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**ABSTRACT**

Structural failure of post-and-beam w-beam guardrails during impact is sometimes due to the rupture of the w-beam rail where two sections are spliced together with bolts. This paper summarizes a study of the mechanics of failure of the splice connection. The causes of rupture are identified and a design alternative is formulated that will reduce the likelihood of rupture of the splice connection. The tensile forces in the w-beam rail and the mode of deformation of the splice connection during impact were critical factors considered in the study. The results of full-scale crash tests, laboratory tests and finite element analysis indicate that relocating splices to mid-span locations would greatly reduce the chance of observing a rupture of the guardrail in full-scale crash tests as well as real-world collisions.

**KEYWORD**

Roadside safety, guardrails, splices, splice rupture, Report 350, crash testing, simulation.

## INTRODUCTION

Splices in post-and-beam w-beam guardrails where two w-beam elements are connected are sometimes the point of structural failure during impact. W-beam guardrails are connected by overlapping the ends and clamping them together using eight 16-mm diameter bolts and nuts. The splice connections in most guardrail and guardrail terminal systems are located at the guardrail posts so the loading experienced by the splice is a combination of the axial guardrail tension, torsion in the guardrail section about its longitudinal axial as well as lateral bending due to displacements of the posts. The purpose of this paper is to explore the mechanics of the W-beam splice connection in typical collisions. The behavior of splices is examined using laboratory component tests, finite element analysis and full-scale crash tests. The cause of typical splice failures is determined and a simple design change to reduce the likelihood such failures is recommended. While splice failures occasionally occur on all types of w-beam guardrail systems, the weak-post w-beam guardrail system is the specific focus of this investigation. Weak-post systems generally experience larger rail deflections in an impact so the axial force in the guardrail and the bending stresses in the splice should be maximized for this type of system. While the weak-post w-beam guardrail is the focus, the results of this study can be applied to any w-beam guardrail system since the same type of behavior is believed to occur is all such similar splice connections.

