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Strengthening Slender Steel Compression Members Using a Fibre-Reinforced Polymer Shell Buckling Restrained Bracing System

MacEachern, D.[1], Sadeghian, P.[1]

[1] *Department of Civil and Mineral Resource Engineering, Dalhousie University, Canada*

Abstract

In this paper, the structural properties of slender steel members reinforced against buckling by fibre-reinforced polymer (FRP) composite shells filled with self-consolidating grout is investigated. A total of 9 small-scale specimens were prepared and tested under uniaxial compression. The main test parameters were FRP shell diameter (36 mm, 49 mm and 61 mm) having a shell length of 600 mm. Each specimen was fabricated using cold rolled steel bars (25.4 mm by 6.35 mm) with lengths corresponding to 30 mm longer than the FRP shell and a self-consolidating grout with a compressive strength of approximately 20. Two failure modes were observed during testing: system buckling and steel yielding. Overall, provided the FRP-BRB system was sufficiently sized the system was successful in changing the failure mode of the steel core from buckling to yielding. On average, the steel carried 94% of the load with the grout and FRP shell carrying only 6% and 0.3% at the yielding, respectively.

Keywords: Slender; Steel, Bracing, Strengthening; FRP, Shell, BR

Corresponding author's email: Pedram.Sadeghian@dal.ca

Introduction

The need for rehabilitation of existing infrastructure is dramatically increasing as the age and conditions continue to deteriorate globally. Economical and efficient solutions that can be applied to improve the condition of slender members, columns, piles and bracings in the field are ideal. This has led to various market solutions that improve resistance to buckling. More conventional methods of reinforcing slender members include bulking the structures up with additional material such as steel, concrete or fibre-reinforced polymers (FRP) [1]–[3]. Recently, a more advanced method of increasing the buckling capacity of slender members was developed called a buckling restrained brace (BRB) [4]–[6]. These are currently shop fabricated, field installed systems that consist of steel members encased in a steel tubing filled with concrete or mortar. For these systems to function properly a lubricant is applied to the member to allow free expansion and contraction as well as eliminate friction and shear transfer [4]. The solution investigated in this paper can be applied in the field through keeping the existing member and increasing its buckling capacity. This method is like the BRB system but involves the wrapping of thin FRP laminate around members in the field instead of steel sections fabricated in a shop. This system will be referred to as a fibre-reinforced polymer buckling restrained brace (FRP-BRB). The FRP laminate is glued shut to form a cylindrical formwork that will remain as part of the structural system. Similar to the BRB system described, a lubricant will be applied to the steel to allow its movement to be independent of the grout. Once cured, the tubing will be filled with a cement-based self-consolidating grout (SCG). This technique, when properly sized, can provide lateral buckling support while allowing the restrained member to reach its yielding capacity. It is noted that the concept of the FRP-BRB explored in this thesis is as per U.S. Patent Number 9,719,255 B1 by Mohammad Reza Ehsani, Tucson, AZ (US) [7].

Experimental Program

Three specimens were fabricated at a constant FRP shell lengths of 600 mm and three different diameters. Hot rolled steel bars, with 25.4 mm by 6.35 mm cross sections, were prepared to be 30 mm longer than the shell length and 45 mm long tapered tabs were welded on all ends. Steel cores were coated in a lubricant and grouted inside the FRP shell. Specimens are referred to in order of increasing diameter as D1, D2 and D3. More details are provided in Table 1.

Table 1: Test Matrix

Specimen ID	Steel Core Length (mm)	FRP Shell length (mm)	Shell Inner Diameter (mm)	Shell Outer Diameter (mm)	Number of Specimens
L600-D1	630	600	34.5	38	3
L600-D2	630	600	49	53	3
L600-D3	630	600	61	65	3

Material Properties

FRP shells were fabricated of a glass fibre reinforced polymer biaxial pre-impregnated laminate with a ply thickness of 0.35 mm in conjunction with a structural adhesive. Shells were constructed to have two layers of the laminate with one quarter of the circumference in overlap for the last layer. Tensile test results showed an average modulus of elasticity of

17.16 ± 0.47 GPa (using longitudinal strain range 1000 – 3000 με) in the warp direction and 14.14 ± 0.20 GPa in the fill direction. The hot rolled steel bars had a tensile yield strength of 353 MPa. The self-consolidating grout had a test-day (28 day) strength of 19.5 MPa.

