13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2761

# DUCTILITY OF R.C. BEAMS REINFORCED WITH FRC

**Zila RINALDI[1], Antonio GRIMALDI[2], Gianluca GALLI[2]**

## SUMMARY

Aim of the present paper is the evaluation of the effectiveness of strengthening interventions with fiber reinforced concrete (FRC), with particular reference to the ductile behavior. As a matter of fact rehabilitation intervention with a material working in tension, but with brittle behavior, cannot be effective for the plastic capacity of the structure. In this framework a high-performance fiber reinforced concrete is defined and applied as thin layers to beam elements. The behavior of the composite schemes is examined with analytical and numerical models, and the effects of the FRC application on the local and global ductility is analyzed.

## INTRODUCTION

The strengthening and repairing of existing structures is nowadays a topical theme, of great interest for both researchers and engineers. In this framework the possibilities provided by new materials and technologies suitable to grant the best performances of the existing constructions, have given a new pulse to the study of composite materials such as fiber reinforced plastics (FRP) and fiber reinforced concrete (FRC). Nevertheless the choice of new technologies requires a deeper evaluation of the capacity of the strengthened structure to achieve, besides an additional strength, also an adequate ductility in order to dissipate the energy developed, for examples, by seismic events. This aspect could be of paramount importance as the rehabilitation intervention with a material working in tension, but with a brittle behavior, can be a suitable tool for increasing strength, but cannot be effective, and in same cases also dangerous, for the plastic capacity of the structure. For this reason, in a first phase the study is devoted to the definition of a "ductile" FRC material, characterized by limited softening, or better by a plastic behavior and higher value of the ultimate strain. The composite material is then applied as thin layer on r.c. beams and the strength and ductility characteristics of the structure are evaluated with analytical and numerical models.

The work is framed in a wider project aiming at examining, with analytical, numerical and experimental models, the behavior of structural elements reinforced with a thin layer of FRC, suitable to recover the damage surface of beams, columns and joints, and to seal the cracks, if present. This technology allows

[1] DiMSAT, University of Cassino, Via Di Biasio, 43, Cassino (FR), Italy
[2] Dep. of Civil Engineering, University of Rome "Tor Vergata", Via del Politecnico, 1- Roma, Italy

granting the perfect bond without any resin interposition as the applied material is quite coincident with the base one.

The evaluation of the structural behavior of fiber reinforced elements cannot neglect the fundamental aspects related to the non-linearity of the materials, to the tension stiffening effects, and to the localization of the steel strain near the cracks. At this aim various studies are devoted to highlight the effect of fiber addition on the mechanical properties of normal and high strength concrete [1, 2]. The analysis of the global behavior of structural members is still in progress and experimental tests or numerical procedures can be found in literature [3, 4].

In the present study the influence of the application of layers of FRC material on the tensile surface of concrete beams is analyzed. The evaluation of the strength and ductility characteristics of the composite schemes is performed by adopting suitable analytical models able to take account of the non-linear behavior of the materials and to consider the presence of a slip between them. Furthermore the model allows pointing out the phenomena connected with the cracks formation and with the localization of steel strain. The comparison with numerical results developed with suitable programs validates the model.

## STRENGTHENING OF R.C. ELEMETS WITH COMPOSITE MATERIALS

Rehabilitation or strengthening of damaged concrete structures, to meet serviceability and ultimate strength requirements, is nowadays a typical problem for the civil engineers. The existing concrete structures, in fact, can show a poor performance under service loading, (deflection and cracking) or can suffer from inadequate ultimate strength. In this framework, the application of external steel plates or FRP laminate or sheets has been widely studied, ad both the techniques present the advantage of producing minimal changes in the section and to be applied on external surface. Nevertheless the adoption of steel plates presents problems related to the difficulty in handling, to corrosion and to the occurrence of undesirable shear failures. On the contrary the FRP sheets or laminates are very light and quite inert, but present problems related to the viscosity of the fibers and resins [5] and to their brittle elastic behavior [6]. The adoption of fiber reinforced concrete materials does not require resin interposition, and the properties of FRC are comparable to the base ones (concrete).

