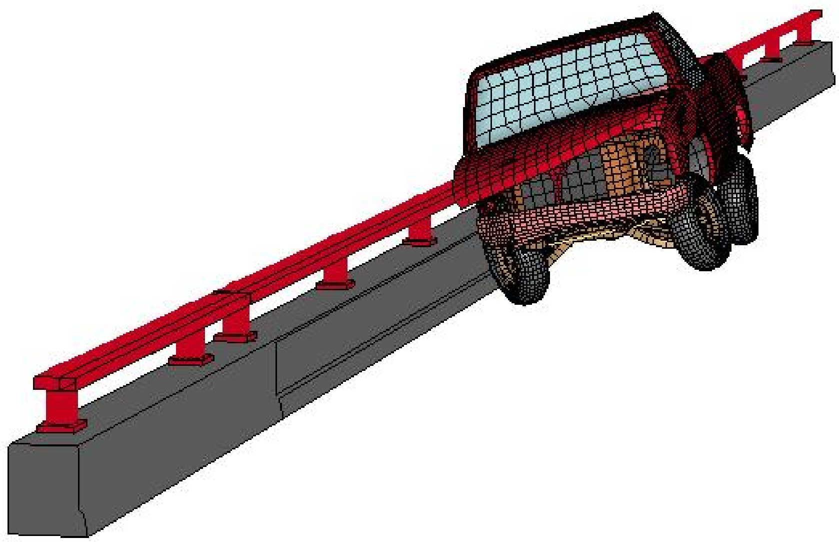
A LS-DYNA Crash Simulation of the Annisquam River Bridge for Report 350 Test level three Conditions

August 27, 2007



Authors
Malcolm H. Ray, P.E., Ph.D
Mario Mongiardini
Department of Civil and Environmental Engineering
Worcester Polytechnic Institute
100 Institute Road
Worcester, MA 01609

Sponsor
Mr. Joseph P. Gill
President
Gill Engineering Associates
85 Franklin Street
Suite 2
Needham MA 02494

Introduction

The Massachusetts Highway Department (MHD) is re-designing the bridge railing for the Annisquam River Bridge in Gloucester, Massachusetts (i.e., Bridge No. G-05-017). MHD would like to use a version of the Minnesota Type Three Combination Bridge Railing which was successfully tested by the University of Nebraska for NCHRP Report 350 Test Level 4 conditions in 1996. [1,2] This system is included in a list of FHWA accepted bridge railings in a memorandum dated May 30, 1997.[3]

MHD would like to modify the bridge railing to conform to the particular design requirements of the Annisquam River Bridge. For historic and aesthetic reasons, MHD would like to use a 32-inch rather than the crash tested 36-inch high bridge railing. In addition, a Test level three system is considered appropriate by MHD for this location since truck traffic is relatively modest (i.e., about five percent) whereas the crash tested version of the Minnesota Type Three Combination Bridge Railing exceeds the design requirements since it is a Test level four system. Changes anticipated include lowering the rail height to 32 inches, making the traffic face of the railing vertical, changing the curb from 20 inches to 17 inches and eliminating the grout pad for the steel post base plate.

The MHD Division of Bridges and Structures requested that researchers at WPI evaluate the new bridge railing design using LS-DYNA finite element simulation to determine if the new configuration satisfies Report 350 Test level three conditions. The following sections present the results of the finite element simulation and assessment of the proposed modifications for the Annisquam River Bridge.

Background

A crash test report documenting the performance of the Minnesota Combination Bridge Railing No. Three was obtained from the University of Nebraska's (UNL) Midwest Roadside Safety Facility (MwRSF). The barrier consists of a concrete parapet with a brush curb and metal rail as shown in Figures 1 and 2. The full-scale crash testing documented in the report involved impacts with a 17,560-lbs (8,000-kg) single-unit truck, a 4,390-lb (2,000-kg) pickup truck, and a 1,800-lbs (820- kg) small car (i.e., Test level four). All the tests were performed using a 116-ft long test installation of the bridge railing connected to a simulated concrete deck.

The initial design of the Minnesota Type Three Combination Bridge Rail was changed several times during the testing program in order to improve its safety performance. In particular, the bridge rail design was modified following the pickup truck test to reduce the potential for wheel snagging by extending both the tubular rail and concrete parapet four inches (102 mm) closer to the roadway. This reduces the effective width of the exposed curb and reduces the tendency for the vehicle tire to climb up the curb. After this modification was made, the system was retested in another pickup truck test. The safety performance of this system was found to be acceptable, meeting the safety standards of Report 350 test 4-11. Only the last pickup truck test and small car

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[1] See http://www.fhwa.dot.gov/bridge/bridgerail/br053505.cfm .
[2] B. G. Pfiefer, J. C. Holloway, R. K. Faller and B. T. Rosson, "Test Level 4 Evaluation of the Minnesota Combination Bridge Rail," Report No. MN/RC 96/08, Midwest Roadside Safety Facility, University of Nebraska, Lincoln, NE (March 1996).
[3] http://safety.fhwa.dot.gov/roadway_dept/road_hardware/bridgerailings.htm

tests were used in this research since those two tests corresponded to the final design recommended by the MwRSF researchers and only the performance in tests 3-10 and 3-11 (i.e., the small car and pickup truck tests) are relevant to assessing the barrier for the test level three conditions required by MHD for the Annisquam Bridge.

The original design of the Minnesota Type Three Combination Bridge Railing consisted of the following five major structural components (i.e., see Figure 1):

1. A simulated concrete bridge deck,
2. A 6-inch (152 mm) high concrete curb,
3. A 20-inch (508 mm) high concrete parapet,
4. A TS 6 x 3 x ¼ rectangular structural steel tube mounted on,
5. 10.25-inch (260 mm) high TS 6 x 6 x ¼ steel posts.

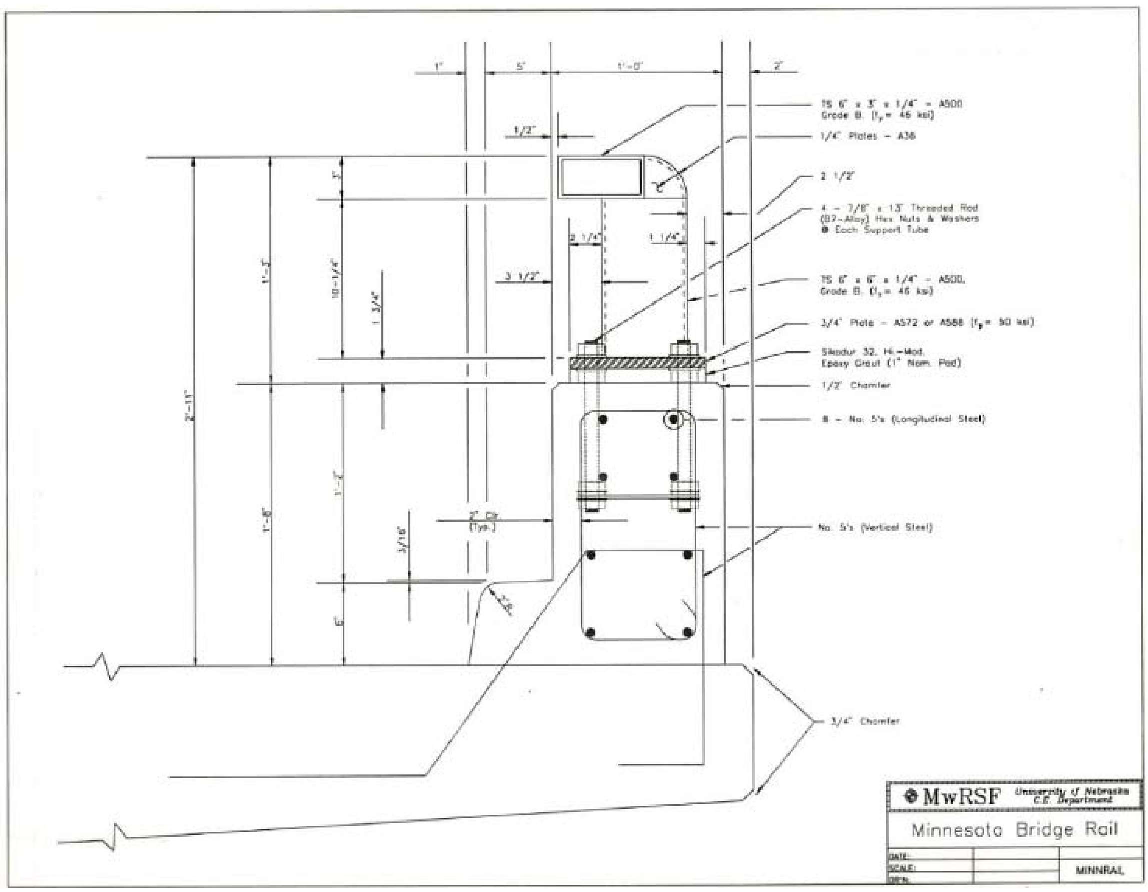


Figure 1. Cross-section of the original crash-tested version of the Minnesota Type Three Combination Bridge Railing.[2]

Figure 2 shows the actual bridge railing built for the crash test at MwRSF.

Figure 2. MwRSF test installation of the Minnesota Type Three Combination Bridge Railing. [2]

During the pickup truck test of the original design (i.e.,Figure 1), a certain amount of wheel snagging occurred on the posts supporting the steel rail. To minimize the chance of snagging, the original design was modified by extending both the tubular rail and concrete parapet four inches toward the roadway as shown in Figure 3. The rail was extended by welding a TS 4 x 3 x ¼ steel tube to the existing TS 6 x 3 x ¼ railing and extending the concrete parapet four inches closer to the roadway as shown in Figure 3.

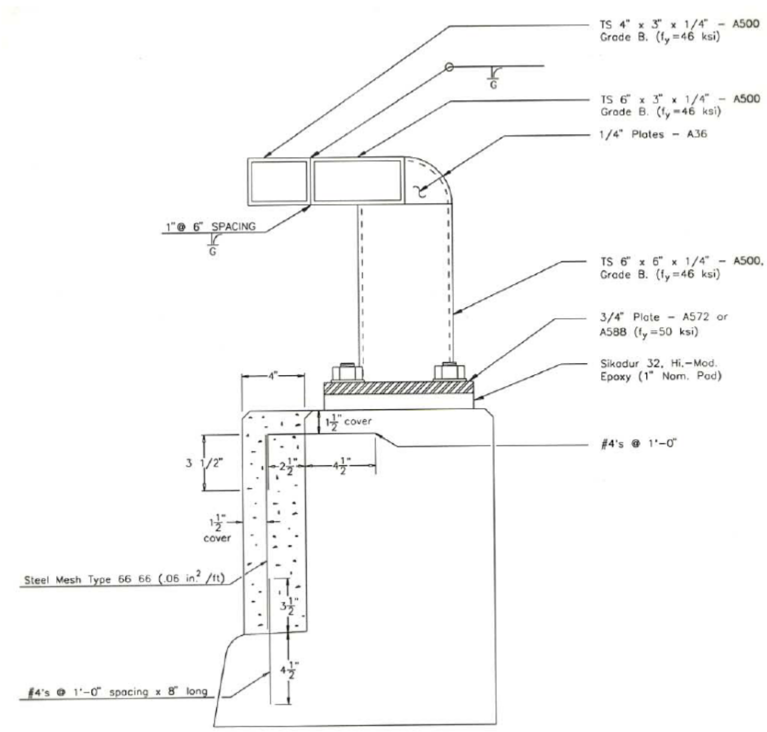


Figure 3. Minnesota Type Three Combination Bridge Railing – modified design.[2]

A reverse cable tow system was used to propel the test vehicle in each test. During the test, the accelerations along the longitudinal, lateral, and vertical directions and the vehicle's angular rates were measured using appropriate devices mounted on the vehicles. Each crash test was filmed using high-speed cameras operating at 500 frames/sec. The details of the crash test results can be found in the crash test report but, in summary, the final design passed all the requirements for test level four.[2]

Validation

A finite element model of the crash tested Minnesota Type Three Combination Bridge Railing was created based on the test report from MwRSF. This was necessary to demonstrate that the finite element model produces correct results with respect to the crash tested results. This is particularly important since MHD would like to avoid performing full-scale crash tests so it is important to establish confidence that the simulation replicates the results of the existing tests. When the finite element model is shown to produce results that correspond with the full-scale crash tests performed by MwRSF, then the finite element model can then be used to assess the modifications desired by MHD. Since MHD desires a test level three system, only the small car (i.e., test 3-10) and pickup truck (i.e., test 3-11) tests were used for validation of the finite element simulation model.

Finite Element Model

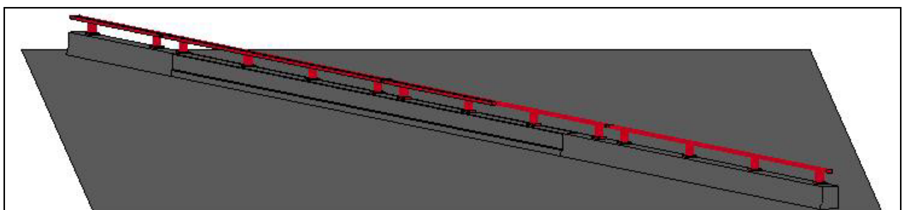
<u>Railing</u>

The Minnesota Combination Bridge Railing is composed of a concrete parapet and a tubular steel rail. The concrete parapet is a large, bulky and heavy component of the barrier; therefore, it was modeled using solid elements with the conventional density of concrete. In the area of the impact between the vehicle and the barrier, the concrete was characterized as an elastic material with properties of concrete as summarized in Table 1 while the part of the concrete parapet away from the impact zone used a rigid material.

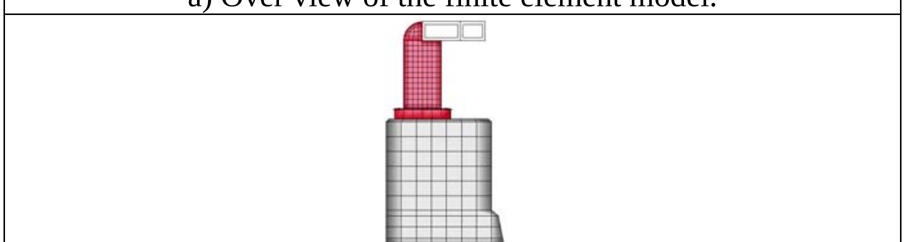
Table 1. Steel and concrete properties used in the FE model of the railing.

	Concrete	**Steel**
LSDYNA material type and number	*MAT_ELASTIC* (20)	*MAT_PIECEWISE_LINEAR_PLASTICITY* (24)
Density [lb/in^3]	0.0867	0.284
Elastic modulus (E) [ksi]	3,000	30,000
Poisson's modulus	0.24	0.30
Yielding stress [ksi]	N / A	50

The steel rail was modeled using shell elements with the same geometry as the actual design used in the full-scale crash tests for both the pickup truck test and the small car test. The density of the mesh was highest in the area of impact and reduced somewhat toward the end of the barrier. The steel properties were defined according to the typical values for the steel used in roadside safety devices and are summarized in Table 1. The actual railing is integrally cast into the bridge deck so the base of the finite element model was rigidly constrained at the bridge deck level. Figure 4 shows an over view of the finite element model of the Minnesota Type Three Combination Bridge Railing developed for the validation with the crash tests.



a) Over view of the finite element model.



b) Cross-section of the finite element model.

Figure 4. Finite element model of the Minnesota Type Three Combination Bridge Rail.

1,800-lbs Passenger Car

The 1,800-lbs small car model used in the simulation of the Report 350 test 3-10 was the model of a Geo-Metro developed by Anghileri at Politecnico di Milano (Figure 5). [1] This model has been successfully used in numerous previous simulations of Report 350 test 3-10 conditions. The original model was characterized by an inertial mass of 2020-lbs so it was necessary to reduce the total mass for this simulation in order to exactly match the crash test. The model of the Geo-Metro used in the simulation is very similar to the Ford Festiva used in the crash test and the Geo Metro meets the requirements for the Report 350 820C vehicle.

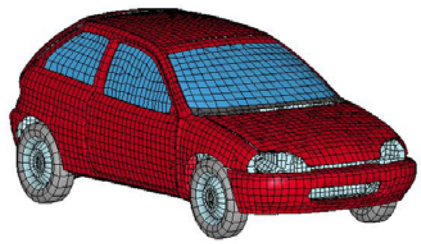


Figure 5. Finite element model of the Geo Metro.

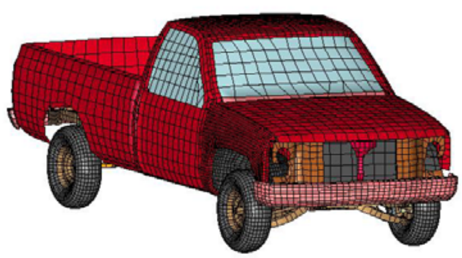


Figure 6. Finite element model of the Chevrolet C2500 pickup truck.

4,390-lbs Pickup Truck

The 4,390-lbs pickup truck model used for the simulation of the test Report 350 3-11 was a finite element model of a Chevrolet C2500 pickup as shown in Figure 6.[2] This model has also been used in numerous simulations of Report 350 test 3-11 conditions and has been found to be very reliable.[3,4,5] Both the inertial and dimensional properties of this model are very similar to those of the actual pickup truck used in the full-scale crash test

[1] Department of Aerospace engineering - Politecnico di Milano, “Geo-Metro Finite Element model (GM_R3): Improvements of Steering System and Suspensions”, Robust Project, Deliverable 5-006, 2006.

[2] P. Tiso, C. A. Plaxico and M. H. Ray, "An Improved Truck Model for Roadside Safety Simulations: Part II -- Suspension Modeling," Transportation Research Record No. 1797, Transportation Research Board, Washington, D.C., 2002.

[3] M. H. Ray, E. Oldani and C. A. Plaxico, "Design and Analysis of an Aluminum F-Shape Bridge Railing," In International Journal of Crashworthiness, Vol. 9 No. 4 pp. 349-363, London, U.K. 2004.

[4] M. H. Ray, C. A. Plaxico, K. E. Engstrand and R. G. McGinnis "Improvements to the Weak-Post W-Beam Guardrail," Transportation Research Record No. 1743,Transportation Research Board, Washington, D.C., 2001.

[5] C. A. Plaxico and M. H. Ray, "Comparison of the Impact Performance of the G4(1W) and G4(2W) Guardrail Systems Under NCHRP Report 350 Test 3-11 Conditions," In Roadside Safety Features and Hydraulic, Hydrology and Water Quality Issues, Transportation Research Record No. 1720, Transportation Research Board, Washington, D.C., 2000.

vehicle even though the crash tested vehicle was a Ford F250. Both the Chevrolet C2500 and the Ford F250 are acceptable Report 350 2000P test vehicles.

Simulation of test 4-10

The impact was arranged such that the vehicle struck the bridge railing at a location 4.33 inches upstream of the centerline of the eight posts in the test installation. The impact velocity was 61 mi/hr and the impact angle was 20.6 degrees. These impact conditions are exactly those observed in the full scale crash test performed at the MwRSF.

Upon the impact with the concrete parapet, the vehicle right-front corner crushed inward and the vehicle began to be redirected. The vehicle became parallel to the railing and was eventually redirected with an exit angle of 4.7 degrees compared to 7.5 degrees in the physical crash test. The overall behavior of both the crash test and the simulation are very similar as demonstrated by Figures 7 and 8. The only noticeable difference between the numerical simulation and the full-scale test is that the impact front tire in the test was ruptured causing the impact-side front corner to drop down somewhat whereas the tire did not rupture in the finite element simulation.

The Report 350 evaluation criteria for test 4-10 are shown in Table 2 for both the full-scale crash test and the finite element simulation. The most important evaluation criteria for test 4-10 are generally considered to be the occupant impact velocity and ridedown accelerations. The simulated occupant impact values were generally within 10 percent of the actual values. The ridedown accelerations were higher in both the longitudinal and lateral directions but this is conservative. In any case, all the test and simulated values were well within the maximum allowable values as shown in Table 2.

As in the actual test, the damage to the railing in the finite element simulation was negligible. Figure 9 shows a comparison of the permanent deformations of the vehicle between the simulation and the full-scale test. The vehicle in the simulation experienced very similar body deformations to the test which, in both cases, was minor. As mentioned above, the only difference was the impact side tire was not ruptured in the simulation.

The simulation resulted in barrier performance, vehicle trajectory, vehicle damage and evaluation parameters that indicate that the simulation accurately replicates the full-scale crash test.

Full-scale crash test	***Simulation***
	
	
	
	
	

Figure 7. Downstream impact sequence of Report 350 test 4-10 for the original Configuration - full-scale test (left) and finite element simulation (right).

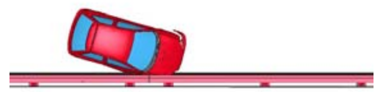
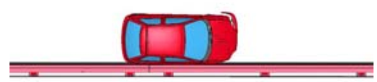
Full-scale crash test	***Simulation***
	
	
	
	
	

Figure 8. Overhead impact sequence of Report 350 test 4-10 for the original Configuration - full-scale crash test (left) and finite element simulation (right).

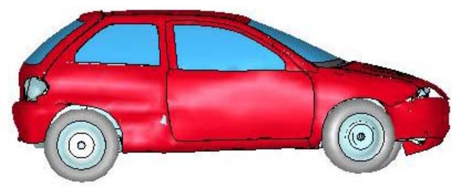
Full-scale crash test	***Simulation***
	
	

Figure 9. Post-test vehicle damage in Report 350 test 4-10 of the original configuration - full-scale test (left) and finite element simulation (right).

Table 2. Report 350 evaluation criteria for test 4-10 on the Minnesota Type Three Combination Bridge Railing – test (left) and simulation (right).

Evaluation Factors		Evaluation Criteria			Crash Test	FE Simulation
Structural Adequacy	A.	Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.			Passed	Passed
	B.	The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.			NA	NA
	C.	Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.			NA	NA
Occupant Risk	D.	Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone.			Passed	Passed
	E.	Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.			NA	NA
	F.	The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable.			Passed	Passed
	G.	It is preferable, although not essential, that the vehicle remain upright during and after collision.			NA	NA
	H.	Occupant impact velocities should satisfy the following:				
		Occupant Impact Velocity Limits (ft/s)				
		Component	Preferred	Maximum		
		Longitudinal and Lateral	30	40	16.4 ft/s 27.82 ft/s	14.1 ft/s 25.9 ft/s
		Longitudinal	10	15	NA	NA
	I.	Occupant ridedown accelerations should satisfy the following:				
		Occupant Ridedown Acceleration Limits (g's)				
		Component	Preferred	Maximum		
		Longitudinal and Lateral	15	20	2.6 g's 10.6 g's	5.8 g's 15.2 g's
	J.	(Optional) Hybrid III dummy responses.			NA	NA
Vehicle Trajectory	K.	After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.			Passed	Passed
	L.	The occupant impact velocity in the longitudinal direction should not exceed 40 ft/sec and the occupant rideown acceleration in the longitudinal direction should not exceed 20 G's.			Passed	Passed
	M.	The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.			7.5˚ (Passed)	4.7˚(Passed)
	N	Vehicle trajectory behind the test article is acceptable.			NA	NA

Simulation of test 4-11

The test 3-11 impact was arranged such that the vehicle struck the bridge railing at a location 4.9 ft upstream of the second extension joint. The impact velocity was 62.5 mi/hr and the impact angle was 25.9 degrees, exactly the same impact conditions as those observed in the full scale crash test performed at the MwRSF.

A comparison of the results from the simulation and the crash test showed good correlation with respect to the vehicle trajectory and barrier performance as shown in Figures 10 and 11. Upon the impact with the bridge railing, the vehicle right-front corner deformed. The left front tire and, subsequently, the left-rear tire lifted from the ground as the pickup truck rolled in toward the barrier. Both the test and simulation show that the vehicle rolls toward the barrier during the crash. In both cases, the vehicle was redirected, first becoming parallel to the barrier and then redirecting away from the barrier. The simulated vehicle behavior is very close to the behavior actually observed during the full-scale test.

The Report 350 evaluation criteria for test 4-11 are shown in Table 3. While the occupant impact velocity and ridedown acceleration are not required evaluation parameters for this test they were calculated and shown in Table 3 to illustrate the similarity of the test and simulated crash. The simulation agreed with the full-scale crash test with respect to all the evaluation criteria and both the test and simulation are judge to pass the test level three criteria.

The damage to the bridge railing was negligible in both the simulation and crash test. Figure 12 shows a comparison of the vehicle permanent deformation between the simulation and the full-scale test. The simulation correctly replicated the vehicle deformations and the partial failure of the steering system observed in the full-scale crash test.

Based on the comparison of the results of the simulation with the full-scale crash test for both test 4-10 and 4-11, the model of the Minnesota Type Three Combination Bridge Railing can be considered validated for test level three conditions. In the comparisons of both the small car and pickup truck tests, the simulation resulted in the same evaluation parameter as the crash test in every case and numerical values were within 10 percent. Had the simulations been done prior to the crash tests, the results would have accurately predicted the results of the test. The finite element model, therefore, can be used to predict the performance of the modified version of the bridge rail proposed by MHD.

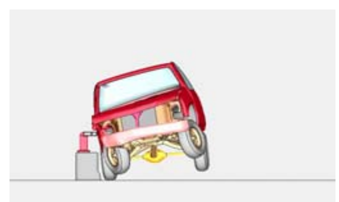
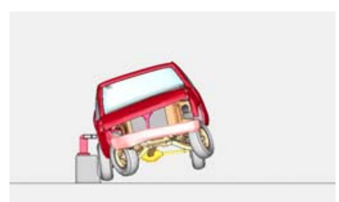
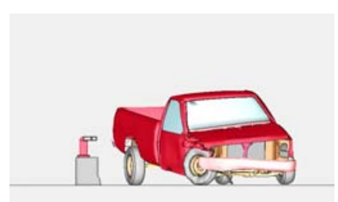
Full-scale crash test	***Simulation***
	
	
	
	
	

Figure 10. Downstream impact sequence of Report 350 test 4-11 of the original configuration - full-scale test (left) and finite element simulation (right).

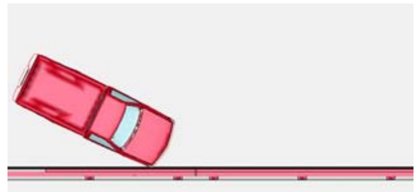
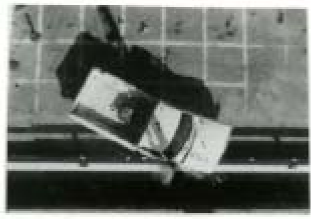
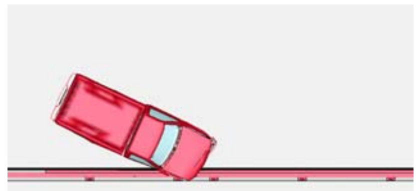
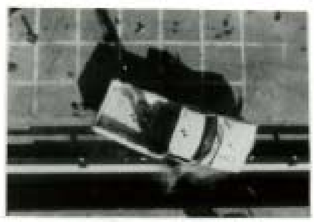
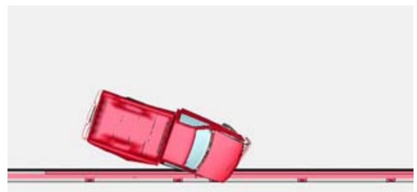
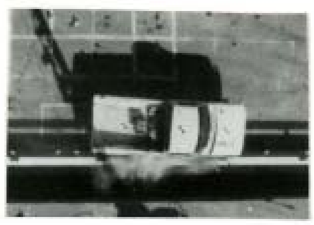
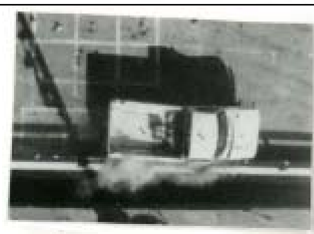
Full-scale crash test	***Simulation***
	
	
	
	
	

Figure 11. Overhead impact sequence of Report 350 test 4-11 of the original configuration - full-scale test (left) and finite element simulation (right).

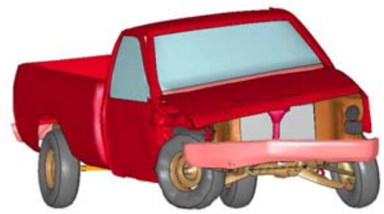
Full-scale crash test	***FE simulation***
	
	

Figure 12: Post-test vehicle damage in Report 350 test 4-11 of the original configuration – full-scale test (left) and finite element simulation (right).

Table 3. Report 350 evaluation criteria for test 4-11 on the Minnesota Type Three Combination Bridge Railing – test (left) and simulation (right).

Evaluation Factors		Evaluation Criteria	Crash Test	FE Simulation
Structural Adequacy	A.	Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Passed	Passed
	B.	The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.	NA	NA
	C.	Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.	NA	NA
Occupant Risk	D.	Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone.	Passed	Passed
	E.	Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.	NA	NA
	F.	The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable.	Passed	Passed
	G.	It is preferable, although not essential, that the vehicle remain upright during and after collision.	NA	NA
	H.	Occupant impact velocities should satisfy the following: Occupant Impact Velocity Limits (ft/s) Component / Preferred / Maximum		
		Longitudinal and Lateral / 30 / 40	25.26 ft/s 24.6 ft/s	21.3 ft/s 30.5 ft/s
		Longitudinal / 10 / 15		
	I.	Occupant ridedown accelerations should satisfy the following: Occupant Ridedown Acceleration Limits (g's) Component / Preferred / Maximum		
		Longitudinal and Lateral / 15 / 20	5.2 g's 9.3 g's	-9.8 g's 9.7 g's
	J.	(Optional) Hybrid III dummy responses.	NA	NA
Vehicle Trajectory	K.	After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	Passed	Passed
	L.	The occupant impact velocity in the longitudinal direction should not exceed 40 ft/sec and the occupant rideown acceleration in the longitudinal direction should not exceed 20 G's.	Passed	Passed
	M.	The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.	1˚ (Passed)	3.8˚(Passed)
	N	Vehicle trajectory behind the test article is acceptable.	NA	NA

Annisquam River Bridge Model

Report 350 test level three involves two crash tests, one with a 1,800-lbs passenger car striking the barrier at 20 degrees and 62 mi/hr and another with a 4,390-lbs full-size pickup truck striking the barrier at 25 degrees and 62 mi/hr. As demonstrated in the last section, a finite element model of the Minnesota Type Three Combination Bridge Railing resulted in good agreement with the crash tests 4-10 and 4-11. Both test levels three and four use the same conditions for the small car and pickup truck tests. The next step was to take the validated model of the Minnesota Type Three Combination Bridge Railing and change it such that it represents the cross-section desired by MHD for the Annisquam River Bridge.

The modifications MHD would like to make to adapt the original Minnesota Type Three Combination Bridge Railing to the Annisquam River Bridge include lowering the rail height to 32 inches, making the traffic face of the railing vertical, changing the curb from 20 inches to 17 inches and eliminating the grout pad for the steel post base plate. Figure 13 shows the cross section of the modified bridge railing considering all these modifications.

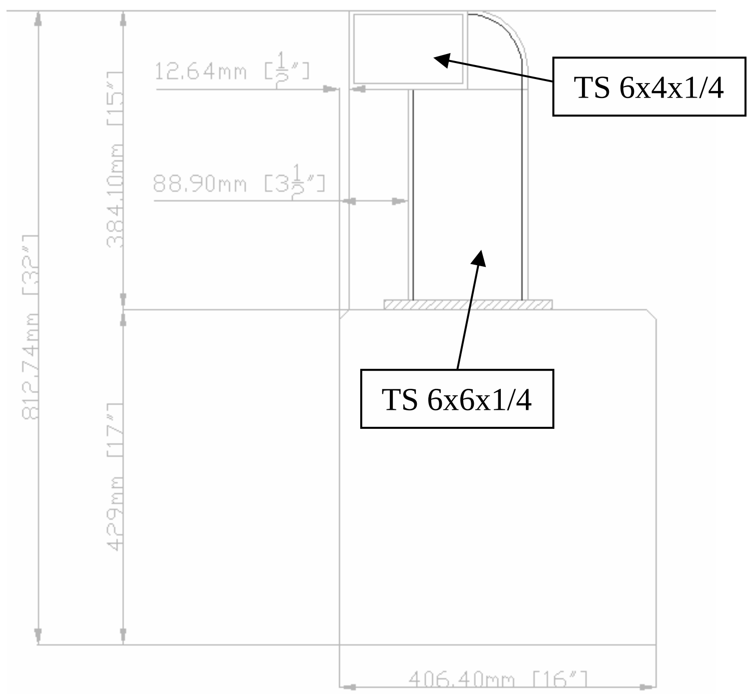


Figure 13. Proposed Annisquam River Bridge railing (cross section).

Four different modified designs of the crash tested Minnesota Type Three Combination Bridge Railing were examined for use on the Annisquam River Bridge.[1] This section of the report describes the modifications for each of the four designs and the corresponding results obtained from the finite element simulations. The modifications involve the height and the thickness of the concrete wall, the geometry of the steel posts and the steel rail tube. The particular characteristics of each design case are shown in Table 4.

Table 4. Design Alternatives for the proposed Annisquam River Bridge Railing.

Design Feature	**Design Alternative**						
	Orig.	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**
Curb	Yes	Yes	No	No	No	No	No
Parapet Height (inches)	20	17	17	20	17	17	17
Parapet Width (inches)	16	12	12	12	16	16	16
Post Type (TS)	5x7x1/4	6x6x1/4	6x6x1/4	6x6x1/4	5x5x1/4	5x5x1/4	5x5x1/4
Rail Type (TS)	10x4x5/16	6x3x1/4	6x3x1/4	6x4x1/4	10x4x5/16	6x3x1/4	6x3x1/4
Total Height (inches)	36	31	31	32	32	32	32

For each of the design alternatives shown in Table 4, the finite element model was obtained starting from the model of the Minnesota Type Three Combination Rail discussed in the first part of this report. Figure 14 shows the cross section of each of the four designs alternatives.

For all four designs, the initial impact conditions for both Test 3-10 and Test 3-11 were the same as those in the test level four validations. For the test 3-10 simulations, the critical impact point (CIP) was the same as in the actual full-scale crash test of the original Minnesota Combination bridge Railing, 67.7 ft (20.6 m) downstream of the barrier beginning (e.g., roughly 1/2 of the barrier length) near the expansion joint between two steel rails. The impact velocity was 61 mi/hr (100 km/h) and the impact angle was exactly 20 degrees, corresponding to an impact severity of 38.8 kJ. The point where the vehicle struck the bridge railing was 26 inches (660 mm) upstream of the centerline of post number eight.

For the tests 3-11 simulations, the critical impact point (CIP) was chosen to be 63.3 ft (19.3 m) downstream of the barrier beginning (e.g., roughly 1/2 of the barrier length), 3.9 ft (1.2 m) upstream of the expansion joint between two steel rails. The impact velocity was 61 mi/hr (100 km/h) and the impact angle was exactly 25 degrees, corresponding to an impact severity of 140.4 kJ. The point where the vehicle struck the bridge railing was at a location about 25.6 inches (650 mm) upstream of the centerline of

[1] The Minnesota Combination Bridge railing referred to in this report is the version which has been accepted by FHWA (i.e. design number three of the crash test report).

post eight. The vehicle curb mass was 1990 kg and the final test inertial mass was 2030 kg.

