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CONSTRUCŢII. ARHITECTURĂ

THE EFFICIENCY OF BASALT FIBRES IN STRENGTHENING THE REINFORCED CONCRETE BEAMS

BY

ANDREEA ŞERBESCU, KYPROS PILAKOUTAS and *N.ŢĂRANU

The technique of externally bonding fibre reinforced polymer (FRP) composite laminates on the tension side of reinforced concrete (RC) beams is already widely accepted as an easy to apply, corrosion resistant and effective solution due to the high strength as well as the low weight of the composite material. The basalt fibres are produced from volcano rocks by a simple process; their applicability as reinforcing material composites utilized for plate bonding of RC beams was not enough researched up to now but it seems to be a cost-effective, durable and fire resistant alternative to traditional fibres. High basalt fiber's advantages, related to physical-mechanical characteristics and cost, stipulate a new high efficient structural composite materials, which can replace asbestos, metal, timber, plastic materials, etc. The paper investigates the applicability of externally bonded Basalt Fibre Reinforced Polymer (BFRP) laminates in strengthening of rectangular reinforced section of a RC beam. The influence of the cross-sectional BFRP area on service and ultimate bending moments and also on service deflection, are analysed. The procedure is based on section analysis, equilibrium of forces and compatibility of strains, considered appropriate for any type of fibres, in case of rectangular RC beams.

1. Introduction

Fibre reinforced polymer (FRP) composite systems have emerged as alternatives to traditional techniques based on steel plates for the strengthening of affected reinforced concrete members. The best well known FRP composite materials for structural applications in civil engineering include carbon, glass and aramid, FRPs which provide advantages in terms of better mechanical and chemical performance, taylorability of selected materials, easier applicability and low self weight. On the other hand as the use of FRP composite materials becomes extended to rehabilitation of load-carrying members, fire resistance, recyclability, simple manufacturing process and cost of product are other important aspects of the materials even at some sacrifice of strength. Some of the new fibres that seem to be promising within the concrete field by answering to those requirements are the basalt ones. As basalt fibres were tried as reinforcing materials for polymers in the 1990s, the following questions arise more and more frequently: what advantageous and disadvantageous properties basalt fibres have, what the application fields are, and what behaviour basalt has compared to other fibres. At the beginning the use of basalt fibres as internal reinforcement (Fig. 1) for concrete beams, has been evaluated using BFRP reinforcing bars with three times tensile strength of steel and 2% reinforcement ratio. It has been concluded that the RC beam with basalt fibres reinforcement showed a significant increase in impact and toughness strength as compared with plain concrete.

In the present paper the authors firstly investigate the suitability of externally bonded BFRP strips (Fig. 2) for structural strengthening purposes, assuming that the beam is properly detailed with respect to FRP anchorage, shear reinforcement and adhesively bonding [2].

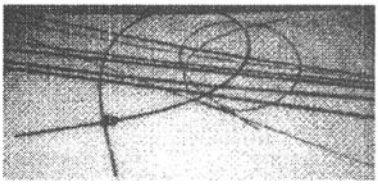

Fig. 1.– Internal reinforcement from basalt fibres.

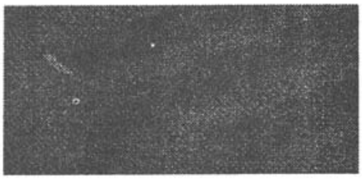

Fig. 2.– External reinforcement made of BFRP.

2. Basalt Fibres and Laminates

The basalt fibres are a single component fibres obtained by melting the crushed volcano rocks as illustrated in Fig. 3. Due to the circumstances of its formation basalt has several convenient properties such as: excellent fire resistance, significant capability of acoustic resistance, outstanding vibration insulating capability and environmentally protective. A brief presentation of basalt fibres properties compared to those of glass fibres is given in Table 1. The main disadvantage is its reduced stiffness due to a low modulus of elasticity compared with that of more advanced fibres such as carbon or aramid fibres. Currently the commercial price of basalt fibres is 0.41 euro/kg while the price of glass fibres is 2.58 euro/kg [3].

