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Abstract

An existing mountable safety barrier system, previously crash tested successfully on a wood bridge deck, was evaluated for use on a fiber reinforced plastic (FRP) bridge deck. In an attempt to avoid expensive full-scale crash testing, components of the existing system were evaluated using worst case conditions on two dynamic bogie crash tests and a series of computer simulations using nonlinear finite-element analysis. Simulation results closely approximated the physical results, with both displaying similar deformation, damage, and force levels. Both testing and simulation demonstrated that the barrier should function sufficiently if used on the FRP deck system. Further, the development of an accurate model makes it possible to evaluate the potential success of the existing system for use on other bridge decks. As an example, a more rigid bridge deck, similar to reinforced concrete, was evaluated. Results showed that due to the stiffer deck, more of the impact energy must be absorbed by the posts and attachment hardware, resulting in significantly more deformation than when used on the flexible FRP deck.

Introduction

There are many different types of bridges throughout the world, but each generally consists of a bridge deck)i.e., the portion a vehicle travels on) and a barrier system (i.e., the portion that keeps a vehicle from driving over the edge of the bridge deck). These barrier systems are either built directly into the bridge deck as part of the deck design, or mounted separately onto the deck after it is built. Occasionally, these barrier systems must be designed specifically for a particular type of bridge.

To be installed on United States Highways, a bridge barrier system must be successfully crash tested according to National Cooperative Highway Research Program Report No. 350 (NCHRP 350) (Ross et al. 1993). Depending on the expected usage of the bridge, there are various test levels that determine the specific crash tests to be performed.

Previously, the Midwest Roadside Safety Facility (MwRSF) at the University of Nebraska—Lincoln (UNL) developed a Test Level 4 (TL-4), deck-mounted, steel post bridge railing system for a bridge deck consisting of thin, transverse, glue-laminated timber panels (Faller et al. 2000), as shown in Fig. 1. The system consisted of a steel thrie-beam and upper tube longitudinal barrier mounted on *W*152 X 22.3 steel blockouts. The blockouts were bolted to *W*152 X 22.3 steel posts, which were in turn bolted to a series of steel attachment plates that anchored directly to the bridge deck. This work was completed for the Forest Products Laboratory (FPL) for use on similar bridge decks found in United States national parks.

According to the NCHRP 350 TL-4 criteria, longitudinal barriers must be subjected to three full-scale vehicle crash tests: (1) an 820-kg small car impacting at a speed of 100 km/h and at an angle of 20° (referred to as the 820c TL-4 test); (2) a 2,000-kg pickup truck impacting at a speed of 100 km/h and at an angle of 25° (referred to as the 2000p TL-4 test); and (3) an 8,000-kg single-unit truck impacting at a speed of 80 km/h and at an angle of 15° (referred to as the 8000s TL-4 test).

For the timber deck research project, crash testing was performed using only the pickup truck and single-unit truck impact conditions. Although the small car test is used to evaluate the overall performance of the length-of-need section and occupant risk problems arising from snagging or overturning of the vehicle, it was deemed unnecessary in this project because the structural adequacy of the higher service level barrier systems is not a concern for the small car test due to the relatively minor impact severity when compared to the impact severity for the pickup truck and single-unit truck impact conditions.

In the 2000p and 8000s TL-4 crash tests on the FPL bridge railing system, several steel posts yielded, resulting in slight bending of the posts near the deck attachment locations. This implied that the steel posts reached their peak load capacity without damaging the timber deck nor rupturing the steel attachment hardware away from the timber deck panels. To cause slight bending of *W*152 X 22.3 steel posts, a dynamic lateral yield force of approximately 107 kN must have been applied to the steel posts during the two impact events. Both crash tests conducted met all safety requirements specified in NCHRP 350. Photos taken during the crash tests are shown in Fig. 2.

Recently, bridge engineers and researchers from the Kansas Department of Transportation (KsDOT) presented a need for a crashworthy bridge railing system for use on a bridge deck constructed with light-weight, fiber reinforced plastic (FRP) panels. To that end, a research project was performed at the MwRSF to determine if the deck-mounted, steel post barrier system for the timber bridge deck could be directly used with the FRP bridge deck without undergoing expensive full-scale crash testing. This project consisted of an analysis of the design supported by dynamic bogie testing performed on a single post of the railing system. Additionally, simulation of the bogie testing was performed using nonlinear finite-element modeling in order to enhance the analysis.

Bogie Testing In Lieu Of Full-Scale Crash Testing

MwRSF researchers reasoned that if the FRP deck was capable of withstanding impact loads large enough to cause yielding in the post, without significantly damaging the deck panels nor rupturing the steel hardware away from the deck system, then it too would pass similar full-scale crash testing. Thus, two bogie tests were designed to apply significant lateral and torsional loads to a single steel post and blockout mounted on the FRP deck. If these tests were successful, then full-scale crash testing would be deemed unnecessary, and the FPL TL-4 bridge railing could be used on the FRP deck panel system.

For the bogie test program, 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, researchers designed and attached a horizontal spreader beam to the front face of the blockouts so that the dynamic impact load would be imparted to the posts at the appropriate load height.

Details of the deck-mounted steel post and attachments to the FRP deck are shown in Fig. 3. A 640-kg bogie, fitted with an impact head positioned 630 mm above the deck surface, impacted the spreader beam at two different locations, as shown in Fig. 4. Results for each of the bogie tests are provided later in this paper.

Based on full-scale crash testing of the FPL system it was determined that the post in the bogie load test should deflect backward at least 200 mm in order to demonstrate that this magnitude of displacement would not significantly damage the FRP deck nor 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 350 mm post displacement at the load height was selected. If this deformation did not damage the FRP deck or rupture the post and associated hardware, then it would have been demonstrated that the FRP deck panel was an acceptable alternative to the thin timber deck panel. Using a bogie weight of 640 kg, a yield force of 107 kN, a post stiffness of 5.25 kN/mm, and a limiting deflection of 350 mm, a target bogie impact speed was determined to be 38 km/h.

