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Local bond stress–slip relationships of glass fibre reinforced plastic bars embedded in concrete

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The bond relationships between glass fibre reinforced plastic bars with polyester matrix and concrete is investigated in order to obtain information concerning the possible use of these bars for the reinforcement of concrete constructions, where the use of ordinary steel bars could have certain disadvantages due to the possibility of corrosion. The results obtained are used to develop a model of the stress–slip relationship and to estimate the anchorage lengths needed to embed these bars in concrete casts.

1. INTRODUCTION

The use of steel bars as reinforcement for concrete has many advantages but also some disadvantages: in particular the possibility of corrosion which can eventually lead to the total collapse of structures. In some cases, steel itself is a problem, e.g., malfunctioning caused by the magnetic properties of steel in automatic toll systems and through-way stations have been reported recently. For these reasons it is sometimes advisable to resort to an alternative to ordinary reinforcement steel bars, and stainless steel and epoxy resin coated bars have already been tried. Recently, the use of glass fibre reinforced polymer (GRP) bars has been investigated [1, 3]. According to their suppliers they have the following advantages: high tensile strength, thermal expansion coefficient similar to that of concrete, satisfactory behaviour in the alkaline environment of concrete, especially after cover carbonation, and low weight. These types of bar have been used in the construction of road gutters, in anchorage cables for road work [6], and in the consolidation and restoration of monuments; they may also be employed in the construction of other concrete structures. Before they can be recommended for reinforced concrete, we need to know other properties such as their bond with concrete [5], their chemical stability and other conditions associated with their usage.

2. EXPERIMENTATION

The main aim of this study is to analyse three mechanical characteristics of GRP bars: the uniaxial tensile behaviour; the longitudinal modulus of elasticity, and the bond between GRP bars and concrete. As far as bonding is concerned, we have tried to emphasize the eventual dependence on the bond stress of some important parameters, e.g., compressive strength of concrete, cast curing, bar position in the cast, diameter of the bar, and external surface of the bar.

2.1 Materials

2.1.1 *Glass fibre reinforced polyester bars*

The bars, containing continuous glass fibres, obtained by means of the well known pultrusion process, have been supplied by Soc. Rurmec of Milan, Italy. Two diameters (8 mm and 12 mm) and two surface finishes have been utilized: smooth surface bars, as obtained by the pultrusion process, and rough surface sandblasted-like bars (the roughness obtained by a proprietary method). Table 1 shows the range of values of the main properties of this type of bar. The specific gravity and the glass percentage by weight found for the bars used during tests were respectively 1.9 g cm^{-3} and 70%.

2.1.2 *Steel bars*

Plain steel bars (FeB 32 k according to UNI 6407-69) [7] were employed in the series of comparison tests performed, because the comparison between the bond

Table 1 Properties of glass fibre reinforced polyester

Property	Range of values	
	Long.	Trans.
Tensile strength (N mm^{-2})	140–700	30–70
Tensile strain (%)	2	2
Compressive strength (N mm^{-2})	150–400	70–100
Impact strength (kJ m^{-2})	80–125	60–100
Thermal dilatation coeff. (°C^{-1})	12×10^{-6}	18×10^{-6}
Specific gravity (g cm^{-3})	1.5–2.1	
Glass by weight (%)	40–80	

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relationship of GRP bars and deformed steel bars is not appropriate.

2.1.3 *Concrete*

For the pull-out tests (excluding series 4 and 5), samples using a concrete mixture of the same combination (natural gravel and sand obtained by crushing calcareous rock) and having a maximum diameter of 25 mm were used. The grading of the aggregate followed a Fuller's curve, according to Italian Standard UNI 7163 [8]. The cement used was Portland 425 with a 350 kg m^{-3} dosage. The slump was a constant 120 ± 20 mm, with a water/cement ratio $w/c = 0.4$. A high range water reducing admixture was used (Rheobuild 561 by MAC, Treviso, Italy) according to UNI 8145 [9]. Two of the mixtures used for series 4 and 5 had higher (0.42) and lower (0.38) w/c ratios, respectively, obtained by varying the dosage of the admixture and of the water at equal slump.

2.2 Tests

2.2.1 *Tensile testing*

The tests were carried out on thirteen 650 mm long GRP bars, as follows.

Group a: 5 specimens, diameter 8 mm with a smooth surface.
Group b: 4 specimens, diameter 8 mm with a rough surface.
Group c: 4 specimens, diameter 12 mm with a smooth surface.

