Engineering Science

GFRP Bars in Structural Design: Determining the Compressive Strength versus Unbraced Length Interaction Curve

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To mitigate the durability issues arising from steel reinforced structures, current research in the structural engineering field has been focused on the feasibility of replacing steel with corrosion resistant materials. A promising alternative has been glass fibre reinforced polymer (GFRP) bars as internal reinforcement. While extensive testing has certified that GFRP bars perform adequately as tensile reinforcement, structural design codes have yet to adopt provisions for its implementation as compressive reinforcement. Quantifying the compressive behaviour of GFRP bars – the relationship between strength and unbraced length, as well as the modulus of elasticity – is the first step toward developing code provisions.

This experimental program consisted of 34 specimens of 25M GFRP bars tested under direct compression; the lengths of the specimens were varied to establish the relationship between length and strength. A pure crushing failure with an ultimate compressive strength of 730 MPa was observed for all specimens under the nominal unbraced length of 230mm. Longer specimens failed through a global buckling of the bar, with ultimate compressive strength decreasing with increasing unbraced bar length. The average compressive modulus of elasticity was determined to be 60 GPa.

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Les structures renforcées par l'acier risquent souvent de manquer de durabilité. Pour minimiser ce risque, des études actuelles dans le domaine de l'ingénierie des structures se focalisent sur la possibilité de remplacer cet acier avec des matériaux qui sont plus résistants à la corrosion. Une nouvelle option possible pour renforcer les structures est le polymère renforcé de fibre de verre (PRF). Malgré le fait que les barres en PRF performent systématiquement de façon adéquate comme renforcement extensible, elles n'ont pas encore été adoptées par les codes de construction comme renforcement contre la compression. Pour pouvoir utiliser les barres en PRF selon le code, il faudra quantifier leur comportement lorsqu'elles sont soumises à la compression, soit la module d'élasticité et la relation entre leur force et leur longueur.

Ce programme expérimental comporte 34 exemplaires de barres PRF de 25M, sans support externe, qui ont été testés sous compression direct. La longueur des exemplaires varie pour mieux établir la relation entre longueur et force. Un échec total à cause de la compression après 730 MPa a été observé pour tous les barres en dessous de 230 mm. Les barres qui étaient plus longues que 230 mm se sont déformées sous compression; globalement, la résistance à la compression a diminuée lors de l'augmentation de la longueur de la barre. La moyenne de compression élastique a été déterminée à 60 GPa, selon les dimensions données par l'équipement utilisé au début de chaque essai. Cette valeur est identique à la moyenne publiée pour les barres sous tension.

Introduction

Reinforced concrete is a building material traditionally consisting of steel bars embedded in concrete members. While both concrete and steel are effective building materials in their own right, their combination allows for unparalleled versatility, resulting in final structures that are both stronger and cheaper than would have been possible utilizing solely one material. The major limitation in using reinforced concrete for outdoor structures is the eventual corrosion of the steel bars – weakening the structure and increasing the potential for failure. It is estimated that in Ontario there are currently over 10,000 bridges classified as structurally deficient due to steel corrosion, with repairs estimated to cost $57 billion[1].

As a replacement for steel, glass fibre reinforced polymers (GFRP) offer a potential solution to the durability issue in exposed structures. GFRP has been proven to be corrosion resistant, and recent research in the field has been focused on determining its overall performance as a structural reinforcement. Large scale testing has yielded positive results, allowing for the inclusion of GFRP in the Canadian building code through the CSA S806 (Design and Construction of Building Structures with Fibre-Reinforced Polymer) and CSA S6 (Canadian Highway Bridge Design Code)[2,3]. The most recent edition of this standard, published in 2012, allows GFRP to be used with less conservative design assumptions. However, the application of GFRP as compressive reinforcement is still deemed unsafe in the codes, as the strength and stiffness of GFRP bars under compression is not well understood[2]. In 2013, Tavassoli et al. tested 9 columns internally reinforced with GFRP bars under cyclic loading and demonstrated that the columns had significant strength and ductility. Failure was initiated by the compressive crushing of concrete, followed by the crushing of the longitudinal reinforcement (Figure 1). While this revealed the overall capabilities of GFRP bars as compressive reinforcements in columns, the failure mechanics within the bars themselves were still unknown. There is no American Society

