Strengthening of historic masonry structures with fibre reinforced plastic composites

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Abstract

The paper deals with the application of unidirectional fibre reinforced plastics for strengthening of masonry monuments. The materials are applied in the form of either externally applied circumferencial tendons to provide horizontal confinement, or laminates, which are epoxy-bonded to the facades of masonry buildings serving the role of tensile reinforcement.

1 Introduction

The importance of consolidation, repair and strengthening of monuments for the conservation of the architectural heritage is becoming increasingly important. Structural interventions in monuments often follow special principles, e.g., those of the Charter of Venice [1]. Very important among these principles are the requirements that interventions should not adversely affect the *character* of the monument, that they must be *reversible*, especially when they have not been proven by a very long-in-service performance, and that they must be *distinct* from the original architectural composition, bearing the stamp of their time.

Two of the methods most commonly used to strengthen historic masonry structures comprise (a) external post-tensioning with steel ties, to tie structural elements together into an integrated three dimensional system, and (b) application of reinforced concrete or shotcrete jackets (e.g., UNDP/UNIDO [2]). The first method combines efficiency, simplicity and reversibility. It has been applied in many historic structures, such as the Rotunda and the San Andreas domes in Thessaloniki, the Martinego rampart of the Old Castle in Corfu, the Pisa Tower, etc., but presents some practical difficulties in protecting the strands against corrosion and handling them at the construction site (due to their considerable weight). The second method is more effective in terms of increasing the strength, stiffness and ductility of old masonry buildings, but suffers from the disadvantage that the heavy concrete jackets needed to increase the masonry's bearing capacity and also to protect the reinforcement from corrosion cannot always be applied to the facades, because: (a) they add considerable weight to the structure, which cannot be carried down to the ground level if columns and arches exist there, and (b) the added thickness (in the order of 10 cm) may violate the aesthetics requirements.

As an alternative to the first method, the steel ties can be replaced with fibre reinforced plastic (FRP) materials (composites), which offer excellent physical and mechanical properties, they are lightweight and immune to corrosion, and may be applied to historic structures in a reversible manner, in the form of external tendons in a colour matching that of the external surface of the structure. An alternative to the second method involves bonding of FRP laminates to the surface of the masonry in the locations and parallel to the directions of the maximum principal tensile stresses, thus serving the role of tensile reinforcement. Both of these innovative techniques are briefly described next.

2 Composites as strengthening materials

Over the last decades, the Chemical Industry developed various types of high strength organic and inorganic fibres (made of glass, aramid or carbon, with diametre in the range 5-25 μm) and composite materials made of such fibres in combination with polymeric matrices (epoxy, polyester, vinylester, etc.). These materials offer the designer an outstanding combination of properties, such as low weight (which is approximately 4 times less than that of steel), very high strength, and excellent chemical resistance, at a (materials) cost which is 2-4 times higher compared with steel on a strength basis. However, when overall construction costs (labor, maintanance, etc.) are considered, the cost comparisons become quite favourable for the composites. As a result, composite materials are increasingly becoming important in the construction industry too, with great potential in many areas. For instance, unidirectional FRPs (that is, with continuous and parallel fibres at a high volume fraction, around 50-70%) find numerous applications, including the development of tendons for prestressing (e.g., Nanni [3], Machida [4]) and strengthening of concrete and wood structures with nonprestressed or prestressed composite laminates, bonded externally to the tension faces using epoxy adhesives (e.g., Meier [5], Triantafillou & Deskovic [6], Plevris & Triantafillou [7], Triantafillou and Plevris [8]).

For the common case of unidirectional FRPs, their mechanical properties compare as follows with those of steel: Young's modulus = 50 GPa, 65-120 GPa and 135-190 GPa, and ultimate strain = 3%, 2-3% and 1-1.5% for materials with glass, aramid and carbon fibres, respectively, versus 200 GPa and 3-5% for high-strength steel. Note though that the short-term tensile strength, which is in the order of 1500-2100 MPa (versus 400-1700 MPa for mild or prestressing steel), drops to approximately 45%, 55% and 75% of these values for composites with glass, aramid and carbon fibres, respectively, when the loads are sustained (e.g., Nanni [3], Machida [4]).

3 Strengthening by external prestressing

Concepts

Old masonry structures can be strengthened using FRP ties as shown in Fig. 1a. The tendons, in the form of either round rods or strips attached to the masonry only at their ends, are circumferentially applied on the facades of the structure and post-tensioned to provide horizontal confinement (Triantafillou & Fardis [9]).