2.2.2 *Pull-out testing*

The tests were carried out on 160 cubic concrete specimens (200 mm) containing a GRP bar. The specimens were cast as illustrated in Fig. 1, allowing two positions (A, B) for the bar. The embedded length of the bar for each specimen was equal to $5d_b$ (d_b = diameter of the bar). The pull-out tests were performed using a servo-controlled testing machine, with a prescribed displacement of 2 mm min^{-1}. The slips were measured at the unloaded bar end, using two linear differential transducers (LVDT). The 160 specimens were divided into 8 groups, each containing 20 specimens; in order to carry out a comparison, plain steel bars type FeB 32k of 12 mm diameter were used in group 8 (Table 2). For each group 10 cubic specimens (150 mm) were cast for compression testing and 4 cylindrical specimens (Ø150 mm × 300 mm) for indirect tensile testing. The results obtained are shown in Table 3.

Table 2 Specimen groups for pull-out tests

Batch	Ø (mm)	Strength	Surface	Curing
1	12	Medium	Rough	Natural
2	12	Medium	Rough	Acceler.
3	12	Medium	Smooth	Natural
4	12	Low	Rough	Natural
5	12	High	Rough	Natural
6	8	Medium	Rough	Natural
7	8	Medium	Smooth	Natural
8*	12	Medium	Plain	Natural

* Steel bar.

Table 3 Compressive and tensile strength of concretes tested

Strength class		Low	Medium	High
Compressive	Mean val.	49.38	53.54	69.99
strength (N mm^{-2})	Std. dev.	1.48	3.30	1.52
Tensile	Mean val.	3.23	3.33	3.54
strength (N mm^{-2})	Std. dev.	0.19	0.49	0.21

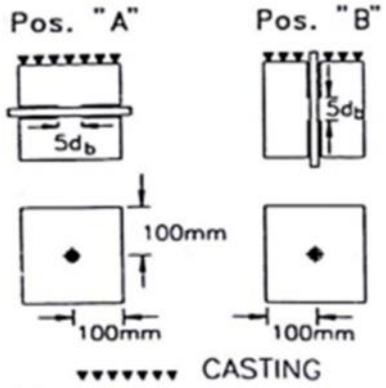

Fig. 1 Pull-out specimens.

3. RESULTS

3.1 Tensile testing

Fig. 2 shows a stress–strain diagram obtained during testing of a GRP bar, and a diagram of an Italian FeB 44k steel for reinforced concrete is also presented. Table 4 gives the mean values of the tensile strength f_t, the relative strain ε_u and the elastic modulus E of groups a, b and c.

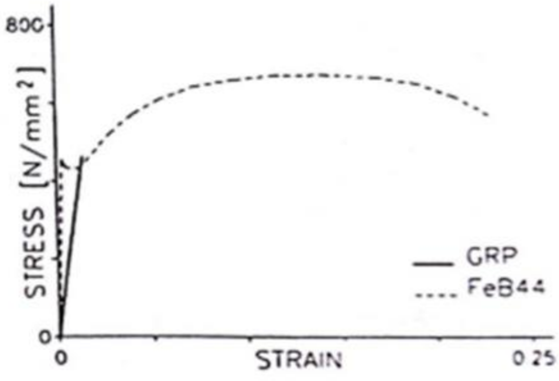

Fig. 2 Stress–strain curves of GRP and steel bars in tension.

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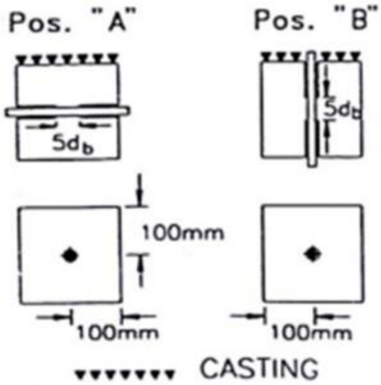

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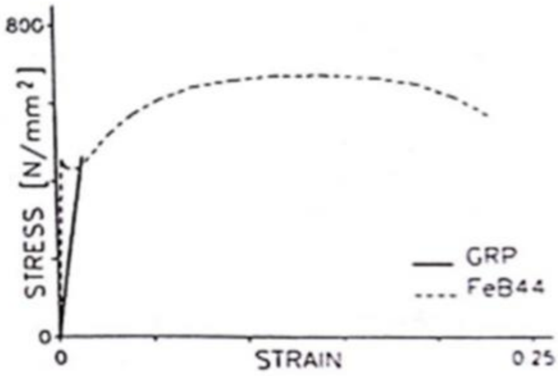

