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Composite Construction in California Bridge Seismic Retrofitting

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Summary

The California Department of Transportation has funded research at the University of California at San Diego for the past six years to develop field applications of advanced composite materials for both repair of older structures and construction of new bridges. The most highly developed application to date is the use of advanced composites in repair of bridge columns and other supporting elements to improve their ductility for seismic resistance. Epoxy impregnated fiberglass and carbon fiber materials have been tested in the laboratory on half-scale models of bridge columns to determine the ductility that can be achieved in an older, non-ductile concrete column. The tests have confirmed the viability of these materials for strengthening existing structures and field application quality control specifications have been developed.

1. Introduction

Following the October, 1989 Loma Prieta earthquake the California Department of Transportation (Caltrans) began a research program, in cooperation with the University of California at San Diego (UCSD), to develop techniques for utilizing epoxy impregnated fiberglass sheets to wrap around older, non-ductile concrete bridge columns as an alternative to the already proven steel jacket technique. The jackets provide sufficient confinement in the concrete to allow them to perform in a ductile manner under seismic loading. It was known that the Japanese had used high strength carbon strands to similarly reinforce industrial stacks and chimneys but the use of glass fiber sheeting had not been used. The major unknown was the durability of the fiberglass materials under cyclic loading and to what level of ductility the columns could be designed. The testing program was conducted under the same conditions that were used in the testing of steel plate jackets. Half scale models of the prototype bridge columns were constructed, wrapped with the desired layers of glass fiber sheets and tested through several cycles of loading at various levels of ductility until the column failed due to degradation of its hysteretic performance. These laboratory tests proved that the epoxy impregnated fiber glass column wraps could develop nearly the same ductile performance as the steel plate jackets.

Material properties are readily available from the manufacturers but there remained the issue of adequate quality control specifications for the field application. These early applications were rather crude, being hand laid in a similar manner as hanging wallpaper. It required some months to fully develop adequate quality control (QC) specifications so the materials tested in the laboratory could be replicated with confidence in the field. The application using epoxy impregnated fiber glass has been approved for two systems and field applications have been in place for over five years.

In 1993, following the end of the cold war and reduction of major aerospace and defense applications, the advanced composites industry began looking for applications of advanced composites in the civil infrastructure. The Caltrans-UCSD testing program was expanded to develop similar applications for the higher strength carbon fibers. This testing program has continued as more manufacturers submit their materials for approval and there are at least five systems approved for field application in California at this time. The carbon fibers are applied by automatic wrapping machines which wrap several 1/4 inch strands simultaneously and can fully wrap a typical four to six foot diameter, 20 foot long bridge column in two hours. Because of the higher strength to weight ratio these materials are very competitive with the steel shell retrofit technique, and they can be applied with much less heavy lifting equipment. The materials are much more resistant to corrosion than the steel jackets and they will require very little maintenance.

Working in cooperation with the University of California at San Diego research team and the ARPA and FHWA technology transfer programs we have been testing other applications of advanced composites in the seismic reinforcing of older bridges and in the construction of major bridge components and ultimately, a complete highway bridge designed for AASHTO loads. The first applications involve resin impregnated fiberglass or carbon sheets on non circular bridge members. These include the use of sheets to wrap and confine the spandrel columns and rib members on several arch bridges where it is difficult to access the locations with heavy equipment. The second application involves the use of small diameter carbon fiber tubes, constructed by the same technology as rocket bodies, for bridge girders. This application has been tested at the laboratory and design details are being developed for a bridge on the state highway system in southern California. The bridge will include deck units which are composed entirely of advanced composite materials and construction is scheduled for late Fall of 1997. The testing program for these bridge components has been underway at UC San Diego for over three years, under the ARPA grant.

2. Column Strengthening

The most widely used application of advanced composite materials for bridges in California and other states, to date, is the seismic strengthening of bridge columns to improve their ductile performance in an earthquake. However, there is a larger market for this technology in the simple repair and strengthening of columns which have deteriorated from corrosion. It is relatively easy to clean and repair these columns and encase them with the non-corrosive composite materials. This application will undoubtedly increase the life of the columns or piers. Three manufacturers have developed prefabricated resin impregnated-fiberglass shells which can also be used as the form for concrete in the repair process. Figure 1 illustrates the prefabricated fiberglass column shell which has been approved and can be used also for repair of piling below the water line.

