THE USE OF ARAMIDIC FIBRES TO IMPROVE THE STRUCTURAL BEHAVIOUR OF MASONRY STRUCTURES UNDER SEISMIC ACTIONS

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SUMMARY

The paper deals with the favourable mechanical characteristics and performances of the aramidic fibre reinforced plastics (or aramidic FRP) and with the way on which those characteristics may give important advantages in strengthening masonry structures in order to improve the historical buildings structural behaviour under seismic actions.

1. FRP AND ARAMIDIC FRP PROPERTIES

Fibre-reinforced plastic is widely used in the aeronautic industry, ship-building and mechanics, wherever strength has to be combined with lightweight and durability. The new generation of FRP is composed of high strength continuous fibres of carbon, aramidic and glass, in polymer matrices. Table 1 compares various types of fibres and metals.

From a technological standpoint, the advantages of using FRP for reinforcement, renovation, restoration, or retrofitting masonry buildings for earthquake-proofing, spring from its high mechanical strength, resistance to chemical agents and impermeability to water. Steel, on the other hand, has several disadvantages, such as reduced durability caused by its vulnerability to chemical agents (against which masonry is no protection) and corrosion by water. Moreover, steel has little reversibility (for example in reinforced injections). FRP is completely reversible since adhesive materials that transmit stresses can be removed. This advantage is particularly interesting for buildings of historic significance and architectural value because using the FRP is non-invasive. In general FRP possesses high residual strength and well responds to the application of cyclical loads.

Table 1 – Materials characteristics

Fibre / Material	Density	E(GPa) Elastic modulus	?$_r$ (MPa) Tensile strength	? % Ultimate elongation
Carbon fibre	1.7 – 1.9	200 – 600	2000 – 3000	? 1
Fibre glass	2.5	70 – 85	3000 – 4500	4 – 5
Aramide fibre	1.45	60 – 130	2700 – 3000	2 – 3
Steel	7.8	200 – 210	500 – 2000	2 – 10
Aluminium	2.8	75	500	10
Titanium	4.5	110	1200	14

Its viscous deformation is characterised by a rather high coefficient of viscosity. The rise of temperature beyond a critical threshold causes progressive deterioration in the polymer matrix, resulting in deterioration of the FRP. This effect can be mitigated by taking protective measures, as in the case of metal. In any case, it seems unlikely that the FRP would be exposed to both fire and extreme mechanical stresses simultaneously. This consideration becomes even more important when the FRP comes into play as static protection only during earthquakes. Any effects caused by viscous deformation under extremely heavy loads could be disregarded.

FRP made with aramidic fibres and epoxy resins (aramidic fibres are impregnated with epoxy resin, in an average ratio of 50% fibre to 50% epoxy resin) achieved the best results in studies carried out on the choice of fibre for reinforcing masonry with FRP. Aramide fibres have a lower modulus of elasticity than steel and appreciably higher final strength (table 1). The lower value of modulus of elasticity in comparison to steel is far from being a limitation because it is much closer to the modulus of elasticity of the material to be reinforced, i.e. the masonry, than that of steel. FRP with aramide fibres also has excellent resistance to alkaline agents, unlike FRP made with fibreglass.

Aramide is a synthetic long chain polyamide fibre in which at least 85% of the amide bonds are linked directly to two aromatic rings, like a linear chain synthetic polyamide. Generally an aramide fibre has a tensile strength five times greater than that of steel of equal weight. Moreover, it has 50% more elastic strength, greater flexibility in size variations in adverse atmospheric conditions, and is extremely resistant to high temperatures. The raw materials used in manufacturing aramide fibres are basically derived from petroleum and natural gas which contains the essential chemical elements, i.e. hydrogen, nitrogen, oxygen and carbon. When these are combined they form a macromolecular polymer that is extruded as an aromatic polyamide filament.

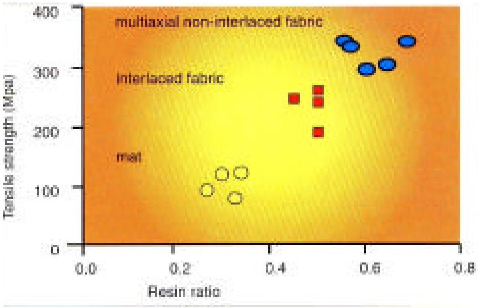

Fig. 1

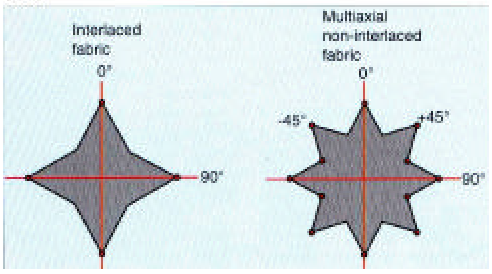

Fig. 2

Table 2 – Composite materials compared to metal materials

Reinforced plastic / Materials	Density	E(GPa) Elastic modulus	?$_r$ (MPa) Tensile strength
Carbon fibre composites	1.5	195	1125
Fibreglass materials	2.0	34	1300
Aramide fibre composites	1.4	77	1750
Steel	7.8	200 – 210	500 – 2000
Aluminium	2.8	75	500
Titanium	4.5	110	1200

The change of the molecular composition during the process yields to different types of aramides (high modulus, intermediate modulus, etc.)

