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Concrete Confinement with BRM Systems: Experimental Investigation

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ABSTRACT: The paper deals with a new class of composites based on the use of basalt fibers bonded using a cement-based matrix (Basalt Reinforced Mortar, BRM) as an innovative strengthening material for RC members. In particular, the potential of BRM system as a confinement technique has been investigated by means of experimental tests on concrete cylindrical specimens. Two different confinement schemes were experimentally investigated in order to evaluate the effectiveness of the proposed innovative strengthening technique: 1) uniaxial Glass Fiber Reinforced Polymer (GFRP) laminates; 2) bidirectional basalt laminates pre-impregnated with epoxy resin and then bonded with a cement based mortar. The main experimental outcomes are discussed and reported in the paper. The results of the experimental study have shown that BRM confining system could become a promising solution to overcome some limitations of commercially available epoxy based FRP mainly related to both resins and reinforcing fibers typically used.

1 INTRODUCTION

Over last years FRP effectiveness for strengthening interventions has been clearly confirmed. Despite evident advantages of FRP technique over other strengthening methods, the use of FRP is not entirely problem-free. In particular organic epoxy resins imply some drawbacks such as: low performances under temperatures above the glass transition temperature and under direct fire; potential for emission of poisonous fumes under elevated temperatures (Lee, 2002); relatively high costs; potential hazards for the manual workers due to solvent contents; non-applicability in case of wet surfaces or of low temperatures; lack of vapour permeability; incompatibility of resins and substrate materials; importance for quality control of the chemical reactions. Some other issues are raised when historical structures are dealt with. In these cases, properties like reversibility, compatibility and sustainability could become critical for the selection of the strengthening technique. A few studies are available about the sustainability and the recycling of epoxy resins; however, it is clear that the exceeding material has to be treated as a special waste and this requirement about its disposal is not common in the construction industry. In addition to the discussed issues about the organic resin, there are other concerns related to the reinforcing fibers. As concerns CFRP, during the last 2-3 years, FRP suppliers are facing significant trouble to obtain carbon fibers and it is expected that in the immediate future the amount of these fibers available for the construction industry will be not sufficient to satisfy the increasing market demand. Moreover, glass fibers require improvements to overcome issues related to the low resistance to alkaline environments and lack of bio-solubility. With a view to provide a response to these needs, existing and new knowledge has to account for advances on fibers and matrices. A possible action that could be taken to improve the performance of composite materials for the strengthening of RC structures would be the replacement of organic resins with inorganic matrices such as cement-based mortars (Triantafillou et al., 2006). This would also require exploring new possibilities for reinforcing fibers that should be compatible with the alkaline environment generated by the contact with the cementitious binder. The development of an innovative strengthening system based on basalt fibers and cement based matrix could offer interesting opportunities in the immediate future.

2 BASALT FIBERS

Basalt is a natural, hard, dense, dark-brown to black volcanic igneous rock; its origins are at a depth of hundreds of kilometers beneath the earth and it reaches the surface as molten magma. Basalt density ranges between 2.7 and 2.8 g/cm³. Basalt fibres are produced with the same technology utilized for E-glass or AR-glass fibers but their production-process requires less energy and the raw materials are widely diffused all around the world. This justifies the lower cost of basalt fibers compared to glassy fibers. Basalt fibers offer also the opportunity to modulate the mechanical properties over a wide range modifying the chemical composition. In this way it is possible to develop fibers having either elastic modulus higher than conventional glassy ones and very high bio-solubility. While the commercial applications of cast basalt have been well known for a long time, it is less known that basalt can be formed into continuous fibers having unique mechanical and chemical properties. Basalt fibers are characterized by a good resistance against low and high temperatures and are superior to other fibers in terms of thermal stability, heat and sound insulation properties, vibration resistance and durability. They are characterized by a Young modulus at least 18% higher than that of glass fibers; they are linear elastic up to failure with ultimate strain in the order of 2%. Basalt has a good acid and solvent resistance overcoming that of many mineral and synthetic fibers.

3 CONCRETE CONFINEMENT BY USING BASALT FIBERS BONDED WITH CEMENT BASED MATRIX

Studies have already investigated fundamental properties of basalt fiber as a replacement of reinforcing steel in concrete structures (Brik, 1999). Basalt reinforced polymers have already been used in structural members (Brik, 1997, Sim et al., 2005). However, their use has been coupled to epoxy resins and focused on the flexural strengthening of RC members. Due to its modulus of elasticity closer to glass fibers rather than carbon, basalt fiber application has been investigated in this study as a GFRP alternative for confinement of RC members. In particular, the effectiveness of basalt fibers bonded with a cement based matrix (BRM) has been investigated by an experimental campaign on concrete cylindrical specimens.