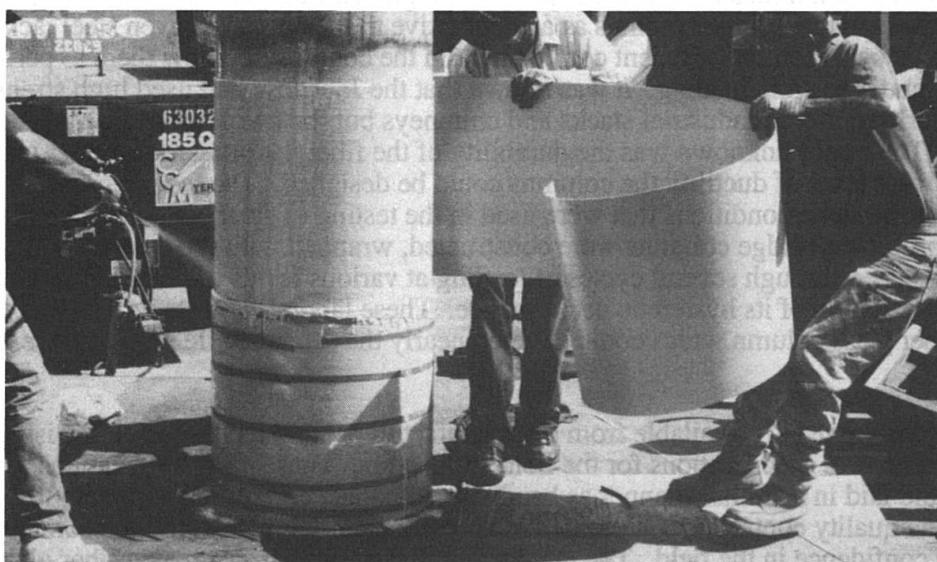


Figure 1 *Installing Prefabricated Fiberglass Shell*

Figure 2a) shows the clamping system utilized to hold the pre-fabricated shell tight until the adhesive cures. This system is the "Clockspring" system, utilizing an Isothalic Polyester resin. Several layers of shells are applied to provide the required ductility. Figure 2b) shows the installation of a full height prefabricated shell. This is the Du-Pont Hardcore system, utilizing a Vinylester resin. These applications were installed in 1996 on the Santa Monica Freeway, Interstate 10, in Los Angeles.

