
IDEA

Use of Energy Absorbing Breakaway Posts for W-Beam Guardrail in Frozen Soil Conditions

TRANSPORTATION RESEARCH BOARD

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DETAILS

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IDEA

Innovations Deserving Exploratory Analysis Programs

Highway IDEA Program

Use of Energy Absorbing Breakaway Posts for W-Beam Guardrail in Frozen Soil Conditions

Final Report for
Highway IDEA Project 149

Prepared by:
King Mak and John Rhode
Safety by Design Co.

November, 2013

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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Final Report

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Executive Summary
The goal of this project was to develop, test, and demonstrate the application of breakaway posts with energy absorbing capability to enhance the safety performance of W-beam guardrail in frozen soil conditions. From the four initial concepts, two designs were selected for further evaluation based on potential impact performance, manufacturability, and cost. The bent-plate design (Figure 1) showed the desired failure mechanism though the force level was lower than that required for proper impact performance. The bogie test was then simulated using the LS-DYNA computer simulation program. Based on the calibrated simulation model, the thickness of the bent plate was optimized to increase the force level while maintaining the manufacturability. Additional bogie tests were conducted on the optimized design, and the results showed acceptable force levels. Computer simulation of a guardrail system with breakaway posts was then conducted with satisfactory results indicating that implementation of this new guardrail post could potentially reduce the severity of guardrail crashes and the associated serious and fatal injuries. The next step was to conduct a full-scale crash test at the Midwest Roadside Safety Facility. The post manufacturer, Road Systems, Inc., had agreed on the finalized design and to contribute to the cost for the full-scale crash test. However, after reevaluating the potential market for the new posts, Road Systems, Inc. determined them to be not viable in the current market and withdrew support from the full-scale crash test. Implementation of the new posts requires fabrication and full-scale crash testing followed by field tests in collaboration with State Departments of Transportation.

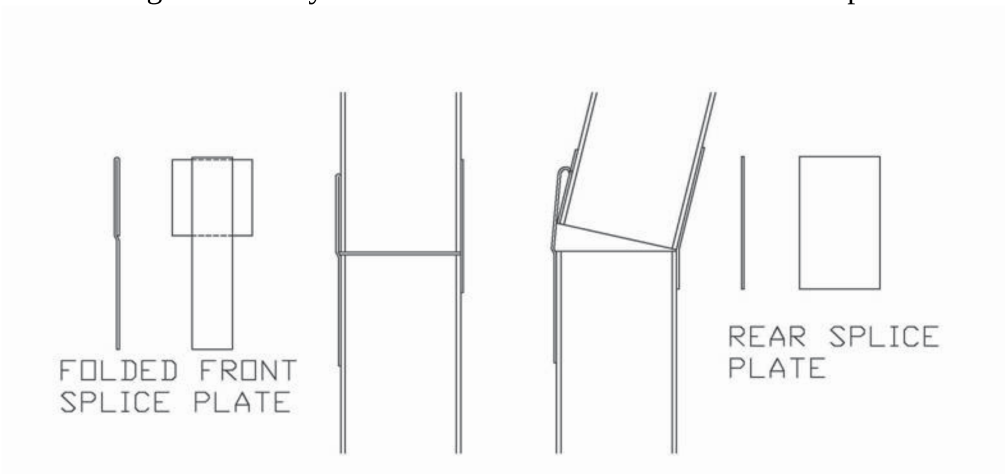


Figure 1
Schematic of bent plate design.

Definition of Problem

It is well known that the impact performance of existing W-beam guardrail systems is adversely affected by rigid foundation conditions, such as frozen ground, paved shoulders or mow strips, and bedrock. Computer simulations of guardrail impacts have shown that, when properly installed in soil, guardrail posts absorb approximately half of all of the energy dissipated by the barrier. Thus, when posts are prevented from rotating in the soil, the amount of energy dissipated is dramatically reduced and the excess energy will have to be absorbed by the W-beam rail element. Full-scale crash testing has demonstrated that the W-beam rail element is incapable of absorbing the additional energy, resulting in rupture and penetration of the guardrail, thus allowing the impacting vehicle to strike the shielded hazard, as illustrated by the sequential photographs shown in Figure 2.

Although the adverse effects of frozen ground on guardrail performance have been well understood for many years, no significant funding has been dedicated to solving this problem. Thus, no treatment is now available that can allow W-beam guardrail installed in frozen ground to meet current safety performance criteria. A recent study of guardrail performance in a Midwestern state was undertaken to examine the potential effects of frozen ground. Guardrail crashes that occurred on icy pavements were excluded to eliminate the effects of winter driving conditions on operating speeds. This unpublished study found that the risk of a guardrail crash producing a serious injury or fatality (A+K accident) during January and February, when soil was most likely to be frozen, was 70 percent higher than during the months of April through November, when roadside soils are seldom frozen. This finding indicates that the effect of frozen ground on guardrail performance is producing significant numbers of serious injuries and fatalities along the nation's highways. However, most highway agencies believe that it is not possible to resolve this problem in an economical fashion. Furthermore, there is the concern that conducting full-scale crash tests of guardrail in frozen ground will demonstrate the problem without developing a reasonable solution.

The solution to frozen ground can be explored indirectly by limiting testing to other rigid foundation situations, such as guardrails installed in pavement or mow strip. An industry representative has estimated that as much as 25 percent of the more than 3.2 million new guardrail posts installed each year are placed in pavement of one kind or another. Highway agencies utilize pavement cutouts behind guardrail posts to provide proper post rotation for guardrails installed in paved shoulders or mow strips. Low strength surfacing, such as a flowable fill or lightly compacted asphalt is then placed on top of the cutout to limit vegetation growth. This surfacing creates special problems for guardrail erectors and maintenance forces. First, the strength of the surfacing must be carefully controlled in order to prevent vegetation growth without preventing post rotation. Inadequate inspection of the surfacing material or the placement procedures could lead to excess resistance to post rotation which would represent a major tort risk. Even when the proper fill material strength is obtained and proper placement procedures are implemented during construction, the same problem arises each time that a guardrail post is damaged during a crash and must be replaced. The added labor and potential tort risk associated with constructing the cutouts, placing, and repairing the surfacing of the cut-outs greatly increases the cost of installing guardrail in paved shoulders and mow strips.

Guardrail installed in bedrock is another situation of rigid foundation condition. Multiple overlapping holes and select granular backfill are used when guardrail must be installed in bedrock. Although existing installation procedures should produce acceptable barrier performance, the need to drill multiple holes and install select materials in the holes also increases the cost of installing guardrails in rock.

As mentioned previously, guardrail posts must be capable of absorbing a significant amount of energy in order to provide proper barrier function. Existing breakaway guardrail posts were designed for use in terminals where energy absorption must be limited. Thus, it is not surprising that crash tests have shown that conventional breakaway guardrail posts do not alleviate the safety performance problem associated with guardrail installed in rigid foundations.

