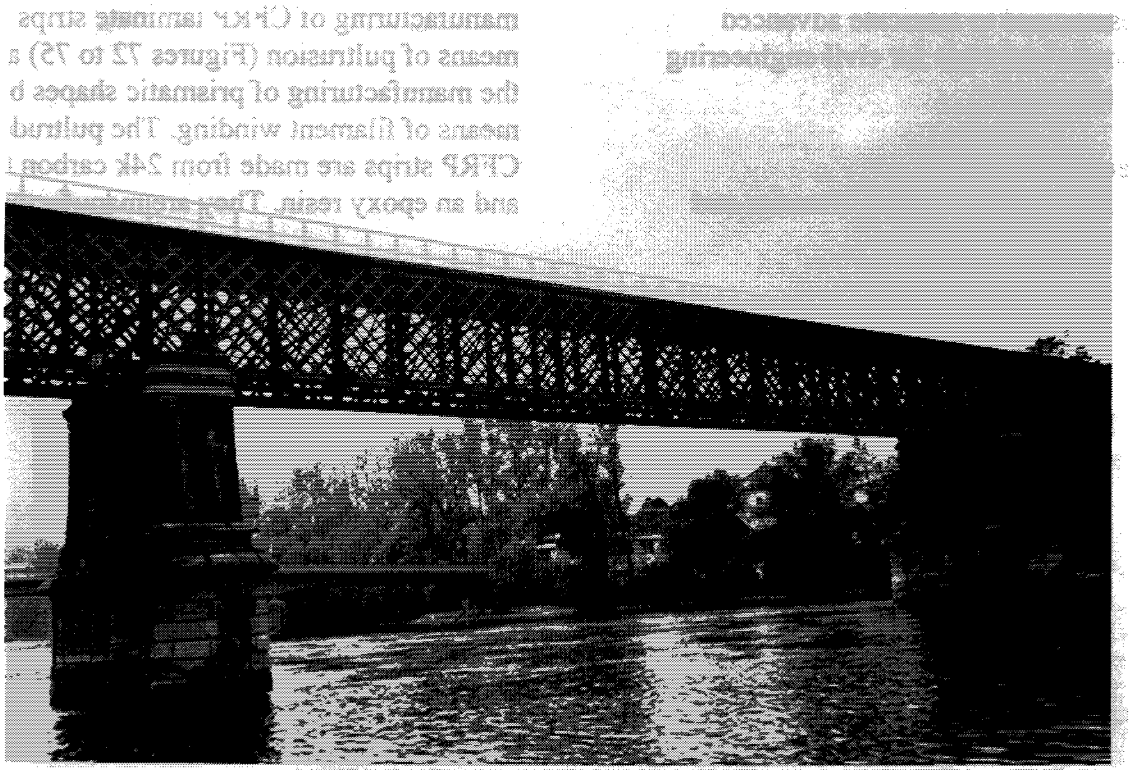

Figure 71. The Historic Koblenz/Waldshut Wrought Iron Bridge, 1996

4.14	ADVANCED COMPOSITES MANUFACTURING (PROJECT E14)

Project Summary
An overview of advanced composite manufacturing was provided by Stesalit AG, a Swiss manufacturer of advanced composite systems and components in Zullwil, near Basel.

Project Objective
Demonstrate materials and manufacturing processes used to fabricate advanced composite materials for civil engineering applications.

Project Contact
Mark A. Erath, Managing Director and CEO, Stesalit AG.

Project Description
Stesalit's principal line of business is the manufacturing of aerospace components and materials and laminates for printed circuit boards. The discussions focused on fiber, resin, and curing technologies for advanced composite materials.

Processes observed at Stesalit were the manufacturing of CFRP laminate strips by means of pultrusion (Figures 72 to 75) and the manufacturing of prismatic shapes by means of filament winding. The pultruded CFRP strips are made from 24k carbon tows and an epoxy resin. They are manufactured

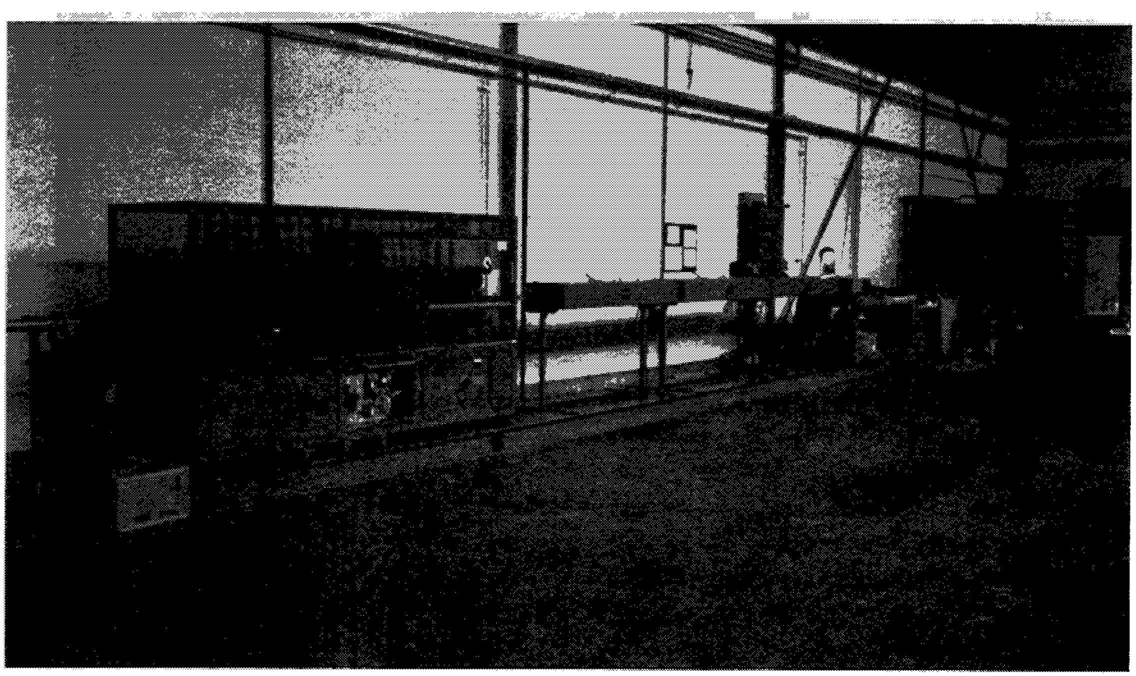

Figure 72. CFRP Laminate Pultrusion Setup at Stesalit AG
Included with permission from Stesalit AG.

in thicknesses of 1.0 to 2.5 mm (0.04 to 0.1 in) and widths of 50 to 150 mm (2 to 6 in).

The filament winding process uses the same base materials and allows for the inclusion of brackets, attachments, and fittings of different materials during the process.

The material systems used and the observed manufacturing technology were identical to comparable materials and manufacturing methods used in the United States.

After the plant visit, Mr. Erath made a presentation covering the plant's history and product development. The presentation included in-depth information on the adhesives developed and used by the plant in the manufacturing of various products. The presentation also offered an excellent overview of adhesive properties, applications, and limitations. Both the presentation and subsequent discussion provided additional assurance that, when used properly, adhesives developed for an application will serve the intended function.

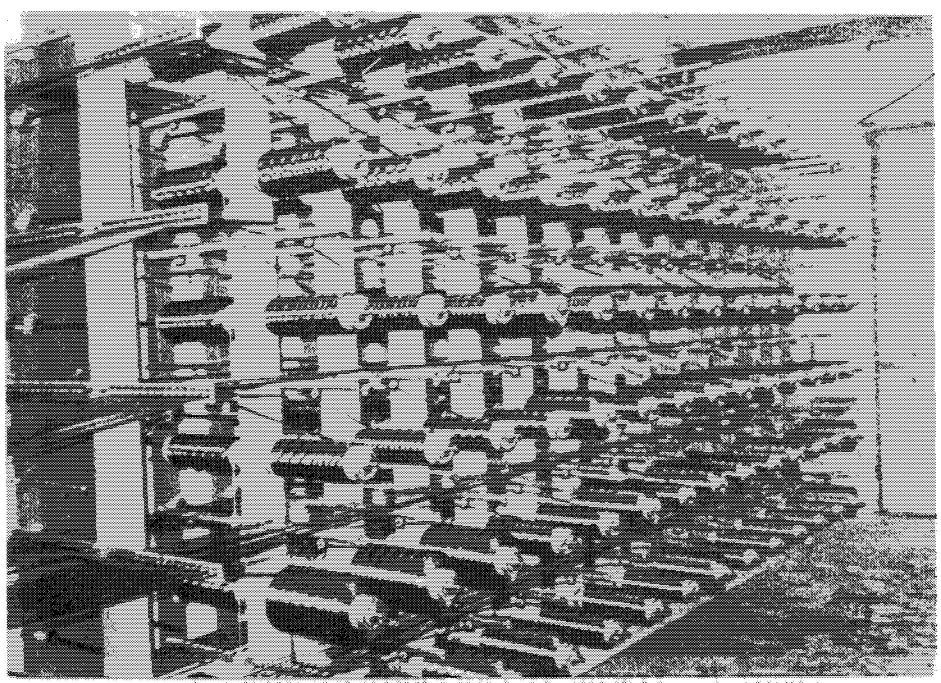

Figure 73. Creel Rack
Included with permission from Stesalit AG.

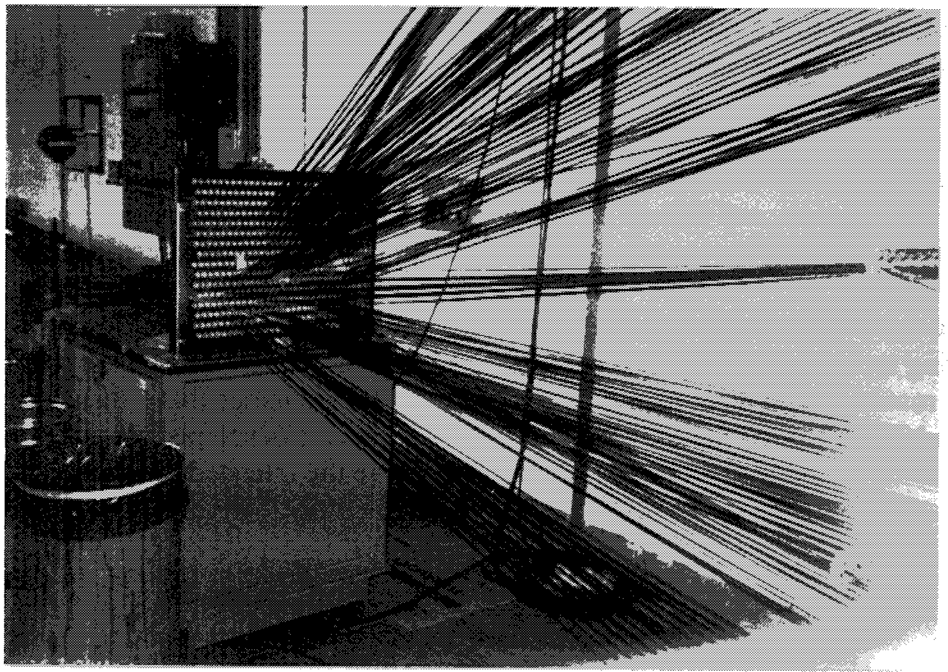

Figure 74. Alignment Screen for Carbon Tools
Included with permission from Stesalit AG.

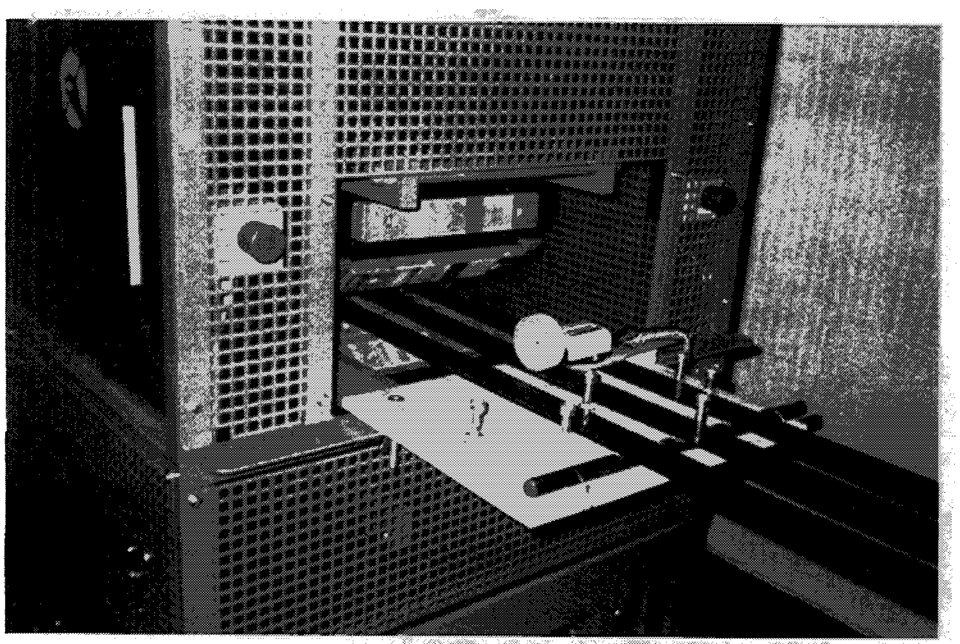

Figure 75. Tractor To Pull Pultruded Member
Included with permission of Stesalit AG.

4.15 HALTINGEN BRIDGES (PROJECT E15)

Project Summary
Complete rehabilitation and strengthening of three reinforced concrete bridges, required by high levels of chloride contamination in the bottom soffit.

Project Data

Designer:	Eglin Ristic AG	
Owner:	Kanton City of Basel	
	Original	*Rehabilitated*
Designed:	1935	1977
Completed:	1936-38	1981

Project Objective
Remove carbonated concrete and corroded rebar and strengthen for increased transverse load-carrying capacity with steel plate bonding (Figures 76 and 77).

Alternative Concepts
Complete replacement at an estimated cost of SFR15 million (US$12.5 million).

Design Considerations
Structures needed to be open for traffic at all times. Epoxy bond joints needed to be protected against direct exhaust/temperature from steam locomotives in one bridge, and steamships in another (see Figure 78).

Project Contact: Mr. V. Ristic, Partner, Eglin Ristic AG, Basel.

Project Description
Three reinforced-concrete bridges on the main access road to the German border needed to be repaired and strengthened.

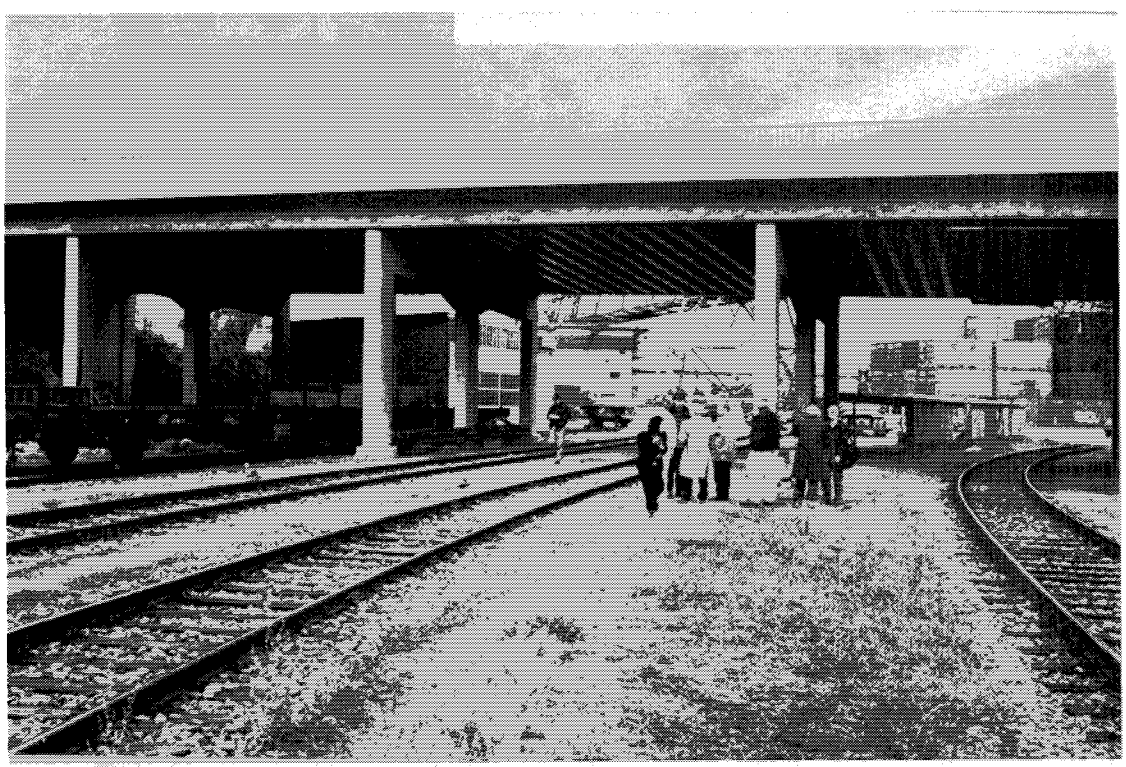

Figure 76. One of the Steel-Plate-Strengthened Bridges in Haltingen

Figure 77. Transverse Steel Plate Strengthening of Continuous Road Slab Bridge

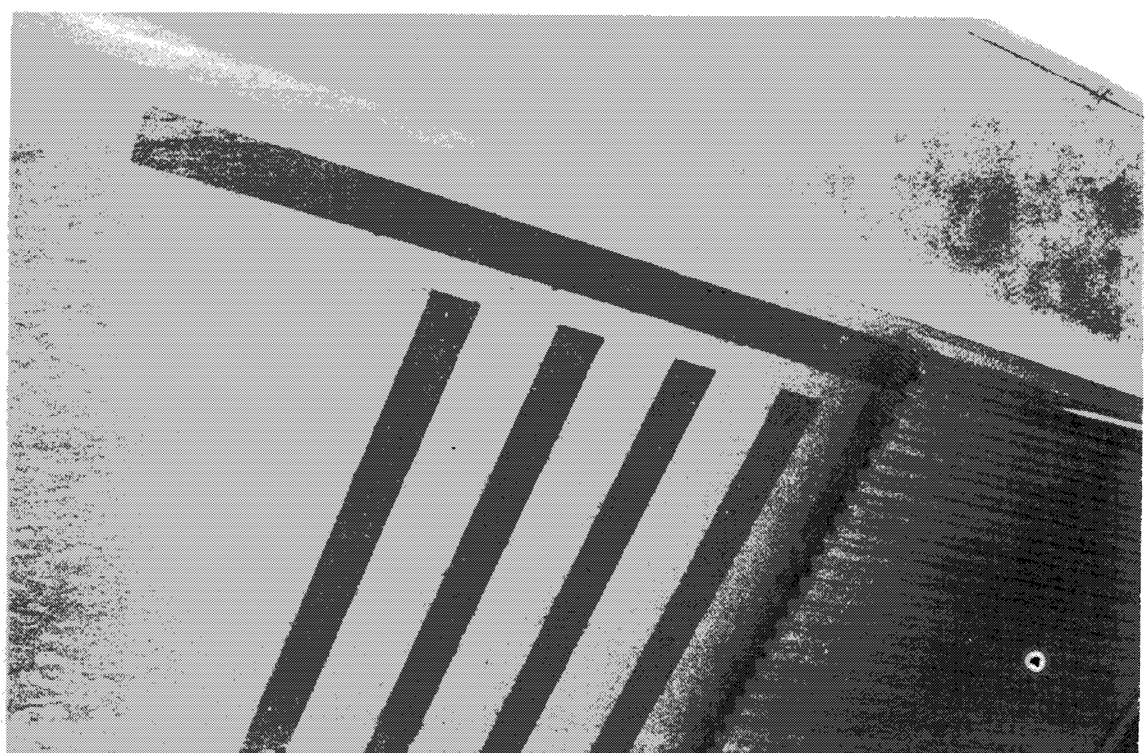

Figure 78. Steel Plate Bonding and Exhaust/
Temperature Protection Over Railway Line

In the original design, the predominantly longitudinal slab reinforcement led to the formation of longitudinal cracks. These cracks limited the tributary slab/reinforcement width and resulted in transverse cracks under wheel loads in the longitudinal slab strips. These extensive crack patterns allowed water penetration, which led to extensive concrete carbonation and reinforcement corrosion. One of the bridges was rehabilitated by complete soffit replacement with rebar and shotcrete. The other two bridges were strengthened with transverse steel plate bonding to the bridge soffit to provide the missing transverse reinforcement.