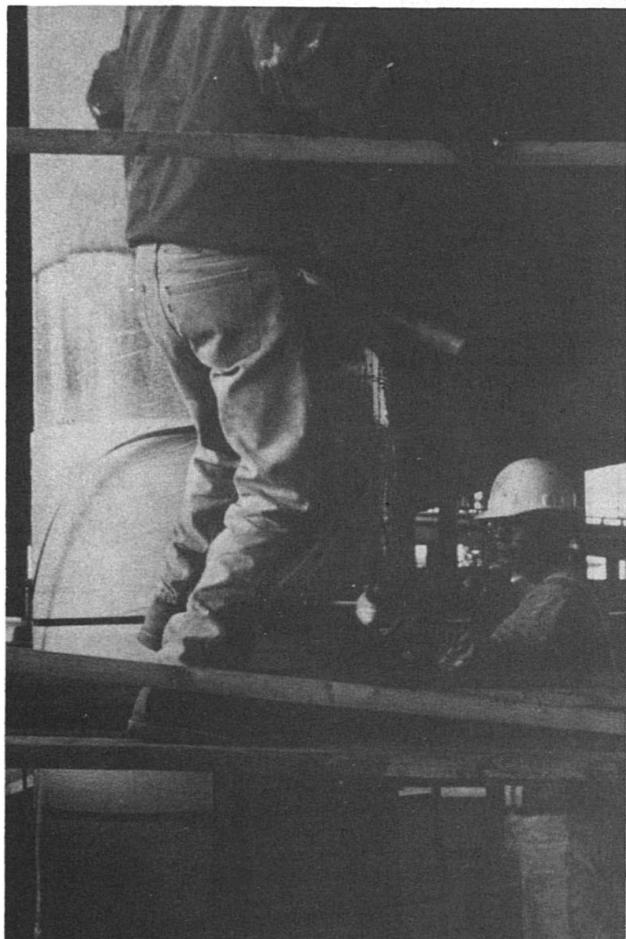


Figure 2 a) Clamping the Pre-Fabricated Shell In Place

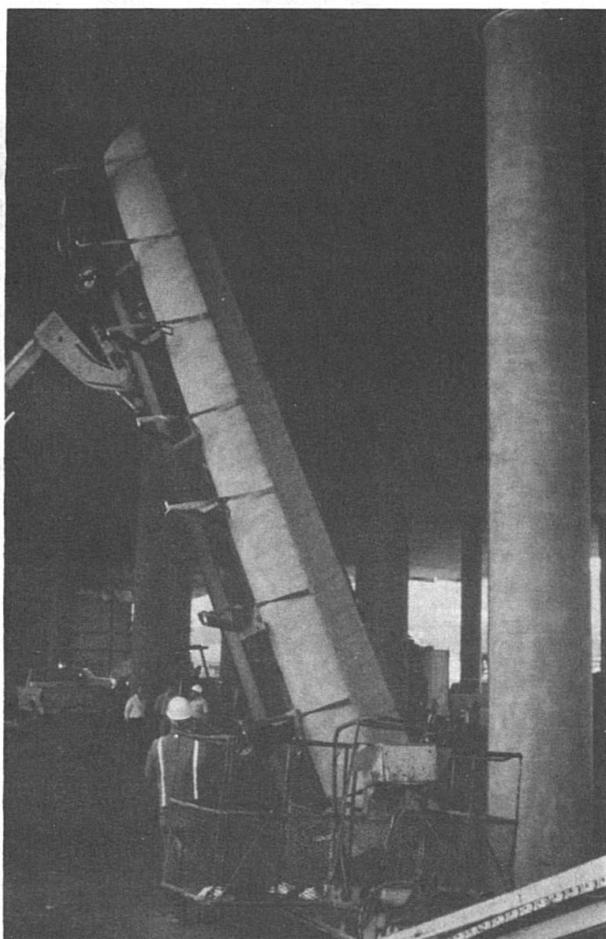


Figure 2b) Installing Full Height Shell

A third prefabricated system has been developed by NCF which utilizes several layers of four foot high single shells. The system, known as "Snaptite" is fabricated and heat cured on a mandrel under controlled curing conditions in the manufacturing plant and shipped to the field much the same as the two systems illustrated in figures 1 and 2. This system appears much less cumbersome to install than the other two prefabricated systems.

Figure 3 shows the use of epoxy-fiberglass as a confinement membrane to increase column ductility and toughness. This was the first application to be tested and approved in California. The material has been used for both circular and rectangular columns. The aspect ratio of the rectangular columns cannot be more than 2:1 or the longer face will buckle under dynamic loading and the needed confinement will not be maintained. This material can be applied as a pre-preg or dry application with the epoxy being applied in the field. One of the initial problems with these materials was uniformity of the final appearance because they are hand laid sheets about three feet wide. Final appearance is dependent on the expertise of the field crew. Attempts have been made to design a machine to improve the application and insure more uniformity, but we have not seen that machine in use in California yet. Careful quality control of the field application and material mixing is necessary to guarantee a quality final product. Figure 4 shows the same material after field

application and painting have been completed. The paint serves two functions; one is protection from ultra-violet light and the second is for aesthetics. The concrete colored paint does an excellent job for both functions. This application was implemented in 1991 on the Glendale Freeway (State Route 134) in Los Angeles. These materials had been tested at the UC San Diego Powell Laboratories in 1990 with excellent results. Both shear and moment ductilities of over eight (8) have been achieved in these tests.

