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# EVALUATION THE SEISMIC BEHAVIOR OF BRIDGE PIERS UTILIZING HYBRID REINFORCEMENTS

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**Abstract:** To improve the performance of concrete against corrosion, Glass Fiber Reinforced Polymer (GFRP) bars were introduced RC structures. However, the challenge lies in its brittle failure. Hence, in a seismically active region, GFRP rebars cannot be used as reinforcement in the critical regions of concrete structures (Plastic hinge) unless being backed by another ductile material. In this study, double reinforced section is introduced which will be named hybrid reinforcement section. Longitudinal rebars will be arranged into exterior (GFRP) and interior (steel) cages. Two layers of transverse reinforcements, either made from GFRP (for exterior cage) or steel (for interior cage), are also provided. The prescribed hybrid reinforcement is one potential alternative to mitigate corrosion. Currently, limited research has been directed towards identifying the nonlinear behaviour of hybrid RC section. Yet, concrete bridge piers with hybrid reinforced were not investigated before under axial and later loads. To achieve this objective, the behavior of hybrid bridge piers will be experimentally and numerically investigated under quasi-static lateral load and axial compression on a scaled-down (1:2) models. The expected outcome of this research is developing a new design tool, for hybrid bridge piers, to determine the moment-curvature, load-deflection relationship, yielding capacity, post-peak stiffness, curvature ductility, energy dissipation capacity. From the conducted research, it was reported in the MC analysis that post GFRP rapture, the steel did carry almost 50% of the section capacity, providing some sort of ductility. In the quasi-static analysis, minimal and reparable damages were reported at 1% and 4% drift values. On the other hand, up to 2.75% drift, the minimal damage was not yet reported for the hybrid sections.

## 1 INTRODUCTION

Reinforced concrete bridge piers is an important element in the Infrastructure system that constitutes a substantial portion of national wealth of Canada. However, more than 40% of Canadian infrastructure has passed its service life, and the overall infrastructure deficit has grown from $123B in 2007 to $141B in 2016 and increases at a rate of $2B annually (CIRC 2016). Such important structural element, bride piers, is usually exposed to aggressive environments that corrode the steel reinforcement. Alternatively, the use of fiber-reinforced polymer (FRP) has emerged as a reliable and efficient material to resist corrosion. (Mufti et al. 2007) conducted a field evaluation of five existing bridges reinforced with GFRP bars. The outcomes showed that GFRP reinforcement was in a great condition. However, no post-peak extension is expected when using such a brittle material (GFRP). Within its elastic range, GFRP reinforced concrete (RC) structures exhibit a predominantly elastic behavior with low energy dissipation capacity, which is considered as a major problem in seismic design. In the proposed research, GFRP rebars will be used along with steel to introduce ductility in FRP reinforced concrete (RC) elements, e.g. in large bridge piers where GFRP rebar cage will be placed in the exterior cage to provide corrosion resistance whereas steel will be used in the inner cage to provide ductility.

Over the past two decades, FRP has been introduced to fully or partially replace steel in RC elements [(Sheikh and Uzumeri 1980),(Paultre and Légeron 2008)]. In parallel to such continuous research, design standards are implementing research outcomes to develop provision and limits of use (ACI440 2006),(CSA 2002) ,(CSA 2006). In the proposed hybrid-reinforcement, concrete within the schematic cross-section, of a two-layers of stirrups, will be classified into three different levels of confinement, namely single and double confined concrete as well as unconfined concrete (*Figure 1*). Numerous advantages are expected from such hybrid-reinforcement form. For example, the provided confinement will enhance the ductility (Brubaker 2017) yet the mechanism of failure, under earthquake excitation, is not thoroughly investigated (Lin-Zhu Sun 2017). In general, little research has been directed towards hybrid reinforcement. In particular, very limited research works available on the seismic behavior of hybrid steel-FRP RC columns.

This study will determine the seismic behavior of such concrete bridge piers utilizing hybrid reinforcement and compare its performance to that of a conventional steel RC bridge pier in terms of load-displacement, moment-curvature and energy dissipation capacity, and strains in the longitudinal and transverse reinforcements. Another important objective of this study is to develop numerical tools to predict the response of RC elements having hybrid reinforcements in terms of moment-curvature response, pushover response, and seismic response. These tools will assist in developing performance-based design guidelines and generate fragility curves for such hybrid RC elements and structures.