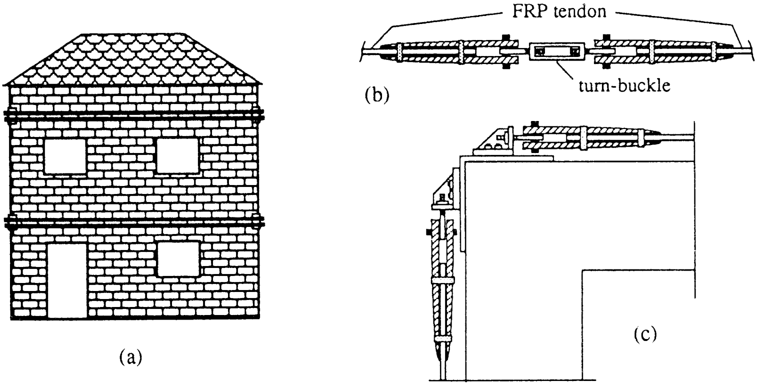

Figure 1: (a) Application of external FRP ties; (b) anchorage for circumferential prestressing of semi-spherical domes; and (c) anchorage/attachment for masonry structure corners.

Due to their anisotropic nature, unidirectional composites have relatively low transverse compressive strength (approximately 10% of tensile strength) and even lower (interlaminar) shear strength. Furthermore, because of their brittle nature, the materials are sensitive to stress concentrations and hence cannot be pierced or threaded. Finally, their abrasion resistance allows only limited frictional stresses. Thus, conventional anchoring solutions (upset heads, threads, wedges, etc.) are not applicable, and relatively large anchor lengths are required. Strip-like tendons may be better than round ones for external post-tensioning of masonry, because they minimize anchor lengths (due to their large surface area) and simplify the attachment of anchorages on the masonry walls. Proposed concepts for anchorages and their attachment on masonry are illustrated in Fig. 1b, c.

Figure 1b refers to circumferential prestressing of structures with a circular plan and involves a single FRP tendon around the perimetre, gripped at each end between a pair of steel plates to which it is epoxy-bonded. The two pairs of plates extend into a threaded steel bar and are coupled by a usual turn-buckle. Because FRP tendons cannot be bent to a large curvature, they cannot turn around sharp corners of the structure and have to be individually anchored there. For this latter case the anchorage in Fig. 1c is proposed, involving a steel or FRP angle weakly attached to the corner of the wall and transferring prestressing forces to the masonry through bearing stresses. The two tendons anchored at the same corner angle have to be prestressed gradually, by alternate turning of the nuts at their end anchorage, so that at each corner the moments of the individual

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tendon forces with respect to the corresponding wall mid-surface counterbalance each other. For no such end moment to develop during tensioning at a dead or passive anchorage, the two pairs of tendons actively anchored at two diagonally opposite corners have to be tensioned simultaneously.

Behaviour of FRP-confined masonry - Simple case studies

Monument-type masonry structures are often made of unreinforced stone masonry, which can be idealised as isotropic material. The ultimate strength condition of this material under multiaxial loading can be described by the failure criterion of Ottosen [10], which, in agreement with experimental evidence, predicts an increase in the compressive strength of biaxially loaded masonry up to about 100%, depending on the level of confinement. The confinement stress is provided by the transfer of prestressing forces to the masonry. Assuming that the tendons are prestressed to the maximum allowable level and that the prestressing forces are distributed so that the reinforcement can be considered as smeared, the confinement stress is equal to

$$\sigma_{wp} = \frac{\alpha_s}{\gamma_p} \frac{f_{fc,k}}{\gamma_{fc}} \varrho_{fc} \tag{1}$$

where $f_{fc,k}$ = characteristic tensile strength of fibre-composite material, γ_{fc} = fibre-composite material partial safety factor (= 1.15 for steel tendons), α_s = composite material tensile strength reduction factor due to sustained loading ($\alpha_s < 1$ for composite tendons and $\alpha_s = 1$ for steel tendons), γ_p = partial safety factor for prestressing (which, according to FIP [11], is equal to 1.2), and ϱ_{fc} = area fraction of fibre-composite material or reinforcement ratio, that is the ratio of FRP cross-sectional area to the area of the prestressed masonry. Typical values of $f_{fc,k}$, α_s, and γ_{fc} for GFRP (glass fibre reinforced plastic), AFRP (aramid FRP) and CFRP (carbon FRP) are given in Table 1 (Triantafillou & Fardis [12]).

Table 1. Characteristic FRP tensile strength and reduction factors for typical FRP tendons.