3.1 *Experimental Campaign*

The main objectives of the experimental program were: to investigate on the effectiveness of confinement based on basalt fibers pre-impregnated in epoxy resin and then bonded with a cement based mortar (BRM); and to compare the performance of BRM technique with that based on the use of GFRP laminates bonded with epoxy resin. The investigation was carried out on 10 concrete cylindrical specimens with a diameter of 150 mm and height of 300 mm. To reproduce members with a low concrete compressive strength, as typically found in many deficient existing RC structures, specimens were cast using a concrete mix design characterized by a high water/cement ratio (W/C = 0,78). In such a way, a cylindrical concrete average compressive strength, f_{cm}, of about 15 MPa was attained (at 28 days from casting). The specimens were divided in two series, respectively named “Series A” and “Series B” as they were tested at different concrete curing time. Those of Series A (four specimens) were tested 150 days after casting; the remaining six of Series B were tested at 240 days from casting. Each series included: 1) one control specimen without wrapping; 2); one specimen wrapped with one ply of uniaxial GFRP laminates with unit weight of 900 g/m^2 and thickness of 0.480 mm/ply; 3) and specimens wrapped with one or two plies of bidirectional basalt laminates (unit weight of 254 g/m^2 and thickness of 0.046 mm/ply for each direction) pre-impregnated with epoxy resin and then bonded with a cement based mortar (two for Series A, and four for Series B). In each confined specimen an overlap length equal to 120 mm was provided in order to prevent premature failure due to debonding. Importantly, in the case of BRM wrapping the installation was done according to the following steps: application of a layer of cement based mortar with a thickness of 4 mm; in-situ pre-impregnation of bidirectional basalt laminates with epoxy resin; installation of one ply of basalt laminates; application of a layer of cement based mortar with a thickness of 4 mm. Specimen types and labels along with number of reinforcing applied plies are summarized in the first three columns of Table 1; in the fourth column the product of the external reinforcement ratio (ρ_f=4t_f/D, expressed in percentage with t_f, glass or basalt laminates thickness, D cylinder diameter) and the Young modulus of fibers are reported for each strengthening system.

3.2 *Materials properties and basalt laminates characterization*

The used basalt fibers had a density of 2.75 g/cm^3. According to ASTM D 3039 provisions experimental tests on samples made by the bidirectional basalt laminates used for the wrapping of the concrete cylinders were carried out at the laboratory of the Department of Structural Engineering of the University of Naples Federico II. The results have been processed according to ACI 440.3R, 2004 provisions; The experimental characterization provided the following results: ultimate tensile strength equal to 1814 MPa, Young modulus equal to 91.0 GPa and ultimate strain equal to 0.020. A two-component cement based mortar Planitop HDM distributed by Mapei Spa, Italy, was used to bond the biaxial laminates to the concrete substrate; the properties given by the manufacturer are: flexural strength of 9 MPa and compressive strength of 30 MPa. Finally, GFRP uniaxial laminates with a density of 2.62 g/cm^3 were used. The manufacturer provides the following properties of these laminates: ultimate tensile strength equal to 1370 MPa, Young modulus equal to 65.6 GPa and ultimate strain equal to 0.021.

3.3 *Test Setup*

Concrete cylinders were tested in compression through monotonically applied loading in force control up to the strength peak; then loading was applied at a rate of 0.002 mm/s in displacement control. Axial displacements were obtained using two stringer-type linear variable displacement transducers (LVDTs) mounted on two opposite sides of the specimen; 14 strain gages were also installed on each cylinder: 2 in the vertical direction to measure axial strains; and 12 in the horizontal direction (four at ¼, four at ½ and four at ¾ of cylinder height) to record lateral strains.

3.4 *Discussion of Experimental Results*

Tests were performed at different concrete cylinders curing time (150 days for specimens of Series A and 240 days for those of Series B); thus, control specimens of each series showed different values of peak strength, f_{co}, and strain, ε_{cc}, as well as of ultimate strain, ε_{cu} (computed as the strain recorded at 95% of peak strength on the descending branch). In particular, for control specimen S0 (Series A) f_{co} = 15.52 MPa, ε_{cc} = 0.0017, and ε_{cu} = 0.0023 were recorded; for control specimen S4 (Series B) f_{co} = 17.83 MPa, ε_{cc} = 0.0024, and ε_{cu} = 0.0029 were achieved. The significant increase in terms of peak strength (about 15%) of S4 with respect to S0 could be explained considering the high water cement ratio used for the concrete mix; this could have implied a considerable change of concrete mechanical properties as a function of the curing time.

