First Middle East Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures
8 – 10 February 2011, Dubai, UAE

SMAR 2011

Applied research and recent developments on composite material technology for structural strengthening

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ABSTRACT: The current paper presents results of recent applied research projects and testing programs on composite materials technology where Fyfe Company has participated. Real case studies utilizing the new technologies developed from aforementioned research are also presented.

A selection of research topics for presentation is: a) passive fire protection of Fiber Reinforced Polymers (FRP), b) development of epoxy resins for high working temperatures, c) anchoring technology of FRP with fiber anchors, d) development of compatible Reinforced Mortar Systems (RM) for strengthening of historic masonry structures.

1 PASSIVE FIRE PROTECTION OF FRP

Fire is one of the major concerns regarding FRP because of epoxy's sensitivity to high temperatures. Many efforts in the last decade have taken place in developing a passive fire protection system for FRP. Following extensive full scale, under load testing in Canada and USA, the AFP (Advanced Fire Protection) system has been approved as the first FRP fire protection system. The system is already available internationally since 2004 while the second generation of the system is currently under development. Selective results of the tests and brief system description are presented.

It is known that the mechanical properties of the epoxy resins used in FRP degrade at high temperatures. Therefore, gradual loss of strength and bonding of the FRP is expected at a case of a fire event. As a result the engineers should ensure that the service temperature remains below a certain level and assume complete loss of the FRP strengthening during a fire event, unless a suitable fire protection system has been installed to protect the FRP in such case.

Extensive fire endurance experiments have been conducted by Kodur et al. (2006) on full scale under load FRP retrofitted columns, beams and slabs in accordance with ASTM E-119. All assemblies were retrofitted with carbon or glass FRP and covered with AFP system. The system consists of a noncombustible, zero flame spread, spray-applied fire insulation layer, covered by a surface hardening sealing compound. The insulating component thermal conductivity is about 0.082 W/m ^{o}C, when for gypsum plaster is approximately 0.25 W/m ^{o}C at room temperature. AFP thickness varied to obtain several fire endurance performances.

Columns achieved per ASTM E-119 fire endurances greater than 4 hours under the retrofitted service loads. AFP thickness varied from 32mm to 57mm. Temperatures recorded at various locations (Figure 1) evident the good thermal insulation provided by the AFP system.

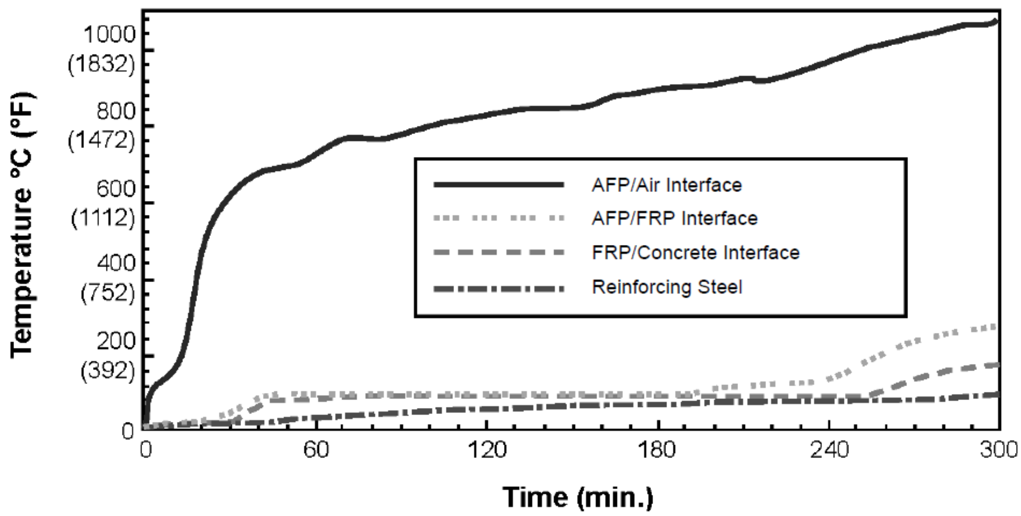

Figure 1. Temperatures recorded during testing of a circular column.

All T-beam assemblies retrofitted with carbon FRP and protected with AFP thickness 25mm to 38mm, achieved fire endurances in excess of 4 hours under retrofitted service loads. Based on the results of these tests, standard fire ratings have been developed through Underwriters' Laboratories (UL) for insulated FRP retrofitted beams and columns. These rated assemblies are listed in the UL directory.