Study Objective

The objective of this study is, therefore, to develop an energy absorbing breakaway post that will work under frozen soil conditions.

Study Approach

To accomplish the study objectives, the project is divided into two stages and six tasks as follows.

Stage I Work Plan

Task 1. Identify, Screen, and Select Breakaway Post Designs.
Task 2. Evaluate Selected Breakaway Post Designs.
Task 3. Conduct Full-Scale Crash Test.
Task 4. Conduct Field Test

Task 1. Identify, Screen, and Select Breakaway Post Designs.

A number of candidate energy absorbing guardrail post designs were developed that could potentially be used in rigid foundations. These conceptual designs were based on different failure mechanisms, such as tearing of welds or tabs of splice plates, bent or folded splice plate, etc. These candidate designs were then screened to identify the most promising concepts.

Factors to be considered in evaluating the proposed energy absorbing breakaway posts include:

- Impact performance. The basic goal of the design effort is to produce a breakaway post that replicates the force-deflection characteristics of a post rotating in soil. However, even if this goal is achieved, it may not be sufficient to provide adequate safety performance for locations with rigid foundation conditions. Posts rotating in soil deflect laterally at the ground line to reduce the risk of wheel snag. Because posts mounted in rigid foundations do not deflect at the ground line other design features may be needed, such as allowing the upper post to become detached from the base during wheel snag.

- Manufacturing and cost. The post should be readily adaptable to mass production and the incremental cost over standard guardrail posts should be kept to a minimum. The project staff worked with Road Systems, Inc., the project's industrial partner, to review the candidate designs in terms of the manufacturing procedure and fabrication details as well as a cost analysis.

- Field installation. The guardrail system with breakaway posts must be easy to install in the field using existing equipment and be capable of being driven through asphalt and stiff soils.

- Maintenance. The new guardrail post must be easily replaced after a crash. Ideally, the post will slide into and out of the pre-existing hole to simplify guardrail repair. A method for preventing Portland cement from bonding to the post will be developed to facilitate repair.

Based on results of the evaluation, the two most promising candidate designs were selected for further evaluation:

1. Welded tab design, and
2. Bent plate design.

Schematics of these two candidate designs are shown in Figures 3A and 3B, respectively, and more detailed descriptions of these two candidate designs are presented as follows.

<u>Welded Tab Design</u>: This concept incorporates a tearing splice plate energy absorbing mechanism. As shown in Figure 3A, tabs are cut out of the front splice plate. The tabs are inserted between the upper and lower post and welded to the upper post. When the guardrail is struck, the upper post begins to pull up on the tabs until the out-of-plane tearing stresses reach the capacity of the splice plate. The tabs will then tear at a constant force as the top of the post is pushed back. After the post has deflected approximately 24 inches, the tearing in the splice plate will have progressed for approximately 4 inches. When the tearing reaches the end of the splice plate, the front of the post will break away and offer no more resistance to lateral displacement.

Bent Plate Design: This concept provides another configuration that relies on out-of- plane tearing of the front splice plate, as shown in Figure 3B. In this case, the splice plate is folded 180 degrees onto itself with one side of the fold much shorter than the other. The shorter portion is welded on each side to the upper portion of the post. The longer portion of the folded plate is then bent up against the base post and securely welded to prevent any deformation.

When the upper portion of the post is loaded, the front splice plate again goes into tension and begins to pull the upper portion of the folded plate away from the post to put an out-of-plane shear stress on the welds and the edges of the plate itself. When the tearing shear stress reaches the capacity of the weld or the base metal, the splice plate will begin to progressively tear away at a constant force. The length of the folded plate controls the lateral distance at which the front splice plate releases from the upper post to allow it to breakaway.

Task 2. Evaluate Selected Breakaway Post Designs

The two candidate designs identified in Task 1 were then subjected to the following additional evaluations:

1. Bogie testing to determine the dynamic force levels and the energy absorbing capabilities,
2. LSDYNA modeling, and
3. Manufacturability.

Bogie Testing: While the two candidate designs appeared to be promising, it is necessary to conduct some component testing to assess if the designs would perform as designed and to determine the dynamic force levels and the energy absorbing capabilities. Two initial bogie tests, one for each candidate design, were then conducted at the Midwest Roadside Safety Facility (MwRSF). The test results are presented as follows.

The bogie tests were designed to simulate the loading of a post during a critical impact under current full-scale crash test criteria. The two candidate designs, the welded-tab post (Test SDCB-1) and the bent-plate post (Test SDCB-1) were impacted with a bogie vehicle weighing 1,744 lbs, traveling at a speed of 20.9 mph for Test SDCB-1 and 22.5 mpg for Test SDCB-2. Brief descriptions of the test results are presented as follows.

Figure 4 shows the load-deflection plot for welded tab post bogie test (Test SDCB-1). The load increased over the first 1.5 in. of travel to about 7 kips. This is within the targeted range of force level for resisting post rotation. Unfortunately, the weld failed at that point and the loading dropped precipitously. Also, as shown in Figure 5, plate tearing was initiated prior to weld failure. While the force level prior to weld failure is encouraging, the failure mechanism is not acceptable due to the premature weld failure.

Figure 6 shows the load-deflection plot for the bent plate post bogie test (Test SDCB-2). The load over the first 20 in. of travel was reasonably consistent at about 2 kips. Figure 7 shows the post after test. While this force level was too low for good impact performance, the failure mechanism was ideal over the necessary range of post travel. The results of the initial bogie tests indicated that the bent plate concept is the better design in terms of impact performance. Furthermore, the manufacturer also preferred this design due to ease of fabrication. Thus, the bent plate design was selected for further development.

LS-DYNA Simulation: As mentioned previously, while the failure mechanism was ideal for the bent plate post, the force level was too low. The LS-DYNA finite element computer simulation model was then used to increase the force level and to optimize the post design. The computer simulation model was first calibrated using results of the bogie test (Test no. SDCB-2). The calibration ensured that the model properly simulates the impact performance and failure mechanism of the bent plate post. As shown in Figure 8, results of the simulation and the resulting force-deflection plot closely resembled the actual bogie testing.

The bent plate design was then optimized using the calibrated LS-DYNA model. As may be expected, the thicker the bent plate, the higher is the force level and energy absorption capability of the breakaway posts. On the other hand, excessively thick plates pose problems in the manufacturing process, resulting in higher costs.

Manufacturability: The manufacturer was then consulted about the manufacturability of the optimized post design. It was eventually decided that a thickness of 3/16 inch provides the best compromise between force and energy absorption level and manufacturability. Prototype posts of the optimized design were fabricated. The posts were fabricated from standard W6x9 line posts, 72 inches long with an embedment depth of 40 inches. In addition, the prototype post was tested for drivability in thick asphalt and hard soils and found to perform satisfactorily.

Additional Bogie Testing: Two additional bogie tests were then conducted on the prototype posts (Test nos. SBDC-3 and SBDC-4). Again, the tests were designed to simulate the loading of a post during a critical impact under current full-scale crash test criteria. The prototype posts were impacted with a bogie vehicle weighing 1,744 lbs, traveling at a speed of mph for Test SDCB-3 and 21.3 mpg for test SDCB-4. Brief descriptions of the test results are presented as follows.