Specimen Fabrication

Sheets of FRP laminate were cut to the appropriate length and width to allow for two wrapped layers with approximately one quarter the circumference in overlap. The material was cut so that the warp (i.e. rolling) direction of the fabric corresponded to the hoop direction of the shell. A two-part structural adhesive was mixed and applied at a uniform thickness of approximately 1 mm over all but one circumference of the shell. The FRP was then slowly wrapped around the tube and secured with another sheet of plastic and taped to secure during curing at the room temperature. Shells were cured for 24 hours and removed from the PVC. Stages of shell fabrication are shown in Figure 1. Steel was cut to a length of 630 mm and 45 mm long tabs were cut with 20 mm tapered on one end and welded onto the ends of the steel. 6.35 mm was left on either end to allow for the connection with the test setup. Small pieces of expanded polystyrene were glued on these tabs to limit the transfer of force into the grout under compression. The steel cores were then coated in a thin layer of petroleum jelly to inhibit bonding and interaction between the grout and the steel. The steel details are shown in Figure 1. A wood stand was designed to keep the steel centred within the FRP shell while casting and curing the grout. The self-consolidating grout was funnelled into the shell. After one day of curing specimens were removed from frame and cured for 28 days in plastic bags.

Figure 1: Specimen fabrication: (a) FRP sheet and formwork; (b) shell rolling; (c) shell removed; (d) steel details; (e) lubricated steel, (f) pouring grout, (g) frame, and (h) curing.

Instrumentation and Test Setup

Both ends of each specimen were wrapped with a 75 mm width of basalt fibre using an epoxy resin as the matrix. Two layers were applied with the fibres in the axial direction and two and a half layers were applied with fibres in the hoop direction. Pin-pin conditions were simulated via a 5-mm deep slot allowing the steel core to rotate about its weak axis. Two axial strain gauges were installed at mid-height on the steel core and two on the FRP shell. Two linear potentiometers were set up along the longitudinal axis of the specimen to measure the extent of the lateral displacement at mid-height. Specimens were tested in compression using a 2 MN universal testing machine at a loading rate of 2 mm/min recording at 100 Hz frequency. This setup is shown in Figure 4 as well as tested specimens.

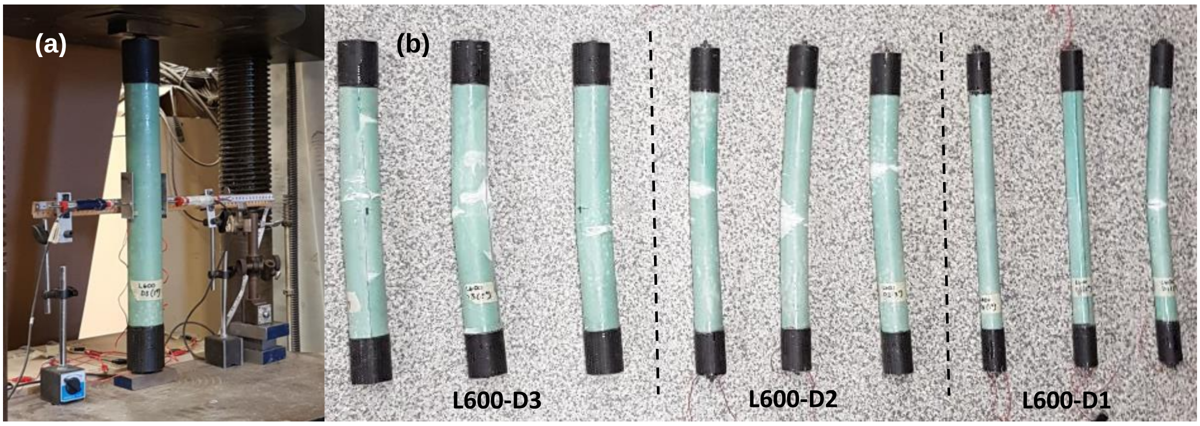

Figure 2: (a) FRP-BRB test setup; (b) tested specimens

Results and Discussions

Two methods of failure were considered for the compression testing of the small scale FRP-BRB specimens, yielding of the steel core and overall system buckling. The system was successful if yielding of the steel core was the initial failure mode. L600-D2 and L600-D3 were successful at reaching yielding of the steel core while L600-D1 buckled prior to reaching yielding.

