Design and Testing of Two Bridge Railings for Transverse Nail-Laminated Timber Deck Bridges

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Nail-laminated timber deck bridges represent an economical and convenient solution for rural low-volume roads, but a need exists to develop effective railing systems for this type of roadway structure. This paper describes the development of two bridge railings that are specifically designed for transverse nail-laminated timber deck bridges and that meet the requirements for Test Level 1 (TL-1) of the *Manual for Assessing Safety Hardware* (MASH) and TL-2 of *NCHRP Report 350.* The design for each of the railing systems was based on retrofit modifications applied to existing bridge railings that were previously successfully tested: one for a longitudinal glue-laminated timber deck and the other for a transverse glue-laminated timber deck. For both railing systems, component testing was performed to investigate the behavior of the proposed design and the potential advantage of various solutions. A full-scale crash test assessed the safety performance of the TL-1 curb-type railing under the new MASH criteria, while dynamic component tests were deemed sufficient for the assessment of the steel railing under TL-2 conditions for *NCHRP 350.*

A growing number of timber bridges are being constructed throughout the United States. Not only does timber represent a green solution as a natural and recyclable material, but it also represents an economical alternative to traditional materials like concrete and steel. Wood is particularly economical when used in the construction of small bridges along low-speed and low-volume roads. Moreover, the use of timber instead of steel or concrete guarantees improved aesthetics in rural environments.

For more than three decades, numerous bridge railing systems have been designed and tested in accordance with established vehicular crash testing standards. In the most recent years, bridge rails had to meet the crash test requirements of *NCHRP Report 350* (*1*) or the newer *Manual for Assessing Safety Hardware 2008* (MASH) (*2*) to be installed on U.S. highways. For timber bridge decks to become an effective alternative to traditional concrete bridge decks, additional railing systems must be developed and crash tested.

In the past two decades, a number of crashworthy bridge railing systems have been designed for use on longitudinal timber deck bridges; however, little research has been conducted for transverse timber deck bridges. In particular, no full-scale crash testing has been conducted on bridge railings designed for transverse nail-laminated decks.

This paper describes the development of two types of bridge railing specifically designed for transverse nail-laminated timber deck bridges. The first design complies with the requirements for Test Level 1 (TL-1) set forth in MASH (*2*), while the second meets TL-2 impact safety standards of *NCHRP Report 350* (*1*). The design for each of the two railing systems was based on retrofit modifications applied to existing bridge railings previously developed for glue-laminated timber (glulam) deck bridges.

A key component in the design of the two crashworthy bridge railings was the use of standardized barrier components that allow maintenance personnel to remove and replace any damaged components easily and in a timely and efficient manner without long periods of lane closure.

TRANSVERSE NAIL-LAMINATED TIMBER DECK

Both bridge railings have been developed for the West Virginia Department of Transportation (DOT) which, historically, has been responsible for the construction, maintenance, and repair of many bridges that use transverse nail-laminated timber deck systems on steel wide-flange girders. Transverse nail-laminated bridge decks represent an asset to the overall bridge program in the state of West Virginia for several reasons. First, these bridge deck systems are relatively inexpensive and can be installed quickly. Second, these systems can be installed while intermittent traffic on the bridge is maintained. Third, the cost of new bridges with transverse nail-laminated decks on steel structural girders is usually approximately one-third that of a concrete box-beam bridge.

To simulate real-world conditions, a full-scale transverse nail-laminated deck was constructed at the outdoor test facility of the Midwest Roadside Safety Facility (MwRSF). The support structure for the bridge deck consisted of two rows of wide-flange steel girders positioned along the length of the 120-ft (36.58-m) bridge deck (Figure 1*a*). Both simulated abutments and bridge piers were constructed, with the latter being spaced approximately 40 ft (12.2 m) apart. In addition, three intermediate concrete platform supports with wood shim blocks were used for vertical support of the steel girders at the midpoint of each 40-ft (12.2-m) span. Steel C-channel diaphragms were used as lateral bracing for the girders and spaced approximately

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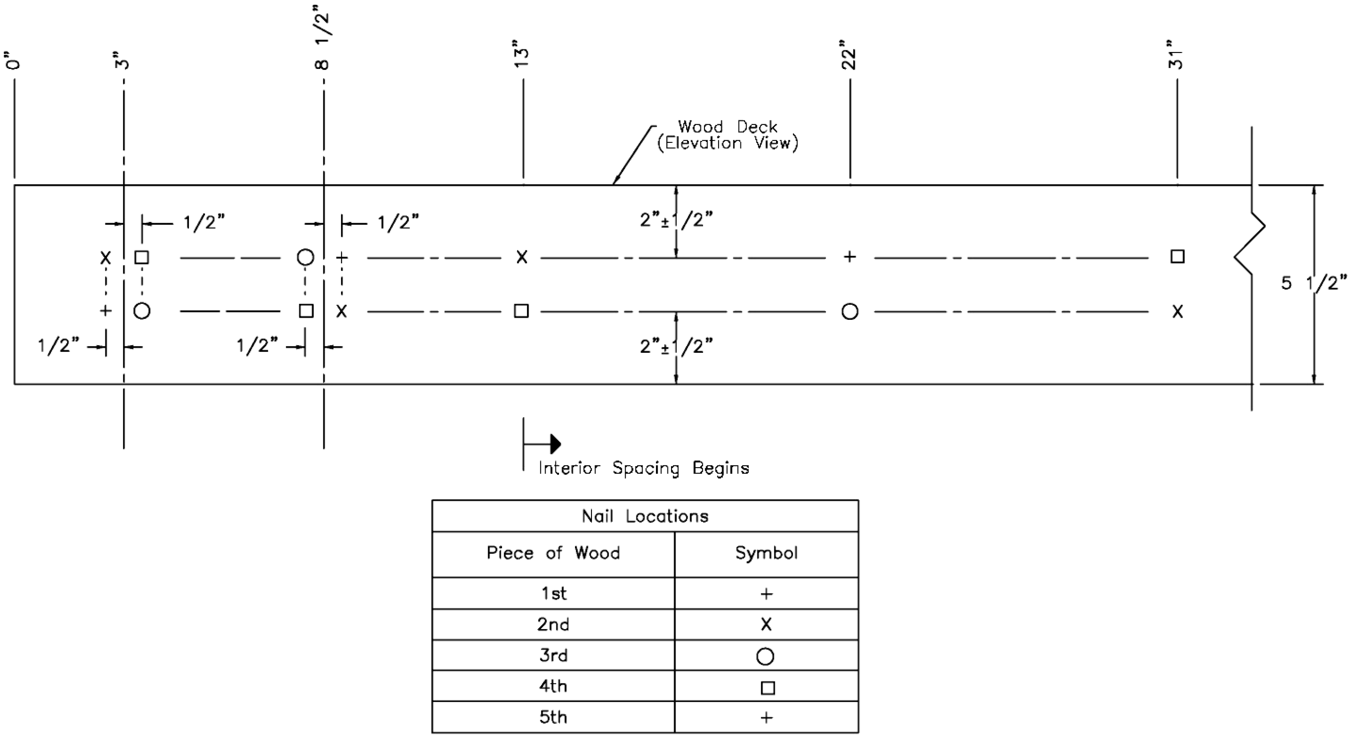
(a) (b)

