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DUCTILE-TO-BRITTLE TRANSITION IN GFRP-BAR REINFORCED CONCRETE: BAR-ROUGHNESS EFFECT ON PSEUDO-PLASTIC ROTATION CAPACITY

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Abstract: The Cohesive/Overlapping Crack Model (COCM) is able to describe the transition between flexural cracking and flexural crushing failures occurring in high-performance GFRP-bar reinforced concrete (GFRP-RC) beams by increasing beam depth and/or GFRP reinforcement percentage. In this framework, tensile and compression ultimate behaviours of the concrete matrix are modeled through two different process zones that advance independently one of another. The application of this nonlinear fracture mechanics model to GFRP-RC highlights that the ductility, which is represented by the plastic rotation capacity of the beam, occurs for high-strength concrete matrix only when the internal reinforcement can slip. Thus, the slippage of the GFRP-bar inside of the concrete matrix becoming a basic new requirement for this type of reinforcement, a comprehensive preliminary campaign is devoted to optimize the surface roughness of this internal reinforcement, to obtain a suitable pull-out behaviour. In particular, the GFRP-bar roughness is varied following a geometrical progression in rib spacing, to investigate the slippage behaviour, thanks to which the pseudo-plastic rotation capacity of the composite beam is guaranteed.

1 GFRP-RC AS A SOLUTION TO THE PROBLEM OF STEEL-BAR CORROSION IN REINFORCED CONCRETE

In the past few years, a study performed by the International Association of Corrosion Engineers [1] estimated that the impact to the global world economy of the corrosion of steel-bars used in reinforced concrete structures was around 2.5 trillion US dollars (mainly due to emergency decommissioning of structures). It results the need for maintenance, retrofitting, or eventually rebuilding from the ground the infrastructure network (Figure 1).

Due to this issue, starting from the end of the last century, the potential use of a new type of internal reinforcement, which substitutes the corrosion-sensitive steel-bars, has been taken into consideration. The optimal solution to this problem is represented by glass-fibre-reinforced polymer (GFRP) bars [2-4] that, thanks to the properties of the polymer matrix, are completely corrosion-free and long-lasting without a sacrifice in terms of strength and performance (Figure 2).

In addition, GFRP-bars are electromagnetic transparent, sustainable, and lightweight, the latter being a promising advantage for building contractors, which makes the transportation, handling, and installation easy and cost-effective.

Generally speaking, if we consider the stress-strain behaviour of a GFRP-bar, no ductile behaviour can be expected (Figure 3). On the other hand, GFRP-bars can show a ductile post-peak behaviour if we consider their bond-slip constitutive law [5]. In particular, it has been proven that, in the case of perfect bond between GFRP-bar and concrete matrix, an elastic-perfectly brittle constitutive law is described, whereas in the case when the bond level between bar and concrete matrix is low, we acknowledge a ductile behaviour due to the bar pull-out from the concrete matrix (Figure 4).

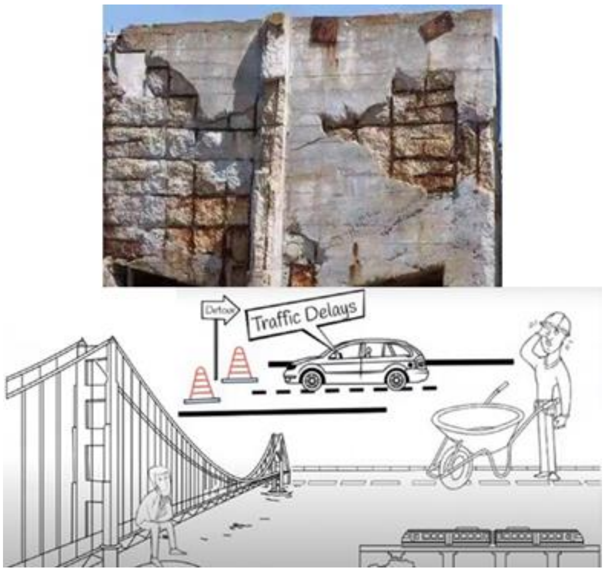


Figure 1. Impact of corrosion of steel-bars in concrete structures and infrastructures.

