INTERNATIONAL WORKSHOP ON PRESERVATION OF HISTORICAL STRUCTURES WITH FRP COMPOSITES

Final Report

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This report is the result of the collective work of the Workshop Chairmen (Drs. Antonio Nanni and Antonio La Tegola) along with the subtopical area leaders (Drs. Thomas Boothby, Timothy Ibell, John Ochsendorf, Michael Schuller, Luc Taerwe, Jason Weiss) and the Workshop technical secretary (Dr. Laura De Lorenzis).

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The opinions expressed in this document are those of the writer and do not necessarily represent NSF policy.

EXECUTIVE SUMMARY

In the last two decades, advanced composites (fiber-reinforced polymer or FRP) have gained considerable worldwide interest and growing acceptance in the construction industry. The preservation of historical structures is one of the most appealing applications of FRP composites in the construction field. However, this application presents some critical issues still not sufficiently investigated: 1) long-term durability of FRP-repaired structures; 2) compatibility of the FRP system with the parent material; 3) minimal invasiveness and reversibility of the upgrade; and 4) optimal material selection. All the aforementioned issues, of paramount importance for intervention on structures of architectural/historical interest, are also relevant when dealing with any other category of structure, when looking at long-term performance and global cost-benefit balance. Each of these issues requires an interdisciplinary effort between researchers and practitioners with material-oriented and structural-oriented backgrounds and experts of architectural restoration.

The International Workshop on Preservation of Historical Structures with FRP Composites held in Lecce, Italy, on June 9-10, 2004, aimed at a) discussing the aforementioned key issues in a multidisciplinary environment of leading experts; b) prioritizing research needs for the future; c) proposing and assessing a novel format for a possible series of coordinated activities to follow.

The research tasks were subdivided into five subtopical areas: causes and modes of material/structural degradation; traditional and emerging materials/technologies for preservation; compatibility requirements of traditional and emerging materials; non-destructive assessment, evaluation and monitoring; existing practice and standards on preservation of historical structures and case histories. Within the five subtopical areas, the issues relevant to the four fundamental questions raised above were discussed.

This document reports the outcomes of the discussion during the preparation phase and the working sessions of the Workshop and outlines directions of the activities to follow.

1. BACKGROUND

1.1 Advanced Composites in Construction

In the last two decades, advanced composites (fiber-reinforced polymer or FRP) have gained considerable worldwide interest and growing acceptance in the construction industry. The preservation of historical structures is one of the most appealing applications of FRP composites in the construction field. However, this application presents some critical issues still not sufficiently investigated: long-term durability of FRP-repaired structures; compatibility of the FRP system with the parent material; minimal invasiveness and reversibility of the upgrade; and optimal material selection. These issues were the key topics of the Workshop, i.e. they represented the four fundamental questions the Workshop aimed to answer.

All the aforementioned issues, of paramount importance for intervention on structures of architectural/historical interest, are also relevant when dealing with any other category of structure, when looking at long-term performance and global cost-benefit balance. Each of these issues requires an interdisciplinary effort between researchers and practitioners with material-oriented and structural-oriented backgrounds and experts of architectural restoration.

2. WORKSHOP PROGRAM

2.1 Overall Objectives

The primary objectives of the workshop were to:

- Review the advances in research on the topic of the workshop, as emerged in particular from the IMTCR'04 Conference preceding the workshop;
- Provide to researchers with material-oriented and structural-oriented backgrounds and to experts in architectural restoration the opportunity to interact on a common topic, and to develop a cooperation network;
- Identify the gaps of knowledge on the four fundamental issues on which the workshop focused (long-term durability, compatibility, minimal invasiveness and reversibility, and optimal material selection);
- Identify major barriers to the effective utilization of advanced composites for preservation of historical structures;
- Establish the human network of experts in the field, integrate new participants and propose future activities;
- Prioritize and document the needs for effective research policies and programs.

2.2 Methodology

<u>First Planning</u>. First discussions on the Workshop started during planning and preparation of the First International Conference on "Innovative Materials and Technologies for Construction and Restoration" (IMTCR-04), held in Lecce, Italy on June 6-9, 2004. The Conference was envisioned to be an ideal venue for the Workshop, due to the presence in Lecce of experts from the three main topical areas Materials, Construction and Restoration, and to the possible support and synergy of organizational efforts with the Conference organizing committee. Also, the location of the events in Italy would also fit well with the topic of preservation of historical structures. The Chairmen of the Conference, Drs. Antonio Nanni and Antonio La Tegola, would act as Chairmen of the Workshop as well with Dr. Laura De Lorenzis as the Workshop technical secretary.

<u>Venue</u>. The International Workshop on Preservation of Historical Structures with FRP Composites followed immediately the First International Conference on "Innovative Materials and Technologies for Construction and Restoration" (IMTCR-04), held in Lecce, Italy on June 6-9, 2004. Following a welcome cocktail on June 6, the working sessions of the Conference started on June 7 at 9.00 a.m. and finished on June 9 at 1.30 p.m. All sessions were held at the University of Lecce Conference Center within the Science, Economics and Engineering University Campus. More than 110 papers from 20 different countries were received, focusing on

the three main topic areas of interest for the Conference: Materials, Construction, and Restoration. A member of the NSF delegation, Dr. P. Balaguru, accepted the invitation to give a keynote lecture.

The Workshop took place immediately after the Conference, starting on June 9 at 3.00 p.m. and closing on June 10 at 6 p.m. It was held in the "Monastero degli Olivetani", a beautiful former monastery of the middle of the 16th century, built with the typical calcareous stone of Salento ("pietra leccese"), recently restored and currently venue of the School of Art and Literature of the University of Lecce.

Participants. Workshop participants were selected by the Chairmen seeking a certain equilibrium of a) area of expertise (material-oriented, structural-oriented and architectural/restoration-oriented backgrounds), b) geographical distribution. The list of participants is reported in appendix A. Also listed are young researchers who, after participating to the IMTCR'04 Conference, attended the workshop taking part in discussions and deliberations. This was not initially planned, but added an interesting new dimension to the workshop itself. The young researchers contributed with their ideas and positions and, equally importantly, walked away with a good set of new concepts that should help them in moving more rapidly to leadership positions.

Participants were divided into five subgroups, as indicated in Table 1 (including also young researchers). The five subgroups met separately during the parallel subgroup sessions, and discussed within their subtopics the issues relevant to the four fundamental questions: long-term durability of FRP-repaired structures; compatibility of the FRP system with the parent material; minimal invasiveness and reversibility of the upgrade; and material selection. Each subgroup was coordinated by a subgroup leader (name underlined in table below) who was responsible for a) coordinating the development of a subgroup white paper during the pre-workshop preparation phase; b) chairing the parallel subgroup sessions; c) reporting activities of the subgroup during plenary sessions; d) coordinating the update of the subgroup white paper in light of the outcomes of discussion during the post-workshop phase.

Table 1. Subtopics and subgroups

Subtopic	Group	Participants
Causes and modes of material/structural degradation	1	L. Ascione, V. Berardi**, J. Berman, A. Ede**, F. Micelli**, A. La Tegola, J. Ochsendorf, P. Rocchi*
Traditional and emerging materials/technologies for preservation	2	A. Borri*, G. Fava**, L. Hollaway, T. Ibell, G. Karydis**, A. Maffezzoli, F. Matta**, C. Poggi, S. Rizkalla
Compatibility requirements of traditional and emerging materials	3	P. Balaguru, C. Blasi, L. Castelluzzo**, J. Davalos, M. Frigione, D. Galati**, M. Leone**, S. Mindess, M.S. Sciolti**, R. Serrano**, D. van Gemert, J. Weiss
Non destructive assessment, evaluation and monitoring	4	B. Bonfiglioli**, A. Di Tommaso, J. Kenny, P. Lourenco, F. Masetti**, J. Popovics, M. Schuller
Existing practice and standards on preservation of historical structures and case histories	5	M.A. Aiello, N. Baglivi**, A. Barbieri**, T. Boothby, N. Grace, A. Grimaldi, S. Matthys, C. Modena, L. Taerwe, T. Triantafillou*

* Contributed to the preparation phase but could not attend the workshop
** Young researcher

The major emphasis of each of the subtopics (and their coordinators) are as follows:

1. Causes and modes of material/structural degradation — possible causes and modes of structural damage to historic buildings and their constituent materials. For which causes/modes can composites be a viable/effective option (J. Ochsendorf)
2. Traditional and emerging materials/technologies for preservation — traditional and innovative materials/technologies for strengthening of members/structures in an historic context (masonry, timber, metallic, concrete members/structures) (T. Ibell)
3. Compatibility requirements of traditional and emerging materials — problems related to the microstructural level including bond, deformation compatibility, volume stability, durability (J. Weiss)
4. Non destructive assessment, evaluation and monitoring — procedures for diagnostics of existing conditions, quality assurance of FRP applications, and long-term monitoring (M. Schuller)

5. Existing practice and standards on preservation of historical structures and case histories — general criteria of intervention on historical structures as stated by the relevant organizations; codes available for design, application and quality control; case studies (T. Boothby, L. Taerwe)

Pre-Workshop Activities. Invitation to prospective participants was circulated by e-mail and statements of interest were collected in the summer of 2003. In the fall of 2003 subgroups were formed. At this stage, each participant was asked to work out a position paper related to the subtopic of his/her subgroup and send it by e-mail to the Workshop secretariat. A Workshop website (http://lecce-workshop.unile.it) was created (hosted on the website of the University of Lecce) and updated with relevant information, including a restricted area where position papers of the participants could be downloaded. During the spring of 2004, each subgroup leader coordinated the development of a subgroup white paper. Prior to the Workshop meeting, most individual and subgroup white papers had been sent to the secretariat and uploaded on the website.

