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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

Editor:
Dat Duthinh[1]

Session secretaries:	Session chairs:	Session co-chairs:
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Gaithersburg, MD 20899-001

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United States Department of Commerce
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U.S. Department of Commerce
William M. Daley, *Secretary*
Technology Administration
Gary Bachula, *Acting Under Secretary for Technology*
National Institute of Standards and Technology
Raymond G. Kammer, *Director*

ABSTRACT

Keywords: beams; building technology; columns; fiber reinforced polymers; masonry; rehabilitation; reinforced concrete; repair; retrofit; seismic; standards; slabs; walls.

One of the impediments to the expansion of the use of fiber-reinforced polymer (FRP) composites for the rehabilitation of structures is the lack of design standards, which is the subject of this workshop. By bringing together researchers from academia, practitioners from industry and regulators from government, it aims at providing a snapshot of the state of the practice and establishing research needs to develop national standards on the use of FRP composites for the rehabilitation of concrete and masonry structures. The workshop included a plenary session where nine speakers defined the issues and established a framework for the discussion. Next, participants broke out into three separate sessions, on columns, beams and slabs, and walls, respectively.

Areas in need of further research include anchorage of FRP to beams and walls, ductility of beams and walls reinforced with FRP, durability, material safety factors, fire resistance, and nondestructive evaluation methods for quality assurance of field installation. The workshop participants encouraged NIST to be active in researching solutions to all the above issues and to work closely with standards writing organizations, such as ACI, ASTM, ASCE, AASHTO in developing the technical bases for standards for the use of FRP composites in the rehabilitation of civil infrastructure. In particular, the participants would like to see NIST take a leading role in tests of FRP-reinforced concrete and masonry structures subjected simultaneously to fire and loads; to serve as a national data center for FRP material properties, laboratory tests and field performance; and to develop a comprehensive *Handbook on Structural Repair with FRP* similar in scope to the EUROCOMP *Design Code and Handbook* (1996).

ACKNOWLEDGMENTS

The editor wishes to thank all workshop participants and the following reviewers: Nicholas Carino, Joannie Chin, Geraldine Cheok and Shyam Sunder, all with the Building and Fire Research Laboratory of NIST.

DISCLAIMER

EXECUTIVE SUMMARY

A significant percentage of the Nation's infrastructure is in need of *repair* due to aging, exposure to the natural environment, de-icing salts, etc. Beside repair, there is a need for structural *retrofit* in many structures, due to higher service loads, more stringent seismic or blast requirements, etc. The market for structural *rehabilitation*, which encompasses both of these activities, is potentially in the billions of dollars.

Fiber-reinforced polymer (FRP) composites have proved to be an effective solution to structural rehabilitation. Carbon, glass or Aramid fibers imbedded in a polymeric resin (CFRP, GFRP or AFRP) exhibit high strength, light weight and ease of installation that make them competitive with more traditional construction materials, such as steel. The disadvantages, compared with steel, is higher material cost, lower stiffness, the absence of a long experience in the application of these materials to civil engineering, and the lack of design standards.

It is this last aspect that is the subject of this workshop. By bringing together researchers from academia, practitioners from industry and regulators from government, it aims at providing a snapshot of the state of the practice and establishing research needs to develop national standards on the use of FRP composites for the rehabilitation of concrete and masonry structures. The workshop took place on 7-8 January, 1998, immediately following the Second International Conference on Composites in Infrastructure (ICCI 98) held in Tucson, Arizona. It started with a plenary session where nine speakers were invited to define the issues and establish a framework for the ensuing discussion. The following day, participants broke out into three separate sessions, on columns, beams and slabs, and walls, respectively. At the end of the day, all participants reconvened together, to listen to and discuss the summaries of each session.

State of the practice:

The most advanced area is the rehabilitation of columns with FRP composites, thanks to the pioneering research at the University of California at San Diego and seismic retrofit work contracted by the California Department of Transportation (Caltrans). The wrapping of columns with FRP composites increases the strength and ductility of columns significantly by improving resistance to failures caused by shear, poor confinement or lap splice debonding. The Caltrans Guidelines will undoubtedly serve as a useful starting point for AASHTO (American Association of State, Highway and Transportation Officials) Technical Committee T21, which is developing national standards for the use of FRP composites for transportation structures.

Design methods for the external strengthening of beams in flexure with FRP composites were first developed at the EMPA (Swiss Federal Laboratories for Materials Testing and Research) in Dübendorf, Switzerland. They are based on hypotheses of strain compatibility (no slip) and plane sections remaining plane. Design for shear is also similar to steel reinforced concrete (RC) beams: shear strength consists of the sum of a concrete, or masonry, term and a reinforcement term based on a truss model.

Least advanced is the rehabilitation of RC and masonry walls. Structural walls resist loads by a combination of in-plane compression, shear, bending and out-of-plane bending. As in-plane compression increases, the need for and the effectiveness of FRP composites as tensile reinforcement decrease. Horizontal FRP strips are effective against in-plane shear and vertical strips against bending. Continuous sheets are also effective, but moisture entrapment may be a durability problem.

Material test standards for FRP exist, thanks to ASTM (American Society for Testing Materials), and work is in progress to adapt them from aerospace to civil engineering applications. ACI (American Concrete Institute) Committee 440 is working on *Guidelines for Selection, Design and Installation of Fiber Reinforced Polymer (FRP) Systems for Externally Strengthening Concrete Structures*.

Research Needs:

- **Anchorage:** Most of the test beams externally strengthened with FRP composites fail by debonding of the laminate. Because of this problem, the FRP reinforcement is designed for a rather low level of stress (less than 40 % of ultimate), resulting in an inefficient use of this expensive material. Anchorage for shear strips is particularly problematic as the beam top surface is often inaccessible. For walls, the difference in performance of an FRP sheet anchored to floor slabs compared to an unanchored one is drastic. As proper anchorage is sometimes difficult and expensive, practical devices and methods need to be developed.

- **Ductility:** The rehabilitation of columns and walls with FRP composites results usually in a considerable increase in the ductility of these structural components and thus enhances their seismic performance. For RC beams strengthened with FRP in flexure, the preferred mode of failure is by crushing of the concrete, a relatively brittle mode of failure. The alternatives, debonding or rupture of the FRP, are even more catastrophic. Research is needed to show that this strengthening method still allows sufficient ductility to permit load redistribution and provide warning of impending failure.

- **Durability:** Much of the interest in the use of FRP composites in infrastructure is in response to the corrosion of steel reinforcement due to exposure to the environment, de-icing salts, etc. For FRP composites, numerous accelerated aging tests have been performed, but they are no substitute for a long experience in the use of these materials. Whereas carbon fibers are the most resistant to **chemical attack**, glass fibers deteriorate in the alkaline environment of concrete pore water, and Aramid fibers are vulnerable to ultra-violet radiation. More resistant resins, new types of glass fibers (alkali resistant or AR glass) and protective coatings may provide the answers.