Figure 2. Fibre-reinforced polymer (FRP) bars: Carbon-epoxy (CFRP), glass-epoxy (GFRP), aramid-epoxy (AFRP).

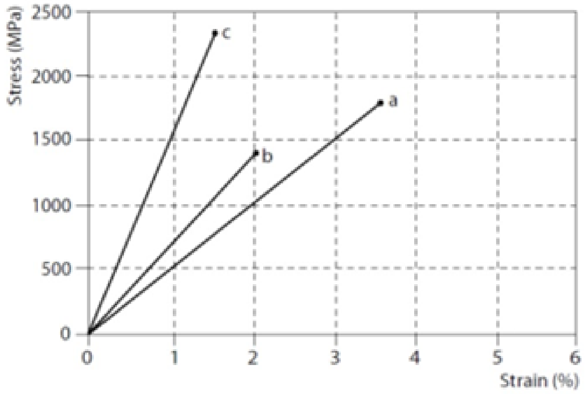


Figure 3. Stress vs strain brittle behaviour of FRP bars: CFRP (c), GFRP (a), AFRP (b).

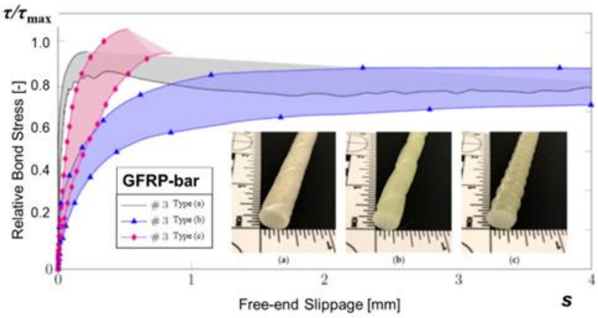


Figure 4. Pull-out behaviour of different GFRP bars: Sand-coated; Helycal wrapped; Ribbed.

Being the GFRP-RC a rather new structural material, only few international codes provide a framework of standards in order to design GFRP-RC. In particular, referring to the theoretical framework offered by the American Association of State Highway and Transportation Officials (AASHTO) [6], the American Concrete Institute (ACI) [7], or the International Federation for Structural Concrete (FIB) [8], current structural design is based on a GFRP-bar constitutive law that can be represented by the stress-strain relationship showing brittle rupture after peak stress, without any possibility of plastic rotation capacity for the RC structural element. These codes identify the optimum structural condition in the so-called «balanced condition», or «maximum reinforcement condition», which is treated as the lower limit for a correct design (Figure 5). It is worth recalling that the maximum reinforcement condition gives the quantity of reinforcement beyond which brittle crushing in the concrete matrix is triggered. From a Fracture Mechanics point of view, considering that no plastic plateau can be envisaged in the stress-strain behaviour of GFRP-bars, current AASHTO, ACI, and FIB codes offer an unsafe approach that takes into account only structural brittleness instead of ductility, which, on the contrary, is a crucial characteristic for a correct structural design. To this end, a more advanced approach is needed in order to highlight the possibility of a ductile post-peak behaviour of this promising structural composite.

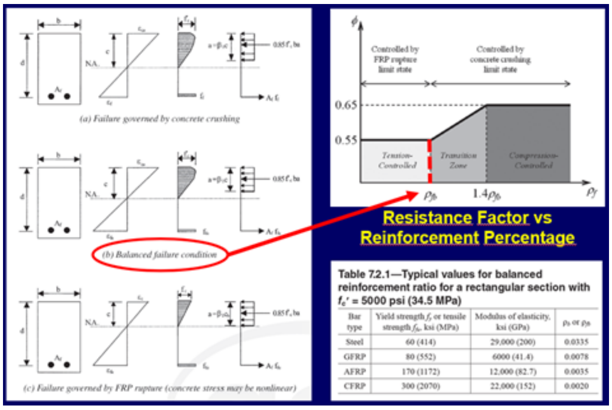


Table 7.2.1—Typical values for balanced reinforcement ratio for a rectangular section with f_c' = 5000 psi (34.5 MPa)

Bar type	Yield strength f_y or tensile strength f_{fu}, ksi (MPa)	Modulus of elasticity, ksi (GPa)	ρ_b or ρ_{fb}
Steel	60 (414)	29,000 (200)	0.0335
GFRP	80 (552)	6000 (41.4)	0.0078
AFRP	170 (1172)	12,000 (82.7)	0.0035
CFRP	300 (2070)	22,000 (152)	0.0020

Figure 5. Unsafe approach adopted by current International Standards and regulations on GFRP-RC.

