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Full Scale Testing and Modeling of GFRP-Reinforced Concrete Guideway Beams for Elevated Transit Systems

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Abstract: To date, most of the effort and focus in the field of fibre reinforced polymer (FRP) reinforcement in concrete has been on highway bridges and structures, and very little work addresses mass-transit infrastructure systems. Many experimental studies have been conducted on small scale beams reinforced with FRP to evaluate short and long term performance. However, the number of studies on full scale specimens in service is comparatively small. This study will be the first of its kind on a full scale guideway reinforced concrete beam with Glass-FRP (GFRP) flexural and shear reinforcement. The guideway to be studied is comprised of 30 tonne reinforced concrete beams (up to 11.6 metres in length, each) laid end-to-end. The beams will be subjected to real life loading of monorail vehicles passing at speeds of up to 90 km/hr. This study will examine and compare the full size GFRP-reinforced beam with an adjacent one on the same track, which is conventionally reinforced with steel bars. These beams will be studied to directly compare short and long term performance as well as dynamic behaviour. In parallel to this study, half scale models of the GFRP-reinforced beam are to be constructed and tested in the lab to evaluate their complete performance to failure. This paper presents the analysis, and techniques used to predict the response of the full size beam, and by extension, design lab scale specimens which emulate the shear and flexural responses of their full size counterparts.

1 Introduction

Due to the current state of deterioration in present day infrastructure, fibre reinforced polymers (FRPs) are gaining acceptance not only as retrofitting materials but also in new construction. Typically, FRPs are used to mitigate deterioration of reinforced concrete structures where the corrosion of steel (by chlorides, climate, etc.) results in decreased service life and large cost expenditures to repair or replace (Kara and Ashour, 2011). This particular study will examine the application of FRP to mass-transit infrastructure rather than highway bridges. While the use of de-icing salts is not a prevalent cause of deterioration to this type of structure, recent studies done by Bertolini et al. (2006) have shown that reinforcing steel can corrode significantly in the presence of stray direct current.

Although FRPs present a corrosion resistant alternative to conventional steel reinforcement in reinforced concrete structures, little work has been done to validate its long term performance in structures currently in service.

In this study, a direct comparison of the performance of a steel-reinforced concrete beam will be made to that of an equivalently designed glass-FRP (GFRP)-reinforced (in both flexure and shear) beam. These beams are segments of an in-service guideway whose purpose is the testing of a newly developed rapid transit vehicle. This test program will provide insight in two important ways:

- As a direct comparison of the performance (and viability) of steel to GFRP as reinforcement in mass-transportation infrastructure, under controlled and repeatable testing scenarios
- As one of the first tests of its kind on GFRP-reinforced rapid transit infrastructure (RTI).

The field testing program will involve testing of vehicles on the 1.86 km long guideway at speeds up to 90km/h and passing over the two instrumented test beams. These 11.6m long beams are located at the point of highest speed on the test guideway.

In order to validate GFRP as a usable alternative for RTI, a better understanding of its long term performance is needed to ensure that the strict serviceability tolerances of RTI are met. Of particular concern is the potential for reduced stiffness of the members after many load cycles. For this reason, the second portion of the test program will be to evaluate the long term fatigue performance of small scale GFRP reinforced beams in a laboratory setting. The following sections will describe methods used to predict the responses of the Full-Scale beams and the analysis used in order to design the equivalent Half-Scale beams.

2 Full-Scale Test Program

As the Full-Scale test beams are to be in service for many years for vehicle testing, their design is governed by applicable design codes, and designed by a third-party structural engineering consultant. The 1.86 km long guideway is comprised of conventionally reinforced concrete beams (approximate dimensions of 11,600x690x1500mm) laid end to end. The beam's dimensions are constrained by both transportation requirements (precast beams had to be shipped to site) and the shape of the vehicle being tested. Both the steel and GFRP reinforced beams were designed using the Canadian Highway Bridge Design Code, S6-06 and meet requirements at both ultimate and serviceability limit states.

