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Development of Two TL-2 Bridge Railings and Transitions for Use on Transverse Glue-Laminated Deck Bridges

by

Ronald K. Faller, Ph.D., P.E.
Midwest Roadside Safety Facility
University of Nebraska-Lincoln

Michael A. Ritter, P.E.
Forest Products Laboratory
USDA - Forest Service

Barry T. Rosson, Ph.D., P.E.
Civil Engineering Department
University of Nebraska-Lincoln

Eric A. Keller
Midwest Roadside Safety Facility
University of Nebraska-Lincoln

Sheila R. Duwadi, P.E.
Federal Highway Administration

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ABSTRACT

The Midwest Roadside Safety Facility, in cooperation with the U.S. Department of Agriculture Forest Service, Forest Products Laboratory and the Federal Highway Administration, designed two bridge railing and approach guardrail transition systems for use on transverse glue-laminated timber deck bridges. The bridge railing and transition systems were developed and crash tested for use on medium service level roadways and evaluated according to the Test Level 2 (TL-2) safety performance criteria provided in the National Cooperative Highway Research Program (NCHRP) Report No. 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features*. The first railing system was constructed using steel hardware, while the second railing system was built using glulam timber components. Four full-scale crash tests were performed, and the bridge railing and transition systems were determined to be acceptable according to the current safety standards in NCHRP Report No. 350.

Key Words: Bridge Rail, Approach Guardrail Transition, Timber Bridges, Compliance Tests, Crash Testing

INTRODUCTION

Problem Statement

For more than 30 years, numerous bridge railing systems have been developed and evaluated according to established vehicular crash testing standards. Most of the bridge railings previously tested have consisted of concrete, steel, and aluminum railings attached to concrete bridge decks. It is well known that a growing number of timber bridges with transverse and longitudinal timber bridge decks are being constructed throughout the country. Therefore, the demand for crashworthy railing systems has become more evident with the increasing use of timber deck bridges located on secondary highways, county roads, and local roads. During the past eleven years, several crashworthy bridge railing systems were developed for use on longitudinal timber deck bridges and for multiple service levels, ranging from low-speed, low-volume roads to higher service level roadways. In addition, one recent research study led to the development of two higher performance level railing systems for use on transverse timber deck bridges. However, little research has been conducted to develop crashworthy railings for use on transverse timber deck bridges located on low to medium service level roadways. For timber to be a viable and economical alternative in the construction of transverse timber decks, additional railing systems must be developed and crash tested for timber deck bridges located on these roadways.

In recognition of the need to develop bridge railing systems for this medium service level, the United States Department of Agriculture (USDA) Forest Service, Forest Product Laboratory (FPL), in cooperation with the Midwest Roadside Safety Facility (MwRSF) and the Federal Highway Administration (FHWA), undertook the task of developing two medium service level bridge railings and approach guardrail transitions.

Research Objective

The primary objective of this research project was to develop and evaluate two bridge railings and approach guardrail transitions for use on transverse glue-laminated (glulam) timber deck bridges located on medium service level roadways. The bridge railing and transitions systems were developed to meet the Test Level 2 (TL-2) evaluation criteria described in the National Cooperative Highway Research Program (NCHRP) Report No. 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features* (1).

The first bridge railing, referred to as System No. 1, was a steel system that was constructed with a thrie beam rail, an upper structural channel rail, and wide-flange posts and blockouts. Photographs of the steel bridge railing system and the attached thrie beam approach guardrail transition are provided in Figure 1. The second bridge railing, referred to as System No. 2, was a wood system that was constructed using a rectangular rail, posts, and blockouts, all of which were manufactured from glulam timber. Photographs of the wood bridge railing system and the attached W-beam approach guardrail transition are provided in Figure 2.

Another objective of the research project was to determine the forces imparted to key components of the bridge railing systems during impact of the test vehicles. Knowledge of these force levels can allow researchers and engineers to make minor modifications to the crash tested designs without additional full-scale crash testing, and it provides insight into the development of future systems.

Research Plan

The research objectives were accomplished with the successful completion of several tasks. First, a literature search was performed to review the previously-developed, low to medium performance level bridge railing systems, as well as bridge railings developed for timber deck bridges. This review was deemed necessary because it was envisioned that the two new bridge railing designs would likely use technologies and design details from existing crashworthy railing systems. Second, bridge railing concepts were prepared so that an analysis and design phase could be performed on all structural members and connections.

Subsequently, computer simulation modeling was conducted using BARRIER VII to aid in the analysis and design of the bridge railing and approach guardrail transition systems (2). For each bridge railing system, strain gauge instrumentation was placed on selected structural components to help determine the actual dynamic loads imparted into the bridge railing and deck systems. The researchers deemed that the dynamic load information was necessary because additional economy could be provided with the downsizing of specific structural components.

Next, a total of four full-scale vehicle crash tests (two crash tests on each bridge railing and transition system) were performed using ¾-ton pickup trucks. Test results were analyzed, evaluated, and documented. Conclusions and recommendations that pertain to the safety performance of each bridge railing and transition system were then made.

BRIDGE RAILING HISTORY

The primary purpose of a bridge railing is to safely contain errant vehicles crossing a bridge. Therefore, railings must be designed to withstand the force of an impacting vehicle without endangering the occupants in the vehicle and without significant damage to the bridge deck. In designing railing systems for highway bridges, engineers have traditionally assumed that vehicle impact forces can be approximated by equivalent static loads that are applied to railing elements. Until recently, the American Association of State Highway and Transportation Officials (AASHTO) *Standard Specifications for Highway Bridges* (3) required that bridge railings be designed to resist an outward transverse static load of 44.5 kN. Despite the widespread use of design requirements based primarily on static load criteria, the need for more appropriate full-scale vehicle crash test criteria has long been recognized. The first U.S. guidelines for full-scale vehicle crash testing were published in 1962 (4). In 1981, NCHRP published Report No. 230, *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances* (5). This comprehensive report provided recommendations relative to crash testing and evaluation of longitudinal barriers and served as the basis for future bridge rail crash testing requirements.