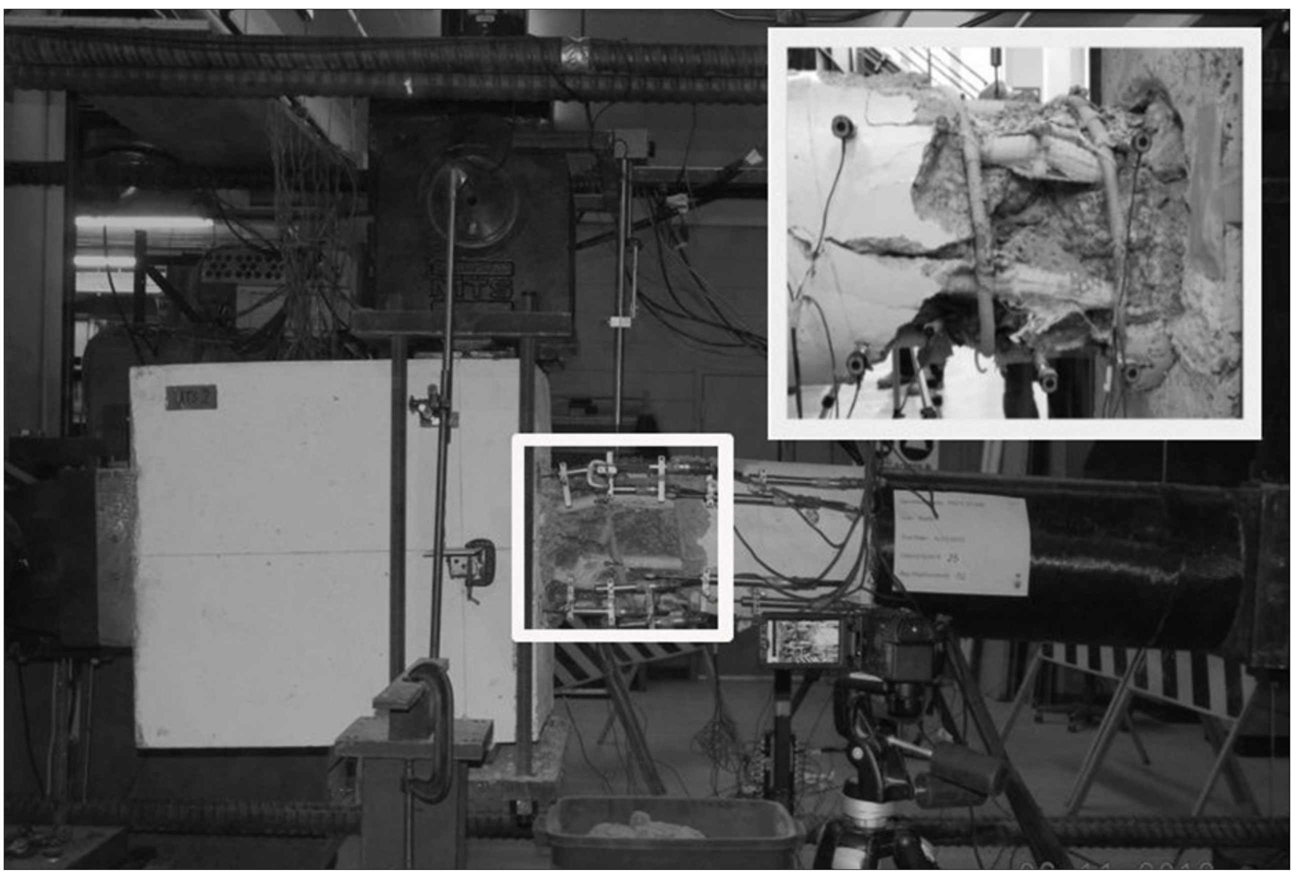

Figure 1. Test setup for concrete column internally reinforced with GFRP and close-up of the compressive failure region.

for Testing and Materials (ASTM) standard that addresses the compressive strength of bars, nor is there any conclusive published data on the subject[5]. Since the unbraced length of the longitudinal bars may vary in a column depending on the spiral/stirrup spacing chosen by the designer, it is essential to establish the relationship between compressive strength and unbraced length for these bars (Figure 2).