Workshop Meeting. The workshop participants were invited to Lecce, Italy, June 9-10, 2004, for a workshop meeting. Some participants attended also the IMTCR'04 conference. This document is the culmination of this process. The purposes of the workshop meeting were to review the state of current research and practice, and to discuss objectives, philosophy, directions, and priorities of coordinated activities for a more synergetic effect.

The closing plenary session was streaming video live on the Internet, using Microsoft Windows Media Encoder, so that any web user was able to receive video and audio signal from the Workshop by simply connecting to the dedicated URL. Also a dedicated e-mail address and instant messaging account were set up to allow communication between web users and Workshop participants. Instructions to connect had been located on the Workshop website and sent by e-mail to potentially interested public and private institutions. Connected web users during this session included research groups at the Universities of Lecce, Salerno, Pisa and the National Institute of Applied Optics in Italy, the University of Missouri – Rolla in the USA, the Technical University of Eindhoven in the Netherlands.

A copy of the detailed agenda for the workshop appears in Appendix B.

Workshop Review. A review of the significant discussions held during the Workshop sessions is provided in section 3 as a series of five excerpts of subgroup white papers.

Post-Workshop Activities. During the closing plenary session, a consensus was reached on the following items:

- Subgroup leaders would update pre-workshop subgroup position papers with outcomes of the discussion and circulate them among participants for input and approval;
- Results of the workshop would be disseminated as follows: the workshop website would be updated with final position papers and presentations given by subgroup leaders during the workshop; links would be established with the website of the International Institute of FRP in Construction (IIFC);
- the workshop would possibly become the first of a series of events aiming at establishing a wide research and technology transfer network on preservation of historical structures with FRP composites.

3. SUMMARY AND CONCLUSIONS

Topic Area: 1. CAUSES AND MODES OF MATERIAL/STRUCTURAL DEGRADATION (J. Ochsendorf)

Background

There are three broad causes of deterioration in historic structures:

- Environment degradation: Material decay due to environmental attack caused by moisture, air pollution, corrosion, freeze/thaw cycles, chemical or biological attack, etc. can cause local damage, as in the case of localized water problems, as well as global damage, such as the decay of surfaces due to widespread chemical attack on a stone façade. Localized material damage can lead to long-term structural damage by de-stabilizing key structural elements. For example, a timber roof truss with moisture damage in one of the connections will endanger the safety of the entire structure.

- Displacements: Over the course of centuries, imposed displacements due to foundation movements, material creep, earthquakes, temperature variations, etc. can destabilize a historic structure. Small changes in geometry can drastically alter the equilibrium conditions and may lead to collapse. For example, foundation movements in a masonry vaulted structure will case the walls or buttresses to lean outwards, threatening the stability of the masonry vault.
- Overloading: Extreme loading may be caused by increased road traffic (for bridges), earthquakes, water loading, or structural interventions which have overloaded existing elements. Because traditional structures generally have high self-weight and low levels of material stress, overloading is not typically a problem.

Research issues

For each type of degradation there are possibilities for repairs with new materials. However, engineers must exercise caution in applying new technologies to historic structures. There is a long history of misapplication of new materials, which have often caused more damage to historic buildings over the long term. For example, in the repair of masonry monuments, preservation architects today view standard interventions of the 20th century, such as the use of Portland cement and reinforced concrete, as outdated and harmful to the historic masonry fabric. Engineers must take a long-term view and must consider the whole life design of an intervention, including the reversibility and the future repair of each intervention.

For historically significant structures, engineers must justify the use of materials that differ from the original fabric. In cases where materials decay regularly, it is generally accepted that it is better to replace in kind, that is, to use the same materials for the repair. The Eiffel Tower is a classic example of replacement in kind. Every iron element of the tower has been replaced at least once during its lifetime. Many historic structures are the same. In Gothic buildings, masonry pinnacles are replaced approximately every 200 years, using the same source of stone each time, as in the case of the King's College Chapel. In such cases, there is no question of using new materials to repair elements which have decayed. It is more important to use the same materials and the same technology to maintain the structure, even if new materials have better mechanical properties.

New materials, such as FRP, are more appropriate in cases where there is a lack of strength in a historic structure. For example, FRP may be used to compensate for local decay of a single element in a historic timber roof truss. Similarly, a historic metal bridge may require strengthening to carry greater traffic loads. Because such strengthening methods may be irreversible in historic structures, engineers should carefully consider all options before applying materials which are not in keeping with the historic fabric.

The seismic resistance of historic masonry buildings is a special scenario to consider. The seismic analysis of unreinforced masonry structures is a field in its infancy, with most earthquake engineers insisting that historic buildings do not have sufficient ductility to resist a major seismic event. Many engineers would propose that a structure needs to be strengthened to improve its seismic resistance, but as a profession, we should caution that our understanding of the seismic response of masonry buildings is limited at present.

In the repair of historic monuments, FRP may offer some advantages including high strength and improved durability over metallic reinforcing. Such materials may also minimize aesthetic impacts in comparison to other materials. The long term stability of FRP in various moisture and temperature conditions is untested and there is a need for additional research on the long-term compatibility of FRP with traditional materials.

Outcomes of the discussion

As emerged from the discussion, the following procedure is recommendable for the design and installation of a major structural intervention:

- Identify the root cause of structural degradation, such as movements in the foundation or corrosion due to moisture penetration.
- Examine global and local structural behavior to determine the level of risk.
- Describe the possible failure mechanism and justify the need for an intervention.
- Identify the requirements for a successful rehabilitation.

- Design a solution and justify its appropriateness. Identify the specific system which satisfies the needs for repair or restoration.
- Provide options for removal or repair of the intervention in the future.
- Implement a scheme for long-term monitoring and maintenance of the intervention.
- Document interventions locally and identify critical locations of the repair to assist future interventions.

Though each structural problem will be unique, these guidelines provide a framework for engineers engaged in rehabilitation of historic structures.

Future work

There are a number of areas which require future work in the application of new materials for structural rehabilitation. As non-research items, the following issues must be addressed:

- Determine the cases in which it is useful to apply FRP to historical structures. What is the threshold for application?
- Prepare critical review of existing repair and rehabilitation technologies.
- Develop a certification system for engineers working on historic structures.
- Classify different typologies of structural problems and evaluate the most appropriate interventions.

In addition, there is a need for research in the near term (next 5-10 years) on the following topics:

- The global structural implications of FRP and understanding of the structural behavior of strengthened elements;
- Systems that minimize intervention effects (smaller areas of bond, new connections, etc);
- Modeling and experimental validation of FRP interventions;
- Detailing and implementation of new materials for traditional construction; and
- Better reinforcement matrix (besides traditional polymers) to match the existing material and problem.

Finally, long term research needs can be anticipated as follows:

- Long-term studies of compatibility with traditional materials (time scale of centuries).
- Invent systems which warn of problems and *adapt* behavior (even better, systems which repair themselves!).
- Systems which allow large strain over time and are capable of absorbing energy in extreme loading events (such as shape memory alloys).
- Repairs that monitor and record strain over time.

Topic Area: 2. TRADITIONAL AND EMERGING MATERIALS/TECHNOLOGIES FOR PRESERVATION (T. Ibell)

Background

Historical structures are made from one of the following construction materials:

- Stone/masonry
- Concrete
- Metallic (cast-iron, wrought-iron or steel)
- Timber

Issues to be satisfied in the preservation of historic buildings include:

- Structural repair should be undertaken with minimum intervention. Therefore, the structural assessment of an historic structure involves a much more detailed analysis than merely referring to codes of practice.
- Structural repair, although critically important (for some projects) is in the second or third consideration of the general technical problem that needs to be solved for historic preservation.