  Moisture absorption can result in a loss of strength of 25 % to 30 % in cross-linked polymers. Design of FRP reinforcement should allow the structure to "breathe", i.e., moisture to escape. Moisture is especially harmful when it acts in conjunction with high temperatures or freezing and thawing cycles.

  Creep rupture is a concern when FRP composites are subjected to sustained loads. Glass fibers have a lower creep rupture time than carbon. Based on limited testing, researchers have recommended that for loads not exceeding 50 years in duration, the level of stress be limited to 30 % of ultimate for GFRP, 50 % for AFRP and 80 % for CFRP. More research is needed to confirm or refine these results.

- **Material safety factors:** Considerations of durability, concerns for brittle failure, the lack of a long experience in designing with FRP composites, and the desire to use the Load Resistance Factor Design (LRFD) format of some building codes are reasons for material safety factors. There is a need for more test data to justify and refine these factors.

- **Fire resistance:** As the use of FRP for structural rehabilitation expands from highway bridges to buildings, concerns for their fire performance increase. FRP combustion properties appear to be in the acceptable range for construction materials in terms of flame spread and smoke developed (ASTM E 84). Combustion products also appear to be in the "normal range". Although polymers have been used in a variety of buildings as plastic foam insulation, membrane roofs, asphalt roofs, vinyl siding, and home furnishings, their further acceptance requires more test data and possibly the use of protective coatings or improved resins.

- **Nondestructive evaluation methods and quality control of field installation:** The performance of an FRP external strengthening depends strongly on its bond to the concrete or masonry substrate. Quantitative means of assessing the residual strength of the structural component to be repaired, the quality of its surfaces, and the surface preparation required are desirable. Fast, reliable, and inexpensive methods of quality control of field installation are also needed. One of the workshop papers presents a thermographic method that shows great promise for locating delaminations.

NIST role:

The workshop participants encouraged NIST to be active in researching solutions to all of the above issues and to work closely with standards writing organizations, such as ACI, ASTM, ASCE, AASHTO in developing the technical bases for standards for the use of FRP composites in the rehabilitation of civil infrastructure. In particular, the participants would like to see NIST take a leading role in tests of FRP-reinforced concrete and masonry structures subjected simultaneously to fire and loads; to serve as a national data center for FRP material properties, laboratory tests and field performance; and to develop a comprehensive *Handbook on Structural Repair with FRP* similar in scope to the EUROCOMP *Design Code and Handbook* (1996).

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

A significant percentage of the Nation's infrastructure is in need of *repair* due to aging, exposure to the natural environment, de-icing salts, etc. Beside repair, there is a need for structural *retrofit* in many structures, due to higher service loads, more stringent seismic or blast requirements, etc. The market for structural *rehabilitation*, which encompasses both of these activities, is potentially in the billions of dollars.

Fiber-reinforced polymer (FRP) composites have proved to be an effective solution to structural rehabilitation. Carbon, glass or Aramid fibers imbedded in a polymeric resin (CFRP, GFRP or AFRP) exhibit high strength, light weight and ease of installation that make them competitive with more traditional construction materials, such as steel. The disadvantages, compared with steel, is higher material cost, lower stiffness, the absence of a long experience in the application of these materials to civil engineering and the lack of design standards.

1.1 Objective

It is this last aspect that is the subject of this workshop. By bringing together researchers from academia, practitioners from industry and regulators from government, it aims at providing a snapshot of the state of the practice and establishing research needs to develop national standards on the use of FRP composites for the rehabilitation of reinforced concrete (RC) and masonry structures.

1.2 Format

The workshop took place in Tucson, Arizona, on 7-8 January, 1998, immediately following the Second International Conference on Composites in Infrastructure (ICCI 98). It started with a plenary session where nine speakers were invited to define the issues and establish a framework for the ensuing discussion. The following day, participants broke out into three separate sessions, on columns, beams and slabs, and walls, respectively. At the end of the day, all participants reconvened together, to listen to and discuss the summaries of each session. Details of the workshop organization are given in Chapter 4. In editing these proceedings, for completeness and coherence, the editor has combined with the oral discussion some of the written responses to a questionnaire sent to all participants and a review of the current literature (Chapter 2).

An overview of bridge column seismic retrofit in California and design guidelines are given by Roberts in Chapter 3. These guidelines are based on work performed at the University of California at San Diego, presented in two papers by Seible et al., and are commented on by Ma. Two of the requirements in the California Department of Transportation (Caltrans) guidelines are addressed in two papers by Hawkins et al.: durability and quality control of field installation. These papers present results of environmental durability tests on FRP composites, and thermographic measurements of delamination in column casings. Another way of ensuring field performance is shown by Nanni in a paper on in-situ testing of a structure strengthened with FRP. Finally, Ganga Rao et al. propose design guidelines for the external strengthening of RC beams with FRP composites.

CHAPTER 2

WORKING GROUPS

2.1 WORKING GROUP ON COLUMNS

Participants: Grant Corboy, Dat Duthinh (Secretary), Roger Green, Vistasp Karbhari, James Korff, Gloria Ma, Barry Olson, James Roberts, Hamid Saadatmanesh (Chair), Milan Vatovec, Yan Xiao (Co-chair).

2.1.1 INTRODUCTION

Some of the most successful structural uses of FRP (fiber-reinforced polymer) composites have been in the seismic retrofit of bridge columns. This includes, not only repair of columns damaged in earthquakes, but also upgrading of old columns to higher seismic standards. In the U.S.A., the seismic retrofit of concrete columns with FRP wraps was pioneered by the California Department of Transportation (Caltrans) and the University of California at San Diego (UCSD). Further work was also performed at the University of Arizona at Tucson.

In addition to seismic retrofit, FRP has also been used successfully to strengthen against blasts, to repair columns deteriorated by exposure to de-icing chemicals or cycles of freezing and thawing, and to minimize the infiltration of water, which acts as a catalyst for alkali-silica reaction.

Fyfe (1994) mentioned seventeen applications (as of May 1994), about half of which were in California, where FRP jackets were used to seismically strengthen bridges and buildings (about an equal number of each). Roberts (1997) described more recent (up to 1996) repair applications. In some of them, a wrapping machine was used, which required no heavy lifting equipment and could wrap a 6 m (20 ft) high column in two hours. The column was heat cured under controlled conditions by electrically heated blankets or enclosures. In addition to California, Washington and Pennsylvania have initiated at least one project to seismically retrofit one existing highway bridge.

This summary of the working group discussion on column retrofit using FRP has been expanded with the available literature to make it more readable and complete. It starts with the reasons for the seismic retrofit of columns, then continues with issues of current interest.

2.1.2 REASONS FOR COLUMN SEISMIC RETROFIT

The lessons of the San Fernando (1971) earthquake prompted Caltrans to raise design standards for new bridges and to retrofit old ones. This retrofit was performed by strengthening bridge piers, among other members, with steel jackets, and more recently, after the Loma Prieta (1989) earthquake, with FRP jackets (carbon fiber pre-impregnated with resin). The structural effectiveness of steel jackets was demonstrated by their excellent performance during the Northridge (1994) earthquake. Fifteen wrapped columns in a major interchange in the Los Angeles area survived this magnitude 6.8 event without serious damage (Mc Ghee and Gomez 1996). Tests have shown that FRP jackets, with fibers horizontal, perpendicular to the column axis to address deficiencies in the amount or detailing of the transverse reinforcement, work just as well as steel jackets. Although their material cost is higher than that of steel, the handling, installation and maintenance of FRP jackets are much easier.

