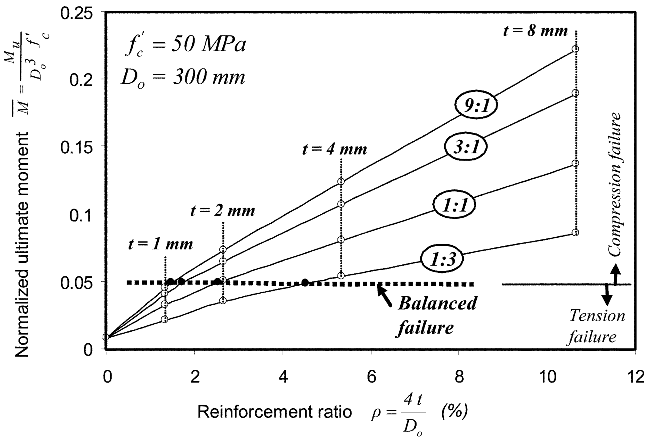


Fig. 9.9—Variation of flexural strength with reinforcement ratio for different laminate structures (Fam and Rizkalla 2002.)

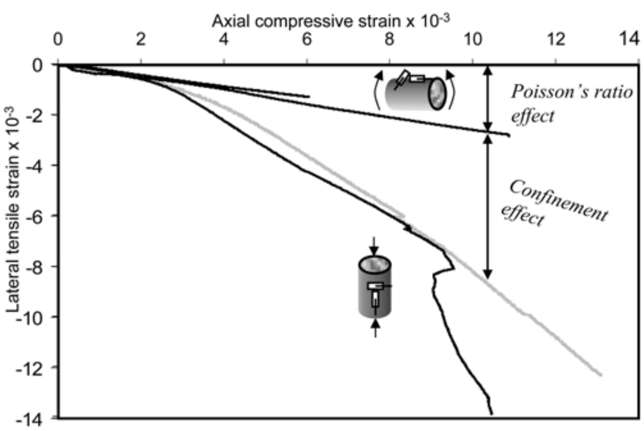
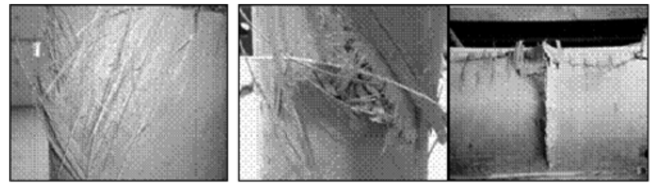


Fig. 9.10—Comparison between axial-lateral strain behavior in beams and columns (Fam and Rizkalla 2002).



(a) Tension failure *(b) Compression failure*

Fig. 9.11—Failure modes of CFFT: (a) tension failure; and (b) compression failure (Fam et al. 2003b).

governed by both the reinforcement ratio ρ and the laminate structure of the tube, where ρ = 4*t*/*D*, *D* is the diameter, and *t* is the thickness. Figure 9.9 shows the variation of the flexural strength with ρ for different laminate structures of the FRP tube, which had fibers oriented in the axial and hoop directions with various proportions designated as 1:3, 1:1, 3:1, and 9:1. A 1:3 laminate indicates that only 25% of the fibers are oriented in the axial direction. For a given laminate structure, increasing the wall thickness could change the failure mode from tension to compression. Similarly, for a given ρ, changing the laminate structure by increasing the stiffness in the axial direction could change the failure mode from tension to compression. Figure 9.9 also shows that the balanced ρ is reduced as the tube becomes stiffer (or thicker) in the axial direction.

9.8.4 *Confinement effect in CFFTs in bending*—When CFFT round members are subjected to bending, experimental studies (Burgueño 1999; Davol et al. 2001; Fam and Rizkalla 2002) have shown that the effect of confinement of concrete is insignificant. Figure 9.10 shows the axial strain versus the lateral strain behavior of the FRP tube in the compression zone of a beam, tested by Fam and Rizkalla (2002), versus that of a column of the same type. The figure shows that the behavior is bilinear for columns, with significant increase in lateral strains due to confinement. For beams, however, the behavior is linear, with a slope proportional to the longitudinal Poisson's ratio of the tube, which indicates lack of confinement. This is attributed to the strain gradient, where most of the cross section of the beam is in tension.

9.8.5 *CFFTs subjected to combined bending and axial loads*—Round CFFTs have been tested under constant axial loads and increasing bending (Seible et al. 1995; Mirmiran et al. 2000b) and under increasing eccentric axial loads (Fam et al. 2003b). Compression and tension failures were achieved as shown in Fig. 9.11. Fam et al. (2002) studied the effect of both the wall thickness and laminate structure (different proportions of fibres in the axial and hoop directions) on the interaction curves. The study showed that, for thin tubes, increasing the ratio of fibers in the hoop direction would increase the axial strength and reduce the flexural strength as evident from the curves in Fig. 9.12(a), which intersect at the optimal points for laminate design for each eccentricity. For thick tubes, increasing the amount of fibers in the axial direction increased both the axial and flexural strength, as shown in Fig. 9.12(b). Additionally, for thick tubes, the entire interaction curve could be governed by compression failure.

9.8.6 *Splices and joints in CFFTs*—Because of the limited lengths of CFFTs, splices could be needed. Parvathaneni et al. (1996) produced a 13.7 m (45 ft) long CFFT pile using three 4.57 m (15 ft) long units, spliced using short steel tubing 0.6 m (2 ft) long, which matched with the inside of the GFRP tubes. Ductile joints have been proposed between CFFT bridge columns and footings using short steel dowels (Seible et al. 1998). Pseudoductile plastic hinges have also been proposed for girders (Wernli and Seible 1998; Wernli 1999) using CFRP dowels that provide ductility through gradual slip between the concrete and the bars. The achieved ductility, however, is only in one direction, and the deformation and damage cannot be reversed. The load-slip characteristics for CFRP dowels with varying anchorage details were determined through numerous pullout tests. The behavior of the connection concepts was validated through full-scale flexural testing of longitudinally spliced girders (Wernli 1999). Seible et al. (1998) have also introduced connections between CFFT beams and deck slabs using steel dowels. The connections were studied through pushout tests and full-scale testing of CFFT beam/slab assemblies, which led to the development of design and analysis recommendations (Zhao 1999). Steel dowels for CFFT columns in seismic zones were introduced by Seible et al. (1995) and Burgueño (1999).