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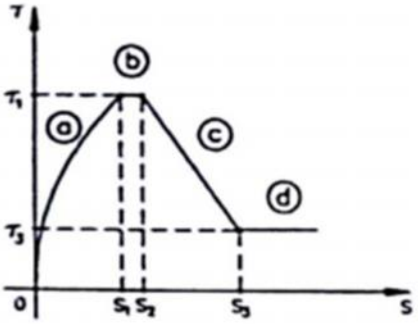

$$ⓐ\ s \le s_1 \qquad \tau = \tau_1 (s/s_1)^{\alpha} \qquad 0 \le \alpha \le 1$$

$$ⓑ\ s_1 < s \le s_2 \qquad \tau = \tau_1$$

$$ⓒ\ s_2 < s \le s_3 \qquad \tau = \tau_1 - (\tau_1 - \tau_3)[(s - s_2)/(s_3 - s_2)]$$

$$ⓓ\ s > s_3 \qquad \tau = \tau_3 = \beta\tau_1 \qquad 0 \le \beta \le 1$$

Fig. 5 Theoretical bond stress-slip (τ-s) curve.

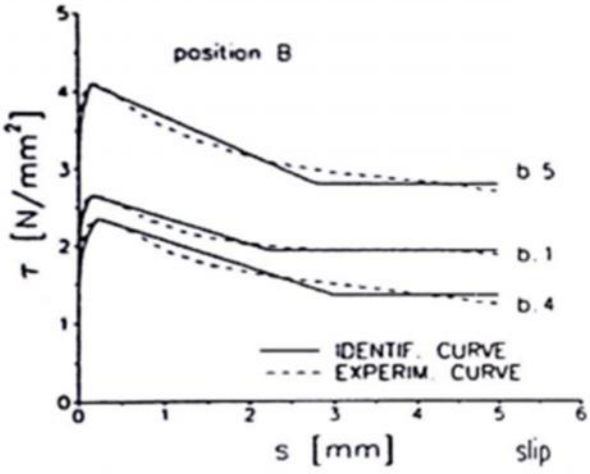

Fig. 6 Best theoretical fits of some experimental τ-s curves

Table 6 Mean values of s_2, s_3, α, β

Batch	s_2(mm)	s_3(mm)	α	β
1-A	0.76	2.83	0.25	0.73
1-B	0.25	3.47	0.16	0.77
2-A	1.19	4.01	0.37	0.81
2-B	0.25	2.93	0.24	0.66
3-A	2.54	4.23	0.16	0.82
3-B	0.54	3.66	0.15	0.63
4-A	1.18	3.74	0.39	0.72
4-B	0.37	3.08	0.12	0.70
5-A	0.37	3.79	0.12	0.72
5-B	0.20	2.64	0.12	0.67
6-A	5.00	5.00	0.39	1.00
6-B	5.00	5.00	0.32	1.00
7-A	2.22	3.76	0.29	0.82
7-B	4.49	5.00	0.14	0.98
8-A	4.31	4.66	0.22	0.98
8-B	5.00	5.00	0.19	1.00

Table 7 Stresses σ (N mm^{-2}) in the bars and anchorage lengths l_a (mm) at various slips

Slip (mm)	Batch							
	1-B		4-B		5-B		5-A	
	σ	l_a	σ	l_a	σ	l_a	σ	l_a
1	204	386	175	436	258	285	191	395
2	296	527	251	601	366	395	275	546
3	358	636	300	731	-*	-	333	664
4	-*	-	338	844			377	764
5			372	944			-*	-

* Bar failure.