Prior to 1971, California bridge piers typically used minimal transverse reinforcement consisting of 13 mm (#4) ties or hoops spaced at 300 mm (12 in). This reinforcement was independent of longitudinal reinforcement, column size, or seismic demands. Furthermore, short laps of the column hoop reinforcements in the cover concrete and 90° L-shaped corner hooks for rectangular column ties (present ACI Code requires 135° hooks) contributed to premature column failure, which occurred as soon as the cover concrete spalled under seismic attack. Failure could be one or a combination of the following modes (Seible, Priestley and Innamorato 1995, included in this volume):

1- **shear failure** manifested sequentially by inclined cracking, cover concrete spalling, rupture of the transverse reinforcement, buckling of the longitudinal reinforcement, and finally disintegration (at times explosive) of the column core. To insure against this failure mode, the shear capacity of columns needs to be checked both in the end regions or potential plastic hinge regions, where the concrete shear capacity can degrade with increasing ductility demand, and the central region between flexural plastic and/or existing built-in column hinges.

2- **confinement failure** of the flexural plastic hinge region, manifested sequentially by flexural cracking, crushing and spalling of the cover concrete, buckling of the longitudinal reinforcement, and finally compression failure of the column core. These failures, which occur after some inelastic displacement, are limited to a small portion of the column and are thus more desirable than the shear failure mode. This desired ductile flexural plastic hinging at the column ends can be achieved by added confinement through external jacketing in the case of existing columns.

3- **lap splice debonding** which occurs at the base of the column, a region of maximum flexural demand, where the column longitudinal reinforcement is lap-spliced with the starter bars that extend from the footing. Lap splice debonding occurs once vertical cracks develop in the cover concrete and progresses with increased dilatation and cover concrete spalling.

None of the above failure modes can be viewed separately, since retrofitting for one deficiency may only shift the seismic problem to another location or failure mode, without necessarily improving the overall deformation capacity. For example, a shear critical column strengthened over the column center region with composite wraps is expected to develop flexural plastic hinges at the column ends, which in turn need to be designed and retrofitted for the desired confinement levels. Furthermore, lap splice regions need not only be checked for the required clamping force to develop the capacity of the longitudinal column reinforcement, but also for confinement and ductility of the flexural plastic hinge.

2.1.3 DESIGN PROCEDURES

Based on extensive research at UCSD, Caltrans has developed design guidelines for the seismic retrofit of reinforced concrete (RC) bridge columns. The UCSD research, presented in the present volume in a paper by Seible, Priestley and Innamorato, covers strengthening for shear, flexural hinge confinement, lap splice clamping, and apply to circular and rectangular columns limited to certain aspect ratios. The Caltrans guidelines, in the form of a memorandum to designers, are also presented in this volume in an appendix to Roberts's paper. It is likely that the Caltrans design guidelines will form an important part of the American Association of State, Highway and Transportation Officials (AASHTO) Committee T21 *Standards for Highway Bridge Rehabilitation.*

As the use of FRP composites for structural rehabilitation expands from bridges to buildings, the question arises as to whether the technology developed for highway bridges can be adapted directly to building applications. More than likely, changes will need to be made, e.g., on issues of constructibility, axial load levels and slab continuity. ACI Committee 440 is working on *Guidelines for Selection, Design and Installation of Fiber Reinforced Polymers (FRP) Systems for Externally Strengthening Concrete Structures.* These guidelines will apply to buildings as well as transportation structures.

Beside resistance to earthquake loads, there are other reasons for strengthening with FRP. They include strengthening of industrial, offshore, military and other installations against blast; repair of structures deteriorated by exposure to the environment; upgrading to higher service load requirements; and provision of extra protection against water infiltration. There is a need for guidelines for such rehabilitation, e.g., where there is a severe loss in cross-section due to corrosion.

2.1.4 MATERIAL PROPERTIES AND RESISTANCE FACTORS

Most material tests used for Caltrans job qualification are based on ASTM Standards that were developed originally for FRP applications in the aerospace industry. There is still disagreement about the appropriateness of some of these tests (e.g., tensile test of a straight coupon versus a ring test) or how to interpret the results (e.g., two different ASTM test methods give two different glass transition temperatures for the same resin). ASTM Committees D20 and D30 are working on adapting composite material testing standards to civil engineering applications.

Other noteworthy efforts concerning material properties and resistance factors have more to do with FRP structural members than with FRP repair of RC structures. They include the American Society of Civil Engineers (ASCE) and the Pultrusion Industry Council (PIC) of the Society of Plastics Industry (SPI) *Prestandards for Structural Design of Pultruded Structural Products* and the European Structural Polymeric Composites (EUROCOMP) *Design Code and Handbook* (1996). The approach taken in these two references is that resistance factors, as in Load Resistance Factor Design (LRFD), need to be determined not just for materials, but also for the entire building system.

To help achieve a consensus on resistance factors, it would be useful to have a repository for material and structural rehabilitation test and field data. This would be an ongoing project, a database constantly updated and available to the research and design communities. The working group suggested that NIST undertake such a project.

The working group recommended that NIST work with AASHTO, ASTM, ACI and ASCE to provide the technical bases to develop national standards on design procedures, materials tests and resistance factors. The group also encouraged NIST to develop a comprehensive *Handbook on Structural Repair with FRP* similar to the EUROCOMP *Design Code and Handbook* (1996).

Durability and fire resistance are two sets of material properties of special interest to the participants. They are discussed in the next sections.

2.1.5 DURABILITY

Durability is of prime economic importance and is frequently invoked by FRP manufacturers and designers as a justification and selling point in their argument to replace corroding steel. Although FRP materials are not all new, their application to infrastructure is relatively recent and issues of durability are frequently raised by owners and regulating agencies. Aerospace experience, where durability is often expressed in hundreds of hours of flight, might not be directly translated into the decades of exposure required by civil engineering applications because of differences in quality control in manufacturing and installation, among others. It is also not clear how to correlate laboratory tests (e.g., immersion in an alkaline solution) with actual field exposure (e.g., contact with concrete). Accelerated aging must also be calibrated against real time measurements.

There has been relatively little research on resistance to freeze-thaw cycles, and more data are needed. A good example of such work is provided by Soudki and Green (1996) who tested the effectiveness of carbon fiber reinforced polymer (CFRP) wraps in strengthening and increasing the ductility of RC columns under room temperature, cold temperature (-18 °C), freeze-thaw cycles (-18 °C to +20 °C) or water immersion. Their results showed that:

1- CFRP wraps were effective in improving the strength, stiffness and ductility of concrete columns. CFRP wraps could restore the strength of columns damaged by freezing and thawing to that of unwrapped columns at room temperature. CFRP-wrapped columns exposed to freeze-thaw cycles showed a significant increase in strength (up to three times) compared with unwrapped columns exposed to the same conditions. The ductility also improved by a factor of five. A second layer of wrap provided an extra 15 % in strength.

