NISTIR 6288

NIST Workshop on Standards Development for the Use of Fiber Reinforced Polymers for the Rehabilitation of Concrete and Masonry Structures, January 7-8, 1998, Tucson, Arizona. Proceedings

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United States Department of Commerce
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APPLICATION OF COMPOSITES IN CALIFORNIA BRIDGES QUALITY CONTROL SPECIFICATIONS AND TESTING PROGRAM

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ABSTRACT

The California Department of Transportation has been engaged in cooperative research with 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 the repair of bridge columns and other supporting elements to improve their ductility for seismic resistance. Both 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 specifications have been developed. Since March 1996 these specifications have been published and included as alternatives in over 50 % of the seismic retrofit strengthening contracts advertised for construction.

The more exciting application of advanced composites is for new bridges and bridge deck replacement units. The research conducted so far has resulted in the design of a highway bridge composed of 0.9 m (3 foot) diameter carbon fiber tubular bridge girders and a fully advanced composite bridge deck. Development of these elements has been underway for three years and laboratory testing is currently underway. The bridge design will be utilized on two state highway bridges in Southern California, to be advertised for construction in November 1998. Further development of bridge deck replacement elements composed of advanced composite materials is continuing, with emphasis now on the connection details.

Although these advanced composite materials are expensive, their long life expectancy and resistance to corrosion makes them competitive if the life cycle cost of a bridge in a highly corrosive environment is considered.

Future plans in the Caltrans-UC San Diego-ARPA-FHWA cooperative research program include the construction of a fully composite vehicle bridge on the UCSD campus which will cross over Interstate 5 north of San Diego. Construction of smaller bridges is a preliminary step in the development and testing of the various components which will be utilized on this larger bridge.

1. Introduction

Following the October 1989 Loma Prieta earthquake, the California Department of Transportation (Caltrans), in cooperation with the University of California at San Diego (UCSD), began a research program 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 the columns to perform in a ductile manner under seismic loading. It was known that Japanese researchers had used high strength carbon strands to similarly reinforce industrial stacks and chimneys but glass fiber sheeting had not been used. The major unknown was the durability of the fiberglass materials under cyclic loading and the level of ductility to which 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 columns wrapped with epoxy impregnated fiberglass could perform with nearly the same level of ductility as the columns jacketed with steel plates.

Material properties are readily available from the manufacturers but the issue of adequate quality control specifications for field application remains. These early applications were rather crude, being hand laid in a manner similar to hanging wallpaper. Several months were required to fully develop adequate quality control (QC) specifications so the materials tested in the laboratory could be replicated with confidence in the field. The use of epoxy impregnated fiber glass has been approved for two column wrap 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 6 mm (1/4 in) strands simultaneously and can fully wrap a typical 1.2 m to 1.8 m (4 ft to 6 ft) diameter, 6 m (20 ft) 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 (advanced Research Projects Agency) and FHWA (Federal Highways Administration) 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 (American Association of State, Highway and Transportation Officials) loads. The first applications involve resin impregnated fiberglass or carbon sheets on noncircular 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 with 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. 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 to be able to consistently replicate in the field the laboratory performance. To ensure the necessary quality control, Caltrans, in conjunction with the Aerospace Corporation of El Segundo, California, 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 ensure 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 ensure a quality product.

2.1 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).

2.2 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 simple and inexpensive, yet capable of demonstrating the structural performance of a given system. This objective has been accomplished.

3 - Develop analytical and modeling techniques appropriate for the intended application. Such analysis should take into account the interaction between the composite material and the structure. Dr. Frieder Seible of UC San Diego has produced design guidelines for column strengthening, based on his extensive research and testing program (Appendix 3.1a). Work in this area is in progress to develop design guidelines for other applications.

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. Field Quality Control Specifications were developed for those contracts.

6 -Develop and adopt design guidelines taking into account environmental and physical factors. Current design guidelines incorporate an environmental factor of safety. This factor will be re-examined at the conclusion of the program for any possible adjustment. In addition to the column strengthening design guidelines produced by Dr. Seible, the SIKA Corporation has produced design guidelines for Carbon Strip Repair of Concrete Bridges.

2.3 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 radiation;
  - Other;
- Quality control in manufacturing, mixing and installation;
- 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 and
- 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 larger than those used for 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.

2.4 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 38 °C (100°F), immersion in salt water, immersion in an alkali solution, ultraviolet light, dry heat at 60 °C (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.

2.5 Structural Testing

All composite column casing systems are required to satisfy reduced scale cyclic column testing requirements to verify the casing constructibility 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-Built". Manufacturers may elect to qualify only one shape (circular or rectangular) by satisfying all test 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 2.1 MPa (300 psi) in the lap splice and/or plastic hinge zone;
2. Maximum material strain of 0.001 in the lap splice zone and 0.004 in the plastic hinge zone;
3. Minimum confinement stress of 1.0 MPa (150 psi) and material strain of 0.004 must be maintained elsewhere in the column with appropriate transition; and

4. Minimum displacement ductility for the retrofitted column of 8 to 12 is to be expected. An expected concrete strength of 34 MPa (5 000 psi) at the time of testing and Grade 60 reinforcing steel shall be used, although Grade 40 is preferable when available.

2.6 Summary Of Program Tasks

The following briefly summarizes tasks that 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. Recommend 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 ensure 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: **Nondestructive Evaluation (NDE)**
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 model studies.

Preliminary results are now available and are published in a report by Steckel of Aerospace Corporation and Sultan of Caltrans (1997). More complete results will be available during the winter of 1997-98.

3. 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. These documents have been developed over the past seven years to achieve a process for field application that can be replicated by reasonably skilled construction workers. Design guidelines are also available for determining the proper thickness of materials. Both documents are appended to this report.

4. 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. The advantages of these advanced composite materials are known from the testing and field applications to date. In the process, some of the obstacles to be overcome have also been identified. 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.

References

1. California Department of Transportation, Draft Special Provisions-Section 10-1. Alternative Column Casing, June 1997

2. Priestley, M.J.N., Seible, F., and Calvi, G.M., "Seismic Design and Retrofit of Bridges" John Wiley & Sons, 1996, 686 pp.

3. Seible, F., "Advanced Composites for Bridge Infrastructure Rehabilitation and Renewal" International Conference on Composite Construction, Innsbruck, September 1997

4. Steckel, G.L., and Sultan, M., "Evaluating Advanced Composites For Application In Transportation Structures-A Program Overview" Second FHWA/Caltrans National Seismic Conference, Sacramento, CA, July 1997

APPENDIX 3.1A

UCSD RESEARCH

In conformance with NIST policy, SI versions of unit-dependent equations have been added to the original report.