FIGURE 1 Full-scale bridge deck constructed for testing: (*a*) substructure and (*b*) details of transverse nail-laminated deck.

on 12.5-ft (3.8-m) intervals. The transverse nail-laminated deck consisted of 2- × 6-in. (51- × 152-mm) lumber (Figure 1*b*), which was eventually covered by a wearing surface 2 in. (51 mm) thick. Particular attention was paid to the definition of a nailing pattern for use at both the interior and the exterior deck locations to avoid interference between nails during the installation and presence of nails at locations where vertical bolt holes would be drilled for the attachment of the bridge railing.

In addition, the nailing pattern had to guarantee that the region of the deck near the connection to the railing would provide adequate punching resistance and load transfer to adjacent boards. Eventually, the suggested nailing pattern for the exterior of the deck formed two tight squares located, respectively, at 3 in. (76 mm) and 8½ in. (216 mm) from the deck edge (Figure 2). This pattern ensured adequate shear resistance by guaranteeing that at least one nail would be located between the vertical bolt holes and the deck edge. Furthermore, Liquid Nails heavy-duty construction adhesive (Item N-901) was used to provide a more uniform shear load distribution along the wide face of the boards over the end length of 36 in. (914 mm).



Nail Locations	
Piece of Wood	Symbol
1st	+
2nd	X
3rd	○
4th	□
5th	+

FIGURE 2 Exterior and interior nail pattern used to connect boards (with key to symbols at bottom).

DEVELOPMENT OF BRIDGE RAILINGS

Wood Railing (TL-1)

Methods

Although many of the transverse nail-laminated timber deck systems in use by West Virginia DOT have standard roadway widths of 32 ft (9.8 m) or more, some bridges are configured with widths of only 12 to 14 ft (3.7 to 4.3 m), as measured curb to curb. To allow for the passage of large trucks and house trailers across these narrow bridges, a need exists to use a low-profile railing system. Unfortunately, no crashworthy curb-type bridge railing systems have been developed for use on transverse nail-laminated timber bridge decks.

Initially, an analysis was conducted on earlier curb-type timber bridge railings that were successfully crash tested to meet TL-1 safety performance criteria defined in *NCHRP Report 350.* Once a design was selected from the review of existing railings, necessary modifications had to be included to improve the original geometry and to increase both the vehicle containment and the structural adequacy. In fact, the new railing was designed to satisfy the TL-1 safety criteria of the recently released MASH impact safety standards, which introduced changes deemed necessary to accommodate the larger and heavier vehicles that characterize the actual fleet circulating in the United States.

Then, a static testing program was conducted on five scupper-block post assemblies. These tests were used to ensure that the bridge rail posts would provide adequate strength and to determine the appropriate use for timber shear connectors in the post-to-deck and post-to-rail connections.

Upon completion of the static testing program, the bridge railing design was finalized, and an appropriate safety end treatment was configured. A section of bridge rail 120 ft (36.6 m) long was constructed on top of a transverse nail-laminated timber bridge deck equipped with an end treatment 35 ft (10.7 m) long, on the upstream end. Eventually, a full-scale vehicle crash test adhering to the impact conditions of T-1-11 of MASH standards was conducted.

Design Details

Several low-height, curb-type bridge railings have previously been developed for longitudinal glulam bridge decks at MwRSF (*3–6*). For a curb-type bridge railing that met the TL-1 safety performance criteria defined in *NCHRP Report 350,* it was believed that the railing could be modified to also satisfy the TL-1 safety performance criteria of the MASH standards. This bridge railing was designed for longitudinal glulam deck bridges and was characterized by 6¾-in. × 10½-in. (171- × 267-mm) rectangular glulam beam elements with a top rail mounting height of 17¾ in. (451 mm) (*6*). Adjacent rail elements were connected by steel plates and supported by scupper blocks, while steel split rings and vertical bolts were used to transfer the impact loads from the rail through the wooden support blocks and to the deck (Figure 3).

During testing of the original design, the striking front wheel overrode the curb, and eventually the vehicle came to a stop with the front axle on top of the rail. The height of the original glulam rail was raised two extra inches by increasing the height of the lower scupper block by the same amount. This modification also allowed both the lower and upper scupper blocks to use the same dimensions, limiting the number of possible different components for the barrier. Moreover, to allow the use of southern yellow pine as an alternative to a stronger Douglas fir, the cross section of the rail was increased. The former wood type was actually used in the full-scale test. Consequently, the resistance of the rail splices was increased by doubling the thickness and adding a third-plate orthogonal to the two original plates at their midpoints to form an H-shaped connection (Figure 4*a*). This modification was intended to prevent any relative displacement between the rail ends at the splice locations during impact. In addition, to reduce the bending loads imparted to the rail splice as well as the corresponding loads applied to the bolts, the timber rails were jointed together near the quarter-span location of the scupper blocks.

In the original design, 24 shear plates (or split rings) were used for each post assembly, thus increasing the final cost of the railing system. To investigate alternative types and quantities of timber shear connectors, static component testing was conducted.

Static Post Testing

For the original curb-type bridge railing system, the timber posts were statically tested and found to have an average maximum strength of 14 kips (62 kN) when loaded through the middle of the rail (*6*). Thus, a similar lateral resistance under static loading was also expected for the posts of the new bridge railing system for the railing to be capable of redirecting a 5,000-lb (2,268-kg) pickup truck at the TL-1 impact conditions.

Static testing was conducted on the bridge railing posts to investigate the behavior of various configurations of the connections between the rail, scupper blocks, and bridge deck as well as to determine the characteristics of lateral force versus deflection of each of the following specific designs:

- Scupper block with no connection,
- Scupper block with timber split-ring grooves,
- Scupper block with shear plate grooves, and
- Split ring grooves between scupper block and deck.

For each of the analyzed configurations, a timber glulam rail segment 23 in. (584 mm) long was supported by two timber scupper blocks and bolted to the nail-laminated timber bridge deck by means of four bolts ¾ in. (19 mm) in diameter (Figure 5). A lateral load was applied to the back of each built-up post through a steel rod ⅞ in. (22 mm) in diameter placed through the center of the rail segment.

