VEHICLE CRASH TESTING ON A GFRP-REINFORCED PL-3 CONCRETE BRIDGE BARRIER

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ABSTRACT

Corrosion of steel reinforcement due to environmental effects is a major cause of deterioration problems in bridge barriers. Glass fibre reinforced polymers (GFRP), not only addresses this durability problem but also provides exceptionally high tensile strength, and Young's modulus. The special ribbed surface profile of the studied GFRP bars and end anchorage heads ensure optimal bond between concrete and the bar and eliminate the use of custom made bar bends. A recent design work conducted at Ryerson University on PL-3 bridge barrier proposed the use of 16 mm and 12 mm diameter GFRP bars as vertical reinforcement in the barrier front and back faces, respectively, with 12 mm diameter GFRP bars as horizontal reinforcement in the barrier wall, all at 300 mm spacing. The connection between the deck slab and the barrier wall utilized the GFRP headed end bars for proper anchorage. This paper summarizes the procedure and the results of a recent vehicle crash test conducted on the developed barrier. The crash test was performed in accordance with MASH Test Level 5 (TL-5), which involves the 36000V tractor trailer impacting the barrier at a nominal speed and angle of 80 km/h and 15° degrees, respectively. Crash test results showed that the barrier contained and redirected the vehicle. The vehicle did not penetrate, underride or override the parapet. No detached elements, fragments, or other debris from the barrier were present to penetrate or show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. No occupant compartment deformation occurred. The test vehicle remained upright during and after the collision event.

INTRODUCTION

Bridges built prior to the 1970's did not use air-entrained concrete and coated reinforcing steel bars to protect from the effects of freeze-thaw cycles and the application of winter de-icing salt. This leads to corrosion-induced degradation in bridge elements as shown in Fig. 1. Accordingly, exposed bridge elements are all likely candidates for expensive replacement on the majority of these older bridges. It is estimated that over 40% of all bridges in Canada are older than 40 years and are in need of rehabilitation or replacement. The backlog of maintenance, rehabilitation and replacement of highway bridges is estimated at \$10 billion. The current traditional bridge rehabilitation/replacement systems in most situations are very time consuming and costly. The prohibitive costs needed to upgrade bridge structures require the development of innovative technologies to accelerate bridge replacement/repair; and (ii) provide sustainable bridge systems that prolong the service life of the structure.

In November 2007, The Residential and Civil Construction Alliance of Ontario, Canada, (RCCAO 2007) released a report on the state of Ontario bridges, entitled "Ontario's Bridges: Bridging the Gap." The report warns that the integrity of Ontario's municipal bridge infrastructure and public safety are at risk after years of deferred maintenance, irregular inspections, and lack of government oversight. Recent media coverage on bridge collapses in Laval, Quebec and Minneapolis, Minnesota, has highlighted the serious consequences of postponing actions to rehabilitate or reconstruct deteriorated bridges and the urgent need to take timely responsible action to safeguard the public from potential infrastructure failure. The study noted that many of Ontario's bridges were built in the 1950s and 1960s, and "it is expected that most bridges will require costly rehabilitation or replacement after 50 years of

life." According to the Provincial Auditor's report in 2004, almost one-third of the approximately 2,800 provincial bridges under Ministry of Transportation of Ontario's (MTO) jurisdiction are in need of major rehabilitation or maintenance based on MTO's own figures. However, for the estimated 12,000 municipal bridges in Ontario, the RCCAO report stated that there is a lack of information on their conditions and a capital investment of at least \$2 billion will be required over the next five years to rehabilitate this aging infrastructure. The RCCAO report stated some recommendations to be made to promote the public's safety and the sustainability of Ontario's bridges. One of these recommendations includes promoting bridge engineering designs that improve the life expectancy and reduce maintenance costs of bridges. This can be achieved by using fibre reinforced polymer bars.