Due to the large section and relatively short span of the design, the two test beams were cast with lower strength concrete (28 day compressive strength of 22 MPa) than the rest of the guideway to increase the magnitude of the cracked-section observed response of the beams. Both the steel and GFRP reinforced beams were internally instrumented with strain gauges to monitor the strains during vehicle testing. External instrumentation will be later added to monitor surface strains on the concrete and the deflection of the beams.

2.1 Specimen Geometry and Material Properties

The geometry of the Full-Scale steel and GFRP reinforced beams as design is shown in Figure 1 (below).

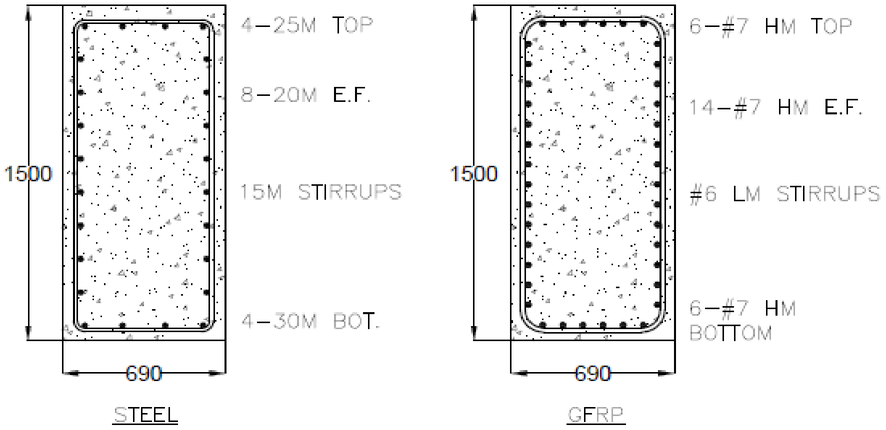

Figure 1: Full-Scale Beam Cross Sections

In Figure 1, the steel reinforced beam uses four 30M bars as primary tension reinforcement, four 25M bars of top reinforcement, and eight rows of 20M bars as skin reinforcement evenly distributed along each face of the beam. The "closed" stirrups are constructed as two overlapping "U" shaped 15M bars, spaced

250mm apart. The GFRP reinforced beam uses considerably more bars with 6 bars top and bottom and 14 rows of skin reinforcement. All GFRP longitudinal bars are #7 HM (high modulus), approximately 25mm in diameter. The GFRP stirrups are #6 LM (low modulus) overlapping "U" pieces, spaced 200mm apart. The GFRP bars are sand coated during manufacturing to enhance bond performance. All steel reinforcement is 400MPa steel and the GFRP physical properties are listed in Table 2 (below).

Table 1: Material properties of GFRP bars for Full-Scale beam

Bar Type	$f_{frp\ ult}$ (MPA)	$f_{frp\ bend}$ (MPA)	E_{frp} (MPa)	ε_{frp} (mm/m)	d_{frp} (mm)	A_{frp} (mm^2)
#6 LM	666		44,500	14.3	18.1	285
#7 HM	1,059	-	62,600	16.9	25.1	388

3 Half-Scale Test Program

To conduct laboratory testing, two identical scaled down versions of the GFRP beam were produced. These beams have dimensions roughly 1:2.15 scale of the Full-Scale GFRP beam. The first of these two beams will be test monotonically to failure to establish a baseline comparison of strength and stiffness for the long-term cyclic loading test. The second beam will be loaded cyclically at a prescribed load level for two to four million cycles, with monotonic tests done at predetermined intervals to track changes in behaviour over time. Figure 2 (below) shows the experimental test setup for the Half-Scale beams.