- Repair in place is highly preferred to replacement or reconstruction. Consequently, inspections have to be much more thorough than a simple structural repair. Removal of any historical fabric is considered a last resort.
- The most commonly undertaken repair is to remove the source of moisture intrusion or to protect the structure from moisture.
- If the deterioration is severe and well advanced, repair of cracks is preferred to replacement of surface material, and replacement of surface material is preferred to full-depth repair.
- Structural repairs are undertaken in such a way that the existing material is left in place, if this is possible.
- It is necessary to understand the structural properties of existing materials.
- As much as possible of the deteriorated material should be left in place.
- The rehabilitation should be reversible.
- The design life of a conventional building will be about 50 years. In undertaking an historic preservation scheme, the design life is intended to be much longer.
- In repairing historic buildings, there could be a conflict of aims. The items to be satisfied are (i) permanence of repairs, (ii) reversibility of the repairs, and (iii) preservation of historic fabric.

Increased interest in improving sustainability and durability has added impetus to the development of repair and strengthening techniques to prolong the life of existing infrastructure. Requirements have focused on effective and economic repair and strengthening solutions, leading to the use of high-performance materials and innovative corrosion prevention methods.

Historic structures usually need strengthening due to deterioration or for seismic upgrade. Cost remains the primary consideration when selecting the most suitable repair and strengthening scheme. The actual cost of repair and strengthening extends well beyond that of materials and labor. The primary cost is usually that to society due to disruption. Hence, repair and strengthening techniques that offer quick application and long durability are clearly preferred. For effective remedial work, an understanding of the cause of the deterioration or deficiency is essential, as well as an appreciation of the chosen repair/strengthening technique. In other words, there is no point in merely treating the symptoms.

The use of bonded FRP composites for repair and strengthening of historic structures is currently considered an exciting research and development topic to have evolved from the use of FRP materials in construction. The number of strengthening applications is increasing rapidly as clients start to appreciate the benefits of this cost-effective technique. FRP reinforcing materials have superior properties compared with steel reinforcement in respect of strength, weight, durability and fatigue. They exhibit several properties that make them suitable for use with historic structures. The most important characteristic of FRP in repair and strengthening applications is the speed and ease of installation. Reduced labor, shut-down costs and site constraints typically offset the material cost of FRP, making FRP strengthening systems very competitive when compared with traditional strengthening techniques, such as steel plate bonding and section enlargement.

Research issues

Historic Masonry Structures

The following items would normally be satisfied when dealing with the preservation of masonry structures:

- Decision making strategies for the repair of masonry structures. These must include diagnosis of the deterioration process.
- Methods for analyzing the properties of mortar and composite repair compounds that are desirable for long-term performance.
- Applying and finishing mortar and composite repairs, in terms of surface preparation, anchoring and reinforcement.
- Techniques for the repair and stabilization of masonry structures, namely adhesive repairs and injection grouting.
- Design issues related to repointing and repair, with reference to visual compatibility of repair to existing elements.

If it proves impossible to restore the degraded unit using the original or similar material, FRP composites provide a challenging alternative. For instance, GFRP can replicate the appearance of other materials; it can combine many of the degraded elements of the structure into a single, lightweight, readily-handled structural member. The material is durable; a gel coat would normally be used on the surface of the laminating resin to give UV radiation protection, weather resistance and custom matching to virtually any color. However, it does require washing down occasionally to remove dirt. GFRP exterior cornices are one of the most popular replacement materials.

Problems with this approach include:

- Different physical properties to the original sandstone material.
- Different coefficients of thermal expansion; this may cause buckling of flat surfaces or material failure at joints unless properly designed.
- Attraction of dirt.
- The 'weathering' process is different to that of other more conventional materials. Consequently, the relative appearance of the two dissimilar materials after a period of time will be different.

From a structural preservation perspective, materials and methods are developing rapidly, along with new approaches, such as the use of near-surface-mounted (NSM) reinforcement. There are distinct advantages to using NSM for masonry structures due to the protection that an embedded system provides, and due to the minimal intervention which such a system exhibits.

Guidance is still required on strengthening elements with globally and locally curved soffits. Ideally, the applied FRP should be straight, following the tensile load path. Provided the deviations are small, local curvature or undulations can be taken out by additional thickness of adhesive. Use of pultruded plate, rather than wet lay-up sheet laminate, is therefore appropriate in such a situation. In the case of globally concavely-curved soffits (a common occurrence in masonry structures), there is no option but to follow the curve of the soffit. The flexural strength enhancement of FRP is therefore reduced due to the straightening effect in the curved system, causing premature debonding.

Whilst detailed guidelines on strengthening circular columns can be given with relative confidence, guidelines on strengthening columns with non-circular cross-sections requires further understanding. In particular, square and rectangular columns are common in masonry structures. Although it is evident that only modest increases in axial strengthening can be achieved by wrapping rectangular columns, such increases are often sufficient.

Historic Concrete Structures

It is now commonplace worldwide for existing concrete structures to be strengthened using FRP composite materials. The techniques available for this are well documented in the literature. The major issue, however, which relates to FRP-strengthening of *historic* concrete structures more so than to more modern concrete structures (be they unreinforced, reinforced, prestressed, cast-in-situ or precast) is that of deterioration of the concrete itself.

Causes of concrete deterioration in historic structures include:

- Environmental effects, whereby moisture is readily absorbed into the relatively porous material. This is particularly serious in the event of freeze-thaw cycles.
- Carbon dioxide in the atmosphere, which can cause the concrete to deteriorate over a long period of time, by reacting with cement paste at the concrete surface.
- Materials and workmanship. Historically, contractors were not aware of the problems associated with aggregate types, sizes and other concrete mix materials used (for instance, clean water), leading to poor quality concrete by modern standards.
- Improper maintenance, which is a serious concern even in modern concrete structures, but particularly in historic structures, as neglect can cause long term deterioration of the concrete.

Major signs of concrete deterioration are cracking of the material, structural cracks, spalling, stains, erosion etc. The above problems would require attention before application of in-situ prepregs or wet-lay-up composite systems were applied to the concrete surfaces to restore the original strength of the structural member. This leads to another major issue, which is aesthetics of the strengthened historic concrete structure.

Designers will sometimes need to address situations or problems that are not covered by the current techniques described in design guidelines. Whilst these techniques may not currently be at a stage where designers can confidently use them, the following technologies have been shown to be feasible, and their use for historic concrete structure strengthening could be considered.

- Technologies already used in practice
  - Post-tensioned cable and rope systems
  - FRP anchorage techniques
  - Bolted plate anchors
  - Strengthening against blast

- Technologies at the research stage
  - Gradually-anchored prestressed CFRP laminates
  - Prestressed NSM bars
  - FRP anchor systems
  - Steel-reinforced polymers
  - Deep embedded bar for shear strengthening
  - Prestressed CFRP straps for shear strengthening
  - Mechanical fastening techniques
  - Hybrid glued and bolted systems
  - Strengthening for torsion
  - Life expectancy modeling

Historic Metallic Structures

Common problems encountered with cast–iron construction include badly rusted or missing elements, impact damage, structural failures, broken joints, damage to connections and loss of anchorage. The causes of corrosion are oxidation or rusting when exposed to moisture and air, sea water, salt air, acids and sulphur compounds present in the atmosphere which act as catalysts in the oxidation process. Galvanic corrosion is another potential problem area.

There are recognized methods for repairing surface defects of cast iron (e.g. epoxy grouting). If, however, structural upgrading is required, it is difficult to use a similar material because of the joining of present day cast iron to historic cast iron. There are, however, a number of substitute materials which could be used. A number of metallic and non-metallic materials have been used for restoring cast iron structures, including aluminum and ultra high carbon fiber reinforced polymers (uhCFRP). The latter material is the one which is currently used to upgrade/strengthen cast iron members and is permanently joined (adhesively bonded) to the parent material. The advantages of it over other materials is that it has a high tensile strength (cast iron tends to have a low tensile strength), a higher stiffness than that of the parent material and it is relatively lightweight which allows for easy joining to the structural member. In addition, it is relatively thin, thus not incurring height restrictions on bridges. A disadvantage of the uhCFRP material is that it has a low strain to failure. The cost of the material is high but this is offset by the relative speed and the ease of erection on site which, in turn, reduces the disruption of traffic to a minimum and reduces any closure costs of the bridge or building.

Thus, the advanced mechanical and fatigue properties, the ability to resist fire and the low thermal conductivity of CFRP materials make them an excellent candidate for repair and retrofit of metallic girder bridges. Epoxy bonding of CFRP plates to the tension flange of the girder is generally used to increase load-carrying capacity and fatigue strength. The high strength and stiffness-to-weight ratios prevent any substantial increase in dead weight. Furthermore, composites are also advantageous due to their high design flexibility, and their corrosion resistant properties reduce the need for regular maintenance and painting.