Type of FRP	$f_{fc,k}$ (MPa)	α_s	γ_{fc}
GFRP	1700	0.45	1.25
AFRP	1500	0.55	1.20
CFRP	1900	0.75	1.15

Rectangular building The state of stress in a typical masonry element of a rectangular building subjected to both vertical and horizontal loading and strengthened with horizontal FRP ties is given in Fig. 2a. The increase in the shear capacity (τ) of such a masonry structure, as obtained by the failure criterion for isotropic masonry under biaxial stress, is given in Fig. 3a in terms of the level of prestressing and for three different values of vertical stress (σ_v). Note that all the stress values are normalised with respect to the design uniaxial compressive

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strength of masonry, f_{wd}, assumed here for convenience to be equal to 1.5 MPa. In Fig. 3b, the shear capacity is given as a fraction of σ_v for three different types of prestressing tendon materials and for just one vertical stress level, in terms of the FRP area fraction.

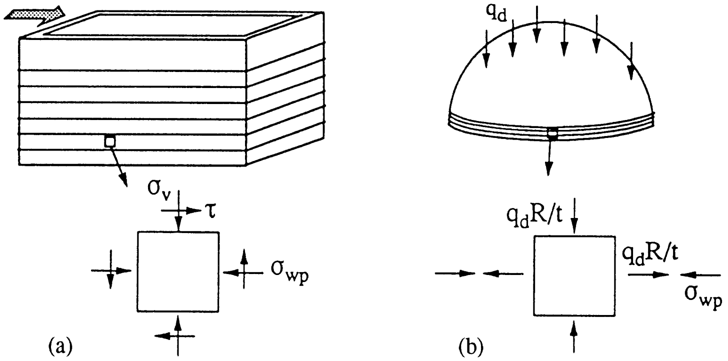

Figure 2: State of stress in (a) rectangular masonry structure under vertical and horizontal loading, and (b) semi-spherical dome under vertical loading.

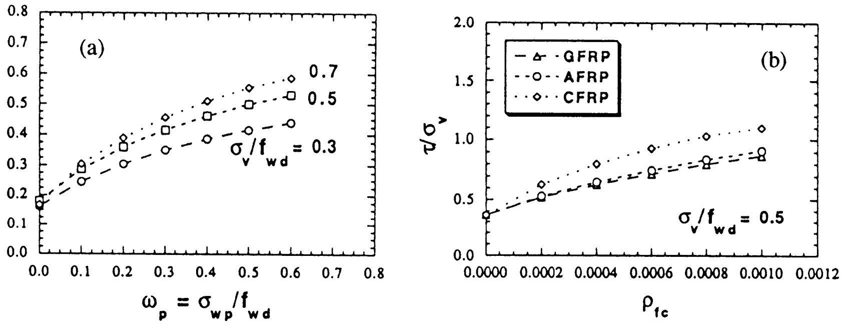

Figure 3: (a) Normalised shear strength versus normalised confinement due to prestressing, for different vertical loads. (b) Shear strength (as a fraction of vertical stress) versus FRP area fraction for different composites.

It is clear that increasing the level of confinement (or, in other words, the area fraction of FRP tendons) gives a remarkable increase in the shear capacity (e.g. earthquake) of the structure, which is more pronounced for the higher levels of gravity loading. Moreover, this increase is highest for CFRP tendons and approximately the same for GFRP or AFRP (of the same area fraction).

Semi-spherical dome Figure 2b shows the state of stress near the base (worse case) of a semi-spherical masonry dome with radius to wall thickness ratio equal to R/t, subjected to uniformly distributed over the dome surface vertical loading q_d, and strengthened with horizontal ties in the base area. The increase in the maximum vertical load (normalised with respect to f_{wd} = 1.5 MPa) for such a structure, as obtained by the failure criterion for isotropic masonry under biaxial stress, is given in Fig. 4, for the three different types of composite materials (Fig. 4a) and two R/t ratios (Fig. 4b, for CFRP only), in terms of the tendons area fraction. It is shown that increasing the FRP tendon area fraction gives a remarkable increase in the vertical load capacity of the structure, which is more pronounced for CFRP tendons and almost independent of the R/t ratio.