Table 1
Basalt and Glass Fibres Properties

	Basalt fibres	Glass fibres
Maximum temperature, [°C]	982	650
Thermal conductivity, [W/m.K]	0.031...0.038	0.034...0.04
Density, [g/cm^3]	2.8	2.57
Compression strength, [MPa]	9...23	9...13
Tensile strength, [MPa]	4,840	3,450
Elastic modulus, [GPa]	89	77
Ultimate tensile strain, [%]	3.15	4.7

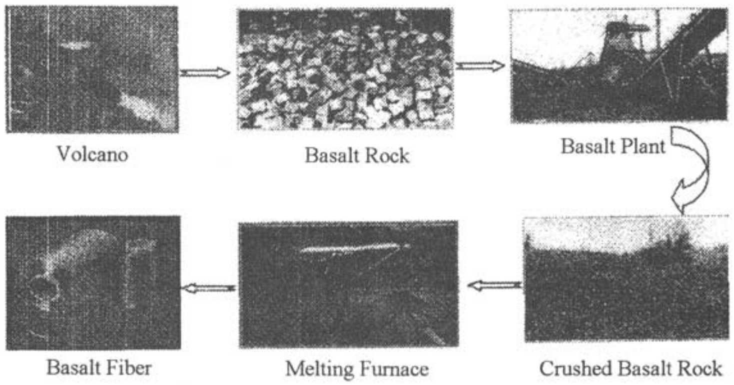

Fig. 3.– The manufacturing process of basalt fibres.

The basalt laminates utilized for RC strengthening are generally produced by resin transfer moulding. Some main mechanical characteristics for laminates reinforced with basalt fibres and glass fibres, respectively, with 44% fibre volume fraction and epoxy resin, are given in Table 2.

Table 2
Basalt Laminates Properties [2]

Quasi-isotropic laminates	Basalt laminate	Glass laminate
Elastic Modulus, [GPa]	34	17.2
Ultimate Strength, [MPa]	579	207

3. Material Models for Analysis and Design

To evaluate the load bearing capacity of RC structural members the stress–strain characteristic diagrams of constituent materials up to the ultimate stage have been selected as shown in Fig. 4.

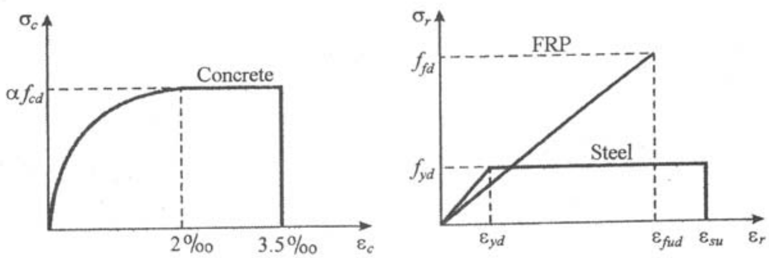

Fig. 4.– Material models at ultimate limit states.

It can be seen that concrete has non-linear behaviour from the very beginning of its loading while the reinforcing materials behave linearly. The design strength of the concrete, αf_{cd} (Fig. 4), is based on the characteristic value of the compressive strength, f_{ck}, a partial factor of safety, $\gamma_c = 1.5$, and a reduction factor, $\alpha = 0.85$, to account for the reduced compressive strength under long term loading, $\alpha f_{cd} = \alpha f_{ck}/\gamma_c$ [6]. A bilinear stress – strain relationship is considered for the steel reinforcement with design yield strength, $f_{yd} = f_{yk}/\gamma_s$ (f_{yk} is the characteristic yield stress of steel and $\gamma_s = 1.15$ – the steel material safety factor). The tensile stress – strain behaviour of FRP composite for the ultimate limit state verifications is also illustrated in Fig. 4. The design tensile strength of the FRP composite is calculated with the relation

$$f_{fd} = \frac{f_{fk}\varepsilon_{fue}}{\gamma_f \varepsilon_{fum}}, \tag{1}$$

where: f_{fk} is the characteristic value of the FRP tensile strength, γ_f – the FRP material safety factor depending on the application type [1], [5], ε_{fue} – the effective ultimate FRP strain expected *in-situ*, and ε_{fum} – the FRP mean strain determined from tensile testing.

