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by : H. Aljewifi[1], X. B. Zhang[2]

[1] University of Cergy-Pontoise, neuville, France
[2]Blaise Pascal University of Clermont II, Montluçon, France.

**e-mail address:* hana.aljewifi@u-cergy.fr

Abstract: The study of the interaction between multi-filament yarn and cementitious matrix can give a good comprehension of bond and failure mechanism of this type of composite. This study may be carried out by means of pull-out test which is an applicable tool to investigate the shear bond properties. In order to better understand the bond behavior of a continues glass fiber /matrix system, in this work a series of pull-out tests is performed with different types of fiber. Applied a uniform tensile load uniaxial from one side on the composite, hence matrix cracking strength are required as soon as crack begin formed along continuous fiber. Furthermore, it has been shown that the load bearing capacity do not only depend on the properties of materials constitutive (micro concrete / fibers) but in reality the principal feature depends on the interaction of the fiber and the matrix. This interaction between fiber and matrix is characterized by different parameters such as bond strengths Gc, τc, bond modulus k, ascending stiffness k_{bond}, descending stiffness k_{debond} and pull-out toughness A. These parameters are determined from pull-out experiment curves for different types of fiber. The comparison of these parameters for different types of fiber allows us to analyse the bond behaviour of the fiber/matrix system.

1. Introduction

Composite materials combining cementitious matrix with multi-filaments yarns reinforcement have been used more and more in civil engineering applications because of their numerous advantages. The study of the interaction between multi-filament yarn and cementitious matrix can give a good comprehension of bond and failure mechanism of this type of composite. This study may be carried out by means of pull-out test which is an applicable tool to investigate the shear bond properties. Complex bonding model analysis due to the inhomogeneous internal structure of the glass multi-filaments yarn and non-uniform bond conditions in the longitudinal direction and within the cross-section lead to a different stressing of the filaments forming the roving was studied by [1]. Since the filaments of the yarn aren't fully enclosed to the cementitious matrix from which it depends on their geometrical position in the yarn [2]. Interaction the filaments of the yarn within the matrix is characterized by difference stress-displacement relationship. Konrad et al. [3] shown the elementary behavior describes the interaction filament-matrix including the bonding, debonding and friction, and interaction filament /filaments is negligibly for greatest part of authors (i.e. they stress only by bonding).
This paper gives an investigation on fragile matrix reinforced by glass multi-filaments yarn. Besides, mechanical parameters observed at the micro level were studied. Different parameters which have major influence on pull-out behaviour are determined from pull-out experiment curves for different types of yarns.

2. Interaction of multi-filaments yarn and cementitious matrix

The study of the interaction between multi-filament yarn and cementitious matrix can give a good comprehension of the bond and failure mechanism. This interaction is studied by analyzing the pull-out behavior of a yarn/matrix composite. Mechanical behaviour depends on interface characteristics because the filaments/matrix interaction is at this level. When a uniaxial tensile load applied on free end of the multi-filament yarn reaches a critical value, the yarn is pulled out of the matrix. This phenomenon can be considered as yarn debonding and the propagation of a tunnel crack along the yarn/matrix interface from the free end toward the embedded end. We have studied this process and developed an analytical model to analyse this pull-out behaviour [4]. The relationship between the pull-out displacement u_c of a multi-filaments yarn and the pull-out force F can be established using this model. The model is based on fracture mechanics concept. The shear failure of the interface between the yarn and the matrix is considered as the creation of a tunnel crack at interface.

In present work, we use this model to calibrate some bonding behaviour parameters such as bond strengths Gc, τc and bond modulus k. Here we present briefly main formulas of this model. The following hypotheses are made: (a) The multi-filaments yarn is considered as one entire; (b) The materials of the yarn and the cementitious matrix are respectively homogeneous, isotropic and linearly elastic; (c) The shear stress τ at interface between yarn and matrix is in proportion to the displacement of the yarn u in the bonding part ($\tau = ku$ where k is the bond modulus). It reaches its maximal value at the outset of debonding and then it becomes constant τ_c (called frictional bond strength) along the debonded part of the yarn.

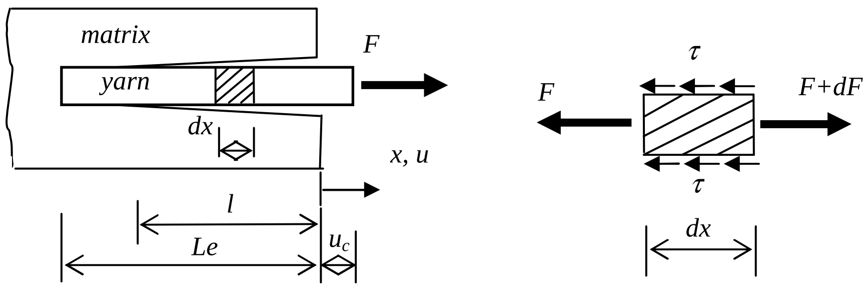

Figure 1. (a) Yarn in cementitious matrix (b) Equilibrium of the yarn

By analyzing the equilibrium of a small length dx of the yarn (Fig.1), the pull-out displacement of the yarn can be obtained:

$$u_c = u(x=0) = \frac{4(F - \pi D \tau_c l)}{\lambda \pi D^2 E th \lambda (L_e - l)} + \frac{4F}{\pi D^2 E} l - \frac{2\tau_c}{DE} l^2 \qquad (1)$$

