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Experimental Load Carrying Capacity of Fiber-Reinforced Concrete (FRC) TL-5 Concrete Barriers Subjected to Equivalent Vehicle Impact Loading at End Location

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Abstract – As the repair and maintenance of concrete bridge barriers are becoming important issues in bridge engineering, a sustainable and cost-effective design of concrete bridge barriers is more significant. Recent investigations have recommended the use of fibers in structural concrete elements, while there have been limited experimental studies on the practicality and efficiency of implementing fibers in concrete bridge barriers to conclude a safe and economical design to be added to design specifications and standards. In this research, the design of Test Level 5 (TL-5) concrete bridge barriers, as identified in the Canadian Highway Bridge Design Code (CHBDC), is modified by adding synthetic macro-fibers to the wall concrete and removing one mesh of conventional reinforcement at the back side to be cast and tested experimentally. The 5-m length Fiber-Reinforced Concrete (FRC) barrier was tested at the end location, and initially, two arrangements of conventional reinforcement were considered using stainless-steel rebars while back mesh reinforcement was removed; the first sample with no rebars at the back, and a second sample with two top horizontal rebars. However, the design of the second sample was adjusted based on the results of the first sample, as discussed in this research. The studies presented in this paper include details on the design, construction, test setup and results of the two FRC barriers cast and tested at the end location. While the results show an acceptable wall capacity with using FRC and removal of the back mesh of reinforcement, the effect of proper reinforcement at the barrier-deck junction was observed.

Keywords**:** Fiber-reinforced concrete (FRC), bridge barrier, impact resistance, stainless steel, experimental barrier test

1. Introduction

The Canadian Highway Bridge Design Code (CHBDC) [1] defines different Test Levels (TL) of bridge barriers to withstand the impact of vehicles passing on bridges. Concrete barriers or metal railings must be designed in order to prevent different types of vehicles from overturning if impacted. Therefore, barrier Test Levels 1, 2, 4, and 5 are categorized based on various traffic conditions and based on criteria such as impact speed, impact angle, and vehicle mass. In addition to Test Levels defined in CHBDC, barriers can also be designed in different shapes such as an F-Shape that is with two tapered surfaces on the traffic side, or with a constant thickness over the height of the barriers. Such details are provided in standards such as CHDBC or design manuals such as NCHRP Report 350 [2], MASH [3], or AASHTO LRFD Bridge Design Specifications [4].

Concrete bridge barriers are currently designed using two mesh of reinforcement included with horizontal and vertical rebars in the barrier wall, as indicated in CHBDC. However, for different barrier Test Levels and shapes, the arrangement and spacing of rebars would change. Thus, a significant amount of reinforcement is used in traditionally designed RC barriers. This concludes in substantial maintenance requirements and costs due to issues such as corrosion, especially with using of de-icing salt. Therefore, the quality and serviceability of RC barriers with conventional reinforcement will decrease rapidly over time. One solution to reducing such issues is using Fiber-reinforced Concrete (FRC) in lieu of normal concrete, as suggested in recent literature, generally for concrete elements to reduce the traditional reinforcement. This will reduce steel corrosion and repair requirements resulting in a decrease in cost and an increase in the sustainability of bridge barriers. Moreover, utilizing fibers will modify the nature of the non-reinforced matrix of the element's material to a more flexural behaviour considering the cement included in the concrete, with an increase in tensile strength. Using fibers would increase the post-cracking tensile capacity, modulus of elasticity, and tensile strength and improve the impact resistance in the result. Also, it is expected to see improved durability, better freeze-thaw properties, and lower creep strain. Conducted studies on FRC elements' behaviour include investigating the environmental properties of FRC [5], and the mechanical properties of small FRC beams ([6], [7], and [8]).

