ABSTRACT

Fibre Reinforced Polymers (FRPs) constitute a class of advanced composite materials which have the potential to change significantly masonry rehabilitation and strengthening. Their light weight means that they do not alter the mass of a structure and thus the inertial forces from seismic excitation. Their strength and, in the case of sprayed Glass FRP, their toughness, indicate that they can alter the load deformation response considerably for the better. Further testing is required, but FRP’s open an exciting new line of possibilities for masonry.

1. INTRODUCTION

Fibre Reinforced Polymer (FRP’s) are a class of advanced composite materials that emanated from the aircraft and space industries. They have been used extensively in the medical, sporting goods, automotive and small ship industries and are now finding uses elsewhere. Over the past few years there has been extensive research into their potential applications in the construction industry. Recent special issues of journals like Construction and Building Materials [1] and the Canadian Journal of Civil Engineering (CJCE) [2] have been devoted exclusively to the use of FRP’s in construction, while the American Society of Civil Engineers has a journal dedicated to the subject – the Journal of Composites for Construction [3]. In the former, there is no mention of masonry; in the CJCE issue there is only one paper (co-authored by this writer), and only half-a-dozen articles on masonry appear in seven volumes of the ASCE Journal. The main emphasis in research has been on reinforced concrete structures – strengthening deteriorated
structures, particularly beams and columns – and substituting FRP rods as reinforcement in new construction. The underlying objective is to provide longer service life by avoiding problems associated with steel corrosion or increasing the load capacity of older or deficient structural members. Holloway [4] gives an overview of many applications in FRP and FRP/traditional material composite structures: he like many others, does not mention masonry.

As there are more masonry structures in the world than concrete, masonry researchers have not been oblivious to the opportunity, but have not examined the possibilities as rapidly or extensively as in the concrete arena. In a recent review [5], Lissel and Gayevoiy cite only 47 references (in English), although there are others in other languages as indicated for example, in Lourenco and Pocas Martins [6], and there has been continuing publication over the last year.

The purpose here therefore is to provide a brief introduction to FRP’s, to examine research results pertinent to the possible performance of masonry subject to seismic loading and to make suggestions as to possible avenues of further research.

2. FIBRE REINFORCED POLYMERS

FRP’s consist of high strength fibres embedded in a resin matrix. The fibres are usually Carbon (CFRP’s), Glass (GFRP’s) or Aramid (AFRP’s). The fibres are strong – many times stronger than steel – in the longitudinal direction and generally weak laterally. Typically the fibres show no ductility, so FRP’s are linear elastic to failure. CFRP’s have the highest modulus, around 150 GPa, and strengths in the range of 2500-3000 MPa. The properties of FRP’s have been summarized in various publications (e.g. [7]), and are continually improving. Recent introductions involve combinations of fibres to provide non-linear responses to stress – attempts to achieve some “ductility” in the material.

FRP’s not only have the advantage of very high strength over “conventional” materials, but are also light weight and highly durable in many environments. The light weight makes rehabilitation techniques much easier as heavy handling equipment is not needed in constricted spaces. The high durability is very attractive for applications where steel deteriorates rapidly (e.g. corrosion of reinforcing bars in bridges and parkades). One drawback is the susceptibility of the resin in FRP’s to ultraviolet light. The resin slowly becomes brittle – often seen in plastic objects as they “weather” over the years when exposed to sunlight. Thus, FRP must be protected from exposure to direct sunlight – which can easily be achieved indoors and with paint. New resin formulations are being developed which will not suffer from this problem.