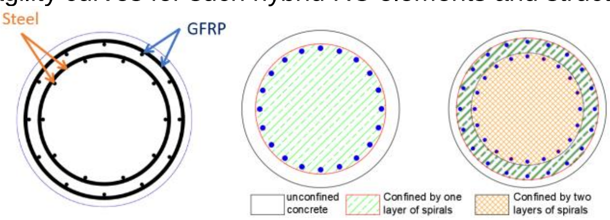


Figure 1. schematic cross-section, showing different confinement levels

## 2 Moment-curvature (MC) and Curvature ductility

For conventional RC sections, steel ratio provided, from a design perspective, is usually kept below the balanced design value to ensure ductile behavior. Elastic deformations followed by cracking of concrete then yielding of steel are the three simplified stages in a typical MC analysis (*Figure 2*). Post yielding of steel reinforcement, higher curvatures values occur due to strain hardening. Curvature ductility are identified by the ratio of the value measured at the steel ultimate state to that measured at steel yielding. When sections fully reinforced with FRP, the ductility index has been addressed through various formulas by [(Abdelrahman 1995), (Mufti, Newhook, and Tadros 1996) and (Zhou, Ou, and Wang 2003)] because the behavior is different as FRP by nature do not yield. Two commonly used methods are the energy-based and the deformation-based approaches. In the energy-based approach, ductility is calculated using the area under the MC curve, ignoring deformation levels which is considered a major drawback for this approach. To illustrate, same index could be achieved through two totally different sections if the area under the curve is the same. Thus, the deformation-based approach might be more representative and yet could be applied for FRP if a nominal yield point has been set for FRP bars that don't yield by nature. From the sectional analysis we can measure the compression strain at the extreme concrete fiber reaching 0.001 and use that a nominal yield point while calculating the ductility index [(Zhou, Ou, and Wang 2003)]. The finite element modelling of the hybrid-reinforcement sections and effect analysis of hybrid reinforcement will be first validated and then interpreted in the next section.

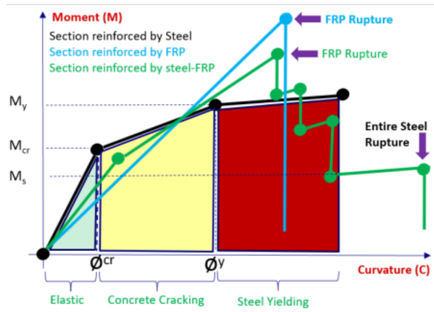


Figure 2. Schematic MC relation of hybrid-reinforced RC sections

### 2.1 Validation

The moment-curvature of FRP-RC sections modeled using simplified material models that are commonly used for design purposes, as well as being introduced in the literature [(Chen 2007), (Hadhood, Mohamed, and Benmokrane 2018b)], are interpreted in this current research. Experimental and numerical results from the literature have been demonstrated to establish the validity of the used software. The research reported on herein used experimental program conducted by (Aiello and Ombres 2002) on FRP-RC members. The experimental work did use Aramid FRP (AFRP) and Steel bars that was later validated against the numerical work done by (Kara, Ashour, and Köroğlu 2015). In general, Figure shows good agreement of conducted analysis compared to both experimental and numerical work from the literature. Error in experimental readings near failure may be the reason behind the deviation from the numerical analysis. However, up to a certain limit (@ M = 22 KN.m and Curvature = 0.035), *Figure 3* still shows good agreement.

