



## Cyclic Performance of Glass-Fibre Reinforced Polymer (GFRP) Bars and their Seismic Application in Reinforced Concrete Bridge Piers

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### **Abstract**

The corrosion of steel in reinforced concrete (RC) structures has developed into an issue of paramount importance due to its well-documented impact on structural performance and service life. With the ever-growing amount of corrosion-damaged infrastructure requiring repair and maintenance, international interest has grown in the use of non-metallic reinforcing such as Glass-Fibre Reinforced Polymer (GFRP). Current literature suggests the bars can be an effective substitute for steel reinforcing due to their high tensile strength, lightweight and non-corrosive nature. Despite this, previous testing has shown the compressive strength of the bars to be much less than the tensile strength and the lack of sufficient data means most codes ignore or disallow their contribution in compression members. Moreover, the linear-elastic nature of GFRP is an intimidating factor for practitioners when considering the common reliance on the ductility of steel reinforcing to dissipate energy in RC structures in seismic settings. As a result, current applications of the bars are still largely limited to non-seismic zones and members under flexure and shear.

A research project being undertaken at the University of Canterbury aims to explore the potential of GFRP as a primary reinforcement in compression members, such as columns and piers, located in seismically active regions. The first phase of this project looks to capture the monotonic compression and cyclic tension-compression behaviour of the bars including the effect of buckling. A modified RILEM four-point beam test is utilised where single bars are cast in concrete half-beams with a specified central clear length, before being tested under displacement-controlled monotonic or cyclic loading until failure. Next, a series of one-third scale bridge piers reinforced with varying configurations of steel and GFRP bars are to be tested under simulated gravity and cyclic lateral loading, with a particular focus on the post-peak behaviour of the plastic hinge region.

In this paper, a review of literature will be presented regarding the current state-of-the-art of GFRP bars in compression and their seismic application to reinforced concrete columns. Secondly, initial results of the modified RILEM beam test will be analysed, with an emphasis on the impact of buckling and cyclic loading on the peak compressive strength of the bars. Finally, some details of experimental testing being undertaken on the seismic performance of GFRP-reinforced bridge piers will be discussed. The results and conclusions drawn from this project are envisioned to provide the foundation for new tools and confidence in the application of GFRP as a primary reinforcement in RC structures.

*Keywords: Reinforced Concrete, FRP, Buckling, Cyclic, Durability*



## 1. Introduction

The ongoing evolution of materials and technologies within the construction industry has allowed engineers globally to push the boundaries of structural performance and efficiency. Steel-reinforced concrete is the most recent of which to be heavily utilised in structures throughout the world due to its versatility, constructability and robustness – all while incorporating conventional, easily sourced materials. Despite the various benefits associated with this composite material, the corrosion of the internal steel reinforcing has proven to be a significant weakness. The long-term effects associated with the maintenance and reparation of RC structures are phenomenal. A recent report by the American Society of Civil Engineers (ASCE) stated that in America alone, 9.1% of the 600,000 bridges have been labelled as structurally deficient or functionally obsolete (primarily due to corrosion related anomalies). The report also concluded that approximately 40% of the bridges that were constructed after 1945 need to be replaced by the end of this decade [1].

The overwhelming magnitude of this degradation, along with the ever-growing demand for increased construction speeds, functionality and robustness, has led to the development of new innovative structural solutions consisting of state-of-the-art materials. Among these new materials, significant interest in fibre-reinforced polymers (FRP) has been shown by the wider construction industry due to their high tensile strength, lightweight and non-corrosive nature. Currently, FRP bars are available in a range of forms depending on the type of fibre they incorporate: Glass, Carbon, Aramid or Basalt. Of these options, Glass FRP (GFRP) bars are typically the most economically competitive solution and are therefore the most feasible option for implementation into RC infrastructure.

Despite increased acceptance of the material within the industry, the structural applications of the bars are still largely limited to members under flexure and shear [2]. The compression strength of the bars is typically much less than the tensile strength and although testing has shown positive results, limited research in the area means the bars have not yet been utilised widely in compression members such as columns or piers. Moreover, the linear-elastic nature of GFRP up until brittle failure is an intimidating factor when considering the common reliance on the ductility of steel reinforcing to dissipate energy in RC structures in seismic settings. To this day, insufficient data has been gathered on the behaviour of GFRP-reinforced members under seismic loading to allow acceptance of such use. This leaves a window of opportunity for future research, with particular applicability to the seismic, coastal areas of the world, where the aggressive environment proves to be a critical issue.