4. Failure Modes of the Full Composite Beam

Assuming a perfect bond between the FRP laminate plate and the reinforced concrete beam, the so called *Classic beam theory* can be utilized to predict the following possible failure modes [1]:

1° *Tension failure*, caused by yielding of longitudinal tension steel bars followed by concrete crushing and before the fibre reinforced polymer composite plate rupture; this mode is preferred due to its ductility.

2° *BFRP rupture*, caused by tensile rupture of the FRP laminated plate, after yielding of steel reinforcing longitudinal tension steel bars and before compressive concrete crushing; theoretically, this mode can be avoided by selecting a minimum cross-sectional area for the externally bonded BFRP plate. Generally, in practical cases the BFRP plate will debond before fracture.

3° *Compression failure* caused by concrete crushing in compression before yielding of steel reinforcing bars and rupture of the composite plate; this mode can be avoided by limiting the BFRP maximum cross-sectional area.

The most desirable mode of failure is concrete compressive failure after internal steel has yielded with the FRP strengthening system still attached [1]. A strengthening system can detach in many ways. It can delaminate from the concrete substrate (due to failure in the concrete cover, in the adhesive layer or in the composite laminate) at the ends of the laminates (caused by shear or peeling stresses) or in the interior of the beam due to flexural and shear cracks in the beam. In the current analysis it is assumed that the beam is properly detailed with respect to FRP plate anchorage, shear reinforcement and adhesive bonding, and only one of the first three modes of failure might occur. A schematic presentation of acceptable failure modes is given in Fig. 5.

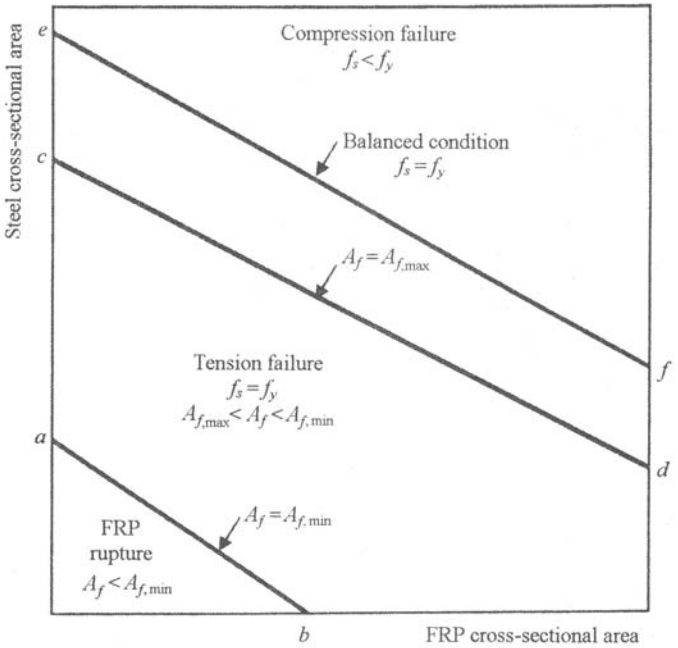

Fig. 5.– Schematic illustration of failure modes for the strengthened beam [2].

The significance of notations and symbols utilized in Fig. 5 is: f_s – stress in the reinforcing steel; f_y – yield strength of the reinforcing steel; A_f – the FRP cross-sectional area; $A_{f,\max}$ – maximum permissible cross-sectional area of FRP for the given section to avoid failure controlled by concrete crushing; $A_{f,\min}$ – the minimum area of FRP required to prevent rupture of the composite reinforcement.

5. Limits of FRP Area for Ensuring a Ductile Failure

In order to enable the strengthened system to develop its full flexural capacity the area of the applied FRP reinforcing material has to be limited. Using the drawings and notations from Fig. 6 the following assumptions are accepted in the analysis:

a) rectangular equivalent block for stress distribution in the concrete compression zone;

b) linear strain distribution across the whole section depth of the RC beam;

c) the tensile strength of concrete is neglected;

d) BFRP plate thickness is negligible;

e) the premature debonding of the BFRP plate is avoided by U-wraps along the beam to enable the development of full flexural capacity.

