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FAILURE MODE ANALYSIS OF BUCKLING-RESTRAINED BRACES WITH FRP SHELLS

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Abstract: In this paper, the failure mode of a new buckling-restrained brace (BRB) system with fibre-reinforced polymer (FRP) composite shell filled with self-consolidating grout is analyzed. The objective of this research is to determine the behaviour and structural capabilities of the FRP-BRB system as well as its feasibility to real-life applications. An analytical model is developed to predict the governing failure mode of the system, whether it be overall buckling or yielding of the steel core. Different parameters are considered, including slenderness ratio of steel, diameter of FRP shell, strength and modulus of FRP, and strength of grout. The parametric study will review the contributions of the components to the overall flexural rigidity of the system. The solution can be applied in the field allowing for the existing bracing to remain while increasing its buckling capacity and ductility. The results will also establish a platform to develop design procedures applicable for rehabilitation of existing steel structures. Based on the results from a verification study, the model appears to accurately predict the mode of failure of the system. A design example is also presented to determine required FRP shell diameter for a full-size brace made of different angle cross-sections. More verification is required to confirm this conclusion. This research is in-progress and more results will be provided at the conference.

1 INTRODUCTION

As the condition of the large amount of aging infrastructure in Canada continues to decline, it is important that solutions to remediate rather than replace are investigated. While full replacement of all structures reaching the end of their design life or functionality would be ideal, it is not possible with almost 35% of all Canadian infrastructure in need of repair or replacement (CSCE 2016). This is due to not only costs, but time and labour as well. Efficient and economical solutions are a necessity. Currently various solutions that increase the buckling capacity of slender and deteriorating members are available. One solution to this problem is known as a buckling-restrained brace (BRB) system, which is shop fabricated and installed in the field. A lubricant is applied to a steel core to inhibit bonding which is then encased in a grout filled steel shell. The way this system works is by increasing the cross-sectional area of the member, which in turn, increases the buckling capacity. The downfall being that this system requires a member to be removed and replaced, requiring in depth analysis into the effects on the structure (Black et al. 2004; Tremblay et al. 2006).

Fibre-reinforced polymer (FRP) composites have also been used in rehabilitation of slender members in compression. Harries et al. (2009) implemented the concept applying FRP material to a steel compression member to improve global and local buckling behavior. Shaat and Fam (2009) studied the behavior of slender steel columns strengthened using high-modulus carbon FRP (CFRP) plates. The study showed the longitudinal FRPs are effective for strengthening slender steel columns through changing flexural stiffness of the column. Recently, Sadeghian and Fam (2014) studied the effect of longitudinal high-modulus FRPs on enhancing the flexural rigidity of slender concrete columns for buckling control. The system discussed in this paper includes the application of FRPs in a different way that is based on the concept of BRB system, which is called FRP-BRB system, as is described in the following section.

2 CONCEPT OF FRP-BRB SYSTEM

The FRP-BRB system is a method of rehabilitation of existing steel frames and braces, with a composite bracing system. The technique described in this paper is covered in the recently issued U.S. Patent No. 9,719,255 (Ehsani 2017). The system is comprised of a fibre reinforced polymer tube, filled with a self consolidating grout encasing a slender steel bar. The existing brace is cleaned, all rust removed, and is then coated with a lubricant, to inhibit bonding with the grout. The member is then wrapped in place with a sheet of FRP, held in place by an adhesive and strap. Following the curing of the shell, a self consolidating grout is then used to fill the gap between the shell and the existing member. This procedure allows for the rehabilitation without removal of the member in the field. Figure 1 shows the concept as well as the test set up that will be used to test the small-scale specimens for verification. The purpose of the system is then to change the failure mode of the original steel member from buckling to yielding, thus increasing the overall strength of the member.