This project was undertaken to establish a consistent and repeatable experimental method for testing GFRP bars under direct compression. The goal was to determine the compressive modulus of elasticity of the bar and the effect of bar length on strength and failure modes. It was expected that shorter bars could be crushed with a constant load up until theyexperienced buckling and thus failed at a lower load. Establishing the strength vs. bar length curve is a necessary first step if the GFRP design codes are to be modified to allow the use of GFRP bars as the compressive reinforcement.

Materials and Methods

The same fabrication and testing procedure was used for each specimen, the only variables in the process being the length of the specimen and the loading rate during testing. All specimens were cut from 3 m long 25 mm diameter GFRP bars, manufactured in the same batch to ensure uniform material properties.

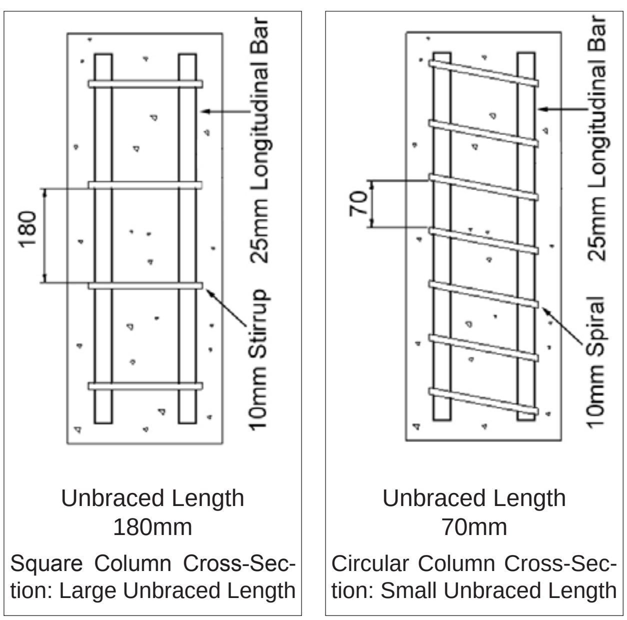

Figure 2. The unbraced length of the longitudinal reinforcement varies depending on the design

The specimen preparation and testing followed these steps (Figure 3):

1. Individual specimen lengths were measured and marked.
2. Specimens were cut to size using a fiber saw blade.
3. Ends were made perpendicular with a rotating lathe.
4. For strain gauge placement, two points on opposite ends of the bar were filed down.
5. Strain gauges were glued to the bar on the smoothed surface.
6. Specimens were placed in the testing apparatus grip.
7. Strain gauges were hooked up to machine, and the loading rate was determined.

For consistent and repeatable results, the loading rate chosen in step 7 was important. For tensile tests, the loading rate was generally specified around 400 MPa/min, so that failure occured before 10 minutes[6]. Since the compressive behaviour was relatively unknown, this experimental program used a loading rate of about 100 MPa/min.

Results

The Relationship Between Strength and Bar Length

The experiment consisted of 34 individual compression tests on GFRP bars. The length of the specimens varied from 50 mm to 600 mm, capturing the wide range of potential unbraced lengths used in design. Two or more specimens were tested at every length and their strength values were averaged. Figure 4 plots all individual test results plotted, with unbraced length (mm) on the x-axis and strength (MPa) along the y-axis. It is important to note that each data point at lengths of 300 mm and greater consists of 3 separate tests that yielded overlapping results. Averaging the three test results at each length yields a less cluttered graph, simplifying future interpretation of the data (Figure 5). A pure crushing failure with an ultimate compressive strength of 730 MPa was observed for all specimens under the nominal unbraced length of 230mm. Longer specimens failed through a global buckling of the bar, with ultimate compressive strength decreasing with increasing unbraced bar length.

Modulus of Elasticity

Critical to understanding the compressive behaviour of the GFRP bars was the relationship between strain (change in length/initial length) and stress (force per unit area), known as the modulus of elasticity.

Every specimen was equipped with gauges to measure incremental changes in length and a cell to measure the applied load. The compressive modulus of elasticity could thus be determined. Since the modulus is a material property, it is independent of the specimen's length (Figure 6). The average compressive modulus of elasticity was determined to be 60 GPa, based on measurements provided by gauges during the initial part of each test. This value is identical to the reported nominal modulus in tension.

