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Experimental behavior of novel GFRP reinforcing bars under compressive loads

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Abstract. Glass fiber-reinforced polymer (GFRP) bars have been used in RC structures due to their high tensile strength capacity and resistance to corrosion in comparison with steel. However, international standards do not recommend their use in RC structure elements subjected to compressive loads. Currently, there is no standard method to determine the compressive characteristics of FRP bars. This article presents a new type of GFRP bars designed specially to support compressive loads: they have additional winding GFRP layers around the longitudinal fibers. An exhaustive experimental study was carried out to obtain compressive properties of the bars: compressive strength, Young's modulus and stress-strain relation. After post-processing the experimental results of the study, this paper showed compressive strength between 50% and 60% of tensile strength, which allows employing the bars as internal reinforcement in RC structures. Their obtained Young's modulus is the same in both tensile and compression, which enables the linear stress-strain relation to be extended to the entire range of deformations. This is most advantageous for structural analysis procedures in the linear elastic regime. Finally, based on the experimental results of failure modes, some limitations about the cross-sectional area or the slenderness were proposed for the use as internal reinforcing in RC structures, which helps the researchers in the design procedure for members reinforced with FRP bars.

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1. Introduction

Rapid technological advances in building materials have contributed to significant progress in civil engineering in areas like security, economy, and functionality. They serve society's needs by improving people's standard of living. One of them has been used since the early 1940s. Still, it has recently drawn the engineers' attention in the construction of civil structures: composite material made of fibers embedded in polymeric resin, also known as fiber-reinforced polymer (FRP).

Conventional concrete structures are reinforced with non-prestressed or prestressed steel. Initially, the alkalinity of concrete protects steel and usually results in durable and serviceable construction.

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However, many structures like bridges, parking garages, and marine structures are subjected to aggressive environments with salt, moisture, chlorides, and temperature changes. These conditions reduce concrete's alkalinity and allow corrosion to build up on reinforced steel. Finally, the corrosion process causes concrete deterioration and loss of serviceability.

Composite materials offer considerable benefits if correctly applied, given their cost and durability. These materials provide other advantages like high tensile strength, stiffness-to-weight ratio, ability to resist corrosion and chemical attack, controllable thermal expansion, damping conditions, and higher electromagnetic neutrality compared to other materials.

The use of fiber-reinforced polymer bars is one technique that enhances conventional reinforced concrete structures [1, 2]. In particular, FRP bars offer a very high potential to be used as reinforcement under conditions in which concrete reinforced with steel offers unacceptable service conditions [3–7].

The study of FRP bar behavior as a reinforcement of concrete structures has undoubtedly evolved since 1954, when Brandt Goldsworthy spoke of this material's high potential for specific construction applications. Since that time and until 1970s, only a few studies have analyzed the feasibility of using GFRP rods as reinforcement of reinforced concrete.

Since 1980s and early 1990s, the FRP reinforcement use in civil engineering applications promoted the development of scientific research, and methods were tested on bars. Collections of documents and published reports describe the research and work done in Europe, the USA, Japan, and Canada. International interest in investigating the use of FRP bars as internal reinforcement for reinforced concrete has quickly grown and led to an increasing number of publications about hundreds of studies and tests conducted in this field [1, 8–11].

Table 1. International codes and guidelines FRP design.