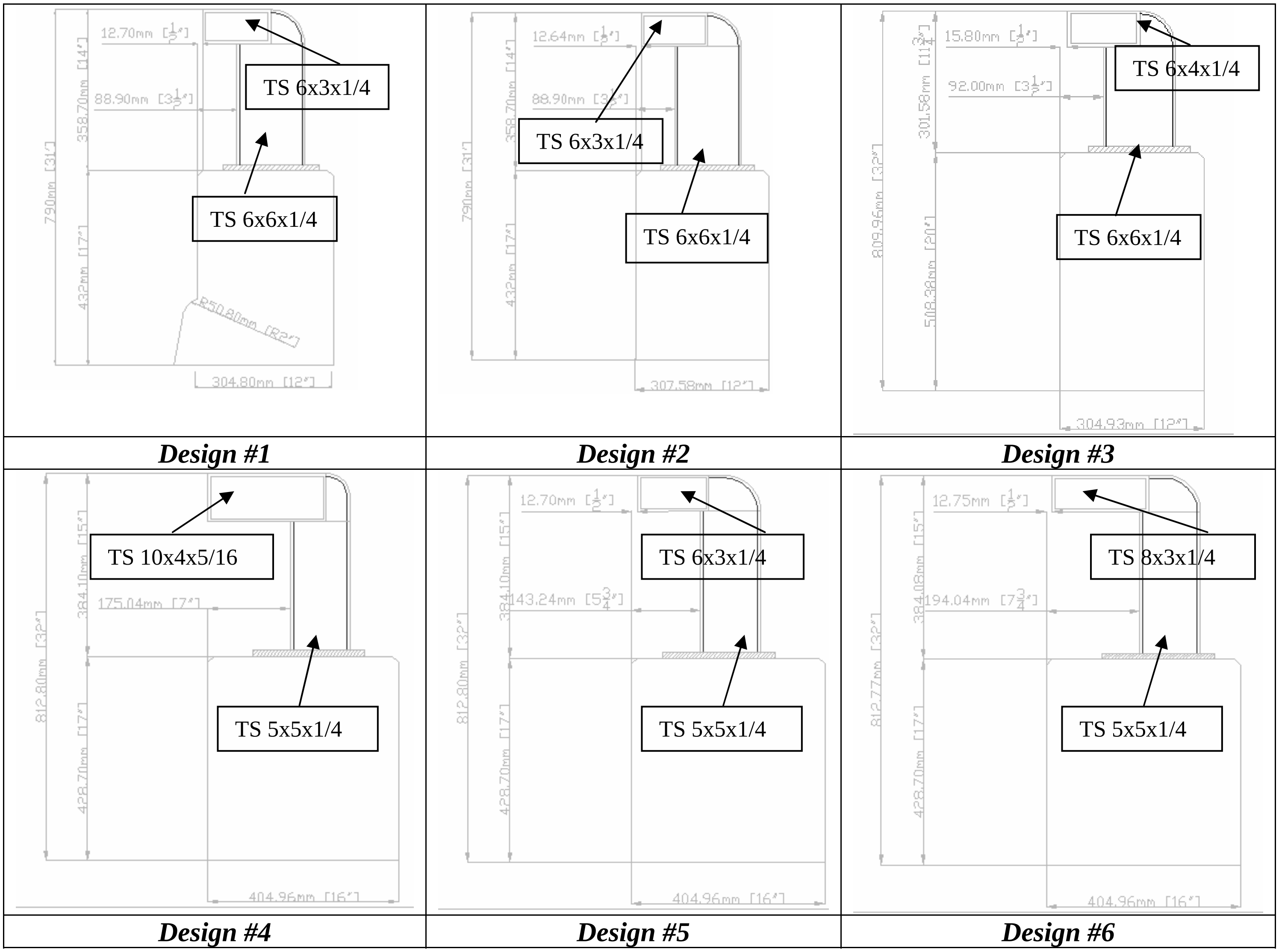


Figure 14. Cross section of the four design alternatives.

A detailed description of the finite element simulations for each of the four design alternatives is given in the following sections

Design #1

Design #1 had the following characteristics with respect to the original Minnesota Combination Bridge Railing:

- The concrete wall was narrowed by 4 inches (from 16 inches to 12 inches),
- The concrete wall was lowered from 20 inches to 17 inches,
- The grout pad was eliminated,
- The tubular steel rail was changed from a 10x4x1/4 to a TS 6x3x1/4 and
- The horizontal distance from the face of the steel tube rail to the face of the concrete was retained as ½ inch.

After these modifications, the barrier overall height was 31 inches. Figure 15 shows the finite element model for Design #1.

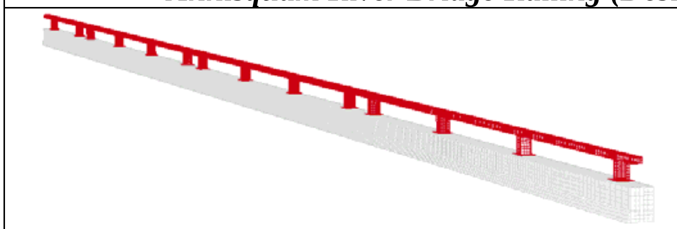
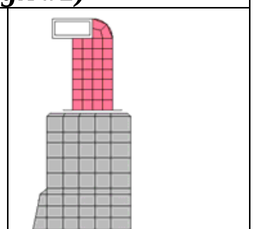
Annisquam River Bridge Railing (Design #1)	
	
a) Over view	***b) Cross-section***

Figure 15. Finite element model of Design #1.

Design #1 – Test 3-10

Figure 16 shows the impact sequence from four different points of view. After the contact against the concrete parapet, the front right wheel was forced to steer and, immediately after, the car body hit the metal tube rail with its front-right headlight. Immediately after, the impacting wheel started riding the curb at the bottom of the concrete wall. This caused the front of the vehicle to lift. Both front wheels lost contact with the ground. Because of the concrete wall reaction force applied to the vehicle right-front corner, the vehicle began to change direction. Due to this reaction force, the vehicle became parallel to the railing and was eventually redirected with an exit angle of 4.5 degrees and a velocity of 52.8 mi/hr (85 km/h). After the rear of the car struck the concrete wall, both the front and rear right hand-side wheels came back in contact with the ground while the left side wheels were still out of contact. The vehicle reached a maximum roll angle of 11.6 degrees. Once the right front wheel came back to the ground, the vehicle rebounded with all the four wheels in contact with the ground. During the impact, the vehicle was lifted 8.6 inches (220 mm) from the ground.

The Report 350 evaluation criteria for test 3-11 are shown in Table 5. Also, the evaluation criteria for the proposed update to Report 350 are shown in Table 6.
The theoretical occupant impact velocities (OIV) in the longitudinal and lateral directions were 14.4 ft/s (4.4 m/s) and 25.6 ft/s (7.8 m/s) respectively. The theoretical ridedown accelerations in longitudinal and lateral directions were -4.5 g's and -15.4 g's. The

Theoretical Head Impact Velocity (THIV) was 19.32 mi/hr (31.1 km/h) and the Post Impact Head Deceleration (PHD) was 16.1 g's. The Acceleration Severity Index (ASI) was 1.79. The simulation of test 3-10 resulted in evaluation parameters that indicate a passing test.

The barrier damage was negligible. All components were judged to be reusable with a minor permanent deformation of the steel tube rail in the area of the impact. No significant debris was expelled from the both the bridge railing and the test vehicle during the impact.

A summary of the vehicle damage is shown in Figure 17. The impact resulted in a crushed front-right headlight and some bumper deformation. The right-front fender and the right door were slightly damaged but there was no intrusion inside the vehicle. The right front suspension was broken and the steering system was locked with the wheels turned towards right. No portions of the vehicle were dislodged or released. There was negligible deformation of the vehicle interior and the windshield was not damaged.

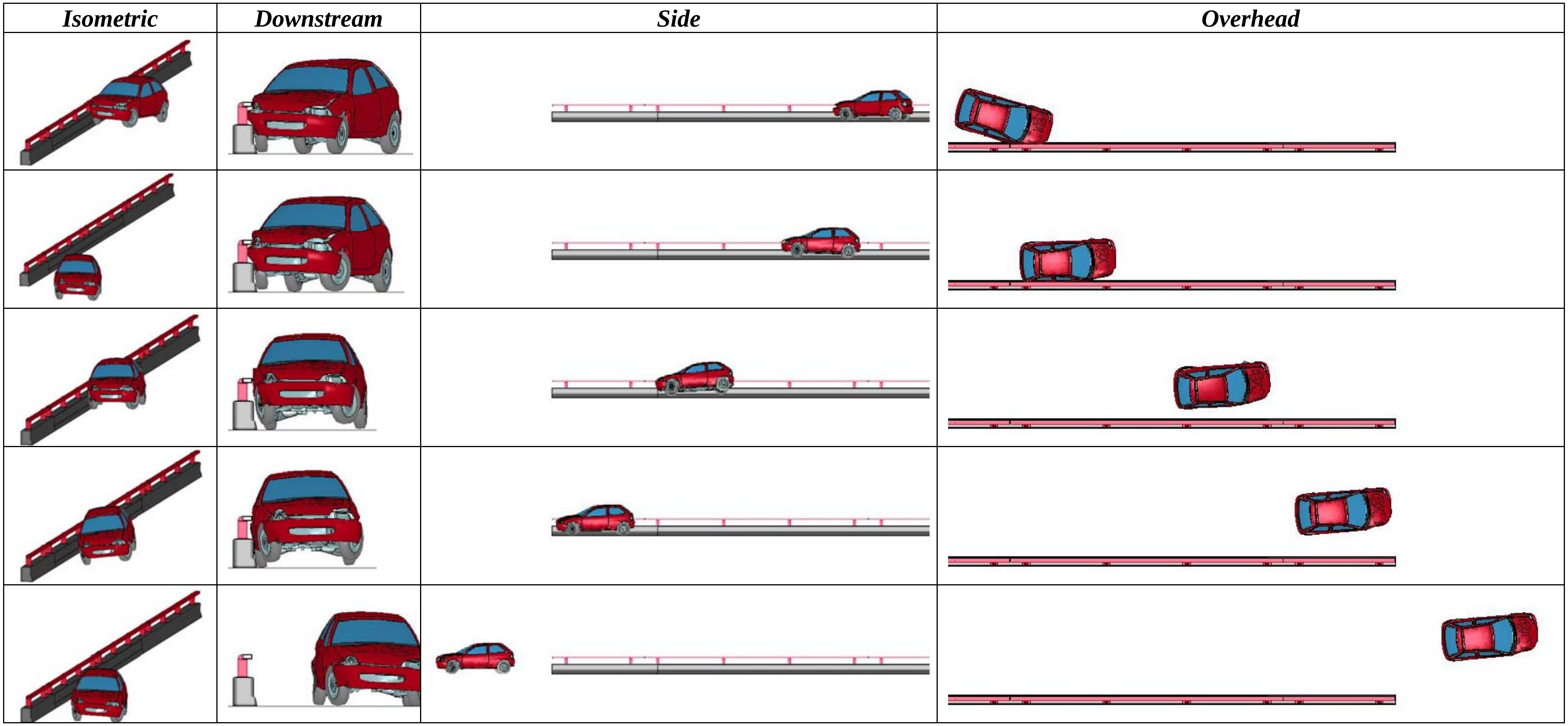


Figure 16. Impact sequence – Annisquam River Bridge Railing Test 3-10 (Design #1).

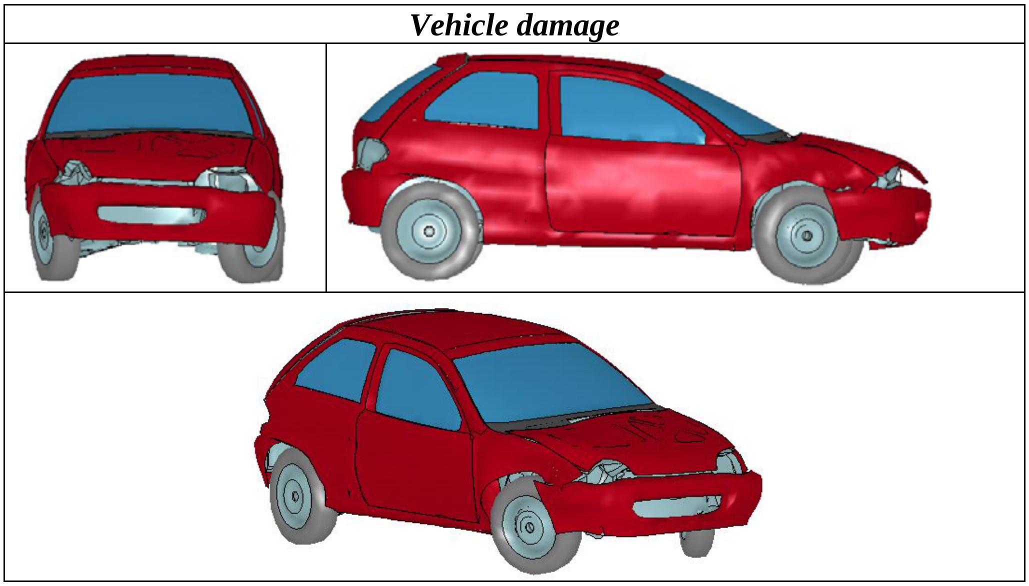


Figure 17. Vehicle damage –Test 3-10 (Design #1).

Design #1 -- Test 3-11

Figure 18 shows the impact sequence from four different points of view. Upon impact with the bridge railing, the pickup truck right-front corner crushed against the steel rail and the bumper contacted one of the posts. During this initial phase of the impact, the front part of the vehicle snagged one of posts of the steel rail. As a consequence of the reaction force exerted by the concrete wall, the impacting front right wheel steered and the truck started redirecting away from the barrier. Because of the lifting effect due to the curb at the bottom of the concrete wall, both front wheels lost contact with the ground. When the rear right wheel came in contact with the concrete wall, the vehicle reached the maximum roll angle of 37 degrees and all four wheels lost contact with the ground. The vehicle became parallel to the barrier and then was redirected away towards the roadside face with an exit angle of 2.8 degrees and a velocity of 45 mi/hr (72.7 km/h). In the exit phase, the vehicle remained on its two impact-side wheels with a relatively high roll angle.

The Report 350 evaluation criteria for test 3-11 are shown in Table 5. Also, the evaluation criteria for the proposed update to Report 350 are shown in Table 6.
The theoretical occupant impact velocities (OIV) in the longitudinal and lateral directions were 23.3 ft/s (7.1 m/s) and 30.2 ft/s (9.2 m/s) respectively. The theoretical ridedown accelerations in longitudinal and lateral directions were -3.8 g's and -8 g's. The theoretical Head Impact Velocity (THIV) was 25.3 mi/hr (40.8 km/h) and the Post Impact Head Deceleration (PHD) was 8.3 g's. The Acceleration Severity Index (ASI) was 2.05. All the parameters indicate that this would be judged a successful test according to both criteria.

The barrier damage was negligible. All components were judged to be reusable with minimal permanent deformation of the steel tube rail in the area of the impact. The damage around the zone of the rail sleeve, where the impact took place, was minor and is considered not serious enough to require repair. No debris was expelled from either the bridge railing or the test vehicle during the impact.

A summary of the vehicle damage is shown in Figure 19. The front right part of the vehicle body and bumper was crushed; the suspension of the front right wheel, which first impacted against the concrete wall, was broken and the wheel remained turned inward. The hood bent due to buckling and the bumper was crushed. The right-front fender was damaged as well and the right door was slightly damaged. No significant deformation of the vehicle interior was observed. The rear right side of the pickup truck was slightly damaged due to the impact against the concrete wall when the vehicle was redirected by the railing. No portions of the vehicle were dislodged or released.

While the evaluation criteria for both Report 350 and its update indicate acceptable performance, the amount of snagging between the pickup truck and the posts was not considered desirable. Also, the curb tends to cause both the small car and pickup truck to launch and create additional roll angle and a less than desirable post-impact trajectory. For these reasons, some additional changes were made to improve the performance.

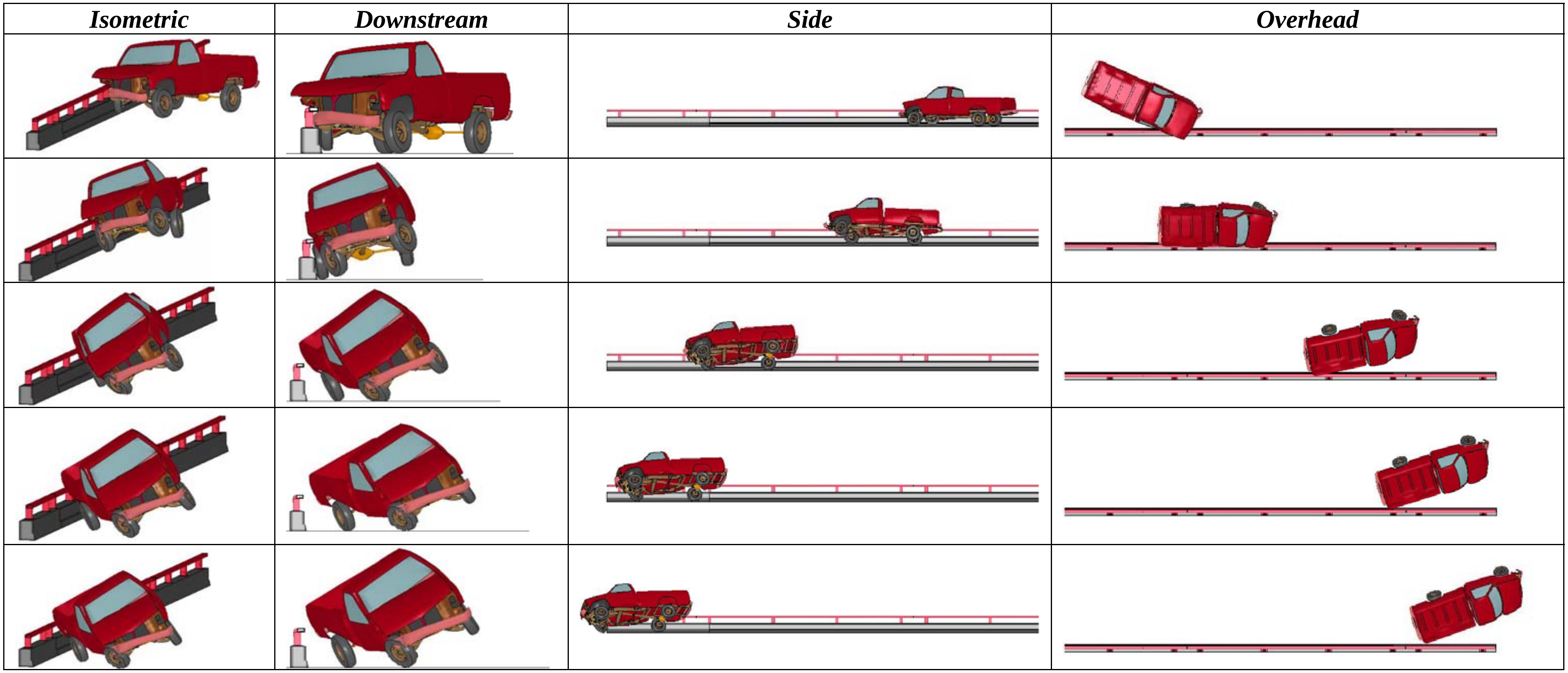


Figure 18. Impact sequence – Annisquam River Bridge Railing Test 3-11 (Design #1)

Vehicle damage

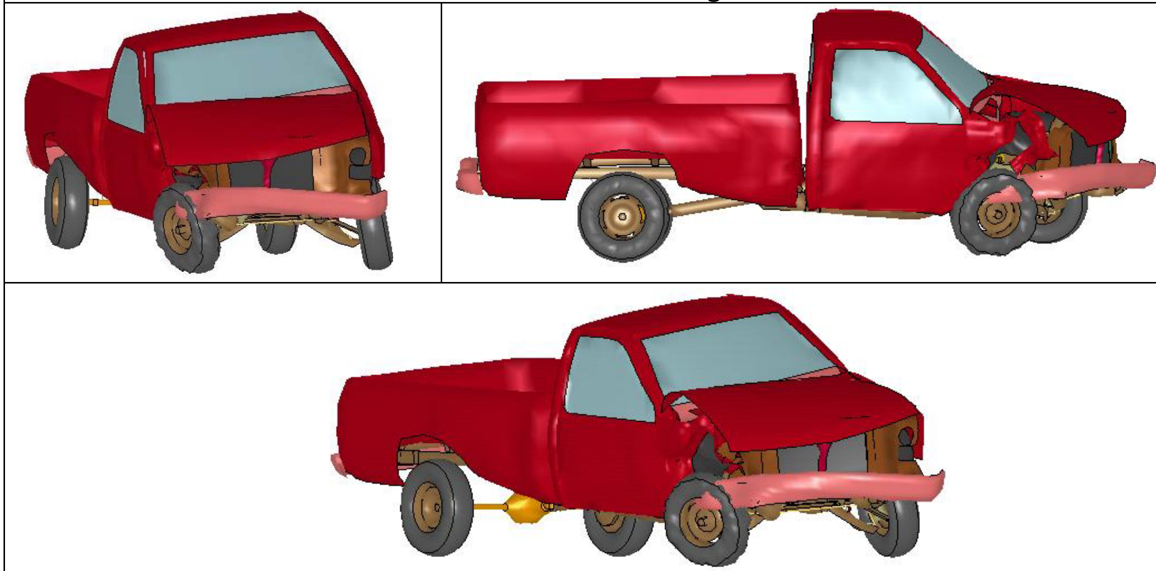


Figure 19. Vehicle damage –Test 3-11 (Design #1).

Table 5. NCHRP Report 350 Evaluation criteria for Design #1 - Test 3-10 (left) and Test 3-11 (right).

<table>
<tr><th>Evaluation Factors</th><th colspan="4">Evaluation Criteria</th><th>Test 3-10</th><th>Test 3-11</th></tr>
<tr><td rowspan="3">Structural Adequacy</td><td>A.</td><td colspan="3">Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>B.</td><td colspan="3">The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.</td><td>NA</td><td>NA</td></tr>
<tr><td>C.</td><td colspan="3">Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.</td><td>NA</td><td>NA</td></tr>
<tr><td rowspan="15">Occupant Risk</td><td>D.</td><td colspan="3">Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>E.</td><td colspan="3">Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver’s vision or otherwise cause the driver to lose control of the vehicle.</td><td>NA</td><td>NA</td></tr>
<tr><td>F.</td><td colspan="3">The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>G.</td><td colspan="3">It is preferable, although not essential, that the vehicle remain upright during and after collision.</td><td>NA</td><td>NA</td></tr>
<tr><td rowspan="5">H.</td><td colspan="3">Occupant impact velocities should satisfy the following:</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td colspan="3">Occupant Impact Velocity Limits (ft/s)</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>30</td><td>40</td><td>14.4 ft/s
25.6 ft/s</td><td>23.3ft/s
30.2 ft/s</td></tr>
<tr><td>Longitudinal</td><td>10</td><td>15</td><td>NA</td><td>NA</td></tr>
<tr><td rowspan="4">I.</td><td colspan="3">Occupant ridedown accelerations should satisfy the following:</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td colspan="3">Occupant Ridedown Acceleration Limits (g’s)</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>15</td><td>20</td><td>-4.5 g’s
-15.4 g’s</td><td>-3.8 g’s
-8 g’s</td></tr>
<tr><td>J.</td><td colspan="3">(Optional) Hybrid III dummy responses.</td><td>NA</td><td>NA</td></tr>
<tr><td rowspan="4">Vehicle Trajectory</td><td>K.</td><td colspan="3">After collision it is preferable that the vehicle’s trajectory not intrude into adjacent traffic lanes.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>L.</td><td colspan="3">The occupant impact velocity in the longitudinal direction should not exceed 40 ft/sec and the occupant rideown acceleration in the longitudinal direction should not exceed 20 G’s.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>M.</td><td colspan="3">The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.</td><td>4.5˚
(Passed)</td><td>2.8˚
(Passed)</td></tr>
<tr><td>N</td><td colspan="3">Vehicle trajectory behind the test article is acceptable.</td><td>NA</td><td>NA</td></tr>
</table>

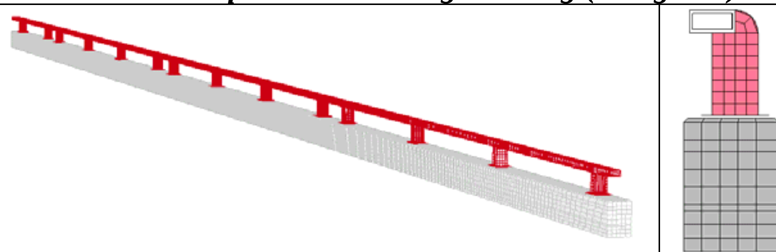
Table 6. NCHRP Report 350 Update Evaluation criteria for Design #1 - Test 3-10 (left) and Test 3-11 (right).

<table>
<tr><th>Evaluation Factors</th><th colspan="4">Evaluation Criteria</th><th>Test 3-10</th><th>Test 3-11</th></tr>
<tr><td rowspan="3">Structural Adequacy</td><td>A.</td><td colspan="3">Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>B.</td><td colspan="3">The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.</td><td>N/A</td><td>N/A</td></tr>
<tr><td>C.</td><td colspan="3">Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.</td><td>N/A</td><td>N/A</td></tr>
<tr><td rowspan="14">Occupant Risk</td><td>D.</td><td colspan="3">Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>E.</td><td colspan="3">Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver’s vision or otherwise cause the driver to lose control of the vehicle.</td><td>N/A</td><td>N/A</td></tr>
<tr><td>F.</td><td colspan="3">The vehicle should remain upright during and after the collision The maximum roll and pitch angles are not to exceed 75 degrees.</td><td>Roll angle: 11.6˚ (Passed)</td><td>Roll angle: 37˚ (Passed)</td></tr>
<tr><td>G.</td><td colspan="3">It is preferable, although not essential, that the vehicle remain upright during and after collision.</td><td>N/A</td><td>N/A</td></tr>
<tr><td rowspan="5">H.</td><td colspan="3">Occupant impact velocities (OIV) should satisfy the following limits:</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td colspan="3">Occupant Impact Velocity Limits (ft/s)</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>30</td><td>40</td><td>14.4 ft/s
25.6 ft/s</td><td>23.3 ft/s
30.2 ft/s</td></tr>
<tr><td>Longitudinal</td><td>10</td><td>15</td><td>NA</td><td>NA</td></tr>
<tr><td rowspan="4">I.</td><td colspan="3">Occupant ridedown accelerations should satisfy the following limits:</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td colspan="3">Occupant Ridedown Acceleration Limits (g’s)</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>15</td><td>20</td><td>-4.5 g’s
-15.4 g’s</td><td>-3.8 g’s
8 g’s</td></tr>
<tr><td>Vehicle Trajectory</td><td>N.</td><td colspan="3">Vehicle trajectory behind the test article is acceptable.</td><td>N/A</td><td>N/A</td></tr>
</table>

Design #2

Design #2 was identical to Design #1 with the exception that the six-inch brush curb was eliminated.. Figure 20 shows the finite element model for Design #2.

Annisquam River Bridge Railing (Design# 2)



a) Over view ***b) Cross-section***

Figure 20. Finite element model of Design #2.

Design #2 -- Test 3-10

Figure 21 shows the impact sequence from four different points of view. After striking the concrete parapet, the front right wheel was steered right and the car hit the metal tube rail with its front-right headlight. Upon the impact with the concrete parapet, the vehicle right-front corner crushed inward and the vehicle began to change direction. Due to the barrier reaction force, the vehicle became parallel to the railing and was eventually redirected with an exit angle of 3.5 degrees and a velocity of 51.6 mi/hr (83 km/h). During the impact, the vehicle was lifted with all four wheels off the ground about two inches (50 mm) resulting in a maximum roll angle of 5.5 degrees. After the first phase during which the vehicle was rebounded by the railing, the car was directed back towards the barrier due to the fact that the front wheels were locked to the right after the impact. This is fairly common during this kind of impact involving rigid concrete barriers.

The Report 350 evaluation criteria for test 3-11 are shown in Table 7 and the evaluation criteria for the proposed update to Report 350 are shown in Table 8. The theoretical occupant impact velocities (OIV) in the longitudinal and lateral directions were 15.4 ft/s (4.7 m/s) and 24.9 ft/s (7.6 m/s) respectively. The theoretical ridedown accelerations in longitudinal and lateral directions were -5.6 g's and -15.4 g's. The Theoretical Head Impact Velocity (THIV) was 20 mi/hr (32.2 km/h) and the Post Impact Head Deceleration (PHD) was 16.6 g's. The Acceleration Severity Index (ASI) was 1.9. All the evaluation criteria indicate that this would be a passing test under both sets of criteria.

The barrier damage was negligible. All components considered to be reusable with minor permanent deformations of the steel tube rail in the area of the impact. No significant debris was expelled from the both the bridge railing and the test vehicle during the impact.

A summary of the vehicle damage is shown in Figure 22. The impact resulted in a crushed front-right headlight with some minor damage to the bumper. The right-front fender and the right door were slightly damaged and there was no intrusion inside the vehicle. The right front suspension failed and the steering system was locked with the wheels turned towards right. No portions of the vehicle were dislodged or released during the crash. There was negligible deformation of the vehicle interior and the windshield was not damaged.

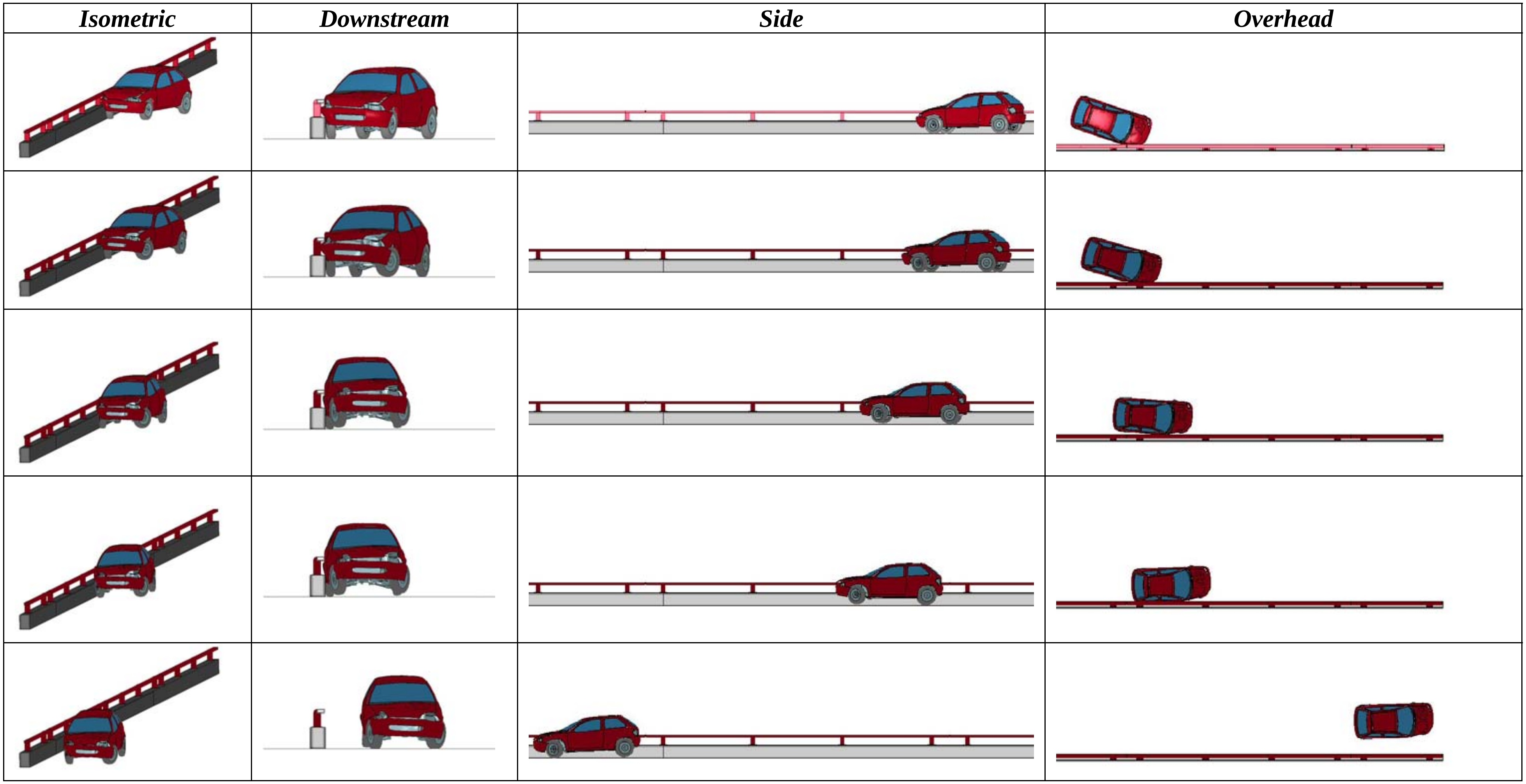


Figure 21. Impact sequence – Annisquam River Bridge Railing Test 3-10 (Design #2).

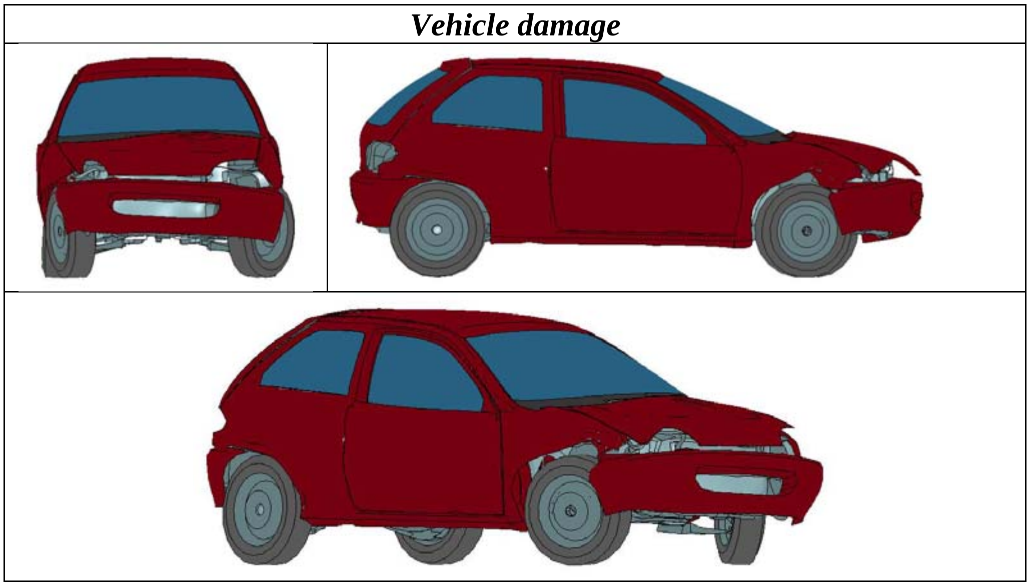


Figure 22. Vehicle damage –Test 3-10 (Design #2).

Design #2 - Test 3-11

Figure 23 shows the impact sequence from four different points of view. Upon impact with the bridge railing, the pickup truck right-front corner crushed. The left front tire and, subsequently, the left-rear tire lifted from the ground as the pickup truck rolled in toward the barrier. When the rear right tire hit the concrete parapet, the rear left tire also lifted off the ground leaving the vehicle sliding parallel to the barrier with just the right wheels on the ground. The vehicle became parallel to the barrier and then was redirected away towards the roadside with an exit angle of 8.5 degrees and a velocity of 66 km/h. During the exit phase, the vehicle remained on its left wheels lifted from the ground, rolled towards the barrier with a maximum angle of 29.3 degrees. Eventually, all four wheels re-contacted the ground.

The Report 350 evaluation criteria for test 3-11 are shown in Table 7 and the evaluation criteria for the proposed update to Report 350 are shown in Table 8. The theoretical occupant impact velocities (OIV) in the longitudinal and lateral directions were 24 ft/s (7.3 m/s) and 29.5 ft/s (9 m/s) respectively. The theoretical ridedown accelerations in longitudinal and lateral directions were -8.3 g's and 6.9 g's. The theoretical Head Impact Velocity (THIV) was 24.8 mi/h (39.9 km/h) and the Post Impact Head Deceleration (PHD) was 9.8 g's. The Acceleration Severity Index (ASI) was 2.04. All these values indicate successful performance in test 3-11 conditions.

The barrier damage was negligible. All components were considered to be reusable since there was minimal permanent deformation of the steel tube rail in the area of the impact. The damage around the zone of the rail sleeve, where the impact took place, was minor and not serious enough to require repair. No debris was expelled from the both the bridge railing and the test vehicle during the impact.

A summary of the vehicle damage is shown in Figure 24. The front right part of the vehicle was crushed; the suspension of the front right wheel, which first impacted against the concrete wall, was broken and the wheel remained turned inward.

Consequently, the steering system was seriously as well. The hood bent due to buckling, the bumper was crushed toward the rear on the right side and the right-front fender was damaged as well. The right door panel was only slightly damaged. No significant deformation of the vehicle interior was observed. The rear right side of the pickup truck was slightly damaged due to the impact against the concrete wall when the vehicle was redirected by the railing. No portions of the vehicle were dislodged or released.

As shown in Tables 6 and 8, removing the brush curb did reduce the maximum roll angle observed for both the small car and pickup truck test. In the small car test, the roll angle was reduced from 11.6 degrees to 5.5 degree, and in the truck test the maximum roll angle was reduced from 37 degrees to 29 degrees. Both vehicles appeared to be more stable in crashes without the brush curb so. The snagging potential for the bumper and hood on the pickup truck test still appeared to be relatively high and this is reflected in the essentially identical values of OIV in the test 3-11 conditions (i.e., 23.3 ft/s Design #1 and 24 ft/s in Design #2). One alternative for reducing the snag potential in the pickup truck test is to raise the height of the concrete parapet from 17 to 20 inches.