2 LOOKING FOR GFRP-RC DUCTILITY: APPLICATION OF THE COHESIVE/OVERLAPPING CRACK MODEL

In order to overcome the above mentioned dangerous shortcomings, the Cohesive/Overlapping Crack Model (COCM) [9-15], is applied as a powerful analytical tool in the investigation of the scale-dependent ductile-to-brittle transitions occurring in GFRP-RC, which are functions of a suitable combination of the beam depth, *h*, the reinforcement percentage, *ρ*, and the material properties (Figure 6).

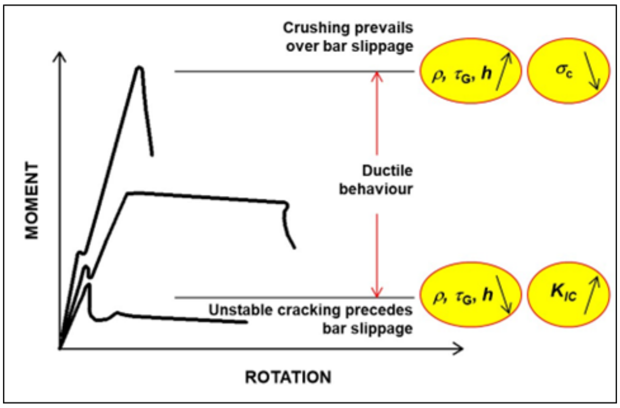


Figure 6. Ductile-to-brittle transition in GFRP-RC.

By means of the COCM, recent studies demonstrated how the post-cracking response of GFRP-RC structures is strongly affected also by the bond-slip behaviour of the GFRP internal reinforcement [16]. In particular, the scale-dependent GFRP-RC ductility, which is represented by the plastic rotation capacity of the beam, occurs for high-strength concrete matrix only when the reinforcement can slip.

3 VARIATION OF GFRP-BAR SURFACE ROUGHNESS AND BEAM BOND TESTS

The slippage of the GFRP-bar inside of the concrete matrix becoming a basic new requirement for this type of reinforcement −in order to have ductility of the composite element− a comprehensive campaign will be devoted to optimize the surface roughness of this internal reinforcement to obtain a suitable pull-out behaviour. In particular, new GFRP-bar typologies are manufactured with rib spacing *c* (Figure 7) varied in a geometrical progression as 1:2:4:8:16:32. On the contrary, the rib height is kept constant.

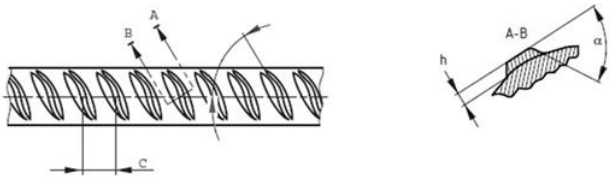


Figure 7. GFRP-bar roughness.

The investigation on the new GFRP-bars will take place by means of Beam Bond Test (Figure 8) on 36 specimens (Table 1). As a result, the identified GFRP-bar with the optimum slippage behaviour −thanks to which the pseudo-plastic rotation capacity of the composite beam is guaranteed− will represent the ideal internal reinforcement typology in next-generation GFRP-RC design.

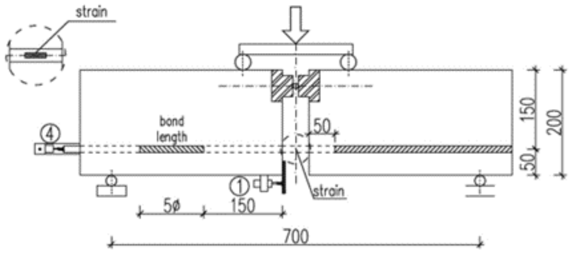


Figure 8. Beam Bond Test [17].