	Codes – Guidelines
USA	ACI 440R-07 "Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures", ACI Committee 440, American Concrete Institute, 2007.
	ACI 440.1R-15 "Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars", ACI Committee 440, American Concrete Institute, 2015.
	ACI 440.5-08 "Specification for Construction with Fiber-Reinforced Polymer Reinforcing Bar", ACI Committee 440, American Concrete Institute, 2008.
	ACI 440.6-08 "Specification for Carbon and Glass Fiber-Reinforced Polymer Bar Materials for Concrete Reinforcement", ACI Committee 440, American Concrete Institute, 2008.
	ACI 440.3R-04 "Guide for Test Methods for Fiber Reinforced Polymers (FRP) for Reinforcing and Strengthening Concrete Structures", ACI Committee 440, American Concrete Institute, 2004.
	BDGS-GFRP "AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete", 2nd Edition, 2018.
CANADA	CSA-S806-12 (R2017) "Design and Construction of Building Components with Fibre-Reinforced Polymers", Canadian Standards Association, 2012.
	CSA-S6-06 "Canadian Highway Bridge Design Code" Canadian Standards Association, 2006.
	CSA S807-19 "Specification for fibre-reinforced polymers", 2019.
	Design Manual No. 3 "Reinforcing Concrete Structures with Fiber Reinforced Polymers"*
JAPAN	Japan Society of Civil Engineers (JSCE) "Recommendation for Design and Construction of Concrete Structures Using Continuous Fiber Reinforced Materials", Concrete Engineering Series 23, Research Committee on Continuous Fiber Reinforcing Materials, 1997.
EUROPE	fib Bulletin N° 40 "FRP reinforcement in RC structures", Technical Report. France, 2007
	CNR-DT 203/2006 "Guide for the Design and Construction of Concrete Structures Reinforced with Fiber-Reinforced Polymer Bars". Italy, 2006

* The Canadian Network of Centers of Excellence on Intelligent Sensing for Innovative Structures (ISIS CANADA).

This FRP reinforcement behavior knowledge has resulted in several design codes or guidelines (Table 1) for FRP-reinforced concrete (FRP-RC) systems.

These guidelines or standards provide the limit states to design reinforced concrete with FRP. In fact, of current design guidelines and codes of practice for FRP-RC systems, only the Japan Society of Civil

Engineers (JSCE) has established a design procedure for FRP-RC columns. ACI 440.1R does not recommend employing FRP bars in columns, while CSA S806 ignores the compression contribution of FRP bars owing to their little compression [12, 13]. In this design of FRP-RC systems, all these standards reach the same conclusion when compression reinforcement is required: none considers its contribution to the design of these elements. International tests show that the compression strength of GFRP bars is lower than tensile. There are many kinds of research on FRP bars used as reinforcement in columns, flexural members, and reinforced walls in which GFRP bars are subjected to compressive stresses contribution [14–18]. However, they all indicate that the compressive strength of GFRP bars should be neglected, thus requiring further research in this area.

Many studies have shown the effectiveness of using GFRP bars in compression for RC elements [19–23]. Researchers describe some attempts made to evaluate the compressive strength of GFRP bars. Moreover, no generalizations can be made about the results because different researchers have employed a limited number of specimens, a single bar diameter, or a specific slenderness ratio. Further research into this and a more systematic approach are needed to examine the compressive behavior of GFRP bars. Moreover, the linear behavior of FRP bars until failure creates a significant concern for design engineers regarding safety.

The main objective of this research is to investigate the compressive behavior of new GFRP bars and provide technical information to design engineers seeking guaranteed solutions for using GFRP bars as internal reinforcement of reinforced concrete. This paper presents an experimental compressive strength study for new GFRP bars for RC structures (Fig. 1). This study aims to obtain ultimate compressive strength, compressive loads, modulus of elasticity, and stress-strain relation for specimens with different diameters. The experimental results show that these bars' specific design regarding compressional behavior enables their use as concrete reinforcement with compression loads according to the theoretical conditions set by international standards.

Figure 1. RTHp GFRP bars.

1.1. Case study: new GFRP bars

FRP bars' mechanical behavior differs from traditional reinforced steel. FRP bars' mechanical properties depend on several factors: fiber quality, orientation, fabric reinforcement, fiber-resin volume ratio, resin type, manufacturing process, curing time, etc. FRP materials are anisotropic due to fibers' orientation in rebars, and FRP bars do not possess plastic behavior (yielding).

Tested bars are a new-patented technology No. ES2325011B1 [24] was designed specially for compressive loads for concrete reinforcement in FRP-RC systems, provided by RTH Pultrusystems (RTHp) [25].