The meanings of notations used in Fig. 6 are: x – depth of the compression zone; $\alpha \approx 1$ – effective strength coefficient; A_s – area of tensile steel reinforcement; A'_s – area of compressive steel reinforcement; b – width of the beam cross-section;

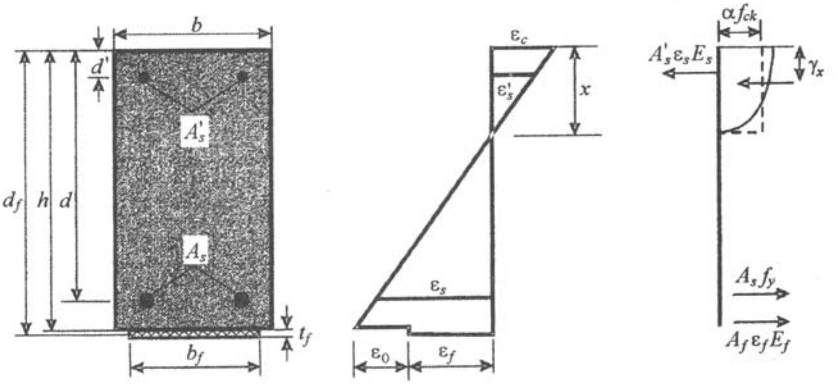

Fig. 6.– Strain and stress distribution on a composite section subjected to bending at the ultimate limit state.

b_f – width of the FRP strip; t_f – thickness of the FRP strip; d – depth to the centroid of the tensile reinforcing steel, A_s; d' – depth to the centroid of the compressive reinforcing steel, A'_s; d_f – depth to the centroid of the FRP strip; h – depth of the RC beam section; ε_c – concrete strain in the extreme compression member; ε_s – tensile steel strain; ε'_s – compressive steel strain; ε_f – FRP strain; ε_0 – initial strain at the extreme tensile fibre before strengthening with FRP; x – depth of the equivalent rectangular concrete stress block; $\gamma \approx 0.85$ – stress block centroid coefficient, E_s – modulus of elasticity for the reinforcing steel; E_f – modulus of elasticity for the FRP composite. The desired mode of failure is yielding of steel reinforcement followed by concrete crushing *prior* to FRP rupture.

5.1. Minimum FRP's Cross-Sectional Area

If the required increase load bearing capacity is low, the necessary FRP cross-sectional area will also be small. In order to avoid the brittle FRP rupture, the minimum selected BFRP area has to be larger than the minimum one needed to attain the FRP ultimate strength upon the concrete crushing, meaning that A_f(FRP area) $> A_{f\,\min}$(minimum FRP area). It is assumed that the maximum concrete strain reaches the ultimate concrete strain (ε_{cu}), the tensile steel strain is equal to the yield strain (ε_y) and the direct stress in the FRP strip equals the FRP tensile strength (f_{fu}) as in equations set

(2) $$\varepsilon_c = \varepsilon_{cu}, \quad \varepsilon_s = \varepsilon_y, \quad f_f = f_{fu}, \quad \text{(conditions)}.$$

Depending if the strain in the compressive reinforcement has reached or not the yielding value, the stress in the compressive reinforcement (f_s') is evaluated as in equations set

$$(3)\qquad \begin{cases} \text{if } \ \varepsilon_s' \geq \varepsilon_y \ \text{ then } \ f_s' = f_y, \\ \text{if } \ \varepsilon_s' < \varepsilon_y \ \text{ then } \ f_s' = \varepsilon_{cu}\dfrac{x_{\min} - d'}{x_{\min}}E_s \leq f_y, \ \text{(checks)}, \end{cases}$$

where $x_{\min}$ is the minimum required depth of the compressed concrete zone.