The literature review showed that limited studies had been conducted on using FRC in bridge barriers for evaluating the performance and possible reduction of conventional reinforcement. Extensive experimental and numerical studies are required to assess the capacity of bridge barriers with FRC and conclude parameters such as the proper percentage of fiber, the type and amount of reinforcement that can be removed in either wall, deck, or wall-deck junction of the barrier, potential practical casting issues, etc. Experimental studies of the flexural performance of small FRC beams were conducted elsewhere [9, 10], while more recently, larger FRC beams were tested in another study by Fadaee and Sennah [11] to evaluate the flexural performance of FRC bridge barrier applications.

Chapter 16 of CHBDC provides guidelines for using GFRP and FRC for bridge barriers, however, very limited information is provided regarding the design of FRC barriers including fiber and reinforcement details. In order to conclude an acceptable FRC bridge barrier design to be implemented in CHBDC, additional studies are required for barrier testing at the interior and end locations, as suggested by Fadaee and Sennah [11]. Fadaee and Sennah [12] tested two new designs of TL-5 FRC barriers at interior locations using 1% fiber content mixed with concrete and stainless steel mesh on the traffic side of the barrier wall. Results showed that removing the back mesh of reinforcement in the barrier wall while using FRC did not affect the barrier load-carrying capacity. This paper extended this research by designing an FRC barrier wall with front stainless steel mesh at the end location (i.e. location of barrier end or at expansion joints). Two full-scale TL-5 FRC barriers were fabricated and then tested to collapse by applying transverse line load at its end, simulating traffic load. This paper describes this experimental testing and results, followed by conclusions and recommendation for the use of FRC in practice.

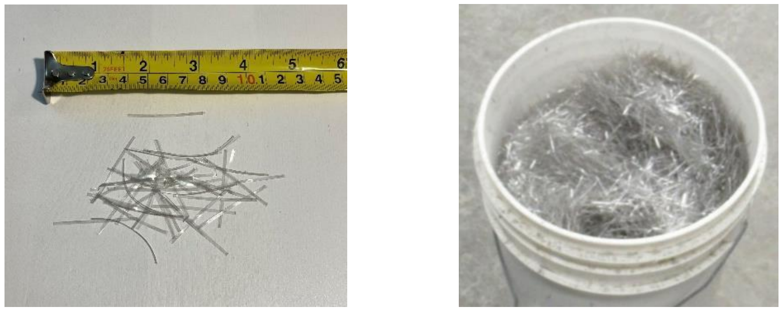
2. Fiber Properties for Bridge Barriers

Chapter 16 of CHBDC provides limited details and instructions for utilizing fibers in bridge elements including bridge barriers. The acceptable types of fiber reinforcement for bridge components include glass, carbon, aramid, low-modulus polymer, and steel, while fibers of carbon, nylon, polypropylene, polyvinyl alcohol, steel, and vinylon are permitted to be used in FRC. Other general guidelines include fibers being randomly distributed in FRC so they can be used as deck slabs and barrier walls [1]. Regarding the amount of fiber, which may be the most important aspect of using fibers in the concrete mix, CHBDC specifies that the fiber percentage in terms of volume must be such that the conditions of Clause 16.6.2 be satisfied. A parameter, namely, residual strength index (R_i) is defined in this clause that should be a minimum of 0.25 for FRC barriers cast with one mesh of reinforcement [1].

3. Fiber Content Considered in This Study

The fiber type in this study is similar to the conditions in the previous studies by the authors ([11, 12]) which is STRUX 90/40 synthetic macro-fiber. The STRUX 90/40 macro-fiber is designed to provide high, post-crack control performance, unlike traditional fibers. This type of fiber has flexural toughness and structural properties similar or improved compared to steel fiber. The producer also indicates an easier construction process of STRUX 90/40 fibers as the pumping, placement, and finishing process are easier than steel fibers [13]. Other benefits of using STRUX 90/40 compared with steel fibers include being safer in different aspects such as handling and finishing, as well as less shrinkage with similar fiber dosages, compared with steel fiber.