## 2. State-of-the-Art Literature Review

### 2.1 Glass Fibre-Reinforced Polymer (GFRP) Reinforcing Bars

GFRP bars are a composite material consisting of small glass fibres embedded longitudinally in a polymeric resin matrix. These fibres carry the load along the length of the bar and provide the required strength and stiffness in one direction. This matrix has the crucial role of transferring the load between the glass fibres and protecting them from any degrading environmental effects. FRP bars exhibit a linear-elastic stress-strain behaviour when subject to longitudinal tensile loads. The consequence of this elastic behaviour is that the bars do not undergo any yielding before rupture and failure occurs in a sudden, brittle manner. This tensile behaviour is very different to steel, which exhibits ductile behaviour. Despite having a higher ultimate strength than steel, GFRP bars have a significantly lower modulus of elasticity that needs to be carefully considered in the design phase due to the larger resulting deformations.

Previous testing on GFRP bars have indicated that the compressive strength is lower than the tensile strength and in most cases their contribution in compression is ignored [3, 4]. Testing of the bars in compression is made difficult by the occurrence of fibre micro-buckling due to the nonhomogeneous and



anisotropic nature of the material. The failure mode under longitudinal compressive stress depends on a range of factors including the type of glass fibre, the fibre-volume fraction, and the type of resin used. Potential failure modes include transverse tensile failure, longitudinal shear failure or fibre micro-buckling [5]. Generally, the compressive strengths are higher for bars that have higher tensile strengths. Mallick [6] and Wu [5] reported compressive strengths of 55% of the tensile strength for GFRP, while Deitz et al. [7] reported values of around 50%. Other researches have argued within the range of 30-65%. The compressive modulus of elasticity of GFRP bars have been reported as approximately 80% [5, 6] and 100% [7] of the tensile modulus. However, it should be noted that the lower values of the modulus may have been a result of premature failure during testing due to end brooming and internal fibre micro-buckling under compressive forces.

An investigation by Bruun [8] aimed to quantify the compressive buckling behaviour by testing 34 specimens of 25M GFRP bars under direct axial compression. The lengths of the specimen were varied to determine the relationship between unbraced length and strength. The interaction curve can be seen in Fig. 1 below, showing a distinct transition in the failure mechanism from crushing to buckling, with a transition zone in between.

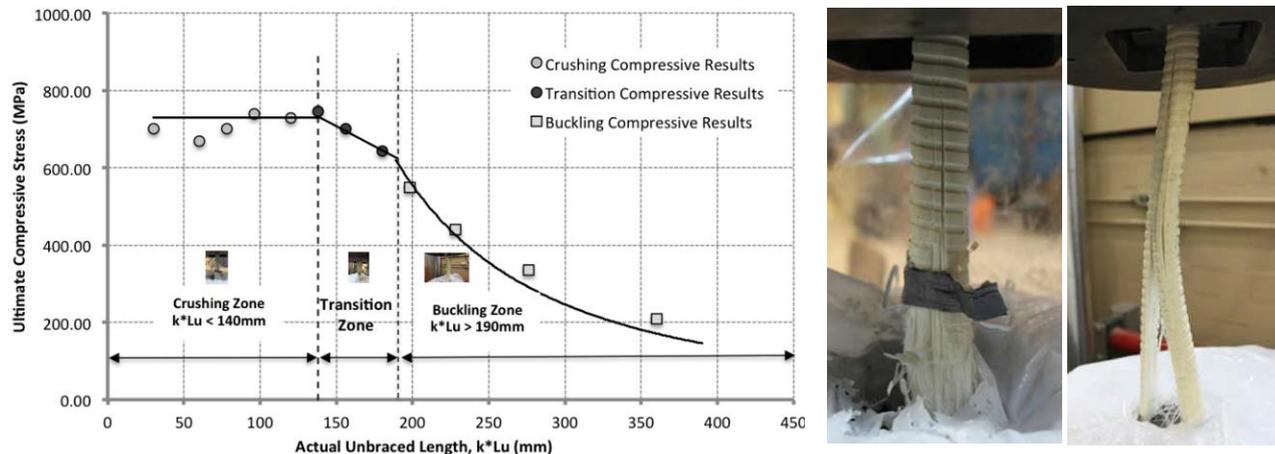


Fig. 1 - Strength and unbraced length interaction curve for 25M GFRP bars (left) and examples of compressive crushing (middle) and compressive buckling (right) failure [8]

Limited research has been published on the cyclic behaviour of GFRP reinforcing bars. An experiment from Noel and Soudki [9] aimed to determine and compare the tensile fatigue life of bare bars and bars encased in concrete beams subject to bending. The study concluded that bars embedded in concrete may suffer shorter fatigue lives by a full order of magnitude when compared to an equivalent bare bar. This behaviour was mainly attributed to the abrasion that occurs from the cyclic bond-slip between the bar and the concrete. To the authors' knowledge, no research has been undertaken to understand the low-cycle axial tension-compression behaviour of the bars themselves.

One of the primary challenges hindering a more detailed understanding of the axial behaviour of GFRP bars is the lack of suitable gripping devices and standard testing procedures. The low compression strength in the transverse direction makes them very sensitive to transverse pressure. As a result, the application of conventional gripping mechanisms leads to strain concentrations and ultimately premature failure of the bar within the gripped region [9]. This phenomenon can significantly affect test results. Specifically designed grips have been developed in the past for monotonic testing with mostly positive results [10], however, a device capable of accurately investigating the cyclic tension-compression behaviour of the bars is non-existent.