Where D is diameter and E is Young's module of the yarn, Le is embedded length and l is debonded length of the yarn. l is considered as the length of a crack. λ is a bond parameter witch depends on the quality of the interface between yarn and matrix: $\lambda = \sqrt{4k / DE}$.

According to the concept of fracture mechanics, the energy release rate G for the creation of a new length of a crack is introduced:

$$G = -\frac{\partial \Pi}{\partial S} = -\frac{\partial \Pi}{\pi D \partial l} = \frac{1}{\pi D}\frac{\partial}{\partial l}\int_0^F u_c dF \qquad (2)$$

Where S is the area of the crack ($S=\pi Dl$). Π is the potential energy. Replacing G by its critical value G_c (called chemical bond strength [5]), one can obtain follow expression:

$$G_c = \frac{2F^2}{\pi^2 D^3 E} - \frac{2\tau_c}{\pi D^2 E} Fl - \frac{2\tau_c F}{\lambda \pi D^2 Eth\lambda (L_e - l)} + \frac{2F^2 - 2\pi D \tau_c Fl}{\pi^2 D^3 Esh^2 \lambda (L_e - l)} \quad (3)$$

The pull-out curve can be obtained by using equations (1) and (3). This allows us to calibrate the essential bonding behaviour parameters Gc, τ_c and k according to experiment pull-out curves performed in this work.

3. Experimentally study

3.1 Materials

An ordinary Portland cement (CEM 52.5 I) and maximum aggregates size of micro concrete in mixtures no except 1.25 mm has used, it permits to undamaged filaments of the fiber during manufacturing process and no hinder the penetration in the fine meshed than grain size ordinary concrete moreover the reduce of aggregate size results in a composite of high fiber holding capacity. Admixture is an active material added in small quantities (often liquid) in order to influence certain chemical or physical properties. A polycarboxylate based superplasticizer type of high water reducing CIMFLUID 2002 with solid content of 35.6%, according to the standard NF P18-380 was used. Consequently, mortar compositions were W/C= 0.48 % (water/cement ratio), S/C = 1.4% (sand/cement ratio), SP/C = 0.0035% (Superplasticizer/cement ratio), the matrix of these systems could consider as a mortar. The composition of matrix is listed in Table 1.

Table 1. Composition of cementitious matrix.

Mixture ingredients	Micro-concrete [kg/m3]
CEMI 52.5 (C)	735.84
Sand (S)	1030.35
Water (W)	364.91
Superplasticizer (SP)	0.917
Package density	2203.6

Five kinds of fibres were used to produce cylinder specimens compound of glass fibre as structural reinforced: Owens Corning 359A-AA multi-end continuous E-glass fibres (nominal fibre diameter 12 µm, called OC1), Owens Corning 111A*11 type 30 single end continuous E-glass strand (nominal fibre diameter 17 µm, called OC2) and three types of Saint Gobain Vetrotex AR-glass fibres consisting from thousand of filaments with ones diameter of 14 µm, called SG1, SG2 and SG3. All these yarns coated by sizing dissimilar from one another except OC1 and OC2 have approach composition of sizing material. The fineness of the yarn known by tex (gram per 1000m) depend on this average filament diameter, the number of the filaments and the density of the yarn. Furthermore, the proprieties of the yarn influence heavily by the applied size. The sizing material is a mixture composition of polyhydroxy phenols or silane and a polymer emulsion (PVAC). This size helps to protect the filament as to combine hundreds of filaments in the yarn because stretching and bobbing operations aren't sufficient effect (the glass is fine to agglomerate). Sizing has major influence on the quality of the adhesion between the filaments and the matrix thus on strength composite performance.

Yarn mechanical proprieties such as tensile strength direct of the yarn have been determined according to ISO 3341.

Table 2. Data on Filament, yarns proprieties according to fineness fibers.