The first recognition of full-scale crash testing in a national bridge specification came in 1989 when AASHTO published *Guide Specifications for Bridge Railings* (6). This specification presents recommendations for the development, testing, and use of crash-tested bridge railings and refers extensively to NCHRP Report No. 230 for crash testing procedures and requirements. For this specification, recommended requirements for rail testing were based on three performance levels: Performance Level 1 (PL-1), PL-2, and PL-3. The PL-1 requirements represent the "weakest" system and PL-3 the "strongest" system. The recently published NCHRP Report No. 350 provides for six test levels for evaluating longitudinal barriers - Test Level 1 (TL-1) through TL-6. Although this document does not include objective criteria for relating a Test Level to a specific roadway type, the lower test levels are generally intended for use on lower service level roadways and certain types of work zones while the higher test levels are intended for use on higher service level roadways.

In 1994, AASHTO published the *LRFD Bridge Design Specifications* (7) as an update to the *Standard Specifications for Highway Bridges* (3) and the *Guide Specifications for Bridge Railings* (6). For crash testing bridge railings, three performance levels were provided and guidelines followed procedures provided in both the AASHTO *Guide Specifications* and NCHRP Report No. 350. Yield line and inelastic analysis and design procedures, as originally developed by Hirsch (8), were also provided for bridge railings as a replacement to the 44.5-kN equivalent static load procedures.

Emphasis on the use of crash-tested rails for new Federally funded projects has significantly increased the role of full-scale crash testing as a means of evaluating railing performance. Recently, the FHWA officially adopted NCHRP 350 as a replacement for NCHRP 230 and has strongly suggested that AASHTO also adopt the test level definitions contained in NCHRP Report No. 350, thus making crash-tested railings mandatory for most bridges. Most highways with wood bridges will require railings that meet the NCHRP Report No. 350 requirements of TL-1, TL-2, TL-3, or TL-4.

As of August 1986, twenty-two bridge rails had been successfully crash tested in accordance with the guidelines specified in NCHRP Report No. 230 and approved for use on Federal-aid projects by the FHWA (9). By August 1990, twenty-five additional bridge rails had been successfully crash tested in accordance with the requirements of the AASHTO *Guide Specifications* and also approved by the FHWA for use on Federal-aid projects (10). Of these crash-tested railings, forty-six were for concrete bridge decks and only one was for a wood deck (11).

During the 1990's, two other research programs lead to the development of crashworthy railing systems for timber deck bridges. The first program, a collaborative effort between MwRSF, FPL, and FHWA engineers, resulted in the development of nine railing systems for longitudinal timber deck bridges (12-17) and two railing systems for transverse timber deck bridges (18-20). Subsequently, standard plans were developed for adapting several of these wood systems to concrete deck bridges (21). Researchers at West Virginia University also conducted a research effort to develop three AASHTO PL-1 railing systems for transverse wood decks (22).

TEST REQUIREMENTS AND EVALUATION CRITERIA

According to the TL-2 criteria of NCHRP Report No. 350, longitudinal barriers must be subjected to two full-scale vehicle crash tests: (1) an 820-kg small car impacting at a speed of 100.0 km/hr and at an angle of 20 degrees; and (2) a 2,000-kg pickup truck impacting at a speed of 100.0 km/hr and at an angle of 25 degrees. For this research project, crash tests were performed using only the pickup truck impact conditions. Although the small car test is used to evaluate the overall performance of the length-of-need section and to assess occupant risk problems that arise from snagging or overturing of the vehicle, it was deemed unnecessary for several reasons.

First, during the design of both barrier systems, special attention was given to prevent geometric incompatibilities that would cause the small car tests to fail as a result of excessive snagging or overturning. Second, the structural adequacy of the medium service level barrier systems is not a concern for the small car test due to the relatively minor impact severity as compared to the impact severity for the pickup truck impact conditions. The impact severity for the pickup truck test is approximately 270 percent greater than that provided by the small car test. Third, a small car crash test was successfully conducted on a similar wood bridge railing system previously developed by MwRSF (12). Finally, thrie beam barriers struck by small cars have been shown to meet safety performance standards and to be essentially rigid (23-25), with no significant potential for occupant risk problems that arise from snagging or overturning. For these reasons, the small car crash test was considered unnecessary for the systems that were developed under this research project.

Evaluation criteria for full-scale crash testing is based on three appraisal areas: (1) structural adequacy; (2) occupant risk; and (3) vehicle trajectory after the collision. Criteria for structural adequacy are intended to evaluate the ability of the railing to contain, redirect, or allow controlled vehicle penetration in a predictable manner. Occupant risk evaluates the degree of hazard to occupants of the impacting vehicle. Vehicle trajectory after collision is concerned with the path and final position of the impacting vehicle and the probable involvement of the impacting vehicle in secondary collisions. Note that these criteria address only the safety and dynamic performance of the barrier and do not include service criteria such as aesthetics, economics, bridge damage, or post-impact maintenance requirements. The evaluation criteria are summarized in NCHRP Report No. 350.

DEVELOPMENT PHASE

Transverse Panels

Highway bridges using transverse timber decks and those requiring crash tested railing systems are most commonly constructed using glulam timber deck panels. Transverse glulam timber decks are constructed of panels that are oriented with the lumber length perpendicular to the direction of traffic. Individual lumber laminations are placed edgewise and glued together with waterproof structural adhesives. These panels are typically 1.22-m wide, 127 to 171-mm thick, and effectively act as a thin plate. To form the bridge deck, panels are placed side by side and are supported by longitudinal glulam or steel beams. These longitudinal beams are designed to carry the vertical loads and are braced by either glulam or steel diaphragms in order to provide lateral stiffness to the bridge structure. Given that the panel orientation is perpendicular to traffic, railing loads primarily introduce tension and bending in the panels parallel to the wood grain. Unlike the longitudinal glulam timber decks, tension perpendicular to the wood grain is not a primary design consideration.

Bridge Rail Design

The primary emphasis of the railing design process was to develop rails that would meet the requirements of the NCHRP Report No. 350. In addition, it was determined that consideration should be given to: (1) the extent of probable damage to the structure after vehicle impact and the difficulty and cost of required repairs; (2) the adaptability of the railing to different types of wood decks; (3) the cost of the rail system to the user, including material, fabrication, and construction; (4) the ease of railing construction and maintenance; and (5) bridge railing aesthetics.