Figure 9 shows the load-deflection plot for Test SDCB-3. The load increased over approximately the first 1.5 inch of travel to about 7 kips. This is within the targeted range of force level for resisting post rotation. The force level then dropped to a sustained level of about 3.5 kips through a deflection of roughly 22 inches. The initial linear stiffness was 4.5 kips/in with a total energy dissipation of 113 kip-in.

Figure 10 shows the load-deflection plot for Test SDCB-4. The load-deflection characteristics are similar to Test SDCB-3, but at slightly lower force levels. Again, the load increased over approximately the first 1.5 inch of travel to 6.8 kips. The force level then dropped to a sustained level of slightly less than 3 kips through a deflection of roughly 24 inches. The initial linear stiffness was 3.6 kips/in with a total energy dissipation of 100 kip-in.

Unlike Test SDCB-2, there was no failure of the welds for Tests SDCB-3 and SDCB-4. However, as the posts deflected beyond the fully extended length of the bent plates, the plates started to tear as shown in Figure 11.

Results of the bogie tests indicated that the failure mechanisms of the optimized posts are performing as intended. The force levels are slightly lower than those of a standard line post, but still within the acceptable range. Further increase in the bent plate thickness would be counter-productive due to concern over the manufacturability of the posts while increasing the force and energy levels only marginally. Thus, no further modification to the post design or additional bogie testing was deemed necessary. Figure 12 shows a schematic of the final design of the bent- plate energy absorbing line post.

LS-DYNA Simulation of Full-Scale Crash Test: To ensure that the energy absorbing breakaway posts would function properly with the W-beam guardrail system, the LS-DYNA finite element model was used to simulate a full-scale crash test. Results of the simulation indicate that the energy absorbing breakaway posts would improve the impact performance of the W-beam guardrail system under frozen or rigid soil conditions.

Figure 13 shows the simulation results of an impact of a W-beam guardrail system with standard line posts. The simulation results closely duplicate the kinematics of the failed full-scale crash test (shown in Figure 2), in which the vehicle vaulted over the rail.

Figure 14 shows the simulation results of an identical crash test for a W-beam guardrail system with the energy absorbing breakaway posts. The vehicle was successfully contained and redirected, indicating satisfactory impact performance.

Based on results of the bogie tests and the LS-DYNA simulation, it was concluded that the bent plate post design would perform satisfactorily for guardrail systems in rigid foundation and should be further evaluated with full-scale crash testing.

Task 3. Prepare and Submit Interim Report

This Stage 1 report summarizes the work conducted under Stage I of the project and the applicable and submitted to the IDEA committee and staff for review and approval. In addition, the Co-Principal Investigator made a presentation to brief to the IDEA Committee and staff on the study results from Phase I in November 2011.

Work Plan for Stage II

Upon approval by the IDEA committee, work will proceed with the Stage II activities, including:

Task 4. Conduct Full-Scale Crash Test.
Task 5. Conduct Field Trial Test
Task 6. Prepare and Submit Final Report.

More detailed descriptions of the individual tasks are presented in the following sections.

Task 4. Conduct Full-Scale Crash Test

One full-scale crash test will be conducted at the Midwest Roadside Safety Facility to verify the impact performance of the recommended design. Under MASH, two crash tests are recommended for evaluation of the length-of-need section of a barrier system:

1. Test No. 3-10—a 1,100-kg (2,420-lb) car impacting the barrier at a speed and angle of 100 km/h (62.2 mph) and 25 degrees.

2. Test No. 3-11—a 2,270-kg (5,000-lb) pickup truck impacting the barrier at a speed and angle of 100 km/h (62.2 mph) and 25 degrees.

For this specific application, test 3-11 would be the more critical test since the concern is with the strength of the guardrail. Thus, only one crash test is proposed under this study. Details of the proposed crash test presented as follows.

Figure 15 shows the schematics of the proposed test installation. Note that the manufacturer has agreed to provide all the materials needed for the test installation and the funding for the full-scale crash testing. Testing could commence upon approval to proceed with Stage 2 activities.

The proposed test installation has a total length of 175 feet, consisting of two end posts, one at each end of the test installation, and 27 energy absorbing posts installed in rigid foundations. The W-beam rail will be mounted at metric height; i.e., 21-5/8 inches from ground to center of the rail, with recycled plastic blockouts. The metric W-beam rail system is used since it is more critical than the MGS system which has a higher mounting height, deeper blocks, and mid-span rail splices. It may be argued that if the energy absorbing posts work with the metric rail system, then it would work with the MGS rail system.

The end posts are the same as those for the Sequential Kinking Terminal (SKT)/flared Energy Absorbing Terminal (FLEAT), consisting of a 6-ft long W6 x 15 lower portion and a 29-in. long 6 x 6 x 1/8 tubular section upper portion. The anchor cable is attached to post 1 on the upstream end and to the W-beam rail with a quick release cable anchor bracket

If necessary, modifications to the post design and/or system design will be made to alleviate any problems identified during guardrail construction or the full-scale crash test.

Finally, if the result of the full-scale crash test is satisfactory, a request for approval will be submitted to the Federal Highway Administration for use of the energy absorbing posts on the National Highway System.

Task 5. Conduct Field Trial Test

Upon approval by the Federal Highway Administration, a field evaluation will be conducted to ascertain the actual costs associated with using the post in pavement and identify any potential installation problems. Two state highway agencies, Nebraska DOR and Wisconsin DOT, have agreed to participate in the field test. The field test would involve installing the new posts in one to two highway construction jobs in each of these two states. The participating manufacturer, Road Systems, Inc., will manufacture the new posts and coordinate with the cooperation of local guardrail contractors and the participating state DOTs to install the new posts. The project staff will provide any needed technical assistance to this effort, but will not be directly involved in the field tests.

Details for the field trial test are not developed yet pending on approval of the posts by Federal Highway Administration.

Task 6. Prepare and Submit Final Report

A final report summarizing all the work conducted under this study and the results will be prepared and submitted to the IDEA committee for review and approval. The final report will include materials from the Stage 1 report plus results of the full-scale crash test conducted under Task 4 and the field test under Task 5.

Project Status

A report summarizing the work accomplished under Stage I of the project was completed and submitted to the IDEA program for review and approval. In addition, the Co-Principal Investigator made a presentation to brief to the IDEA Committee and staff on the study results from Phase I in November 2011.

Approval was received to proceed to Stage II tasks. Under the original Stage II, a full- scale crash test of the new energy absorbing post design will first be conducted to evaluate its impact performance. If the crash test is successful, a letter requesting approval of the new design will then be submitted to FHWA with all the supporting documents. Upon approval by FHWA, a field evaluation will then be conducted at selected States. Finally, a final report summarizing all work accomplished under the project will be prepared and submitted.