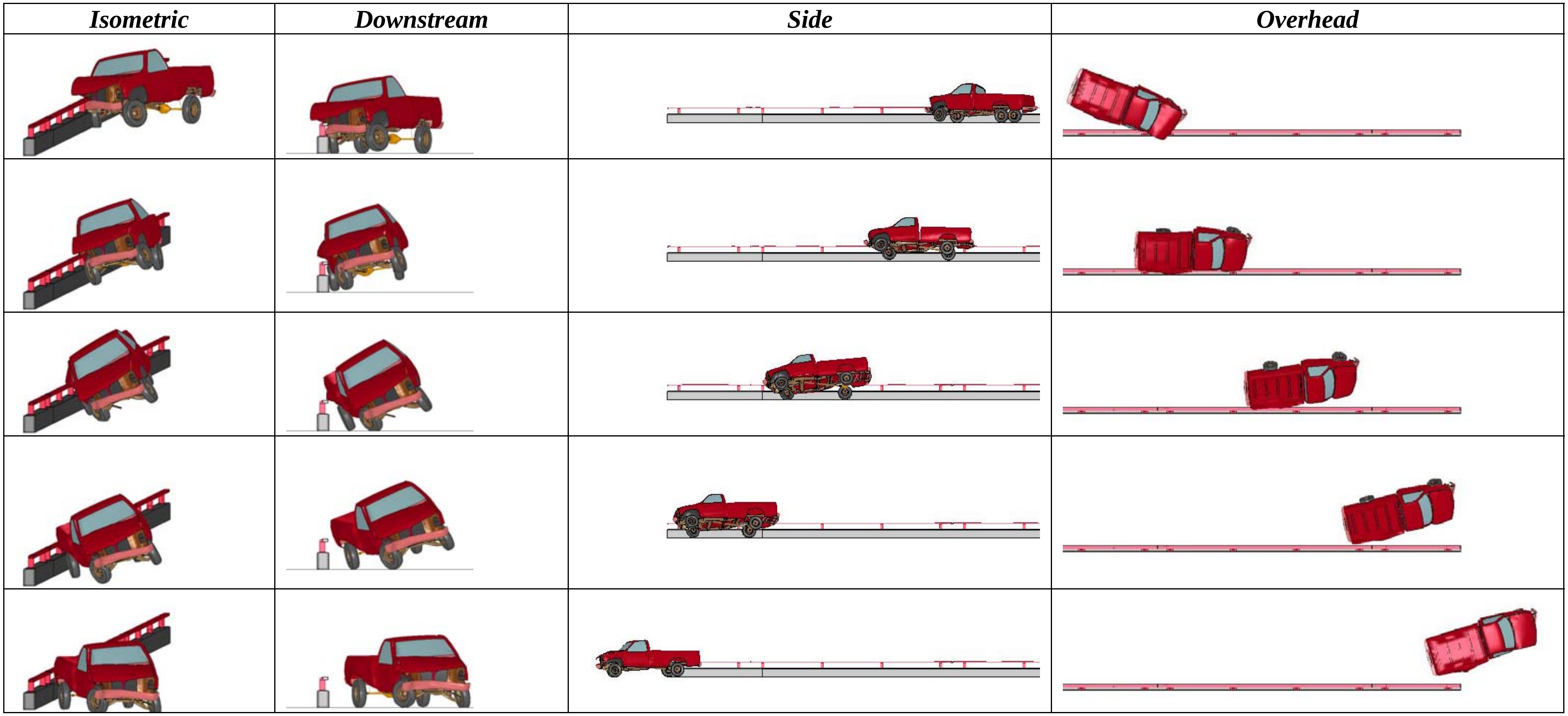


Figure 23. Impact sequence – Annisquam River Bridge Railing Test 3-11 (Design #2)

Vehicle damage

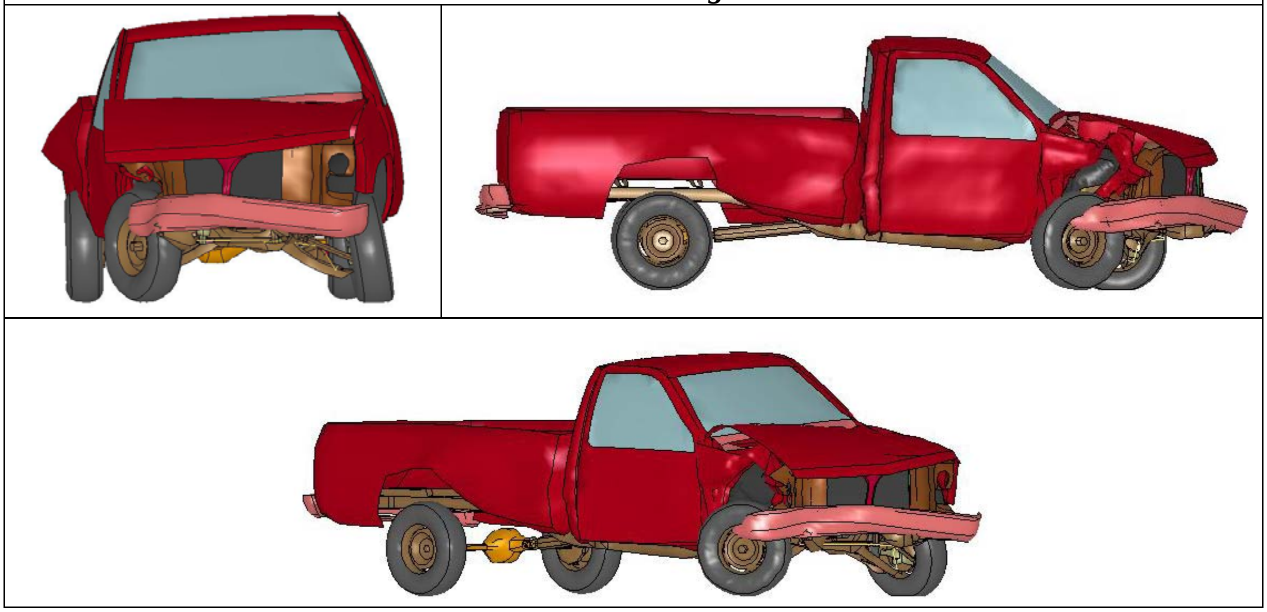


Figure 24. Vehicle damage –Test 3-11 (Design #2).

Table 7. NCHRP Report 350 evaluation criteria for Design #2 - Test 3-10 (left) and Test 3-11 (right).

Evaluation Factors		**Evaluation Criteria**			***Test 3-10***	***Test 3-11***
Structural Adequacy	A.	Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.			Pass	Pass
	B.	The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.			NA	NA
	C.	Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.			NA	NA
Occupant Risk	D.	Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone.			Passed	Passed
	E.	Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.			NA	NA
	F.	The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable.			Passed	Passed
	G.	It is preferable, although not essential, that the vehicle remain upright during and after collision.			NA	NA
	H.	Occupant impact velocities should satisfy the following:				
		Occupant Impact Velocity Limits (ft/s)				
		Component	Preferred	Maximum		
		Longitudinal and Lateral	40	40	15.4 ft/s 24.9 ft/s	24 ft/s 29.5 ft/s
		Longitudinal	10	15	NA	NA
	I.	Occupant ridedown accelerations should satisfy the following:				
		Occupant Ridedown Acceleration Limits (g's)				
		Component	Preferred	Maximum		
		Longitudinal and Lateral	15	20	-5.6 g's -15.4 g's	-8.3 g's 6.9 g's
	J.	(Optional) Hybrid III dummy responses.			NA	NA
Vehicle Trajectory	K.	After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.			Passed	Passed
	L.	The occupant impact velocity in the longitudinal direction should not exceed 40 ft/sec and the occupant rideown acceleration in the longitudinal direction should not exceed 20 G's.			Passed	Passed
	M.	The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.			3.5˚ (Passed)	8.5˚ (Passed)
	N.	Vehicle trajectory behind the test article is acceptable.			NA	NA

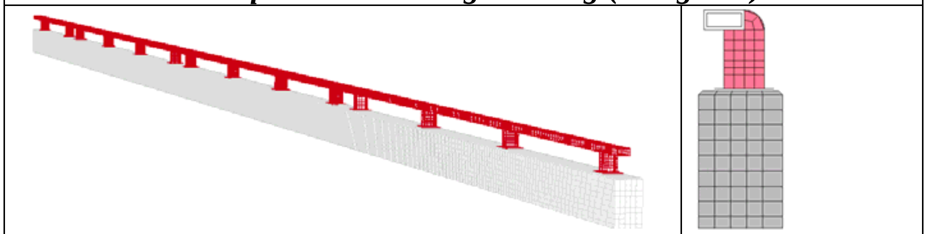
Table 8. NCHRP Report 350 Update evaluation criteria for Design #2 - Test 3-10 (left) and Test 3-11 (right).

<table>
<tr><th>Evaluation Factors</th><th colspan="4">Evaluation Criteria</th><th>Test 3-10</th><th>Test 3-11</th></tr>
<tr><td rowspan="3">Structural Adequacy</td><td>A.</td><td colspan="3">Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>B.</td><td colspan="3">The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.</td><td>N/A</td><td>N/A</td></tr>
<tr><td>C.</td><td colspan="3">Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.</td><td>N/A</td><td>N/A</td></tr>
<tr><td rowspan="14">Occupant Risk</td><td>D.</td><td colspan="3">Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>E.</td><td colspan="3">Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.</td><td>N/A</td><td>N/A</td></tr>
<tr><td>F.</td><td colspan="3">The vehicle should remain upright during and after the collision The maximum roll and pitch angles are not to exceed 75 degrees.</td><td>Roll angle:
5.5˚
(Passed)</td><td>Roll angle:
29.3˚
(Passed)</td></tr>
<tr><td>G.</td><td colspan="3">It is preferable, although not essential, that the vehicle remain upright during and after collision.</td><td>N/A</td><td>N/A</td></tr>
<tr><td rowspan="5">H.</td><td colspan="3">Occupant impact velocities (OIV) should satisfy the following limits:</td><td></td><td></td></tr>
<tr><td colspan="3">Occupant Impact Velocity Limits (ft/s)</td><td></td><td></td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td><td></td><td></td></tr>
<tr><td>Longitudinal and Lateral</td><td>30</td><td>40</td><td>15.4 ft/s
24.9 ft/s</td><td>24 f/s
29.5 f/s</td></tr>
<tr><td>Longitudinal</td><td>10</td><td>15</td><td></td><td></td></tr>
<tr><td rowspan="4">I.</td><td colspan="3">Occupant ridedown accelerations should satisfy the following limits:</td><td></td><td></td></tr>
<tr><td colspan="3">Occupant Ridedown Acceleration Limits (g's)</td><td></td><td></td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td><td></td><td></td></tr>
<tr><td>Longitudinal and Lateral</td><td>15</td><td>20</td><td>-5.6 g's
-15.4 g's</td><td>-8.3 g's
6.9 g's</td></tr>
<tr><td>Vehicle Trajectory</td><td>N.</td><td colspan="3">Vehicle trajectory behind the test article is acceptable.</td><td>N/A</td><td>N/A</td></tr>
</table>

Design #3

Design #3 retained all the features of Design #2 except the concrete parapet was raised from 17 to 20 inches in order to reduce bumper snagging in the pickup truck test. The rail height was also raise by one inch in Design #3 such that the total height was 32 inches. Figure 25 shows the finite element model for Design #3.

Annisquam River Bridge Railing (Design #3)



a) Over view ***b) Cross-section***

Figure 25. Finite element model of Design #3.

<u>*Design #3 - Test 3-10*</u>

Figure 26 shows the impact sequence from four different points of view. The impact with the parapet steered the right front wheel of the small car away from the barrier. The front right quarter panel struck the steel rail on the top of the barrier. Upon the impact with the concrete parapet, the vehicle right-front corner and bumper crushed inward and the vehicle began to redirect. The vehicle became parallel to the railing and was eventually redirected with an exit angle of 4.6 degrees and a velocity of 53.4 mi/hr (86 km/h). During the initial phase of the impact, the left wheels lost contact with the ground lifting to an approximate height of 4.3 in (110 mm) and attained a maximum roll angle of 6.6 degrees. After losing contact with the barrier, the vehicle re-contacted the ground with all four wheels. After the vehicle was redirected by the railing it maintained a straight trajectory for about 30 feet and after that it became parallel to the barrier. This was due to the fact that the front wheel was turned to the right side after the impact due to damage to the front suspensions arms and the respective steering system. This type of post-impact steering is fairly common during this kind of impact involving rigid concrete barriers.

The Report 350 evaluation criteria for test 3-11 are shown in Table 9 and the evaluation criteria for the proposed update to Report 350 are shown in Table 10. The theoretical occupant impact velocities (OIV) in the longitudinal and lateral directions were 13.5 ft/s (4.1 m/s) and 24.6 ft/s (7.5 m/s) respectively. The theoretical ridedown accelerations in longitudinal and lateral directions were -3.9 g's and -20 g's. The Theoretical Head Impact Velocity (THIV) was 18.6 mi/hr (30 km/h) and the Post Impact Head Deceleration (PHD) was 20.7 g's. The Acceleration Severity Index (ASI) was 1.8. All these evaluation criteria are well within the guidelines indicating that the impact satisfied the requirements of both Report 350 and its update.

The barrier damage was negligible. All components were considered to be reusable since there was only minor permanent deformation of the steel tube rail in the area of the impact. No significant debris was expelled from the both the bridge railing and the test vehicle during the impact.

A summary of the vehicle damage is shown in Figure 27. The impact resulted in a crushed front-right headlight and some minor damage to the front bumper. The right-front fender and the right door were slightly damaged and the hood was slightly buckled but there was no intrusion inside the vehicle.   The right front suspension was deformed and the steering system was locked with one of the front wheels turned towards left and the other to the right. No portions of the vehicle were dislodged or released. There was negligible deformation of the vehicle interior and the windshield was not damaged.

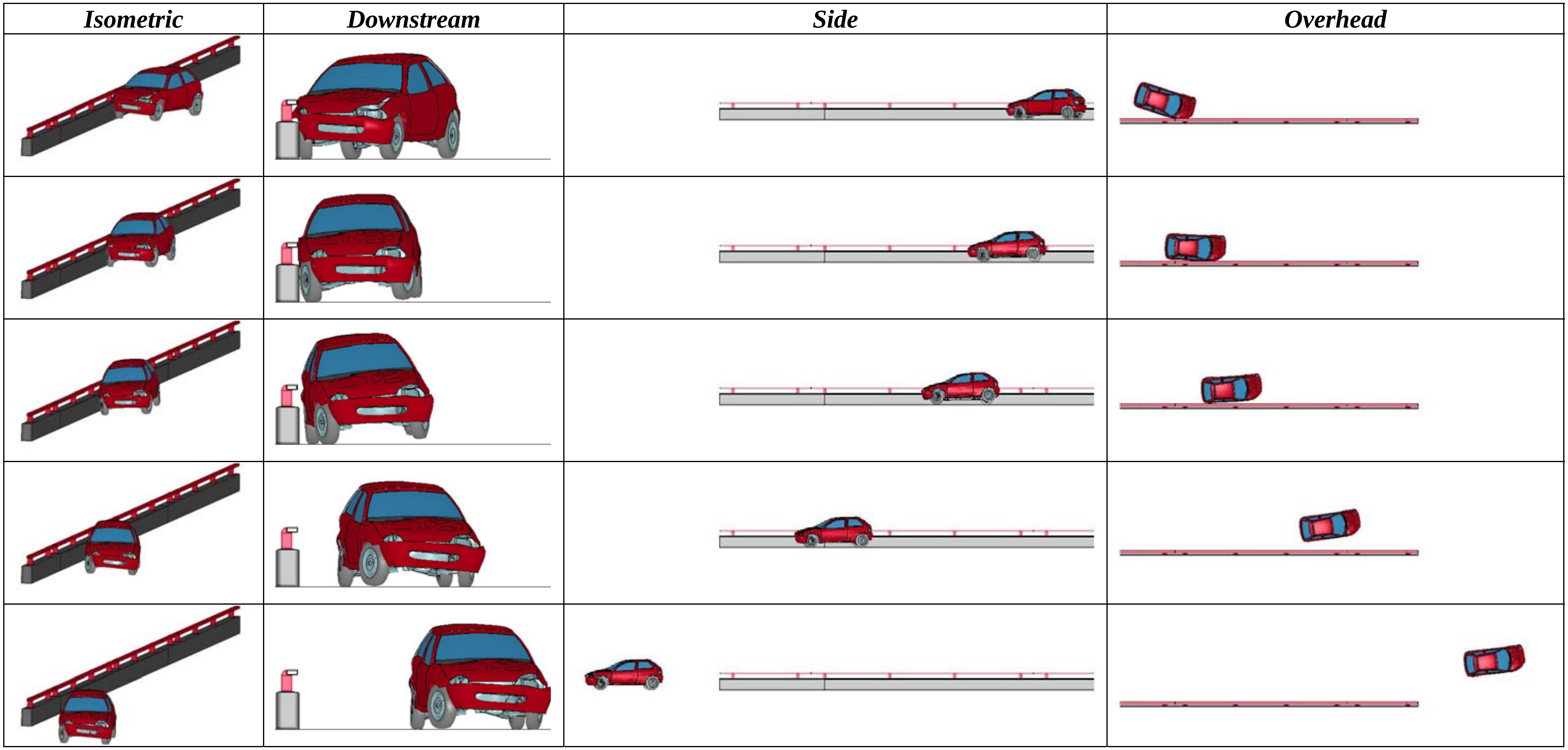


Figure 26. Impact sequence – Annisquam River Bridge Railing Test 3-10 (Design #3).

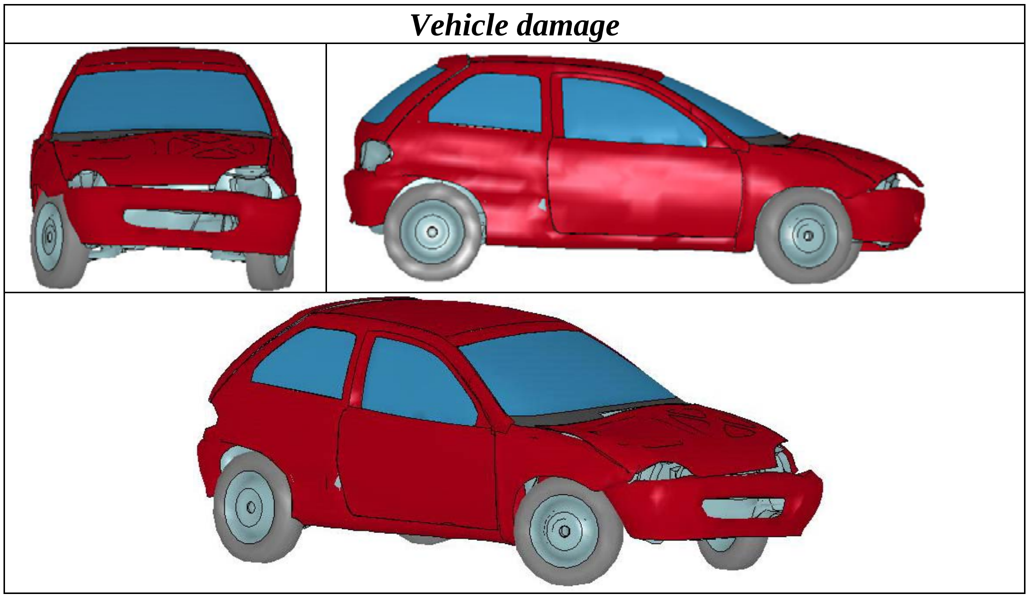


Figure 27. Vehicle damage –Test 3-10 (Design #3).

Design #3 - Test 3-11

Figure 28 shows the impact sequence from four different points of view. Upon impact with the bridge railing, the pickup truck front bumper crushed into one of the posts of the steel rail. Immediately after, the front right corner crushed against the top of the steel rail and the front right wheel was force to steer in the direction opposite to the concrete wall. The left front tire and, subsequently, the left-rear tire lifted from the ground as the pickup truck rolled in toward the barrier. When the rear right tire hit the concrete parapet, the rear left tire lifted to the ground leaving the vehicle sliding parallel to the barrier with all the four wheels out of contact with the ground. The vehicle became parallel to the barrier and then was redirected away towards the roadside face with an exit angle of 4 degrees and a velocity of 44 mi/hr (74 km/h). During the exit phase the vehicle stayed with all the four wheels over the ground and then the right wheels came back in contact with the ground leaving the vehicle on its left wheels lifted from the ground. During this phase, the vehicle reached a maximum roll angle of 26.3 degrees towards the barrier. At the end, the vehicle re-contacted the ground with all four wheels and maintained a straight trajectory after exiting the barrier.

The Report 350 evaluation criteria for test 3-11 are shown in Table 9 and the evaluation criteria for proposed update to NCHRP Report 350 are shown in Table 10. The theoretical occupant impact velocities (OIV) in the longitudinal and lateral directions were 23.3 ft/s (7.1 m/s) and 29.2 ft/s (8.9 m/s) respectively. The theoretical ridedown accelerations in longitudinal and lateral directions were -5.2 g's and -8.8 g's. The theoretical Head Impact Velocity (THIV) was 24.4 mi/h (39.3 km/s) and the Post Impact Head Deceleration (PHD) was 9 g's. The Acceleration Severity Index (ASI) was 1.97. All these values indicate successful performance in the test 3-11 conditions.

The barrier damage was negligible. All components were considered to be reusable with a minimal permanent deformation of the steel tube rail in the area of the impact. The damage around the zone of the rail sleeve, where the impact took place, was minor and it was considered not serious enough to require repair. No debris was expelled from the both the bridge railing and the test vehicle during the impact.

A summary of the vehicle damage is shown in Figure 29. The front right part of the vehicle was crushed. The suspension of the front right wheel, which first impacted against the concrete wall, was broken and the wheel remained turned inward. The hood bent due to buckling and the bumper was crushed and the right-front fender was damaged as well. No deformation of the vehicle interior was noticed. The rear right side of the pickup truck was slightly damaged due to the impact against the concrete wall when the vehicle was redirected by the railing. No portions of the vehicle were dislodged or released.

Increasing the parapet height to 20 inches appeared reduce the OIV and ORA values somewhat and the maximum roll angle in the pickup test was reduced. Using a taller parapet did improve the performance of the design although not nearly as much as was expected. The Annisquam Bridge, however, is a high-visibility bridge that overlooks a large body of water and aesthetics are considered an important feature of the bridge. Keeping the height of the parapet as low as possible while not compromising safety is, therefore, a high priority. On the hand, the planned deck rearrangement has sufficient room for a 16 inch wide barrier so using a narrower 12-inch wide barrier was not considered to be very important. If the wider parapet is used, the posts could be positioned father from the face of the barrier and it was thought that this might have a positive affect on minimizing snagging in the pickup truck impact.

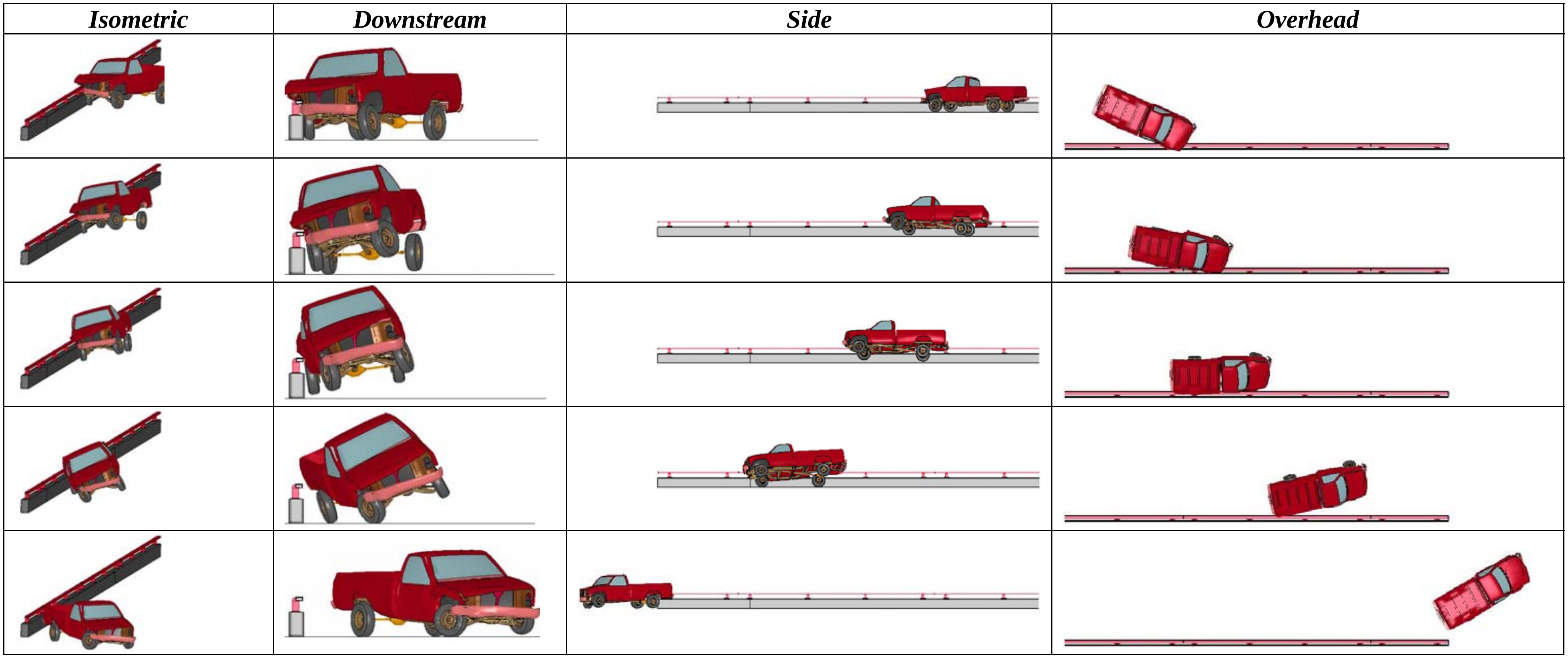


Figure 28. Impact sequence – Annisquam River Bridge Railing Test 3-11 (Design #3)

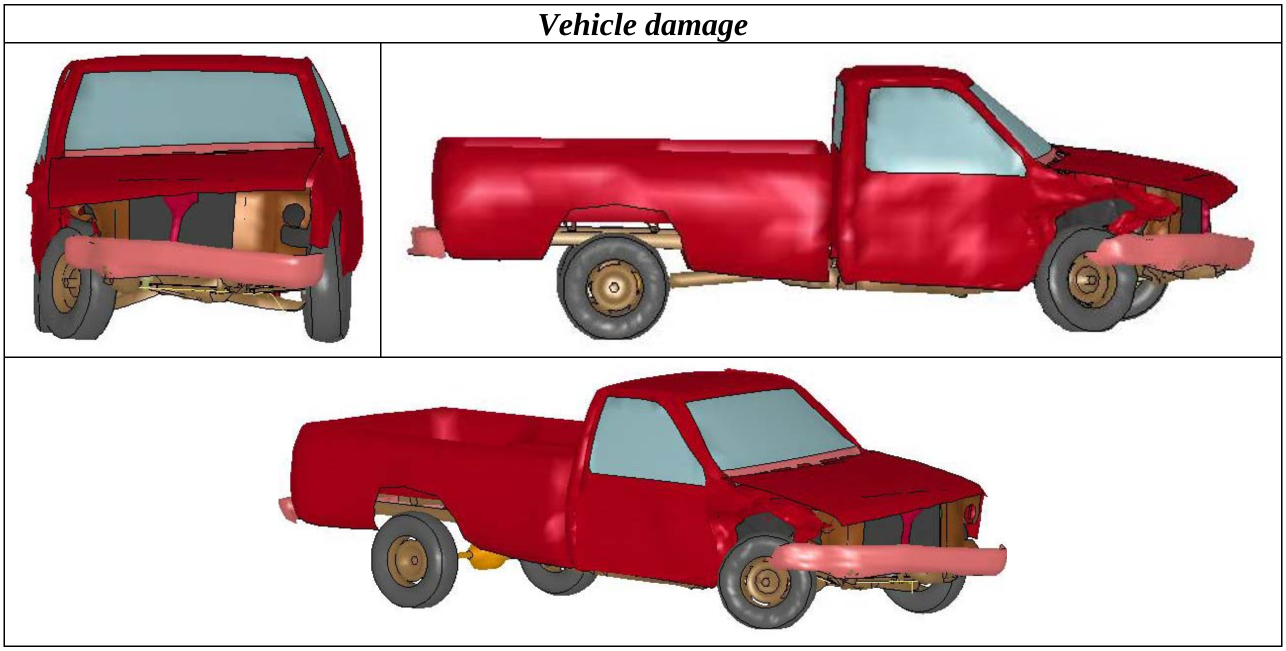


Figure 29. Vehicle damage –Test 3-11 (Design #3).

Table 9. NCHRP Report 350 evaluation criteria for Design #3 - Test 3-10 (left) and Test 3-11 (right).

Evaluation Factors		**Evaluation Criteria**	***Test 3-10***	***Test 3-11***
Structural Adequacy	A.	Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Passed	Passed
	B.	The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.	NA	NA
	C.	Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.	NA	NA
Occupant Risk	D.	Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone.	Passed	Passed
	E.	Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.	NA	NA
	F.	The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable.	Passed	Passed
	G.	It is preferable, although not essential, that the vehicle remain upright during and after collision.	NA	NA
	H.	Occupant impact velocities should satisfy the following: Occupant Impact Velocity Limits (m/s) Component / Preferred / Maximum		
		Longitudinal and Lateral / 30 / 40	13.5 ft/s 24.6 ft/s	23.3 ft/s 29.2 ft/s
		Longitudinal / 10 / 15	NA	NA
	I.	Occupant ridedown accelerations should satisfy the following: Occupant Ridedown Acceleration Limits (g's) Component / Preferred / Maximum		
		Longitudinal and Lateral / 15 / 20	-3.9 g's -20 g's	-5.2 g's -8.8 g's
	J.	(Optional) Hybrid III dummy responses.	NA	NA
Vehicle Trajectory	K.	After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	Passed	Passed
	L.	The occupant impact velocity in the longitudinal direction should not exceed 40 ft/sec and the occupant rideown acceleration in the longitudinal direction should not exceed 20 G's.	Passed	Passed
	M.	The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.	4.6˚ (Passed)	4˚ (Passed)
	N.	Vehicle trajectory behind the test article is acceptable.	NA	NA

Table 10. NCHRP Report 350 Update evaluation criteria for Design #3 - Test 3-10 (left) and Test 3-11 (right).

<table>
<tr><th>Evaluation Factors</th><th colspan="4">Evaluation Criteria</th><th>Test 3-10</th><th>Test 3-11</th></tr>
<tr><td rowspan="3">Structural Adequacy</td><td>A.</td><td colspan="3">Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>B.</td><td colspan="3">The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.</td><td>N/A</td><td>N/A</td></tr>
<tr><td>C.</td><td colspan="3">Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.</td><td>N/A</td><td>N/A</td></tr>
<tr><td rowspan="13">Occupant Risk</td><td>D.</td><td colspan="3">Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>E.</td><td colspan="3">Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.</td><td>N/A</td><td>N/A</td></tr>
<tr><td>F.</td><td colspan="3">The vehicle should remain upright during and after the collision The maximum roll and pitch angles are not to exceed 75 degrees.</td><td>Roll angle:
6.6˚
(Passed)</td><td>Roll angle:
26.3˚
(Passed)</td></tr>
<tr><td>G.</td><td colspan="3">It is preferable, although not essential, that the vehicle remain upright during and after collision.</td><td>N/A</td><td>N/A</td></tr>
<tr><td rowspan="5">H.</td><td colspan="3">Occupant impact velocities (OIV) should satisfy the following limits:</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td colspan="3">Occupant Impact Velocity Limits (ft/s)</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>30</td><td>40</td><td>13.5 ft/s
24.6 ft/s</td><td>23.3 ft/s 29.2 ft/s</td></tr>
<tr><td>Longitudinal</td><td>10</td><td>15</td><td></td><td></td></tr>
<tr><td rowspan="4">I.</td><td colspan="3">Occupant ridedown accelerations should satisfy the following limits:</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td colspan="3">Occupant Ridedown Acceleration Limits (g's)</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>15</td><td>20</td><td>-3.9 g's
-20.1 g's</td><td>-5.2 g's
-8.8 g's</td></tr>
<tr><td>Vehicle Trajectory</td><td>N.</td><td colspan="3">Vehicle trajectory behind the test article is acceptable.</td><td>N/A</td><td>N/A</td></tr>
</table>

Design #4

As discussed above, raising the parapet three inches did not have as dramatic an affect on the safety performance of the barrier as was anticipated. Since keeping the parapet height at 17 inches was a priority for aesthetic reasons, the Design #4 was modified such that the barrier was four inches wider (i.e., 16 inches). This allowed the posts to be positioned farther away from the face of the barrier which would in turn minimize the chance of bumper and hood snagging in the pickup truck test. A smaller tubular post (i.e., TS5x5x1/4) was used to create further space from the barrier face and a deeper rail section (i.e., TS10x4x5/16) was used to ensure the face of the steel rail was aligned with the face of the concrete parapet. The overall height of the barrier was retained at 32 inches. Figure 30 shows the finite element model for Design #4.

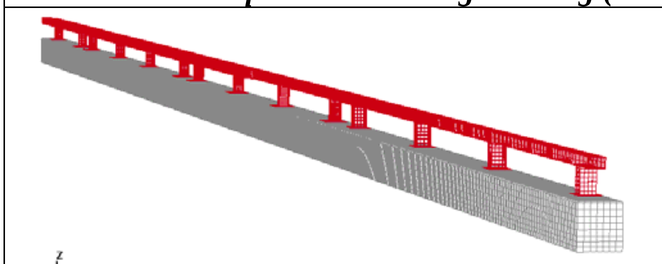
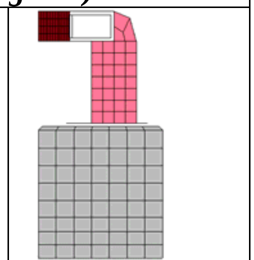
Annisquam River Bridge Railing (Design #4)	
	
a) Over view	***b) Cross-section***

Figure 30. Finite element model of Design #4.

Design #4 - Test 3-10

Figure 31 shows the impact sequence from four different points of view. After the bumper hit the concrete wall, the front right wheel contacted the railing and was steered away from the barrier. Immediately after, the front right quarter panel of the car struck the metal tube rail and the front-right headlight crushed inward. Upon the impact with the concrete wall, the front wheels lifted and the vehicle began to change direction. When the rear part of the vehicle body contacted the concrete wall, the car set parallel to the barrier and, after a while, all the four wheels came back in contact with the ground. Eventually, it was redirected with an exit angle of 1.6 degrees and a velocity of 43.5 mi/hr (70 km/h). During the impact, the vehicle was lifted from the ground by a maximum height of approximately 4.5 in (115 mm) with the front wheels and at the end was able to come back on the ground gaining a horizontal asset. The maximum roll angle was about 3 degrees. After a first phase during which the vehicle was rebounded by the railing, the car pointed back towards the barrier due to the fact that the front left wheel was locked on the right side after the impact. This event is fairly common during impacts involving rigid concrete barriers.

The Report 350 evaluation criteria for test 3-11 are shown in Table 11 and the evaluation criteria for the proposed update to Report 350 are shown in Table 12. The theoretical occupant impact velocities (OIV) in the longitudinal and lateral directions were 18.4 ft/s (5.6 m/s) and 24.3 ft/s (7.4 m/s) respectively. The theoretical ridedown accelerations in longitudinal and lateral directions were -11.1 g's and 5.4 g's. The

Theoretical Head Impact Velocity (THIV) was 19.5 mi/hr (31.4 km/h) and the Post Impact Head Deceleration (PHD) was 16 g's. The Acceleration Severity Index (ASI) was 1.82. All these values are in the acceptable range indicating that the barrier performance is successful in the test 3-10 conditions.

The barrier damage was negligible. All components were judged reusable with minor permanent deformation of the steel tube rail in the area of the impact. No significant debris was expelled from the both the bridge railing and the test vehicle during the impact.

A summary of the vehicle damage is shown in Figure 32. The impact resulted in a crushed front-right headlight and deformation of the front right quarter panel. The right door was slightly damaged but there was no intrusion inside the vehicle. The front bumper was not significantly damaged. The hood buckled to a minor extent and was partially damaged. The right front suspension was deformed and the steering system was locked with the left wheel turned inwards. The right front quarter panel was partially dislodged and released. There was negligible deformation of the vehicle interior and the windshield was not damaged.

