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NEW TESTING METHOD OF GFRP BARS IN COMPRESSION

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Abstract: Although Glass fiber-reinforced polymer (GFRP) bars have been recognized as an alternative for steel bars in concrete structures and there are standard methods for test them in tension, there is no standardized and convenient test method to figure out their compressive characteristics. Due to lack of information on compressive performance of GFRP bars, their contribution in compression is neglected in current design guidelines. This study introduces a new test method for testing GFRP bars in compression. This test method focuses on providing a circumstance under which the evaluation of compressive crushing strength and modulus of elasticity of GFRP bars would be possible without experiencing buckling of bars. A total of fifteen rebar coupons from two different manufacturers were prepared and tested under concentric compressive loading using the proposed test method. The coupons were divided into three groups including five similar specimens in each group. Different bar dimensions and material properties were considered. Two strain gauges were installed on each specimen to capture the strains at the middle height of the GFRP specimens. Moreover, two steel caps were attached to the end of each specimen to avoid premature failure as well as adjusting the alignment of the coupons. The results showed that the compressive modulus, strength, and crushing strains are consistently predicted using the proposed method. Also, the average ratio of compressive to tensile modulus of elasticity, strength, and strain for each group were between 1.02 to 1.09, 0.67 to 0.85, and 0.58 to 0.82, respectively. The results show the strength and modulus of GFRP bars in compression are close to those of in tension. Thus, GFRP bars can sustaining compression loads and ignoring their compressive contribution in concrete members is not reasonable.

1 INTRODUCTION

Glass fiber-reinforced polymer (GFRP) bars have been considered as an alternative to tensile steel reinforcing bars in construction industry. The major advantage of GFRPs over steel material is their corrosion resistance ability which makes it suitable for structural components susceptible to harsh environmental situations. Moreover, the electromagnetic transparency property of GFRPs make them appropriate for structures which operate magnetic resonance imaging (MRI) units. Because of the demand of GFRP bars in practice, there have been many researches on the flexural behavior of concrete beams reinforced with GFRP bars (Alsayed 1998, Ashour 2006, Benmokrane and Masmoudi 1996, Toutanji and Saafi 2000) as well as concrete slabs (El-Salakawy, Benmokrane and Desgagné 2006, Michaluk, et al. 1998), where the bars used as tensile reinforcement. However, there are a few researches on the capability of GFRP bars in compression (Khorramian and Sadeghian 2017, Tobbi et al. 2012, De Luca et al. 2010), mainly because of the doubts about the function of GFRP bars as well as lack of studies on their behavior in compression.

The reason why the demand for using GFRP bars in compression is not as high as in tension is many negative comments and guideline suggestions to neglect their contribution in the load-carrying capacity of structural members (ACI 440.1R. 2015, CAN/CSA S806-12 2012, Fib Bulletin 40 2007). This mainly arise from lack of research in studying the compressive behavior of FRP bars in compression. Another example is De Luca et al. (2010) that tested concentrically loaded concrete columns reinforced with GFRP bars and conclude that the contribution of FRP bars in compression can be conservatively.

However, the neglection of the contribution of FRP bars in compression is too conservative. Researchers showed that the contribution of GFRP bars in compression is comparable to steel (Tobbi et al. 2012) and experimentally observed considerable strains in compressive GFRP bars, which was more than concrete crushing strain (Mohamed et al. 2014, Khorramian and Sadeghian 2017). Therefore, GFRP bars under compressive stresses can be expected to be accepted and demanded for the solutions which requires corrosion resistance and electromagnetic transparency by considering their contribution to the member strength and stiffness.

The questions then would be evaluation of the characteristics of GFRP bars under compressive loads such as their stress-strain curve, ultimate compressive strength, and their crushing strain. The latter can be assessed using a test method for testing GFPR bars in compression. However, there is no standardized test method which evaluate the crushing strain, ultimate strength, and modulus of elasticity of GFRP bars in compressions. Khan et.al (2015) performed an experimental study on tension and compression testing of FRP bars by adapting the method recommended in standard test method for compressive properties of rigid plastics (ASTM D695 2015) by placing two hardened flat steel plates on top and bottom of specimens. However, their focus was mainly on the comparison of compressive characteristics of GFRP and CFRP specimens tested under compression, and it is noted that the mentioned ASTM standard was not designed specifically for FRP bars. Thus, are some gaps in finding a standardized test method to determine the compressive characteristic of GFRP bars. Therefore, this study is designed to propose a new test method for test of GFRP bars in compression.