The original proposal was based on the assumption that the manufacturer would sponsor the project and provide the following assistance to the project staff:

1. Evaluate the candidate post designs from the manufacturer's perspective, such as ease of fabrication, cost. and field application,
2. Provide the prototype posts at no cost to the project,
3. Provide funding for the full-scale crash test, and
4. Assist in the conduct of the field performance evaluation.

Unfortunately, the manufacturer decided to withdraw their sponsorship for Stage II of the project. As such, Safety by Design Co. does not have the financial or human resources to bring the Stage II activities to a successful completion. Thus, the Safety by Design Co. requested for the termination of the project and offered the developed design as non-proprietary to any state(s) that may be interested in pursuing this technology.

Figure 2: Sequential photographs full-scale crash test.

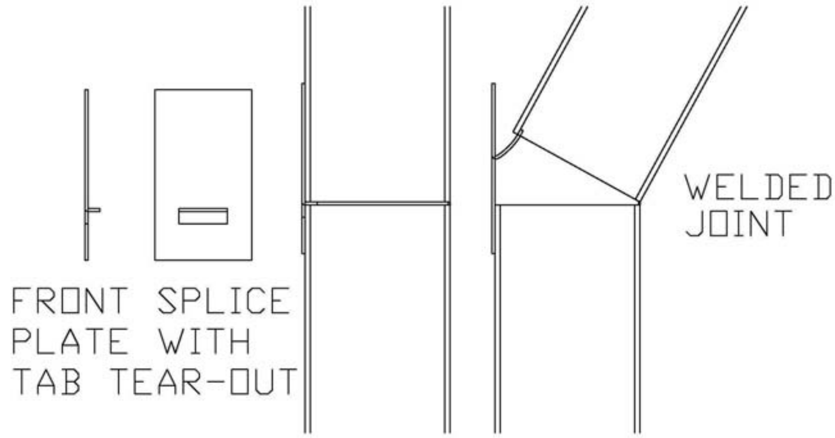


Figure 3A: Welded tab energy absorbing mechanism.

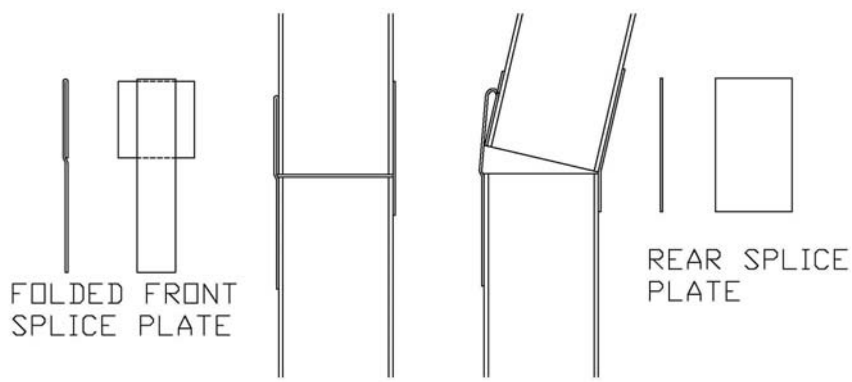


Figure 3B: Bent plate energy absorbing mechanism.

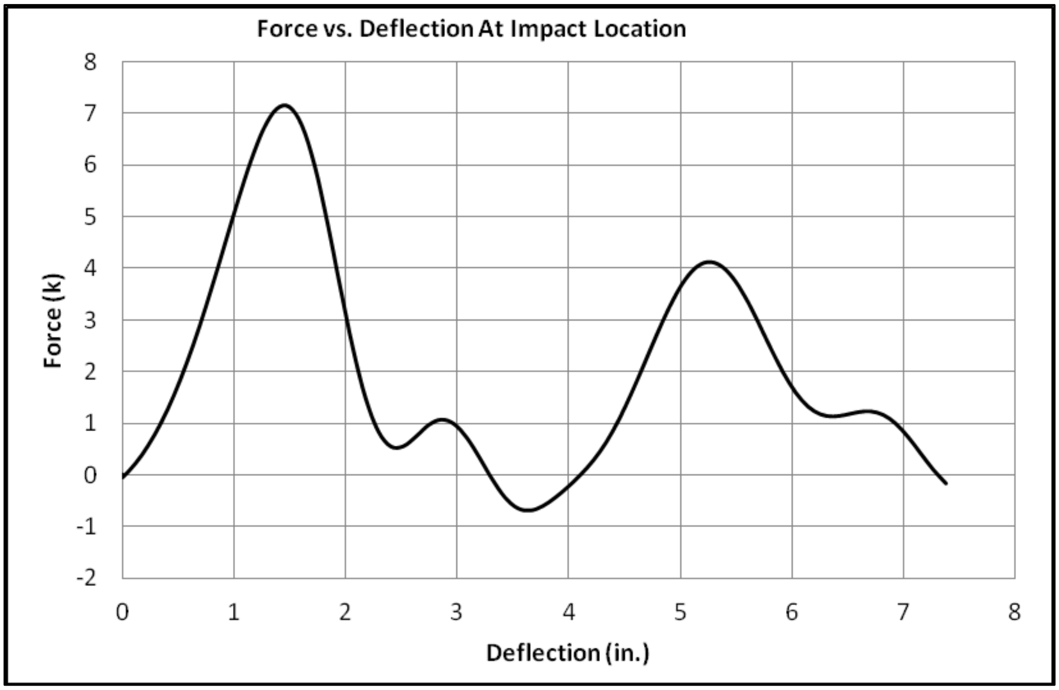


Figure 4: Force deflection relationship for welded tab post (Test SDCB-1).

Figure 5: Welded tab post after test (TEST SDCB-1).

