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The Development of Crashworthy Rails for Fiber Reinforced Polymer Honeycomb Bridge Deck System

Moni El-Aasar, Ph.D., P.E., FASCE

BG Consultants, Inc.

Kansas Department of Transportation

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Final Report

Prepared by

Moni El-Aasar, Ph.D., P.E., FASCE

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Abstract

Fiber reinforced polymer (FRP) honeycomb panels offer an efficient and rapid replacement to concrete decks. The system consists of FRP honeycomb sandwich panels with adequate guardrails. Although FRP bridge deck panels have already been designed and used over the past several years on a number of through truss bridges, they could not be used on steel girder bridges until approved crashworthy bridge railing attachments could be validated. Two systems have been successfully crash tested, one with steel thrie beams/guardrails on steel posts and the other with concrete barriers. Both systems are now ready for use on temporary/detour bridges, or as permanent deck replacement allowing higher live load while keeping the existing steel girders and substructure.

The light weight of FRP honeycomb panels (about 75% lighter than concrete) allows heavier truck loads, while keeping the existing girders and substructure without compromising the safety of the public. The roadway can be made wider by increasing the overhangs, thus allowing for wider farm equipment on narrow bridges in rural areas. The replacement of the concrete deck using this system may be completed in a matter of a few days, or even hours, as opposed to several months when using the conventional methods.

Table of Contents

List of Figures

Introduction

As trucks and farming equipment have become wider and heavier in the past years, the Kansas Department of Transportation (KDOT) and bridge engineers around the state have recognized the need for wider, greater load capacity bridges in Kansas. Many of the existing bridges still have structurally sound substructures, but the decks are deteriorating and are too narrow to carry the current vehicles and equipment. A deck system consisting of fiber reinforced polymer (FRP) panels has been developed to replace and widen some of these bridge decks without adding undue burden to the existing substructure. Another proposed use of the FRP panel deck is for temporary detour bridges. The ease of construction, short installation time, and reusability of the FRP panels make this a very appealing prospect.

However, conventional rail barriers could not be attached to the FRP panels. This meant FRP panels could not be used in practice on highway bridges designed according to the AASHTO specifications until acceptable bridge railing systems could be developed. The bridge guardrail/barrier system had to be successfully crash tested according to National Cooperative Highway Research Program (NCHRP) Report No. 350 by Ross, Sicking, Zimmer, and Michie (1993). Under the sponsorship of KDOT and with funding from the Federal Highway Administration (FHWA)/United States Department of Transportation, the research directive was to develop two crashworthy rail options. This report is to summarize the steps taken to achieve this result.

Steel Post Thrie Rail

The first option utilized a previously developed and tested steel guardrail post assembly revised to be used with the lightweight FRP panels. The revision included a steel connection plate with a 12 bolt pattern in two lines to attach the rail to the FRP panels. The connection was designed to resist the shear force generated due to an impact on a guard rail post placed at the center edge of an 8-foot panel. A test panel and steel post assembly was set up in Russell, KS, at Kansas Structural Composites, Inc., for the static testing.

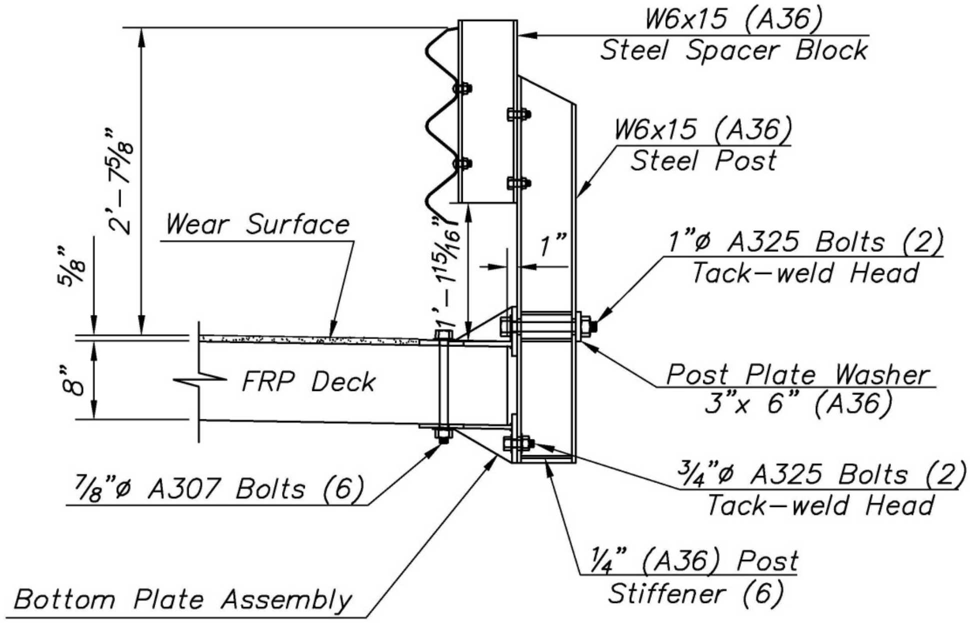
The first static test took place on August 23, 2000, in which steel guardrail posts were attached to both ends of a 16-ft-wide deck panel. Figures 1a and 1b illustrate the setup of the static tests. Loading was achieved by applying a horizontal force to the posts through a hydraulic actuator to determine its effect on the bridge deck and the attachment system. This steel guardrail post assembly was previously crash tested for use on timber deck bridges. The top and bottom plates would use 12 anchor bolts through the deck, placed in two rows parallel to the direction of traffic. The traffic side row of six bolts would typically extend into the roadway. The deck panels and posts performed extremely well when tested with two lines of bolts.

