Criteria for Restoration of Longitudinal Barriers, Phase II

Task 4C-1 – Simulate Tests C08C3-027 to Reevaluate Cause of Test Failure

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April 2013
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INTRODUCTION

This report presents the results of a study for developing inspection guidelines for highway maintenance engineers and maintenance supervisors to assess the level of damage and effectiveness of damaged guardrail installations based on quantitative assessment criteria. The guidance developed in this study will build upon and add to the guidelines presented in Report 656. The purpose of this task is to resolve any discrepancies or confirm the differences in results between the results obtained in Task 4A-4 and those in Report 656.

In Task 4A-4 finite element analysis was used to evaluate the impact performance of the G4(2W) guardrail system with various levels of pre-existing crash-induced rail deflection. The initial crash-induced damage for the guardrail model was created by simulating low-speed impacts into the guardrail with the 4,568-lb pickup truck model. The results from these low-speed impacts, which included guardrail component deformations and residual stresses, were then used as initial conditions for secondary high-speed impact simulations (i.e., Report 350 Test 3-11) into the damaged guardrail system. Two rail-to-post connection strength cases were investigated. In one case a w-beam splice was located at the critical connection point, in which the post-bolt head has to pull through two layers of w-beam in order to release; and in the second case the critical connection point was at a non-splice location, in which the post-bolt has to pull through only a single layer of w-beam in order to release.

The results of the subsequent high-speed impact analyses indicated that as the severity of the pre-existing crash-induced rail deflections increased:

- The maximum lateral deflections of the rail increased,
- The tensile load in the rail increased,
- The deflection of the upstream anchor increased,
- The post-bolt connection at w-beam splice locations allowed greater post deflections before releasing,
- The post-bolt connection at non-splice locations released consistently regardless of pre-damage deflections,
- Potential for splice rupture increased,
- Occupant ridedown accelerations in the longitudinal direction increased (primarily due to increased wheel snag on posts), and
- All other occupant risk measures were less affected.

The results of those analyses also indicated that the potential for override was relatively low for all cases investigated. This was contradictory to the full-scale crash test results from Gabler’s study in Phase I, where a post-bolt did not release properly and allowed the rail to be pulled down with the post, resulting in the vehicle overriding the guardrail. In that test the guardrail system was the G4(1S) (i.e., steel post w-beam guardrail) and the pre-existing crash-induced rail deflection was 14.5 inches. One possible explanation is that the G4(2W) and the G4(1S) respond differently to this particular damage mode. These two systems differ only by the type of guardrail post; i.e., the G4(2W) uses rectangular or round wood posts while the G4(1S)
uses W6x9 structural steel section posts - all other aspects of these two systems are identical. Further, bogie impact tests have shown that the lateral force-deflection response for these two posts is essentially equivalent. [Hascall07] However, the results of full-scale crash tests have shown that the steel-post system results in lower impact forces. For example, tests on the modified G4(1S) with wood blockouts resulted in longitudinal ORA values of 7.9 G and 7.6 G [Bullard96; Bligh97]; while tests on the G4(2W) resulted in longitudinal ORA values of 10.2 G, 10.9 G and 11.6 G [Bullard09; Bligh95; Mak99a].

In order to understand the differences in the performance of these two seemingly identical systems, it is first important to understand the differences in the response of the two different types of posts under loading conditions typical of real-world collisions. In particular, guardrail posts generally experience both lateral and torsional loads during vehicle collisions – whereas bogie impact tests induce only lateral loads onto the post. The lateral load from vehicle collision arises directly from the lateral deflection of the w-beam rail against the posts. The torsional loads on the posts result from the tensile load in the w-beam rail acting at the front of the blockouts; the blockouts are offset 8 inches from the front face of the posts, thus creating a torsional moment about the vertical axis of the posts. The wood posts tend to resist this torsion, while the W6x9 steel posts do not. The torsion of the steel posts not only reduces the blockout distance between the rail and the post, but also significantly reduces its resistance to lateral deflection.