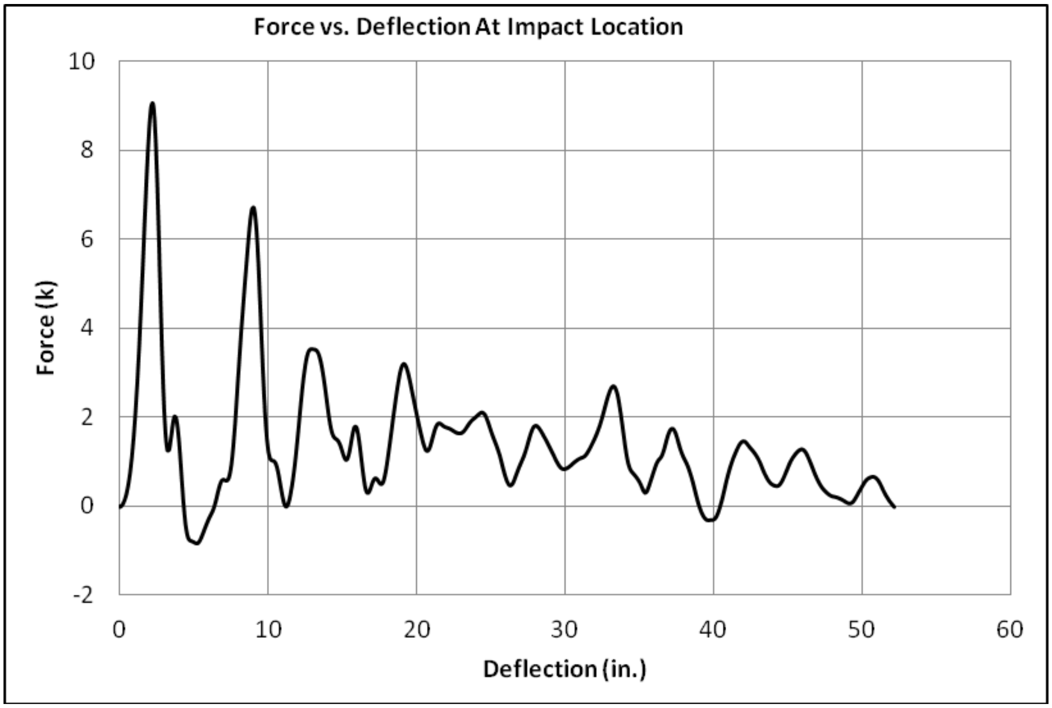


Figure 6: Force deflection relationship of bent plate post (TEST SDCB-2).

Figure 7: Bent plate post after test (TEST SDCB-2).

LS-DYNA

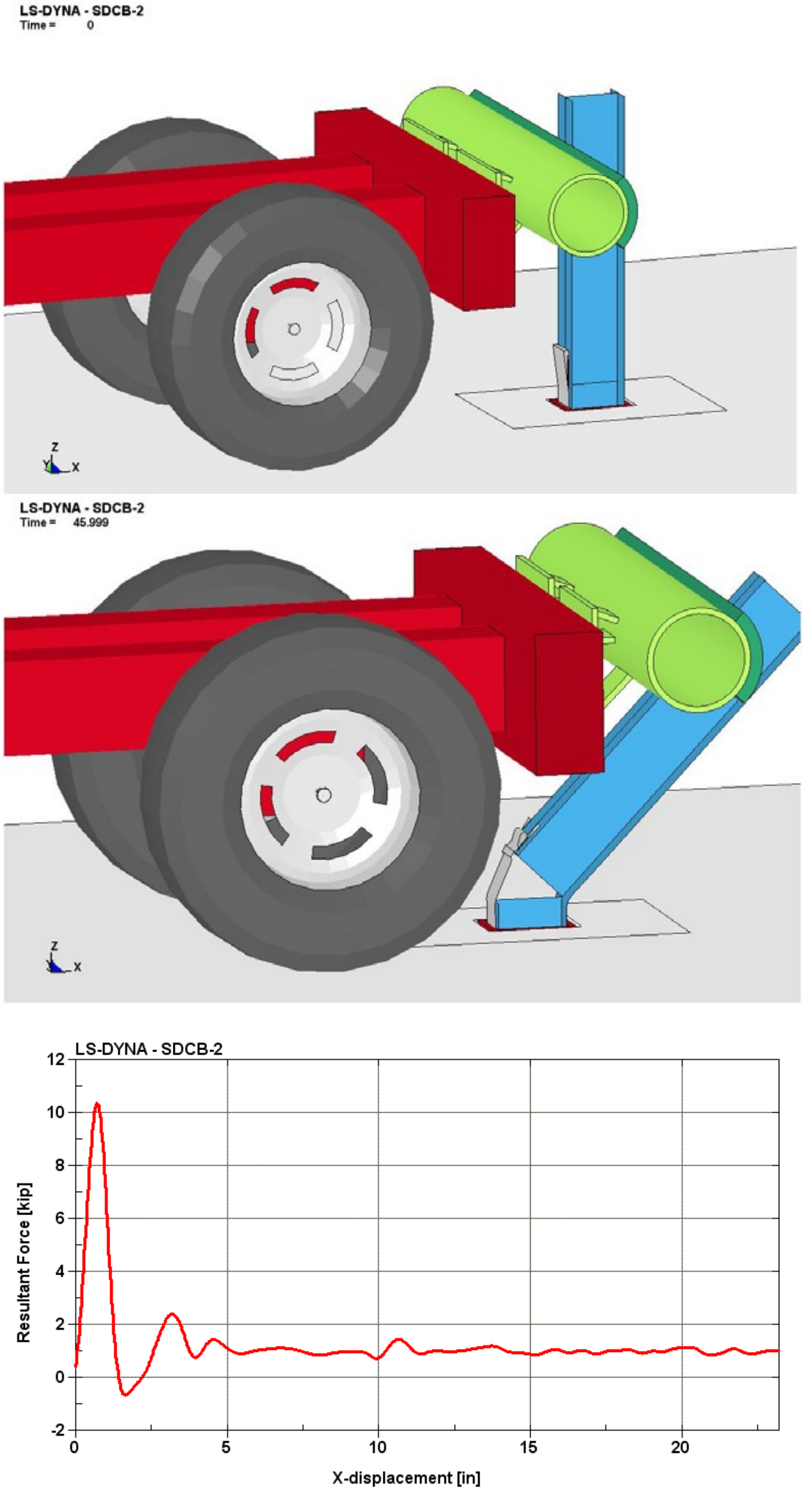


Figure 8: LS-DYNA simulation results for test SBDC-2.

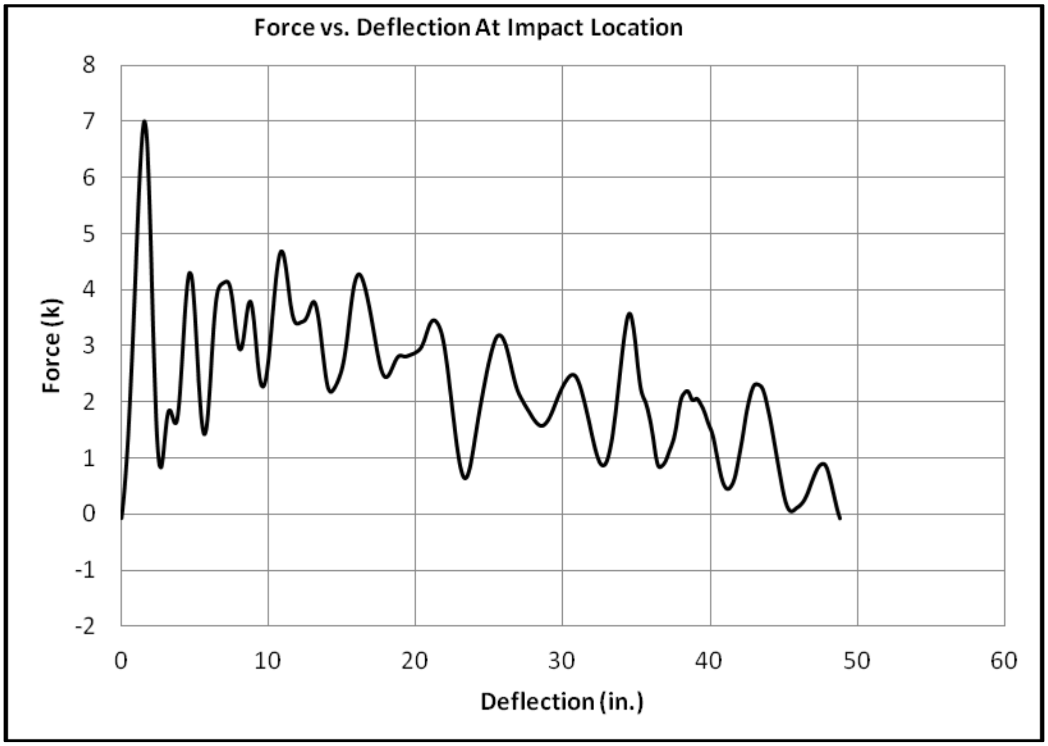


Figure 9: Force deflection relationship for test SDCB-3.