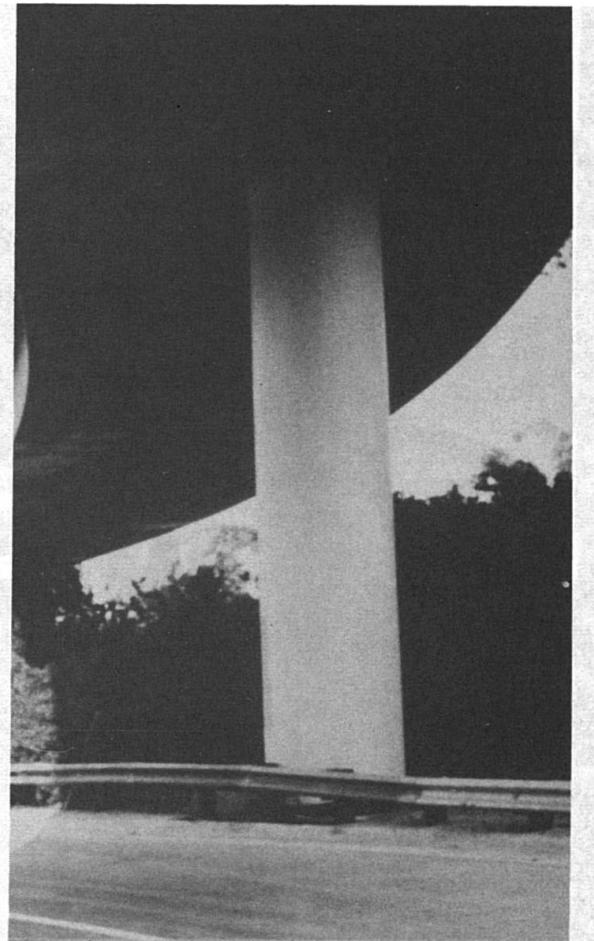


Figure 3 Epoxy-Fiberglass Column Wrap in Laboratory Test Figure 4 Field Application

Figure 5 illustrates the application of pre-preg carbon fiber wrapping on bridge columns at the field test site. The wrapping machine does not require heavy lifting equipment and a later version now applies more strands simultaneously but can wrap a column of 20 foot height in two hours. The columns are heat cured under controlled conditions by electrically heated blankets or enclosures. The columns are painted concrete color for aesthetic purposes, but the coating does provide protection against the elements. This system has been developed by XXSys Technologies and a second, similar system is being tested by Mitsubishi Industries. The thickness can be varied as the ductility requirements dictate. In the field applications on the Santa Monica Freeway the white paint was also used for the same purposes as on the resin impregnated fiberglass wraps. Figure 6 shows the field application on a seismic retrofit project in San Diego. This material has the potential of becoming the most cost effective column wrapping system because of its high strength to weight ratio. The system does not require heavy lifting equipment and can generally compete favorably against the steel shell retrofit systems. Since it is not as labor intensive as some of the other systems being approved, it will ultimately be the system of choice for most contractors. The controlled heat curing system that is used by XXSys provides a material that is very reliable and has the best chance of guaranteeing the same properties as those of the laboratory samples. This reliability is more difficult to achieve with many of the other systems.