Applying the force equilibrium equation, the minimum required BFRP cross-sectional area is

$$(4)\qquad A_{f\min} = \frac{A_s' f_s' - A_S f_y + 0.85 f_c b \gamma x_{\min}}{f_{fu}}.$$

5.2. Maximum FRP's Cross-Sectional Area

If the required increase of load bearing capacity is large, the necessary FRP cross-sectional area will be large too. In order to ensure a pseudo-ductile mode of failure, the steel yielding needs to take place *prior* concrete compressive failure. This type of failure can occur if the FRP cross sectional area is less than that causing failure by simultaneous concrete crushing and yielding of steel (balanced failure), meaning that A_f(FRP area) $< A_{f\max}$(maximum FRP area). It is assumed that the maximum concrete strain reaches the ultimate concrete strain (ε_{cu}), the tensile steel strain is equal to the yield strain (ε_y) and the direct stress in the FRP at balance failure is f_{fb}, as presented in equations set

$$(5)\qquad \varepsilon_c = \varepsilon_{cu}, \ \ \varepsilon_s = \varepsilon_y, \ \ f_f = f_{fb}, \ \text{(conditions)},$$

$$(6)\qquad \begin{cases} \text{if } \ \varepsilon_s' \geq \varepsilon_y \ \text{ then } \ f_s' = f_y, \\ \text{if } \ \varepsilon_s' < \varepsilon_y \ \text{ then } \ f_s' = \varepsilon_{cu}\dfrac{x_{\max} - d'}{x_{\max}}E_s \leq f_y, \ \text{(checks)}. \end{cases}$$

The concrete strain in the compressed fibre at the time of strengthening can be ignored if cracking moment (M_{cr}) exceeds the service moment (M_s); if not, then should be computed as in equations set

$$(7)\qquad \begin{cases} \text{if } \ M_s \geq M_{\text{cr}}, \ \ \varepsilon_0 = 0, \\ \text{if } \ M_s < M_{\text{cr}}, \ \ \varepsilon_0 = \varepsilon_c\dfrac{h - x_{\text{cr}}}{x_{\text{cr}}}, \end{cases}$$

where: x_{cr} is the neutral axis position for transformed fully cracked section, M_s – service moment corresponding to a stress in the concrete of $\sigma \leq 0.45 f_{ck}$ for quasi-permanent loads [5].

The force in FRP at balanced failure is

$$f_{fb} = E_f\left(\varepsilon_{cu}\frac{d - x_{\max}}{x_{\max}} - \varepsilon_{f0}\right) \le f_{fu}. \tag{8}$$

Applying the force equilibrium and to ensure a ductile failure by limiting the total maximum tensile force to 75% [6], the maximum allowable FRP cross-sectional area is

$$A_{f\max} = \frac{A'_s f'_s - A_S f_y + 0.75(0.85 f_c b\gamma x_{\max})}{f_{fb}}, \tag{9}$$

where $x_{\max}$ is the maximum allowable neutral axis depth.

6. Analytical Study

In order to investigate the influence of BFRP area and initial steel reinforcement ratio on the ultimate and serviceability limit states, the section analysis has been applied for RC beam represented in Fig. 7.

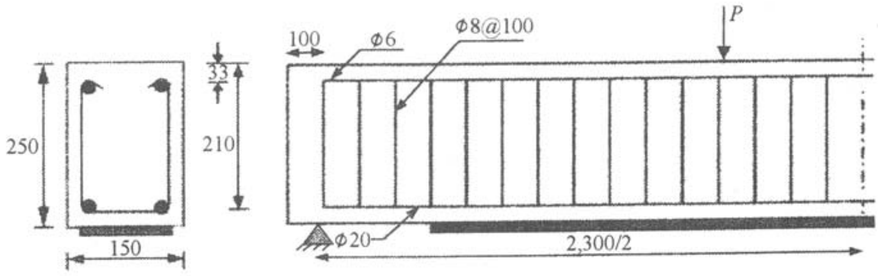

Fig. 7.– Beam geometry and reinforcement.