Table 1. Beam Bond Test specimens

Beam height (mm)	Beam width (mm)	Beam span (mm)	Diameter of FRP-bar (mm)	FRP-bar rib spacing	Number of FRP-bar	Number of Specimens
200	200	1600	12	standard	2	3
200	200	1600	12	twice	2	3
200	200	1600	12	4 times	2	3
200	200	1600	12	8 times	2	3
200	200	1600	12	16 times	2	3
200	200	1600	12	32 times	2	3
400	200	3200	25	standard	2	3
400	200	3200	25	twice	2	3
400	200	3200	25	4 times	2	3
400	200	3200	25	8 times	2	3
400	200	3200	25	16 times	2	3
400	200	3200	25	32 times	2	3

4 PRELIMINARY TEST RESULTS ON BAR ROUGHNESS EFFECT

In the following, the load vs displacement diagrams are reported of specimens with beam depth equal to 200 mm, GFRP-bar diameter equal to 12 mm, and two different rib spacing. In particular, Figure 9 shows the bond behaviour of the GFRP-bar having the standard rib spacing, whereas Figure 10 shows the bond behaviour of the GFRP-bar with the twice rib spacing.

As anticipated above, the bond between internal reinforcement and concrete matrix is a crucial parameter governing the behaviour of GFRP-RC beams. Provisionally, Figures 9 and 10 show a slight decrement in the interfacial bond by increasing the rib spacing, as evidenced by the step-wise slippage behaviour.

More beneficial effects should come from larger rib spacing values, as planned in the framework of the ongoing experimental campaign.

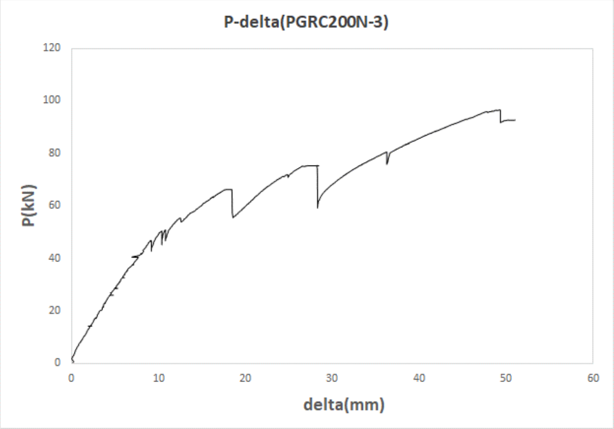


Figure 9. Load vs displacement of specimen with beam depth equal to 200 mm, GFRP-bar diameter equal to 12 mm, and standard rib spacing.

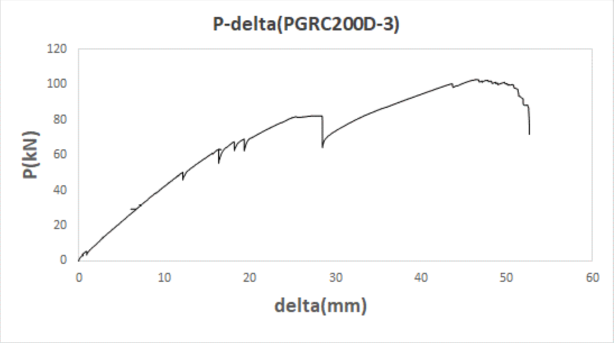
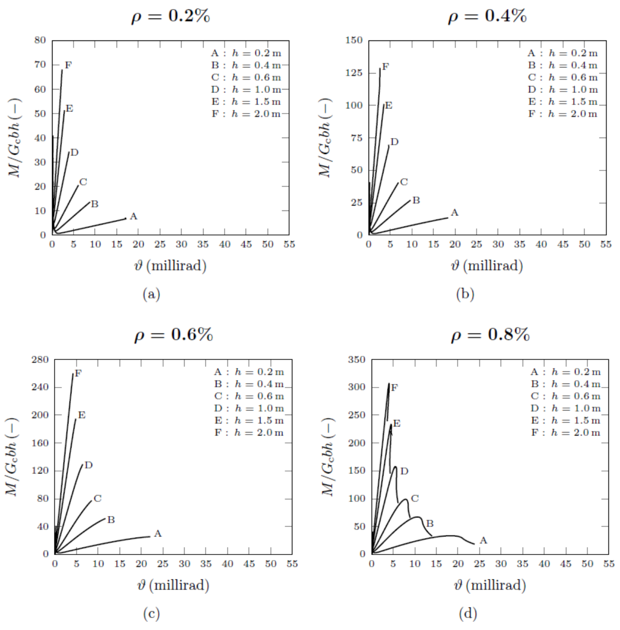


