Nonlinear moment-curvature response of hybrid reinforced concrete sections using S-CALC

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ABSTRACT

Harsh winter is an important factor behind the deterioration of concrete infrastructure in Canada because of using salt for deicing. A hybrid reinforcement for reinforced concrete (RC) sections utilizing Glass Fiber Reinforced Polymer (GFRP) or Carbon Fiber Reinforced Polymer (CFRP) as along with steel can provide a good solution to mitigate corrosion problem where steel can provide good ductility against sudden FRP bar rupture. Currently, little research has been directed towards identifying the nonlinear attributes of hybrid RC members. Moment-curvature (MC) analysis is conducted for RC sections utilizing hybrid reinforcement. The MC relationship is an effective representation to the non-linear material and sectional properties. Curvature ductility as well as flexural stiffness are indicators for the non-linear characteristics of the section. In this study the experimental and numerical MC analysis of hybrid RC section from the literature will be presented. S-CALC software (by S-FRAME Software Inc.) is used to numerically simulate the MC response of hybrid RC sections, which was also validated with the experimental results. In a parametric study, the softening characteristics and post-yield behaviour of concrete are presented by using various material models for confined and unconfined concrete. Similarly, strain hardening, yield and rapture states of different reinforcement material (Steel, GFRP and CFRP) are demonstrated. The parametric study is applied to study the effect of the simplifying assumptions that are usually applied to the stress-strain relationship of steel and concrete. The expected outcome of this research is developing a new design tool for hybrid RC section, to determine the moment-curvature relationship, energy dissipation capacity, and strains in the longitudinal and transverse reinforcements under combined normal and shear stresses.

Keywords: hybrid reinforcement; moment-curvature; corrosion resistance.

INTRODUCTION

Infrastructure systems, such as bridge piers, are 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. The use of FRP as full or partial replacement of steel in RC elements has been under continuous research over the past two decades ([1], [2]). Design standards and codes are adapting research outcomes through developing provisions and limitations of use ([3], [4], 5]). Since FRP is a brittle material, it fails within its elastic range with no post-peak extension. Thus, FRP 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, FRP (CFRP or GFRP) rebars will be used along with steel rebars to introduce ductility in FRP reinforced concrete (RC) elements, e.g. in large bridge piers where FRP 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. RC columns confined by two-layers of stirrups has good ductility [6] yet their failure mechanism is not thoroughly investigated under earthquake excitation [7]. RC columns confined using two layers were addressed by [6] and [8]. There are very limited research works available on the seismic behavior of hybrid steel-FRP RC columns. Numerous advantages are expected from such hybrid-reinforcement form. Mainly, the core (steel) to provide ductility and exterior (FRP). The 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).

The moment-curvature of FRP-RC sections modeled using simplified material models that have been validated in the literature [9], [10] and commonly used for design purposes, 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 objective of this study is to study concrete bridge piers having hybrid reinforcement and compare its performance to that of a regular steel RC bridge pier in terms of moment-curvature and energy dissipation capacity, and strains in the longitudinal reinforcements.

