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Numerical simulation of tests for the evaluation of the performance of the reinforced concrete slabs strengthening by FRCM

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Abstract: In this work the attention is focused to the numerical simulation of the experimental bending tests carried out on a total of six reinforced concrete r.c. plates the latter aimed to provide a basic understanding of the its performance when strengthened by Fiber Reinforced Cementitius Matrix (FRCM) Composites. Three of those were used as control specimens. The numerical simulation was carried out by LUSAS software. A good correlation between the FE results and data obtained from the test, both in the load–deformation behavior and the failure load was highlighted. This permits to prove that applied strengthening system gives back an enhancement 2.5 times greater in respect of the unreinforced case. A greater energy dissipation ability and a residual load-bearing capacity makes the proposed system very useful in the retrofitting as well as in the case of strengthening of bridge structures. Based on the validation of the FE results in bending, the numerical analysis was also extended to characterize the behavior of this strengthening system in tensile.

Keywords: FRCM; Composite materials; numerical simulation; retrofit; slab; plates; strengthening FE simulation

Introduction

In the past years there was an increasing demand for the restoring and rehabilitation of exiting structures including bridges, due to the deterioration as well as to the introduction of more strict design requirements especially under seismic hazard so that in many cases a strengthening of the existing structures or parts of them is required [1, 2]. The increasing use of Fiber Reinforced technology for the strengthening and the rehabilitation of exiting and historical buildings [3–7] has generated considerable research interest in understanding the structural behavior in such systems in order to define also a first design guidelines in the use of FRP [8–10]. Several studies highlighted how FRP composites can be an effectiveness material capable of increasing flexural [11, 12] and shear [13–18] performance of the real structure.

Despite all his advantages the FRP strengthening technique shows few disadvantages due to the presence of resin used as matrix to bind the fibers, as poor resistance to high temperatures, high cost of epoxy resin, easy debonding of FRP to the concrete substrate [19], inability of applying FRP on wet surfaces, incompatibility of epoxy resins and substrate material. An alternative solution should be to replace of organic by inorganic mortar. Different solutions to design cement based strengthening systems for concrete structures are proposed; among these the Textile Reinforced Concrete (TRC), the Textile Reinforced Mortar (TRM), the Fiber Reinforced Concrete (FRC), the Mineral Based Composites (MBC) and the Fiber Reinforced Cementitious Mortar (FRCM) [20–28]. The reinforcement of the structural elements by means of FRCM, unlike FRP, is based on the use of a fabric meshes with dry fiber strands disposed orthogonally and bonded to the support by an inorganic matrix mixed to the water so as to be suitable under the chemical, physical and mechanical point of view with support, especially if we refer to the masonry and concrete structures. This also thanks to its high mechanical performance comparable to the traditional FRP composite with epoxy matrix. Besides a faster installation, greater resistance to moisture, fire and temperature, a lower toxicity faced by operators is achieved. It is well-known that the performance of FRCM system is correlated to the mechanical characteristics of the employed fibers. The use of a new class of ultra-high strength fibers nets, the Polyparafenilinen Benzo-bis-Oxazolo PBO, very significant in terms of elastic modulus and tensile strength can highly improve structural performance [29–37]. The use of this kind of strengthening materials in civil engineering is not yet widespread even though the few available tests car-

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Table 1: Mix design of the concrete

Material	Value	unit
Water	11.0	L
Cement	25.5	kg
Sand	54.6	kg
inert	46.5	kg
Total aggregate	101.1	kg
Total mixture	137.6	kg
Additive 0.5%	80	c.c.

ried out on reinforced concrete beams have shown a good evidence of their structural performance. Literature lacks of test results carried out on two-dimensional r.c. members even if this member is typical in the bridge structures [38].

1 Materials background

A non-linear three-dimensional FEM preliminary analysis was necessary in order to calibrate the strength in play during the lab test, it was carried out by software LUSAS. The input parameters of the mechanical properties of the materials, to be used for the FE modelling, were derived from experimental tests on materials, as: bending and compression tests on special matrix of the FRCM, compression tests on employed concrete cubes, tensile testing of segments of bars of r.c. plate reinforcement, etc.. The results of the numerical simulations were compared with the experimental ones conducted on the reinforced plates and the subject of other publications [39].