## 2.2 GFRP-Reinforced Concrete Columns in Compression

The lack of sufficient data and understanding of GFRP bars in compression, means they have yet to be effectively implemented into RC compression members on a wide scale. The lower compressive strength and the potential for micro-buckling within the bar increase the risk of a premature brittle failure occurring within the member. Also, the lower modulus of elasticity of the material means the GFRP reinforcing is likely to contribute less to the compressive axial load capacity when compared to steel. Extensive understanding and experimental data are essential in designing safe and efficient compression members when incorporating novel materials.

Alsayed et al. [11] explored the behaviour of RC columns under monotonic axial compressive loads when the steel longitudinal bars and ties were replaced with an equal amount of GFRP. The study concluded that replacing the longitudinal reinforcing with GFRP led to a 13% reduction in axial capacity, irrespective of what material was used for the ties. When only the lateral ties were replaced with GFRP, the axial load capacity reduced by 10% and there was no effect on the load-deformation response up to 80% of peak capacity. In similar testing shown in Fig. 2, Afifi et al. [12] found that ignoring the contribution of the longitudinal bars in compression, as per the Canadian code, underestimated the total capacity of the specimens on average by 35%.



Fig. 2 - Comparison of failure mechanisms under monotonic compressive loading: Rupture of GFRP spirals (left), buckling and rupture of longitudinal GFRP bars (middle) and buckling of longitudinal steel bars and rupture of spirals (right) [12]

A series of monotonic compression tests on full-scale square RC columns that were internally reinforced with GFRP bars and ties were performed by De Luca et al. [13]. The test results showed the behaviour of the GFRP-RC columns were very similar to steel-RC columns. However, the longitudinal GFRP bars contributed 5% of the axial capacity, compared to 12% for steel. Tobbi et al. [14] also performed similar experiments and found that the GFRP bars contributed 10% to the axial capacity of the RC columns, indicating the bars could be used in compression members if there was adequate confinement to eliminate bar buckling.

Despite some of the weaknesses associated with GFRP bars in compression, the linear-elastic stress-strain behaviour under tension makes the material very effective for use as transverse reinforcement to confine the concrete core. As the axial deformation of the member increases under axial load, the confining pressure from the GFRP keeps increasing with lateral expansion of the concrete core until the brittle failure of the section occurs due to rupture of the bars. This behaviour is very different to steel-confined concrete, where the steel bars yield, and the stress-strain plateau of the material becomes horizontal i.e. the elastic modulus becomes zero. This means the steel contribution to confinement declines and the lateral confining stress remains basically unchanged. The overall confined concrete behaviour in this phase is therefore dominated by the properties of the concrete.



A range of research has been completed to characterise the confinement behaviour of GFRP bars, develop analytical models and produce recommendations for their use. It was generally concluded that the GFRP and steel-RC columns behaved in a similar manner and exhibited linear load-strain behaviour up until around 85% of their peak load. The failure of the GFRP-RC columns with a large spiral spacing or small volumetric ratio (0.7%) was governed by buckling of the longitudinal bars, while the well-confined columns failed due to crushing of the concrete core and rupture of the GFRP spirals. The spacing of the GFRP spirals had a much greater impact on the confinement efficiency and ductility than on the strength capacity. Smaller spirals with closer spacing were more effective in resisting longitudinal bar buckling and showed ductile behaviour in the post-peak stage, meaning the columns failed in a more gradual manner than those with larger diameter bars at greater spacing. Larger GFRP transverse bars are needed when compared to steel due to the material's lower modulus of elasticity [15].

### 2.3 GFRP-Reinforced Concrete Columns under Seismic Loads

The linear-elastic behaviour of GFRP bars up until brittle failure raises concerns about the capability of the material as reinforcement in earthquake-resistant structures where the dissipation of the seismic-energy is typically expected by the inelasticity of the structural members. The low modulus of elasticity may also lead to reduced stiffness and shear strength of columns under lateral loads. Despite this, research suggests that if the unique properties of the material are explicitly accounted for within the design phase then GFRP-RC columns can achieve high levels of performance within seismic environments. Moreover, the elastic nature of the material means significantly less repair work would be required post-earthquake due to the lack of yielding within the reinforcement and reduction in residual drift. Only a limited amount of experimental research has been completed within this area thus far.