Yarn type	Fineness [tex= g/km]	Glass density [kg/m^3]	$D_{filament}$ [μm]	Nr. Strands	Nr. filaments	Yarn strength [N/tex]	Young's modulus [GaPa]
OC1	2400	2530	12	39	8388	0.465	57.73
OC2	2400	2530	17	/	4180	0,375	58.89
SG1	2450	2680	14	55	5939	0,292	62.24
SG2	2450	2680	14	30	5939	0.349	49.12
SG3	3000	2680	14	36	7272	0.277	40.59

3.2 Preparation of specimens and curing

Specific molding has been used to precisely center the fibers in a cylindrical matrix of 3.4 cm of diameter and the higher was varied from 3cm to 15 cm. Cement was dry mixed with the sand for 1 min in a Hobart mixer. Afterward the water mixed with the superplasticizer were added and the mixing was continued with slowly speed for a period of 15 sec. stopping the mixing during 15 sec for descending the dispersion mixing on the side of the Hobart mixer and continued the mixing with quickly speed for a period of 30 sec.
After 24h all specimens were removed from mould and immerge under water 28 days at 20 °C. For the specimens after curing time, the free end (fibre no embedded in micro concrete) was constant 10 cm and glued in between two plats epoxy by help epoxy resin.

3.3 Mechanical tests

In order to characterize micromechanical behaviour of cementitious matrix reinforced by glass multi-filaments yarn, one way pull-out test has been used to illustrate interfacial bonding between the fiber and the matrix. Micro concrete (described in part 3.1) was placed on a flat beam in basket was clamped to upper grip of the tension device (Instron 5567, maximum capacity of 30 kN) centered specimens mad by a specific support to avoid inclining them so as to ensure that the tension load is applied parallel to the embedded yarn. The free end of the yarn was clamped on the lower grip of the tension device. In this test a displacement is applied on free end loaded of the yarn under constant speed of 0.01 mm/min and continues to increase until the yarn is fully pulled and debonded of the matrix. A monotonic increasing of load is realized by a relative displacement of specific basket on the upper grip [6].

4. Results

4.1 Load pull-out-displacement measurement

Figure 2 presences the load / displacement curves for different kinds of glass yarn used as structural reinforcement in a cementitious matrix. Each figure is correspondent to the mean of three tests identical. From behaviour curves, it should be noted that pull-out strength of cementitious composite is increased function with embedded length [6]; again demonstrating that tensile failure after reached to peak depends mainly on yarn/matrix interface rather than yarn and matrix strength. It is importance noting that chemical composition and cell structure of multi-filaments yarn are quite complicated because their sizing [7]. The interface between the yarns and the matrix heavily influence by chemical bonding with them [8]. Therefore, the displacement measured here is not directly the extracted length of the yarn but also take into account the strain of the free length of the yarn. From displacement measured, it necessary to remove the displacement generates by undulation of yarn (manufacture process) for force measured (P) is less than P_{min}. Naaman et al. [9] shown that a displacement at the end of embedded fibre is accompanied by a displacement at the tip of free end. Load –displacement curve can be divided in three parts [10]. The first part is determined by elastic adhesion bond between the yarn and the matrix. In beginning of loading core filaments needed to stretch out before activated while sleeve filaments directly submit to stress? Due to filaments’ waviness (manufacture process), then is accompanied by increasing loading. In second part the chemical bond between the yarn and the matrix broken then frictional bond become weaker due to smoothing interface between the filaments and the matrix. In third part, frictional bond remains constant and residual load tends to decrease. The curves don’t need have zero ordinate to intercept [11].