Test KCBP-1 was a centerline impact, implying the bogie impact head was aligned 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 230 mm. 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 triaxial 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.

FRP Bridge Deck Panels

The steel posts were anchored to FRP bridge deck panels, which were placed transversely across longitudinal steel bridge girders. The panels were fabricated by Kansas Structural Composites, Inc. (KSCI). Each FRP panel measured 4267 mm long X 2438 mm wide X 203 mm thick, and was fabricated using 12.7-mm-thick elements using 40% fiberglass and 60% polyester. The fiber architecture utilized a standard KSCI layup in conjunction with a polyester resin material. A honeycomb core was used for the panels, consisting of alternating flat and corrugated layers. The flat FRP elements were 2.3 mm thick, while the corrugated layers had a 50.8 mm amplitude and a wave length of 102 mm. The core height was 178 mm. Panel edges and closeouts were constructed with 3.0-mm-thick FRP elements and wet layups of 102–152 mm overlapping on the primary surfaces. The panel to support beam connections utilized steel bent-plate connectors measuring 6.35 mm thick by 127 mm 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 and using a stud gun. The low-carbon steel anchor studs had a 345 MPa minimum yield strength and a 414 MPa minimum tensile strength.

Model Development

Nonlinear, finite-element analysis was used as a supplement to the project in order to gain further insight into the behavior of the deck-mounted steel post barrier system; the software used was LS-DYNA (Hallquist 2003).

Geometric Model

The geometric model developed for use in the simulation effort is shown in Fig. 5. The *W*152 X 22.3 post and blockout, mounting hardware, plate, and spreader beam were all modeled using a simplified, square-corner geometry constructed of deformable shell elements. Thicknesses were specified according to the actual parts being modeled.

Solid elements were used to model the FRP deck, which was divided into two parts. One part was defined near the connections to the mounting plates. This part underwent permanent deformations, and thus was modeled with a relatively fine mesh compared to the rest of the deck. The other part defined the remainder of the deck which exhibited significant elastic vibrations during testing, but no measurable permanent deformations. The deck panel was supported by two rigid I-beams, forming a cantilever situation for the deck at the location where the post was attached, just as in the physical tests.

Bolted connections were modeled using a discrete based clamping technique, detailed by Reid and Hiser (Reid and Hiser 2005), in which a discrete spring connected the bolt and the nut, which were modeled using solid, rigid elements; examples are shown in Fig. 6. A preload of 90% of the proof load was desired for each bolt since they were considered to be permanent connections. Preloads were applied to each of the bolts by specifying a certain elongation in the spring. Washers were also modeled with solid, rigid elements, and were rigidly attached to their respective bolt or nut to reduce computation time and to simplify contacts. The last simplification was reasonable because the washers did not deform during physical testing nor was there any noticeable sliding between those parts. In total, there were 18 bolted connections, using four different sizes of bolts.

Material Models

Three material models were required for the simulation: one for the steel post system and two for the FRP deck. Although the steel parts used in the system were not tested for precise material properties, they were all specified as typical A36 steel. A piecewise linear plasticity model available within LS-DYNA was used for the steel. Parameters used for that model were based on standard coupon tensile testing completed at the University of Nebraska, results of which are shown in Fig. 7. Validation was achieved by simulating the actual coupon testing.

Although the FRP deck was composed of a highly complex composite material, simplified materials were used in the model. Determining precise material models was beyond the scope of this project, but information was reviewed from several sources in order to have reasonable confidence in the results.

As mentioned previously, the deck was modeled in two parts. The part behaving elastically was modeled with an elastic material with estimated properties consisting of a density of 2.452E-06 kg/mm^3, a modulus of elasticity of 1.5 GPa, and a Poisson's ratio of 0.4. The part of the deck that underwent large, permanent deformations was modeled using a modified honeycomb material model. This material simulates a crushable foam with anisotropic behavior, similar to that shown by the FRP panels during testing.

Initial Simulation Complications

In the first complete run of the centerline impact model, it became apparent that the thickness of the shell elements was not being accounted for correctly in the contact definitions. Upon impact, the post rotated with minimal resistance until it contacted the plate washer held by the 228.6 mm bolts. Accounting for the thickness, the post and plate washer should have been in contact at the onset of the impact, preventing such free rotation.

When adjustments were made in the post processor to display the thickness of the shell elements, the problem became apparent. The contact definition was not working as desired. As shown on the left in Fig. 8, the compression flange of the post was penetrating nearly halfway through the washer plate. Noting this, the contact definition was changed to a segment versus segment penetration check rather than a node versus segment penetration check. With changes made, the contact between the plate and post flange behaved as desired, as shown on the right in Fig. 8.

A second flaw in the model was the failure of the post flange. During an early simulation, the post flange fractured on the impact side at the upper slotted bolt holes as shown in Fig. 9. This fracture allowed excessive post deformation which did not effectively stop the bogie vehicle. The result indicated that either the forces applied to the post during simulation were higher than those in the test, or the failure criteria specified in the material model was not an accurate representation of the steel used in the system. Since the initial kinetic energy of the bogie model (i.e., bogie mass and speed) was determined to be accurate, the impact loads were considered to be correct.

Thus, the material model was adjusted to increase the failure criteria and in the subsequent simulations, the post flange did not fail. Although this modification corrected the physical behavior of the tensile flange of the post, it may not have been correct. Accurately modeling rupture of steel is complex, and often requires a fracture mechanics approach, which is beyond the scope of this project. Fortunately for this project, no steel ever ruptured during testing and the modified failure criteria was deemed accurate enough.