An investigation into this seismic performance was completed by Ali and El-Salakawy [16], where eight full-scale rectangular column prototypes reinforced internally with GFRP were tested under constant axial and increasing lateral cyclic quasi-static load. The authors looked to investigate the effect of longitudinal reinforcement type and ratio, level of axial load and stirrup spacing. The GFRP-RC columns showed a stable hysteresis behaviour up until failure at a drift capacity of 8.5-12.5% as shown in Fig. 3. This exceeded the limitations of North American building codes and is a clear indication that the deformability of the prototype columns replaced the ductility of steel reinforcing in dissipating some of the seismic energy when under axial load. However, the energy absorbed by the well-confined GFRP-RC columns was approximately one-half that of the steel-RC column. Columns with higher axial loads showed very rapid deterioration with relatively low strength gain and deformability at failure. Increasing the longitudinal reinforcement ratio enhanced the stiffness and lateral capacity of the column, however, a lower level of deformability at failure was achieved.

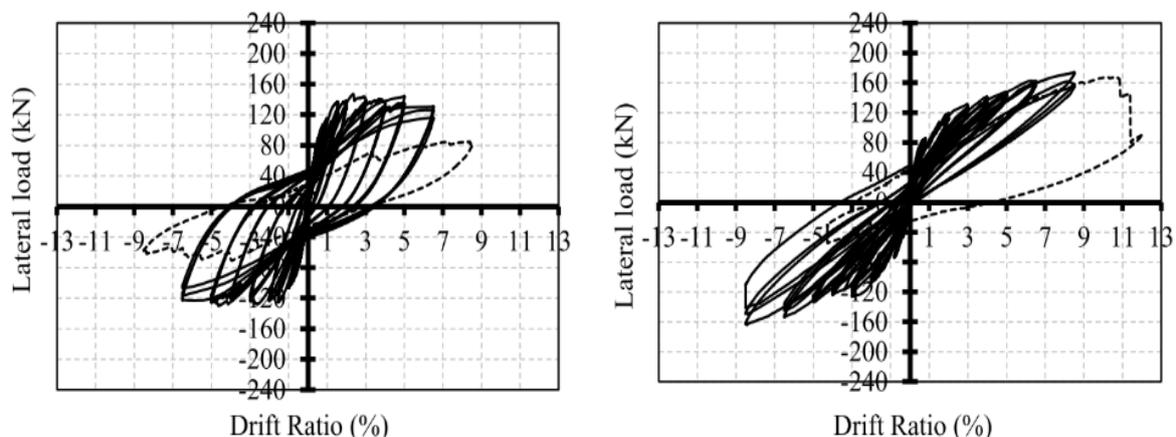


Fig. 3 - Hysteresis response for steel-reinforced (left) and GFRP-reinforced columns (right) with equal longitudinal reinforcement ratio, axial load level and transverse spacing [16]



In a similar experiment completed in Canada by Tavassoli et al. [2], nine circular RC columns reinforced longitudinally and transversely with GFRP were tested under combined lateral cyclic quasi-static and constant axial loading. The main variables investigated included the axial load level, the type of GFRP and the size and spacing of GFRP spirals. The authors found that, if designed accordingly, the columns could achieve much higher lateral drift capacity than design expectations and perform in a stable manner up until failure. The GFRP bars, due to their constant stiffness at large strains, performed in a more stable manner than the steel bars resulting in little strength degradation of the column. Despite the steel providing significant confinement at early stages, the GFRP bars provided increasing levels of confinement with increasing deformation, which delayed the crushing of the concrete core.

### 3. Compressive and Cyclic Performance of GFRP Bars

#### 3.1 Experimental Setup

The first experimental phase of this project aims to explore the effectiveness of GFRP bars as primary reinforcement in compression members by capturing their monotonic and cyclic stress-strain behaviour, including the effect of buckling. To achieve this, a RILEM beam test proposed by Soleymani-Ashtiani [17] is utilised, which has been modified to allow for cyclic loading as shown in Fig. 4 and Fig. 5. The primary testing bar is fully bonded within concrete half-beams ensuring a specified central clear length, before being tested under displacement-controlled monotonic or cyclic loading until failure. When the specimen is loaded, the bending moment induced at the centre of the beam is resisted only by the steel hinge and the testing bar. Variation of the bars slenderness ratio between specimens triggers a transition in the failure mechanism from compressive crushing to buckling. This test setup is favoured over conventional axial bar testing methods as the embedment of the bars in concrete removes the difficulties associated with the gripping of GFRP reinforcing that can lead to premature failure and inconclusive test results [9]. It also subjects the bar to both compressive and bending stresses that are more realistic in a column subject to lateral loads.

The GFRP bars used in this experiment have an average tensile strength of 930 MPa and elastic modulus of 58 GPa. A total of 30 specimen were tested with diameters of 12, 16 and 18 mm and varying slenderness ratios of 5, 8, 11 or 14. One rotary potentiometer and two linear variable differential transformers (LVDT) are used to monitor the vertical deflection of the beam and any undesired slip of the testing bar, respectively. A loading cell measures the magnitude of the load applied to the beam, which is used to calculate the stress in the bar using simple statics.