Furthermore if high performance fiber-reinforced concrete are defined, characterized by suitable amount of fiber volume fraction and matrix properties, the ductile characteristics of the reinforced element can be adequately improved. The interest about the advantages provided by these materials is witnessed by studies [7, 8, 9] and actual applications recently developed.

## BRITTLE-DUCTILE BEHAVIOR OF FRC MATERIAL

The addition of fibers in a concrete matrix particularly affects the tensile behavior of the FRC material, as the crack widening and propagation is delayed and reduced. The peak tensile strength is slightly affected by the fibers, but when this threshold is exceeded they provide a residual strength, function of the content and of the mechanical and geometrical characteristics of the fibers. Very often, for the purpose of analysis, and as suggested by some authors [10], the stress – strain curve after cracking is idealized as horizontal, with a limit placed on the tensile strain in order to account for its degenerative nature ($\varepsilon_{ctu}$). The properties of the composite material are empirically related to the properties of its components matrix and fibers [11], and the residual tensile strength $f_{tr}$ is related to the average ultimate pullout bond strength $\tau_u$ of the fiber.
The definition of $\tau_u$ is not a simple tool. An empirical expression for straight steel fibers and normal concrete is in [11], while particular values for both hook-ended and straight fibers are suggested in [12].

The tensile behavior of a typical FRC material cannot be considered completely satisfactory for increasing the structural ductility. The presence of the softening branch, in fact, can give rise to localization of strains and then to brittle phenomena. First tests on materials, carried out by the authors and still in progress, highlight the strong influence of geometrical characteristics and volume fraction of the fibers, together with mechanical properties of the matrix, on the constitutive relationship of the material and particularly in defining its brittle/plastic behavior. Tests performed at the Laboratoire Central des Ponts et Chausses [8] confirm this aspect.

In order to define a more ductile composite material, a parametric enquire has been carried out by varying the mechanical and geometric characteristics of the components (concrete and fibers), on the basis of available constitutive relationships suitably modified [13].
In Fig. 1 the influence of the concrete strength (concrete classes C20/25, $f_c$ =25 MPa, C55/60, $f_c$=60MPa) and volume fraction ($V_f$ =1%, 5%) is pointed out. Comparing the tensile behavior of a FRC material with $f_c$=60 MPa and $V_f$ =1% with a typical FRC ($f_c$=25 MPa, $V_f$ =1%) it can be noticed an increase of the peak and residual stresses, even if the softening behavior is still present. On the contrary if the volume fraction is equal to 5% ($f_c$=25 MPa) the material is characterized by an almost plastic constitutive relationship. The values of the peak ($f_{tf}$) and residual ($f_{tr}$) stresses define the transition from brittle to ductile behavior of the FRC. In particular when the ratio between them is equal to one the composite material can be considered ductile, while, when the peak stress is higher than the residual one, the presence of a softening branch makes the material brittle. Experimental tests are now in progress for validating the proposed model.

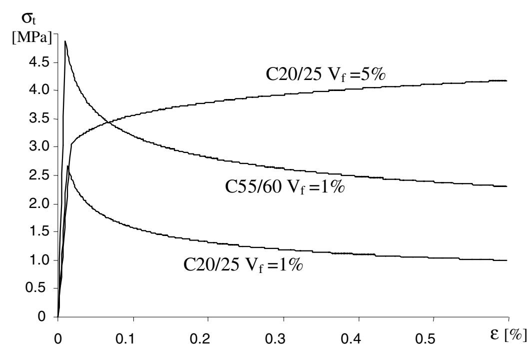


**Fig.1. Influence of $f_c$ and $V_f$ on the tensile behavior of FRC materials**

In order to define a "ductile" FRC material a parametric enquire is carried out by varying the concrete strength, the geometrical characteristics and the volume fraction of the fibers. In the following some of the obtained results are reported, related to fibers with area equal to 0.25 $mm^2$ and aspect ratio equal to 50. In Fig. 2 the ratios between the residual and peak stresses are reported versus the fiber volume fraction for different values of the compression strength of the matrix. When the ratio $f_{tr}/f_{tf}$ =1 the FRC material shows an almost plastic behavior, higher values indicate the presence of a hardening branches. The obtained results show that the plastic behavior of the material can be obtained for normal concrete ($f_c$ =30 MPa), by adding a fiber volume of about 4%, while it is sufficient $V_f$ = 2% for high strength concrete characterized, for example, by $f_c$ =100 MPa. Anyway it can be noted the presence of a softening branch in the tensile behavior of FRC materials for any value of the compression strength if the fiber volume fraction is less than 2%. The relationship between the concrete strength matrix and the fiber volume fraction necessary to obtain a so-called ductile material (plastic behavior: i.e. $f_{tr}$ / $f_{tf}$ = 1), and then to the transition from brittle to ductile behavior is reported in Fig. 3.

