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FLEXURAL CHECK AT HIGH TEMPERATURES
of reinforced concrete bridge decks strengthened with EBR-FRP

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Abstract

In this paper the thermo-mechanical behaviour of RC bridge decks strengthened with externally bonded FRP laminates is investigated by considering environmental conditions responsible of thermal states different from the normal ones. A parametric analysis is performed by varying the slab thickness, the FRP reinforcing percentage, the type of fibre and the thickness of the protection layer. The results are given in terms of ultimate bearing capacity of the slabs, which allows individuating the conditions responsible of premature FRP-to-concrete debonding or temperature levels greater than the glass transition temperature of the adhesive.

Keywords: concrete slabs, FRP, fire resistance, debonding

INTRODUCTION

Fibre reinforced polymers (FRP) are composite materials successfully applied to repair and/or strengthen RC structures. For external strengthening of reinforced concrete structures the FRP laminates are bonded to the exterior of concrete using adhesive resins, like epoxy resins, phenolic resins and other types, ensuring to transfer forces between the concrete and FRP through shear stresses that develop in theadhesive layer. However, degradation of mechanical properties of composites by variousenvironmental effects such as elevated temperatures,moisture absorption and cycling loads is a very importantfactor in durability predictions of composite materials(Springer, 1984 – Buggy et al, 1994). Especially, a critical condition occurs when the glass transition temperature T_g of the polymer matrix is achieved,determining shear capacity reduction in resin and the following fibre’s overloading.Application of FRPs have been limited primarily to bridges, where fire is not a primary consideration during design (Bisby et al 2005). Nevertheless, in this paper the thermo-mechanical behaviour of RC bridge decks strengthened with externally bonded FRP laminates is investigated by considering environmental conditions responsible of thermal states different from the normal ones. The examined cases are: (a) bituminous paving cast in place on a bridge deck at temperature T=180°C; (b) fire exposure over the bridge deck.

1 BEHAVIOUR OF FIBRE-REINFORCED COMPOSITES AT ELEVATED TEMPERATURE

Several researches on thermal behaviour of FRP materials are nowadays available in the scientific literature. In the following the main results are briefly summarised in order to deduce basic information on the thermo-mechanical properties of the various FRPs types and the FRP-to-concrete interface behaviour at high temperature.

1.1 Thermo-mechanical behaviour of FRPs

In order to study the behaviour of RC slabs strengthened with FRP at high temperatures it is necessary to know the thermo-mechanical properties of the constituent materials; Eurocode 2 - Part 1-2 gives the thermo-mechanical properties for concrete and steel bars, while the main theoretical and experimental contributions concerning the behaviour of FRP composite materials and adhesive resins at elevated temperature are summarised in(Blontrock et al, 1999) and in (Bisby et al, 2005). Based on experimental data assembled by (Blontrock et al, 1999).Fig. 1show exponential best-fit curve of the temperature-dependent reduction coefficient of the tensile strength referred to various types composites with carbon fibres and epoxy matrix. Temperature-dependent curves may be still obtained in an analogous way for the FRP elastic modulus. Finally, the assumption of elastic-brittle constitutive law is still suitable, obviously defined by values of tensile strength and elastic modulus reduced due to elevated temperature.

1.2 FRP to concrete bond at elevated temperature

FRP-to-concrete bond ensures to transfer the interaction forces between RC beam and external FRP plate or sheet, assuring suitable performances of the strengthened structural member as a whole. The interaction forces are transferred through the polymer matrix or adhesive, whose mechanical properties deteriorate as temperature increases. In particular, loss of bond may occur if the glass transition temperature T_g is achieved in the adhesive.

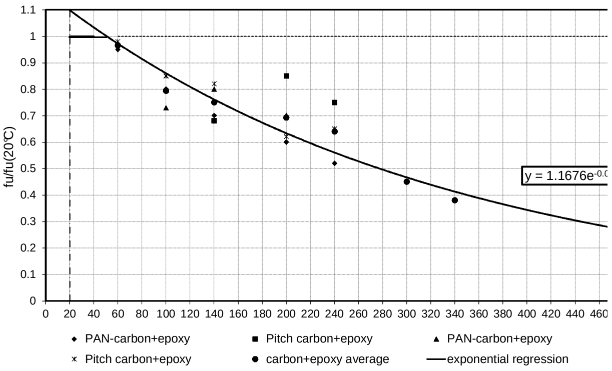


Fig. 1Temperature-dependent tensile strength reduction of various carbon fibre composites.