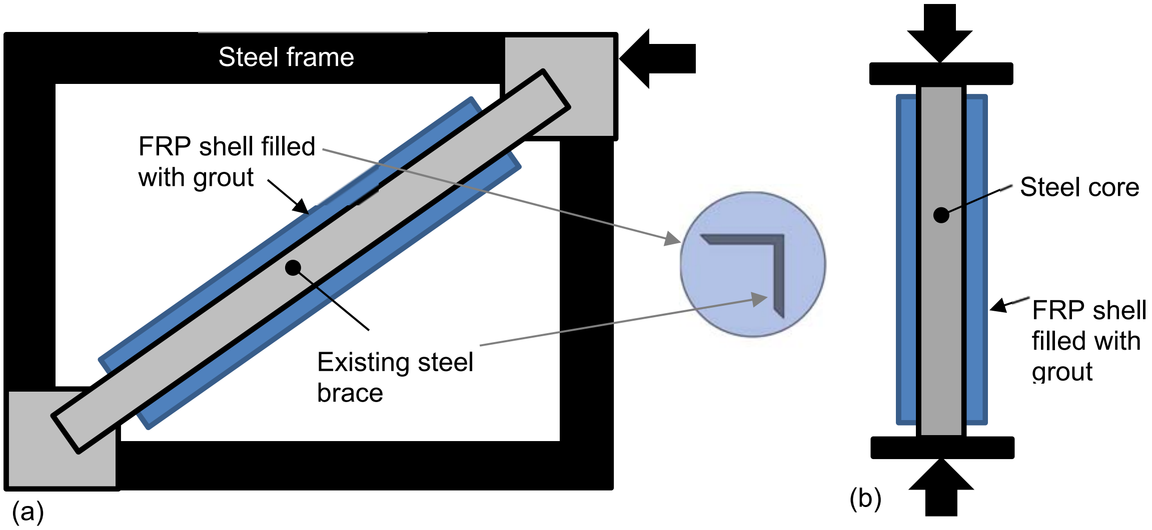

Figure 1: FRP-BRB system: (a) concept of FRP-BRB bracing; and (b) test method

This paper investigates a model of a possible solution to increasing the buckling capacity of slender members quickly and efficiently in the field. The system consists of an FRP shell wrapped around the existing core with a self-consolidating grout in between the two, as described previously. This paper aims to demonstrate and verify a model to predict the behaviour of the buckling restrained bracing system. A design example is also presented to determine required FRP shell diameter for a full-size brace made of different angle cross-sections.

3 ANALYTICAL MODELING

3.1 Description of Model

An analytical study was conducted to predict the governing failure mode for each specimen, whether it be buckling or yielding of the steel core. By setting the load required to yield the steel core (P_y), Equation 1, equal to the load required to buckle the FRP-BRB system (P_{cr}), Equation 2, a critical flexural rigidity (EI_{cr}) was found as presented in Equation 3. The steel cores all have the same cross-sectional area (A_s) with varying lengths (L).

[1] $P_y=A_sf_y$

[2] $P_{cr}=\frac{\pi^2EI}{L^2}$

[3] $EI_{cr}=\frac{A_sf_yL^2}{\pi^2}$

To determine whether the composite specimens would have a yielding failure or buckling failure, the actual flexural rigidity (EI) was calculated and compared to the critical values. The composite EI is calculated by adding the EI for each components of the specimen as follows:

[4] $EI=EI_s+EI_g+EI_f$

The contribution of steel (EI_s) was calculated about the weak axis. The contribution of grout (EI_g) was calculated by Equation (5). The contribution of FRP shell (EI_f) was calculated using the experimental modulus of elasticity and the moment of inertia for a thin walled cylindrical shell. Once the EI was determined, it was compared to the critical EI to predict the mode of failure of the specimen. If the buckling strength of the composite member was greater than the yield strength of the steel, it was predicted that the specimen would yield first. If the composite EI was less than the steel critical buckling EI it was predicted that the specimen would buckle first. Predictions and actual failure modes for the specimen are presented in Table 1.