The characteristics of materials have been assumed as those presented in Table 3

Table 3

Concrete	Steel	BFRP
$f_c = 40$ MPa $\varepsilon_{cu} = 0.0035$ $\alpha = f(\varepsilon_c)$ $\gamma = f(\varepsilon_c)$	$f_{sy}(\varnothing\,20) = 460$ MPa $f_{s'y}(\varnothing\,6) = 250$ MPa $\varepsilon_y = 0.002$	$\varepsilon_0 = 0$ $E_f = 35$ GPa $f_{fu} = 500$ MPa

In view of non-linear behaviour of concrete and reinforcing steel, the analysis should be performed by an iterative procedure. Each possible case has been checked for a given load or FRP stress at a certain section such as whether:

a) the strain in the extreme fibre of concrete in compression reached its ultimate value;

b) the compression or tension rebars yields or not.

For simplicity and accuracy, the analysis was performed by using Excel program. Each point of the curves from Figs. 9,...,11 represents the FRP areas (0, 200, 400, 600, 800, 1,000 mm^2) added to the initial steel reinforcement.

Firstly, the un-strengthened RC beam with tension reinforcement ⌀20 has been investigated and the obtained results compared with those resulted by strengthening the beam with 400 mm^2 BFRP (Fig. 8). The ultimate load was increased by 40%, the ultimate deflection reduced by 10 mm but the behaviour up to failure was found to be less ductile.

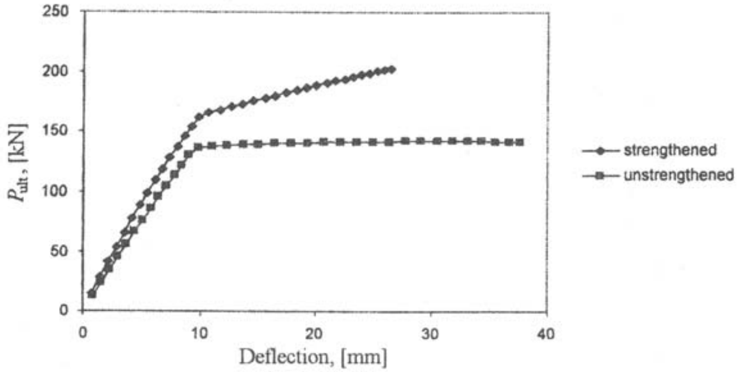

Fig. 8.– Load *vs.* deflection curves.

Figs. 9,...,11 prove that the application of BFRP plate bonding technique is more efficient for concrete beams with low initial steel reinforcement. For example, the service deflection is reduced with 75% by using 1,000 mm^2 BFRP on a beam initially reinforced with 0.5% steel, while the same BFRP reinforcement ratio can reduce the deflection for a beam with initial steel ratio of 2.5% by only 14% (Fig. 9).

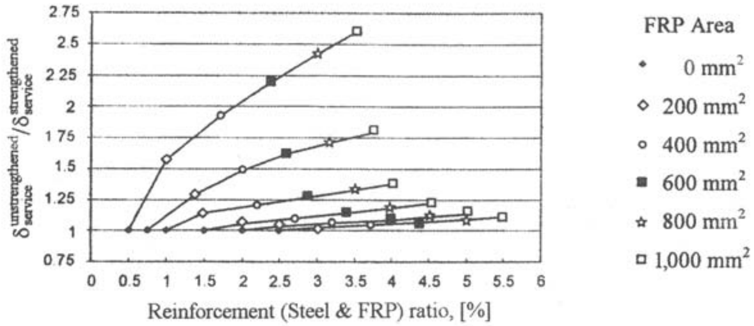

Fig. 9.– Reinforcement ratio *vs.* deflection curves.

The same influence is observed when calculating the normalized service moment (Fig. 10) and normalized ultimate moment (Fig. 11).