9.8.7 *Prestressed members*—Parvathaneni et al. (1996) proposed using filament-wound CFFTs prestressed in the

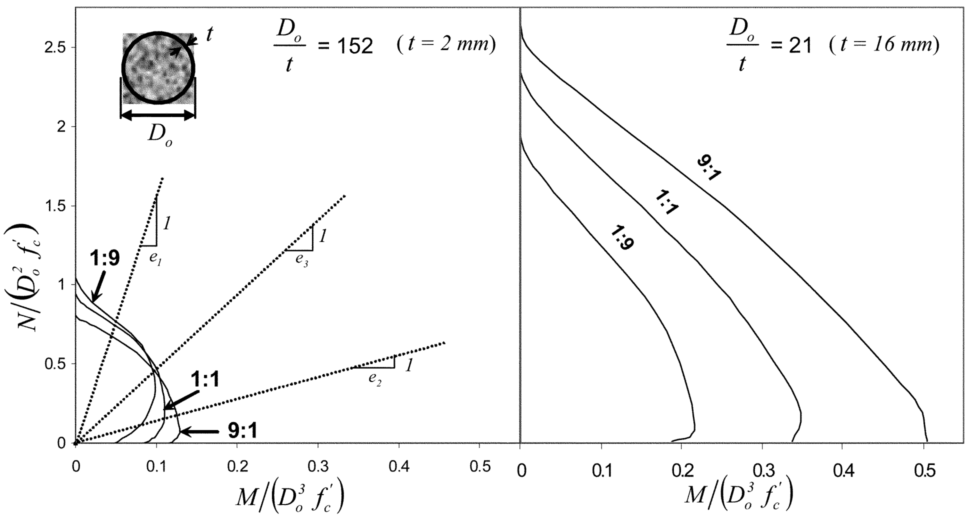


Fig. 9.12—Effect of thickness and laminate structure of tubes on interaction curves of CFFT (Fam et al. 2003b).

axial direction to produce alternative mooring piles. It was decided to take advantage of the high confined strength by prestressing the concrete to a high compressive stress, which was described as super-prestressing. Three 35 mm (1.4 in.) diameter steel Dywidag bars were pretensioned inside the tubes; 35 MPa (5 ksi) concrete was cast and cured; and finally, the bars were destressed, producing a 31 MPa (4.5 ksi) compressive stress in concrete. The conventional method of driving the pile was used. The maximum recorded dynamic strain in concrete was 1360 microstrains in compression, and no tension stresses were induced.

9.8.8 *Hysteretic behavior of CFFTs*—Seible et al. (1995) have tested carbon shell CFFTs with and without mild steel reinforcement anchorage bars as the CFFT-to-footing connection to study the response of CFFT bridge columns under simulated seismic loads. Shao (2003) has modeled and tested CFFTs under low-cycle fatigue, including the effect of loading and unloading on FRP-confined concrete and the seismic behavior of CFFTs with and without internal reinforcement, as shown in Fig. 9.13. Fan et al. (2000) have reported a ductility factor of 10 for CFFTs with internal mild steel reinforcement.

9.8.9 *Sustained loading*—Recent experimental and analytical investigations by Naguib and Mirmiran (2001) have shown that creep effects reduce the flexural stiffness of CFFT. Ultimate strength, however, is not significantly altered. A slow rate of loading and short-term creep at 70% of static capacity may cause premature rupture of the tube. Fiber analysis of CFFT beam-columns by discretizing the section into filled and hollow FRP tubes can adequately simulate the flexural creep behavior. Isochronous sustained stress-creep strain curves may be used as a constitutive nonlinear relationship for creep analysis in flexure. Creep deflection of beam-columns is much less than that of beams, mainly because axial compressive loads tend to retard cracking of concrete and tensile creep of the FRP tube. The axial stiffness ratio of the FRP tube with respect to the concrete core has a pronounced effect on creep deflection of CFFT beam-columns. As the stiffness ratio increases, creep deflections decrease. There exists, however, a threshold beyond which stiffer tubes do not provide additional benefit.

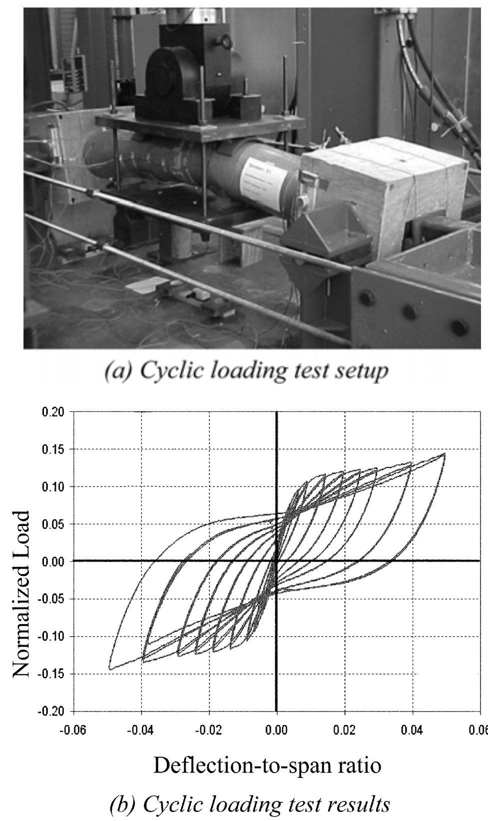


Fig. 9.13—Cyclic loading test of CFFT (Shao 2003).

CHAPTER 10—MASONRY APPLICATIONS

10.1—Introduction

"Building Code Requirements for Masonry Structures" (ACI 530/ASCE 5/TMS 402) covers the design and construction of masonry structures. The code provides requirements for design and construction of new structures. Repair, retrofitting, and rehabilitation of masonry structures are not included in the document.

FRP composites using various polymer and cementitious matrixes, and fiber reinforcement of treated and untreated glass, carbon, and aramid fibers have all been applied for strengthening of masonry. This chapter summarizes work that has been focused on FRP composite systems for strengthening of masonry structures.

Potential advantages of retrofitting masonry using FRP composites include low installation costs, flexibility of use, and minimum changes in the member size after repair. Disturbance to occupants and loss of usable space are also minimized. From a structural point of view, the dynamic properties of the existing structure remain unchanged because there is little addition of weight. If stiffness change is required, it may be engineered on a case-by-case basis by properly designing the composite retrofit.

Even though most of the research on FRP composites and field applications has focused on strengthening reinforced concrete members, available literature shows high potential for reinforcing and strengthening masonry. A research project between the U.S. Army Corps of Engineers and the Market Development Alliance (MDA) of the FRP Composites Industry (Marshall et al. 1999) tested over 100 clay and concrete masonry walls under in-plane loading, and produced a wealth of data on the increased strength and ductility of these walls. The efforts ended with a seismic simulation test in which four FRP composite systems were used to seismically retrofit a half-scale two-story brick building with dimensions of 3.66 x 3.66 x 3.66 m (12 x 12 x 12 ft). The main conclusions were:

- FRP composites can be applied to increase the strength of masonry walls in shear;
- FRP composites enable greater wall drift before failure occurs;
- For shear, glass fiber is preferred over carbon fiber because of the lower stiffness of glass; and
- The failure mode of masonry wall sections can be changed by the application of FRP. By the proper placement and selection of FRP composites on an unreinforced or a lightly reinforced masonry wall, failure modes such as x-cracking can be prevented while transferring the failure to a more ductile mode such as bed joint sliding or rocking before toe crushing.

