NEW GFRP BARS AS INTERNAL REINFORCEMENT IN CONCRETE STRUCTURES

A. Almerich Chulia[1*], P. Martin Concepcion[1], J.M. Molines Cano[1], J. Rovira Soler[1]

[1]*Dept. of Continuous Medium Mechanics and Theory of Structures, Universitat Politècnica de Valencia, Camino de Vera s/n, 46022 Valencia (Spain)*
**analchu@mes.upv.es*

Keywords: GFRP rebar, internal reinforcement, compression strength, reinforced concrete

Abstract
The use of GFRP bars as concrete reinforcement is relatively new, with very few applications, although use of externally applied FRP sheets, strips and bars for rehabilitation is not uncommon. There is a lack of research in performance and design of new FRP reinforced concrete structures. This use is a new concept with limited experimental and analytical information. Because of these shortcomings, the current codes and standards, including the CSA S806-02, ISIS Manual (2001) and ACI 440 (2006), have severe limitations for structural use of internally placed FRP reinforcement, and all of them ignore the compression strength of the bar in the design, ignoring its contribution due to its low elasticity modulus.

1 Introduction
Rapid advances in technology have allowed construction materials in civil engineering to obtain impressive advantages in security, economy and functionality of the structures built to meet the needs of society. Among these materials, one has been in use since the early 40's, but it has recently gained the attention of the engineers involved in construction of civil structures: fiber reinforced polymer (FRP).

The use of FRP as a reinforcement concrete element has been in development since the early 1960's in the United States [1] and the 1970 in Europe [2] and Japan [3], although the global level of research, manufacturing and commercialization has increased significantly since the 1980's, using mainly FRP reinforcement concrete structures that require high resistance to corrosion or absolute electromagnetic transparency.

In the market you can find a huge variety of FRP reinforcement, which together with the international guidelines and rules [4] [5] [6] that exist, establish the criteria for use in design of concrete elements, resulting in a lack of uniformity in guidelines to follow in the test methods for each of the materials. However, one of the conclusions that seem to have been reached throughout all these years of research is that the behaviour of FRP reinforced concrete sections, when they are submitted to compression, is not taken into account in the guidelines and rules for the design and calculation of concrete elements.

The material characteristics of FRP reinforcement need to be considered when determining whether FRP reinforcement is suitable or necessary in a particular structure. When compared with conventional, steel reinforcement, the FPR results are clearly superior in certain cases. FRP reinforcement has a nonductile behavior that is partially balanced by its high tensile strength. The use of FRP reinforcement should be limited to structures that will significantly benefit from other properties such as the noncorrosive or nonconductive behavior of its materials. Due to lack of experience in its use, FRP reinforcement is not recommended for moment frames or zones where moment redistribution is required. FRP reinforcement should not be relied on to resist compression. Available data indicate that the compressive modulus of FRP bars is lower than its tensile modulus.

Due to the combined effect of this behaviour and the relatively lower modulus of FRP compared with steel, the maximum contribution of compression FRP reinforcement calculated at crushing of concrete (typically at ε_{cu}= 0.003) is small. Therefore, FRP reinforcement should neither be used as reinforcement in columns nor in other compression members, nor as compression reinforcement in flexural members. It is acceptable for FRP tension reinforcement to experience compression due to moment reversals or changes in load pattern. The compressive strength of the FRP reinforcement should not, however, be neglected. Further research is needed in this area.

2 RTHp bar characterization

The composite material used consists of filaments of glass fiber (rovings and mats) with different characteristics, and a resin matrix. The glass fiber rovings have a high tensile strength, high modulus of elasticity and are resistant composite components. The matrix is the linkage material used to bind the fibers to reach homogenization among them, but also serves to confer protection and dimensional stability to the GFRP bar. We use vinyl ester resin because it is easier to handle during the manufacturing process, has better resilience, presents a better performance in wet environments, has high interfacial resistance and high resistance to the alkali of concrete.

