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ULTIMATE LOAD TESTS ON A 40-M LONG TL-5 BRIDGE BARRIER REINFORCED WITH GFRP BARS AND SPECIAL PROFILE 180º HOOKS

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Abstract: A new Canadian manufacturer recently developed high-modulus glass fibre reinforced polymer (GFRP) bar with 180º hooks. One of the application of the developed bars is Test Level 5 (TL-5) bridge barrier. To qualify the use of these barriers, a crash test was conducted on a constructed 40-m long GFRP-reinforced barrier, followed by static load tests to-collapse on barrier segments under simulated vehicle impact load. The barrier was subjected to transverse line loading at interior and exterior locations to determine its structural behavior, crack pattern and ultimate load carrying capacity. This paper reports the construction of this barrier along with the static load test setup, procedure and results. Test results showed that failure mode of the tested barrier wall was punching shear at the line load location although both flexural cracks appeared at the tapered faces of the barrier wall during loading. The experimental ultimate load carrying capacities of the barriers were observed to be far greater than the factored design load specified in the Canadian Highway Bridge Design Code.

1 Introduction

After successful crash test and static load tests on a developed TL-5 GFRP-reinforced, barriers (Sennah and Khederzadeh, 2014; Khederzadeh and Sennah, 2014), Ontario Ministry of Transportation, MTO, established Standard Drawing MTO-S110-92 for dimensioning and GFRP details for use by designers and contractors. In this design, the diagonal bar reinforcing the barrier wall in the tension side at the barrier-deck junction was of headed end embedded in the supporting deck slab cantilever. Most recently, a Canadian manufacturer developed GFRP bars of different diameters and shapes as shown in Fig. 1. As such, a revised GFRP bar detailing for the MTO TL-5 barrier incorporating the developed bars with 180º hooks was developed as shown in Fig. 2 with hook details shown in Fig. 3. It should be noted that the diagonal bar with headed end reinforcing the lower tapered portion of the barrier wall and embedded into the deck slab as in the crash-tested barrier was replaced with a the newly-developed bar with the 180º hook with dimensioning showing in Fig. 3. Table 1 summarizes the materials properties of the GFRP bars considered for the revised design shown in Fig. 2, as supplied by the manufacturer. The proposed TL-5 barrier shown in Fig. 2 incorporated M15 and M13 GFRP bars as vertical reinforcement in the barrier front and back faces, respectively, at 300 mm spacing. M15 GFRP bars was proposed as horizontal reinforcement with bar spacing as shown in Fig. 2. The connection between the deck slab and the barrier wall utilized GFRP bars with 180º hook for proper anchorage. All vertical and diagonal bars in the barrier wall were embedded in the deck slab with 195 mm vertical embedment length. Concrete cover to reinforcement was taken as 50 mm for the barrier wall reinforcement except for the hooked bar at the barrier-deck junction at which the concrete cover was taken as 35 mm.