Bogie Test KCBP-1—Lateral-Load Test

Comparisons between the physical test and simulation for KCBP-1 are shown in Figs. 10 and 11. Both test and simulation sustained noticeable permanent damage. Clearly, both resulted in a buckle in the upper deck mounting plate between the two sets of mounting bolts. The lower mounting plate was also damaged, in both cases being pried away from the underside of the deck. In addition, posts were kinked backward slightly at the location of the 228.6-mm-long attachment bolts, with a buckle appearing in the rear flange between the two web stiffening plates. Bolt hole damage on the FRP deck was noticeable but limited to local deformation.

Force–deflection results, shown in Fig. 11, exhibited an oscillation behavior during the initial portion of both the test and simulation.

These oscillations suggest that the first peak resulted from the inertial resistance generated when the post mass was initially accelerated. Inertia loads caused by impact are difficult to discern during physical testing, but in this case the simulation provides some insight. During this portion of the impact, which occurred during the first 10 ms of the event, there was very little deformation (or energy absorbed) in the system components. Instead, during this time, the post basically bounced off of the impact head and the system "tightened" up. It was during the second impact, which was sustained for the remainder of the event, that permanent deformations occurred. A detailed analysis and discussion on inertia loads during bogie testing was performed by Hascall (Hascall 2005).

Bogie Test KCBP-2—Combine Lateral- and Torsional-Load Test

Combined lateral and torsional loading was conducted in order to evaluate the dynamic performance of the FRP deck when subjected to a worst-case impact condition. In actual bridge applications, longitudinal rail elements are positioned across the bridge posts and/or blockouts. When a vehicle impacts a barrier system upstream of a post, the bridge rail often deforms and causes the bridge post to be loaded laterally about its strong axis of bending and twisted when eccentric axial and perpendicular rail loads are not directed through the post's center. These torsional loads, combined with the lateral post load, create a critical condition where the deck capacity may be compromised from that performance observed under a purely perpendicular loading condition.

For KCBP-2, it should be noted that four additional steel gusset plates were welded to the top of the post and to the blockout— two on the post and two on the blockout. These gusset plates were placed between the flanges on both sides of each web in order to prevent the flanges, near the load application, from warping or collapsing during the offset impact test. This approach was taken to help ensure that the maximum torsional and lateral loading would be transmitted to the base of the post, the post-to-deck connection hardware, and the FRP deck panel itself.

Similarly, gusset plates were added to the LS-DYNA model to simulate KCBP-2. The only other change made to the model was the repositioning of the bogie in order to impact the spreader bar in the same location as in the test.

Comparisons between the physical test and simulation for KCBP-2 are shown in Figs. 12 and 13. Damage was similar to that of KCBP-1.

The main difference was in the post rotation during KCBP-2 that occurred due to the offset impact condition.

After thoroughly reviewing test and simulation results for both bogie tests, it was concluded that: (1) the FRP deck panel resisted the peak impact force without failure; (2) inertia loading occurred during the initial portion of the event and did not load the system in a manner that caused permanent deformations; (3) the model developed as part of this project accurately simulated the physical test; and (4) the post-to-deck attachment system provided acceptable dynamic performance during lateral loading and combined lateral and torsional loading in what is believed to be the worst-case conditions.

Further Analysis

In both tests and in both simulations, the FRP deck underwent significant vertical vibrations, with a peak magnitude deflection of about 50 mm. The deck vibrations essentially damped out in all cases after about four oscillations. Since the deck was relatively large, it must have taken a significant amount of energy to cause the vibrations. A question arose as to what might happen if the deck was composed of an extensively stiffer material, such as reinforced concrete.

Now, because the LS-DYNA model was considered to be a good representation of the physical system, various alternatives to the bridge deck and/or the post attached hardware could be confidently investigated. One such case is a stiffened bridge deck.

The material of the bridge deck in the model was changed to have much stiffer properties, similar to that of reinforced concrete. Results of the simulation showed almost no bolt hole deformations and practically zero vertical vibrations in the deck. This stiffer deck caused the steel post and attachment hardware to absorb almost all of the energy of the impact; enough to cause the steel post and blockout flanges to yield in a torsional buckling mode and the overall post to yield in a global buckling mode (as shown in Fig. 14).

The observed failure mode, under most circumstances, would be the preferred method of failure in an extreme loading case on a bridge deck. In this way, the maximum amount of energy is absorbed by the components. If the attachment hardware had broken off or ruptured, resistance to loading would have been cut off. With buckling, loading resistance is maintained as the post twists and bends away. In a full barrier system, this extreme loading case would probably not occur due to the other posts along the barrier and the attachment rail(s);

those components would help take up the extra energy. However, if a design was required to handle such extreme loading, the design could easily include additional posts in the system.

Summary and Conclusions

Following a review of the test and simulations results for both bogie impacts, the following observations have been made. During the 90° centerline lateral-load test, KCBP-1, 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. During the 90° offset combined load test, KCBP-2, the post and post-to-deck attachment hardware were also found to plastically deform. Once again, the mounting hardware did not fracture away from the FRP deck panel. Since inelastic material deformations were observed in 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.

Based on the successful bogie testing on the two steel posts attached to the FRP deck panels and in lieu of full-scale vehicle crash testing, it is further believed that the bogie tests are a valid indicator of the post and post-to-deck attachment hardware's dynamic performance. As such, it is our opinion that the bogie test program has demonstrated that the FPL TL-4 steel thrie beam and steel tube bridge railing system can be adapted to this FRP deck panel system with the connection tested herein. Therefore, it is concluded that it is appropriate to seek FHWA approval for the bridge railing anchored to this FRP deck panel system according to the TL-4 criteria of NCHRP Rep. No. 350.

Further, it is believed that the simulation model developed in this project is an accurate representation of the deck-mounted, steel post barrier system and could be successfully used to help evaluate the crashworthiness of other bridge decks.