Based on this characterization, the final target of our study has been to verify that with a suitable design and respecting the theoretical conditions set by the international standards in this area, it is feasible to obtain an optimal response of GFRP bars to compression efforts without modifying their behaviour in the rest of situations [7].

2.1 Mechanical characterization

The mechanical behaviour of GFRP bars differs from the behaviour of traditional steel reinforcement, since the mechanical properties of these depend on several factors such as fiber quality, orientation, reinforcement fabrics, the fiber-resin volume ratio, the resin type, the manufacturing process, the curing time and others. GFRP materials are anisotropic due to the orientation of the fibers in the bars, and they have a linear behaviour to fracture without yielding as steel.

The break in the form of "explosion" produced in a traditional pultrusion rebar is similar to what happens in a concrete column without stirrups in the absence of this external strapping as shown in Figure 1.

Figure 1. Compression of a traditional GFRP bar

At present, the mechanical characteristics that can be obtained, as a result of the design of the bars of fiberglass, are superior to those of the traditional steel reinforced concrete. In the first manufacturing stages, the GFRP bars had only a high tensile strength; however, after the study and investigation carried out, it is possible to say that the compressive strength of these bars is a fact, because of the results obtained.

After extensive research, we have obtained a solution so that these bars work both in tension and compression, like traditional steel reinforcement. This has resulted in the patent No ES 2 325 011, known as "RTHp" bars [7]. This solution (Figure 2) consists of putting two types of fibres: % longitudinal fibres (1), and a mat to strap longitudinal fibres, (2), with transverse fibre with different angles, which confers stability to the longitudinal ones to resist compression and avoid the possibility of local buckling of longitudinal fiber because of the avoidance of free spaces for buckling. This is the principal contribution of these bars with regard to the existing products.

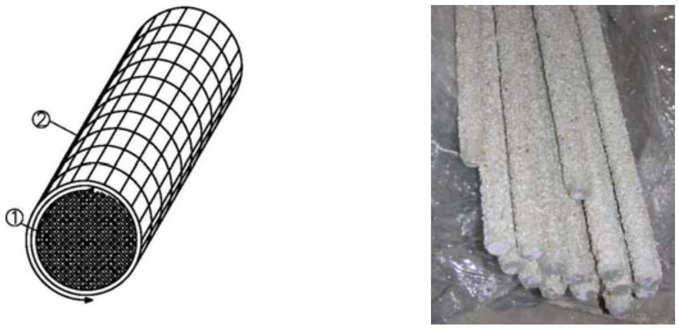

Figure 2. Configuration of RTHp bar – final product

The RTHp bars consist of fiberglass and vinyl ester resin, with an approximate volume fiber content of 75%, and manufactured by the pultrusion process. They also present a superficial recovering of sand of silica to facilitate its adhesion to the concrete.

In recent years, some organizations, such as the American Concrete Institute (ACI), the European Committee for Standardization (CEN), the Japan Society for Civil Engineers (JSCE) and the Canadian Standards Association (CSA), have developed standardized test methods to characterize the FRP composite at whole section level for structural engineering applications. To carry out the characterization of RTHp bars different rules have been used, modifying the aspects that do not correlate with the experimental results. The study of the mechanical properties of the RTHp bars, including their behaviour in tension, compression, shear and adhesion to concrete, results in different processes/stages to achieving the objectives [8].

2.1.1. Tension test

In the tensile test, according to the UNE-EN ISO 527-1:1996, we get the load and the elongation at break suffered by the specimen. The evaluation and analysis of the results of this test allow us to know the tensile mechanical properties of the GFRP bar, such as its strength and its modulus of elasticity (Table 1).