The U.S. Army Corps of Engineers has published guidelines on the specification and construction of masonry repaired with FRP composites (UFGS 2004a,b). Furthermore, ACI Committee 440 and the Existing Masonry Committee of The Masonry Society (TMS) have established a joint task group for the development of design provisions.

10.2—FRP strengthening techniques

FRP composite products, in the form of externally bonded laminates and grids, and NSM bars are the typical approaches used to strengthen masonry structures. FRP composites have been primarily investigated for enhancing the structural capacity of masonry walls and columns (Masia and Shrive 2003).

10.3—FRP repair and strengthening of masonry

10.3.1 *Flexural strengthening*—Many research projects have been conducted to study FRP systems for flexural strengthening of masonry walls. Ehsani and Saadatmanesh (1996) investigated the flexural behavior of small-scale unreinforced masonry (URM) walls strengthened with GFRP sheets and found that the flexural capacity was increased up to 24 times compared with the unreinforced control specimen. According to the test results, the effect of the mortar strength appeared to be negligible, and both specimens failed by crushing of the masonry.

Velazquez-Dimas et al. (2000) reported test results of half-scale URM walls tested under out-of-plane cyclic loading. Two of the walls were strengthened on both faces with GFRP strips. Substantial increases in strength and deformation capability were achieved. The retrofitted walls resisted pressures up to 24 times the weight of the wall and deflected as much as 5% of the wall height. To avoid very stiff behavior and improve the hysteretic response, the authors recommended limiting the reinforcement ratio to two times the balanced condition. The balanced condition is defined as the point at which failure of the masonry in compression and rupture of the composite in tension occur at the same time. Although the brittle URM walls were retrofitted with a linear elastic material, the combination resulted in a system capable of dissipating some energy representing system nonlinearity.

Hamilton and Dolan (2001) investigated the flexural behavior of small-scale URM walls strengthened with different composite materials. Strengthening with high-strength composite materials such as CFRP and AFRP (with vertical fiber orientation) led to modes of failure such as delamination and shear in the masonry. To use the composite material more efficiently, two alternatives were recommended: first, to increase the spacing of the material until rupture of the laminate governed failure, and second, to use less expensive materials such as GFRP. These more efficient alternatives resulted in four failure modes: debonding, laminate rupture, masonry shear, and face shell pullout. They reported that debonding from the masonry substrate caused the failure of most of the test specimens.

The successful use of NSM bars for improving the flexural capacity of reinforced concrete members (De Lorenzis et al. 2000) led to extending this technique to URM walls. As an example, masonry panels of concrete blocks were tested by Tumialan et al. (2002). One specimen was strengthened with one No. 3 GFRP bar (9.5 mm [0.375 in.] nominal diameter), the second with two No. 3 GFRP bars, and the third was strengthened with an externally bonded GFRP laminate (width = 76 mm [3 in.]). For comparison purposes, specimens one and three had an equivalent axial stiffness $E_{FRP} \times A_f$ (modulus of elasticity × area) to each other. The wall strengthened with one GFRP bar failed due to debonding of the paste from the masonry. Initial flexural cracks formed at the mortar bed joints perpendicular to the reinforcement, and caused secondary cracks at the epoxy paste-masonry interface resulting in debonding and subsequent wall failure. The wall strengthened with two bars failed due to masonry shear, while the specimen with the GFRP laminate failed due to debonding. This experimental program was used as a validation for the strengthening of two URM concrete walls at an educational facility in Kansas City, Missouri, where the walls exhibited cracking in the bed joints at the midheight region.

By using epoxy strengthened with short fibers, Bajpai and Duthinh (2003) were able to prevent debonding of NSM GFRP bars and consistently rupture the bars in flexural tests of masonry walls. This method resulted in higher wall strength and a more brittle behavior.

The capacity of flexural walls strengthened with FRP laminates is a function of the axial load level (Triantafillou 1998b). Moreover, FRP composites are highly effective in the case of walls that can be treated as simply supported (that is, walls exhibiting a large slenderness ratio). For a wall with a low slenderness ratio built between rigid supports, FRP is less effective because arching action of the wall dominates over the effect of the FRP because crushing of the masonry units at the boundary regions controls ultimate behavior (Tumialan et al. 2002; Galati 2002).

In summary, available literature indicates that URM walls strengthened with FRP exhibit the following modes of failure: 1) debonding of the FRP laminate from the masonry substrate; 2) flexural failure (that is, rupture of the FRP laminate in tension or crushing of the masonry in compression); or 3) shear failure in the masonry. Of these three modes of failure, the literature has shown that the controlling mode is mostly debonding of the FRP laminate. Thus, the quantity of FRP reinforcement should be balanced against the masonry shear strength; if a large amount of FRP reinforcement is provided, a brittle masonry shear failure may result. Proper masonry design philosophy dictates that brittle shear failure should be avoided by ensuring masonry flexural capacity is exceeded by its shear capacity.

Debonding is directly related to substrate surface characteristics such as roughness, soundness, and porosity. For instance, Roko et al. (1999) observed that absorption of epoxy is limited in extruded brick units as compared with that in molded bricks, leading to a reduction of the bond strength at the FRP laminate-masonry interface.

Tumialan et al. (2002) suggested that, rather than attempting to predict bond failure, the strain in the FRP laminates could be limited. The effectiveness of the FRP reinforcement depends on the bond of the FRP laminate to the masonry substrate. Because the flexural capacity is dependent on the strain developed in the laminate, effective strain in the laminate ε_{fe} can be expressed as the product $\kappa_m \varepsilon_{fu}$, where κ_m is the bond-dependent coefficient, and ε_{fu} is the design rupture strain of FRP. Tumialan et al. (2002) concluded that for nonputtied surfaces, κ_m can be assumed to be 0.45, and for puttied surfaces, κ_m can be 0.65.

Luciano et al. (2001) investigated the possibility of reinforcing masonry arches using FRP composite materials and found that the FRP laminates greatly enhanced the capacity of masonry arches.

To enhance the out-of-plane seismic resistance of the facades of historic masonry buildings, unobtrusive FRP rehabilitation techniques that incorporate intermittently bonded NSM carbon fiber rope and unbonded and intermittently bonded NSM carbon fiber composite cables (CFCC) were developed at McMaster University (Korany 2004). Ten full-size clay brick wall panels were retrofitted and tested under both monotonic loading and quasi-static cyclic loading using an airbag. Korany and Drysdale (2004) reported significant increases in ultimate capacities, energy absorption, and deformability compared with the behavior of the unreinforced walls.

