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FIRE PROTECTION OF TIMBER STRUCTURES STRENGTHENED WITH FRP MATERIALS

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ABSTRACT

Modern, progressive methods of structures' strengthening based on the use of composite materials composed of high strength fibers (carbon, glass, aramid or basalt) and matrices based on epoxy resins brings, among many indisputable advantages (low weight, high effectiveness, easy application etc.) also some disadvantages. One of the major disadvantages is a low fire resistance of these materials due to the low glass transition temperature T_g of the resin used. Based on an extensive research of strengthening of historic structures with FRP materials [1], the article outlines possible approaches to this problem, especially while strengthening timber load-bearing structures of historic buildings.

KEYWORDS

timber, strengthening, joint stabilization, FRP, fire protection

INTRODUCTION

Timber structures are significant part of load bearing structures of historic buildings (buildings built around the 1st half of the 20th century), such as roof trusses, corduroy (log) or beamed ceilings, internal skeletons, etc. While reconstructing these buildings, we often face the necessity of strengthening individual wooden elements or their connections. Traditionally, wood and steel in the form of various straps or prostheses or in the form of additional fasteners is used. In the last decade, new progressive FRP (Fiber Reinforced Polymers) based methods are being used. These methods use composite materials composed of a matrix (usually an epoxy resin) and reinforcing fibers (mostly carbon and glass, less often aramide, basalt or natural fibers). Depending on the type of fibers used the resulting strength of composite ranges from 500 to 2000 MPa. Similarly, the elastic modulus reaches values up to 250 GPa. The advantages of FRP materials lie in their high tensile strength, low weight, and their ability to conform to varying shapes. The versatility and ease of installation make FRP retrofit solutions extremely effective. One of the limiting factors is the low fire resistance of FRP materials and therefore the need for additional fire protection of strengthened or stabilized timber structures.

STRENGTHENING OF TIMBER STRUCTURES WITH FRP MATERIALS

The reinforcement of structural timber elements is designed to supplement the ductile behaviour of such elements. This can be improved by forcing the ratio between ultimate tensile strength and ultimate compressive strength with higher ultimate strength. This result can be achieved by improving the behaviour of the tension zone so as to permit a plastic behaviour in the compression zone. This amounts to taking full advantage of the material properties, resulting in higher ductility at collapse.

For strengthening of timber elements stressed mainly by bending or shear, FRP materials (in the form of lamellas, rods, or fabrics) placed on the surface of strengthened element (Externally Bonded Reinforcement - EBR) or in the grooves near the surface (Near Surface Mounted - NSM) are used. FRP materials can also be used to stabilize or strengthen joints of the wooden elements. Fig. 1 shows some examples of possible strengthening interventions for timber load bearing elements and Fig. 2 shows examples of the possible joint stabilization or strengthening. In all cases, it is vital that the adhesive used for the bonding of wood in structural applications should be characterised by high shear strength and good compatibility with different kinds of wood types [2].