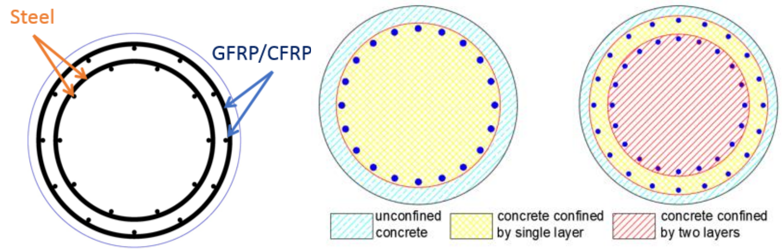

Figure 1. schematic cross-section, showing different confinement levels

MOMENT-CURVATURE (MC) AND CURVATURE DUCTILITY

For sections fully reinforced with steel, the amount of steel assigned (from a design perspective) in a section is usually kept below the balanced design value to ensure ductile behavior. The MC for such sections can be simplified by three stages. Elastic deformations followed by cracking of concrete then yielding of steel (Figure 2). Higher curvature values occur after yielding of steel reinforcement. The curvature measured at the steel ultimate state to that measured at the steel yield state defines the curvature ductility. For sections fully reinforced with FRP, the behavior is different because FRP by nature do not yield. Ductility index has been addressed through various formulas by [11], [12] and [13]. The energy-based and the deformation-based approaches are the two commonly used approaches. The area under the moment-curvature curve is used for the energy-based approach to define ductility. Deformation is not considered which is considered a major drawback. For example, you can achieve the same ductility index from two sections that do behave quite differently but overall the area under the curve is the same. Meanwhile, the conventional concept of ductility can be still applied if a nominal yield point has been set for FRP bars that don't yield. For example, the curvature values when the compression strain at the extreme concrete fiber reaches 0.001 could be used as a nominal yield point while calculating the ductility index [13]. finite element modelling of the hybrid-reinforcement sections and effect analysis of hybrid reinforcement on ductility and strength are covered in the next sections.

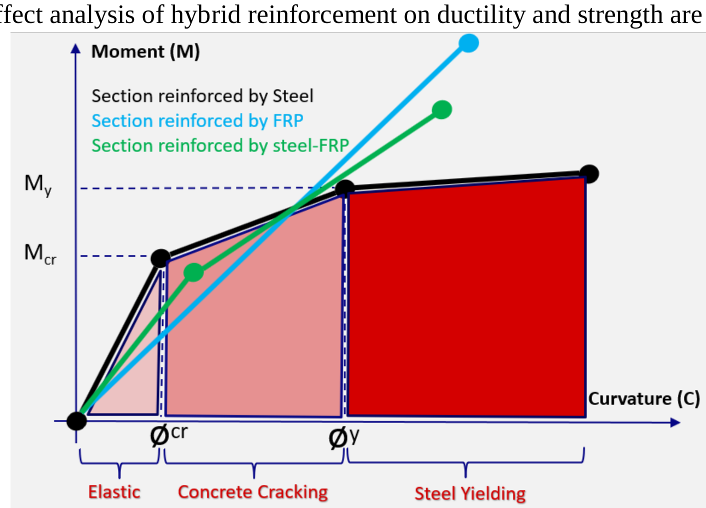

Figure 2. Schematic MC relation of hybrid-reinforced RC sections

SIMPLIFIED MATERIAL MODELS

The behavior of RC structures under different loading conditions could be captured by efficient material modeling that was tailor-made to the minimum input data from the user and the ease of use. In this study, the concrete softening characteristics as well as the post-peak trend are presented in a parametric study. Similarly, strain hardening and FRP compressive strength are demonstrated to study the effect of the simplifying assumptions that were proposed by [14], [15] and [10].

Concrete

Over the past decade, many studies addressed the behavior of unconfined and confined concrete. Two models are examined in this study, a stress-strain model has been proposed [14] to overcome the shortcoming of existing stress-strain models regarding numerical integration. The proposed stress-strain curve for confined and unconfined concrete, where the behavior of the concrete in compression depends on the confinement of the cross section. A confinement ratio of K = 1.0 was used for unconfined concrete and 1.3 for confined concrete based on section and reinforcement properties calculated using [15]. second material model utilized the average stress-strain curve of singly-confined and doubly-confined concrete proposed by [8]. In their research, the average effective confinement (uniform) pressure was applied by considering the effective confinement pressure twice for concrete confined by single layer of stirrups as well as the core that is doubly confined. (Figure 3)

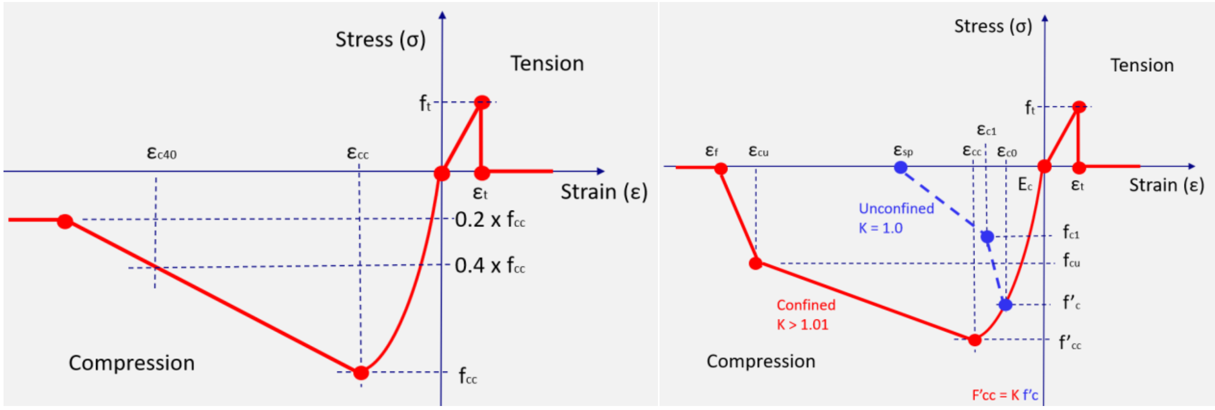

Figure 3. Different Concrete models implemented in this study

Steel and Fiber Reinforced Polymer (CFRP and GFRP)