The development phase concluded with the design of several railing and transition systems and the preparation of plans and specifications for testing. The selection and design of these final systems were based on a review of other railings that had been successfully crash tested, as well as those that are currently used on wood bridges but have not been crash tested. To the extent possible, feasible designs were evaluated using BARRIER VII computer simulation modeling (2). Although several computer models were used, it was sometimes difficult to adapt the programs for wood components because the behavior and properties of the wood systems at ultimate loading were unknown.

For the wood railing system, six dynamic bogie tests were conducted on glulam timber posts. The base of each post was placed vertically into a rigid steel sleeve. For each test, the bogie vehicle impacted the cantilevered post specimen at a prescribed height above the fixed base. The results from the bogie tests provided valuable information deemed necessary for determining the size of the glulam posts as well as selected input parameters for the computer simulation analysis.

SIMULATED TEST BRIDGE

Testing of the bridge railing and approach guardrail transition systems was conducted at MwRSF’s outdoor test site located in Lincoln, Nebraska. To perform all the barrier testing, a full-size test bridge was constructed, as shown in Figure 3. The test bridge measured approximately 3.96-m wide and 36.58-m long and consisted of three simply-supported spans measuring approximately 12.19 m each.

The transverse deck system was constructed of 130-mm thick by 1.22-m wide glulam timber panels. The glulam timber for the deck was Combination No. 47 Southern Yellow Pine, as specified in the

AASHTO *LRFD Bridge Design Specification* (7). The timber was treated according to the American Wood Preservers' Association (AWPA) Standard C14 (26). Thirty glulam timber panels were placed side by side to achieve the 36.58-m length and were attached to the longitudinal glulam beams with standard aluminum deck brackets.

The test bridge was positioned on concrete supports that were placed in a 2.13-m deep excavated test pit. The concrete supports were placed so that the top of the test bridge was 51 mm below the concrete surface to allow for placement of the bridge deck wearing surface. A detailed discussion of the test bridge is beyond the scope of this paper and is presented in detail by Fowler (20).

STEEL RAILING - SYSTEM NO. 1

Design Details

The first bridge railing system was designed as an all-steel system. This system was constructed with a thrie beam rail, an upper structural channel rail, wide-flange bridge posts and rail blockouts, and deck mounting plates. Specific details of this system are provided in Figure 4. For the steel system, a 10-gauge, thrie beam rail was blocked away from wide-flange posts with wide-flange spacers. A structural channel rail was then attached to the top 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.

System No. 1 was configured similarly to the TL-4 steel thrie beam and structural tube bridge railing system previously developed for transverse decks (18-19). However, since the TL-2 impact condition provided a reduced impact severity from the TL-4 impact condition, several design modifications were deemed necessary. As a result, the upper structural tube rail on the TL-4 system was replaced with a channel rail section. This modification not only provided reduced weight but improved constructability. Other design modifications included a reduction in the size of the deck mounting plates as well as a decrease in the number of vertical bolts used to attach the mounting plates to the timber deck panels. A 2,438-mm post spacing, also used with the TL-4 railings for transverse decks, was selected instead of the usual 1,905-mm post spacing. The increased post spacing was selected to optimize the design and significantly improve the constructability of the railing system, which was based on 1,219-mm wide deck panels. Researchers believed these changes in the bridge railing design were necessary in order to provide additional economy over the TL-4 bridge railing system.

During the railing development, researchers considered whether to design the bridge railing with or without the upper channel rail section. If an upper channel rail was not used, dynamic deflections would likely be excessive, thus potentially resulting in vehicle pocketing between bridge posts or vehicle rollover upon redirection. If an upper channel rail was used, then greater load distribution would occur between the bridge posts, thus resulting in the reduced pocketing and improved stability of the pickup truck upon redirection. For the final system, a more conservative design approach was chosen, and the upper channel rail was retained.

A TL-2 approach guardrail transition system was designed for attachment to each end of the bridge railing system. The system was constructed using a steel thrie beam rail, a sloped structural channel end rail, guardrail posts, and rail blockouts. Specific details of the approach guardrail transition used with System No.1 are provided in Figure 5.

Bridge Rail Crash Test

The steel bridge railing system was subjected to one full-scale vehicle crash test. Details of the crash test are provided in the following section. It is noted that instrumentation sensors were strategically placed on selected bridge railing components. However, a detailed discussion of the instrumentation results is beyond the scope of this paper and will be provided in future publications.

The first crash test, test STCR-1, was successfully performed with a 1990 Chevrolet 2500, ¾-ton pickup truck with a test inertial mass of 1,966 kg and at the impact conditions of 66.6 km/hr and 25.6 degrees. During the impact event, the truck became parallel to the railing at 0.229 sec and with a speed of 46.1 km/hr. At 0.519 sec after impact, the vehicle exited the railing system at a speed of 45.2 km/hr and at an angle of 14.7 degrees. The maximum lateral permanent set and dynamic rail deflections were observed to be 102 and 157 mm, respectively. The location of the vehicle impact with the bridge railing, vehicle damage, and barrier damage are shown in Figure 6.

Following an analysis of the test results, it was determined that the steel bridge railing system met the TL-2 safety performance criteria provided in NCHRP Report No. 350. No significant damage to the test bridge was evident from the vehicle impact test. For the bridge railing system, damage consisted primarily of permanent deformation of the thrie beam rail, channel rail, wide-flange posts, and rail spacers. Although visual permanent set deformations of the steel components were found in the vicinity of the impact, all of the steel members remained intact and serviceable after the test. Thus, replacement of bridge railing components would be based more on aesthetics versus structural integrity.

Transition Crash Test

The approach guardrail transition that is used with the steel bridge railing system was also subjected to one full-scale vehicle crash test. Details of the crash test are provided in the following section.