Aramide fibre reinforced plastic is manufactured in cylindrical bars and rectangular fabric sheets. The bars are generally used to make reinforcements to be inserted into masonry walls, then securely sealed by injecting grout. These elements can be treated with quartz powder to facilitate bonding. The sheets are used for plating vaults and arches and for making binders and wrappings for partition walls. They are very easy to shape and mould difficult contours.

Studies show that multi-axial fabrics make the ideal reinforcement for this type of FRP.

Lab tests have proven that multi-axial fabrics perform better because their fibres are not woven but spun in several directions. These one-directional fibres are arranged in layers at different angles, (0°, 90°, +45°, -45°) and with varying weights, in a tricot or chain pattern with a very thin polyester thread. In this way the fibres are not strained by knots, as they are in woven fabrics, so their strength remains unchanged. When a load is transmitted along knotted fibres in woven fabric, a concentration of stresses is automatically caused by the resin and the knots themselves, so the cyclical application of loads will cause a rapid disintegration of the final laminate. The diagram in Figure 1 illustrates how a multi-axial non-woven fabric has greater tensile strength than woven fabric or mat. Figure 2 also shows the almost isotropic nature of the quadri-axial, non-woven fabric which makes it perform better in every direction, increasing both mechanical strength and resiliency.

Multi-axial fabrics need to be impregnated with less polymer and yet perform better because there are no voids where the polymer can lodge, unlike the woven fabrics. Table 2 shows comparisons of various types of FRP and metal. The table refers to one-directional fabrics. Using a multi-axial fabric improves results by 30%.

2. IMPROVEMENTS OF MASONRYS STRUCTURAL BEHAVIOURS

The usual masonry buildings structures may be compared to boxes: they are composed by a series of continuous interconnected vertical elements, separated by floors which act as diaphragms supporting the vertical loads directly applied to them. In general, ancient buildings were basically designed to bear vertical loads, and are not strong enough to withstand horizontal actions. This deficiency must be carefully studied and corrected when making a building earthquake proof. Floors play a fundamental role in resisting horizontal movement. They distribute that movement to the vertical walls (in pro portion to their relative rigidity) and also ensure that the transverse sections, at each floor level, do not suffer deformation in their plane, helping to simplify the behaviour of the whole structural system. In light of the above, it is critical to ensure that horizontal sections are “sufficiently” rigid and effectively attached to the vertical walls. Unfortunately, static reinforcement of masonry buildings must frequently compensate for the (often congenital) lack of integration of the various elements that make up the structural system. There are several “treatments” for fighting these “diseases” and they have been constantly improved upon. “Binding” has always been an effective technique and this has been checked in the course of subsequent earthquakes. This technique can be remarkably improved by using FRP, fibre-reinforced plastic, as an alternative to steel. The use aramidic fibre reinforced sheet for peripheral binding is an alternative to conventional steel chains. Installing the latter is always invasive since holes have to be drilled through the wall panels, damaging the stones. They are also used for binding and wrapping wall panels (consolidating and reinforcing hammer beams and quoins in masonry). They can even be used for wrapping the entire masonry exterior, placing the sheets along lines at various levels around the sides of the building. Depending on the building’s state of preservation, this peripheral binding can be connected to vertical strips to form a chain net. For binding a masonry structure it is also possible to use aramide fibre reinforced bars in the same way of steel bars, but with the advantage of a reduced tensile and shear elastic module and thus reduced stresses concentrations. For the same reason in the case of stone block masonry structures, for avoiding the risk of sliding it is better to use aramide fibre reinforced pins or dowels instead of steel ones. In fact during an horizontal action to use aramide instead of steel for vertical connections between the blocks, reduces the local stresses reducing the risk of cracking the blocks themselves; moreover the aramide reduced shear stiffness allows little relative movements increasing the energy dissipation. When it is necessary to counteract tensile stresses, it is possible to use simple sheets (or simple bars) on one side of the masonry panel; when there are also dangerous bending moments it is useful to apply the sheets on both the panel side faces.

In the case of masonry domes it is generally necessary to counteract simple tensile stresses and, thus, it is possible to use simple aramide fabric strips as horizontal circumferential chains on the extrados. In the case of masonry vaults it is sometime necessary to counteract tensile stresses and bending moments together. In the case of decorated surfaces, paintings or frescos, it is necessary to improve the bending resistance using only the free side face, generally the extrados face, for the intervention. An example of such a typology of intervention is the consolidation of the vaults of the Basilica of St. Francis in Assisi: to improve the bending resistance of the vaults it was necessary to fix bending resistant elements on the extrados of the vaults themselves.

3. THE CASE OF THE VAULTS OF THE ST FRANCIS BASILICA IN ASSISI

The choice about this intervention philosophy was, in this case, a very delicate matter: the deformations in the vaulting could not be corrected without damaging their frescoed surfaces, yet without being restored to its proper curvature the vaulting could not support loads independently. The idea of building a reinforced concrete slabs or ribs was excluded because they would have been too intrusive: they would not be in keeping with the original nature of the structure and would be difficult to remove. Steel ribs were also excluded because they would be difficult to mould to the complex and deformed shape of the vaults, thus making it difficult to build a continuous link with the masonry.