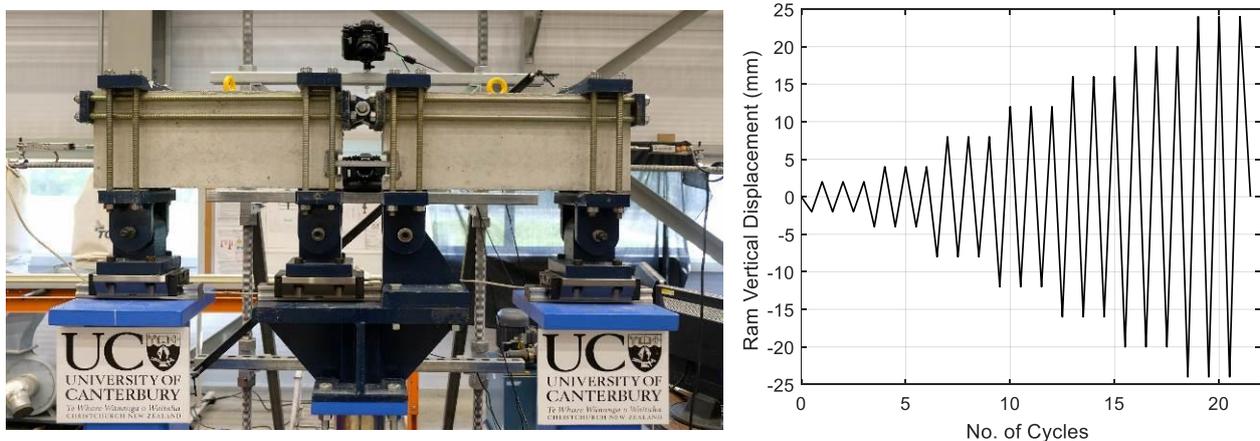


Fig. 4 - Front view of the modified RILEM beam test setup (left) and the cyclic loading protocol (right)



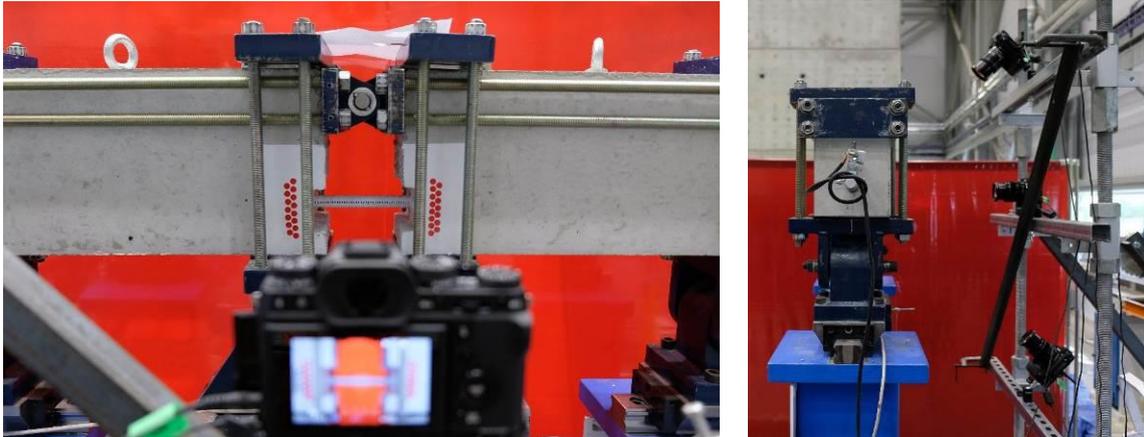


Fig. 6 - Central camera capturing particles on the bar and surrounding concrete (left) and camera configuration to capture the out of plane behaviour of the bar (right)

### 3.2 Initial Results

All specimen tested within this experimental phase failed due to compressive crushing, buckling or a combination of both. The peak compressive strengths for the GFRP reinforcing bars under monotonic and cyclic loading can be seen in Fig. 7 below. The GFRP bars performed very well under monotonic compression when compared to results from previous literature. For specimen with a slenderness ratio of five, the bars failed in the form of crushing with an average compressive strength of 914 MPa – 98% of the average tensile strength specified by the supplier. As the slenderness ratio increased to eight, eleven and fourteen, the average compressive strength reduced to 763 MPa, 507 MPa and 363 MPa, respectively. This is primarily attributed to bending effects for stocky specimen and a combination of bending and buckling effects for slender specimen. As the bar deforms, the resulting bending stresses reduce the compressive stress on the top tension face but amplify it on the bottom compression face, leading to an earlier initiation of fibre micro-buckling and eventual global failure.