10.3.2 *Shear strengthening*—Schwegler (1995) investigated strengthening methods for masonry shearwalls with FRP laminates. CFRP laminates were bonded diagonally to the masonry walls and mechanically anchored to the adjoining reinforced concrete slabs. The test results showed that the strengthened walls exhibited 50 and 300% increases in ultimate capacity and displacement, respectively, as compared with unstrengthened walls.

Cracked URM concrete block walls were repaired by Gergely and Young (2001) using CFRP laminates attached to both sides of the specimens and subjected to cyclic out-of-plane loads and in-plane loads. The symmetric laminates significantly increased the flexural and shear capacity of damaged walls. The specimens failed as a result of severe shear damage in the concrete masonry blocks.

Concrete masonry walls strengthened with FRP laminates in the horizontal direction only and tested with in-plane loading along the wall diagonal were observed to fail due to sliding shear along an unstrengthened joint (Tumialan et al. 2001; Morbin 2001). This mode of failure, which is undesirable if there are adjacent columns such as in the case of infill walls, may be controlled by placing FRP bars in the vertical direction to act as dowels.

As in the case of URM walls strengthened for flexure with FRP laminates, the type of masonry has been observed to be one of the factors influencing the in-plane wall behavior. Thus, in the case of clay brick masonry walls strengthened with laminates for shear, FRP strengthening has been observed to be more efficient than in the case of concrete masonry (Grando et al. 2003). This can be attributed to characteristics of the parent material such as height of masonry courses (that is, smaller in the case of brick masonry) and better mortar-masonry unit bond characteristics. Grando et al. (2003) also reported that the in-plane capacity of clay masonry walls strengthened on one and two faces doubled when the amount of FRP reinforcement was doubled.

Valluzzi et al. (2002) reported experimental results on small-scale clay brick masonry specimens using variables such as the type of FRP laminates (CFRP and GFRP) and strengthening configurations (single-side versus double-side strengthening, and square grid and diagonal). Double-sided strengthened specimens were more effective than single-sided specimens. In general, the diagonal strengthening configuration was observed to be more effective than the grid configuration; also, GFRP laminates were more effective than CFRP at increasing shear capacity.

Bastidas et al. (2002) investigated the strengthening with GFRP laminates of small-scale nonstructural masonry walls built with clay tiles. In addition, a full-scale wall was tested to validate the technology. The strengthening configurations included vertical and horizontal laminate strips, combinations of both, and diagonal laminates (cross-pattern). The test results showed the efficiency of the GFRP reinforcement for increasing the shear strength as well as the ductility of the system. The cross-pattern layout on both sides of the wall proved to be the most effective configuration. A significant global reduction of damage levels was observed for the strengthened masonry wall when compared with results reported by the same authors on similar URM walls. Also, global stability and overall seismic behavior were greatly improved with the GFRP reinforcement for in-plane loading.

Strengthening by FRP structural repointing can also remarkably increase the shear capacity of URM walls. Repointing is a technique used in masonry to repair and replace the mortar in the joint. With FRP repointing, the mortar is cleaned out, epoxy is placed into the groove, and an FRP bar is placed into the same groove into the epoxy. This was evident from the results of tests conducted on concrete masonry walls loaded along the diagonal (Tumialan et al. 2001; Morbin 2001). The maximum increase in shear capacity was 80% for walls strengthened with GFRP bars placed at every bed joint. Walls with reinforcement staggered on both wall faces exhibited the largest pseudoductility.

FRP structural repointing was also used to improve the in-plane structural performance of masonry infill walls (Tumialan et al. 2003a,b,c). Full-scale specimens were subjected to in-plane cyclic load. The specimens were surrounded by reinforced concrete frame and a stand-alone reinforced concrete support. The results indicated that FRP-strengthened specimens could reach lateral drifts of 0.7% without losing lateral carrying capacity, and, that for this drift level, the degradation of lateral stiffness in the strengthened walls did not implicate degradation of lateral carrying capacity.

With the objective to find alternative embedding materials to epoxy-based paste, Turco et al. (2003) investigated the in-plane behavior of concrete masonry walls strengthened with GFRP bars embedded in two different materials: epoxy-based paste and latex-modified cementitious paste. The in-plane test results showed that the performance of walls with both materials yielded similar results. The use of less expensive pastes, such as the latex-modified ones, makes the FRP structural repointing technique more appealing because the structural performance is not reduced and the appearance of the filled joints is similar to conventional mortar joints.

The effectiveness of increasing the shear strength of brick masonry by epoxy-bonding FRP overlays to the exterior surfaces was evaluated by Ehsani et al. (1997a). The variables in the test included the strength of the composite fabric, fiber orientation, and anchorage length. Specimens were tested under static loading. The results showed that both the strength and ductility of tested specimens were significantly enhanced. The orientation of the angle of fibers with respect to the plane of loading had a major effect on the stiffness of the retrofitted system, but did not affect the ultimate strength significantly.

The experimental results of three half-scale unreinforced brick walls retrofitted with vertical composite strips were presented by Ehsani et al. (1999). The specimens were subjected to cyclic out-of-plane loading. Five reinforcement ratios involving two different glass fabric composite densities were investigated. The mode of failure was controlled by tensile failure when wider and lighter composite fabrics were used and by delamination when stronger ones were used. The strengthened specimens were able to support a lateral load up to 32 times the weight of the wall. A deflection as much as 2% of the wall height was measured.

Avorio and Borri (2001) studied the problem of seismic strengthening of monumental arches and vaults. The interest in this technique came about from the examination of the types of collapse involving arches and vaults and from problems shown by structures strengthened with traditional methods. In formulating the criteria, attention was paid to the behavior of the vaults according to their constructional type and the type of texture and pattern.

Moon et al. (2003) and Moon (2004) tested, under lateral loads, a full-size two-story URM brick building that was strengthened using several FRP techniques. On one three-wythe wall, GFRP was epoxy-bonded vertically on the inside face, while NSM glass rods were epoxy-bonded into horizontal bed joints on the exterior face. This two-way retrofit increased the lateral strength, caused cracks to be well distributed, and produced a ductile-type failure mode with broad hysteresis loops and considerable energy dissipation. The four FRP systems used in this project included: precured structural grids embedded in trowel-applied epoxy adhesive (Fig. 10.1); wet lay-up unidirectional glass fabrics with an epoxy matrix (Fig. 10.2); epoxy adhesive-applied NSM GFRP rods (Fig. 10.3); and glass grids in cementitious trowel-applied matrix (Fig. 10.4). Application of GFRP systems on the other multiwythe walls worked well in in-plane shear retrofit because header bricks every sixth course generally maintained continuity between wythes.