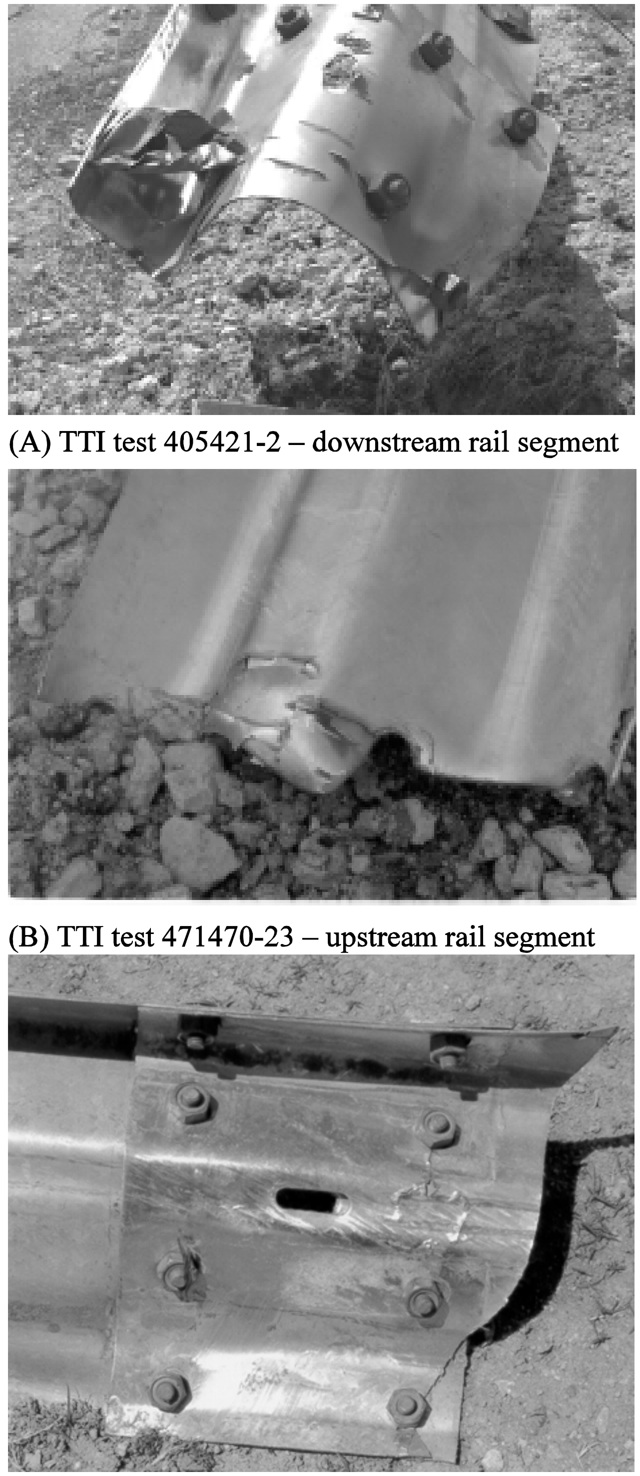
## LITERATURE REVIEW

Guardrail ruptures occurring at a splice have been observed for a wide variety of w-beam barrier types including strong-post w-beam guardrails, weak-post w-beam guardrails, w-beam guardrail terminals and w-beam transitions. *(1)(2)(3)(4)* The recent crash testing literature was searched to find examples of guardrail rupture and splice failure. Unfortunately, when a guardrail ruptures during a full-scale crash test it is often difficult to determine the cause. Such failures are usually not well documented in the test report since they were unexpected. The guardrail tension, for example, is rarely known since it is not a typical test procedure to measure the rail tension. While there are probably other examples of guardrail rupture, the cases discussed below are believed to be reasonably typical of splice failure in general.

Kilareksi *et al* reported the results of a full-scale crash test involving a 2000-kg pickup truck striking a weak-post w-beam guardrail at 100 km/hr and 25 degrees.*(1)* The guardrail ruptured at a splice location downstream of the vehicle prior to the vehicle being redirected. The maximum dynamic deflection just prior to the guardrail rupture was 1.5m.

Buth *et al* reported the results of a full-scale crash test involving a strong-post w-beam guardrail with larger than standard blockout.*(2)* A 2000-kg pickup truck struck the barrier at 100 km//hr and 25 degrees. The rupture occurred downstream of the vehicle which penetrated the guardrail system. A photograph of the rupture guardrail is shown in the top portion of Figure 1. Coupons cut from the guardrail were used to perform standard ASTM A370 tensile tests to determine if the material satisfied the requirements of AASHTO M-180.*(5)* The material exceeded all the requirements for M-180 guardrail material. Fortunately, strain gauges had been included on the up and downstream ends of the guardrail so the maximum tension prior to the rupture was known to be 130 kN.

Mak and Menges report the results of a full-scale test involving a 2000-kg passenger car striking a Mini-MELT (i.e., a MELT terminal modified for use



(A) TTI test 405421-2 – downstream rail segment

(B) TTI test 471470-23 – upstream rail segment

(C) TTI test 405421-2 – downstream rail segment

Figure 1. Typical splice failures from full-scale crash tests.*(2)(3)(4)*

with a weak-post w-beam guardrail) at 100 km/hr and 25 degrees.*(3)* During the impact the guardrail ruptured downstream of the vehicle allowing the vehicle to penetrate the system. The maximum dynamic deflection just before the rupture was 0.30 m. The ruptured guardrail is shown in the middle portion of Figure 1.

Lastly, Mak *et al* reported the results of a full-scale test of the MELT-2 guardrail terminal.*(4)* In a test involving an 820-kg small car striking the second post at 100 km/hr and 15 degree, the w-beam guardrail ruptured at a downstream splice. The dynamic deflection of the system near the rupture location was 0.53 m. The ruptured guardrail is shown in the lower portion of Figure 1.

These examples illustrate several interesting points. First, whenever material from a ruptured guardrail has been subjected to tensile tests, the tests have confirmed that the material satisfies the minimum requirements of AASHTO M-180. This indicates that guardrail rupture is not usually caused by defective or substandard material.

Second, in every case where it could be determined, the rupture occurred downstream of the vehicle. The rupture usually occurs in front of, rather than behind the vehicle as might be expected. Also, in the one case where the guardrail was instrumented with upstream strain gauges, the rail tension was no more the 130 kN, a relatively modest guardrail tension considering the yield strength of the w-beam section is 356 kN. Similarly, the dynamic deflections when noted were usually modest and failures have been observed with both large and small vehicles. The moderate rail tension, small lateral deflections and location of the failures suggest that the ruptures are not caused by exceeding the tensile capacity of the rail.