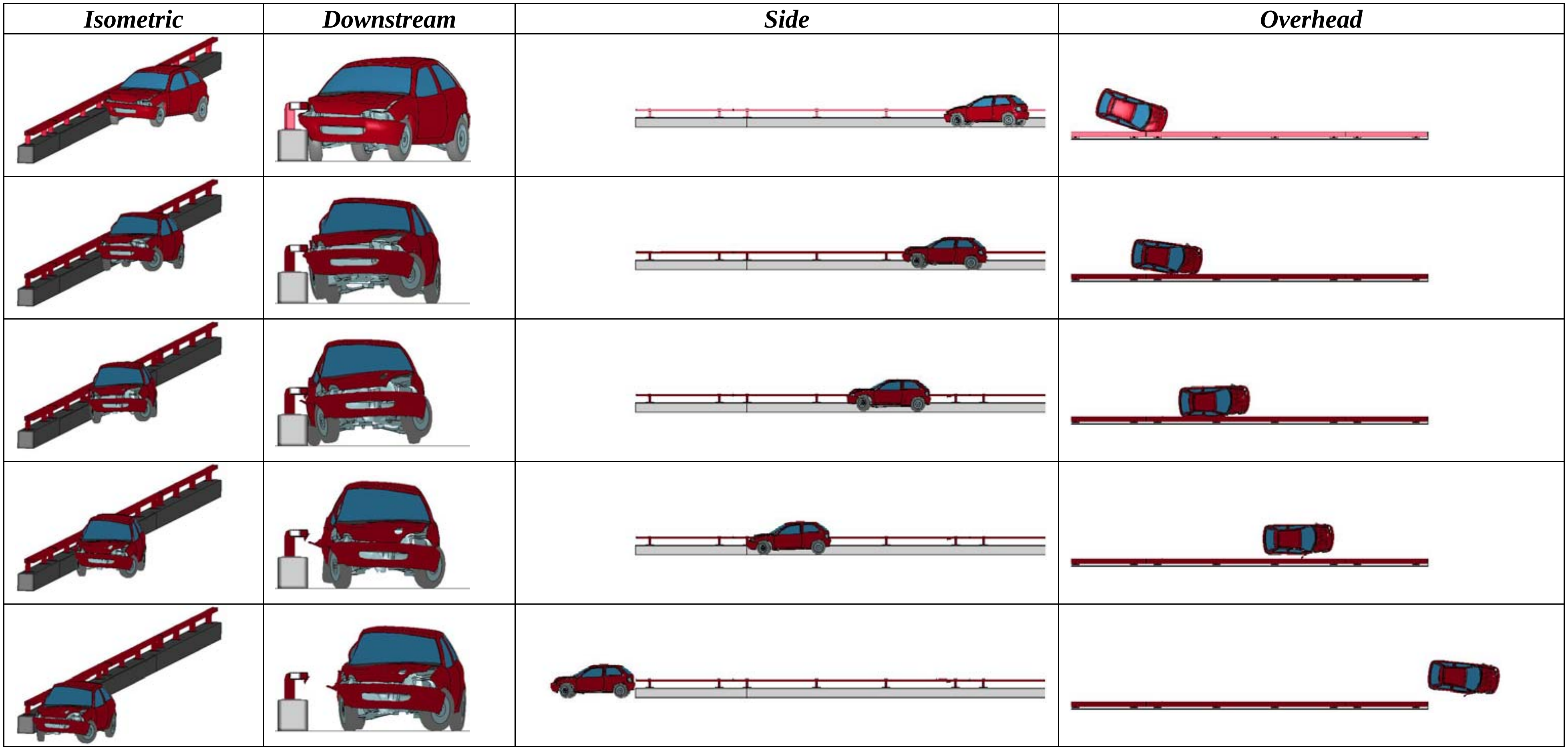


Figure 31. Impact sequence – Annisquam River Bridge Railing Test 3-10 (Design #4).

Vehicle damage

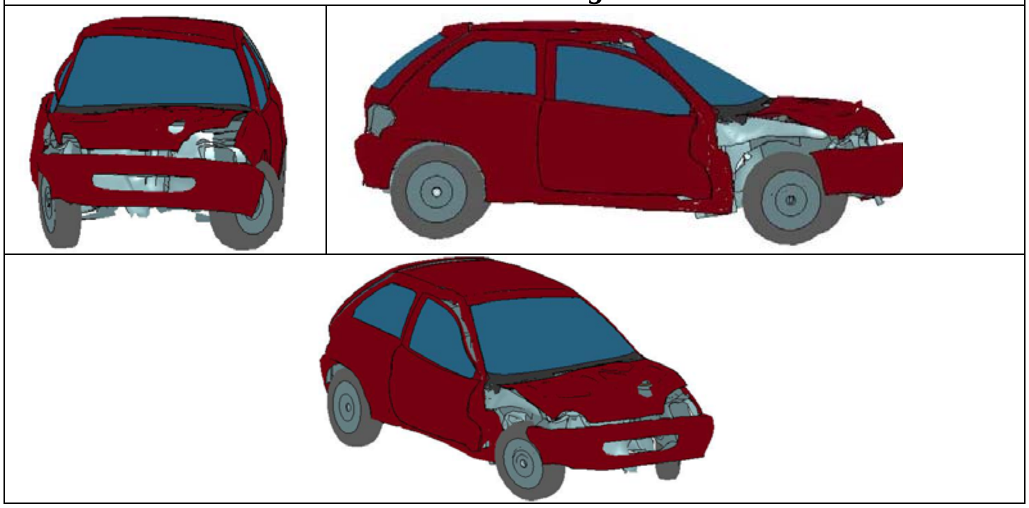


Figure 32. Vehicle damage –Test 3-10 (Design #4).

<u>Design #4 - Test 3-11</u>

Figure 33 shows the impact sequence from four different points of view. Upon impact with the bridge railing, the vehicle right-front corner crushed against the steel rail at the top of the barrier. Immediately after, the front bumper slightly hit one of the posts but did not snag hard. At the same time, the right front tire hit the concrete parapet and was forced to steer away from the barrier. Due to this steering movement, the vehicle started spinning around the front quarter panel which was crushed against the steel rail. As a consequence, the vehicle rolled towards the barrier and the both the front and rear left wheels lost contact with the ground. The vehicle became parallel to the barrier and then was redirected away towards the roadside face with an exit angle of 6.7 degrees and a velocity of 44.7 mi/hr (72 km/h). During the exit phase the vehicle remained on its left wheels lifted from the ground eventually coming back into contact with all four wheels in contact with the ground. The maximum roll angle was about 26 degrees.

The Report 350 evaluation criteria for test 3-11 are shown in Table 11 and the evaluation criteria for the proposed update to Report 350 are shown in Table 12. The theoretical occupant impact velocities (OIV) in the longitudinal and lateral directions were 22 ft/s (6.7 m/s) and 30.5 ft/s (9.3 m/s) respectively. The theoretical ridedown accelerations in longitudinal and lateral directions were -5.5 g's and -8.9 g's. The theoretical Head Impact Velocity (THIV) was 24.6 mi/hr (39.6 km/s) and the Post Impact Head Deceleration (PHD) was 9.3 g's. The Acceleration Severity Index (ASI) was 2.1. These values indicate that the barrier performs well in the test 3-11 conditions.

The barrier damage was negligible. All components were judged reusable with minimal permanent deformation of the steel tube rail in the area of the impact. The damage around the zone of the rail sleeve, where the impact took place, was minor and not serious enough to require repair. No debris was expelled from the both the bridge railing and the test vehicle during the impact.

A summary of the vehicle damage is shown in Figure 34. The front right quarter panel of the vehicle was crushed and the hood buckled as a consequence of the contact between the front right headlight and the steel rail. The bumper was slightly damaged.

The extent of the damage to the right door was limited. The suspension of the front right wheel, which first impacted against the concrete wall, was broken and the wheel remained turned inward. No relevant deformation of the vehicle interior was observed. The rear right side of the pickup truck was slightly damaged due to the impact against the concrete wall when the vehicle was redirected by the railing. No portions of the vehicle were dislodged or released during the crash test.

The Von-Mises stress contour plots for test 3-11 of Design #4 were examined at the most demanding phases of the crash event and are shown below. As shown in Figure 35, the stresses in the steel rail and post generally were below the yield stress although there were several higher stresses at locations where there was direct contact between the vehicle and rail and post. The maximum stress of 82 ksi (565 MPa) occurred in the steel rail where it was slightly deformed near the splice. The peak stresses were above the 50 ksi yield stress but they were concentrated in very small areas of the rail and post causing only minor local deformations.

Likewise, the bending stress in the wall was generally less than the 3,000 psi, strength of the concrete, as show in Figure 36. There were local areas on the concrete wall that reached values as high as –10 ksi (-69 MPa) in compression and 4.6 ksi (31.7 MPa) in tension. These maximum values occurred in areas where there was direct contact with the vehicle and indicate there would be some localized spalling and scraps. Outside the area of direct contact, the stresses acting on the concrete parapet are soon distributed over a larger surface with values under the ultimate stress. Thus, the maximum stress value decreased to –1.3 ksi (-9 MPa) in compression and 1.3 ksi (9 MPa) in tension in the middle phase of the impact and to -1 ksi (-6.9 MPa) in compression and 1 ksi (6.9 MPa) in tension at the end of the contact. The stresses in Figures 35 and 36 indicate good structural performance of the barrier with relatively minor local deformations due to direct contact.

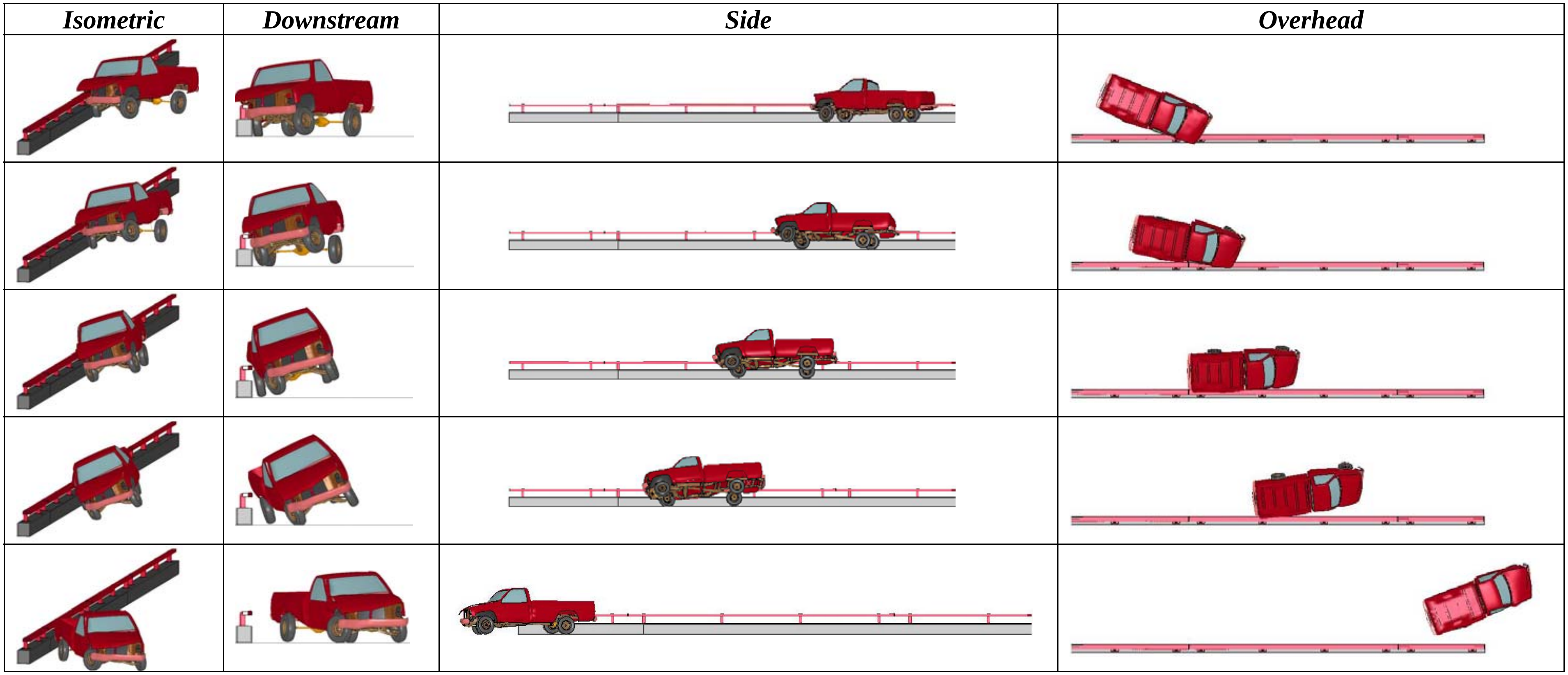


Figure 33. Impact sequence – Annisquam River Bridge Railing Test 3-11 (Design #4)

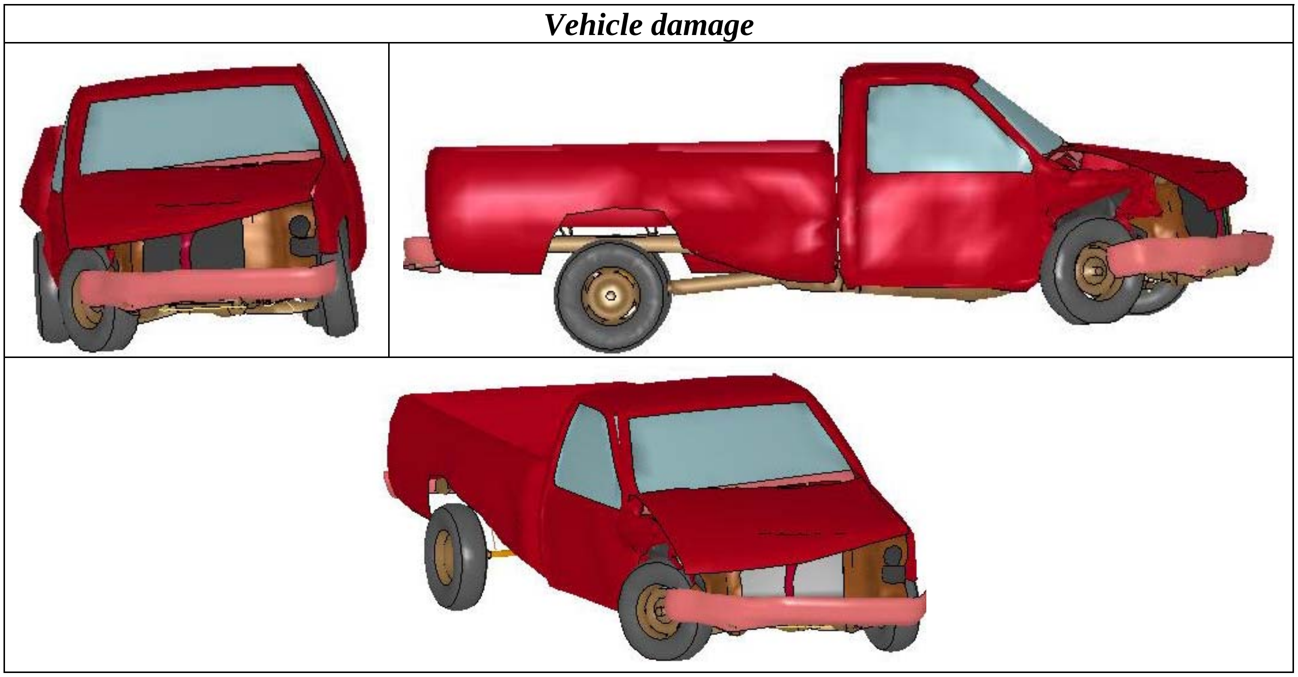


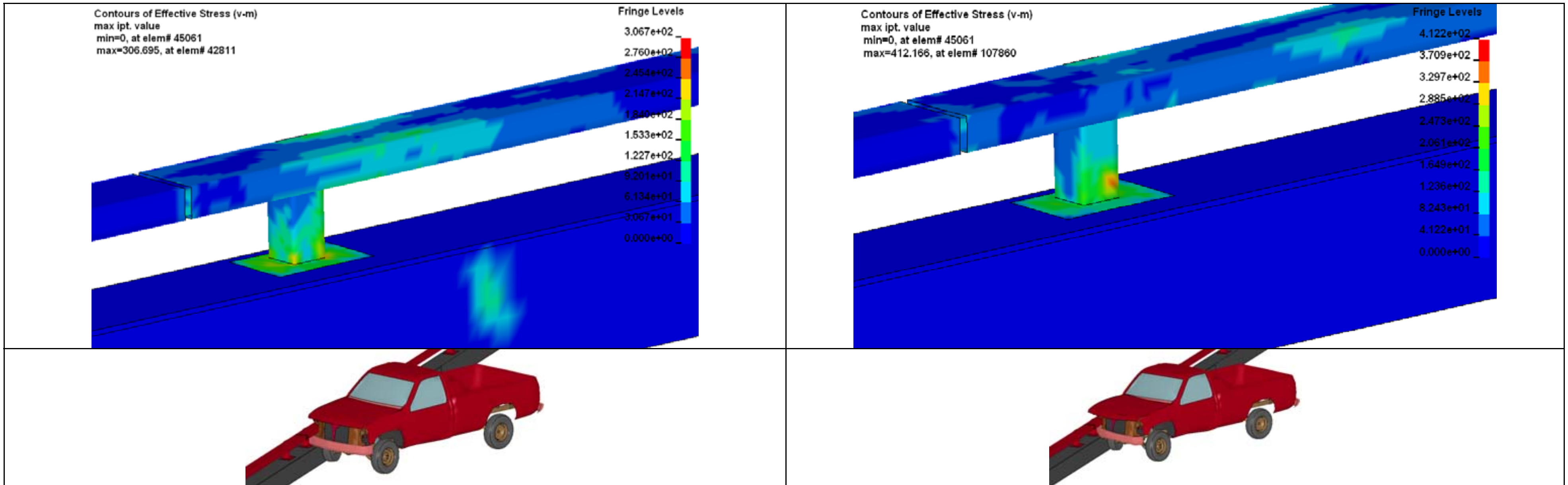
Figure 34. Vehicle damage –Test 3-11 (Design #4).

Table 11. NCHRP Report 350 evaluation criteria for Design 4 - Test 3-10 (left) and Test 3-11 (right).

<table>
<tr><th>Evaluation Factors</th><th colspan="2">Evaluation Criteria</th><th>Test 3-10</th><th>Test 3-11</th></tr>
<tr><td rowspan="3">Structural Adequacy</td><td>A.</td><td>Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>B.</td><td>The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.</td><td>NA</td><td>NA</td></tr>
<tr><td>C.</td><td>Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.</td><td>NA</td><td>NA</td></tr>
<tr><td rowspan="12">Occupant Risk</td><td>D.</td><td>Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>E.</td><td>Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver’s vision or otherwise cause the driver to lose control of the vehicle.</td><td>NA</td><td>NA</td></tr>
<tr><td>F.</td><td>The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>G.</td><td>It is preferable, although not essential, that the vehicle remain upright during and after collision.</td><td>NA</td><td>NA</td></tr>
<tr><td rowspan="3">H.</td><td>Occupant impact velocities should satisfy the following:
<table><tr><td colspan="3">Occupant Impact Velocity Limits (ft/s)</td></tr><tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr></table></td><td></td><td></td></tr>
<tr><td><table><tr><td>Longitudinal and Lateral</td><td>30</td><td>40</td></tr></table></td><td>18.4 ft/s
24.3 ft/s</td><td>22 ft/s
30.5 ft/s</td></tr>
<tr><td><table><tr><td>Longitudinal</td><td>10</td><td>15</td></tr></table></td><td>NA</td><td>NA</td></tr>
<tr><td rowspan="2">I.</td><td>Occupant ridedown accelerations should satisfy the following:
<table><tr><td colspan="3">Occupant Ridedown Acceleration Limits (g’s)</td></tr><tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr></table></td><td></td><td></td></tr>
<tr><td><table><tr><td>Longitudinal and Lateral</td><td>15</td><td>20</td></tr></table></td><td>-11.1 g’s
5.4 g’s</td><td>-5.5 g’s
-8.9 g’s</td></tr>
<tr><td>J.</td><td>(Optional) Hybrid III dummy responses.</td><td>NA</td><td>NA</td></tr>
<tr><td rowspan="4">Vehicle Trajectory</td><td>K.</td><td>After collision it is preferable that the vehicle’s trajectory not intrude into adjacent traffic lanes.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>L.</td><td>The occupant impact velocity in the longitudinal direction should not exceed 40 ft/sec and the occupant rideown acceleration in the longitudinal direction should not exceed 20 G’s.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>M.</td><td>The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.</td><td>1.6˚
(Passed)</td><td>6.7˚
(Passed)</td></tr>
<tr><td>N</td><td>Vehicle trajectory behind the test article is acceptable.</td><td>NA</td><td>NA</td></tr>
</table>

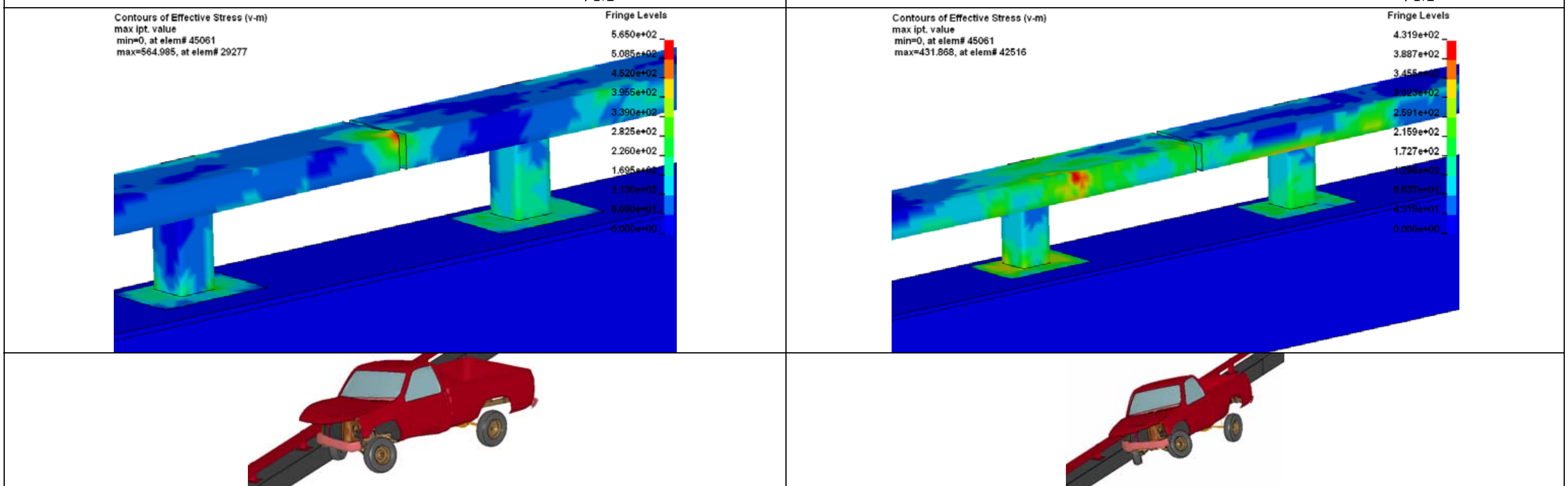
Table 12. NCHRP Report 350 Update evaluation criteria for Design #4 - Test 3-10 (left) and Test 3-11 (right).

<table>
<tr><th>Evaluation Factors</th><th colspan="4">Evaluation Criteria</th><th>Test 3-10</th><th>Test 3-11</th></tr>
<tr><td rowspan="3">Structural Adequacy</td><td>A.</td><td colspan="3">Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>B.</td><td colspan="3">The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.</td><td>N/A</td><td>N/A</td></tr>
<tr><td>C.</td><td colspan="3">Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.</td><td>N/A</td><td>N/A</td></tr>
<tr><td rowspan="14">Occupant Risk</td><td>D.</td><td colspan="3">Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>E.</td><td colspan="3">Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver’s vision or otherwise cause the driver to lose control of the vehicle.</td><td>N/A</td><td>N/A</td></tr>
<tr><td>F.</td><td colspan="3">The vehicle should remain upright during and after the collision The maximum roll and pitch angles are not to exceed 75 degrees.</td><td>Roll angle: 3˚ (Passed)</td><td>Roll angle: 26˚ (Passed)</td></tr>
<tr><td>G.</td><td colspan="3">It is preferable, although not essential, that the vehicle remain upright during and after collision.</td><td>N/A</td><td>N/A</td></tr>
<tr><td rowspan="5">H.</td><td colspan="3">Occupant impact velocities (OIV) should satisfy the following limits:</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td colspan="3">Occupant Impact Velocity Limits (ft/s)</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>30</td><td>40</td><td>18.4 ft/s
24.3 ft/s</td><td>22 ft/s
30.5 ft/s</td></tr>
<tr><td>Longitudinal</td><td>10</td><td>15</td><td></td><td></td></tr>
<tr><td rowspan="4">I.</td><td colspan="3">Occupant ridedown accelerations should satisfy the following limits:</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td colspan="3">Occupant Ridedown Acceleration Limits (g’s)</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>15</td><td>20</td><td>-11.1 g’s
5.4 g’s</td><td>-5.5 g’s
-8.9 g’s</td></tr>
<tr><td>Vehicle Trajectory</td><td>N.</td><td colspan="3">Vehicle trajectory behind the test article is acceptable.</td><td>N/A</td><td>N/A</td></tr>
</table>



(a) Beginning of the impact (t=0.035 sec) $MAX\ \sigma_{VM} = 44.5\,ksi$

(b) Impact between bumper and post (t=0.05 sec) $MAX\ \sigma_{VM} = 59.8\,ksi$

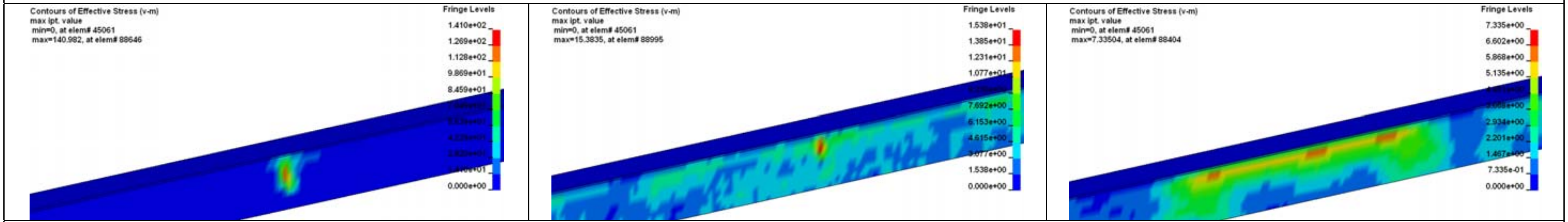


(c) Maximum stress in the steel rail (t=0.075 sec) $MAX\ \sigma_{VM} = 81.9\,ksi$

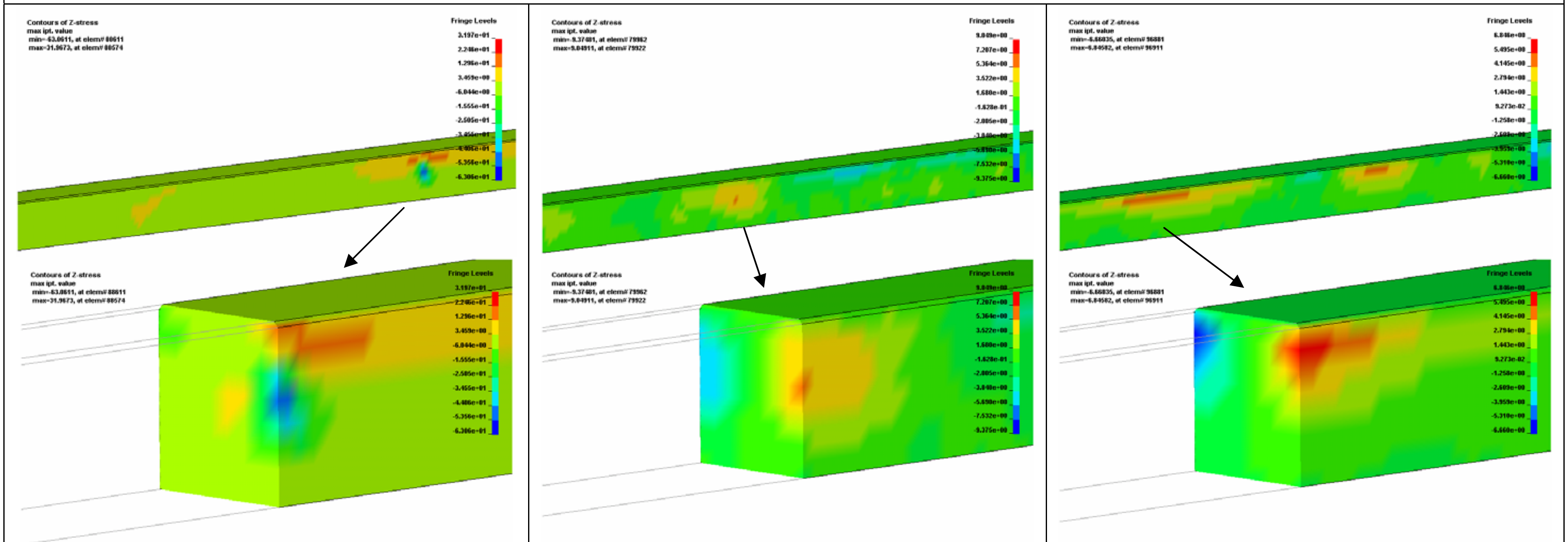
(d) End of the impact (t=0.19 sec) $MAX\ \sigma_{VM} = 62.7\,ksi$

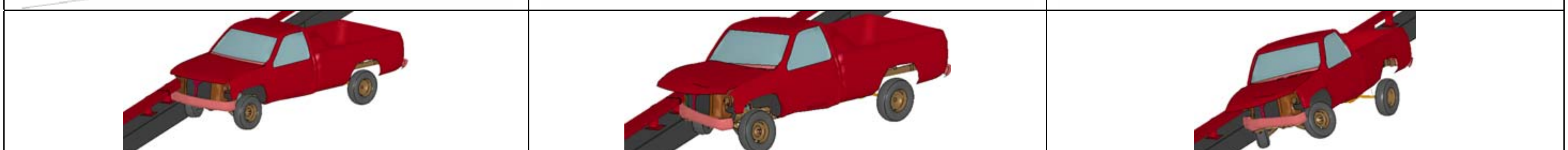
Figure 35. Stress distribution for the steel rail and posts for Design #4 - Test 3-11 (units in MPa).

Von-Mises stress



Bending stress σ_Z





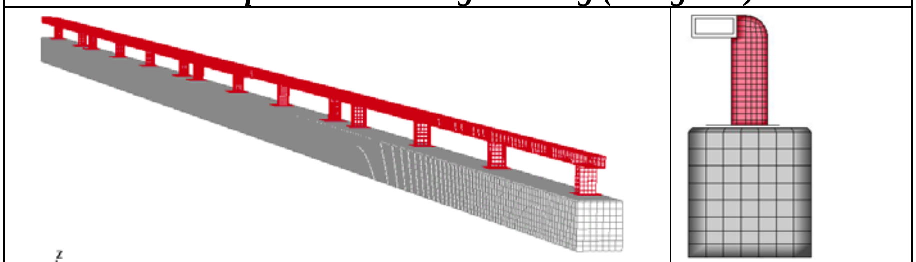
(a) Beginning of the impact (t=0.035 sec)	(b) Middle phase of the impact (t=0.06 sec)	(c) End of the impact (t=0.2 sec)
Max σ_{VM} =20.5 ksi; -10 ksi < σ_Z <4.6 ksi	***Max σ_{VM} =2.2 ksi; -1.3 ksi< σ_Z <1.3 ksi***	***Max σ_{VM} =1.1 ksi; -1 ksi< σ_Z <1 ksi***

Figure 36. Stress distribution for the concrete wall for Design #4 - Test 3-11.

Design #5

Considering the results obtained in the previous designs and the fact that keeping the parapet height at 17 inches was a priority for aesthetic reasons, a new design (Design #5) was modeled which could combine the positive characteristics of the previous designs while resulting in a more aesthetically acceptable design. Design #5 uses the same width and height for the concrete wall (i.e., 16 inches and 17 inches, respectively), the same steel posts (TS5x5x1/4) and the same overall height as the previous Design #4. To improve the aesthetics of the railing, a smaller steel tube for the top rail was chosen (TS6x3x1/4). In order to minimize the possibility of wheel and bumper snagging, the post was notched only ¾ of inch to set the rail into it (in the previous designs, the notch was 2.75 inches wide) and the face of the steel rail was set back ½ inch as in Designs #1, 2 and 3. These two modifications allowed the posts to be positioned farther away from the face of the barrier while still retaining the overall railing height of 32 inches. Figure 37 shows the finite element model for Design #5.

Annisquam River Bridge Railing (Design #5)



a) Over view ***b) Cross-section***

Figure 37. Finite element model of Design #5.

<u>*Design #5 - Test 3-10*</u>

Figure 38 shows the small-car impact sequence from four different points of view. After the bumper strikes the concrete wall, the front right wheel contacted the railing and was steered away from the barrier. Immediately after, the front right quarter panel of the car struck the metal tube rail and the front-right headlight crushed inward. Upon the impact with the concrete wall, the front wheels lifted and the vehicle began to change direction. Upon the contact of the rear part of the vehicle body with the concrete wall, the car was redirected parallel to the barrier and, when all the four wheels came back in contact with the ground, the vehicle was redirected with an exit angle of 2.5 degrees and a velocity of 52.1 mi/hr (83.9 km/h). During the impact, the vehicle was lifted from the ground a maximum height of approximately 4.5 in (115 mm) with the front wheels and at the end was able to come back on the ground regaining a horizontal orientation. The maximum roll angle was about 7 degrees. After a first phase during which the vehicle was rebounded by the railing, the car pointed back towards the barrier due to the fact that the front left wheel was locked on the right side after the impact. This event is fairly common during impacts involving rigid concrete barriers.

The Report 350 evaluation criteria for test 3-11 are shown in Table 13 and the evaluation criteria for the proposed update to Report 350 are shown in Table 14. The theoretical occupant impact velocities (OIV) in the longitudinal and lateral directions were 16.1 ft/s (4.9 m/s) and 24.6 ft/s (7.5 m/s) respectively. The theoretical ridedown accelerations in longitudinal and lateral directions were -3.7 g's and -13.1 g's. The Theoretical Head Impact Velocity (THIV) was 19.7 mi/hr (31.7 km/h) and the Post Impact Head Deceleration (PHD) was 13.7 g's. The Acceleration Severity Index (ASI) was 1.85. All these values are in the acceptable range indicating that the barrier performance is successful in the test 3-10 conditions according to both Report 350 and the proposed update.

The barrier damage was negligible. All components were judged reusable with minor permanent deformation of the steel tube rail in the area of the impact. No significant debris was expelled from the both the bridge railing and the test vehicle during the impact.

A summary of the vehicle damage is shown in Figure 39. The impact resulted in a crushed front-right headlight and a slight deformation of the front right quarter panel. The right door was slightly damaged but there was no intrusion inside the vehicle. The front bumper was not significantly damaged. The hood buckled to a minor extent and was partially damaged. The right front suspension was deformed and the steering system was locked with the left wheel turned inwards. There was negligible deformation of the vehicle interior.