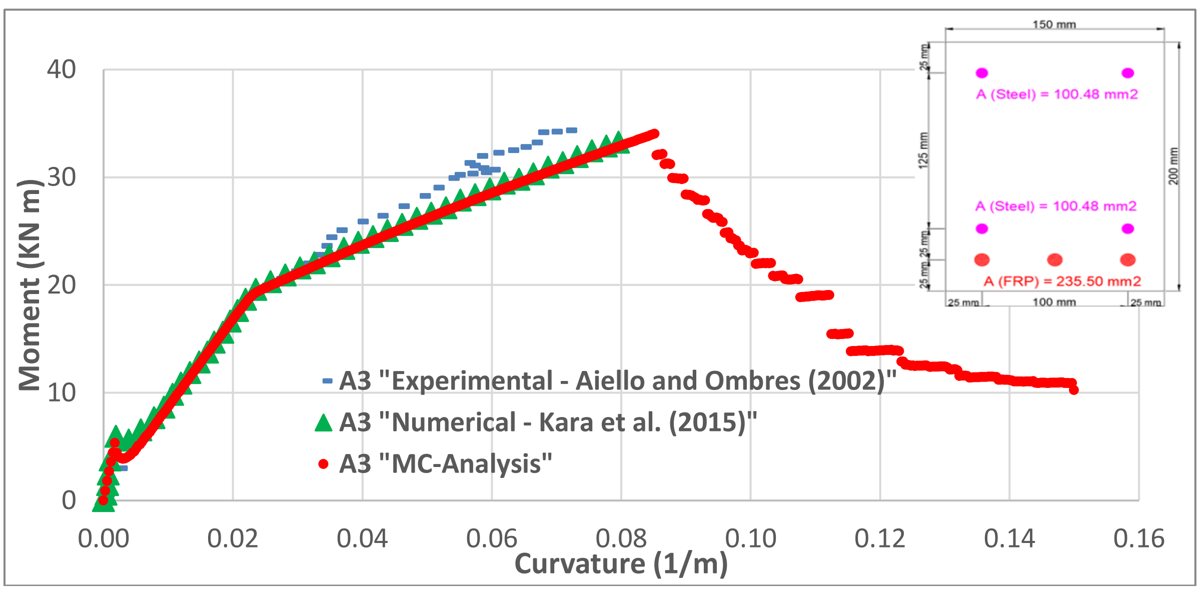


Figure 3. Numerical results validated against both experimental and numerical results from the literature

After validating the numerical program used, we will analyze RC sections having two layers of reinforcement where GFRP will be the exterior and steel the interior reinforcement. A section with two layers of steel was also included to investigate the enhancement achieved due to the double confinement effect. Finally, a control specimen with conventional steel-RC section was added for comparison. (*Figure 4*).

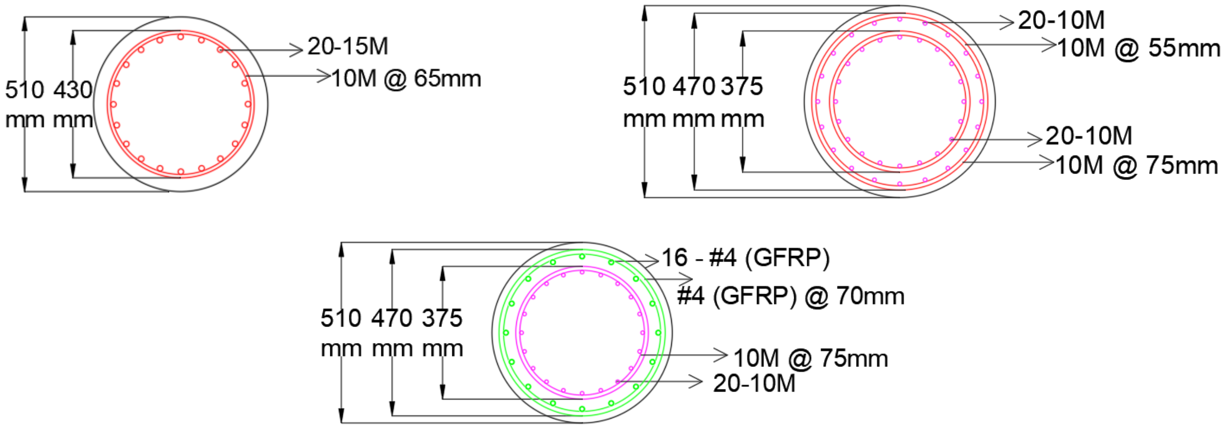


Figure 4. Cross section and reinforcement layout of the scaled models; (a) Steel (Control), (b) two layers of spirals (both Steel), and (c) two layers of spirals (GFRP and Steel)