Historic metallic structures are usually fabricated from cast iron or wrought iron, and the main concern in strengthening arises from the nature of the material from which the structure is made, due to large variations in material properties arising from the manufacturing process.

Cast iron (1700-1880) consists of an alloy of iron with 4% graphite flakes; it is smelted at high temperatures in the liquid state, and becomes saturated with carbon present from the furnace fuel. It was historically poured out into a mould to produce blocks. The high carbon content made it stiff in compression, but weak and brittle in tension, where the elastic limit coincides with the first localized yield at the end of the graphite flakes, which act as stress raisers.

Wrought iron (1820-1900) is very pure, with a carbon content of less than 1%, which makes it resistant to corrosion, strong in tension and malleable. The two main constituents are iron and about 3% slag, a silicate of iron Fe_2SiO_4. It has been traditionally produced by raising cast iron to high temperatures and subjecting it to a strong blast of air in order to remove carbon and impurities. It is then heated to a welding temperature and rolled to remove further slag. Wrought iron has a laminar structure and directional mechanical properties. In the rolling direction during forming (the direction of the slag fibers), the metal is ductile in tension, while in the cross fiber direction it is brittle.

As structural materials, cast iron and wrought iron have now been totally eclipsed by steel production, so there has been little research interest in these metals. However, among the existing bridges in Europe, as well as in Japan and in the U.S., a considerable number of structures have been built using cast iron or wrought iron, many of which need strengthening.

The major points of concern in the use of CFRP plates are related to the durability under various environmental conditions and to the compatibility with the metal from a structural, mechanical and configurational point of view. The final material selection is based on simultaneous consideration of both durability and performance criteria.

Environmental attack is time-dependent and tests may not reflect the actual degradation mechanism, due to the lack of long periods of environmental exposure. Under freeze-thaw and sea-water environments, CFRP shows degradation. Above all, hot water (70°C) produces irreversible damage and severe breakdown of the bond due to the formation of oxides at the interface. Temperatures below zero cause polymer hardening, matrix cracking and fiber/matrix bond degradation; fracture toughness of metal decreases and brittle failure is likely. The ultraviolet component of sunlight degrades the composite as well, leading to breakdown of the surface of the composite and discoloration. Other troubles are connected with the resin, which dominates the creep stress relaxation properties of the composite and softens at elevated temperatures, lessening the mechanical performance and increasing susceptibility to moisture absorption. In fire, the concern is for the organic resin binder of the composite as well.

In the case of direct contact between carbon fibers and iron in the presence of an electrolyte, such as seawater or de-icing salts, galvanic corrosion causes rusting of metal and creates blistering and debonding. Non-uniformities in the material accelerate the deterioration process leading to localized corrosion. Oxidation reduces the cross-sectional area of bridge members and, as a result, the overall load-carrying capacity decreases. Furthermore, since the anodic reaction is the oxidation of iron, while, for CFRP, the cathodic reaction is the reduction of oxygen and the formation of hydroxide ions (OH^-) on the surface, the use of matrices with hydrolysable links (ester bonds) should be avoided. Electrical isolation of CFRP from iron using GFRP or organic fiber plies and sealer coatings is considered as a possible solution to both galvanic corrosion and contact potential.

Fatigue life of bridges can be extended by bonding a CFRP patch, thereby arresting crack growth. It has been shown that in retrofitted specimens, the curve representing the stress vs. the number of cycles shows a remarkable upgrade. The curing period between a CFRP plate and metal is about 24 hours, during which the adhesive develops its full strength. If it is not possible to close the bridge during the curing period, cyclic loads can cause a reduction in stiffness. Additionally, if the slip between the FRP and the metal is above a certain value, some of the chemical chains forming in the adhesive will be broken and bond will fail to develop.

The points mentioned above refer equally to steels. The steel member, which requires upgrading, or strengthening would invariably use uhCFRP. The elastic modulus of the high stiffness carbon fiber composite (hsCFRP) has a lower value than the steels which it is upgrading and, therefore, the composite would only be effective when the steel has yielded.

It should be mentioned that joining the uhCFRP or the hsCFRP to the metallic member can be reversed only after considerable effort. This method may preclude the use of CFRP composites for upgrading historic structures because of the permanent nature of the upgrade.

Historic Timber Structures

Historic timber structures, such as covered bridges, building frames, long-span arches, roof trusses and waterfront facilities require case-specific methods of restoration and strengthening. Deterioration of timber occurs due to environmental factors, biological agents, natural hazards and man-induced degradation.

The repair and strengthening of timber structures using traditional construction materials has always been challenging due to directional properties of timber, and dimensional changes under moisture variation. CFRP and GFRP materials have been used to strengthen existing historic timber structures. There are two main options for this type of retrofit:

- Use of CFRP or GFRP composites as direct ‘reinforcement’ in timber. This is known as the resin repair technique.
- Removal of decayed timber, followed by splicing in of a new section of timber. The joining method is via drilled slots or grooves into which FRP members are adhesively bonded.

Epoxy polymer/glass fiber members have an advantage in that they are flexible and are readily installed (similar stiffness to that of timber). However, the successful behavior of FRP composites in the repair and strengthening of timber structures requires careful characterization of interface durability. The successful performance of FRP bonded to timber under harsh environmental exposure conditions also needs careful design. The interdisciplinary understanding of biodegradation processes and interface mechanics on the long-term performance of historic timber structures with bonded FRP materials is a major challenge to the advancement of this particular application of FRP materials.

There are considerable gaps in knowledge in this technology, particularly with respect to durability, compatibility, minimization of invasiveness, reversibility of repair and optimal material selection.

Outcomes of the discussion

Structural strengthening is a small area in the larger scheme of historic preservation. However, in some instances it may be necessary to undertake strengthening of the historic structure. Where such structural strengthening is undertaken, it must be approached judiciously and cautiously. A detailed assessment effort must be carried out for an historic building, not just relying on present day codes and standards. Where structural repairs are found necessary they must be guided by legal documents. The selection of repair materials for historical preservation is necessarily biased towards materials that have a long proven history of successful applications. Materials closely matching the materials used in the original construction are invariably preferred. Otherwise, new materials must closely match the historical fabric.

FRP materials show extraordinary promise in the development of inconspicuous repair schemes, offering significant strengthening through the use of small amounts of material. The following areas in which FRP structural materials have been used or are under investigation are:

- External upgrading of structural members (for improvements in flexural, shear, axial, torsional, seismic, ductility, impact or blast resistance), and
- Use of FRP for new or replacement structural systems (such as replacement of an existing bridge deck using FRP).

Although FRP composites have been used in the rehabilitation of historic and modern structures, there are still a number of deficiencies in knowledge of the structural engineer regarding the joining of the FRP to the structural system and the failure modes of the rehabilitated systems.

The critical issues regarding present state-of-the-art can be listed as follows:

- Material and System Issues
  - Uncertainty of long-term behavior of FRP – 30 years seems promising, but much longer..?
  - Compatibility of materials.
  - Minimum intervention.
  - Historic materials preferred.
  - Removable schemes presently specified, but difficult to achieve.
  - Understanding fundamental properties of parent and strengthening material.
  - Post-tensioning anchorage issues.

- Knowledge Issues
  - Cultural shift for engineers and wider construction industry in this area.
  - Training of entire project personnel, with strict quality control.
  - Understanding causes of deterioration prior to strengthening.
  - Respect for structural intentions of original designer.
  - Too wide a choice of materials.

Future work

Gaps in Knowledge:

- Life expectancy models.
- Long-term behavior (creep, fatigue).
- Environmental effects (temperature, moisture, UV, alkali) on repair system.
- Fire resistance.
- Inter-disciplinary understanding.
- Construction inspection for compliance (threshold defect sizes).

Research Needs and Wish List:

- Structural transparent resins, FRP or inorganic coatings.
- Smart patches.
- Piezoresistive systems.
- Piezoelectric systems.
- Wireless structural health monitoring.
- Innovative bonding and curing systems.
- Simple post-tensioning systems.
- Long-term anchorage of FRP.
- Nano particles to tailor permeability.
- Long-term field testing.
- Mechanical fixing.
- Fire resistance.
- Interdisciplinary teams required, involving architects, engineers and materials scientists.

