COST IFER TU0904
Integrated Fire Engineering and Response

Training School for Young Researchers

Fire Engineering Research - Key Issues for the Future II

6-9 June, 2013
Naples - Italy

Fire resistance of concrete slabs reinforced with FRP bars. Experimental investigations and numerical simulation on the thermal field and the mechanical behaviour

Antonio Bilotta, PhD

DIST – Department of Structures for Engineering and Architecture
University of Naples Federico II, Naples, Italy

The presentation deals with the structural behaviour of concrete slabs reinforced with FRP bars in the case of **high temperatures**, due to fire event.

Fibre Reinforced Polymer (FRP) bars are made of:

Continuous Fibres + impregnated with **Polymeric Resins**

- glass
- carbon
- aramid
- basalt

- thermoplastic
- thermosetting

The **mechanical properties** of FRPs deteriorate when high temperatures arise, resulting in a significant **decrease of performances** of the FRP-reinforced structural members.

Even if several international codes are available for the design of concrete structures reinforced with FRP bars, **few provisions and calculation models** taking account of fire condition are suggested.

What does practitioner Engineer need ? → **Simplified Formulae** — Mechanical model

Direct calibration / Parametric Analysis, Estrapolation

Experimental Results — Validation → **Numerical Models**

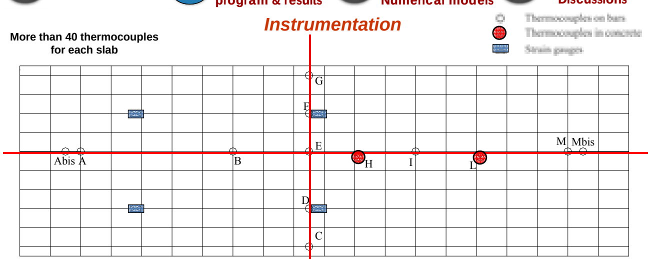
Tests on Materials (at different temperatures)	Thermal Properties	Conductivity, thermal expansion, etc…
	Mechanical Properties	Strenght, stiffness, bond (more than 1 material)
Tests on Structural Members	Heat transfer	Define temperature
	Mechanical Behaviour	Strenght Deformability

Experimental tests were performed to evaluate resistance and deformability of **nine concrete slabs** reinforced with Glass Fiber Reinforced Polymer (GFRP) bars in fire situation, by exposing them to heat in a furnace according to the time-temperature **curve ISO834.**

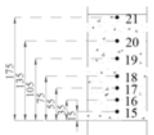
- **Tests results** are briefly summarized and discussed, making possible a comparison between the efficiencies of different bar anchorages
(Nigro et al. 2011a,b - Composites Part B & Nigro et al. 2013 - Journal of Structural Fire Engineering).
- The behavior of the bar anchorage is carefully examined based also on both the results of **numerical thermal analysis** and the predictions of a **bond theoretical model adjusted for fire situation.**
(Nigro et al. 2012 – Journal of composites for constructions)
- A **3D nonlinear finite element model** of the tested slabs is shown
(Nigro et al 2012 – SiF 2012 Zurich)
- The predictions of an **incremental - iterative procedure and a simplified method** are compared with the experimental results
(Nigro et al. - 2012 Advances in Structural Engineering)

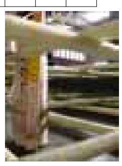
Instrumentation

More than 40 thermocouples for each slab

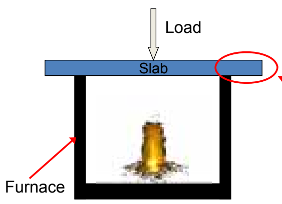


top
BAR
bottom





Test setup



Parameters

- Concrete cover
- Length of zone outside the furnace
- Bars type (straight or bent)
- Fire load level $\eta_{fi} = M_{Ed,fi}/M_{Rd}$

End zone of slab not directly exposed to fire → Anchorage length

Note: A continuous reinforcement from side to side of the concrete element is used .