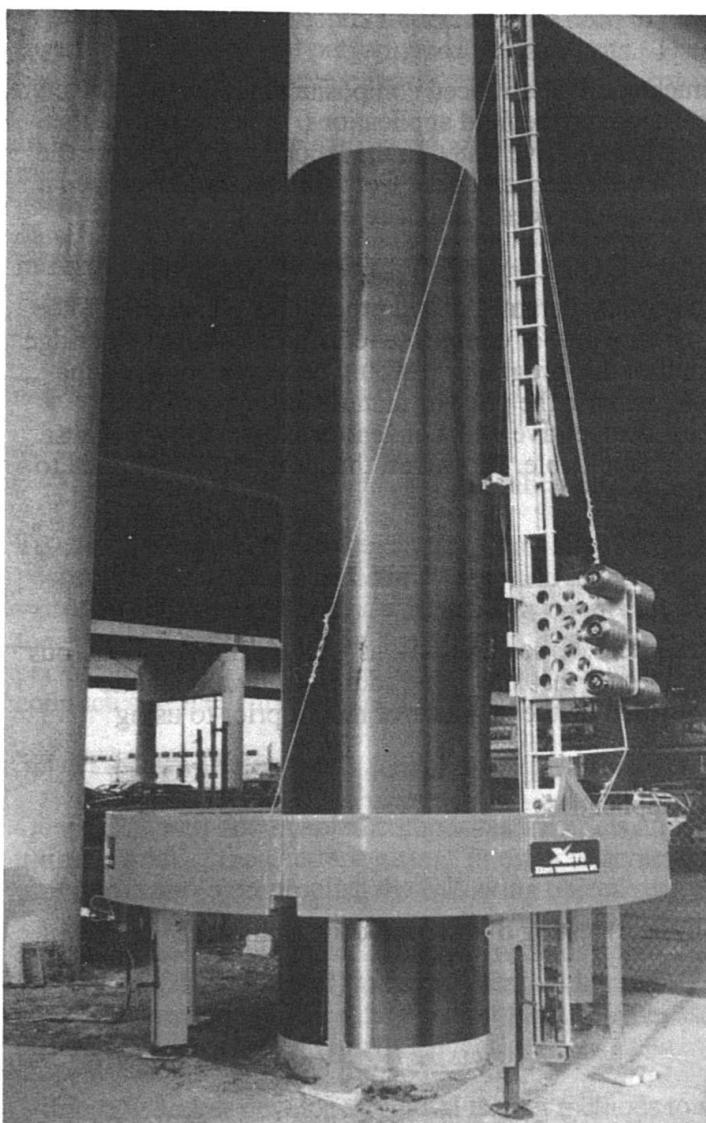


Figure 5 Application of Carbon Fiber ColumnWrap

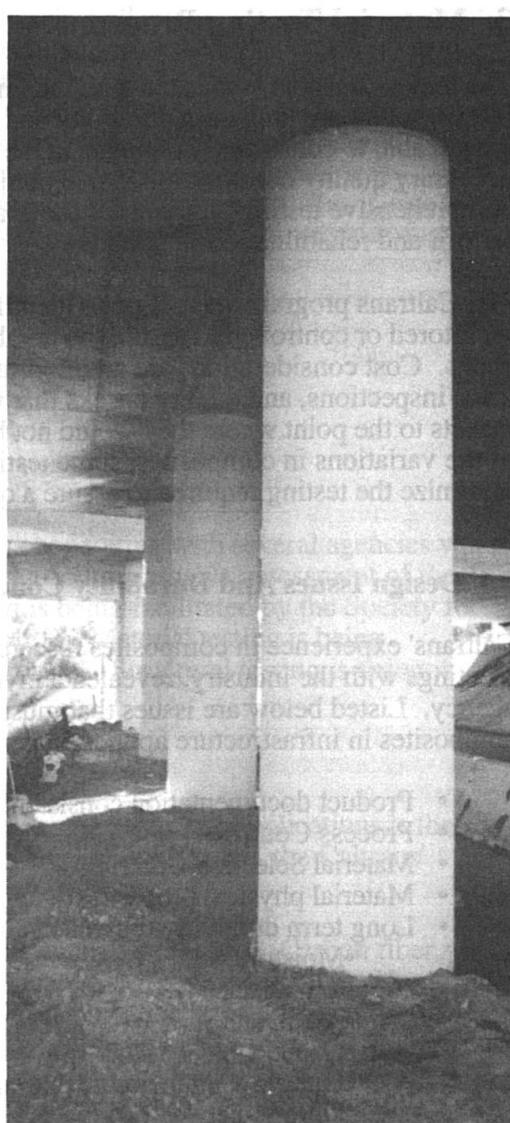


Figure 6 Completed Carbon Fiber Wrap

2. Strengthening Arch Ribs and Spandrel Columns

Analysis has shown that the typical arch bridge is extremely vulnerable to seismic forces in the transverse direction and, therefore, it is necessary to retrofit strengthen the main ribs and spandrel columns. Getting any type of erection and application equipment into these locations is very costly and difficult so Caltrans has developed retrofit solutions using carbon or fiberglass sheets. Portions of the arch ribs and the joint where spandrel columns frame into the ribs are being reinforced by wrapping with these sheets. Testing has also been conducted at UC San Diego to evaluate the various sheet systems over the past three years. Results show that the shear capacity increase and confinement can be achieved to the levels required. Full scale tests are being conducted during this summer (1997) on the column-rib joint to determine the material thickness needed to provide the required performance in a seismic event. Use of these materials on older arches is also important from a historical preservation perspective because the sheets do not significantly alter the appearance of the bridges.