A pultrusion process manufactures the employed experimental bars with fiberglass and vinyl ester resin. They are glass-fiber-reinforced polymers (GFRP). The percentage of fiberglass per volume on the core is 77 % and 23 % of vinyl ester, as reported by the manufacturer.

In the early stages of this research, these bars only had a high tensile strength like more classical GFRP rebars. After an exhaustive study, it was eventually possible to design a new GFRP bar to support specific compression loads and obtain its performance as compression reinforcement. Fig. 2 illustrates this final solution.

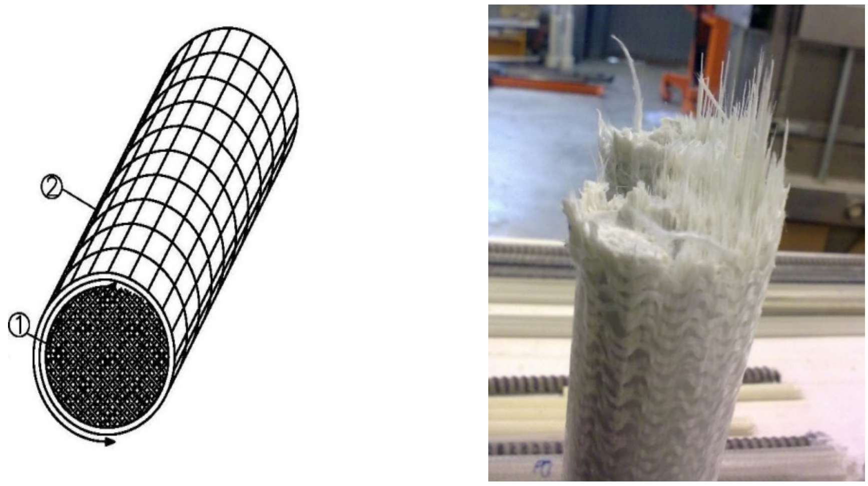

Figure 2. Configuration RTHp bar: (a) Schematic: (1) central core of fiberglass rovings, (2) fiberglass fabrics; (b) Real.

In this structural solution, not all the fiber is longitudinally arranged. There is a central core of fiberglass rovings (1), bonded together through polymeric resins, and a second zone composed of fiberglass fabrics (2), which covers the entire surface to act as a blanket and to provide a strapping to the longitudinal fibers in the first zone. The employed fabric type is taffeta (very tight mesh). Expressly, this woven mesh confers longitudinal rovings stability to work under compression. This is the main contribution of these bars to the products on the market.

Table 2 shows this solution according to the bar's diameter, which includes a variable number of fiberglass rovings, type 4800TEX, arranged longitudinally for the central core, coaxed by woven rovings of different widths and grammage for the second zone.

Table 2. GFRP bar composition.

	UD	Ø 8	Ø 10	Ø 12	Ø 16	Ø 20	Ø 25	Ø 32
Diameter	mm	8	10	12	16	20	25	32
pultrusion core (kg/m)	kg	0.100	0.156	0.225	0.400	0.625	0.975	1.596
Nº rovings 4800 TEX	--	12	21	29	54	110	136	230
Weight woven roving	gr/m^2	220	300	300/220	300/220	300/220	300/300	300/300
Width woven roving	mm	60	80	80/40	80/60	80/60	120/140	140/120
Nº woven rovings	--	1	1	2	2	2	2	2

Finally, an outer layer of silica-based granules with a variable granulometry bonded using resin to the second zone. This outer layer allows the bar to adhere to the reinforced concrete.

2. Method

Currently, there is no standard method to determine the compressive characteristics of FRP bars. This document provides a model test method to determine the mechanical compression properties of bars. The compression test was done according to ISO 5893 [26], UNE 13706-2 [27], and ISO 604 [28]. This last European standard is similar to ASTM D695-10 (compression test) [29] but with some modifications because this standard is not applicable to round GFRP bars.

