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FRP for Sustainable, Resilient, and Seismically Resistant Concrete Structures

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Abstract **-** The research, underway at the University of Toronto, investigates FRP-reinforced concrete structures under extreme environments and extreme loads such as seismic to establish robust design guidelines**.** This article summarizes the performance of FRP and FRP-reinforced concrete structures under extreme weather conditions, addressing durability concerns exacerbated by climate change. FRP composites, including bars and sheets, offer corrosion resistance, lightweight properties, and high strength-to-weight ratios, making them viable alternatives to steel reinforcement. However, their susceptibility to degradation under extreme temperatures necessitated rigorous evaluation. A multi-phase experimental and analytical research program was conducted, encompassing tensile tests, bond assessments, beam analyses, and FRP-wrapped cylinder studies under varied thermal and environmental conditions. Test results revealed critical insights: FRP sheets exhibited a 30–40% bond strength reduction at 60°C (exceeding resin glass transition temperatures), while GFRP bars experienced up to 26% bond strength loss after prolonged 80°C exposure. Over-reinforced beams, aligned with Canadian design codes (CSA S806-12/S6-19), demonstrated minimal strength degradation (≤5%) under thermal conditioning, underscoring the importance of design philosophy. Externally FRP-wrapped shear-critical beams showed enhanced strength (up to 112% for GFRP and 96% for CFRP under ambient conditions), though elevated temperatures reduced effectiveness by 10–20%. FRP confinement improved concrete cylinder ductility by 600%–700%, yet epoxy softening at 60°C diminished strength gains by 15% to 53%. Freeze-thaw cycles had a negligible impact on FRP-wrapped specimens. Analytical efforts yielded empirical models predicting GFRP bar tensile strength decay at elevated temperatures and theoretical models for the shear capacity of FRP-reinforced beams, validated with experimental data (average predicted-to-test ratios of 0.96–1.00). The findings summarized in this article advocate for revised code provisions to account for temperature-dependent FRP performance, ensuring sustainable, resilient infrastructure. By integrating material behaviour, structural response, and environmental effects, this research advances FRP applications in climate-adaptive construction.

Keywords**:** FRP bars, climate change, FRP sheets, FRP-reinforced concrete, extreme temperatures, resilient, sustainable.

1. Introduction

In a world increasingly affected by climate change, the durability and sustainability of construction materials and structures are critical. The research program underway at the University of Toronto over the last three decades explores the performance of fibre-reinforced polymers (FRP) and FRP-reinforced concrete structures under a variety of loads and environmental effects including rising global temperatures caused by climate change. FRP composites (bars and sheets) have been gaining popularity among the engineering community to mitigate the deterioration issues in structures. FRP bars when used internally in reinforced concrete structures offer remarkable advantages over traditional steel reinforcement, including resistance to corrosion, lightweight properties, and an exceptional strength-to-weight ratio. Likewise, for external applications to retrofit existing structures, FRP sheets have become one of the most feasible options for life extension because of their lighter weight, higher tensile strength, ease of application and cost efficiencies.

While FRP composites offer great advantages, they can still deteriorate under extreme environments [1]. The behaviour of FRP composites under various high-temperature scenarios, a direct consequence of climate change [2], necessitated deeper investigation. In this paper, an overall view of the ongoing research is presented focusing on selected areas including the performance of FRP materials and FRP-reinforced concrete members exposed to elevated temperatures. Experimental work is followed by robust analytical work which developed empirical models for the tensile strength of FRP bars and FRP sheets at elevated temperatures, theoretical models for the shear capacity of FRP-reinforced concrete beams and FRP-confinement models for the seismic design of structures.

2. Research Phases and Objectives

Over the past several years, an extensive experimental program has been conducted, encompassing various studies aimed at evaluating the resilience of FRP materials under extreme weather conditions and seismic loading. This article presents a summary of the objectives and key findings from these investigations. For clarity in this article, the overall research program is categorized into six distinct phases. The six phases—four experimental (Phases 1-4) and two analytical (Phases 5-6)—focus on recent studies examining the effects of climate change on FRP bars and sheets.