A second static test was completed on September 21, 2000, using a larger hydraulic actuator to apply larger loads. The results of this test were high enough that the possibility of cutting the connection plate in half longitudinally and using a six bolt pattern instead of a 12 bolt pattern was discussed. By doing this, the connection plate would lie under the guardrail and not extend into the roadway, reducing the possibility of snagging maintenance equipment such as snow plows. The connection plate was modified and retested on July 26, 2001. The modified connection plate successfully passed the static testing, and was determined to be the design to further test dynamically. See Figure 2 for a detailed drawing of the modified steel post assembly.

(a) Testing of Original Steel Post Assembly

(b) Testing of Modified Steel Post Assembly

Figure 1: Static Testing of Steel Guardrail



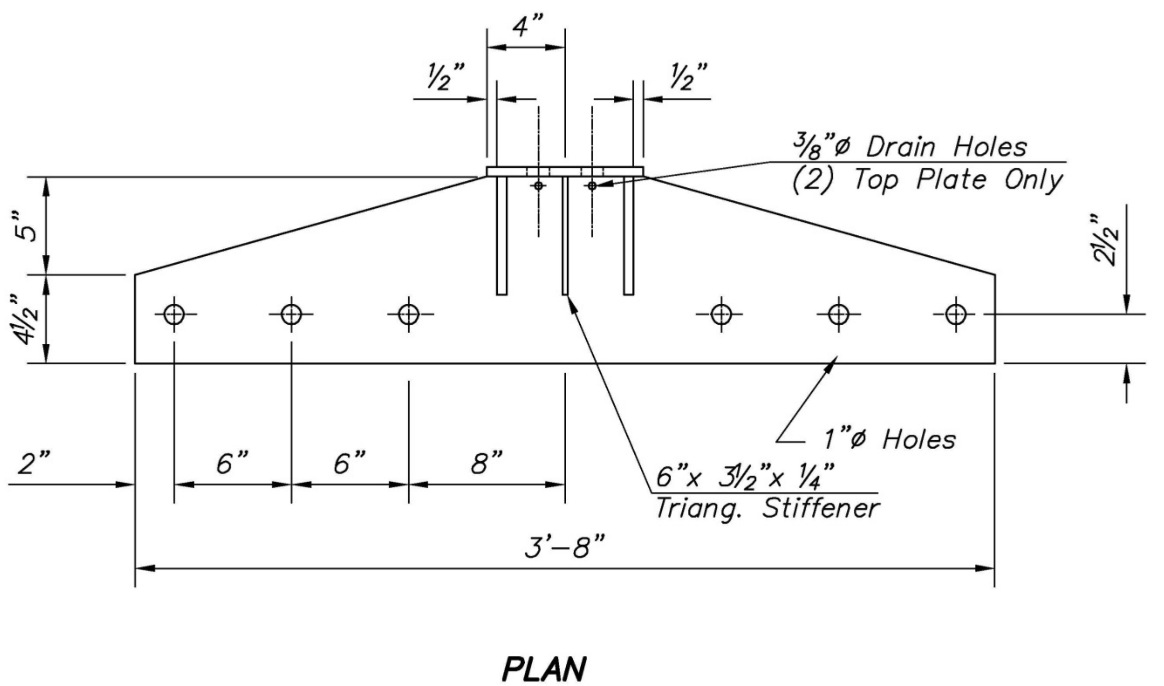


Figure 2: Modified Steel Post Assembly

Another advantage of FRP deck panels that was discovered during these bench tests is that when pressure was put upon the guardrails and then removed, the bridge deck did not suffer any permanent distortion. Currently, steel deck frames in bridges are often distorted and become misaligned when vehicles strike the bridge rail. This often creates problems in repairing the bridge rails, since the bridge deck usually suffers a certain amount of distortion from the impact.

Crash Testing of Steel Post Guardrail System

All crash tests were performed at the Midwest Roadside Safety Facility (MwRSF) at the University of Nebraska–Lincoln. Depending on the expected usage of the bridge, there are various test levels that determine the specific crash tests to be performed. A Test Level 4 (TL-4) was previously conducted at MwRSF on a deck-mounted, steel post bridge rail system for a bridge deck consisting of thin, transverse, glue-laminated timber panels, as described by Faller, Ritter, Rosson, Fowler, and Duwadi (2000). The system consisted of a horizontal steel tube mounted on W6x15 steel blockouts. The blockouts were bolted to steel posts, which were in turn bolted to a series of steel attachment plates that anchored directly to the bridge deck. The NCHRP Report 350 TL-4 criteria require that longitudinal barriers be subjected to three full-scale vehicle crash tests (Ross et al., 1993):

1. A 1,808-lb small car impacting at a speed of 62.1 mph and at an angle of 20° (referred to as the 820c TL-4 test);
2. A 4,409-lb pickup truck impacting at a speed of 62.1 mph and at an angle of 25° (referred to as the 2000p TL-4 test); and
3. A 12,636-lb single-unit truck impacting at a speed of 49.7 mph and at an angle of 15° (referred to as the 8000s TL-4 test).