Figure 1 shows the results of full-scale test C08C3-027.2 on the G4(1S) guardrail system conducted by the MGA Research Corporation in Phase 1 of this study, illustrating the torsional deformation of the posts.[Fleck08b] The photo on the right in Figure 1 further illustrates the apparent reduction in lateral stiffness of the “twisted” post, where the post buckled at the groundline rather than displacing the soil. It is theorized that the combined effects of (1) reduced blockout distance, (2) the post buckling at the groundline, and (3) loss of rail tension as the anchor failed resulted in the rail being pulled down with the post rather than releasing from the post as it was intended. In contrast, Figure 2 shows the results of full-scale test 471470-26 on the G4(2W) guardrail conducted by TTI. In this case the posts do not show any apparent torsional deflections and tend to deflect only in the lateral direction. When wood posts fail under the longitudinal-torsional load, it is usually a brittle failure in which the posts split or fracture, as illustrated in Figure 3.
Figure 1. Results of TEST MGA C08C3-027.2 illustrating torsional deformation of the W6x8 steel guardrail posts during vehicle collision.[Fleck08b]

Figure 2. Results of Test 471470-26 illustrating the response of the wooden guardrail posts during vehicle collision.[Mak99]

Figure 3. Results of Test 404201-1 illustrating brittle fracture of wood posts due to tensile forces in the w-beam rail.[Bullard00]
OBJECTIVES

The objective of this study was to determine if the cause of the vehicle overriding the barrier in test C08C3-027.2 was the combination mode of rail deflection and weak anchor. It was theorized by the research team that the undetached post-rail connection in Test C08C3-027.2 was a symptom of low rail tension resulting from the excessive movement of the anchor during the test. The anchor system used in test C08C3-027 (Figure 4(c)) included only a single foundation tube, and was therefore not as strong as the standard anchor system used in the earlier tests of the G4(1S) (Figure 4(a) and Figure 4(b)), which included two foundation tubes connected via a groundline strut.

Figure 4. Anchor used in evaluation of the modified G4(1S) with wood blockouts in test (a) 405421-1 [Bullard96], (b) 2214-WB2 [Polivka06b] and (c) C08C3-027 [Fleck08a;08b].

RESEARCH APPROACH

A model of the G4(1S) guardrail was developed and finite element analysis was used to simulate full-scale crash test C08C3-027-1 to create low-level crash-induced damage of the system. The results from this low-speed impact case, including guardrail component deformations and residual stresses, were then used as initial conditions in a secondary high-speed impact simulation of full-scale crash test C08C3-027-2. For these analyses, the upstream and downstream end-terminals for the system were modeled using non-linear springs attached to the ends of the rail. To represent the response of the single-foundation tube anchor system used in the full-scale tests, the force-deflection properties of the end-terminal springs were scaled to 47 percent of the baseline anchor stiffness defined in Task 4A-2.

The results of the analysis were compared to those of the full-scale crash test to determine if the model reasonably reproduced the results of the full-scale test. If so, then it may be reasoned that likely cause for the override was the collective effects of the low-stiffness anchor system combined with the initial crash-induced rail deflections – rather than the rail deflections alone. It would also further validate the accuracy of the model.
SIMULATION OF TEST C08C3-027-1

Test C08C3-027-1 Summary

The test article consisted of 12.5 feet long 12-gauge w-beam rail; the rail was supported with W6x9 structural steel posts that were 72 inches long, embedded 44 inches in the soil and spaced at 75 inches on centers; the rail was blocked out from the post using 6x8x12 inch routed wood blockouts; the blockout and rail were attached to the post using 5/8-inch diameter carriage bolts. The top height of the guardrail was 27.8 inches. The overall length of the test installation for test C08C3-027-1 was 162.4 feet including two single-foundation tube anchors – one at each end of the system.

Full-scale test C08C3-027-1 involved a 1997 Chevrolet 2500 pickup impacting the G4(1S) guardrail at 30.0 mph and at an impact angle of 26 degrees; the impact point was at 45.8 inches upstream of the splice connection at Post 11. The gross static mass of the test vehicle was 4,632 lb. The damage to the test installation is shown in Figure 5 and Figure 6. The maximum deflection of the rail was 14.5 inches and occurred at the midspan between Post 11 and Post 12.