A second unavoidable disadvantage of FRP’s is their degradation under heat, and their lack of fire resistance. At the service temperature of most structures, the binding resins are stable, but as the temperature increases, the resin breaks down and evaporates. Sayed Ahmed and Shrive [8] showed that at 500°C it only took two hours for the resin to evaporate from CFRP tendons, to leave the carbon fibres as a package of uncooked spaghetti. The effect of lower temperatures, was less drastic. Fire retardants can be sprayed over the FRP’s to provide some fire resistance but this is one area where further work is necessary.
For the construction industry, FRP’s are available in sheets, strips, tendons (for pre-or post-tensioning) and reinforcing bars and meshes. If all the fibres are aligned in the longitudinal direction of the sheet, strip, tendon or rod, then highly anisotropic behaviour is obtained. Very high strength and much greater stiffness occur in that direction compared to others. Some sheets are now available with multidirectional fibres, providing more orthotropic properties, and other structures can be specifically filament–wound to give desired multidirectionality to the fibres [9].

FRP’s and their fabrication techniques are evolving quite rapidly: the price relative to other material options is dropping. The economics of using FRP’s are thus improving, whether it be for rehabilitation of old structures or for use in new construction.

FRP’s can therefore be more-or-less selected in form and property for a particular intended use. This then leads to the third area of concern for the use of FRP’s in composite construction: how to bind the FRP to the structures. In some instances this is not too problematic, for example with a GFRP mesh which can be embedded in fresh concrete. However in many instances, there has been need to develop new understanding and new techniques. For example, to increase the bond strength between GFRP rods and concrete, some rods were produced with sand embedded on the surface. Delamination of strips and sheets from the underside of concrete beams can be the limiting condition in design, requiring new anchorage techniques and design methods [10]. Surface preparation is very important to the success of FRP application as unfilled cracks or unsmoothed irregularities can cause premature debonding. This poses a concern for masonry which must be investigated to determine the essential requirements for positive results.

3. FRP’S IN MASONRY

Research into the use of FRP’s in masonry has been reasonably wide ranging, with the same issues in mind as with concrete. From the durability perspective, GRFP’s have been examined as possible substitution for steel ties in cavity wall construction [11, 12]. The use of GFRP to make connectors between intersecting walls has been broached [13]. Such approaches might well be able to improve the ability of masonry not to disintegrate under seismic loading. Undoubtedly, further work is warranted.

Post-tensioning has also been investigated [14, 15]. A major problem has been anchorage of the tendons. Standard anchors for steel tendons rupture CFRP tendons very easily, so new anchorage systems are under development (e.g: [16, 17]). Post-tensioning increases both the cracking moment of resistance and the ultimate moment of masonry walls, so has some attraction for application in seismic areas. However, there would be a need in design to have some component of the masonry fail in a stable manner at ultimate rather than the prestressing tendon.

Of greatest interest with respect to seismic applications are the studies on strengthening walls, columns and arches/vaults with FRP’s.
3.1. Walls

Various researchers have examined the use of various FRP’s to enhance masonry wall performance under monotonic or seismic loading [16-32]. Initial work centred on bonding FRP’s to the tension side of clay-brick beams subject to bending [16]. Large increases in both load and strain capacity to failure were observed, with the amounts depending on the quantity and type of the FRP used. Further testing followed, leading to reverse cyclic loading on half-scale reinforced brick walls with GFRP strips bonded to both sides of the walls. The ultimate flexural strength of the walls was increased up to 32 times the self weight of the wall – as applied pressure. The walls resisted deformations up to 14 times that permitted in the relevant specifications, with inelastic behaviour being observed.

Triantafillou [21] also tested wallettes in both in-plane and out-of-plane bending. He used perforated clay units as opposed to the solid ones above. The out-of-plane bending wallettes reinforced with CFRP strips failed through masonry crushing, whereas in-plane loading caused the CFRP laminates to peel off. The theoretical model of performance was verified, with a set of graphs provided to determine load increases.

Seible [22] reported on the retrofit of damaged masonry walls. These were from the US-Japan TCCMAR 5-story full-scale reinforced masonry building test. The building consisted of two reinforced concrete masonry walls on each story. The walls were coupled at each floor level through a precast, prestressed concrete floor system. The seismic load excitation was provided at each floor level and at the roof. The structure was subject to progressively increasing limit states from simulated earthquake ground motions, rather than predetermined lateral load patterns. The walls were then repaired with carbon FRP laminates: further testing indicated the repair improved performance.