New series of tests are undergoing for developing a new Super-AFP system with advanced performance (smaller required thickness) suitable for external use as well.

Figure 2. Application of AFP System on FRP strengthened beams (Fyfe Company).

2 DEVELOPMENT OF EPOXY RESINS FOR HIGH WORKING TEMPERATURES

By now, lots of investigations have been done to reveal the evolution of the mechanical properties of FRP with the temperature (Foster and Bisby, 2005). High temperature is a major concern regarding strengthening applications in warm climates or where the working temperature is exceptionally high (e.g. industry). In such cases, conventional epoxies fail to meet the requirements. A new generation of epoxy resins for high temperatures is introduced

(Tyfo® S-T Epoxy) that is characterized by especially high Glass Transition Temperature (T_g) and Critical Temperature (T_c). Part of the development study is presented.

All studies show that the mechanical properties of FRP at elevating temperature are dominated by the properties of the polymer matrix (epoxy). As known, the structural role of epoxy in FRP is to hold the fibers in place and transfer stresses among them. Softening due to elevating temperature of the epoxy will lead to decrease of the mechanical properties of FRP, as the softened epoxy will not effectively transfer the force between fibers. The fibers will fail at different strain levels because of minor waviness and misalignment further reducing the mechanical properties of FRP.

Deeper study in the properties of epoxy show that after its curing, a cross-linking structure is created, and therefore the epoxy can not be molten anymore but only be softened. The temperature at which epoxy changes from brittle (glass) to soft (rubbery) form is the T_g. As the temperature gets close to the T_g the polymer matrix starts to soften and exhibit a lowered modulus. With the further increase on the temperature the matrix becomes softer until the matrix shows a temperature-independent modulus (rubbery modulus). Above the T_g, the epoxy still possesses a low degree of modulus and strength. This characteristic is very important for the much higher T_c of FRP in tension. T_c is defined as the temperature at which FRP loses 50% of its tensile strength and can no longer support the applied load.

Correspondingly, the variation of the mechanical properties of the FRP is similar to the epoxy with the temperature. As the temperature increases the mechanical properties slowly decrease. As temperature gets close to Tg, the mechanical properties start to dramatically decrease. At much higher temperatures, the mechanical properties become temperature independent until the occurrence of severe degradation of the epoxy or the interfaces. If the tensile strength of FRP at the latter stage is higher than the 50% of the original strength, then the T_c of the FRP will be much higher than the Tg of the epoxy.

While developing the new generation of epoxy resins the major concern was to create a polymer matrix for FRP used for structural strengthening that will be characterized by exceptionally high T_g and even higher T_c. The result was Tyfo® S-T Epoxy that possesses a Tg of 101^{o}C, while the FRP (Tyfo® Composite System) formed with that epoxy possesses an even higher T_c of 260^{o}C. As a result, the new material is capable to conform with demanding design requirements set by structural strengthening needs at exceptionally high ambient temperatures (e.g. warm climates, industrial plants etc.).

3 ANCHORING TECHNOLOGY OF FRP WITH FIBER ANCHORS

Mechanical anchorage of FRP on bond critical application has been always a subject of utmost importance. Mechanical steel anchors should be avoided due to stress concentrations and galvanic corrosion problems when in contact with FRP. Fully compatible anchors made out of fibers (Fibr™ Anchors) have been developed and tested extensively. Recent tests revealed the advanced performance of "U-shape" FRP for shear strengthening of T-beams when anchored with Fibr™ Anchors. Testing further proved that anchoring of FRP applied to columns for flexural enhancement is possible by application of Fibr™ Anchors at the footings or joints.

Typical lay out of a Fibr™ Anchor is shown in Figure 3. Fibr™ Anchors made of special type of glass, carbon or glass/carbon (hybrid) fibers have been developed and patented by Fyfe Company in USA in the decade of 1990. Diameter, length and shape of anchors vary on design requirements. Special types such us pre-cured, pre-saturated, pinned have been produced and installed in special applications. The anchors are forced in a predrilled hole of specific diameter and depth filled with epoxy in concrete, wood or masonry. Anchor fibers are splayed out between the FRP layers in a pattern per the design detail and cure with the FRP system as one monolithic system.