Figure 5. Damage to guardrail in low-speed impact test C08C3-027-1.[Fleck08a]
Figure 6. Damage to guardrail in low-speed test C08C3-027-1 (overhead view). [Fleck08a]
Model Development

The finite element model of the G4(1S) guardrail is shown in Figure 7. The guardrail model consisted of eleven 13.5 feet lengths of 12-gauge w-beam rail, twenty-two W6x9 structural steel posts, and twenty-two 6x8x13 inch routed wood blockouts. The posts were spaced at 75 inches on center and the w-beam rail was positioned such that the top of rail was 27-5/8 inches above ground. The posts were embedded 44 inches in the ground. The model included 138.6 feet of the guardrail including Post 3 through Post 24. The boundary conditions at the ends of the rail were modeled using nonlinear springs with properties corresponding to 47 percent of the baseline anchor stiffness; this was based on the assumption that the single-foundation tube anchor would have approximately half the stiffness of the baseline two-foundation tube anchor system. The overall effective length of the model (including the simulated end-terminals) was 162.4 feet.

The rail element, the blockouts and the connection hardware were adopted from the G4(2W) guardrail model (refer to Task 4A-1 for more model details). The blockout was modified by including the “routed” section that fits over the flange of the W6x9 steel posts. The finite element model of the W6x9 posts were modeled with the fully-integrated Type 16 shell elements in LS-DYNA with warping stiffness. The nominal element size was 0.4 x 0.5 inches for the post flange and 0.6 x 0.5 inches for the post web. The material properties for the post were characterized based on the properties determined in an earlier study by Wright and Ray.[Wright96] This material model has been used in numerous analyses and has been validated in simulations of full-scale crash tests. For consistency with the G4(2W) model, the soil response was modeled using the non-linear spring concept with the springs attached directly to the post. The properties of the spring elements were defined according to [Plaxico98] using a soil density of 134 pcf and no moisture content (refer to Task 4A-1 for more information).
Figure 7. Finite element model of G4(1S) for simulation of Test C08C3-027-1.
FEA Simulation

Finite element analysis was then used to simulate the impact conditions of Test C08C3-027-1. At the beginning of the analysis the post-bolts that fasten the w-beam and blockouts to the post was tightened to approximately 2000 lb by imposing an initial strain-time history to the bolt elements via the LOAD_THERMAL card in LS-DYNA. The vehicle model used in the analysis was the NCAC C2500D version 5B with modifications described in Task Report 4A-1. The total mass of the vehicle model was 4,568 lb. The vehicle model struck the guardrail at 45.8 inches upstream of the splice connection at Post 11 at an impact speed and angle of 30.0 mph and 26 degrees, respectively.

The analysis was conducted with a time-step of 1.26 microseconds for a time period of 0.6 seconds. Figure 8 shows sequential snapshots of the impact event from an overhead viewpoint comparing the results from the FEA with the full-scale test. The yaw angle of the model was greater than that of the test, due primarily to the difference in the response of the wheel assemblies during impact, as illustrated in Figure 9. In the full-scale test the wheel snags on Post 11 turning the front wheels “full-steer” toward the barrier; whereas in the simulation the wheel’s contact with the post was not sufficient to significantly alter the steer angle. In the full-scale test, the steer angle of the wheels resulted in higher deceleration of the vehicle and also altered the trajectory during the impact event, compared with the results of the FE analysis.