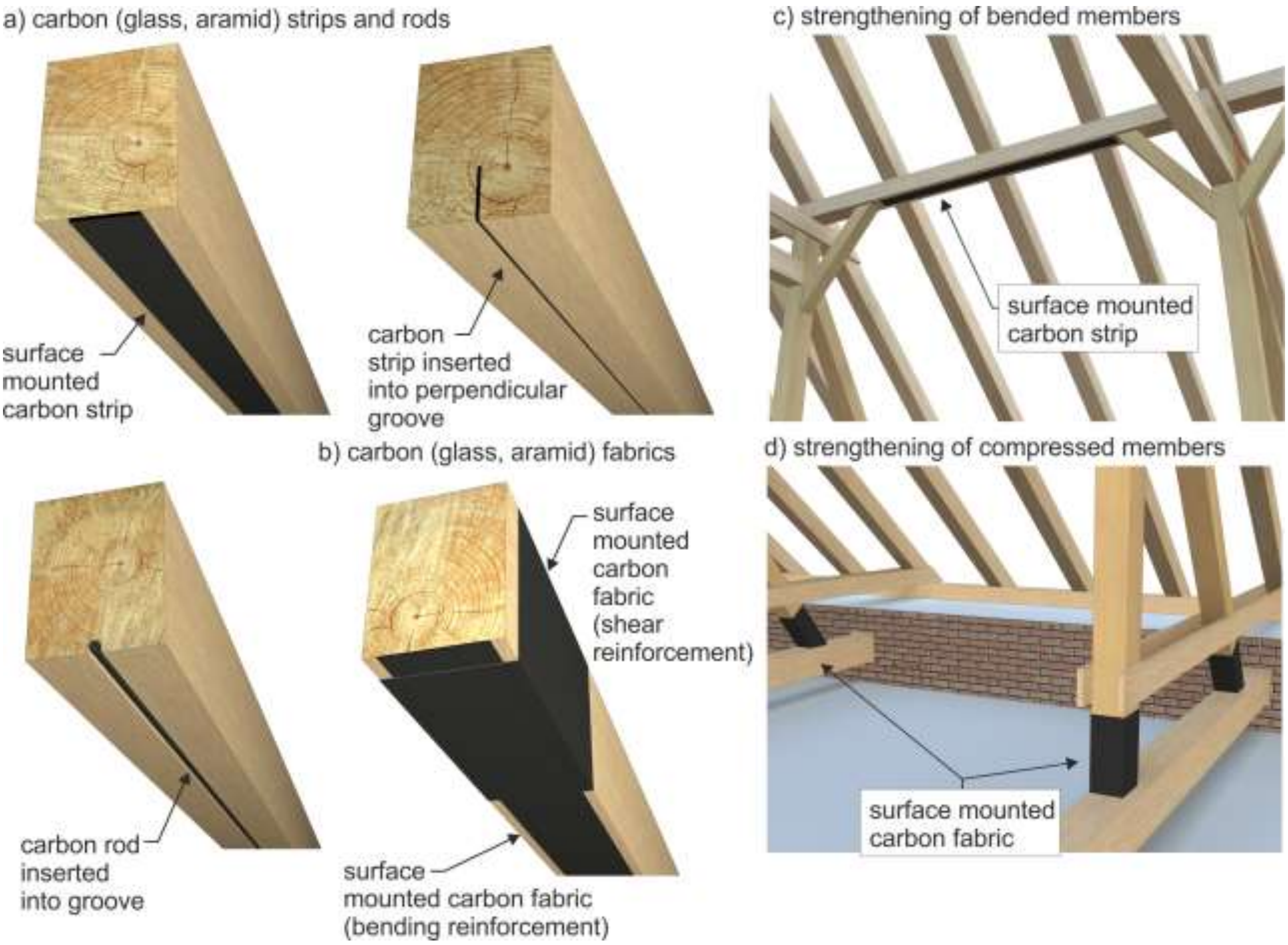

Fig. 1 Examples of strengthening of timber structures using externally bonded FRP materials (EBR)