2 PROPOSED TEST METHOD

Overall, this test method proposes GFRP bar, embedded in adhesive anchors and steel caps at the end, to be tested in a mechanical testing machine under monotonic compressive load up to failure while tracking the load and longitudinal strain. The purpose of designing this test method was to assist researchers and designers to assess compressive strength, modulus of elasticity, and crushing strain of GFRP bars as well as the stress-strain curve for their compression part. One of the features of this test method is the gripping and alignment is done during the process of preparation of test specimen instead of in the testing machine. The steel cap and adhesive anchors function as gripping method by confining the ends of GFRP bars to avoid premature failure and allow them to obtain their full compressive capacity. In addition, the alignment simply can be done when the adhesive anchors are installed using a level, which can avoid excessive bending and premature failure, and increase the accuracy of test results especially longitudinal strains. Testing five specimens, as shown in Figure 1, is recommended for each test condition to record consistent and accepted data sets.

The schematic illustration of the test specimen is presented in Figure 1. The components of test fixture include steel plates, steel rings, and adhesive anchors. The diameter of steel ring suggested to be considered twice the effective bar diameter while its length recommended to be the same as effective bar diameter, as shown in Figure 1. The steel ring must be thick enough not to be yielded or distorted by lateral pressure of adhesive anchors. The steel ring welds to a steel plate with an square cross section with a width equal 4 times the effective bar diameter with a thickness of at least five millimetres or thick enough not to be punched by the GFRP bars under compression loading. The GFRP bar should be 4 times as long as its diameter to give a free length equal to twice of its diameter.

The procedure begins with the preparation of specimens by building steel caps, the welded steel ring to the steel plates, followed by putting GFRP bars in place for first end of specimen while controlling the alignment, and concluded with doing the same for the other end. The ends of GFRP bar must be completely flat and perpendicular to its longitudinal axis. The alignment of specimen must be checked after putting GFRP bar at the center of steel cap and inserting adhesive into steel ring immediately using level the bar is at the center and completely perpendicular to the surface of the steel cap.

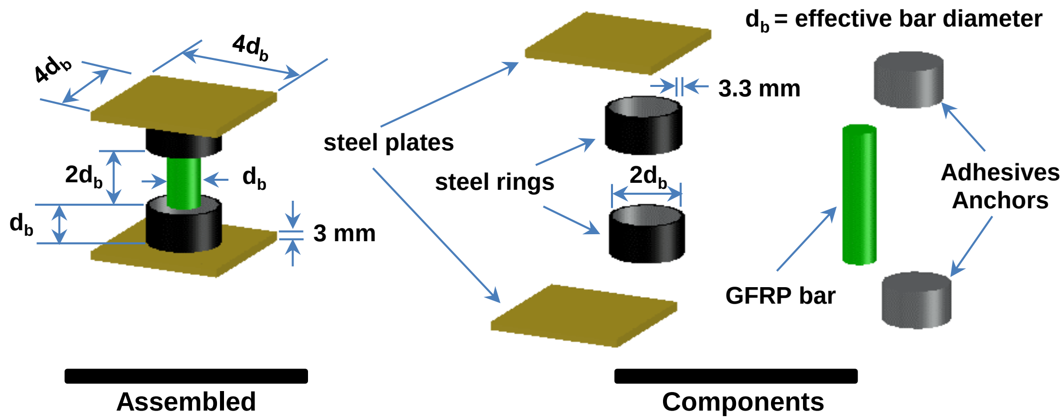

Figure 1: Proposed test fixture

For instrumentation, two strain gauges installed on two opposite sides at the middle of the bar is recommended to record the longitudinal strains. Strain gauges are proper measurement devices for this test set up due to the fact that the free length of bars is very limited, and, from another perspective their accuracy is reliable. The average of two strain gauges is an strong measure of alignment if properly installed. If the difference between the measured strains are not significant, the average value of two strain gauges is considered as longitudinal strain, otherwise, the existing misalignment leads to the creation of bending in bars and test results are not valid.