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Figures

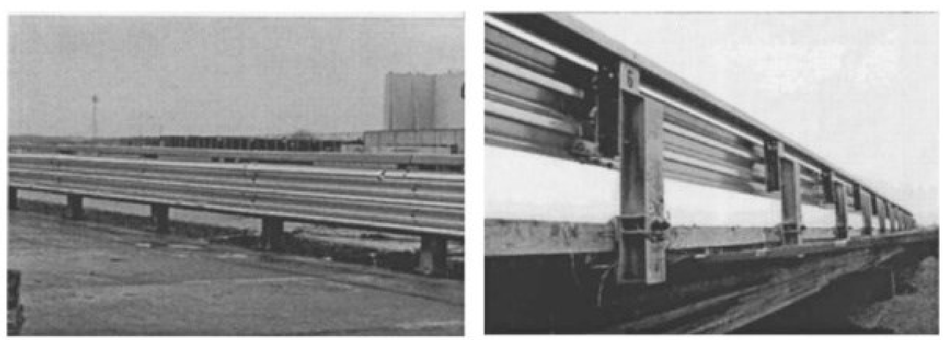
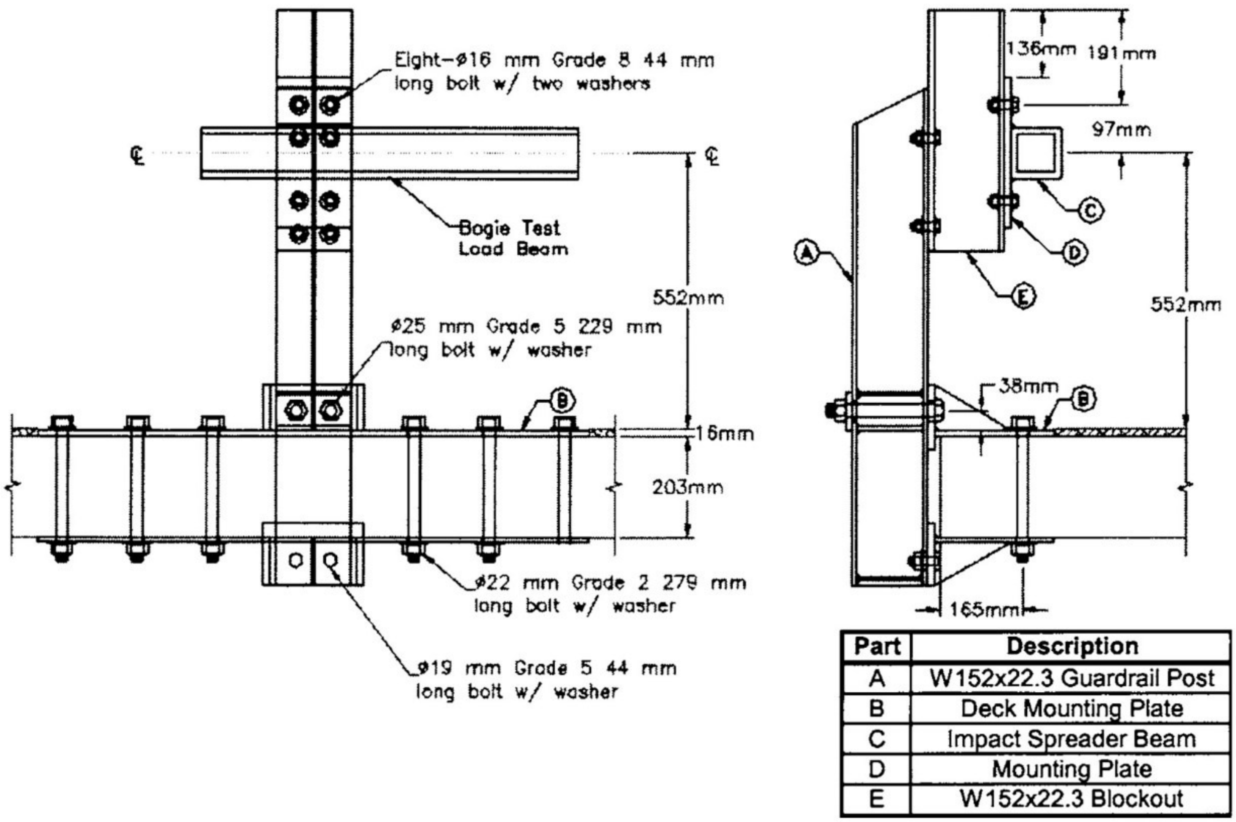


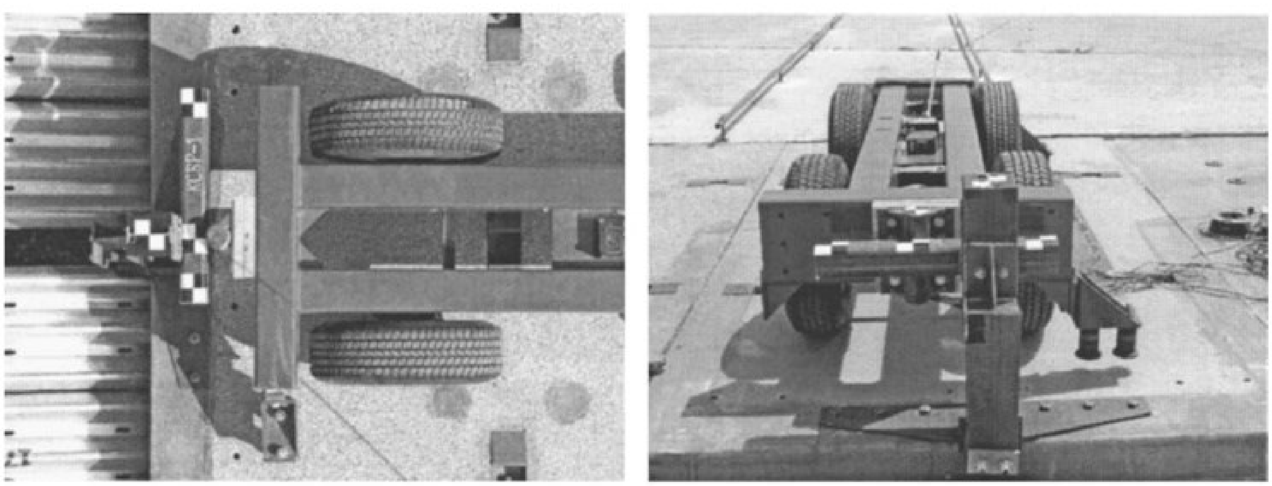
Fig. 1. FPL deck-mounted bridge railing system