In-place tests were performed by Corradi et al. (2002) on FRP retrofitted masonry walls damaged by recent earthquakes. Both CFRP and GFRP unidirectional laminates were used to retrofit the masonry panels, followed by in-plane tests. The tests confirmed that the shear capacity of the masonry panels was significantly increased by the FRP materials.

10.3.3 *Settlement repair*—Hartley et al. (1996) tested two full-sized 200 mm (8 in.) concrete block walls, 2.4 m (8 ft) high and 6.0 m (20 ft) long to investigate the feasibility of using unidirectional CFRP sheets to repair settlement damage. In the study, settlement loads were first applied to induce characteristic step cracking. CFRP was then applied to one surface, and the wall retested. Strength gains of over 50% were recorded. The results suggested that CFRP was suitable for rehabilitating concrete block walls damaged by foundation settlement.

10.4—Design and application considerations

10.4.1 *FRP system selection requirements*—Several suitable FRP systems are currently available to repair or retrofit masonry structures. To select the proper FRP system for a particular project, several factors have to be considered by the design engineer and building owner. Some of these factors are:

- Types of masonry construction: non-load bearing, load bearing, or retaining walls, and parent material (that is, concrete or clay masonry unit);

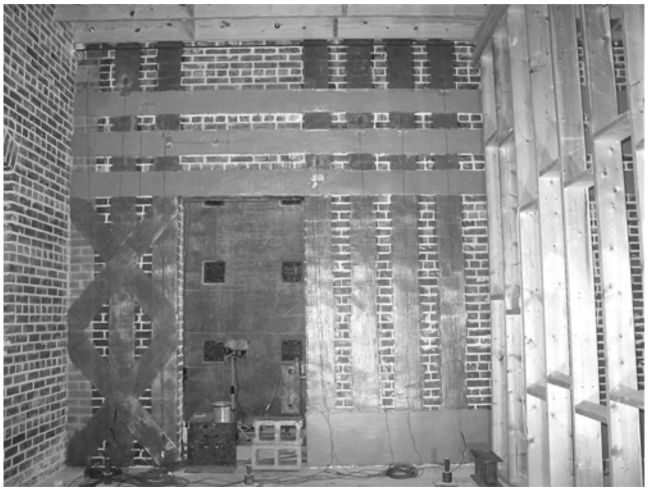


Fig. 10.1—Precured structural grids embedded in trowel-applied epoxy adhesive (Moon 2004).

Fig. 10.2—Wet lay-up unidirectional glass fabrics with epoxy matrix (Moon 2004).

Fig. 10.3—Epoxy adhesive-applied NSM GFRP rods (Moon 2004).

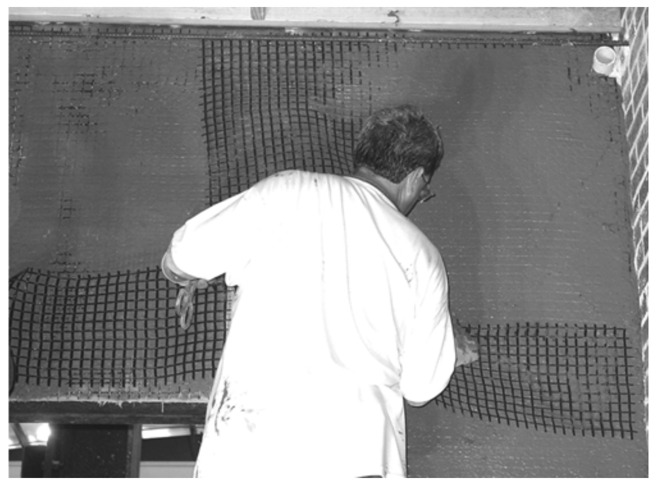


Fig. 10.4—Glass grid in cementitious trowel-applied matrix (Moon 2004).

- Overall building condition (damage level, presence of cracks, surface coatings, accessibility), with particular emphasis on the condition of the substrate. The condition and strength of the masonry substrate is an important parameter for bond-critical applications, including flexure or shear strengthening. The existing masonry substrate should possess the necessary strength to develop the design stresses of the FRP system through bond;
- Repair or retrofit impact on building operation;
- Building occupancy and use;
- Architectural considerations; and
- Building code and fire code requirements. Coatings can be used to limit smoke and flame spread.

Many of these factors have been addressed in several publications. Saadatmanesh (1994) provided an overview of the FRP applications for existing structures, including seismic retrofit of URM buildings. Christensen et al. (1996) studied the architectural implications of reinforcing existing masonry walls with FRP composite materials, the problems associated with the various substrates, and building code issues related to smoke and fire hazards. In the study, they also evaluated FRP-compatible architectural finishes.

10.4.2 *Detailing requirements*—In addition to strength and stiffness requirements, FRP retrofit or strengthening of masonry walls should also address application specific requirements. Among these are FRP composite reinforcement strength development, anchoring systems, and connections for the composite systems and between structural elements (Hamilton and Dolan 2001).

Proper FRP reinforcement detailing at wall boundaries is necessary to ensure expected performance and avoid premature failure due to debonding. For externally bonded laminates, this may be attained with anchorage systems that include steel angles, steel bolts, and FRP bars. Different systems offer their own advantages and disadvantages. Steel angles are easy to install, but aesthetically problematic. Angles in direct contact with the masonry surface may locally fracture the wall due to displacement and rotation restraint. Steel bolts have shown high effectiveness, but require a demanding installation effort (Schwegler 1995).

A technique similar to the one used for anchoring laminates in reinforced concrete joists strengthened in shear (Annaiah 2000) can be used for anchoring laminates in masonry applications. The installation technique consists of grooving a slot in the upper and lower boundary members. The ply is wrapped around an FRP bar that is placed and bonded in the slot with a suitable epoxy-based paste (Carney and Myers 2003a,b). For NSM or structural repointing construction, bars can be easily anchored into adjacent concrete members by drilling and embedding their extended terminations (Tumialan et al. 2003a,b,c).

NSM FRP bars can also be used to improve the anchorage of masonry walls to boundary reinforced concrete beams or foundations (Tumialan et al. 2002; Carney and Myers 2003a,b). Multiwythe steel reinforced masonry parapets built using clay units with standard dimensions were tested in-place. Several steel bars were missing or irregularly placed in the original construction. Before installing the GFRP bars, the holes in the reinforced concrete beam and slots in the masonry were filled with an epoxy-based paste. The design rationale was to provide enough flexural reinforcement to force the occurrence of shear failure. The masonry walls were loaded in-plane as cantilever walls. The control wall lost carrying capacity due to the crack growth caused by rocking. In the retrofitted wall, the opening of the horizontal crack in the strengthened side was controlled. Because of the eccentricity of the GFRP anchors, the wall tilted, preventing the development of the full flexural capacity. The improvement in capacity with respect to the unanchored parapet, however, was over 100%.