Third, as shown by the photographs in Figure 1, the tear always passes through at least one splice hole and usually the bottom, downstream hole is located on the tear-line. Often, as shown in the top and bottom portions of Figure 1, the tear line starts at the bottom downstream hole and progresses at an angle away from the downstream row of splice holes.

The examples found in the literature suggest that splice failures cannot be adequately explained by material deficiencies or axial rail capacity. The cause of these failures appear to be much more complex and a better understanding of the splice performance is necessary.

**UNIAXIAL SPLICE PERFORMANCE**

Axial tension is one possible mechanism for failure of the guardrail splice. A recent series of full-scale crash tests of the weak-post w-beam guardrail is summarized in Table 1.*(6)(7)(8)(9)* The largest rail tension was 326 kN under test 3-11 conditions (i.e., a 2000-kg pickup truck striking the barrier at 100 km/hr and 25 degrees). Since a weak-post guardrail experiences large lateral deflections, this value should represent a reasonable upper bound for the tension experienced by guardrail in the standard test 3-11 conditions.

Table 1. Maximum rail tension and dynamic deflection in tests with the weak-post w-beam guardrail.

| Test | NCHRP Test Condition | Maximum Tension (kN) | Maximum Deflection (m) | Ref. |
|---|---|---|---|---|
| 473750-1 | 3-11 | 275 | 1.60 | *(6)* |
| 473750-2 | 3-11 | 326 | 1.86 | *(7)* |
| 473750-3 | 3-11 | 231 | 2.12 | *(8)* |
| 473750-4 | 3-10 | 112 | 1.03 | *(9)* |

A series of laboratory experiments were performed to determine the axial capacity of guardrail splices and the typical failure mechanisms. Uniaxial tension tests of full-scale splice sections were performed using the 1,780 kN load tester shown in Figure 2 in WPI's Structural Mechanics Impact Laboratory. Special grips, shown in the bottom left portion of Figure 2, were fabricated and attached to 610-mm long sections of guardrail. Two sections of guardrail were spliced together using the standard splice holes, bolts and nuts. The splice was pulled axially by the load tester until the splice could no longer support load.

The results of the three axial tests are shown in Table 2. The maximum axial force was always at least 400 kN and the splice displacement was always less than 25 mm. The failure mechanism in all three cases, shown in the right portion of Figure 2, was that the bolts rotated and the head of the bolt pulled through the splice slot. While the guardrail material did tear in the longitudinal direction, there was no evidence of a tear in the lateral direction.

Table 2. Quasi-static uniaxial tension test results for a guardrail splice.

| Test | Maximum Axial Force (kN) | Maximum Displacement (mm) | Failure Mechanism |
|---|---|---|---|
| 9912201 | 438 | ¶ | Bolt heads pulled through holes |
| 0001171 | 408 | 22.9 | Bolt heads pulled through holes |
| 0003221 | 409 | 24.1 | Bolt heads pulled through holes |

¶ Test interrupted due to grip fixture failure. Fixture was repaired and strengthened and the test resumed. Subsequent tests were performed using the stronger grips.

(A) Uniaxial test setup

(C) Typical uniaxial splice failure

(B) Test grip

(D) Typical splice failure – closeup

Figure 2. Uniaxial tension test setup and typical splice failure mode.

The failure mechanisms shown for the laboratory tests in Figure 2 are of a very different nature than those observed in full-scale crash tests illustrated in Figure 1. To the authors's knowledge, a failure mechanism like that observed in the laboratory tests has never been observed in a full-scale crash test. The axial load required to produce failure in the uniaxial laboratory test was always above 400 kN yet the maximum axial load in weak-post w-beam guardrail collisions was always less than 326 kN. These laboratory tests indicate that guardrail ruptures are not caused by exceeding the axial capacity of the guardrail cross-section. In fact, the guardrail only uses 80 percent of its tensile capacity in a typical weak-post w-beam guardrail test with a 2000-kg pickup truck. The cause of splice failures is, therefore, unlikely to be related to the axial capacity of the guardrail.

## MULTI-AXIAL SPLICE PERFORMANCE

### Finite Element Model of the Splice

The loads and deformations in the splice caused during full-scale impacts are very complex and it was not possible to conduct laboratory tests that would replicate such behavior. In order to investigate the performance of the splice connection under loading conditions similar to those in a crash event, the finite element software LS-DYNA was used to analyze a submodel of the weak-post w-beam guardrail consisting of a single guardrail post and two w-beam rails spliced together with eight bolts and nuts, as shown in Figure 3.