ϕ [mm]	**Strength [MPa]**		**Elastic Modulus [MPa]**	
	Nominal	Charact	Nominal	Charact
8	855,8	916,1	38276	36107
10	779,1	745,0	42634	38488
12	637,9	620,5	41125	39573
16	695,5	637,7	42477	40140
20	723,7	700,6	43590	40970
25	722,8	623,5	39929	35453
32	720,1	635,5	39681	33370

Table 1. Tensile properties

Following the recommendations of ACI 440.3R-04 and UNE-EN 527-1:1996, the specimens were prepared with their respective diameters and lengths, formed by a central section, object of the test, and two extreme sections, which are adequately prepared to allow their attachment to the gags of the press, depending on the diameter of the specimen.

The experimental values for each of the samples ranged from a null value for the effort until the breaking of the specimen. The measurement of the elastic modulus, in the longitudinal direction, was performed using an extensometer between 20% and 50% of the fracture load, value recommended by ACI 440.3R.

2.1.2. Compression test

In the compression test according to ISO 5893:2002, a specimen is subjected to a compressive load along its longitudinal axis and at constant speed up to its failure, measuring the load and the shortening of the specimen. The evaluation and analysis of this type of test, allow us to know the mechanical characteristics to compression of GFRP bar, such as its strength and modulus of elasticity (Table 2).

ϕ [mm]	**Strength [MPa]**		**Elastic Modulus [MPa]**	
	Nominal	Charact	Nominal	Charact
8	463,5	425,5	39934	32713
10	449,5	398,2	46295	38492
12	469,7	418,5	41894	35966
16	449,1	426,7	50804	46302
20	443,6	408,8	44861	40791
25	371,9	351,2	41993	37956
32	319,2	299,8	40766	36590

Table 2. Compression properties

The specimens consisted of a central section, object of the test, and two extreme sections covered by two steel bushings. GFRP bars characteristic compression length was the combined result of personal experience in compression tests and the recommendations of the standards codes, although at present there are not rules for characterization of compression GFRP bars.

To perform the compression test, a set of plates was designed and built for each family of bars, one of the dishes being articulated on the other to facilitate the implementation of the test (Figure 3). The compression plates are plates of hardened steel, constructed so that the load on the specimen is entirely axial, transmitted through the polished surfaces, whose flatness is parallel in a plane perpendicular to the axis of the load.

Figure 3. Configuration and compression test of RTHp bar

In the compression tests, measurement of elastic modulus in the longitudinal direction was performed using an extensometer between 20% and 50% of the fracture load.

2.1.3. Bond test

The bond properties of the bars as internal reinforcement concrete structures have been obtained using the "pull out" test, taking as reference Annex D of the UNE-EN 10080. The specimens for the "pull out" tests passed through the curing and setting process, respecting the minimum time before performing the test, as determined by UNE-EN 1766:2000 and ACI 440.3R-04.

The "pull out" test consists of applying a tensile load to a GFRP bar, which is embedded in a certain length within a concrete cube, leaving the other end of the bar without any other cargo. The pulling force is increased until failure occurs or until the bond breaks the GFRP bar, obtaining the relationship between the tensile force applied and the produced slide, which allows us to assess nominal and failure strength (Table 3).

ϕ [mm]	Nominal Strength [MPa]	Failure Strength [MPa]
8	9,21	11,94
16	5,53	6,12
25	5,72	6,16

Table 3. Bond properties

Specimens were prepared for three types of rounds, the diameter 8, 16 and 32 mm, when taken as representative of the following groups: fine series (8, 10 and 12 mm), medium series (16 and 20 mm) and thick series (25 and 32 mm), respectively.

2.1.4. Shear test

The objective of this test is to determine the shear strength of the bars for use as stirrups, so bars have been tested at 12 mm in diameter, considered the most common size (Table 4).

ϕ [mm]	**Failure Load [kN]**	**Characteristic Tensile Strength [kN]**
12	11,6	10,22

Table 3. Bond properties

2.1.5. Test results

Mechanical behaviour of tested RTHp bars can be observed in Figure 4. These values are considered as typical and characteristic for the material to design and check sections.