The load was incrementally applied by using a 50-kip (222-kN) hydraulic ram, and a string potentiometer was used to measure the post deflection. A plate washer ½ in. (13 mm) thick was placed to the front face of the rail segment to distribute the load.

The use of different types of shear connectors (i.e., shear plates, split rings, or none) and of quantities of shear connectors was investigated. Eventually, the static tests indicated that the use of shear connectors had little or no effect on the maximum lateral load capacity. Moreover, shear connectors did not improve the strength of the post assembly, as the variance of the curve of force versus deflection measured with or without shear connectors occurred only in the plastic region. In addition, the use of shear connectors affected the damage observed to the timber deck because of the grooves that had to be cut to accommodate connectors in the deck surface. In fact, these grooves weakened the deck boards and led to the formation of fracture when the lateral load was applied (Figure 6). For these two reasons and

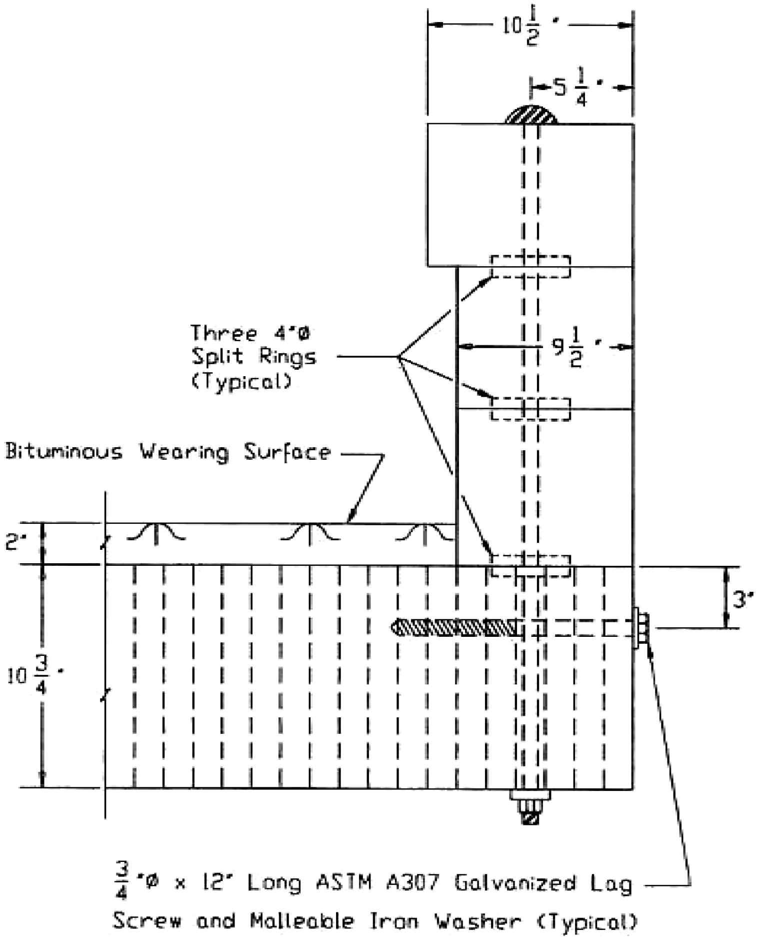
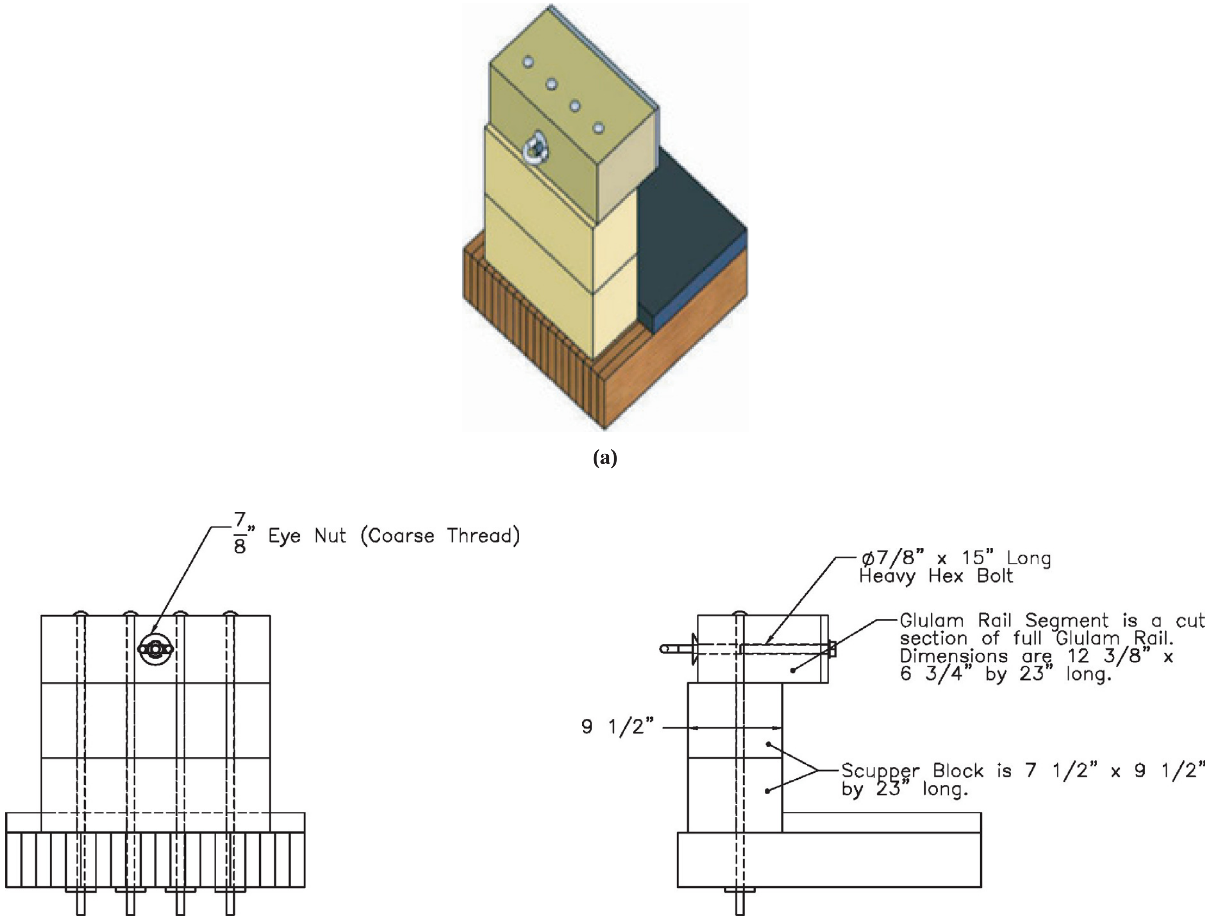


FIGURE 3 Cross section of rail and scupper blocks used in original curb-type railing.