[5] $EI_g=0.2E_gI_g$

[6] $E_g=4700\sqrt{f'_g}$

3.2 Verification

In order to verify the results of the analytical model three sample specimens were made with a steel core length of 625 mm and an FRP shell length of 600 mm, with one for each of the proposed diameters. The self consolidating grout used had a 28-day compressive strength of approximately 35 MPa. The shells were glass fibre biaxial pre-impregnated laminate sheets (0.66 mm thick) held together by a structural epoxy (adhesive). Shells were fabricated by wrapping the FRP sheet with the adhesive around a pipe while curing to ensure a constant diameter for the test. As the sheets are pre-impregnated and flexible, they are easily formed into cylinders that will be held in position with multiple straps while the adhesive cures in the field. This allows for the shells to be formed in-field and wrapped around any pre-existing member. Petroleum jelly was used as a lubricant between the steel core and the grout. Steel used in the test was hot rolled steel flat bars (25.4 mm by 6.35 mm) with tensile yield strength recorded by the manufacturer of 310 MPa. This strength will be confirmed in a tensile test in the near future.

Specimens were tested under axial compression with a universal testing machine at a constant strain loading rate of 2 mm/min. Photos of tested specimens are shown in Figure 2. The data from each specimen was analyzed to determine if the steel yield before overall buckling occurred, or vice versa. The mode of failure was determined by comparing the load vs stroke to the load vs axial strain. The point of buckling could be determined from the load vs axial strain graph and this point when referenced back to the load vs stroke graph would determine if the buckling occurred before or after the yielding load of the steel. It was found that the predictions from the analytical study matched the test results. A summary is provided in Table 1. Experimental flexural rigidity was not recorded as these tests were preliminary and lateral deflection data was un reliable. In future tests this will be corrected, and moment-curvature will be provided.

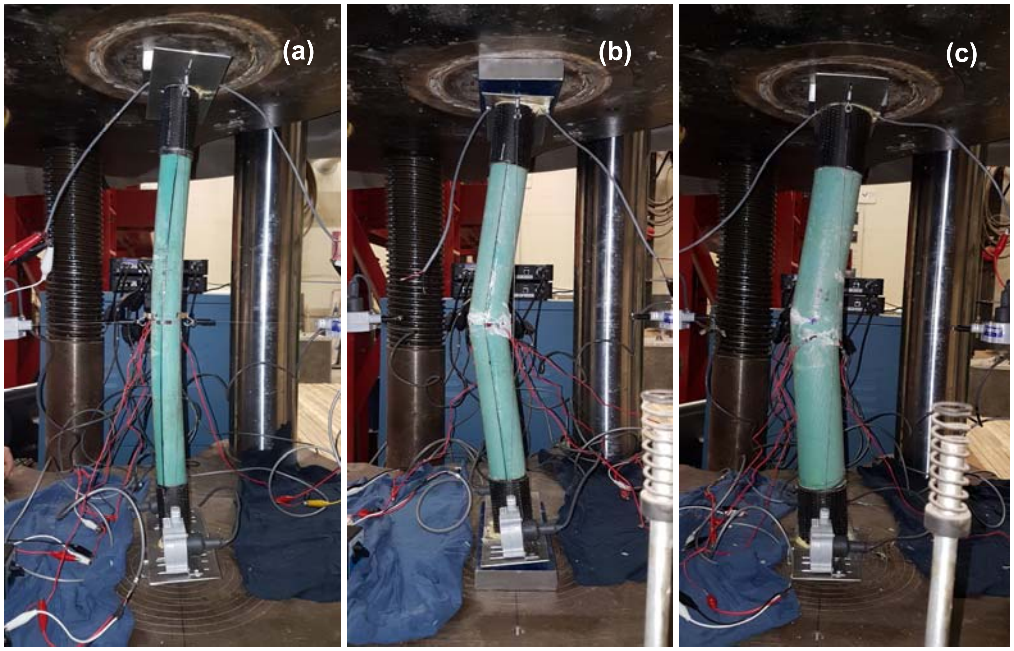

Figure 2: Failure modes of the test specimens with the total length of 625 mm and the FRP shell outer diameter of: (a) 36 mm; (b) 49 mm; and (c) 61 mm