The W-Beam rail element was deformed from posts 9 through 14 as shown Figure 10. The maximum permanent deflection of the rail in the FE analysis was 15.5 inches and occurred at 47 inches upstream of Post 12 (compared to 14.5 inches deflection at 37.5 inches upstream of Post 12 in the full-scale test). All the post-bolt connections remained attached throughout the impact for both the full-scale test and the FE analysis. The maximum permanent groundline deflections of Posts 10 through 13 in the FE analysis were 0.7 inches, 7 inches, 4.2 inches and 0.24 inches, respectively. Although it cannot be confirmed, it appears from visual inspection of the damaged test article that the deflections of the posts are of similar magnitude. The maximum deflection of the rail at the upstream boundary was 1.2 inches. Figure 11 shows the post-test photograph of the upstream anchor after Test C08C3-027-1. The separation between the back of the post and the soil in the photo is evidence of upstream anchor movement, but the actual amount of displacement was not included in the test report. Overall, the barrier damages resulting from the simulated impact were reasonably representative of that observed in the full-scale test.
Figure 8. Sequential views of FEA results compared with Test C08C3-027-1.
Figure 9. Impact response at 0.18 seconds for (a) full-scale test and (b) FEA illustrating wheel orientation.
Figure 10. Comparison of guardrail damage for (a) Test C08C3-027-1 and (b) FEA model.

Figure 11. Post-test photo of upstream anchor after Test C08C3-027-1.[Fleck08a]
SIMULATION OF TEST C08C3-027-2

Test C08C3-027-2 Summary

The damaged guardrail from test C08C3-027-1 was subjected to a subsequent high-speed impact test to evaluate the performance of the crash-damaged system. Test C08C3-027-2 was performed by MGA Research Corporation on August 6, 2008 under Report 350 test 3-11 conditions. No repairs of the pre-damaged guardrail were made prior to this second test.

In Test C08C3-027-2, a 1997 Chevrolet 2500 pickup impacted the damaged rail at 38.5 inches upstream of Post 11 at an impact speed and angle of 62.1 mph and 26.4 degrees, respectively. At 16 milliseconds after impact Post 11 started to deflect back, and at 44 milliseconds Post 12 began to deflect. At 56 milliseconds the right-front tire impacted against Post 11, pushing the post over. As the tire interacted with the post, the tire-rod released and the tire steered 90 degrees toward the barrier. The left-front tire remained straight. At 60 milliseconds Post 10, which was upstream of the truck, began to twist such that the blockout was rotating in the downstream direction. At 98 milliseconds the front bumper was at Post 12. At 108 milliseconds the height of the w-beam at Post 12 began to reduce as the post and blockout began to rotate. At 112 milliseconds Post 12 was deflected significantly, the blockout on the post was rotated almost 90 degrees, and the post-bolt at Post 12 released. The rail began to drop and at 120 milliseconds the right-front corner of the truck bumper was visible above the rail. At 146 milliseconds Post 12 was pushed to the ground as the truck overrode the post and the front bumper of the truck at this time was completely over the top of the rail. At 174 milliseconds, the front of the truck was at Post 13; all the upstream posts had rotated essentially 90 degrees about their vertical axis at this time, which inferred substantial movement of the upstream anchor system. As the test continued, the front bumper continued to pass over the top of the rail. At 270 milliseconds Post 13 was pushed to the ground without releasing the post-bolt connection; the w-beam rail was pulled down with the post and the vehicle overrode the barrier.

Model Setup

The results from the low-speed impact case were then used as initial conditions in a secondary high-speed impact simulation of full-scale crash test C08C3-027-2. The initial conditions for the pre-damaged guardrail included component deformations and residual stresses. These values were recorded for all shell, solid and beam elements in the model via the SPRINGBACK option in LS-DYNA. The residual forces for discrete elements (e.g., non-linear spring elements for the soil and rail end-boundaries), however, are not recorded with this option. For initialization of all the spring elements in the model, LS-PrePost was used to determine the final displacements of the spring nodes; these displacement values were then used to define the initial offset for each spring element in the FE model. This methodology directly imposes the force-deflection response of the spring elements for the soil and the end-anchor from the low-speed analysis onto the model for the high-speed impact case. Figure 12 shows a contour plot of effective plastic strain for the initial state of the guardrail model used in the simulation of Test C08C3-027-2.
Finite element analysis was then used to simulate the impact conditions of Test C08C3-027-2. Two analysis cases were conducted:

- The crash-induced damage of the guardrail (including displacements and residual stresses) from the analysis of C08C3-027-1 was imposed directly onto the model as initial conditions. The post-bolt position at Post 12 was then re-positioned to the corner of slotted hole in the w-beam (i.e., to be consistent with the test article) and re-tightened.