Once the preparation and instrumentation are done, the specimens can be tested by applying uniform and monotonic compression force. To distribute the load more uniformly to the steel caps, extra steel plates can be added to the ends of the specimens. It is recommended that tests perform using displacement control method with a testing rate that result in conclusion of test in five minutes. The test results are considered as acceptable if no premature failure in caps or buckling in the unbraced length observed. In other words, the tests are successfully performed if crushing of GFRP bars happens at the free length of the specimen.

3 EXPERIMENTAL PROGRAM

In this section, the application of the proposed test method is evaluated through testing three different groups of GFRP bars, differentiating by bar diameter, surface pattern, and manufacturer.

3.1 Test matrix

A total of fifteen GFRP bar specimens with different diameters and material properties were prepared and examined under compression. These specimens divided into three main group consisting five similar specimens. Each specimen is labeled with identification (ID) code as “Gx-y”, where “G” stands for group, “x” represents the group number, and “y” shows the specimen number in each group. The test matrix is presented in Table 1. It is noted that the first group of specimens were tested by Fillmore and Sadeghian

(2018), and the second group were tested by Khorramian and Sadeghian (2017) using the test method explained earlier in this paper. The last group was specifically tested for this paper.

Table 1: Test matrix

No.	Group	GFRP bar number	Nominal bar diameter (mm)	Specimen IDs	Reference
1	G1	#4	13	G1-1, G1-2, G1-3, G1-4, G1-5	Fillmore and Sadeghian (2018)
2	G2	#5	16	G2-1, G2-2, G2-3, G2-4, G2-5	Khorramian and Sadeghian (2017)
3	G3	#6	19	G3-1, G3-2, G3-3, G3-4, G3-5	The current paper

3.2 Fabrication

Figure 3 presents the fabrication steps for the third group of testing specimens. The steel caps as well as the machined surface of all five specimens is shown in Figure 2(a). The specimens were put at the center of steel caps and a fast curing anchoring adhesive was applied and filled the empty space between steel cap and GFRP bar while the bar kept leveled and perpendicular to the cap [Figure 2(b)]. After curing of adhesive for both ends, two strain gauges were installed on the machined surface [Figure 2(c)]. The prepared specimens of G3 group are shown in Figure 2(d). It should be noted that the width of the steel square plate used at the ends of the steel caps were kept 50 mm and the same for all groups (instead of four times effective diameter as recommended earlier).

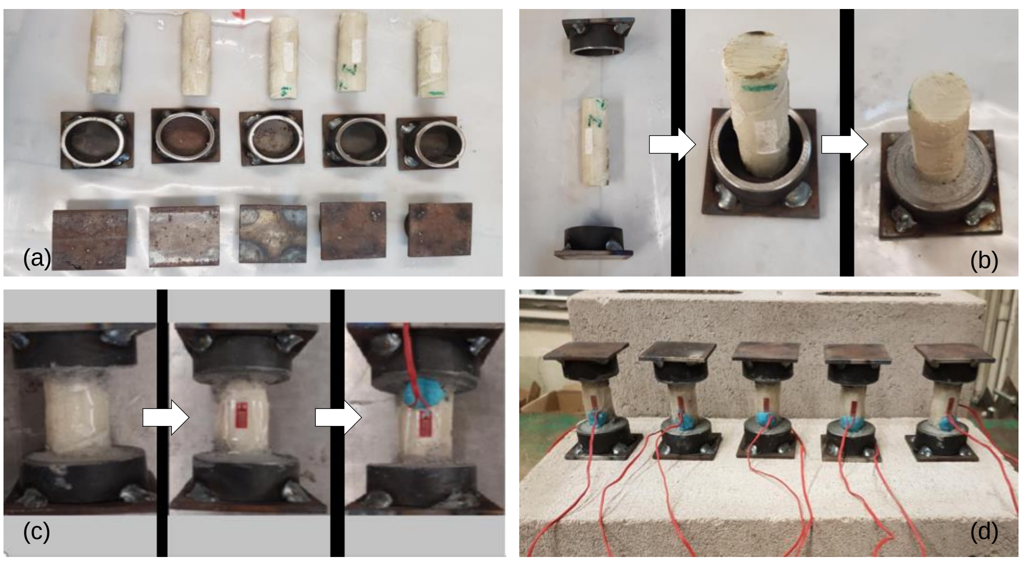

Figure 2: Fabrication of G3 group: (a) specimen components; (b) applying adhesives to bottom end; (c) installation of strain gauges; and (d) prepared specimens