The previous crash tests of the steel posts on the timber deck were performed using the pickup truck and single-unit truck impact conditions. One 2000p and one 8000s TL-4 crash tests were used on the timber deck. The crash tests conducted met all safety requirements specified in NCHRP Report 350 (Ross et al., 1993). Details on the timber deck research project can be found in Faller et al. (2000).

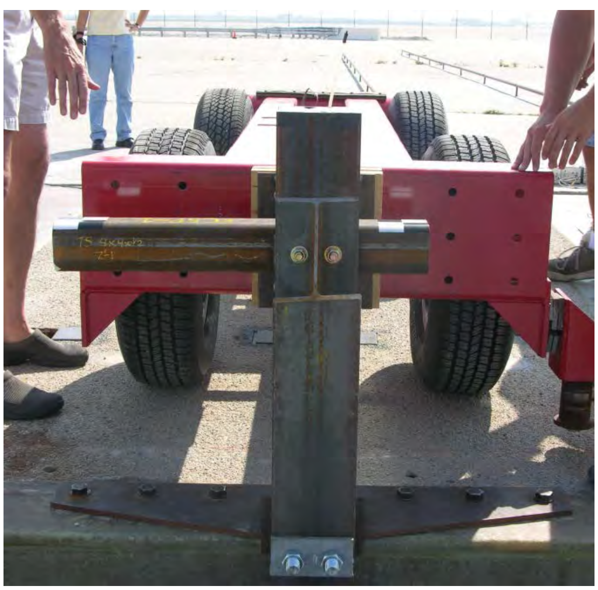
Fiber Reinforced Polymer Honeycomb Bridge Deck Panels

The modified steel posts were anchored to fiber reinforced polymer honeycomb (FRPH) bridge deck panels, which were placed transversely across two longitudinal steel bridge girders spaced at 8 ft 2 inches with a 4.5 ft overhang. Each FRP panel measured 14 ft long × 8 ft wide × 8 inches thick, and was fabricated using 0.5-inch-thick elements that are 40% fiberglass and 60% polyester. The fiber architecture utilized a standard manufacturer layup in conjunction with a polyester resin material. The honeycomb core consists of alternating flat and corrugated layers. The flat FRP elements were 0.09 inches thick, while the corrugated layers had an amplitude of 2 inches and a wave length of 4 inches. The core height was 7 inches. Panel edges and closeouts were constructed with 0.12-inch-thick FRP elements and wet layups with 4 to 6 inches overlapping on the primary surfaces. The anchoring system for attaching the FRP panels to the steel beams consists of steel bent-plate connectors measuring 0.25 inches thick × 5 inches wide. The connector plates were anchored with studs welded to the beams with washers and nuts at panel joints. The anchor studs were attached with a full penetration weld by using a stud gun. The low-carbon steel anchor studs had a 50 ksi minimum yield strength and a 60 ksi minimum tensile strength.

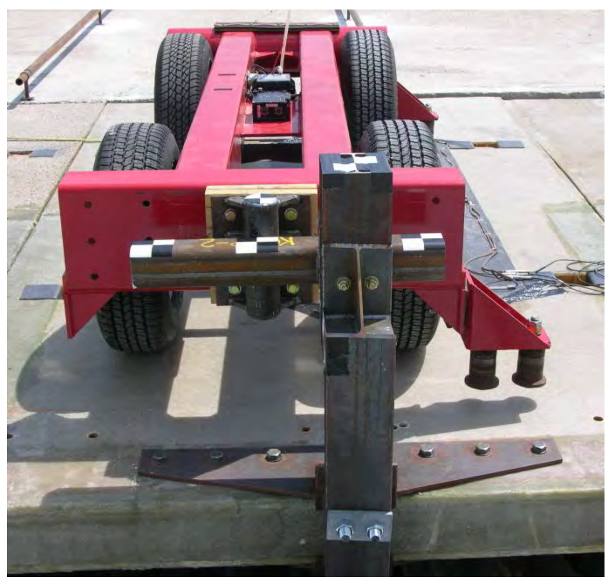
Bogie-Tests Instead of Full-Scale Crash Testing

First, it was necessary to determine if the deck-mounted, steel post barrier system for the timber bridge deck can be directly used with the FRP bridge deck without undergoing expensive full-scale crash testing. For this purpose, an analysis was performed on the system subjected to dynamic bogie testing applied to a single post of the railing. Additionally, a series of computer simulations using nonlinear finite element analysis of the bogie testing were performed in order to enhance the analysis. Two bogie tests (KCBP-1 and KCBP-2) were designed to apply significant lateral and torsional loads to a steel post and blockout mounted on the FRP deck.

The bogie tests were performed in the summer of 2005. The individual steel posts were attached to the FRP deck panels without the placement of the thrie-beam rail on the traffic-side face of the blockouts and without the use of the top-mounted steel tubular rail. However, a horizontal spreader beam was designed and attached to the front face of the blockouts, so that the dynamic impact load would be imparted to the posts at the appropriate load height. A 1,414-lb bogie, fitted with an impact head positioned 24.875 inches above the deck surface, impacted the spreader beam at two different locations. Test KCBP-1 was a centerline impact, aligning the bogie impact head with the center of the steel post, and KCBP-2 was an eccentric impact, with the impact head offset from the centerline of the post by 9 inches. KCBP-1 was run to investigate a simple lateral loading situation, while KCBP-2 was run to investigate a combined lateral and torsional loading situation. Two axial accelerometers were mounted to the bogie vehicle to record acceleration throughout the events. From the recorded data and the initial speed of the bogie, displacement, force, and energy were derived for each impact event. Figure 3a shows the centerline bogie impact test KCBP-1, while Figure 3b shows the eccentric (torsional) bogie impact test KCBP-2. In all tests, neither the FRPH panels nor the post connection to the panel suffered any significant damage. The deformed posts following the crash test are shown in Figure 4.