2.1 Experimental Phases and Objectives

The main objectives of the four experimental phases are listed below and a brief summary of the experimental work is provided in Table 1a and Table 1b for the work done on FRP bars and sheets, respectively.

1. To investigate the tensile behaviour of FRP bars/sheets at elevated temperatures under different test protocols.
2. To study bond behaviour between FRP bars and concrete, and FRP sheets and concrete under accelerated conditioning including elevated temperatures.
3. To investigate the structural performance of beams reinforced with internal GFRP bars or externally wrapped with FRP sheets under ambient conditions, long-term thermal conditioning and at elevated temperatures.
4. To study the behaviour of FRP-wrapped concrete cylinders under different environmental conditions including elevated temperatures and freeze-thaw cycles.

Table 1a: Summary of experimental phases on FRP bars

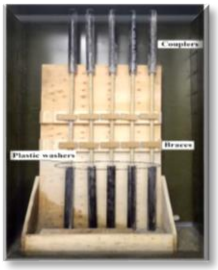
	Experimental Phases		
Phases	Phase 1	Phase 2	Phase 3
Specimens	Tension Coupons	Bond Specimens	Beam Specimens
Summary of specimens	• 46 GFRP Coupons • Tested under three temperature protocols • Temperature range: 25ºC-300ºC	• 37 bond specimens (24 pullout + 13 beam bond) • Conditioning: 50ºC and 80ºC for four months under 60% relative humidity.	• 12 large beam specimens (10 flexural- + 2 shear- critical). • Conditioning: 50ºC for four months under 60% relative humidity and sustained load.
Construction of specimens (images)			
Testing of specimens (images)			

Table 1b: Summary of experimental phases on FRP sheets

Experimental Phases				
Phases	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**
Specimens	**Tension Coupons (FRP sheets)**	**Bond Specimens (FRP sheets-concrete)**	**Beam Specimens (external FRP sheets)**	**FRP-wrapped concrete cylinders**
Summary of specimens	**[1]** 78 CFRP and GFRP coupons **[2]** Tested under three protocols **[3]** Temperature range: 25ºC-150ºC	**[1]** 42 bond specimens (30 doubles-shear +12 flexural) **[2]** Tested up to 60ºC temperature exposure	**[1]** 12 FRP-wrapped shear critical beams **[2]** Tested up to 60ºC temperature exposure	**[1]** 28 FRP-wrapped concrete cylinders **[2]** Tested up to 60ºC temperature exposure
Construction of specimens (images)				
Testing of specimens (images)				

2.2 Analytical Phases and Objectives

Several analytical studies were carried out in conjunction with the experimental work to develop models for design purposes. The analytical work was divided into two phases of which the objectives are briefly outlined here.

5. Development of an empirical model to predict tensile properties of GFRP bars at elevated temperatures for use in design as well as numerical modelling. Also, to establish a minimum dependable limit for bar strength at elevated temperatures.
6. Development of a theoretical model to predict the shear capacity of GFRP-RC beams.

3. Summary of Findings from each Phase

This section presents the key findings from all the phases summarized above. These results offer a robust foundation for understanding the resilience of FRP-reinforced members. The investigations encompass behaviour of these members under both extreme weather conditions and seismic loading. The key findings, along with relevant publications, are outlined below.

3.1 Tensile Behaviour at Elevated Temperature

3.1.1 FRP Bars

46 coupon specimens were tested in three different protocols to simulate real-life load conditions, and the results are summarized in Figure 1(left). Sustained temperature (ST) protocol involved conditioning the specimens to target temperatures first and then subjecting the specimen to monotonically increasing load until failure. Sustained Stress Displacement Held constant during heating (SSDH) involved inducing a specific deformation in the specimens under load and then exposing the specimen to increasing heat until failure. Finally, Sustained Stress Load Held constant during heating (SSLH) protocol involved applying a specific preload to a specimen and then subjecting it to increasing heat until failure. These temperature protocols reflected field conditions in various scenarios and provided boundary envelopes for bar behaviour. The GFRP bars behaved differently under different loading protocols providing critical values for design purposes in different applications. SSLH tests yielded the most critical results for most conditions because of the constant load level during the entire heating process.