Fig. 1. Corrosion-induced degradation of steel-reinforced bridge barrier wall



FRP TECHNOLOGY

Fibre-reinforced polymers (FRPs), as non-corrodible materials, are considered as excellent alternative to reinforcing steel bars in bridge decks to overcome steel corrosion-related problems. Since it is less expensive than carbon and aramid FRPs, Glass FRP (GFRP) bars are more attractive to bridge deck and barrier applications. The GFRP bars used in this study have tensile strength of 1188 MPa, compared to 400 MPa yield strength of the currently used reinforcing steel bars. The special "ribbed" surface profile of these bars, shown in Fig. 2, ensure optimal bond between concrete and the bar. Until recently, the installation of GFRP bars was often hampered by the fact that bent bars have to be produced in the factory since GFRP bars cannot be bent at the site. Also, bent GFRP bars are much weaker than straight bars, due to the redirection and associated rearrangement of the fibres in the bend. As a result, number of bent GFRP bars is increased and even doubled at such locations where bar bents are required. The use of headed-end GFRP bars is intended to eliminate the unnecessary and expensive use of custom made bar bends. In case of concrete bridge barriers, GFRP bars with headed ends are used as straight bars at the inside face of the barrier walls with an end head at the bottom to reduce their development length in the deck slab, avoiding the use of hooks. This headed end is made of a thermo-setting polymeric concrete with a compressive strength far greater than that of normal grade concrete. It is cast onto the end of the straight bar and hardened at elevated temperatures. The concrete mix contains an alkali resistant Vinyl Ester resin, the same material used in the straight bars, and a mixture of fine aggregates. The maximum outer diameter of the end heads is 2.5 times the diameter of the bar. The head of the 16 mm bar is approximately 100 mm long. It begins with a wide disk which transfers a large portion of the load from the bar into the concrete. Beyond this disk, the head tapers in five steps to the outer diameter of the blank bar. This geometry ensures optimal anchorage forces and minimal transverse splitting action in the vicinity of the head.

BACKGROUND OF THE DEVELOPED GFRP-REINFORCED BARRIER SYSTEM

The design process of bridge barrier walls specified in the Canadian Highway Bridge Design Code (CSA, 2006a; CSA, 2006b) is based on the AASHTO Guide Specification for bridge railings (AASHTO, 1989) and the AASHTO Guide for Selecting, Locating and Designing Traffic Barriers (AASHTO, 1977). CHBDC Clause 12.4.3.5 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. For an anchorage to be considered acceptable, significant damage shall not occur in the anchorage or deck during crash testing. It also specifies that if crash testing results for the anchorage are not available, the anchorage and deck shall be designed to resist the maximum bending, shear and punching loads that can be transmitted to them by the barrier wall. As such, the initial design of the proposed PL-3 precast bridge barrier (Sennah et al., 2010) was carried out to meet the CHBDC design criteria specified for static loading at the anchorage between the deck slab and the barrier wall. CHBDC specifies transverse, longitudinal and vertical loads of 210, 70 and 90 kN, respectively, that can be applied simultaneously over a certain barrier length. CHBDC specifies that transverse load shall be applied over a barrier length of 2400 mm for PL-3 barriers. Since transverse loading creates the critical load carrying capacity, 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 impact load on PL-3 barrier wall over 2.4 m length is 357 kN. For the anchorage resistance of the GFRP bars embedded in the deck slab, Pahn (Pahn 2008) conducted pullout tests on 16 mm diameter GFRP bars provided with headed ends to determine their pullout capacity when they are embedded in concrete over bond lengths of 100 mm and 200 mm. The results from this testing formed the basis for the developed PL-3 barrier-deck joint. As for the design of the vertical and horizontal reinforcement in the barrier wall, the yield-line analysis conducted (Sennah et al., 2010) on the ultimate flexural capacity of the concrete components as specified in the AASHTO-LRFD Bridge Design Specifications (AASHTO, 2004). In the analysis, it was assumed that the yield-line failure pattern occurs within the barrier wall only and does not extend into the deck slab. This means that the deck slab must have sufficient resistance to force the yield-line failure pattern to remain within the barrier wall. The LRFD yield-line analysis is also based on the assumption that sufficient longitudinal length of barrier wall exists to result in the desired yield-line failure pattern.

Such design work for the PL-3 bridge barrier proposed the use of 16 mm and 12 mm diameter GFRP bars as vertical reinforcement in the barrier front and back faces, respectively, with 12 mm diameter GFRP bars as horizontal reinforcement in case of PL-3 barrier wall, all at 300 mm spacing. The connection between the deck slab and the barrier wall utilized the GFRP headed end bars for proper anchorage. Figure 3 shows a schematic diagram of the GFRP reinforcement on the designed barrier wall. Two full-scale PL-3 barrier models of 1200 mm length were erected and tested to-collapse to determine their ultimate load carrying capacities and failure models (Sennah et al., 2010). The first barrier was a control one with reinforcing steel bars, while the second barrier model was reinforced with GFRP bars with headed ends. Based on the data generated from the experimental study, it was concluded that GFRP bars with headed anchorage can be safely used in bridge barrier walls to resist the applied vehicle impact load specified in CHBDC at the barrier wall-deck slab anchorage. However, CHBDC Clause 12.4.3.4.4 specifies crash testing for the design of the barrier wall itself (i.e. both vertical and horizontal reinforcement).