10.4.3 *Surface preparation*—Once the adequate FRP system has been selected and designed for the repair or retrofit project, the masonry surface to which the FRP system will be applied should be properly prepared. Surface preparation is necessary to adequately transfer the forces between masonry elements and surface-bonded FRP composite overlays. This preparation consists of complete removal of all mortar droppings, dust, dirt, oil, existing paint or coatings, and efflorescence from the masonry surface. Smooth-faced epoxy-coated or glazed units should first be roughened by grinding or sandblasting.

For unspoiled new clay or concrete masonry surfaces, wire brushing proved to be adequate to remove any loose particles or dust. The surface preparation of older clay or concrete masonry structural members, however, may require more intrusive techniques such as water blasting, grinding, or wire brushing with power tools. Concrete masonry units may be lightly sandblasted (Hamoush et al. 2001), but this method should be used with caution for clay units.

10.4.4 *Installation of FRP system*—For the installation of an FRP system, the recommendations of the system manufacturer should be precisely followed, with deviations requiring approval of the manufacturer and the design engineer. Typical masonry details such as weep holes, concrete masonry control joints, and clay masonry expansion joints should be maintained in their original condition. For example, no resin or FRP laminate should cover weep holes, and no FRP material should bridge masonry movement joints.

CHAPTER 11—DURABILITY OF FRP USED IN CONCRETE

A significant design issue for FRP composites is the consideration of overall durability of these materials, especially as related to their capacity for sustained performance under harsh and changing environmental conditions under load.

Although FRP composites have been successfully used in the automotive, marine, industrial, and aerospace sectors, critical differences exist in loading, environmental exposure, and the types of materials and processes used in these applications as compared with those likely to be used in civil infrastructure applications. Anecdotal evidence provides substantial reason to believe that, if appropriately designed and fabricated, these systems can provide longer lifetimes and lower maintenance than equivalent structures fabricated from conventional materials. Experimental data on durability, however, is sparse, not well documented, and not readily available. Additionally, some evidence has been found of rapid degradation of specific types of FRP composites exposed to certain environmental conditions found in civil engineering.

11.1—Definition of durability

In the context of this report, the durability of FRP or structural members using FRP is their ability to resist cracking, oxidation, chemical degradation, delamination, wear, fatigue, the effects of foreign object damage, or a combination of these for a specified period of time, under the appropriate load conditions, and under specified environmental conditions.

11.2—Durability of FRP composites

11.2.1 *Materials*—Without the protection of the appropriate resin, E-glass fibers are the most susceptible to degradation due to moisture and alkalinity. Similarly, aramid fibers are resistant to abrasion and impact, but show a propensity to creep, absorb moisture, and degrade under ultraviolet exposure. Carbon fibers are relatively inert to the environment. In composite design, however, the individual fibers are encapsulated in a suitable resin system to form the composite. Thus, the fibers are protected from the environment by the resin. The durability of the resin system is dependent on several factors, including the resin components and proportions as well as curing time and conditions. The composites industry has many resin systems that are designed for specific end-use applications and should be chosen based on the mechanical, physical, chemical, electrical, or other considerations in the operating environment. Properties of materials typically used in FRP composites used with concrete can be found Chapters 4 and 5 of this document or in 440.1R and 440.2R.

Both the fiber system and the resin system should be chosen based on requirements of structural performance, constructibility, and durability. Different fibers and resin systems provide differing degrees of resistance to environmental conditions such as moisture, alkaline solution, UV radiation, or extreme temperatures. Thus, the constituents need to be chosen based on both performance and durability requirements. The processing method and quality assurance and quality control used during processing are important predicators of quality and durability of the fabricated composite component. A summary of the significant factors affecting durability was presented by Porter at a SAMPE Symposium (Porter 1999).

11.2.2 *Overview of ASCE/CERF document*—The ASCE/CERF (Karbhari et al. 2003) document "Durability Gap Analysis for Fiber Reinforced Polymer Composites in Civil Infrastructure" provides the results of a gap analysis identifying critical areas in which data are needed. In this document, the use of FRP composites in the form of reinforcing bars, external reinforcement of concrete structures, seismic retrofit of concrete and masonry structures, replacement and new bridge deck systems, and wall panels and profiles were identified to be of the maximum interest. Therefore, the evaluation of durability issues with these applications was assigned the highest priority in the report. The following durability issues were addressed: moisture or aqueous solutions, alkaline environment, thermal effects, creep and relaxation, fatigue, and UV radiation. An analysis of the existing data was performed to rank the importance and availability of data in each of the topic areas.

11.2.3 *Environments*—The intent of this section is to outline the environments that FRP composites used with concrete and masonry are likely to encounter. Each section gives a brief summary of the effect that each of these environments has on the constituents usually found in FRP composites used with concrete.

11.2.3.1 *Moisture (water and salt solution)*—All resins absorb moisture, with the percentage of moisture sorption depending on the resin structure, degree of cure, and temperature. The two primary effects of moisture uptake are plasticization and a reduction in glass transition temperature. In general, moisture effects over the short term cause more pronounced degradation in strength as opposed to stiffness of the composite. Salt solutions can cause blistering due to osmotic effects. In some cases, moisture has been observed to wick along the fiber-matrix interface, resulting in a loss of structural integrity. Moisture can also affect the fracture toughness of FRP composites, with reported results being somewhat contradictory (Karbhari et al. 2003).

In the case of glass fibers, degradation is initiated by moisture-extracting ions from the fiber. Fibers need protection of the resin to avoid such deterioration. Aramid fibers absorb moisture, causing loss of transverse and compressive strength (Karbhari et al. 2003).

11.2.3.2 *Chemical solutions*—In most cases, the effect of chemical solutions is on the resin system, with the absorption following a diffusion-based process similar to that of water (Karbhari et al. 2003). The presence of specific salts or other chemicals in the solution can accelerate deterioration in the presence of inappropriate resin systems. A large number of specialty resin systems are available that are resistant to varying levels of chemical attack and exposure.

11.2.3.3 *Alkaline environment*—Alkaline solutions, such as the pore water of concrete, have a high pH and a high concentration of alkali ions (Neville 1995). Carbon fibers are resistant to alkaline solutions. Resin damage via alkali attack is generally more severe than that due to moisture. E-glass fiber systems should be properly designed and fabricated with the appropriate resin system to protect the reinforcement from alkali attack. Alkali-resistant glass fibers are available and can decrease the rate of deterioration substantially. A significant amount of extremely high pH testing has been conducted at Iowa State University, resulting in several investigations, such as by Mehus (1995). These tests show that, under a loading resulting in a stress of 40% of ultimate, some FRP reinforcing bars can fail while submerged in a solution with a pH of 12.8. Tests from the same source also show that the reinforcing bar that had been submerged in the high pH solution lost as much as 60% of its tensile strength. Later tests from the same location indicated that when improved resins were used, the results improved significantly; thus, durable resins need to be used for these environments (Boris and Porter 1999).