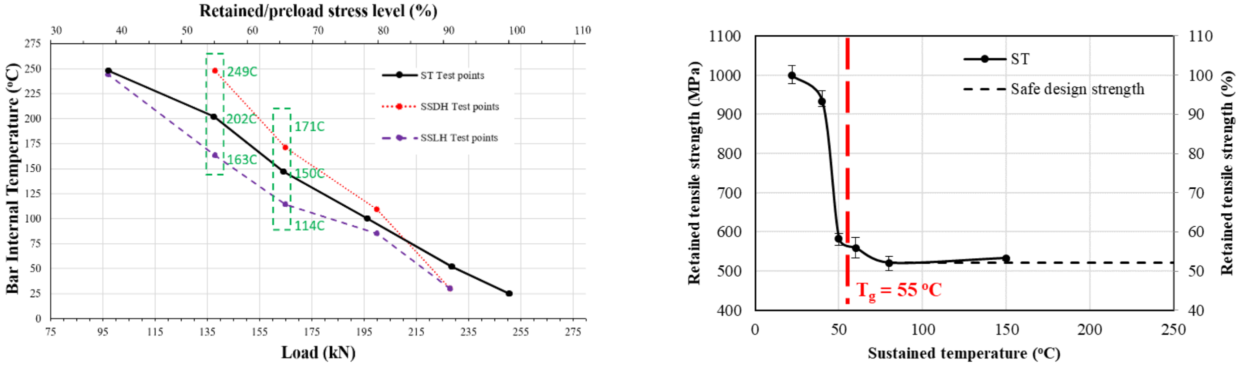


Fig. 1: Left-Summary of coupon test results at higher temperatures [3]; Right- Tensile strength variation of CFRP sheets under ST protocol [4]

3.1.2 FRP Sheets

A total of 78 FRP sheet specimens were tested in three different protocols as discussed above for FRP bars. FRP sheets exposed to sustained elevated temperatures showed a significant drop in strength around 55^{o}C which is approximately the glass transition temperature, T_g, of the resin (Figure 1-right). Moreover, ST protocol yielded lower tensile properties compared to the other two protocols and is most appropriate for design purposes.

3.2 Bond Behaviour under Thermal Conditioning

3.2.1 FRP Bars

Test results of 37 bond specimens displayed in Figure 2(left) show that long-term thermal exposure adversely affects the bond performance of GFRP bars. Pull-out specimens experienced a reduction in the average bond strength of about 10% and 23% as a result of 4-month-long exposure to 50^{o}C and 80^{o}C, respectively, for specimens with bond length of $5d_b$. The comparable reductions for $10d_b$ specimens were about 12% and 26%. Beam specimens with $5d_b$ and $10d_b$ bonded length experienced a reduction of about 20% in average bond strength at 50^{o}C. Beam specimens experienced significantly larger bond reductions than pullout specimens which is significant for most design applications.

3.2.2 FRP Sheets

To study the effects of elevated temperatures on the FRP (CFRP and GFRP) sheets to concrete bond, double-shear and beam bond tests were conducted at 20^{o}C, 40^{o}C, and 60^{o}C. Regardless of the test type and fibre types, it was found that the bond strength of FRP sheet to concrete experienced no significant reduction at 40^{o}C; however, exposure to a temperature of 60^{o}C (beyond T_g) showed a large (30% to 40%) reduction in bond properties (Figure 2-right) due to epoxy softening.