This research aims to determine the critical compressive properties, including modulus of elasticity, yield strength, strain beyond yield strength, and compressive strength. The specimen was subjected to a compressive load along its longitudinal axis at a constant speed to failure during the test. The evaluation and analysis of these values will allow us to know the compressive mechanical characteristics of the bars as an internal reinforcement for RC systems, which helps in the design procedure for members reinforced with FRP bars.

2.1. Specimen dimensions

Using bars as the internal reinforcement of reinforced concrete elements establishes their dimensions. For example, limiting bars' unbraced length is necessary as internal reinforcement of reinforced concrete elements.

The researchers used various test fixtures to characterize GFRP bars in compression. The free length varies from test to test. Deitz studied the effect of the slenderness ratio, with unbraced lengths ranging from 50 to 380 mm [30], and another study investigated bars with a low slenderness ratio [31]. Chaallal and Benmokrane tested three different diameters with a slenderness ratio of 11 [32]. Khan studied GFRP bars with a slenderness ratio of 5 for compression [33]. Bruun varied the unbraced lengths from 50 mm to 600 mm as the potential unbraced length used in reinforced concrete (RC) columns [34]. Khorramian and Sedeghian are considered free length two times diameter as indicated in ISO 604 and ASTM D695-10 [35]. AlAjarmeh et al. studied the effects of the bar diameter and the unbraced length-to-bar diameter ratio for high modulus GFRP bars [36] and under elevated temperatures [37].

Standards for the compressive testing of materials define limitations on the free length to the diameter or the width ratio to avoid buckling and reach material failure.

Nevertheless, ACI standards offer no recommendations for compression tests. ACI tensile test for FRP reinforcement describes the recommended specimen's free length according to the FRP bar's diameter, which should be no less than 40-fold effective bar diameter [38, 39]. For FRP-reinforced concrete (FRP-RC) systems, when FRP bars in the compression zone cannot be avoided, ACI recommends that the transverse reinforcement should have a spacing more minor than the least cross-sectional dimension or 16 longitudinal bar diameters [12].

For Eurocode 2 [40] and Concrete Spanish Code [41], the unbraced length for steel-RC systems should be less than 15-fold the bar's diameter in a typical environmental situation. Still, it should be less than 12-fold the bar's diameter for the structures located in seismic risk zones or exposed to wind effects.

According to the last recommendations, researchers conducted several tests with different slenderness. Finally, they took an unbraced specimen length of 12-fold the tested diameter, L_0, which is the minimum free length between stirrups in reinforcement concrete, conforming with the Spanish code.

$$L_0 = 12 \cdot \phi. \tag{1}$$

For each diameter, the total length was calculated following the formula:

$$L_T = L_1 + L_0 + L_1, \tag{2}$$

where L_0 is the free distance between anchorages, unbraced length, and L_1 is anchor length embedded in steel sleeves, whose depth is required to bond the bar to steel tube and was established as 50 millimeters [39]. The gap between the bar and sleeves was filled with epoxy resin, and the ends of the sleeves were cut facing so they would be parallel and smooth. All these features allowed bars to be placed on compression plates.

Table 3 presents and tabulates bars' length values (in millimeters) for the compression test. The total length of the specimen is the free length plus two times the anchor length (Fig. 3). For the Ø8 mm and Ø10 mm diameter rods, two series of different lengths were made: Serie 1 with L_0 (fc) length to obtain the compression strength values; Serie 2, L_0 (E) length to get Young's modulus, being able to place the extensometer (Fig. 4).

Table 3. Lengths of the GFRP bars in the compression test: Serie 1, Serie 2.