Fig. 2. Crash testing of FPL system



Part	Description
A	W152x22.3 Guardrail Post
B	Deck Mounting Plate
C	Impact Spreader Beam
D	Mounting Plate
E	W152x22.3 Blockout

Fig. 3. Details of post and attachments



KCBP-1 KCBP-2

Fig. 4. Bogie testing initial conditions

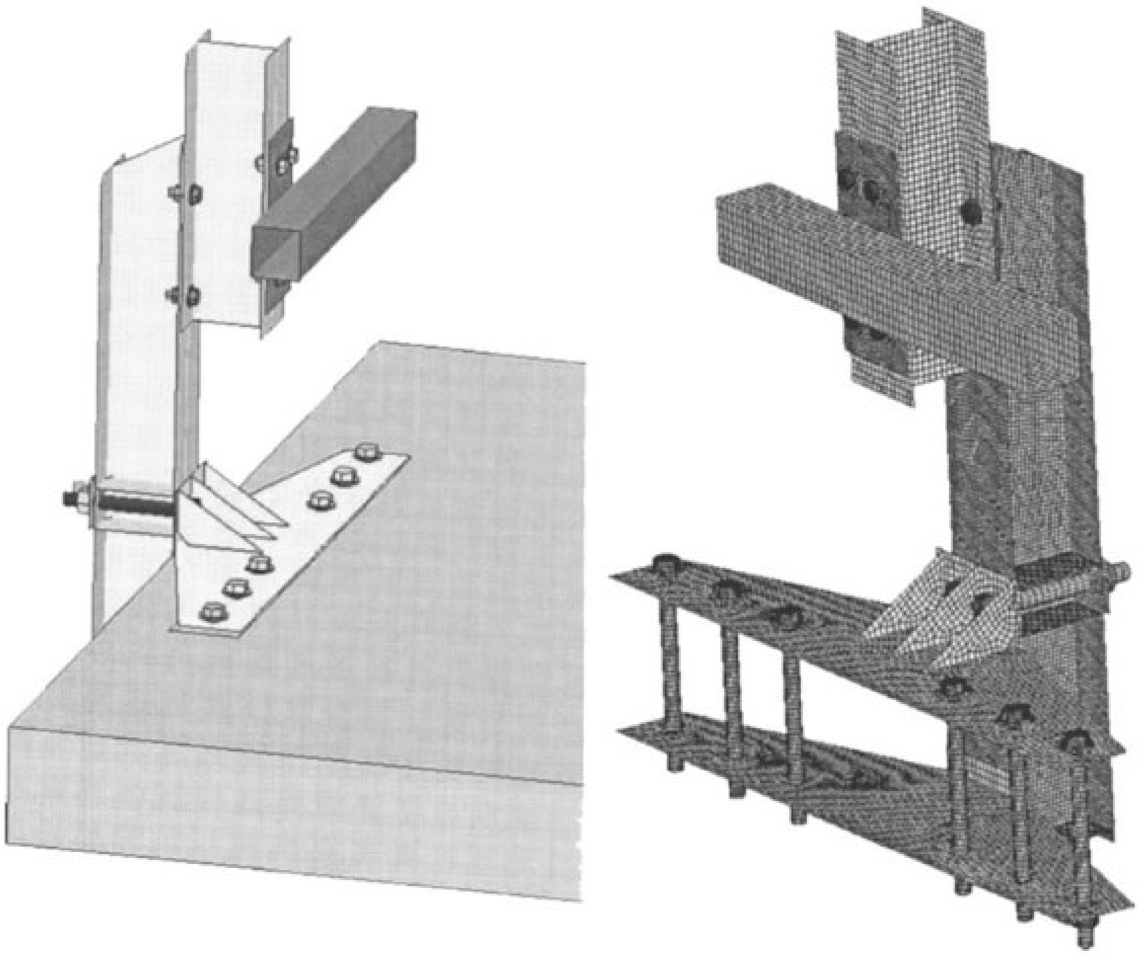


Fig. 5. Geometric model

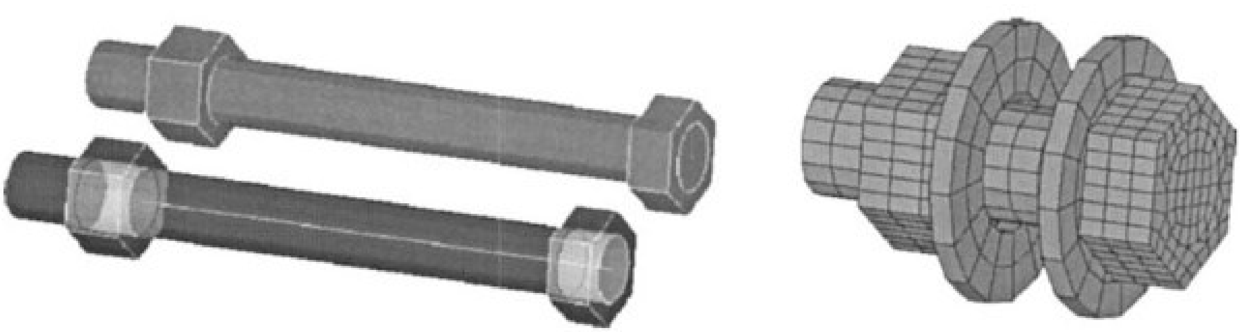


Fig. 6. Discrete based bolt, nut, and washer models

Density (kg/mm^3)	7.86E-06
Modulus of Elasticity (GPa)	208.7
Poisson's Ratio	0.28
Yield Stress (GPa)	0.322