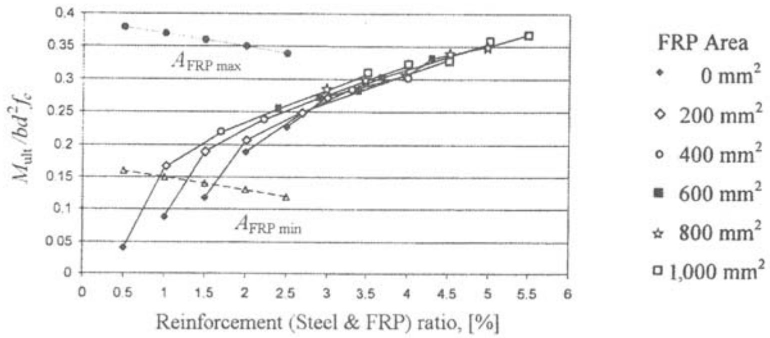

Fig. 10.– Reinforcement ratio *vs.* ultimate moment curves.

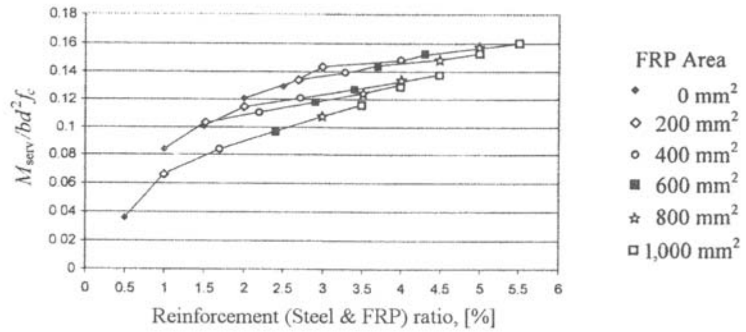

Fig. 11.– Reinforcement ratio *vs.* service moment curves.

7. Conclusions

The plate bonding technique using FRP external reinforcement has been proved by several investigations that can significantly improve the flexural behaviour of the RC beam. The laminate acts as an external reinforcement and takes the tensile force. The present analysis shows that the yielding of the reinforcement has delayed, the deflection has decreased and the load-bearing capacity has increased by using laminates reinforced with basalt fibres. Hence it is thought that increasing in the BFRP plate's area also increases the stiffness of the strengthened beam. In practical cases, as the thickness of the plate is increased, the mode of failure can be changed to a non-ductile or a debonding one. The use of basalt fibres in composites for external reinforcement seems to be a promising solution and can become an alternative to the traditional FRP in those cases when strengthening requirements can be reduced in favour of heat resistance or total cost.

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University of Sheffield, Great Britain,
Department of Civil and
Structural Engineering
and
* *"Gh.Asachi" Technical University, Jassy,*
Department of Civil and
Industrial Engineering

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EFICIENŢA FIBRELOR DIN BAZALT LA CONSOLIDAREA GRINZILOR DIN BETON ARMAT

(Rezumat)

Aplicarea prin lipire a platbandelor din materiale compozite polimerice armate cu fibre pe partea întinsă a grinzilor din beton armat este deja acceptată ca fiind o soluţie eficientă datorită raportului ridicat rezistenţă/greutate specifică, uşurinţei în aplicare şi, nu în ultimul rând, rezistenţei la coroziune. Noul tip de fibră (cea bazaltică), produs direct din roca vulcanică, a fost introdus de curând ca alternativă rezistentă la foc şi economică a fibrelor tradiţionale însă aplicabilitatea acesteia nu a fost îndeajuns studiată. Proprietăţile fizico-mecanice şi economice fac din materialul compozit polimeric armat cu fibre de bazalt (PAFB) un potenţial înlocuitor al altor materiale ca: azbestul, metalul, lemnul sau materialele plastice. Se analizează aplicabilitatea platbandelor PAFB în reabilitarea grinzilor din beton armat cu secţiune dreptunghiulară. Se analizează influenţa ariei secţiunii transversale a compozitului bazaltic asupra capacităţii de exploatare şi a celei ultime precum şi a săgeţii în exploatare. Procedura analitică este bazată pe analiza secţiunii transversale, echilibrul forţelor şi compatibilitatea deformaţiilor specifice pe secţiune, fiind considerată aplicabilă independent de tipul fibrei oricărei secţiuni rectangulare.