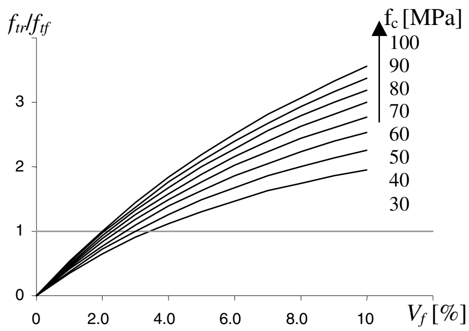


**Fig.2. $f_{tr}$ / $f_{tf}$ ratio vs $V_f$ for different $f_c$**

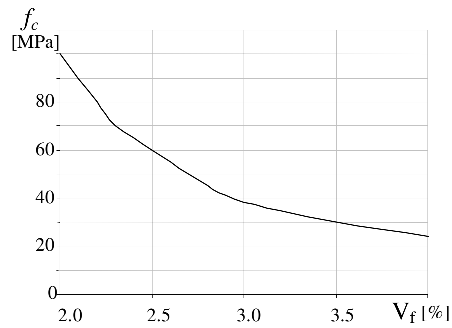


**Fig.3. Ductile FRC material**

The simulation of the direct tensile tests on FRC material, in progress at the Laboratories of University of Rome “Tor Vergata”, is carried out by means of a numerical model. The geometry of the specimen, able to provide an homogeneous state of stress in the core, and the adopted mesh for the numerical analysis is reported in Fig. 4, with the detail of the steel rebars embedded in the edges:

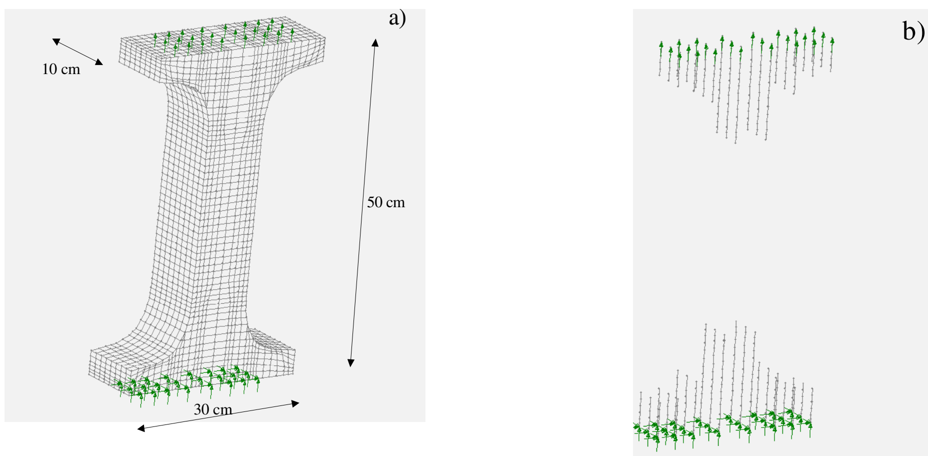


**Fig.4. a) Model geometry for tensile tests and adopted mesh (numerical analysis); b) steel bars detail**

The numerical model can simulate the whole stress-strain relationship in tension and can catches the softening branches. The obtained results agree with the analytical model and confirm the influence of the concrete strength and fiber volume fraction in governing the brittle-ductile transition.