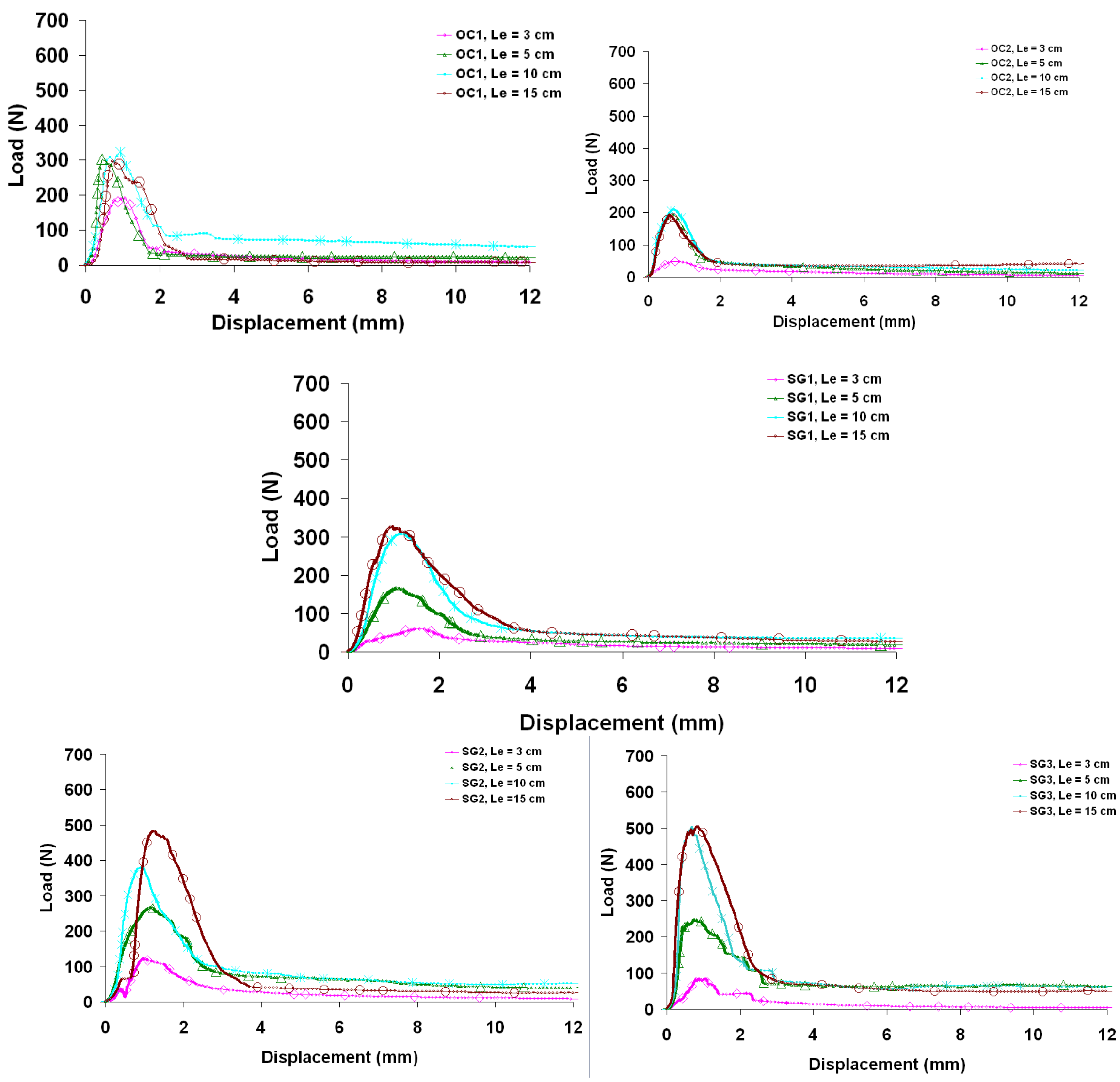

Figure 2. Load pull-out versus displacement of means curves.

Break up of the fiber depend on maximal anchored length. With short embedded length all filaments slipped and pulled up even case with all filaments of the difference yarns. On the other hand, fiber diameter doesn’t constant on its cross section or along the yarn, thus variable filaments impregnation induce difference behaviour very complex to understand.

4.2 Bonding behaviour parameters

4.2.1 Maximum pull-out strength

Maximum pull-out strength F_{max} is increasing as function of embedded length Le. Furthermore, influence each yarn on the strength is related to yarn impregnation capacity in the cementitious matrix (effect if sizing) as appear in fig 3. In reality, maximum strength measurement is far to being equal in all filaments forming in the roving. Despite the maximum strength of OC1 is less than SG2 and SG3, its strength tends to stabilize or almost constant after then after Le= 3 cm. On the other hand, maximum strength of other yarns approximately stable after embedded length of 10 cm. In addition, yarn structure has a major influence on maximum strength when lower strength was drawn with OC2 (without strand) or direct roving (see fig 3).

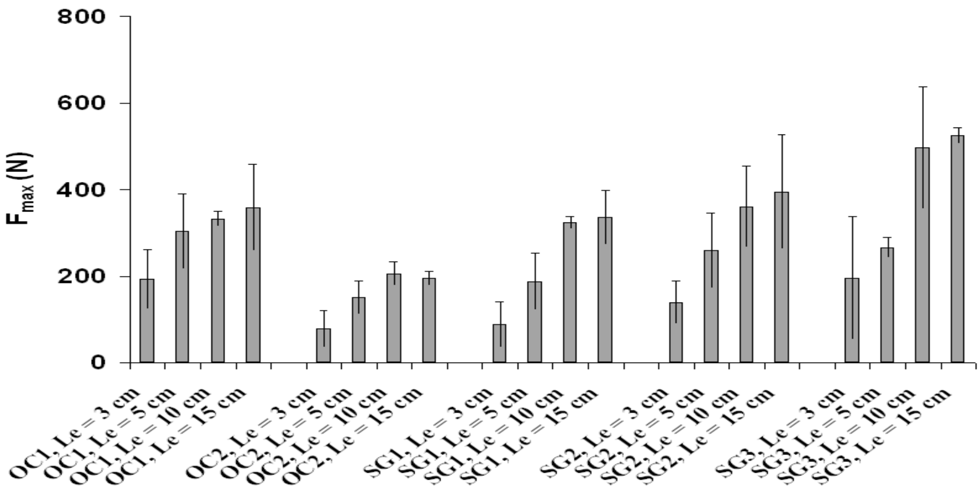

Figure 3. Maximum pull-out strength measurement in function of embedded length.

Due to insufficient yarn impregnation in the matrix in results with OC2, poor adhesion between yarn and the matrix reduces the maximum strength. SG1 and SG2 measured approximately approach values of maximum strength. SG3 remains the once yarn able to measured maximum strength in function of embedded length.