(a) Centerline Impact Test KCBP-1



(b) Eccentric (Twist) Impact Test KCBP-2

Figure 3: Bogie Tests on Steel Posts Attached to FRP Panels


Figure 4: Deformed Rail and Post After Impact

Based on the earlier full-scale crash testing of the previous timber deck system, it was determined that the post in the bogie load test should deflect backward at least 8 inches in order to demonstrate that this magnitude of displacement would not significantly damage the FRP deck or the attachment hardware. However, to assure adequate capacity, it was reasoned that the FRP deck and post components should be subjected to a greater post deformation; thus, a 14-inch post displacement at the load height was selected. If this deformation does not damage the FRP deck or rupture the post and associated hardware, then it will demonstrate that the FRP deck panel is an acceptable alternative to the thin timber deck panel. Using a bogie weight of 1,414 lbs, a yield force of 24 kips, a post stiffness of 30 kips/inches, and a limiting deflection of 14 inches, a target bogie impact speed was determined to be 24 mph.

Conclusions from the Bogie-Tests

Results of both bogie tests showed that during the 90° centerline lateral-load test and the 90° offset combined load test, the post and post-to-deck attachment hardware were observed to plastically deform without the rupture of the steel mounting hardware off of the FRP deck panel. Since inelastic permanent material deformations were observed in the steel posts on both bogie tests, it is believed that these FRP deck panels are capable of resisting the peak impact loads that would be imparted into the barrier and deck systems under full-scale crash testing. These tests, supplemented by results of the dynamic simulation study, were a valid indicator of the post and post-to-deck attachment hardware's dynamic performance. It was concluded that the steel thrie-beam and steel tube bridge railing system crash tested previously for TL-4 level on timber deck can also be adapted to the FRP deck panel system with the connection provided, and was recommended to obtain FHWA approval for the bridge railing anchored to this FRP deck panel system in accordance to the TL-4 criteria of NCHRP Report No. 350 (Ross et al., 1993). See Reid, Faller, and Hascall (2007) for detailed results for each of the bogie tests, conclusions, and recommendations.

Concrete Jersey Barriers

The second type of barrier tested was the F-shaped concrete Jersey Safety Barrier. The individual barriers were fastened to the FRP composite bridge deck with six 1-inch diameter Grade 5 anchor bolts with heavy hex nuts. An 18 inch × 8 inch × 0.5 inch thick ASTM A36 steel plate washer was located between the bottom of the deck and the hex nuts at each set of two anchor bolt positions. The back sides of the barriers were placed at 2 inches from the back edge of the FRP bridge deck panels. Details of the modified Jersey barriers and their attachment to the FRP deck panels are shown in Figures 5 and 6.

Static Testing

The static testing, similar to that on the steel post assembly, was set up in Russell, KS, on July 26, 2001. A concrete barrier was attached to both ends of the FRP panel. The concrete barrier passed the static testing successfully. The researchers decided to try the test again after removing the two center connecting bolts. Although the barrier with the four bolt connection successfully passed the testing, it was the consensus to leave the six bolt pattern for further testing. The F-shaped concrete barrier was also successfully static tested at MwRSF, University of Nebraska-Lincoln. The next step was dynamic testing at the MwRSF.