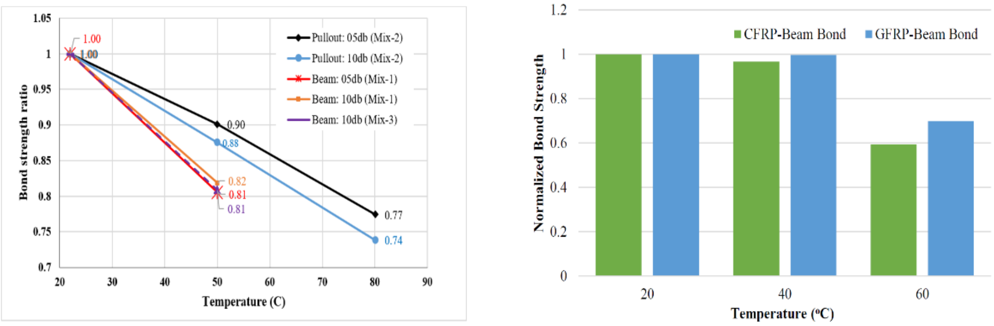


Fig. 2: Left-Reduction in bond strength due to long-term thermal exposure [5]; Right- Reduction in bond strength of FRP sheets in beam specimens [6]

3.3 Beam Specimens

3.3.1 Flexural behaviour of beams reinforced with FRP bars (before and after thermal conditioning)

Figure 3 (Left) shows the ambient response of 5-flexural critical beams involving different variables such as stirrup shapes, and longitudinal and transverse reinforcement ratios. All the beams in this study were tested until ultimate failure to investigate post-concrete crushing behaviour. Closely spaced stirrups in a pure flexural zone substantially improved the flexural behaviour of the beam due to the confinement of concrete in the compression zone. Of the two types of stirrups investigated, it was found that R-type closed stirrups (closed rectangular shape) provided better confinement than U-type stirrups and resulted in a significant increase in ultimate load and deformation capacity

Thermal conditioning (50°C for four months) caused a reduction of about 22% in the ultimate load capacity of the under-reinforced beam (Figure 3 right – red dashed curve shows the behaviour of the conditioned beam). Over-reinforced beams (1.72% longitudinal reinforcement) observed a maximum of 5% reduction in the ultimate failure load due to the same conditioning (Figure 4). Likewise, conditioning caused a reduction of about 2% in the ultimate load capacity of the shear critical beams. Overall, it may be concluded that the thermal exposure resulted in no significant degradation if the beams are designed in an over-reinforced manner as recommended by Canadian design codes (CSA S806-12 and CSA S6-19).

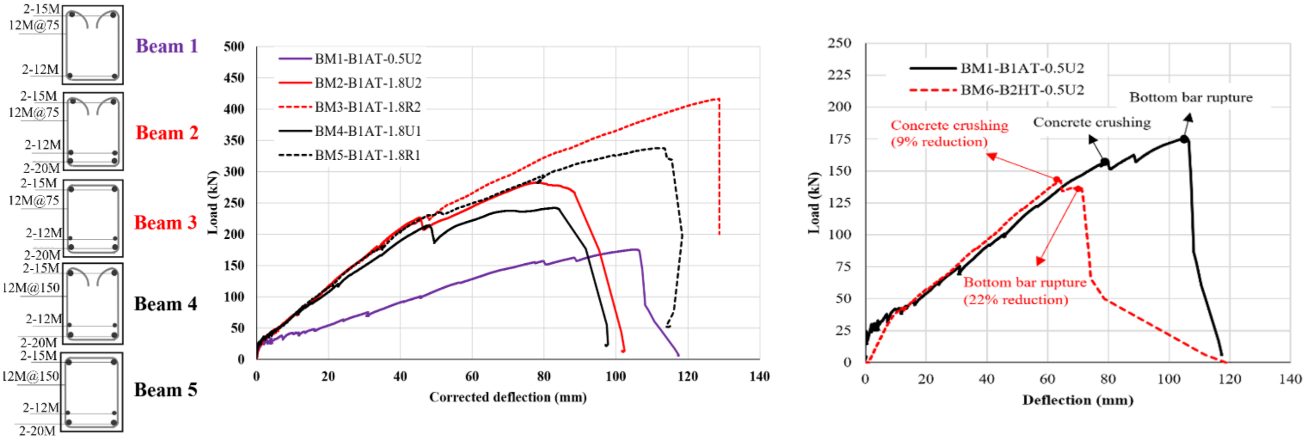


Fig. 3: Left-Ambient responses of 5 flexural critical beams; Right-Thermal behaviour of under-reinforced beam [7]