Reinforcing steel is modeled using two models. Firstly, as a linear elastic followed by linear strain hardening. The other material model utilized has a linear elastic followed by initial yield extension then by non-linear strain hardening. Necking is not considered in both models. FRP reinforcing bar is well known by its linear elastic performance in tension up to rapture. It has been agreed on, in several guidelines and codes (ACI 440.1R-15; CSA S806-12), to ignore the contribution of FRP bars in compression. For design purposes, some researchers proposed to consider the area occupied by the FRP bar in compression as concrete ([16] and [17]). [18] did account for the FRP bar strength in compression by assuming a modulus of elasticity 85% (CFRP) and 80% (GFRP) of the tensile modulus of elasticity, while the compressive strength was kept at 35% (CFRP) and 85% (GFRP) of the maximum tensile strength. The three different approaches of modelling FRP in compression are interpreted in the next section.

VALIDATION

The research reported on herein used experimental program conducted by [19] on FRP-RC members. This experimental work, which had different layout of FRP and steel reinforcement, was validated against the numerical work done by [20]. Four rectangular concrete sections reinforced with Aramid FRP (AFRP) and Steel bars, were chosen to be numerically validated here. (Figure 4)

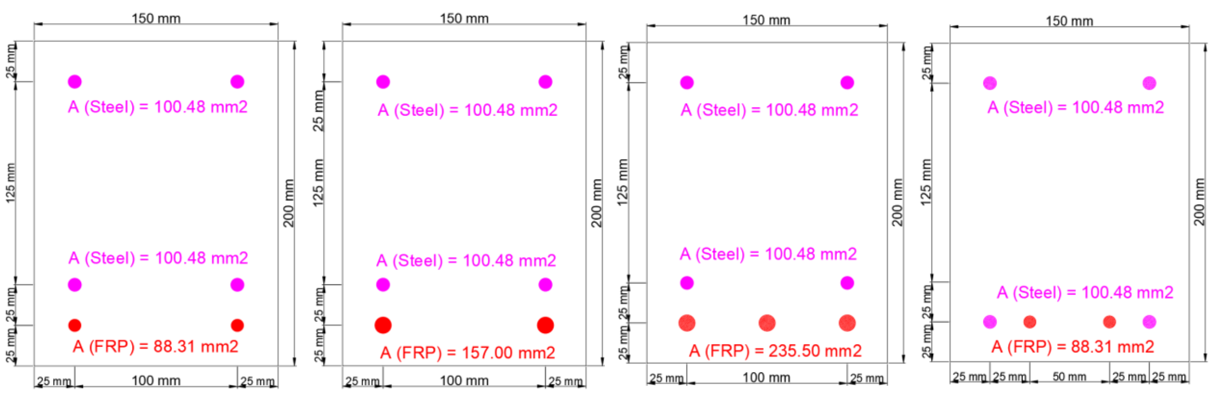

Figure 4. Cross section and reinforcement details

As shown in Table 1, the maximum moment and corresponding curvature are matching with [20]. Variation from the experimental work [19] might be because of error in reading the experimental results near failure. However, Figure 4 still shows good agreement up to a certain limit (@ M = 22 KN.m and Curvature = 0.035) where the experimental results start reading higher values than what were numerically expected by both numerical results.