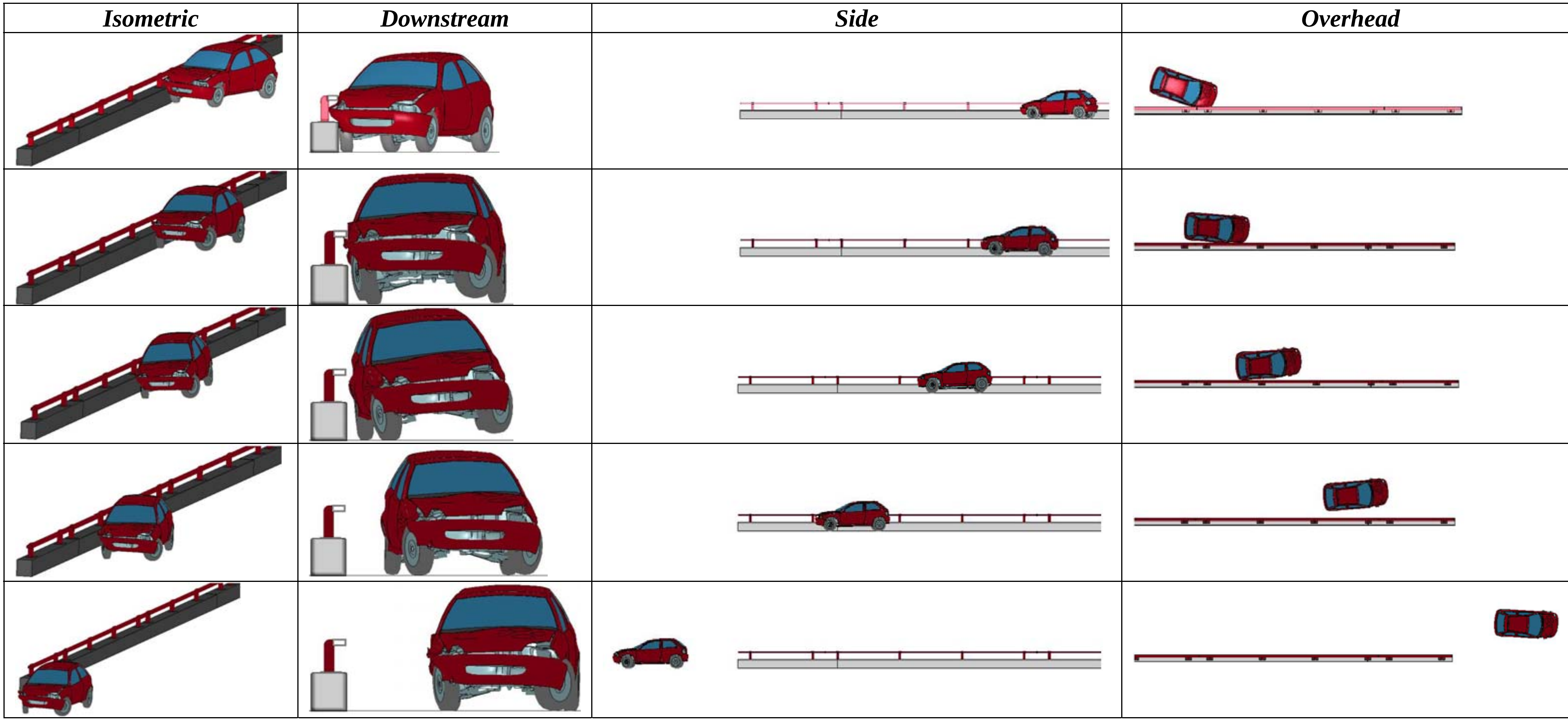


Figure 38. Impact sequence – Annisquam River Bridge Railing Test 3-10 (Design #5).

Vehicle damage

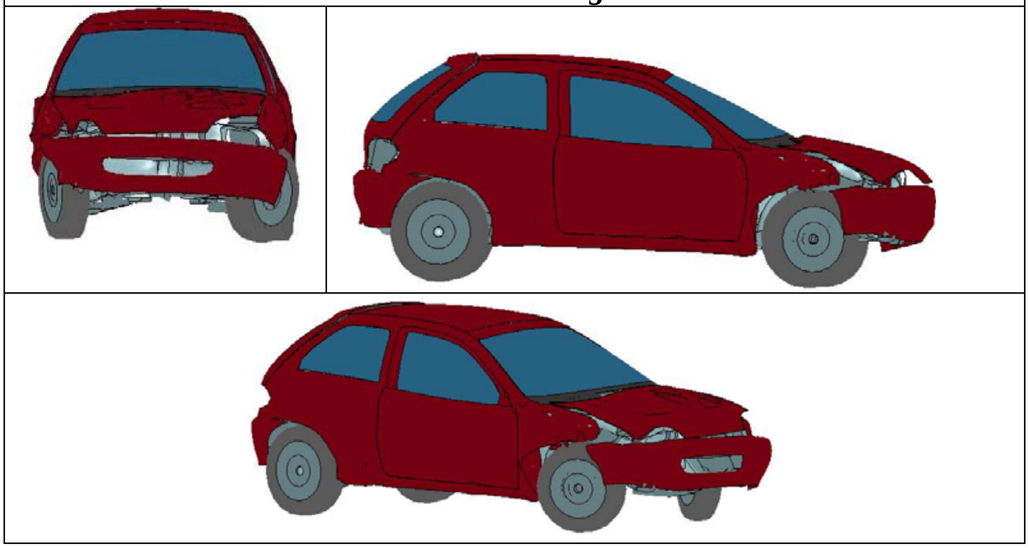


Figure 39. Vehicle damage –Test 3-10 (Design #5).

<u>Design #5 - Test 3-11</u>

Figure 40 shows the pickup truck impact sequence from four different points of view. Upon impact with the bridge railing, the vehicle right-front corner crushed against the steel rail at the top of the barrier. Immediately after, the front bumper slightly hit one of the posts causing a limited amount of snagging. During the first phase of the impact, the right front tire hit the concrete parapet and was forced to steer away from the barrier. The front quarter panel crushed against the steel rail and, as a consequence, the vehicle rolled towards the barrier. During this roll motion, both the front and rear left wheels lost contact with the ground. After the rear of the vehicle hit the railing, the right wheels also lifted from the ground and the vehicle lost the contact with the road surface for a short time. The vehicle became parallel to the barrier and then was redirected away towards the roadside face with an exit angle of 2.3 degrees and a velocity of 45.1 mi/hr (72.6 km/h). During the exit phase the right-side wheels returned in contact with the ground but the vehicle was redirected with its left wheels still off the ground

At the end of the simulation (1 second) the left wheels were still not in contact with the ground yet. The maximum roll angle was about 26 degrees. During the impact, the vehicle rear right wheel was lifted from the ground a maximum height of approximately 29.5 in (750 mm).

The Report 350 evaluation criteria for test 3-11 are shown in Table 13 and the evaluation criteria for the proposed update to Report 350 are shown in Table 14. The theoretical occupant impact velocities (OIV) in the longitudinal and lateral directions were 24 ft/s (7.3 m/s) and 30.5 ft/s (9.3 m/s) respectively. The theoretical ridedown accelerations in longitudinal and lateral directions were -4.6 g's and 9.7 g's. The theoretical Head Impact Velocity (THIV) was 25.3 mi/hr (40.7 km/s) and the Post Impact Head Deceleration (PHD) was 10.5 g's. The Acceleration Severity Index (ASI) was 2.09.

The barrier damage was negligible. All components were judged reusable with minimal permanent deformation of the steel tube rail in the area of the impact. The damage around the zone of the rail sleeve, where the impact took place, was minor and not serious enough to require repair. No debris was expelled from the both the bridge railing and the test vehicle during the impact.

A summary of the vehicle damage is shown in Figure 41. The front right quarter panel of the vehicle was crushed with evident damage due to some snagging and the hood buckled. The bumper was slightly damaged. The extent of the damage to the right door was limited. The suspension of the front right wheel, which first impacted against the concrete wall, was broken and the wheel remained turned inward. No relevant deformation of the vehicle interior was observed. The rear right side of the pickup truck was slightly damaged due to the impact against the concrete wall when the vehicle was redirected by the railing. No portions of the vehicle were dislodged or released during the crash test.

The Von-Mises stress contour plots for test 3-11 of Design #5 were examined at the most demanding phases of the crash event and are shown below. As shown in Figure 42, the stresses in the steel rail and post generally were below the yield stress although there were several higher stresses at locations where there was direct contact between the vehicle and rail and post and in interface between the steel rail and the posts. The maximum stress of 83 ksi (570 MPa) occurred in the steel rail where it was slightly deformed near the splice. The peak stresses were above the 50 ksi yield stress but they were concentrated in very small areas of the rail and post causing only minor local deformations. Also, the maximum stress in correspondence of the post/rail welded interface was around 48.7 ksi(336 MPa), which is still a reasonable value.

Likewise, the bending stress in the wall was generally less than the 3,000 psi, strength of the concrete, as show in Figure 43. There were local areas on the concrete wall that reached values as high as –10.1 ksi (-69.6 MPa) in compression and 6.8 ksi (46.9 MPa) in tension. These maximum values occurred in areas where there was direct contact with the vehicle and indicate there would be some localized spalling and scraps. Outside the area of direct contact, the stresses acting on the concrete parapet are soon distributed over a larger surface with values under the ultimate stress. Thus, the maximum stress value decreased to 0.6 ksi (4.1 MPa) in compression and 0.6 ksi (4.1 MPa) in tension in the middle phase of the impact and to 0.4 ksi (2.8 MPa) in compression and 0.4 ksi (2.8 MPa) in tension at the end of the contact.

The stresses in Figures 42 and 43 indicate good structural performance of the barrier with relatively minor local deformations due to direct contact.

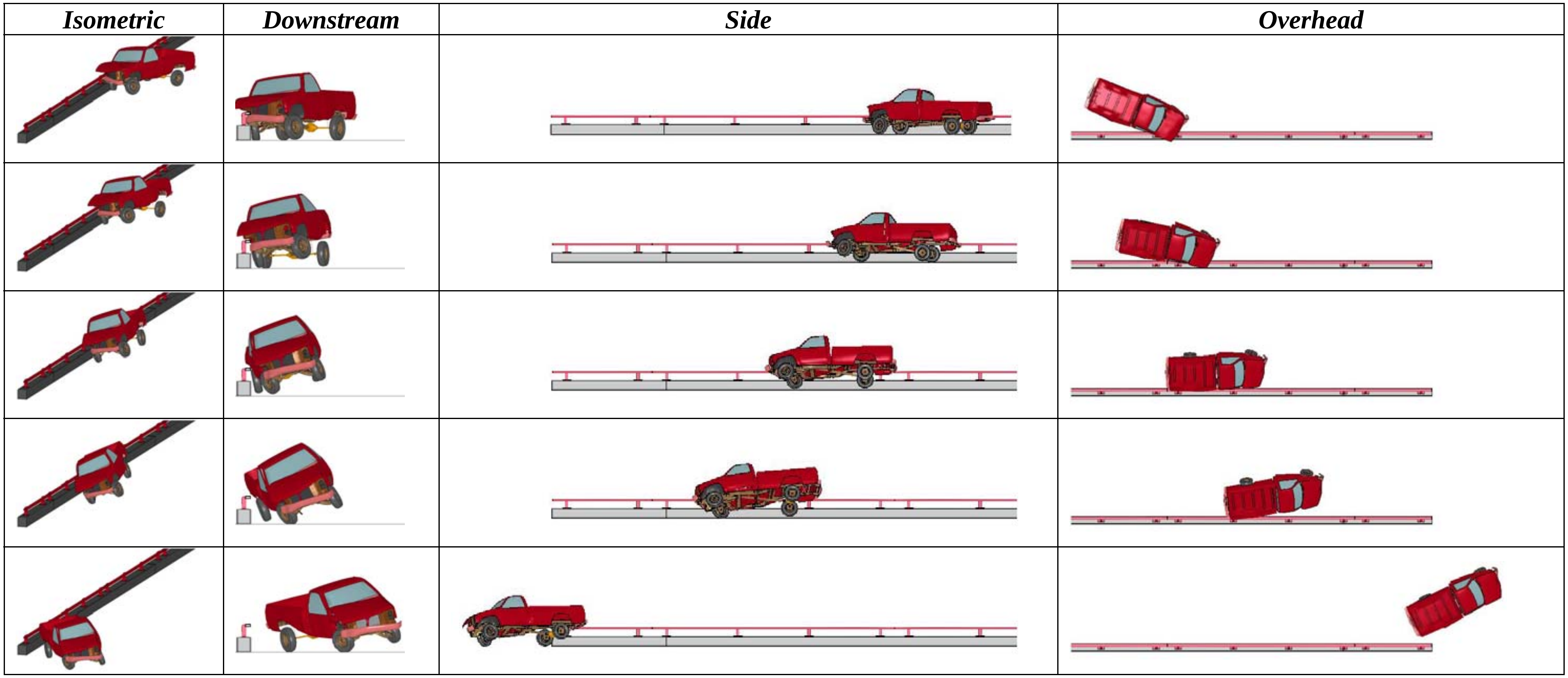


Figure 40. Impact sequence – Annisquam River Bridge Railing Test 3-11 (Design #5)

Vehicle damage

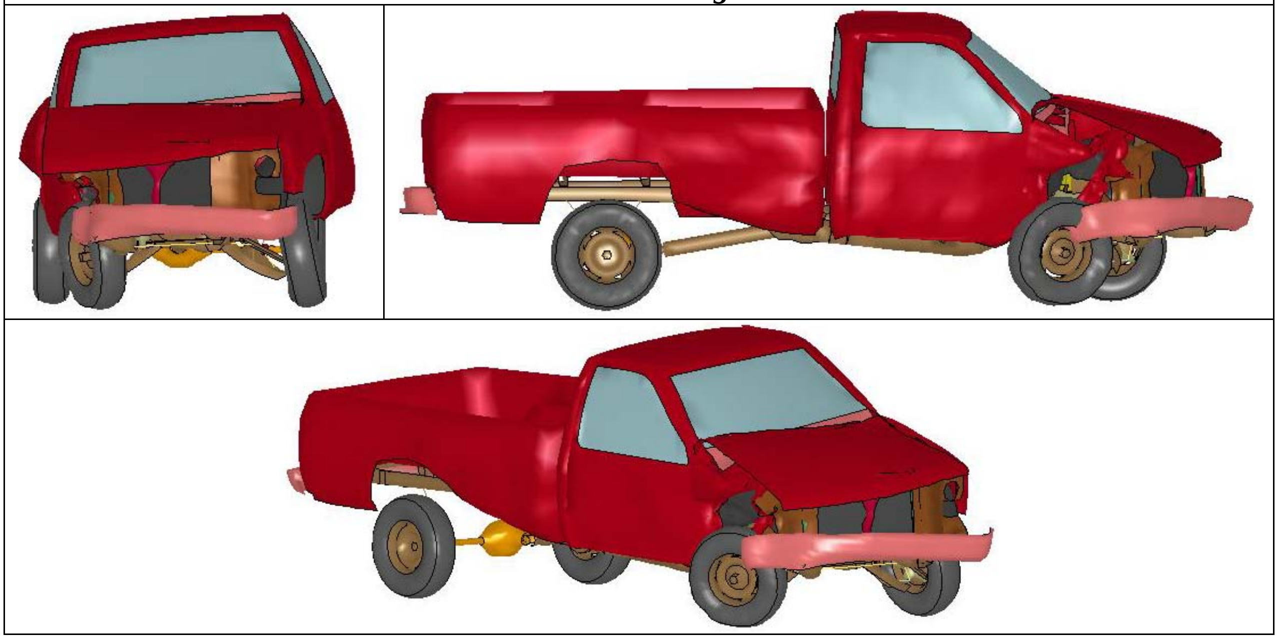


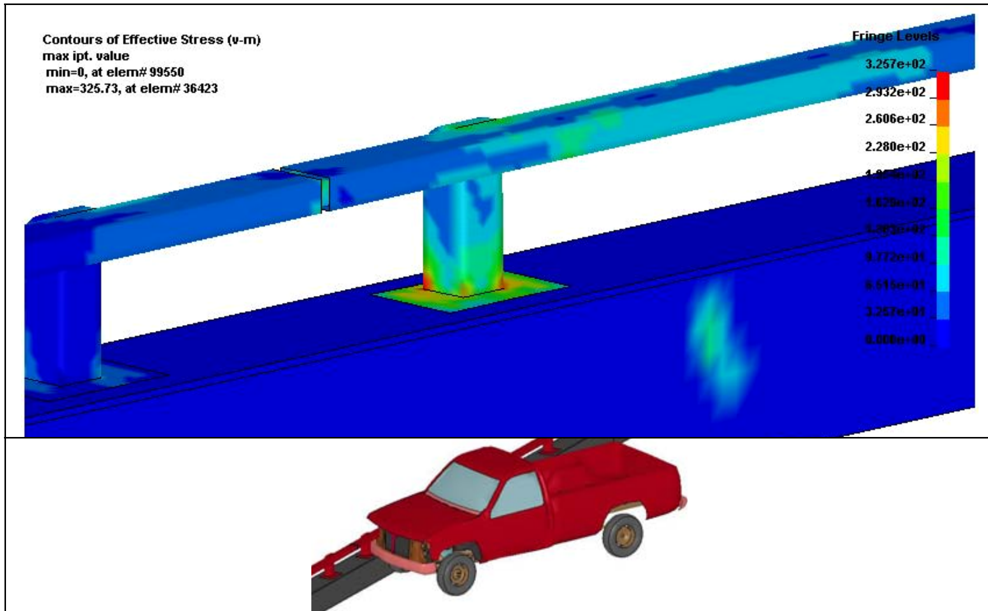
Figure 41. Vehicle damage –Test 3-11 (Design #5).

Table 13. NCHRP Report 350 evaluation criteria for Design 5 - Test 3-10 (left) and Test 3-11 (right).

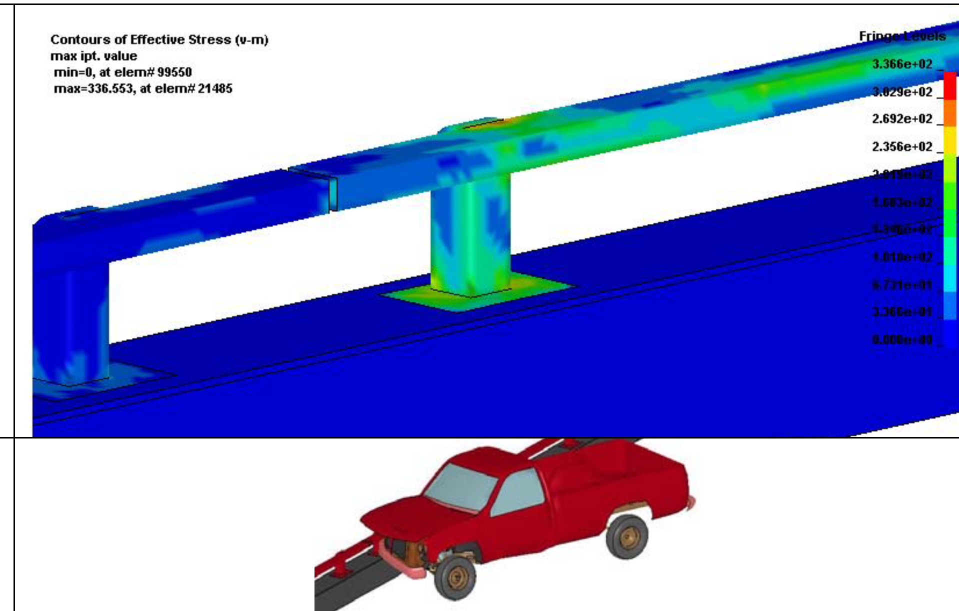
Evaluation Factors		**Evaluation Criteria**	***Test 3-10***	***Test 3-11***
Structural Adequacy	A.	Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Passed	Passed
	B.	The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.	NA	NA
	C.	Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.	NA	NA
Occupant Risk	D.	Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone.	Passed	Passed
	E.	Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.	NA	NA
	F.	The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable.	Passed	Passed
	G.	It is preferable, although not essential, that the vehicle remain upright during and after collision.	NA	NA
	H.	Occupant impact velocities should satisfy the following: Occupant Impact Velocity Limits (ft/s) Component / Preferred / Maximum		
		Longitudinal and Lateral / 30 / 40	16.1 ft/s 24.6 ft/s	24 ft/s 30.5 ft/s
		Longitudinal / 10 / 15	NA	NA
	I.	Occupant ridedown accelerations should satisfy the following: Occupant Ridedown Acceleration Limits (g's) Component / Preferred / Maximum		
		Longitudinal and Lateral / 15 / 20	-3.7 g's -13.1 g's	-4.6 g's 9.7 g's
	J.	(Optional) Hybrid III dummy responses.	NA	NA
Vehicle Trajectory	K.	After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	Passed	Passed
	L.	The occupant impact velocity in the longitudinal direction should not exceed 40 ft/sec and the occupant rideown acceleration in the longitudinal direction should not exceed 20 G's.	Passed	Passed
	M.	The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.	2.5˚ (Passed)	2.3˚ (Passed)
	N	Vehicle trajectory behind the test article is acceptable.	NA	NA

Table 14. NCHRP Report 350 Update evaluation criteria for Design #5 - Test 3-10 (left) and Test 3-11 (right).

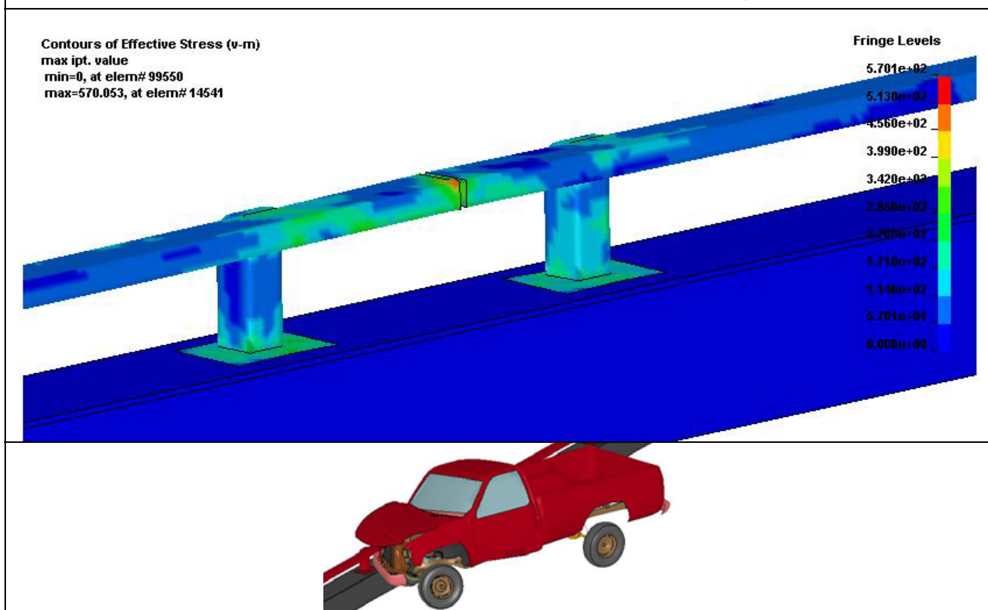
Evaluation Factors		**Evaluation Criteria**			***Test 3-10***	***Test 3-11***
Structural Adequacy	A.	Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.			Passed	Passed
	B.	The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.			N/A	N/A
	C.	Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.			N/A	N/A
Occupant Risk	D.	Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.			Passed	Passed
	E.	Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.			N/A	N/A
	F.	The vehicle should remain upright during and after the collision The maximum roll and pitch angles are not to exceed 75 degrees.			Roll angle: 6.9˚ (Passed)	Roll angle: 26˚ (Passed)
	G.	It is preferable, although not essential, that the vehicle remain upright during and after collision.			N/A	N/A
	H.	Occupant impact velocities (OIV) should satisfy the following limits:				
		Occupant Impact Velocity Limits (ft/s)				
		Component	Preferred	Maximum		
		Longitudinal and Lateral	30	40	16.1 ft/s 24.6 ft/s	24 ft/s 30.5 ft/s
		Longitudinal	10	15		
	I.	Occupant ridedown accelerations should satisfy the following limits:				
		Occupant Ridedown Acceleration Limits (g's)				
		Component	Preferred	Maximum		
		Longitudinal and Lateral	15	20	-3.7 g's -13.1 g's	-4.6 g's 9.7 g's
Vehicle Trajectory	N.	Vehicle trajectory behind the test article is acceptable.			N/A	N/A



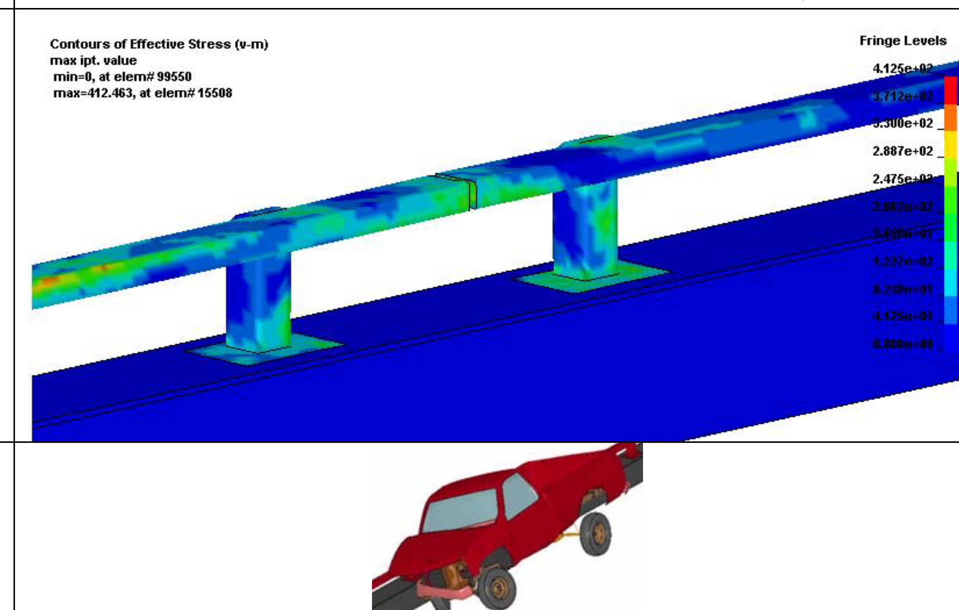
(a) Beginning of the impact (t=0.035 sec) $MAX\ \sigma_{VM} = 47.1 ksi$



(b) Impact between bumper and post (t=0.05 sec) $MAX\ \sigma_{VM} = 48.7 ks$

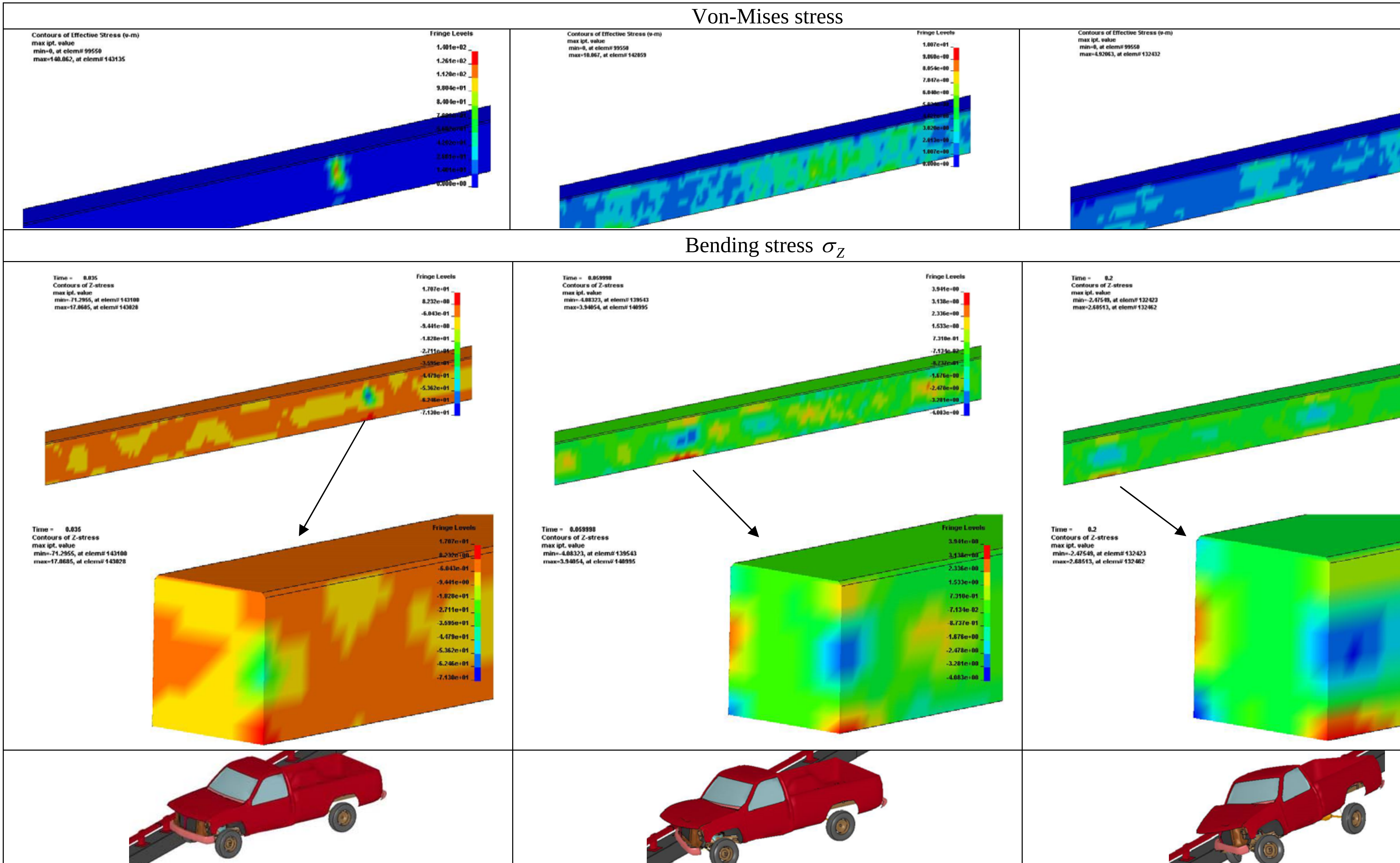


(c) Maximum stress in the steel rail (t=0.09 sec) $MAX\ \sigma_{VM} = 82.7 ksi$



(d) End of the impact (t=0.28 sec) $MAX\ \sigma_{VM} = 59.8 ksi$

Figure 42. Stress distribution for the steel rail and posts for Design #5 - Test 3-11 (units in MPa).



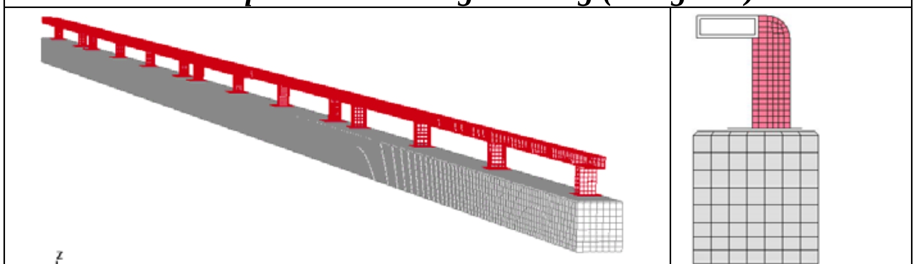
(a) Beginning of the impact (t=0.035 sec) Max σ_{VM} =20.3 ksi; -10.7 ksi< σ_Z <6.8 ksi	(b) Middle phase of the impact (t=0.06 sec) Max σ_{VM} =1.6 ksi; -0.6 ksi< σ_Z <0.6 ksi	(c) End of the impact (t=0.2 se Max σ_{VM} =0.7 ksi; -0.4 ksi< σ_Z <

Figure 43. Stress distribution for the concrete wall for Design #5 - Test 3-11.

Design #6

Design #6 is basically the same as Design #5 with the exception a deeper rail section (i.e., TS8x3x1/4) was used to increase the distance between the edge of the concrete wall and the posts. The overall height of the barrier was retained at 32 inches. Figure 44 shows the finite element model for Design #6.

Annisquam River Bridge Railing (Design #6)



a) Over view ***b) Cross-section***

Figure 44. Finite element model of Design #6.

<u>*Design #6 - Test 3-10*</u>

Figure 45 shows the small-car impact sequence from four different points of view. After the bumper hit the concrete wall, the front right wheel contacted the railing and was steered away from the barrier. Immediately after, the front right quarter panel of the car struck the metal tube rail and the front-right headlight crushed inward. Upon the impact with the concrete wall, the front wheels lifted and the vehicle began rotating around its vertical axis as it began to redirect. Upon contact of the rear part of the vehicle body with the concrete wall, the car was oriented parallel to the barrier. The contact with the concrete wall caused the vehicle to roll towards the railing and the right wheels came back in contact with the ground. The vehicle was redirected with an exit angle of 2.8 degrees and a velocity of 53.6 mi/hr (86.3 km/h). During the impact, the front wheels of the vehicle were lifted from the ground by a maximum height of approximately 4 in (100 mm). The maximum roll angle was about 7 degrees. After a being redirected from the barrier, the car steered back towards the barrier due to the fact that the front left wheel was locked on the right side after the impact. This event is fairly common during impacts involving rigid concrete barriers.

The Report 350 evaluation criteria for test 3-11 are shown in Table 15 and the evaluation criteria for the proposed update to Report 350 are shown in Table 16. The theoretical occupant impact velocities (OIV) in the longitudinal and lateral directions were 14.1 ft/s (4.3 m/s) and 25.9 ft/s (7.9 m/s) respectively. The theoretical ridedown accelerations in longitudinal and lateral directions were -4.9 g's and -18.1 g's. The Theoretical Head Impact Velocity (THIV) was 19.5 mi/hr (31.4 km/h) and the Post Impact Head Deceleration (PHD) was 18.5 g's. The Acceleration Severity Index (ASI) was 1.87. All these values are in the acceptable range indicating that the barrier performance is successful in the test 3-10 conditions.

The barrier damage was negligible. All components were judged reusable with minor permanent deformation of the steel tube rail in the area of the impact. No significant debris was expelled from the both the bridge railing and the test vehicle during the impact.

A summary of the vehicle damage is shown in Figure 46. The impact resulted in a crushed front-right headlight and deformation of the front right quarter panel. The right door was slightly damaged but there was no intrusion inside the vehicle. The front bumper was not significantly damaged. The hood buckled to a minor extent and was partially damaged. The right front suspension was deformed and the steering system was locked with the left wheel turned inwards. There was negligible deformation of the vehicle interior and the windshield was not damaged.

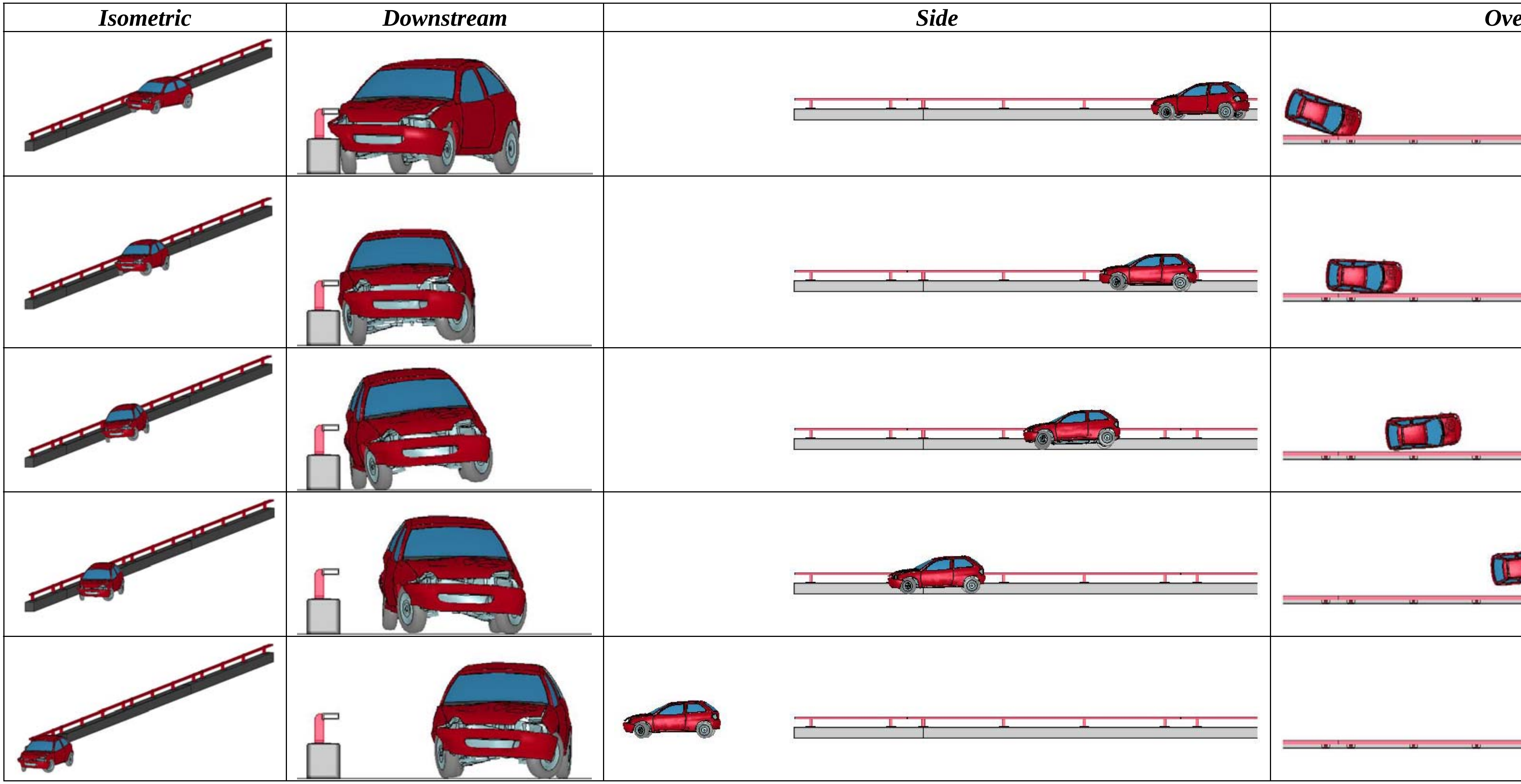


Figure 45. Impact sequence – Annisquam River Bridge Railing Test 3-10 (Design #6).