Figure 5: Static Testing of Concrete Jersey Barrier Attached to the FRPH Panel

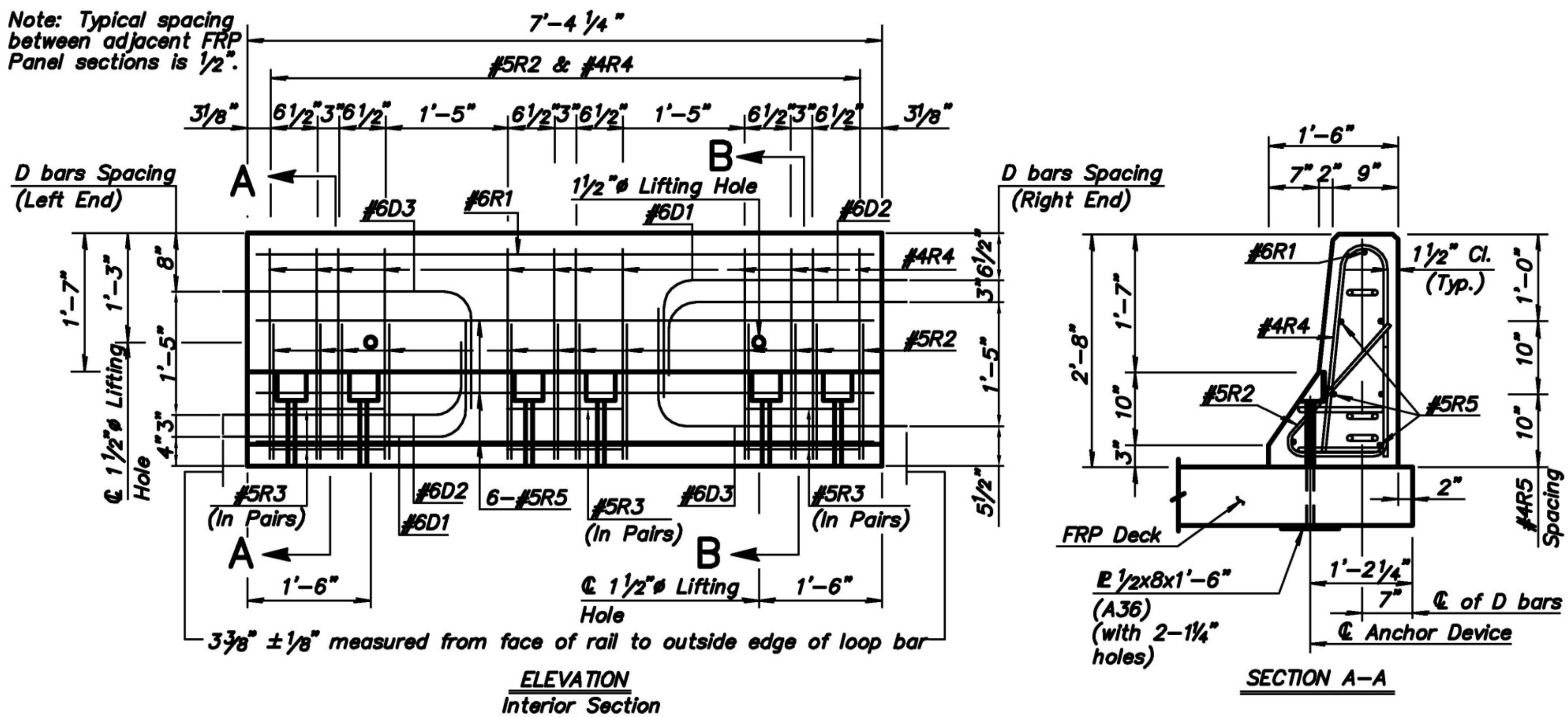


Figure 6: Modified Jersey Barriers and their Attachment to the FRP Deck Panels

Dynamic Testing

The next step in the testing process was a full-scale dynamic crash test on the F-shaped concrete Jersey barrier. Evaluation criteria for full-scale vehicle crash testing are based on three appraisal areas: (1) structural adequacy; (2) occupant risk; and (3) vehicle trajectory after collision. Also, according to TL-3 of NCHRP Report No. 350, the longitudinal barriers must be subjected to two full-scale vehicle crash tests, which are similar to the first two tests (820c and 2000p) of the TL-4 mentioned earlier (Ross et al., 1993). However, rigid Jersey safety shape barriers struck by small cars have been shown earlier to meet safety performance standards. Moreover, temporary Jersey safety shape concrete median barriers were reported elsewhere to have encountered only slight barrier deflections when impacted by small cars. Therefore the 1,808-lb small car test was deemed unnecessary for this project and only the 4,409-lb (2,000 kg) vehicle was used, as explained below.

On July 15, 2005, a full-scale vehicle crash test was performed on the concrete bridge barrier system attached to a composite panel bridge deck using a 3/4-ton pickup truck (1998 GMC 2500) at an impact speed of 62.3 mph and an impact angle of 26 degrees. The test inertial and gross static weights were 4,470 lbs. The FRP bridge deck panels were similar to those used in the bogie tests described earlier. These too were placed transversely across the longitudinal steel bridge girders. The 85-ft test setup consisted of specially designed Jersey safety shape barriers attached to FRP composite bridge deck panels. The 11 half-section Jersey shape barriers were 7 ft 4.5 inches long, and were 18 inches and 9 inches wide at the base and the top, respectively, with a 32-inch top mounting height, as measured from the top of the FRP composite bridge deck to the top of the barrier. They were bolted into place with six bolts per barrier and connected to the next barrier with a pin and loop assembly. A full-size pickup truck was used as the crash vehicle. It was pulled with a cable by a tow vehicle until it was ready to be released to impact the center of a barrier. The truck impacted the barrier at a 26 degree angle and at 62.3 mph.

The modified concrete Jersey barrier did not pass the crash test. Although no serious damage was noticed to the barrier, to the FRPH panels, or to the connections, the vehicle rolled over, as seen in Figure 7.

Figure 7: Vehicle Rollover Following the Crash Test of the Jersey Barriers

During the crash test, the vehicle's front end climbed the concrete parapet, causing the barrier segments to deflect laterally backward. This lateral barrier movement occurred as a result of deck panel shift, girder deformation, and rotation of the deck cantilever. In addition, the effective height of the barrier was reduced as the barrier rotated backward and downward with the deck cantilever. Although this barrier rotation increased the propensity for the pickup truck to climb the parapet, it was apparent that significant counter-clockwise roll motion was induced into the pickup truck at a particular time during the impact sequence. From high-speed video analysis, it was found that the right-rear wheel contacted and snagged on the upstream end of one barrier, thereby inducing significant vehicle roll and subsequent vehicle rollover (see Figure 7). Furthermore, several factors may have contributed to the wheel snag and are noted:

- The joint width between barrier sections, varying between 3.5 and 4 inches, may have allowed the wheel (tire and rim) to wedge into the gap and snag on it.