Materials	
Strips	Grade 36 Steel
Assembly	External Bonding of Steel Plates
Adhesive	Epoxy

Construction/Installation

After complete deck replacement and waterproofing, the two bridge soffits that were to be strengthened with steel plate bonding were sandblasted and checked for concrete tensile strengths, and the cracks were repaired with epoxy injection. Steel mounting rods were drilled and set into the bridge soffit. Steel plates that were 10 m (33 ft) long, 200 mm (8 in) wide, and 6 mm (0.24 in) thick were cleaned, epoxy buttered, and pressed against the bridge soffit with lifting beams and mounting rods. Steel plate strips can be spliced or extended with epoxy-bonded steel plate overlays on top of a butt splice. Care must be taken that all steel surfaces are free of dust and grease before epoxy application.

Instrumentation, Monitoring, Testing

Some initial monitoring and load testing were performed in the early 1980's. Visual inspection shows that the bridges are in excellent condition 15 years after the rehabilitation measures.

Special Issues

Although the strengthening was performed with steel plates and *not* with advanced composites, there are strong indications that this kind of strengthening would now be executed with CFRP laminates bonded to the bottom soffit of the bridge slabs.

4.16 GIEZENEN BRIDGE (PROJECT E16)

Project Summary
First bridge in Switzerland strengthened with external steel plate bonding.

Project Data

Rehab. Contractor:	Stahlton AG
Designed:	Before 1912
Completed:	1912
Rehabilitated:	1980

Project Objective
Increase load-carrying capacity and correct original design deficiencies that neglected temperature stresses.

Alternative Concepts
External post-tensioning or complete replacement.

Design Considerations
The bridge carries a low volume of traffic, but heavy loads on lumber trucks from the Stoosg Forest. Because the traffic volume is low, expenditures needed to be kept low.

Project Contact
Prof. Urs Meier, Director, EMPA.

Project Description
The Giezenen bridge is a reinforced-concrete dual-tied arch bridge with vertical concrete hangers and an orthotropic beam and slab deck system. The bridge was built between 1911 and 1912 and spans 31 m (102 ft) over the Muota River connecting the village of Ried-Muotathal with the Stoosg Forest (Figures 79 to 82).
The original bridge was designed for horse-drawn carriages and without consideration of temperature variations (which are between -20°C and +30°C, even in daytime). The external steel plates on the longitudinal beams and cross-beams were designed under the assumption that the original reinforcement had completely corroded. The bridge was strengthened in 1980 with steel plate bonding; however, with current CFRP laminate bonding technology, strengthening of the Giezenen Bridge would most likely be executed with carbon laminates to avoid clearly visible corrosion problems with steel plates.

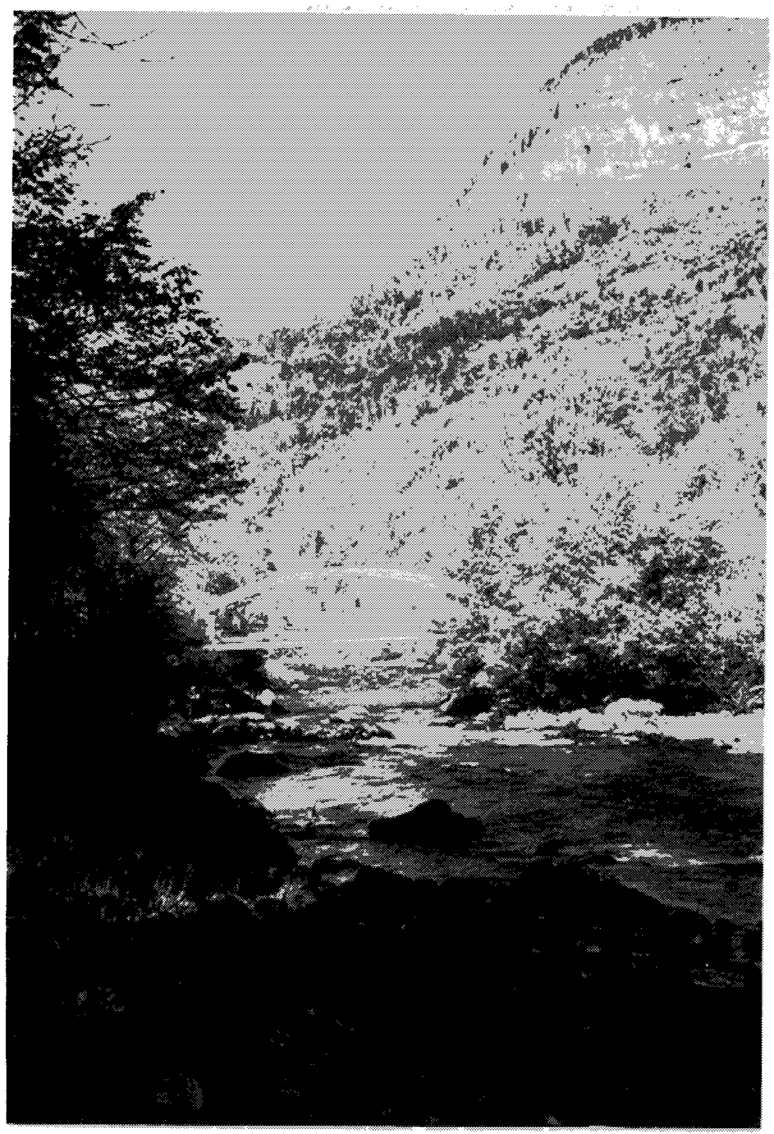

Figure 79. Giezenen Bridge, Overview

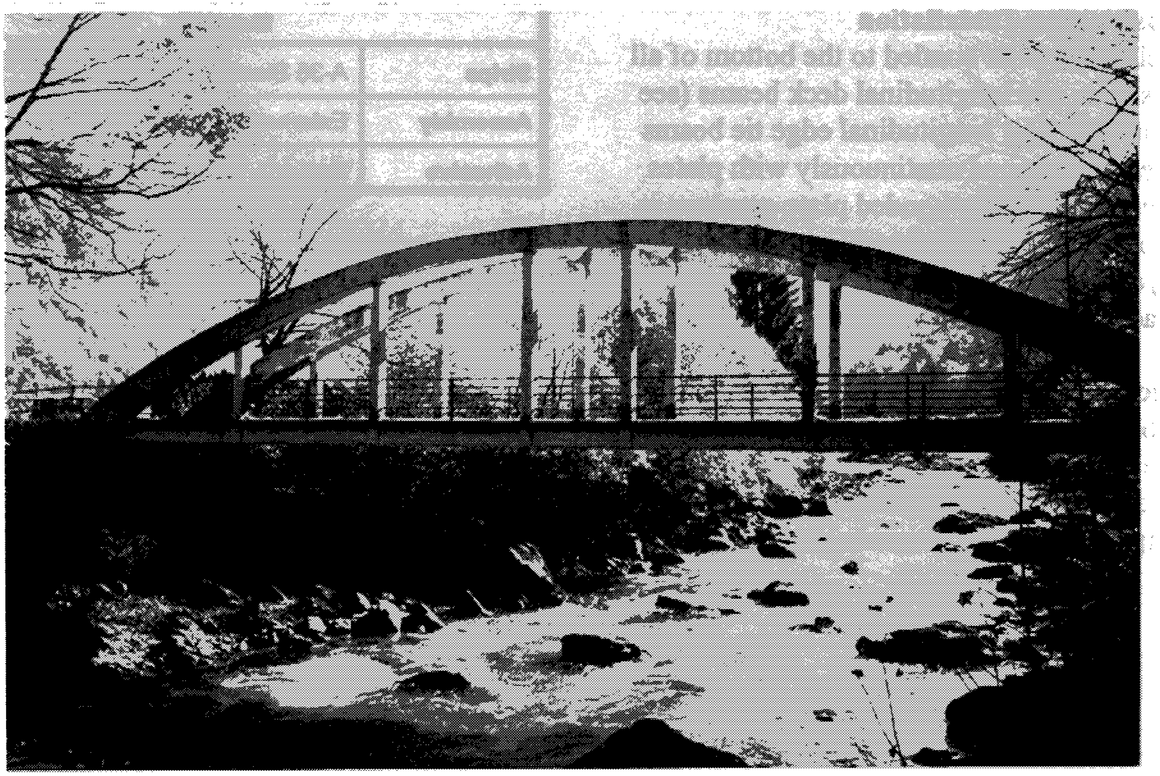

Figure 80. Giezenen Arch Bridge

Figure 81. Dual-Tied, Reinforced-Concrete Arch Bridge

Construction/Installation
Steel plates were bonded to the bottom of all transverse and longitudinal deck beams (see Figure 83). The longitudinal edge tie beams were strengthened continuously with plates spliced with epoxy-bonded plate overlays in the butt splice region (see Figure 84). After 16 years, corrosion damage and calcium stalactites are clearly visible.

Special Issues
Problems include durability and maintenance of bonded steel plates, in addition to more difficult handling and installation compared to CFRP laminate strengthening.

Materials	
Strips	A-36 Steel
Assembly	External Bonding of Steel Plates
Adhesive	Epoxy

Figure 82. Dual-Tied Arch Bridge

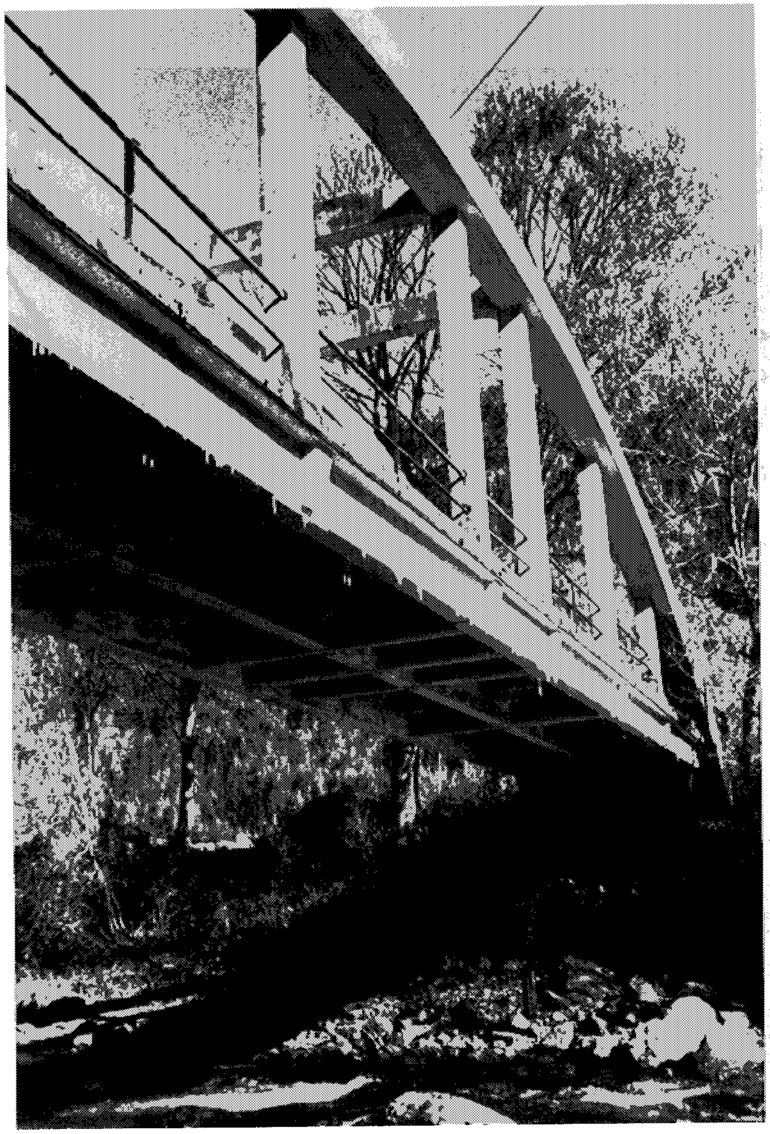

Figure 83. Steel Plate Strengthening of Orthotropic Concrete Deck Beams

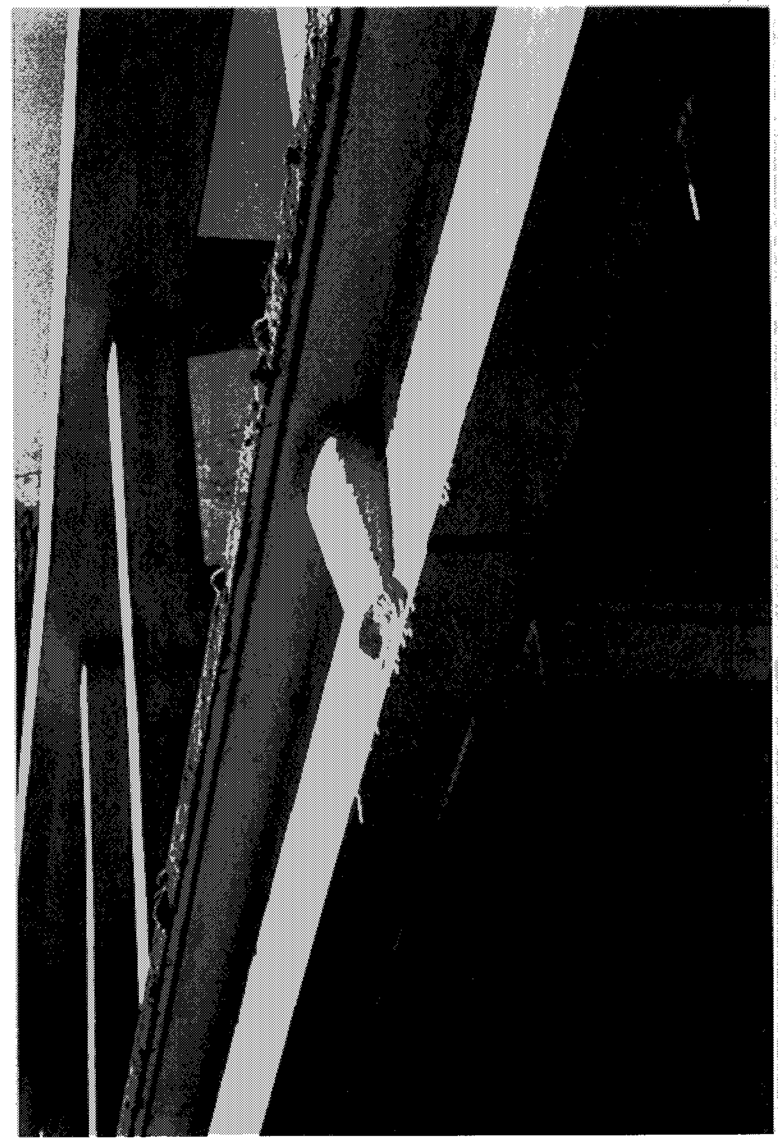

Figure 84. Corrosion Damage and Calcium Stalactites on Steel Plate Strengthening

4.17	IBACH BRIDGE (PROJECT E17)

Project Summary
Repair/strengthening of a prestressed concrete box girder bridge with CFRP laminates.

Project Data
Designer: Prof. Urs Meier
Contractor: EMPA
Owner: Kanton of Luzern
Completed: 1969
Rehabilitated: 1991

Project Objective
Restore original load-carrying capacity after one of the grouted post-tensioning tendons was inadvertently damaged during traffic signal installations (see Figures 85 and 86).

Alternative Concepts
Steel plate bonding or external post-tensioning on the side of the box girder superstructure.

Design Considerations
Restore load path continuity for live load in region of damaged tendon through carbon laminates.

Project Contacts
Prof. Urs Meier, Director, EMPA; Dipl. Ing. Heinz Meier, Research Engineer, EMPA; Dipl. Ing. Giovanni Terrasi, Research Engineer, EMPA.

Figure 85. Ibach Bridge, Overview

Project Description
The Ibach Bridge is a multispan continuous post-tensioned multicell box girder constructed in 1969. The bridge has a total length of 228 m (748 ft). During traffic signal installations in 1991, coring of the exterior box girder web damaged one of the post-tensioning tendons. The damaged span, crossing the Swiss National Highway N2, had a length of 39 m (128 ft). Special permit loads on the bridge were restricted pending completion of the repair work. Repair work had to be conducted at night to limit traffic impact. To provide a new force transfer path for live load around the damaged tendon area, three 5-m-long (16.4 ft) and 150-mm-wide (6 in) strips of CFRP laminates, 1.75 mm thick (0.07 in), were epoxy bonded to the bridge soffit slab (Figure 87).

Composite Materials	
Fiber	Carbon
Matrix	Epoxy
Manufacturing	Pultrusion
Assembly	External Bonding
Adhesive	Epoxy

Construction/Installation
Installation of the three CFRP laminates occurred at night from lift trucks, without additional lifting equipment. The total weight of CFRP laminates installed was 6.2 kg (13.7 lb). A total of 175 kg (385 lb) of steel laminates would have been required for steel plate bonding repair.

Instrumentation, Monitoring, Testing
The carbon laminates and the adjacent concrete were instrumented with strain gates and Demec points, and load tests with test trucks were performed following the repair work.

Figure 86. CFRP Laminate Strengthening of Ibach Bridge

Figure 87. Ibach Bridge Strengthened With Three Strips of CFRP Laminate

4.18	SINS WOODEN BRIDGE (PROJECT E18)

Project Summary
Strengthening of historic wooden arch bridge designed by Joseph Ritter and built in 1807.

Project Data	***Original***	***Rehabilitation***
Designer:	Joseph Ritter	EMPA
Contractor:	n/a	EMPA
Designed:	Before 1807	1991
Completed:	1807	1992

Project Objective
Increase service-load capacities to allow 20-ton truck traffic. Demonstration of transverse beam strengthening with CFRP laminates.

Alternative Concepts
Replacement, transverse post-tensioning.

Project Contacts
Prof. Urs Meier, Director, EMPA; Dipl. Ing. Giovanni Terrasi, Research Engineer, EMPA; Dipl. Ing. Heinz Meier, Research Engineer, EMPA.