Ø (mm)	L1 (mm)	Serie 1: fc		Serie 2: E	
		L_0 (fc)	L_T (fc)	L_0 (E)	L_T (E)
8	50	38	138	102	202
10	50	70	170	102	202
12	50	102	202	102	202
16	50	166	266	166	266
20	50	230	330	23	330
25	50	310	410	310	410
32	50	470	570	470	570

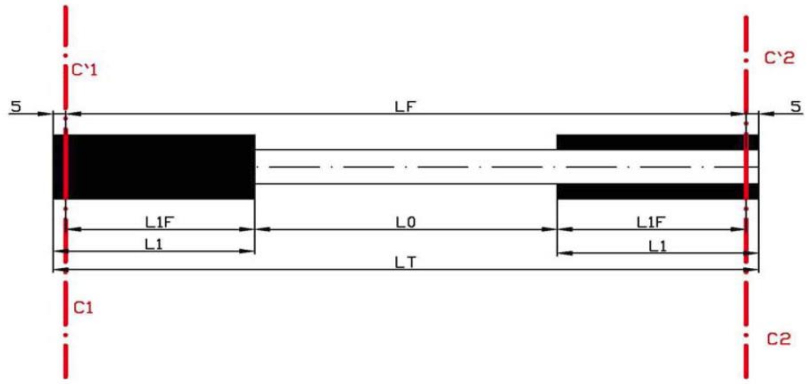

Figure 3. Length of the GFRP bars.

Figure 4. Bars for the compression test. Serie 2.

2.2. Test procedure

According to ISO 5893, a testing machine was used that maintains a constant speed of 5 mm/minute as recommended by ISO 604, while recording axial load, strain, and displacement values. To perform the compression test, it was necessary to design and build a set of plates for each bar family. These plates were made of hardened steel (Fig. 5), with a concentric hole for the required diameter to hold steel sleeves in position and align FRP bars properly. These plates are essential and need to ensure that bars are subjected to pure compression during tests and, thus, disregard any bending produced by possible eccentricity upon load application, which contributes to the consistency of the results.

Figure 5. Compression test plate.

The testing machine transmits a compression load through these plates, which lies the perpendicular plane parallel to the loading axis. Specimen and plates are coupled by a free-rotation joint so that the load on the tested bar is entirely axial. Fig. 6 shows the bar's deformation upon a rupture with the set of plates in motion.

Figure 6. Compression test. Set of plates.

According to ISO 604, there were nine test specimens for each diameter, except for Ø8 and Ø10 mm, for which there were five. If a tested bar failed, another test was carried out with another bar taken from the same lot as the failed specimen.

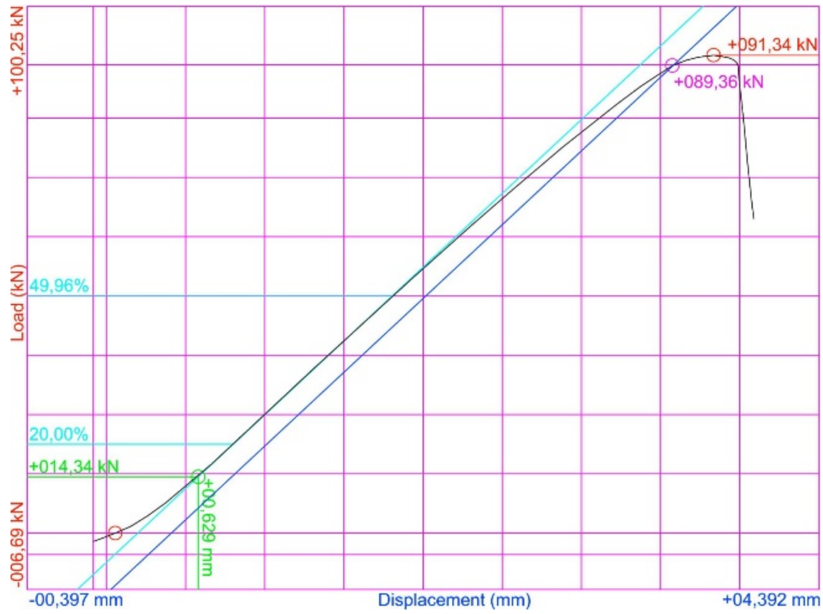

Figure 7. Curve load/elongation compression test: Ø16 mm.