Figure 5 shows the application of carbon fiber wraps to a bridge column. The wrap is being applied to the side of the column, and a worker is visible at the base of the column. The wrap is a thick, white material that covers the entire circumference of the column. The worker is wearing safety gear and is using a tool to apply the wrap. The column is a large, cylindrical structure, likely made of concrete. The wrap appears to be made of a composite material, possibly carbon fiber, which is being used to reinforce the column. The wrap is applied in a series of overlapping layers, ensuring a strong bond. The worker is wearing a hard hat and safety harness, emphasizing the importance of safety during the application process. The background shows a construction site with other equipment and structures visible.

3. Material Testing Program

The major concerns associated with the implementation of advanced composite materials into the civil infrastructure are long term durability and consistency in the field applications. It is imperative that we are able to consistently replicate in the field what we have tested in the laboratory. To insure the necessary quality control Caltrans, in conjunction with the Aerospace Corporation, has developed a comprehensive testing program for the evaluation of advanced composite materials for seismic retrofit and rehabilitation of structures.

The Caltrans program was set up to identify the critical parameters and procedures which need to be monitored or controlled to assure the reliable performance of composite retrofitted columns or bridge decks. Cost considerations are an important part of this program. It would be very easy to define tests, inspections, and quality checks that would increase the price of manufacturing composite jackets to the point where they would not be cost competitive with conventional materials. Because of the variations in composites, some testing is unavoidable. However, this program is designed to minimize the testing required to assure a quality product.

3.1 Design Issues And Durability Concerns

Caltrans' experience in composites research, trial field demonstrations, as well as through numerous meetings with the industry, revealed a myriad of issues that should be addressed by any public agency. Listed below are issues that must be verified by the engineer of record prior to using composites in infrastructure applications.

- Product documentation consistent with application
- Process Control
- Material Selection Criteria
- Material physical properties
- Long term durability (chemical and physical) testing of the composite against:
 - Moisture
 - Salt attack
 - Alkali attack
 - Ozone
 - High/low temperature extremes
 - Ultra violet
 - Other
- Quality control in manufacturing, mixing and applying
- Fiber content, voids, resin ratio
- Design guidelines for the specific composite
- Safety factors
- Damage and failure modes
- Adequate specifications
- Repeatability and consistency
- Acceptable field erection methods
- Effect of fatigue on bond behavior
- Performance under dynamic load
- Testing under sustained loading
- Qualifications of suppliers and product designers
- Cure temperature
- Transportation, handling
- Maintenance issues

Our experience has also revealed crucial issues that are unique to each fiber, resin, and equally important, the manufacturing process and application method. Composites material testing which was conducted by various research institutions show sensitivity to certain environmental factors and possible strength degradation. These results should not necessarily eliminate the use of composites

in infrastructure; they merely underscore the need to properly select all components of the composite to suit applications and performance requirements. These results further show the need for safety factors of such magnitude typically not common in conventional construction materials.

In addition to column retrofit concepts, some manufacturers have tested upgrading structural members, such as beams and slabs, using carbon fiber. However, only empirical data was generated, with no significant design or durability guidelines. Even though the industry is rich in data related to aerospace and marine applications, the data we need, relevant to civil engineering infrastructure applications, is very limited.

3.2 Program Overview

The Caltrans program primarily focuses on two areas of applications:

- 1 - Seismic retrofit of bridges.
- 2 - Bridge strengthening and rehabilitation methods.

To ensure a sound objective technical evaluation, Caltrans is cooperating with several agencies which possess viable technologies, knowledge and tools to conduct a comprehensive assessment of the various systems under consideration. This cooperative effort is being facilitated by the Society for the Advancement of Material and Process Engineering (SAMPE). Material testing is being performed by the Aerospace Corporation (El Segundo, California). Structural testing is being conducted at the University of California at Irvine (UCI).