1.1 Concrete

The mixture was designed in order to obtain a concrete belonging to C35/45 concrete class according to the Italian Codes. For the aggregate a maximum diameter of 20 mm was chosen. Finally a consistency class of S5 was adopted according to the Collepardi suggestions [40]. The concrete mixture in terms of volume amount employed for each sample including the cube specimens is reported in Table 1. Compression tests aimed to the assessment of the real average compression strength of the concrete (at the time of the test on the plates) were carried out on twelve cubes of concrete, two for each slab samples. The obtained data are reported in the Table 2.

1.2 FRCM

The composite material employed in this study was a material patented by RUREDIL and called X MESH GOLD, a fiber-based high-performance, consisting in a PBO fibers net and stabilized by inorganic matrix able to get solidified to the concrete; this material has high tensile strength in bending and good cubic compressive strength (about 30 MPa).

The tensile strength of the cement matrix was determined by bending tests carried out on three prismatic 40x40x150 mm^3 in size, whereas compressive strength was determine by compression test on the cubes 40x40x40 in size, obtained from the prismatic pieces gotten after bending tests conforming to UNI 1015-11. The main mechanical features of the reinforcement employed are reported in Tables 3, 4, 5 respectively for mortar, net and PBO.

2 Studied specimen

Two specimens were investigated by numerical point of view: one represents the reference non-strengthened specimen, the other the strengthened one. The model was a 3D r.c. concrete slab 70 cm long and 70 cm wide in dimensions with a thickness of 10 cm. In the numerical model the steel bar reinforcement was located at the top and bottom with a schematized by a 10 cm x 10 cm steel bars mesh of Φ5 mm diameter. In the strengthened model, the ratio between the amount of steel bar reinforcement and the CFRM was investigated in order to ensure that the reinforcing steel bars, located in the area subjected at tensile strength, were in yield strength when the crisis for delamination occurred to the CFRM composite by assuming failure delamination stress equal to 1400 MPa. Then application of 2-plies of the FRCM reinforcement on the specimen, occurred.

3 The bending test

Three reinforced concrete plates, 70x70x10 cm^3 in size, supported by steel framed structure (Figure 3) located at the bottom undergo to bending. The clean span was equal to 60 cm. The load was applied in displacement control in the mid-span of the plate by a steel beam connected to a hydraulic jack of 300kN (Figure 4) in quasi static loading and unloading pattern for a total of one complete cycle plus loading to the failure. The vertical deflection was measured by means of two displacement transducers W50.

Figure 1: Concrete batch

Figure 2: Concrete samples for compressive test

Table 2: Concrete properties

Specimen batch	Weight for volume unit (kN/m^3)	Compression strength (MPa)
Control specimens	24.05	50.89
Strengthened specimens	24.19	51.16

Data were gathered at a frequency of 2,0 Hz by HBM acquisition data system with Catman software interface. The collapse mode obtained is represented in Figure 5 for an applied ultimate load of 64 kN The first crack appears at a load level of 56.6 kN and it propagates opposite when the load level achieved the value of 64.4 kN (Figure 6). At this stage the lower steel bars reinforcement yielded.

The strengthened sample was obtained by following these steps:

1. Uniform application of mortar thickness of 4 mm (Figure 7);
2. Application of the first layer of PBO with warping in east-west direction, making sure to press on it with the racket to sink it in the layer of mortar (Figure 8);
3. Drawing up of the second layer 4 mm (Figure 9);
4. Application of the second layer of PBO with wrapping orthogonal to the previous, spreading it with attention and sinking it in the layer of mortar (Figure 10).

The testing set up in this case was completed by employing two 60 mm long strain gauges glued at the tensile face of the slab in order to correlate the transversal and longitudinal stresses as well as the load level at which the debonding from the concrete substrate occurs.