Fig. 3. PL-3 FRP-reinforced bridge barrier



Fig. 4. View of the GFRP reinforcement in the barrier wall

CRASH TESTING OF THE DEVELOPED GFRP-REINFORCED BARRIER SYSTEM

In November 2010, vehicle crash test was conducted in accordance with Test Level 5 (TL-5) of MASH (MASH, 2009), 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 15° degrees, respectively (MASH, 2009). This test was intended to evaluate the strength of the barrier in containing and redirecting heavy vehicles. Figures 4 and 5 show views of the GFRP reinforcement and deck slab reinforcement before making the timber forms and casting concrete. While Fig. 6 shows view of the built 40-m long barrier before vehicle impact. Figure 7 shows view of the test vehicle, while Fig. 8 shows the test vehicle during a mock test before impacting the barrier at 15° angle.



Fig. 5. Close-up view of barrier anchorage to deck slab Fig. 6. View of the barrier wall before crash testing



Fig. 7. View of the test vehicle



Fig. 8. View of the test vehicle before impacting the barrier

CRASH TEST RESULTS

On the day of the crash testing, concrete cylinders were tested to-collapse to determine their compressive strength. The resulting concrete characteristic compressive strength was 32 MPa. At the time of the test, the tractor trailer was guided into the test installation using a remote control steering system. The tractor trailer impacted the barrier at 620 mm upstream of the control joint located at 10.8 m from the barrier downstream end. At 0.100 s, the cab of the test vehicle began to redirect, and at 0.203 s, the lower right front corner of the van-trailer contacted near the top of the barrier. At 0.403 s, the cab of the test vehicle was traveling parallel with the barrier at a speed of 79.7 km/h. The van-trailer began traveling parallel with the barrier at 0.667 s, and was traveling at a speed of 76.3 km/h. At 0.695 s,

the lower right rear corner of the van-trailer contacted near the top of the barrier, and at 0.748 s, the right rear edge of the van-trailer ruptured. As the test vehicle continued along the barrier, it righted itself and rode off the end of the barrier wall. The brakes on the test vehicle were not applied, and the test vehicle subsequently came to rest 35.66 m downstream of the end of the barrier and 2.7 m toward the field side. Sequential photographs for the crash test are presented in Figs. 9 and 10 for frontal and side views, respectively.



Fig. 9. Sequential photographs for the crash test (frontal views)



Fig. 10. Sequential photographs for the crash test (side views)

Evaluation criteria for full-scale vehicle crash testing are based on three appraisal areas, namely: (i) structural adequacy; (ii) occupant risk; and (iii) vehicle trajectory after collision. Structural adequacy is judged upon the ability of the barrier to contain and redirect the vehicle, or bring the vehicle to a controlled stop in a predictable manner. The vehicle should not penetrate, underride, or override the barrier although lateral deflection of barrier is acceptable. Occupant risk criteria evaluate (i) the potential risk of hazard to occupants in the impacting vehicle and to some extend other traffic, pedestrian, or workers in construction zones, if applicable; (ii) deformation of, or intrusions into, the occupant compartment should not exceed preset limits set forth in MASH; and (iii) whether the vehicle remain upright during and after collision. Post impact vehicle trajectory is assessed to determine potential for secondary impact with other vehicles or fixed objects, creating further risk of injury to occupants of the impacting vehicle and redirected the 36000V vehicle. The vehicle did not penetrate, underride or override the parapet. No detached elements, fragments, or other debris from the barrier were present to penetrate or show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. No occupant compartment deformation occurred. The 36000V test vehicle remained upright during and after the others in the area.



Fig. 11. General view of the barrier wall after vehicle impact



Fig. 12. View of the barrier wall and the test vehicle at rest

After the crash test, minor cracks in the front and back side of the barrier were observed. However, no complete damage was observed. Figures 11 and 12 show views of the barrier, reflecting this finding. In practice, these minor cracks may need to be repaired to avoid possible crack propagation resulting from other possible vehicle impact. In February 2011, Ryerson University research team conducted static load failure tests on the barrier segments to provide research information that will be used further to evaluate the applicability of AASHTO-LRFD yield-line equations, developed for reinforcing steel bars, to the design of GFRP-reinforced barrier under equivalent static vehicle impact loading. More information about this comprehensive research program can be found elsewhere (Buth and Menges, 2011; Sennah, 2011).

CONCLUSIONS

A vehicle crash test was conducted on a newly developed GFRP-reinforced PL-3 bridge barrier system. Results from tests qualified such innovative barrier system to resist vehicle impact per MASH crash test requirement. Crash test results showed that the developed barrier contained and redirected the vehicle. The vehicle did not penetrate, underride or override the parapet. No detached elements, fragments, or other debris from the barrier were present to penetrate or show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. No occupant compartment deformation occurred. The test vehicle remained upright during and after the collision event.

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