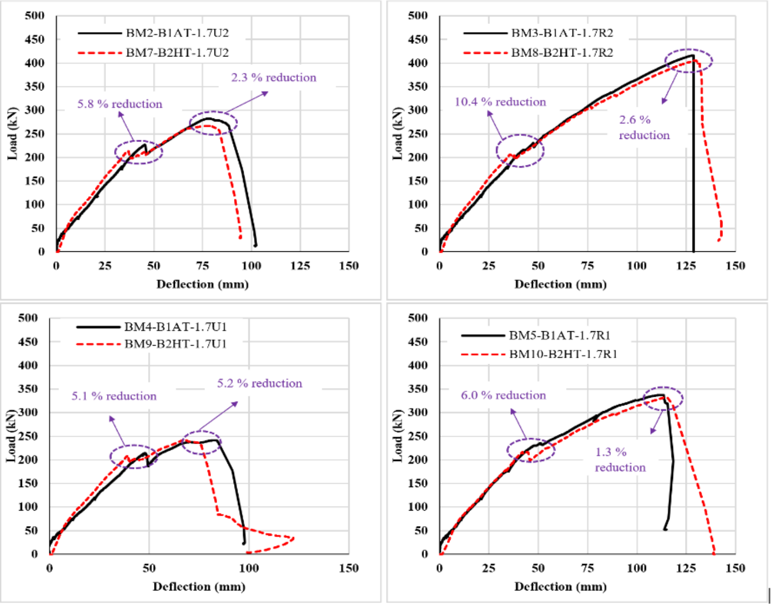


Fig. 4: Thermal performance of conditioned (dashed curves) over-reinforced beams [7]

3.3.2 Shear critical beams strengthened with FRP wraps

To understand the effects of climate change on the effectiveness of anchored FRP wraps, twelve shear-critical RC concrete beams were tested including two unwrapped, six CFRP-wrapped, and four GFRP-wrapped beams. CFRP-strengthened beams were wrapped with a single layer of CFRP U-wrap and CFRP anchors whereas, for GFRP-strengthened beams, two layers of GFRP U-wraps were used along with GFRP anchors. The beams were subjected to combined sustained load and elevated temperature (40°C or 60°C). Both monotonic and cyclic loadings were investigated. It was found that a single layer of anchored CFRP U-wraps enhanced RC beam strength by up to 96% under ambient conditions which reduced to a maximum increase of 79% on exposure to 60°C under both monotonic and cyclic loadings [8]. In comparison, two-layered anchored GFRP U-wraps enhanced the shear strength of beams by up to 112% under ambient conditions and up to 96% in specimens exposed to 60°C under both monotonic and cyclic loadings.

3.4 FRP-wrapped concrete cylinders

To address the effects of climate change, twenty-eight unconfined and FRP-confined concrete cylinders were studied under ambient conditions, at elevated temperatures, and after freeze-thaw exposure [9]. Single-layer of CFRP and GFRP sheets were used to wrap the concrete cylinders with an overlap of 100 mm. To investigate the thermal behaviour, the cylinder was either subjected to an elevated temperature of 40°C or 60°C for about 30 minutes and then tested at the same temperature or exposed to 300 or 500 freeze-thaw cycles following which testing was carried out under room conditions.