- The transverse slack between the inner loops and the drop pin may have allowed the downstream end of one barrier to be pushed back before the upstream edge of the adjacent barrier began to move back.
- The barriers were attached to the bridge deck panels using a configuration which allowed one barrier to be anchored to only one deck panel instead of anchoring to multiple deck panels.

In conclusion, the crash test did not meet the TL-3 safety performance criteria presented in NCHRP Report No. 350 for which it was designed; therefore, this design was not suitable for use on Federal-aid highways (Ross et al., 1993). However, following an analysis of the unsuccessful test results and the identification of the wheel snag problem, it was determined that modifications could be made to the system in order to increase its chances of successfully meeting the TL-3 requirements. See Stolle, Polivka, Faller, Rohde, and Sicking (2007) for the complete data and report. The changes and modifications resulted in a new concrete barrier, as described in the next section.

Modified Precast Concrete Barriers

Following the design and crash testing performed on the concrete barrier, an alternative system was designed as a modification to the Jersey barriers tested above. Construction was done in preparation of a full-scale crash test, as shown in Figure 8. The additional overhang of over 4.5 ft allows for a wider roadway on bridge rehabilitation projects, especially for narrow bridges in rural areas.

Figure 8: Full-Scale FRPH Bridge Panels with Vertical-Faced Concrete Barrier

In the summer of 2009, a decisive crash test was successfully conducted at MwRSF on the alternative system of precast, vertical-faced concrete barriers fastened to the deck panels by a specifically designed attachment using anchor rods, plate washers, and nuts (see Figure 9). Each barrier segment was fastened to the FRP deck panels using eight 1-inch diameter Grade 5 anchor rods. An 18 inch long × 8 inch wide × ½ inch thick ASTM A36 steel plate washer was located between the bottom of the deck and the hex nuts at each set of two anchor rod positions. The back side of the barriers was placed 3.375 inches from the back edge of the FRP bridge deck panels. A special X-joint tie rod assembly was used to connect the ends of adjoining barriers together, as shown in Figure 10.

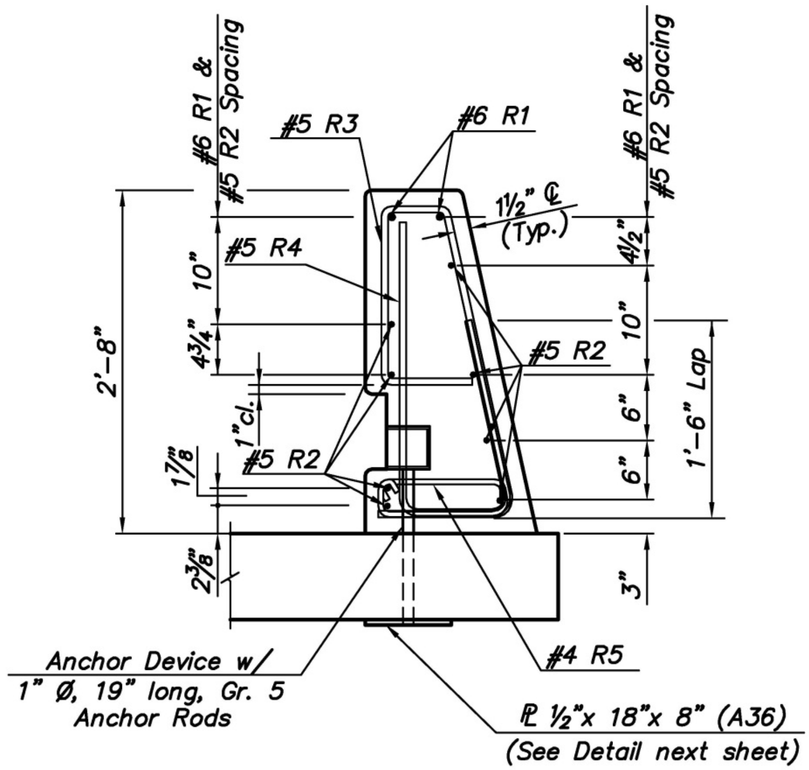
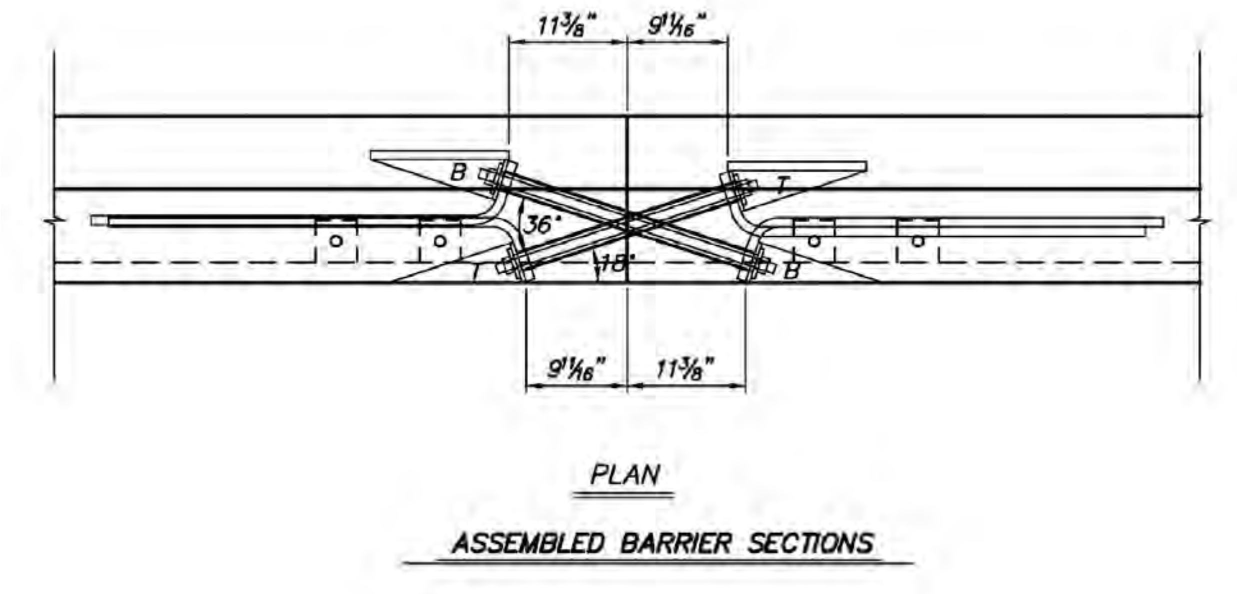