Point No.	Strain	Stress (GPa)
1	0.000	0.322
2	0.021	0.328
3	0.024	0.361
4	0.041	0.428
5	0.062	0.478
6	0.101	0.528
7	0.138	0.555
8	0.270	0.638

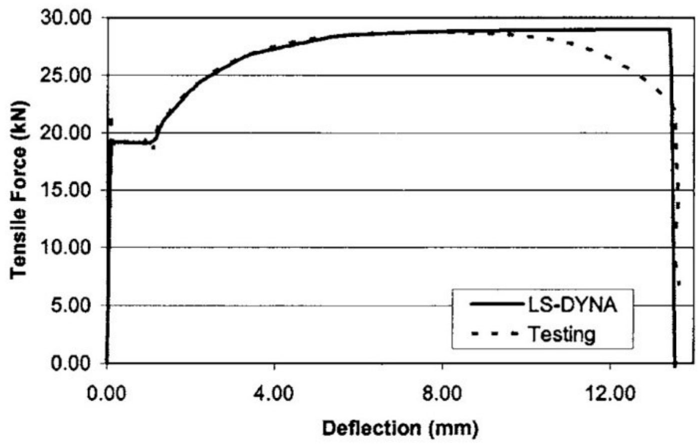


Fig. 7. A36 material properties and validation

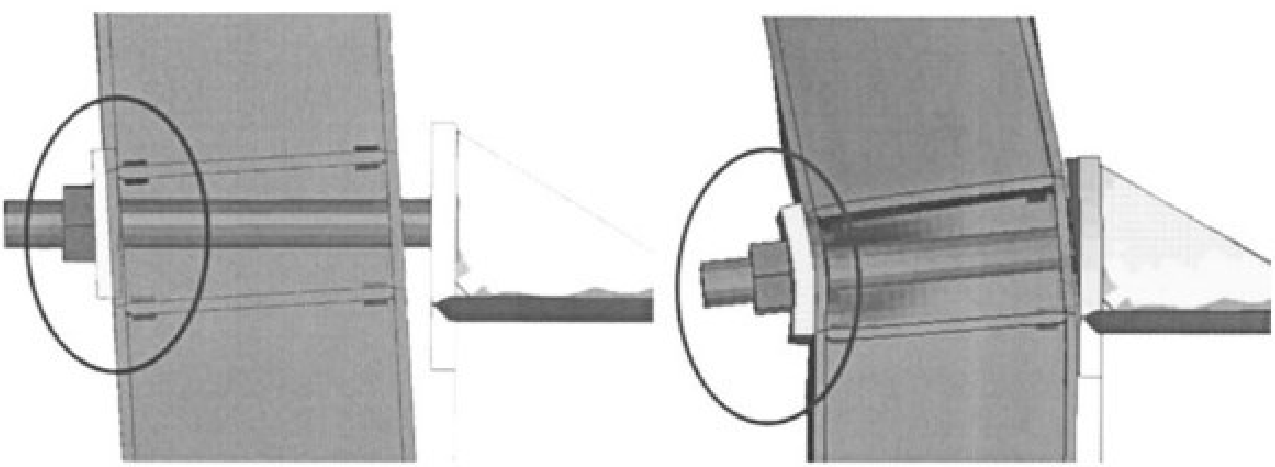