Project Description
The covered wooden arch bridge near Sins was built in 1807 and designed by Joseph Ritter of Lucern. The eastern side of the bridge was blown up during the 1852 Civil War and rebuilt with a modified super-structure (see Figures 88 to 90). The bridge was designed for horse-drawn carriages and needed strengthening to accommodate 20-ton truck loading. A new wooden deck consisting of 200-mm-thick (8 in) pre-stressed wooden planks was added in 1992, and two of the transverse crossbeams were

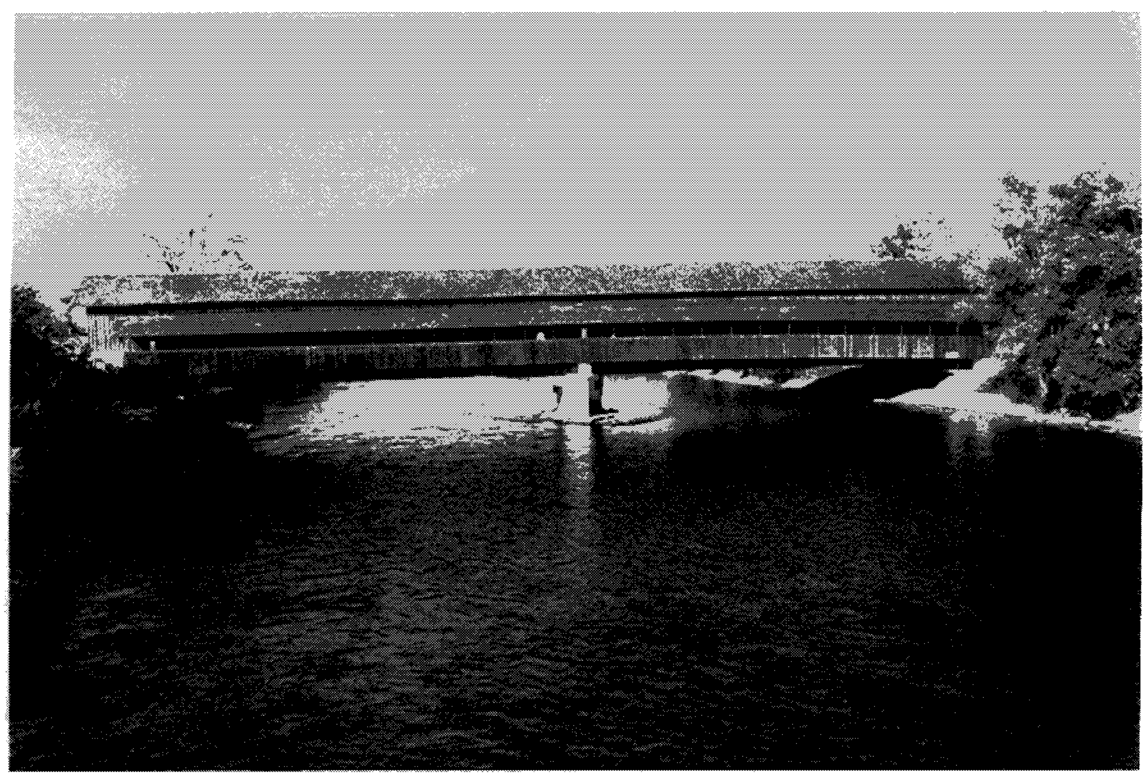

Figure 88. Sins Wooden Bridge, Overview

strengthened with CFRP laminates to monitor their performance under traffic loads (see Figures 91 and 92).

Composite Materials		
Fibers	Carbon	
Matrix	Epoxy	
Manufacturing	Pultrusion	
Assembly	Bonding	
Adhesive	Epoxy	
	Beam 1	**Beam 2**
Tensile Modulus	305 GPa (44 x 10^6 psi)	152 GPa (22 x 10^6 psi)
Tensile Strength	2,600 MPa (377 ksi)	2,300 MPa (334 ksi)
Ultimate Strain	0.85%	1.5%

Each of these crossbeams was constructed from two solid oak beams placed directly or with spaces on top of each other. One of the crossbeams was strengthened with CFRP laminates that were 1 mm thick (0.04 in), 250 mm wide (10 in), and 5 m long (16 ft) and consisted of high-modulus fibers. The second was constructed of high-strength fibers that were 1 mm thick (0.04 in), 300 mm wide (11.8 in), and 5 m long (16 ft).

Construction/Installation
The wooden oak beams were planed with a portable planer, the surfaces were cleaned, and epoxy was applied to both the beam and the CFRP laminate. The CFRP laminates were installed manually from construction scaffolding.

Instrumentation, Monitoring, Testing
Selected crossbeams, as well as the CFRP-overlaid crossbeams, were instrumented for load test with electrical resistance gauges and Demec gauge joints. Pulse infrared thermography was also used to check the quality of the adhesive line under the CFRP sheet.

Figure 89. Covered Wooden Arch Bridge, Exterior

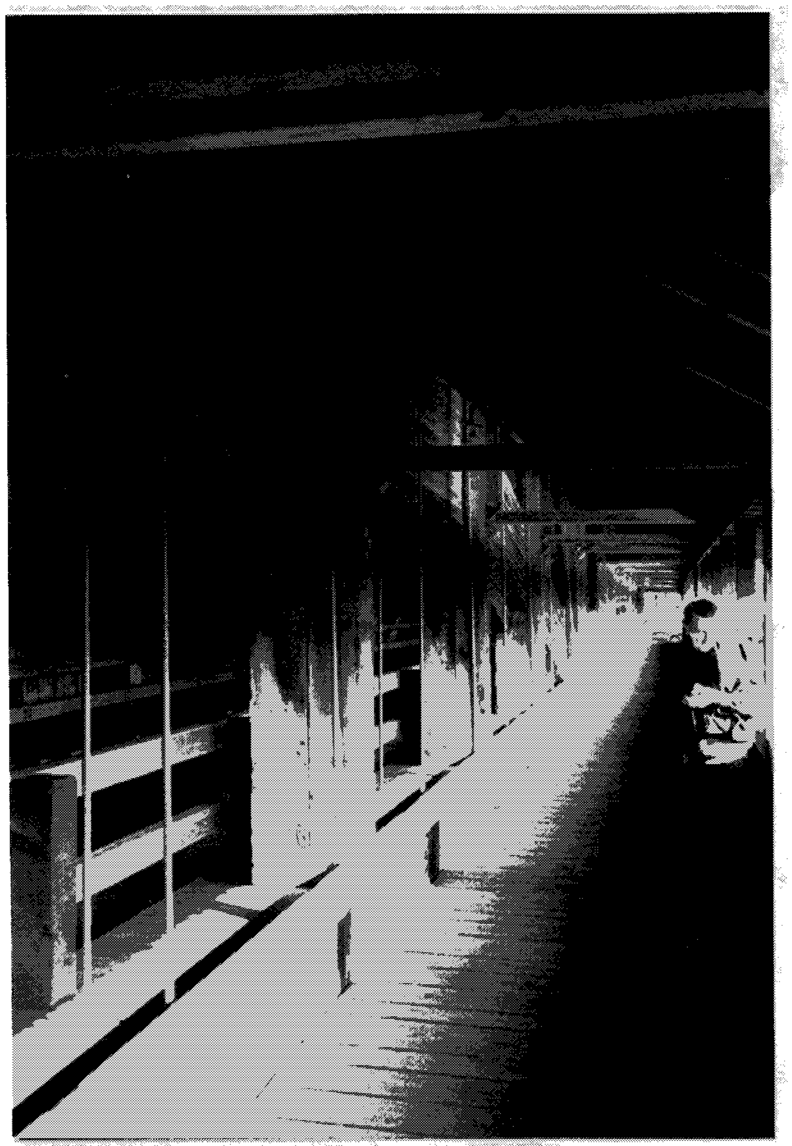

Figure 90. Covered Wooden Arch Bridge, Interior

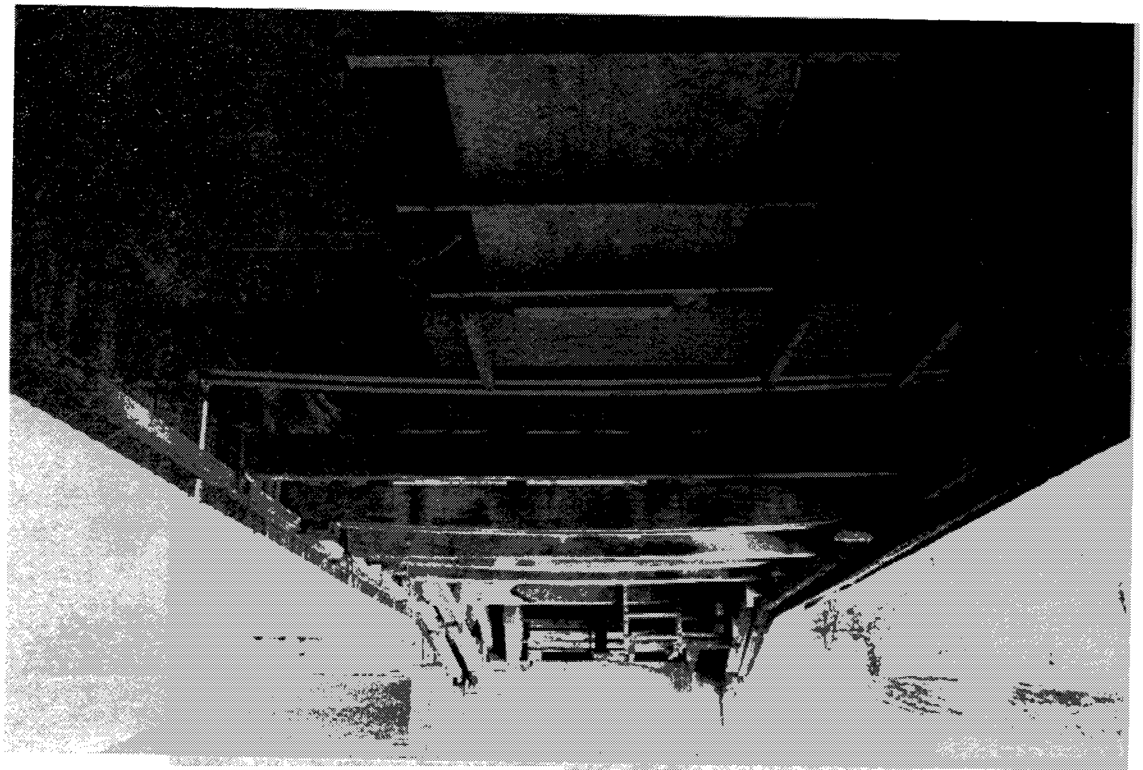

Figure 91. Crossbeams Strengthened With CFRP Laminates

Figure 92. Strain Gauge and Demec Point Instrumentation on CFRP-Strengthened Crossbeams

5.0 ADVANCED COMPOSITES IN BRIDGES IN JAPAN

Applications of advanced composite materials in the bridge industry in Japan focus on two areas: nonmetallic reinforcement and prestressing tendon systems and structural rehabilitation with carbon fiber sheet overlays. Both are driven by specific national needs, which are to:

- Develop more durable concrete structures, particularly in aggressive ocean environments
- Develop bridge deck strengthening systems to allow higher legal truck loads
- Meet regional seismic criteria.

Nonmetallic reinforcement and prestressing systems for structural concrete use all three basic advanced composite fiber types—glass, aramids, and carbon. Close to 100 demonstration projects [15] using this newly developed nonmetallic reinforcement approach have been completed in Japan. A workshop organized by the Advanced Composite Cable (ACC) Club of Japan was held in Tsukuba City (J1) to provide a general overview on research, product development, design criteria, and demonstration projects. The carbon fiber sheet rehabilitation systems for both concrete deck strengthening and bridge column seismic retrofitting were introduced in the Osaka Workshop (J2) and applied in numerous projects observed during the study tour (J6, J8, and J10).

This section summarizes the 11 projects and workshops visited in Japan.

5.1 TSUKUBA CITY WORKSHOP (PROJECT J1)

Workshop Objective
The workshop was organized by PWRI and the ACC Club. Discussion focused on the development and use of nonmetallic reinforcement and prestressing systems for concrete structures in Japan.

Workshop Contacts and Meeting Participants
Mr. K. Nishikawa, Head, Bridge Division, PWRI; Mr. M. Kanda, Chief Research Engineer, Bridge Division, PWRI; Mr. S. I. Kumagai, Deputy General Manager, Sumitomo Construction Co., Ltd.; Dr. H. Kimura, Chief, Research Laboratory, Tokyo Rope Mfg., Ltd.; Mr. S. Kenzo, Senior Research Engineer, Shimizu Corporation; ACC Club members and technical advisers, Tatsuhiko Iwasaki, Secretary, ACC Club, General Manager, A-M Engineering Co., Ltd.; T. Hoshijima, Mitsubishi; Dr. H. Maikuma, Nippon Steel Corp.; M. Kamigoshi, Teijin, Ltd.; and PWRI engineering staff.

Workshop Description
The workshop was held at the Mitsubishi Research and Conference Facilities in Tsukuba-shi and was organized by the Bridge Division of PWRI and the Japan ACC Club. ACC is a group of construction companies, material suppliers, and research and design engineering firms organized to promote nonmetallic reinforcement and prestressing systems for concrete structures.

Following a basic introduction to advanced composites, Mr. Kanda of PWRI summarized two documents, "Design and Construction Guidelines for Prestressed Concrete Highway Bridges Using FRP Tendons" (draft March 1994) [12] and "Study Reports and Papers on Prestressed Concrete Highway Bridges Using FRP Tendons" (September 1994) [13, 14], to demonstrate the state of nonmetallic reinforcement for concrete structures in Japan.

Worldwide development of GFRP began in the 1950's. Research and development on AFRP and CFRP started in the 1970's; the first applications in Japan took place in the late 1980's. Japanese FRP developments and applications can be identified by the fiber system in three groups:

- Aramid fiber systems in vinyl ester or epoxy matrix (Technora® rod, Arapree® rectangular rod, and Fibra® braided tendons)
- Carbon fiber systems in epoxy matrix (Leadline® rod, CFCC® wire strands, and NACC® wire strands)
- Glass fiber or hybrid glass/carbon fiber systems in vinyl ester matrix (Nefmac,® reinforcement grids).

Basic manufacturing procedures are pultrusion, braiding, or stranding.

About 100 civil engineering projects using nonmetallic tendons and reinforcement have been completed in Japan [15]. They range from bridges (24.4 percent) (Figures 93 and 94) to ground anchors (23.2 percent) and from architectural engineering or building applications (11 percent) to marine structures (8.5 percent). Industrial facilities, dams, underground tanks, or drainage systems account for the remainder (32.9 percent).

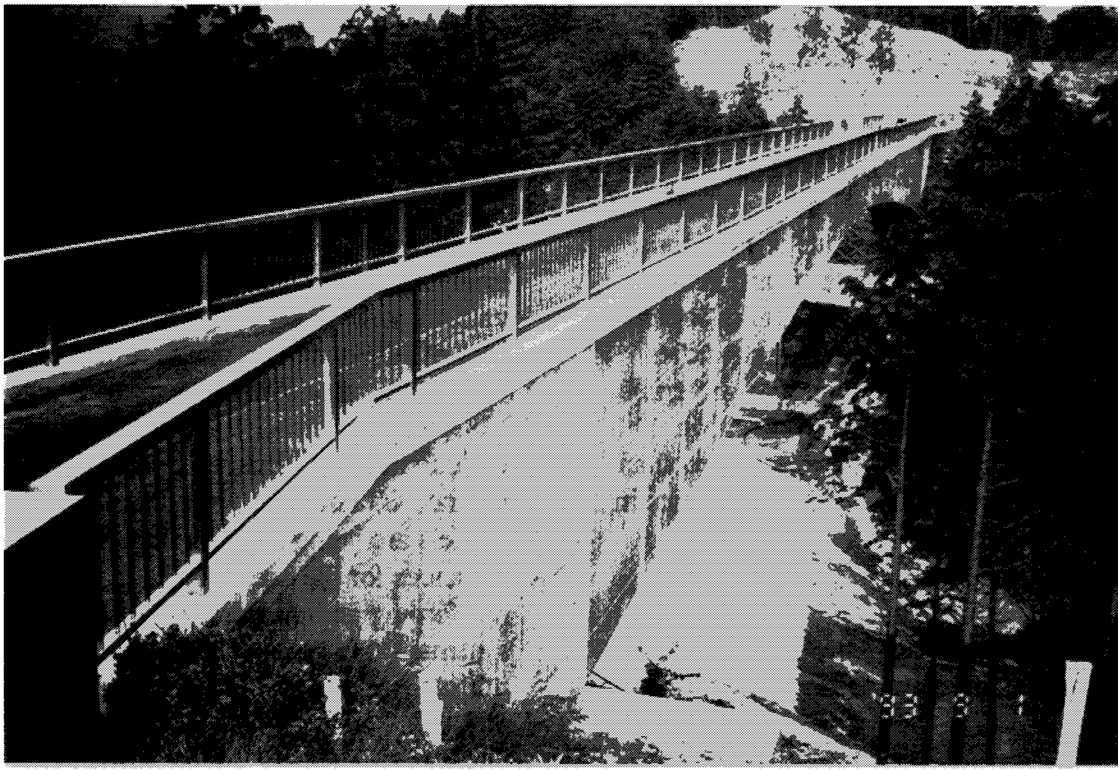

Figure 93. Example of Arch Bridge Post-Tensioned With Carbon Laminates

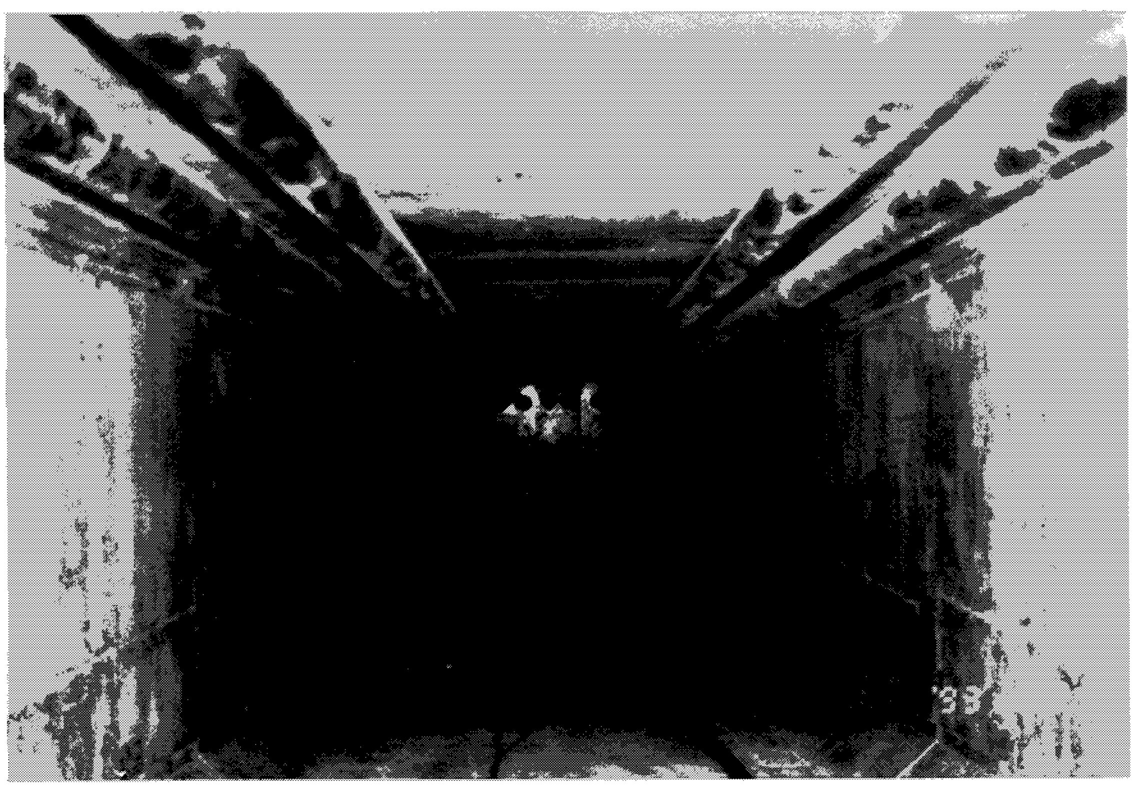

Figure 94. External Carbon Tendons in Post-Tensioned Arch Bridge

Mr. Kumagai of Sumitomo Construction provided an overview of the formation of the ACC Club in 1991 and described the membership makeup and club objectives. Dr. Kimura of Tokyo Rope Mfg., Ltd., discussed the various applications of FRP materials. The actual amounts of materials used (see Figure 95) deviate significantly following the economic recession in Japan in 1993, at which point industry subsidies for the use of advanced composite materials were significantly reduced. Finally, Mr. Sekijima of Shimizu Corporation offered an excellent overview of the various projects in which FRPs have been used in civil engineering applications.