Table 1. Summary of the validation results

Specimen	**[19]**		**[20]**		**S-CALC**	
	Mu	Phi	Mu	Phi	Mu	Phi
A1	25.17342	0.153409	19.97814	0.127671	19.94437	0.1448

A2	28.06696	0.118942	25.62854	0.10624	25.70136	0.1092
A3	34.34787	0.071635	33.25147	0.079579	34.02614	0.0852
C1	23.27721	0.149241	-	-	21.76438	0.137502

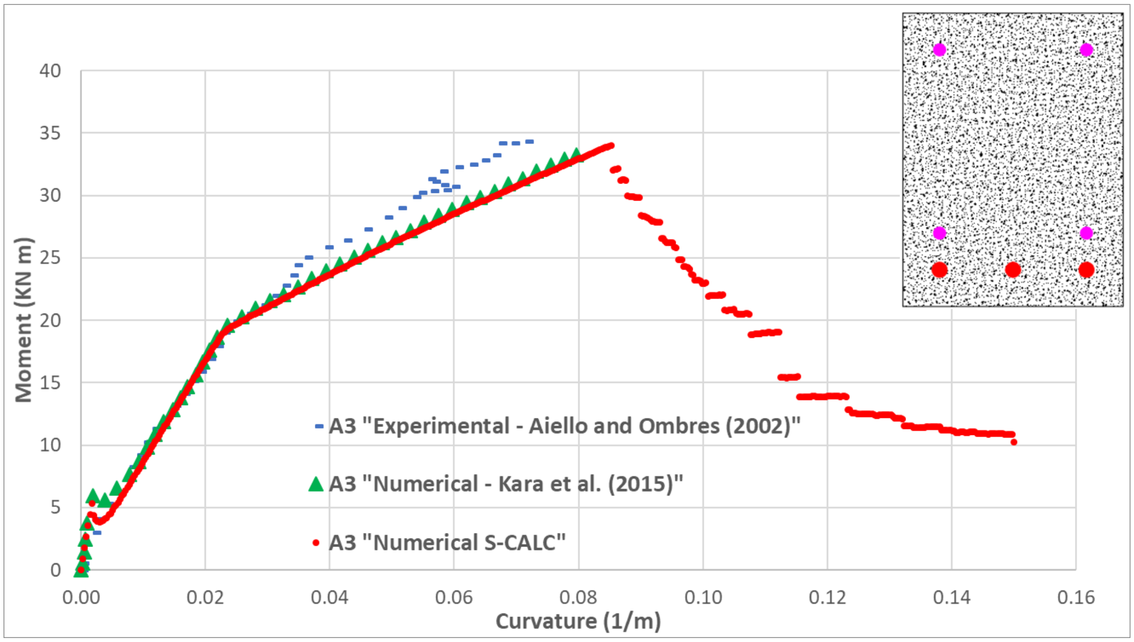

Figure 5. Numerical results validated against both experimental and numerical results from the literature

MC OF RC SECTIONS UTILIZING HYBRID REINFORCEMENTS

After validating the numerical program used, in this section, we will discuss RC sections having two layers of reinforcement where Glass Fiber Reinforced Polymer (GFRP), or Carbon Fiber Reinforced Polymer (CFRP) will be the exterior and steel the interior reinforcement. A section with two layers of steel was also included. Finally, a control specimen with conventional steel-RC section was added for comparison. (Figure 6). All sections were efficiently meshed to represent different section parts (Figure 7).