### 2.2 Analysis

In the conducted MC analysis, the steel material model utilized has a linear elastic followed by non-linear strain hardening (Necking is not considered). Linear elastic under tensile stresses up to rapture is the model used for GFRP. Several guidelines and codes agreed on ignoring the FRP bars in compression [ACI 440.1R-15; CSA S806-12]. However, for design purposes, some went to ignore the FRP in compression while considering the area occupied by the FRP bar as concrete under compression ([(Zadeh and Nanni 2013)] and [(Hadhood et al. 2017)]). Alternatively, (Hadhood, Mohamed, and Benmokrane 2018a) did simulate the FRP bar strength in compression using a modulus of elasticity 80% and compressive strength of 85% from the corresponding values in tension. In this section, the three mentioned approaches of modelling FRP are presented. The Concrete material model utilized is based on the average stress-strain curve of singly-confined and doubly-confined concrete proposed by (Li et al. 2018). In their research, the average effective confinement (uniform) pressure was applied for concrete confined by single and double layers of stirrups. (*Figure 5*)

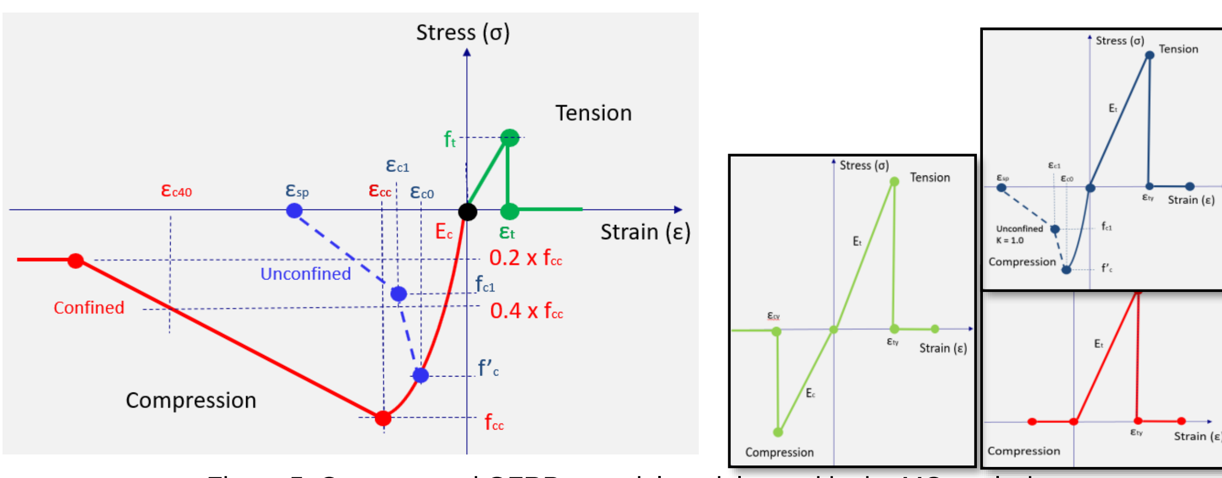


Figure 5: Concrete and GFRP material models used in the MC analysis

### 2.3 Results

The use of GFRP on the exterior cage did lead to an increase in the maximum moment capacity of the section due to the higher tensile strength compared to steel as observed in *Figure 6*. However, following the series of FRP bar rapture, the steel bars placed in the inner cage could carry almost 50% of the entire section capacity. The presence of steel in the hybrid section did improve the ductility significantly compared to sections reinforced with FRP rebars only. The GFRP specimen utilizing the material characteristics of GFRP in compression based on the modulus of elasticity and strength of 85% of the tensile values did generate slightly higher moment capacity compared to the one that totally ignores the contribution of CFRP in compression or considering the area occupied by the GFRP as unconfined concrete. For the control specimen, the MC analysis conducted was used to identify the yielding point of steel and the corresponding curvature. Those was used with the cracked section properties to calculate the displacement that cause the steel to start yielding. This value will be later used in the loading protocol.