11.2.3.4 *Extreme temperature and thermal cycling*—The primary effects of temperature are on the viscoelastic response of the resin, and hence, of the composite. As temperature increases, the modulus of the resin will decrease. If the temperature exceeds the glass transition temperature T_g, FRP composite performance will decrease substantially. Thermal cycling below T_g generally does not cause deleterious effects, although extended thermal cycling of brittle resin systems can result in microcrack formation (Karbhari et al. 2003).

The coefficients of thermal expansion (CTEs) for FRP composites are generally quite different from those of steel and concrete. For the case of glass FRPs, the CTE is generally higher than that of steel and concrete. For carbon and aramid FRPs, the CTE is generally lower than that of steel and concrete in the direction of fibers (Hollaway and Leeming 1999). The CTE will vary considerably with fiber and resin type as well as fiber orientation and constituent volume fractions. The difference in CTE should be considered when composites are used in direct combination with steel and concrete systems.

11.2.3.5 *Low temperature and freezing and thawing*—In general, low temperature and freezing-and-thawing exposures do not affect fibers, although they can affect the resin and the fiber-resin interface. Polymeric resin systems are known to embrittle, resulting in increased strength and stiffness under sub-zero (but noncryogenic) conditions (Chawla 1998). Freezing-and-thawing effects can be more severe due to moisture-initiated effects, causing microcrack growth and coalescence because of cycling. The presence of road salts in wet conditions with subsequent freezing and thawing can cause microcrack formation and gradual degradation due to crystal formation and increased salt concentration.

11.2.3.6 *Creep and relaxation*—Polymer resins generally exhibit creep and relaxation behavior. The addition of fibers increases the creep resistance of the resins. Consequently, creep and relaxation behavior are more pronounced when load is applied transverse to fibers or when the composite has a low fiber volume fraction (Karbhari et al. 2003). Typically, thermosetting resins (unsaturated polyesters, vinylesters, epoxies, and phenolics) are more resistant to creep than are thermoplastics (polypropylene, nylons, and polycarbonates).

Carbon fibers are the least susceptible to creep rupture; aramid fibers are moderately susceptible; and glass fibers are most susceptible to creep rupture (Hollaway and Leeming 1999). Extrapolations of short-term creep data to longer service lifetimes in room-temperature air suggest rupture strengths of 29 to 55%, 47 to 66%, and 79 to 93% of the initial strength for essentially unidirectional GFRP, AFRP, and CFRP materials, respectively (Yamaguchi et al. 1997; Ando et al. 1997; Seki et al. 1997; Greenwood 2002).

E-glass fibers are also susceptible to environmental stress corrosion cracking. This is a delayed brittle fracture effect that is caused by synergism between stress and the environment (Jones 1999).

Stress limits for FRP composites under sustained load to avoid premature failure due to stress rupture can be found in ACI 440.1R and 440.2R.

11.2.3.7 *Fatigue*—The fatigue performance of FRP composite materials depends on the matrix composition and, to some extent, on the type of fiber (Curtis 1989). The individual fibers within unidirectional composites have few defects, and are consequently resistant to crack initiation. Additionally, any crack that does form travels through the matrix and is not transmitted through adjacent fibers. These toughness and crack-arresting properties contribute to the good fatigue performance of FRP materials.

11.2.3.8 *UV radiation*—Polymeric materials undergo degradation when exposed to UV radiation between 290 and 400 nm due to dissociation of chemical bonds (Karbhari et al. 2003). The subsequent reaction with oxygen can lead to oxidation, chain scission, or cross-linking. In general, effects are rarely severe in terms of mechanical performance, although some resins can show significant embrittlement and surface erosion. The most deleterious effect of UV exposure is generally not the UV-related damage, which is surface limited, but the potential for increased penetration of moisture and other agents via the damaged region. In some cases, degradation at the surface has been found to affect mechanical properties disproportionately because flaws can serve as stress concentrations (Chawla 1998). FRP composites can be protected from UV-related degradation with appropriate additives in the resin, appropriate coatings, or both.

11.3—Internal reinforcement

11.3.1 *Introduction*—This section covers the degradation process and mechanisms affecting hygro-thermo-mechanical properties of FRP reinforcing rods under exposure to alkaline environments, alternate wet and dry cycles (in corrosive and noncorrosive mediums), freezing-and-thawing conditions, temperature and humidity variations, and loads (creep and fatigue).

11.3.2 *Moisture*—Sen et al. (1998) conducted a 45-month study on the long-term performance of AFRP and CFRP pretensioned elements used to reinforce piles driven in tidal waters, based on destructive tests. Results indicated that bond degradation adversely affected the ultimate capacity of AFRP-reinforced piles, but the CFRP-reinforced piles were largely unaffected.

11.3.3 *Alkaline environment*—The reaction of FRP composites to alkaline conditions in concrete is a major design consideration. The internal concrete environment initially has high alkalinity, with the pH between 12 and 13. This alkaline environment can have an effect on fibers, such as glass and aramid, as discussed in the previous section.

Although an appropriate resin matrix (vinylester, epoxy) provides a high level of protection to fibers from this degradation, migration of high pH solutions and alkali salts through the resin (at voids, cracks, and interface between the fiber and matrix) to the fiber surface is possible (ACI 440.1R). In addition, the application of special surface coatings or fillers, selection of suitable chemistry, and improvement in manufacturing processes can all improve the durability of FRP composite reinforcement in an alkaline environment. For instance, Shah et al. (2002) observed a 50% reduction in the room-temperature diffusion rate of water into vinylester resin filled with montmorillonite nano-clay, although the equilibrium moisture content increased compared with the same resin without filler.

Aqueous solutions with high pH are known to degrade the tensile strength and stiffness of GFRP bars (Porter and Barnes 1998; Rostasy 1997; Sen et al. 1998; Takewaka and Khin 1996; Sheard et al. 1997; GangaRao and Vijay 1997). On the other hand, Devalapura et al. (1998) concluded that GFRP reinforcement exposed to both alkaline and acidic environments retained significant load-bearing capacities for extended life cycles under conditions harsher than expected in field service. Al-Dulaijan et al. (1996) detected a considerable reduction in bond strength of bars immersed in a high-pH solution for 28 days. This reduction appeared to be a result of degradation of the resin.