Vehicle damage

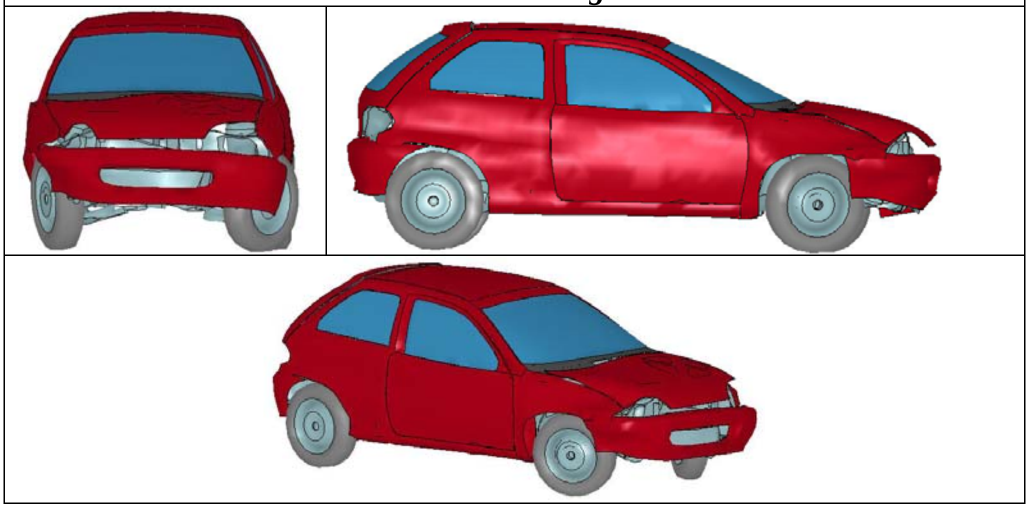


Figure 46. Vehicle damage –Test 3-10 (Design #6).

Design #6 - Test 3-11

Figure 47 shows the pickup truck impact sequence from four different points of view. Upon impact with the bridge railing, the vehicle right-front corner crushed against the steel rail at the top of the barrier. Immediately after, the front bumper slightly hit one of the posts but did not snag hard. The degree of snagging was much less as compared to Design #5. When the right front tire hit the concrete parapet it was steered away from the barrier. Consequently, the vehicle started rotating around the front quarter panel which was crushed against the steel rail. During this movement, the vehicle rolled towards the barrier and both the front and rear left wheels lost contact with the ground. When the rear of the vehicle body hit the concrete wall the right wheels also lost contact with the ground. During the impact the maximum height the rear wheels were lifted was about 23 inches (585 mm). The vehicle became parallel to the barrier and then was redirected away towards the roadside face with an exit angle of 3.4 degrees and a velocity of 45.4 mi/hr (73 km/h). During the exit phase the vehicle remained with its left wheels lifted from the ground eventually coming back into contact with all four wheels on the ground. The maximum roll angle was about 22 degrees. The vehicle dynamics in the pickup truck test with Design #6 shows better stability of the pick-up truck than in Design #5.

The Report 350 evaluation criteria for test 3-11 are shown in Table 15 and the evaluation criteria for the proposed update to Report 350 are shown in Table 16. The theoretical occupant impact velocities (OIV) in the longitudinal and lateral directions were 21.7 ft/s (6.6 m/s) and 29.9 ft/s (9.1 m/s) respectively. The theoretical ridedown accelerations in longitudinal and lateral directions were -5.6 g's and 7.9 g's. The theoretical Head Impact Velocity (THIV) was 25.1 mi/hr (40.4 km/s) and the Post Impact Head Deceleration (PHD) was 8.2 g's. The Acceleration Severity Index (ASI) was 1.99. These values indicate that the barrier performs well in the test 3-11 conditions. Compared to Design#5, the values of the Occupant Impact Velocities were slightly lower. This is a further indication that the extent of the bumper snagging was reduced using a deeper rail section.

The barrier damage was negligible. All components were judged reusable with minimal permanent deformation of the steel tube rail in the area of the impact. The damage around the zone of the rail sleeve, where the impact took place, was minor and not serious enough to require repair. No debris was expelled from the both the bridge railing and the test vehicle during the impact.

A summary of the vehicle damage is shown in Figure 48. The front right quarter panel of the vehicle was crushed due to the impact against the tube of the steel rail and the consequent sliding along that. The hood buckled as a consequence of the contact between the front right headlight and the steel rail. The bumper was slightly damaged. The extent of the damage to the right door was limited. The suspension of the front right wheel, which first impacted against the concrete wall, was broken and the wheel remained turned inward. No relevant deformation of the vehicle interior was observed. The rear right side of the pickup truck was slightly damaged due to the impact against the concrete wall when the vehicle was redirected by the railing. No portions of the vehicle were dislodged or released during the crash test.

The Von-Mises stress contour plots for test 3-11 of Design #6 were examined at the most demanding phases of the crash event and are shown below. As in the two previous cases, the stresses in the steel rail and post generally were below the yield stress although there were several higher stresses at locations where there was direct contact between the vehicle and rail and post (Figure 49). The maximum stress of 78.9 ksi (544 MPa) occurred in the steel rail in the side facing the roadway close to post #6. The peak stresses were above the 50 ksi yield stress but they were concentrated in very small areas of the rail and post causing only minor local deformations. In particular, the most relevant locations with stress concentration were the welded interface between the tube rail and the post and the connection between two different segments of the steel rail.

Likewise, the bending stress in the wall was generally less than the 3,000 psi, strength of the concrete, as show in Figure 50. There were local areas on the concrete wall that reached values as high as 6.1 ksi (42 MPa) in compression and 2.2 ksi (15.2 MPa) in tension. These maximum values occurred in areas where there was direct contact with the vehicle and indicate there would be some localized spalling and scraps. Outside the area of direct contact, the stresses acting on the concrete parapet are soon distributed over a larger surface with values under the ultimate stress. Thus, the maximum stress value decreased to 0.8 ksi (5.5 MPa) in compression and 0.7 ksi (4.8 MPa) in tension in the middle phase of the impact and to 0.4 ksi (2.8 MPa) in compression and 0.3 ksi (2.1 MPa) in tension at the end of the contact.

The stresses in Figures 49 and 50 indicate good structural performance of the barrier with relatively minor local deformations due to direct contact.

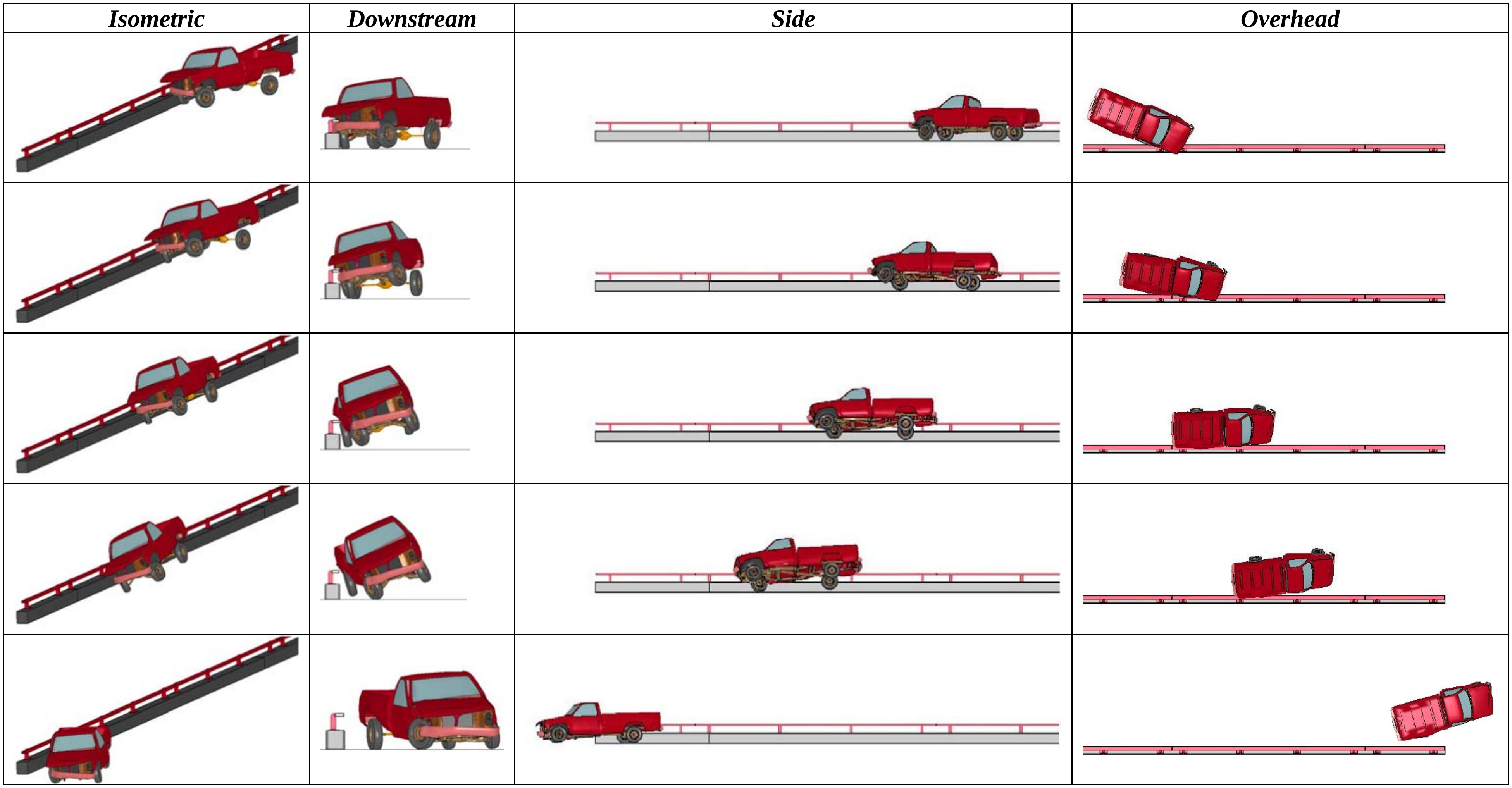


Figure 47. Impact sequence – Annisquam River Bridge Railing Test 3-11 (Design #6)

Vehicle damage

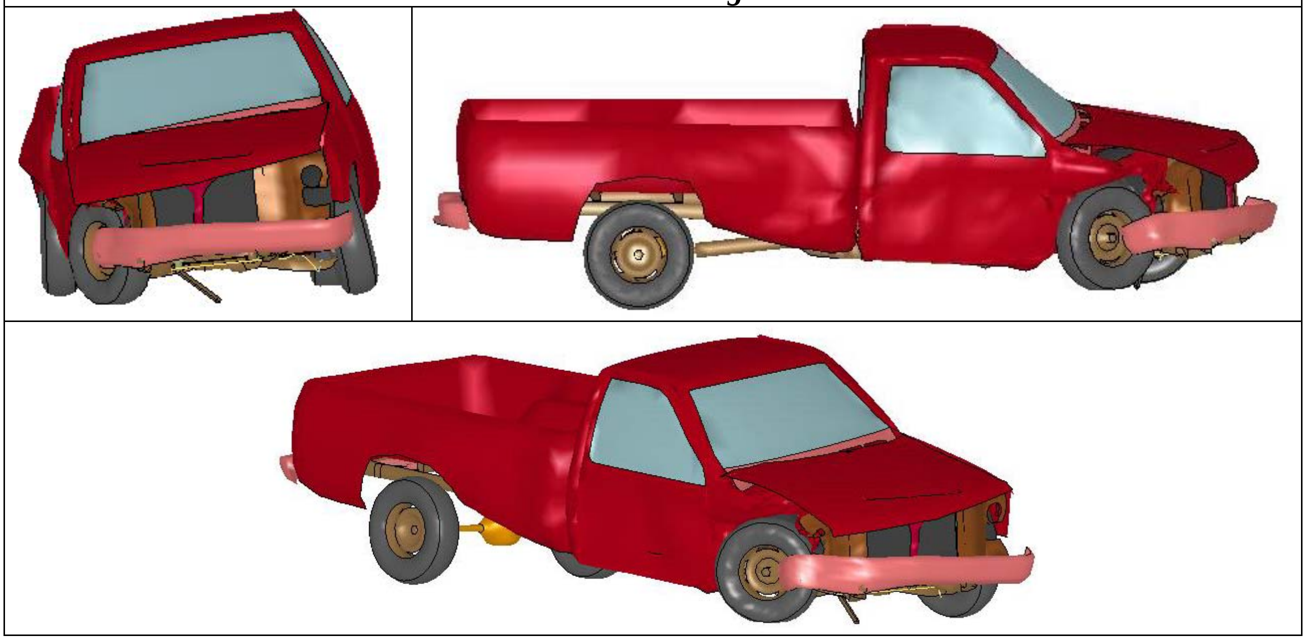


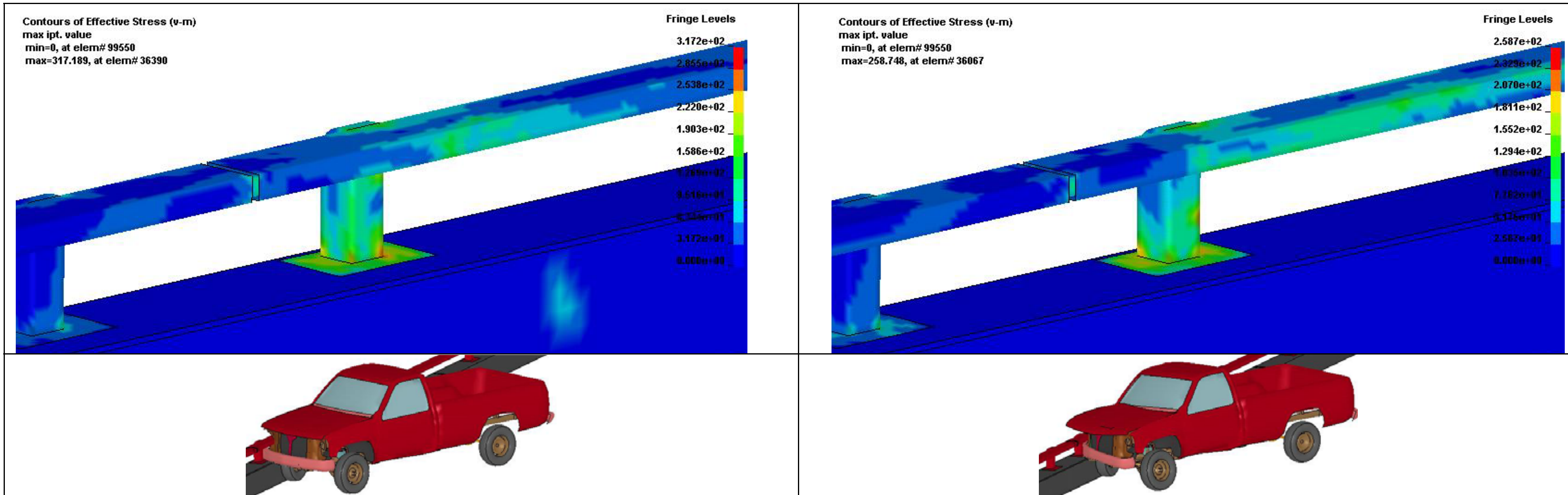
Figure 48. Vehicle damage –Test 3-11 (Design #6).

Table 15. NCHRP Report 350 evaluation criteria for Design 6 - Test 3-10 (left) and Test 3-11 (right).

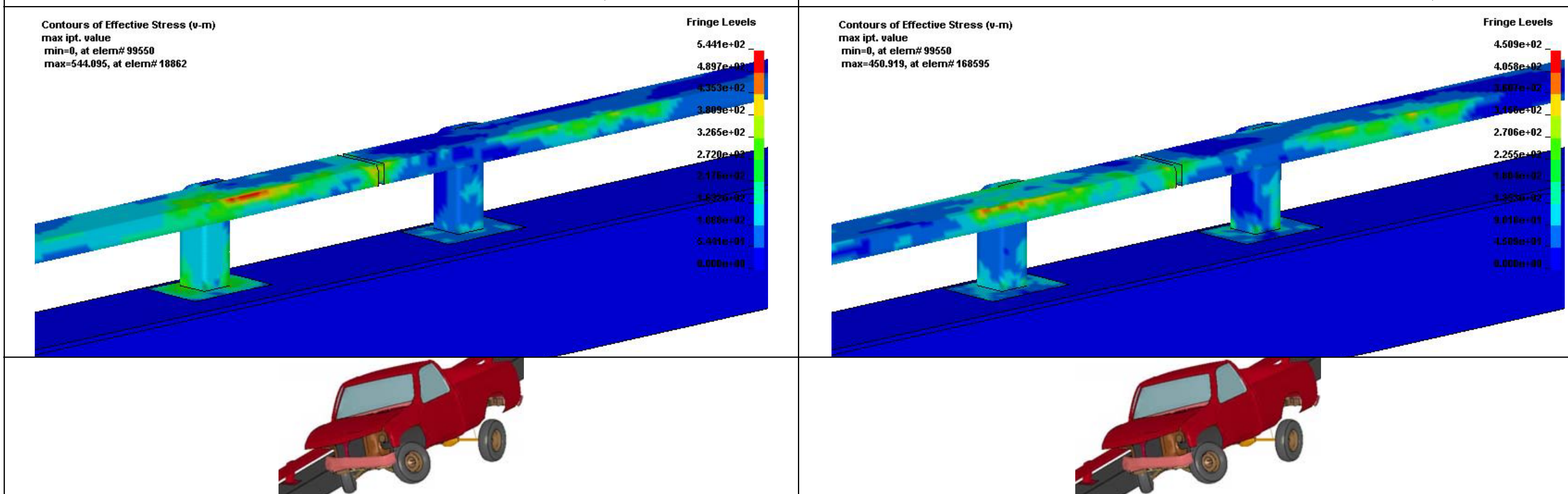
Evaluation Factors	Evaluation Criteria		*Test 3-10*	*Test 3-11*
Structural Adequacy	A.	Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Passed	Passed
	B.	The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.	NA	NA
	C.	Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.	NA	NA
Occupant Risk	D.	Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone.	Passed	Passed
	E.	Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.	NA	NA
	F.	The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable.	Passed	Passed
	G.	It is preferable, although not essential, that the vehicle remain upright during and after collision.	NA	NA
	H.	Occupant impact velocities should satisfy the following: Occupant Impact Velocity Limits (ft/s) Component / Preferred / Maximum		
		Longitudinal and Lateral / 30 / 40	14.1 ft/s 25.9 ft/s	21.7 ft/s 29.9 ft/s
		Longitudinal / 10 / 15	NA	NA
	I.	Occupant ridedown accelerations should satisfy the following: Occupant Ridedown Acceleration Limits (g's) Component / Preferred / Maximum		
		Longitudinal and Lateral / 15 / 20	-4.9 g's -18.1 g's	-5.6 g's 7.9 g's
	J.	(Optional) Hybrid III dummy responses.	NA	NA
Vehicle Trajectory	K.	After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	Passed	Passed
	L.	The occupant impact velocity in the longitudinal direction should not exceed 40 ft/sec and the occupant rideown acceleration in the longitudinal direction should not exceed 20 G's.	Passed	Passed
	M.	The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.	2.8° (Passed)	3.4° (Passed)
	N	Vehicle trajectory behind the test article is acceptable.	NA	NA

Table 16. NCHRP Report 350 Update evaluation criteria for Design #6 - Test 3-10 (left) and Test 3-11 (right).

<table>
<tr><th>Evaluation Factors</th><th colspan="4">Evaluation Criteria</th><th>Test 3-10</th><th>Test 3-11</th></tr>
<tr><td rowspan="3">Structural Adequacy</td><td>A.</td><td colspan="3">Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>B.</td><td colspan="3">The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.</td><td>N/A</td><td>N/A</td></tr>
<tr><td>C.</td><td colspan="3">Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.</td><td>N/A</td><td>N/A</td></tr>
<tr><td rowspan="14">Occupant Risk</td><td>D.</td><td colspan="3">Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.</td><td>Passed</td><td>Passed</td></tr>
<tr><td>E.</td><td colspan="3">Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.</td><td>N/A</td><td>N/A</td></tr>
<tr><td>F.</td><td colspan="3">The vehicle should remain upright during and after the collision The maximum roll and pitch angles are not to exceed 75 degrees.</td><td>Roll angle: 6.9° (Passed)</td><td>Roll angle: 21.5° (Passed)</td></tr>
<tr><td>G.</td><td colspan="3">It is preferable, although not essential, that the vehicle remain upright during and after collision.</td><td>N/A</td><td>N/A</td></tr>
<tr><td rowspan="5">H.</td><td colspan="3">Occupant impact velocities (OIV) should satisfy the following limits:</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td colspan="3">Occupant Impact Velocity Limits (ft/s)</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>30</td><td>40</td><td>14.1 ft/s
25.9 ft/s</td><td>21.7 ft/s
29.9 ft/s</td></tr>
<tr><td>Longitudinal</td><td>10</td><td>15</td><td></td><td></td></tr>
<tr><td rowspan="4">I.</td><td colspan="3">Occupant ridedown accelerations should satisfy the following limits:</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td colspan="3">Occupant Ridedown Acceleration Limits (g's)</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>15</td><td>20</td><td>-4.9 g's
-18.1 g's</td><td>-5.6 g's
7.9 g's</td></tr>
<tr><td>Vehicle Trajectory</td><td>N.</td><td colspan="3">Vehicle trajectory behind the test article is acceptable.</td><td>N/A</td><td>N/A</td></tr>
</table>

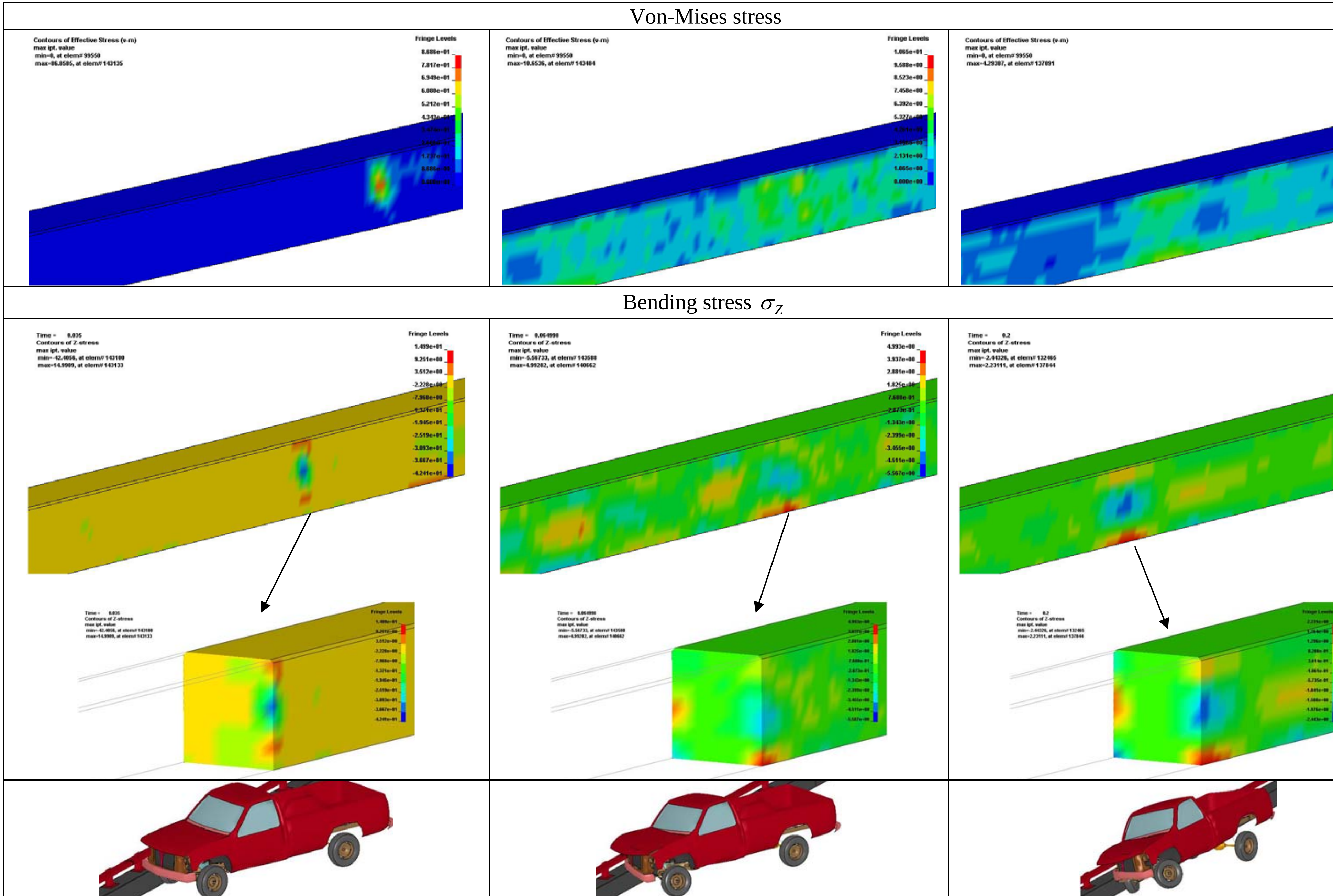


(a) Beginning of the impact (t=0.035 sec) $MAX\ \sigma_{VM} = 46\,ksi$ | ***(b) Impact between bumper and post (t=0.05 sec)*** $MAX\ \sigma_{VM} = 37.4\,ks$



(c) Maximum stress in the steel rail (t=0.195 sec) $MAX\ \sigma_{VM} = 78.9\,ksi$ | ***(d) End of the impact (t=0.200 sec)*** $MAX\ \sigma_{VM} = 65.3\,ksi$

Figure 49. Stress distribution for the steel rail and posts for Design #6 - Test 3-11 (units in MPa).



(a) Beginning of the impact (t=0.035 sec)	(b) Middle phase of the impact (t=0.065 sec)	(c) End of the impact (t=0.2 sec)
σ_{VM} =12.5 ksi; -6.1 ksi< σ_Z <2.2 ksi	σ_{VM} =1.5 ksi; -0.8 ksi< σ_Z <0.7 ksi	σ_{VM} =0.6 ksi; -0.4 ksi< σ_Z <0.3 ks

Figure 50. Stress distribution for the concrete wall for Design #6 - Test 3-11.

Conclusions

This report described the results obtained from finite element crash simulations performed with six different modified designs of the Minnesota Type Three Combination Bridge Railing. The purpose was to investigate if the modifications MHD would like to make to adapt the original Minnesota Type Three Combination Bridge Railing to the Annisquam River Bridge are likely to satisfy the test level three criteria of both Report 350 and the proposed update to Report 350.

Before performing the finite element analyses of the modified designs, simulations of the full scale tests with the small car and the pick-up truck performed on the original Minnesota Type Three Combination Bridge Railing were performed. The comparison between the numerical and the full-scale results showed that the finite element simulations provided good agreement with the crash tests so the model could be used to examine the safety performance of the design modifications proposed by MHD.

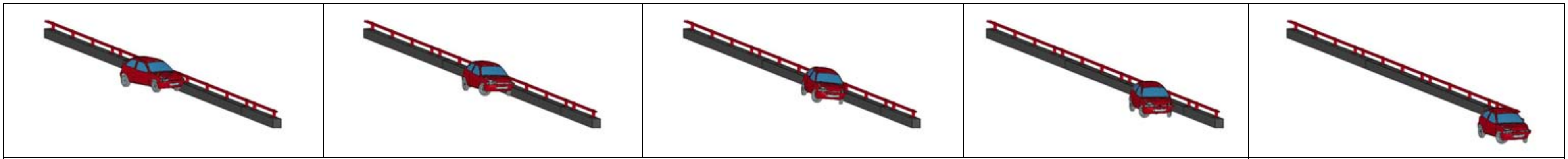
The finite element simulations presented earlier in the document show that all six design alternatives pass both the Report 350 and Report 350 update evaluation criteria for test level three. Design #6 represents the most suitable choice in the case of the Annisquam River Bridge, however, because it combines an aesthetically sensitive design with a small roll angle in the pickup truck test (T 3-11) and one of the smallest snagging potentials among all the other five designs. This was accomplished by balancing the relatively low concrete parapet height with a steel post and rail design that feature a relatively large offset that helps reduce the snagging potential. The finite element simulations for Design #6 indicate that this design is very likely to pass the test level three conditions and should be approved for use on the Annisquam Bridge. This design strikes an acceptable compromise between having a lower concrete parapet that will not obstruct the view with a steel railing system that will contain and redirect typical passenger vehicles according to test level three requirements. Fortunately, the width of the concrete wall is not particularly important for the Annisquam Bridge so it is possible to keep the crash-tested width of the wall (i.e., 16 inches) and place the post base plate in exactly the same location using the same details as in the full-scale crash test. This provides additional horizontal space that minimizes the snagging potential and also will allow the bridge designer to use the same base plate and connection details used in the crash tested system.

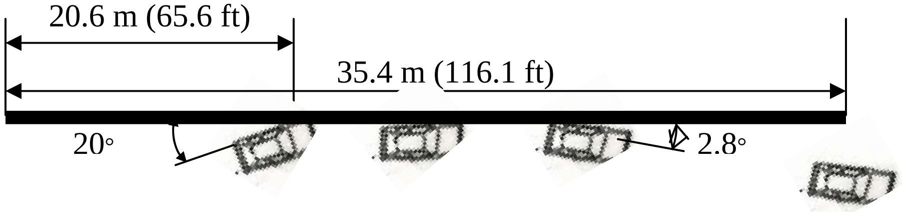
Table 17 summarizes the main design features and the results obtained from the simulations for all six design alternatives. Table 18 and 19 the summarize simulation results for Design #6, the preferred alternative Appendix A shows the graphs of the forces acting along the welds at the rail-post connections and post-baseplate connections for the four posts directly involved in the impact for Design #6 and Appendix B shows the force history acting along the concrete wall for the Design#6. Appendix C shows the verification of the railing structural resistance for the Design #5 and Design #6 according to the AASHTO LRFD Bridge Guide. Appendix D shows the acceleration time histories for all the designs simulated and described in this report.

Table 17. Design features and NCHRP Report 350 evaluation criteria for the six design alternatives.

	Design Alternative						
Design Features	**Original**	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**
Curb	Yes	Yes	No	No	No	No	No
Parapet Height [in]	20	17	17	20	17	17	17
Parapet Width [in]	16	12	12	12	16	16	16
Post Type (TS)	5x7x1/4	6x6x1/4	6x6x1/4	6x6x1/4	5x5x1/4	5x5x1/4	5x5x1/4
Rail Type (TS)	10x4x5/16	6x3x1/4	6x3x1/4	6x4x1/4	10x4x5/16	6x3x1/4	6x3x1/4
Total Height [in]	36	31	31	32	32	32	32
NHCRP 350 Evaluation Criteria							
Test 3-10							
Occupant Impact Velocity [ft/s]							
Longitudinal	16.4	14.4	15.4	13.5	18.4	16.1	14.1
Lateral	27.8	25.6	24.9	24.6	24.3	24.6	25.9
Occupant Ridedown Acceleration [g's]							
Longitudinal	2.6	-4.5	-5.6	-3.9	-11.1	-3.7	-4.9
Lateral	10.6	-15.4	-15.4	-20.1	5.4	-13.1	-18.1
Exit angle [deg]	7.5	4.5	3.5	4.6	1.6	2.5	2.8
Max Roll angle [deg]	N/A	11.6	5.5	6.6	3	6.9	6.9
Test 3-11							
Occupant Impact Velocity [ft/s]							
Longitudinal	25.3	23.3	24	23.3	22	24	21.7
Lateral	24.6	30.2	29.5	29.2	30.5	30.5	29.9
Occupant Ridedown Acceleration [g's]							
Longitudinal	5.2	-3.8	-8.3	-5.2	-5.5	-4.6	-5.6
Lateral	9.3	8	6.9	-8.8	-8.9	9.7	7.9
Exit angle [deg]	1	2.8	8.5	4	6.7	2.3	3.4
Max Roll angle [deg]	N/A	37	29.3	26. 3	26	26	21.5

Table 18. NCHRP Report 350 test summary for Design #6 (Test 3-10).





General Information

Test Agency ....Worcester Polytechnic Institute (WPI)
Test Designation....NCHRP 350 Test 3-10
Test No. 001-07
Date 06-11-07

Test Article

Type ....Bridge Railing (Test Level 3)
Barrier Length ....35.4m (116.1 ft)
Height (mm - relative to approach) ....812.8 mm (32 in)
Material and key elements ....vertical concrete parapet steel rail

Foundation Type and Condition....N/A

Test Vehicle

Type....Production Model
Designation....820C
Model....1992 Geo Metro
Mass (kg)
Mass....860
Test inertial 860
Dummy....N/A
Gross Static....860

Impact Conditions

Speed (km/h) 100
Angle (deg) 20
Impact Severity (kJ) 38.8

Exit conditions

Speed (km/h) ....86.3 (53.8 mph)
Angle (deg) 2.8

Occupant Risk Values

Impact Velocity (m/s)
x-direction ....4.3 (14.1 ft/s)
y-direction....7.9.(25.9 ft/s)
Ridedown Acceleration (g's)
x-direction....-4.9
y-direction....-18.1

European Committee for Normalization (CEN) Values

THIV (km/h)....31.4
PHD (g's)....18.5
ASI 1.87

Test Article Deflections (m)

Dynamic....0
Permanent....0.01

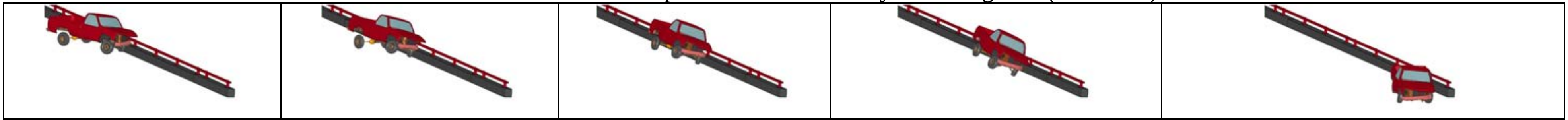
Vehicle Damage (Primary Impact)

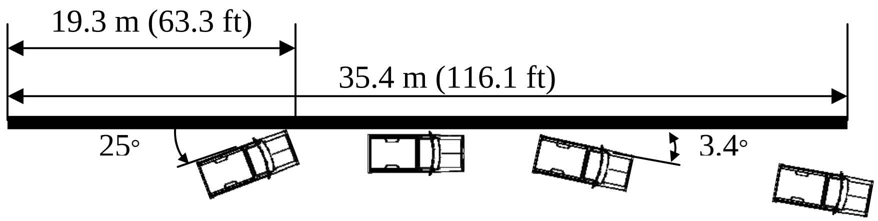
Exterior
VDS....N/A
CDC....N/A
Interior
OCDI....N/A

Post-Impact Vehicular Behavior

Maximum Roll Angle (degrees)....7
Maximum Pitch Angle (degrees)....N/A
Maximum Yaw Angle (degrees)....N/A

Table 19. NCHRP Report 350 test summary for Design #6 (Test 3-11).