	Rupture Strength [MPa]	**Elastic Modulus [MPa]**
Tensile	676,25	38555
Compression	318,70	42000

Table 4. Design properties

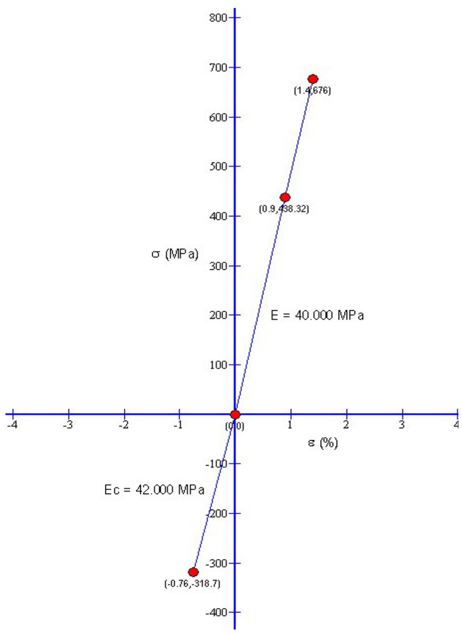

Figure 4. GFRP constitutive equation σ – ε

2.1.6. RTHp bar certification.

After research in Mechanics of Continuous Medium and Theory of Structures Department (DMMCTE) of Universitat Politècnica de Valencia (UPV) (Spain), with previous results about mechanical behaviour of fiberglass bars RTHp, Institute of Sciences of the Construction "Eduardo Torroja" (ITCcc) completed test battery, performing them in the same institute or in UPV DMMCTE laboratories under its supervision, to determine experimentally the modulus of elasticity and strength, both tensile (based on standards ASTM) and compression, of different diameter RTHp bars, and the ultimate shear load bar diameter of 12 mm [9].

3 Experimental results and design rules

Spanish structural concrete standard, EHE-08, is current design code for concrete structures with structural safety requirements in Spain, giving sufficient techniques to meet guarantees. This code, in its article 2, when the structure can be considered special or unique, it indicates that the rules will apply with adaptations and additions, under the liability established by the author. We are in this case; we want to design reinforced concrete structures with GFRP internal reinforcement. For this purpose, we studied EHE-08 code, changing the rules and establishing the necessary adjustments and additional provisions, to obtain solutions, partially or totally different from the procedures laid down in it, but according to the mechanical characteristics that this material has for building these structures, with a valid characterization of RTHp fiberglass bar as described in the previous tables.

To ensure the above requirements, EHE-08 uses the Limit States theory, analysing the situations that exceed the structure, and needs to ensure durability. The purpose is to verify, for each limit state, that the design values are equal or less than the ultimate strength. The general design recommendations for concrete elements reinforced with GFRP bars are based on principles of equilibrium and compatibility and the constitutive laws of the materials. Furthermore, the brittle behaviour of both FRP reinforcement and concrete allows consideration to be given to either FRP rupture or concrete crushing as the mechanisms that control failure.

Strength and working stress design approaches were considered by this investigation. We took strength design approach of reinforced concrete members reinforced with GFRP bars to ensure consistency with other documents. These design recommendations are based on limit state design principles in that an FRP-reinforced concrete member is designed based on its required strength and then checked for serviceability criteria, fatigue endurance, creep rupture endurance. FRP-reinforced concrete members have a relatively small stiffness after cracking. Consequently, permissible deflections under service loads can control the design.

The design of GFRP-reinforced concrete members for flexure is similar to the design of steel-reinforced concrete members. Experimental data on concrete members reinforced with GFRP bars showed that bending capacity can be calculated based on assumptions similar to those made for members reinforced with steel bars, modified them with GFRP characteristic coefficient. The different mechanical properties of GFRP bars, however, affect shear strength and must be considered. The shear capacity were studied and the use of GFRP stirrups. The serviceability provisions given in EHE-08 need to be modified for FRP-reinforced members due to differences in properties of steel and FRP, such as lower stiffness, bond strength, and corrosion resistance.