Also in this case the failure mode consists in a complete opening of the vertical crack in the mid-span (Figure 12), then the failure of the reinforcement steel bars was recorded but a residual load can be still brought up to the delamination of the support occurred.

Figure 13 represents the comparison between the performance, in terms of load - vertical displacement trend, of the slab in the studied cases . The strengthened sample collapses for an ultimate load equal to 160 kN more than 2.5 times greater than that of the original non-strengthened slab.

Both a greater dissipation ability, and a residual load-bearing capacity can be observed; the latter makes the strengthened system very flexible and secure against sudden collapse induced by the overloading of those exceptional cases not considered in the bridge design.

It seems very interesting to observe the strain gauges trend (Figure 14) applied on the cementitious matrix at the intrados of the plate The load-displacement capacity curve (in green) of the FRCM PBO reinforced plate overlaps to the trend of the longitudinal strain (black) while the trend of the transversal strain (red) gauges demonstrates the plate effect.

4 Numerical simulation of the test

This analysis seemed to be very useful in predicting the orders of magnitude of the loads and displacements acting during the tests so as to choose the most suitable test set-up. Moreover, this investigation was also essential to define the class of concrete as well as the bar reinforcement required to obtain a ductile behavior during the test and therefore not characterized by premature failure of the compressed concrete.

Table 3: Experimental properties of the special binding mortar

Specimen	Apparent specific gravity kN/m^3	Tensile strength in bending N/mm^2	Averaged compressive strength N/mm^2
1	18	8.3	27.86
2	19	8.0	27.84
3	17	3.6	26.07

Table 4: Characteristics of the net

PBO Fiber weigth in the net	88 g/m^2
Equ. thickness of dry fabric warp direction	0,0455 mm
Equ. thickness of dry fabric weft direction	0,0115 mm
Collapse load of the warp for unit length	264,0 kN/m
Collapse load of the weft for unit length	66,5 kN/m
Net weigth	110 – 126 g/m^2

LUSAS [35], a general purpose finite element program, was employed for the numerical simulation of the test. The 3-D finite element model was developed on a model geometry derived by the real specimen 70x70 cm^2 wide and 10 cm thick.

The effectiveness of the FRCM with PBO fibers as strengthening in r.c. slabs has been tested through experimental laboratory tests on real models of plates.

The following lab tests have been implemented:

1. Bending test with supports on two sides of the plate, in order to compare the behavior in the presence and in the absence of reinforcement by means of PBO-FRCM.

Besides, experimental simulation of three kind of tensile test was carried out in order to design the real test equipment:

1. Plate with angular head and foot.
2. Plate with cross members bolted in the upper face and lower.
3. Plate bolted to the sides and corners.

4.1 Material modelling

The material model Cracking Concrete with Crushing Model (Figure 15) was employed to model both the concrete for the plate and the mortar for FCRM. This is a model available in LUSAS and capable of catching the non linear effects related to the concrete failure. The mechanical features adopted in this model were derived directly from the laboratory tests. Namely the uniaxial compressive strength was fck = 38 MPa, tensile strength (ft) = 3,43 MPa, strain at peak compressive stress (ε_{cp}) =0,0027, Strain at end of compressive softening curve (ε_{c0}) =0,0035, strain at end of tensile softening curve (ε_{t0}) = 0,0035. The material model Stress potential (Figure 16) was employed to represent the steel reinforcement, which is suited to model non linear isotropic material with hardening. The latter was considered by introducing hardening gradients which, in the contemplated case, were a plastic strain equal to 0,025 yield strength of 450 MPa, ultimate strength of 475 MPa and slope C_1 equal to 1000 MPa.
FCRM mechanical features adopted were derived by the manufacture details (E_{fiber}= 270.000 MPa, E_{matrix} = 8.000 MPa) and computed by referring to the formula below (1,2), where E_1 is the longitudinal elastic modulus, E_2 the transversal elastic Modulus, G defined by (3) is the shear modulus, ν the poisson coefficient assumed equal to 0,2, by considering a fibre volume fraction (V_f) referred to a thickness of 0,057 mm and embedded in a mortar volume fraction (V_m) referred to a 10 mm in thickness.