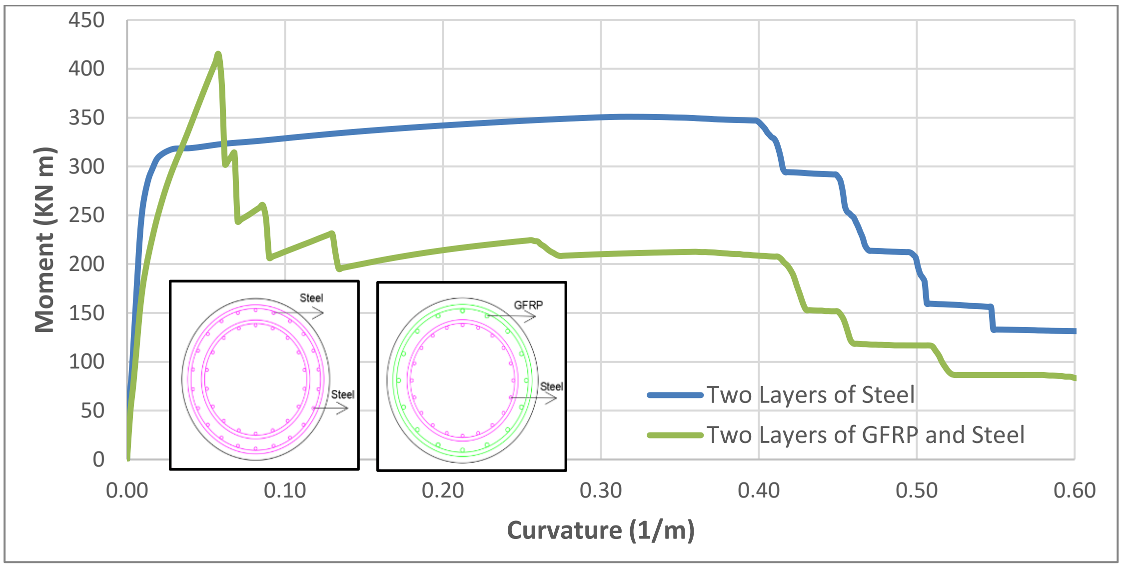


Figure 6. MC (Hybrid-reinforcement utilizing steel, CFRP and GFRP)

## 3 Quasi-static Time-history Analysis

### 3.1 Validation

In this section, we have validated the developed model and the software used using experimental work conducted on section reinforced with steel and FRP. As shown in *Figure 7*, good agreement with the experimental work done by (Kowalsky, Priestly, and Seible 1999). However, the experimental did show higher values in the pull-direction compared to the push cycles. This might be due to not symmetric section details that were not considered in the numerical model. On the other side, (Tavassoli, Liu, and Sheikh 2015) experimental results were picked to validate the model reinforced by FRP rebars and spirals. As shown in *Figure 8*, both the experimental and numerical results show better agreement.

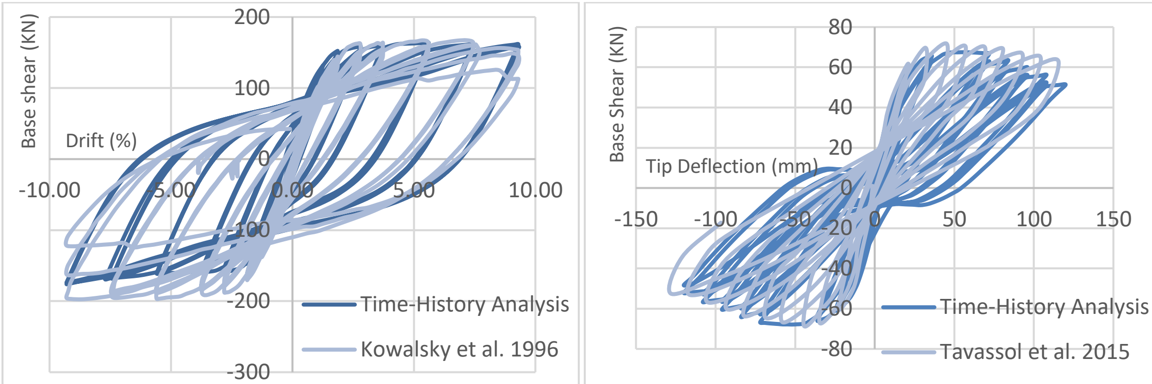


Figure 7: Validation the numerical model with specimens reinforced with steel or GFRP

### 3.2 Balanced, Tension and Compression Failure mechanisms

For sections reinforced by FRP, the balanced failure is not governed anymore by yielding as for the RC structures reinforced by steel. In this case, the balanced failure is when the crushing of concrete occurs at the same time of the FRP rapture. It is very important not to design under-reinforced sections when reinforced with FRP. The reason behind that there will be no yielding before the sudden failure. To control not having such tensile failure, sections should be over-reinforced to ensure that concrete will develop its ultimate strength while FRP still in the elastic zone, being secured from rapture. This is what is called a compression failure that was not desired to have in structures reinforced by steel yet much better for those reinforced by FRP. *Figure 9*shows the stress-strain behavior of different material used in the control (Spc0) and the hybrid reinforced specimen (Spc3).