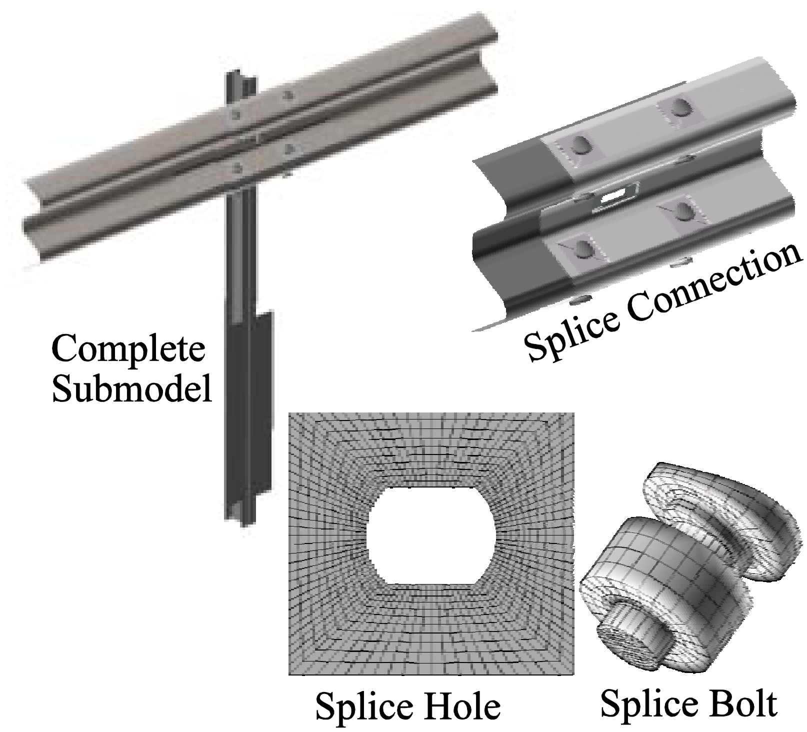



Figure 3. Components of the finite element model of a weak-post w-beam guardrail splice.

The preprocessor Truegrid (version 1.4.0) was used to generate the various constituents of the finite element model of the splice connection and guardrail post, including the geometry and mesh of all the parts, as well as the springs, dampers, load curves and material definitions of the model.*(10)* The geometry of the w-beam was created in Truegrid using the dimensions specified in the AASHTO-AGC-ARTBA Highway Barrier Hardware Guide.*(11)* The mesh of the w-beam consisted of 50 elements through the cross-section, which made it easy to accurately model the shape of the w-beam. To facilitate the modeling process, the region around the bolt holes in the w-beam rail were modeled separately. This made it possible to generate a more refined mesh around the edge of the holes without adversely affecting the density of the mesh throughout the rest of the w-beam model and unnecessarily increasing the required run time. It was necessary to use a "fine" mesh around the splice holes in order to obtain accurate stress and strain measurements (i.e., magnitudes and distributions) in these critical regions of the model.

A mesh sensitivity study was conducted to determine the optimum mesh density for modeling the bolt holes in the splice. LS-DYNA is a nonlinear, explicit finite element program, thus the time-step used in the analysis is affected by the size of the element (i.e., smaller element requires a smaller time-step), thus a mesh too fine would be very computationally demanding and would make the model impractical to use. The mesh of the bolt holes that was used in the study is shown in Figure 3. The bolts and nuts in the splice connection were modeled as rigid materials since the deformations of these components are very small compared to the deformations of the bolt holes in the w-beam on which the bolts bear during loading. Although material properties of the bolts and nuts were modeled crudely, the geometry of these components were very important to the model since they affect how the load is transferred through the splice connection. The geometry of the bolts were modeled precisely according to the dimensions specified in the AASHTO-AGC-ARTBA Highway Barrier Hardware Guide.*(11)* Figure 3 shows the model of the bolt and nut assembly. The nut was clamped onto the bolt using spring and dashpot elements, thereby clamping the two w-beam sections together.