2- Low temperature exposure and water immersion did not affect the strength significantly but affected the failure mode. Low temperature increased the brittleness of the wrap, which failed in a manner similar to the specimens subjected to freeze-thaw: the wraps suddenly broke off in the form of series of broken hoops. The concrete columns, though cracked, remained intact. Submerged columns failed "in shear through the sheet along the height of the column."

3- For comparison, at room temperature, one layer of wrap increased the strength by 20 %, two layers by 30 %.

There is also a need to research the performance of FRP retrofits in retarding corrosion; and their performance after continued corrosion of the steel reinforcement, which could cause dilatation of the bars, cracking and further deterioration of the concrete. Some structures have been rehabilitated with FRP composites between five and ten years ago, and they could be examined to establish a database for durability under actual field conditions.

2.1.6 FIRE RESISTANCE

Fire resistance is of interest as the use of FRP for structural rehabilitation expands to the building market after proving itself in highway bridges. Of special concern is the performance of FRP near its glass transition temperature and its residual structural strength after exposure to high temperatures. Working group participants mentioned applications where they felt uncomfortable with how close temperatures on a sunny summer afternoon came to the glass transition temperature of the resin. They also related numerous instances where the major impediment to an FRP application was the building fire permit.

As with other material properties, there is a need for standard test methods and a national database, so designers and manufacturers do not have to repeat fire tests to convince individual owners. It might be useful to test the fire resistance of the RC-FRP system and not just the individual FRP components. Since NIST has an active fire research program, and most universities do not, the working group recommended that NIST play a leading role in this area.

2.1.7 QUALITY CONTROL

Since structural repair is typically a field operation, quality control is of particular concern. The FRP themselves are of high strength, but the quality of the concrete substrate, the surface preparation and the bond between FRP and concrete can be weak links. It is desirable to have an economical means to detect incomplete adhesion between FRP wraps or between wrap and concrete by non-destructive means, e.g., by infra-red thermography (see the paper by Hawkins, Johnson and Nokes). There is also a need to have good control of the amount of fibers used (presently ensured by measuring wrap thickness in-situ) and correct statistical sampling of field measurements.

2.1.8 NONDESTRUCTIVE EVALUATION (NDE) METHODS

Development of NDE methods to control the quality of field installation and to monitor performance over time is highly desirable. The successful methods would be fast, inexpensive and easy to operate. Infra-red thermography and ultra-sound techniques appear promising. As design standards are being developed and durability data collected, these NDE methods can be used to monitor structural performance and provide owners with a margin of comfort. The same purpose can be achieved by in-situ load testing, as presented by Gold and Nanni in this volume.

NDE techniques could probably be used also to study the interfaces between fiber and resin, composite and concrete, and successive layers of composite wraps. These interfaces may very well hold the key to durability and quality control issues. They need to be studied further.

2.1.9 RECOMMENDATIONS

The recommendations from the working group are summarized below. For NIST:

- to work with AASHTO, ASTM, ACI and ASCE to provide the technical bases to develop national standards on design procedures, materials tests and resistance factors.
- to develop a comprehensive *Handbook on Structural Repair with FRP* similar in scope to the EUROCOMP *Design Code and Handbook* (1996).
- to play a leading role in testing the fire resistance of RC-FRP systems and developing performance standards for them.
- to develop and maintain a database on material properties and structural performance both in the laboratory and in the field.

For the FRP research community in general:

- to generate more durability test data, especially concerning accelerated aging; freeze-thaw cycling; exposure to alkaline environment; moisture absorption; etc.
- to develop better ways to control quality during field installations.
- to develop NDE techniques for quality control and structural monitoring.

2.2 WORKING GROUP ON BEAMS AND SLABS

Participants: Craig Ballinger, Edward Fyfe (Co-chair), Hota GangaRao, John Gross (Secretary), Steven Morton, Antonio Nanni (Chair), Fred Policelli, Gary Steckel, Benjamin Tang.

2.2.1 INTRODUCTION

The use of FRP composites for the rehabilitation of beams and slabs started about ten years ago with some pioneering research performed at EMPA (Swiss Federal Laboratories for Materials Testing and Research) in Switzerland. Most of the work focused on timber and reinforced concrete structures, although some steel structures have been renovated with FRP as well. The high material cost of FRP might be a deterrent to its use, but at closer look, FRP can be quite competitive. Carbon fibers now cost about 35 times as much as steel, on a mass basis. However, they are five times lighter and six times stronger than steel, so in fact, for the same structural purpose, the weight of carbon required can be 30 times less than its steel equivalent. This light weight also provides considerable cost saving in terms of labor: a worker can handle the FRP material, whereas a crane would be required for its steel equivalent. FRP strips and fabrics come in great lengths, which can be cut to size in the field, as compared with welding of steel plates. FRP strips or fabric are thin, light and flexible enough to be slid behind pipes, electrical cables, etc., further facilitating installation. With heat curing, epoxy can reach its design strength in a matter of hours, resulting in rapid bonding of FRP to the structure and consequently, minimum disruption to its use.

FRP composites are used in the repair of beams and slabs as external tensile reinforcement. As such, they increase the strength (ultimate limit state) and the stiffness (serviceability limit state) of the structure. Thus, FRP repair is motivated by requirements for earthquake strengthening, higher service loads, smaller deflections, or simply to substitute for deteriorated steel reinforcement. The increase in strength and stiffness is sometimes realized at the expense of a loss in ductility, or capacity of the structure to deflect inelastically while holding a load close to its capacity.

A number of issues still impede the routine use of FRP as a structural repair material. Chief among them is the absence of a long record of use, causing concern about durability with potential users. Another concern is fire resistance, especially as rehabilitation with FRP expands from highway bridges to buildings. The absence of standards is also an impediment, but this is being remedied by efforts such as this workshop and by organizations such as ACI. At the time of this writing, Committee 440 has produced a draft *"Guidelines for Selection, Design and Installation of Fiber Reinforced Polymer (FRP) Systems for Externally Strengthening Concrete Structures"*. This is a substantial effort, but it is a living document and some issues still need further research.

As in the previous section, this summary of the workshop discussion has been supplemented with current publications to make it more complete and readable.

2.2.2 FLEXURE

The design of FRP external reinforcement for flexure is fairly rational and straightforward. It is based on Bernoulli's hypothesis of strain compatibility that plane sections remain plane, which requires perfect bond between FRP and concrete. Some European manufacturers and designers are at variance with ACI 318 and recommend against using the rectangular (Whitney) stress block for concrete at compression failure strain levels. This particular practice is being revised to penetrate the U.S. market.