Table 1: Predicted and actual failure modes of FRP-BRB test specimens (L = 625 mm)

FRP shell diameter	D = 36 mm		D = 49 mm		D = 61 mm	
Mode of failure	Predicted	Actual	Predicted	Actual	Predicted	Actual
	B	B	Y	Y	Y	Y

* Note: Y = yielding failure and B = buckling failure

3.3 Parametric Study

The strength of grout (f'_g) was assumed to vary from 10 to 50 MPa and three diameter shells were considered, 36 mm, 49 mm and 61 mm. The numbers of layers of FRP laminate was also considered and its effect on the structural behaviour of the proposed system. Figure 3 shows the composite flexural rigidities for each diameter shell as the number of layers of FRP increases from 1 to 5. The dashed horizontal lines show the critical buckling flexural rigidity for each length system, as calculated in the previous section. The compressive strength of the self consolidating grout was kept constant as 35 MPa. Points, or specific diameter and layer combinations, on the graph that are below the critical buckling line for each length represent systems that would experience a buckling failure where as above the line would fail by yielding of the steel. For example, a 61-mm diameter shell with a 300 mm or 600 mm shell length, the system would fail by yielding for all layer combinations. As another example. a shell with 3 layers of FRP, at length 625 mm, would experience a buckling failure with a diameter of 36 mm, but would yield with a diameter of 49 mm.

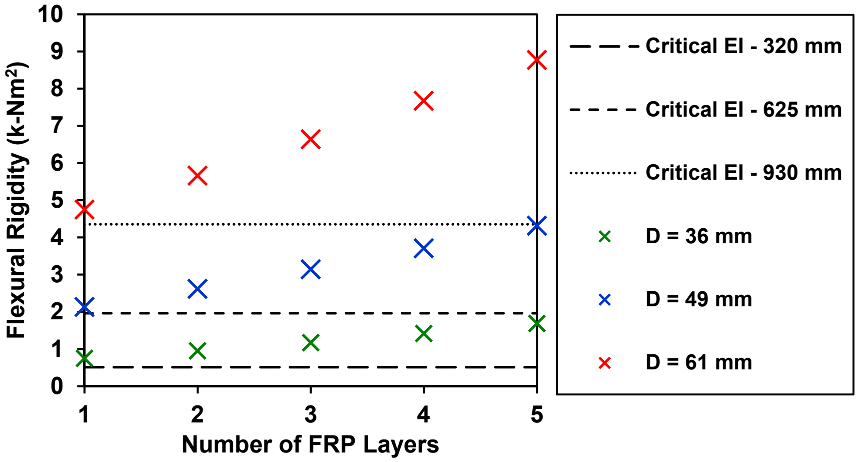

Figure 4: Flexural rigidity for varying diameter and number of FRP layers in shell.

The ratios of each component of the EI, steel, FRP or grout, to the total composite EI for each shell diameter against grout strength was calculated and is shown in Figure 4. Overall, the total flexural rigidity of the system is proportional to its buckling resistance, as it increases the critical buckling load also increases. On each graph in Figure 3 the failure mode of a specimen with a total length of 625 mm is noted for all grout strengths by a B or Y for buckling an yielding, respectively.

It is seen that as the strength of the grout increases, for the same diameter shell, the contribution of the grout to the buckling resistance increases. For the smallest diameter, 36 mm, the contribution to the composite EI increases 19.5% from grout having a compressive strength of 10 MPa of to 50 MPa. This effect is similar with the other diameters of 49 mm and 61 mm, increasing 19.7% and 18.8% respectively. This is inversely proportional to the effect of the FRP shell on the total flexural rigidity as the grout strength increases. As the grout strength increases the contribution of the shell decreases 15.1%, 17.6% and 17.8% for diameters 36 mm, 49 mm and 61 mm, respectively. The contribution of the steel core to the buckling resistance remains relatively constant as the grout strength increases with only a slight decrease of 4.3%, 2.1% and 1.1% for increasing diameters. These relative changes are similar between changing diameters.