The first crash test, test STCR-2, was successfully performed with a 1990 Chevrolet 2500, ¾-ton pickup truck with a test inertial mass of 2,035 kg and at the impact conditions of 69.9 km/hr and 25.8 degrees. During the impact event, the truck became parallel to the railing at 0.272 sec and with a speed of 50.0 km/hr. At 0.500 sec after impact, the vehicle exited the transition system at a speed of 45.5 km/hr and at an angle of 17.6 degrees. The maximum lateral permanent set and dynamic rail deflections were observed to be 117 and 202 mm, respectively. The location of the vehicle impact with the approach guardrail transition, vehicle damage, and barrier damage are shown in Figure 7.

Following an analysis of the test results, it was determined that the approach guardrail transition for use with the steel bridge railing system met the TL-2 safety performance criteria provided in NCHRP Report No. 350. No significant damage to the upstream end of the test bridge was evident from the vehicle impact test. For the approach guardrail transition system, damage consisted primarily of deformed thrie beam rail and bridge posts as well as displaced guardrail posts. Although visual permanent set deformations of the thrie beam rail were found in the vicinity of the impact, the rail remained intact and serviceable after the test. Thus, replacement of the guardrail would be based more on aesthetics versus structural integrity.

WOOD RAILING - SYSTEM NO. 2

Design Details

The second bridge railing system was designed to be an all-wood system, except for the structural steel connections. This system was constructed using a rectangular rail, rectangular bridge posts, rail blockouts, and deck mounting plates. Specific details of this system are provided in Figure 8. For the wood system, glulam timber for the rail and post members was Combination No. 48 Southern Yellow Pine (SYP), as specified in AASHTO's *LRFD Bridge Design Specifications* (7), and treated with pentachlorophenol in heavy oil to AWPA Standard C14 requirements (26). Glulam timber for the spacer blocks were fabricated with Combination No. 47 SYP, as specified by AASHTO (7) and treated in the same manner as described previously according to AWPA Standard C14 (26).

System No. 2 was configured similarly to the PL-1 glulam timber rail without curb system previously developed for longitudinal decks (12,15-16,18). However, for this system, all wood components were fabricated from glulam timber, whereas the previous system used glulam rail and sawn lumber posts and blocks. From the PL-1 railing system, the steel box that was used to support the posts was replaced with a more economical steel, U-shaped bracket which attached to the deck surface. In addition, all structural members, as well as the steel hardware, were resized to account for the increased post spacing from 1,905 to 2,438 mm. Once again, the new post spacing was selected to optimize the design and improve the constructability of the railing system, which was based on 1,219-mm wide deck panels.

A TL-2 approach guardrail transition system was designed for attachment to each end of the bridge railing system. The system was constructed using two nested steel W-beam rails, guardrail posts, and rail blockouts. Specific details of the approach guardrail transition used with System No.2 are provided in Figure 9.

Bridge Rail Crash Test

The wood bridge railing system was subjected to one full-scale vehicle crash test. Details of crash test are provided in the following section. It is noted that instrumentation sensors were strategically placed on selected bridge railing components. However, a detailed discussion of the instrumentation results is beyond the scope of this paper and will be provided in future publications.

The first crash test, test WRBP-1, was successfully performed with a 1994 Ford F-250, ¾-ton pickup truck with a test inertial mass of 2,031 kg and at the impact conditions of 69.0 km/hr and 26.2 degrees. During the impact event, the truck became parallel to the railing at 0.280 sec and with a speed of 47.2 km/hr. At 0.452 sec after impact, the vehicle exited the railing system at a speed of 47.1 km/hr and at an angle of 5.9 degrees. The maximum lateral permanent set and dynamic rail deflections were observed to be 63 and 189 mm, respectively. The location of the vehicle impact with the bridge railing, vehicle damage, and barrier damage are shown in Figure 10.

Following an analysis of the test results, it was determined that the wood bridge railing system met the TL-2 safety performance criteria provided in NCHRP Report No. 350. No significant damage to the test bridge was evident from the vehicle impact test. For the bridge railing system, damage consisted primarily of rail gouging and scraping as well as permanent set deformations of the steel deck mounting plates. The glulam timber railing remained intact and serviceable after the test. Railing replacement would not be considered necessary unless to provide improved aesthetics.

Transition Crash Test

The approach guardrail transition that is used with wood bridge railing system was also subjected to one full-scale vehicle crash test. Details of crash test are provided in the following section.

The first crash test, test WRBP-2, was successfully performed with a 1993 Ford F-250, ¾-ton pickup truck with a test inertial mass of 2,011 kg and at the impact conditions of 71.6 km/hr and 26.3 degrees. During the impact event, the truck became parallel to the railing at 0.261 sec and with a speed of 55.9 km/hr. At 0.422 sec after impact, the vehicle exited the transition system at a speed of 54.6 km/hr and at an angle of 3.5 degrees. The maximum lateral permanent set and dynamic rail deflections were observed to be 29 and 125 mm, respectively. The location of the vehicle impact with the approach guardrail transition, vehicle damage, and barrier damage are shown in Figure 11.

Following an analysis of the test results, it was determined that the approach guardrail transition for use with the wood bridge railing system met the TL-2 safety performance criteria provided in NCHRP Report No. 350 (1). No significant damage to the upstream end of the test bridge was evident from the vehicle impact test. For the approach guardrail transition system, damage consisted primarily of deformed W-beam rail and displaced guardrail posts. Although visual permanent set deformations of the W-beam rail were found in the vicinity of the impact, the rail remained intact and serviceable after the test. Thus, replacement of guardrail would be based more on aesthetics versus structural integrity.

DISCUSSION AND RECOMMENDATIONS

As stated previously, the researchers installed instrumentation sensors on key components of the railing systems in an attempt to measure the actual forces imparted into the timber deck. The researchers deemed that the dynamic load information was necessary because additional economy could be provided with the downsizing of specific structural components.