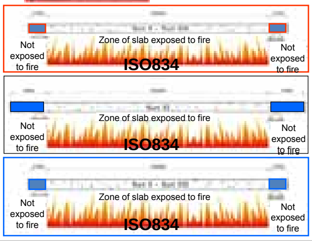
Test matrix

Geometrical properties
Slabs thickness = 180 mm
Slabs width = 1250 mm
Span length = 3200 mm

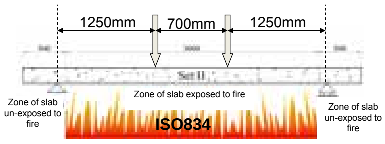
Materials
Concrete C35/45
GFRP bars (E glass fibers and ortophtalic polyester resin, T_g = 100°C)

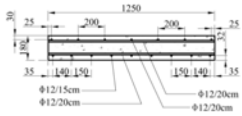
straight bars | bent bars

Set	Slab	Concrete cover [mm]	Anchorage length [mm]	Longitudinal (diameter/spacing) [mm/mm]	Longitudinal Bars no.	M_{Rd} [kNm]
I	S1	32	250 straight bars	Φ12/150	9	65
	S2					
	S3			Φ12/225	6	46
II	S4	51	500 straight bars	Φ12/125	10	65
	S5					
	S6			Φ12/200	7	46
III	S7	32	250 bent bars	Φ12/150	9	65
	S8					
	S9			Φ12/225	6	46



Load





Fire Load level ⟶ $\eta_{fi} = M_{Ed,fi,t}/M_{Rd}$

M_{Rd} according to CNR-DT203/2006

S1, S4, S7 ⟶ 10% of M_{Rd} (own weight)
S2, S5, S8 ⟶ 40% of M_{Rd} (F=17.5kN)
S3, S6, S9 ⟶ 60% of M_{Rd} (F=17.5kN)

loads in the range of the service loads

Observations after tests

Slabs S4-S5-S6: Fiber failure at midspan
c = 51mm, L_{unexp} = 500mm

Inside the furnace: bars

Section: end of slab

Observations after tests concerning the anchorage zone – STRAIGHT BARS

Slabs S1-S2-S3: Pull out of bars
c = 32mm, L_{unexp} = 250mm

Section: end of slab

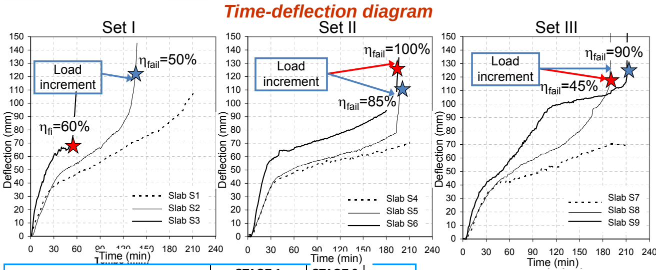
Cracks on transverse section at the end of the slab (correspondence crack/bar)

Observations after tests concerning the anchorage zone – BENT BARS

Slabs S7-S8-S9: no pull out of bars
c = 32mm, L_{unexp} = 250mm

Cracks on transverse section at the end of the slab in correspondence of each bar without pull out.

Time-deflection diagram



Set	Slab	c [mm]	L_{unexp} [mm]	Bar's end	STAGE 1 η_{fi} [%]	STAGE 1 t_e [min]	STAGE 2 η_{fail} [%]	Type of failure
I	S1	32	250	Straight	10	>180	55 *	Bars pull out
	S2				40	120	50	
	S3				60	60	-	
II	S4	51	500	Straight	10	>180	100 *	Bars rupture
	S5				40	>180	85	
	S6				60	>180	100	
III	S7	32	250	Bent	10	>180	60 *	Bars rupture
	S8				40	>180	45	
	S9				60	>180	90	

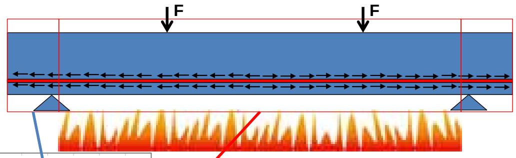
STAGE 1: constant load
STAGE 2: increasing load

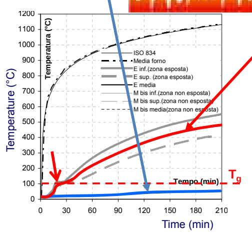
c = concrete cover
L_{unexp} = un-exposed length
$\eta_{fi} = M_{Ed,fi,t}/M_{Rd}$ (constant load)
$\eta_{fail} = M_{Ed,fi,t}/M_{Rd}$ (at failure)

* *Residual strength*

Background | Experimental program & results | Mechanical & Numerical models | Conclusions and Discussions

Experimental outcomes



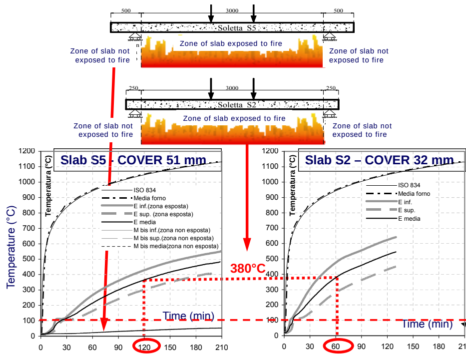


- When the bars temperature achieves the *glass transition value*, there is a significant reduction of bond between FRP bars and concrete.
- With the increasing of temperature the bond between FRP bars and concrete can be assumed negligible.
- The mechanical behaviour of tested slabs has been characterized by the *migration of bars stresses* from the zone directly exposed to fire to the anchoring zone (i.e. the zone not directly exposed to fire) in which the temperature is lower than T_g.