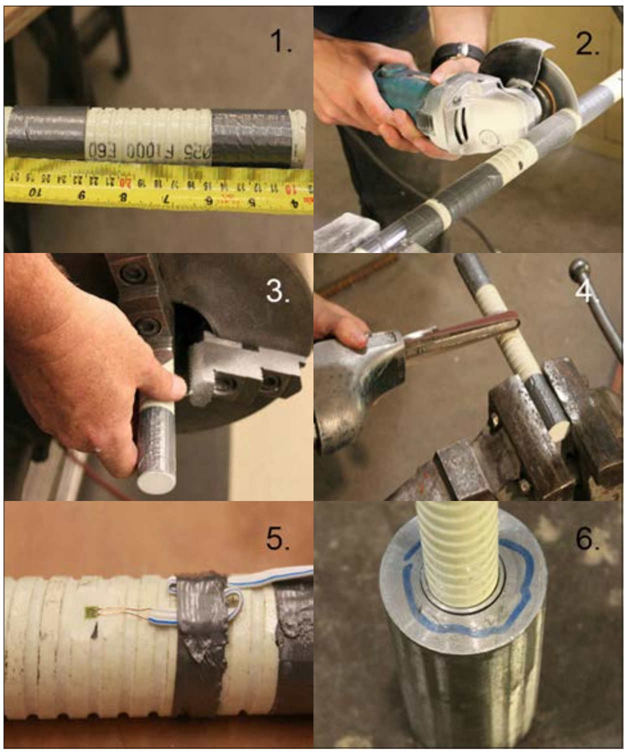

Figure 3. Specimen Preparation Procedure.

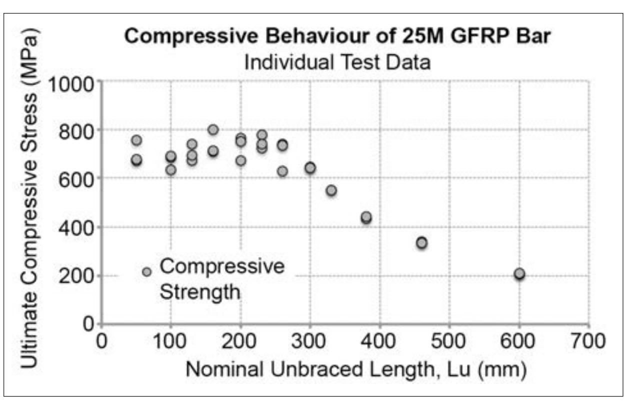

Figure 4. Results for 34 direct compression tests performed on 25M GFRP bar.

Crushing and Buckling Failure

Two distinct failure modes were observed during the test program. While the exact relationship between unbraced length and failure mode requires further analysis, it was clear from testing that short specimens failed by crushing while longer specimens failed by buckling. Crushing failure was reached at the constant upper bound test strength of the bar, approximately 730 MPa, represented by a plateau in the strength for the shorter specimens (Figure 5). In general, crushing failure consisted of a linear stress-strain response up until failure. Both gauges, on opposite sides of the bar (named East and West), provided almost equal strain values since loading was concentric throughout the bar. Bar crushing can be visually described as a pancaking of the fibers at the point of failure (Figure 7).

Buckling failure occurred in the longer specimens with failure strengths inversely proportional to the

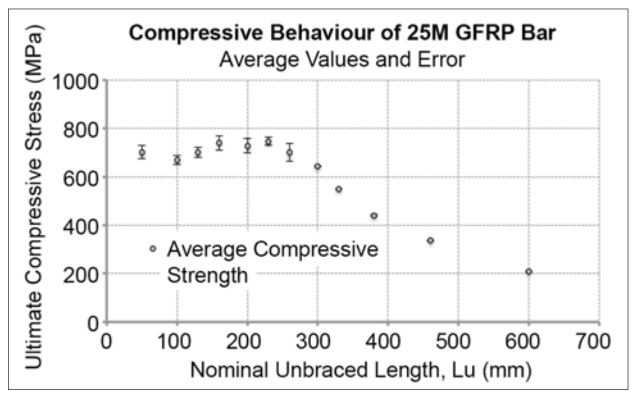

Figure 5. Averaged test results including experimental scatter.