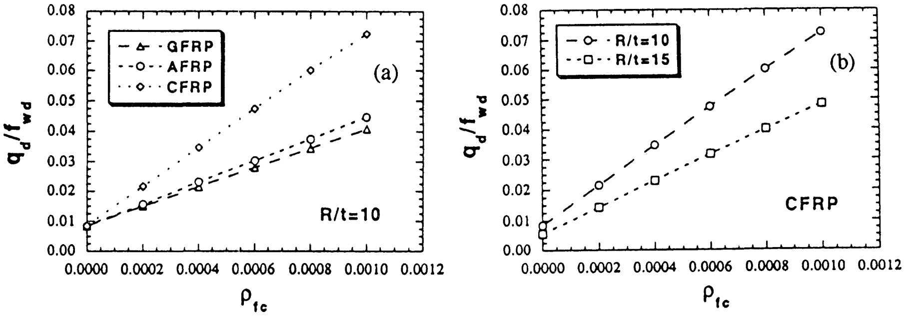

Figure 4: Vertical load capacity of semi-spherical dome in terms of FRP area fraction for: (a) three types of tendons and constant R/t, and (b) CFRP tendons.

4 Strengthening with bonded laminates

Concepts and practical application

The facades of old masonry buildings can be strengthened through the surface application of FRP laminates, as illustrated in Fig. 5a. The laminates are bonded (through epoxy adhesives, which are spread over their whole length) to the surface of the masonry in the locations and parallel to the directions of the maximum principal tensile stresses, thus serving the role of tensile reinforcement.

The application of this technique involves various steps, which can be summarised as follows: (a) determine optimum laminate dimensions and locations based on detailed structural analyses of the structure; (b) prepare the masonry surface by exposing, grinding and vacuum-cleaning the masonry in the zones where the laminates are to be bonded (± 5 cm approximately from each laminate edge); (c) provide suitable anchorage zones for the laminates by cutting in the masonry (Fig. 5b); (d) apply primer to the masonry bonding area; (e) apply epoxy adhesive to the masonry bonding area; (f) clean the laminates thoroughly; (g) push the laminates against the masonry and press firmly until the adhesive starts hardening; (h) remove pressure; and (i) cover the laminates with plaster (preferably reinforced with a low-cost polyester fabric).

The effectiveness of this strengthening technique has been proven in laboratory tests conducted at the Swiss Federal Laboratories for Materials Testing and Research (EMPA) by Schwegler [13]. Schwegler's results show considerable increases in the strength and ductility of unreinforced brick masonry, for both in-plane and out-of-plane loading. Remarkably, the first worldwide application of the strengthening method using epoxy-bonded CFRP laminates is expected to be realised in a 150 year old 3-storey building in the historic centre of Patras, Greece, by the summer of 1995 (Fig. 5a).

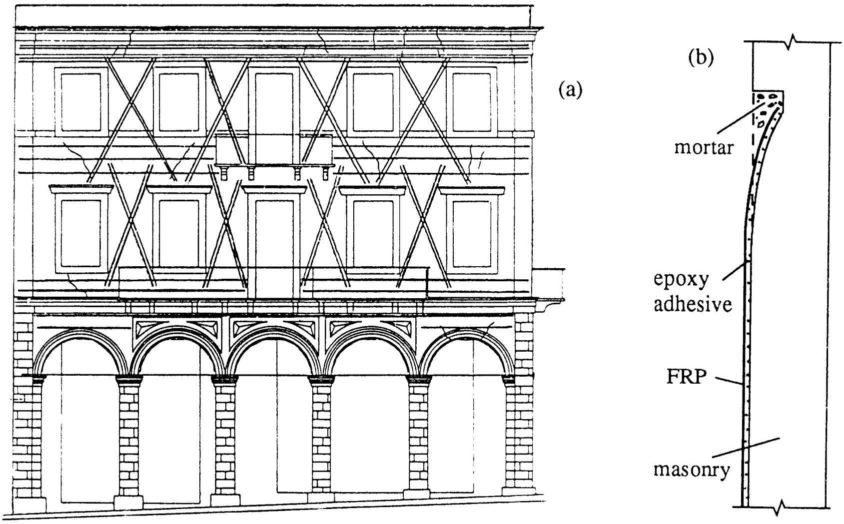

Figure 5: (a) The concept of surface reinforcement of old masonry building facades with epoxy-bonded FRP laminates. (b) Elevation illustrating the FRP anchorage.

5 Conclusions

Fibre reinforced plastics offer many advantages as strengthening materials of historic structures: they have excellent physical and mechanical properties, are lightweight and immune to corrosion, and may be applied either in a reversible manner in the form of circumferential externally attached tendons in a colour matching that of the external surface of the structure, or as epoxy-bonded laminates to the facades of masonry buildings which cannot be strengthened by concrete jacketing. Post-tensioned FRP ties may increase the strength of unreinforced masonry under horizontal (shear-type) and/or vertical loads considerably, especially if they are made of CFRP. Externally epoxy-bonded laminates, on the other hand, appear to give efficient solutions in the cases where aesthetics or other considerations call for a strengthening scheme of low weight.

6 Acknowledgements

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