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GFRP BARS AS COMPRESSIVE REINFORCEMENT IN EXPOSED STRUCTURES

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ABSTRACT

This paper presents the development of a repeatable and consistent test procedure for further research into the compressive behaviour of GFRP reinforcement bars. The findings demonstrate the material strength in compression, to further the use of GFRP as longitudinal reinforcement in structural bridge columns. In this application, the highest load capacity was observed when the stirrup spacing limited the un-braced length of the longitudinal reinforcement – leading to crushing of the bars as the primary failure mode.

The experimental program consists 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 un-braced length of 230mm. Longer specimens, with a nominal un-braced length larger than 315mm, failed through a global buckling of the bar, with ultimate compressive strength being an inverse function of the un-braced bar length. The average compressive modulus of elasticity was determined as 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.

1. INTRODUCTION

1.1 Reinforced Concrete and the Problem of Corrosion

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.

While effective, the major limitation in using reinforced concrete for outdoor structures is the potential 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 (Ministry of Infrastructure, 2012).

1.2 Glass Fibre Reinforced Polymers in Design Standards

To mitigate the durability issues arising from corrosion in steel reinforced concrete bridges, a promising alternative for new projects has been the use of glass fibre reinforced polymer (GFRP) bars as internal reinforcement. As GFRP has been proven to be corrosion resistant, 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 implementation of GFRP in the Canadian building code through the CSA S806 standard – Design and Construction of Building Structures with Fibre-Reinforced Polymer and CSA S6 Canadian Highway Bridge Design Code (CSA, 2006 & 2012).

The most recent edition of this standard, published in 2012, reflects the engineering community's growing understanding of the material, allowing GFRP to be used with less conservative design assumptions (CSA, 2012). 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. For example, Clause 8.4.3.1 in CSA S806-12 states that longitudinal GFRP reinforcement may be used in concrete members experiencing compression, but the strength and stiffness of GFRP bars in compression shall be ignored in design (CSA, 2012).

To determine if GFRP bars can act as adequate compressive reinforcement, 9 columns internally reinforced with GFRP bars were constructed and tested under cyclic loading in the University of Toronto's structural laboratory. The test results, published by Tavassoli in 2013, showed significant strength and ductility in the columns, with failure initiated by the compressive crushing of concrete followed by the crushing of longitudinal reinforcement (Figure 1). These results justify the need for further revisions to the code, allowing GFRP in compression to be included in structural designs (Tavassoli, 2013). Quantifying the compressive behaviour of GFRP bars – the relationship between strength and un-braced length, as well as the modulus of elasticity – is the first step in furthering the use of this material.

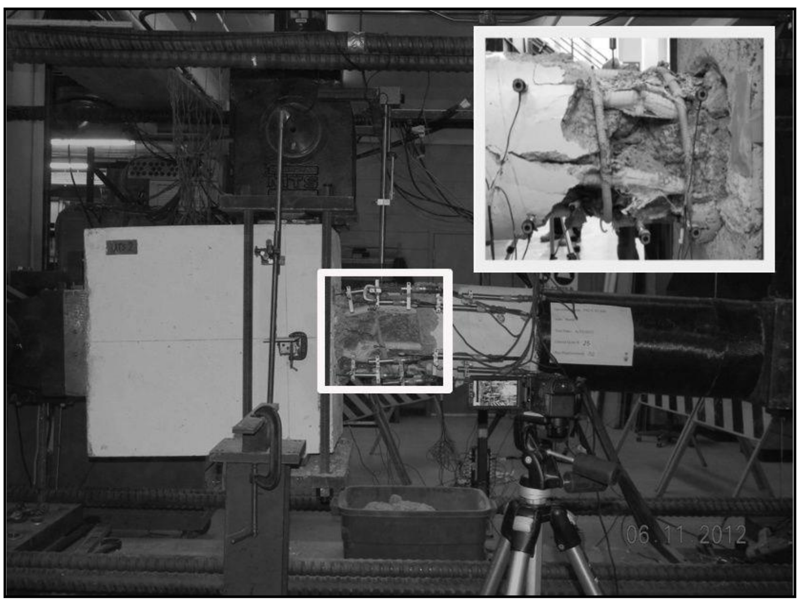

Figure 1. Test setup for concrete column internally reinforced with GFRP and close-up of the compressive failure region (Tavassoli, 2013).