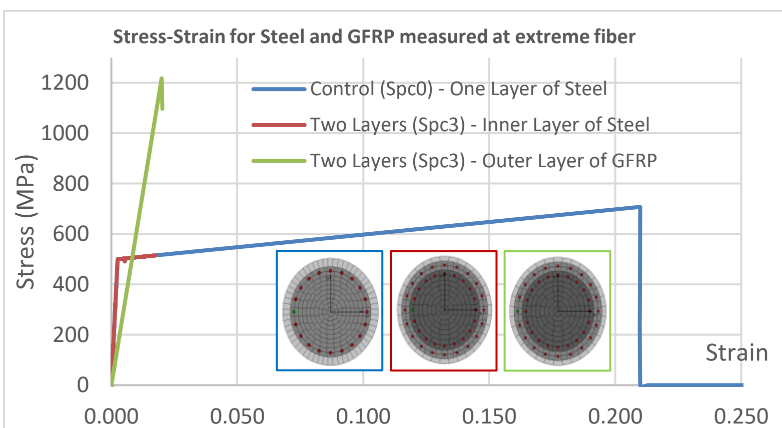


Figure 8: Stress -Strain measured at extreme fiber of the single layer and double layer of reinforcement

### 3.3 Loading protocol

A displacement-controlled loading protocol was developed to suite the specimens reinforced by steel, GFRP, and hybrid reinforced. The recommendations of the ACI Committee 374 Report (ACI 2013) was applied. One-half of $\Delta y$, yielding displacement, is enough to capture the elastic performance. Two cycles at each deformation level was chosen to allow a wider range of drift values prior to stiffness degradations. The subsequent loading steps were a multiplier of the first step as follows; $\Delta y$, $2\Delta y$, $3\Delta y$, $4\Delta y$, $5\Delta y$, and $6\Delta y$ which is corresponding to 1.04 %,2.08 %,3.12 %,4.15 %,5.19 %, and 6.23 % drift respectively. As per the ACI report recommendations, a service cycle was allocated after some drift values to quantify the stiffness degradation. As per the standards ((2014) and (2012)) [(Ali 2015)] used a service displacement that yields to 60% and 25% of the yielding strain and the ultimate strength of the steel and GFRP respectively. (*Figure 9*)

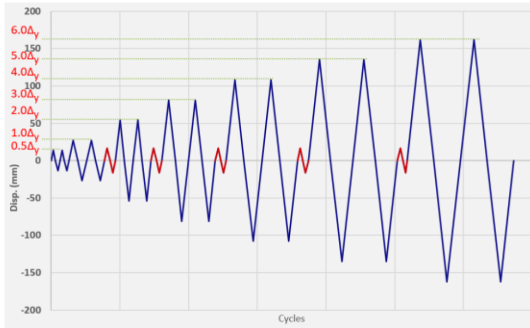


Figure 9: Loading protocol

### 3.4 Results and Performance Measures

The pushover analysis that was conducted in this section is shown in *Figure 10*. The specimens reinforced with one (Specimen 0) and two layers (Specimen 1) of steel were reinforced with the same total reinforcement ratio to develop the same capacity. Since the inner layer was shifted to the center, a small (3%) loss in the max base shear was recorded for Spc1; however, the concrete confinement was better for the same specimen (Spc1), leading to 4% increase in the shear load post peak until failure. For specimen 3 (Spc3), as a starting point the reinforcement ratio was split between the GFRP at the outer layer and steel at the inner layer. This led to the same sectional capacity, but the bridge pier was not able to achieve the 4% drift value that is set to be one of the design-based extreme performance measures. Accordingly, the GFRP was raised by 25% to account for the lower modules of GFRP compared to steel and achieve higher drifts values within the elastic zone of GFRP.