## BEAM ELEMENTS REINFORCED WITH FRC LAYERS

### Analyzed beam schemes

The effectiveness of the ductile FRC material, described in the previous paragraph, to be adopted for structural rehabilitation is verified by means of applications on beams subjected to flexural loads. The geometrical scheme, defined on the basis of the available laboratory equipment, in order to carry out experimental tests in a following phase, is reported in Fig. 5. The 20x30 $cm^2$ reference section is reinforced with 2∅16 steel bars in tension and compression, the transversal reinforcement is constituted by ∅8/30” stirrups. Normal concrete ($f_c$=25 MPa) is considered for the reference un-reinforced beam scheme (named NC). Furthermore a layer of fiber reinforced concrete is applied at the tensile surface with a thickness equal to 5 cm. Different fiber volume fractions and matrix concrete strengths are considered, as reported in the table 1. The non-linear response of the beams is analyzed with analytical and numerical simulations.

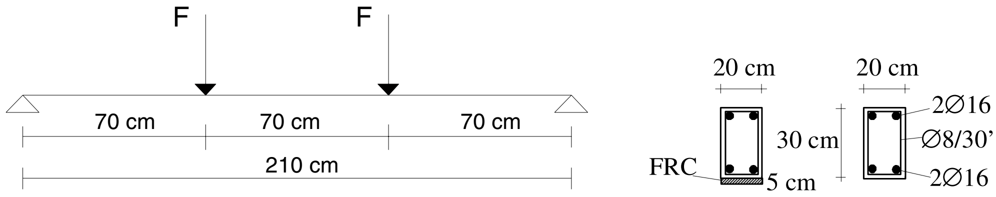


**Fig.5. Beam geometry**

**Table 1: Beam geometries considered in the analyses**

| | Section | FRC reinforcement | |
|---|---|---|---|
| Beam | Concrete strength $f_c$ [MPa] | Fiber volume fraction $V_f$ | Matrix strength $f_c$ [MPa] |
| NC | 25 | - | - |
| RN1 | 25 | 1% | 25 |
| RN5 | 25 | 5% | 25 |
| RH1 | 25 | 1% | 60 |
| RH5 | 25 | 5% | 60 |

**Analytical model**

The strength and ductile behavior of the beam elements of Fig. 5 and table 1 is firstly evaluated by adopting the local analytical model proposed in [14] that allows defining a relationship between resultant forces and mean deformations, taking account of the inelastic behavior of the materials, tension stiffening effects and strain localization near the cracks. The model is based on the analysis of a beam element with a length equal to the crack distance, subjected to tensile load, or loaded by bending moment and axial forces. The mean strain applied at the element is the loading parameter and the structural behavior is analyzed for subsequent steps by means of equilibrium conditions, up to the failure, defined by the achievement of the ultimate strain in one of the constitutive materials. The whole methodology, reported in detail in [14], allows removing the hypothesis of perfect bond and taking account of the inelastic behavior of the materials and of the presence of slip at the interfaces. The FRC in tension is simulated as proposed by the authors in [13] and reported in Fig. 1. The FRC behavior in compression is schematized with the relationship proposed in [11].

**Numerical model**

The numerical analyses are developed with the FEM program ATENA [15]. The code, specifically developed for the non linear analysis of concrete structures has been adapted to the case of FRC reinforced beams, and it allows following the crack pattern evolution.

The fiber presence in the FRC reinforcement is simulated at constitutive relationship level, by modifying the concrete properties in compression and tension, accordingly to the ones adopted for the analytical model. The rebars are characterized by elastic-plastic behavior with hardening and the interfaces between concrete and steel rebars and between concrete and FRC layers are simulated with plastic bond-slip laws.

**Results**

The obtained results related to the schemes of table 1 are summarized in the following. In Fig. 6 the analytical behavior of all the examined beams, expressed by moment-mean curvature and load-displacement relationships is reported and compared. It can be noted a lack of ductility for beams reinforced with low ductility fiber reinforced concrete, due to the softening behavior of the material in tension, while a significant increase of ductility (about 35%) and strength (up to 70%), occurs for beams reinforced with a layer of FRC characterized by $V_f = 5\%$ and with a matrix strength equal to 60 MPa.