2. TESTS

While the full-scale column tests revealed the overall capabilities of GFRP bars as compressive reinforcement in columns, there is still significant ambiguity as to the failure mechanics within the bars themselves. There is no American Society for Testing and Materials (ASTM) standard that deals with determining the compressive strength of bars, or conclusive published data on the subject beyond the exploratory work conducted by the United States Federal Highway Administration (Deitz et. al., 2003). Since the unbraced length of the longitudinal bar varies in a column, depending on the spiral/stirrup spacing chosen by the designer, it becomes essential to have a compressive strength versus unbraced length behaviour established for these bars (Figure 2).

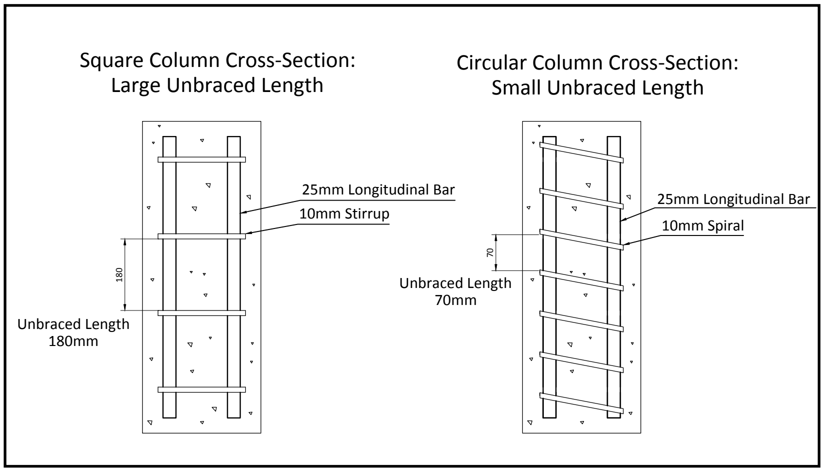

Figure 2. Unbraced Length varying as Stirrup/Spiral Spacing changes

This experimental program was undertaken to establish a consistent and repeatable experimental method for testing GFRP bars in direct compression. The goal is to employ this method to determine the compressive modulus of elasticity of the bars and how the ultimate strength and failure modes change as the bar length varies. It is expected that at smaller lengths, the bar will be crushing at a constant load up until a point where the bar experiences buckling and hence fails at a lower load. Having the strength vs. bar length curve available 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.

3. RESULTS

The experimental test program 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. To minimize experimental error and to obtain consistent results, two or more specimens were tested at every length investigated and their strength values averaged. The following graph shows all individual test results plotted, with unbraced length (mm) on the x-axis and strength (MPa) along the y-axis (Figure 3). It is important to note that test results at lengths of 300 mm and greater appear to be just a single data point on the graph. They are in fact 3 separate tests that yielded such consistent results that they are effectively overlapping data points. Averaging the three test results at each length yields a less cluttered graph, simplifying future interpretation of the data (Figure 4).