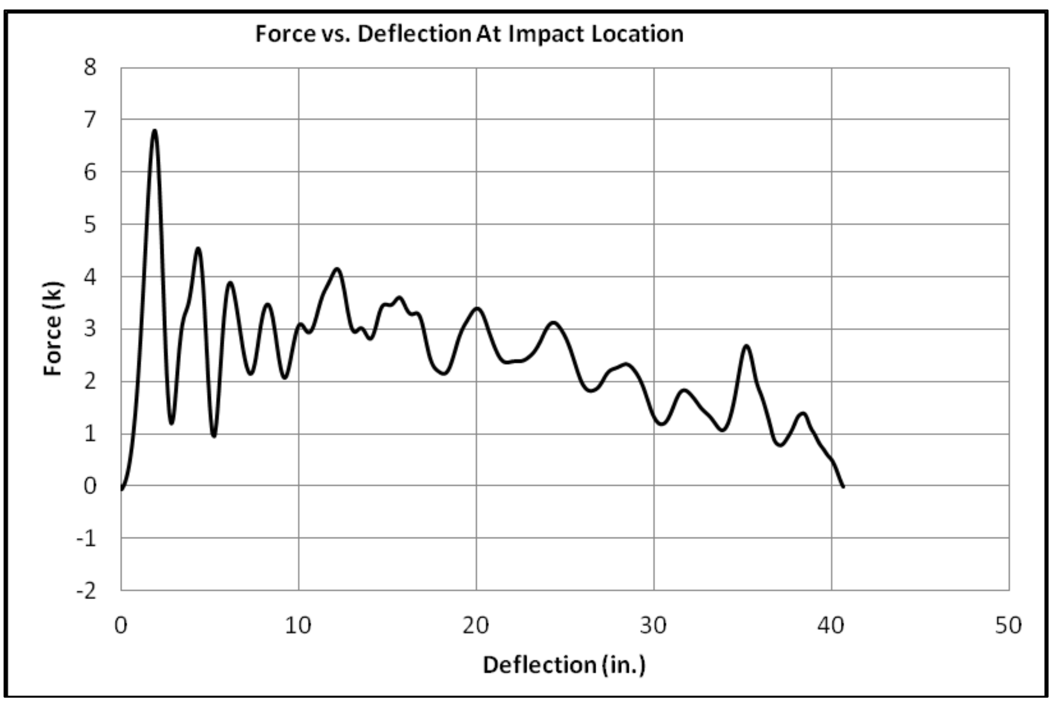


Figure 10. Force deflection relationship for test SDCB-4.

Figure 11: Photographs of posts after tests SDCB-3 and SDCB-4.

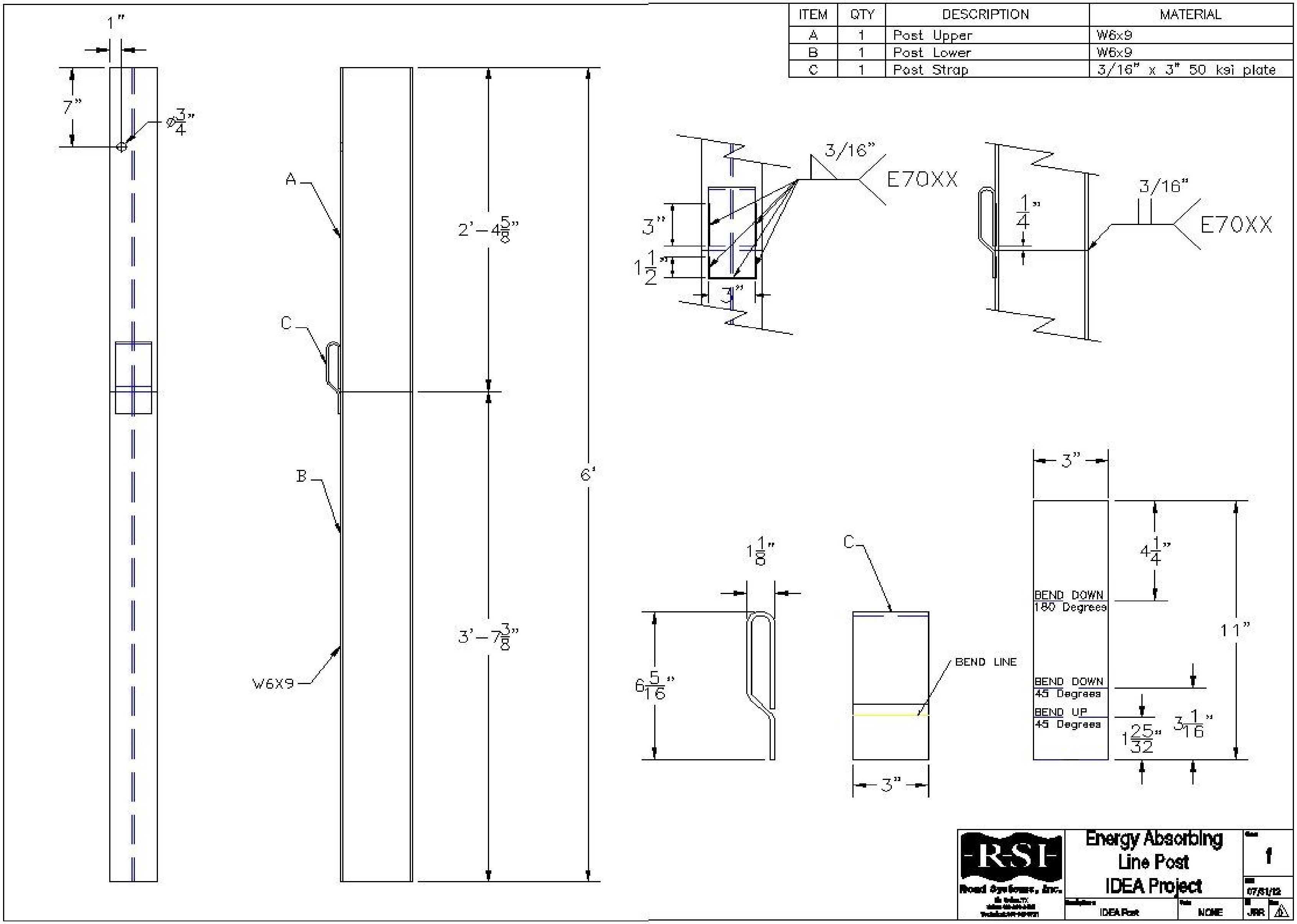


Figure 12: Schematic of bent-plate energy absorbing line post.