Fig. 8. Post washer surface penetration

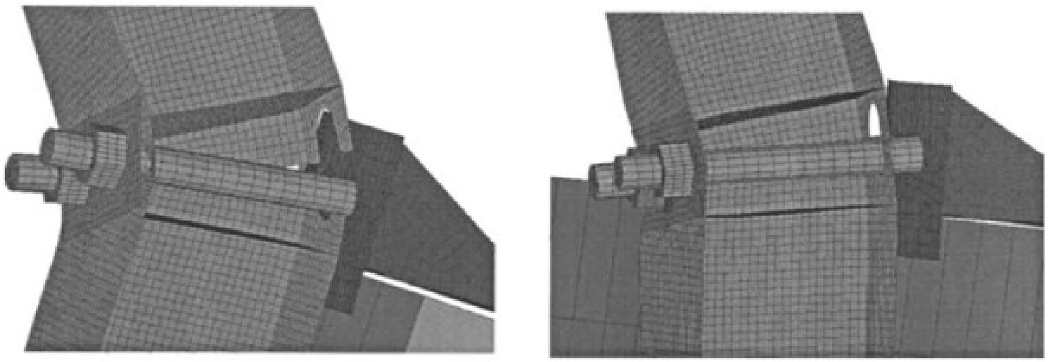


Fig. 9. Post impact with and without fracture

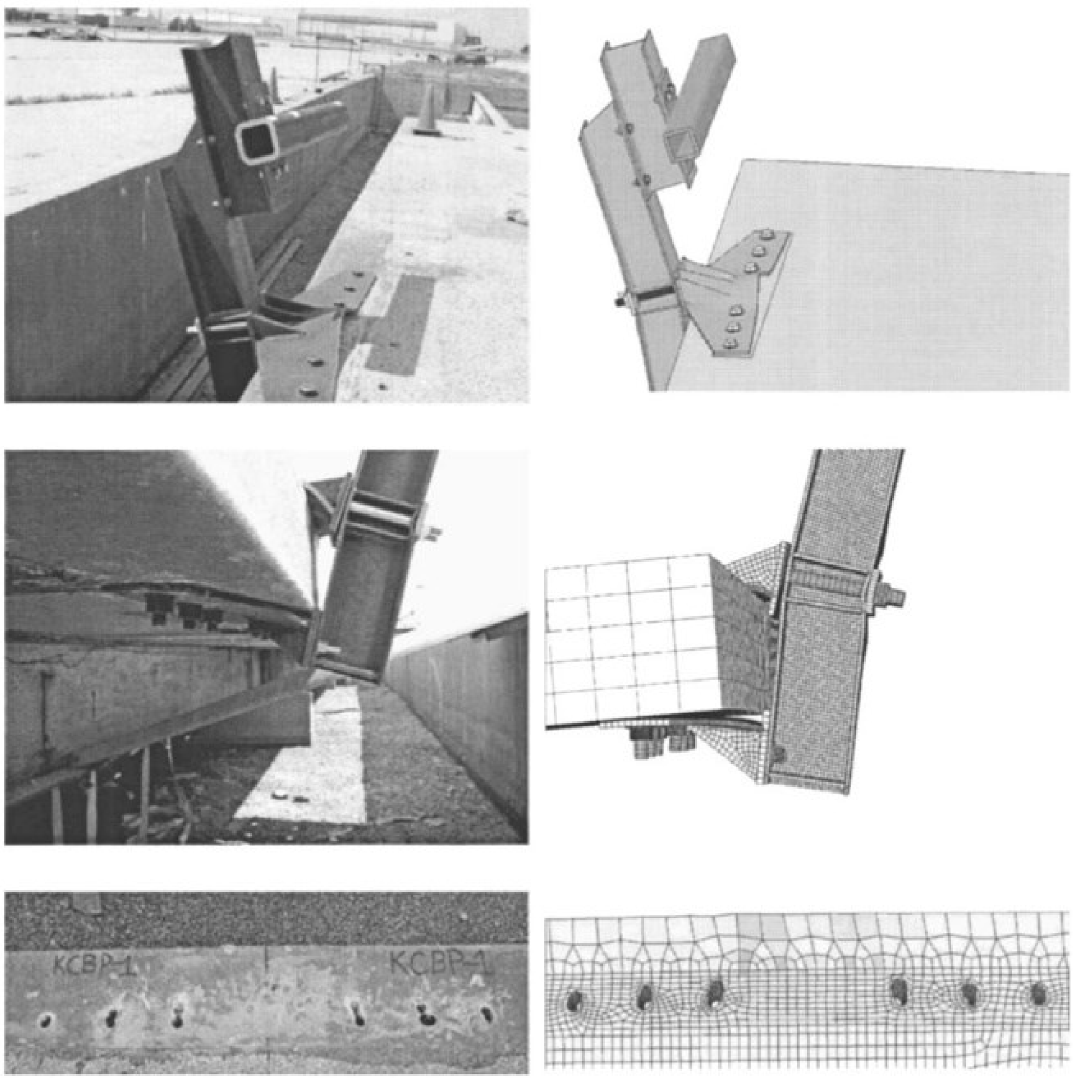


Fig. 10. KCBP-1 results

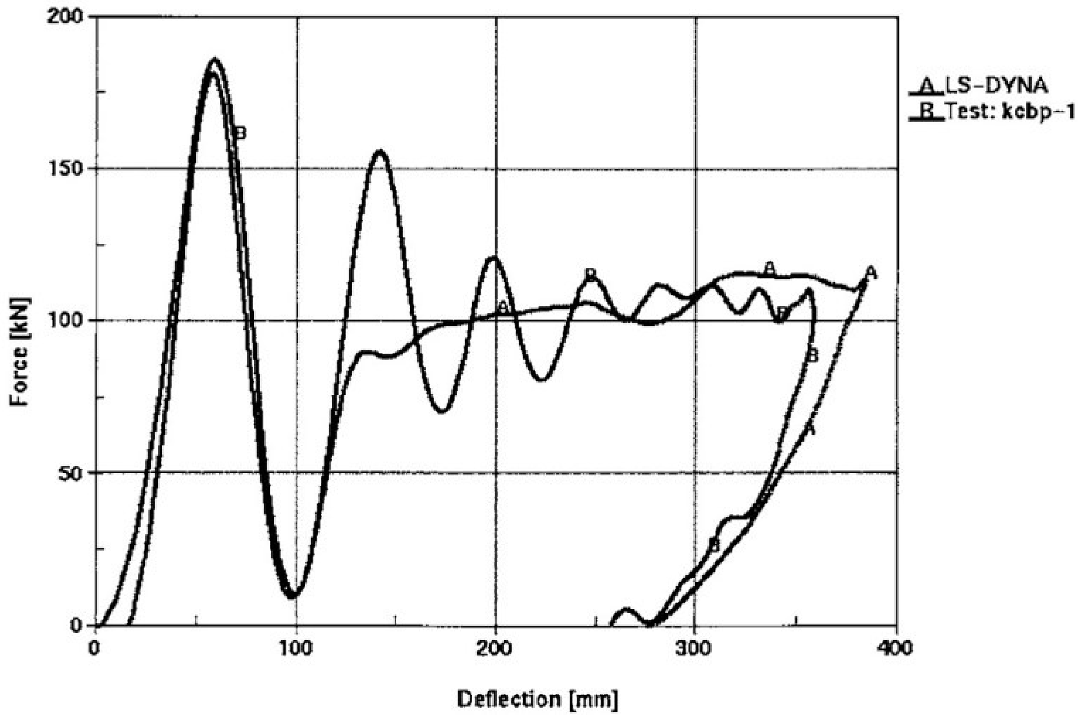