(a)

(b)

FIGURE 4 TL-1 curb-type railing: (*a*) splice connections and (*b*) barrier overview (with end terminals).



(a)

(b)

(c)

FIGURE 5 Views of setup for static testing: (*a*) isometric, (*b*) back with eye nut, and (*c*) side.

(a)

(b)

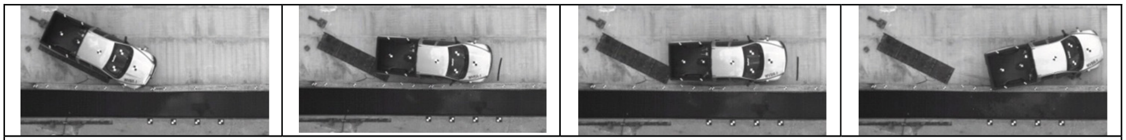
FIGURE 6 Damage in static post testing to bridge deck (*a*) with shear plates at all interfaces (Test WVS-3) and (*b*) with no shear connectors (Test WVS-4), both for TL-1 bridge railing.

because of the increased labor and material costs associated with the production of the railing system, use of shear connectors in the proposed design was rejected.

Full-Scale Crash Testing

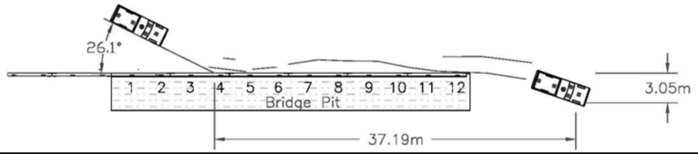
After the post connection was successfully tested, a full-scale vehicle crash test was conducted on the proposed design of the railing system. Although TL-1 safety criteria defined in MASH require both a test with a small car and a pickup truck, only the test with a pickup truck was deemed necessary because of the limited propensity for small-car wheel snag attributable to the geometrical characteristics of this railing. A rigid end treatment was also developed for the curb-type timber bridge railing system to prevent blunt impacts to the end of the low railing. For this system, the geometry for the end treatment was adopted from a prior TL-2 end treatment used with a low-profile concrete barrier. Thus, the upstream end of the timber bridge rail was sloped downward to the ground with the same geometry used for the approved treatment for the rigid concrete end after the railing extended off the bridge. The end rail segments, including the sloped section, were mounted to W6 × 15 (W152 × 22.3) steel posts to provide a structurally adequate foundation for the end treatment.

The barrier system successfully contained and redirected the 2270P pickup truck with only minimal damage to the rail and no visual damage to the deck. The impact conditions and the results obtained from the crash test are summarized in Figure 7, while the vehicle behavior during the full-scale test is indicated in the sequence in Figure 8. Eventually, the bridge railing system was determined to be acceptable in relation to the TL-1 safety performance criteria presented in MASH.



Vehicle kinematics

(a)



Schematic view

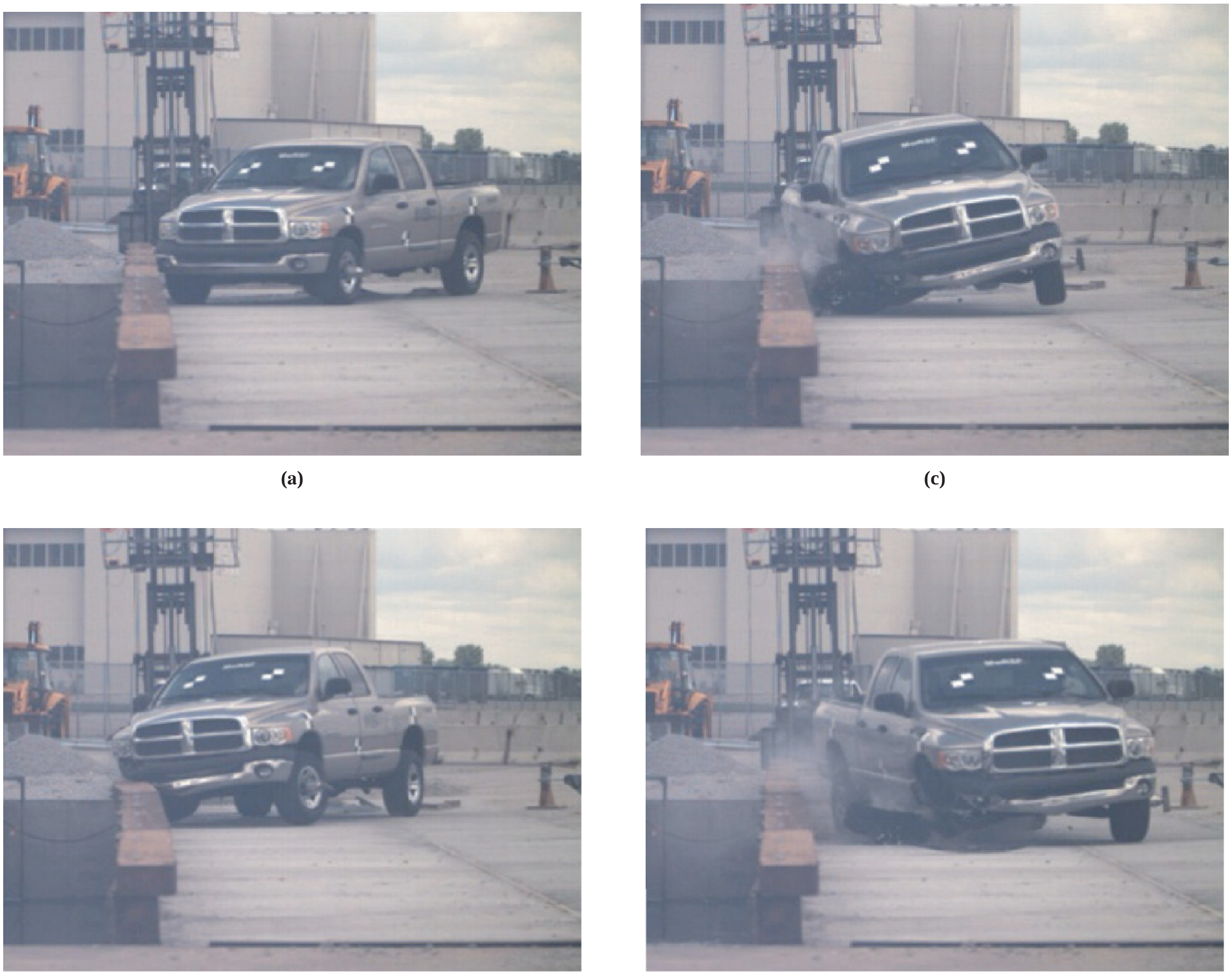
(b)