For the steel system, eight 22-mm diameter ASTM A307 bolts were used to attach the steel mounting plates to the top and bottom surfaces of the timber deck. Measured strain readings on the plates near the outer bolt locations were found to be significantly lower than those observed near the central bolt locations. In addition, no bearing deformations of the deck mounting plates and vertical bolts, nor damage to the timber deck near the shear connectors, were found. Therefore, the researchers believe that the TL-2 steel bridge railing system would have performed in an acceptable manner if each deck plate was attached with only six vertical bolts instead of eight. It is noted that strain gauge results were used in a similar manner when the number of vertical bolts were reduced in the TL-4 steel bridge railing system (19). However, for a reduction of two vertical bolts, there exists the potential for a slight increase in deck damage as well as increased difficulty in removing and repairing the plates and bolts following an impact.

For the wood system, six 22-mm diameter ASTM A307 bolts were used to attach the steel mounting plates to the top and bottom surfaces of the timber deck. For the three top plates that were instrumented, measured strain readings showed that the load was better distributed throughout each plate and to all six of the vertical bolts. As a result, no design changes were believed to be necessary.

CONCLUSIONS

Two bridge railing and approach guardrail transition systems were successfully developed for use on transverse glue-laminated (glulam) timber deck bridges located on medium service level roadways. The bridge railing and transition systems were evaluated according to the TL-2 guidelines presented in NCHRP Report No. 350. For all crash tests, the bridge railing and transition systems performed well with no damage to the bridge superstructure. With the development of the two crashworthy railing systems, a significant barrier to the widespread use of transverse wood deck bridges on medium service level roadways has been overcome. At the onset of this research program, no TL-2 crash tested bridge railing system was available for use on 130-mm thick, transverse wood deck bridges, although two TL-4 railing systems had previously been developed (19). Now, bridge engineers have two railing systems for use on transversely-laminated timber deck bridges located on medium service level roadways, and an approach guardrail transition system has been developed and crash tested for use with each bridge railing system.

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DISCLAIMER

The contents of this paper reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of FPL or FHWA. This report does not constitute a standard, specification, or regulation.

REFERENCES

1. Ross, H.E., Jr., Sicking, D.L., Zimmer, R.A., and Michie, J.D., *Recommended Procedures for the Safety Performance Evaluation of Highway Features*, National Cooperative Highway Research Program (NCHRP) Report No. 350, National Research Council, Transportation Research Board, Washington, D.C., 1993.

2. Powell, G.H., *BARRIER VII: A Computer Program for Evaluation of Automobile Barrier Systems*, Report FHWA RD-73-51, Federal Highway Administration, U.S. Department of Transportation, April 1973.

3. *Standard Specifications for Highway Bridges*, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 1989.

4. *Full-Scale Testing Procedures for Guardrails and Guide Posts*, Highway Research Circular No. 482, National Research Council, Highway Research Board, National Cooperative Highway Research Program, Washington, D.C., 1962.

5. Michie, J.D., *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*, National Cooperative Highway Research Program (NCHRP) Report No. 230, National Research Council, Transportation Research Board,, Washington, DC, 1981.

6. *Guide Specifications for Bridge Railings*, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 1989.

7. *AASHTO LRFD Bridge Design Specifications*, First Edition, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 1994.

8. Hirsch, T.J., *Analytical Evaluation of Texas Bridge Rails to Contain Buses and Trucks*, Report No. FHWA/TX78-230-2, Submitted to Texas State Department of Highways and Public Transportation, Texas Transportation Institute, Texas A&M University, August 1978.

9. *Memorandum on Bridge Rails*, August 28, 1986, File Designation HNG-10/HHS-10, Federal Highway Administration (FHWA), Washington, D.C., 1986.

10. *Memorandum on Crash Tested Bridge Railings*, August 13, 1990, File Designation HNG-14, Federal Highway Administration (FHWA), Washington, D.C., 1990.

11. Hancock, K.L., Hansen, A.G., and Mayer, J.B., *Aesthetic Bridge Rails, Transitions, and Terminals for Park Roads and Parkways*, Report No. FHWA-RD-90-052, Submitted to Office of Safety and Traffic Operations R&D, Federal Highway Administration, Performed by The Scientex Corporation, May 1990.

12. Faller, R.K., Ritter, M.A., Holloway, J.C., Pfeifer, B.G., and Rosson, B.T., *Performance Level 1 Bridge Railings for Timber Decks*, Transportation Research Record 1419, Transportation Research Board, National Research Council, Washington, D.C., October 1993.

13. Rosson, B.T., Faller, R.K., and Ritter, M.A., *Performance Level 2 and Test Level 4 Bridge Railings for Timber Decks*, Transportation Research Record 1500, Transportation Research Board, National Research Council, Washington, D.C., July 1995.

14. Faller, R.K., Rosson, B.T., Ritter, M.A., and Sicking, D.L., *Design and Evaluation of Two Low-Volume Bridge Railings*, Sixth International Conference on Low-Volume Roads, Volume 2, Conference Proceedings 6, University of Minnesota, Minneapolis, Minnesota, June 25-29, 1995, Transportation Research Board, Washington, D.C., 1995.

15. Ritter, M.A., Lee, P.D.H., Faller, R.K., Rosson, B.T., and S.R. Duwadi, *Plans for Crash Tested Bridge Railings for Longitudinal Wood Decks*, General Technical Report No. FPL-GTR-87, United States Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, Wisconsin, September 1995.

16. Faller, R.K., Rosson, B.T., Ritter, M.A., Lee, P.D.H., and Duwadi, S.R., *Railing Systems for Longitudinal Timber Deck Bridges*, Presented at the National Conference on Wood Transportation Structures, Madison, Wisconsin, October 23-25, 1996, General Technical Report No. FPL-GTR-94, United States Department of Agriculture - Forest Service - Forest Products Laboratory and Federal Highway Administration, October 1996.

17. Ritter, M.A., Faller, R.K., Bunnell, S., Lee, P.D.H., and Rosson, B.T., *Plans for Crash-Tested Railings for Longitudinal Wood Decks on Low-Volume Roads*, General Technical Report No. FPL-GTR-107, United States Department of Agriculture - Forest Service - Forest Products Laboratory and Federal Highway Administration, August 1998.

18. Faller, R.K., Rosson, B.T., Ritter, M.A., and Duwadi, S.R., *Railing Systems for Use on Timber Deck Bridges*, Transportation Research Record No. 1656, Transportation Research Board, Washington, D.C., July 1999, 110-119.