A single layer of GFRP wrap improved the compressive strength of an unconfined concrete cylinder by 21% to 29% and ductility by about 600%, while a single layer of CFRP wrap enhanced concrete strength and ductility by about 70% and 600% to 700%, respectively, when tested under room conditions. Exposure to a temperature of 40°C showed no significant effect on the behaviour of FRP-confined concrete whereas conditioning at 60°C dropped the strength enhancement to about 15% for GFRP-confined concrete cylinders and 53% for CFRP-confined concrete cylinders due to the epoxy softening. Deformation capacities of the concrete were also reduced at 60°C conditioning. Unconfined concrete cylinders tested after the freeze-thaw conditioning displayed about 9% and 11% loss in the ambient compressive strength corresponding to 300 cycles and 500 cycles, respectively. In comparison, FRP-wrapped concrete cylinders showed no significant effect of freeze-thaw cycles on strength and ductility when compared with the ambient FRP-wrapped cylinders.

3.5 Empirical model to predict temperature-dependent tensile strength of GFRP bars

A database of more than 500 specimens from 11 different studies was created to study the factors affecting the tensile strength retention of GFRP bars at elevated temperatures. The thermal behaviour of GFRP bars is influenced by numerous factors, such as the FRP bar surface, bar size, test methodology, loading rate, and the free bar length exposed to elevated temperatures. While the variations in data were significant, a statistical analysis was carried out to develop an empirical model to evaluate the reduction in the tensile strength as a result of temperature exposure and to determine the fire ratings of GFRP-RC members. Only the proposed model for the properties of GFRP bars is presented here. The model is expressed in three stages in a piecewise manner (Figure 5) and was validated against the assembled database and numerical modelling. This model can be used for the design of members under extreme weather conditions and develop procedures for the behaviour of FRP-reinforced concrete structures under fire.

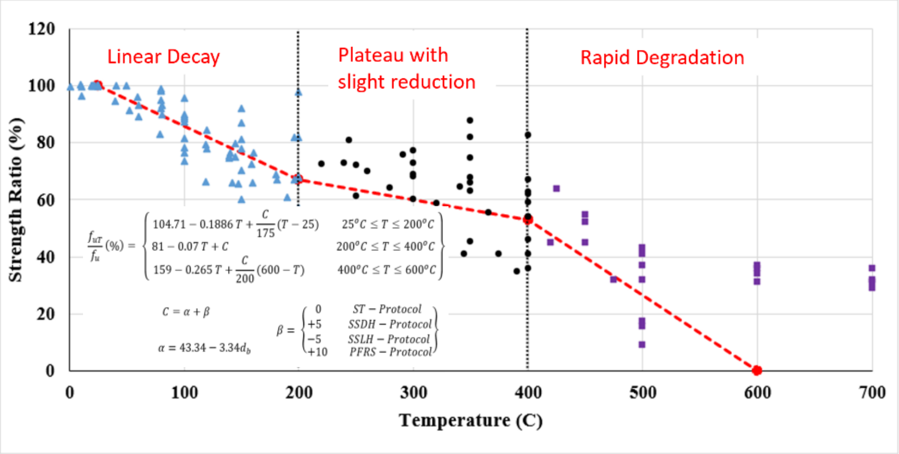


Fig. 5: Empirical model to predict temperature-dependent tensile strength of GFRP bars [10]

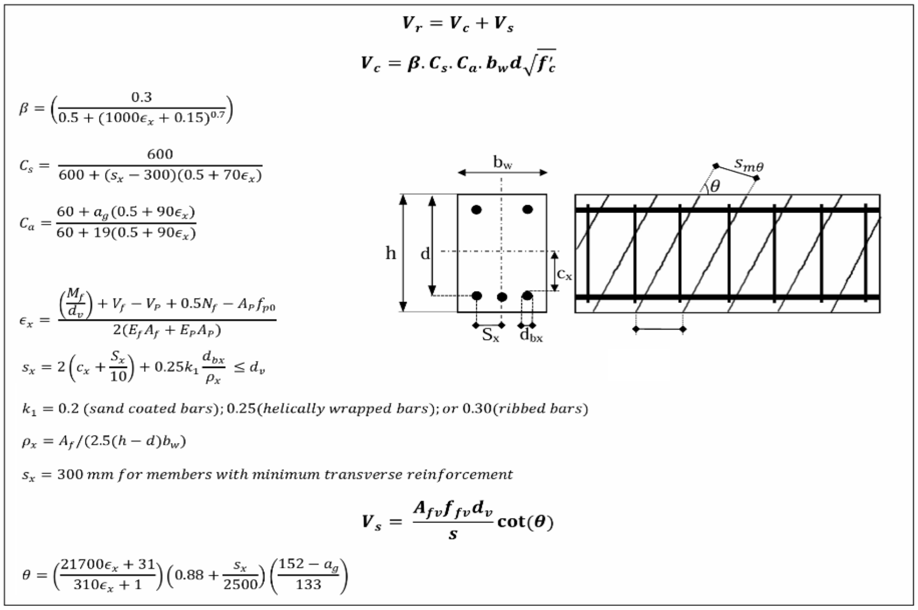
3.6 Theoretical model to predict shear capacity of GFRP-reinforced beam