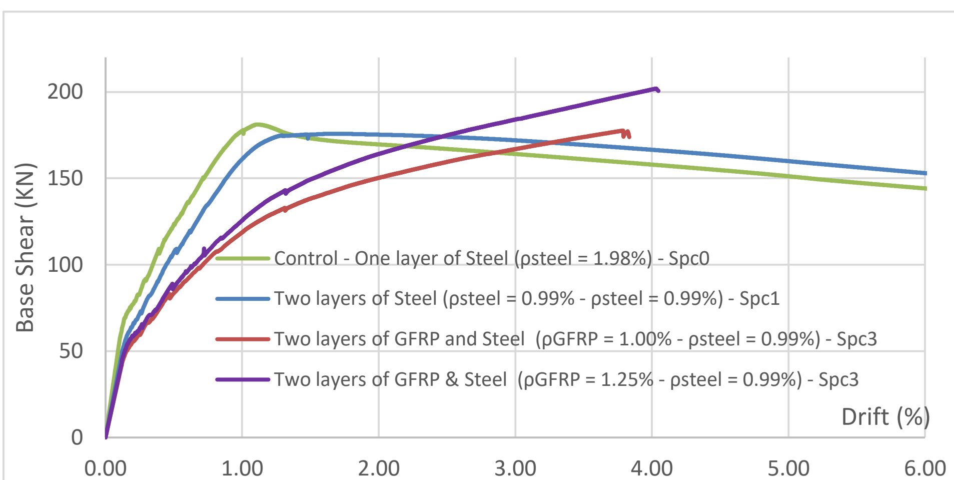


Figure 10: Backbone curve for different specimens tested

It worth to mention that upon the rapture of GFRP, the numerical model couldn't converge leading to the stop of the analysis. This problem prevented the display of post-peak performance, showing the portion of load that was initially carried by GFRP and now will be re-distributed to the steel.

To tackle this problem, performance measures were set according to (CSA 2014) and the supplement to (CSA 2014). Table shows, the performance criteria under different damage levels

Table 1: Performance measures according to CHBDC 2014 and the supplementary part

| **Damage** | **Performance Criteria (CHBDC 2014)** | **Performance Criteria (CHBDC 2014 supplement)** |
|---|---|---|
| Minimal | • Concrete compressive strain ≤ 0.004<br>• Reinforcing bars should not yield | • Concrete compressive strain ≤ 0.006<br>• Tensile strain in steel ≤ 0.01 |
| Repairable | • Tensile strain in steel ≤ 0.015 | • Tensile strain in steel ≤ 0.025 |
| Extensive | • Concrete should not crush<br>• Tensile strain in steel ≤ 0.05 | • Core concrete strain ≤ 80% of the max. confined strain limit<br>• Tensile strain in steel ≤ 0.05 |

As shown in *Figure 11*, at 1% and 4% drift values the control specimen (Spc0) did experience minimal and reparable damage respectively. On the other hand, up to 2.75%, the hybrid section (Spc3) was not yet classified as minimal damage because the strain in concrete didn't exceed the 0.006 nor the strain in the steel reached the 0.01. Just before GFRP raptures, at 4.25% drift, the strain in steel was 0.0175. This is still classified as minimal damage. It worth to mention that these performance measures don't include the GFRP. After conducting parametric analysis, considering multiple cases and validating with the experimental program, such measures could be pointed out.