Figure 1: View of the developed GFRP bar types

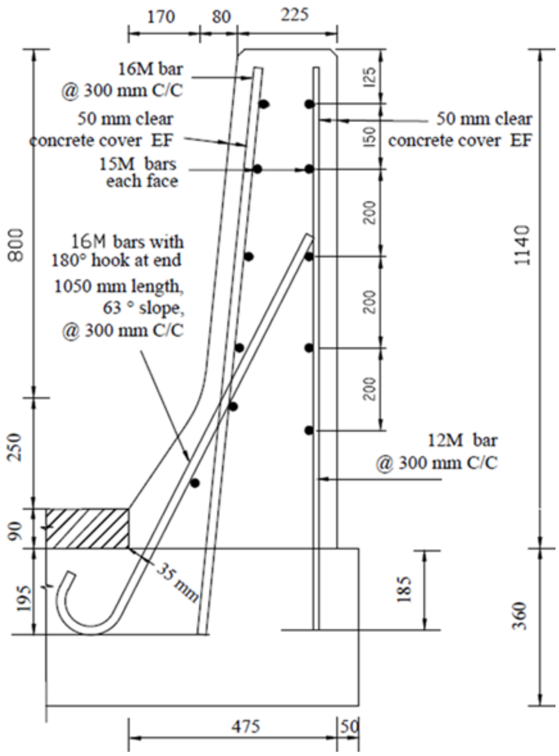

Figure 2: Developed GFRP-reinforced barrier-deck system

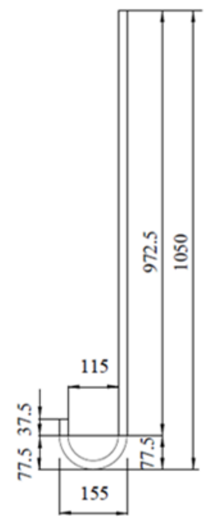

Figure 3: Developed GFRP bar with 180˚ hook

Table 1. GFRP material properties (TEMCORP, 2016)

Product type	Bar size	Minimum guaranteed tensile strength on 0.1 percentile (MPa)	Modulus of elasticity (GPa)	Strain at failure	Nominal (net) cross-section area (mm²)	Gross cross-section area (mm²)
Straight bar	#4 (M13)	1135	65	1.75%	129	132.7
	#5 (M15)	1620	61	2.66%	199	240
Bar with 180˚ hook	#5 (M15) short un-anchored straight portion of bent bar	905	55	1.65%	199	240
	#5 (M15) long anchored straight portion of bent bar	1485	60	2.4%	199	240

CHBDC specifies that a traffic barrier shall be certifies for use in Canada's highway bridges if it has been crash tested to requirements that test its geometry, strength and behavior to an equivalent or more severe level than the requirements for its type. Also, CHBDC specifies that the suitability of a traffic barrier anchorage to the deck slab shall be based on its performance during crash testing of the traffic barrier. As such, the crash test was performed on the developed GFRP-reinforced barrier in Fig. 2 in accordance with Test Level 5 (TL-5), which involves the 36000V van-type tractor trailer (cab-behind-engine model of 36,000 kg gross weight) impacting the barrier at a nominal speed and angle of 80 km/h and 15º degrees, respectively (Sennah, 2016). After the crash test, the constructed barrier wall was subjected to static loading to collapse at two locations to determine to determine the load carrying capacity, crack pattern and deformation at overloads to-collapse. CHBDC specifies transverse, longitudinal and vertical loads of 210, 70 and 90 kN, respectively, that can be applied over a certain TL-5 barrier length. CHBDC specifies that transverse load shall be applied over a barrier length of 2400 mm fort TL-5 barriers. Since transverse loading creates the critical load carrying capacity in the barrier as well as the barrier-deck junction, both the longitudinal and vertical loads were not considered in the design of barrier wall reinforcement and anchorages between the deck slab and the barrier wall. It should be noted that CHDBC specifies a live load factor of 1.7. Thus, the design equivalent impact load on TL-5 barrier wall over 2.4 m length is 357 kN. This paper presents the results from the static load tests along with correlation between the equivalent factored transverse loading of 357 kN and the experimental ultimate loading at both interior location (within the barrier length) and end location (at construction joints).

2 Experimental Program

A 40-m long barrier wall was built at Texas Transportation Institute with the cross-section configuration and GFRP bar arrangement shown in Fig. 2. Figure 4 shows barrier elevation with locations of control joints every 6 m. It should be noted that vertical bars at the front face of the barrier wall, within a barrier length of 2450 mm, was doubled by taking their spacing as 150 mm as the common practice in Ontario. The barrier wall was supported over a deck slab cantilever of 1000 mm length. The cantilever was anchored to existing foundation to ensure stability during testing. More details of the barrier construction can be found elsewhere (Sennah, 2016). Figures 5 and 6 show views of the GFRP bar arrangement in the barrier wall and steel reinforcement in the deck slab cantilever. Figure 7 shows view of the barrier wall after casting concrete. After the crash testing, the barrier wall was tested under increasing static load to-collapse to determine its structural behavior, crack pattern and ultimate load carrying capacity under equivalent static load simulating vehicle impact at exterior and interior locations shown in Fig. 8. In order to determine the strength of the concrete, 12 - 100×200 mm concrete cylinders collected from the concrete used to cast the supporting wall and the deck slab cantilever, leading to concrete characteristic compressive strength for the barrier wall of 34.43 MPa.