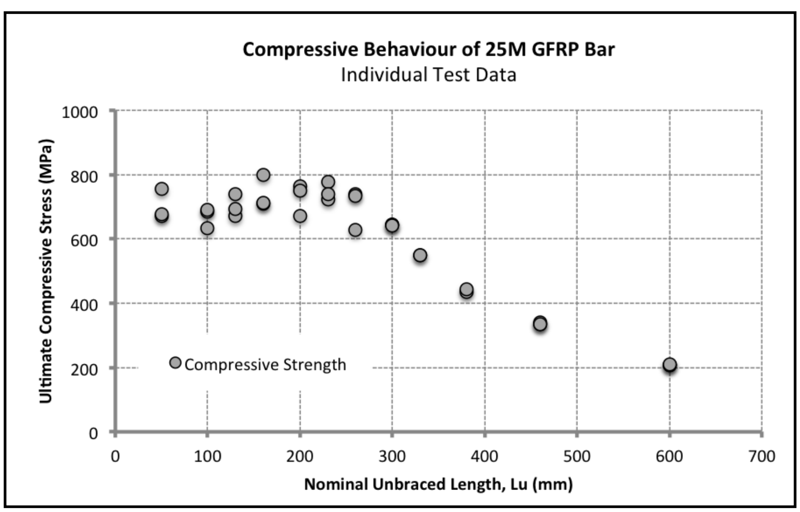

Figure 3. Individual compression test results

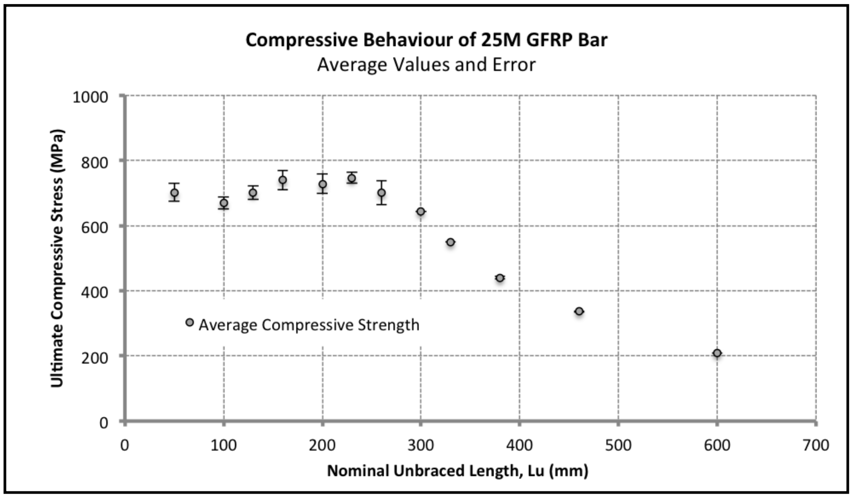

Figure 4. Averaged compression test results including experimental scatter

The final piece of gathered information, 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 the incremental changes in length, along with a cell in the test apparatus to measure the applied load. Based on these data the compressive modulus of elasticity could be determined. Since the modulus is a material property, it is independent of the specimen's length. Instead it is based on the material properties of the bar from which the specimen was originally fabricated (Table 1).

Table 1: Average Compressive Modulus of Elasticity

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	1,2,3,4,5,6,7,8,9,21	55.86
OVERALL AVERAGE		**59.85**

3.1 Crushing and Buckling Failure

Two distinct failure modes were observed during the whole 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 4). 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 fibres at the point of failure (Figure 5).

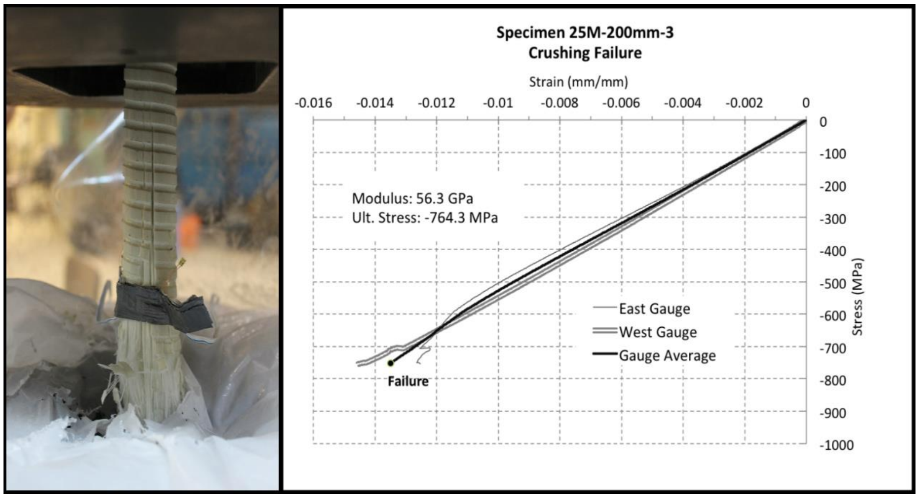

Figure 5. Stress-strain graph and photo of a 200mm specimen failed by crushing

Buckling failure occurred in the longer specimens with failure strengths inversely proportional to the length of the bar. The downward sloping curve in the averaged data graph is consistent with the decreasing strength associated with buckling (Figure 4). 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 6)