Arockiasamy and Sandepudi (1994) concluded from experimental studies that the Young's modulus of CFRP composite reinforcement in a combined seawater and alkaline solution with sustained tension was reduced by approximately 12% over exposure periods from 3 to 9 months. The same exposure, however, did not affect the ultimate strength.

In 2004, ISIS Canada approved a project to study the performance of GFRP reinforcement that has been used in many demonstration concrete structures across Canada (Mufti et al. 2005). The objective of the study was to provide the engineering community with the results of the performance of GFRP reinforcing bars that have been exposed to a concrete environment in built structures and to calibrate the Canadian Highway Bridge Design Code (CHBDC) performance factors on the GFRP reinforcement. Core specimens of GFRP reinforcement were collected from five field demonstration projects across Canada. Analytical methods, such as scanning electron microscopy and energy-dispersive x-ray, optical microscopy, differential scanning calorimetry, and infrared spectroscopy, were used to determine the degradation of GFRP in concrete structures.

Based on the results of the aforementioned analyses described, Mufti et al. (2005) found no visible degradation of the GFRP reinforcement (rods and grids) in the concrete environment in real engineering structures exposed to natural environmental conditions for 5 to 8 years. The results from scanning electron microscopy and x-ray analyses suggest no degradation of the GFRP reinforcement materials in the demonstration concrete structures. The x-ray analyses indicate no alkali ingress in the GFRP reinforcement from the concrete pore solution. The conclusion of the project was that the GFRP reinforcement is durable and highly compatible with the concrete material. Also, the team concluded that the CHBDC is conservative; therefore, the material performance factors of the GFRP bars should be increased. This change has been incorporated in the new addendum for the CHBDC.

11.3.4 *Low temperature and freezing and thawing*—At low temperatures, complex residual stresses arise within FRP composites as a result of matrix stiffening and mismatch of CTEs of matrix and resin as well as FRP and concrete (Chawla 1998). Residual stresses can cause microcracks in the matrix and fiber-to-matrix interface, which can grow under low-temperature thermal cycling and coalesce to form transverse matrix cracks and debonding between the fibers and the matrix.

In general, the reported literature shows that unidirectional tensile strength decreases when exposed to temperatures between –10 to –40 °C (14 to –40 °F), whereas the off-axis and transverse strengths may increase due to matrix hardening. Increasing freezing-and-thawing cycles have been shown to accentuate residual stresses, resulting in increased severity and density of cracks. An apparent increase in matrix brittleness and decrease in tensile strength has also been reported (Lord and Dutta 1988).

Mashima and Iwamoto (1993) determined that bond strength of GFRP and CFRP rods was not influenced by freezing and thawing, but AFRP (both braided and coiled) rods showed a gradual reduction of bond strength up to about 20% with continued freezing and thawing.

11.3.5 *Temperature*—Researchers reported that extremely elevated temperatures (above the glass transition temperature) have a detrimental effect on bond, probably because of lower shear stiffness in the FRP. The GFRP achieved the highest residual bond strength, while the AFRP achieved the lowest, but slip increased dramatically with increases in temperature in all the materials (Nanni et al. 1995; Katz et al. 1999).

11.3.6 *Creep and relaxation*—Odagiri et al. (1997) investigated relaxation characteristics of 6 and 7.4 mm (0.24 and 0.29 in.) diameter AFRP tendons with anchorages. Overall, the relaxation rates for AFRP rods were found to be approximately 11% at 1000 hours, and 15% at 17,700 hours (2 years).

Creep rupture is another important concern when FRP reinforcing bars are subjected to long-term loading. Creep-rupture is the tensile rupture of a material subjected to sustained high stress levels over a period of time. The creep-rupture behavior of 3 mm (0.12 in.) diameter FRP composite circular rods of glass, aramid, and carbon fiber was evaluated by Dolan et al. (1997) by nonaccelerated techniques. Aramid specimens were more susceptible to stress concentrations at anchor points. Substantial decay was found in the long-term resistance of the glass tendons, especially when in direct contact with cementitious material.

Nikurunziza et al. (2002) conducted stress rupture tests on GFRP bars. After 60 days of exposure, the loss of tensile strength was 4% for a water exposure and 11% for alkaline exposure at temperatures of 65 to 75 °C (149 to 167 ºF).

Almusallam et al. (2002) conducted stress rupture tests on GFRP bars embedded in concrete beams and exposed to water. The strength losses were less than 5% for unstressed specimens, but as high as 30% for stressed specimens.

Den Uijl (1991) predicted the long-term performance of aramid bars in an alkaline environment using temperature as the varying parameter. The tests indicated that the time to failure under constant load at 60 °C (140 °F) was between 10 and 15 times shorter than when tested at 20 °C (68 °F). Ando et al. (1997) found similar results.

Sheard et al. (1997) studied durability of FRP-reinforced concrete in aggressive alkali and wet and dry environments at different temperatures and stress levels. Based on the test results, the authors suggested a 100-year life threshold stress limit of about 25% for GFRP, 50% for AFRP, and 75% for CFRP.

Creep experiments performed by Apinis et. al. (2000) showed that carbon fibers do not creep at strain levels as high as 0.69% for 17,700 hours. Aramid fibers, starting at a strain level of 1.38%, creep by 69% after 16,800 hours. Glass fibers creep by 5% from a starting strain level of 0.78% after 16,600 hours. Experiments and analysis performed by Tamužs et. al. (2001) concluded that hybrid composites, CFRP+AFRP and CFRP+GFRP, have a considerably higher creep resistance compared with pure aramid and glass composites. If brittle components such as carbon fibers are used in the hybrid composite, however, a certain risk of overloading the component exists due to the large creep of aramid fibers. After the breakage of carbon fibers, the creep will accelerate and may lead to the failure of the whole composite if the load level for the remaining fibers is high.

11.3.7 *Fatigue*—As described in Section 11.2.3.7, FRP composites generally have very good resistance to fatigue. In the case of internal reinforcement, fatigue loading is more likely to affect the concrete and the bond between the concrete and the FRP reinforcement than the FRP itself. It should, however, be noted that cracking in concrete could cause abrasion related damage to the FRP surface, which could result in higher environmental exposure to moisture and solutions.

11.3.8 *UV exposure*—In the case of internal FRP reinforcement, there is no direct exposure of the FRP to UV and hence this is not of concern except through any deterioration that UV may cause to concrete at the systems level.

11.4—External reinforcement

This section is devoted to the performance of external FRP reinforcement for concrete that has been adhesively bonded to the surface of the concrete. Included in this classification are both confinement systems such as column wrapping and flexural and shear reinforcement. External reinforcement is likely to see a more varied environmental exposure than that of internal reinforcement including moisture cycling, chemical solutions, and UV radiation.

In adhesively bonded FRP systems, one face of the material is adhered to the concrete and one is exposed to the envi-