3.3 Test set-up and instrumentation

It is noted that each specimen prepared according to the test preparation mentioned in the proposed test method section. The schematic test set-up and instrumentation is presented in Figure 3(a). To record the strains corresponding to each load step, two strain gauges (namely SG1 and SG2) were installed at the center of the GFRP bar as shown in Figure 3(a). For the sake of preparing the surface of bars for strain gauging, two different approach were used. The first one is to just machine the surface of bar and install the strain gauge directly to the GFRP bar while the second approach is to apply some resin around the center of the GFRP bars and apply the strain gauge on the surface of machined resin instead. In the second approach, it is believed that the cross-sectional area used to calculate the stresses is more accurate. Moreover, in the first approach, by grinding the surface of bar, the probability of hurting specimens by damaging the fibers in GFRP bar due to deeper surface preparation is increased. For group 1 and group 3 the second approach was used to prepare the surface for strain gauging. However, for the specimens in group 2 the first approach was used because of extra sand coat of the bars. As presented in Figure 3(a), the specimen with steel caps sits at the center of a steel plate where the load applies from the top using the loading machine which is presented in Figure 3(b).

To achieve the pure axial state of stress and avoid load eccentricities, a spherical platen was placed in the bottom of the specimens whose function was self centering the specimen in case of accidental eccentricities, as shown in Figure 3(b). In addition, to have more uniform stress in the specimen, two thick steel plates were put at top and bottom of the specimen to distribute the load uniformly at both ends of specimen [Figure 3(b)]. The tests were performed by a universal testing machine, capable of applying 2MN axial load. The loading method was selected to be in displacement increments to give a rate of 0.5 mm/min.

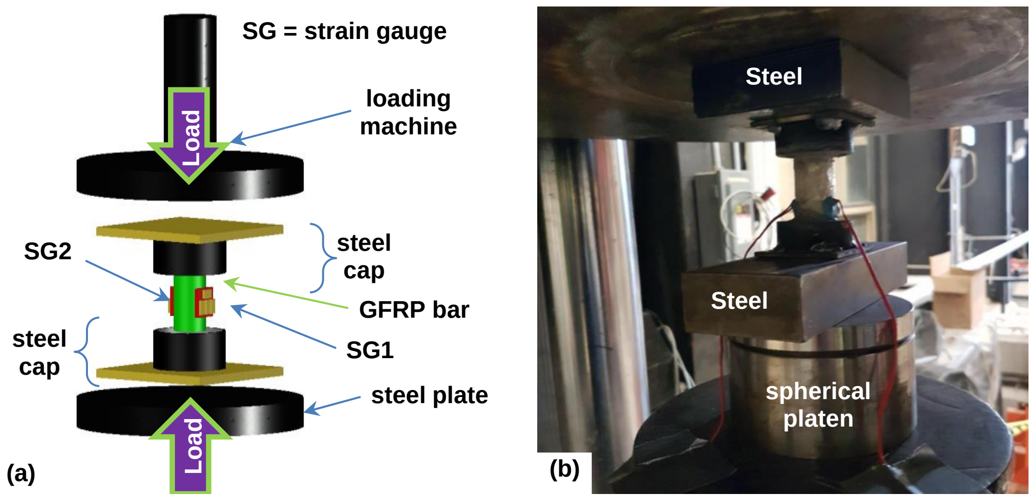

Figure 3: Test set-up and instrumentation: (a) schematic and (b) G3-1 specimen

4 RESULTS AND DISCUSSION

In this section, the results of experimental test data are presented. The modes of failure as well as the stress-strain behavior of GFRP bars tested under pure compression using the proposed test method are presented and a brief discussion and comparison of these compression test results and the tensile characteristics of the same material is presented.