Background | Experimental program & results | Mechanical & Numerical models | Conclusions and Discussions

Main remarks on temperature levels and concrete cover

Comparison between thermal field in two typologies of slabs



Cover

T_g after about 15min for S2
T_g after about 25min for S5

- ✓ Cover thickness affects the time needed to achieve *T_g in the bars*
- ✓ In the *unexposed zone* T_g in the bars is not achieved
- ✓ In the zone exposed to fire the *overlapping of bars* cannot be used

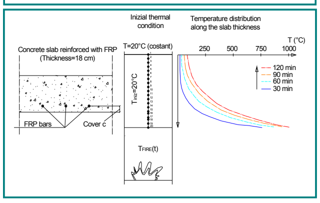
Fire resistance of concrete slabs reinforced with FRP bars.
Experimental investigations and numerical simulation on the thermal field and the mechanical behaviour
Antonio Bilotta, PhD - University of Naples Federico II – Department of Structures for Engineering and Architecture

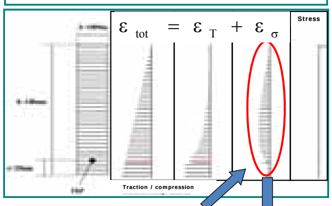
Background | Experimental program & results | Mechanical & Numerical models | Conclusions and Discussions

ASPECT OF THE FRP REINFORCED CONCRETE SLABS BEHAVIOUR

Decoupling the thermal behaviour from the mechanical behaviour as well as suggested by EN1992-1-2

Thermal Analysis | **Mechanical Analysis**





Law s-ε(T)

$$\varepsilon_\sigma = \varepsilon_{tot} - \varepsilon_T$$

Fire resistance of concrete slabs reinforced with FRP bars.
Experimental investigations and numerical simulation on the thermal field and the mechanical behaviour
Antonio Bilotta, PhD - University of Naples Federico II – Department of Structures for Engineering and Architecture

Background | Experimental program & results | Mechanical & Numerical models | Conclusions and Discussions

INCREMENTAL-ITERATIVE PROCEDURE

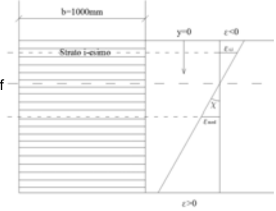
Nigro et al. 2008

determining the bending moment-curvature law of the critical cross-section in fire condition

- slab or beam cross-section is divided into a sufficient number of layers;
- external axial force N_{ext}=0 for pure bending;
- assigned a curvature χ_1 and the average strain ε_{med} of the cross-section;
- $\varepsilon_i = f(y_i, \chi_1)$;
- from the stress-strain law of the layer i:

$$\sigma_i = f(\varepsilon_{\sigma,i}, \theta_i)$$

$$\sigma_i = f(\varepsilon_i) \longrightarrow N_{int} = \sum_1^{n_c} A_{c,i}\cdot\sigma_{c,i} + \sum_1^{n_f} A_{f,i}\cdot\sigma_{f,i}$$



- Iterations varying the average strain ε_{med} of the section need up to satisfying the longitudinal equilibrium equation within a suitable error $(N_{int} - N_{est}) \le \delta$
- Check of ultimate limit strains of the materials:

$$\varepsilon_{cls,i} \le \varepsilon_{cls,u}(T_i);\quad \varepsilon_{FRP,i} \le \varepsilon_{FRP,u}(T_i);$$

- Evaluation of the ultimate bending moment:

$$M_j = \sum_1^{n_c} A_{c,i}\cdot\sigma_{c,i}\cdot(y_{c,i} - y_G) + \sum_1^{n_f} A_{f,i}\cdot\sigma_{f,i}\cdot(y_{f,i} - y_G)$$

Fire resistance of concrete slabs reinforced with FRP bars.
Experimental investigations and numerical simulation on the thermal field and the mechanical behaviour
Antonio Bilotta, PhD - University of Naples Federico II – Department of Structures for Engineering and Architecture

Background | Experimental program & results | Mechanical & Numerical models | Conclusions and Discussions