Figure 9: Cross Section Detail of the Modified Vertical-Faced Precast Concrete Barrier

(a)

(b)



(c)

Figure 10: Special X-Joint Tie-Rod Assembly Connecting the Concrete Barriers
(a) Viewed from Outside the Roadway; (b) From Inside the Roadway; (c) Detail Drawing

One full-scale vehicle crash test (test designation No. 3-11) was performed on the bridge railing system according to the TL-3 safety performance criteria specified in the Manual for Assessing Safety Hardware (MASH), as presented in Sicking, Mak, Rohde, and Reid (2009).

The full-scale crash test (Test No. KSFRP-1) was conducted with a 5,179-lb pickup truck impacting 4 ft 3.25 inches upstream from the downstream end of barrier No. 2 at a speed of 61.1 mph and at an angle of 25.8 degrees. The vehicle was safely redirected, and did not show potential to override the barrier or cause vehicle instability. Although this system was not crash tested with a small car according to test designation No. 3-10, MwRSF researchers believed that the vertical-faced barrier system would have performed in a satisfactory manner. Photographs of the vehicle during the crash test at the moment of the impact are shown in Figure 11.

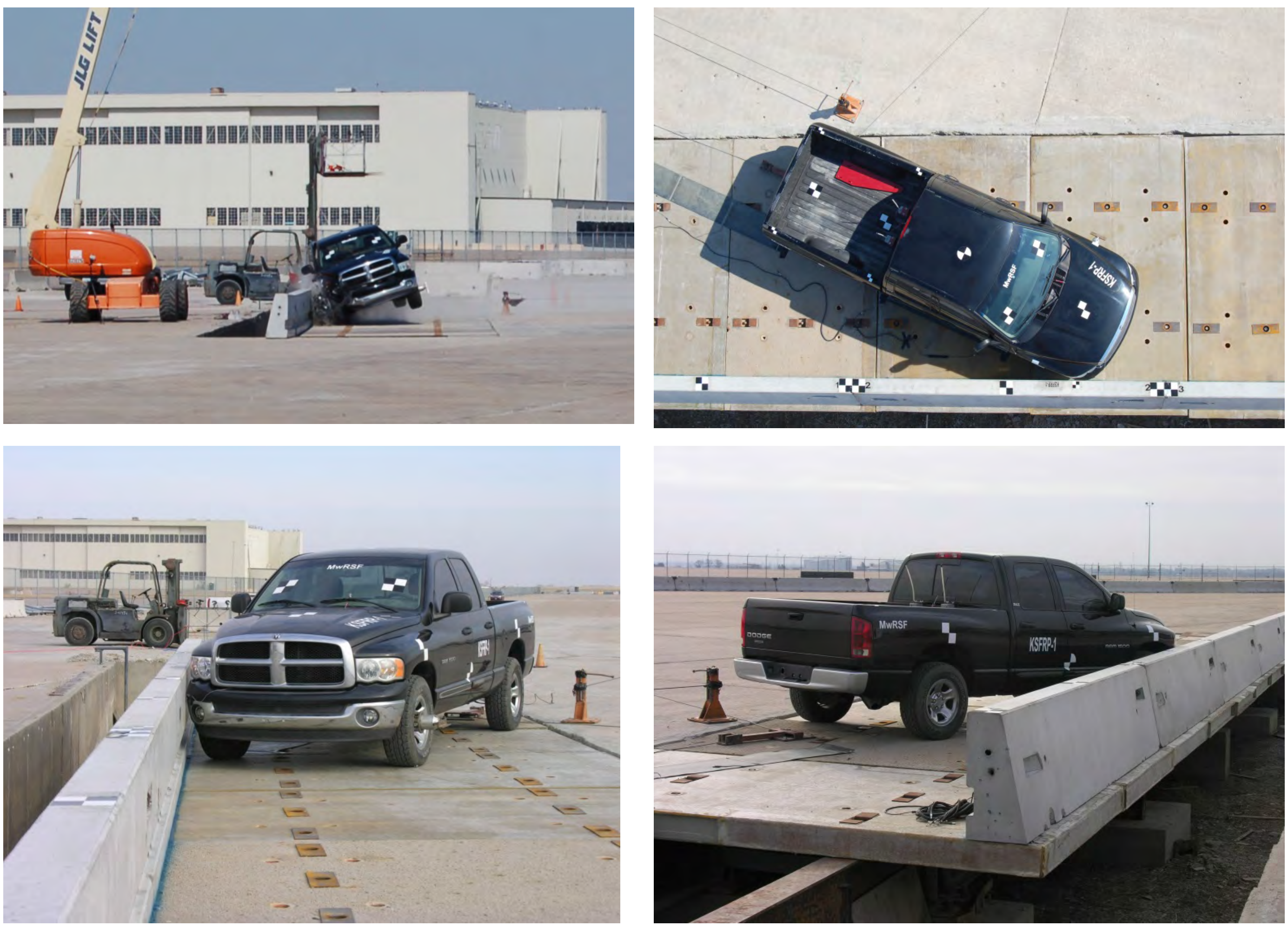


Figure 11: Crash Test of Vertical-Faced Concrete Barriers on the FRPH Panels

The impact of the pickup truck, reaching a speed of 60 mph at the time of the collision and crashing into the concrete barrier at an angle of 26 degrees, resulted in re-directing the vehicle into the traffic lane. The vehicle did not overturn, and only minor damage was observed in the concrete barrier (Figure 12a), and despite the damage to the vehicle body, no damage resulted in the cabin or in the windshield, as seen in Figure 12b.

(a) (b)

Figure 12: Results of the Crash Test on Vertical Faced Concrete Barrier
(a) Concrete Barrier; (b) Vehicle Passing Crash Test

As a result, the vertical-faced bridge railing system attached to an FRP composite panel bridge deck system was determined to be acceptable according to the TL-3 safety performance criteria presented in MASH (Sicking et al., 2009). Further details about this design and the crash test description, results, and conclusions can be found in Schmidt, Faller, Lechtenberg, Sicking, and Reid (2009).

Conclusions

FRPH panels offer a great efficient replacement to concrete decks, as their lighter weight (approximately 25% the weight of concrete) allows higher live loads, while keeping the existing girders and substructure without compromising the safety of the public. The accelerated replacement of a concrete deck using this system would only take one day or just a few days, depending on the size of the bridge, compared to several months using conventional methods. Also, the roadway can be made wider by increasing the overhang. These features are much needed to accommodate increasingly heavier trucks and farming equipment. The FRP deck system consists of honeycomb sandwich panels with adequate guardrails. Two valid types of rails have been crash tested and are now available. The first consists of steel thrie-beams/rails with steel posts, validated in 2005, and the second is pre-cast concrete barriers, validated in 2009. The system with either type of guardrail attachments is now fully implemented, and ready to be used as a permanent replacement to concrete decks on state and interstate highways. It also may be used on temporary/detour bridges, as the system may be easily disassembled and used in different locations without affecting the integrity of the panels.