General Information
- *Test Agency* .... Worcester Polytechnic Institute (WPI)
- *Test Designation* .... NCHRP 350 Test 3-11
- *Test No.* 002-07
- *Date* 06-15-07

Test Article
- *Type* .... Bridge Railing (Test Level 3)
- *Barrier Length* .... 35.4m (116.1 ft)
- *Height* (mm - relative to approach) .... 812.8 mm (32 in)
- *Material and key elements* .... vertical concrete parapet steel rail

Foundation Type and Condition .... N/A

Test Vehicle
- Type .... Production Model
- Designation 2000P
- Model .... 2001 Chevrolet C2500
- Mass (kg)
  - Mass 2030
  - Test inertial 2030
  - Dummy .... N/A
  - Gross Static 2030

Impact Conditions
- *Speed (km/h)* 100
- *Angle (deg)* 25
- *Impact Severity (kJ)* 140.4

Exit conditions
- *Speed (km/h)* .... 73 (45.4 mph)
- *Angle (deg)* 3.4

Occupant Risk Values
- *Impact Velocity (m/s)*
  - x-direction .... 6.6 (21.7 ft/s)
  - y-direction .... 9.1 (29.9 ft/s)
- *Ridedown Accelerations (g's)*
  - x-direction .... -5.6
  - y-direction .... -7.9

European Committee for Normalization (CEN) Values
- *THIV (km/h)* *40.4*
- *PHD (g's)* *8.2*
- *ASI* *1.99*

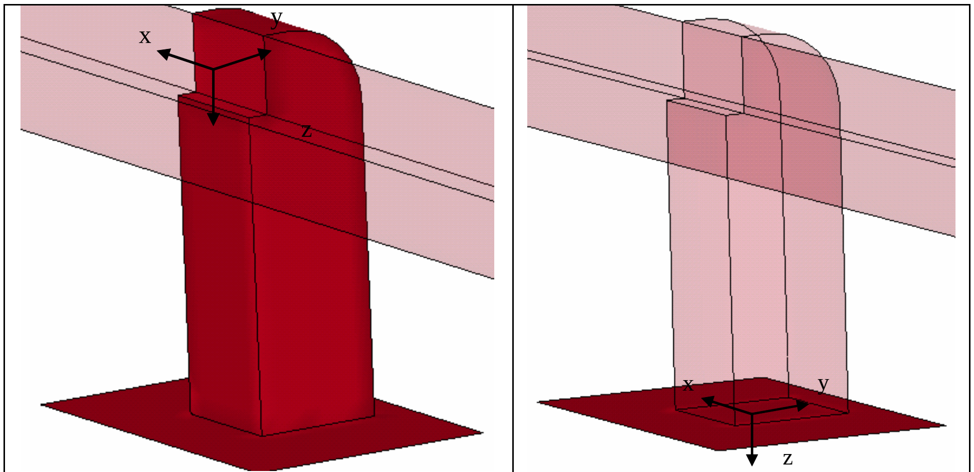
Test Article Deflections (m)
- *Dynamic* *0*
- *Permanent* *0.02*

Vehicle Damage (Primary Impact)
- *Exterior*
  - VDS .... N/A
  - CDC .... N/A
- *Interior*
  - OCDI .... N/A

Post-Impact Vehicular Behavior
- *Maximum Roll Angle (degrees)* 22
- *Maximum Pitch Angle (degrees)* .... N/A
- *Maximum Yaw Angle (degrees)* .... N/A

Appendix A: Forces/moments along the welds of the posts directly involved in the impact for Design #6 Test 3-11

The forces/moments acting along the rail-post and the post-baseplate connections for the four posts directly involved in the impact have been collected according to the coordinate system showed in Figure 51



Rail-Post connection	Post-Baseplate connection

Figure 51. Coordinate system for the Rail-Post and Post-Baseplate connection.

All the forces and moment components obtained from the finite element simulations were filtered using a SAE 60 filter. The posts considered for the collection of forces and moments are shown in Figure 52.

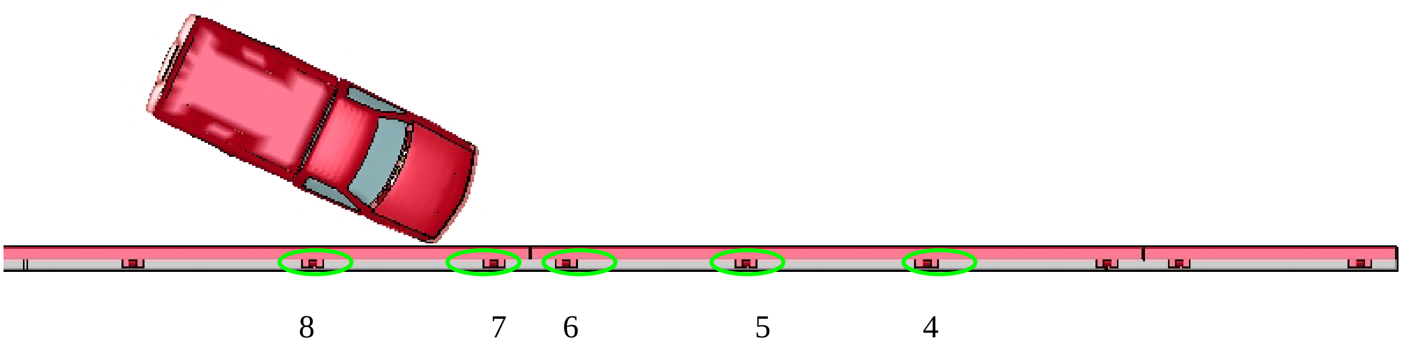


Figure 52 Posts involved in the impact for the Test 3-11 of Design #6.

Forces

The maximum and minimum values for each of three force components for both the Rail-Post connection and the Post-Baseplate connection are shown respectively in Table 20 and Table 21.

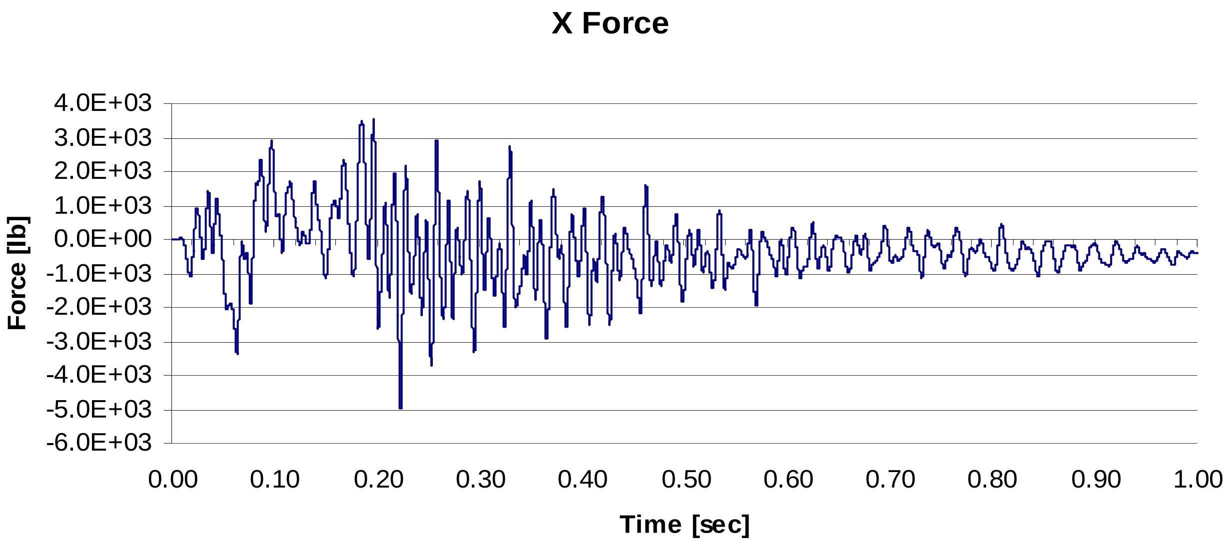
Table 20. Maximum and minimum values of the forces acting along the Rail-Post connection.

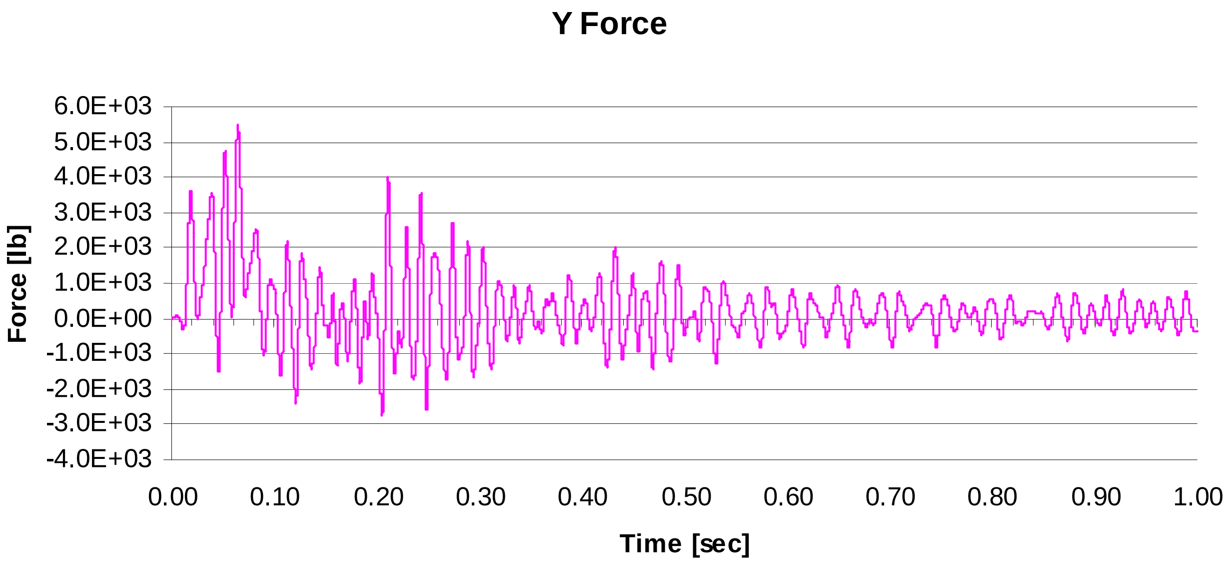
	X component [lb]		**Y component [lb]**		**Z component [lb]**	
	min	**Max**	**min**	**Max**	**min**	**Max**
Post #4	-2.698E+03	7.058E+03	-2.850E+03	2.296E+03	-1.368E+03	1.565E+03
Post #5	-2.2414E+03	1.3191E+04	-3.3568E+03	4.4853E+03	-3.4508E+03	3.9700E+03
Post #6	-4.9929E+03	8.9366E+03	-1.0967E+03	1.7394E+04	-6.6456E+03	9.7781E+03
Post #7	-4.9009E+03	6.9271E+03	-3.5284E+03	2.2560E+04	-2.9876E+03	7.4305E+03
Post #8	-4.988E+03	3.541E+03	-2.733E+03	5.488E+03	-2.066E+03	3.408E+03

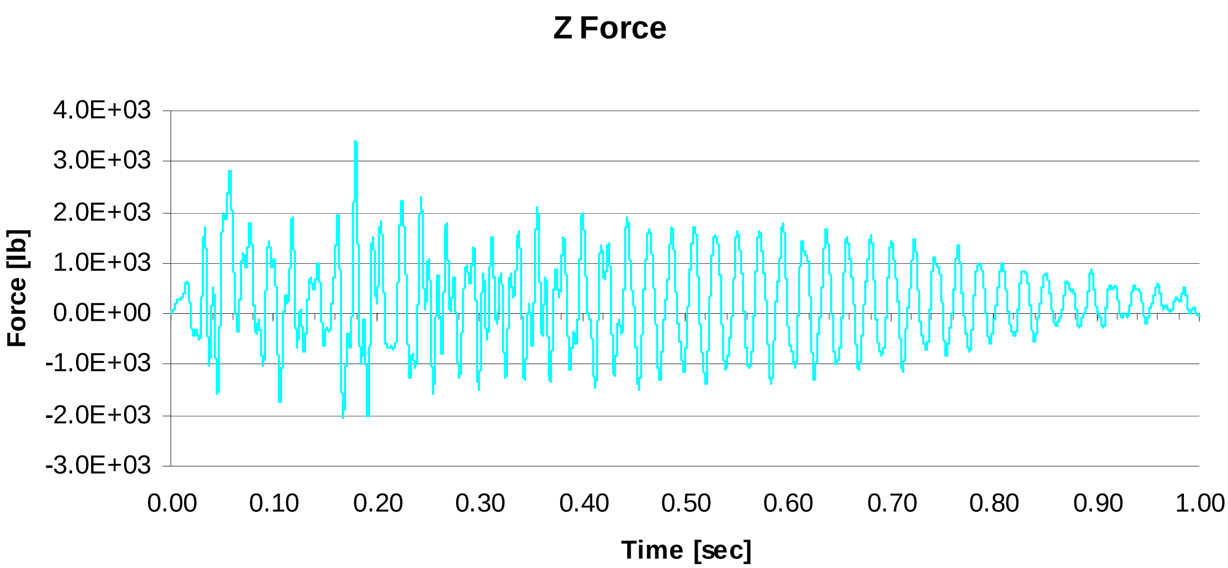
Table 21. Maximum and minimum values of the forces acting along the Post-Baseplate.

	X component [lb]		**Y component [lb]**		**Z component [lb]**	
	min	**Max**	**min**	**Max**	**min**	**Max**
Post #4	-2.901E+03	7.477E+03	-3.153E+03	2.504E+03	-1.414E+03	1.635E+03
Post #5	-2.2648E+03	1.3472E+04	-3.7969E+03	4.6151E+03	-3.4724E+03	4.0735E+03
Post #6	-5.2361E+03	9.6167E+03	-1.2696E+03	1.7380E+04	-6.6886E+03	9.7071E+03
Post #7	-4.9236E+03	1.1683E+04	-3.8623E+03	2.3978E+04	-4.8180E+03	7.9364E+03
Post #8	-5.207E+03	3.746E+03	-2.983E+03	5.737E+03	-2.087E+03	3.525E+03

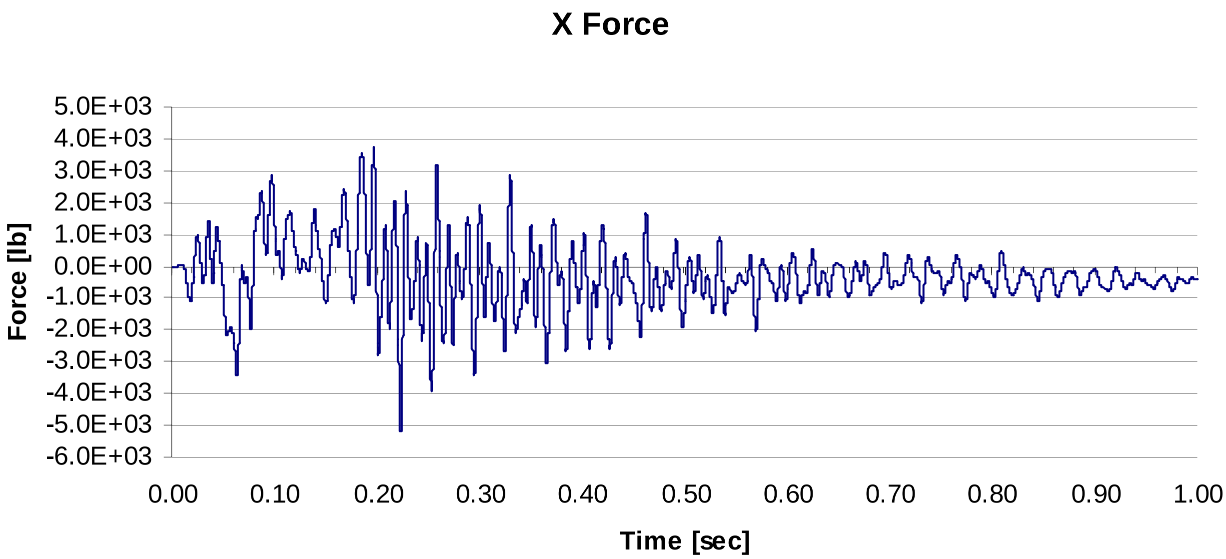
Post #8 (Rail-Post connection)

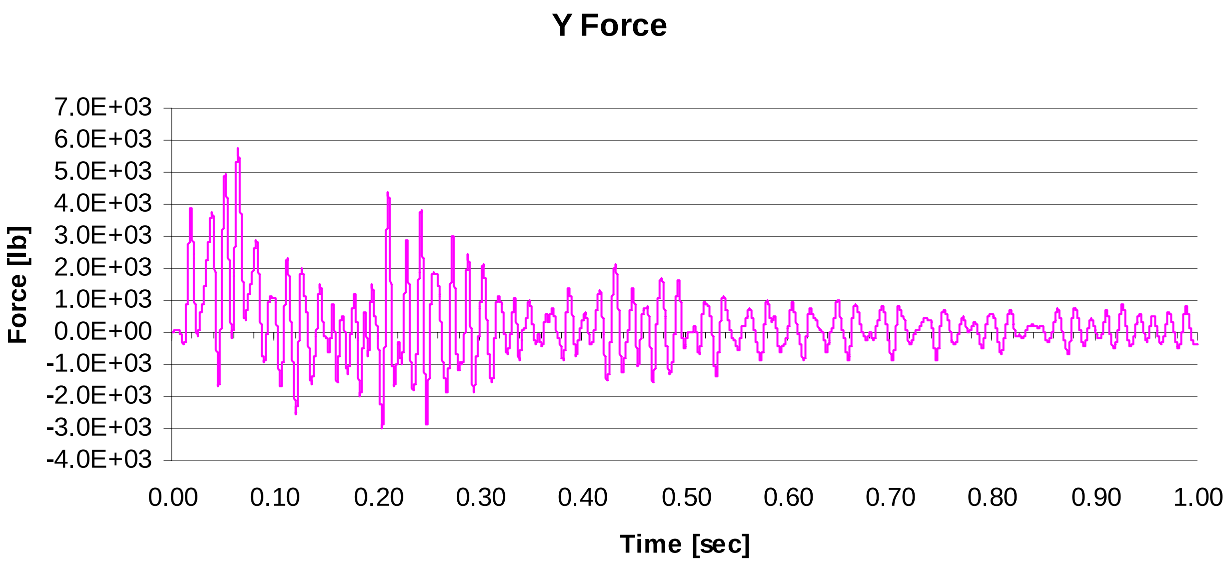


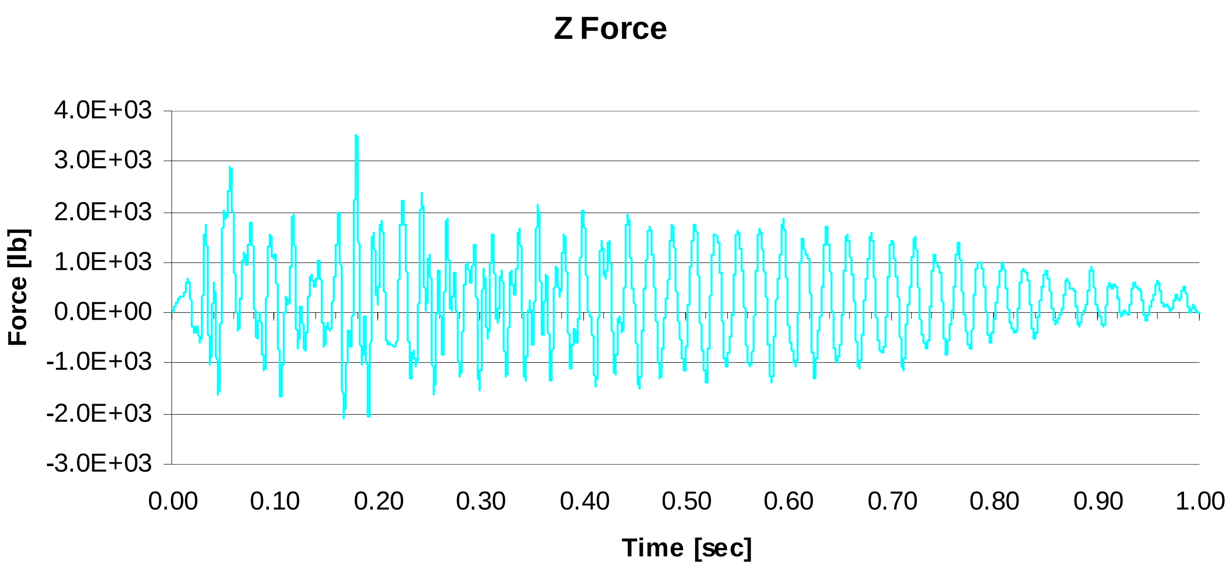




Post #8 (Post-Baseplate connection)







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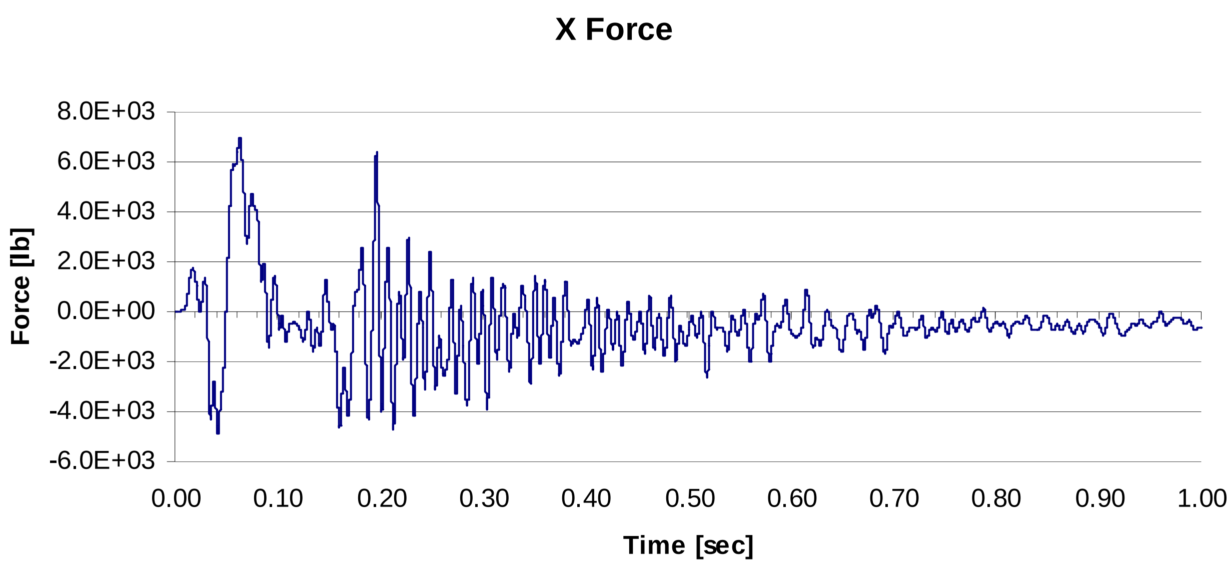
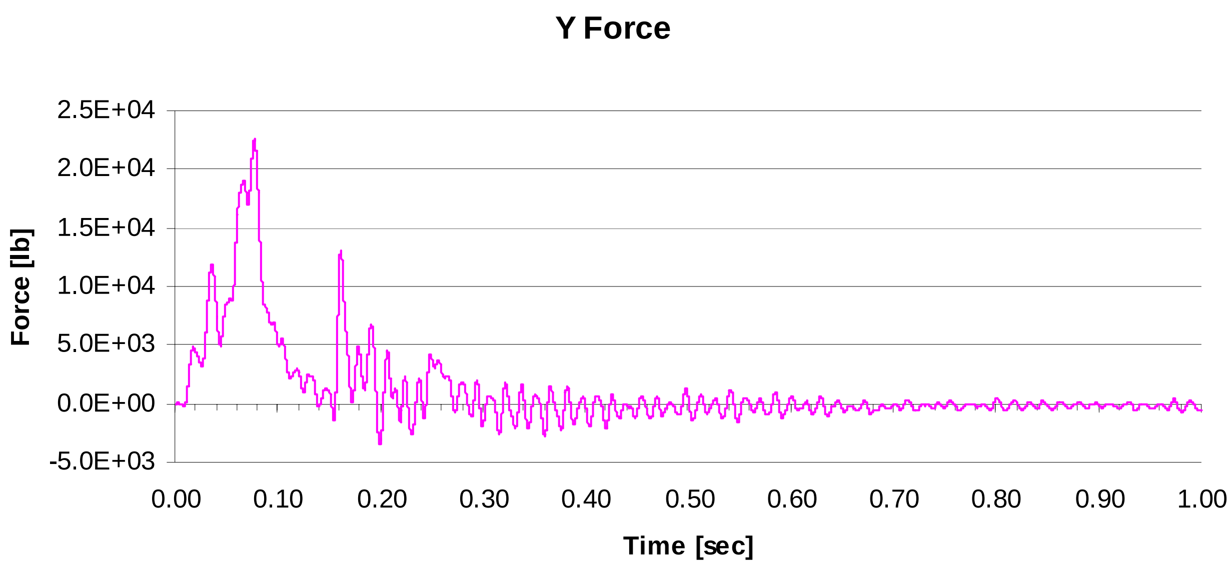
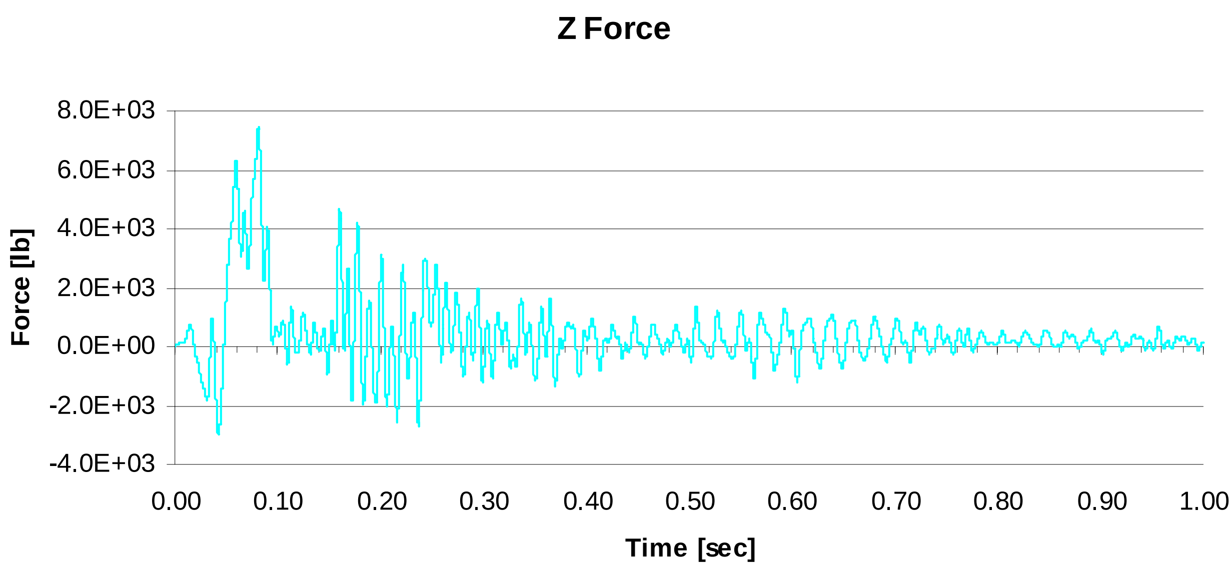
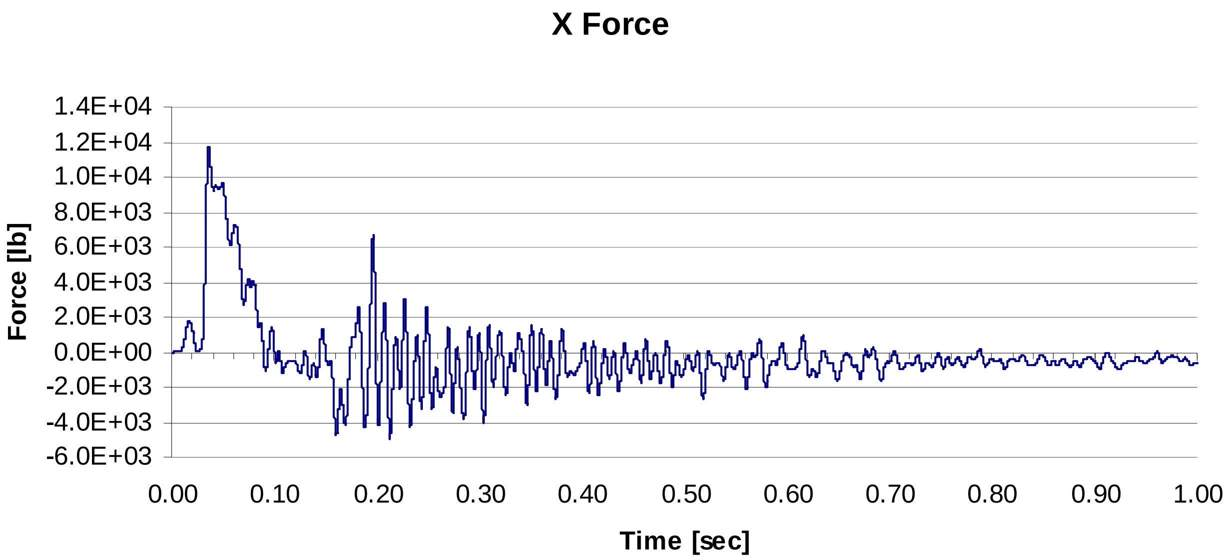
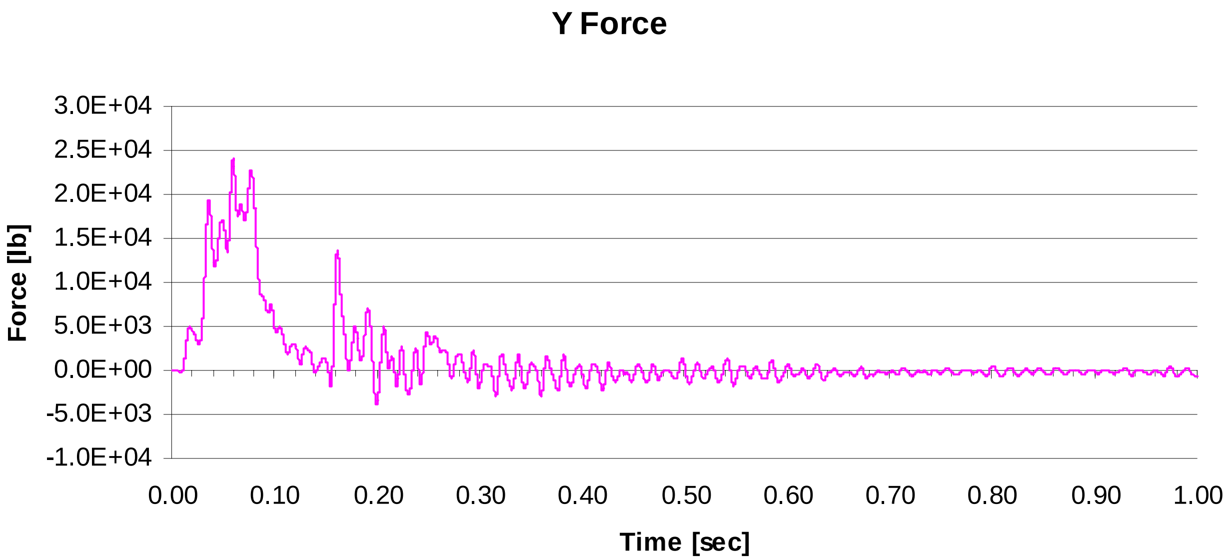


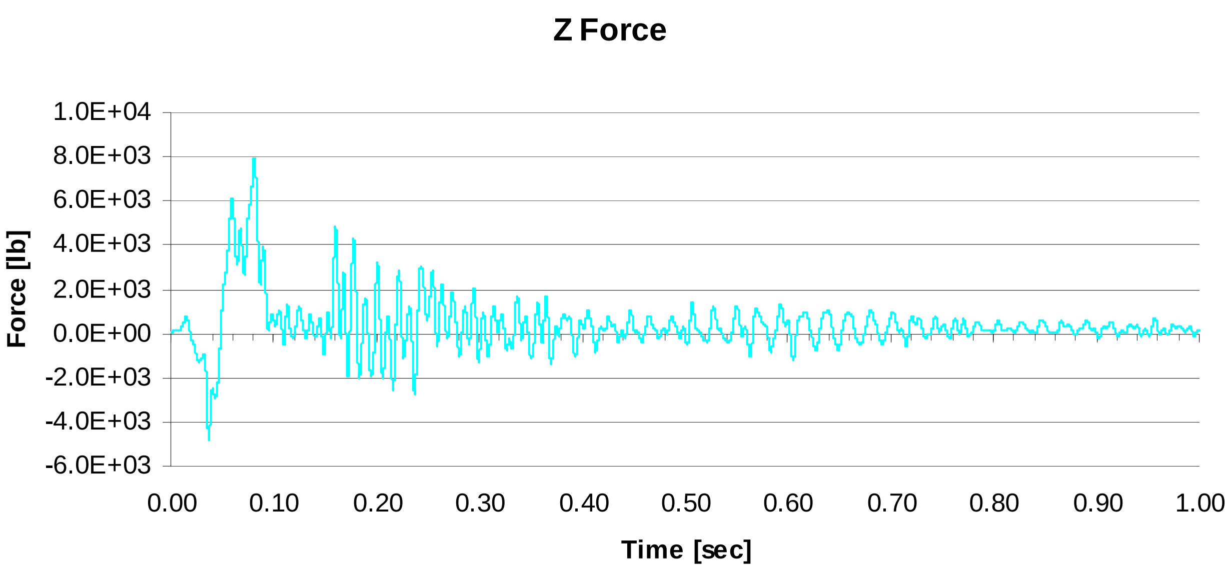




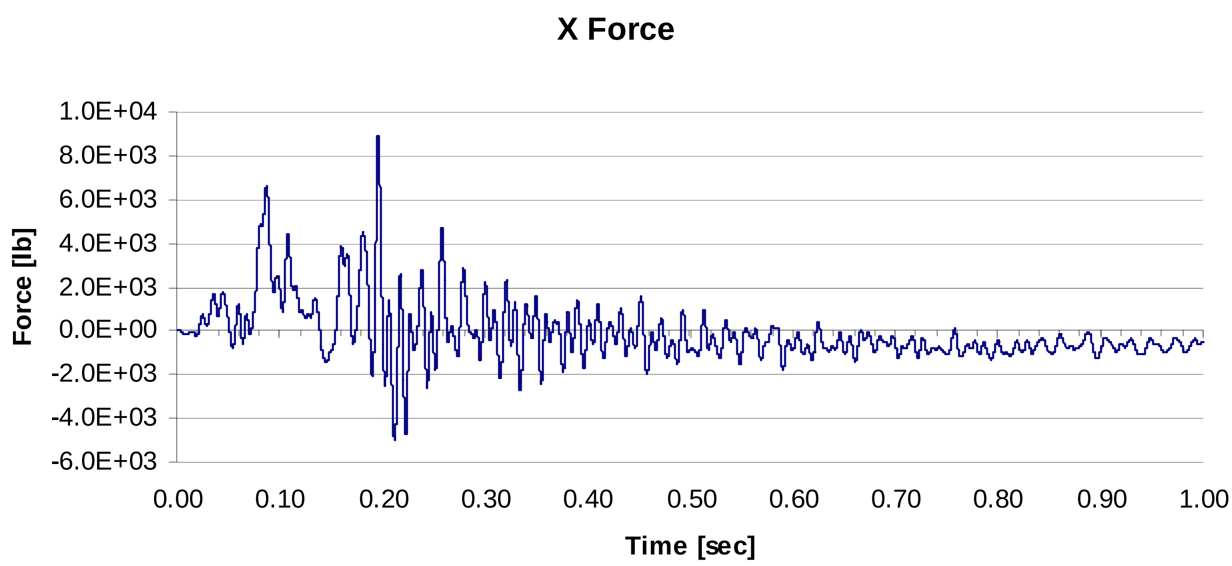
Post #7 (Post-Baseplate connection)