In a comprehensive experimental study conducted by Fadaee and Sennah [11], three percentages of fiber content, namely, 0.5%, 1.0%, and 1.5%, were examined based on the surface profiles of tested beams and the resulting residual strength index (R_i). The study concluded that the 1.0% fiber content of STRUX 90/40 synthetic macro-fiber provides the acceptable result of residual strength index (R_i) while maintaining the acceptable workability of concrete so practical challenges would be minimized. Therefore, the 1.0% fiber content of STRUX 90/40 synthetic macro-fiber was chosen for this study and the experimental program. Figure 1 shows views of the fibers used in this study, while Table 1 presents the FRC mixture properties used in this study.



(a) Fiber length (b) Fibers before adding them to concrete mix

Fig. 1: STRUX 90/40 synthetic macro-fibers

Table 1: FRC mixture properties for target compressive strength of 35 MPa

Ingredient	**Quantity**
Cement type GU	390 kg/m^3
Sand	733 kg/m^3
Aggregate 20 mm	1070 kg/m^3
Water	155 L/m^3
Air	6.5 %
Synthetic fiber (STRUX 90/40)	1.0% = 9.4 kg/m^3
ADVA® 190*	400.0 mL/m^3
MasterAir**	230 mL/m^3
W/C	0.397

* *ADVA® 190 is a polycarboxylate-based high-range water-reducing admixture*

** *MasterAir is an air-entraining admixture*

4. Experimental Program

4.1. Materials and Test Matrix

The experimental program conducted in this study included casting two full-scale TL-5 FRC bridge barriers and tested at the end location. TL-5 bridge barriers are used for the highest traffic and speed level per CHBDC specifications and thus have the largest size among the defined barrier test levels (TL-1 through TL-5). The proposed FRC design in the program included an FRC mix with 1.0% STRUX synthetic macro-fiber as described in the previous sections. The concrete mix was designed to have a 28-day compressive strength of 35 MPa (Table 1), reinforced with stainless-steel bars of 500 MPa yield strength for the wall segment, and 35 MPa normal concrete reinforced with steel bars of 400 MPa yield strength for the barrier base. Since synthetic fibers would decrease the workability of concrete, a water-reducing mixture (superplasticizer) was added to the FRC mix for the wall to maintain the required workability. Two full-scale specimens were constructed based on the TL-5 FRC barrier dimensions provided in chapter 16 of CHBDC. Both specimens were of 5 m length, as depicted in Figure 2. The specimens were loaded with a line load of 2.4 m length at 990 mm from the top surface of the deck base.

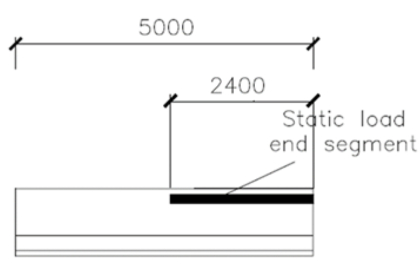


Fig. 2: Elevation of the 5-m long bridge barrier loaded at the end location (units in mm)

4.1. Reinforcement Details

The reinforcement arrangement of the first specimen (designated as S1-FRC10) is similar to the design indicated in chapter 16 of CHBDC. While the back mesh reinforcement was removed, two horizontal bars were placed at the top back side of the barrier. All wall bars were of stainless steel (SS); vertical bars were SS#5 placed at 275 mm and horizontal bars were SS#4 placed at 225 mm. Additionally, SS#5 bent bars were placed at 275 mm spacing and embedded over 185 mm depth into the deck base. The top two horizontal bars were also SS#5 and placed at 50 mm from the back face of the barrier wall. Figure 3 shows the cross-sectional view of specimen S1-FRC10.