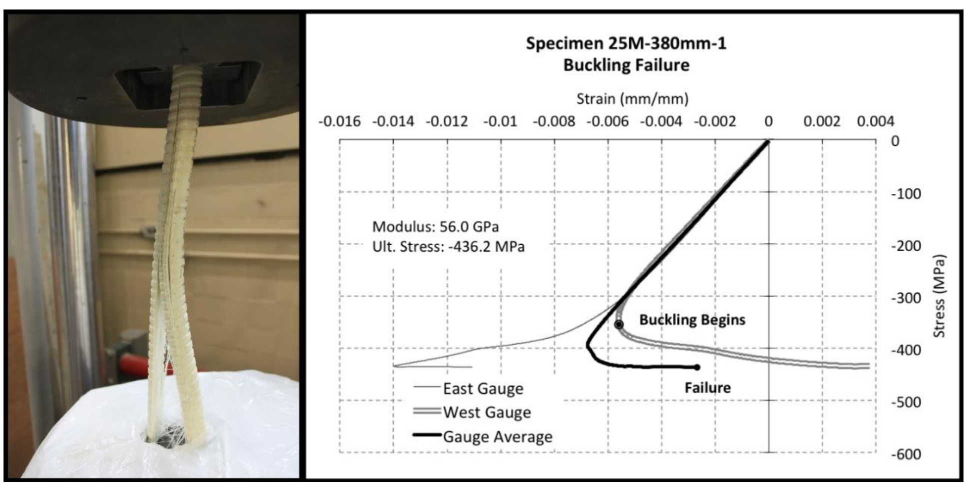

Figure 6. Stress-strain graph and photo of a 380mm specimen failed by buckling

4. 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 specimen ends, however, has reduced the scatter of the data, which was less than ±25 MPa as shown by the data displayed in Figure 4.

4.1 The Mechanics of Buckling Failure

While crushing is a localized failure mode, related to the material properties of the fibre 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 (Timoshenko, 1963).

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

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 it is acknowledged that this formula is not completely accurate for GFRP, since it is not a homogeneous material, it is an adequate approximation. Figure 7 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.

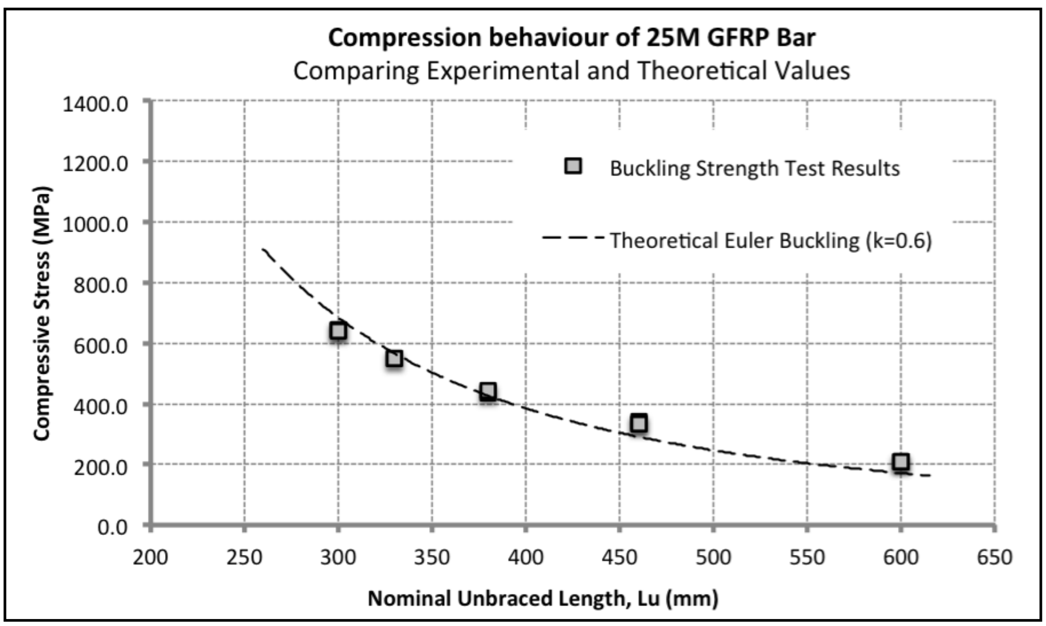

Figure 7. Comparing the Experimental Results with the Theoretical Euler Buckling Loads (k=0.6)

4.2 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 8)