From the applied load and average axial displacement measurements, recorded by LVDTs applied on the cylinders, the stress-strain curves were obtained for each test. For all tested specimens, the ratios between the compressive peak strength attained in the confined configuration, f_{cc}, and that achieved in the control specimen, f_{co}, as well as the ratios between the ultimate strain of the confined specimens, ε_{ccu}, and that recorded in the control specimen, ε_{cu}, are summarized in Table 1. Moreover, ratios between experimental laminates hoop strains at failure, ε_{fl}, and laminates ultimate strains under uniaxial load, ε_{fu}, are summarized in Table 1. Importantly, the jacket strain at failure, ε_{fl}, was computed as the strain recorded at 95% of peak strength on the descending branch; in case of brittle failure such strain was assumed equal to the ultimate strain recorded during the test. The average gains in compressive strength and ultimate strain of

GFRP and BRM confined specimens are reported in Table 2 along with standard deviation (SD) and coefficient of variation (COV).

Table 1 – Experimental results.

Spec. Type	Spec. Label	No. of plies	$E_f\rho_f$	f_{cc}/f_{co}	$\varepsilon_{ccu}/\varepsilon_{cu}$	$\varepsilon_{fl}/\varepsilon_{fu}$
Series A*						
Unconfined	S0	-	-	1.00	1.00	-
GFRP	S1	1	83.9	2.69	10.64	0.54
BRM	S2	1	10.9	1.45	2.30	0.22
	S3	2	21.8	1.47	2.62	0.43
Series B**						
Unconfined	S4	-	-	1,00	1,00	-
GFRP	S5	1	83.9	2.44	6.70	0.48
BRM	S6	1	10.9	1.35	1.34	0.21
	S7	1	10.9	1.49	1,51	0.15
	S8	2	21.8	1.61	2,23	0.22
	S9	2	21.8	1.57	1,27	0.46

Series A: specimens tested after 150 days from casting, f_{co} = 15,52 MPa; ε_{cu} = 0,0023.MPa;;

*****Series B: specimens tested after 240 days from casting: f_{co} = 17,83 MPa; ε_{cu} =0,0029.MPa***

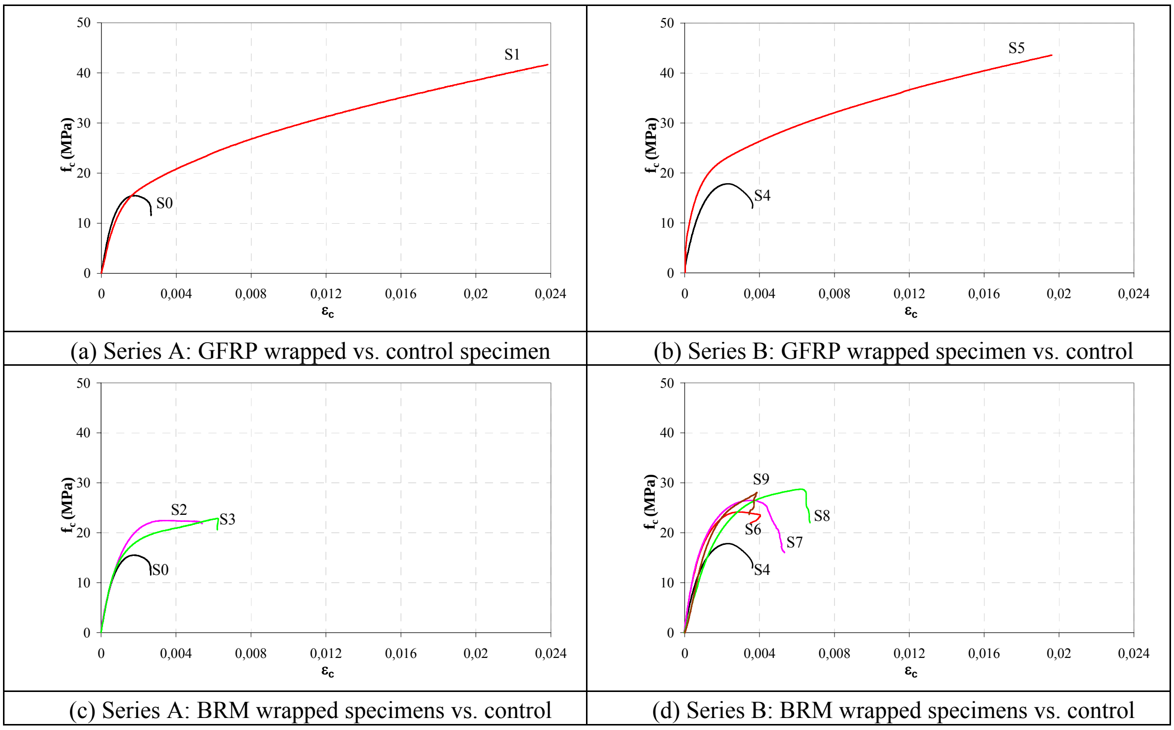
Table 2 – Strength and ultimate strain average increase.