- Test Number WVBR-1
- Date 7/18/08
- Test Article
  - Type .... Bridge Rail
  - Key Elements .... Low-Profile Curb Type
Glulam Segments
Scupper Blocks
- Total Length .... 47.2 m
- Scupper Post Spacing .... 3.05 m
- Vehicle Model .... 2002 Dodge Ram 1500 Quad Cab
  - Curb .... 2,322 kg
  - Test Inertial .... 2,271 kg
  - Gross Static .... 2,349 kg
- Vehicle Speed
  - Initial .... 48.6 km/h
  - Exit .... 30.7 km/h
- Vehicle Angle
  - Initial .... 26.1 deg
  - Exit .... 12.6 deg
- Impact Location ..... 775 mm Upstream from Post No. 4
- Vehicle Stability .... Satisfactory
- Maximum Roll Angle .... 8.7 degrees
- Vehicle Stopping Distance .... 37.2 m Downstream IP
- Occupant Ridedown Acceleration (DTS)
  - Longitudinal .... -4.74 g's < 20.49 g's
  - Lateral .... -3.23 g's < 20.49 g's
- Occupant Impact Velocity (DTS)
  - Longitudinal .... -3.34 m/s < 12.2 m/s
  - Lateral .... -3.96 m/s < 12.2 m/s
- Occupant Ridedown Acceleration (EDR-3)
  - Longitudinal .... -5.33 g's < 20.49 g's
  - Lateral .... -2.69 g's < 20.49 g's
- Occupant Impact Velocity (EDR-3)
  - Longitudinal .... -3.60 m/s < 12.2 m/s
  - Lateral .... -3.84 m/s < 12.2 m/s
- THIV .... 4.79 m/s < 12.2 m/s
- PHD .... 5.25 g's < 20 g's
- Vehicle Damage .... Minimal
  - TAD 1-RFQ-3
  - SAE 01-RFLW1
- Test Article Damage .... Minimal
- Maximum Rail Deflections
  - Permanent Set .... 61 mm
  - Dynamic .... 155 mm
- Working Width .... 315 mm

Impact conditions and results

(c)

FIGURE 7 Summary of full-scale test of TL-1 curb-type bridge railing: (*a*) vehicle kinematics sequence, (*b*) schematic view of vehicle path, and (*c*) impact conditions and results.



(a)

(c)

(b)

(d)

FIGURE 8 Sequence of full-scale test of TL-1 curb-type bridge railing: (*a*) $t = 0$ s, (*b*) $t = 0.154$ s, (*c*) $t = 0.454$ s, and (*d*) $t = 0.836$ s.

TL-2 Steel Railing

Design Details

In 1998, MwRSF developed a steel bridge railing system for transverse glulam deck bridges (*7*). That system was adapted for the TL-2 transverse nail-laminated deck of this project.

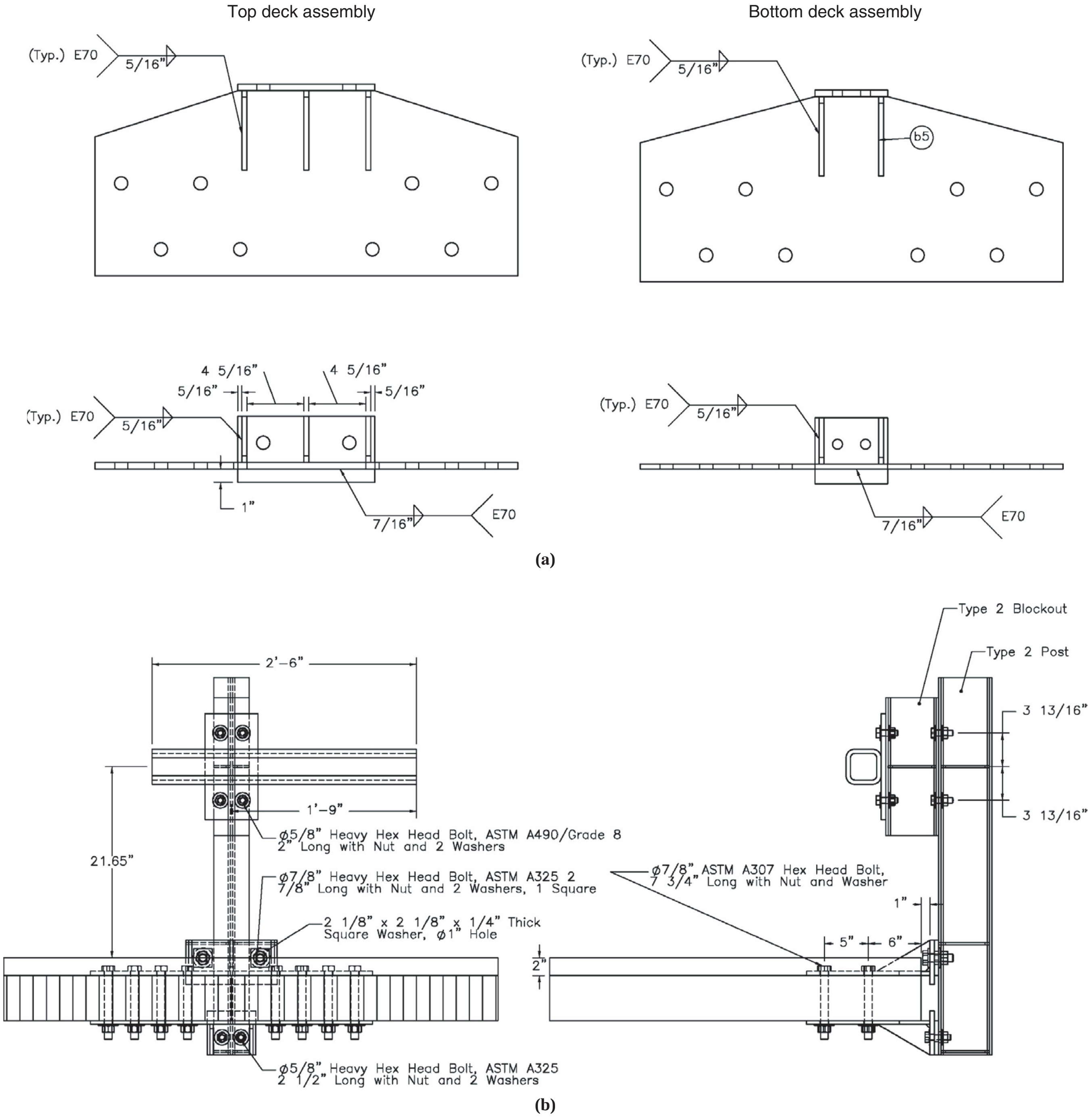
The original bridge railing system was composed of a thrie beam rail blocked away from the wide-flange posts by wide-flange spacers and a structural channel rail attached to the tops of the posts. The lower end of each post was bolted to two steel plates that were connected to the top and bottom surfaces of the bridge deck with vertical bolts. A guardrail transition system with a similar TL-2 approach, with a sloped end rail from a structural channel, was designed for attachment to each end of the railing system. Eventually, both the bridge railing and the transition systems were successfully crash tested in accordance with TL-2 criteria defined in *NCHRP Report 350.*