- Case 2: The same initial conditions as Case 1, and then a rigidwall was also included to simulate the boundary at the backside of the soil pit at the test site.

**Analysis Case 1**

The vehicle model used in the analysis was the NCAC C2500D version 5B with modifications described in Task Report 4A-1. The vehicle model impacted the damaged rail at approximately 38.5 inches upstream of Post 11 at an impact speed and angle of 62.1 mph and 26.4 degrees, respectively (i.e., the same impact conditions as the full-scale test). At 25 milliseconds after impact Post 11 started to deflect back, and at 55 milliseconds Post 12 began to deflect. At 60 milliseconds the right-front tire impacted against Post 11; however, there was no tire snag on the post and the tie-rod did not fail. At 80 milliseconds Post 11 reached its maximum lateral groundline deflection of 14 inches. At 50 milliseconds Post 10, which was upstream of the truck, began to twist such that the blockout was rotating in the downstream direction. At 100
milliseconds the front bumper was at Post 12, and Post 13 started to deflect. At 110 milliseconds the head of the post-bolt at Post 12 pulled through and released the rail; the rail did not begin to drop prior to release. At 120 milliseconds Post 14 began to deflect. At 130 milliseconds Post 12 reached its maximum groundline deflection of 12.3 inches; the post continued deflecting about the groundline until 135 milliseconds when the top of the post was pressed to the ground. The front tire of the vehicle contacted Post 12 at 140 milliseconds and proceeded to roll over the post and blockout.

At 185 milliseconds, the front of the truck was at Post 13. At this time all the upstream posts had rotated significantly and the post-bolt connection had released at all upstream non-splice locations. These factors inferred substantial movement of the upstream anchor system. At 200 milliseconds the post-bolt at Post 13 pulled through the double-slot of the splice and released the rail; at this time the rail was still at its original height. Post 15 also began to deflect slightly at this time. At 210 milliseconds Post 13 reached its maximum groundline deflection of 15 inches, and at 215 milliseconds the top of the post contacted the ground. At 225 milliseconds the front tire on the vehicle contacted Post 13 and its blockout; the tire proceeded to ride over the post and passed behind the blockout.

At 280 milliseconds the front of the vehicle was at Post 14. At 295 milliseconds the post-bolt at Post 14 released from the rail; at this time the rail was still at its original height. Also at this time Post 15 began to deflect significantly. At 315 milliseconds Post 14 reached its maximum groundline deflection of 10.5 inches. At 325 milliseconds the front tire on the vehicle contacted the post just as the top of the post contacted the ground.

At 380 milliseconds the front of the vehicle was at Post 15. The analysis was manually terminated at this time and will be restarted after Case 2 completes.

**Analysis Case 2**

As mentioned previously, Analysis Case 2 included the same model that was used in Analysis Case 1, except that a “rigidwall” was added to the model to represent the boundary at the backside of the soil pit at the test site. Comparing the results of Analysis Case 1 to the full-scale test (C08C3-027-1) revealed that the groundline deflections of Posts 11 and 12 were notably higher in the analysis. This phenomenon resulted in the posts in the analysis rotating about a lower point below grade, which affected the tire’s interaction with Post 11 and the height of the w-beam as the posts deflected and rotated back. After further review of the full-scale test it was determined that the limited width of the soil pit at the test site may have restricted the posts’ deflection through the soil. Figure 13 shows the test setup for the low-speed Test C08C3-027-1 illustrating the limited distance between the back of the posts and the back edge of the soil pit. It has not been confirmed, but it appears that the area outside the soil pit was composed of concrete or asphalt material.

From a review of the high-speed video of the test, Post 11 stopped abruptly at around 160 milliseconds of the impact event. Figure 14 shows snapshots from the test video for low-speed test C08C3-027-1 illustrating the position of the guardrail posts (relative to the backside of the soil pit) at the beginning of the test and at 0.16 seconds of the test event. Post 11 showed no signs of further deformation (e.g., torsional deflection, collapsing of the post cross-section or further bending at the groundline), so it can be assumed that the soil pit area was sufficient for the low-speed test.
Figure 13. Test setup for low-speed test C08C3-027-1 illustrating the limited distance to the back-edge of the soil-pit for the test article.