The ACC Club primarily promotes the use of advanced composite reinforcement and prestressing systems for use in new structures and construction, not in repair and rehabilitation. Most of the materials testing and validation is performed by the composite material manufacturers. These manufacturers in turn provide "guarantees" for minimum performance levels for their products, which are used as nominal design values by the design engineers. The high cost of advanced composite reinforcement and prestressing systems was acknowledged. No efforts to establish cost models that include life-cycle cost estimates and maintenance data have been undertaken, but such models are being investigated. Significant advances for the use and application of FRP reinforcing and prestressing materials and systems were made in Japan with the issuing of draft design and construction guidelines in 1994.

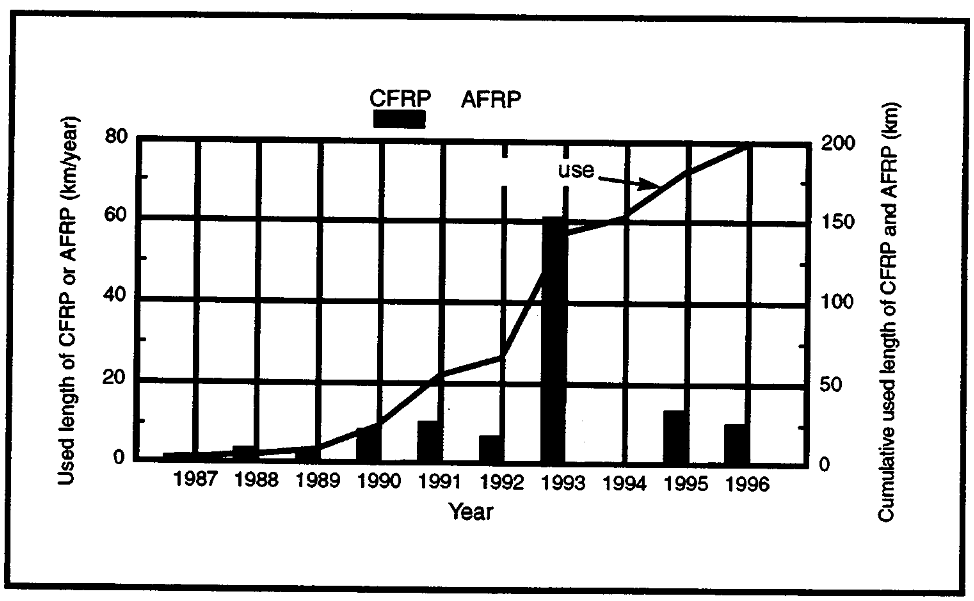

Figure 95. Cumulative Quantity of FRP Bars and Tendons Used in Japan (Since 1987)
Reproduced with permission from Sumitomo Construction and ACC Club.

5.2 OSAKA WORKSHOP (PROJECT J2)

Workshop Summary
The Osaka workshop provided an overview of carbon sheet strengthening developments and applications in Japan.

Workshop Objective
Carbon fiber sheet for seismic retrofitting and structural rehabilitation/strengthening is manufactured at three companies in Japan: Mitsubishi Chemical (Replark®), Tonen Corporation (Towsheet®), and Toray Corporation (Torayca Cloth®).

To date, two main areas of bridge-related applications exist: seismic column retrofitting and superstructure deck strengthening (see Figures 96 and 97).

In seismic retrofitting, over 200 bridge columns have been completed with carbon sheet overlays, and another 800 have been designed and implemented. The seismic column retrofitting is primarily aimed at flexural column strengthening and shear strengthening, rather than plastic hinge confinement (see Figures 98 and 99). Carbon sheets are preferred over glass or aramids, because of the chemical inertness of the carbon fiber and the expected excellent durability characteristics. In addition, carbon absorbs UV rays and, therefore, protects the resin system from degradation. Furthermore, carbon exhibits good strength-retention characteristics at high temperatures.

Figure 96. Carbon Sheet Column Retrofitting

Strengthening of bridge decks is required as a result of an increase in legal truck weights from 20 to 25 tons.

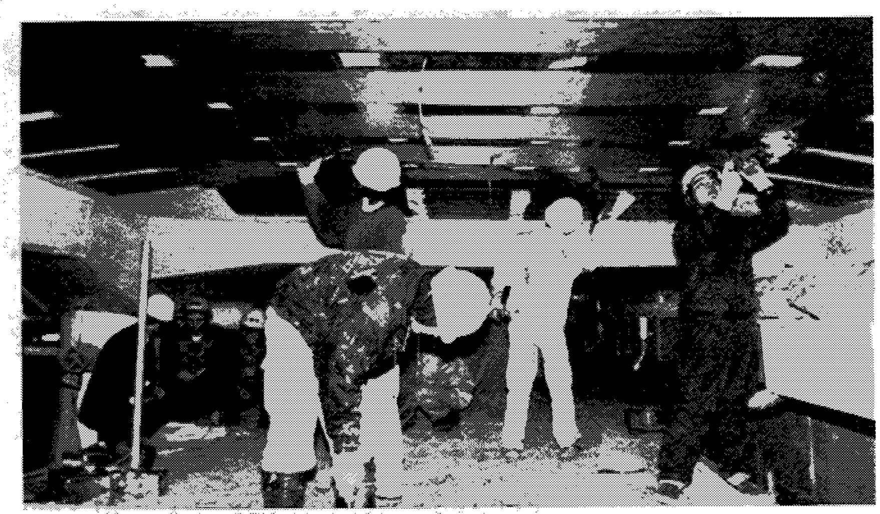

Figure 97. Bridge Deck Strengthening

In Japanese bridge design, concrete decks typically span transversely between longitudinal girders. To increase the load-carrying capacity of the deck between girders, carbon fiber sheets are applied in primarily transverse strips to the bottom of the deck (Figure 97). In addition to flexural strengthening, repair of cracked decks and punching shear deficiencies are addressed using carbon sheets bonded to the bottom of the deck (Figure 100). Another application is the lining of tunnel sections for local flexural problems (Figure 101).

Carbon sheet overlays are tested by coring and direct tension tests on the strengthened core plug. Tests are successful when the tensile failure occurs in the concrete substrate, not in the carbon overlay.

In Japan, an association for carbon sheet rehabilitation has been formed—the Carbon Fiber Rehabilitation and Reinforcement Research Association (CFRRA). Draft design guidelines for seismic column retrofitting and bridge deck strengthening exist but are not yet available in English.

Composite Materials	
Fiber	Carbon
Matrix	Epoxy
Assembly	Wet Layup
Adhesive	Epoxy
Curing	Ambient
Tensile Modulus	238 GPa* (34.5 x 10^6 psi*)
Tensile Strength	4,370 MPa* (634 ksi*)
Ultimate Strain	1.8%

*fiber volume normalized

Figure 98. Seismic Retrofit of Tsushi Viaduct Column With Carbon Sheets

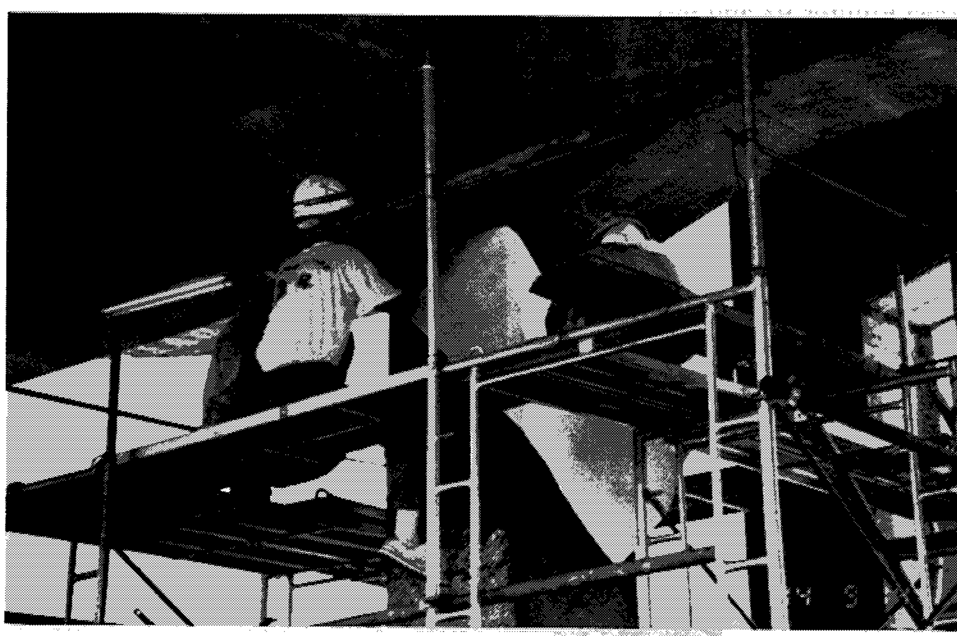

Figure 99. Retrofitting of Tsushi Viaduct Column With Carbon Sheets

Workshop Contacts
Mr. M. Uemara, Secretary, CFRRA and General Manager, Tonen Corp.; Mr. T. Hoshikima, General Manager, Mitsubishi Chemical Corp.; Dr. M. Koga, General Manager, Obayashi Construction Corp.

Figure 100. Carbon Sheet Strengthening Against Punching Shear in Deck Cantilever

Figure 101. Carbon Sheet Strengthening of Tunnel Section

5.3 PWRI COMPOSITE CABLE-STAYED BRIDGE (PROJECT J3)

Project Summary
Experimental cable-stayed pedestrian demonstration bridge made entirely of advanced composite materials. Shown in Figures 102 and 103.

Project Objective
Demonstrate feasibility of construction and assembly of a bridge system made entirely of advanced composite materials and monitor durability of materials and components under normal environmental exposure.

Design Considerations
Use of nonmetallic connectors made entirely of advanced composites. Keep member/ component weights less than 150 kg (330 lb) to allow manual assembly without lifting equipment. Design live load is 350 kg/m^2 (72 psf).

Project Contacts
Mr. K. Nishikawa, Head, Bridge Division, PWRI; Mr. M. Kanda, Chief Research Engineer, Bridge Division, PWRI; Mr. K. Uchido, Research Engineer, Bridge Division, PWRI.

Project Description
The PWRI advanced composite experimental pedestrian bridge project features a three-span cable-stayed bridge with an 11.0-m (36-ft) mainspan and 4.5-m (15-ft) side spans. The width of the walkway is 2.0 m (6.5 ft). The total weight of the bridge is only 4.4 tons or 110 kg/m^2 (22 psf), resulting in a dead load/ live load ratio of 0.3. The bridge is built on conventional RC foundations and anchored with steel anchor bolts (Figure 104).

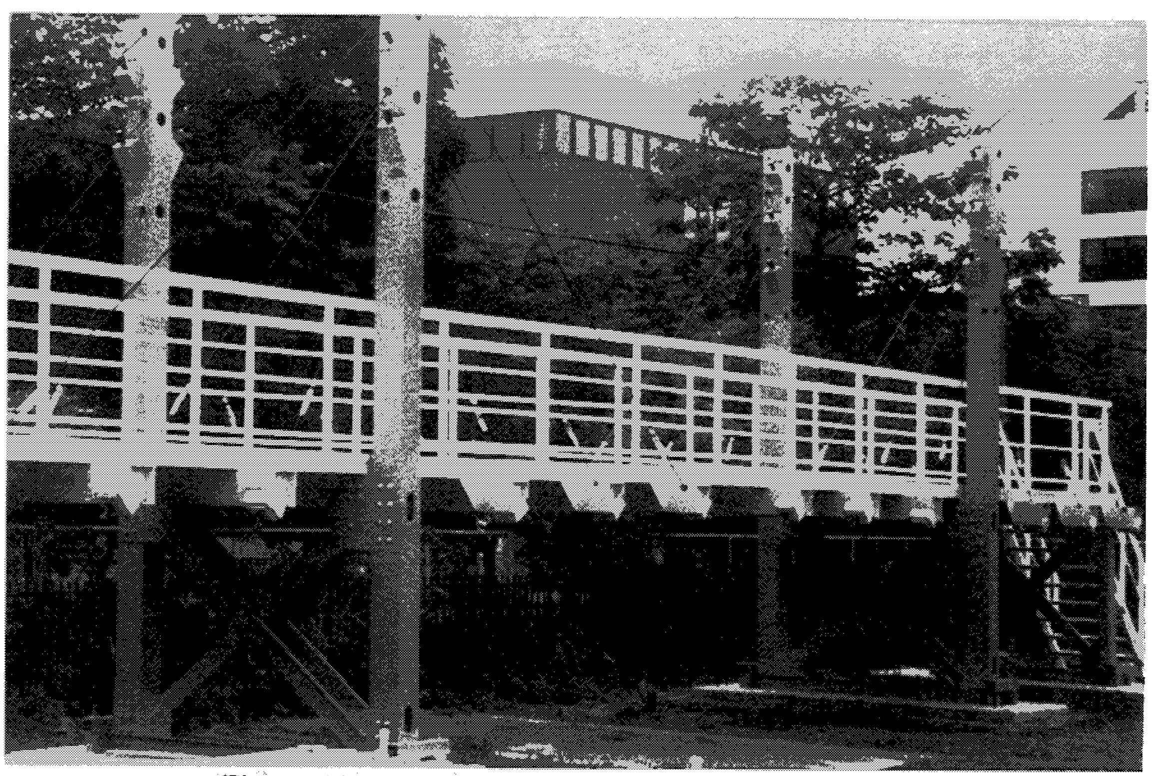

Figure 102. PWRI Composite Cable-Stayed Bridge

Pylons and deck are manufactured as pultruded GFRP sections strengthened in some areas with carbon sheets. The longitudinal girders are supported by transverse beams, which, in turn, are supported by CFRP cable stays. Both Leadline and Tokyo Rope carbon cables of different sizes are used as stay cables.

Composite Materials	
Fiber	Glass/Carbon
Matrix	Epoxy
Manufacturing	Pultrusion
Assembly	FRP Bolted Connections

Construction/Installation

All components have limited weight, less than 150 kg (330 lb), and are bolted together with 16-mm-diameter (⅝-in) FRP bolts for manual assembly and disassembly without the use of lifting equipment.

Instrumentation, Monitoring, Testing

The experimental all-advanced-composite pedestrian bridge was load tested upon completion. Similar load tests are planned for the future to determine the effects of environmental exposure and aging. Environmental exposure/ durability and creep tests are conducted onsite in a special creep test stand (see Figure 105).

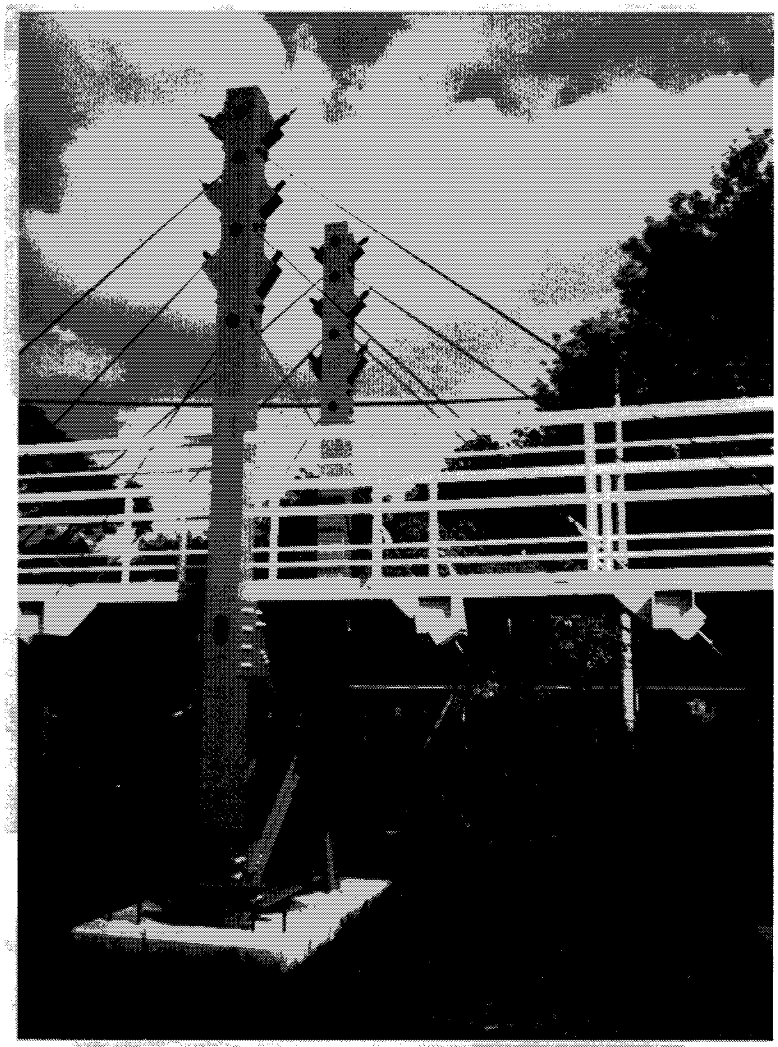

Figure 103. Pylon and Cable Stays

Figure 104. Carbon Fiber Cable Stay Anchorage Assembly

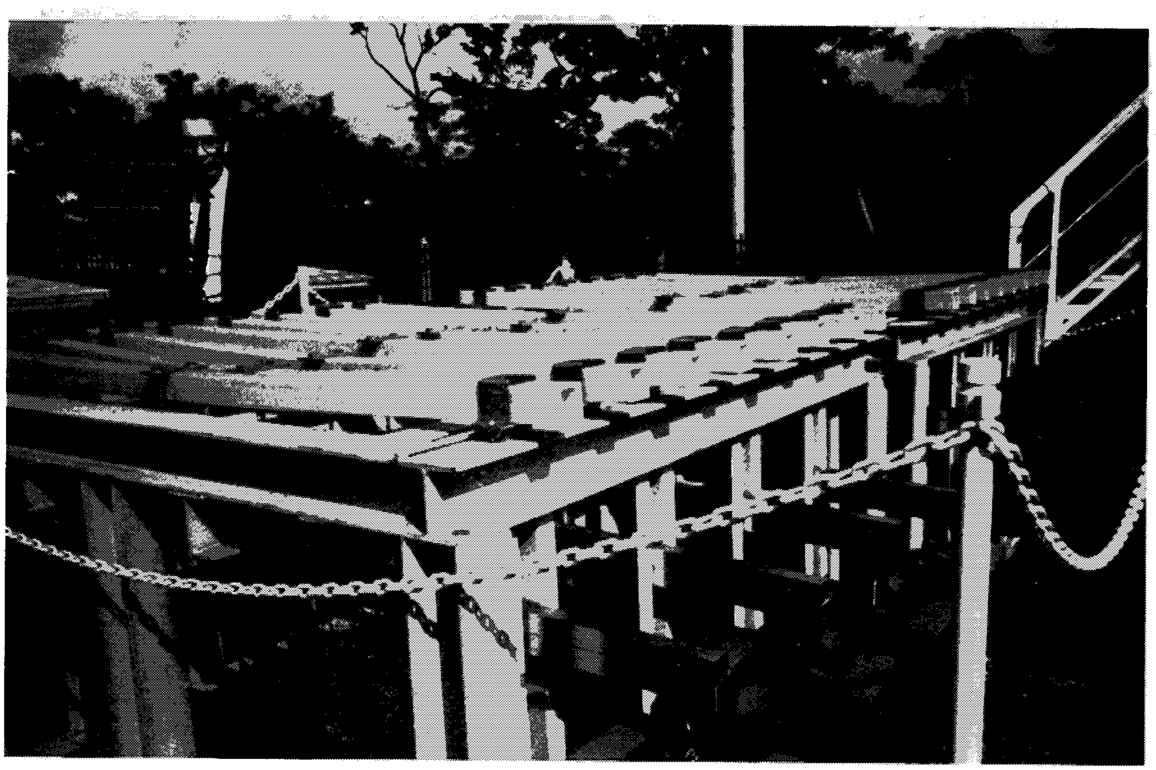

Figure 105. Durability and Creep Test Stand

5.4 SUMITOMO BRIDGES (PROJECT J4)

Project Summary
Pre- and post-tensioned demonstration bridges with AFRP reinforcement.