4.2.2 Bond strength and bond modulus

According to equations (1) and (3), the pull-out curves can be obtained. Experiment pull-out curves obtained from different types of fibers are used to calibrate the bond strengths *Gc*, τ_c and bond modulus *k*.

As example, figure 4 shows some pull-out curves used to calibrate the values of *Gc*, τ_c and *k*.
It is found that few variation of chemical bond strength *Gc* for different types of fibers. *Gc* is equal about 1 J/m^2 for all types of fibers. However, the values of τ_c and *k* vary with the type of fiber. Table 3 shows the average values of τ_c and *k* for different types of fiber.

As indicated in table 3, presence OC2 in the matrix as that it induces very lower bond strength resulting to its structure but the adhesion of OC1 and SG3 were robustly as SG1 and SG2 of so the bond shear stress distribution at interface level aren't homogenous where which each filament independently done (heterogeneous in the structure of the yarn) and the effect of sizing material.

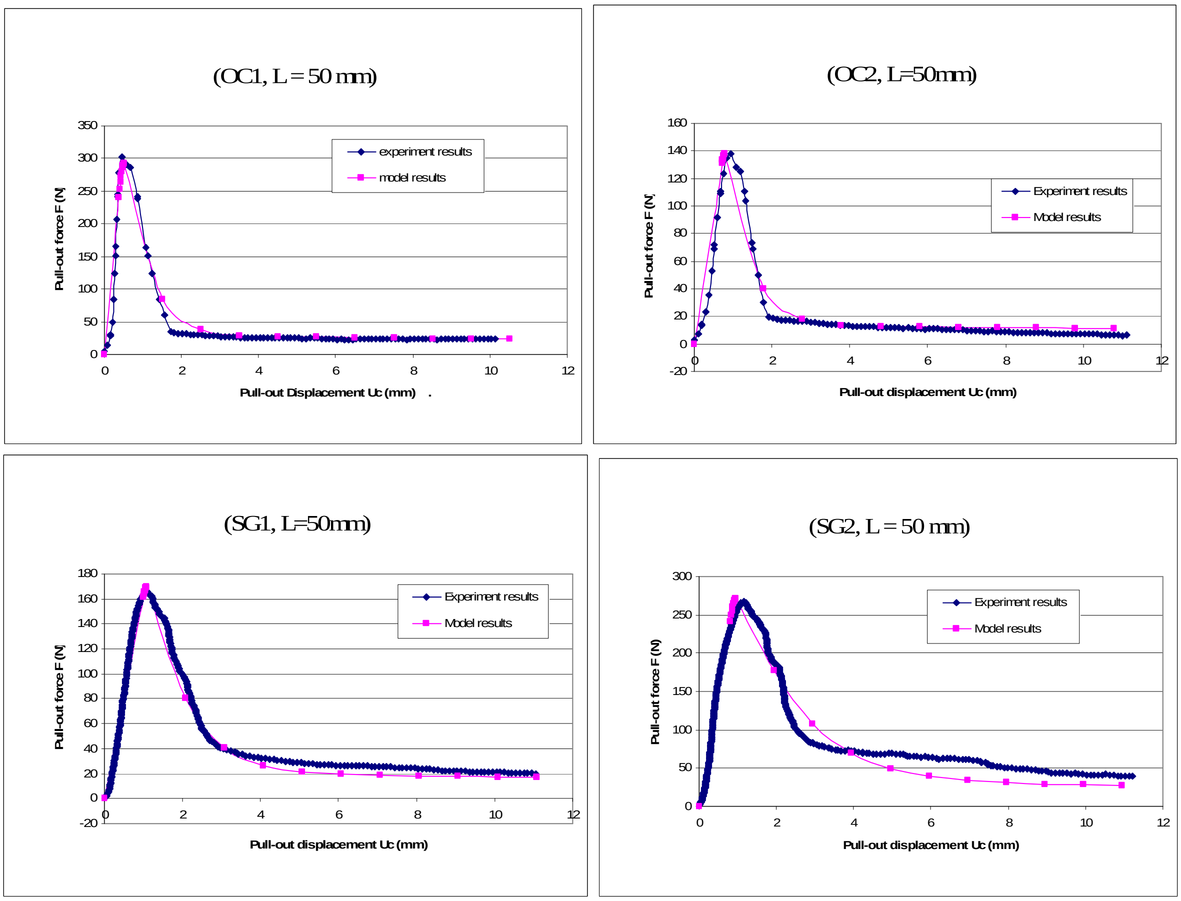

Figure 4. Pull-out curve for different types of fiber.

Table 3. Values of frictional bond strength τ_c and bond modulus k for different types of fiber.