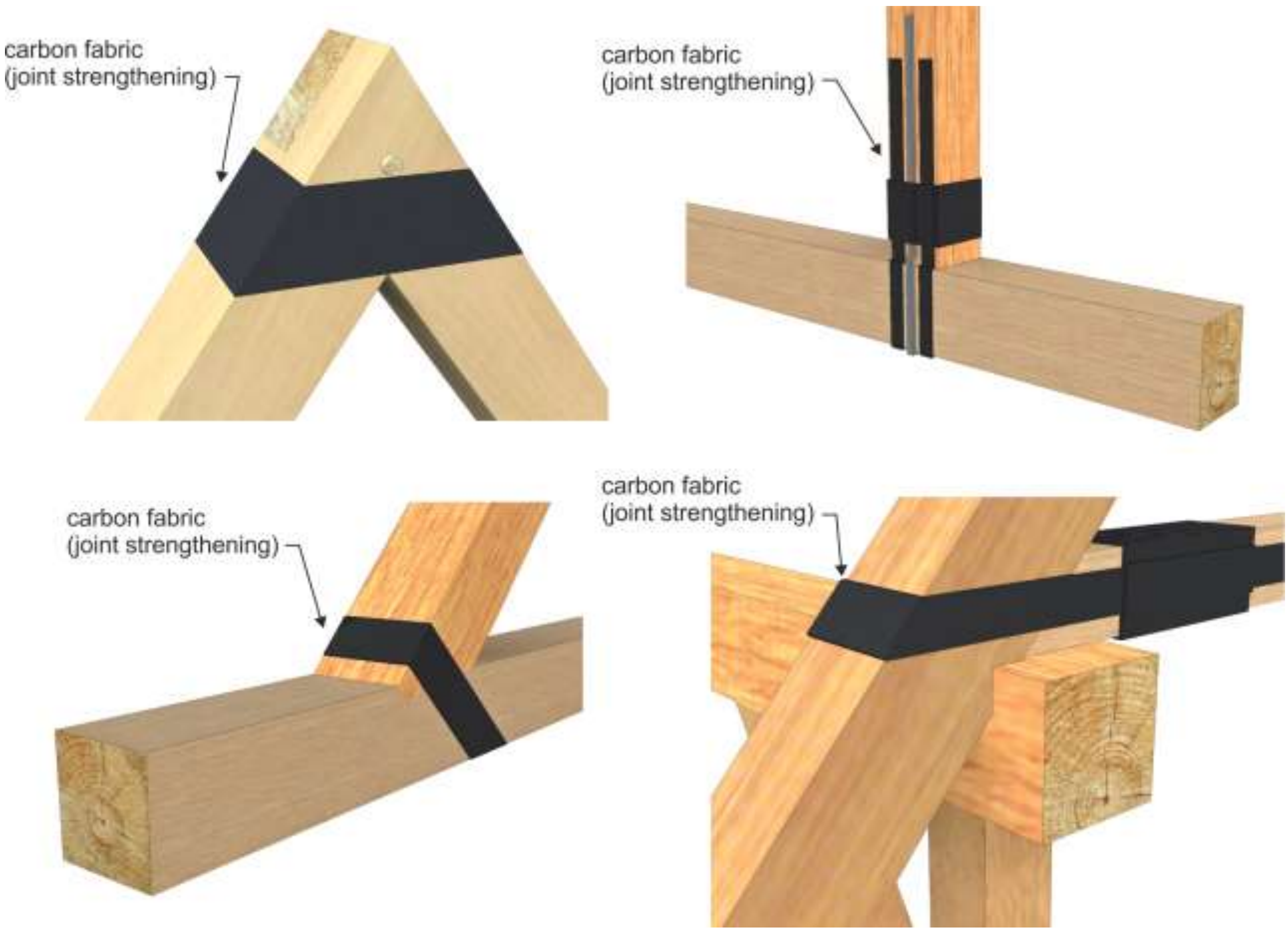

Fig. 2 Examples of possible joint stabilization and strengthening using externally bonded FRP materials (EBR)

WOOD BEHAVIOUR IN FIRE CONDITIONS

The behavior of wood in the fire conditions is sufficiently theoretically and experimentally described. The fire resistance of unprotected wood element is usually determined by standard procedures pursuant to Eurocodes (EN 1995-1-2) [3], which provide two different methods for determining the fire resistance - method of reduced timber properties in fire conditions and method of reduced (weakened) cross-section as a result of surface charring of the wood element. A tabular (rather conservative) approach is often used in practice for determining a structure's fire resistance [4] based on Eurocodes or tabular approach based on the national standards (eg. ČSN 73 0821 ed. 2 [5], ČSN 73 0834 [6]). In case of fire protected timber structures, in particular using external encasing, the limit temperature of layers can be considered 120 °C while the glowing temperature, according to the wood type used ranges from 200 to 300 °C (ČSN 73 0810 [7]).

The temperature of the non-charred part of the section during the fire resistance period does not usually exceeds 110-120 °C. Therefore the limiting strength of the wood during fire can be considered the value of strength of wood at 120 °C. The decrease in strength depends directly on the temperature and indirectly on moisture content in wood. The burning rate increases with the content of resin, fats, etc., and decreases with increasing moisture content and density of wood. The burning and ignitability of wood also depends on the surface quality and surface finish, its

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dimensions and porosity. Experimental research of wooden elements (spruce beams) exposed to a standard fire demonstrated an average speed of burning off the surface layers in the direction to the core cross-section from the side of 0.65 mm/min and from below 0.95 mm/min. Joints of individual wood members are other very sensitive part of timber structures, especially for roofs trussed and load bearing skeletons. Original wooden fasteners (e.g., pins, wedges, liners etc.) were later usually replaced by steel fasteners (e.g. bolts, screws, dowels etc.). For these fasteners their thermal conductivity must be respected as they will warm faster due to the increasing thermal conductivity. The heat is also transmitted to the connected wood members [8].