Fig. 3

Fig. 4

It was decided to use composite materials (aramide fibre, fibreglass and marine mahogany plywood) to build a series of very thin ribs on the extrados of the vaulting, following a typical Gothic design and leaving the original structure clearly visible. The plan called for stiffening ribs to be built on the extrados of the vaults (fig. 3) and positioned to correspond with the masonry ribs of the intrados and the vaulted spaces between the ribs. The ribs were fashioned in situ so they could be shaped adjusting their height in relation to the deformation of the underlying vaulting. This way the extrados of the new ribs could follow a regular curve. The use of aramidic composite ribs allows to stiffen and to reinforce the vaults avoiding too high stress concentration and without altering too much the natural structural behaviour of the gothic vaulting; but it can allow too large deformations for the stability of the intrados frescos, in case of exceptional seismic actions. Thus, in order to control the larger deformations of the vaults, the composite ribs system is connected to the roof structure by a system of suspension steel bars with helicoidal springs not preloaded (fig. 3).

The ribs were formed out of fabric made of quadri-axial aramidic fibres (0°, ± 45°, 90°) weighting 230/360 g/m^2, and bonded with the epoxy resins around a wooden core (mahogany marine plywood, fig. 4), with longitudinal strips of aramidic fibres on the intrados (subjected to tensile stress) and glass fibres on the extrados (subjected to compression stress). Very resistant ribs may be created with this method; at the same time they are very light and less stiff than steel in such a way to be compatible with the masonry stiffness. The aramidic fibre fabrics completely cover the wooden core and then extend 10-15cm out onto the extrados of the vaulting and are bonded to it. For the transverse masonry arches position (the weaker ones) two adjoining ribs are planned, 22cm high and 10cm wide, equipped with transversal reinforcement to help to improve the stiffness of a substantial portion of the vault. A single rib 30cm high and 12cm wide of the same type as the one described above will reinforce the diagonal ribbing. One or two intermediate ribs 18÷20x5cm will radiate out from the pilasters over each vault between the arches. All the ribs are connected to each other at the crown of the vaults as well as at the springing of the arches. As mentioned above, in this typology of intervention it is important that the ribs are made directly in situ by layering various materials. First the extrados of the vault must be micro-sanded. Then a first quadri-axial aramidic fibre sheet (230 g/m^2) and just impregnated with epoxy resin, is bonded to the surface of the extrados of the vaulting with an epoxy mortar. At this point aramidic fibre bars are fixed and covered with a second quadri-axial aramidic fibre sheet. Over such a base 1cm thick strips of mahogany marine plywood (fig. 5) are bonded in layers to form the wood core of the rib.

Fig. 5

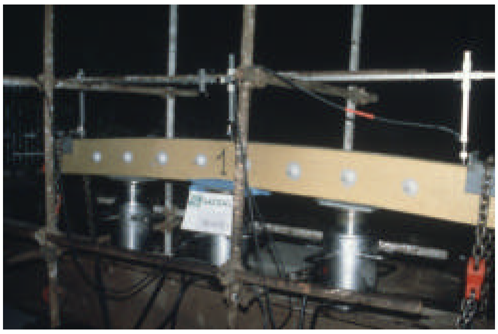

Fig. 6

The wood core has to be covered with a third sheet of quadri-axial aramidic fibre fabric. This sheet has to be heavier than the previous ones (360 g/m^2) because it has to form part of the side wall of the rib. Fibreglass bars are then bonded. The whole composite element is then covered with one last sheet of quadri-axial aramide fibre fabric (360 g/m^2). Near the springing and the crown where the shear stress is greatest, each rib has to be reinforced with additional sheets of quadri-axial aramide fibre fabric.

The reinforcement has to be connected to the masonry of the vaulting in part by directly bonding it with the epoxy resins and partly by pins driven into the masonry. These pins (Ø5.5 mm) are made of unidirectional aramide fibre and epoxy resin and it is better if they are driven into the body of a brick, rather than into the joints between, in order to reduce the risk of the resin's filtering down through the joints to the intrados below. In the case of the St. Francis Basilica the masonry ribs of the intrados had also to be fastened to the reinforcement as they are not structurally connected to the vaults: the latter merely rest over them, as in many Gothic vaulting structure. For this reason longer aramidic fibre pins (Ø7.5 mm) were driven in.

In determining the size of the various sub-elements which form the ribs, the fact that assembly is done manually in situ has to be taken into account and a failure/yield safety coefficients of 2.5÷3.5 must be adopted. Tests performed on rib prototypes (fig. 6) confirmed overall safety coefficient of 2÷3 for the ribbing as a whole, in the case of Assisi. The tests also revealed the rib prototypes' remarkable capacity for retaining resistance after surpassing the elastic limit and the yield point, with good ductile performance even after several loading cycles.

9. ACKNOWLEDGEMENTS

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