To adapt this existing railing to a transverse nail-laminated deck, a new post-to-deck connection was designed and investigated by using dynamic bogie impact tests. These component tests were necessary to verify that both the post connection to the deck and the damage to the deck itself were appropriate to resist a load representative of a pickup truck crash test under the conditions required by the TL-2 impact standards of *NCHRP Report 350*. In addition, the bogie tests provided valuable information about the benefits of using shear plates in the post-to-deck connection.

The W6 × 12 (W152 × 17.9) post of the original railing was connected to the bridge deck through two plates, one attached to the top surface and one to the bottom surface of the deck. The upper plate was bolted to a second vertical plate welded to the post, while the bottom plate was directly bolted to the lower end of the post. The deck mounting plates were attached to the timber deck by eight Grade 5 hex-head bolts ⅞ in. (22.2 mm) in diameter by 8 in. (203 mm) long. Details of the deck attachment are shown in Figure 9*a*.

Dynamic Post Testing

The dynamic bogie impact tests were conducted to evaluate the structural capacity of both the post-to-deck attachment and the transverse



(a)

(b)

FIGURE 9 Drawings of (*a*) deck mounting plates and (*b*) dynamic post testing schematic (eccentric impact without shear connectors), both for TL-2 steel barrier.

nail-laminated timber bridge deck. During full-scale vehicle crash testing of the original bridge railing system (thrie beam and channel rail) attached to a transverse glulam deck, yielding of the steel bridge posts was observed. However, no visible damage to the timber bridge deck or rupture of the post-to-deck attachment hardware occurred. Therefore, if the bogie tests demonstrated that the steel posts could withstand peak impact loading and yield without damaging the nail-laminated timber deck or rupturing the post-to-deck attachment hardware, then it was deemed appropriate to adapt the thrie-beam-and-channel bridge rail system to transverse nail-laminated timber bridge decks without the need to repeat the full-scale crash tests.

Four bogie impact tests were performed. The bogie vehicle struck the posts with the rigid head aligned with the centerline of each post for the first two tests and offset by 9 in. (229 mm) from the centerline of each post for the remaining two tests. The latter set of tests was performed to induce both torsion and bending loads into the post, post-to-deck attachment, and timber deck. The second test for each of the two types of impact—head-on and offset—focused on investigating the effects of using shear plates. The target impact speed and angle were respectively 16 mph (25.7 km/h) and 90° relative to the post's strong axis of bending. A rigid vertical cylinder was mounted to the front of a 1,711-lb (776-kg) bogie vehicle, while a 4- × 4- × ½-in. (102- × 102- × 13-mm) steel tube was horizontally mounted to the front of the posts at a height of 21⅝ in. (550 mm) above the bridge deck.

The same transverse nail-laminated timber bridge deck that was constructed for testing the TL-1 curb-type barrier was used for the dynamic post tests for the TL-2 railing. The post and the proposed post-to-deck hardware were mounted to the outer edge of the deck, as shown in Figure 9*b*.

During each bogie test, posts were plastically deformed through bending, torsion, or both, and the post-to-deck attachment hardware did not rupture or pull away from the deck edge. The timber deck did not sustain any significant damage, and only slight bearing damage was observed surrounding a few of the bolt holes in those tests in which shear connectors were not used. Figure 10 shows the damage to the post and the deck for the case without shear plates for the head-on and eccentric bogie tests, respectively.

Although approximately the same total energy was absorbed by each post assembly in all tests, the behavior of force versus deflection was rather dependent on the target impact point. In fact, the average resistive forces with a centerline impact were found to be twice those with an eccentric impact and similar results were found for the behavior of energy versus displacement. The curves for force versus deflection and energy versus deflection for all four bogie tests are shown in Figure 11. As for the timber shear connectors, their inclusion in the centerline impact events did not provide any significant increase in strength, while in the eccentric impact events, they provided only a limited increase in strength.

These dynamic bogie tests demonstrated that the post-to-deck connection was able to withstand loads sufficient to yield the steel posts without any rupture or damage to the deck. In fact, the bogie testing showed that the nail-laminated deck and the new connection design without shear connectors could replicate the dynamic behavior of the posts from the prior full-scale crash testing. Therefore, no additional full-scale testing was deemed necessary to investigate the TL-2 railing system. The proposed post-to-deck configuration for the TL-2 bridge railing is shown in Figure 12.