The universal press employed to conduct the experimental research has an acquisition system of analog data that records the maximum compression load Fu (kN) and the shortening corresponding to breakage ΔL (mm). The PC2K software, by SERVOSIS, was used to establish an automatic recording system, resulting in the compression test's load/elongation curve (Fig. 7).

Moreover, researchers employed an extensometer to determine the relative variation of the specimen's reference length in each instant. Its reference length was 50 mm, defined in ISO 5893. The extensometer was placed in the test free length's center (Fig. 8). It was delay-free due to both inertia and the specified test speed, and it could measure the variation of the reference length at an accuracy of 1 %.

Then, with the tested information and geometric data obtained from the bars, namely specimen length, nominal diameter (mm), and cross-section (mm^2), the researchers were able to determine compression strength, modulus of elasticity, and the stress-strain relation for the compression test based on brittle materials' linear elastic mechanical behavior.

Figure 8 Extensometer.

3. Results and Discussion

In this section, after carrying out the test campaign and the post-processing of the experimental data, the results of the compressive tests on the performance of GFRP pultruded bars are presented and discussed in detail.

3.1. Mechanical compression test results

This performance of glass fiber reinforced polymer (GFRP) bars subjected to compression loads was investigated by repeating the process two times. Table 4 shows the results obtained in the compression tests for each tested diameter (Serie 1), where:

- P (kN) is the compression load applied.
- $f_{u,c}$ (MPa) is the ultimate compressive strength obtained by dividing the peak compressive load by the specimen's cross-section.
- E_c (MPa) is the modulus of elasticity in compression, obtained by the linear regression of the stress-strain curve between 20 % and 50 % of ultimate stress.

Table 4. Experimental results of the compression testing of GFRP bars – Serie 1.

		#1	#2	#3	#4	#5	#6	#7	#8	#9	σ	SD	$\delta\%$	Fk
Ø8	P	22.63	23.38	24.61	23.00	22.88								
	$f_{u,c}$	467.6	483.1	499.5	469.2	468.0					477.48	11.06	2.32	451.48
	E_c	46753.5	46020.3	41863.1	38748.6	38512.2					42380	3205.90	0.08	34846
Ø10	P	34.06	35.47	38.09	34.39	34.51								
	$f_{u,c}$	448.8	461.7	493.8	446.8	449.2					468.9	14.17	3.02	435.61
	E_c	53551.0	47080.9	52450.6	47923.9	42135.5					48628	3497.93	0.07	40408
Ø12	P	52.70	49.81	50.40	54.01	51.68	57.32	53.88	57.09	51.20				
	$f_{u,c}$	444.1	452.4	482.4	463.1	515.4	482.0	512.4	457.3	444.1	475.61	19.94	4.19	438.52
	E_c	46237.8	47134.3	40658.8	40027.2	39612.3	40916.3	40139.5	43019.5	46237.8	42351	2311.26	0.05	38052
Ø16	P	90.89	92.14	88.45	92.42	91.14	88.24	86.28	91.50	91.54				
	$f_{u,c}$	454.9	461.1	442.7	462.5	456.1	441.6	431.8	457.9	458.1	451.88	8.78	1.94	435.54
	E_c	48358.2	51079.0	48153.7	52558.3	54512.4	53671.3	51735.7	49306.2	50566.1	51105	1791.00	0.04	47773

		#1	#2	#3	#4	#5	#6	#7	#8	#9	σ	SD	$\delta\%$	Fk
Ø20	P	138.03	137.94	140.78	136.62	150.42	130.76	139.52	139.85	140.45				
	$f_{u,c}$	452.8	452.6	461.9	448.2	493.5	429.0	457.7	458.8	460.8	457.26	10.31	2.26	438.07
	E_c	48918.1	49056.8	47253.2	44035.7	44875.9	44229.5	45378.8	47545.6	43606.8	46100	1860.78	0.04	42639
Ø25	P	171.97	181.42	184.39	181.69	184.63	186.09	183.52	189.06	180.35				
	$f_{u,c}$	360.4	380.2	386.4	380.7	386.9	389.9	384.6	396.2	377.9	382.56	6.91	1.81	369.71
	E_c	40517.5	46901.1	43393.5	43187.1	42549.4	44782.1	40702.1	44511.2	42687.5	43248	1465.81	0.03	40522
Ø32	P	261.45	253.04	266.81	265.46	258.76	247.06	248.34	250.26	180.35				
	$f_{u,c}$	332.3	321.6	339.1	337.4	328.9	314.0	315.7	318.1	329.4	326.28	7.94	2.43	311.51
	E_c	43606.1	44503.2	43974.5	41716.1	41008.7	38270.9	43948.5	41149.2	43126.9	42367	1627.46	0.04	39340