As the shell diameter increases, the contribution of the FRP shell to the buckling resistance changes very little, however, the contribution of the grout becomes more important as the diameter increases. As an example, for 25 MPa grout, the contribution of the FRP shell to the overall composite decreases only 4.1% between a diameter of 36 mm and 49 mm. It then decreases another 4.4% between 49 and 61 mm diameter shells. For an increasing shell diameter from 36 to 49 mm and 49 mm to 61 mm, an increase in grout contribution of 11.8% and 6.9%, respectively, is seen for a constant strength of 25 MPa. As the diameter of the FRP shell increases, the contribution of the steel to the overall system becomes less important. For 25 MPa grout this contribution decreases 7.8% between 36 and 49 mm shell diameters and decreases another 2.5% between 49 and 61 mm.

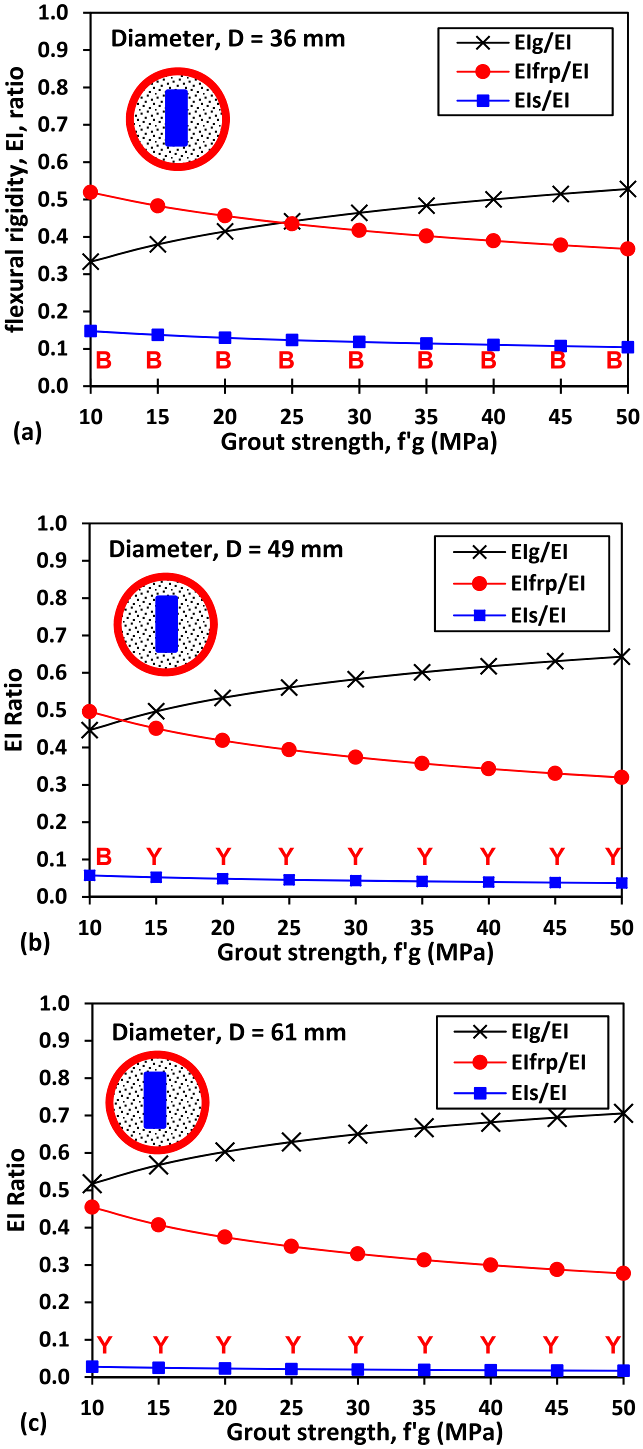

Figure 3: Ratio of EI components to total EI for each diameter against grout strength: (a) D=36 mm; (b) D=49 mm; (c) D=61 mm. Mode of failure (Y or B) denoted for a total length of 625 mm shell