	τ_c [MPa]	*K* [MPa/mm]
OC1	1.78	3.45
OC2	0.68	1.11
SG1	0.80	0.75
SG2	1.43	1.17
SG3	1.33	1.60

4.2.3 Stiffness

Ascending part of load-displacement behaviour curve is assumed linear-elastic, [11] designed by ascending stiffness k_{bond}, it corresponds to the relation between crack-opening and crack-bridging force transferred by the sleeve filaments [1]. Descending stiffness of behaviour curve k_{debond} was determined too with the accuracy. k_{bond} and k_{debond} correspondent to load values in rang 0.5 to 0.8 F_{max}. All results ware obtained of k_{bond} and k_{debond} are shown in fig 5.

Despite OC2 impregnated yarn measured lower strength and gives poor impregnation in the matrix, it appears average bonding stiffness, whereas SG1 is slightly higher than OC2, but it is less than SG2 and SG3, see table 4. On the other hand, due to sizing material this determines the adhesion between the yarn and the matrix. SG1 and SG2 appear difference stiffness parameters. However, glass volume in the matrix doesn't has major influence on the bonding (i.e. OC1 roving). When the first crack appears after reaching to peak, we can assume that a debonded process between the fiber and the matrix induces. For glass yarn the debonded fiber of the matrix is very complex due to inhomogeneous yarn structure and heterogeneous penetration cement particles in between the filaments, and interaction with matrix away. k_{bond} and k_{debond} tend to increase with short embedded length and they become approximately stable with higher embedded length than 10 cm, again see fig 5.

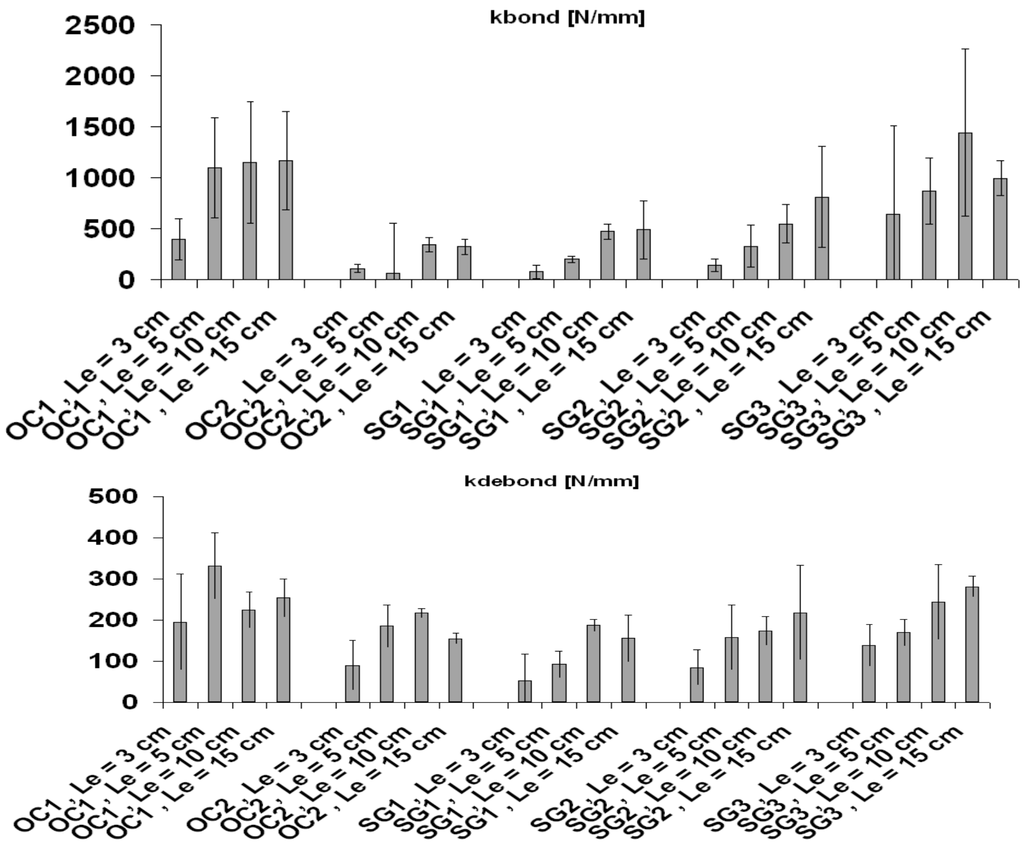

Figure 5. Bonding and debonding parameters between multi-filaments yarn / cementitious matrix.

Maximum displacement U_{max} indicated in table 4 correspondent to alignment the filaments to rupture then no all filaments aligned at the same time. Core filaments can be induced delayed activation with the small displacement or they remain without activation. U_{max} tends to decrease with embedded length except with Le = 15 cm and for OC2 is approximately stable.

Table 4. Mean pull-out parameters calculated of different embedded length.