To simulate the two load scenarios specified in Fig. 8, it was decided to load the barrier wall at its end with a horizontal line load at a height of 900 mm from the top surface of the asphalt and over 2400 mm length as shown in Fig. 9. As for loading the barrier internally, it was decided to load the barrier with a line load over 2400 mm length centered at the control joint as shown in Fig. 11. The interior location shown in Fig. 11 represents the barrier wall segment located in the middle of the constructed barrier wall and centered at the control joint. Six potentiometers (Pots) were placed at 990 from top of the deck concrete surface and oriented horizontally to measure lateral deflection of the barrier wall at the level of the applied load every 1200 mm length of the barrier wall, while three Pots were placed at the bottom of the deck to measure its vertical deflection during load application process. Views of the Pots, supported over timber frame, are shown in Figs. 10 and 12 for exterior and interior locations, respectively. The load was applied using a jacking load of 2500 kN capacity. The jacking load was applied on a steel I- beam oriented horizontally, that transferred that load to two spread beams to form a line load over 2400 mm length of the barrier wall. A trapezoidal timber wedge was inserted between the tapered face of the barrier and the spread beam to ensure that the transferred load acted horizontally on the barrier wall. This load transfer system ensured that a uniformly distributed line load was applied on the barrier wall. The hydraulic jack was rest on a steel curved plate attached to a steel column and the push steel beams were rest on a steel table on the front size of the barrier wall as shown in Figs. 9 and 11.

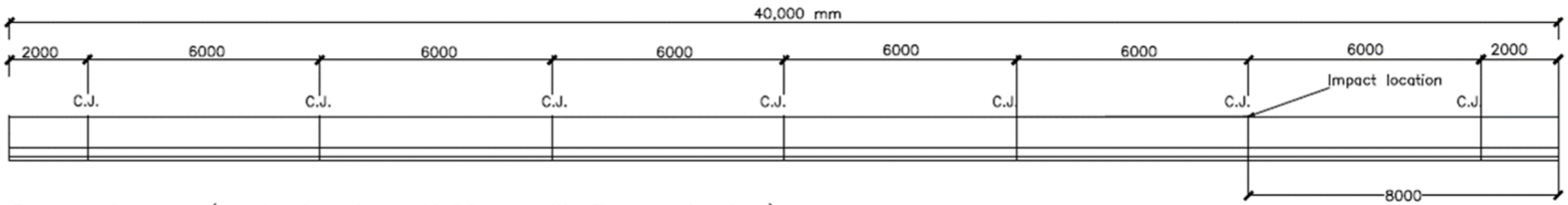

Figure 4: Elevation of the constructed barrier dimensioning and locations of the control joints (C.J.)

Figure 5: View of GFRP and steel bar arrangement at the beginning of the constructed barrier-deck system

Figure 6: Close-up view of the hooked GFRP bars and deck

Figure 7: View of the barrier wall after removing the formwork and asphalt paving

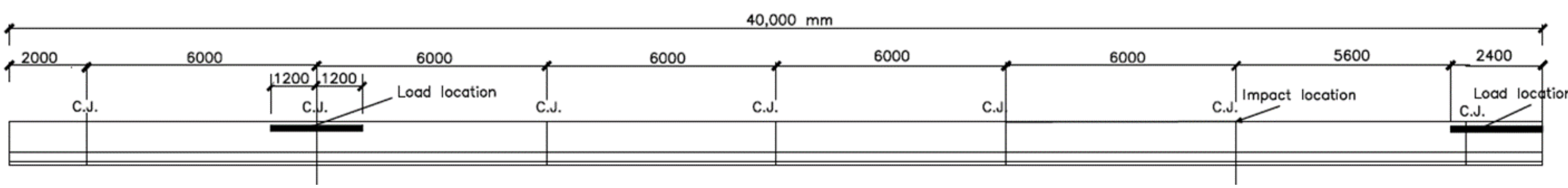

Figure 8: Elevation of the barrier wall showing location of crash test and static tests

Figure 9: View of the loading setup for the static load test at exterior location of the barrier wall

Figure 10: View of the loading setup and sensors' supporting frame at exterior location of the barrier

Figure 11: View of the test setup at for static load test at interior location

Figure 12: View of the timber frame supporting petontiometers at interior location

3 Experimental Results

Each barrier location was subjected to increasing static load using the jacking system and steel frame shown in Figs. 9 and 11. At a load increment of 25 kN, the barrier wall was inspected to mark crack initiation and propagation until collapse. The barrier was considered failed when the sensors continued to record increasing deflections with no increase in applied load (i.e. the barrier could not absorb an increase in the applied load).