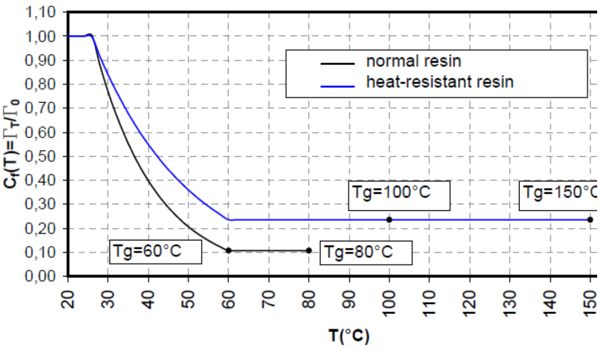


Fig. 2Temperature-dependent specific fracture energy of the bond law for normal and heat-resistant resins.

In accordance with CNR-DT 200/2004 the maximum force transmitted by the FRP-to-concrete interface in normal temperature condition is related to so called “specific fracture energy” Γ_F of the interface bond law, whose characterization can be found in (Wu at al, 2004), that provides experimental data concerning the reduction of the specific energy fracture with the temperature. Fig. 2 shows typical temperature-dependent reduction curves of the specific energy fracture for normal and “heat-resistant” resins: it has to be remarked the great reduction of the interface effectiveness, in the case of normal resins (NR) which exhibit glass transition temperatures T_g variable in the range (60÷80°C), whereas heat-resistantresins (HR) are characterised by greater values of T_g (100÷150°C).

1.3 Structural behaviour of FRP-strengthened concrete beams or slabs at elevated temperature

The bond between external FRP reinforcement and concrete beam vanishes suddenly if the member bottom is directly heated by fire, due to the low glass transition temperature of the epoxy resins (Deuring, 1994). In the tests a similar behaviour has been observed when conventional steel strengthening is utilised, although composite sheets without protection behave better than steel plates without protection because of the lower heat conduction in the fibre direction and their smaller weight. Therefore, FRP externally strengthened RC beams or slabs need the protection with supplemental insulation in order to avoid the debonding between FRP sheets or laminates and concrete support. Some researches are devoted to study the performances of FRP strengthened elements protected by different insulation systems in order to individuate the minimum requirements to obtain satisfactory performances in fire

(Bisby et al, 2005). Obviously, if the FRP strengthening is not directly heated by fire or other sources of heat, the performances may be better.

2 SAFETY CHECK AT ELEVATED TEMPERATURE AND DESCRIPTION OF NUMERICAL MODEL

According to the provisions of European and Italian codes (EN1991 1-2, D.M. 14-02-08), the safety check of structural members subjected to elevated temperature may be carried out, in strength domain, comparing design value of the relevant effects of actions in the fire situation at time t($E_{fi,d,t}$) with the corresponding design value of the resistance of the member in the fire situation at same time t ($R_{fi,d,t}$):

$$E_{fi,d,t} \leq R_{fi,d,t} \qquad (1)$$

Unlike the safety checks in normal temperature conditions, in equation(1)the member resistance decreases due to material thermal damage and the effects of actions may vary due to thermal expansions and deformations.

The relevant effects of actions $E_{fi,d,t}$for the fire situation are obtainedfor time t=0 through the combination of mechanical actions in accordance with EN 1990 “Basis of structural design” for accidental design situations.The design resistance $R_{fi,d,t}$of a structural member in the fire situation is evaluated considering the temperature-dependent reduction of the material mechanical properties $X_{d,fi}=K_T X_k$, and assuming unit partial safety factors $\gamma_{M,fi}$.