DISCUSSION AND RECOMMENDATIONS

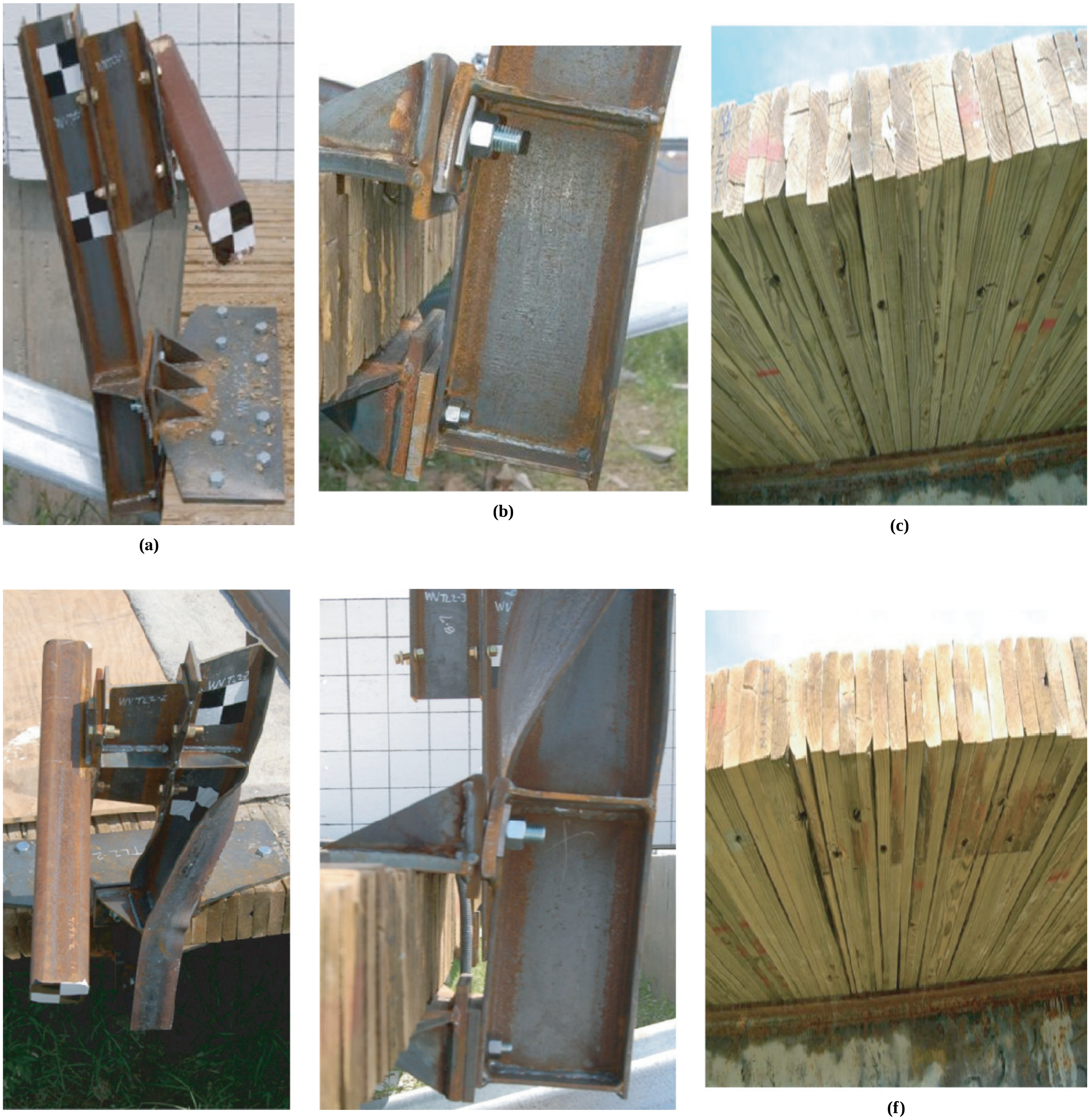
For the static or dynamic post tests and the full-scale crash testing programs, all timber components were fabricated from southern yellow pine. However, successful barrier performance would also have been obtained had the curb-type timber bridge railing system been fabricated of Douglas fir. In fact, the sawn lumber scupper blocks and glulam rail segments manufactured from Douglas fir have higher-rated strengths than the comparable southern yellow pine blocks and rails. Therefore, the curb-type railing system can be safely fabricated from either southern yellow pine or Douglas fir.

The purpose of the static and dynamic bogie testing was to investigate post strength with different types and quantities of shear connections. The tests indicated that use of these connections had little or no effect on the maximum lateral load capacity of the posts. Moreover, shear connectors did not improve the strength of the post assembly, as all posts failed because of steel yielding. In addition, the use of shear connectors produced damage in the timber deck attributable to the grooves that had to be cut in the deck surface to accommodate the connectors. In fact, these grooves weakened the deck boards and led to fracture when lateral load was applied. For these two reasons and also in consideration of the increased labor and material costs associated with production of the railing system, it was decided not to employ shear connectors in the proposed design.

Historically, full-scale vehicle crash testing has primarily been used to evaluate the safety performance of a bridge railing system. However, for the TL-2 bridge railing, it was deemed appropriate to use dynamic component testing to determine whether the prior crashworthy bridge rail could be adapted to an alternative bridge deck configuration. This opinion was based on two main factors. First, post yielding and plastic deformations were observed in the component testing program, and these conditions indicated that the steel posts, post-to-deck attachment hardware, and timber deck had withstood a peak load event similar to the loading imparted during vehicular crash tests. Second, the peak load was reached without damaging the timber deck and without rupture of the post-to-deck attachment hardware. For these two reasons, the assessment was made that the prior crashworthy bridge railing system would also have performed in an acceptable manner when attached to a transverse nail-laminated deck bridge.

CONCLUSIONS

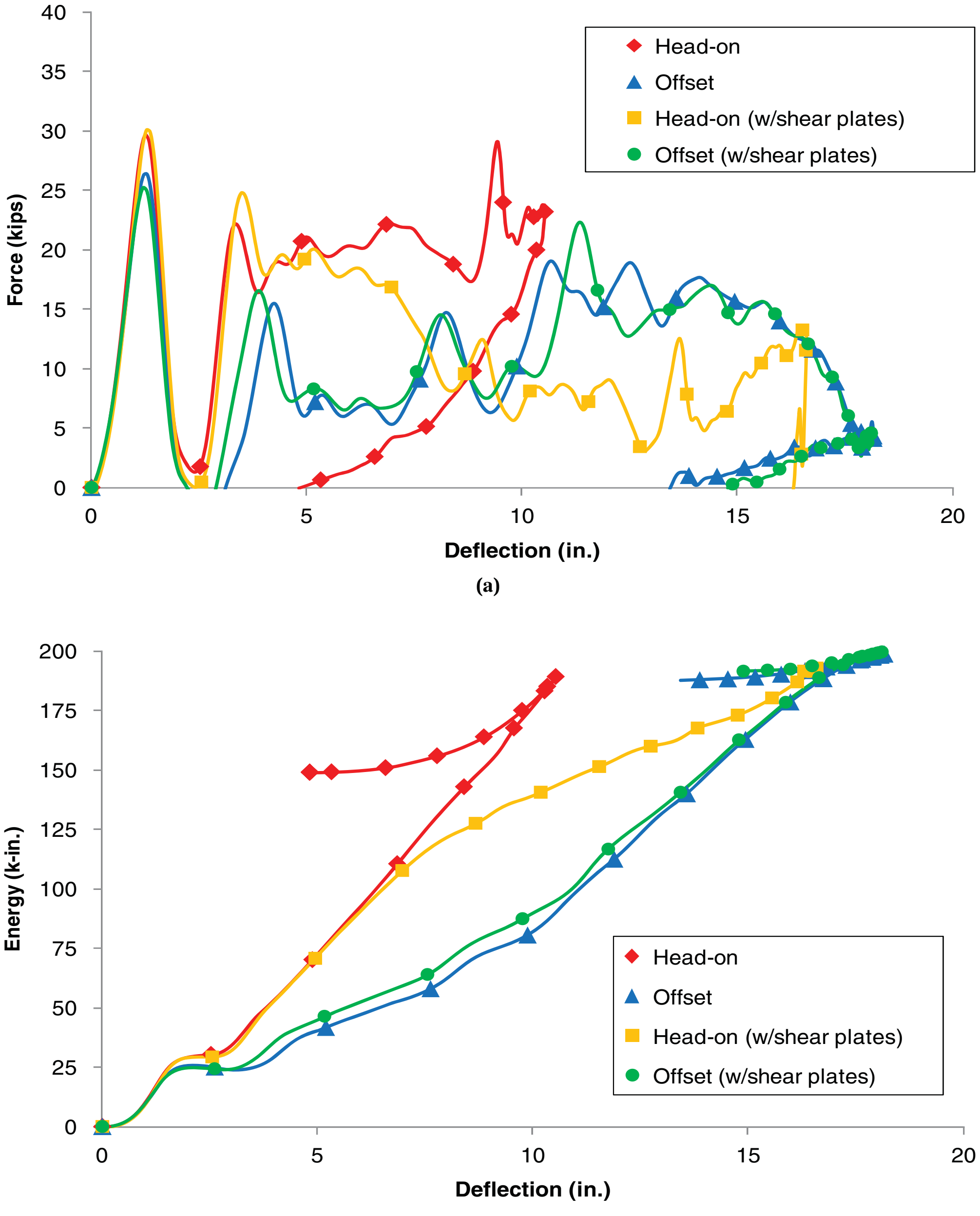
This paper described the development of two bridge railings for are specifically for use on transverse nail-laminated deck bridges and that satisfy the safety requirements for TL-1 of MASH or TL-2 of *NCHRP Report 350*. The TL-1 railing was a curb-type system completely made of timber and specifically designed for narrow bridges, while the TL-2 railing consisted of a steel thrie beam, an upper structural channel rail, and steel posts. The two railing systems were developed by retrofitting existing bridge rails that were originally tested with transverse glulam deck bridges. For both railings, component testing on the post-to-deck connection was performed, with particular attention to the damage caused to the deck by the connections. In addition, the effectiveness of using shear connectors between the post and the timber deck was investigated, and it was concluded that not only did they not provide a relevant increase in the post-to-deck connection strength, they also caused additional deck damage. For the TL-1 curb-type railing, a full-scale crash test was performed. For the TL-2 steel rail, the successful dynamic bogie