	F_{max} [N]	U_{max} [mm]	k_{bond} [N/mm]	k_{debond} [N/mm]	$A._{total}$ [N.mm]	$A._{pre\ peak}$ [N.mm]	$A._{post\ peak}$ [N.mm]
OC1, Le = 3 cm	193.4	0.86	399.8	195.0	403.2	80.5	322.7
OC1, Le = 5 cm	303.4	0.72	1100.5	331.3	603.8	83.4	520.4
OC1, Le = 10 cm	333.1	0.66	1151.3	224.0	1437.0	108.2	1328.7
OC1, Le = 15 cm	359.3	0.81	1169.5	253.5	479.4	133.1	346.3
OC2, Le = 3 cm	78.1	0.74	113.0	89.7	215.9	39.2	176.6
OC2, Le = 5 cm	150.9	0.72	66.0	185.3	365.7	66.0	299.7
OC2, Le = 10 cm	205.8	0.90	344.7	217.0	700.9	86.5	614.4
OC2, Le = 15 cm	194.9	0.78	324.0	154.5	1721.5	84.8	1636.7

SG1, Le = 3 cm	89.1	1.52	80.2	52.6	449.8	89.3	360.5
SG1, Le = 5 cm	187.8	1.21	201.7	91.9	793.3	129.9	663.3
SG1, Le = 10 cm	324.7	1.04	474.6	186.7	1172.7	170.2	1002.6
SG1, Le = 15 cm	336.4	1.09	491.2	155.0	1800.7	184.3	1616.3
SG2, Le = 3 cm	140.0	1.28	145.9	83.9	508.3	101.6	406.7
SG2, Le = 5 cm	259.6	1.08	331.1	157.9	1214.4	151.8	1062.6
SG2, Le = 10 cm	361.0	1.10	551.8	174.0	2125.4	197.5	1927.9
SG2, Le = 15 cm	395.2	1.37	814.8	218.1	1893.7	211.4	1682.3
SG3, Le = 3 cm	196.5	0.94	645.4	138.3	677.5	72.3	605.2
SG3, Le = 5 cm	266.5	0.88	873.3	169.0	1833.2	139.8	1693.4
SG3, Le = 10 cm	496.9	0.78	1446.5	243.5	1628.8	166.1	1462.7
SG3, Le = 15 cm	525.2	1.01	999.6	280.5	1398.7	319.5	1079.2

4.2.5 Pull-out toughness

Pull-out toughness of the specimen was calculated as an area (noted $A._{total}$) under the load-displacement pull-out curve up to failure of the specimen correspondent to the average of three curves of the same the yarn. The full debonding of the continuous glass yarn from the matrix can be characterized by the integral measurement based on the energy dissipation interpretation of the surface under the load-displacement curve until F_{max} (noted $A_{.prepeak}$). Since the composite exhibited a fairly complex load-displacement relationship for every curve. Besides, it appears the behaviour as while pull-out toughness tends approximately to increase with embedded length, see table 4. From figure 6, it can be observed again that the energy dissipation of OC2 (direct roving) is lower than the other fibers. With SG3, create debonded process is needed more energy dissipation; SG1 and SG2 appear approach behaviour. The estimated $A._{post\ peak}$ values were made by subtracts $A_{.prepeak}$ of total area until the stopping of the test. It tends to increase with embedded length until 10 cm after this it decreases. This due to fibre and matrix interaction away and to speed debonded the yarn from the matrix due to poor yarn impregnation.