Composite Materials	
Fiber	Aramid (Technora®)
Matrix	Vinyl ester
Manufacturing	Pultrusion
Assembly	Mild Reinforcement & Prestressing Tendons
Tensile Modulus	53 GPa (7.7 x 10^6 psi)
Tensile Strength	1,766 MPa (256 ksi)
Ultimate Strain	36%

Project Data
Contractor: Sumitomo Construction
Owner: Sumitomo Construction and Teijin, Ltd.
Completed: 1990-91

Project Objective
Demonstration of AFRP as mild reinforcement, pre-tensioned tendon reinforcement, and post-tensioned tendon reinforcement in two parallel concrete bridge structures.

Design Considerations
Bridge design to standard two-lane traffic load (one lane per bridge).

Project Contacts
Mr. S.I. Kumagai, Deputy General Manager, Sumitomo Construction Co., Ltd.; Mr. M. Kamiyoshi, Project Manager, Teijin, Ltd.

Project Description
The Sumitomo demonstration bridges (Figures 106 to 110) are at Oyama Works, Sumiken Concrete Industry Co., Ltd. The projects consist of two parallel bridge structures, each designed for TL-20 (20-ton) truck loads with a roadway/lane width of 4 m (13 ft). The shorter bridge consists of three pretensioned box girders that are 12.5 m (41 ft) long. These are reinforced with 8-mm- (0.3-in-) diameter stirrups and longitudinal distribution bars made of Technora® deformed aramid/epoxy rods. They are pretensioned with 16 tendons consisting of three 6-mm- (0.24-in-) diameter strands. The three precast, pretensioned box girders were overlaid with a cast-in-place RC slab. The second bridge is 25 m long (82 ft) and consists of a single-cell, cast-in-place box girder with a depth of 1.9 m (6.2 ft). This is post-tensioned internally with 10 Technora® tendons consisting of nineteen 6-mm-diameter (0.24-in) strands. External post-tensioning consists of six Technora® tendons with seven 6-mm-diameter (0.24-in) strands (Figure 106). Stirrups and deck reinforcement consist of 8-mm (0.32-in) AFRP bars.

The initial stressing or jacking force for the tendons was 75 percent f_{pu} for a design prestress of 70 percent f_{pu}, assuming a 7 percent prestress loss due to creep and relaxation. Internal post-tensioning tendons were anchored in epoxy-filled steel housings, whereas GFRP anchorages were used for external tendons (see Figure 107).

Construction/Installation
Conventional pre- and post-tensioning procedures were used. Pretensioning was achieved by group stressing against steel bulkheads. Because of the low modulus of the AFRP tendons, increased tendon elongation and stressing lengths required frequent resetting of the post-tensioning jacks. Tendon elongations were monitored during the stressing operations and were consistent, within 1.5 percent, with theoretical elongation values.

Instrumentation, Monitoring, Testing

A load cell was placed at the anchorage of one of the external tendons to monitor tendon relaxation with time. Strain gauges were installed on the pretensioned girders to monitor concrete strain variations with time. The measured tendon force and concrete strains are consistent with theoretically predicted prestress losses. The bridge structures were load tested after completion and performed as predicted. The assumed 30-year relaxation rate at a load range of 0.5 to 0.6 f_{pu} is expected to be around 14 percent.

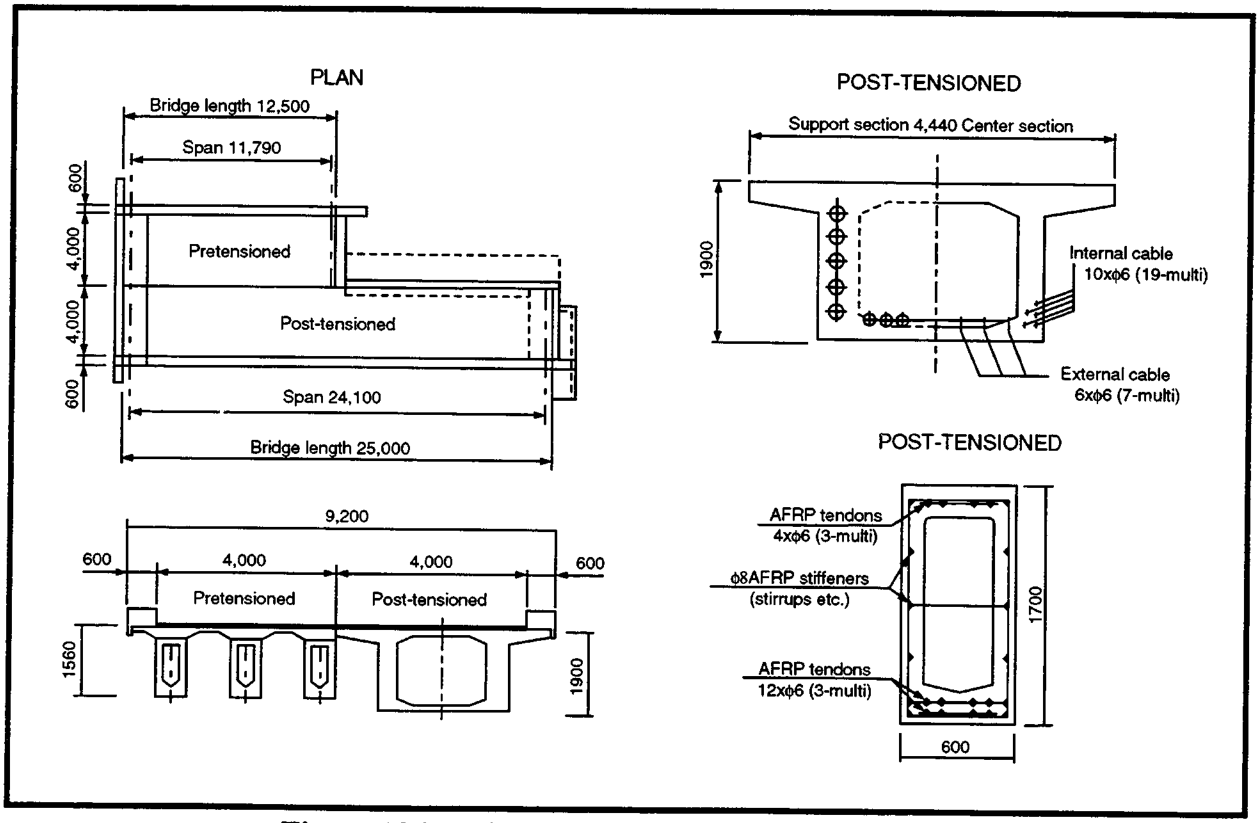

Figure 106. Bridge Geometry and Dimensions [15]

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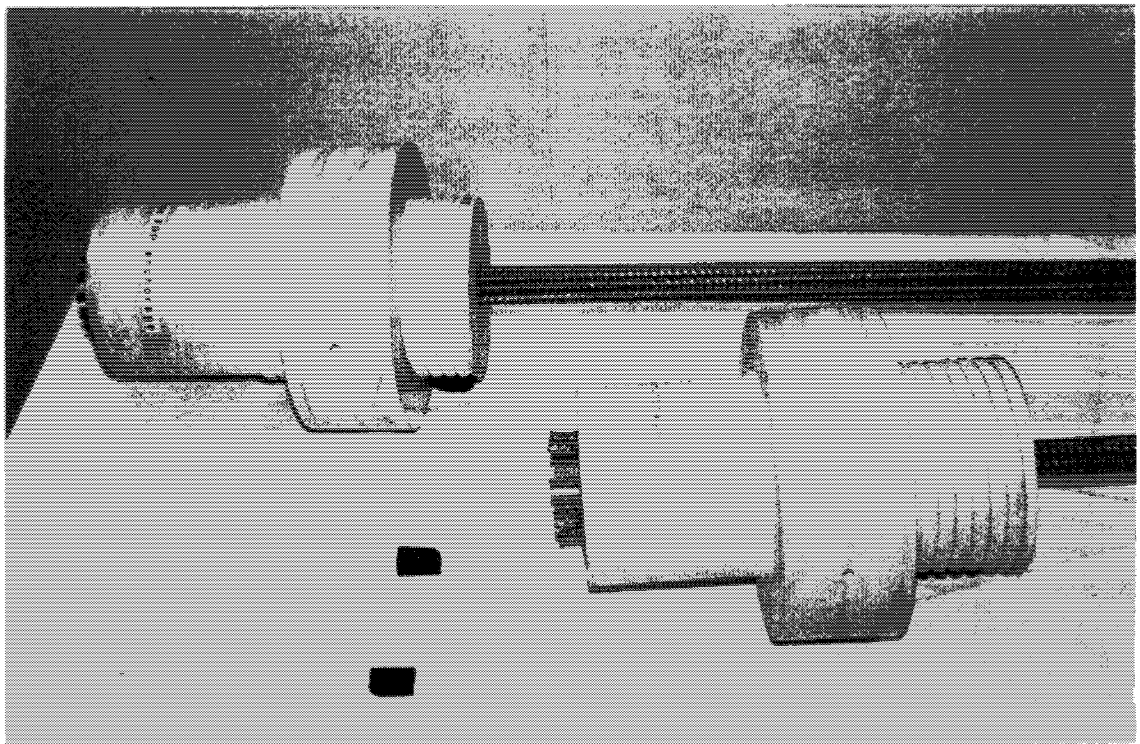

Figure 107. Technora® Deformed Bar Tendons With Composite Anchorages
Included with permission from Sumitomo Construction.

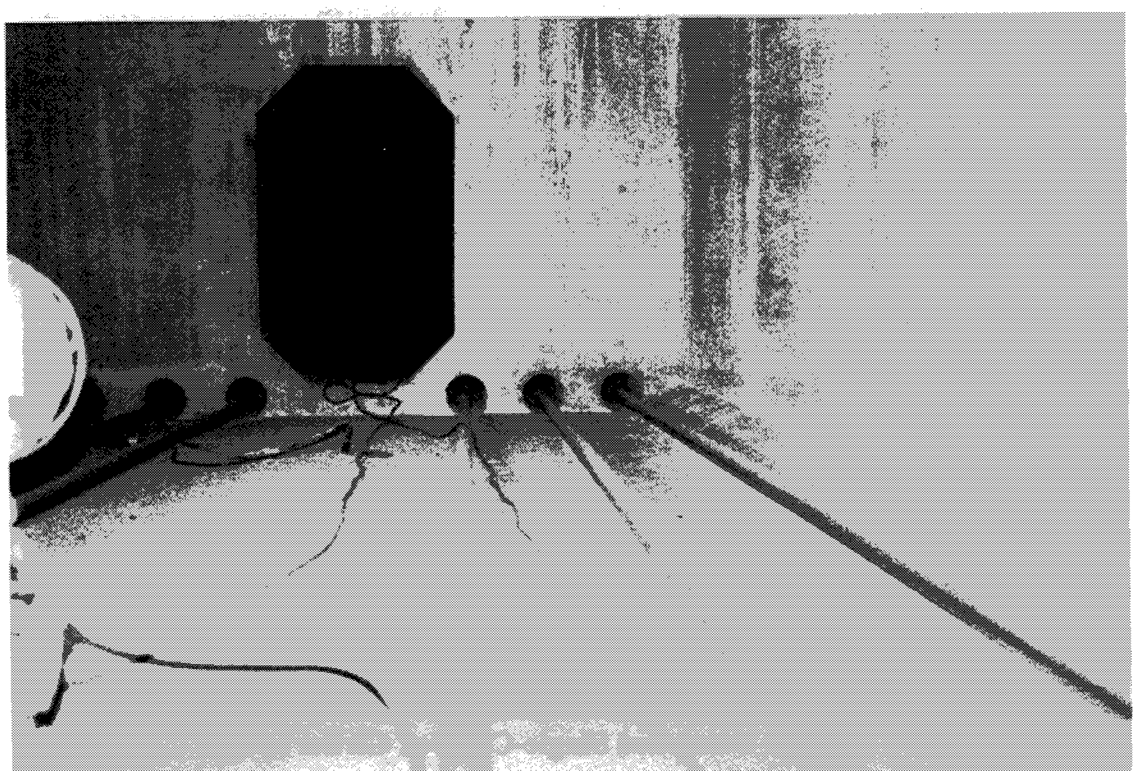

Figure 108. Internal Post-Tensioning

Figure 109. Pretensioned Multicell Box Girder Bridge

Figure 110. Post-Tensioned Single-Cell Box Girder Bridge

5.5	ARAMID ROD ANCHOR BLOCK REINFORCEMENT (PROJECT J5)

Project Summary
Rehabilitation and strengthening of existing concrete bridge girders with external tendons at the Sone Viaduct, Hyogo Prefecture. Anchorage blocks for external tendons are post-tensioned to the existing girders with Technora® multistrand tendons.

Project Data
Designers: Sumitomo Construction, Ltd., and Teijin, Ltd.
Contractors: Sumitomo Construction, Ltd., and Teijin, Ltd.
Owner: Japan Highways Public Corp.
Completed: 1995

Project Objective
Overcome loss of prestressing force in short post-tensioning tendons caused by anchor set and relaxation by means of low-modulus tendon materials (Technora® aramid tendons).

Alternative Concepts
Other low-modulus post-tensioning systems.

Design Considerations
The basic design consideration for the use of Technora® aramid tendons was the low elastic modulus, which is about 1/4 to 1/5 that of comparable steel tendons.

Project Contacts
Japan Highways Public Corp.; Mr. S.I. Kumagai, General Manager, Sumitomo Construction, Ltd.

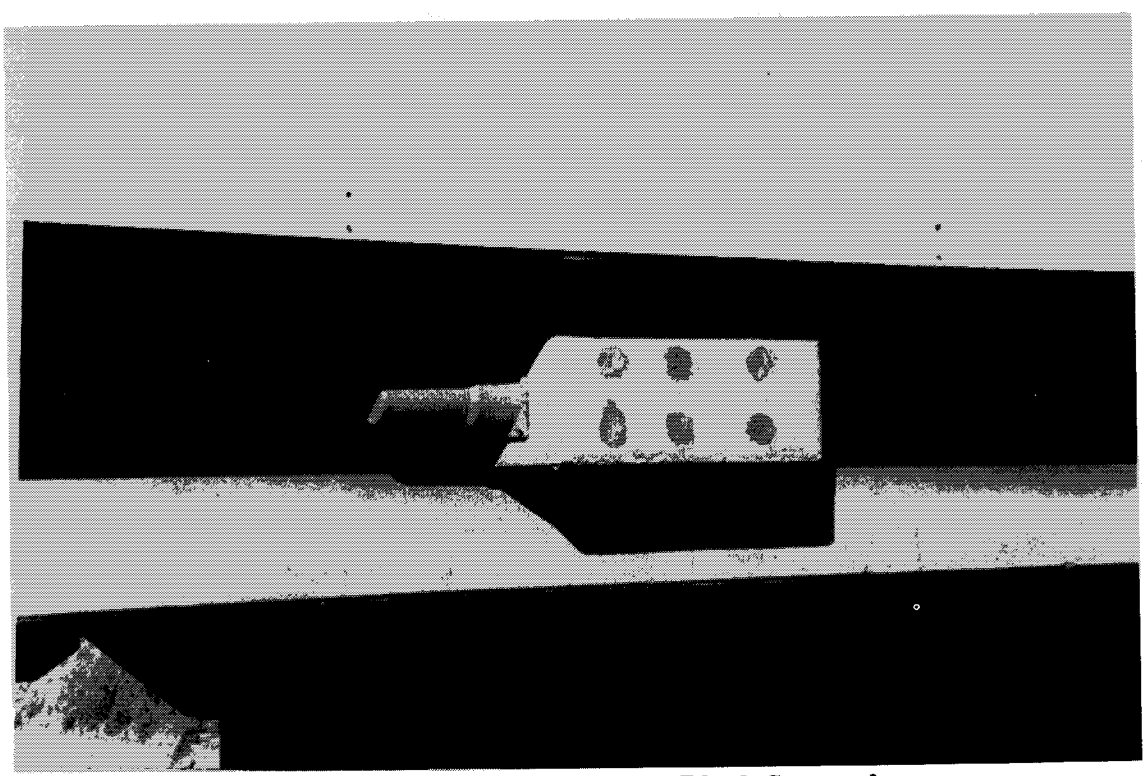

Figure 111. External Anchor Block Stressed to the Girder With Six Technora® Tendons

Project Description

Fifty-six anchor blocks for external post-tensioning have been stressed to ex-isting concrete girders with Technora® 9-strand aramid tendons, made from 7.4-mm-diameter (0.3-in) deformed (spirally wound) aramid rods. The rehabilitation and strengthening was performed for the Japan Highways Public Corporation (JHC). Each tendon has a nominal design load of 850 kN (191 kip), and six tendons were used to anchor each anchorage bracket (Figure 111). The adjustable tendon end anchorages consist of epoxy-mortar-filled steel housings (Figure 112).

Construction/Installation

The existing concrete girders were cored at the anchor block tendon locations. Six 9-strand Technora® tendons were placed over the entire bridge width through multiple girders and anchor blocks and pretensioned against bulkheads at both sides of the bridge. Anchor blocks were cast around the pretensioned tendons. After curing of the concrete, the tendons were cut between girders, and longitudinal external post-tensioning with conventional steel tendons began.

Composite Materials	
Fiber	Aramid (Technora®)
Matrix	Vinyl Ester
Manufacturing	Pultrusion
Assembly	Post-Tensioning Tendons
Tensile Modulus	53 GPa (7.7 x 10^6 psi)
Tensile Strength	1,766 MPa (256 ksi)
Ultimate Strain	3.6%

Instrumentation, Monitoring, Testing

No testing or monitoring of the anchor block tendon force was planned for this project.

Special Issues

The prestress force development perpendicular to the anchor blocks in a pretensioned system is questionable, because of the short block dimensions and bond transfer length in this direction.