3.1 Interior Location

In case of loading the barrier internally at the control joint, Figs. 13 through 16 show views of the crack pattern during the test and after removing the test frame and the timber frame supporting sensors. It was observed that with increase in load, horizontal crack appeared at the front side of the barrier wall-deck slab junction at a load of 312 kN as depicted from deflection readings. Other horizontal flexural cracks appeared at the intersection of the two tapered parts of the front side of the barrier wall at a load of 327 kN. These cracks appeared within the 2400 mm length of the line load, extending diagonally outside the loading region and reaching the top surface of the barrier wall at the same load level. These cracks showed that the barrier wall behaved as a cantilever wall within the 2400 mm length of the line load, while the two-way slab action appeared outside this region (on the left and right sides of the line load) in the form of diagonal cracks extending to the top surface. However, punching shear crack appeared on the left side of the line load at a load greater than 608 kN and propagated though the barrier thickness and to the other side of the line load at an ultimate load of 702.75 kN. The sudden punching shear failure at the line load location may be attributed to the GFRP bar low stiffness, bond characteristics, elastic response till failure, low strength under compression and shear stresses. Diagonal cracks appeared at the back face of the barrier wall at a load of 608 kN as depicted in Fig. 15.

Figures 17 and 18 depict the load-deflection history of the barrier wall and deck slab, respectively. It can be observed that barrier wall has a maximum lateral deflection of 15.12 mm. Also, it can be observed that the maximum deflection of the deck cantilever at failure was 1.54 mm which is very small indicating the deck slab cantilever was insignificantly affected by the maximum load reached experimentally. Failure of barrier at the interior location due to punching shear of the wall at 702.75 kN transverse loading compared to 357-kN CHBDC factored design transverse loading. This leads to a factor of safety in design as 1.97. With the inclusion of 0.75 durability factor for GFRP bars specified in CHBDC Chapter 16, the safety factor becomes 1.48. As such, the proposed barrier details shown in Fig. 2 are considered adequate to resist equivalent vehicle impact loading at interior locations.

Figure 13:View of the horizontal cracks within the loaded length of the barrier, extending diagonally outside outside the right side of the loaded length

Figure 14: View of the punching shear crack at the top of the barrier wall, extending to the back of the wall at failure

Figure 15: View of the punching shear failure at the back face of the barrier wall after removing the timber frame

Figure 16: Front view of the flexural crack pattern and punching shear failure of the barrier interior location