2.2.3 DUCTILITY

Ductility is a desirable structural property because it allows stress redistribution and provides warning of impending failure. Steel-reinforced concrete beams are under-reinforced by design, so that failure is initiated by yielding of the steel reinforcement, followed, after considerable deformation at no substantial loss of load carrying capacity, by concrete crushing and ultimate failure. This mode of failure is ductile and is guaranteed by designing the tensile reinforcement ratio to be substantially below (ACI requires at least 25 % below) the balanced ratio, which is the ratio at which steel yielding and concrete crushing occur simultaneously. The reinforcement ratio thus provides a metric for ductility.

In a beam reinforced internally with steel and externally with FRP, there is substantial reserve capacity at steel yielding. Failure is precipitated by FRP debonding, rupturing, or concrete crushing. All of these modes of failure are brittle, i.e., load capacity is reached with little inelastic deformation (Fig. 1). Here, load keeps increasing, albeit at a lower rate (with respect to deflections) than prior to steel yielding, and the FRP maintains elastic behavior until failure occurs suddenly.

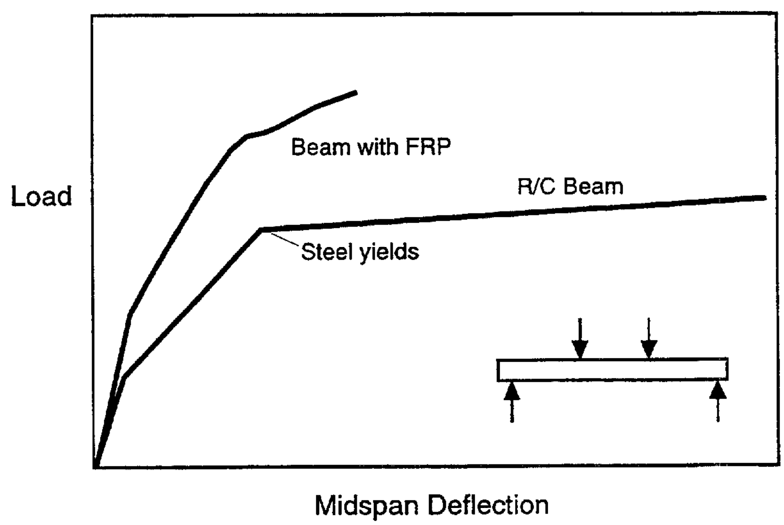

Fig. 1— *Schematic load versus midspan deflection behavior for reinforced concrete beam and beam strengthened with externally applied FRP*

One of the issues raised in the workshop, and which the participants felt needed more research, was how to design repair for a ductile failure. The presence of two tensile materials, steel and FRP, provides a warning when high loads are attained and steel begins to yield. At that point, in general, the FRP is only slightly stressed, but stiffness decreases and deflections increase sharply. If this stage is to be interpreted as a warning of impending failure, then the reserve capacity beyond steel yielding should not be too great. It would therefore seem prudent to design the repair so that the capacity of the repaired beam does not exceed the double of the original.

Clearly, a new measure of ductility is required. Some proposed measures of ductility are deflection, curvature (in the form of ratio of compression depth to section depth) and strain energy (area under load deflection curve). A ductility index could be defined based on the ratio of such measures at failure to their values at some earlier stages, such as yielding of steel, end of concrete linear range, or a given ratio of midspan deflection to span.

Although failure initiated by concrete crushing is considered brittle in steel-reinforced concrete beams, it is the preferred mode for FRP strengthened beams, because the alternative, tensile rupture of the FRP strips, is even more brittle.

2.2.4 PRESTRESSED CONCRETE

The majority of published research on the use of FRP for flexural repair of concrete beams deal with reinforced concrete (RC) rather than prestressed concrete (PC). Whatever the reason - - less benefit, greater difficulty in performing the research, a reluctance to combine passive and prestressed reinforcements -- more research on this topic is called for.

Some researchers have investigated the use of prestressed FRP strips for external strengthening. One of the simplest ways of doing so is to relieve some of the dead load by jacking prior to repair. When the jacks are released, the FRP composites are under tension (prestress), prior to the application of any live load. As expected, deflections are lower than if the FRP composites were not prestressed. Behavior can be predicted by the usual rational analysis of flexure (plane sections remain plane). Some other researchers have tried to prestress the FRP composites themselves prior to affixing them to the concrete. Handling and anchorage are difficult, and the benefits in terms of lower deflections and higher strength do not justify the technique.

Whether the FRP composites are prestressed or not, proper analysis of the behavior of the repaired beam requires accounting for the stresses present prior to the repair. Research indicates that the presence of narrow cracks prior to repair does not have a great influence on ultimate strength. However, wide cracks cause debonding of FRP laminates to occur at these locations and may precipitate failure, unless special anchorages are provided.

2.2.5 ANCHORAGE

Debonding or anchorage failure occurs in the majority of tests of beams strengthened for flexure (64 % according to a survey by Bonacci 1996). In only 22 % of the tests surveyed, rupture of the FRP was achieved, with the rest of the beams failing in shear or compression. It is not unusual for a carbon strip to debond at strains about half of its ultimate strain, oftentimes due to weakness in the substrate rather than the epoxy. In order to achieve a more efficient use of this expensive material, more research on anchorage, development length and measurement of bond stress is called for, e.g., on the use of anchor bolts, U-shaped straps near the laminate cut-off, and staggered cut-off of multi-layer laminates. Some of the design formulas currently recommended are based on development lengths of steel plates and may not be appropriate. It is also not clear that, given the non-uniform bond stress distribution in anchorages, any development length beyond a certain maximum would be beneficial.

High shear is usually present near supports and further complicates external strengthening of zones of high negative moments in continuous beams, which is hampered, in most cases, by the inaccessibility of the tension face. More research is needed here.

2.2.6 SHEAR

External shear strengthening has received less research attention than flexure. However, this deficiency is being corrected with some comprehensive efforts at the University of Alberta and the University of Missouri-Rolla, among others. The principal difficulty resides in proper anchorage. To be effective, shear reinforcement must be capable of intercepting all diagonal shear cracks and developing sufficient tensile strength across these cracks. As cracks cross the depth of the beam, this tensile strength must be capable of being developed everywhere over the depth of the beam. For steel stirrups,anchorage is provided by hooks, bends or overlap at both ends.

By wrapping FRP sheets or straps on the sides and around the bottom of a beam, after properly rounding off corners to eliminate sharp edges, proper anchorage is provided on one end of the FRP stirrups. Anchorage at the upper end is problematic, due to the presence of floor slabs. Extending the FRP laminates onto the bottom of the slab is unsatisfactory, because tension would cause peeling off the reentrant corner (Fig. 2). Some researchers advocate anchoring by piercing through the slab, but this may not be practical.