Although the goal of this project was to develop a crashworthy barrier to be installed on FRP decks, research efforts resulted in the development of a new vertical faced concrete barrier. The initial testing of the Jersey barrier shape did not meet the minimum safety requirements for vehicle rollover. To avoid vehicle rollover and wheel snagging, several modifications were implemented, including the use of a vertical faced barrier and the use of a smoother and stiffer connection between the barrier sections. These modifications led to the development of the vertical-faced barrier. The full-scale crash test of this barrier proved that it limits the propensity of the vehicle to climb up the barrier face and begin to rollover. The successful performance of the vertical-faced barrier in the crash test provided evidence that this type of barrier can be used on any structure and is much less likely to cause rollover than the Jersey barrier shape. Further details on the performance of both the Jersey barrier and the vertical-faced barrier in the full-scale crash test can be found in Mongiardini et al. (2013).

References

Faller, R.K., Ritter, M.A., Rosson, B.T., Fowler, M.D. & Duwadi, S.R. (2000). Two test level 4 bridge railing and transition systems for transverse timber deck bridges. *Transportation Research Record, 1696*, 334-351.

Mongiardini, M., Faller, R.K., Reid, J.D., Meggers, D., El-Aasar, M.G., & Plunkett, J.D. (2013). Design and testing of a concrete safety barrier for use on a temporary FRP composite bridge deck. *Journal of Bridge Engineering, 18*(11), 1198-1208.

Reid, J.D., Faller, R.K., & Hascall, J.A. (2007). Deck-mounted steel post barrier system. *Journal of Bridge Engineering*, *12*(4), 449-455.

Ross, H.E., Sicking, D.L., Zimmer, R.A., & Michie, J.D. (1993). *Recommended procedures for the safety performance evaluation of highway features* (National Cooperative Highway Research Program Report No. 350). Washington, DC: Transportation Research Board.

Schmidt, J.D., Faller, R.K., Lechtenberg, K.A., Sicking, D.L., & Reid, J.D. (2009). *Development and testing of a new vertical-faced temporary concrete barrier for use on composite panel bridge decks* (Report No. TRP-03-220-09). Lincoln, NE: Midwest Roadside Safety Facility.

Sicking, D. L., Mak, K. K., Rohde, J. R., & Reid, J. D. (2009). *Manual for Assessing Safety Hardware*. Washington, DC: American Association of State Highway Transportation Officials.

Stolle, C.S., Polivka, K.A., Faller, R.K., Rohde, J.R., & Sicking, D.L. (2007). *Evaluation of a New Jersey safety shape, segmented concrete barrier for use on composite panel bridge decks* (Report No. TRP-03-181-07). Lincoln, NE: Midwest Roadside Safety Facility.

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