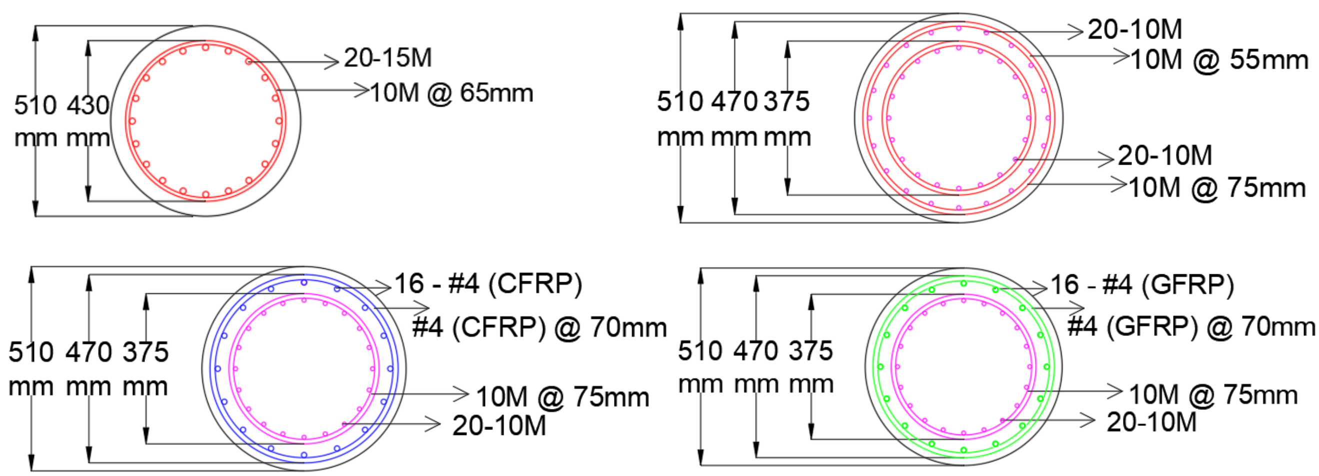

Figure 6. Cross section and reinforcement layout of the scaled models; (a) Steel (Control), (b) two layers of spirals (both Steel), (c) two layers of spirals (CFRP and Steel) and (d) two layers of Confinement (GFRP and Steel)

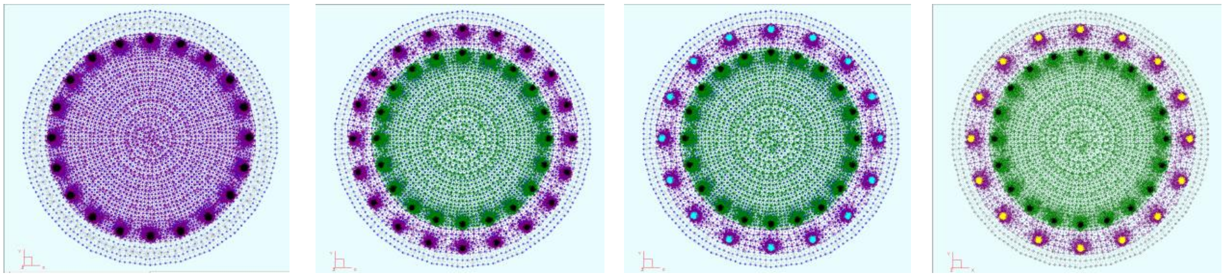

Figure 7. Mesh is tuned to precise element size near rebars while courser mesh is applied in other section parts

In this section we will demonstrate the effect of the section's reinforcement on MC relation. As shown in Figure 8, the bi-linear steel model experienced higher moment values, only at the location of initial yield extension (flat part), compared to the steel model with non-linear strain hardening achieved; Otherwise the latter did show 6.45% higher moment capacity at the same curvature value of 0.3086.