Application of the incremental - iterative procedure

to asses the stresses in the FRP bars

stresses at midspan

Slab	Exposure time [min]	Bending moment [kNm]	Failure type	Bar stress [N/mm²]
S2	120	32.5	pull-out of bars	$\sigma'_{S2,120}$ ≈ **250**
S3	60	27.6	pull-out of bars	$\sigma'_{S3,60}$ ≈ **295**
S5	180	55.2	bars rupture	$\sigma'_{S5,180}$ ≈ **305**
S6	180	46.0	bars rupture	$\sigma'_{S6,180}$ ≈ **295**

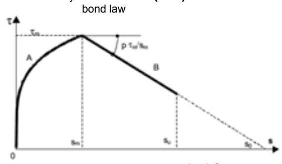
Due to the absence of bond, these values can be assumed as the stresses in the FRP bars as long as the bond returns again effective (i.e. the zone not directly exposed to fire)

Fire resistance of concrete slabs reinforced with FRP bars.
Experimental investigations and numerical simulation on the thermal field and the mechanical behaviour
Antonio Bilotta, PhD - University of Naples Federico II – Department of Structures for Engineering and Architecture

Background | Experimental program & results | Mechanical & Numerical models | Conclusions and Discussions

Bond model

Elingehausen et al. (1983) modified by **Cosenza et al. (2002)** bond law

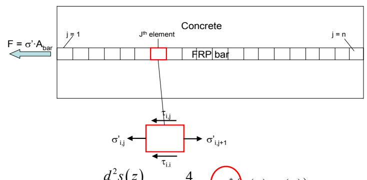


ascending branch $s \le s_m$: $\tau_b(s) = \tau_m \cdot \left(\frac{s}{s_m}\right)^\alpha$

softening branch $s > s_m$: $\tau_b(s) = \tau_m \cdot \left(1 + p - p\frac{s}{s_m}\right)$

s_m = 0.253 mm (0.181); τ_m = 14.65 MPa (0.110); α = 0.245 (0.619); p = 0.128 (0.599).

Carvelli et al. 2009 Personal communication τ_m = 8.9 MPa;



$$\frac{d^2 s(z)}{dz^2} - \frac{4}{E(T(z))\phi}\tau^*(s(z), T(z)) = 0$$

Nigro et al. 2008

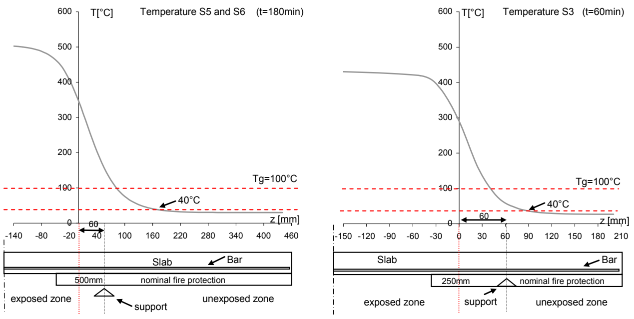
$$\rho_E(T) = \frac{E(T)}{E} = \frac{0,28}{0,28 + 6,0\cdot 10^{-12}\cdot T^{4,3}}$$

$$\sigma_{i,j+1} = \sigma_{i,j} - \Delta\sigma_{i,j} \qquad \Delta\sigma_{i,j} = \tau_{i,j}\cdot(\pi\cdot\phi\cdot\Delta z)$$

$$s_{i,j+1} = s_{i,j} - \left(\frac{\sigma_{i,j} + \sigma_{i,j+1}}{2\cdot E}\right)\cdot\Delta z$$

Fire resistance of concrete slabs reinforced with FRP bars.
Experimental investigations and numerical simulation on the thermal field and the mechanical behaviour
Antonio Bilotta, PhD - University of Naples Federico II – Department of Structures for Engineering and Architecture

Thermal analyses



Background | Experimental program & results | Mechanical & Numerical models | Conclusions and Discussions

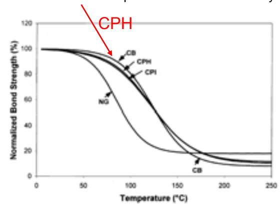
Reduction of bond strength at high temperatures

$$\tau^*(T) = 0.5\cdot\left(1-\tau_r^*\right)\cdot\tanh\left\{-\frac{0.02}{C_r}\left[T-\left(T_g+\frac{k_1}{0.02}C_r\right)\right]\right\}+0.5\cdot\left(1+\tau_r^*\right)$$

Katz & Berman (2000)

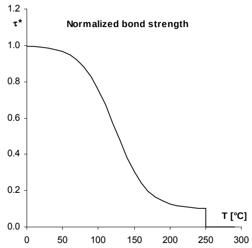
$\tau_r^* = 0.10$; $Cr = 90$; $T_g = 100$ °C.