Topic Area: 3. COMPATIBILITY REQUIREMENTS OF TRADITIONAL AND EMERGING MATERIALS (J. Weiss)

Background

The efficient repair and restoration of both the civil infrastructure and historic structures often requires repair strategies that enable the material to be placed, cured, and loaded in a relatively short period of time. Frequently, temporary repairs are made using materials that are later found to be incompatible with the existing structure and environment. This practice causes these materials to fail prematurely which can further damage the facility and require re-repair. Recently several repair materials and strategies have been developed that include a wide range of possibilities for the selection of binder and reinforcement materials. New hybrid composite systems are being developed that can significantly increase strength, stiffness, resistance to fatigue and long-term durability. While some repair systems are very stable, others can be extremely susceptible to environmental conditions, poor bond, and early-age cracking, delamination and deterioration. An improved understanding of the factors that lead to poor performance is needed. Frequently repairs fail prematurely even though they have sufficient strength due to incompatibility with the parent materials. The development of a single repair material for every application is not appropriate and the materials for a given application must be selected based on the requirements for a given repair.

Research issues

On the outset the compatibility between repair and traditional materials may not seem to be a major problem since much of the experience is available in the field of construction technology. This report however describes some problems which may still need to be clarified. It also indicates the need for communication between the materials and structures communities. While a material knowledge is essential to deal with the topics of durability at the material level, physical and chemical compatibility, and optimal selection of materials, the structural expertise is needed to focus on the macro-scale behavior of the strengthened member and structure and to understand the structural implications of different material systems.

Several aspects of repair techniques are required to demonstrate the best behavior in service with respect to levels or residual stress build up, sufficient bond, and excellent long-term durability. There are five main issues associated with material compatibility: mechanical performance, physical and chemical performance, historical integrity, anticipated use of the facility, and education and training of designers, material suppliers, and laborers.

Achieving adequate bond between repair materials and the existing substructure is a key component for any repair material. This bond is needed to insure adequate stress transfer during loading and expansion and contraction. However, the long-term strength and integrity of the bond is crucial. Standardized test methods and durability protocols are needed to evaluate interface bond performance.

Various techniques are used to prepare the surface for the repair material that may result in the ability to develop differing degrees of mechanical and chemical bond. Several different test methods exist to evaluate bond.

It has recently been observed that many repair materials are susceptible to cracking caused by volumetric instability. These factors can be amplified in rapid setting repair materials due to the rate of material property development. As a result of the rapid development of elastic modulus and decrease in creep compliance, the ability for repair materials to redistribute stresses may be altered thereby increasing the potential for cracking. This can be significant in rapid setting repair materials since significant material property development may have taken place during this time.

To accurately measure early shrinkage and expansion movements, researchers have proposed the use of an external non contact laser to assess volumetric changes while the specimen is still hardening. In the ring test, a concrete annulus is cast around a rigid steel ring and permitted to dry from the outer circumference. In the ring test the concrete ring wants to shrink and get smaller during the course of the test, however the steel prevents the movements resulting in the development of circumferential stresses that can lead to cracking if high enough. The maximum tensile stress that develops in the ring (the radial stress at the inner radius) can be computed directly at any time, *t*, using equation 1:

$$\sigma_{Concrete}(t)\Big|_{r=R_{IC}} = \varepsilon_S(t) \cdot C \qquad (1)$$

where $\varepsilon_S(t)$ is the average strain measured at the inner surface of the steel ring at any time t, and C is a constant for a given ring specimen geometry. This approach is powerful since it greatly simplifies the data interpretation and if compared directly with the time-dependent tensile strength (by taking a ratio of the two) enables cracking potential to be assessed for cases where cracking may not be observed.

Outcomes of the discussion

During the discussion, the fundamental issues related to compatibility requirements of traditional and emerging materials were classified and listed as follows.

<u>Mechanical Issues</u>

- Bond Issues
    - o Experimental methods, test geometry, and conditioning protocol
        - ▪ Testing conditions
            - ❖ Standard surface preparation, curing and conditioning specimens prior to testing, specimen type and size, testing configuration, reported parameters, exposure, testing condition, description of what we think we are measuring (masonry, wood, stone, steel, other materials)
            - ❖ Thinking about issues related to prestressing application
            - ❖ Agreement upon some standard testing protocol in terms of size shape and then there should be discussion on exposure conditions (RILEM could be a home for these activities and it would be suggested that committee members could be organized)
            - ❖ Need for a 'workshop' to bring together the state of the art, state of the practice, research projects on bond in repairs and composites – participation is needed from many interested groups including producers and users as well as people studying bond in several systems
        - ▪ Correlate accelerated tests with some sort of life span
            - ❖ One need may be the development of a database that provides information on testing conditions
            - ❖ Need for real time monitored data
            - ❖ Monitored exposure sites for different climatic conditions – difficulties of extrapolating data for new materials, may be able to be correlated through an accelerated model
            - ❖ How much information do we need before we can use a strategy
            - ❖ Example (Belgium) steel plate bonded 37C failed after 17 years, high temperatures influencing bond
    - o Unbonded approaches can exist as well
            - ❖ Opportunities to monitor and adjust over time, removability, eliminates issues with addition of bars, chemical products or injection
- Ductility Requirements
    - o Stiffness Compatibility
        - ▪ Elastic stiffness
            - ❖ Testing techniques are known well
            - ❖ Information must be conveyed on matching material properties
            - ❖ Do we need materials that are ductile, generally we need to accommodate considerable deformation, lime mortars
        - ▪ Creep, relaxation and damage
            - ❖ Temperature issues as they relate to other material properties (creep stiffness bond), thermal cycling
            - ❖ Information is needed on how to apply the knowledge
    - o Volumetric Stability – thermal and hygral
        - ▪ We know how materials expand and contract – what we need to know are the analysis techniques (different thermal or moisture coefficients)
    - o Action Items
    - o Approaches are needed for recommendations and procedures for matching of material properties
    - o Are new materials needed
        - ▪ FRP - matrix is not ductile enough, fibers are not ductile enough
        - ▪ Strengthening is known for concrete beams not for other structures that exhibit large local deformations
        - ▪ Need exists to design materials that do no become brittle over time
        - ▪ Timber – biological issue and stiffening

Physical and Chemical Issues (Durability)

- Chemical Compatibility
- Aging
  - Degradation, embrittlement
- Environmental CO_2
- Acid Rain
  - Lots should already be known
    - General topic understood, however will this lead to debonding
- Sunlight Exposure
  - UV exposure and degradation
    - Some problems, material solutions exist
- Water Ingress
  - Water ingress due to cracking can lead to freezing and thawing
  - Depending on the manufacturing process this can lead to water ingress
  - Permeability and water ingress should be known though measurement may be an issue
- Volumetric Stability
  - Cycling of temperature effects – fatigue type failure
  - Moisture and chemical reaction
- Fire
  - If composites are a necessity – high temperature may be a problem – depends on the need for the composite, is it essential or is it preferred
  - Can we design it so that structural collapse will not happen
  - Other binder systems (including inorganic binders) do exist, geopolymers
  - A need – understanding of options for high temperature with low 'smoke' emissions
- If the substrate is weak we need to understand this better
- Do not have the long term information on how these will perform in situ

Historical Integrity

- Surface Integrity
- Reversibility/Removability
  - Example, drilling a hole for internal prestressing, or external prestressing – removed
  - Example, metal bars before and after earthquakes – found to be a problem after a quake but not able to be removed
  - Expansive soils
  - No resonance if certain structure rock; however, this can change
  - Proper analysis of a structural repair that is consistent with original design
  - How do we remove a solution if in the future a better solution is obtained or if negative results are experienced with a typical repair
  - Must be able to explain
  - Is it a chemical, mechanical, or loss of element problem
  - Overcoming a material with a low Tg it is possible
- Minimal Invasiveness
- How much of a structure can be removed under normal repair
  - Timber beams that rot, tiles that crack
    - Is the same species of wood
    - If you hide the repair
  - Case by case issue (roman road, public building)
  - Authenticity - Don't make new like old - if the materials are the right solution should we use them, if the composite can be 'hidden' is this acceptable as well
- Cultural Compatibility

Performance Versus Use (function)

- Do we want to restore the original function, change the function, update the facility for the same function (conservation, compromise)

- Compliance with new requirements (altering, public access, public safety) Public safety versus code requirements – differential between monuments and living buildings
- Respect Structural Concept - not change the structural function. The idea is not to build a new building with the same look.
- Upgrade Capacity

Education and Training

- Students have been studying structures like RC concrete and steel which are continuous and their analysis techniques (like FEM) are established to look at these materials, however historical structures may behave in a more discrete fashion and students need to be trained to think in this way
- Workmanship, skilled labor, quality assurance issues
- Conceptual understanding of structural systems and force flow issues, physical understanding needs to be emphasized, emphasis on the basics
- Is a course needed on the analysis of older structures (large masonry structures) for example, on the development of a graduate course on the understanding and analysis of structures
- Repair requirements in terms of time and application, some sort of repetitive inspection and repair process
- Is there a possibility of a field laboratory on an old structure where various solutions can be 'tried' before they may be done on a structure of significant historical significance