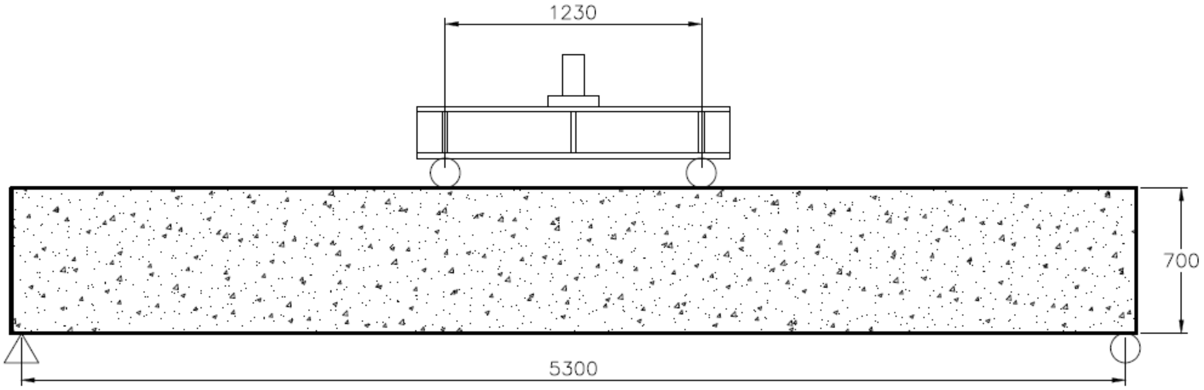

Figure 2: Test configuration for the Half-Scale beams

The beams will be tested in four-point bending with the width of the constant moment region being proportioned from the Full-Scale test setup. Note that all loads hereafter referred to are indicative of the load applied to one half of the beam (i.e. one half of the actuator load).

Before construction of the Half-Scale beams, the behaviour of the Full-Scale beams had to be predicted. Once prediction for the Full-Scale GFRP beam had been made, the Half-Scale beams were designed by comparing the normalized responses in both flexure and shear. In particular, normalized moment-curvature (M-C) and normalized shear-shear strain (V-γ_{xy}) were used as the major "reduced-scale" design parameters. Moment (Eq. 1), curvature (Eq. 2), and shear force (Eq. 3) were normalized by the beam's sectional dimensions as follows:

[1] $M_n = M/(b*d^2)$

[2] $\Psi_n = \Psi*d$

[3] $V_n = V/(b*d)$

This forms the basis for the scaling procedure for producing the 1:2.15 scale test specimens. In Equations 1-3 (above); "M_n", "Ψ_n", and "V_n" represent the normalized moment, curvature, and shear force respectively; "M", "Ψ", and "V" represent the unadjusted values, where "b" and "d" are the beam's width and the effective depth to bottom tension reinforcement respectively. Material properties for the GFRP bars used in the Half-Scale beam are listed in Table 2 (below). Note that the bars for both the Full-Scale and Half-Scale beams are produced by the same manufacturer.

Table 2: Material Properties of GFRP bars for Half-Scale Beams

Bar Type	$f_{frp\ ult}$ (MPA)	$f_{frp\ bend}$ (MPA)	E_{frp} (MPa)	ε_{frp} (mm/m)	d_{frp} (mm)	A_{frp} (mm^2)
#3 Std M	1,080	486	53,400	16.6	11	71.3
#7 HM	1,312	-	65,600	20	15.8	126.7

Predictions of the responses of both the Full-Scale and Half-Scale beams were done with a combination of basic principles, and two computer models: the non-linear finite section program "Response 2000" (R2K) (Bentz, 2000), and the two dimensional non-linear finite element program "Vector2" (Wong and Vecchio, 2002). Estimates of required reinforcement were made, and the trial designs' responses analysed for agreement to the behaviour of the Full-Scale beam. Figure 3 (below) shows the predicted normalized Moment-Curvature for the chosen Half-Scale beam design as predicted by R2K.