FRP BEHAVIOUR IN FIRE CONDITIONS

One of the characteristics of FRPs is their low glass transition temperature (T_g). T_g is the midpoint of the range of temperatures over which the FRP polymer matrix undergoes a change from hard and brittle to viscous and rubbery. Polymer matrices that cure at room temperature and are often used for structural strengthening have glass transition temperatures T_g ranging from 60°C to 130°C. At temperatures above 400 °C, FRPs are susceptible to combustion of polymer matrix and can even evaporate [9]. Without protection from heat, a polymer matrix may also ignite, emit smoke, and support spreading of flame. When exposed to fire, FRP materials may suffer charring, melting, delamination, cracking and deformation. Figure 3 shows that for some types of matrices, debonding can be well advanced at 200°C. It also shows that the fibers themselves lose strength with rising temperatures, with carbon fiber losing the least.

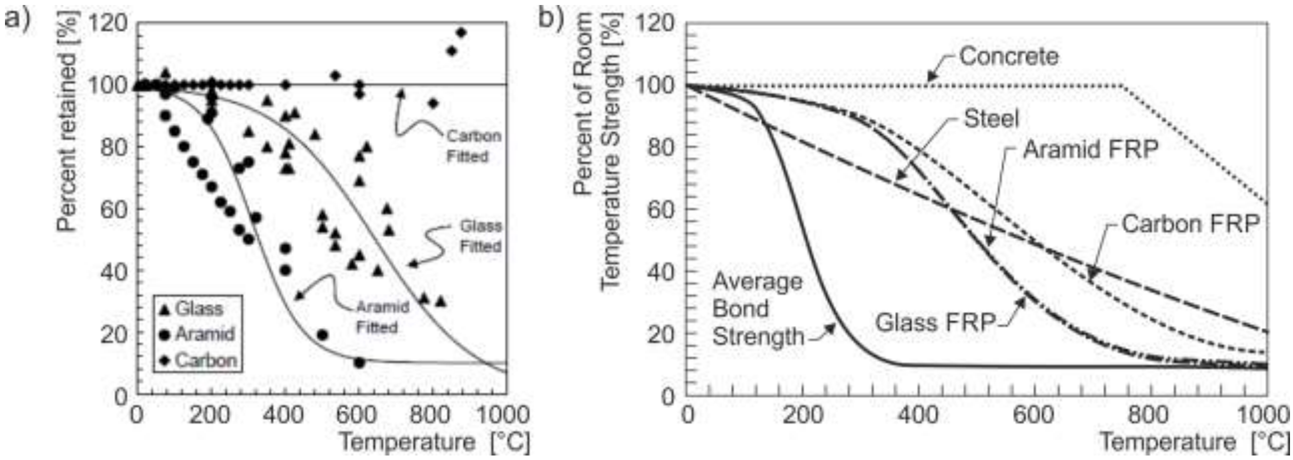

Fig. 3. Approximate variation in tensile strength and bond strength with temperature increase; a) Bare fiber strength [10]; b) FRP, concrete and reinforcing steel [11]

Therefore, it is apparent that a fire protection for structural elements reinforced with FRP materials is essential and that even small temperature increase in FRP-wood contact can have a profound effect on the resulting load bearing capacity and static function of the strengthened timber member or joint.

Experimental research conducted on masonry [12] and concrete structures [11], [13], [14], [15] demonstrated the sufficient usability of externally bonded FRP reinforcement during fire, if the structure is adequately fire protected.

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FIRE PROTECTION OF TIMBER STRUCTURES STRENGTHENED WITH FRP MATERIALS (EBR, NSM)

There are some methods traditionally used for fire protection of timber structures that are also suitable for fire protection of structures strengthened and stabilized with FRP materials such as encasing, mineral fiber coverings and fire resistant plasters. The encasing or fire protection boards are usually based on gypsum, vermiculite, cement, or on lime and cement combination. Mineral fiber coverings are normally basalt based. Fire resistant plasters may be gypsum-perlite, gypsum-vermiculite based, gypsum, gypsum-lime, lime, lime-cement or cement based. In all cases it is necessary to take into consideration the possibility of the element encasing or plastering, both in terms of heritage protection requirements (valuable ornate features of beamed ceilings, roof trusses etc.), and the possible wood degradation due to the encasing (all timber structures that are enclosed in non-porous encasing materials must treated against possible biodegradation).