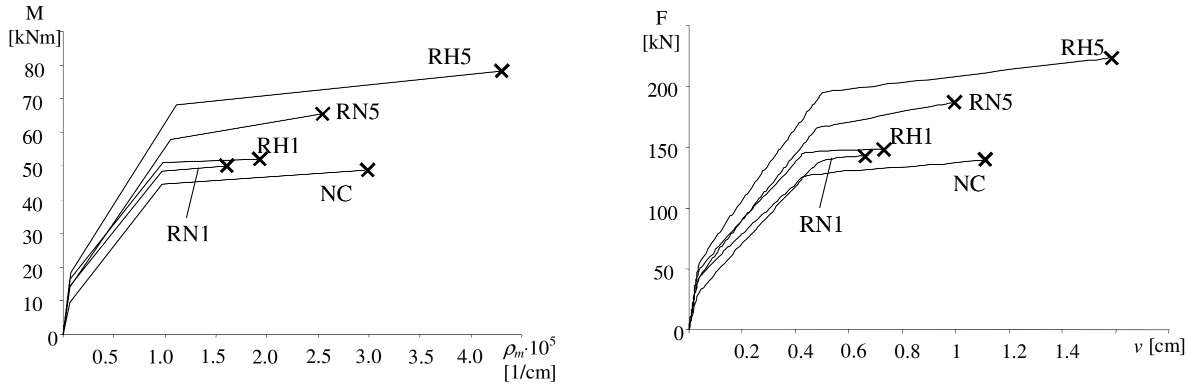


**Fig.6. Analytical model: Moment-mean curvature, load-displacement relationships for the analysed beams**

The improvement provided by the application of high-performance FRC on the strength and particularly on the ductile characteristics of the retrofitted beams is better highlighted in the following figures.

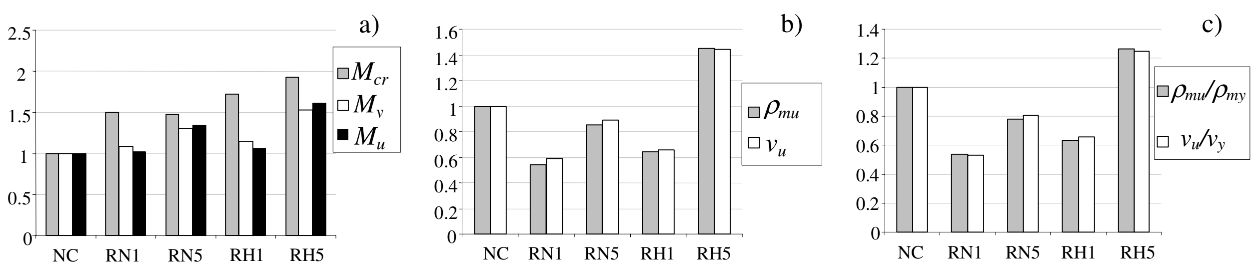


**Fig.7. Effect of FRC layer on moment (a), ultimate curvature and displacement, ductility ratios (c)**

The addition of steel fibers to a concrete mix sharply increases the cracking moment of the beam and if high percentage is present an improvement of the yielding and ultimate moment also occur (Fig. 7a). The effect of the FRC layer on the local and global ductility is represented in Fig. 7 b, where the mean ultimate curvature and the midspan displacement are reported, normalized to the reference r.c. un-reinforced structure (NC). In Fig. 7c the ductility indexes $\rho_{mu}/\rho_{mu}$ and $v_u/v_y$ for all the examined schemes are compared to the NC beam. It is worth noting that ductility increases occur only when the high-performance FRC material is adopted ($f_c$=60 MPa, $V_f = 5\%$).

Finally the analytical results are compared with the numerical ones and reported in the following figures in terms of load-displacement diagrams. A very good agreement is found for the initial stiffness and for the ultimate displacement, while some differences are shown in the postcracking and yielding phase, particularly for the reinforced beams, where the analytical curves present a higher stiffness value.