The fire resistance assessment of a structural member may be performed through experimental tests in furnaces or applying analytical approaches. In both cases conventional temperature-time laws of the environment may be assumed.For fires characterized mainly on burning of oil or other substances with equivalent rate of heat release, the “hydrocarburecurve”, is suggested by Eurocode 1 - Part 1-2. The mentioned fire curve isrepresented inFig. 7.

The assessment of the structural member flexural resistance at elevated temperature is performed, as for normal temperature, determining the bending moment-curvature law (M-χ; N) of the critical cross-section for the imposed value of the axial force N and the current temperature field within the section. The numerical procedure to assess the moment-curvature law of the cross-section is explained in (Nigro et al, 2010).

The failure of the FRP strengthened cross-section is assumed to occur when the ultimate strain is achievedat least in one material. The temperature-dependent ultimate strains of concrete and steel are assumed according to Eurocode 2-Part 1-2, whereas the ultimate strain of the FRP strengthening is assumed as the strain limit for intermediate debonding suggested inCNR-DT 200/2004 and modified according to specific energy fracture reduction shown in Fig. 2. It has to be remarked that if the temperature T_i in the adhesive layer exceeds the glass transition temperature T_g of the epoxy resin, the FRP strengthening may be considered loss, but the structural member keeps the residual resistance as a simple RC member.

The hypothesis of decoupling the thermal behaviour of the materials from the mechanical behaviour is the basis of the Fourier equation for the study of the heat propagation within solid bodies and may be usually accepted.

In most practical cases the thermal field may be considered as uniform along the member axis, therefore the actual 3D thermal problem can be reducedto more manageable 2D or 1D problems. Due to the variability of the material thermal properties with the temperature (thermal conductivity, specific heat, density), a numerical solution of the heat transfer problem has to be performed; in the paper the finite element method is used by means of FIRES-T3 computer program in whichthe heat transfer on the boundary may be assumed to occur through a combination of radiation and convection, linearly or non-linearly modelled.

According to usual FEM approach, the slab or beam cross-section is divided into a sufficient number of layers or elements and in each one the temperature is assumed as uniform and equal to that of its centroid. Each element is characterised by specific thermal properties, different from that of other elements and variable depending on its temperature. In particular, thermal analyses are performed by considering concrete thermal proprieties in accordance with EN1992-1-2, whereas FRP thermal properties are defined in (Weidenfeller et al, 2003) and in (Sweeting et al, 2004).

For the considered time of exposure to prescribed environment conditions (fire or others), the thermal analysis gives the thermal field in the cross-section. A specific stress-strain law (σ–ε;Ti), which is a function of the local temperature and takes into account the variation of the material mechanical properties with the temperature, can be linked to every element of the mesh into which the section has been divided. Obviously different types of constitutive law are employed for concrete, steel rebars and FRP strengthening.

3 PARAMETRIC ANALYSES

The thermo-mechanical behaviour of RC bridge decks strengthened with externally bonded FRP laminates is investigated by considering environmental conditions responsible of thermal states different from the normal ones. As already said, the examined cases are:

a) Maintenance of bituminous paving, cast in place on a bridge deck at temperature T=180°C;
b) Accidental situation, resulting in afire exposure over the bridge deck.

The performed applications concern RC bridge slabs 15 or 20 cm thick, symmetrically reinforced with steel bars (the reinforcement percentages at top or bottom side are equal to 1% of the concrete area). The slabs are externally strengthened with C-FRP; laminates or fabrics; positive or negative bending moment strengthening and different strengthening amounts. A typical bituminous paving 8 cm thick is considered over the RC slab. The one-dimensional analysis, carried out through FEM approach, is obviously exact if a continuous FRP strengthening is used. Due to the slight influence of the FRP laminates on the heat transfer, also when discrete FRP plates or strips are employed (Fig. 4-Fig. 5), the difference in terms of temperature at representative points is negligible.