Future work

- Standard testing practices for bond
- Standard surface preparation, curing and conditioning specimens prior to testing, specimen type and size, testing configuration, reported parameters, exposure, testing condition, description of what we think we are measuring (masonry, wood, stone, steel, other materials)
- Workshop on the state of the art, state of the practice, research projects on bond
- Seminar/information on analysis of older structures (large masonry structures)
  Fidelity to the original design concept (analysis techniques today are established to look at new materials, historical structures may behave in a more discrete fashion).
- Certification for repair teams (training for workmanship, quality assurance)
- Correlate accelerated tests with service life predictions
- Develop a database that provides information on testing conditions and observed response
- Collect data in real time
- Monitor exposure sites for different climatic conditions – difficulties of extrapolating data for new materials, may be able to be correlated through an accelerated model
- Establish historical structure test beds

Topic Area: 4. NON DESTRUCTIVE ASSESSMENT, EVALUATION AND MONITORING (M. Schuller)

Background

Rehabilitation efforts are made more effective when the condition of the structure is established with confidence a priori and when the quality of the retrofit is monitored. Thus in situ condition evaluation methods for rehabilitated historical structures are needed. Nondestructive evaluation (NDE) procedures are particularly attractive for use with historic preservation projects, where damage to historic materials must be minimized, and in fact often is unacceptable. Although there have been recent technological advances in applying NDE for evaluation of historic construction, a set of challenges remain due to the highly variable nature of these buildings, the many types of materials and construction approaches that have been used over the centuries, the lack of documentation on their construction and their considerable cultural value.

Another prime consideration in application of NDE for diagnosis and control of repairs to historic construction is the cost of such investigation techniques. The economic constraints that are encountered when approaching the conservation of historical buildings is a driving force towards an effort of designing low-cost investigation procedures. Simplified methods are needed to fit within the constraints of cost-effective interventions and also to enable the use of local workmanship.

Nondestructive testing methods have potential applications in three main phases of a repair or strengthening project: 1) diagnosis of existing conditions, 2) control and characterization of repairs, and 3) long-term monitoring.

During the evaluation phase, nondestructive methods are used to determine as-built conditions, locate prior repair efforts, and for assessment of damage or deterioration. Nondestructive methods do not provide reliable information on engineering properties, such as in situ material strength or stiffness, and so-called "minor destructive" tests are instead used for this purpose. For example, the flatjack method and in in-place shear test provide general indications of compression and shear stiffness response, and pin penetration tests provide information about material strength. Data from this evaluation phase are used to plan intervention work and identify appropriate (compatible) materials for subsequent strengthening or repair processes.

NDE approaches in particular are useful during or immediately following FRP strengthening and repair work as a means to evaluate the adequacy of the repair. Such testing may be conducted for quality assurance (QA) to characterize the completeness of bond or the filling of internal voids, or the detection of improper FRP application as indicated by blisters or pockets of trapped moisture. A secondary purpose for conducting such tests would be for quality control (QC), in which case mechanical testing of bond strength, or the capacity of strengthened wall sections, will likely be required. NDE methods are not currently being used to provide strength-related information.

A major consideration with using FRP for repairing or strengthening historic buildings is the long-term performance of the repair, considering both structural/mechanical performance and durability of the repaired structure. By definition our historic properties have existed for many years and the current philosophy is that we should strive to provide repair/strengthening approaches that have an expected lifetime that matches that of the structure. Until reliable life-cycle information is developed, long-term monitoring should be a requirement of FRP-related projects. Periodic application of NDE methods has a natural position in such a long-term monitoring program.

Research issues

Most of the NDE applications developed for investigating FRP were developed by the aerospace industry. That industry's expectations of performance, safety, and cost of investigative work vary greatly from the requirements of the construction industry – an industry which is relatively fragmented and risk adverse. Additional major barriers to the wider use of NDE technology for evaluating and monitoring FRP projects include cost, time and effort required to conduct a survey, a lack of simple test standards, and a general lack of NDE knowledge within the construction industry. In order to gain wide acceptance for use in repair or strengthening projects, evaluation methods must not only be accurate, but must be relatively inexpensive, and able to be conducted by trained technicians rather than NDE experts. Monitoring techniques must be robust and able to perform reliably for decades in harsh environments.

Building Evaluation

Development of NDE technology is ongoing, and methods are currently being used to evaluate historic construction as well as to gage the effectiveness of repair procedures. The knowledge of the geometry of the structure (including thickness of leafs in multi-leaf masonry) and detailed information on geometrical irregularities (tilting, rotations, loss of verticality or horizontality, etc.) is of great importance, together with the survey of the global state of conservation and crack pattern. Moreover, historic buildings are very often the result of a long process of superposition, partial demolition and reconstruction. Methods currently in use to evaluate historic construction include sonic and ultrasonic pulse velocity measurement, impact-echo, microwave radar, electrical conductivity measurement and infrared thermography. Recent advances in imaging techniques (such as tomographic analysis and radar imaging) show great promise for determining the nature of existing construction. Further development of such imaging approaches is required before broader implementation into practice.

In recent years, the adaptation of rapid prototyping procedures to determine simple geometry of architectural forms has developed enormously. Non-contact image-based measurement techniques that have been successful in other applications are now available for measuring complex surfaces. The measuring strategy and the algorithms necessary for measuring full-scale buildings still need further development but geometrical parameters (e.g. dimensions and shapes), microstructures (e.g. brick quality, cracks and roughness) and also colors /color variations are measurable. Such highly efficient optical measuring and analysis techniques result in significant productivity increase in the documentation process, besides allowing, by definition, a full 3-dimensional representation.

Evaluation of FRP Repairs

Considerable effort has been expended to develop NDE technology for locating flaws and voids in FRP materials. Much of this work has been conducted for aerospace FRP applications; some of the developed techniques are being used for evaluating FRP applied to civil structures. Little or no work has been done to further adapt these methods for the special needs of historic structures.

Simple sounding approaches are well suited to locating larger flaws and delaminations that may be of concern to the construction industry. However, sounding provides only localized information and, while it may be automated through use of electronic transducers, sounding evaluation can be tedious and time consuming. Ultrasonic testing is able to locate small flaws but, similar to sounding, remains a localized approach. In addition, high frequency ultrasonic waves are attenuated rapidly and the approach is often not feasible for evaluating thick sections.

Infrared thermography scanning provides an essentially global approach for evaluating FRP materials. In a state of heat flux, surface temperature measurements give an indication of the variation in heat transfer characteristics of the underlying material, and near-surface voids at the substrate interface and within multi-ply systems are identified because of their effect on heat transfer. Active scanning methods, which use an external heat source (such as infrared lamps or warm air flows) applied to the FRP surface, can rapidly locate larger flaws. Other methods, such as eddy current holography and near-field microwave measurements, may have applications for identifying localized damage, but research into these methods for evaluating FRP is limited.

Long-Term Monitoring

Many of the methods discussed previously would also be useful for detection of damage or deterioration of FRP applications. The general approach to long-term monitoring has been to characterize the FRP condition immediately following application, followed by repeated characterizations at the same location to provide comparative measurements at future time intervals. Significant variations in the measurements are used as indicators of damage or distress. The current approach is to re-inspect the repair periodically using the procedures described above, such as infrared thermography, ultrasonics, or simple sounding.

There are other approaches developed expressly for locating damage or deterioration over time. For example, monitoring changes in the vibration frequency of structural members (modal analysis) shows some promise as a periodic inspection technique. Optical methods such as Moire interferometry can also be used to identify stress concentrations resulting from changes in bond or material deterioration. Monitoring energy released during damage events by acoustic emission monitoring could be useful to identify the spatial location of damage. Finally, use of embedded sensors such as fiber optic devices can be used to monitor strains and structural movement over the long term.

Outcomes of the discussion

The major barriers to use of NDE techniques are:

- Lack of education/communication
- Lack of standards
- Specialized knowledge/experience required
- Limited capability of techniques
- Cost and market size
- Effectiveness/efficiency/accuracy

These are our “challenges”. Standardization is not always possible due to the many variations in building configurations and the FRP applications themselves. Specialized experience is required as a result – the user of NDE techniques must have the capability of modifying procedures to meet the task at hand.

Current NDE techniques have limited capabilities, and the industry needs to improve the reliability, efficiency, and accuracy of inspection methodologies.

From the discussion about needs and challenges of NDE technologies, the following *“very high-priority”* items emerged:

- Global non-contact inspection techniques
- Improved sensor technology
- Data management
- Diagnostics (decision making and simulation)

Global non-contact inspection techniques should be rapid, reliable, and inexpensive. The aim of such techniques is often to identify variations in material properties or condition, such as moisture content, or the presence of deterioration.