Spec. Type	Spec. Label	$E_f\rho_f$ (GPa)	Average f_{cc}/f_{co}	SD	COV (%)	Average $\varepsilon_{ccu}/\varepsilon_{cu}$	SD	COV (%)
GFRP	S1- S5	83.9	2,57	0,17	7	8.67	2,60	36
BRM	S2- S6-S7	10.9	1,43	0,07	5	1.72	0,51	29
	S2- S8-S9	21.8	1,55	0,07	5	2,04	0,70	34

Stress-strain plots recorded for cylinders wrapped with one ply of GFRP laminates are given in Figure 1a for Series A and Figure 1b for Series B along with curves related to control specimens. GFRP confined cylinders gave a typical nearly bilinear response. They failed in a brittle mode due to tensile failure of glass laminates in the hoop direction.

Table 1 shows that in the case of GFRP wrapping, the ratios $\varepsilon_{fl}/\varepsilon_{fu}$, typically denoted as "reduction factor", ranged between 0.54 and 0.48. This phenomenon, already observed in other experimental campaigns (De Lorenzis and Tepfers, 2003) can be due to different reasons (Matthys et al., 1999). First, quality of confinement execution can be considered one of the most important parameter especially in the case of hand lay-up applications. In the GFRP wrapping, misalignments or wavings may lead to different stretching of fibers inducing the failure of those overstretched before the average hoop strain achieves the laminate ultimate strain. By starting from such rupture, the phenomenon progresses to the second most stretched fiber and so on up to the failure of the specimen. Multi-axial stress state in the GFRP due to the part of the axial load transmitted to the laminates by means of bond stresses at the GFRP-concrete interface, local stresses concentration due to concrete cracking as well as the curved shape of the wrapping (combination of axial and normal stresses) can be also considered as important factors that have limited the experimental value of the GFRP hoop strain at failure. The gains in terms of average compressive concrete strength and ultimate axial strain of about 157% and 767%, respectively, confirm the effectiveness of the GFRP laminates in improving significantly both concrete strength and ductility.

The performance of BRM wrapped cylinders were also encouraging as clearly shown by the stress-strain curves depicted in Figure 1c for Series A and Figure 1d for Series B. The shape of stress-strain curves was quite similar to that typically found in steel confined concrete members. Curves were characterized by an approximately linear ascending branch, followed by a second non linear branch up to the peak stress; after the peak, a gradual post-peak descending branch is observed. Thus, BRM jacketing can be classified as a confinement system more ductile with respect to the GFRP jacketing. Experimental tests showed that two main vertical cracks propagated rather slowly and almost symmetrically along the cylinder surface; once peak strength was achieved, these cracks became gradually wider up to inducing the jacket failure.



(a) Series A: GFRP wrapped vs. control specimen

(b) Series B: GFRP wrapped specimen vs. control

(c) Series A: BRM wrapped specimens vs. control

(d) Series B: BRM wrapped specimens vs. control

Figure 1– Stress-strain relationships

It is interesting to note that experimental reduction factors, $\varepsilon_{fl}/\varepsilon_{fu}$, ranged between a minimum of 0.15 to a maximum of 0.46, in every case lower than those achieved with GFRP wrapping. This phenomenon can be explained considering also the influence of the higher Young modulus of wraps (91.0 GPa vs. 65.6 GPa) that could determine higher differences in load taking (Tepfers, 2001). Moreover, given that the average reduction factors were 0.19 and 0.37 for BRM specimens wrapped with one and two plies of bidirectional basalt laminates, respectively, the influence of the number of reinforcement layers has to be also taken into account. The overlap of more layers could have significantly influenced both the BRM execution quality and the strain measurement (strain in the external surface of the specimen may be significantly lower than that achieved in the inner layer). Although lower values of reduction factors were recorded compared to GFRP, the experiments showed that BRM confinement technique provided substantial gains in compressive strength and axial deformability: 43% and 55% of average compressive strength increase were recorded in comparison to the control specimen, for one and two BRM layers, respectively; increase equal to 72% and 104% in terms of average ultimate axial strain were observed, respectively.