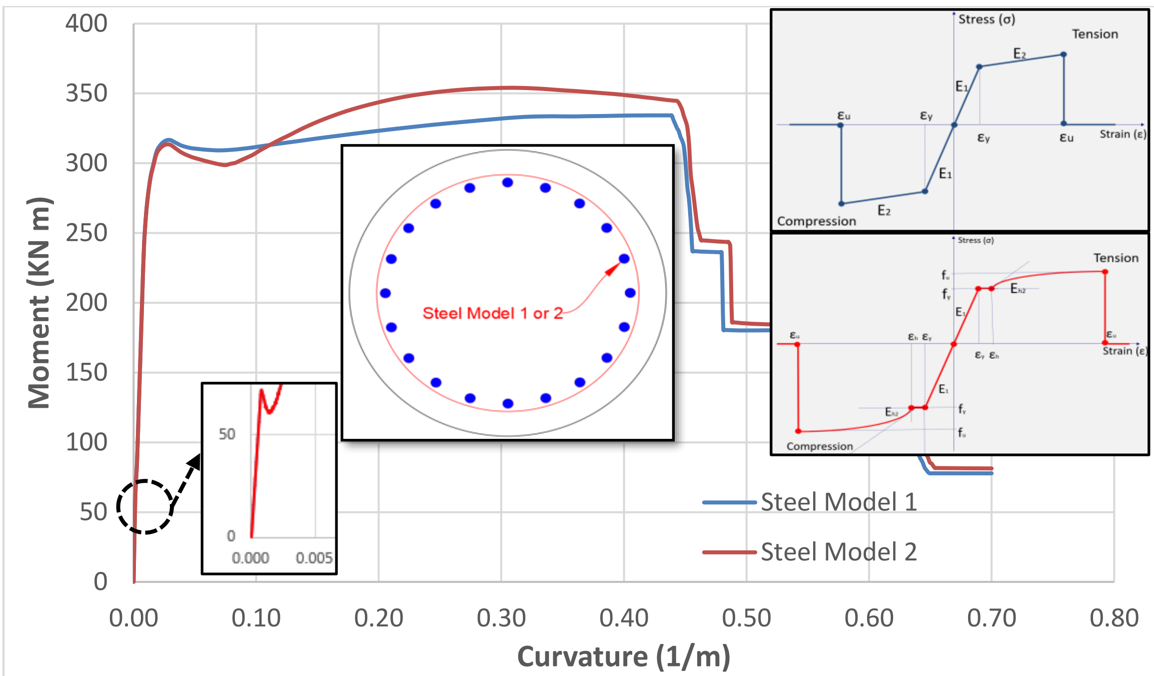

Figure 8. MC (bi-linear steel model vs nonlinear strain hardening steel model)

The use of FRP (CFRP and 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 9. However, following the series of FRP bar rapture, the steel bars placed in the inner cage could carry almost 50% and 30% of the entire section capacity for CFRP and GFRP bars, respectively. The presence of steel in the hybrid section did improve the ductility significantly compared to sections reinforced with FRP rebars only. The CFRP specimen results mentioned in Figure 9 did use the material characteristics of CFRP in compression based on the modulus of elasticity and strength of 85% and 35% of the tensile values, respectively. In Figure 10, it could be shown that this assumption 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 CFRP as unconfined concrete.

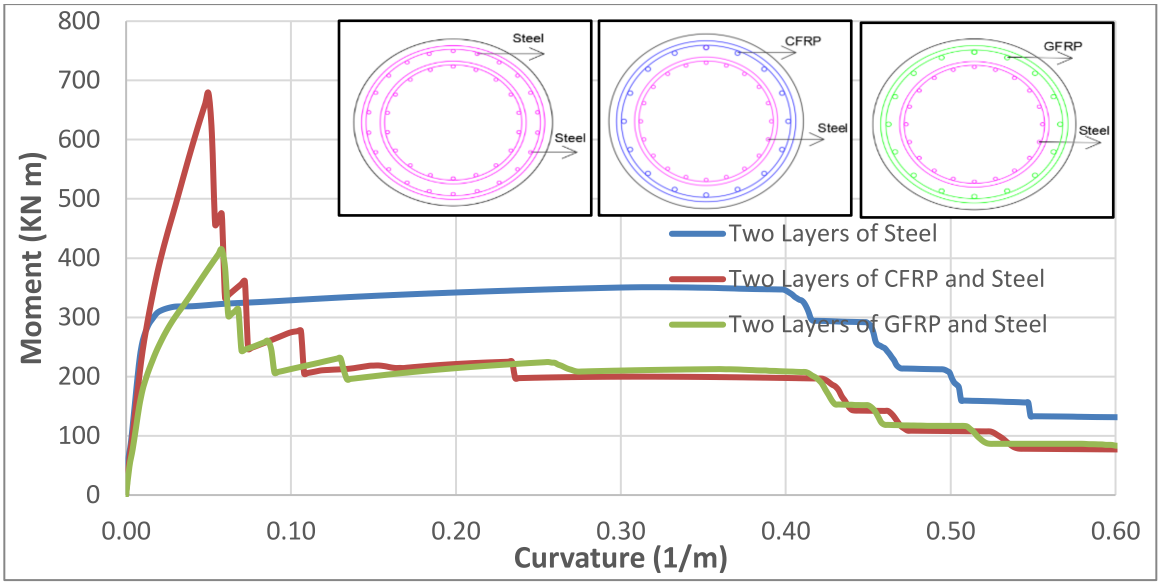

Figure 9. MC (Hybrid-reinforcement utilizing steel, CFRP and GFRP)