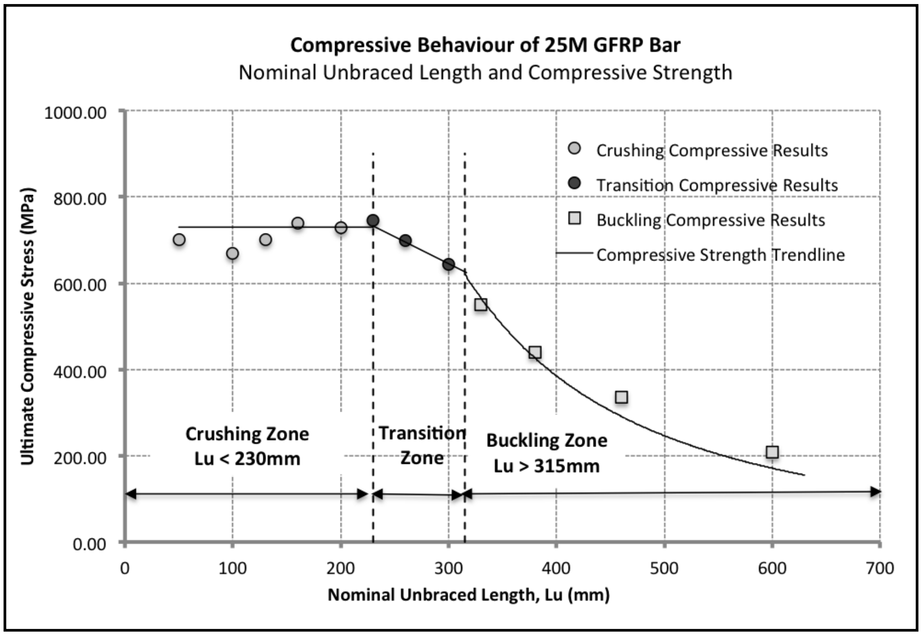

Figure 8. Complete Strength and Unbraced Length Interaction Curve

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 and subjected to monotonic loads, unbraced lengths shorter than 230 mm (l/d < 9.2) 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.

5. FUTURE DIRECTION

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 should 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 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.

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 9.2 and 12.6 to ascertain the strength associated with this failure mode.

6. 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 3m long 25mm diameter GFRP bars, manufactured in the same batch to ensure uniform material properties.

The specimen preparation and testing followed these steps (Figure 9):

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

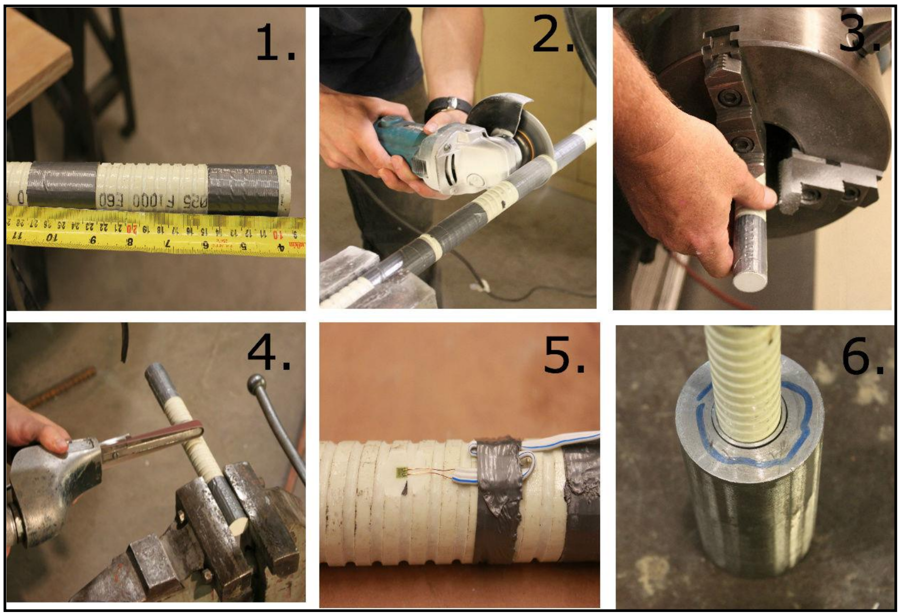

Figure 9. Specimen Preparation Procedure

For consistent and repeatable results the loading rate chosen in step 7 is important. For tensile tests the loading rate is generally specified around 400 MPa/min, so that failure occurs before 10 minutes (CSA, 2010). Since the compressive behaviour is relatively unknown, this experimental program used a loading rate of about 100 MPa/min resulting in tests with longer duration.

7. ACKNOWLEDGEMENTS

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