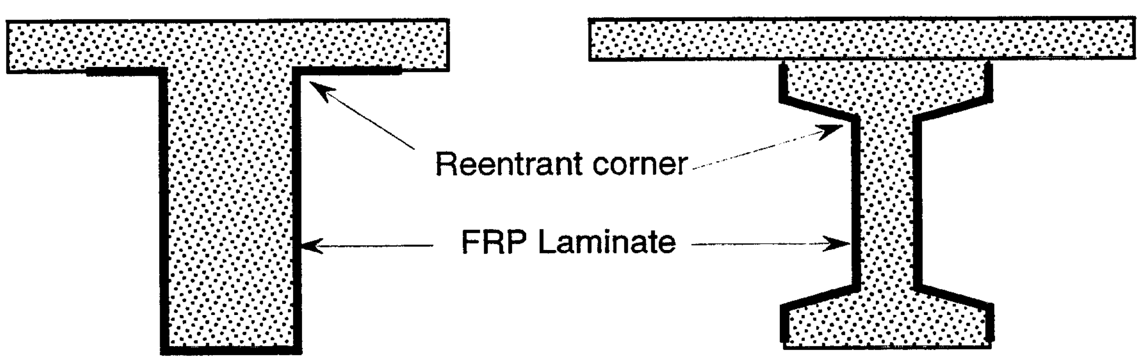

Fig. 2—*External shear strengthening of T- and I-beams*

Difficulty in anchorage causes FRP stirrups to debond at a stress far less than ultimate. This could be accounted for by an efficiency factor less than one. The same approach can be used for flexural strengthening, where the problem is less severe.

Research is needed over a wide range of testing variables. Research on the use of continuous fabric, as opposed to finite strips, presents no conceptual difficulty. Shear resistance can be visualized as a diagonal compression field provided by concrete on which is superposed a diagonal tension field supplied by the continuous FRP. Spacing requirement for FRP strips is similar to the requirement that spacing of steel stirrups be less than a certain maximum which depends on the anticipated shear load.

Another variable is the orientation of the fibers. Limited research results indicate that $\pm 45°$ plies are slightly more efficient than $0°$ - $90°$ plies in resisting shear. Some researchers have also varied the length of coverage, i.e., FRP would cover the sides of a beam only, and not even to full depth. This practice can only be justified if it is impractical to wrap around the bottom of the beam, or if haunches prevent full depth coverage.

2.2.7 FATIGUE

Fatigue resistance is an important long term property of FRP, especially when it is used in highway bridges. Research data are scarce, and more is needed. Findings to date in Japan and Europe indicate that fatigue is not a problem for CFRP reinforcement. In Japanese tests conducted with maximum stresses of less than 87 % of the short term tensile strength and magnitude of up to 1000 MPa (145 ksi), more than 4×10^6 load cycles were attained (Uomoto, Nishimura and Ohga 1995). For external strengthening, the level of service stresses is not expected to exceed 20 % of ultimate, and so fatigue of carbon fibers is not a concern. Tests at EMPA in Switzerland confirm that the fatigue resistance of CFRP is excellent.

Fiber-glass reinforcement also exhibits high fatigue strength, although less than carbon fibers. Tests of glass fiber rods intended for prestressing at a maximum stress of 500 MPa (72 ksi) and a stress range of 345 MPa (50 ksi) showed that they can withstand more than 4×10^6 load cycles before failure initiated at the anchorage zones (Franke 1981).

2.2.8 CREEP RUPTURE

Creep rupture (failure under sustained stress) is a major concern when FRP composites are subjected to long term loading. Important variables are fiber type (with glass fibers having a lower creep-rupture time than carbon), stress level and temperature.

German tests (Budelman and Rostasy 1993) indicate that creep rupture does not occur for glass FRP (GFRP) if sustained stress is limited to 60 % of the short-term strength. Since the level of service stress for external strengthening is usually much less than that, it would appear, according to this research, that there is no problem with creep rupture of GFRP.

Based on tests conducted at room temperature (Dolan et al. 1997, Ando et al. 1997, Yamaguchi et al. 1997, Seki et al. 1997), conservative recommendations have been made to limit the level of sustained stress for FRP rods and for loads not exceeding 50 years in duration to 30 % of ultimate for GFRP, 50 % for Aramid FRP (AFRP) and 80 % for carbon FRP (CFRP). These limits are conservative and more tests are required, not only to measure the time to creep-rupture but also the magnitude of creep strain.

2.2.9 OTHER RESEARCH ISSUES

Multiple Plies: Multiple layers of FRP fabric are sometimes used, and due care is required to ensure that the resin wets through all layers and has sufficient strength to transfer the shear force between layers. Even then, there is a loss of effectiveness of multiple plies compared with the strength of a single ply multiplied by the number of layers, due to shear lag. Research is needed to provide an effectiveness factor for multiple plies.

Protective Coating: Fire resistance is a concern as the use of FRP for external reinforcement expands from bridges to buildings. One possible solution is the use of protective coatings, such as intumescent coatings, for fire protection. Coatings for ultra-violet radiation protection may also be required for FRP. In regions of high traffic, and where the risk of collision is high, coatings to protect against abrasion and impact are also desirable.

2.2.10 SUMMARY OF RESEARCH NEEDS

More research is needed in the following areas:

- Ductility of beams strengthened for flexure with FRP.
- Strengthening of beams in zones of negative moment and high shear.
- Strengthening of beams for shear.
- Anchorage, both for flexure and shear.
- Strengthening of prestressed concrete beams.
- Creep strain and creep rupture, especially for GFRP and AFRP.
- Effectiveness of multi-ply FRP.
- Protective coating against fire, UV radiation, abrasion and impact.

2.3 WORKING GROUP ON WALLS

Participants: Oscar Barton (Secretary), Mohammad Ehsani (Co-chair), Gary Hawkins, Fred Isley, Vistasp Karbhari, Gloria Ma, Orange Marshall (Chair).

2.3.1 INTRODUCTION

Walls are essential components of buildings, not only for their obvious architectural functions of visual and sound barriers and defining rooms, but also for important structural reasons. These include resisting their own dead weight and that of parts of the building above (by in-plane compression), and resisting lateral loads caused by wind, blast or earthquakes (by a combination of in-plane shear, in-plane and out-of-plane bending- see Fig. 3). In buildings more than 30 stories high, walls are imperative and contribute significantly to the strength, stiffness and ductility of these buildings in resisting lateral loads (Paulay and Priestley 1992).

Of interest to this working group are reinforced concrete walls and masonry walls, reinforced or not. Unreinforced masonry (URM) walls have been used since the dawn of civilization and are present in many historical structures. Typically, older brick walls do not meet modern seismic standards and need retrofit (in the early 1970s, the building code requirements for lateral resistance of newly designed masonry buildings were increased by as much as 50 %).

In the U.S., there is a huge inventory of URM walls exposed to potential earthquake or blast. URM walls may very well represent the largest market for structural strengthening, which traditionally include the following methods:

- adding framing elements such as steel beams and columns;
- adding reinforcement by inserting vertical steel rods into the wall cavities and grouting them in place;
- and adding a layer of shotcrete or ferrocement reinforced with a steel mesh on one or both wall faces.