All the deformable components of the guardrail model are steel and were modeled using a piecewise linear stress-strain curve with isotropic plasticity (material type 24 in LS-DYNA). The material properties of the w-beam and guardrail post used in the simulation were obtained from a study performed by Wright and Ray.*(12)* The material properties for the components correspond to AASHTO M-180 and AASHTO M-183 steel, respectively.*(5)* Strain-rate effects were not included in the analysis and no failure conditions were specified for the elements in the model. The failure mechanism in LS-DYNA material model 24 uses the effective plastic strain as failure condition. When the effective plastic strain reaches a certain value the deviatoric stresses in the element are set to zero, effectively removing the element from the model. This failure mechanism is mesh sensitive, therefore, a specific value of the maximum effective plastic strain has to be set for each mesh.

The 4-node Belytschko-Tsay element in LS-DYNA, which is a very simple, computationally cost-effective element, was used to model the guardrail post and much of the w-beam. The 4-node Hughes-Liu element was used to model the region around the bolt holes due to the large deformations that occur in these regions. Five integration points were used through the thickness of all the thin shell elements to obtain a more accurate stress distribution through the thickness of the elements. The model consisted of 44,000 shell elements making up the w-beam and post and 18,000 solid elements making up the bolts and nuts. The time-step required for analysis was 0.8 microseconds as was controlled by elements near the edge of the bolt holes.

In a related study, a finite element model of the G2 guardrail was developed and used to simulate a full-scale crash test that was conducted by the Texas Transportation Institute.*(13)* The splice connections in the full-scale simulation were not modeled in detail due to exorbitant computational requirements of such an analysis, rather, they were modeled using nonlinear springs that simply clamp the w-beam sections together and provide limited slip of the connections. The w-beam was attached to the post using the nodal rigid body spot weld option in LS-DYNA with a failure condition set to fail at a tensile load of 21 kN corresponding to the average failure load of the 7.94 mm diameter A307 bolt connection used in a standard G2 post-rail connection.*(13)(14)* That model produced results that closely matched those from the full-scale test until the point where the guardrail ruptured in the test.

Since the displacements and loads of the w-beam in the full-scale simulation were similar to those of the full-scale test, the displacement-time history of the w-beam cross-section at specific locations up-stream and down-stream of the splice connection that failed was used as boundary conditions in the submodel. The displacement-time histories were applied directly to the ends of the w-beam in the submodel analysis in order to simulate realistic loading conditions and, thereby, obtain realistic behavior in the splice connection. The full-scale simulation from which the loads were collected and the methodology of how these loads were applied to this sub-model, as well as the material properties and post-ground interaction are discussed in detail elsewhere.*(13)*

**Results of the Submodel Analysis**

The rail displaced longitudinally upstream relative to the study section due to large lateral deflections in the impact event. The post was twisted as it bent back allowing the sharp edge of the twisted post to come in contact with the back layer of W-beam, as shown in figure 4. When the post-rail connection failed the w-beam started to slide up against the edge of the post flange and eventually pulled over the top of the post. As the rail is being bent around the post, stress concentrations develop on the back layer of w-beam around the column of bolts on the down-stream side of the splice connection (figure 4). The stresses in the front layer of W-beam, however, were much lower than those in the back layer and showed little indication of a potential for rupture, as shown in figure 5. The high stresses in the back layer were relieved by flattening out the W-beam at the stress concentration. A plastic hinge was developed at the cross-section through the four right splice bolts and the W-beam was somewhat folded around the post at this location.

The plastic hinge is clearly visible in figure 4 which shows the effective plastic strain in the back layer of the guardrail. The sharp edge of the post flange is pressed against the back layer of w-beam at the lower edge of the rail where the effective plastic strain is considerably high. It is probable that a tear would be initiated at this point in a crash event. A plastic hinge always follows a path through the highest stresses and strains as it propagates through material. Based on that fact, the most probable path for a tear to propagate through the cross-section of the back layer of W-beam was predicted from the finite element analysis and is sketched in figure 4. The tear is most likely to follow a path close to, or through, the four splice holes on the down-stream side of the splice connection in the back layer of w-beam.