Bar #	Used to Make Test Specimen #	Average Compressive Modulus (Gpa)
1	10,11,12,22,27	58.20
2	23,24,25,26	65.28
3	28,29,30	67.07
4	31,32	56.45
5	33,34	57.65
6	13,14,15,16,17,18,19,20	58.45
7	1,2,3,4,5,6,7,8,,21	55.86
		59.85

Figure 6. Link between the coupon specimens and the GFRP bars, along with average compressive modulus of elasticity.

length of the bar. The downward sloping curve in the averaged data graph is consistent with the decreasing strength associated with buckling (Figure 5). Buckling consisted of a similar linear stress-strain curve as was seen in crushing, up until about 75% of the failure load, at which point the strain gauges started to deviate due to the overall buckling of the bar. The failure can be visually described as global bending of the specimen, leading to the rupture and delamination of parts of the bar. (Figure 8)

Discussion

The results indicate that a crushing strength of approximately 730 MPa is reached before failure in the GFRP bars tested during this program. A precise answer cannot be determined based solely on testing, since crushing failure is inherently prone to deviation in the results due to the nature of the material. Small imperfections at the ends of the specimen and deformations along the length of the bar will lead to different strengths in every bar. The machining of the

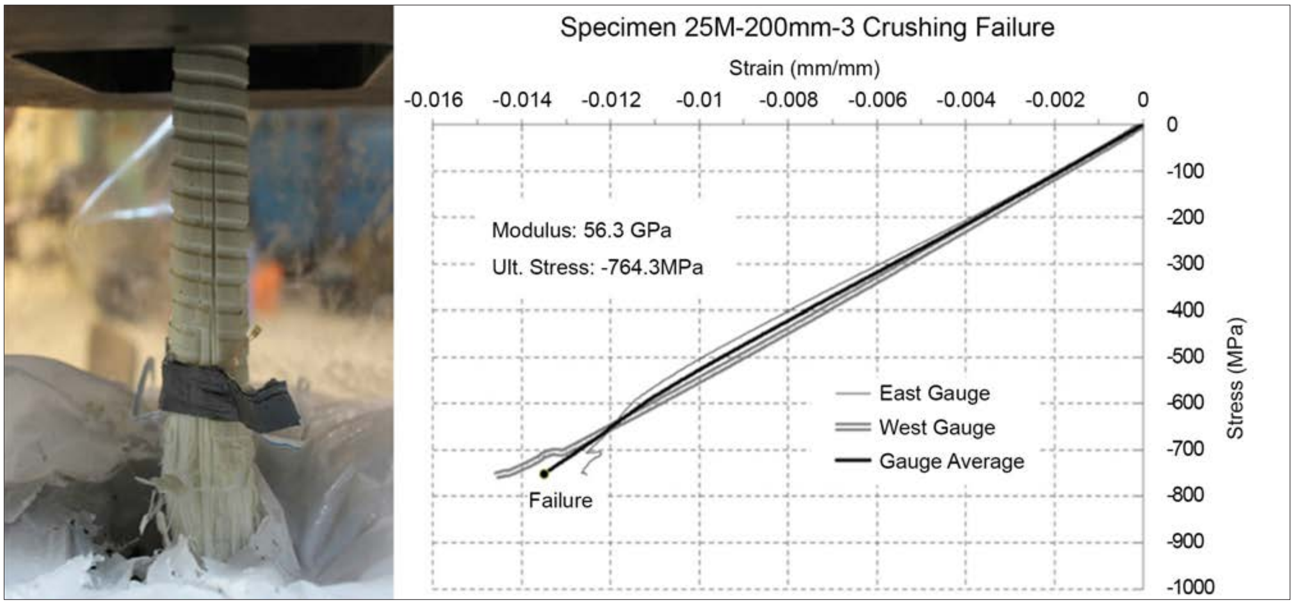

Figure 7. Stress-strain graph and photo of a 200mm specimen failing by crushing.