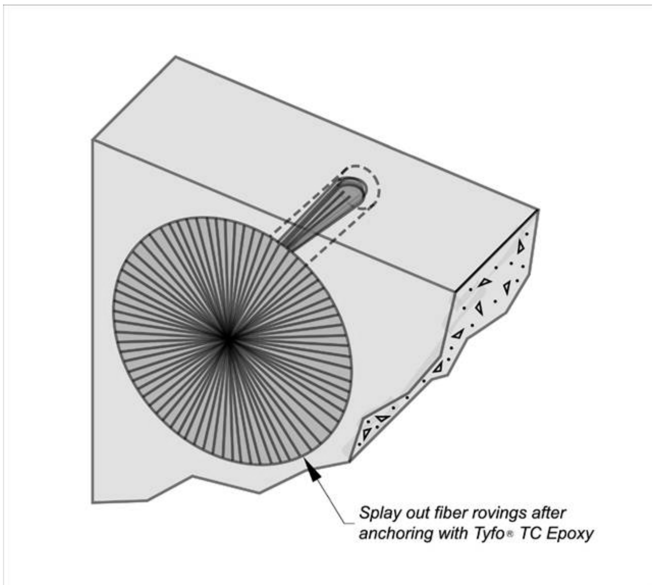

Figure 3. Fibr™ Anchor lay-out (Fyfe Company).

Recent T-beams shear testing conducted in Structural Materials Laboratory (SML) in University of Patras (UPatras), with the support of Fyfe Company, showed the enhanced performance of the strengthened beams when Fibr™ Anchors used to anchor the "U-shape" FRP. In Figure 4 is shown the maximum load under which the beams failed in shear: non-strengthened beam (105kN), strengthened with non-anchored "U-shape" FRP (147kN) and strengthened with Fibr™ anchored "U-shape" FRP with two different configurations of anchorage (169kN, 228kN).

The load carrying capacity increased almost 50% (228kN/147kN) comparing anchored versus non-anchored "U-shape" FRP and almost 120% (228kN/105kN) comparing strengthened with Fibr™ anchored "U-shape" FRP versus non-strengthened beam. Papers will be published soon, by the SML-UPatras with more detailed information on the work done.

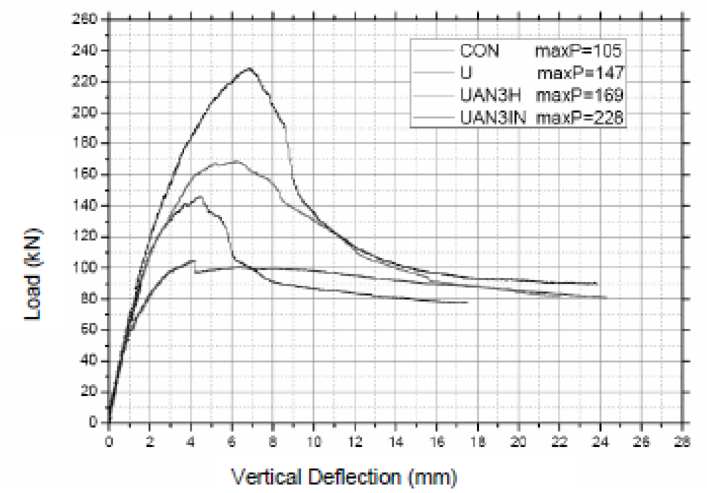

Figure 4. T-beams shear strengthening with FRP, (Structural Materials Laboratory - University of Patras).

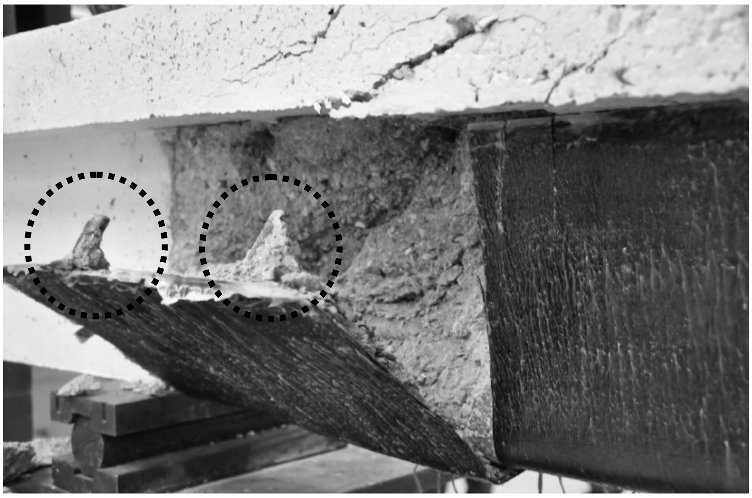

Figure 5. Fibr™ Anchors on a beam after testing and removing the FRP system (Structural Materials Laboratory - University of Patras).