While the detail of this work is beyond the scope of this extended abstract, a summary of the theoretical model developed to predict the shear capacity of GFRP-RC beams is shown in Figure 6. The model achieved an average predicted-to-test strength ratio of 0.96, with a 13% coefficient of variation (COV) for beams without transverse reinforcement, and a ratio of 1.00 with a 16% COV for beams with GFRP stirrups. The main feature of the model is that it accounts for higher mid-depth strain in the case of GFRP-reinforced members compared to those reinforced with steel.

4. Conclusion

Given the challenges posed by climate change, it is crucial to address the effects of a warming climate and extreme weather events. This study summarizes the work on data-driven insights into the risks associated with FRP-reinforced concrete members (internal FRP bars or external FRP sheets) subjected to elevated temperatures. The detailed results from this holistic investigation can be found in the listed published articles. A wide variety of specimens (tension, bond, beam, and compressive cylinders) were tested in this program to provide a strong database for design provisions. Results can be used to develop appropriate correction factors for design codes to address the reductions in tensile strength and bond strength of FRP bars and sheets as a result of elevated temperatures caused by climate change or fire.

Other work in this extensive research program at the University of Toronto especially on shear in FRP-reinforced beams and seismic behaviour of FRP-reinforced columns, not appropriately addressed here due to a lack of space, provides insights into the new applications of FRP in concrete structures that can help develop more robust and resilient infrastructure.



$$\boldsymbol{V_r = V_c + V_s}$$

$$\boldsymbol{V_c = \beta . C_s . C_a . b_w d\sqrt{f'_c}}$$

$$\beta = \left(\frac{0.3}{0.5 + (1000\epsilon_x + 0.15)^{0.7}}\right)$$

$$C_s = \frac{600}{600 + (s_x - 300)(0.5 + 70\epsilon_x)}$$

$$C_a = \frac{60 + a_g(0.5 + 90\epsilon_x)}{60 + 19(0.5 + 90\epsilon_x)}$$

$$\epsilon_x = \frac{\left(\frac{M_f}{d_v}\right) + V_f - V_P + 0.5N_f - A_P f_{p0}}{2(E_f A_f + E_P A_P)}$$

$$s_x = 2\left(c_x + \frac{S_x}{10}\right) + 0.25k_1\frac{d_{bx}}{\rho_x} \le d_v$$

$$k_1 = 0.2\ (sand\ coated\ bars); 0.25(helically\ wrapped\ bars); or\ 0.30(ribbed\ bars)$$

$$\rho_x = A_f/(2.5(h-d)b_w)$$

$$s_x = 300\ mm\ for\ members\ with\ minimum\ transverse\ reinforcement$$

$$\boldsymbol{V_s = \frac{A_{fv} f_{fv} d_v}{s} \cot(\theta)}$$

$$\theta = \left(\frac{21700\epsilon_x + 31}{310\epsilon_x + 1}\right)\left(0.88 + \frac{s_x}{2500}\right)\left(\frac{152 - a_g}{133}\right)$$

Fig. 6: Theoretical model to predict shear capacity of beams [11]

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