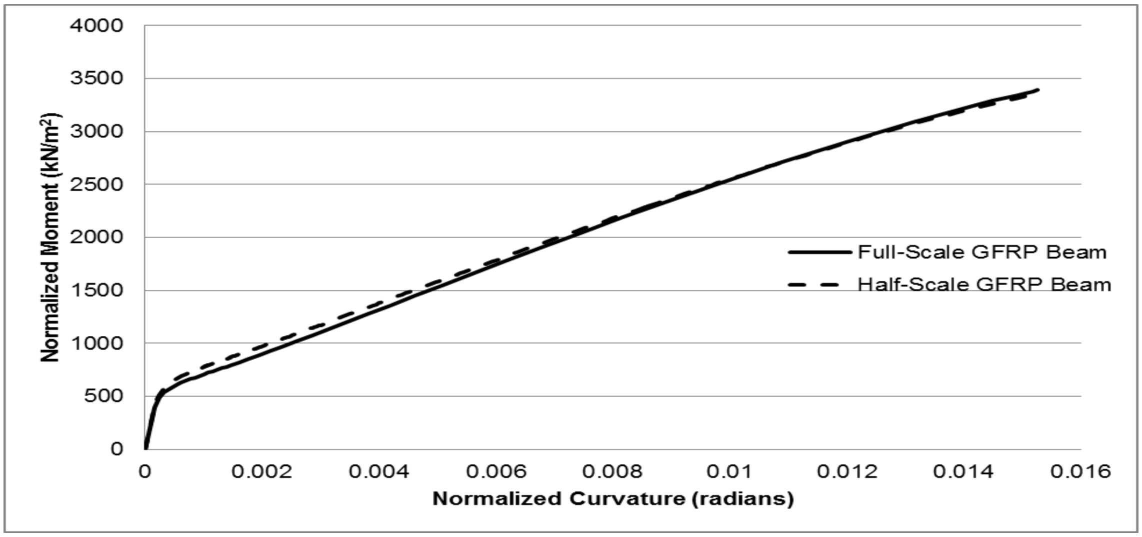

Figure 3: Normalized Moment-Curvature response of the Full-Scale and Half-Scale GFRP beams

In Figure 1, the flexural responses terminate at “compression failure” in this case defined as a strain of 0.0035 in the extreme compression fibre of the beam. These curves coincide closely, and the overall agreement of post cracking stiffness of the two beams is within 1.8%. Better agreement in normalized M-C could be achieved by increasing the effective depth. However, for practicality reasons, the effective depth is restricted to maintain a minimum 25mm clear cover to the reinforcement.

Similarly, Figure 4 (below) shows the predicted normalized shear force-shear strain responses of the two beams at the critical section for shear as predicted by R2K.