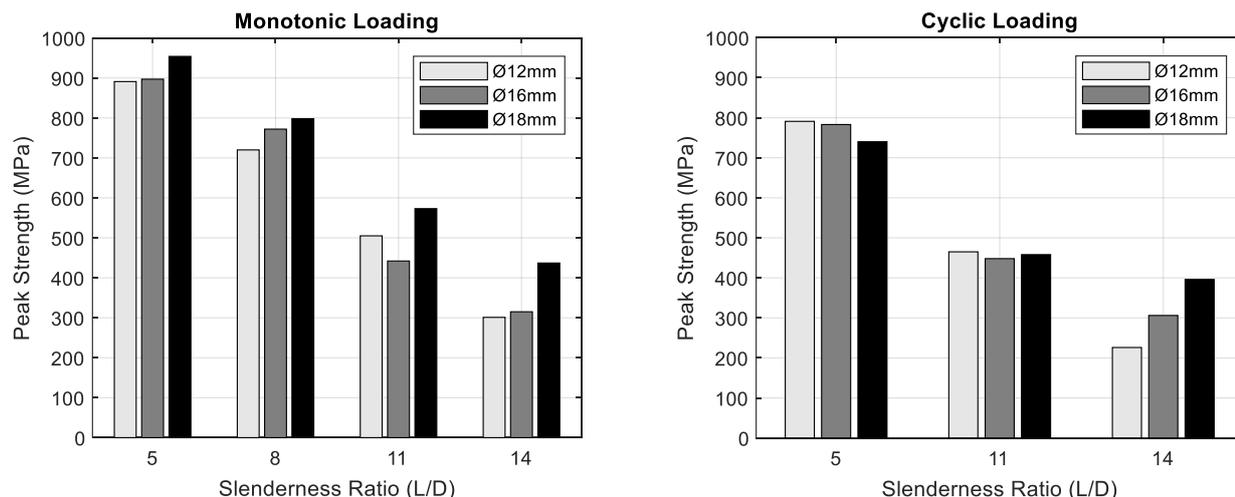


Fig. 7 - Peak strength developed for GFRP reinforcing bars under monotonic loading (left) and cyclic loading (right). Note: Cyclic specimen with a slenderness ratio of eight were used in a separate experiment for sustained loading and so are not presented here



An example of the monotonic and cyclic tension-compression performance of a stocky and slender specimen is shown in Fig 8. The force versus deflection response shows a stable cyclic behaviour with very little stiffness degradation. Any eventual reduction in stiffness is likely attributed to a loss in effective cross-sectional area of the bar due to fibres becoming disconnected and ineffective, rather than any significant change in the material properties that may occur in other materials such as steel. Despite this, bars with lower slenderness ratios displayed a significant reduction in strength when subject to multiple large-displacement cycles. This strength degradation was less noticeable in more slender bars as a buckling mechanism ensued before cyclic fatigue became a factor. It should be noted that any energy dissipation, indicated by the thickness of the hysteretic loops, is likely due to bond-slip interaction between the bar and the concrete rather than from the axial behaviour of the GFRP bar itself.

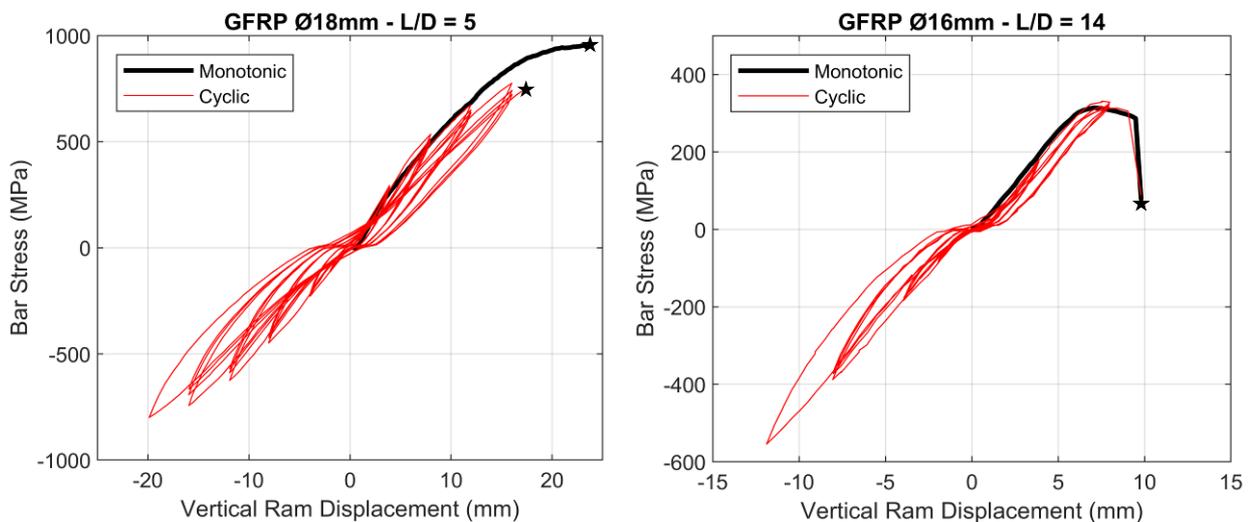


Fig. 8 – Behaviour of GFRP bars under monotonic and cyclic loading for slenderness ratios of five (left) and fourteen (right)