$$E_1 = E_f V_f + E_m V_m, \tag{1}$$

where

$$V_f + V_m = 1.$$

$$E_2 = \frac{E_f E_m}{E_f V_m + E_m V_f}. \tag{2}$$

$$G_{xy} = G_{yz} = G_{xz} = G_{\text{matrix}} = \frac{E}{2(1+\nu)}. \tag{3}$$

4.2 Numerical simulation in bending

The distance between the supports was equal to 60 cm. In order to realistic mimic the real behaviour of the RC

Table 5: Characteristics of PBO

Parameter	Mean
Density	1,56
Tensile Strength (GPa)	5,8
Elasticity modulus (Gpa)	270
Elongation at collapse (%)	2,15
Decomposition temperature (°C)	650
Coefficient of thermal expansion (10^{-6} °C^{-1})	-6

plate, the concrete volume was modeled using 20-node HX20 solid elements, steel reinforcement was modeled using BRS3 bar elements, and CFRM composite was modeled using QTS8-node shell element (Figures 17-18).
The interface between the loading steel beam and the plate was defined by JNT4 3D element represented by springs in all the directions (Figure 18). The JNT4 element was associated to a material with stiffness only in a direction.

4.2.1 Contacting modelling

In the strengthened model, the interface between concrete and CFRM was modeled by IS16 interface element, this element is capable of modeling the mechanism of fiber delamination and crack propagation. The model behaves linearly until the force threshold is not exceeded. When this occurs, the material properties of the interface element are reduced linearly (Figure 19). The complete failure of the bond interface occurs when the fracture energy is overcome. In the present study concrete surface was considered as the master surface, whereas CRFM layer was used as slave surface.

4.3 Numerical simulation in bending

The FE simulation of the test was carried out by referring to the experimental value of Young's modulus as defined before. Figures 20-21 show the mesh and the deformed scheme of the investigated cases (non strengthened and strenghtened specimens) undergo bending.
The numerical investigation is capable to give back the behaviour of the speciment up to the collapse. The predicted ultimate load achieved by means of the FE simulation is exactly the same of the experimental ones. In the specific case, the ultimate load is equal to 160 kN and 60 kN for strengthened and control model respectively. Figure 23 plots the data obtained from FE simulation both in the case of not strengthened and strengthened model.
In other words, the FE results correlate very well with those from the test [36], both in the load–deformation behavior and in the failure load and stiffness, as plotted in Figure 23. For an easier and faster non linear load control analysis we stopped the analysis up to the peak.

4.4 Numerical simulation in tensile

By relating to the good accordance between experimental and numerical investigations, it is possible to investigate, from numerical point of view, the performance of the strengthened plate under tensile strength. Tensile, in fact, is the main solicitation occurring at the intrados of the mid span cross section or, otherwise, at the extrados of the internal support cross section commonly employed in the bridge (e.i. double T cross section or trapezoidal box section).
Three different methods in applying the tensile load on the plate were studied (Figure 24 a-b-c) but the most suitable both in terms of effectiveness and practice point of view is that related to (c) configuration. Namely in LUSAS, in the (a) configuration four steel flanges, 10cmx10cm in dimensions, were connected to the plate and a load of 500kN was applied, bearings are simulated by springs in very low stiffness as a vertical restrain with a low friction; in the (b) configuration the model was implemented with two steel beams, 10cmx10cmx70cm, placed on the top and the bottom of the slab and a load of 500 kN was applied on every beams; in the (c) configuration the model was implemented with two steel squared plates, 12cmx30cmx70cm, placed laterally. A horizontal load of 1000 kN was applied on every beam. The (a) configuration gives back not useful results due to the premature detachment of the steel, the (b) configuration was also neglected since the stress distribution was not uniform because of the stresses concentration (Figures 25-26) , otherwise (c) configuration determines a uniform distribution of the stresses all along the specimen (Figures 27-28). In this configuration is possible to record a load gain in tensile for the strengthened specimen 1,5 times greater than the reference one. Collapse load was equal to 600kN for the strengthened model and 420 kN in the non strengthened one.