The load stroke graph is presented in Figure 5(a). There are various regions noted by i-v. The first region, i, is the linear region of the graph. Region ii is the visual yield point of the specimens, this is the first peak seen on the graph. This region does not occur in specimens that buckled prior to yielding. Region iii corresponds to the relatively flat plateau of the graph that shows increasing load with a much lower incline compared to the initial slope in region i. Region iv is the point at which the load begins to be applied to the grout and shell. This occurs around 15 to 20 mm of stroke which is approximately the amount of free steel outside of the shell. The final region noted, v, is the failure point of the specimens. This region varies for each size and length specimen and is the point of ultimate failure.

Figure 5 (b) shows the results of the strain data collected on the FRP shell using the average of two strain gauges on FRP. It was assumed that the FRP shell was perfectly bonded to the SCG and therefore it could be said that the maximum strain is the grout was equal to the strain in the FRP. This information along with the steel strain data was used to determine how much of the total load was carried by the components of the system at yielding. At the yielding, the steel carried 94% of the axial load with the grout and FRP shell carrying only 6% and 0.3%, respectively, based on the average of three identical specimens.

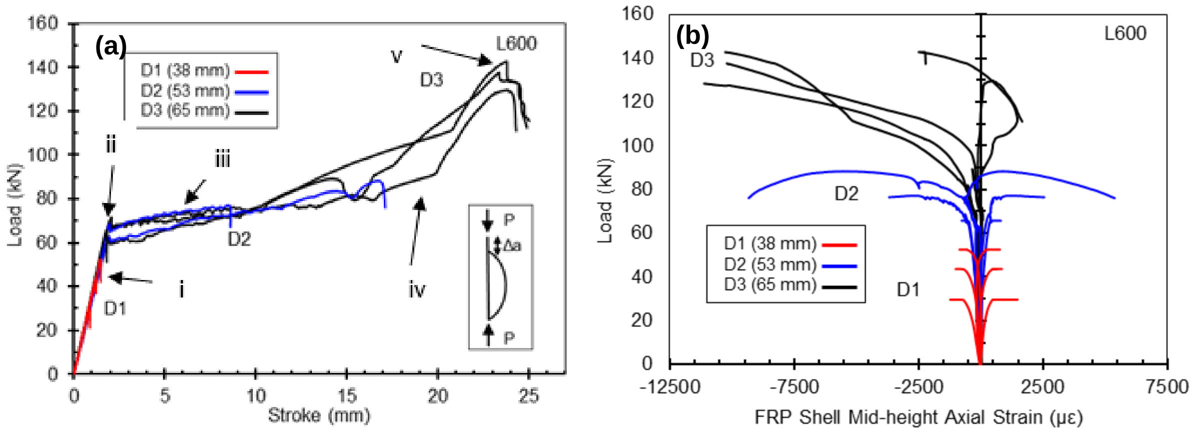

Figure 5: Test results: (a) load-stroke diagram; (b) load-FRP shell mid-height axial strain

Conclusion

Nine FRP-BRB specimens were fabricated and tested under axial compression. Two failure modes were observed for the strengthened specimens, overall buckling of the system, or yielding of the steel core. The system was considered a success when yielding occurred prior to buckling. It was concluded that with an adequately sized FRP-BRB system, the failure of the steel core could be changed from buckling under a compressive load, to yielding of the steel core. The steel was found to carry 94% of the total axial load at yielding, with the grout carrying 6% and the FRP shell carrying only 0.3%.

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