Sensor technology: It needs to be improved not only for evaluation but also long-term monitoring. Embedded sensors may be useful for investigation and monitoring. Increasing the reliability, durability, and decreasing power requirements are all potential sensor improvements. Incorporating wireless technology would eliminate the need for cabling between sensors and processors. There may be a place for nanotechnology in this field as well: one concept is to introduce miniature sensors into a wall section, to interrogate from the interior. Current evaluation processes almost always rely on external instrumentation.

Data management: Large quantities of data are collected with NDE and we need better methods for managing and processing the data. Think of how the medical field manages data from ultrasonic imaging, to provide a representation of a fetus in the womb. Processing data to provide easily-interpretable images is important for gaining acceptance of this technology from the general public. NDE for building applications would benefit from a multi-disciplinary approach, to “borrow” and adapt technology already being used in other fields such as medicine, aerospace, and the military. Data management includes collecting data for use in numerical models.

Diagnostics: Many times the scope of interventions may be reduced or eliminated by proper use and application of investigative techniques. Expert systems may be useful for evaluation of NDE data, considering both material properties and condition surveys. Many NDE techniques rely on stress wave or electromagnetic wave propagation, and it may be advantageous to investigate the use of other energy forms (such as nuclear magnetic resonance or x-radioscopy) to “illuminate” the subject.

“High-priority” items emerged as follows:

- Improved communication and education efforts
- Improved global dynamic (modal) analysis
- “Intelligent,” self-diagnosing, self-healing materials
- Improved prediction of early degradation

Communication and education: A fundamental component of research is technology transfer. This may include training, development of certification programs, standardized approaches, and expert systems. Persons conducting NDE must be qualified, and persons using data (design professionals, conservators) must also have knowledge of the methods used to acquire NDE data. We also need training courses to teach design professionals how to change their approaches when working with historic structures.

Intelligent materials: Providing a visual indication of damage or change in condition such to enable a rapid global evaluation would be advantageous. Self-diagnosing materials could also indicate problems such as improper resin formulation and mixing (for quality assurance), loss of bond (QA and long-term monitoring), and damage assessment such as fiber fracture.

Improved prediction methods: Monitoring systems employing sensors or modal analysis are able to identify major damage as the event occurs, but it would be useful to have improved sensitivity of methods and data interpretation to provide an early indication of impending damage.

Needed input from the experts is related to the following main items:
- Critical flaw/defect size and types
- Cost/benefit information
- Feedback about current NDE capabilities

NDE researchers require input from those using NDE data, including what types of specific information may be needed for designing repairs, choosing repair materials, the expected life time of the repair, and the acceptable level of defects in the work.

Design professionals often look to NDE practitioners for "high-tech" solutions and sometimes have been disappointed by results of NDE investigations. Input from other professionals is needed to aid in future NDE development.

One basic concept is the definition of the size and types of flaws which may be significant, structurally. NDE methods for evaluating FRP have largely been developed for aerospace and military applications, which have very different performance expectations than those for historic structures.

Cost-benefit information: What is our target cost? The high value of our cultural monuments may permit the use of methods that are not in typical use by the general construction industry.

Future work

Potential research and outreach topics include the following:
- Implement educational programs within undergraduate structural engineering programs and the industry to familiarize design and construction professionals with NDE methods.
- Develop standardized quality assurance and quality control procedures.
- Develop global non-contact methods for rapid imaging of large sections.
- Improve systems for imaging limited access members (e.g. wall sections) including development of equipment and methodologies to reduce NDE efforts.
- Refine post-processing software to simplify interpretation of images.
- Define minimum significant flaw size with regard to structural or repair effectiveness significance.
- Define limits for each NDE method in terms of minimum detectable flaw size (for each flaw type), limit of structural element or FRP sheet thickness that can be interrogated, and effect of different types of FRP panels (e.g. glass fiber, carbon fiber, etc.)
- Improve high-energy ultrasonics for inspection of thick members.
- Further develop non-contact air-coupled ultrasonic inspection systems.
- Long term monitoring approach required – must be low cost, relatively foolproof. Objective would be detection of bond separation or material deterioration.
- Embedded sensors for monitoring repairs and performance of repaired structural systems.
- Use of active sensors to initiate response to events.
- Improve capability of acoustic emission to locate acoustic events within massive historic wall sections.

Topic Area: 5. EXISTING PRACTICE AND STANDARDS ON PRESERVATION OF HISTORICAL STRUCTURES AND CASE HISTORIES (T. Boothby, L. Taerwe)

Background

European approach

For the structures of Architectural Heritage general criteria for the restoration are given by ICOMOS International Scientific Committee for Analysis and Restoration of Structures of Architectural Heritage, Recommendations for the analysis, conservation and structural restoration of architectural heritage, Paris (13 September 2001):

- Conservation, reinforcement and restoration of Architectural Heritage requires a multidisciplinary approach.
- Value and authenticity of Architectural Heritage cannot be based on fixed criteria because the respect due to all cultures also requires that its physical heritage be considered within the cultural context to which it belongs.
- The value of Architectural Heritage is not only in its appearance, but also in the integrity of all its components as a unique product of the specific building technology of its time. In particular the removal of the inner structures maintaining only the façades does not fit the conservation criteria.
- When any change of use or function is proposed, all the conservation requirements and safety conditions have to be carefully taken into account.
- Restoration of the structure in Architectural Heritage is not an end in itself but a means to an end which is the building as a whole.
- The peculiarity of heritage structures, with their complex history, requires the organization of studies and proposals in precise steps that are similar to those used in medicine. Anamnesis, diagnosis, therapy and control, corresponding respectively to the searches for significant data and information, individuation of the efficiency of the interventions. In order to achieve cost effectiveness and minimal impact on architectural heritage using funds available in a rational way, it is usually necessary that the study repeats these steps in an iterative process.
- No actions should be undertaken without having ascertained the achievable benefit and harm to the architectural heritage, except in case where urgent safeguard measures are necessary to avoid the imminent collapse of the structures (e.g. after seismic damage); those urgent measures, however, should when possible avoid modifying the fabric in an irreversible way.

<u>US Practice</u>

Treatments of a historic property should follow the Secretary of the Interior's Standards for the Treatment of Historic Properties. Although this is a statement of historic preservation ethics, it does not have legal force unless:

- The property owner wishes to qualify for preservation tax credits
- When dictated by State, or more commonly local historic preservation legislation
- When federal funds or permits are required for the project

The standards are brief statements that reflect the state of the art of historic preservation. As is always the case with brief statements, there is a context of practice guidelines accepted interpretations, arbitrary rules, orthodoxy, accepted deviations, and bias accompanying the enforcement of the standards by SHPO's (State Historic Preservation Officers). The standards recognize four types of treatment:

- **Preservation**: stabilization or arresting deterioration.
- **Rehabilitation**: restoring to service, includes alterations, but requires retention of character-defining features.
- **Restoration**: choosing a time or period of significance, and returning the structure to its state at the time in question.
- **Reconstruction**: depicting by new construction missing structures or features. SHPO's generally don't like reconstruction, but will allow it if the original state of the structure is adequately documented.

Since structural strengthening most commonly accompanies a rehabilitation treatment, the Standards for Rehabilitation are listed hereafter:

- A property will be used as it was historically or be given a new use that requires minimal change to its distinctive materials, features, spaces, and spatial relationships.
- The historic character of a property will be retained and preserved. The removal of distinctive materials or alteration of features, spaces, and spatial relationships that characterize a property will be avoided.
- Each property will be recognized as a physical record of its time, place, and use. Changes that create a false sense of historical development, such as adding conjectural features or elements from other historic properties, will not be undertaken.

- Changes to a property that have acquired historic significance in their own right will be retained and preserved.
- Distinctive materials, features, finishes, and construction techniques or examples of craftsmanship that characterize a property will be preserved.
- Deteriorated historic features will be repaired rather than replaced. Where the severity of deterioration requires replacement of a distinctive feature, the new feature will match the old in design, color, texture, and, where possible, materials. Replacement of missing features will be substantiated by documentary and physical evidence.
- Chemical or physical treatments, if appropriate, will be undertaken using the gentlest means possible. Treatments that cause damage to historic materials will not be used.
- Archeological resources will be protected and preserved in place. If such resources must be disturbed, mitigation measures will be undertaken.
- New additions, exterior alterations, or related new construction will not destroy historic materials, features, and spatial relationships that characterize the property. The new work will be differentiated from the old and will be compatible with the historic materials, features, size, scale and proportion, and massing to protect the integrity of the property and its environment.
- New additions and adjacent or related new construction will be undertaken in such a manner that, if removed in the future, the essential form and integrity of the historic property and its environment would be unimpaired.