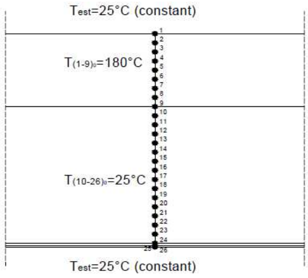


Fig. 3Slab discretization

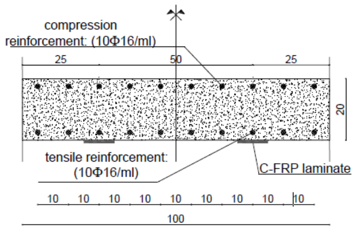


Fig. 4RC slab strengthened to positive bending moment

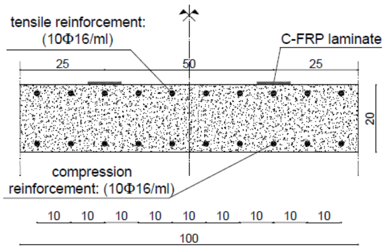


Fig. 5RC slab strengthened to negative bending moment

a) Maintenance of bituminous paving, cast in place on a bridge deck at temperature T=180°C

The realization of a bituminous paving on a bridge deck represents a periodic maintenance operation. The cast in situ is carried out at about 180°C, therefore some significant reduction of safety may arise in the RC slab externally strengthened with FRP. Two schemes of FRP external strengthening are considered: bottom side strengthened slab in the sagging moment zones of continuous or simply supported schemes (Fig. 4); top side strengthened slab in the hogging moment zones of continuous schemes (Fig. 5). For the thermal analysis also the bituminous paving is modelled with appropriate thermal properties; initial temperature conditions T(t=0)=180°C are assumed within the paving thickness. Two situations of environment temperature are considered: T_e=25°C and T_e=35°C.

Based on the performed thermal analyses, Fig. 6shows the curves of the time-dependent temperature which arises in the FRP strengthening on the slab bottom side after bituminous paving laid at time t=0. It is possible to remark that in all the examined cases the maximum temperature is always lower than the glass transition temperature T_g of normal adhesive resins. Moreover, due to the particular heat transfer, the temperature peak occurs some hours after the paving realization. The obtained results are quite not-dependent on the bituminous mix, which changes mainly the time of maximum temperature.

The safety check of the strengthened slab considering the temperature variation in the materials is summarized inTab. 1, where M_{Ed} is the design bending moment in the normal conditions (assumed equal to the “cold” resistant moment M_{Rd} at ULS), $M_{Ed,fi} = \eta_{fi}\, M_{Ed}$ is the design bending moment for the considered situation, and $M_{Rd,t}$ is the resistant moment at ULS of the cross section taking account of the strength reduction due to elevated temperature. The table shows that the safety control ($M_{Ed,fi} \leq M_{Rd,t}$) is always satisfied in the examined cases.If the design level η_{fi} tends to 1, the check control may become critical in the case of small thickness slab and normal adhesive resin, which exhibits a greater resistance reduction of the strengthened slab.

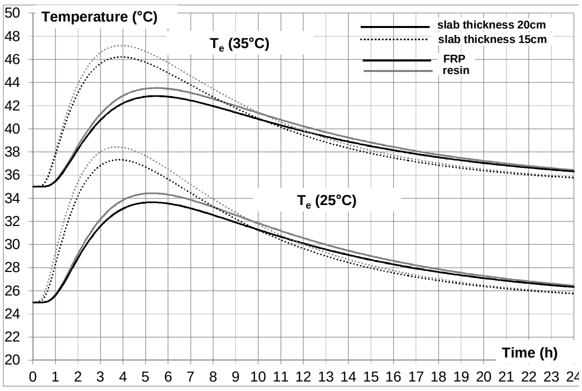


Fig. 6**:** Time-dependent temperature in resin and FRP strengthening on the bottom side.

When a bridge slab is strengthened with FRP plate or sheets on the top side for negative bending moment (Fig. 5), a protective cover needs to avoid damages in the FRP strengthening during the maintenance operations, as the demolition of the old road surface. The protective layer is required to have a good resistance to abrasion and concentrated loads and, if possible, to ensure also some thermal insulation. In the numerical applications a protective layer of concrete is considered. For the purpose of a parametric analysis, four different thicknesses variable from 1 to 4 cm are considered.