Figure 10. Load vs displacement of specimen with beam depth equal to 200 mm, GFRP-bar diameter equal to 12 mm, and twice rib spacing.

5 COCM PARAMETRIC ANALYSIS

To better understand the bar roughness effect on the structural behaviour of GFRP-RC, a three-point bending test of GFRP-RC beams in the case of perfect bond between GFRP-bar and concrete matrix is considered. The beams have variable depth, h, and variable reinforcement percentage, whereas its span, L, is fixed as 4 times the beam depth. The tensile strength of the concrete matrix, σ_t, is equal to 4 MPa, its compressive strength, σ_c, is equal to 40 MPa, the concrete fracture energy, G_F, is equal to 0.08 N/mm, whereas the crushing energy, G_C, is equal to 30 N/mm.

The GFRP-bar, which is considered linear-elastic up to its rupture, has a tensile strength equal to 600 MPa.



(a) (b)

(c) (d)

Figure 11. GFRP-RC parametric analysis considering a perfect bond between GFRP-bar and concrete matrix (brittle behaviour).

In Figure 11, the moment vs. rotation curves of the GFRP-RC beams are reported by considering four different reinforcement percentages: ρ = 0.2, 0.4, 0.6, 0.8%. For ρ = 0.2%, different structural behaviours are shown by varying the beam depth, from curve A (*h* = 0.2 m), to curve F (*h* = 2 m). All the hardening branches represent the different post-cracking behaviours of the GFRP-RC beams, which are characterised by the GFRP-bar rupture, thus showing a negligible rotation capacity. By increasing the reinforcement percentage, we move from a brittle behaviour due to the reinforcement rupture in tension to a similar brittle behaviour due to the matrix concrete crushing in compression. For ρ = 0.8%, we have final softening due to crushing for small beam depth (*h* = 0.2; 0.4 m), whereas for *h* ≥ 0.6 m catastrophic failures due to brittle crushing of the concrete matrix are revealed (snap-back instability). Generally speaking, by varying GFRP reinforcement percentage and beam scale, we move very unsafely from a brittle failure in tension to a brittle failure in compression (snap-back) without any ductile behaviour.

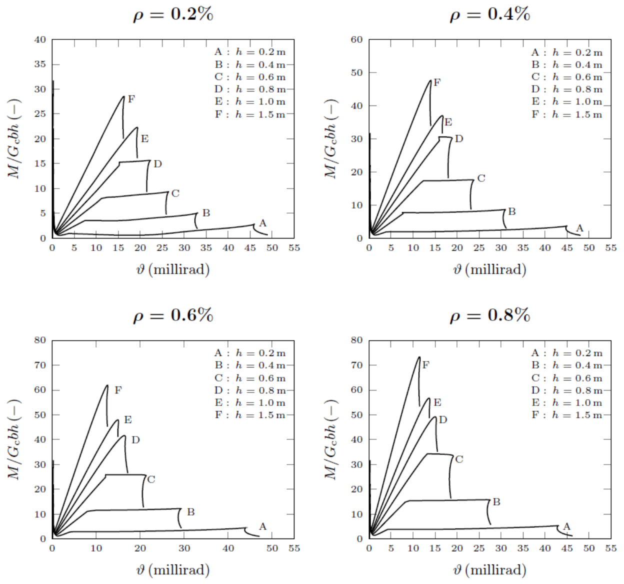


Figure 12. GFRP-RC parametric analysis considering the slippage of the GFRP-bar (pseudo-ductile behaviour).