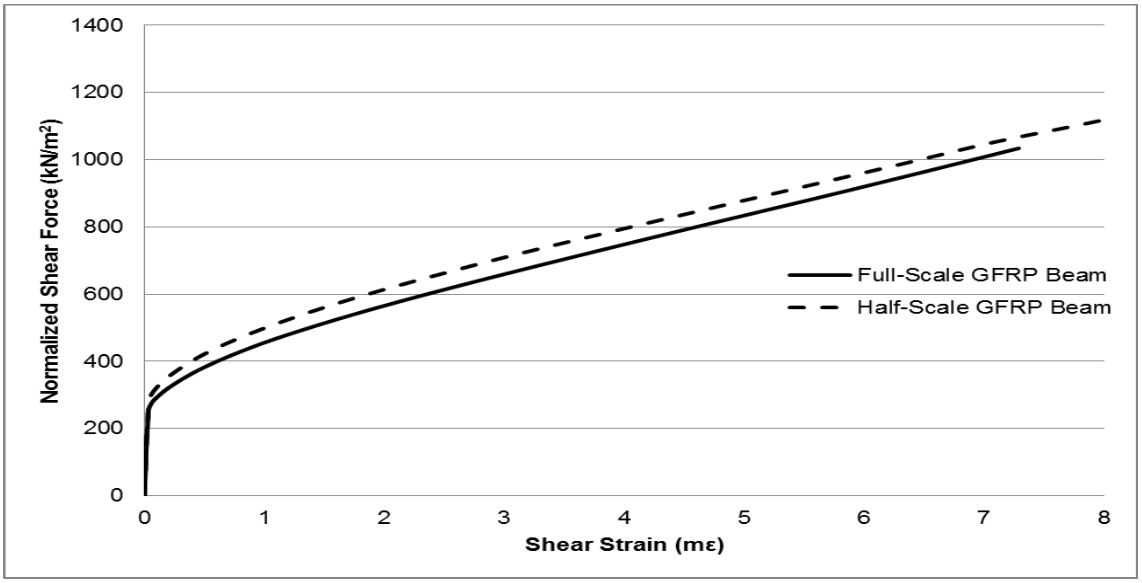

Figure 4: Normalized Shear Force-Shear Strain response of the Full-Scale and Half-Scale GFRP beams

It should be noted that the perceived overstrength in the Half-Scale beam in Figure 4 is due to its much lower M/V ratio (1.5 instead of 3.2). The shear capacity being referred to was predicted choosing the critical section at one effective shear depth (d_v) away from the maximum moment region (Hoult et al., 2008). Because effects in flexure are the primary interest of this investigation, maintaining the same (normalized) width of constant moment region is more critical than the beams’ behaviour in shear. Looking at the reinforcement itself, we can see excellent agreement in the normalized responses between the Moment vs. bottom Longitudinal Bar Stress (M-f_{frp}) and Stirrup Stress variations over cross section depth (Figures 5 and 6, respectively) at ultimate failure (governed in both cases by flexural compression failure). It is noted that the maximum stress in any GFRP bars is ~750 MPa, which is only 57 % of its ultimate tensile strength. This is because designed is governed by compression failure according to S606 code.