4.1 Failure modes

Figure 4 presented the selected modes of failure of the compression coupons. It is noted that for all specimens no buckling happened before the peak load. The observations during the test showed a noise before reaching to the peak load followed by the crushing of some fibers which happened just before the final crushing of the whole bar and drop in the load. For specimens in group G1, the pattern of failure was like the one shown in Figure 4(a) in which an angled diagonal crushing pattern observed. The test specimens presented in Figure 4(b) except the one that is shown in the figure did not show any observable crushing pattern up to peak load, although their strains and peak loads were similar to the one in Figure 4(b). For specimens in group G3, the crushing pattern was still in the GFRP bar and not in the steel caps as shown in Figure 4(c).

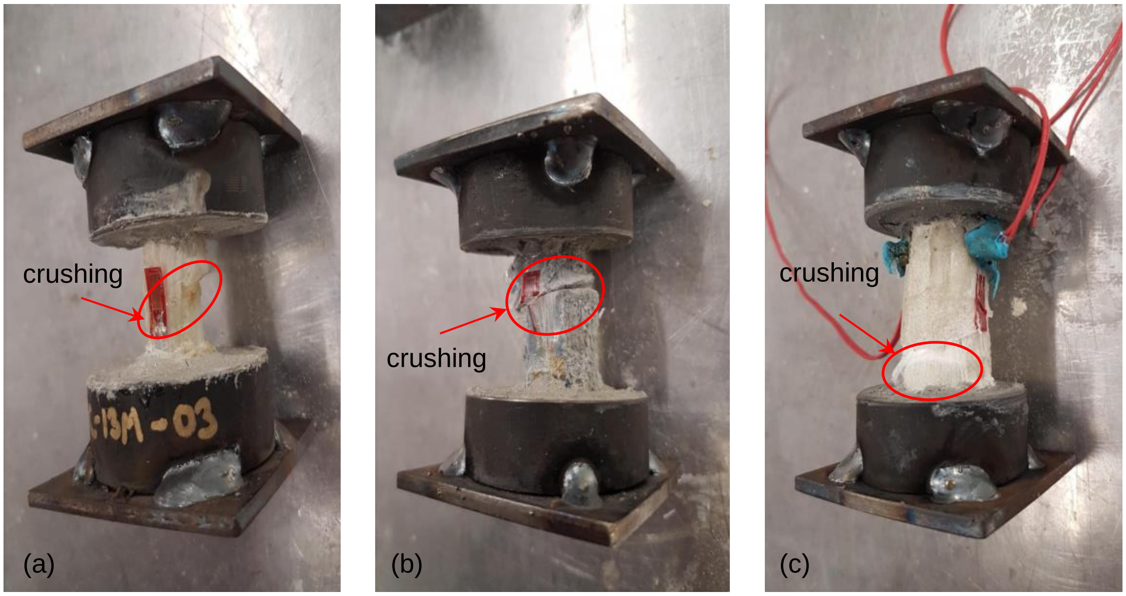

Figure 4: Selected failure of test specimens: (a) G1; (b) G2; and (c) G3

4.2 Stress-Strain Behavior

The stress-strain of relationship of tested specimens for G1 and G2 groups are presented in Figure 5. All specimens experienced a linear stress-strain relationship up to some stage called “proportional limit” in this paper. In other words, if the specimens experience nonlinear behavior (i.e. G2 group), the proportional limit is defined as the point at the beginning of nonlinear part, as shown in Figure 5. For specimens in G1 group, no nonlinear part was observed, however, for G2 and G3 groups a nonlinear part derived by dividing the stroke displacement by a proper gauge length. The gauge length found by setting the slope of stress strain curve derived from stroke equal to the one obtained by the strain gauge [Figure 5(b) and Figure 5(c)]. The average compressive strength, modulus of elasticity, and crushing strain for G1 group was reported by Fillmore and Sadeghian (2018) as 559.03±35.54 MPa, 45.5±1.5 GPa, and 0.0122±0.0012 mm/mm, respectively, while for G2 group, these values were reported by Khorramian and Sadeghian (2017) as 534 MPa, 42.2±1.2 GPa, and 0.0133 mm/mm, respectively, for the graphs up to proportional limit. The average ultimate strength