Methods based on fire retardant coatings are not suitable, especially the use of foam-forming (intumescent) materials that activate (start to foam) only at temperatures higher than the critical - glass transition - temperatures T_g of the epoxy resin.

On the other hand the use of fire protective cladding based on wood elements with sufficient thickness can be applied to protect the FRP strengthened elements. The use of wood cladding appears to be the best option in particular for timber elements reinforced with FRP materials inserted into grooves (NSM). In this case the wooden cladding fulfills both the fire protective and aesthetic functions (Fig. 4).

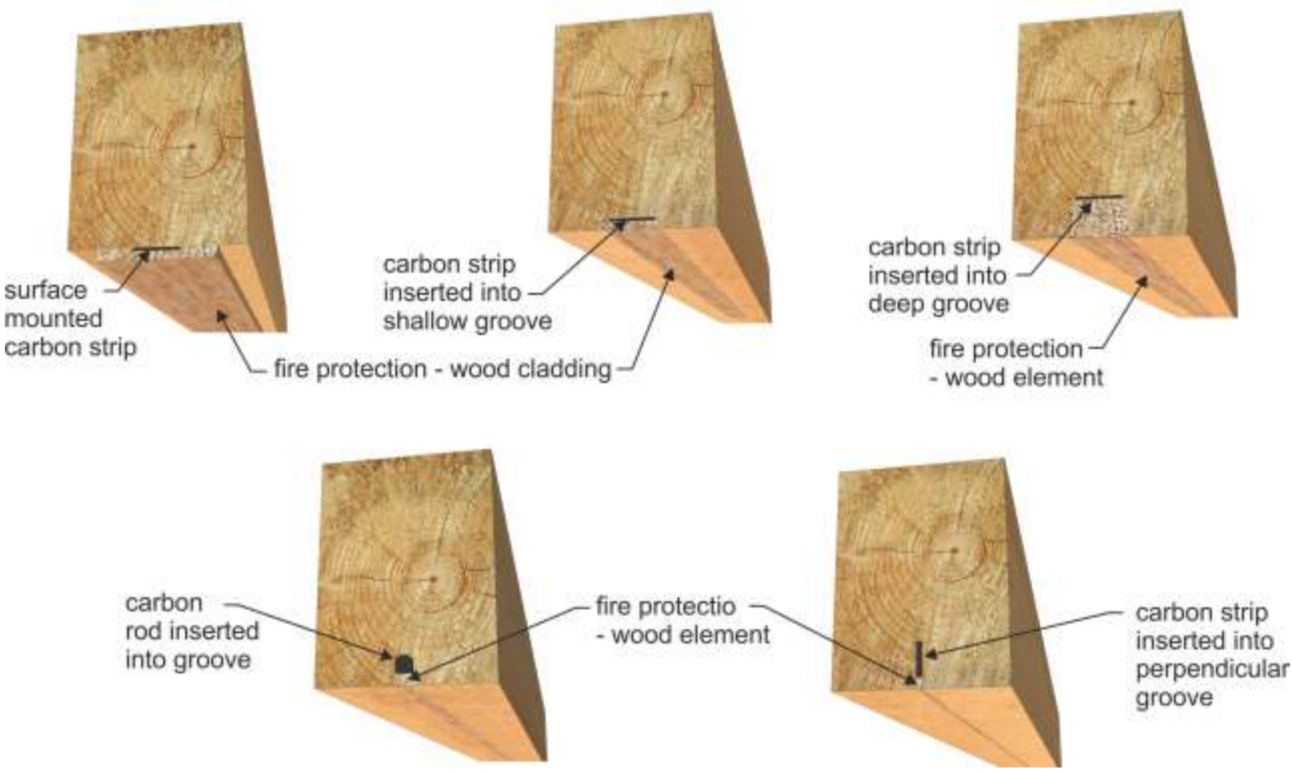

Fig. 4 Fire protection of strengthening FRP elements

To determine the required thickness of the wood cladding needed, a simple parametric study with the following initial and boundary conditions was performed:

- one-dimensional calculation of heat transmission with the use of software Argos (DBI, version 5.8.92.414 [16])
- fire exposure with the nominal standard temperature curve according to ISO 834 [17]
- starting temperature 20 °C, heat transfer coefficient 25 W/(m^2.K) on the side exposed to the fire and 7.7 W/(m^2.K) on the opposite side, surface and fire emissivity 0.9
- two different thicknesses of softwood spruce cladding – 25 mm and 40 mm
- gradual charring expressed by change in density, thermal conductivity and specific heat capacity for the protective cladding was considered (values according to ČSN EN 1995-1-2, Tab. B.2 [3])
- critical - glass transition - temperature T_g of the FRP system was considered 100 °C (depending on the polymer matrix used, temperatures ranging between 60 and 130 °C are mentioned in literature [12]

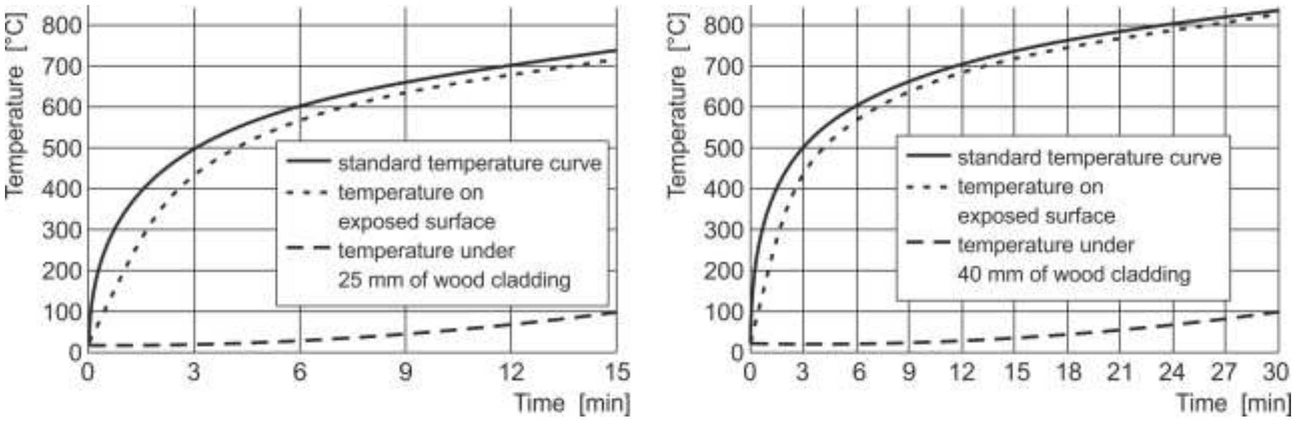

Fig. 5 Temperatures at the FRP reinforcement in case of fire protection system using wood cladding 25 mm (left) and 40 mm (right) thick

The parametric study results show that the wooden cladding with thickness of 25 mm under the conditions of standard fire can provide a critical temperature of the FRP bellow 100 °C for a maximum period of about 15 minutes (Fig. 5, left). If the cladding thickness is increased to 40 mm, fire protection for about 30 minutes (Fig. 5, right) can be achieved.

CONLUSION

Fire protection of a FRP strengthening system providing the required fire resistance of the strengthened structural member must be dealt with especially when the structural element is in the fire zone of a usable storey (e.g. visible elements of the roof truss in the attic). However, if the structural element is situated in a non-usable storey, eg. an unused attic or roof-cavity space (usually above the fire ceiling) the fire risk is not calculated, fire resistance of the structure is not required and therefore the strengthened member, including the strengthening FRP system can be entirely without fire protection.

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If a fire protection is needed, simple encasing with wood elements (cladding) of sufficient thickness can provide the necessary fire resistance of a strengthened or stabilized timber member. Especially, the near surface mounted FRP systems are highly suitable for this kind of fire protection as it also provides the necessary aesthetic requirements.

If the encasing is not possible (due to various reasons) or the required fire resistance is higher than 30 minutes (which would require thicker encasing elements and would be problematic from the point of technology and static efficiency), epoxy matrices with higher glass transition temperatures T_g [9], or other types of bonding materials may be used (such as FRG or FRCM systems).

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