As a second GFRP-RC parametric analysis, we consider, for the same beam geometry mentioned above, a GFRP reinforcement that can slip inside the concrete matrix (Figure 12). The mechanical characteristics of the concrete matrix are the same as in the previous analysis, whereas in this case the GFRP-bar presents an average slippage strength equal to 1 MPa (bond-slip constitutive law). For the moment vs. rotation curves characterised by ρ = 0.2%, the beam with *h* = 0.2 m shows a safe rotation capacity, which is described by a wide pseudo-plastic plateau. By increasing the beam depth, from curve B to curve E, we can acknowledge a progressive decrease in plastic rotation capacity: for *h* = 1 m, we have brittle concrete crushing prior to GFRP-bar slippage. We can say that, whereas for traditional steel-bar RC the maximum reinforcement condition describes the equilibrium point between concrete crushing and steel yielding, in the case of GFRP-RC this condition is balanced between concrete crushing and GFRP-bar slippage. Moreover, by increasing the reinforcement percentage, we see a decrease in plastic rotation capacity also in the intermediate scales.

REFERENCES

[1] NACE, 2016. *International Measures of Prevention, Application, and Economics of Corrosion Technologies (IMPACT) Study*, NACE International, Houston, Texas.

[2] Nanni, A., 1993. Flexural behavior and design of RC members using FRP reinforcement, *ASCE Journal of Structural Engineering*, 119:5098.

[3] De Luca, A., Matta, F., Nanni, A., 2010. Behavior of full-scale glass fiber-reinforced polymer reinforced concrete columns under axial load, *ACI Structural Journal*, 107:589-596.

[4] Nanni, A., De Luca, A., Jawahei Zadeh, H., 2014. *Reinforced Concrete with FRP Bars*, CRC Press, Boca Raton.

[5] Ruiz Emparanza, A., De Caso y Basalo, F., Kampmann, R., Adarraga Usabiaga, I., 2018. Evaluation of the bond-to-concrete properties of GFRP rebars in marine environments, *Infrastructures*, 3:44.

[6] AASHTO, 2018. *LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete*, Washington DC (USA);

[7] ACI, 2022. *Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars*, Farmington Hills (USA).

[8] *fib* (Fédération Internationale du Béton), 2007. *Bulletin 40: FRP Reinforcement in RC Structures*, Lausanne (Switzerland).

[9] Carpinteri, A., 1984. *Interpretation of the Griffith instability as a bifurcation of the global equilibrium,* Proceedings NATO Advanced Research Workshop on Application of Fracture Mechanics to Cementitious Composites, Evanston, USA, 287-316.

[10] Carpinteri A., 1989. *Cusp catastrophe interpretation of fracture instability*, Journal of the Mechanics and Physics of Solids, 37: 567-582.

[11] Carpinteri, A., Corrado, M., Paggi, M., Mancini, G., 2007. Cohesive versus overlapping crack model for a size effect analysis of RC elements in bending, In: *Design, Assessment and Retrofitting of RC Structures*, Vol. 2 of FraMCoS-6, Taylor & Francis, 655-663.

[12] Accornero, F., Cafarelli, R., Carpinteri, A., 2021. The Cohesive/Overlapping Crack Model for plain and RC beams: Scale effects on cracking and crushing failures. *Magazine of Concrete Research*, 74: 433- 450.

[13] Carpinteri, A., Accornero, F., Cafarelli, R., 2021. Scale-dependent maximum reinforcement percentage in RC beams, *Structural Concrete* (*fib*), 22: 2155-2166.

[14] Cafarelli, R., Accornero, F., Carpinteri, A., 2023. Size-scale effects in high- performance reinforced and prestressed concrete T-beams, *Structural Concrete* (*fib*), 24: 5649-5663.

[15] Cafarelli, R., Accornero, F., Carpinteri, A., 2024. Failure-mode scale transitions in RC and PC beams", *Smart Construction and Sustainable Cities*, 2(1): 5.

[16] Accornero, F., Cafarelli, R., Carpinteri, A., Nanni, A., 2021. Scale effects in GFRP-bar reinforced concrete beams, *Structural Concrete* (*fib*), 24:2817-2826.

[17] Szczech, D., Kotynia, R., 2018. Beam bond tests of GFRP and steel reinforcement to concrete, *Archives of Civil Engineering*, LXIV(4):243-256.