19. Faller, R.K., Ritter, M.A., Rosson, B.T., Fowler, M.D., and Duwadi, S.R., *Two Test Level 4 Bridge Railing and Transition Systems for Transverse Timber Deck Bridges*, Paper No. 5B0110, Transportation Research Record No. 1996, Volume 1, Fifth International Bridge Engineering Conference, Tampa, Florida, April 3-5, 2000, Transportation Research Board, Washington, D.C., 334-351.

20. Fowler, M.D., *Design and Testing of a Test Level 4 Bridge Railing for Transverse Glulam Timber Deck Bridges*, M.S. Thesis, University of Nebraska-Lincoln, May 1997.

21. Ritter, M.A., Faller, R.K., Lee, P.D.H., Rosson, B.T., and Duwadi, S.R., *Plans for Crash-Tested Wood Bridge Railings for Concrete Decks*, General Technical Report No. FPL-GTR-108, United States Department of Agriculture - Forest Service - Forest Products Laboratory and Federal Highway Administration, August 1998.

22. Raju, P., R., GangaRao, H.V.S., Duwadi, S.R., and Thippeswamy, H.K., *Development and Testing of Timber Bridge and Transition Rails for Transverse Glued-Laminated Bridge Decks*, Transportation Research Record 1460, Transportation Research Board, National Research Council, Washington, D.C., December 1994.

23. Buth, C.E., Campise, W.L., Griffin, III, L.I., Love, M.L., and Sicking, D.L., *Performance Limits of Longitudinal Barrier Systems - Volume I - Summary Report*, Report No. FHWA/RD-86/153, Submitted to the Office of Safety and Traffic Operations, Federal Highway Administration, Performed by Texas Transportation Institute, May 1986.

24. Ivey, D.L., Robertson, R., and Buth, C.E., *Test and Evaluation of W-Beam and Thrie-Beam Guardrails*, Report No. FHWA/RD-82/071, Submitted to the Office of Research, Federal Highway Administration, Performed by Texas Transportation Institute, March 1986.

25. Ross, H.E., Jr., Perera, H.S., Sicking, D.L., and Bligh, R.P., *Roadside Safety Design for Small Vehicles*, National Cooperative Highway Research Program (NCHRP) Report No. 318, Transportation Research Board, Washington, D.C., May 1989.

26. *AWPA Book of Standards*, American Wood Preservers' Association (AWPA), Woodstock, MD, 1992.

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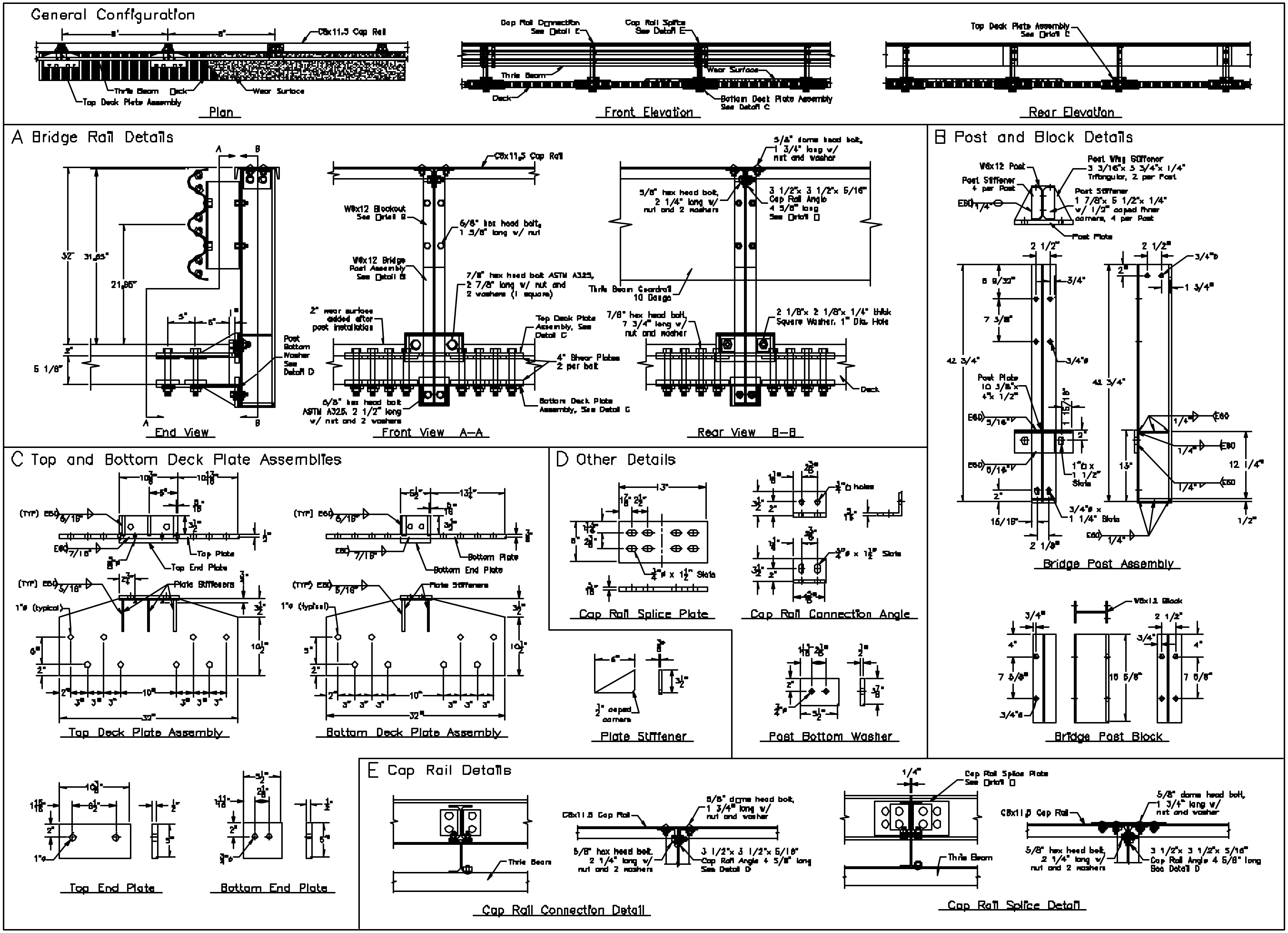

Figure 4. Steel Bridge Railing Design Details, System No. 1 (1 in. = 25.4 mm).