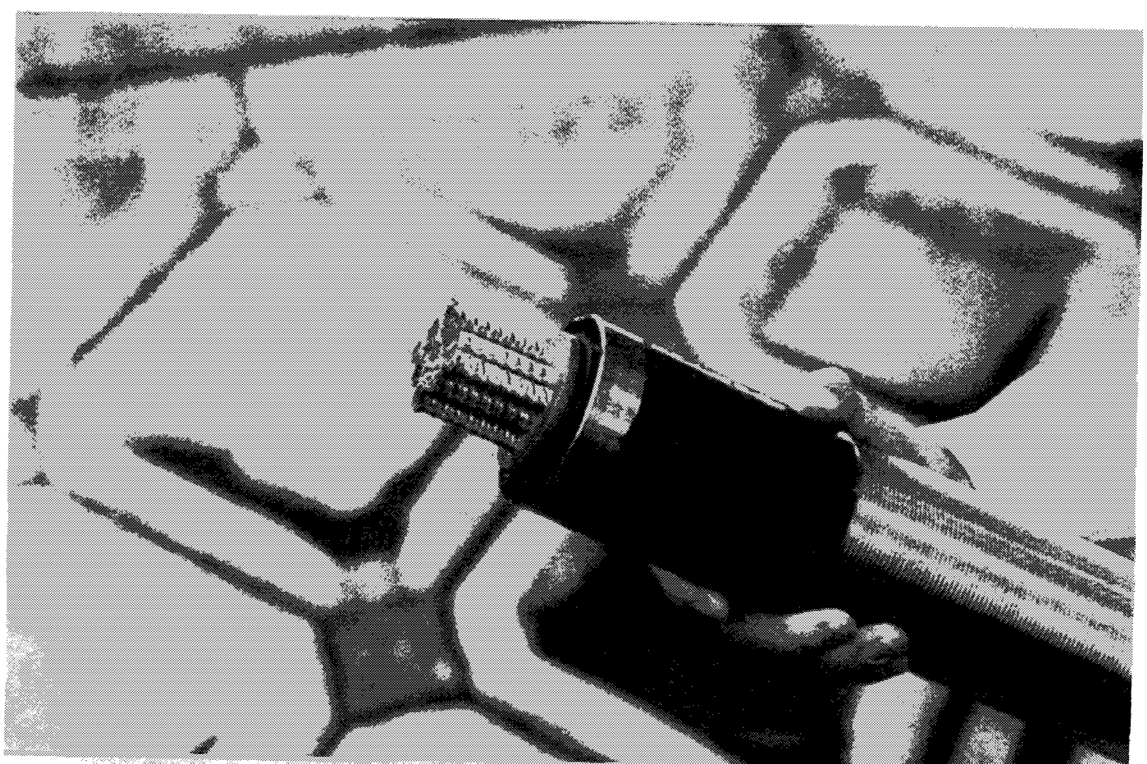

Figure 112. Technora® 9-Bar Tendon and Anchorage

5.6 SEISMIC COLUMN RETROFITTING (PROJECT J6)

Project Summary
Japanese developments in seismic column retrofitting with FRP sheets. Carbon fiber jacketing of columns on the Hanshin Expressway extension in Himeji.

Project Data
Designer: Toray and JHC
Contractor: Sho-Bond
Owner: JHC
Completed: November 1996

Project Objective
Enhance strength and ductility of existing reinforced-concrete columns for seismic loads with fiber-reinforced plastic sheet overlays by manual wet layup and ambient temperature curing.

Alternative Concepts
Automated winding of tows, steel or concrete jacketing.

Design Considerations
Design of retrofit measures follows manufacturers' design recommendations. Composite jackets are designed to carry longitudinal column forces because of column bar cutoffs over the column height.

Project Contacts
Mr. A. Sumida, Manager, DuPont Toray Kevlar, Ltd.; Mr. M. Uemura, General Manager, Tonen Corp.

Project Description
The Kobe earthquake of January 1995 prompted accelerated research and development of advanced composite retrofit systems for existing concrete columns. Examples of this research and development were seen and discussed at Sumitomo Construction Co., Ltd. (Figures 113 and 114). In addition to the enhancement of deformation capacities in the columns under seismic loads, in Japan many columns require longitudinal strengthening because of longitudinal bar dropoffs or cutoffs over the column height (Figures 115 to 117), based on linear elastic design assumptions.

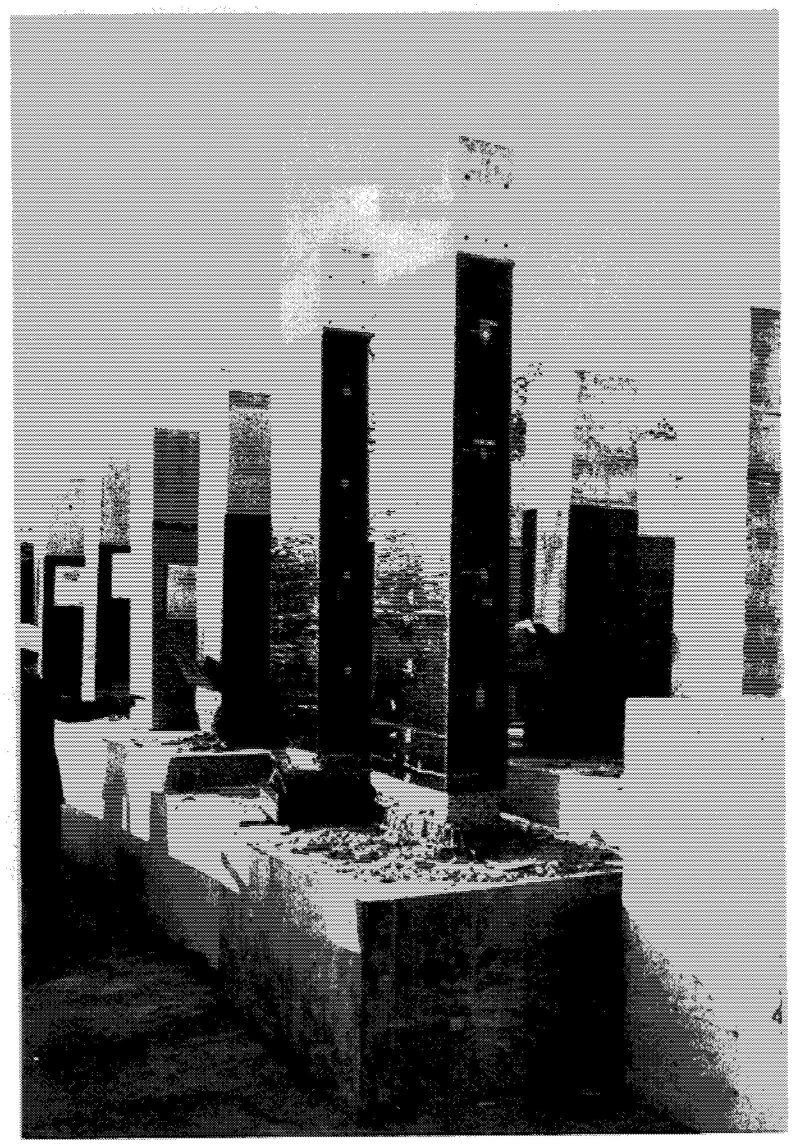

Figure 113. Seismic Column Retrofitting Tests at Sumitomo Construction Co., Ltd.

On the Hanshin Expressway, 19 rectangular columns that are 2 m × 3 m (6.5 ft × 9.8 ft) in plan and 6 m (19.7 ft) tall were retrofitted by Sho-Bond Corporation using Torayca Cloth® carbon sheets by Toray.

Composite Materials	
Fiber	Carbon or Aramid
Matrix	Epoxy
Manufacturing	Fabric
Assembly	Manual Layup

Construction/Installation
Standard manual wet layup techniques were employed. The column was enclosed with plastic barrier sheeting around scaffolding to keep the work area dust free and provide a screen for the public. No special environmental mitigation measures were used during the epoxy application and curing.

Instrumentation, Monitoring, Testing
No monitoring or testing is planned for the seismic column retrofit applications.

Special Issues
The Japanese bridge engineering and construction community is under severe pressure to implement retrofit measures as quickly as possible. Despite the fast pace, there are design concerns with retrofit measures of different stiffnesses for adjacent column bents. The effectiveness of rectangular FRP jackets on large rectangular columns to improve inelastic deformation capacities also needs to be addressed. Both of these issues are currently being investigated at PWRI.

Figure 114. Aramid Sheet Retrofitting

Figure 115. Carbon Sheet Retrofitting

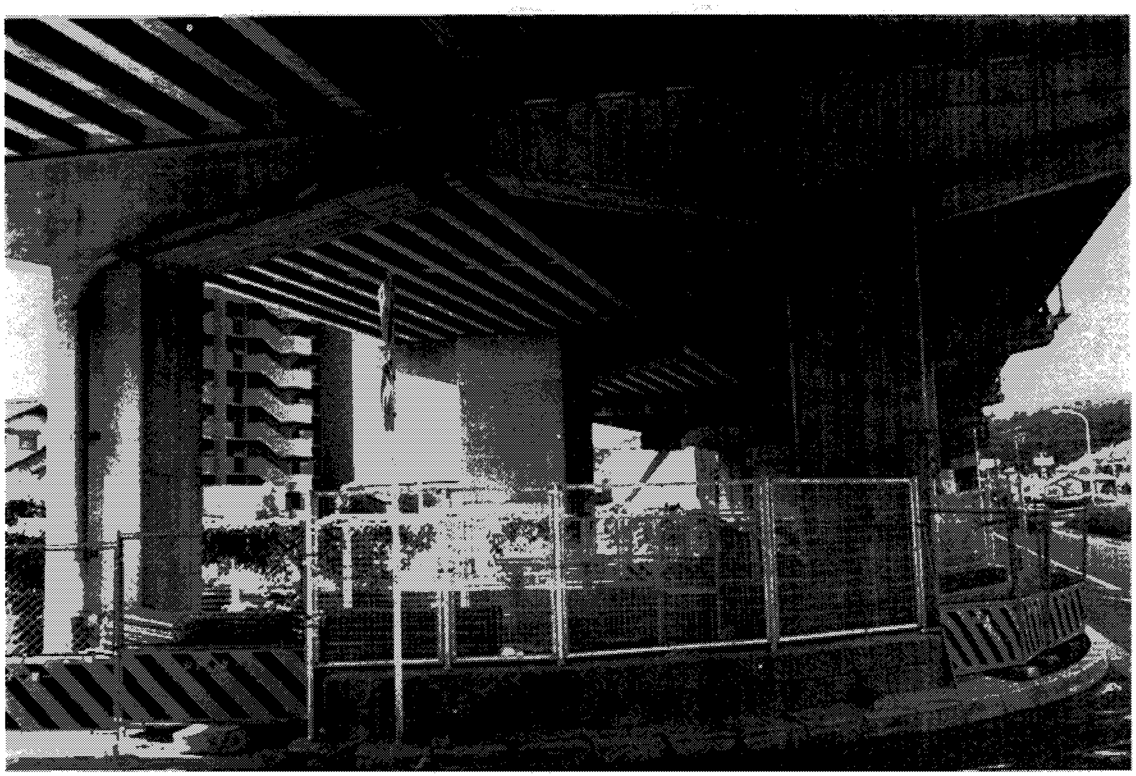

Figure 116. Column Retrofitting on the Hanshin Expressway

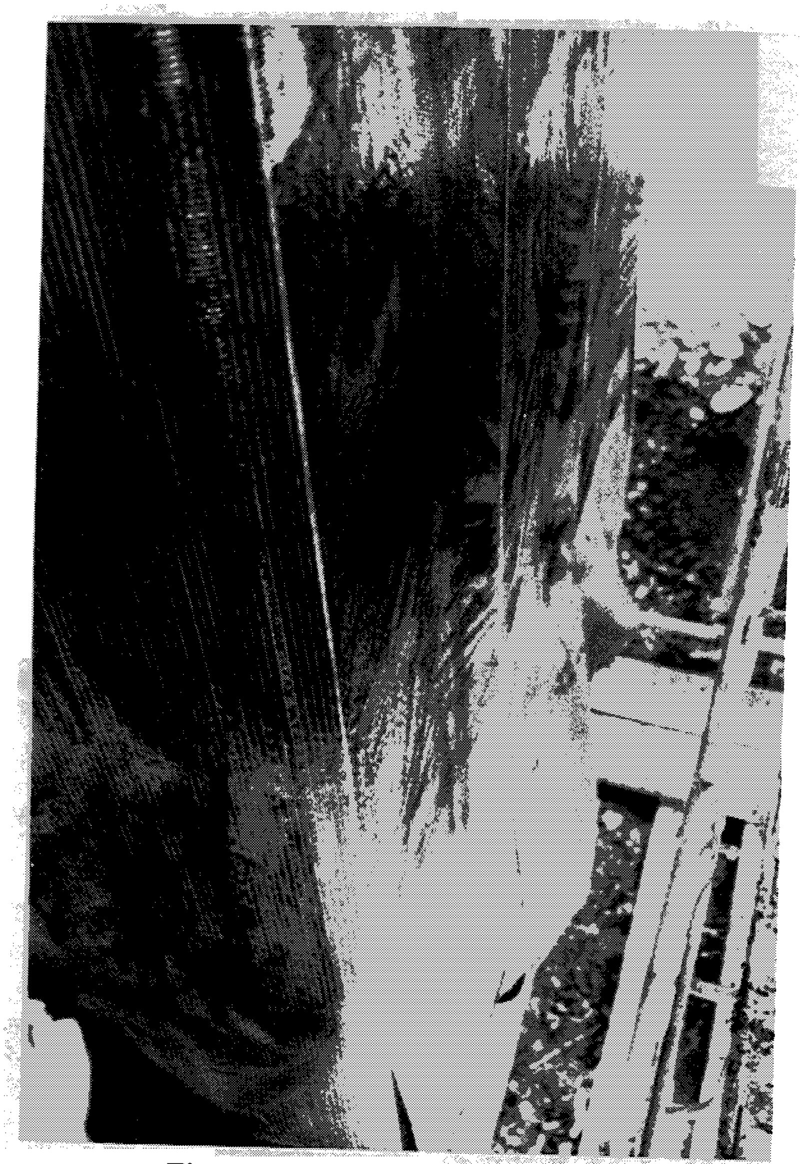

Figure 117. Application of Vertical Carbon Sheet at the Hanshin Expressway

5.7 AKASHI-KAIKYO BRIDGE (PROJECT J7)

Project Summary
Construction of the world's longest suspension bridge across the Akashi Straits from Honshu to Shikoku. Pilot rope for main cables was made of aramids.

Composite Materials	
Fiber	Aramid
Matrix	Dry Fiber
Assembly	Rope

Project Data
Owner: Honshu-Shikoku Bridge Authority
Designed: 1985
Completed: Scheduled for 1998

Project Objective
The project objective was to place a light pilot rope by helicopter over the bridge mainspan between the towers to pull the larger and heavier construction cables.

Alternative Concepts
Placement of pilot rope with ferry or tug boat, which would interrupt ship traffic.

Design Considerations
Reduce pilot rope weight to allow placement by helicopter.

Project Contact
Mr. U. Nishikawa, Head, Bridge Division, PWRI.

Project Description
The Akashi-Kaikyo Bridge is the world's longest span bridge currently under construction (Figures 118 and 119). The mainspan of the suspension bridge is 1,992 m (6,531 ft) long, and the towers are 283 m high (928 ft). Its superstructure consists of

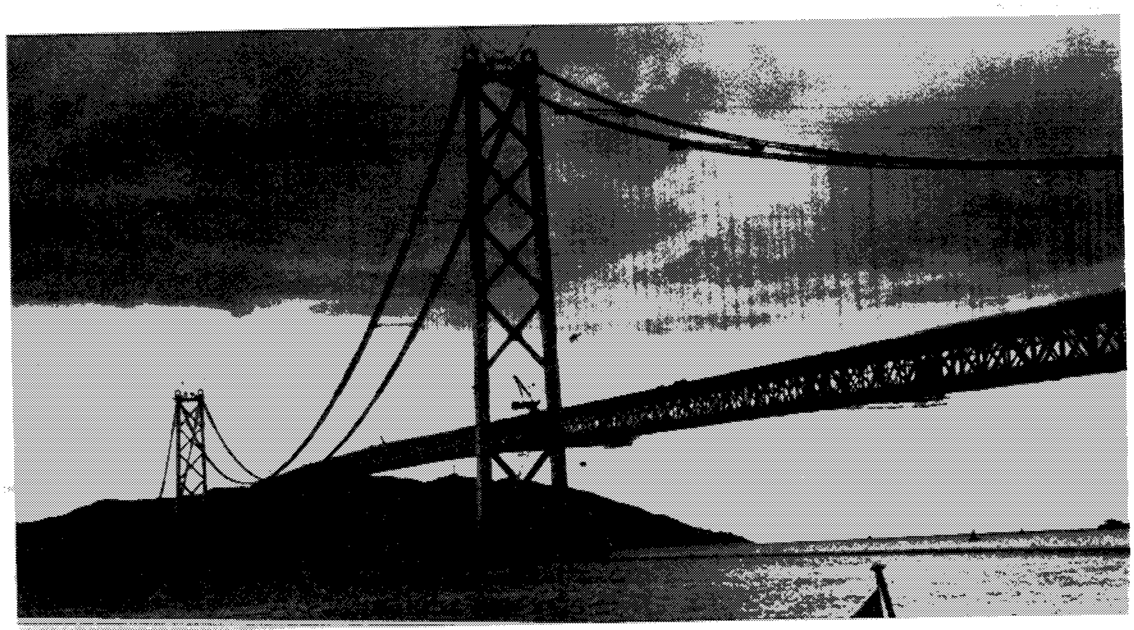

Figure 118. Akashi-Kaikyo Bridge, October 1996

a double-deck stiffening steel truss with six lanes of highway traffic to be carried on an orthotropic steel deck on the upper level. The lower level carries utilities from Kobe to Awaji Island.

Construction/Installation

The aramid pilot rope is 3.6 times lighter than a comparable steel pilot rope of equivalent strength. Because of its light weight, the pilot rope for the Akashi-Kaikyo Bridge could be placed by helicopter with a suspended cable drum. A comparison with steel pilot rope is shown in Table 6.

Instrumentation, Monitoring, Testing

The pilot rope was capacity tested before use.

Table 6. Akashi-Kaikyo Bridge Pilot Rope Comparison

Material	Rope Diameter	Rope Structure	Cross-Sectional Area	Weight/Length	Tensile Strength
Polyaramid	10 mm (0.4 in)	1-mm (0.04-in) sheath 8-mm (0.31-in) bundles	25.9 mm^2 (0.04 in^2)	0.0917 kg/m (0.05 lb/ft)	46.1 kN (10.4 kip)
Steel Wire Rope Strand	10 mm (0.4 in)	6 x 24 wire strands	34.8 mm^2 (0.054 in^2)	0.332 kg/m (0.22 lb/ft)	49.2 kN (11.1 kip)

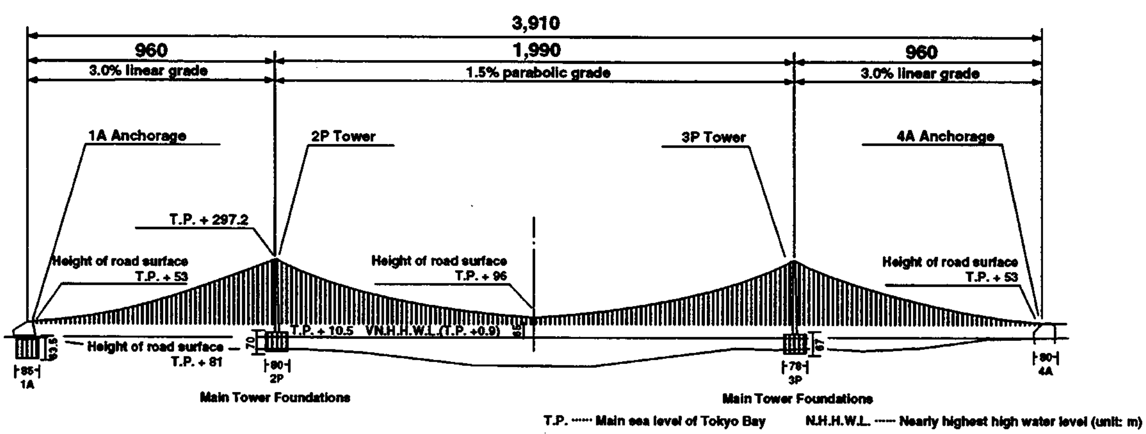

Figure 119. Geometry and Dimensions
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5.8 BRIDGE DECK STRENGTHENING (PROJECT J8)

Project Summary
Strengthening of bridge deck on the Hanshin Expressway for increased traffic loads.