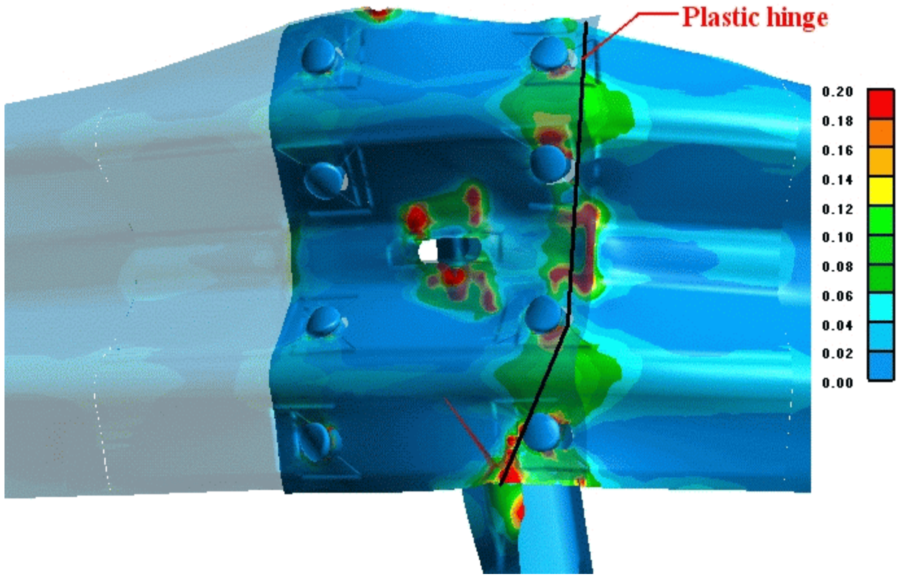



Figure 4. Effective plastic strains in the back layer of w-beam in a guardrail splice showing the formation of a plastic hinge (front layer of w-beam is transparent).

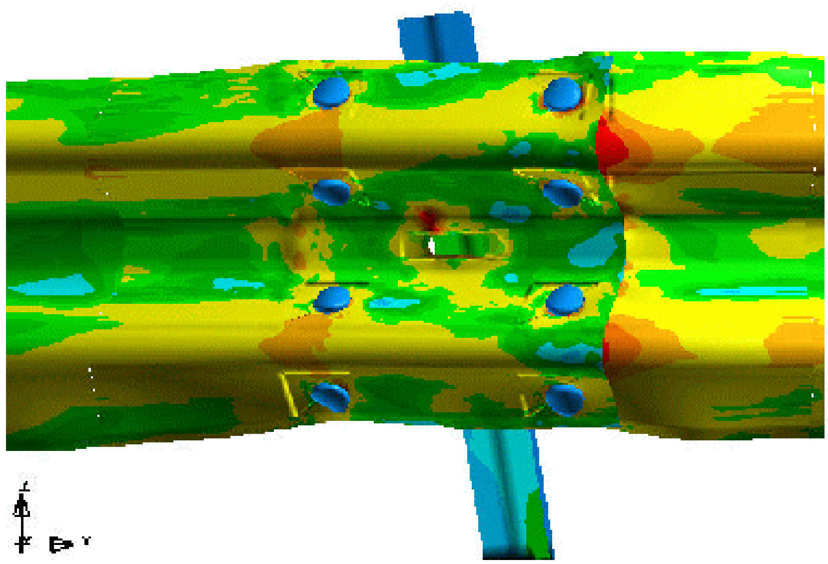


Figure 5. Von Mises stress contour plot

A simple yet very effective means of minimizing the chance of a guardrail rupture is to relocate the splice to the mid-span of the guardrail. In a related study finite element analysis was used to verify that relocating the splice to mid-span between the posts would result in much less complicated stresses and strains in the splice connection and would greatly reduced the likelihood of splice rupture.*(13)(14)* This design alternative was implemented in a modified G2 guardrail system for the Pennsylvania Department of Transportation. Full-scale crash tests were conducted on the system under NCHRP Report 350 test level 3 conditions. The splice connection performed well and the system passed all safety and structural adequacy requirements of Report 350.*(8)(9)*

## CONCLUSIONS

W-beam guardrail splice failures are usually caused by the complex multi-axial state of strain experienced by the splice when it is located near a guardrail post. The splice experiences axial tension resulting from the interaction with the vehicle as well as torsion and bending strains caused by the post. When subjected to these multidirectional loads, stress concentrations develop around the bolt holes in the back layer of w-beam in the splice connection and this often results in a small fracture or tear in those locations. Once a tear is initiated, the tension in the rail may cause the tear to propagate through the whole w-beam section causing the guardrail to rupture completely.

A simple yet very effective means of minimizing the chance of a guardrail rupture is to relocate the splice to the mid-span of the guardrail. When the splice is located at the mid-span, it will experience much less complicated stresses and strains and will be unlikely to rupture.

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