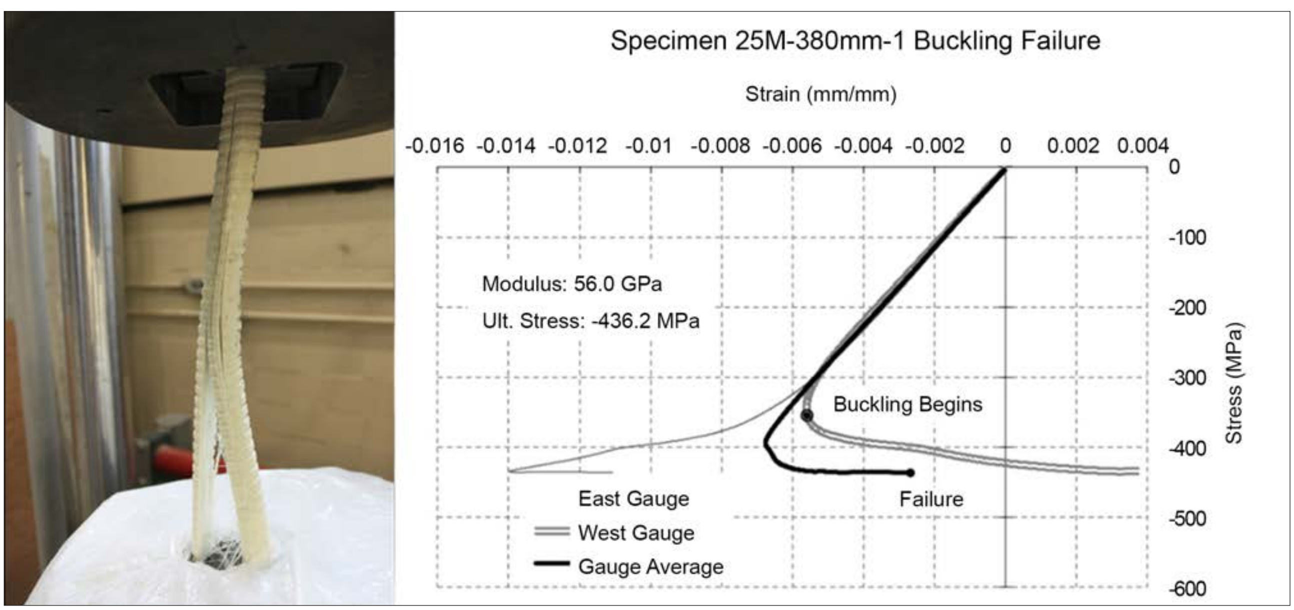

Figure 8. Stress-strain graph and photo of a 380mm specimen failing by buckling.

specimen ends, however, has reduced the scatter of the data, which was less than ±25 MPa as shown by the data displayed in Figure 5.

The Mechanics of Buckling Failure

While crushing is a localized failure mode, related to the material properties of the fiber and resin at the exact point of failure, buckling involves the response of the bar as a whole. The response can be modeled by Leonhard Euler's theory of elastic buckling developed in 1757, which predicts the load a homogenous column can sustain[6].

$$F = \frac{\pi^2 EI}{(kl)^2}$$

Where:
F = Maximum load at buckling
E = Modulus of elasticity
I = Area moment of Inertia
k = Column effective length factor (based on end conditions)
l = Unbraced length

While this formula is not completely accurate for GFRP, since the latter is not a homogeneous material, it is an adequate approximation. Figure 9 illustrates the clear relationship between the experimental buckling results and the theoretical Euler buckling load calculated by using k = 0.6, justifying the use of this formula.

Strength and Unbraced Length Curve

While the distinction between crushing and buckling is simple to make, at short and long specimens respectively, there is certain ambiguity to the failure experienced in specimens of medium length. This region is known as the transition failure region and consists of a combination of buckling and crushing failure modes. Therefore, predicting the strength in this region is difficult, since it is neither constant like crushing or fitted to a curve like buckling. Based on empirical results, the transition zone follows a decreasing linear trend line (Figure 10).

The complete interaction curve illustrates the three different failure modes, and the predicted strength at each length based on a derived experimental trend line. Specimens shorter than 230 mm (l/d = 9.2) are expected to fail by crushing at 730 MPa, while specimens longer than 315 mm (l/d = 12.6) are expected to fail by buckling at the theoretical Euler buckling load. Between 230 mm and 315 mm (l/d = 9.2 and l/d = 12.6), transition failure is expected, where the strength can be determined from the trend line.

Based on these results, it can be stated that for 25 mm diameter GFRP bars with E ~ 60 GPa subjected to monotonic loads, unbraced lengths shorter than 230 mm (l/d ~ 9.0) will result in crushing of the bars. Lengths larger than 230 mm (l/d > 9.2) will result in either unpredictable transition failure or weaker buckling failure.