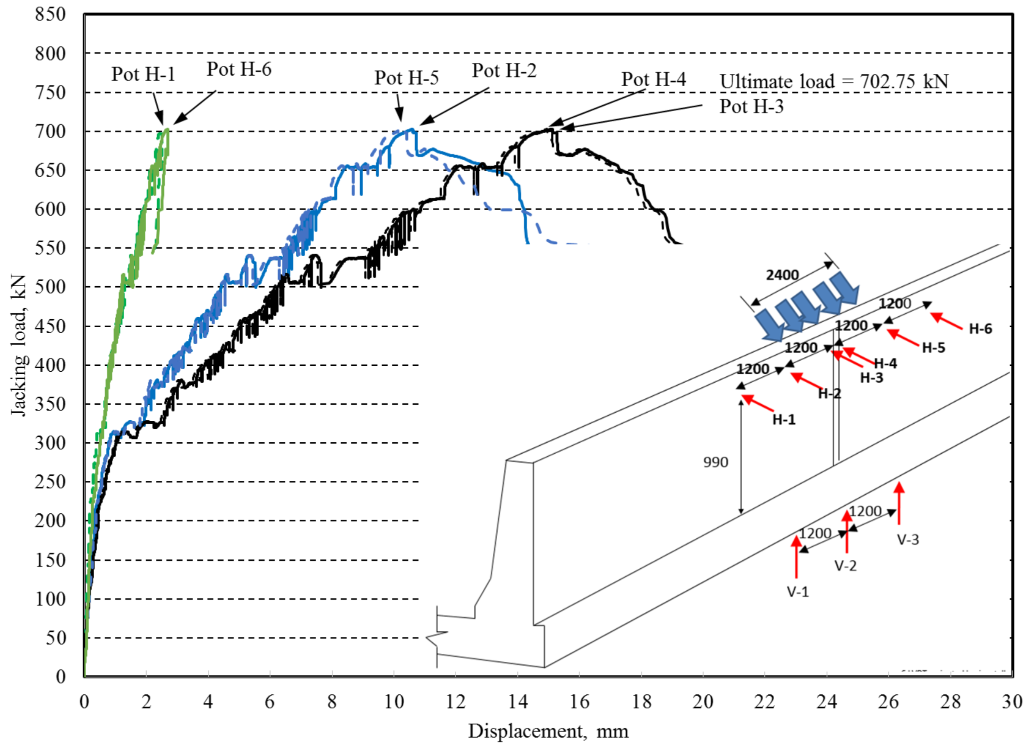

Figure 17: Load-horizontal deflection relationship of the barrier wall at interior location

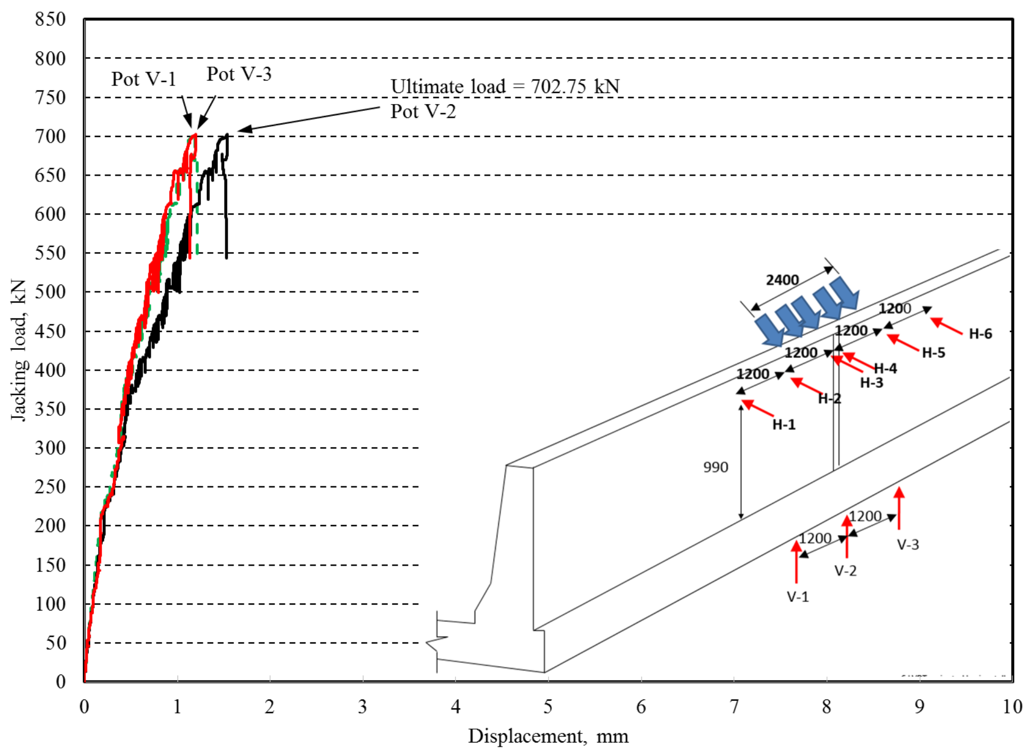

Figure 18: Load-vertical deflection relationship of the barrier wall at interior location