Hollow (unreinforced) concrete masonry walls were tested, retrofitted with CFRP laminates on both sides of the walls and retested by Gergely and Young [23]. Three walls were tested with in-plane reverse cyclic loading and three with out-of-plane loading. The addition of the CFRP increased capacity in terms of displacement by a factor of 4 in shear and 8 in bending, but 31 times in load. The authors emphasized that it is the ability of the FRP’s to resist tension that is the main contributing factor to the increase in capacity of the walls. This is a similar finding to others, both for shear and bending of brick work [24-26] and blockwork [27-28] under monotonic loading.

Capozucca [29] tested clay masonry shear walls with flanges under axial and lateral load. The flanges were then repaired with CFRP sheets. The lateral load was not applied dynamically, but nevertheless the finding was that the repairs were highly effective in increasing stiffness and ultimate loads.

Unreinforced blockwork was tested at the University of Alberta, first with an examination of how various widths, thicknesses and patterns of GFRP sheets improved bending stiffness and strength [30]. Subsequently a reduced number of combinations was applied to both faces of steel-reinforced walls subject to reverse cyclic bending [31]. The conclusion was that amount of GFRP reinforcement on the surface of the walls was the most significant parameter in determining the behaviour of the wall. The walls maintained structural integrity throughout the tests. The failure modes were examined carefully and a numerical model developed [32] to predict behaviour given the failure modes observed. This model provided good agreement with
the experimental results, which provides confidence that economical design methods can be developed for reinforcing masonry with the new materials.

One issue that remains with all of the tests to date, is that where only one side was reinforced, monotonic tests were performed, or repeat tests, where that side was the tension side in bending. Where reverse cycling was employed, reinforcing was applied to both sides of the masonry. This is unsightly and would be unacceptable in the repair of a historical building. Hence there is a need to consider how to achieve the increases in strength and resilience that appear possible, but through application of materials on one side of the wall only (the side that would be hidden from view).

3.2. Columns

Much less work has been done on columns than on walls. However significant effort has been put into strengthening plain and reinforced concrete columns (e.g. [33-37]). The consensus is that simply wrapping a column with an FRP wrap is a passive form of strengthening [10]. The wrap is laid with the fibre direction circumferential so that maximum resistance against circumferential expansion of the column is offered. However, the interaction between the wrap and the column is such that the wrap is not activated until the concrete is actually dilating substantially as it is failing [38]. The same was found for masonry columns [39]. Early work on concrete found that round columns were most effectively confined and that the sharp corners of square columns caused premature failure of the wrap. This was confirmed in masonry [40]. Minimum radii for the corners of concrete columns have been recommended [41] to avoid this problem, so bull-nosed units were used for the corners of some columns, and others had the corners chamfered [39]. The columns were initially loaded to cracking, and then rehabilitated with CFRP wrap [39]. Failure loads exceeded the initial cracking loads considerably, but there was not much increase in strain capacity. Failure appeared to be initiated by complete crushing of the mortar joints, causing wrinkles in the wrap Figure 1, followed by explosive disruption of the CFRP wrap Figure 2.

Figure 1. Wrapped masonry columns at peak load develop wrinkles in the wrap (a), which are associated with crushing of the mortar joint (b) (Courtesy of M. Masia).
The material first rips vertically, then very rapidly circumferentially at failure of both concrete Figure 3 and masonry columns, providing a very exciting end to the test. This mode three failure of the wrap is along the weakest direction of a linearly-aligned FRP laminate – between the fibres. Recent tests on concrete columns sprayed with CFRP, such that the fibre orientation in the plane of the column surface is random, have shown that the increased toughness against the rapid propagation of a circumferential tear Figure 4 increases the strain capacity immensely (Figure 5) [42]. Spraying is a simple and cheap way of applying FRP, and the increase in toughness against cracking in any direction may well be of benefit in numerous applications. Hence this technique warrants much further investigation.

Figure 2. Failure can be explosive as demonstrated by the extensive damage in these columns. Circumferential rips in the CFRP wrap are visible on inspection (Courtesy of M. Masia).