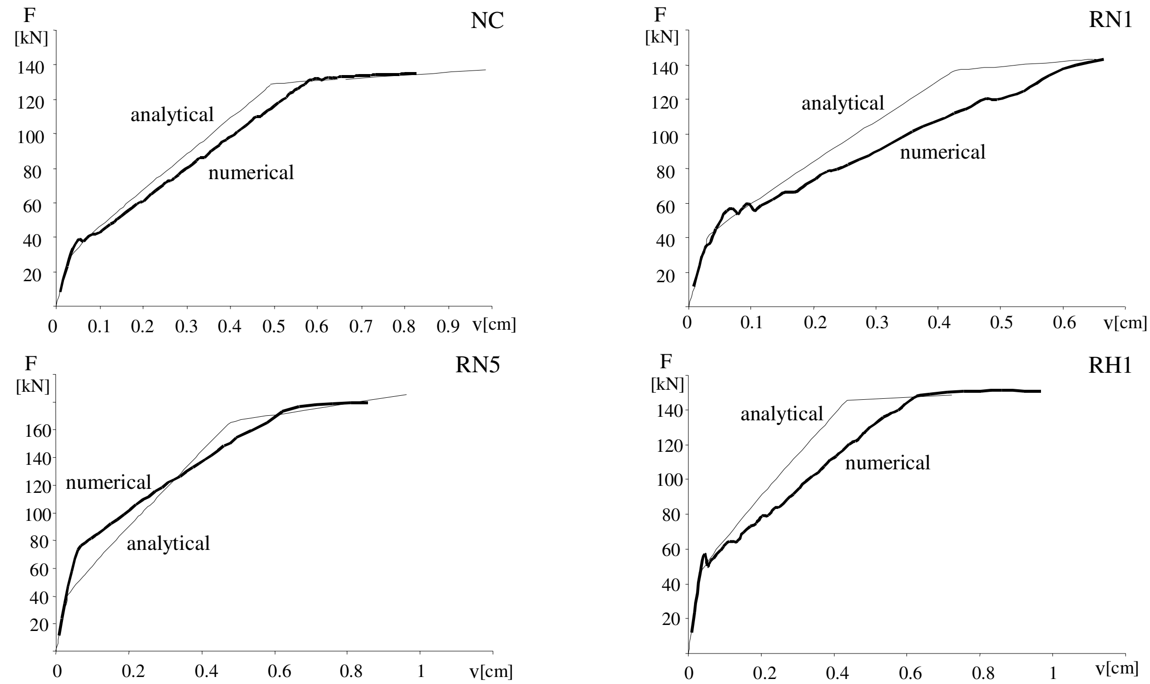


**Fig. 7. Analytical-numerical comparison**

This behavior is related to the shear deformations, which affect the structural response of the analyzed beams, caught by the numerical model, but not accounted for in the analytical procedure. This aspect is better highlighted in the following figures showing the evolution of the crack pattern with the load process. While in the un-reinforced beam mainly flexural cracks occur (Fig. 8), in the FRC strengthened elements, in a first phase the cracks form and spread in the r.c. section (Fig. 9), then they affect the FRC reinforcement. At failure condition (Fig. 10) the presence of shear cracks near the supports is well evident. Improvements of the analytical model in order to account for shear effect are now in progress.