3.3 Program Objectives

Qualifying well documented composites materials and processes for structural applications is the ultimate goal of the Caltrans effort. In order to achieve such level of confidence, the Caltrans' program is set to accomplish the following objectives:

- 1 -Identify acceptable material testing methods appropriate for each material type (Carbon fiber, E-Glass, S-Glass, Aramid) and consistent with intended applications. This item includes identifying environmental and physical factors that must be addressed. This objective has been accomplished through the pre-qualification document.
- 2 -Identify and/or develop structural testing methods to verify shear, confinement and flexural strength of the composite system. The goal is to develop test methods that are capable of demonstrating the structural performance of a given system, yet simple and inexpensive. This objective has been accomplished.
- 3 -Develop analysis and modeling techniques appropriate for the intended application. Such analysis should take into account the interaction between the composite material and the structure. Work in this area is in progress.
- 4 -Establish performance criteria for the various materials.
- 5 -Develop standard specifications and necessary special provisions for viable systems. These specifications should address material types, manufacturing process, mixing and curing, quality control, quality assurance and application methods. Where applicable, ASTM tests will be identified and used. Several projects have been advertised already. Specifications were developed for those contracts.
- 6 -Develop and adopt design guidelines taking into account environmental and physical factors. Current design guidelines incorporate environmental factor of safety. This factor will be re-examined at the conclusion of the program for any possible need to adjust.

3.4 Material Testing

Caltrans issued its pre-qualification requirements in April 1996 and later amended such requirements in January 1997. During the same period, Caltrans issued its Memo-to Designers, which states the conditions under which composite alternatives may be used. To help industry participants qualify, Caltrans is carrying out this program for qualifying composite jackets for seismic retrofit of bridge columns. The Aerospace Corporation is supporting Caltrans in the qualification program and is performing environmental durability qualification tests. Degradation of mechanical and physical properties of composite panels is being determined following exposure to various environmental conditions for periods up to 10,000 hours. Environmental exposures include 100% humidity at 100°F immersion in salt water, immersion in alkali solution, ultraviolet light, dry heat at 140°F, a freeze/thaw test, and immersion in diesel fuel. The effects of the environmental exposures are being quantified by measurements of the composite panel mass, tensile modulus, strength, and failure strain, interlaminar shear strength, and glass transition temperature. Property measurements are being made after exposure intervals of 1,000 hours, 3,000 hours and 10,000 hours to allow estimates of degradation over the projected service life. As of December 1996, property testing following the 1,000 hours and 3,000 hours exposure periods has been completed for three glass fiber/polymer resin systems and for four carbon fiber/polymer resin systems.

3.5 Structural Testing

All composite column casing systems are required to satisfy reduced scale cyclic column testing requirements to verify the casing constructability and effectiveness as a seismic retrofit measure. To qualify a system as an alternative column casing for seismic retrofit, a minimum of two types of retrofit enhancements must be demonstrated and tested in accordance with Caltrans requirements. Test results must satisfy Caltrans requirements relative to ductility performance, shear strength, and flexural enhancement. For each shape, cyclic tests must be conducted to demonstrate the performance of both retrofit enhancements and corresponding unretrofitted "As-Builts". Manufacturers may elect to qualify only one shape (circular or rectangular) by satisfying all tests requirements for either the circular tests or rectangular tests, thus limiting their qualifications to these systems.

For each geometrical shape, and for each corresponding enhancement, a minimum of one retrofitted "As-Built" column and one unretrofitted column shall be built and tested. For example, to qualify a system for circular column retrofit applications, the following four test specimens must be constructed and tested:

1. Circular Shear As-Built Column (Unretrofitted)
2. Circular Lap Splice As-Built Column (Unretrofitted)
3. Circular Shear Retrofitted Column subjected to double bending load
4. Circular Lap Splice Retrofitted Column subjected to single bending load.