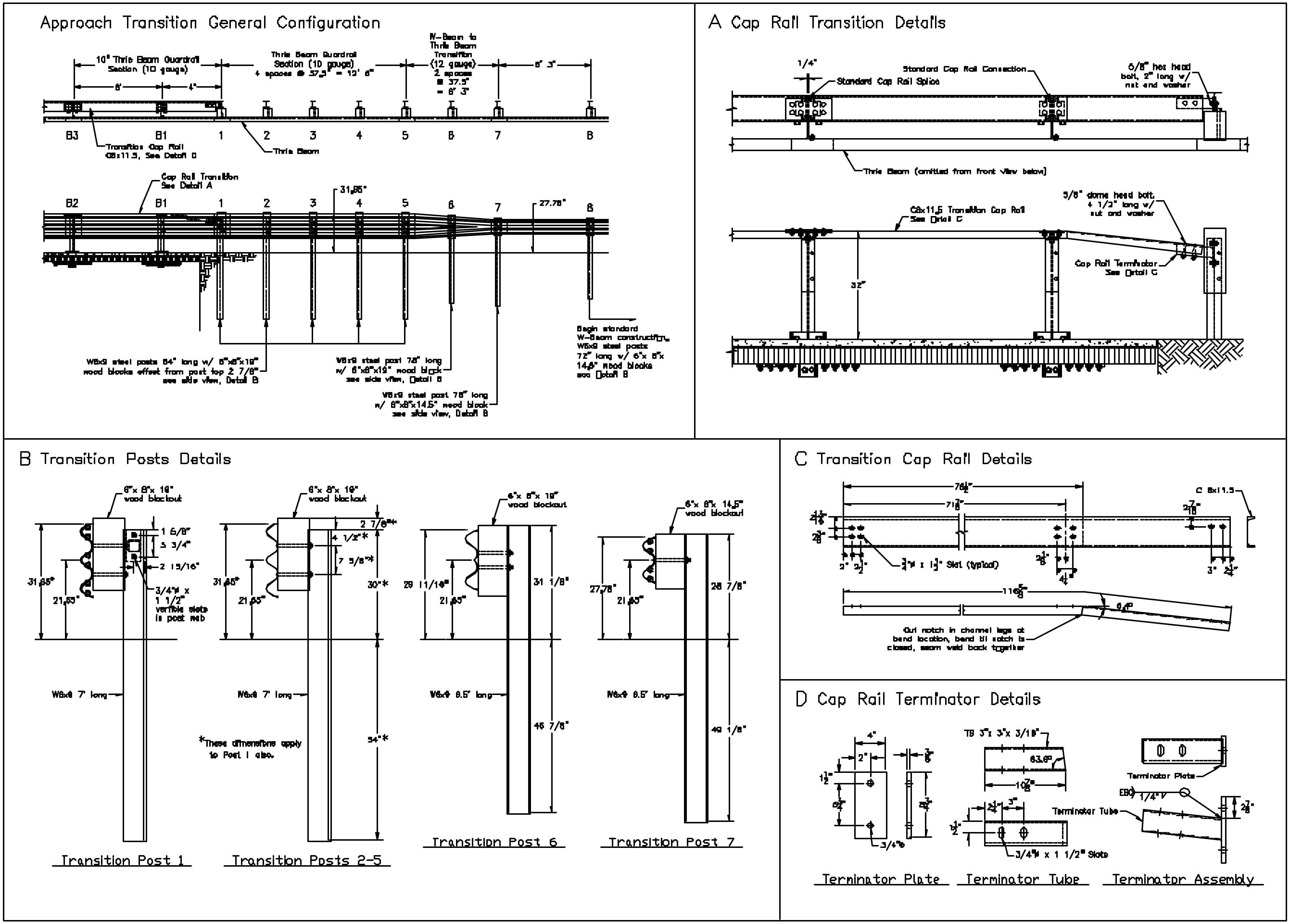

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Figure 6. Impact Location, Vehicle Damage, and Bridge Railing Damage, Test STCR-1.