and strain of G2 groups were 738±74 MPa and 0.0190±0.0017 mm/mm, respectively. For the third group, due to some errors in data acquisition system, the first two specimens were failed, however, the rest of specimens showed a modulus of elasticity, proportional compressive strength, and proportional compressive strain of 49.3±0.84 GPa, 645 MPa, and 0.013 mm/mm, respectively, while the ultimate strength and ultimate crushing strain were obtained as 688.8±38.9 MPa and 0.0140±0.0010 mm/mm, respectively. The calculation of modulus of elasticity was done using the portion of the data between the strains of 0.001 mm/mm and 0.003 mm/mm to be compatible with the procedure used for defining the tensile modulus of elasticity of GFRP bars (ASTM D7205 / D7205M - 06 2016). It should be noted that the values of stress strain curves for both G1 and G2 groups are very similar which shows the tests were consistent in terms of main characteristics such as linearity of stress strain curve up to the proportional limit and the prediction of strength and strain corresponding to the proportional limit. For this study, the proportional limit is found using the average of linear parts which was coincidence with the break of strain gauges, as shown in Figure 5. The proportional limit can be studied in further investigations to find a proper criterion for defining this limit and proposing a method to find it.

The tensile strength, modulus of elasticity and rupture strain of GFRP bars for G1 group (Fillmore and Sadeghian, 2018) were reported as 839±49 MPa, 44.2±1.7 GPa, and 0.0209±0.0021 mm/mm, respectively, by performing tensile tests on five coupon specimens, and the same values for G2 group (Khorramian and

Sadeghian, 2017) were 629±30 MPa, 38.7±1.5 GPa, and 0.0162±0.0011 mm/mm, respectively. The ratio of strength, modulus of elasticity, and strain at proportional limit in compression to the corresponding values in tension are 0.66, 1.02, and 0.58, respectively for specimens in G1 group while these values are 0.85, 10.9, and 0.82 for specimens in G2 groups. It should be noted the tensile test has not been performed for the third group of specimens due to time limitations.