Series of full scale tests have been further conducted on flexural strengthening of columns with FRP properly anchored with Fibr™ Anchors in the foundation (Figure 6). Results showed that proper configuration of large diameter and length Fibr™ Anchors can effectively transfer the stresses under monotonic or cycling loading from the vertical FRP layers into the foundation, in the joints or through the joints to the next floor.

Special cases of Fibrwrap® applications are always under consideration such the ones shown in Figure 7. Special design guidelines for Fibr™ Anchors systems have been developed by Fyfe Company for all cases.

Figure 6. Anchorage in the foundation (Fyfe Company).

Figure 7. Anchorage through walls (Fyfe Company).

4 COMPATIBLE REINFORCED MORTAR SYSTEMS FOR STRENGTHENING OF HISTORIC MASONRY STRUCTURES

New composite systems with inorganic matrices have been developed in the last years. These, so called RM (Reinforced Mortar) Systems or TRM (Textile Reinforced Mortar) Systems, have the advantages of being fully compatible to heritage structures and possessing excellent fire resistance by eliminating the use of epoxy. Research has been contacted, mainly in Europe, and some sample projects have been already completed.

RM Systems comprise of an inorganic mortar (matrix) which can be cement or non-cement based and an open weaved (EP) biaxial fabric as reinforcement which may consist of carbon, AR-glass or basalt fibers. The EP fabric usually has a balanced architecture of main fibers in 0◦/90◦. Important characteristics of the EP fabrics are the stability at the joints and the coating of the fibers. Tests have shown that a coated joint-stable EP fabric has much better performance comparing to an uncoated one with loose joint stability. The coating is a special thin layer high-temperature resistive coating. Bitumen, PVC and other similar fiber coatings can create weak links, at the boding between matrix and EP fabric, and performance in case of a fire event is questionable. Special fiber type anchors (Fibr™ Anchors) have been developed and tested for enhanced bonding of the system to the substrate, especially when non-cement low properties mortar is used as matrix of the RM system.

Basalt fiber EP fabrics have advantageous characteristics because of lower cost comparing to carbon and AR-glass, higher technical properties than AR-glass and good resistance in alkali environment. The durability in time of a RM system used on a heritage structure is important feature and more tests and studies have to be performed on this topic.

Main features of RM system are that it is totally compatible and consistent in physical characteristics (e.g. texture, color) to the substrate, relatively reversible technique comparing to FRP and other traditional methods (e.g. shotcrete), posses excellent fire resistance and is environmental friendly. RM system may also be used for strengthening of non-heritage masonry structures as well as concrete members for contact critical applications (e.g. columns wrapping).

Figure 8. Application of RM Basalt system at the Structural Materials Laboratory in University of Patras (Operha Project).

Extensive research and testing have been performed in the Operha Research project funded by the European Union. Main objective of the Operha were to set the standards and develop a strengthening system compatible to heritage structures. The laboratory research was followed by real life applications on listed monuments. One example is presented in Figure 10.

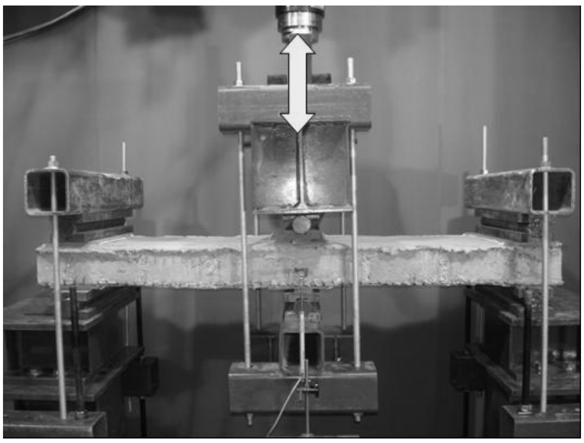

Figure 9. Out of plane cycling flexural testing in Structural Materials Laboratory, University of Patras (Operha Project).

Figure 10: Strengthening a vault of a Romanesque church in Spain (Operha Project).

4.1.1 References

Kodur, V, Bisby, L and Green, M. 2006. FRP Retrofitted Concrete under Fire Conditions, *Concrete International*, Volume: 28, Issue: 12.

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"Open and Fully Compatible Next Generation of Strengthening System for the Rehabilitation of Mediterranean Building Heritage", www.operha.eu