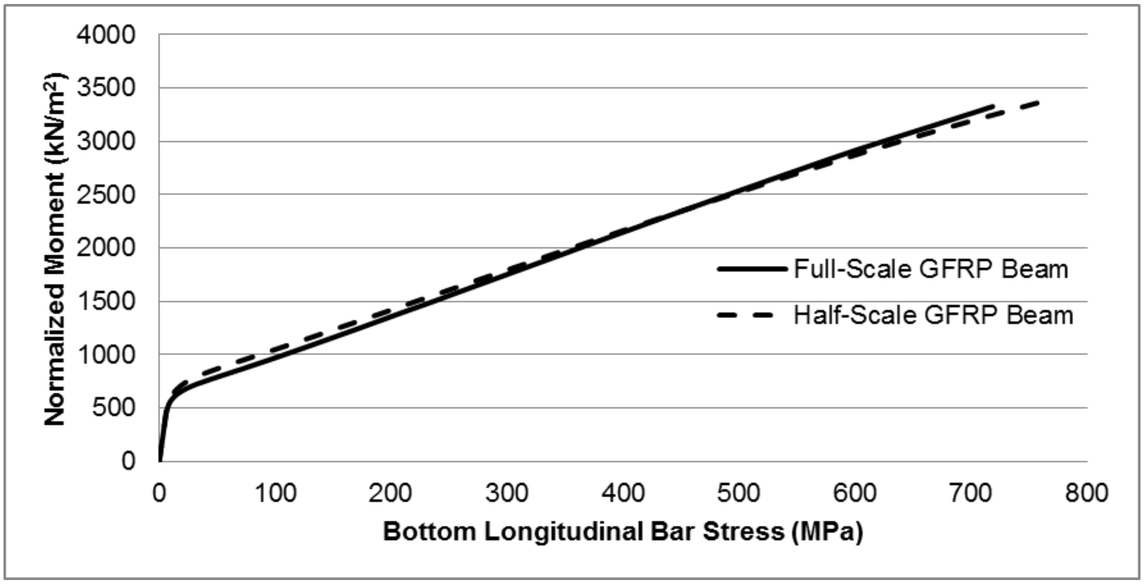

Figure 5: Normalized Moment vs. Longitudinal Reinforcement Stress

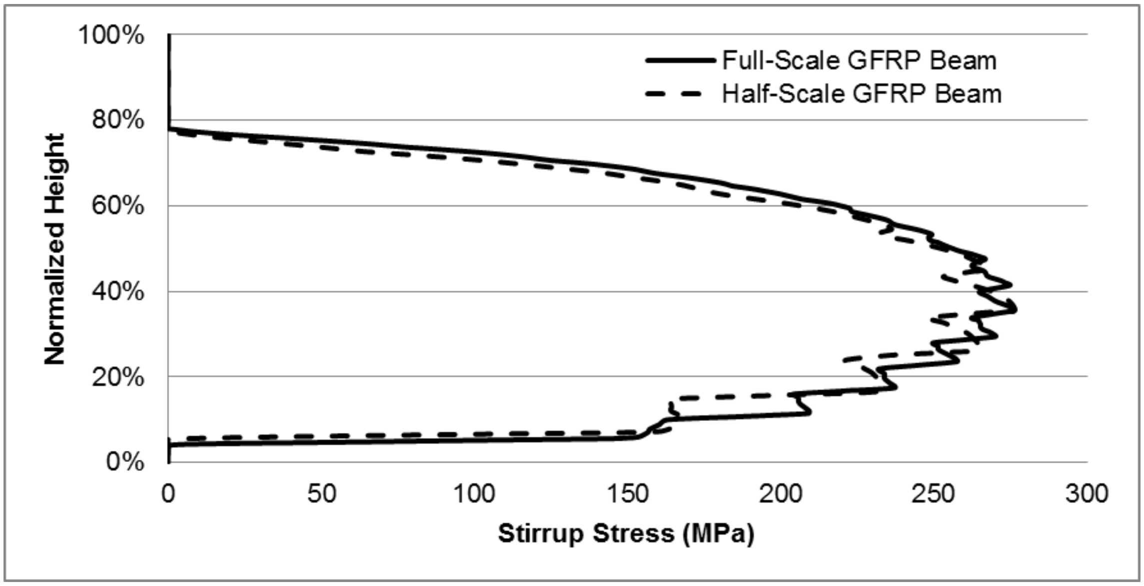

Figure 6: Stirrup stress at ultimate failure of beams

Based on the predicted normalized response for several iterations of Half-Scale beam design, the cross section in Figure 7 (below) was chosen as the preferred alternative for testing. Figure 8 shows the reinforcement cage of one of the Half-Scale beams nearing completion before final casting.

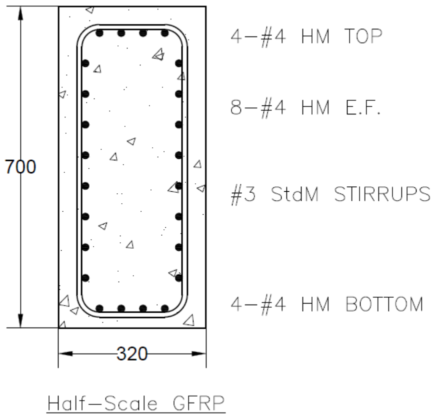

Figure 7: Cross-section of chosen Half-Scale GFRP beam design

Figure 8: Reinforcement Cage being tied at precast plant

4 Selection of loading for cyclic test

Because the service load of the Full-Scale test specimens coincides very closely with the cracking moment of the beam, the ability to accurately predict behaviour at service will be highly dependent on the size, number, and location of the first flexural cracks. In order to replicate the conditions at service in the Full-Scale beam, R2K predicts a service load applied to the test beam of 43.7kN while Vector2 predicts a required load of 51 kN.