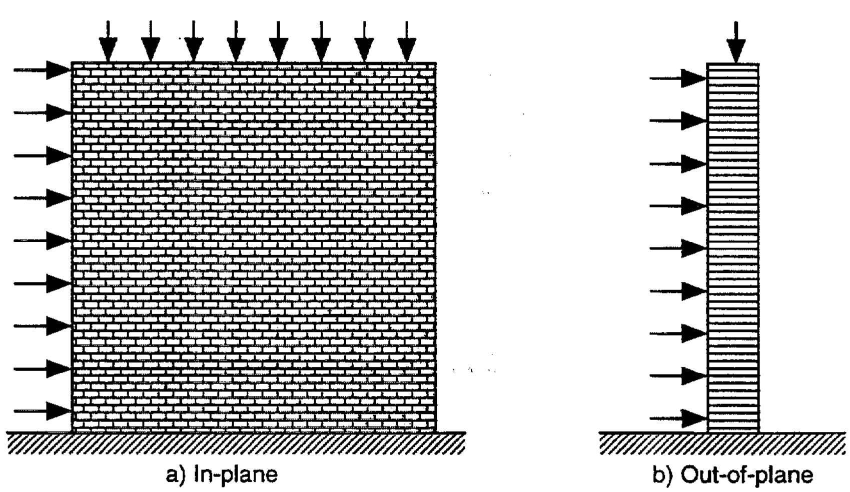

Fig. 3—In-plane and out-of-plane loading of wall

These methods add significantly to the mass of a building, causing more inertial forces in an earthquake and often necessitating strengthening of the foundation. Moreover, retrofit by these methods causes major disruption to the building functions. It is no surprise, therefore, that fiber-reinforced composites are attractive in strengthening and repair applications thanks to their low mass and ease of application. FRP sheets or straps a few millimeters thick can be installed rapidly without removing pipes or cables. They can improve strength, stiffness and ductility dramatically, yet do not add much mass.

As in the previous sections, this summary of the workshop discussion has been supplemented with current literature for completeness and readability. Although there has been less research on the use of FRP composites in the retrofit of walls than of beams and columns, much progress has been achieved in understanding the basic mechanics and establishing design guidelines. Major outstanding issues include fire resistance and anchorage. (Anchorage difficulties are also encountered in the reinforcing of walls with steel rods.)

2.3.2 DESIGN METHODS

The principal source of energy dissipation in a well designed, steel reinforced, laterally loaded cantilever wall is the yielding of the flexural reinforcement in the plastic hinge region, normally at the base of the wall. Failure modes to be prevented are those due to diagonal tension or diagonal compression due to shear, instability of thin-walled sections or of the compression reinforcement, sliding shear along construction joints and shear or bond failure along lapped splices or anchorages. For FRP reinforced walls, the modes of structural action are similar and include the combined effects of axial load and out-of-plane bending, in-plane bending, or in-plane shear.

For both out-of-plane and in-plane bending, the concept of balanced strain reinforcement ratio, similar to that of beams, can be used for FRP-strengthened walls: it is the tensile reinforcement ratio at which masonry crushing and FRP rupture occur simultaneously. The balanced strain reinforcement ratio depends on the axial load, the dimensions of the wall and the material properties of the masonry and the FRP. The moment capacity of walls is a function of the reinforcement ratio and the compression depth (Triantafillou 1998).

Since FRP composites act as tensile reinforcement, their effectiveness decreases with an increase in axial compression and is negligible for axial loads exceeding 25 % of the compressive strength of the unreinforced wall in the case of out-of-plane bending. For lower values of axial compression, the higher the stiffness of the FRP reinforcement, the more effective it is in increasing the moment capacity (Triantafillou 1998). It should be noted that, while the FRP is applied at zero stress, the wall is already under axial compression.

As a mechanism to resist in-plane lateral loads, bending predominates in slender walls (with high ratios of height to length) and shear predominates in squat walls (with low aspect ratios). If FRP reinforcement for in-plane bending takes the form of vertical strips, then only half of the strips are stressed in tension, and they are most effective when placed farthest from the neutral axis.

Relationships similar to out-of-plane bending have been derived. They show that the moment capacity increases linearly with the reinforcement ratio and the FRP reinforcement is effective at all practical levels of axial loads (i.e., the influence of axial force on moment capacity is weak) (Triantafillou 1998).

In-plane shear in masonry is similar to that in reinforced concrete: shear resistance is the sum of an uncracked masonry term and a reinforcement term based on a truss model. According to Triantafillou (1998), vertical FRP strips are ineffective against in-plane shear because of weak dowel effect. However, even a small amount of horizontal FRP composites can increase shear resistance considerably. Detailed design equations concerning coverage methods (sheet or strips) and spacing requirements of the strips still need to be developed.

Most of what is known about masonry walls covers single, or at most double-wythe walls. In the case of multi-wythe walls, especially with internal cavities, bonding of FRP sheets to the external surfaces only may not be effective. It may be necessary to fill the cavities with a low density material, such as polyurethane or isocyanurate foam, or introduce transverse rods to ensure adequate shear transfer between wythes. For strengthening against earthquake and blast, the dynamic and energy absorbing properties of FRP need further investigation.

2.3.3 BOND AND ANCHORAGE

The performance of FRP composites depends greatly on the quality of the bond to the masonry surface. The external reinforcement may not be able to conform to the "high relief" or textured surface of masonry walls. A deeply raked or deteriorating mortar joint may pose problems. Repointing of the joints with a comparable mortar is recommended before affixing the FRP composites (Christensen, Gilstrap and Dolan 1998). Quantitative methods for assessing the residual strength of a wall, its surface condition, and the required surface preparation are needed.

Effective strengthening is only possible if peeling of the laminate does not occur, i.e., sufficient development length and anchorage (e.g., clamping) are provided. One of the earliest tests of strengthening of walls with FRP composites shows clearly the importance of anchorage. A 2.0 m × 3.6 m masonry wall was strengthened with carbon fiber sheets bonded to the wall and anchored to the adjoining concrete slabs above and below it. Ductility increased by 360 % compared with the unreinforced wall. A similar wall, reinforced over its entire surface with a polyester sheet which was not anchored to the adjoining slabs, only exhibited an increase in ductility of 36 % (Schwegler 1994).

Equations have been proposed to predict peak shear and normal stresses in the anchorage zones (Triantafillou 1998). Design equations, in the form of development length, still need to be worked out. In general,development of these design equations require extensive experimental research , which still remains to be done. Practical methods of anchoring FRP strips and sheets need to be developed for various geometries and loads.

2.3.4 MOISTURE

Because absorption of moisture by cross-linked polymers can reduce their strength by 25 % to 30 % and may result in microcracking of the adhesive and delamination, it is important to allow the structure to "breathe", i.e., moisture vapor to escape. Thus, open-weave fabric is preferable to close-weave, although the application of the polymer matrix resin reduces considerably the actual size of the openings. For the same reason, tapes or straps are preferable to continuous fabric. A continuous horizontal tape located at the base of a wall should be avoided if rising dampness is a problem (Christensen, Gilstrap and Dolan 1998).