Rod CPH contains wraps of helical braid of fibers on the surface and with additional fine sand particles embedded evenly on the surface.



Very similar to the bars embedded in the slabs

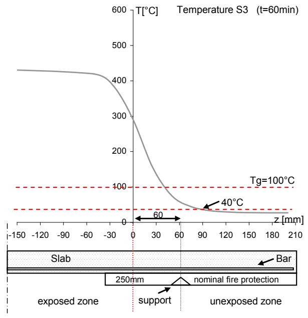
τ–T law assumed for the bars

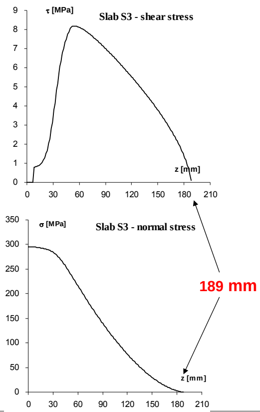


Fire resistance of concrete slabs reinforced with FRP bars.
Experimental investigations and numerical simulation on the thermal field and the mechanical behaviour
Antonio Bilotta, PhD - Universitiy of Naples Federico II – Department of Structures for Engineering and Architecture

Background | Experimental program & results | Mechanical & Numerical models | Conclusions and Discussions

Bond length assessment (S2-S3) - straight bars





S2 (120min) 193 mm

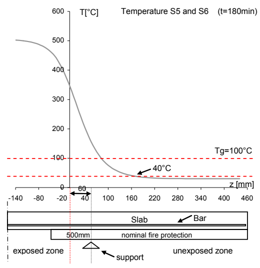
S3 (60min) 189 mm

≈ 200±10 → 10mm for the lateral concrete cover

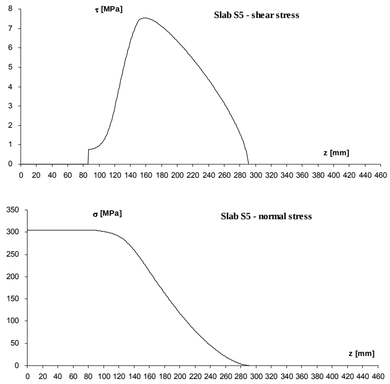
Fire resistance of concrete slabs reinforced with FRP bars.
Experimental investigations and numerical simulation on the thermal field and the mechanical behaviour
Antonio Bilotta, PhD - Universitiy of Naples Federico II – Department of Structures for Engineering and Architecture

Background | Experimental program & results | Mechanical & Numerical models | Conclusions and Discussions

Bond length assessment (S5-S6) - straight bars



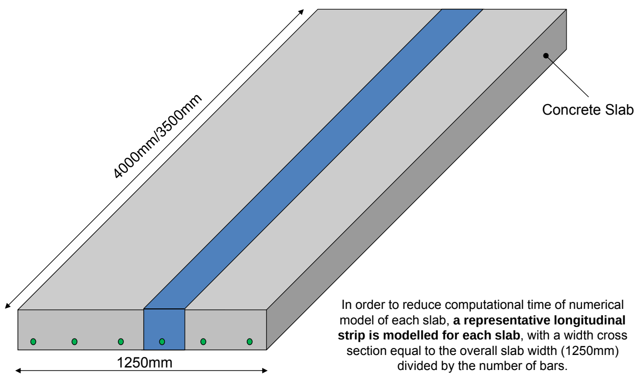
clearly shows that at 180min temperatures are < 40°C between z = 160 - 460mm namely for a length $l_{S5,40°,180}$ ≈ 300mm > $l_{d,S5}$ ≈ 150 mm (normal condition)



Fire resistance of concrete slabs reinforced with FRP bars.
Experimental investigations and numerical simulation on the thermal field and the mechanical behaviour
Antonio Bilotta, PhD - Universitiy of Naples Federico II – Department of Structures for Engineering and Architecture

Background | Experimental program & results | Mechanical & Numerical models | Conclusions and Discussions

Geometry

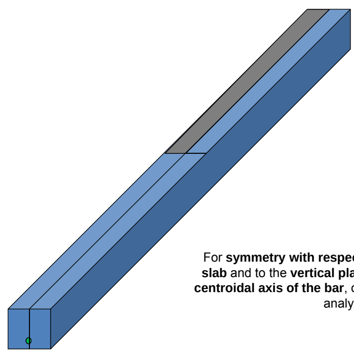


In order to reduce computational time of numerical model of each slab, **a representative longitudinal strip is modelled for each slab**, with a width cross section equal to the overall slab width (1250mm) divided by the number of bars.