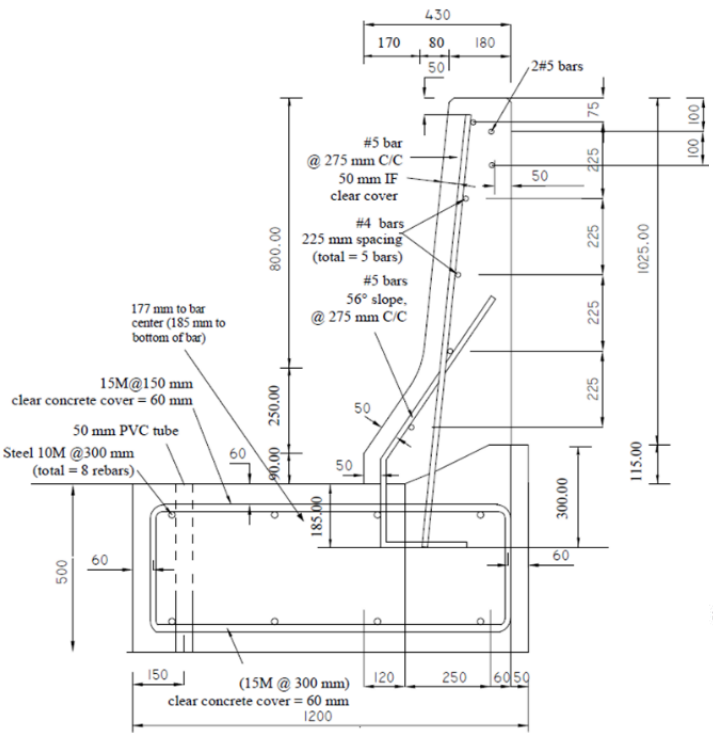


Fig. 3: Specimen S1-FRC10 dimensions and reinforcement details (units in mm)

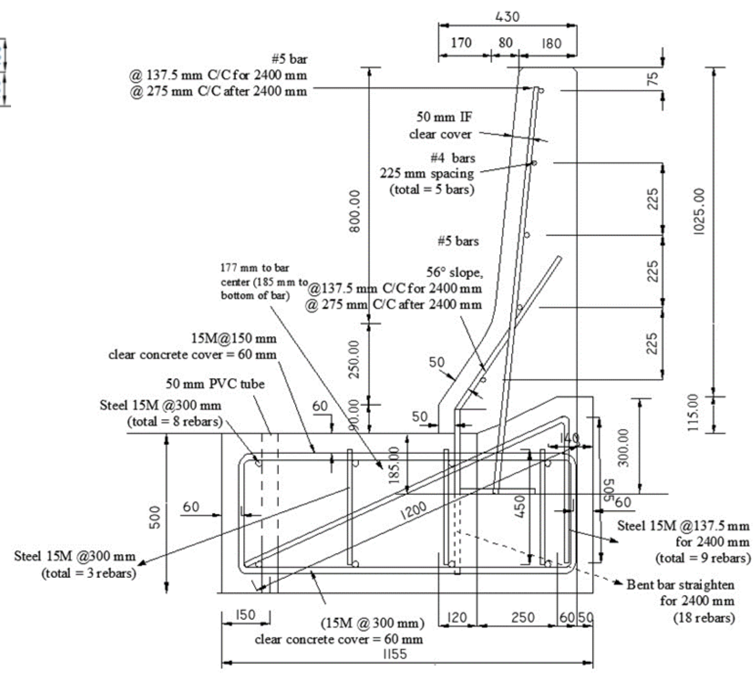


Fig. 4: Specimen S2-FRC10 dimensions and reinforcement details (units in mm)

The second specimen (S2-FRC10) had the same dimensions as specimen S1-FRC10. However, the reinforcement of S2-FRC10 had the following differences from S1-FRC10:

- The two top horizontal bars at the back of the barrier were removed. This was planned in the design and test matrix initially to compare the results with the first specimen and assess the difference in the barrier capacity with and without the two top bars.
- The other difference of the reinforcement of S2-FRC10 was proposed after specimen S1-FRC10 was tested; as the failure of specimen S1-FRC10 was mainly due to anchorage of vertical bars embedded in the deck base. In order to prevent this anchorage failure in the concrete base under the barrier wall, it was decided to increase base reinforcement as indicated in Figure 4. Diagonal steel bars of 15M @ 300 mm spacing along with three vertical steel bars of 15M @ 300 mm spacing were added over the loaded length of 2.4 m.