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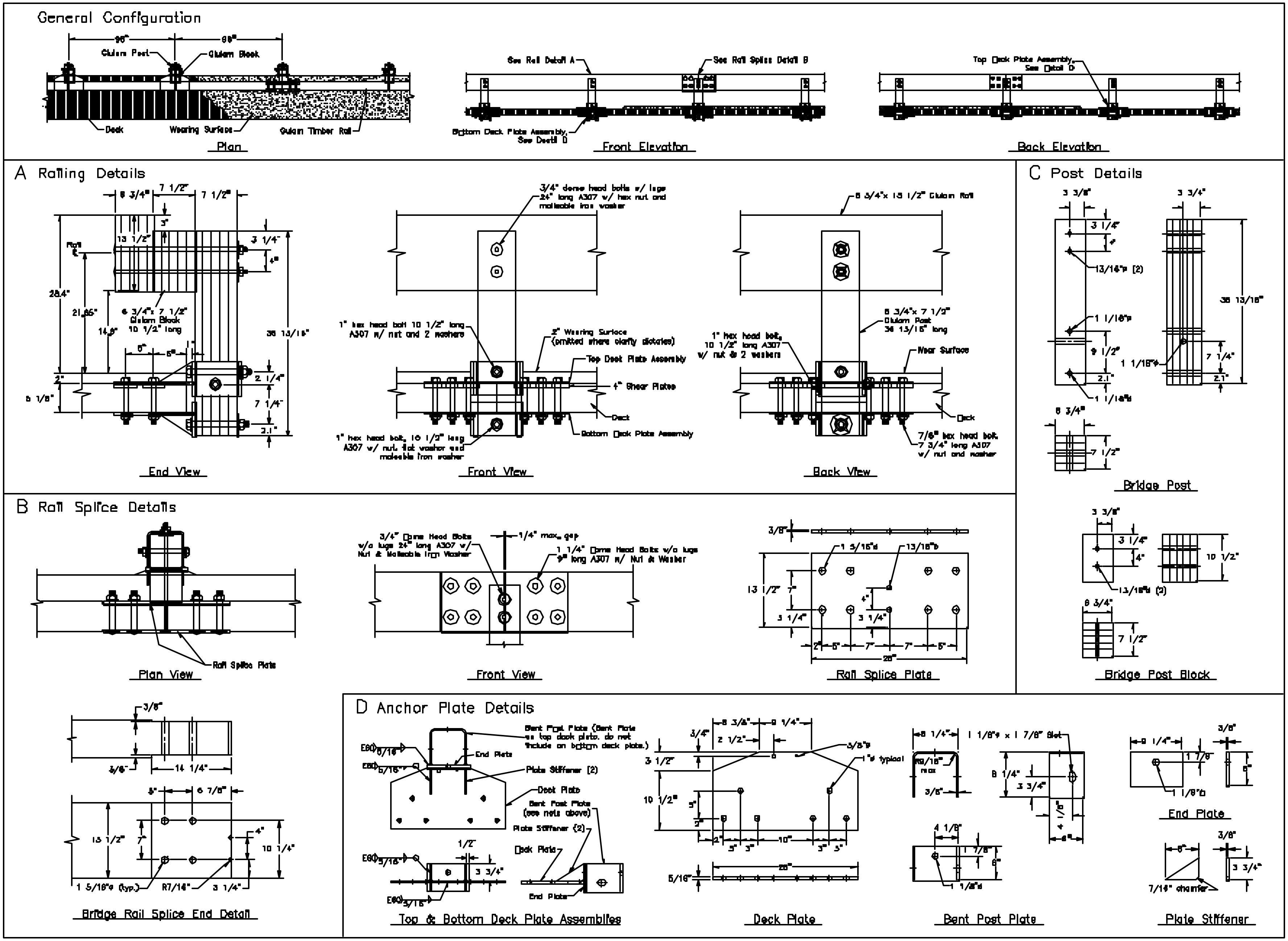
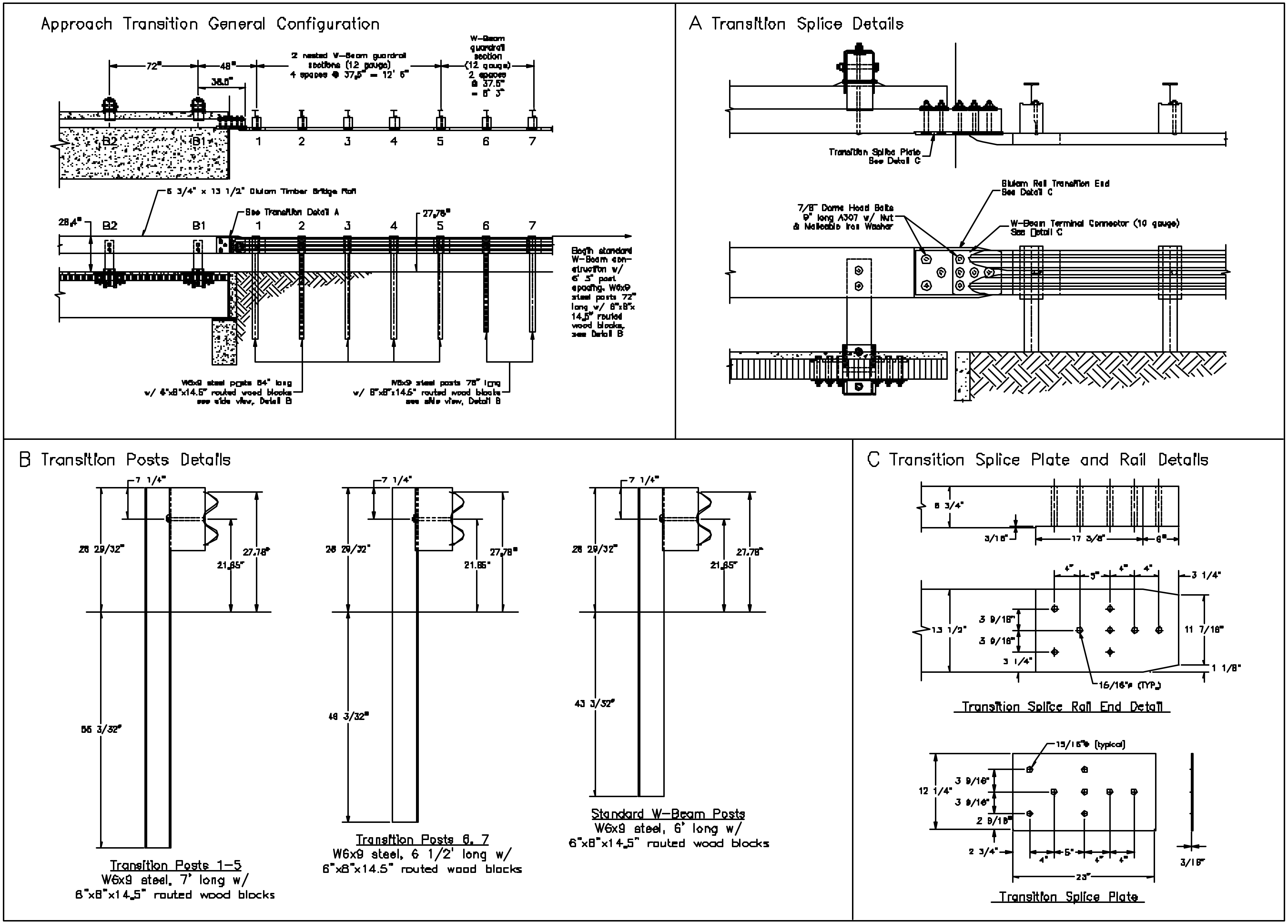


Figure 8. Wood Bridge Railing Design Details. System No. 2 (1 in. = 25.4 mm).



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