Fire resistance of concrete slabs reinforced with FRP bars.
Experimental investigations and numerical simulation on the thermal field and the mechanical behaviour
Antonio Bilotta, PhD - Universitiy of Naples Federico II – Department of Structures for Engineering and Architecture

Background | Experimental program & results | Mechanical & Numerical models | Conclusions and Discussions

Geometry

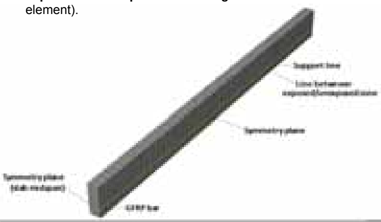


For **symmetry with respect to the midspan of the slab** and to the **vertical plane passing through the centroidal axis of the bar**, only a quarter of the strip is analyzed

Fire resistance of concrete slabs reinforced with FRP bars.
Experimental investigations and numerical simulation on the thermal field and the mechanical behaviour
Antonio Bilotta, PhD - Universitiy of Naples Federico II – Department of Structures for Engineering and Architecture

Thermo-mechanical modeling

- The thermo-mechanical modeling of the slabs tested under fire conditions is performed through the finite element software **ABAQUS/Standard**
- The mechanical analysis is developed by associating to the FEM model the temperature field obtained through a previous thermal analysis (**decoupling of thermal problem and mechanical problem** is assumed)
- In the **zone directly exposed to fire**, the **GFRP bar and the concrete does not transfer bond stresses since the application of external loads** ("Contact pair" interface element).
- The numerical analyses will be performed only for slabs of Set II and Set III, for which in the **zone not directly exposed to fire perfect bonding between bar and concrete can be assumed** ("Constraint" interface element).



Each slab is divided into finite elements "Brick" type "Hex" (parallelepiped elements), with maximum dimensions of 70mm x 28mm x 20mm, 8 linear node (ABAQUS C3D8 element).

Thermo-mechanical modeling

Both the exposed and not exposed to fire surface was defined in accordance with the conditions of thermal exposure of the slabs during the tests.

According to EN1991-1-2:
- constant **convective coefficients** α_c **= 25 W/m²K** and α_c **= 9 W/m²K** were assumed for the exposed and unexposed surfaces, respectively;
- the radiative heat flux was calculated by using a **concrete emissivity** ε **= 0.7**.

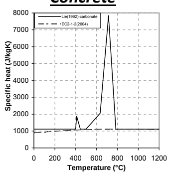
This flux has been considered only for the exposed surface.

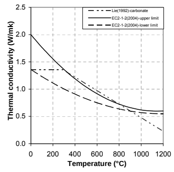
The load application were identical to that used during the **Stage 1** of the test, characterized by a **constant load** during the fire exposure.

Thermal properties

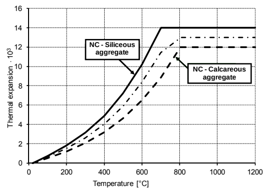
Concrete

Concrete **specific heat and thermal conductivity** relationships provided by **Lie (1992)** were assumed.





Concrete thermal expansion*, three different relationships were assumed:*
- provided by EN1991-1-2 for calcareous concrete
- provided by EN1991-1-2 for siliceous concrete
- the third one was obtained by averaging the first two.

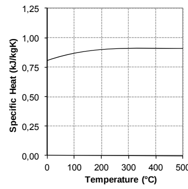


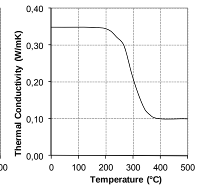
Thermal properties

FRP

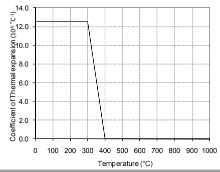
FRP **specific heat and thermal conductivity** relationships provided by **Bai et al** (2007)*.

* Bars characterized by a similar ratio fiber / matrix equal to 61%, not far from the 70% that characterizes the GFRP bars used for the specimens





FRP thermal expansion Bai et al. relationships was **modified** as showed

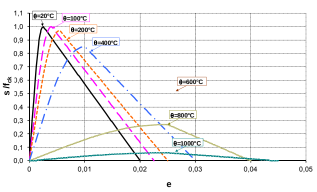


Mechanical properties

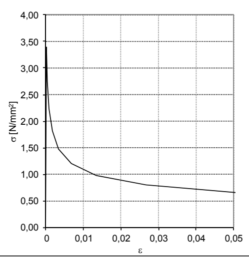
Concrete

damaged plasticity model

Compressive behaviour
Stress-strain relationship provided by **EN1992-1-2**



Tensile behavoiur
Modified stress-strain relationship provided by **Belarbi & Hsu (1994)**



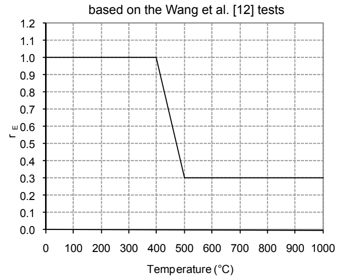
Mechanical properties

FRP

- Linear elastic at the generic temperature T
- Elastic modulus $E_f(T) = \rho_E(T)\cdot E_f$.