The thermal analyses show that the maximum temperature values in the FRP strengthening reaches about 85°C in the case of 1cm concrete protective layer. The maximum temperature decreases to about 65°C for a thickness of 4 cm. Therefore, the realization of a bituminous paving may lead to overcome the glass transition temperature T_g of normal adhesive resins. The safety check of the strengthened slab considering the temperature variation in the materials is not satisfied for the considered cases if a normal adhesive resin is utilised, due to the great reduction of the specific fracture energy and, consequently, of the FRP strain limit for intermediate debonding (see Fig. 2).

Only in the case of 4-cm thick layer the temperature in the FRP-to-concrete interface is lower than the expected glass transition temperature T_g of a normal resin. However, also in this case the significant reduction of the resistant moment at ULS, when normal resins are utilised, leads to a lack of safety with reference to the usual design level $\eta_{fi} = 0.7$ for elevated temperature (see Tab. **2**). On the contrary, if a “heat-resistant” resin is employed, the safety check is satisfied with η_{fi} values greater than 0.7.

Tab. 1: Safety check of the slab in positive moment region
(maintenance of the bituminous paving).

						Normal resin	High resistant resin
Thickness	N° lam/m	b lamina	η_{fi}	M_{Ed}	$M_{Ed,fi}$	$M_{Rd,t}$	$M_{Rd,t}$
cm	\	mm	\	kNm	kNm	kNm	kNm
15	2	100	0.7	69.75	48.83	63.62	78.65
20	2	100	0.7	128.32	89.92	142.84	147.86

Tab. 2: Safety check of the slab in negative moment region
(maintenance of the bituminous paving - s≤3cm).

						Normal resin	High resistantresin
Thickness	N° lam/m	b lamina	η_{fi}	M_{Ed}	$M_{Ed,fi}$	$M_{Rd,t}$	$M_{Rd,t}$
cm	\	mm	\	kNm	kNm	kNm	kNm
15	2	100	0.7	69.75	48.83	37.43	57.94

Tab. 3: Safety check of the slab in negative moment region
(maintenance of the bituminous paving - s=4cm).

						Normal resin	High resistantresin
Thickness	N° lam/m	b lamina	η_{fi}	M_{Ed}	$M_{Ed,fi}$	$M_{Rd,t}$	$M_{Rd,t}$
cm	\	mm	\	kNm	kNm	kNm	kNm
15	2	100	0.7	69.75	48.83	45.64	61.94

In conclusion, for slabs with FRP strengthening on the top side the use of “heat resistant” resins is necessary in order to avoid the achievement of the glass transition temperature in the same resins and satisfy the safety check in the presence of maintenance operations on bituminous paving. A protective layer of concrete is however necessary in order to avoid damages in the FRP strengthening and reduce the temperature in the structural materials.

b) Accidental situation, resulting in a fire exposure over the bridge deck.

A fire event over the bridge deck may occur because of a vehicular accident. For a bridge slab strengthened with FRP plate or sheets on the bottom side, the numerical analyses show that temperature in FRP and resin (Fig. 8) are generally lower than 60°C.When the FRP strengthening is on the top side of the RC slab, the maximum temperature at FRP-to-concrete interface exceeds generally the glass transition temperature of normal and heat-resistant resins, despite the thermal insulation provided by the road surface and the protection layer. The intersection between the assumed glass transition temperature T_g of the adhesive resin and the time-dependent temperature curves allows determining the maximum fire exposure time for the considered protection thicknesses (see Fig. 9a for normal resins and Fig. 9b for heat-resistant resins). It has to be remarked the significant role played by the thickness of the protection layer, which leads to greater fire exposure times.