Figure 14. Snapshots from low-speed test C08C3-027-1 illustrating the position of the guardrail posts relative to the backside of the soil pit at the beginning of the test and at 0.16 seconds.
Figure 15 shows the test setup for the high-speed Test C08C3027-2. The reduced distance from the back of Posts 11 and 12 to the back-edge of the soil pit restricted the movement of the posts at the groundline during the high-speed Test C08C3-027-2. The soil-pit boundary was included in the model using the “finite rigidwall” option in LS-DYNA. The rigidwall was positioned based visual inspection of the overhead view in Figure 15 and is shown in Figure 16 and Figure 17 from an overhead viewpoint and a downstream viewpoint, respectively.

Figure 15. Test setup for high-speed test C08C3-027-2 illustrating the reduced distance from the back of Posts 11 and 12 to the back-edge of the soil-pit.

Figure 16. FE model for Case 2 with vertical “rigidwall” located just below grade to simulate back-edge of soil pit (overhead viewpoint).
Figure 17. FE model for Case 2 with vertical “rigidwall” located just below grade to simulate back-edge of soil pit (downstream viewpoint).

The vehicle model used in the analysis was the NCAC C2500D version 5B with modifications described in Task Report 4A-1. The vehicle model impacted the damaged rail at approximately 38.5 inches upstream of Post 11 at an impact speed and angle of 62.1 mph and 26.4 degrees, respectively (i.e., the same impact conditions as the full-scale test). At 30 milliseconds after impact Post 11 started to deflect back, and at 55 milliseconds Post 12 began to deflect. At 60 milliseconds the right-front tire impacted against Post 11 and began to push the post back as it rode-over the post; the tied rod did not fail but the wheel did steer slightly toward the guardrail during interaction with the post. The post-bolt connection at the splice at Post 11 released at 65 milliseconds. Post 11 was pushed completely to the ground at 95 milliseconds. At 50 milliseconds Post 10, which was upstream of the truck, began to twist such that the blockout was rotating in the downstream direction. At 85 milliseconds the posts upstream (e.g., Post 13, Post 14, etc.) began to twist, such that the blockouts where rotating in the upstream direction. At 100 milliseconds the front bumper was at Post 12. The w-beam at Post 12 began to drop at 110 milliseconds. At 115 milliseconds Post 14 began to deflect laterally. At 120 milliseconds the post-bolt at Post 12 broke releasing both the rail and the blockout (the post-bolt was jammed in the corner of the slotted hole in the w-beam and a numerical contact problem between the bolt and rail resulted in the solid elements of the bolt getting “tangled” with the shell element of the w-beam). At this time Post 12 was twisted almost 90 degrees and the right-front corner of the truck bumper was visible above the rail. The tire of the vehicle impacted Post 12 at 145 milliseconds and continued to push the post to the ground as it rode over the post. At 185 milliseconds, the front of the truck was at Post 13. At this time all the upstream posts had rotated significantly; however, none of the upstream post-bolt connections had released. Post 13 continued to deflect and at 220 milliseconds the top of the post contacted the ground with the w-beam still attached.

As of this reporting, the analysis was still in progress. The differences in results between the analysis and full-scale test are considered minor so far. It is evident from the analysis that the vehicle will over-ride the guardrail in a similar manner as the test vehicle; these results will be updated in a later version of this report.
Figure 18. Sequential Views of Test C08C3-027-2 and FE analysis from downstream-backside view perspective.
Figure 18. [CONTINUED] Sequential Views of Test C08C3-027-2 and FE analysis from downstream-backside view perspective.
Figure 19. Sequential views of Test C08C3-027-2 and FE analysis from an upstream view perspective.
Figure 19. [CONTINUED] Sequential views of Test C08C3-027-2 and FE analysis from an upstream view perspective.
SUMMARY AND DISCUSSION

RECOMMENDATIONS
REFERENCES