A distinct transition in the failure mechanism was observed as the slenderness ratio was varied (Fig 9). For stocky specimen, a very sudden crushing of the GFRP bar occurred close to the concrete interface resulting in the fibres exploding outward and the bar delaminating. The location of this failure is likely due to the testing rig not being perfectly symmetric. As the ram extends or retracts, any small differential displacements between the two sides of the beam induce shear stresses in the bar that may lead to the initiation of failure when it is under high levels of stress. Specimen with a slenderness ratio of eleven showed an interesting combination of crushing and buckling. Failure was generally initiated by micro-buckling of the bottom compressive fibres. This was followed by the tensile failure of the top fibres and delamination throughout the bar's length due to longitudinal shear failure of the resin. As the slenderness was increased to fourteen, global buckling dominated the failure of the bar. The sudden loss of load carrying capacity following the onset of buckling was primarily associated with longitudinal shear failure of the resin that caused the bar to split, rather than local failure of the fibres themselves.

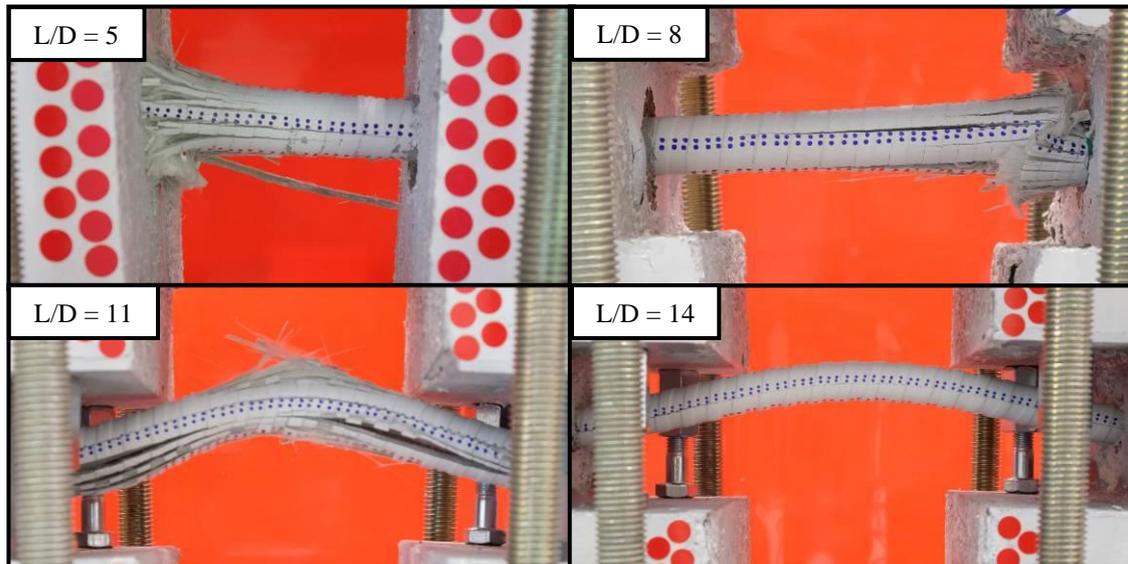


Fig. 9 - Comparison of failure mechanisms for GFRP reinforcing bars of varying slenderness ratio

## 4. Seismic Performance of GFRP-Reinforced Concrete Columns

### 4.1 Experiment Overview

The second experimental phase of this research project aims to further explore the potential of GFRP as a primary compression reinforcement by investigating the seismic performance of GFRP-reinforced bridge piers. The pier specimens are adopted from a prototype bridge (Fig. 10) representing a typical short-span concrete bridge in New Zealand, with a 1.5 m diameter circular pier supporting a pier cap and precast double hollow-core beams. This prototype bridge is scaled down to one-third in accordance with the Cauchy-Froude similitude law, to allow the piers to be tested in the laboratory. The test setup (Fig. 11) has been designed to allow for the application of constant axial gravity load to the specimen, whilst being subject to quasi-static cyclic lateral loading from a hydraulic actuator.

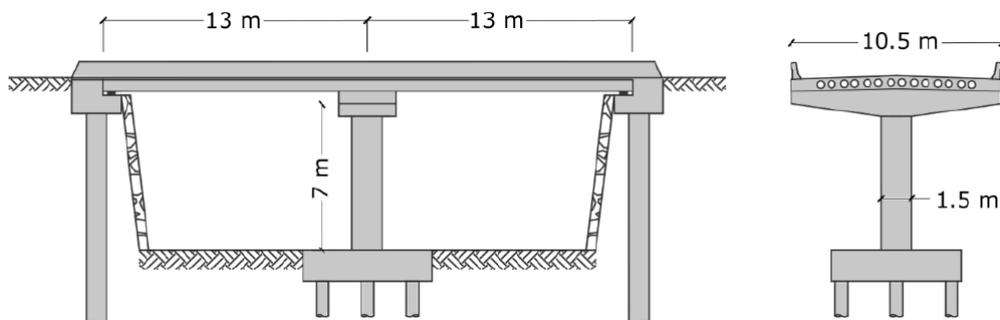


Fig 10. Prototype bridge used for specimen design [20]