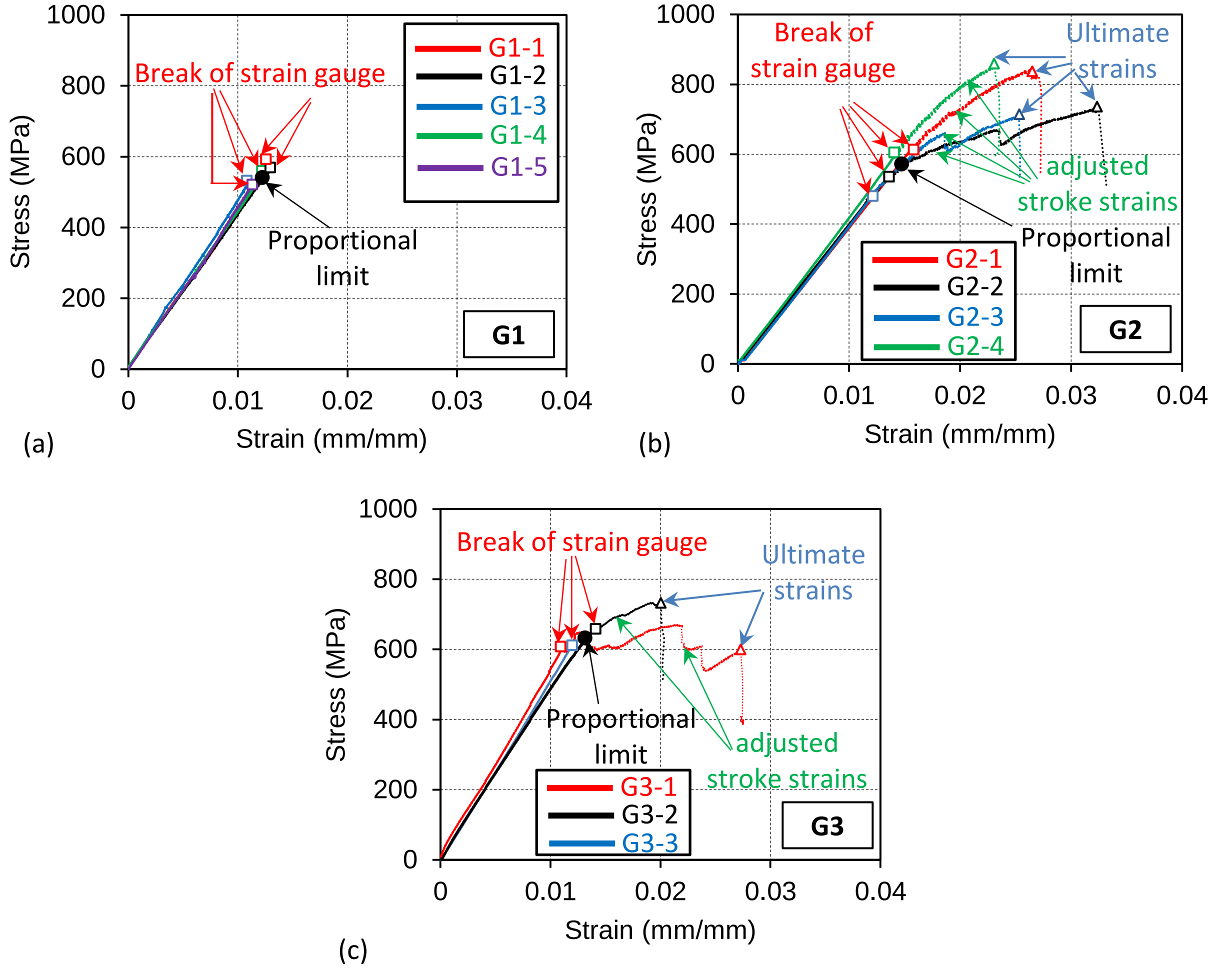

Figure 5: Stress-strain behavior of compressive test specimens: (a) G1; (b) G2; and (c) G3

Overall, these tests showed slightly higher modulus of elasticity in compression and tension, by comparing the results of compressive to tensile tests. However, if the guaranteed tensile characteristics of bars reported by the manufacturer is used for the sake of comparison, the ratio of modulus of elasticity obtained from compressive test of bars to the tensile guaranteed modulus of elasticity (α ratio) will be between 0.99 and 1.07, as presented in Figure 6(c). The compressive strength and strains at the proportional limit were comparable to the tensile corresponding values that emphasizes the potential demand of GFRP bars in compression and the required standardize test method to evaluate their compressive characteristics. The guaranteed tensile characteristics of the tested GFPR bars which were reported by the manufacturer are shown in Figure 6. It was observed that the ratio of compressive strength at the proportional limit to the tensile guaranteed strength (β ratio) is varied between 0.57 to 0.93, and the ratio of the ultimate compressive strength to tensile guaranteed strength (γ ratio) varies between 0.74 to 1.