The *Structural System Guidelines* promulgated by the Technical Preservation Service contain a very interesting discussion of structural system rehabilitation, including treatments recommended and not recommended. These guidelines are broadly categorized under the headings:

- Identify, retain, and preserve
- Protect and maintain
- Repair when remotely feasible
- Replace only when necessary

Under "Identify, retain, and preserve", the guidelines call for a higher-level detailed assessment of the structure in question.

For "Protect and maintain", it is apparent that redirection of water is probably the most important technical issue in cultural resources management.
Under the heading "Repair", it is reasserted that sensitive repair of a historic structure is a recommended preservation treatment.

In addition to general reservations concerning the application of structural strengthening to historic structures, the historic preservation community has significant and unfavorable experience in the application of new materials and new techniques to the rehabilitation of historic structures. Much of the concern over reversibility of repairs, in fact, stems from experience with previous repairs to historic buildings that damaged the building fabric irreversibly.

In spite of great advances in material science, matching material properties on this many levels over the very long term required for historic preservation projects does not yet appear to be within reach.

<u>Italian approach</u>

Several national guidelines for different types of application are available. As global view, the information given in the available documents is rather fragmentized, thus a specific proposal for masonry existing construction is still in need. At this moment suggestions are given by the contextual reading of pre- and post-seismic standards and laws of preservation of the Cultural Heritage. Such documents do not provide specific regulations on FRP materials but they simply allow their use for the repair of historic buildings. Long term behavior, related to intrinsic mechanical properties of materials (creep) and adhesion (debond), or chemical (corrosion) properties related to the support, are not considered. Official documents generally refer to experimental research still to systematize in methods and results.

A cautious approach for applications of FRP in historic constructions is reminded by several authors, especially in connection with the scarce applicability under compressive stress state (at least for laminates and sheets) and the low strength and brittleness under shear loads. The main differences with RC applications in comparison with masonry ones are related to the obtainment of a global improvement of the mechanical behavior rather than punctual, in order to avoid possible kinematics mechanisms which can lead to brittle collapse or function losses; this is obtained by proper positioning of the FRP materials and by exploiting their high tensile strength. The other advantages useful in existing construction applications are mainly the well known low weight, the corrosion inhibition and the high flexibility (laminates, sheets, bars, etc.)

Due to the unavailability of specific standards on FRP applications on historic constructions, the choice of the most proper technique demands a case-to-case analysis, under the respect of the general laws for the preservation of the Cultural Heritage. A general approach should start by a global view and include and/or consider :

- Analysis of the current state, with particular care on the history of the construction;
- Evaluation of the current safety level, by using not only numerical methods;
- Execution of improvement intervention with high respect of the original materials and constructive aspects, and minimum obtrusiveness;
- Use of innovative techniques properly validated about compatibility, durability, reversibility and mechanical effectiveness.

Outcomes of the discussion

Some consideration sprang from the analysis of the analyzed documents:

- An engineer undertaking preservation or rehabilitation treatments of historical properties must bear in mind the underlying principles that dictate that treatments must not subject the historic fabric to irreversible harm. Examples of such principles are Principle 7 of the general criteria published by ICOMOS, or Standard 10 of the US Secretary of the Interior's Standards for Rehabilitation. Local authorities may also dictate similar standards.
- Structural safety is a paramount consideration in the restoration and rehabilitation of any structure accessible to the public.
- Multiple levels of intervention may be required, from repair of small damage, usually repaired with traditional materials, through strengthening under dead load and serviceability conditions, to the maintenance of an acceptable level of safety after an exceptional event.
- Unfavorable experience in the application of new materials and new techniques to the rehabilitation of historic structures suggests some caution in the application of new materials.
- Case-by case analysis, carried out in the following four steps :
    - *Analysis of the current state*, with particular care on the history of the construction.
    - *Evaluation of the current safety level*, by using not only numerical methods (also engineering judgment).
    - *Execution of intervention* with high respect for the existing materials and constructive aspects, and minimum obtrusiveness.
    - *Use of innovative techniques* properly validated for compatibility, durability, removability and mechanical effectiveness.
- Some standards are available for quality control and they could be used for rehabilitation procedure:
    - More general codes applicable e.g. for concrete.
    - EN 1504 part 1-10 "Products and systems for the repair of concrete structures. Definitions, requirements, quality control and evaluation of conformity"; FRP EBR → part 4 Structural bonding.
    - Harmonized code EC label for concrete repair product (2007).
    - Belgium ATG certificate for externally bonded reinforcement systems → on European scale ETA certification will be initiated.
    - *fib* bulletin 14 on FRP EBR chapter on quality control.
    - Under preparation (*fib* TG 5.3) Technical report on assessment and rehabilitation.
- Current Practice of FRP Intervention (reinforced injections; tie-beam, application of ties; jacketing; application of FRP sheets and laminates; bed joints reinforcement and structural repointing). These

strengthening techniques were first conceived for the use of steel reinforcement in masonry structures. It is possible to consider the use of FRP-materials instead of steel. Some of these techniques have been used also for RC structures and they have been investigated also for masonry ones. Recently, some research project were carried out on timber structure strengthening with FRP-materials.

- Opportunities for Use of FRP in Historic Structures:
  - Suitable material in many cases due to tailorability, durability, corrosion resistance, formability, stability.
  - Broad range of applications to masonry, concrete, steel, and timber buildings.
  - Short time of application particularly suited to urgent interventions.
  - Potential for less obtrusive interventions.
  - Lower increment of added weight, particularly applicable to seismic strengthening.

Future work

- Challenges for Use of FRP in Historic Structures:
  - Continuously bonded reinforcement presents challenges in long-term performance.
  - Continuously bonded reinforcement presents challenges in compatibility with historic preservation principles.
  - Limited ability of traditional forms to perform structurally, especially in seismic events.
  - Availability of design standards, effective and inexpensive inspection tools.
  - Understanding and diffusion of guiding principles of historic preservation.
  - Promoting a better understanding of the limitations of technology among cultural resources professionals.
- Long-term objectives:
  - Effective structural interventions are hampered by the difficulty and length of the development of rapid tools for assessment and analysis. The process of structural modeling and design is done as an iterative and interactive process over a long period of time.
  - An effective way to investigate and model a structure and to design a structural intervention rapidly and in real-time would allow rapid, minimum interventions, and more effective conservation of historic resources.
- Next step: involve non-technical historic preservation professionals directly in the process of development of repair techniques and standards.

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(*) Contributed to the preparation phase but could not attend the workshop

APPENDIX B: Workshop Agenda

AGENDA FOR INTERNATIONAL WORKSHOP ON PRESERVATION OF HISTORICAL STRUCTURES WITH FRP COMPOSITES
Monastero degli Olivetani - Lecce - Italy - June 9-10, 2004

DAY 1 - WEDNESDAY JUNE 9, 2004

3.00-3.30 p.m.	Registration Activities: register, obtain badge and information material, meet other delegates/spouses and acquaint yourself with the meeting place
3.30-5.00 p.m	OPENING PLENARY SESSION (Room 1) Review of purpose & organization, introduction of topical area leaders, introduction of all participants and attendees. Moderator: A. Nanni
5.00-5.30 p.m.	*Coffee break*
5.30-7.00 p.m.	PARALLEL SUBGROUP SESSIONS (Rooms 1-5) Activities: according to the specific Topic Area, discuss, distill, and summarize the trends and the knowledge acquired or to be acquired. List research tasks to be accomplished in the future.
8.30 p.m.	*Taste of typical Salento food, Palazzo dei Celestini, Lecce historical center* *Workshop dinner, Hotel Patria, Lecce historical center*

DAY 2 - THURSDAY JUNE 10, 2004

9.00-10.30 p.m	PARALLEL SUBGROUP SESSIONS (Rooms 1-5) Activities: according to the specific Topic Area, discuss, distill, and summarize the trends and the knowledge acquired or to be acquired. List research tasks to be accomplished in the future.
10.30-11.00 p.m.	*Coffee break*
11.00-12.30 p.m	PLENARY SESSION (Room 1) Activities: Reports from subgroup leaders (10 minutes each followed by discussion). Present the findings of the specific subgroups and define a common format and priorities for the final report.
12:30-2:00 p.m.	*LUNCH*
2.00-3.30 p.m	PARALLEL SUBGROUP SESSIONS (Rooms 1-5) Activities: according to the specific Topic Area, discuss, distill, and summarize the trends and the knowledge acquired or to be acquired. List research tasks to be accomplished in the future.
3.30-4.00 p.m.	*Coffee break*
4.00-6.00 p.m	CLOSING PLENARY SESSION (Room 1, streaming live on Internet) Activities: Final reports from subgroup leaders (10 minutes each followed by discussion). Subgroup leaders lead the general discussion with a prepared statement based on their reading of the situation. Summary of the two-day work, agreement on actions to follow for dissemination of outcomes of the Workshop and for set up of a coordinated series of events with similar format and scope.