5 Conclusions

This study aimed to discuss the behavior of two-dimensional reinforced concrete element strengthened by innovative materials base on the use FRCM unlike FRP

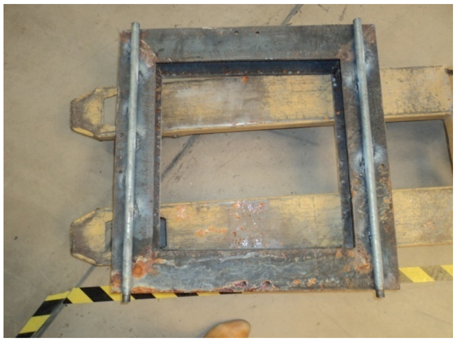

Figure 3: Bearing support frame structure

Figure 4: Testing configuration for reference sample

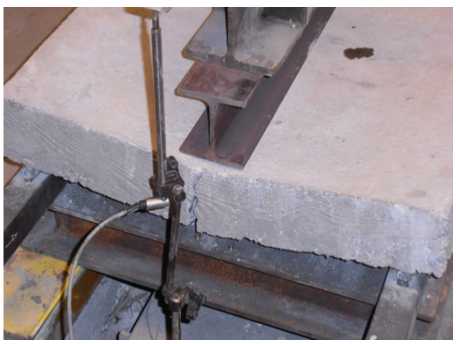

Figure 5: Collapse mode in the reference sample under bending

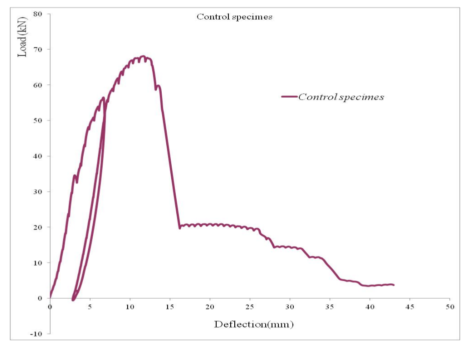

Figure 6: Load vs displacement trend for the reference sample

in order to evaluate the gain in terms of resistance of the composite system.

The study was carried out both by numerical and experimental point of view, since literature lack of experiments in this field. The tests were reproduced by numerical analysis in order to provide a basic understanding of the behavior of a reinforced concrete slab, even in the case different solicitation from the bending. The data obtained permit us to draw the following concluding remarks:

– the use of the PBO-FRCM system improves sensibly the flexural capacity of strengthened slab up to 2,5 times higher in respect to the case related to un-strengthened element;
– the good agreement between numerical simulation and experimental trend permits us to predict also the enhancement of tensile strength for the strengthened element, obtaining a gain up to 1,5 times higher in respect to the case related to un-strengthened element;
– the use of biaxial layer of PBO mesh gives back a failure mode due to concrete crushing after internal steel yielding while a perfect bond FRCM-to-concrete was observed in spite of slippage between the PBO net and the cementitious mortar;
– the ductility of strengthened slab under bending modes sensibly increases in respect to that of un-strengthened model;
– the presence of the FRCM reinforcement avoids local crash of the slab due to the residual load-bearing capacity;
– the plate behavior is confirmed by the strain gauges trend that shows, after the peak load, similar strain amount both in longitudinal and transversal directions.

Thus, the proposed strengthening system may represent a modern technology for the recovery and seismic retrofit of r.c. structures where any significant increasing the mass of the structure must be avoided.