To compare BRM and GFRP wrapping, strength and deformation gains recorded have to be related to the values of the product of the external reinforcement ratio and the Young modulus, $E_f\rho_f$; for GFRP reinforcement, $E_f\rho_f$ was about 7.7 and 3.8 times larger than that of BRM for one and two layers, respectively; however, average peak strength increase on GFRP wrapped specimens was about 3.7 (157%/43%) and 2.9 (157%/55%) (one and two layers, respectively) times larger than that achieved on BRM confined specimens. Average ultimate axial strains increases on GFRP wrapped cylinders were about 10.7 (767%/72%) and 7.4 (767%/104%) times larger than that recorded on BRM wrapped specimens. Although the confinement effectiveness is not linearly proportional to $E_f\rho_f$, such results seems to point out that BRM wrapping effectiveness was more significant on the strength than on the ultimate axial strain.

Finally, the recorded scattering of the data on the BRM confined specimens was very low in terms of strength peak ratios (COV = 5% in each case); larger coefficient of variation were recorded in terms of ultimate axial strain ratios (for $\varepsilon_{ccu}/\ \varepsilon_{cu}$, COV were equal to 29% and 34% for one and two plies of BRM layers, respectively). In all cases COV were lower than those computed for the GFRP confined cylinders.

4 CONCLUSIONS

Despite their advantages over other strengthening methods, the FRP technique still presents some issues that need to be dealt with: behavior under elevated temperatures and fire, carbon fibers availability; durability of GFRP laminates. The opportunities provided by a new class of composites based on the use of basalt fibers bonded using a cement-based matrix for concrete confinement have been investigated through experimental tests on concrete cylinders. Experimental outcomes showed that BRM confining system could provide a substantial gain both in compressive strength and ductility of concrete members inducing a failure mode less brittle than that achieved in the GFRP wrapped members. The presented data have been discussed in order to make a preliminary assessment about the potential of BRM systems. Based on these data, the BRM technique seems to be an extremely promising solution to overcome some limitations of epoxy based FRP laminates. Work is in progress at University of Naples in order to confirm these preliminary results by performing additional investigations on concrete cylinders and by assessing the effectiveness of BRM technique on full scale RC columns. The validation of BRM technique on full scale elements will provide a sound tool for strengthening of structures which goes into the direction of complying with modern requirements of durability, recycling and eco-compatibility of construction products.

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6 REFERENCES

ACI Committee 440, “Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures”, ACI440.3R-04 American Concrete Institute, Farmington Hills, MI, 2004, 40 pp.

ASTM D 3039/D 3039M, “Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials”, Apr 10, 2000.

Brik V.B., “Advanced Concept Concrete Using Basalt Fiber Composite Reinforcement”, *Tech Res submitted to NCHRP-IDEA,* Project 95, 1999.

Brik V.B., “Performance Evaluation of Basalt Fibers and Composites rebars as Concrete Reinfocement”, *Tech Res submitted to NCHRP-IDEA,* Project 45, 1999.

Brik V.B., “Basalt Fiber Composite Reinforcement for Concrete”, *NCHR-IDEA Program Project Final report,* Transportation Research Board, Washington, DC, 1997.

De Lorenzis L., and Tepfers R., “Comparative Study of Models on Confinement of Concrete Cylinders with Fiber-Reinforced Polymer Composites”, *Journal of Composites for Construction ASCE,* Vol. 7, No. 3, 2003, pp. 219-237.

Lee HS., “Fire resistance property of RC structure members strengthened with fiber sheet”, *Mag Korean Conc Inst*, 14 (2), 2002, pp. 45-50.

Matthys S., Taerwe L., and Audenaert K., “Tests on Axially Loaded Concrete Columns Confined by Fiber Reinforced Polymer Sheet Wrapping”, *Proc., FRPRCS-4,* Baltimore, 1999, 217-228.

Tepfers R., “Compatibility related problems for FRP and FRP reinforced concrete”, *Int. Workshop Composites in Construction: A Reality*, 2001, Capri, Italy.

Triantafillou T.C., Papanicolaou C.G., Zissimopoulos P., Laourdekis T., “Concrete Confinement with Textile-Reinforced Mortar Jackets”, *ACI Structural Journal*, Vol. 103, No. 1, January-Febrary 2006, pp. 28-37.

Sim J., Park C., Moon D.Y., “Characteristics of Basalt Fiber as a Strengthening Material for Concrete Structures,” *Composites. Part B Engineering*, Vol. 36, 2005, pp. 504-512.