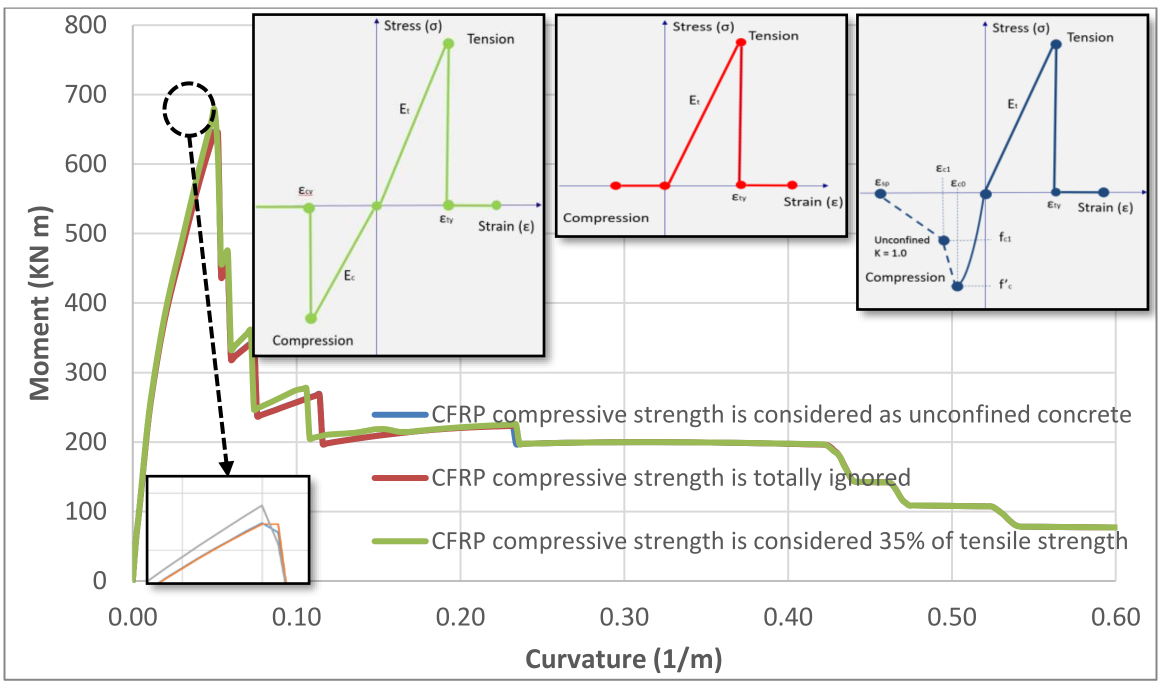

Figure 10. MC (Different approaches to model the compressive behavior of CFRP rebars)

In this section we did demonstrate the average confinement concept proposed by [8] and compare it to [14] modified confined and unconfined material models. Since the reinforcement is not our point of study here, both specimens were reinforced with two layers of steel and kept constant while examining the influence of concrete confinement. As shown in Figure 11, both models did show almost similar behavior. As expected, the average confinement method did simulate the same performance with negligible increase of 1.1% in terms of moment capacity.

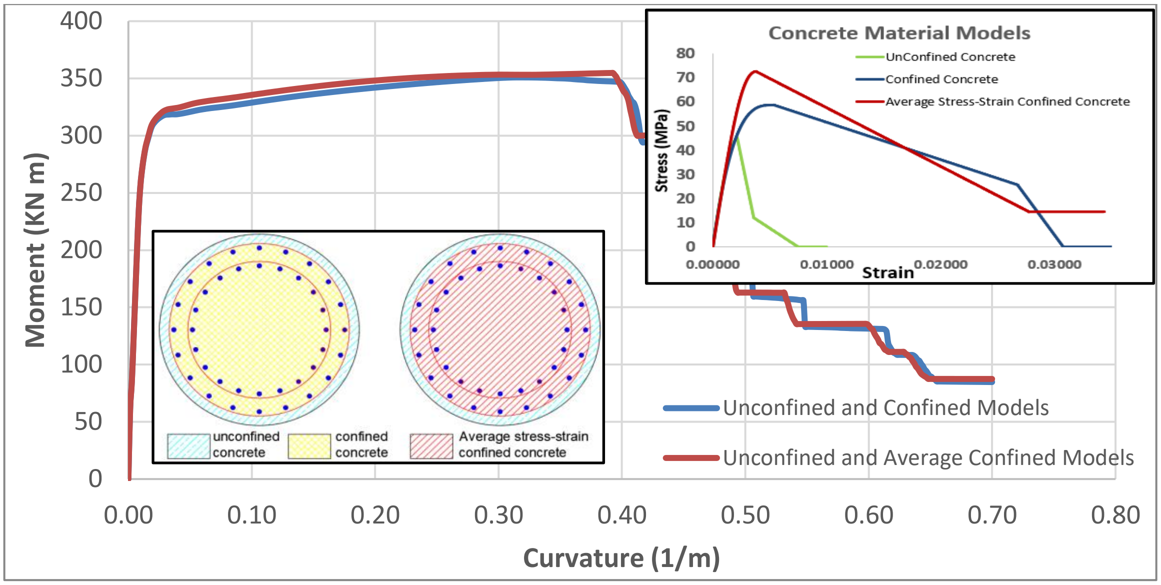

Figure 11. MC (Confined and unconfined concrete vs the average uniform confinement method)