Project Data
Contractor: Mitsubishi/Tonen/Toray
Owner: Hanshin Expressway Public Corporation
Completed: 1996

Project Objective
Demonstrate the application and effectiveness of different carbon sheet strengthening methods [16, 17, 18]. Strengthen deck-load-carrying capacity from 20- to 25-ton trucks.

Alternative Concepts
Steel plate bonding, shotcrete, and added reinforcement.

Design Considerations
Rehabilitation/strengthening must occur under rolling traffic loads. Bridge deck needs to be sealed to prevent water penetration from the roadway.

Project Contact
Mr. M. Uemura, Secretary, CFRRA, and General Manager, Tonen.

Project Description
On a section of the Hanshin Expressway in Kobe, three different carbon sheet types were installed with different layup sequences and orientations. The systems applied were Replark® from Mitsubishi, Towsheet® from Tonen, and Torayca Cloth® from Toray. All systems were applied in an overhead wet layup using rolled-on epoxy adhesive. Costs per layer of installation were about ¥15000/m^2 (US$15/ft^2). Wheel load tests, strain, and deflection measurements are used to evaluate effectiveness.

Construction/Installation
All construction and installation followed standard overhead wet layup procedures (Figure 120). The carbon sheets were delivered onsite with a paper backing and pressed into a rolled-on epoxy adhesive. The applied systems were cured at ambient temperatures.

Figure 120. Carbon Sheet Slab Strengthening

Instrumentation, Monitoring, Testing
Wheel load tests with a 25-ton truck were performed before and after the carbon sheet strengthening. Strain levels in the carbon sheet of 150 to 160 $\mu\epsilon$ were measured after the strengthening.

Deflections reduced by 30 to 40 percent, almost independent of the amount of carbon fiber, which indicates that even small amounts of composite reinforcement are sufficient to keep the deck cracks closed. Draft design guidelines will be reevaluated after a 3-year test and demonstration period.

5.9 ROLLING TRAFFIC LOAD SIMULATOR (PROJECT J9)

Project Summary
Prototype development of rolling traffic test simulator for wheel loads on bridge decks.

Project Objective
Determine influence of rolling traffic loads on installation and durability of carbon overlays. Determine fatigue characteristics of carbon sheet strengthening methods under realistic loading conditions.

Alternative Concepts
Simulate rolling traffic loads with a series of online, servo-controlled hydraulic actuators.

Design Considerations
Duplication of crack patterns encountered in bridge decks for laboratory simulations of loading. Increase of legal truck weight from 20 to 25 tons.

Project Contact
Dr. Engr. S. Matsui, Professor of Civil Engineering, Osaka University.

Project Description
As part of an ongoing research project on bridge deck deterioration and strengthening, Prof. Matsui developed a machine that simulates running wheel loads (Figure 121). Its development was prompted by the observed crack patterns in bridge decks in the field (Figure 122), which start with cracks in the transverse or load-carrying direction of the deck. These cracks limit the tributary width of the transverse deck, resulting also in longitudinal cracks. Eventually, complete orthotropic crack patterns developed with a propensity for local punching shear failures. Laboratory tests with stationary point loads typically result in radial crack patterns, as outlined in Figure 123a. These are significantly different in the resulting failure modes and failure load than those observed in the actual slab shown in Figure 123b. To achieve representative and realistic crack patterns, under laboratory conditions, Prof. Matsui developed the running wheel load machine (see Figure 124). This machine can duplicate observed field crack patterns under laboratory conditions and simulate rolling traffic loads for strengthening application without traffic interruptions and for fatigue load testing with realistic load simulations (Figures 125 and 126).

Based on the prototype machine, two test systems have been built at PWRI. Limitations of the test system are: a constant, though adjustable, applied load during a

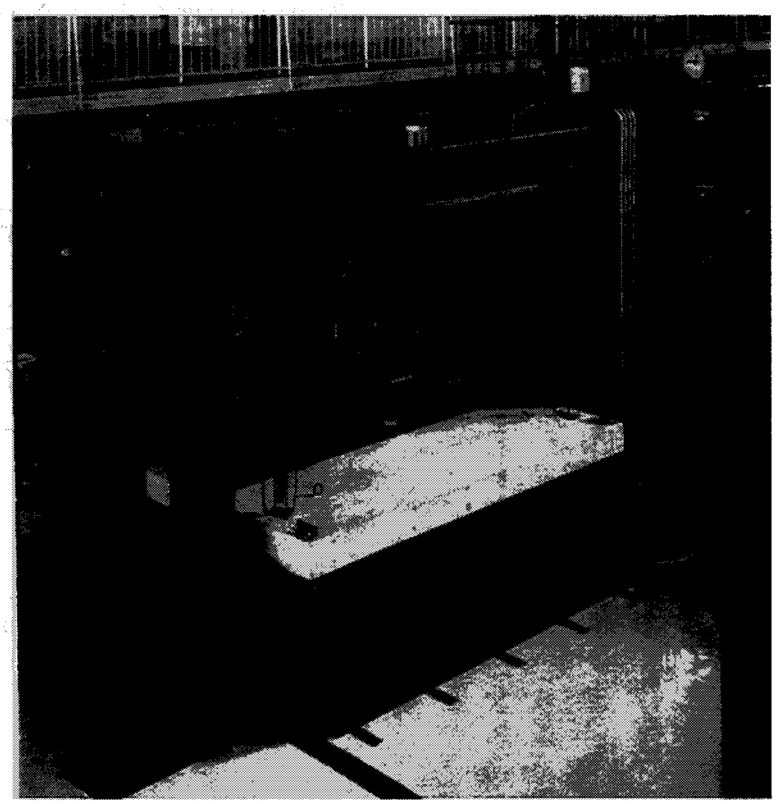

Figure 121. Wheel Running Machine for Fatigue Test of Highway Bridge Slabs
Included with permission of S. Matsui, Osaka University.

single test; a constant speed; and the need for a special rail or raceway track to convert the concentrated line load of a steel wheel to an appropriate tire patch load.

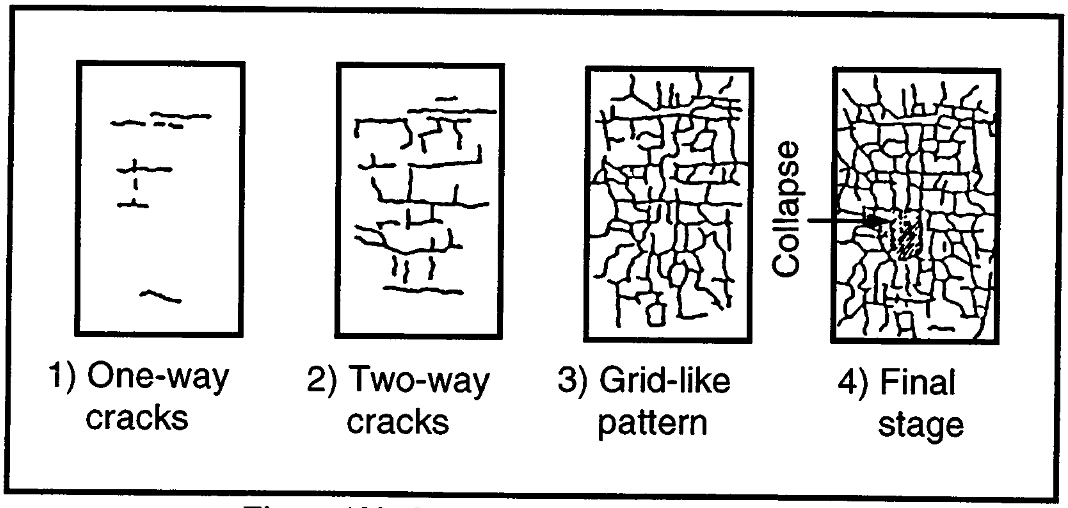

Figure 122. Deterioration Process of Slabs
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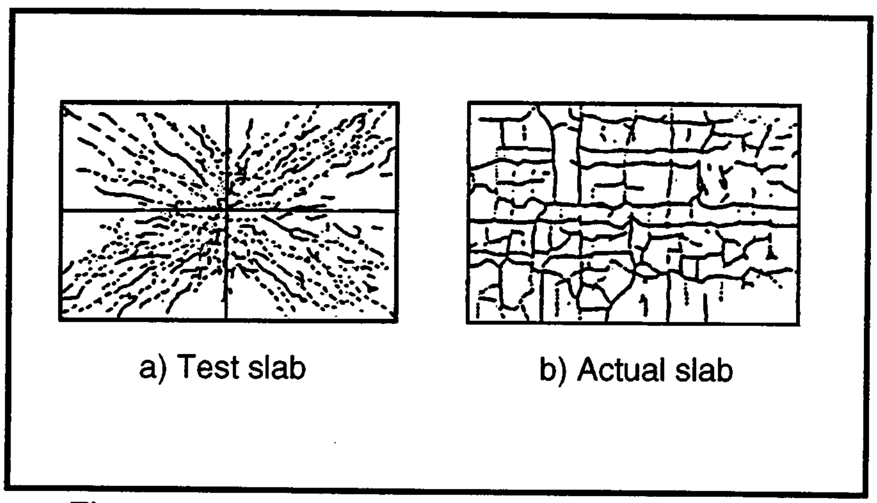

Figure 123a and b. Comparison of Cracking Patterns
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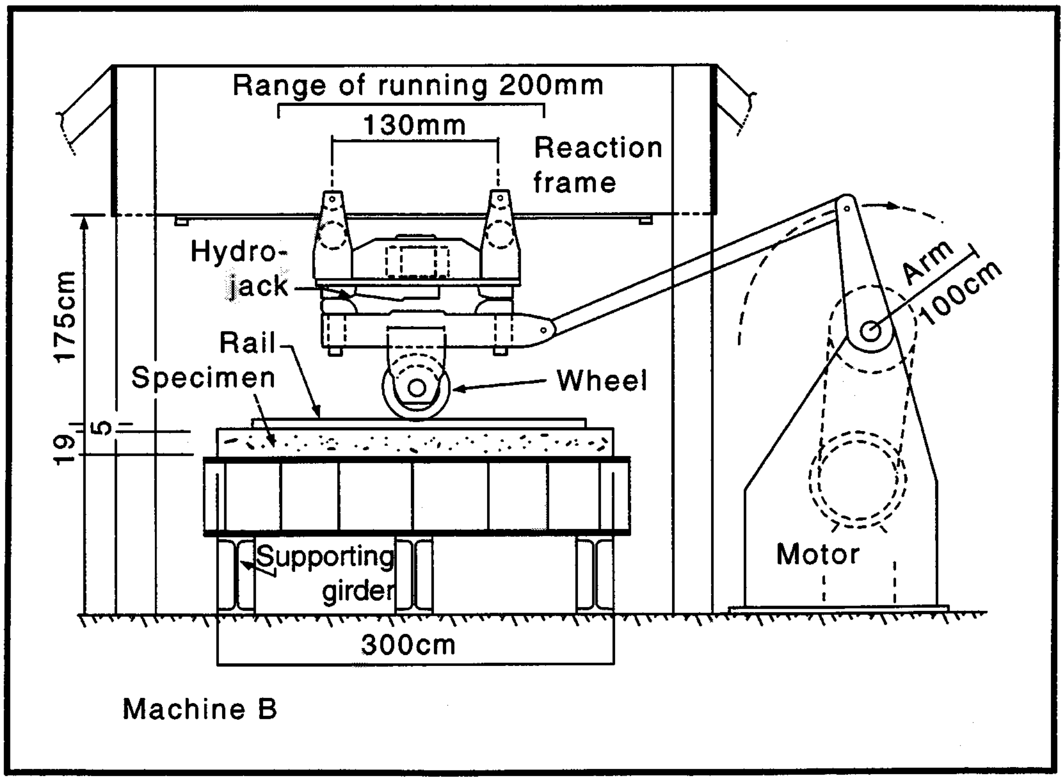

Figure 124. New Type of Fatigue Machines (Wheel Trucking Machines)

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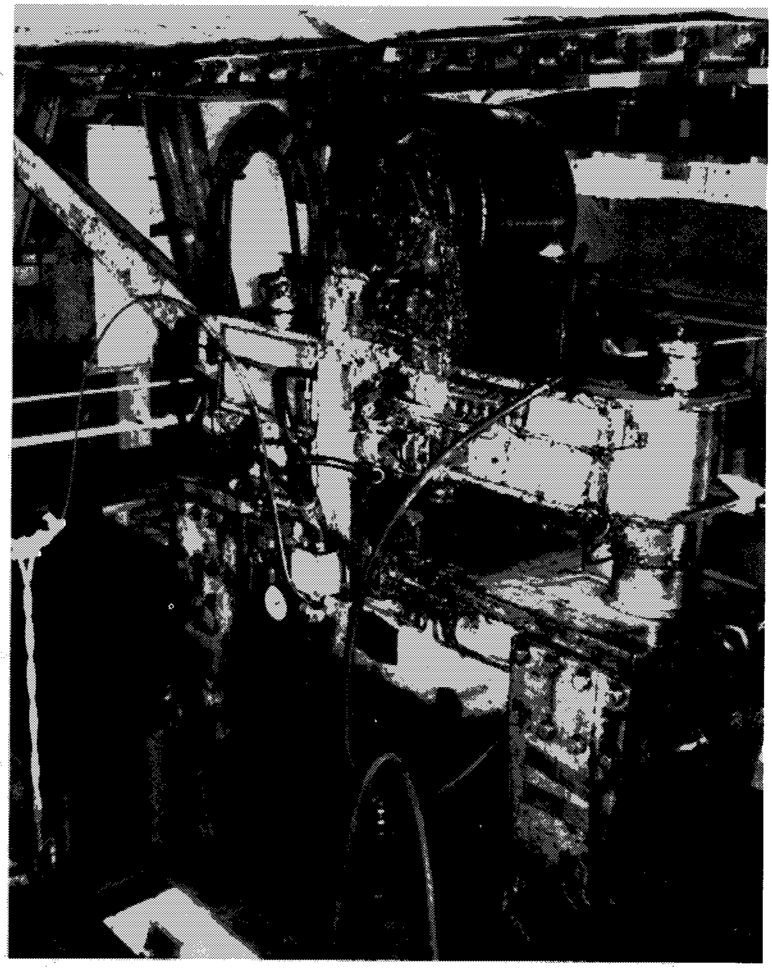

Figure 125. Rolling Traffic Simulator Prototype

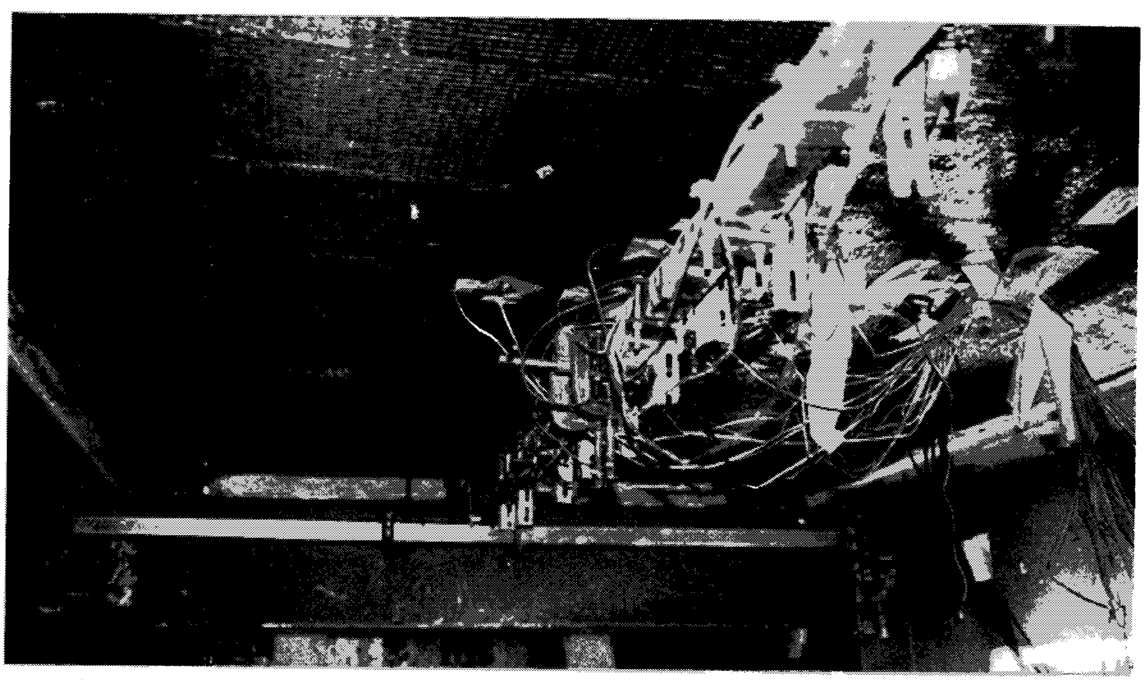

Figure 126. Test of Carbon Sheet Strengthening and Running Wheel Load

5.10 HIYOSHIGURA VIADUCT (PROJECT J10)

Project Summary
Bridge deck strengthening with Tonen Tow-sheet® and Sho-bond CFRP bonding method.

Project Data
Designer: Tonen Corporation
Contractor: Tonen Corporation
Owner: JHC
Designed: 1993
Completed: 1993

Project Objective
Demonstration project for the JHC on the Hiyoshigura Viaduct to show the application and effectiveness of carbon sheet strengthening.

Alternative Concepts
Steel plate bonding.

Design Considerations
Change in live load brought about by code change from TL 20 to TL 25 (truck load increase from 20 to 25 tons).

Project Contact
Mr. M. Uemura, Secretary, CFRRA, and General Manager, Tonen.

Project Description
As a demonstration project for JHC, two deck sections of the Hiyoshigura Viaduct northwest of Narita International Airport were strengthened by Tonen Corporation with carbon sheets (see Figures 127 to 131). The deck sections are 3 m wide (9.8 ft) and 30 m long (98 ft) and were overlaid with two perpendicular layers of 300-g/m^2 high-modulus, pitch-based carbon tow sheets. Before the repair and strengthening measures, deck slabs had exhibited the typical orthotropic distress crack patterns shown in Figure 128.

Construction/Installation
Installation was performed from scaffolds with two crews of two people each for one week doing the actual carbon sheet application. Construction steps consisted of:

1. Sandblast and clean surface
2. Apply primer to surface

Figure 127. Hiyoshigura Viaduct

3. Apply fabric to primer
4. Apply resin to fabric
5. Repeat 3 and 4, but rotate fabric 90 degrees.

Composite Materials	
Fiber	Tonen Towsheet®
Matrix	Epoxy
Manufacturing	Sho-Bond
Assembly	Manual Layup
Adhesive	Epoxy
Curing	Ambient

Instrumentation, Monitoring, Testing
Proof testing with a 25-ton truck has been completed (see Figure 129). Future retesting is possible.

Special Issues
With a continuous watertight CFRP layer at the bottom soffit, questions of moisture drainage have been raised. Can possible problems be detected with only visual inspections?