3.2 Exterior Location

In the static test at exterior location, Figs. 19 through 22 show views of the crack pattern after removing the testing frame and the timber frame supporting sensors. It was observed that with increase in applied load, horizontal crack appeared at the front side of the barrier wall-deck slab junction at a load of 321 kN as depicted from deflection readings. Other horizontal flexural cracks appeared at the intersection of the two tapered parts of the front side of the barrier wall at a load of 327 kN. These cracks appeared within the 2400 mm length of the line load, extending diagonally outside the loading region and reaching the top surface of the barrier wall at the same load level. These cracks showed that the barrier wall behaved as a cantilever wall within the 2400 mm length of the line load, while the two-way slab action appeared outside this region in the form of diagonal cracks extending to the top surface. However, punching shear crack appeared on the left side of the line load at a load greater than 580 kN and propagated though the barrier thickness and to the other side of the line load at an ultimate load of 589.77 kN. The sudden punching shear failure at the line load location may be attributed to the GFRP bar low stiffness, bond characteristics, elastic response till failure, low strength under compression and shear stresses. Diagonal cracks appeared at the back face of the barrier wall at a load of 580 kN as shown in Fig. 21. Also, extensive horizontal flexural cracks appeared within the loaded length of the front face of the barrier wall at loads between 327 and 468 kN, extending diagonally outside the loaded area towards the top surface of the barrier wall at higher loads as depicted in Fig. 20. Figure 19 shows extensive cracks in the deck slab cantilever under the barrier. Flexural cracks in the deck slab between the barrier and the concrete foundation appeared at jacking load between 234 and 327 kN. However, diagonal tension crack appeared in the deck slab cantilever just under the barrier wall at 580-kN jacking load.

Figure 19: View of the crack pattern at the side of the barrier wall and slab cantilever at failure

Figure 20: View of the horizontal flexural cracks within the loaded length, extending diagonally beyond the loaded length

Figures 23 and 24 depict the load-deflection history of the barrier wall and deck slab, respectively. It can be observed that barrier wall has a maximum lateral deflection of 16.79 mm. Also, it can be observed that the maximum deflection of the deck cantilever at failure was 6.57 mm. Failure of barrier at the interior location due to punching shear of the wall at 589.77-kN transverse loading compared to 357-kN CHBDC factored design transverse loading. This leads to a factor of safety in design as 1.65. With the inclusion of 0.75 durability factor for GFRP bars specified in CHBDC Chapter 16, the safety factor becomes 1.24. As such, the proposed barrier details shown in Fig. 2 are considered adequate to resist equivalent vehicle impact loading at exterior locations.

Figure 21: View of diagonal cracks at the back face of the barrier wall

Figure 22: View of the crack pattern at the front face of the barrier wall at exterior location