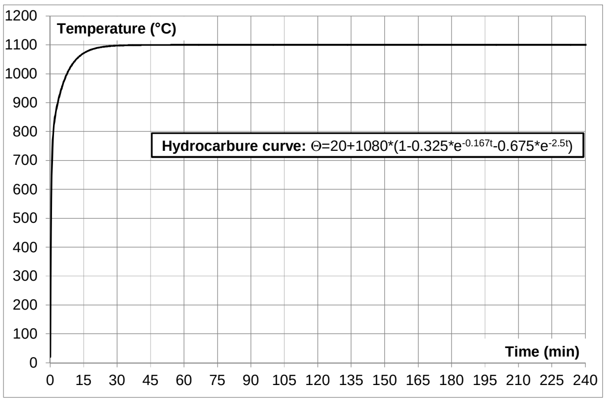


Fig. 7 Nominal Temperature-Time fire curves

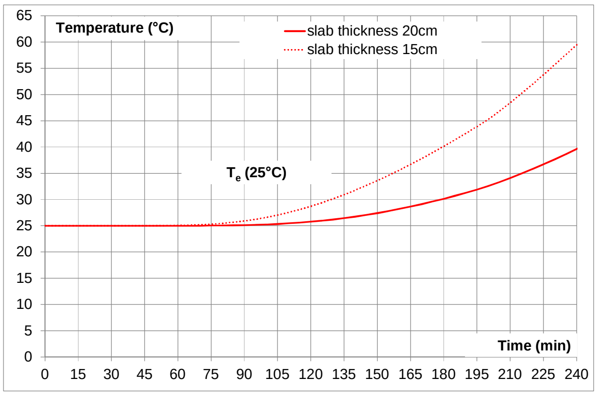
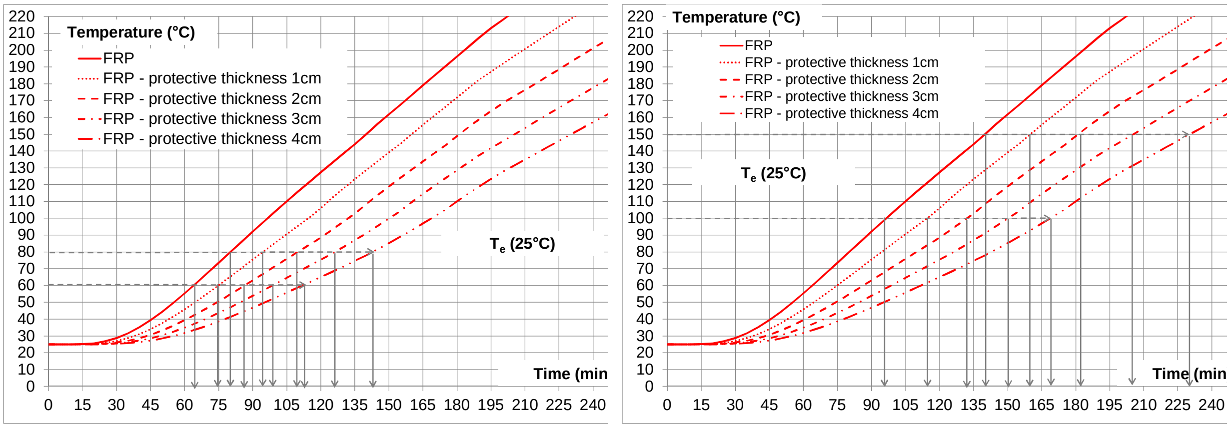


Fig. 8**:**Temperature in FRP on the bottom side



(a) (b)

Fig. 9**:** Temperature in FRP on the top side (a) normal (b) heat-resistant resins

4 CONCLUSION

The paper focused on performing a parametric analysis concerning the behaviour of RC bridge slabs externally strengthened with FRP in the presence of environmental situations responsible of elevated temperatures. In the case of bituminous paving realization, the analyses point out that the use of “heat resistant” adhesive resins is necessary with the aim of preventing the achievement of the glass transition temperature, if the strengthening is located on the top side of the slab. A protective layer of concrete is moreover required in order to avoid damages in the FRP strengthening. For strengthening on the bottom side, if the design level η_{fi} tends to 1, the safety check may become critical in the case of small thickness slab and normal adhesive resin, which exhibits a greater resistance reduction of the strengthened slab. In the case of fire event over the bridge deck and strengthening on the bottom side, the conclusions are quite similar to the ones of the previous environmental situation. If the strengthening is located on the top side of the slab, the use of “heat resistant” resins is recommended in order to increase the maximum time of fire exposure which prevents the achievement of the glass transition temperature in the adhesive resin.

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