A total of fourteen piers are being tested with varying reinforcement configurations. A conventional steel-reinforced specimen designed according to NZS3101:2006 Concrete Structures Standard is used as a benchmark for direct comparison. Next, multiple specimens are detailed with steel longitudinal bars and varying arrangements of transverse GFRP spiral reinforcement, in an attempt to increase the durability of the pier whilst still maintaining the well-documented ductile response associated with the steel longitudinal bars. Finally, a series of fully GFRP-reinforced specimen are to be tested. The main variables of these specimen include the spiral spacing, spiral bar size, the longitudinal reinforcement ratio and the axial load ratio. All



pier specimen that utilise GFRP reinforcing are designed in accordance with the Canadian design code; CAN/CSA-S806-12 [4]. Resulting data from this experiment will provide experimental evidence of the seismic application of these bars and the basis for developing further guidelines and recommendations for their successful implementation.

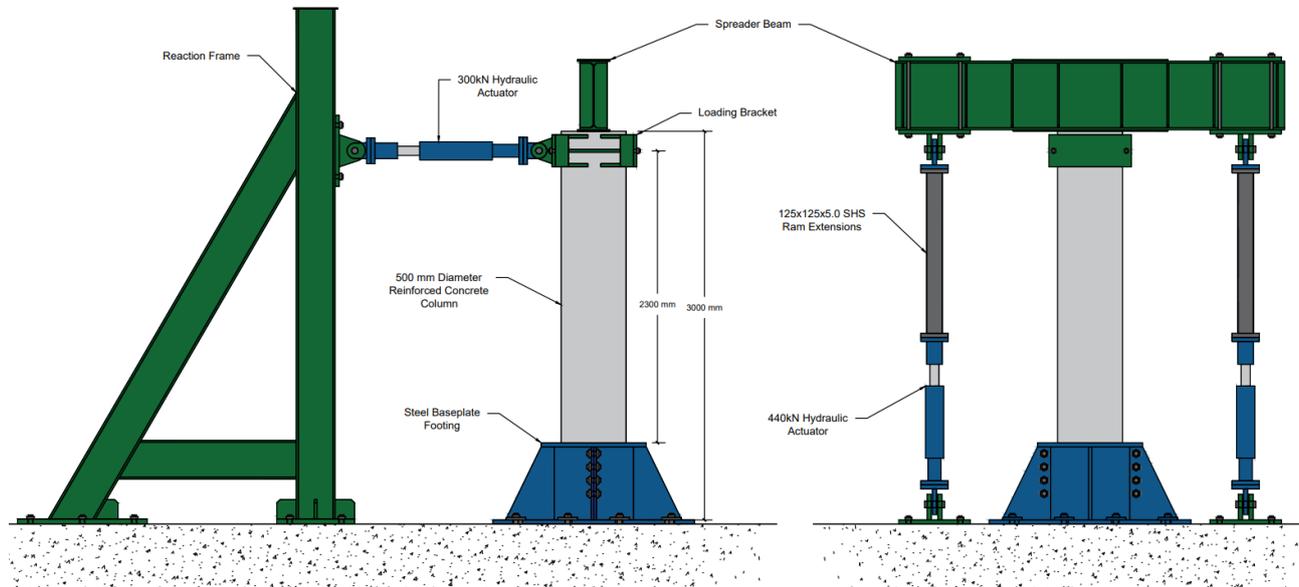


Fig. 11 - Proposed experimental setup for the testing of one-third scale, RC bridge piers under combined gravity and cyclic lateral loading

## 5. Conclusions

Previous literature suggests the compressive strength of GFRP reinforcing bars is significantly less than their tensile strength and a lack of data and guidance in current design codes means the bars have yet to be utilised widely in compression members such as columns or piers. Initial results from experimental testing has showed the crushing strength of GFRP bars is very similar to their tensile strength, indicating they may be effective for use as primary compressive reinforcement if confined well. Larger slenderness ratios resulted in lower compressive strengths due to the adverse effects of bending and buckling. The bars also behaved in a stable manner under cyclic loading with very little stiffness degradation, however, a significant reduction in compressive strength was observed for specimen that went through many large-displacement cycles.

An ongoing experiment at the University of Canterbury aims to further validate the performance and applicability of the bars by testing a series of one-third scale bridge piers reinforced with varying configurations of steel and GFRP under combined gravity and quasi-static cyclic lateral loading. Results from this experiment are expected to provide a detailed insight into the seismic performance of GFRP-reinforced members and allow for the development of guidance and recommendations for the successful implementation of this novel reinforcing material in RC structures.

## 6. Acknowledgements

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