Fig. 11. Force–deflection of KCBP-1

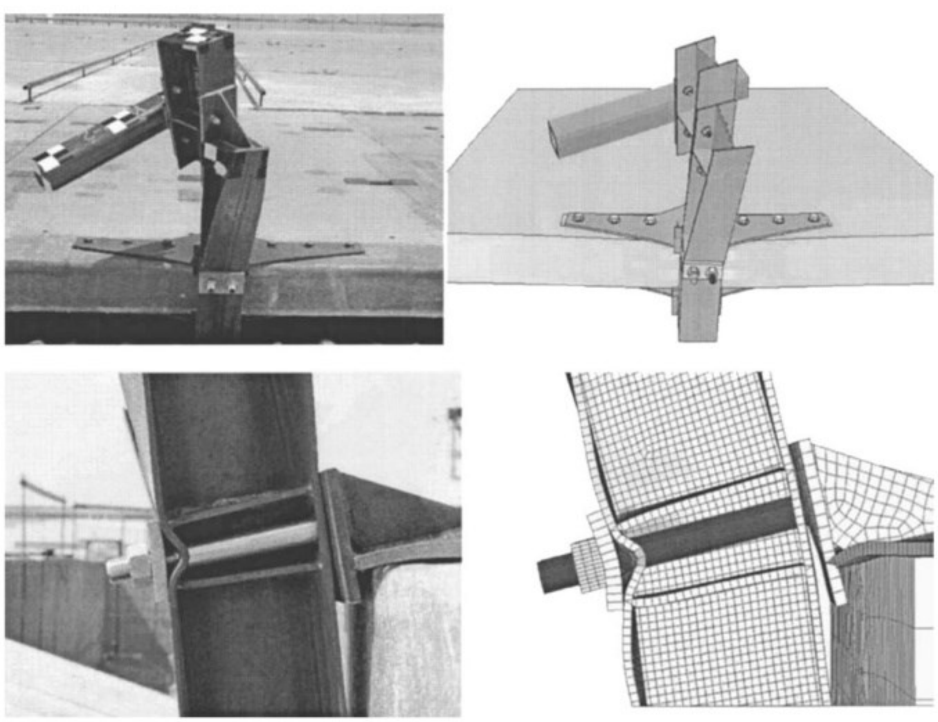


Fig. 12. KCBP-2 results

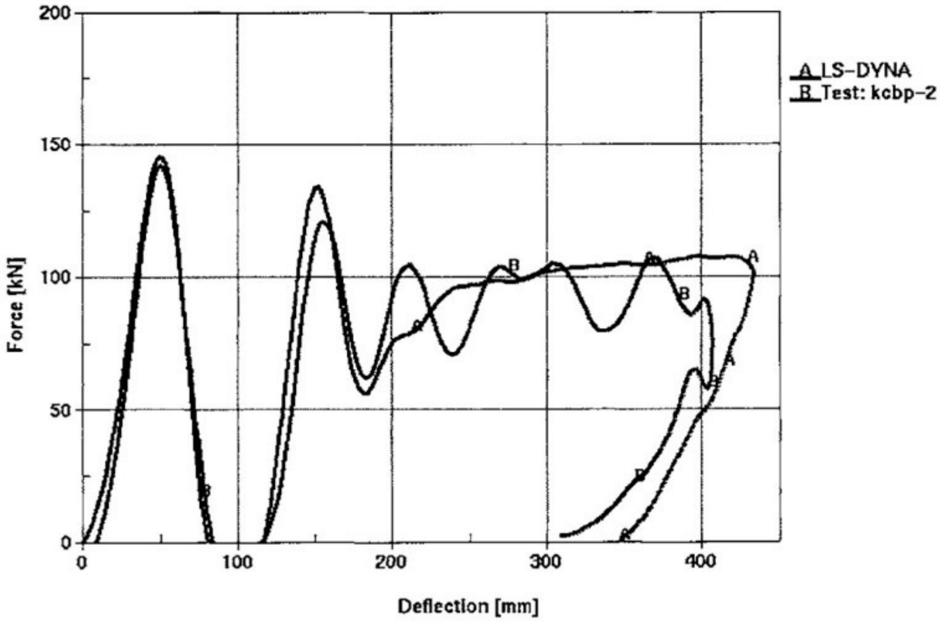


Fig. 13. Force–deflection of KCBP-2

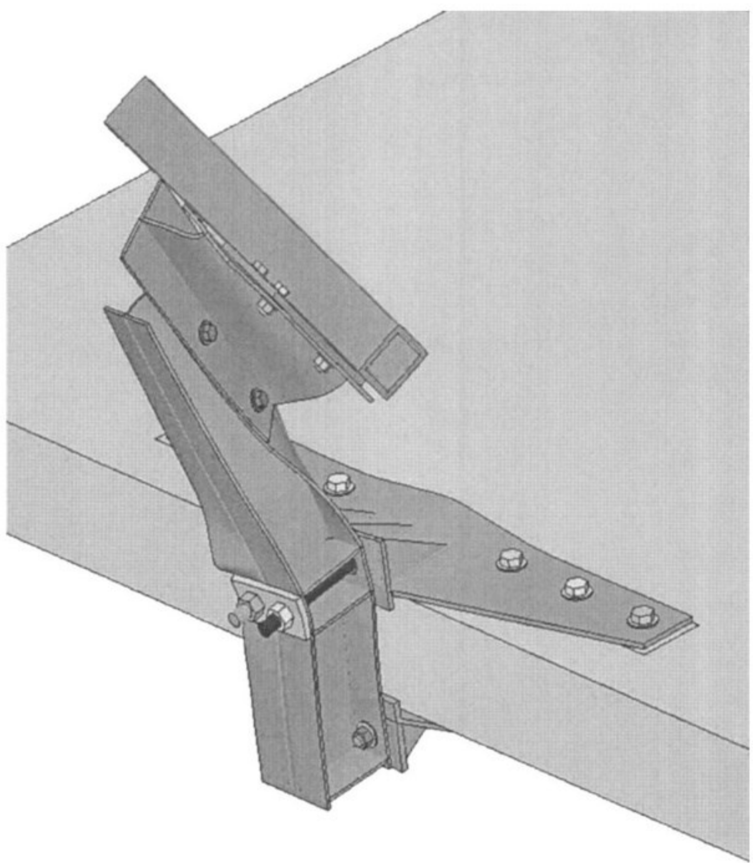


Fig. 14. Stiffened bridge deck simulation results