Although the prescribed cyclic load will be determined by the monotonic test, Vector2 can still be used to model the cyclic test, for now assuming the 51kN applied load. Figure 9 (below) shows the load-deflection plot for the Half-Scale beam subjected to a cyclic 51 kN live load. This results in service bar stresses of approximately 50MPa (4% of ultimate) at the level of bottom reinforcement, depending on the model used.

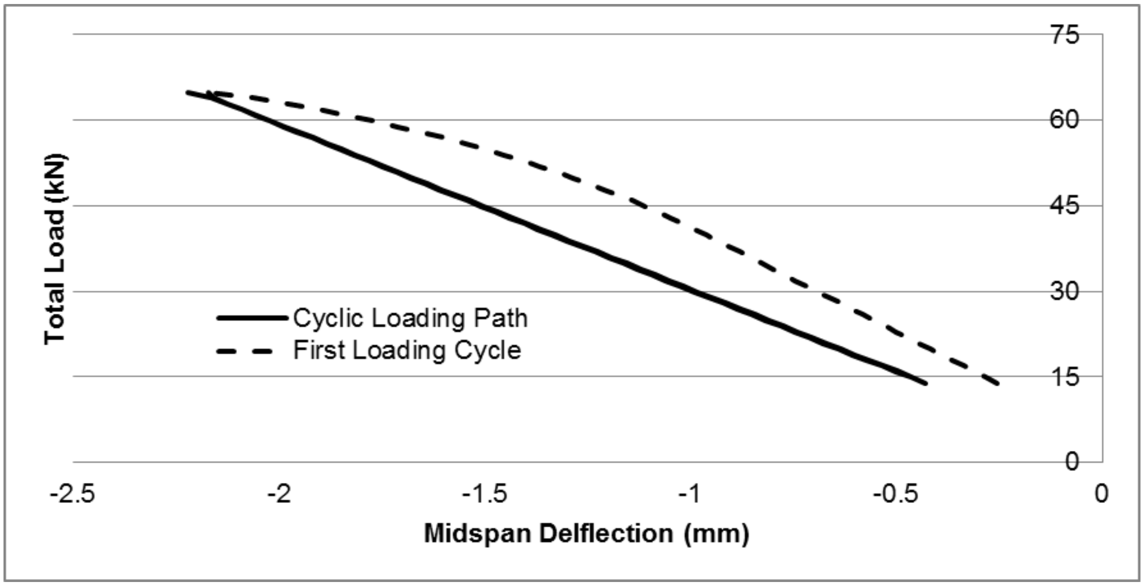

Figure 9: Vector2 Prediction of Half-Scale beam response to cyclic loading

While the understanding of long term behaviour will be provided later by experimental testing, the Vector2 output provides insight to the effects of strain history and predicts the residual deflections after the first load cycle. In this case, minimal residual live load deflection is observed (0.17mm). It is important to note in Figure 8, the gaps between the loading curves and the axes represent the self-weight and deflection at rest of the beam.

5 Conclusions and Future Work

This paper presented herein the methods of analysis used to predict the performance of an in-service rapid transit infrastructure system, allowing for future experimental testing. The resulting predictions were then used for the purpose of procuring Half-Scale specimens of the beams which may be tested beyond service to determine the true long term behaviour.

This model validation from the first Half-Scale test will aid in determining an appropriate service load to be applied for the cyclic loading test. As the predicted service loads will load the reinforcement to only approximately 5-10% of its tensile capacity, a higher load may be selected for fatigue testing. Upon completion of this step, cyclic testing performed on the second Half-Scale beam is expected to take two to four months depending on how many cycles are deemed representative of the life cycle of the guideway. This will allow for better understanding of the magnitude of performance degradation in RTI and provide optimized future designs.

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