As glass fiber composition differs for each diameter, according to UNE 66040 [42], an estimator was used to ensure a minimum value of the tested characteristic, with a 95 % confidence interval (95 % CI) determined according to:

$$M = \sigma - (1 - \delta \cdot t_{1-\alpha}) \tag{3}$$

where σ is the arithmetic mean of the experimentally requested values, δ is the rate between the arithmetic mean, the standard deviation (SD) as %, and $t_{1-\alpha}$ is the t-Student coefficient for confidence α = 95 %.

3.2. Discussion

Unlike steel bars, FRP bars have no constant value but a variable dependent on the cross-sectional area. The characterization process shows that the bearing capacity and modulus of elasticity vary per bar diameter, which rose as the diameter decreased.

Table 5 shows the final rebars' mechanical behavior values. They can be regarded as mechanical characteristic values for designing and checking reinforced concrete sections with this novel GFRP bars.

Table 5. Characteristic values.

Ø	Tensile				Compression			
	f_u (MPa)		E (MPa)		$f_{u,c}$ (MPa)		E_c (MPa)	
	Mean	Charact	Mean	Charact	Mean	Charact	Mean	Charact
8	855.8	799.9	38276	36107	463.5	416.9	39934	32713
10	779.1	731.0	42634	38488	449.5	387.0	46295	38492
12	637.9	614.5	41125	39573	469.7	397.6	41894	35966
16	695.5	626.5	42477	40140	449.1	417.5	50804	46302
20	723.7	691.1	43590	40970	443.6	394.6	44861	40791
25	722.8	627.3	39929	35453	371.9	342.8	41993	37956
32	720.1	611.6	39681	33370	319.2	291.9	40766	36590

Table 6 gives a comparison of the mechanical properties of steel [41] and this novel GFRP rebars [25].

Table 6. Mechanical properties Steel versus GFRP bars.

Property	Steel	GFRP
Yielding strength fy (MPa)	246 – 517	--
Tensile strength fu (MPa)	550	600 – 800
Compression strength fu,c (MPa)		290 – 420
Tensile modulus E (GPa)	200	38 – 42
Compression modulus Ec (GPa)		32 – 45

a) Compressive strength

According to the literature, GFRP bars exhibit meager compressive strength [30], [33], [34], [43], [44], and International Standards do not usually recommend their use in RC structures under compression. The reported results (Table 5) show that the tested bars' compressive strength was 50-60% of the tensile strength for all the diameters [45]. However, the presented experimental results support their use as reinforcement bars in RC structures under compression loads. Thus, tested bars can sustain compression loads, and ignoring their compressive contribution to concrete members is not reasonable.

b) Modulus of elasticity.

Each specimen was equipped with an extensometer to measure the changes in length as the applied load varied. In this way, it was possible to determine the modulus of elasticity, which does not depend on specimen length as a material's property (Table 5). No buckling stability problems occurred as the values were taken between 20 % and 50 % of the load (Fig. 7). The modulus of elasticity in compression is similar to the elasticity modulus of tension, so it should be a material property.

c) Mechanics of failure

It is known that crushing is a localized failure mode related to the material's properties (fiber and resin), while buckling depends on these and specimen length [36, 46, 47].