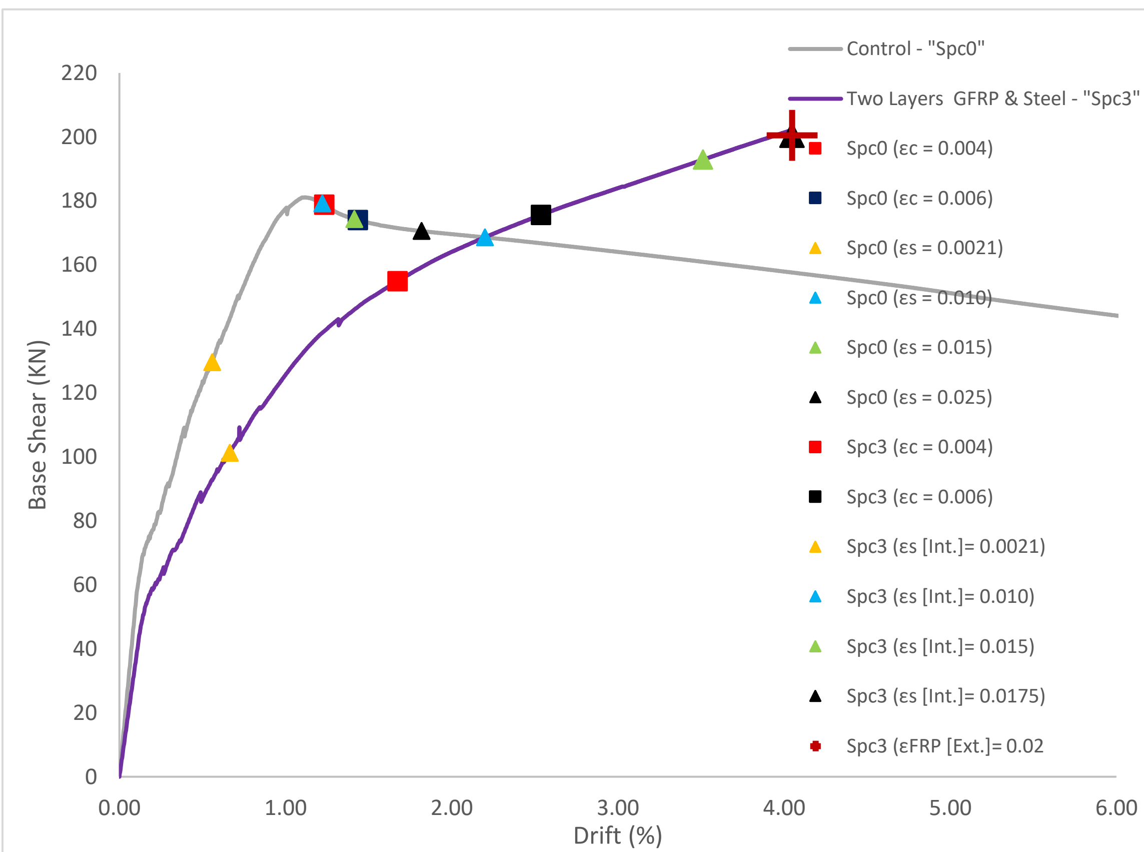


Figure 11: Different performance criteria for the control and hybrid specimens

## 4 Conclusions

Flexural behavior of GFRP-RC members with rectangular sections has been under continuous experimental research over the past decades (ACI 440.1R-15). However, the program conducted in this paper is the first testing program to investigate the behavior of half-scale circular concrete bridge piers hybrid reinforced by GFRP and steel bars and spirals. New insights into the MC sectional analysis and the performance design of circular bridge piers with hybrid reinforced will help in the implementation of such innovative system that will improve the infrastructure performance against corrosion.

Based on the conducted analysis, the following can be concluded:

- For sections reinforced with GFRP, over reinforced design ensures that crushing of the concrete will occur before the FRP reaches rapture, avoiding tensile failure in GFRP.
- MC analysis could be used to identify the start yielding point of steel in case of conventional RC sections. On the other side, performance limits for sections reinforced with GFRP could consider 25% of the ultimate strength of GFRP and/or limiting the strain in concrete to a certain value.
- Ductility index can be better presented by the displacement approach for sections reinforced by steel, GFRP and hybrid refinement. This can be achieved by setting performance limits for sections reinforced with fully or partially by GFRP. For example, 25% of the ultimate strength of GFRP and/or limiting the strain in concrete to a certain value.
- In the MC analysis following the series of FRP bar rapture, the steel bars placed in the inner cage could carry almost 50% of the entire section capacity, providing some sort of ductility. The compressive strength of GFRP was modeled and It was found that the it did generate slightly higher moment capacity compared to the other two conservative approaches, namely the one that totally ignores the contribution of CFRP in compression or considering the area occupied by the GFRP as unconfined concrete
- From the backbone cure for the control specimen, minimal and reparable damage were reported at 1% and 4% drift values as per the CHBDC 2014 supplement. On the other hand, up to 2.75%, the minimal damage was not yet reported for the hybrid section (Spc3) because the strain in concrete didn't exceed the 0.006 nor the strain in the steel reached the 0.01. Just before GFRP raptures, at 4.25% drift, the strain in steel was 0.0175.

## 5 WORK IN PROGRESS

While writing this paper, we have already tested the control Specimen (Spc0) experimentally at "The Applied Laboratory for Advanced Materials and Structures" (ALAMS). (Figure *12*)

Figure 12. Testing the control specimen at ALAMS

## 6 Acknowledgements

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