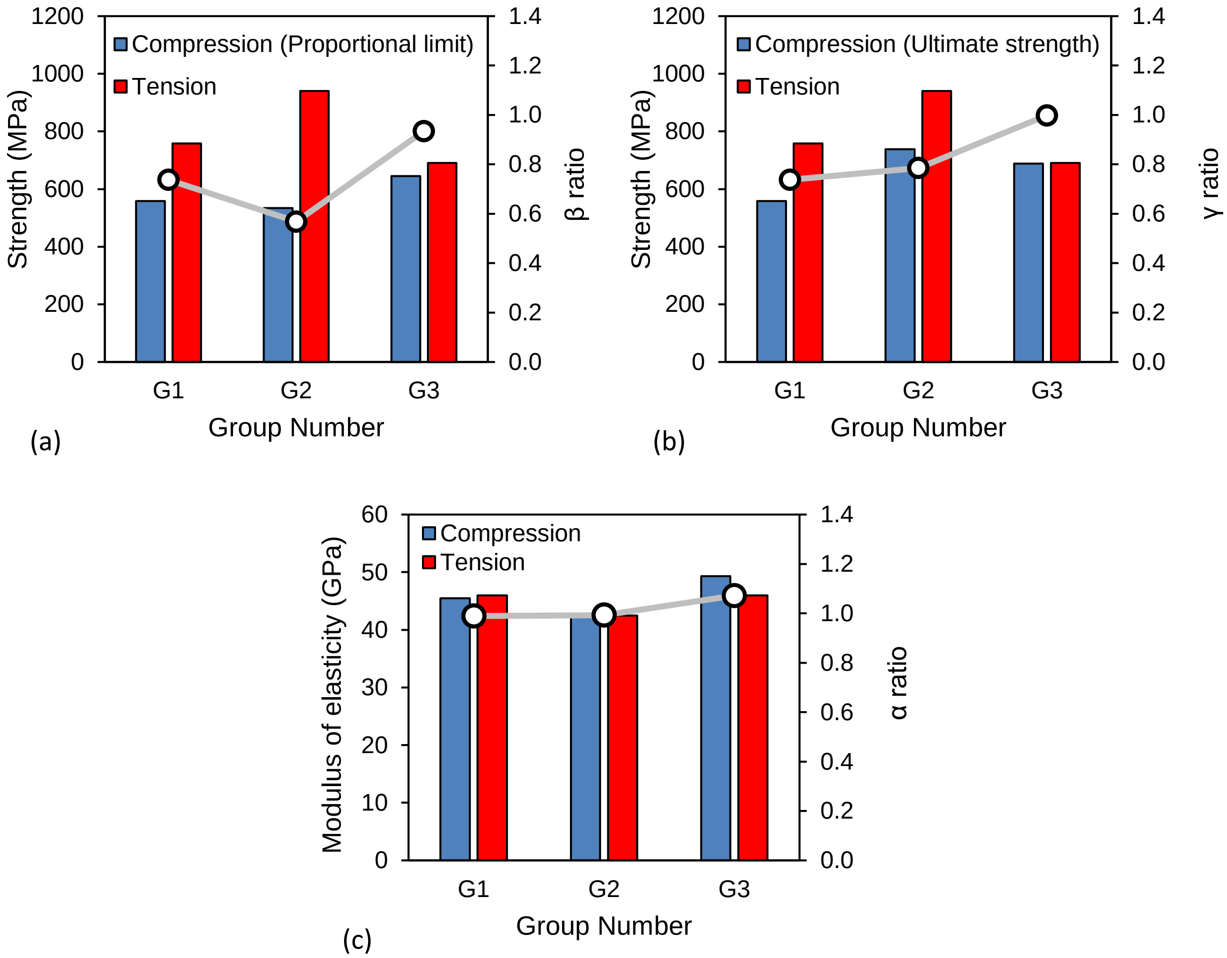

Figure 6: Tensile and compressive characteristics: (a) comparison of strength based on proportional limit; (b) comparison of strength based on ultimate strength; and (c) comparison of modulus of elasticity

5 CONCLUSION

This study proposed a test method for evaluation of the characteristics of GFRP bars tested in compression by providing a condition to avoid the buckling failure mode in bars and obtain crushing mode of failure. The test method suggested in this paper, applied to three set of specimens each of them including five identical specimens. The test groups enable the examination if the test method for GFRP bars with diverse diameters and produced by different manufacturers. The results showed a linear stress-strain relationship of the GFRP bars in compression up to a limit called the proportional limit in this study. The test results were consistent and determined the strength, modulus of elasticity, and the proportional limit or the effective compressive strain of the GFRP bars. The test method has the potential to be improved by introducing a procedure to find the proportional limit. Moreover, the ratio of compressive to tensile strength, modulus of elasticity, and strain for average of tested groups were between 0.66 to 0.85, 1.02 to 1.09, and 0.58 to 0.82, respectively, if the real tensile test results were considered. However, the ratio of compressive modulus of elasticity, proportional compressive strength, and ultimate compressive strength to the corresponding tensile values reported by the manufacturer were between 0.99 to 1.07, 0.57 to 0.93, and 0.74 to 1, respectively. Overall, test results showed that the compressive material properties for GFRP bars are comparable to the tensile properties which strengthened the need for an standardized test method for assessing these properties and showed the potential increase in demand for compressive GFRP bars. Thus, GFRP bars can sustaining compression loads and ignoring their compressive contribution in concrete members is not reasonable.

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