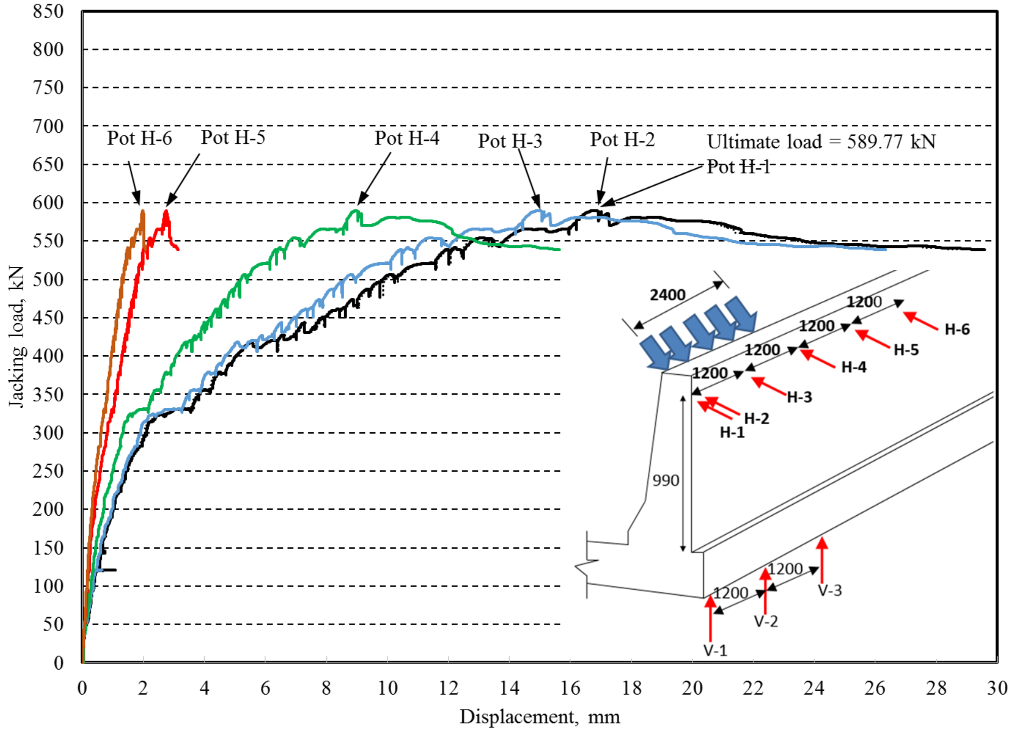

Figure 23: Load-horizontal deflection relationship of the barrier wall at exterior location

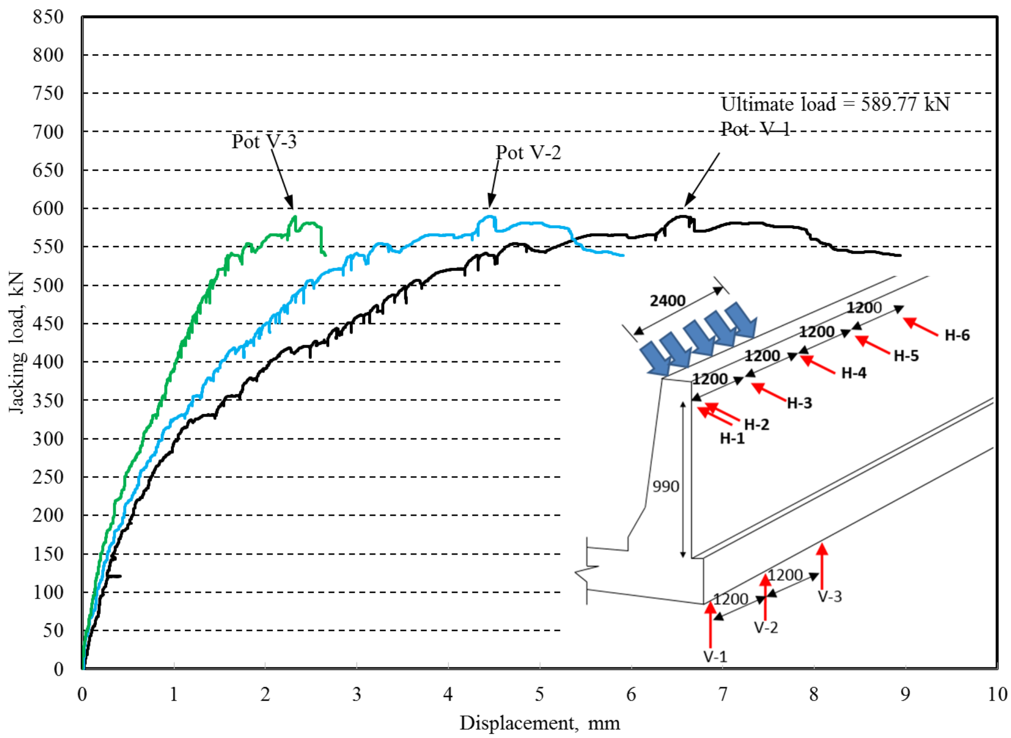

Figure 24: Load-vertical deflection relationship of the barrier wall at exterior location

4 Conclusions

Full-scale TL-5 barrier walls reinforced with GFRP bars were tested under static loading to collapse to study their structural behavior, crack pattern and ultimate load carrying capacities. It was observed that the failure mode of the GFRP-reinforced barrier wall was punching shear at the location of the transverse line loading. Also, the experimental ultimate load carrying capacities at the interior and exterior segments were observed to be far greater than the factored design loads specified in CHBDC. Factors of safety for design of 1.48 and 1.24 were observed for the developed barrier wall at interior and exterior locations, respectively.

5 References

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