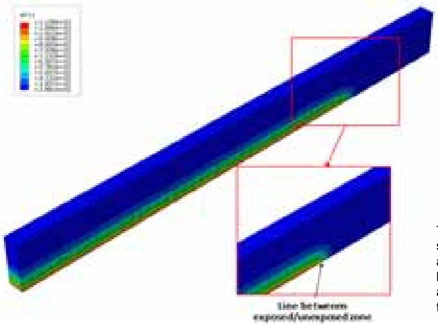
$\rho_E(T)$ is the reductive coefficient of the elastic modulus at temperature T

based on the Wang et al. [12] tests



Results

Temperatures distribution at 60 minutes of fire exposure time (temperature in Kelvin)

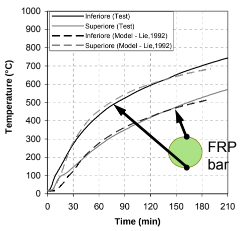


Thanks to the 3D modeling heat diffusion in the neighborhood of the separation line between the surface directly exposed and not directly exposed, near the supports, can be observed.

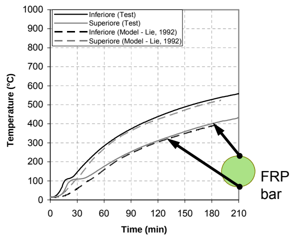
This heat diffusion clearly show that temperatures and hence deterioration of bar-concrete bond in the area not directly exposed to fire are low

Results

Cover 32mm



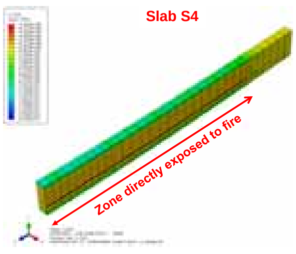
Cover 51mm



Time-temperature curves, above and below the bar, obtained with the FEM model in ABAQUS, are in **good agreement with the experimental results**

Results

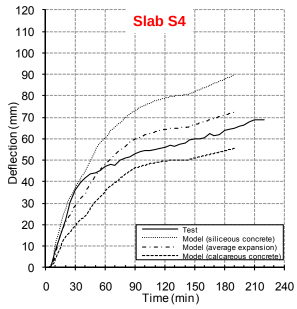
Stresses map at 60 min of fire exposure time

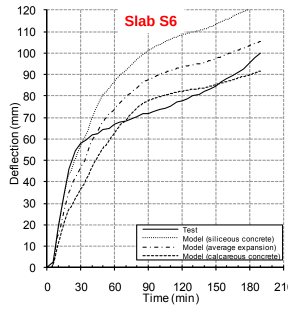


Sresses along the FRP bar are constant and reduce only at the end of the slab, not directly exposed to fire. For simplicity the degradation of the adhesion bar-concrete above mentioned was not modeled, as stated in the FEM model description.

Results

Comparison of **Displacement vs time**

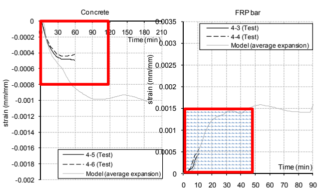


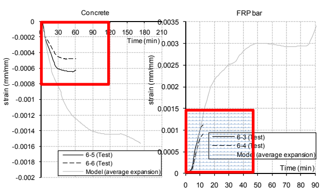


- **The thermal expansion affect the significantly simulation results.**
- **However the trend of displacement vs time curves of experimental test and numerical model are similar.**

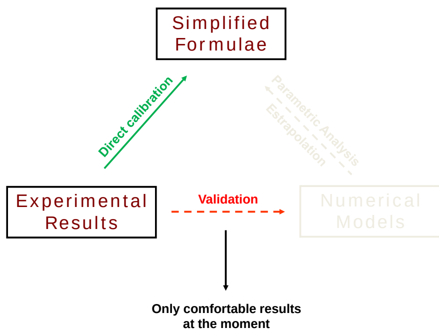
Results

Comparison of experimental and numerical **strains vs time**





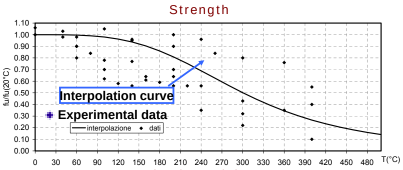
- The figures show a **good agreement between experimental and numerical strains on FRP bars**.
- Instead the model overestimated the strain in the concrete.