All column details must conform to Caltrans requirements. Retrofit jacket thickness (or fiber ratio) must comply with the current Caltrans design criteria, with proper scaling factors when applicable, and shall satisfy the following:

1. Minimum confinement stress of 300 psi in the lap splice and/or plastic hinging zone
2. Maximum material elongation of 0.001 in/in in the lap splice zone and 0.004 in/in in the plastic hinging zone
3. Minimum confinement stress of 150 psi and material elongation of 0.004 must be maintained elsewhere in the column with appropriate transition
4. Minimum displacement ductility for the retrofitted column of 8 to 12 is to be expected.

An expected concrete strength of 5000 psi at the time of testing and Grade 60 reinforcing steel shall be used, although Grade 40 is preferable when available.

3.6 Summary Of Program Tasks

The following briefly summarizes tasks which are used to develop the information necessary to qualify vendors to wrap bridge columns with composites for the purpose of seismic retrofitting. All of the data will be cataloged and the program will be managed under one of the tasks. The proposed work includes an analysis of a variety of designs, materials and application techniques to determine the internal stresses in the composite and the strength of the jacket. Two of the tasks involve extensive testing of the composite materials, to fill holes in the database and, using materials from previously wrapped test columns, determine the effect of weathering/aging. Techniques and specifications will be defined under the quality assurance task to guarantee that the vendor's products are consistent and of sufficient quality to fulfill their function. Under the nondestructive evaluation task, techniques will be developed to verify the quality of the jacket as well as the health of the concrete itself.

Task 1: Analytical Design Verification - Modeling

Objective: Conduct analytical modeling of selected sub-scale tests and estimate a critical flaw size. Help develop a simplified guide for designing composite jackets.

Deliverable: Internal stress analysis of selected sub-scale tests and critical flaw size estimation.

Task 2: Composite Properties Characterization

Objective: Develop specific requirements for manufacturing and testing composite jackets. Identify limits (e.g., temperature and humidity) allowed during manufacture.

Deliverables: List of recommended test methods.
Recommended manufacturing methods and placards.

Task 3: Reduced Scale Test Column Verification

Objective: Determine the quality of the wraps on the test specimens and the resolution of the nondestructive testing techniques.

Deliverables: Nondestructive evaluation maps of selected sub-scale columns both before and after testing.
Comparison of test results to analytical models.

Task 4: Quality Assurance

Objective: Establish the basis for a plan to assure that composite retrofitted columns uniformly meet established performance requirements defined by Caltrans.

Deliverables: Define standard test procedures for incoming inspection and witness specimens.
Specify/define minimum requirements for quality testing, e.g., number of witness specimens required.

Task 5: Non-Destructive Evaluation

Objective: Finalize and document column assessment techniques

Deliverables: Document the most effective NDE techniques.
Demonstrate techniques on sub-scale columns.

Task 6: System Evaluation

Objective: Develop a manufacturing model to compare total costs of composite jackets with steel jackets.

Deliverables: Estimation of labor and material costs for composite jackets and steel jackets
Life cycle cost estimates

Task 7: Database Organization and Project Management

Objective: Collect, assimilate, and store the generated data into a database. Manage tasks 1 through 6.

Deliverables: Management, schedule and cost reports
Database generated by this and related programs including: material properties, NDE methods, manufacturing specifications, processes and modal studies.

Preliminary results are now available and are published in a report by Sultan of Caltrans and Steckel of Aerospace Corporation. More complete results will be available during the winter of 1997.

4. Field Application Quality Control Specifications

Caltrans has developed preliminary construction specifications to ensure quality control for the field applications of advanced composite materials. Separate specifications are available for the various materials but they are generic enough to allow the various vendors of each material to bid, assuming they have passed the qualification tests. Design guidelines are also available for determining the proper thickness of materials.

5. Summary

Caltrans has embarked on a program to utilize the advanced composite materials in seismic retrofit strengthening of bridge columns and other structural members. The goal is to increase the shear capacity and develop ductile performance in these members during a seismic event. It seems obvious that, in the current United States economy, these composite materials are not competitive with the more common bridge materials now being used, unless accurate life cycle costs are considered. We know the advantages of these advanced composite materials from the testing and field applications to date. We also know some of the obstacles to be overcome. These programs across the nation and especially the California program are designed to implement the use of these materials into the bridge and highway infrastructure as research and good engineering practice permit.

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