4.2. Barrier Testing

The construction of the barriers included formwork and reinforcement assembly, followed by two-step concrete casting of the deck and the barrier wall. The solid slab with normal concrete was cast initially as the barrier deck, and the barrier wall was cast separately using FRC, 7 days after deck casting. The wall concrete was delivered as normal concrete to the lab, and synthetic fibers and the water-reducing mixture were then added to the concrete in the lab per supplier's guidelines. Additionally, as part of the ASTM guidelines for casting FRC such as ASTM C1609 [14], external vibration was used for concrete consolidation to prevent segregation. Figure 5 shows the steps of casting the FRC barrier and the cast and painted barrier before testing specimen S1-FRC10. After the curing process and hardening, the formwork was opened, and the barriers were painted with white color. Each specimen was also installed with nine potentiometers (POTs) to measure the displacements as depicted in Figure 6. The barriers were statically tested by applying a horizontal line loading over a 2.4 m length from the barrier end as depicted in Figure 7. The load distribution was done using two timber blocks so it would simulate the truckload impact per CHBDC. The load was increased at 50 kN increments and cracks were marked at each loading step. The applied load and POT readings were recorded using a data acquisition system until collapse. More details about the experimental program can be found elsewhere [15].

a) Wall reinforcement (b) Wall formwork and external vibrators (c) Painted FRC barrier before testing

Fig. 5: FRC barrier specimen S1-FRC10

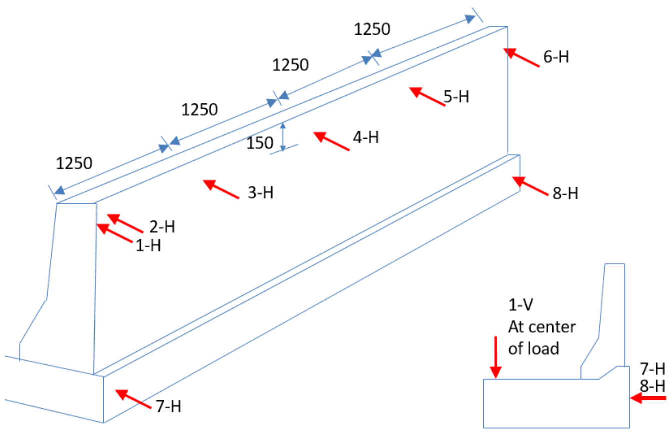


Fig. 6: POT locations for measuring displacement (units in mm)

Fig. 7. Test setup

4. Test Results and Discussion

Results were assessed based on the crack pattern, failure mode, and load-carrying capacity. Figures 8 and 9 show photos of cracks in specimen S1-FRC10 after failure In this specimen, a first flexural crack oriented in the direction of the barrier at the barrier-deck junction at 60 kN, followed by horizontal cracks within the loaded length at 175 kN as depicted in Figure 9. With increased applied load, these horizontal cracks extended diagonally toward the top surface of the wall outside the loaded region. However, a sudden concrete breakout occurred in the base as appeared at the 375 kN applied load, as depicted in Figure 8. The ultimate failure load was recorded as 395 kN which is greater than the CHBDC factored design transverse loading of 357 kN, leading to a capacity-demand ratio (CDR) of 1.11. However, applying a resistance factor for the materials (which is expected to be between 0.75 for concrete and 0.9 for stainless steel bars), makes this design unsuccessful due to excessive bar anchorage cracks that led to concrete breakout in the base. For this reason, it was decided to increase the diagonal reinforcement in the base to assist in precluding such failure mode. Figure 12 shows the load-deflection relationship for specimen S1-FRC10. At the failure load, the maximum recorded deflection at the loaded end of the barrier was 14.6 mm. The recorded barrier uplift at the location of the tie-down system was 2.04 mm at the failure load. The horizontal movements of the concrete base under load were recorded as 5.18 and 2.16 mm at the south and north sides, respectively.