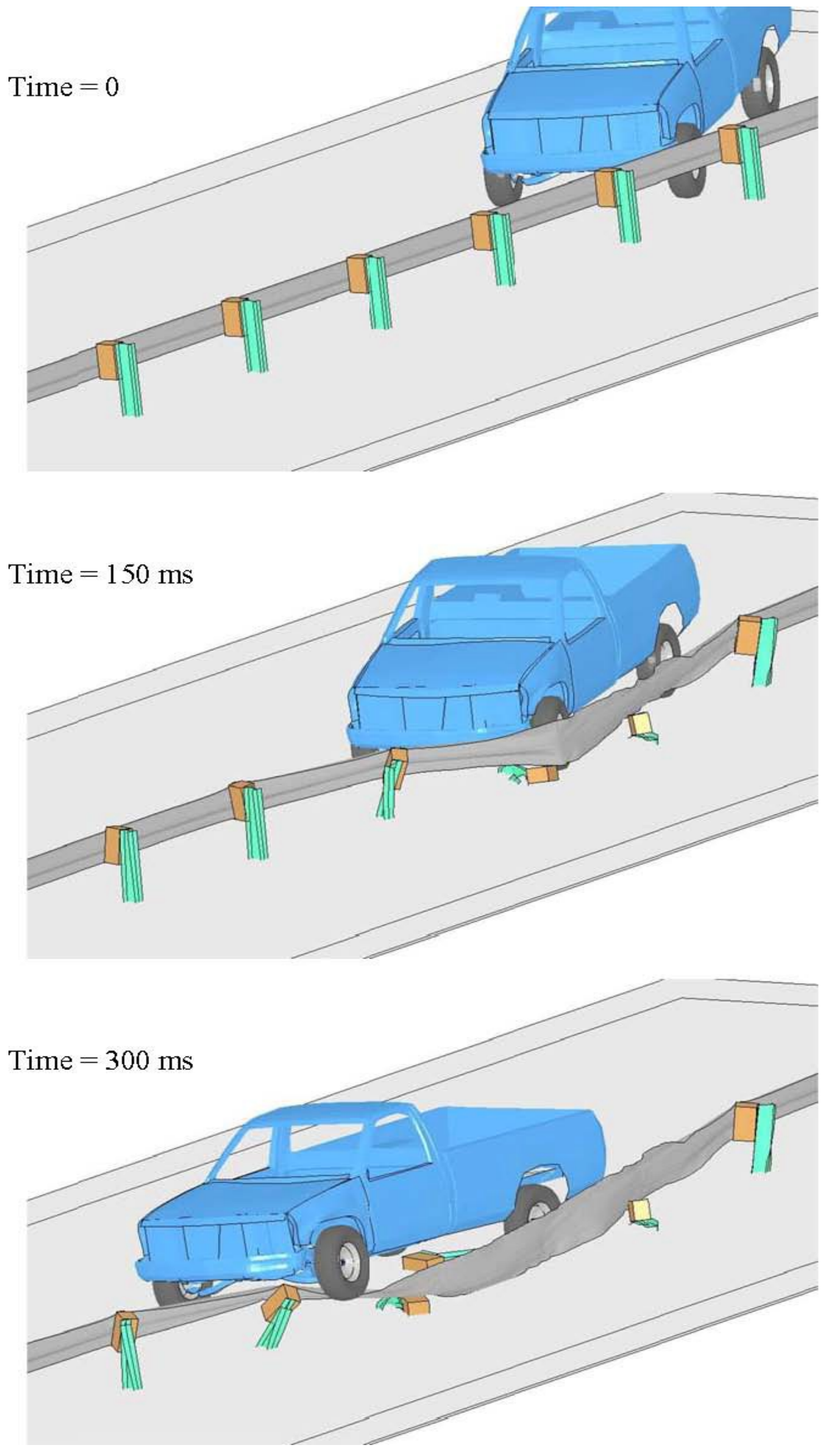


Figure 13: Simulation of crash test of W-beam guardrail system with standard line posts.