Figure 3. The circumferential tearing of the wrap is clear in this view of a failed concrete column (Courtesy of B. Scholefield).
Figure 4. With sprayed GFRP, there is considerably increased toughness against crack propagation, both parallel to the direction of compression and circumferentially as the concrete dilates. This column has failed with no disintegration (Courtesy of B. Scholefield).

Figure 5. There is a highly significant increase in axial strain capacity with the sprayed GFRP [42].

3.3. Arches (vaults)

In the restoration of damaged historical structures there may well be the need to strengthen masonry arches or vaults. There have been a few sets of monotonic tests on the effect of FRP reinforcement on such structures [43-49]. The use of different width FRP strips alters the failure mechanism of the arch [43]. A simple theoretical model, in which the FRP is treated as a tension tie-rod and the masonry an assembly of rigid blocks which can only transmit compression at their contact points, was quite successful in predicting the behaviour. The model can be used to select the width of FRP which will result in the best strength gain while inducing failure through FRP delamination rather than masonry crushing [43,44]. The only
dynamic tests on vaults the author is aware of [45], showed that the reinforcing the extrados of barrel vaults restored the natural frequency of the first mode of vibration almost to that of the undamaged masonry. However, the damping characteristics were not restored, and the authors note that the application of the GFRP fabric did not re-establish the original vault geometry due to cracks and displacements from the loads causing the original damage. They also noted the importance of obtaining good bond. Indeed, debonding of extrados reinforcement was found not to occur if there is sufficient intrados reinforcement to cause failure by crushing, sliding or FRP rupture [45]. Debonding occurs if failure is by the formation of a mechanism. As long as the strengthening technique is sufficient to avoid debonding, considerable strength gain can be achieved. An analytic model was developed to help determine the amount and location of FRP for best strengthening [46].

Valluzzi et al [47] found that failure could occur in a vault strengthened with laminates for one of three reasons: crushing of the masonry, debonding of the FRP or sliding of a mortar joint due to shear. The presence of the reinforcing altered the mechanism of formation of plastic hinges. They studied the behaviour of arches strengthened with CFRP or GFRP laminates placed either on the intrados or the extrados. Strengthening the extrados revealed a brittle mode of failure – sliding between the bricks and mortar close to the springing point. This could be resisted with the application of further material at that site. Placing FRPs on the intrados led to a “ductile” failure caused by progressive debonding of the laminate. A simple model was also proposed to analyse the failures.

A more complex analytic method using constrained optimization has also been proposed [48]. The results suggest that significant increases in strength can be obtained from small amounts of FRP placed strategically on the intrados. Anchorage at the abutments was found to be critical, with thin laminates being more effective than thicker ones. Numerical modelling of FRP strengthened arches shows promise [49], as a tool for improving our understanding of the interplay between the properties, amount and location of the FRP with the properties and dimensions of the masonry. FE analysis lends itself to providing significant insight given the large number of variables, so long as the materials and the bond between them can be modelled well.

4. CONCLUSION

There is great potential for the use of FRP’s to strengthen and rehabilitate masonry with respect to seismic loading. The materials are light weight and very strong. The former is advantageous in not adding weight to the structure while the latter can be very advantageous if used intelligently. However, strength might not be the primary criterion. It may be that toughness is of more importance, since seismic excitation can induce both in-and out-of-plane loading. Reinforcement designed to deal with the known types of load we can apply in the laboratory may not fare so well under the multiple loading scenario in an earthquake. Cracks propagate rapidly and easily between the fibres in uni-directional laminates leading to potentially brittle failures. A layer of a material like sprayed short-fibre GFRP might be more capable of not cracking and not permitting collapse of the masonry.

In new masonry, specially designed FRP connectors, which again have higher toughness in maintaining integrity in the structure need to be developed.
Since so little has been done, but what has been investigated shows exciting promise, further work is needed to explore the many possibilities of improving the performance of masonry, both new and old, under seismic loading.

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6. REFERENCES