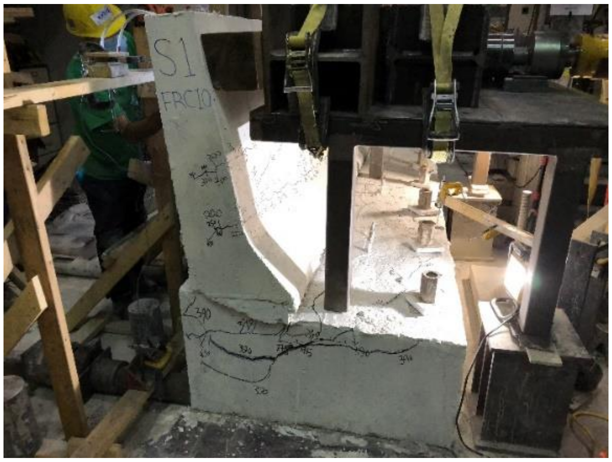


Fig. 8: Concrete breakout failure in the deck (S1-FRC10)

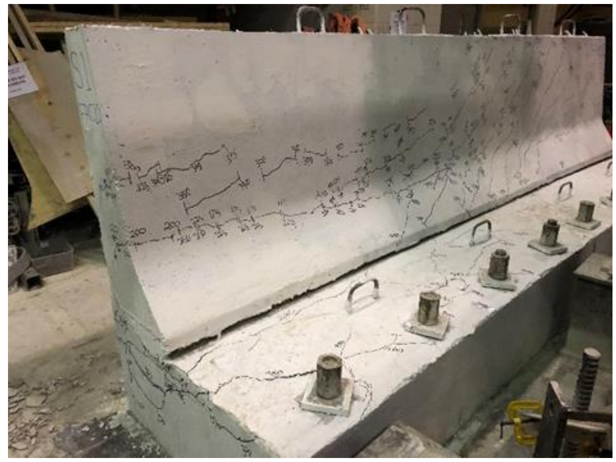


Fig. 9. Wall flexural cracks in specimen S1-FRC10

Fig. 10. Crack pattern at end of specimen S2-FRC10

Fig. 11: Trapezoidal tension-flexural shear crack pattern (S2-FRC10)

Figures 10 and 11 illustrate the cracks in specimen S2-FRC10 after failure. It was observed that the first horizontal crack occurred at the front side of the barrier deck joint at 50 kN, followed by horizontal cracks in the barrier wall within the loaded region at 250 kN as depicted in Figure 11. With increased applied load, diagonal cracks appeared outside the loaded region. Also, the horizontal flexural cracks in the wall penetrated further in the wall thickness with increased applied load while anchorage cracks appeared in the base under the wall as depicted in Figure 10. The test continued until reaching a load of 900 kN which raised a concern that the capacity of the designed loading frame was 1000 kN. So, it was decided to stop the test at this level since flexural-shear cracks were significantly widened with increased applied load. In addition, the flexural-shear cracks were propagating towards the back face of the barrier wall at the level of the junction between the two tapered portions of the wall as a sign of reaching concrete crushing. These flexural-shear cracks appeared to extend horizontally from the south end of the barrier wall to close to the other loaded end and then propagated diagonally towards the top surface of the barrier wall, forming a trapezoidal yield line pattern.

The failure load associated with the crack pattern was 912 kN which is 2.55 times the CHBDC design load of 357 kN. At the failure load, the maximum-recorded deflection at the loaded end of the barrier was 42.31 mm as depicted in Figure 13. The recorded barrier uplift at the location of the tie-down system was 3.25 mm at the failure load which is considered small. The horizontal movements of the concrete base in the direction of the applied load were 3.67 and 0.63 mm at the south and north sides, respectively.