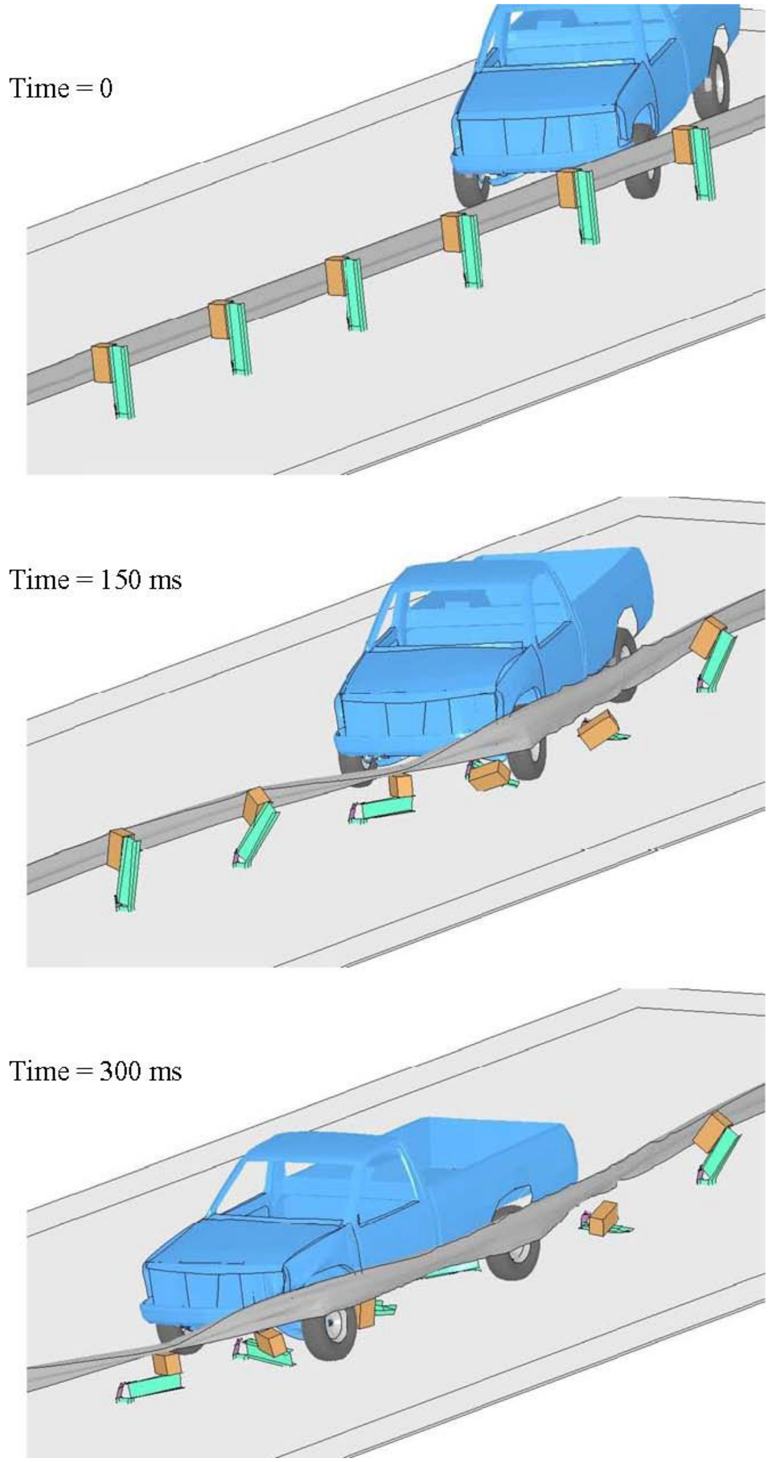
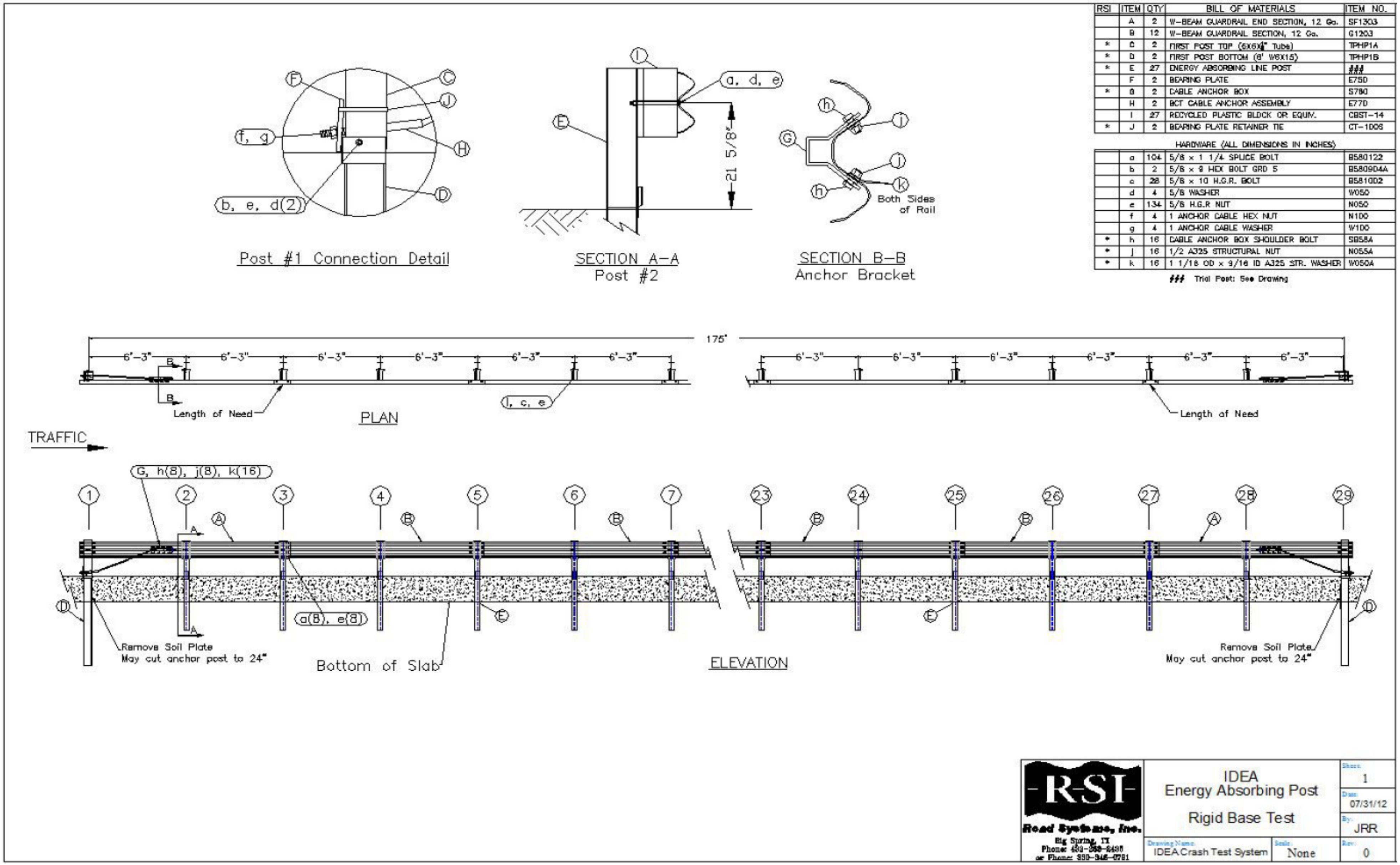


Figure 14: Simulation of crash test of W-beam guardrail system with energy absorbing breakaway posts.



RSI	ITEM	QTY	BILL OF MATERIALS	ITEM NO.
	A	2	W–BEAM GUARDRAIL END SECTION, 12 Ga.	SF1303
	B	12	W–BEAM GUARDRAIL SECTION, 12 Ga.	G1203
*	C	2	FIRST POST TOP (6X6X¼" Tube)	TPHP1A
*	D	2	FIRST POST BOTTOM (6' W6X15)	TPHP1B
*	E	27	ENERGY ABSORBING LINE POST	###
	F	2	BEARING PLATE	E750
*	G	2	CABLE ANCHOR BOX	S760
	H	2	BCT CABLE ANCHOR ASSEMBLY	E770
	I	27	RECYCLED PLASTIC BLOCK OR EQUIV.	CBST–14
*	J	2	BEARING PLATE RETAINER TIE	CT–1006
			HARDWARE (ALL DIMENSIONS IN INCHES)	
	a	104	5/8 x 1 1/4 SPLICE BOLT	B580122
	b	2	5/8 x 8 HEX BOLT GRD 5	B5809D4A
	c	28	5/8 x 10 H.G.R. BOLT	B581002
	d	4	5/8 WASHER	W050
	e	134	5/8 H.G.R NUT	N050
	f	4	1 ANCHOR CABLE HEX NUT	N100
	g	4	1 ANCHOR CABLE WASHER	W100
*	h	16	CABLE ANCHOR BOX SHOULDER BOLT	SB58A
*	j	16	1/2 A325 STRUCTURAL NUT	N055A
*	k	16	1 1/16 OD x 9/16 ID A325 STR. WASHER	W050A

Trial Post: See Drawing

Figure 15: Schematic of test installation.