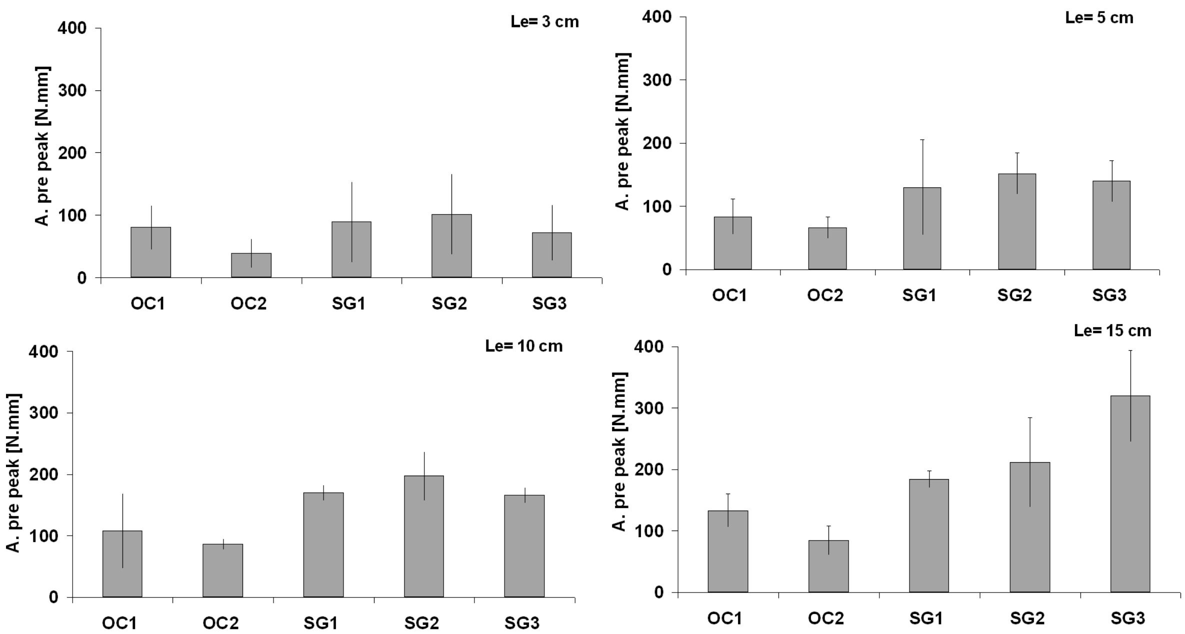

Figure 6. Pull-out toughness of different fibers.

5. Conclusion

Five kinds of glass multi-filaments yarn were successfully used in this research. Despite the specific geometry of the yarn which lead to complex interaction with the matrix. It gave interesting results. This paper appears weaker interface bonding due to smooth mechanical behaviour obtained with short embedded length. Furthermore, the effect of misalignment glass multi-filaments yarn embedded in micro concrete on mechanical behaviour take in account by subtracted from the behaviour curve. Interaction contact way between the yarn and the matrix remain influenced by heterogeneous contact points along interface yarn/matrix. In addition impregnated yarn is very complex behaviour to understand from which several hundred or thousands of filaments interacts with the matrix undependably. In addition, it depends heavily on yarn capacity to saturate to cement paste. Characterization parameters of pull-out experimental test: maximum pull-out load F_{max}, ascending stiffness k_{bond} and descending stiffness $k_{debonded}$ and pull-out toughness were determined. The effect of embedded length on maximum strength and the stiffness was studied. On the other hand, the bonding behaviour parameters G_c, τ_c and bond modulus k according to experiment pull-out curves are also calibrated from pull-out experiment curves according to an analytical model developed recently. The comparison of different parameters for different types of fiber allows us to analyse the bond behaviour of the fiber/matrix system.

References

[1] Hegger J., Bruckermann O., Chudoba R.: A smeared bond-slip relation for multi-filament yarns embedded in fine concrete, Proceedings of the 6th International RILEM Symposium on Fibre Reinforced Concretes (FRC) BEFIB 2004, Varenna, Italy, 1453–1462, (2004).
[2] Ohno S., Hannant, D.J., 1994. Modelling the stress-strain response of continuous fiber reinforced cement composites. ACI Materials Journal, 91, 306-312 (1994).
[3] Konrad, M., Chudoba, R., Meskouris, K., Mombartz, M.: Numerical Simulation of Yarn and Bond Behavior at Micro- and Meso-Level, 2nd Colloquium on Textile Reinforced Structures (CTRS2), 399-410, (2003).
[4] Zhang X.B., Aljewifi H., Li J., Fiorio B.,Etude du comportement à l'arrachement des matériaux cimentaires renforcés par des fibres synthétiques, 28èmes Rencontres Universitaires de Génie Civil, La Bourboule, France, Juin 2010.
[5] Lin Z., Kanda T. and Li V.C.: On interface property characterization and performance of fiber-reinforced cementitious composites», Concrete Science and Engineering, 1, 173-184(1999).
[6] Aljewifi H., Fiorio B., Gallias J.L.: Pull-out behaviour of a glass multi-filaments yarn embedded in a cementitious matrix, EURO-C 2010, Austria, 15-18 March (2010).
[7] Scheffler C., Gao S.L., Plonka R., Mäder E., Hempel S., Butler M., Mechtcherine V.: Interphase modification of alkali-resistant glass fibres and carbon fibres for textile reinforced concrete II: Water adsorption and composite interphases, Journal Composites Science and Technology, 69, 905–912(2009).
[8] Kabele P., Novák L., Nemecek J., Kopecký L.: Effects of chimical exposure on bond between synthetic fiber and cementitious matrix. ICTRC - 1st International RILEM Conference on Textile Reinforced Concrete, 10: 91-99 (2006).
[9] Naaman A.E., Namure G.G, Alwan J.M., and Najm H.S.: Fiber pullout and bond slip. II: Experimental validation. ASCE, Journal of Structural Engineering, 117(9), 2791-2800 (1991).
[10] Hegger J., Bruckermann O., Will N.: Bond characteristics of multifilament yarns in a cementitious matrix: Pull-out tests and their numerical simulation, 12th International. Techtextil-Symposium, Frankfurt a.M., 7.-10. April (2003).
[11] Naaman A.E., Namure G.G, Alwan J.M., and Najm H.S.: Fiber pullout and bond slip. I: Analytical study. ASCE, Journal of Structural Engineering, 117(9), 2769- 2790 (1991).