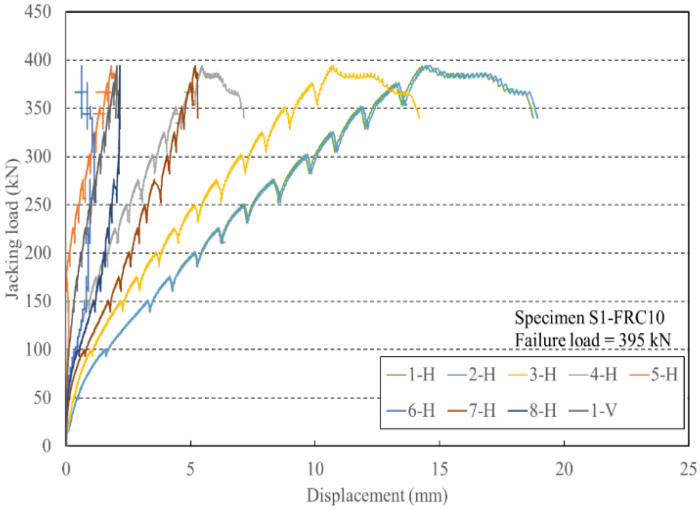


Fig. 12: Load-displacement graph for specimen S1-FRC10

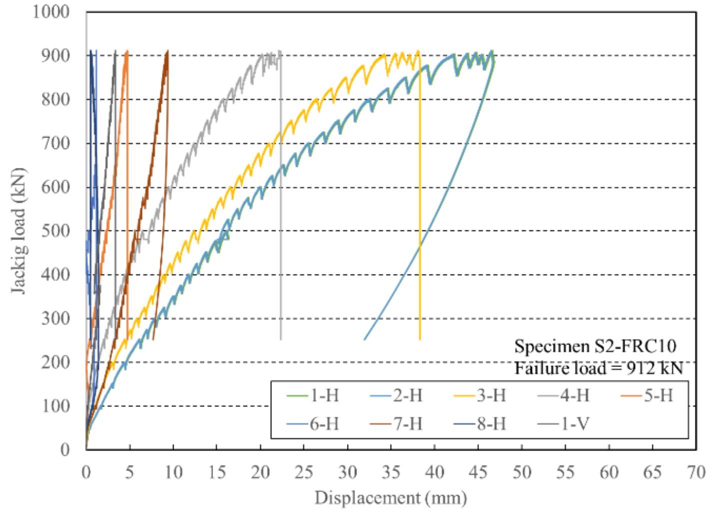


Fig. 13. Load-displacement graph for specimen S2-FRC10

5. Conclusions

The present research included casting and testing two full-scale TL-5 FRC bridge barriers to evaluate their impact resistance and overall structural performance when transversally loaded at the end location. Both specimens were cast with a 1.0% synthetic macro-fiber FRC for the wall and normal concrete at the deck. The first specimen had a similar design to that specified in CHBDC chapter 16 for FRC barriers, in which only one mesh of conventional stainless-steel reinforcement at the front side of the barrier and two horizontal stainless-steel rebars at the top back of the barrier wall in lieu of a back mesh of reinforcement. In the second specimen, the two top back rebars were removed; however, the barrier deck reinforcement was increased since the first specimen results indicated a need for additional reinforcement at the wall-deck junction due to premature anchorage failure. It can be concluded that after addressing the premature anchorage failure of the barrier wall reinforcement into the concrete base, the FRC barrier with a front mesh of stainless steel bars of 15M at 275 mm spacing exhibited transverse load-carrying capacity greater than the CHBDC design factored traffic load. Also, the crack pattern at failure was in the form of a trapezoidal shape.

Acknowledgments

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