Starting point for simplified formulae

Mechanical properties

Strength

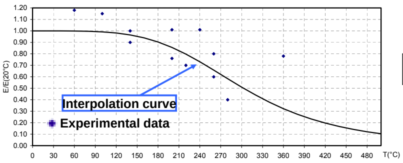


GFRP Bars

Nigro et al. 2008

$$\rho_f(T)=\frac{f_{fu}(T)}{f_{fu}}=\frac{A}{B+C\cdot T^D}=\frac{0,05}{0,05+8,0E^{-11}\cdot T^{3,55}}$$

Elastic modulus

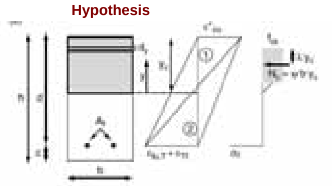


$$\delta_f(T)=\frac{E(T)}{E_0}=\frac{A}{B+C\times T^D}=\frac{0,28}{0,28+6,0E^{-12}\times T^{4,3}}$$

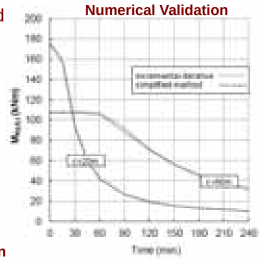
Application of the simplified method

to asses the member capacity

Hypothesis



Numerical Validation



Experimental validation

Table 6. Failure time predicted by simplified method

Slab	Concrete cover (mm)	GFRP Area (mm²)	M_{u}/M_{u0} (%)	Simplified method Temperature (°C)	Simplified method Failure time (min)	Test results Temperature (°C)	Test results Failure time (min)
S1		1017	10%	700	210	>614	>180
S2	32	1017	40%	450	75	505	120
S3		678	60%	395	99	330	60
S4		1130	10%	>700	>210	>460	>180
S5	19	1130	40%	450	145	>460	>180
S6		791	60%	400	115	>460	>180

Experimental Tests

Thermal behaviour

- ***Concrete cover*** *was confirmed particularly meaningful for the protection provided to FRP bars, allowing to* ***delay*** *the attainment of high temperature values in the bars.*
- *In a part of the* ***zone not directly exposed*** *to fire (as a function of fire exposure time) the bars didn't attain the* ***glass transition temperature*** T_g*.*

Mechanical behaviour

- *When the bars temperature achieves the glass transition value, there is a significant* ***reduction of bond between FRP bars and concrete.***
- *The mechanical behaviour of tested slabs has been characterized by the* ***migration of bars stresses*** *from the zone directly exposed to fire to the anchorage zone (i.e. the zone not directly exposed to fire action).*
- *When the glass transition temperature is achieved in the zone directly exposed to fire,* ***the structural behaviour depends mainly on the length of unexposed zone (anchorage length) and on the bars type (straight or bent).***

Structural design details

- ***The anchorage obtained simply by bending bars at the end*** *of member in a short zone (250mm) allowed to attain a good structural behavior in case of fire,* ***equivalent to that shown by slabs characterized by a large anchoring length (500mm).***

Mechanical and Numerical models

- ***Theoretical predictions of the bond model achieved a good agreement with the experimental results.***

The results clearly depend on the properties of the FRP bars *(i.e. fiber type, Young's modulus, tensile strength, diameter, surface treatment)* ***and the strength of the concrete****.*

However, they can be extended to different types of FRP bars as long as the ***manufacturer provides the adhesion properties of the bars, at least under normal conditions.***

- ***Numerical 3D FEM model was useful to evaluate thermal and mechanical behavior of slabs reinforced with GFRP bars:***

- *Preliminary comparisons between numerical and experimental outcomes showed* ***good agreement in terms of temperature and quite comfortable results for the mechanical simulations.***
- *The FEM model will be refined with the aim of addressing future research concerning* ***specific thermal properties of concrete and FRP*** *and introducing the* ***bond model between concrete and FRP bars****.*

- ***Theoretical predictions of simplified method are promising.***

- ***The fitness seems to depend on the properties of the FRP bars*** *(i.e. degradations with temperatures of Young's modulus, tensile strength for different fiber and resins types)*

- ***Material tests are necessary***

Acknowledgement

Dr. Giuseppe Cefarelli co-author of the research activity