3.4 Design Example

A practical design example has been considered. A brace with a buckling length of 5 m was designed to be retrofit with the proposed system in order to prevent buckling. The brace is a steel angle with a leg thickness of 6 mm and yield strength of 350 MPa. The four leg lengths that have been designed for are 50 mm, 75 mm, 100 mm and 125 mm. It was assumed that the grout had a compressive strength of 35 MPa and that two layers of FRP were used. The composite flexural rigidity of each system was calculated as shown in Section 3.1. The optimal diameter for the FRP shell was determined by equating the yielding load to the buckling load for all brace sizes. Table 2 shows summarizes the results of the designs along with three options for shell diameters, depending on how many layers of FRP shell are used. For example, if the brace had an angle cross-section of 50x50x6 mm, a FRP shell with inner diameter of 199.2 mm made of 2 layers of the FRP laminate would be required to match the buckling capacity of the race to its yielding capacity. The table also shows that increasing the number of FRP layers does not decrease the shell diameter significantly. It should be highlighted that full-scale tests are needed to verify the results of the design example.

Table 2: Design example summary a full-size brace with buckling length of 5 m and angle cross-sections

Angle Size (mm x mm x mm)	**50x50x6**	**75x75x6**	**100x100x6**	**125x125x6**
Shell made of 2 layers of FRP laminate				
EI Steel (kN-m^2)	10.8	38.0	92.1	182.7
EI Grout (kN-m^2)	430.1	647.8	842.2	1004.0
EI FRP (kN-m^2)	59.1	80.2	97.6	111.2
EI Composite (kN-m^2)	500.0	766.0	1032.0	1297.9
Yielding Load (kN)	197.4	302.4	407.4	512.4
Buckling Load (kN)	197.4	302.4	407.4	512.4
Optimized FRP Inner Diameter (mm)	199.2	220.7	235.7	246.3
Shell made of 4 layers of FRP laminate				
EI Grout (kN-m^2)	379.3	577.9	756.5	905.8
EI FRP (kN-m^2)	109.9	150.1	183.3	209.5
EI Composite (kN-m^2)	500.0	766.0	1032.0	1297.9
Optimized FRP Inner Diameter (mm)	193.1	214.5	229.4	240.0
Shell made of 6 layers of FRP laminate				
EI Grout (kN-m^2)	335.5	516.8	681.0	818.8
EI FRP (kN-m^2)	153.7	211.2	258.8	296.5
EI Composite (kN-m^2)	500.0	766.0	1032.0	1297.9
Optimized FRP Inner Diameter (mm)	187.2	208.6	223.5	234.0

4 CONCLUSION

In this paper, a rehabilitation system called FRP-BRB system was described to increase the overall strength of slender steel members through inhibiting buckling, thus allowing yielding to occur at a higher load. The system is comprised of an FRP shell surrounding a steel core that has been coated in a lubricant with a self consolidating grout encasing the core. A model was created that evaluated a composite flexural rigidity through superposition of the flexural rigidity of each component of the FRP-BRB system. This was then compared to the critical buckling flexural rigidity to predict whether a system would fail in buckling or yielding. Through verification of the model with experimental results, the model was able to accurately predict the failure mode of three specimens. These specimens were of the same length, but varying diameters. Further investigation will conclude if the model is accurate for various heights as well as with more iterations of the same diameters. A parametric study of the system concluded that the over all contribution of the grout and FRP shell to the composite flexural rigidity are inversely proportional as the strength of the grout increases, as the contribution of the grout increases, the shells contribution decreases. The effect of the diameter on these properties is less noticeable, however, this may be due to the relatively small changes in core diameter. The effect on the number of layers of FRP with respect to the failure mode was also considered and the failure mode for systems having 1 through 5 layers was predicted. Also, a design example was presented to determine required FRP shell diameter for a full-size brace with a buckling length of 5 m and different angle cross-sections. This research is in-progress and more results will be provided at the conference.

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