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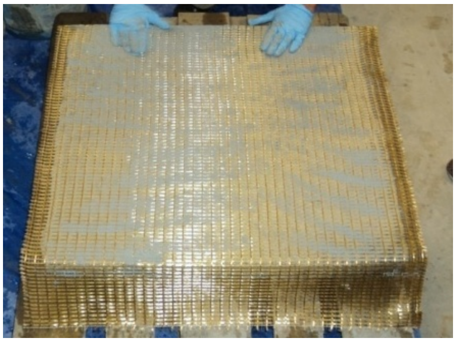


Figure 7: Application of the first layer of PBO

Figure 8: Drawing up of the first mortar layer 4 mm

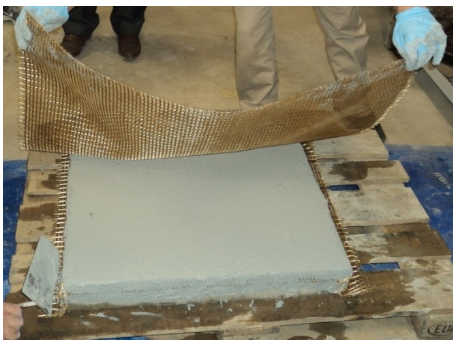


Figure 9: Application of the second layer of PBO with wrapping orthogonal to the previous

Figure 10: Drawing up of the second mortar layer 4 mm

Figure 11: Testing configuration for strengthened sample

Figure 12: Collapse mode for the strengthened sample

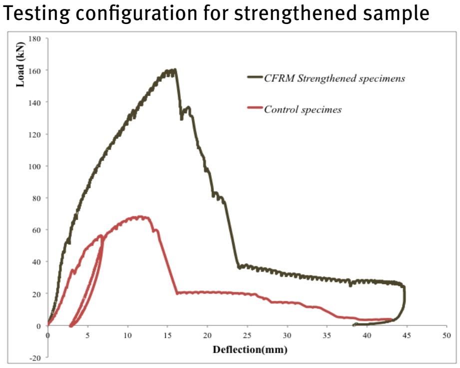


Figure 13: Experimental Load Displacement curve comparison

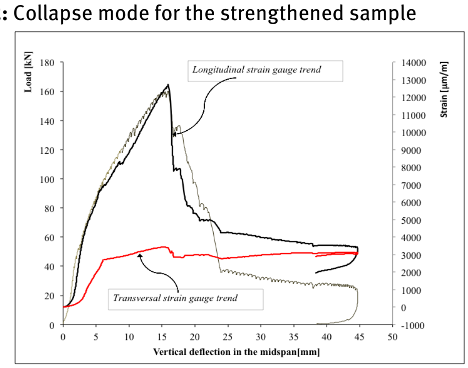


Figure 14: Correlation between the load level and the longitudinal and transversal strain in the FRCM reinforcement:

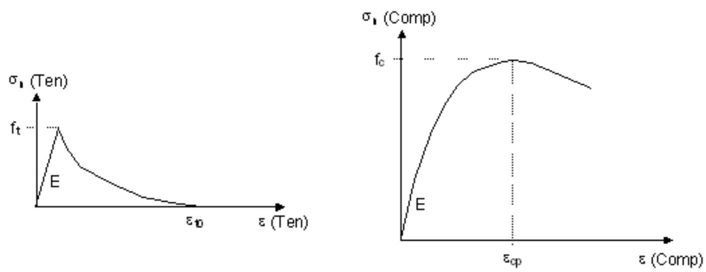


Figure 15: Constitutive law Cracking Concrete with Crushing Model

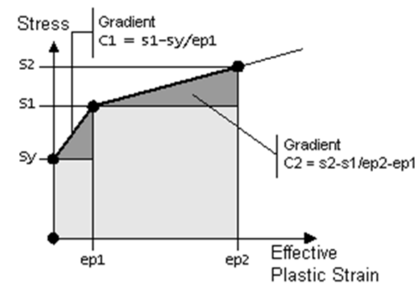


Figure 16: Constitutive law for bar. Stress Potential

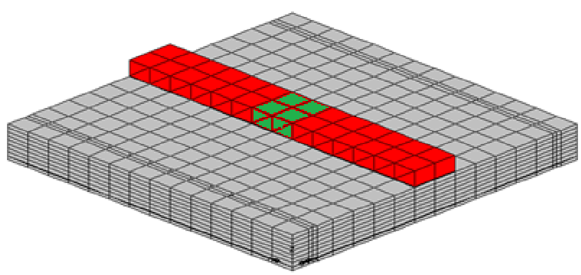


Figure 17: The reference specimen mesh

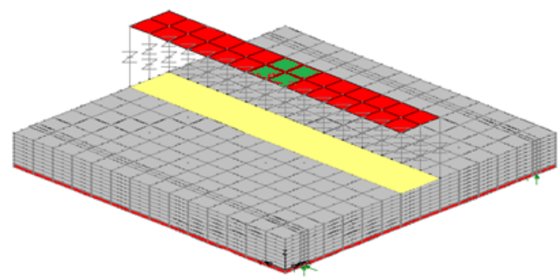


Figure 18: The strengthened specimen mesh

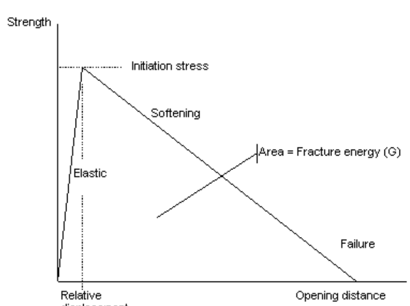
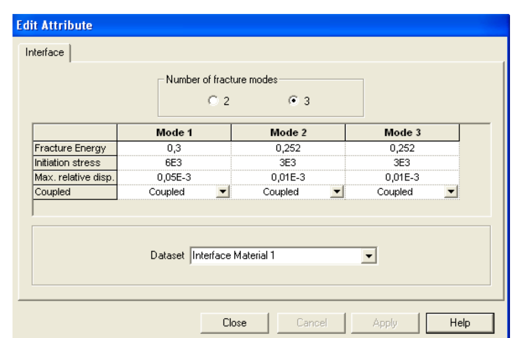


Figure 19: Contact model for FRCM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Interface

Number of fracture modes

2 3

	Mode 1	Mode 2	Mode 3
Fracture Energy	0,3	0,252	0,252
Initiation stress	6E3	3E3	3E3
Max. relative disp.	0,05E-3	0,01E-3	0,01E-3
Coupled	Coupled	Coupled	Coupled

Dataset Interface Material 1

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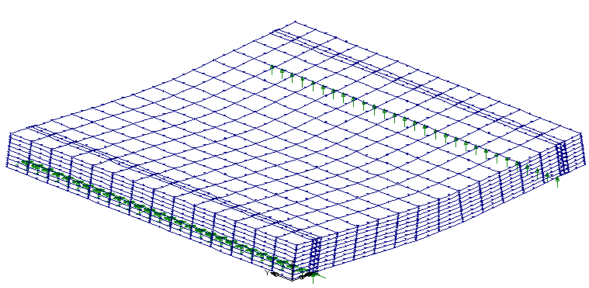