Trapped moisture may go through cycles of freezing and thawing, and as liquid water expands 9 % upon freezing, this process can be especially damaging in porous materials, such as masonry, leading to cracking, spalling and eventual disintegration. Moisture has an even more adverse effect on bond, when it acts in conjunction with high temperatures. For these reasons, some manufacturers recommend that moisture content in the substrate be less than 4 % for optimal use of their adhesive resins. This is not a stringent requirement, as soft bricks have a moisture content of about 1 % of volume in 40 % relative humidity (Christensen, Gilstrap and Dolan 1998).

2.3.5 FIRE RESISTANCE

Polymeric materials are organic in nature and are all flammable to one degree or another. However, building codes have found the use of these materials in buildings acceptable in at least two instances: one is the use of plastic foam insulation, either within the cavity or on the outer face of an exterior wall, provided the interior of the building is separated from the foam insulation by an approved thermal barrier. Composite fibers and resins have fire and smoke properties similar to those of plastic foam insulation, and the masonry wall could serve as the thermal barrier (Christensen, Gilstrap and Dolan 1998). The use of FRP composites on the exterior faces of walls should therefore be acceptable.

The second instance of the use of plastic in commercial buildings is in tensioned membrane structures, which are typically glass fibers with a Teflon coating. Tensioned membrane roofs are routinely approved for various occupancy types (Christensen, Gilstrap and Dolan 1998).

An important test for the fire safety of building materials is the Standard Test Method for Surface Burning Characteristics of Building Materials ASTM E 84 (UL 723, NEPA 255 and UBC 42-1 are similar). This test evaluates flame spread and smoke developed over a 10 minute fire exposure. Building materials are limited to a maximum flame spread index of 25 (with red oak as 100 on this scale) and a maximum smoke developed of 450. For the two examples mentioned above, plastic foam insulation has indices of flame spread of 5 and smoke developed of 165. The manufacturer of the membrane roof of a recently completed major U.S. international airport claims a maximum flame spread and smoke contribution of 10 for its product. Another data point is provided for an epoxy (used in FRP structural repair) that produces maximum flame spread and smoke developed of 5 (Christensen, Gilstrap and Dolan 1998).

As far as toxicity of combustion products is concerned, FRP are in the "normal range". Kevlar[1] produces combustion gases similar to those of wool: carbon dioxide, water and oxides of nitrogen. Unfortunately, the combustion of Kevlar[1] may also produce carbon monoxide, hydrogen cyanide and other toxic gases (Christensen, Gilstrap and Dolan 1998).

High temperatures can be a problem, even in the absence of fire. Surface temperatures of masonry can reach 60 °C (140 °F), and darker surfaces can reach 70 °C (165 °F) or higher in warm climates. For comparison, an epoxy used with CFRP has a glass transition temperature (at which it begins to soften) of 53 °C (128 °F) (Christensen, Gilstrap and Dolan 1998).

Although the above discussion focuses on walls, some of the concerns for the fire resistance of FRP apply to RC beams and columns as well. More research is needed on the behavior at high temperatures of FRP composites bonded to concrete or masonry substrates. This will help in obtaining the acceptance of these materials by building code officials.

2.3.6 OTHER ISSUES

- size effect in testing: Is there a size effect, and if so, how to account for it in tests? This issue is common to beams, columns and walls, but is probably more acute in walls because of the higher costs of wall tests, and the size of bricks or masonry blocks being the same in full or reduced scale tests.
- UV protection: Concern for fire protection and the emission of toxic combustion gases would encourage the use of FRP on the external faces of walls. Protection against ultraviolet radiation may therefore be necessary, especially for Aramid fibers, which may otherwise discolor in the short term and lose strength in the long term. Various coatings may be necessary for architectural reasons as well.

2.3.7 SUMMARY OF RESEARCH NEEDS

Although much progress has been achieved, more research is needed:
- to develop design methods on the use of FRP to strengthen wall elements, especially to ensure ductile behavior and proper anchorage.
- to improve fire resistance and to provide data to encourage adoption of FRP by building codes.

The workshop participants agreed that it would be useful to collect test results from universities such as Arizona, California Irvine, California San Diego, Georgia Tech, SUNY Buffalo, Iowa State, California State Long Beach, Wyoming, Missouri-Rolla, etc. for a critical review of the state of the art.

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[1] Trade or manufacture's names appear herein because they are essential to the objectives of this document. The United States Government does not endorse products or manufacturers.

2.4 OVERALL SUMMARY AND CONCLUSIONS

A number of recurrent themes are common in the discussions of the three working groups. They are:

- **Design methods and standards:** In order of progress of the state of the art, retrofit of columns is the most complete, followed by beams, and lastly, walls.
- **Bond and anchorage:** Proper bond of the FRP composites to the concrete or masonry substrate is crucial to their efficient performance. Correct assessment of the quality of the surfaces to be repaired, and good control of the quality of field installation are desirable.
- **Design for ductility:** This is especially important due to the brittle nature of FRP composites, concrete and masonry.
- **Fire resistance:** This is important for the expansion of the use of FRP composites from highway bridges to buildings.
- **Material safety (knock-down) factors:** The data base for such factors is limited, yet they are crucial for a safe and economical design.

The workshop participants encouraged NIST to be active in resolving all these issues, to serve as a national research resource and repository of data on the use of FRP composites in infrastructure.

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CHAPTER 4

WORKSHOP ORGANIZATION

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

AGENDA

Wednesday Jan. 7, 1998

100-115	Registration	NIST Staff
115-130	Workshop objectives	Dat Duthinh
130-200	Quality control program for Caltrans field applications of FRP	Jim Roberts
200-230	Design and Detailing of FRP Rehab System	Frieder Seible
230-300	Standards, durability and test methods for materials, manufacturing and quality control in repair	Vistasp Karbhari
300-330	Industry perspective on composite column casing specifications	Gloria Ma
330-400	In-situ load testing	Tony Nanni
400-430	Coffee break	
430-500	Overview of seismic strengthening of concrete columns and beams	H. Saadatmanesh
500-530	Standards for flexural strengthening using FRP	H. Ganga Rao
530-600	Research needs for concrete strengthening	Edward Fyfe
600-630	Flaws in composite retrofit discovered in non-destructive evaluation	Gary Hawkins

Thursday Jan 8, 1998

800-1000	Working groups	
1000-1030	Coffee break	
1030-1200	Working groups	
1200-115	Lunch break	
115-215	Presentation by group chairs and general discussion	
215-230	Closing remarks	Dat Duthinh

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

QUESTIONNAIRE

1. What issues would you like the workshop to address ?

2. What areas are mature enough for Standards development (with the understanding that Standards are continually evolving in response to improved knowledge) ?

3. What areas still need further research before Standards should be attempted ? What are the knowledge gaps that need to be filled ?

4. Do you have a vision of what the Standards should look like? Performance based, prescriptive, or hybrid ?

5. Do you have any recommendation for NIST 's role in Standards development and basic research on this topic ?

6. Please describe briefly your own research program or list relevant publications.

Please fax or e-mail answers by December 24, 1997 to:

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Thank you.

NIST Workshop on Standards Development
for the Use of Fiber Reinforced Plastics
for the Rehabilitation of Concrete
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Jan 7-8, 1998, Tucson, Az.

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