Figure 128. Damage to Existing Bridge Deck

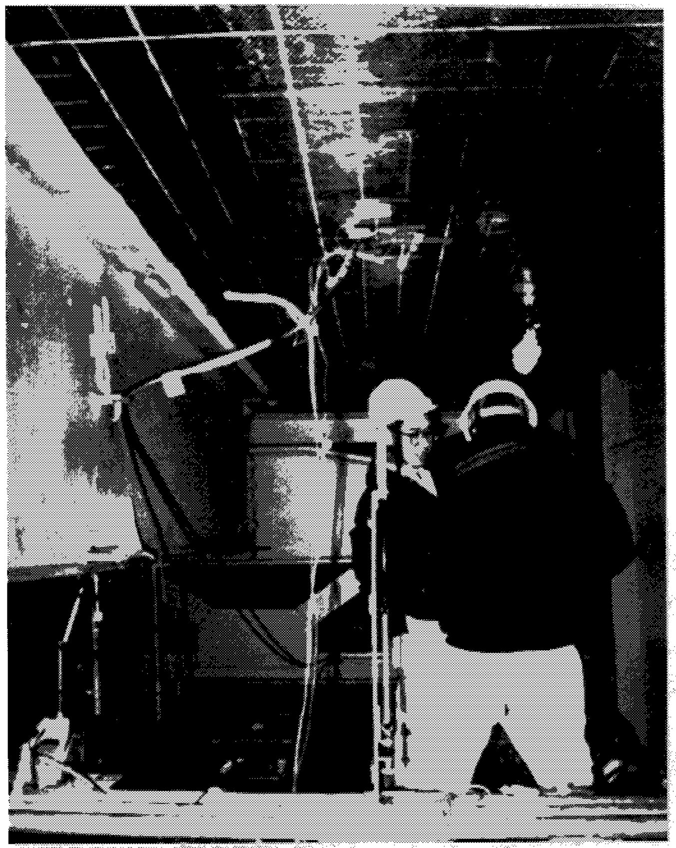

Figure 129. Strain and Deformation Measurements of Strengthened Deck

Figure 130. Closeup of CFRP-Sheet-Strengthened Deck

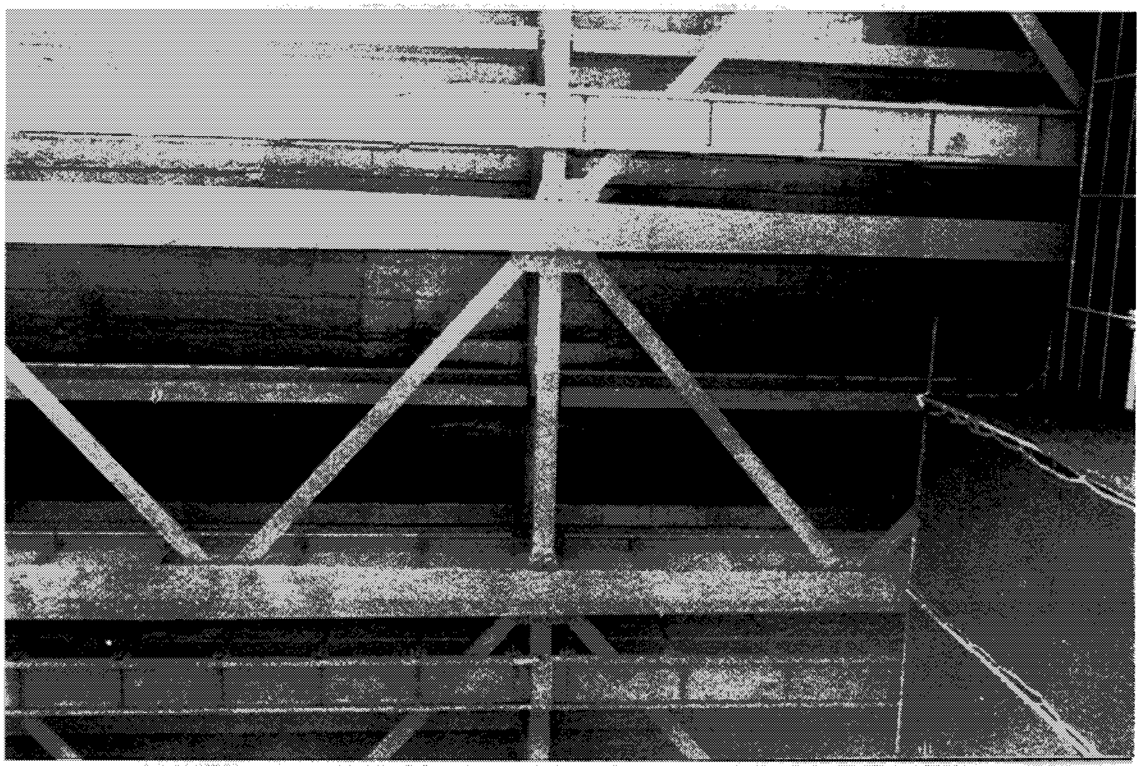

Figure 131. CFRP Strengthening of Hiyoshigura Viaduct

5.11 TOKYO RAINBOW BRIDGE (PROJECT J11)

Project Summary
A double-deck suspension bridge with mainspan of 570 m (1,869 ft) at the entrance of the Port of Tokyo. Fibra® pretensioned aramid rods were used in the southeast abutment boat landing and precast concrete walkway panels (Figure 132).

Project Data
Owner: Tokyo Metropolitan Expressway Public Corporation
Completed: August 1991 (precast concrete panels)

Project Objective
Increase durability and eliminate corrosion in the splash zone through the use of nonmetallic reinforcement (Fibra® aramid bars) of the precast walkway panels around the southeast cable anchorage.

Design Considerations
Elimination of corrosion in the splash zone, increased durability, reduced maintenance.

Project Contact
Mr. K. Nishikawa, Head,
Bridge Division, PWRI.

Project Description
The Rainbow Bridge at the Port of Tokyo is a 918-m-long (3,010-ft) suspension bridge with a 570-m (1,868-ft) mainspan (Figures 133 and 136). The upper level of the double-deck steel truss superstructure carries Route 11, the Daiba Line of the Tokyo Metropolitan Expressway. The lower level accommodates a new commuter transit system, waterfront roads, and a pedestrian promenade. At the base of the southeast cable anchorage housing is a cantilevered service and boat landing walkway, which is in the splash zone of the Tokyo Bay ocean water. The hollow-core, precast concrete walkway panels (Figures 134 and 135) were pretensioned with 9-mm (0.35-in) Fibra® aramid rods to eliminate corrosion and reduce maintenance.

Figure 132. Tokyo Rainbow Bridge

The hollow-core, precast concrete deck panels are 5 m long (16 ft), 0.91 m wide (3 ft), and 200 mm deep (8 in). They are prestressed with 10 Fibra FA 9® tendons that are 9 mm in diameter (0.35 in). A total of 900 m^2 (9,675 ft^2) of precast, prestressed concrete aramid deck panels was used.

Composite Materials	
Fiber	Aramid
Matrix	Epoxy
Manufacturing	Braided
Assembly	Pretensioned Tendons
Tensile Modulus	68.6 GPa (9.9 x 10^6 psi)
Tensile Strength	1,400 MPa (200 ksi)
Ultimate Strain	2%

1 MPa = 145 psi

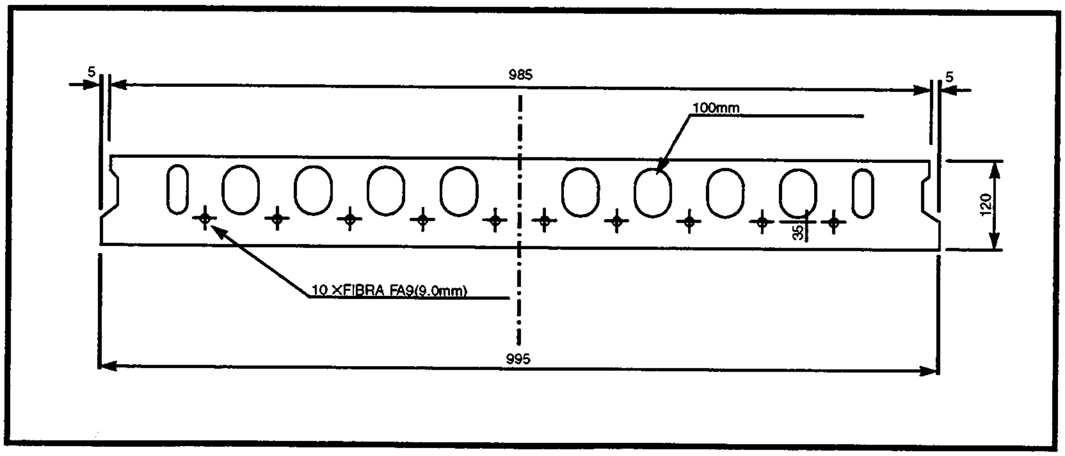

Figure 133. Geometry and Dimensions of Precast Concrete Deck Panels [15]
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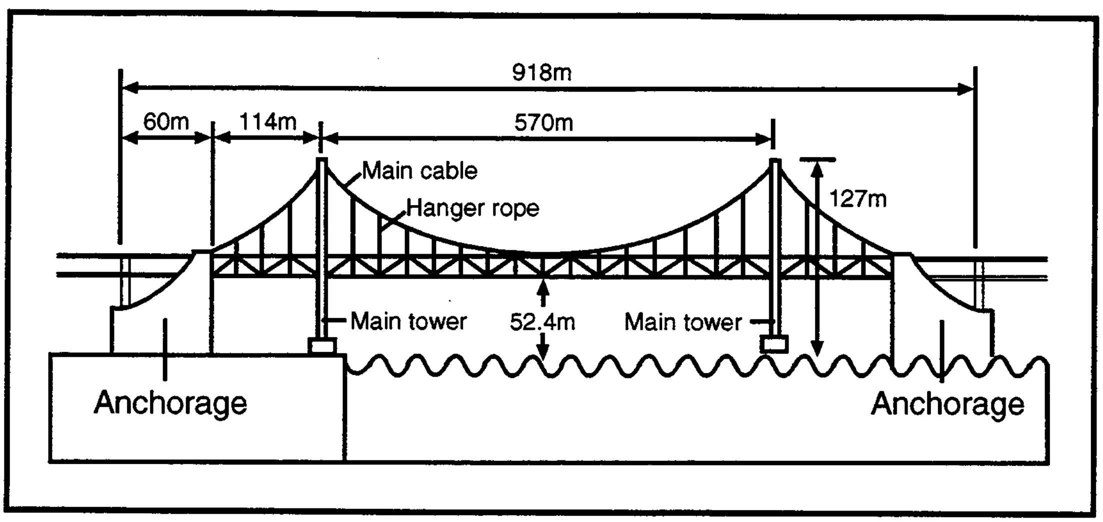

Figure 134. Geometry and Dimensions
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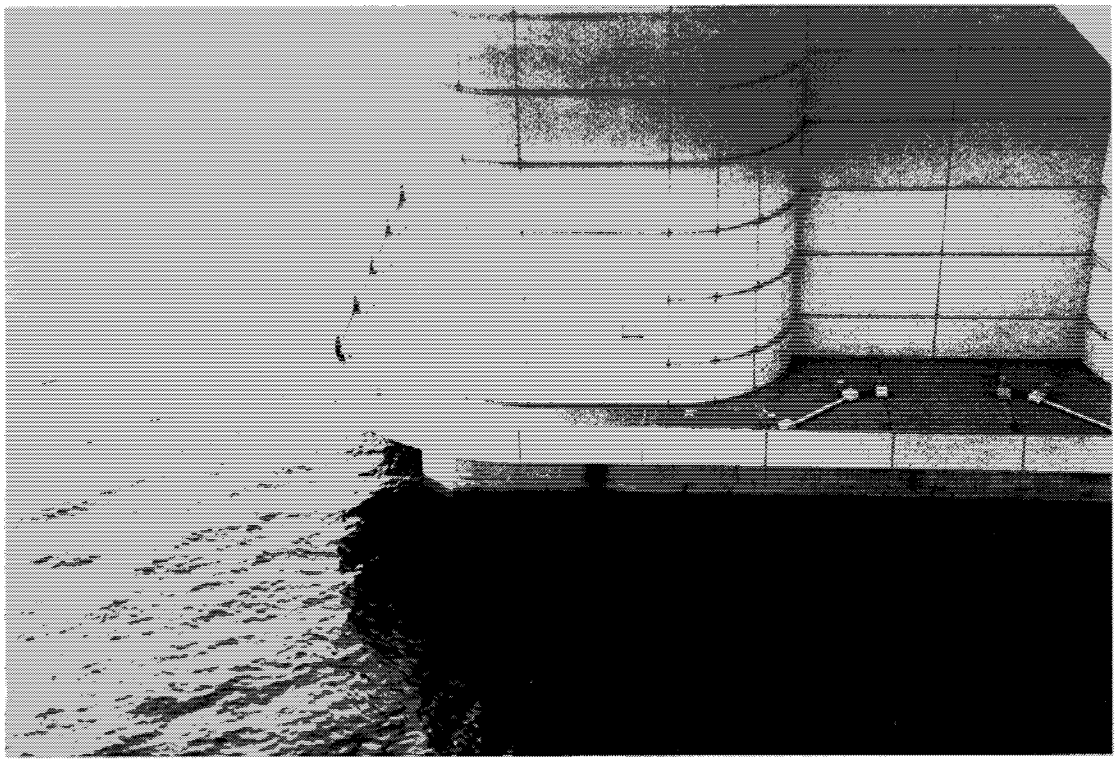

Figure 135. Precast Concrete Walkway at Southeast Cable Anchorage

Figure 136. Port of Tokyo and Rainbow Bridge

6.0 TRANSFERABILITY OF TECHNOLOGY TO THE UNITED STATES

6.1 U.S. Technology Perspective

One of the main objectives of this technology scanning tour was to compare the U.S. advanced composite bridge technology with the state of technology abroad. A general observation from this scanning tour is that U.S. advanced composite bridge technology has developed concurrently with international technology and is neither behind nor significantly ahead of the countries visited. In specific areas, such as FRP cable/tendon and anchorage technology development, the United States has only limited commercial systems available; however, testing and evaluation of cable, anchorage, and reinforcing systems under short- and long-term load and environmental conditions is well advanced. On the other hand, seismic retrofitting systems for bridge columns seem to be more advanced in the United States, particularly in terms of consistent design philosophies and guidelines. Strengthening measures with FRP sheets have been developed and applied both abroad and in the United States.

In the United States, more basic or generic research seems to be performed on the use of advanced composites in civil engineering environments at numerous universities and research laboratories. Abroad, research and development efforts seem to be much more product specific or industry driven, resulting in earlier and more high-visibility demonstration projects than in the United States.

There are, however, significant differences between the United States and the countries visited in the following areas:

- Involvement of the civil engineering community and the construction industry in product development and application

- Partnerships among government agencies, industry, and the research community for specific product developments

- Training of design and construction professionals by government and industry consortia

- Significant industry subsidies for numerous demonstration projects to showcase the new technology.

In the countries visited, there seemed to be a more direct link between research and product development, which is typical for research and development programs initiated and sponsored by industry. In the United States, the fragmented nature of independent and generic research, largely sponsored by government agencies, seems to be more of an obstacle to product development and implementation than a catalyst for it. The United State must strike a better balance between basic and applied research in the form of coordinated research and development programs that include full participation of the advanced composite industry and the civil engineering and construction industries.

6.2 Transferable Technology

During the scanning tour, many different products, procedures, and concepts were encountered that should be further evaluated for transfer to the U.S. industry and market. In some cases, similar U.S. products and processes exist, but in others, the particular technology is not commercially available in the United States at this time. In virtually all instances, however, costs for the demonstrated technologies will make it very difficult to compete in the U.S. bridge market, unless significant reductions can be realized.

Furthermore, transfer of specific technologies observed abroad may require reevaluation of their underlying design concepts and procedures to conform to U.S. practice and standards. For example, it will be difficult to provide external strengthening of bridge decks by bonding CFRP laminates or sheets to the bottom soffit to obtain significant flexural capacity increases. Such techniques would require provisions for continuation of at least parts of the reinforcement into the support region. Also, to ensure aggregate interlock in shear in beam or column strengthening, strict strain and dilation criteria need to be employed. These criteria will automatically result in stiffness-driven design approaches, where the high degree of strength of advanced composite material cannot be fully used. In other words, some of the design approaches observed by the scanning team would need to be evaluated and modified for consistent application in the United States.

Specific technologies that should be further considered for possible U.S. applications are outlined below, in chronological order of the scanning tour.

- In the United Kingdom, the Maunsell ACCS for new bridges or bridge decks is of interest. For highway bridges, connections of barrier rails and rail elements need to be developed and tested. The Maunsell ACCS enclosure system is designed for corrosion protection and maintenance access. However, at a converted cost of US\$473/m^2 (US\$44/ft^2), the system will have a hard time economically in the U.S. bridge market, where complete bridge structures can be built for US\$500 to \$1,000/m^2 (US\$50 to \$100/ft^2) of bridge deck area. Finally, the parafil cable system should be investigated for external post-tensioning and cable-stayed bridges.

- The German HLV-Polystal® system was effectively discontinued because of economic considerations and improvements in the durability of conventional steel post-tensioning systems. However, application still seems reasonable in the form of ground anchors or as external tendons in bridge systems, particularly where high tendon strain loss resulting from creep, shrinkage, and anchor set can be expected. Of particular interest, in terms of technology transfer, however, is the "smart" Polystal® with embedded fiber optic and copper wire sensors for continued health monitoring. The United States needs to focus on smart materials with embedded sensors as part of the manufacturing process.

- In Switzerland, two technologies deserve a closer look: the Sika Carbodur® CFRP laminate-strengthening system and the carbon cable-stay system developed by BBR at EMPA. Although both systems, as observed and presented, may not be competitive at currently quoted costs, parts of the technology could be transferable. For example, the technology of the gradated modulus system in the carbon cable anchorage, using aluminum oxide pellets of varying epoxy-coating thicknesses could be transferred.

- In Japan it was clear that a wealth of FRP reinforcement and tendon technology exists that is already available in the U.S. market. The same applies to the carbon-sheet-strengthening systems that complement U.S. systems that are already widely used.

Beyond direct technology transfer of the specific commercial systems outlined above, there are important lessons to be learned from abroad with respect to the involvement of the civil engineering and construction industries; coordinated applied research and product development, with full industrial backing and support; numerous industry-subsidized demonstration projects to showcase the technology; and comprehensive training and education of design and construction professionals.

Missing items to date, both in the United States and abroad are: (1) comprehensive, performance-based design standards and specifications and (2) demonstration projects with full instrumentation and detailed long-term monitoring and evaluation plans and procedures. Such plan should be implemented to establish actual field data for durability, long-term performance characteristics, maintenance, and life-cycle costs. The technology scanning team hopes that these findings will lead to the necessary initiatives to establish long-term instrumentation and monitoring programs on several prototype demonstration projects throughout the United States.

ACRONYMS AND ABBREVIATIONS

$\mu\epsilon$	micro-strains or 10^{-6} in/in
ACC	Advanced Composite Cable (Club) (Japan)
ACCS	advanced composite construction system
AFRP	aramid-fiber-reinforced polymer
ARP	aramid-reinforced polymer
CFRP	carbon-fiber-reinforced plastic
CFRRA	Carbon Fiber Rehabilitation and Reinforcement Research Association
cm	centimeter
Demec	demountable mechanical
DL	dead load
DOT	Department of Transportation
EMPA	Federal Laboratory for Materials Testing and Research (Switzerland)
ETH	Federal Institute of Technology (Switzerland)
FHWA	Federal Highway Administration
f_{pu}	ultimate strength (stress) in prestress
FRP	fiber-reinforced polymer
ft	foot
g	gram
GFC	glass fiber composite
GFRC	glass-fiber-reinforced composite
GFRP	glass-fiber-reinforced polymer
GPa	gigapascal
GRP	glass-reinforced polymer
HA	Highways Agency (UK)
in	inch
ISTEA	Intermodal Surface Transportation Efficiency Act
JHC	Japan Highways Public Corporation
k	kilogram
kip	kilopound (1,000 pounds)
kN	kilonewton
ksi	1,000 pounds per square inch
LL	live load
m	meter
mi	mile
MPa	megapascal
PMC	polymer matrix composite
psi	pounds per square inch
PWRI	Public Works Research Institute (Japan)
RC	reinforced concrete
SFR	Swiss francs
TL	truck load
TRL	Transport Research Laboratory (UK)

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