Euler's Equation can model the response of a compressed element to predict critical load.

$$P_{cr} = \frac{\pi^2 EI}{(\alpha L)^2} \tag{4}$$

Although this formula does not apply to GFRP for being non-homogeneous material, it is a good approximation. Given the experimental characteristic values (Table 5), it is possible to obtain Euler's critical load. The experimental rupture loads are lower than the critical load for the adopted slenderness ratio, except with larger diameters, where failure occurs by buckling $\left(f_{u,c} > f_{Euler} \right)$ (Table 7). Fig. 9 shows the different failure modes for the compression test.

Table 7. Comparative Critical Loads.

Ø (mm)	L_0 (mm)	E_c (Mpa)	$f_{u,c}$ (MPa)	P_{crit} (kN)	f_{Euler} (MPa)
8	38	32713	416.9	91.75	1825.23
10	70	38492	387.0	77.67	988.91
12	102	35966	397.6	70.87	626.67
16	166	46302	417.5	108.88	541.51
20	230	40791	394.6	121.98	388.29
25	310	37956	342.8	152.54	310.76
32	470	36590	291.9	171.73	213.53

Figure 9. Different failure modes: (a) Crushing, (b) Splitting[1], (c) Buckling.

d) Spacing/unbraced length

According to the experimental characteristic values, Table 8 shows the maximum theoretical unbraced length $\left(L_{\max\_\text{theoretical}}\right)$ to avoid buckling failures compared to the experimentally used L_0. Based on the experimental results, bars with a larger diameter do not comply.

Also, in the Spanish regulation [41], the maximum allowed unbraced length for steel reinforcement is 12-fold the diameter in extreme situations, called $L_{\text{normalized}}$. As in the previous case, bars with a larger diameter do not comply. Likewise, this standard does not recommend employing bars smaller than 12 mm for compression reinforced concrete elements.

Table 8. Comparative Unbraced Length

Ø	L_0 (mm)	Experimental Values			Length		
		E_c (Mpa)	$f_{u,c}$ (MPa)	P (kN)	Max. theoretical (mm)	Normalized (mm)	Recommended (mm)
8	38	32713	416.9	21.39	78.70	96	80
10	70	38492	387.0	31.27	110.31	120	100
12	102	35966	397.6	47.33	124.82	144	120
16	166	46302	417.5	85.79	187.00	192	160
20	230	40791	394.6	128.43	224.16	240	200
25	310	37956	342.8	172.39	291.60	300	250
32	470	36590	291.9	241.11	396.65	384	320

4. Conclusions

This study is focused on the compression behavior of a novel GFRP bar through experimental and theoretical analysis, with the aim of contributing to the experimental database and providing a comprehensive understanding on the variables involved.

An experimental program was planned and carried out to check the new configuration of the GFRP bar to predict the compression mechanical characteristics. The material properties (ultimate compressive strength, compressive loads, modulus of elasticity, and stress-strain relation) for specimens with different diameters were obtained. The experimental results have been compared and discussed. Finally, an analytical discussion on unbraced length has been introduced and evaluated.

After this research, it is possible to affirm that the new tested bars display the correct behavior for compression loads. Although it is possible to optimize compression tests, this study and research recommend their use as internal longitudinal reinforcement in columns, flexural members, and reinforced walls where GFRP bars are subjected to compressive stresses with no loss of other properties. Knowledge of these characteristics helps analyze and design structural reinforced concrete elements with GRP bars.

In addition, this study assumed that bars' elastic modulus in compression is similar to their elastic modulus in tension. The tension and compression behavior of bars are linearly elastic until failure. After a detailed examination of failure modes, some limitations were proposed for using as internal reinforcing in RC structures, which helps the researchers in the design procedure for members reinforced with GFRP bars with safety:

- cross-sectional area: use a minimum diameter of 12 mm for internal longitudinal reinforcement for columns and flexural members.
- slenderness: the maximum distance of stirrups, unbraced length, must be less than 10-fold the bar's diameter, as $L_{\text{recommended}}$ (see Table 8).

This research helps to optimize and standardize the GFRP rebars by maximizing its physical/mechanical performance.

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[1] Combination of crushing and buckling

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