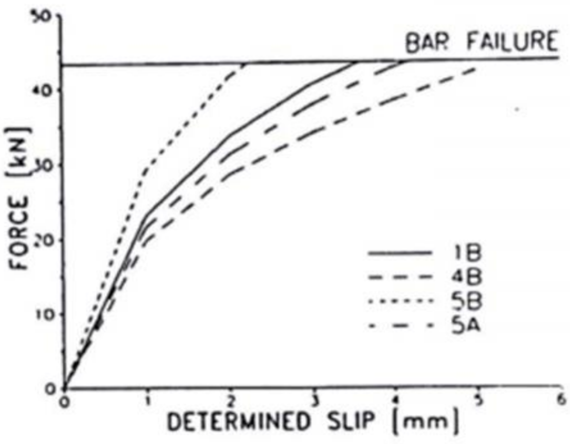

Fig. 7 Forces in GRP bars at various slips.

a computer program [2], able to account for the stress-slip relationships in the case of monotonic loading histories, was used. The program incorporates as basic elements the analytical model used to represent the monotonic τ-s relationship (Fig. 5), and the monotonic stress-strain relationship for GRP bars (Hooke's law, Fig. 2). In order to account for the high scatter of the experimental results, characteristic values of the following mechanical parameters were used during anchorage length measurement: maximum bond stress (τ_1), residual bond stress (τ_3), and ultimate tensile strength (f_t). Table 7 shows some significant results, especially bar tensile stresses and necessary anchorage lengths corresponding to given slip values imposed on the unloaded end of the bar. Figs 7 and 8 also show the force-slip and the anchorage length-slip diagrams for the same results. In some cases bar tensile stress reached ultimate strength. This happens when the deformation values are quite low, and is thus due to brittleness caused by the absence of the plastic behaviour in the σ-ε curve of the GRP bars.

6. CONCLUSIONS

The following conclusions may be drawn from the results of this study.

The tensile strength of GRP bars, with smooth or rough surface, is high (465 MPa) and is comparable

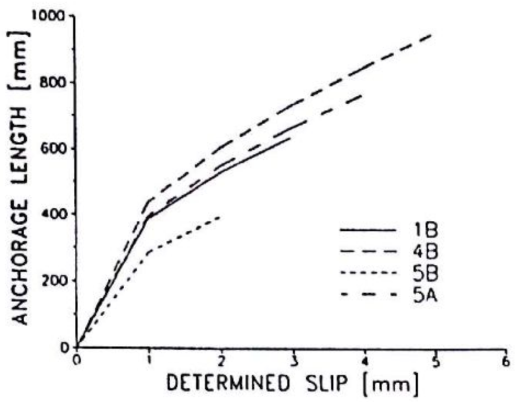

Fig. 8 Anchorage lengths for GRP bars at various slips.

with that of steel for reinforced concrete; nevertheless, the $\sigma-\varepsilon$ diagram remains linear until failure, due to the absence of ductility in the GRP bars.

Since plastic behaviour is absent, in structural applications of GRP bars it is advisable to invoke a safety factor $\geqslant 2$, in accordance with the type of loading used (short loading, repeated loading, . . .).

The elastic modulus is approximately $\frac{1}{5} \div \frac{1}{7}$ that of steel.

The ultimate bond strength between concrete and GRP bars is inferior to that of plain steel and concrete, especially for bars in position A.

Bond resistance increases with increasing concrete compressive strength.

Bars in position A systematically revealed a lower bond than those in position B; this is due to bleeding and segregation.

Due to the relatively low bond values revealed for both positions A and B, it is not advisable to use smooth GRP bars as reinforcement in concrete structures;

An analytical model able to represent local bond stress–slip relationships between GRP bars and concrete was formulated. The model was used, together with the actual tensile stress–strain curve of GRP bars, in a computer program able to calculate the length of a rough bar to be embedded in concrete, keeping in mind the scattering present in bond values. The experimental and theoretical results indicate that rough GRP bars are useful in the following: relatively lightly stressed concrete structures exposed to particularly aggressive environments; longitudinal or transverse joints of concrete pavements; and consolidation of historical buildings and monuments through injected bar reinforcement, especially if large quantities of chloride ion are present.

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RESUME

Relation contrainte d'adhérence–glissement de barres en GRP enrobées dans le béton

On a effectué une recherche sur la relation d'adhérence entre des barres de résine polyester renforcée de fibres de verre (GRP) et le béton, dans le but d'obtenir des informations sur l'emploi éventuel de telles barres comme armatures pour les ouvrages en béton armé, dans lesquels l'emploi de barres ordinaires en acier présente plusieurs inconvénients, dont ceux liés au phénomène de la corrosion. Les résultats obtenus ont permis d'établir un modèle de la relation contrainte d'adhérence–glissement, et de formuler une estimation des longueurs nécessaires pour l'ancrage de telles barres dans des coulées de béton.