(a) (b) (c)

(d) (e) (f)

FIGURE 10 Damage with no shear plates for head-on impact test to (*a*) post, (*b*) baseplate, and (*c*) wood deck and for eccentric impact test to (*d*) post, (*e*) baseplate, and (*f*) wood deck.



(a)

(b)

FIGURE 11 Curves for four dynamic post tests: (*a*) force versus deflection and (*b*) energy versus deflection.

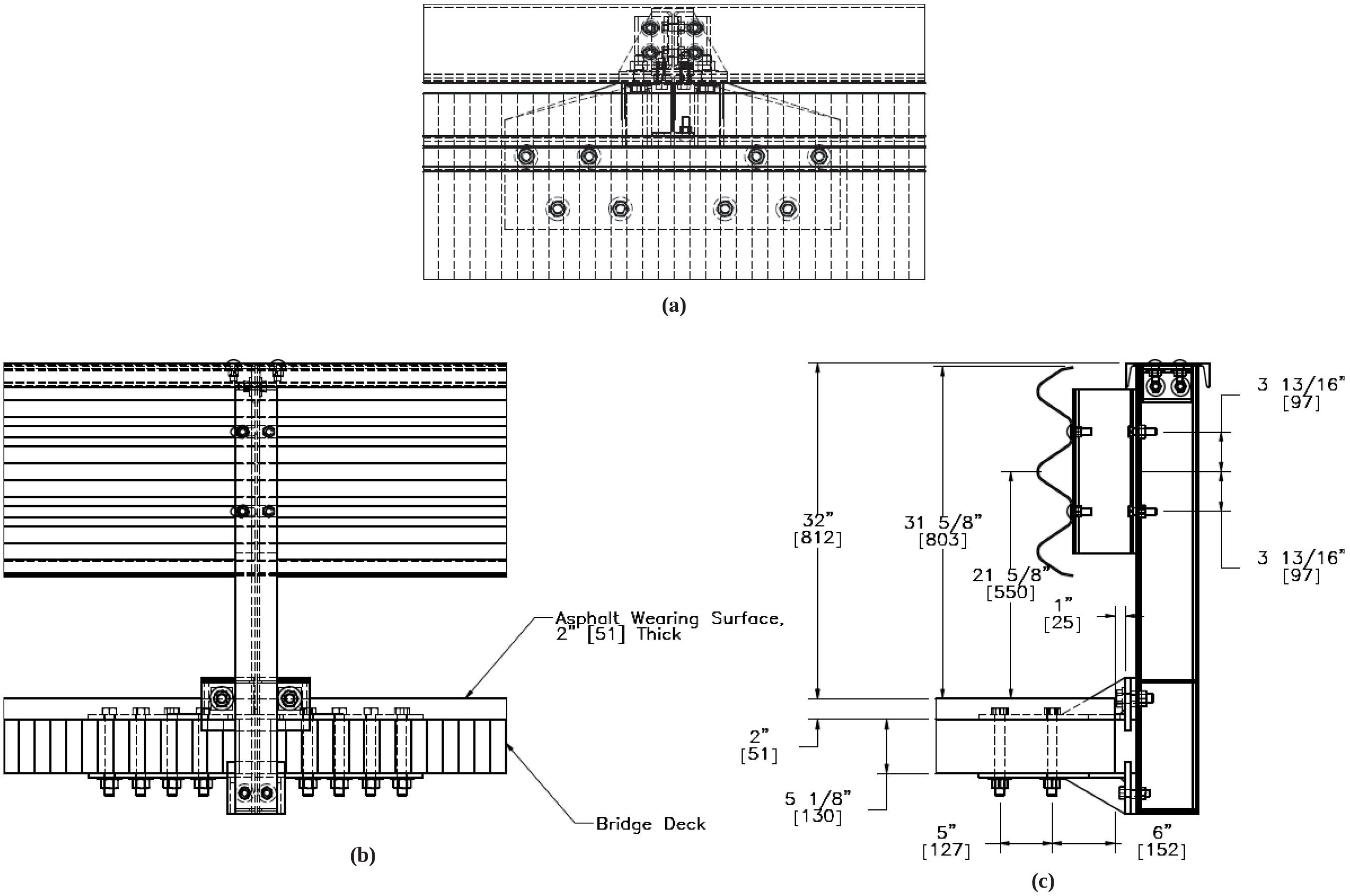


FIGURE 12 Views of post connection to transverse nail-laminated bridge deck for TL-2 rail: (*a*) plan, (*b*) elevation, and (*c*) profile.

tests were deemed sufficient to assess the performance of the bridge railing with a nail-laminated deck in lieu of full-scale vehicle crash testing. Eventually, FHWA issued an official letter of acceptance for both bridge railings developed in this study (*8, 9*).

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