CONCLUSIONS

The proposed research addresses a critical issue that affects the seismic performance of bridge structures in Canada. Within the scope of the project, the program used in the entire research was validated through experimental and numerical investigations from the literature. Studying such hybrid-reinforced sections was not done before. In this research, recent modified material models, that were validated in the literature, were implemented and compared to other material models that are commonly used for design purposes. It was found that the average confinement pressure for section with two layers of spirals is capable of capturing the behavior of concrete in the confined region. It was also shown that the contribution of FRP bars in compression could be ignored without much influence on the capacity of the section. The outcome of this research could be summarized in the following point;

- Strain hardening in steel led to an increase of 6.45% higher moment capacity at the same curvature value of 0.3086.
- The use of FRP (CFRP and GFRP) on the exterior cage did lead to an increase in the maximum moment capacity of the section by 79.8% and 10.5% respectively. However, following the series of FRP bar rapture, the steel bars placed in the inner cage could carry almost 50% and 30% of the entire section capacity for CFRP and GFRP bars.
- Accounting for the contribution of FRP in compression could generates slightly higher moment capacity compared to the one that totally ignores the contribution of CFRP in compression or considering the area occupied by the CFRP as unconfined concrete.
- Modelling concrete confinement using the stress-strain model that was proposed by [14] and [8] did simulate the same performance with negligible increase of 1.1% in terms of moment capacity for the later model.

WORK IN PROGRESS

While writing this paper, we will be testing the first two specimens, Specimen 0 and 1, experimentally at “The Applied Laboratory for Advanced Materials and Structures” (ALAMS) headed by Dr. Shahria Alam

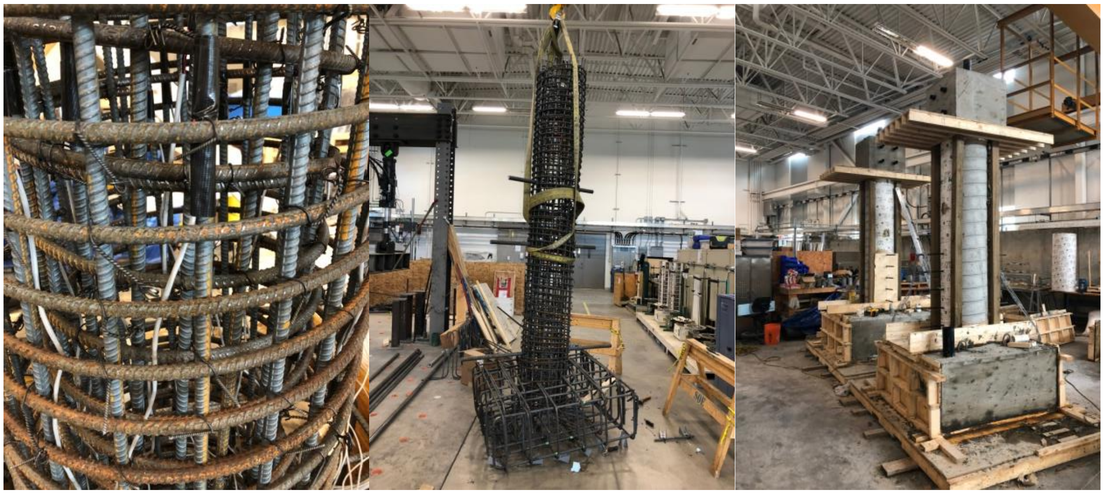

Figure 12.One and two layers of spirals specimens prepared for testing at ALAMS

ACKNOWLEDGMENTS

Financial contributions of Natural Sciences and Engineering Research Council of Canada for conducting this research is acknowledged. The authors also acknowledge S-FRAME Software Inc for their financial contribution, software donation and assistance in implementing various material models in S-CALC to conduct this research.

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