With the experimental results and design guidelines established by Spanish current code, we have proposed a procedure for the design rectangular sections of reinforced concrete with GFRP bars. These rules have been implemented in software called "RTHp Armado" [8], to provide future users and/or designers with its use, as well as to design and test sections of reinforced concrete with RTHp fiberglass rods. Rules considered in this program are EHE-08, ACI 440.1R-06, CAN/CSA-S806-02 and CAN/CSA-S6-06, modified accordingly to the experimental results.

4 Conclusions

RTHp bars tested have a correct behaviour under compression loads, and although they can optimize their characteristics and the tests that determine them, it is believed the study and analysis is enough to justify their use as compression reinforcement in reinforced concrete. In their characterization, both in tension and compression, it has been shown that both the bearing capacity and the modulus of elasticity are functions of bar diameter, increasing with decreasing diameter. However, the internal configuration of the bar itself makes this variation small, so that further investigation and analysis developed, has worked with an average value taken from the characteristics for each diameter.

The capacity of reinforced concrete elements with GFRP round can be estimated using the theory of limit states, as well as with elements traditionally armed with steel. The analytical model developed as part of this research is based on the conditions of equilibrium and strain compatibility, with an ultimate strength prediction which is quite accurate at any level of loading of reinforced concrete elements with GFRP bars.

As GFRP bars have a low modulus of elasticity, this is about one-fifth that of steel ($E_{GFRP}/E_{steel} \approx 1/5$), Service Limit States are determinant in reinforced concrete elements design with this material. EHE-08 equations taken in this study, which are developed for steel reinforced element, minimize the deformation of reinforced concrete with fiberglass bars. Our conclusion is that they must be modified, taking coefficients in relation with the experimental results. This fact has also been revised in the latest version of ACI 440.1R 2006.

References

[1] Nanni, A.(ed.) Fiber-Reinforced-Plastic (GFRP) Reinforcement for Concrete Structures: Properties and applications. *Elsevier Science. Developments in Civil Engineering*, **42**, pp.450. (1993)

[2] Benmokrane, B., Challal, O. Physical and mechanical performance of an innovative glass-fiberreinforced plastic rod for concrete and grouted anchorages. *Canadian Journal Civil Engineering*, **20**, 254-268 (1993).

[3] Neale, K.W., Labossièrie,P. Advanced composite materials on bridges and structures. 1st Int. Conf. Sherbrooke, Quèbec, Canadian Society for Civil Engineering, **700** (1992).

[4] Nanni, A., Dolan, C.W. Fiber-reinforcedplastic reinforcement for concrete structures, International Symposium. *American Concrete Institute (ACI),* SP-**138**, 177 (1993).

[5] Nanni, A. Flexural behavior and design of RC members using FRP reinforcement. ASCE. *Journal of Structural Engineering*, **119** (11), (1993).

[6] Bank, L.C., Bakis, C.E., Bromw, V.L., Cosenza, E. *at el*. Fiber-reinforced polymer composites for construction – State-of-the-Art Review. *Journal of Composites for Construction*. **6** (2), 73-87 (2002).

[7] Rovira, J. *Barra a base de polímero Barra a base de polímeros reforzados con fibras para el armado del hormigón*. Patent nº ES 2 235 011, (2010).

[8] Almerich, A. *Diseño, según estados límites, de estructuras de hormigón armado con redondos de fibra de vidrio GFRP*. Thesis, Universitat Politècnica de Valencia, Spain (2010).

[9] Arteaga, A.; López, C.; *Informe nº 19.596-I. Ensayos de tracción, compresión y adherencia de redondos de materiales compuestos para su uso en hormigón*. Instituto de Ciencias de la Construcción "Eduardo Torroja" (IETcc), Madrid, España, (2009).