Figure 20: Deformed scheme for the control specimen

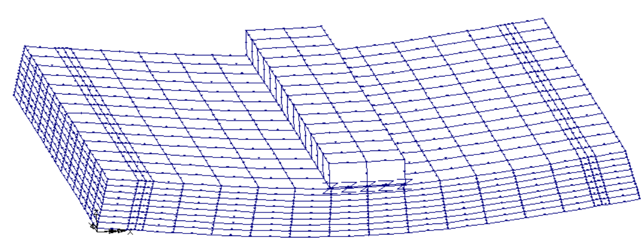

Figure 21: Deformed scheme for the strengthened specimen

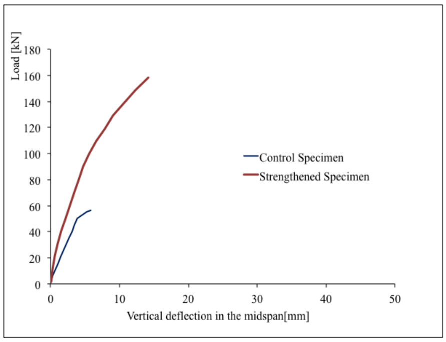

Figure 22: FE simulation of the flexural test

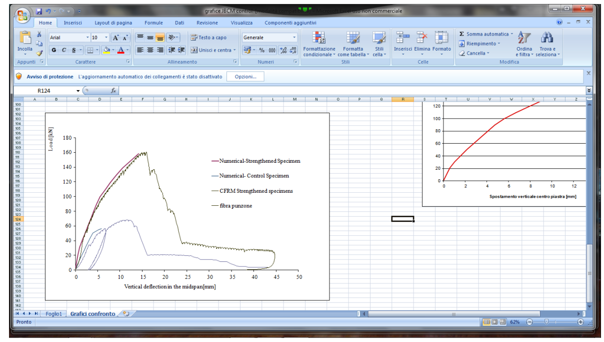

Figure 23: Numerical and experimental comparison in bending

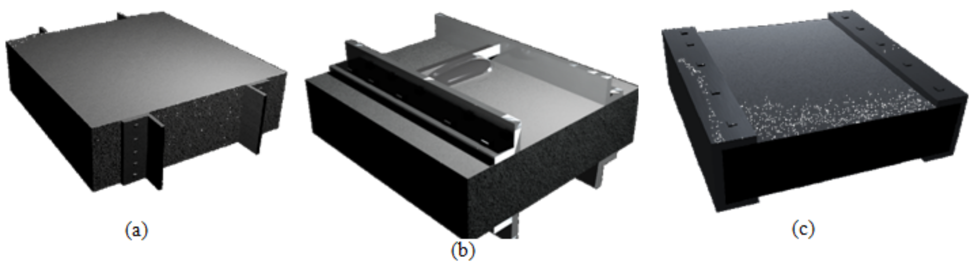

Figure 24: Application of the load for the tensile test

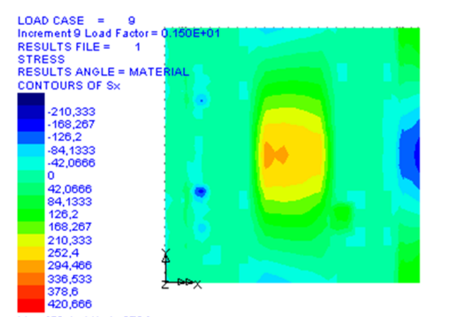

Figure 25: Stress contour in control model (b) configuration l

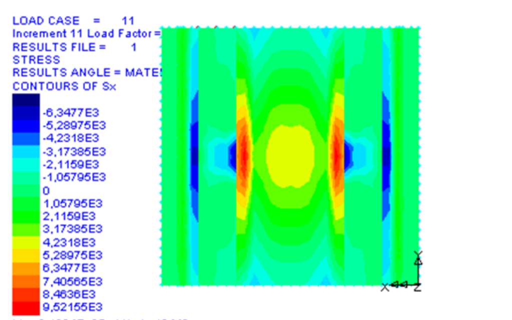

Figure 26: Stress contour in strengthened model (b) configuration

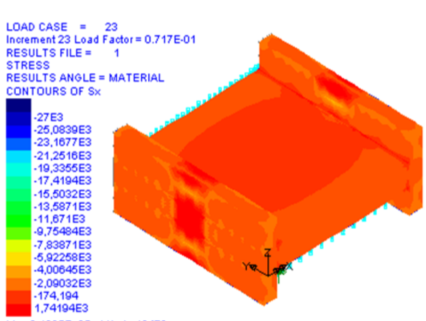

Figure 27: Stress contour in control model (c) configuration

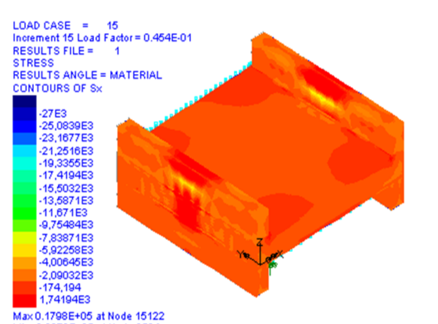

Figure 28: Stress contour in strengthened model (c) configuration

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