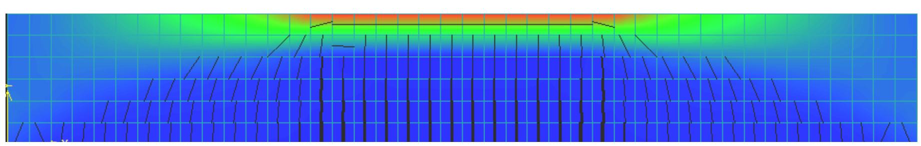

**Fig. 8. Numerical analysis of NC beam: crack pattern at failure**

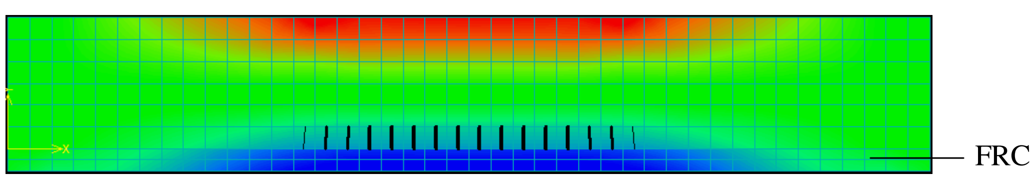


**Fig. 9. Numerical analysis of RN1 beam: cracking onset**

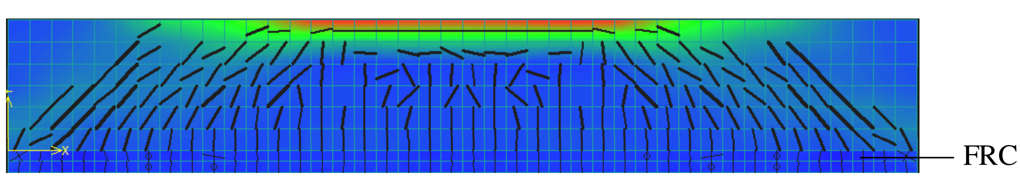


**Fig. 10. Numerical analysis of RN1 beam: crack pattern at failure**

## CONCLUSIONS

The effects of the fibers addition on the concrete material and beam elements is evaluated in this paper. The definition of a ductile FRC material, characterized by a sufficient ductility, has been developed and the optimum relationship between concrete matrix and fiber volume ratio is provided.
The behavior of beam schemes reinforced with FRC has been evaluated with a simplified analytical mono-dimensional model that allows accounting for the non-linearity of the problem, and with a suitable bi-dimensional numerical program. The obtained results highlight the benefit provided by the FRC with higher amount of fibers, or with plastic behavior, in increasing the ductility of the structure. The validation of the constitutive relationship and presented applications is now in progress, by means of experimental analyses.

## REFERENCES


1. Faisal F. W., Ashour S.A. “Mechanical properties of High-strength fiber reinforced concrete”. ACI Material Journal, Vol. 89, No. 5, Sept-Oct 1992, pp.449-455.
2. Nataraja M.C., Dhang N., Gupta A.P. “Stress-strain curves for steel fiber reinforced concrete under compression”. Cement & Concrete Composite 21, Elsevier 1999, pp. 383-390.
3. Ashour S.A., Wafa F. F. “Flexural behaviour of high-strength fiber reinforced concrete beams”. ACI Structural Journal. V. 90, No. 3, May-June 1993.
4. Ashour S.A. “Effect of compressive strength and tensile reinforcement ratio on flexural behaviour of high-strength concrete beams”. Engineering Structures 22 - 2000. Elsevier. Pp 413-423.
5. Ascione L., Feo L., Giordano A. “An optimal design in rehabilitation of r.c. beams with FRP retrofit taking into account viscous effects”. Optimal design workshop, Lab. Mecanique des Solides, Ecole Polytechnique Palaiseau, France, November 2003.
6. Ianniruberto U., Rinaldi Z. “Global ductility of FRP reinforced frames”; FIB Symposium “Concrete structures in seismic regions”, Athens, May 2003
7. Chunxiang Q., Patnaikuni I. “Properties of high-strength steel fiber-reinforced concrete beams in bending”. Cement & Concrete Composites. V. 21 (1999), Elsevier, pp. 73-81.
8. Arca A. " Etude experimentale sur le comportement mecanique du BFUP (beton fibre ultra performance)". Graduation thesis, Laboratoire Central des Ponts et Chausses 2002.
9. Alaee F. J., Karihaloo B. L. “Retrofitting of reinforced concrete beams with CARDIFRC”. Journal of composite for construction.Vol. 7, No. 3, August 1, 2003. ASCE.
10. Lim T.Y., Paramasivam P., Lee S.L. “An analytical model for tensile behaviour of steel fiber concrete”. ACI Materials Journal, V. 84, No. 4, July-Aug. 1987, pp. 286-298.
11. Soroushian P., Lee C.H. “Constitutive modeling of steel fiber reinforced concrete under direct tension and compression”. 1987
12. Lim T.Y., Paramasivam P., Lee S.L. “Bending behaviour of steel fiber concrete”. ACI Structural Journal, November-Dec. 1987, pp. 524-536.
13. Rinaldi Z., Grimaldi A., Galli G. “Optimal design of FRC structural elements”; Optimal design workshop, Lab. Mecanique des Solides, Ecole Polytechnique Palaiseau, France, November 2003.
14. Grimaldi A., Rinaldi, Z. “Influence of the steel properties on the ductility of r.c. structures”. 12WCEE World Conf. on Earthquake Engineering, Auckland New Zealand, January 2000.
15. Cervenka Consulting. 2002. ATENA Program Documentation, Prague, June. ATENA