Future Directions

The test method and results derived from this research are comprehensive enough to lay the groundwork for future research on the compressive behaviour of GFRP bars. For consistency, future work may employ the same methodology and experimental program but use bars of different sizes and different types. While this paper presents the response of a 25mm diameter bar, it is still necessary to determine if the same response will be observed in bars of other

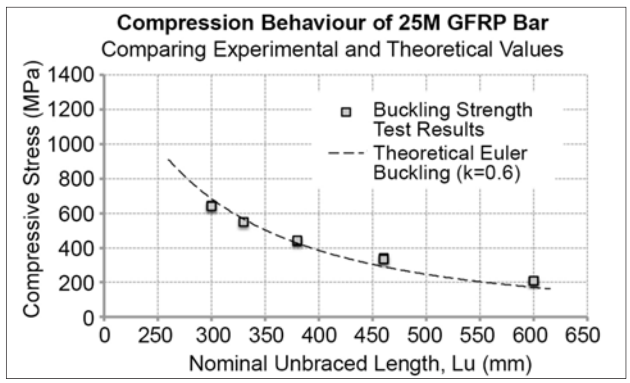

Figure 9. Comparing the Experimental Results with the Theoretical Euler Buckling Loads (k=0.6)

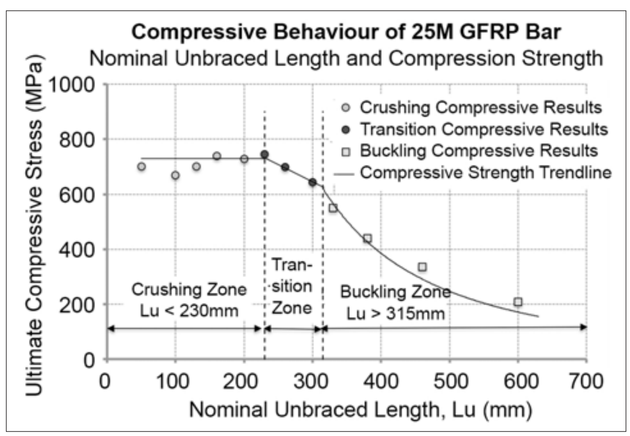

Figure 10. Complete Strength and Unbraced Length Interaction Curve

sizes. The different curves for all bar sizes can then be integrated to create a general compressive strength interaction curve to be implemented in design procedures. Also, the behaviour in the transition zone was not rigorously examined in this experimental program. Further tests should be performed on specimens with l/d ratios between 9 and 13 to ascertain the strength associated with this failure mode.

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Abbreviations

GFRP	Glass Fibre Reinforced Polymer
MPa	Mega Pascal
GPa	Giga Pascal
mm	Millimeter
CSA	Canadian Standards Association
ASTM	American Soceity for Testing and Materials

Keywords

Compression; GFRP bars; Crushing; Buckling; Unbraced

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Review of *GFRP Bars in Structural Design: Determining the Compressive Strength versus Unbraced Length Interaction Curve*

The paper presents results from a study carried out by Edvard Bruun for his undergraduate thesis as part of the B.A.Sc. degree requirements. The experimental program consisted of testing 34 GFRP bar coupon specimens under pure compression. The test series was planned to focus on the effect of unsupported length on the properties of GFRP bars in compression. The bar type and size were kept constant and the test procedure was carefully designed to eliminate all other parameters such as rate of loading, so that the only variable between different specimens was the unsupported length. The length to diameter ratio of bars varied between 2 and 24. Tensile properties of the bars were known from a parallel test series. The tests were carried out in triplicate in most cases and scatter between similar tests was minimal. For example, the scatter for bar stress was less than 25 MPa while the strength of bars was as high as 800 MPa.

Results from the tests displayed three failure zones for bars: crushing for bars with length/diameter ratio less than 9.0, buckling of bars with l/d larger than 12.6 and transition zone for bars with l/d between about 9.0 and 12.6. Crushing strength of bars was higher than 60% of their tensile strength in most cases and the modulus of elasticity was similar in tension and compression and equal to about 60,000 MPa. The buckling phase of the bar behaviour seems to be well-represented by the classical Euler's formulation with the effective length factor of 0.6 for all the specimens.

This work presents a well-instrumented and meticulously carried out test program and makes a significant addition to the limited database available on the subject. It will also be valuable in modelling the properties of GFRP bars in compression for use in design procedures for GFRP-reinforced concrete structures.

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