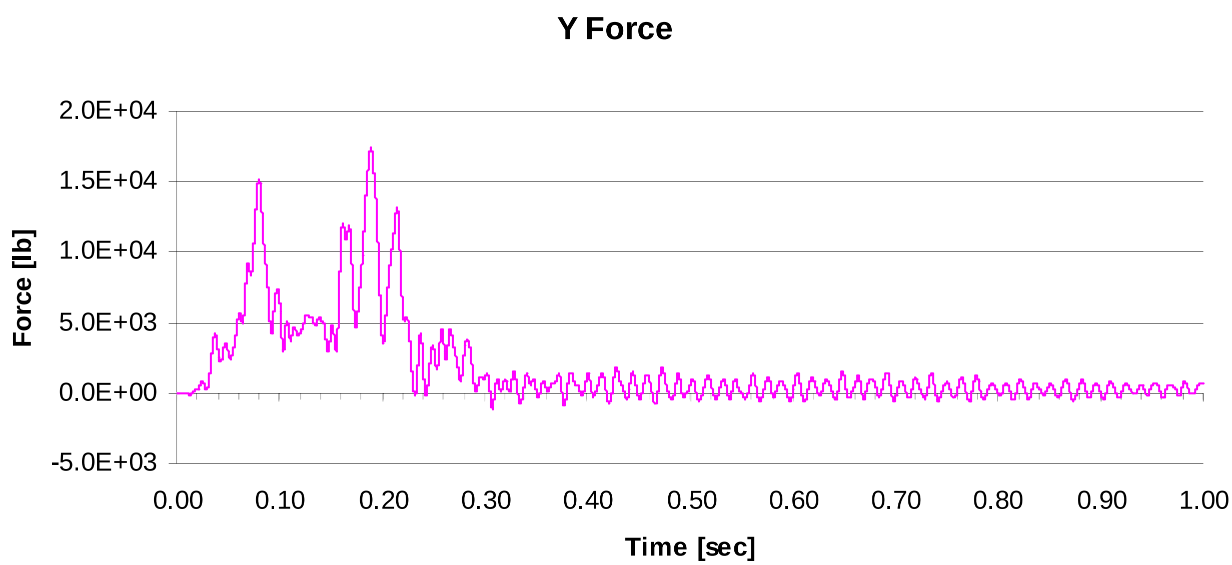


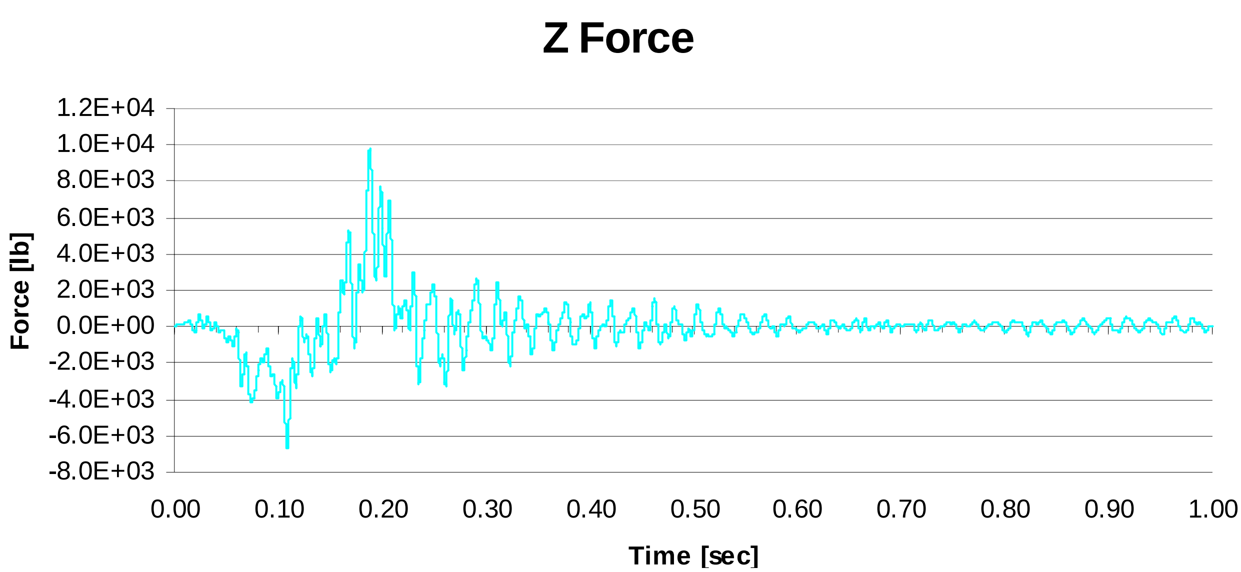




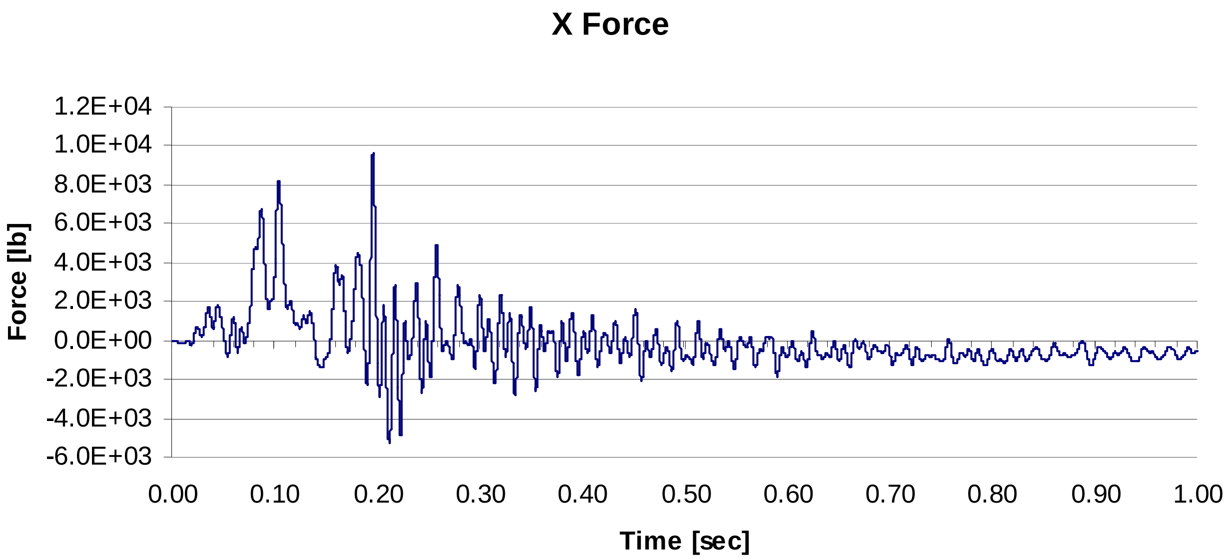
Post #6 (Rail-Post connection)

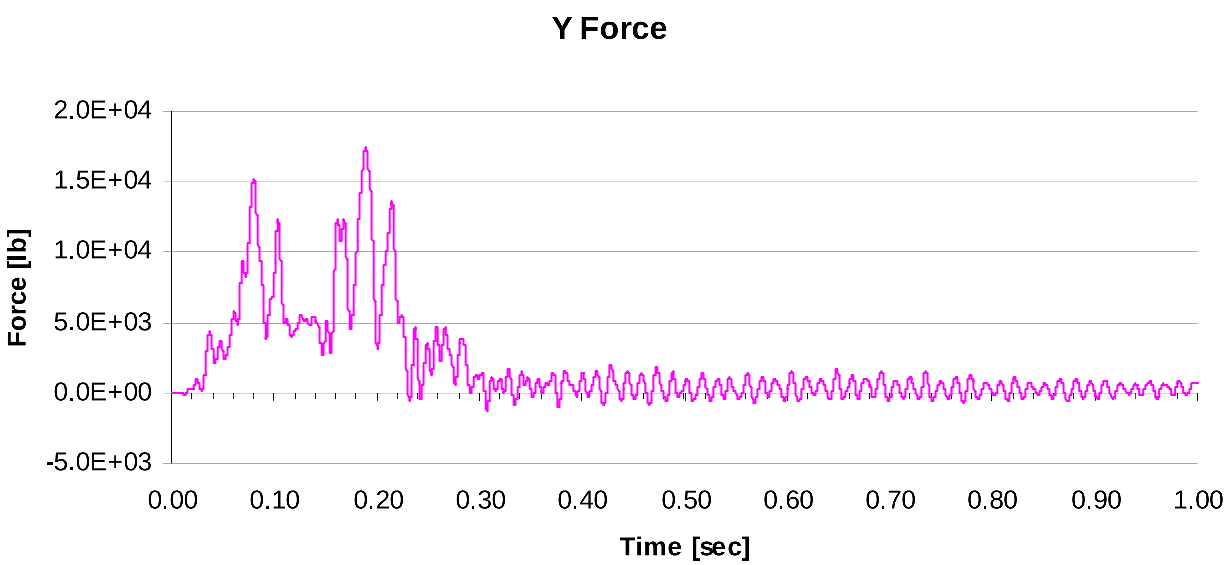


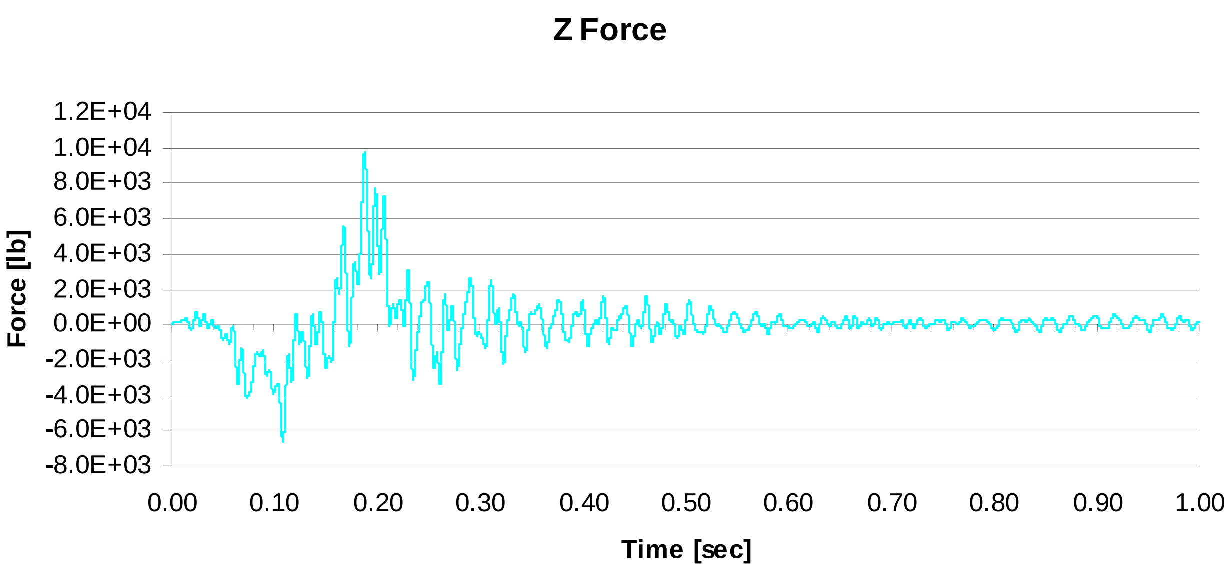




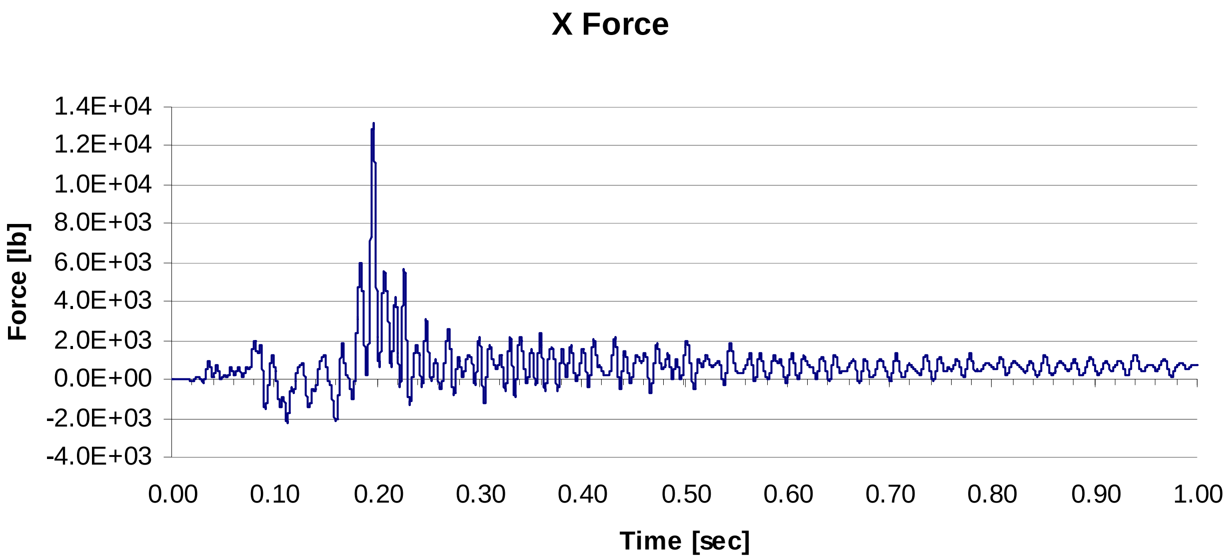
Post #6 (Post-Baseplate connection)

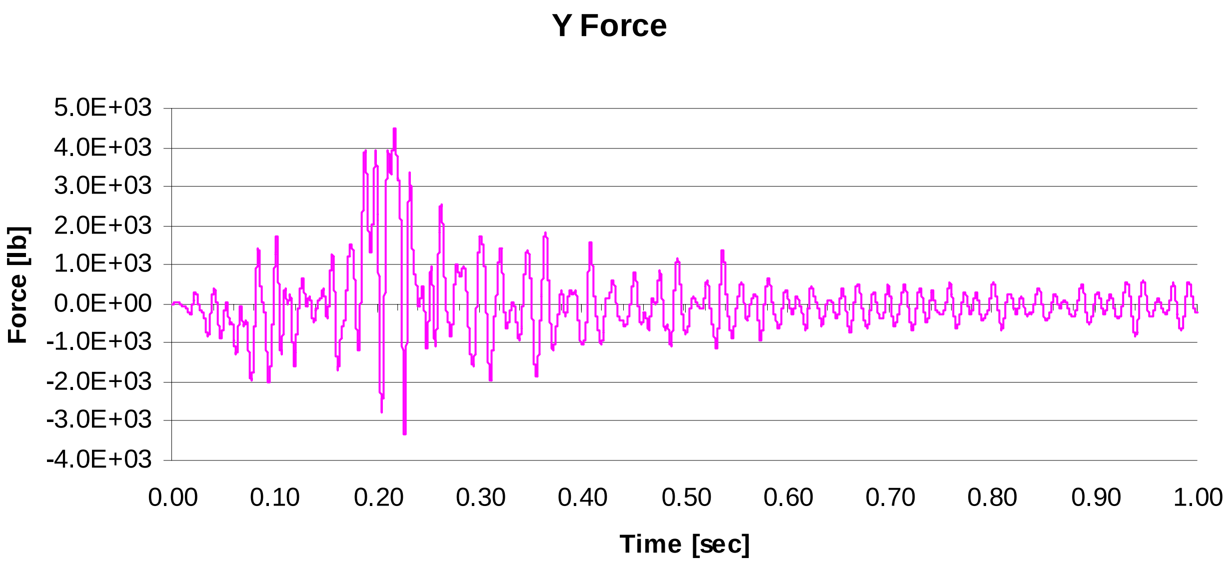


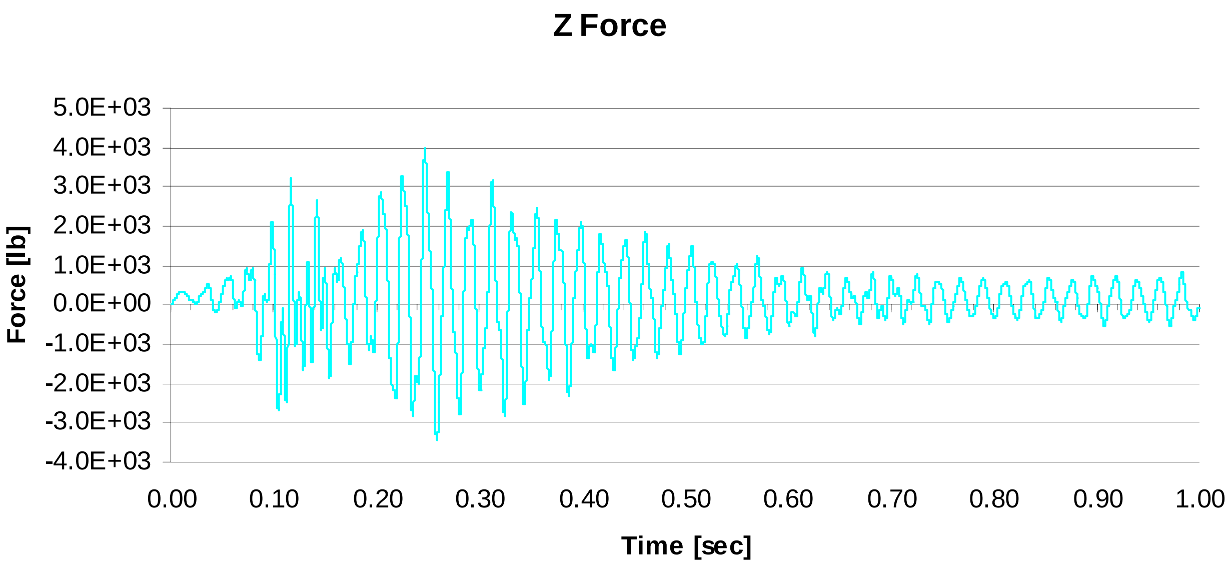




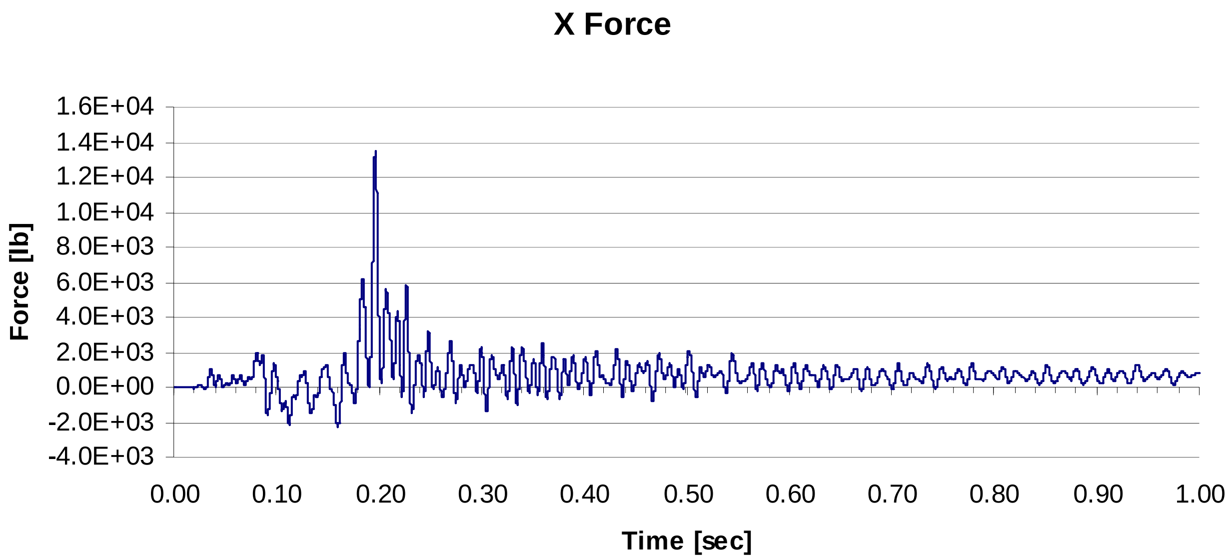
Post #5 (Rail-Post connection)

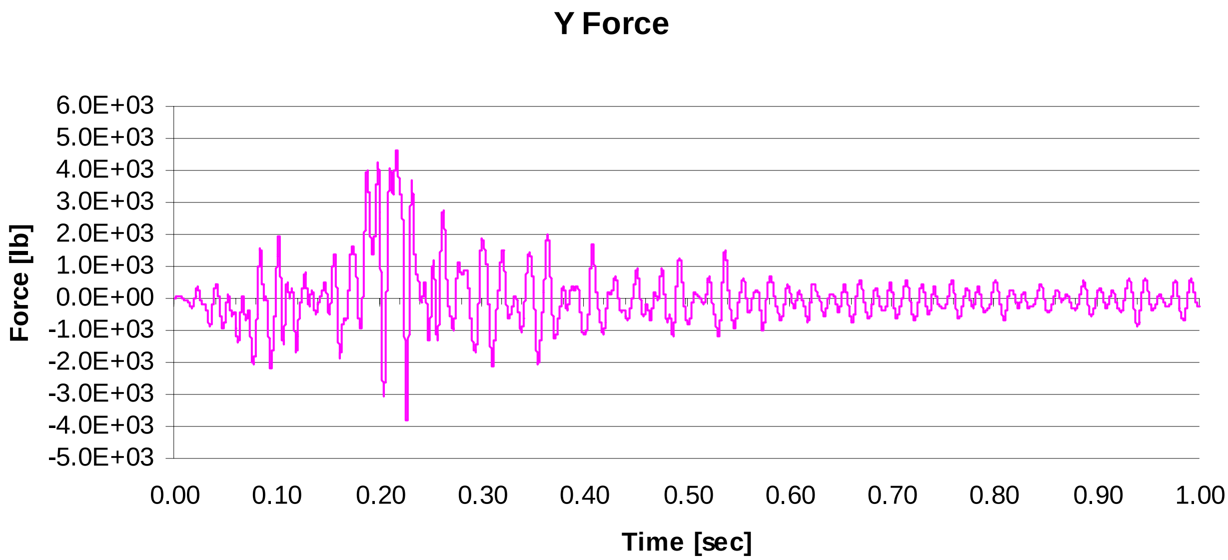


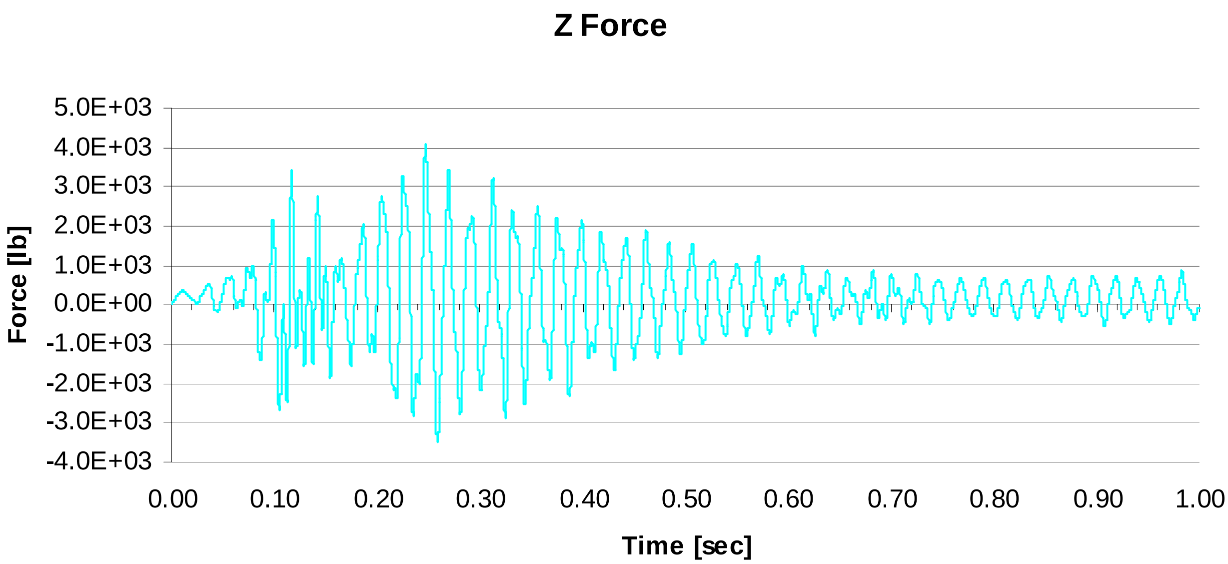




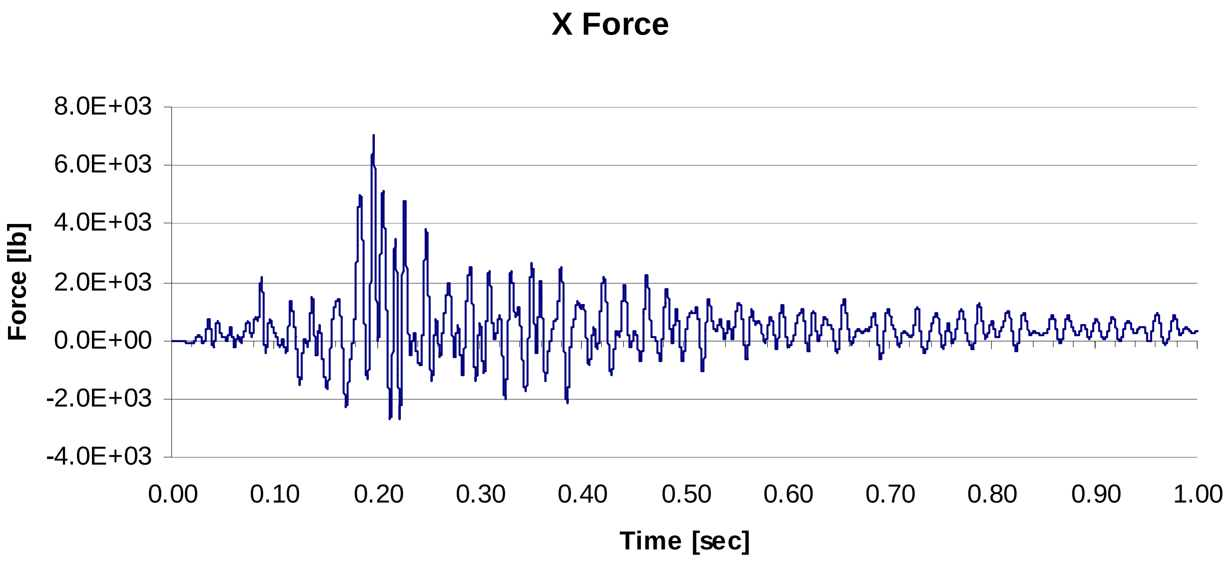
Post #5 (Post-Baseplate connection)

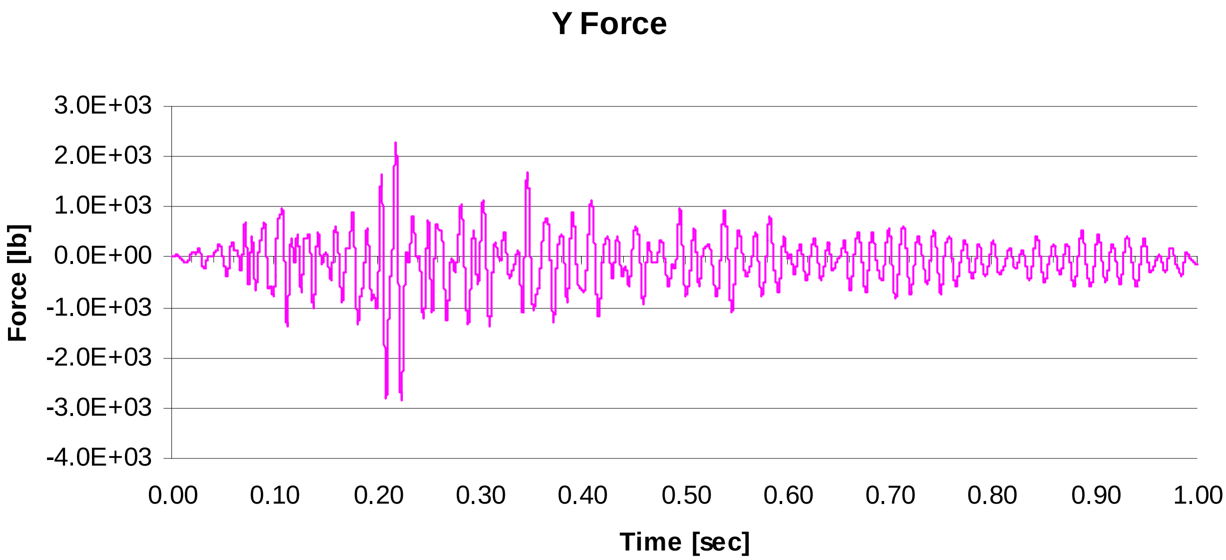


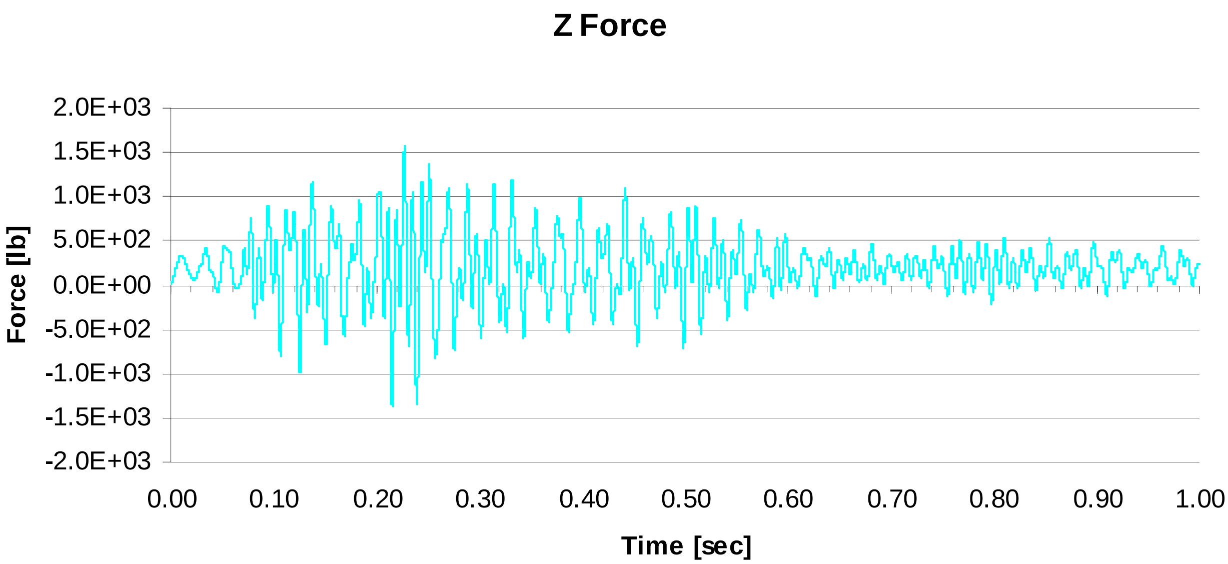




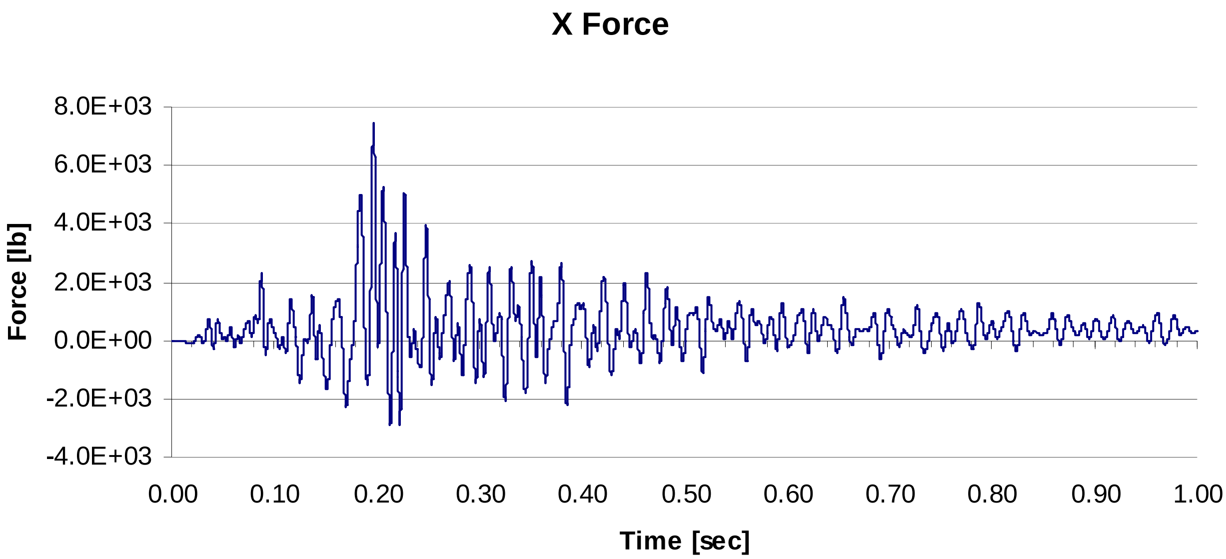
Post #4 (Rail-Post connection)

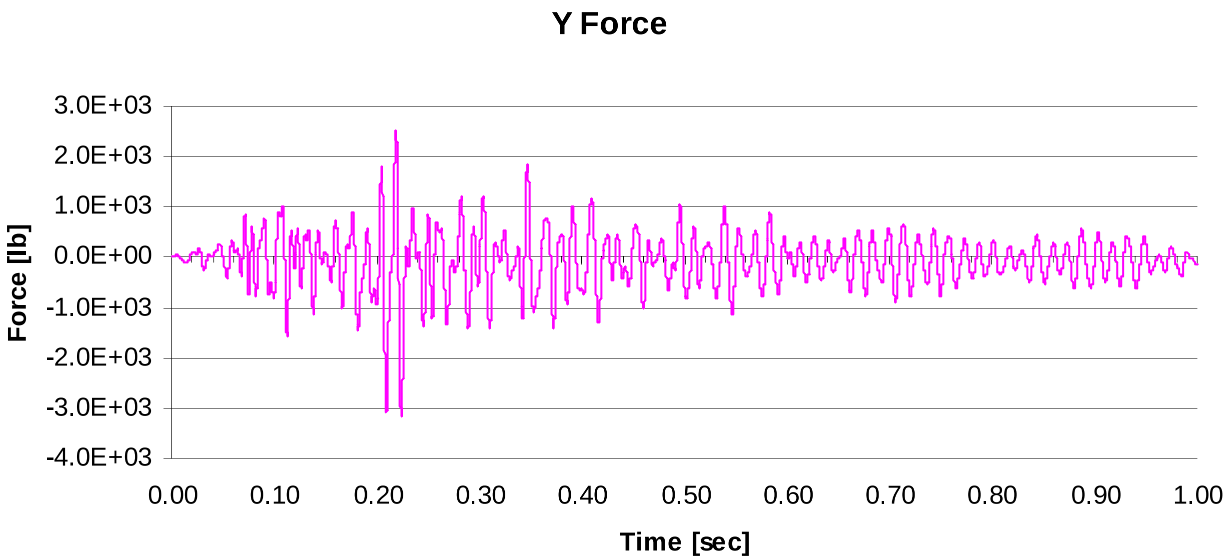


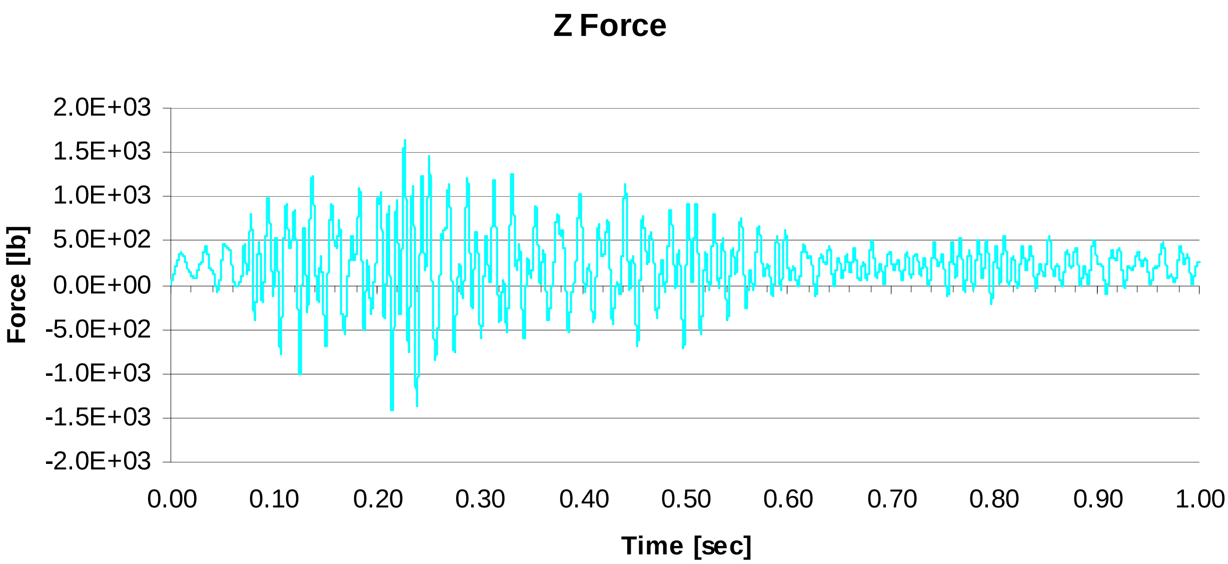




Post #4 (Post-Baseplate connection)







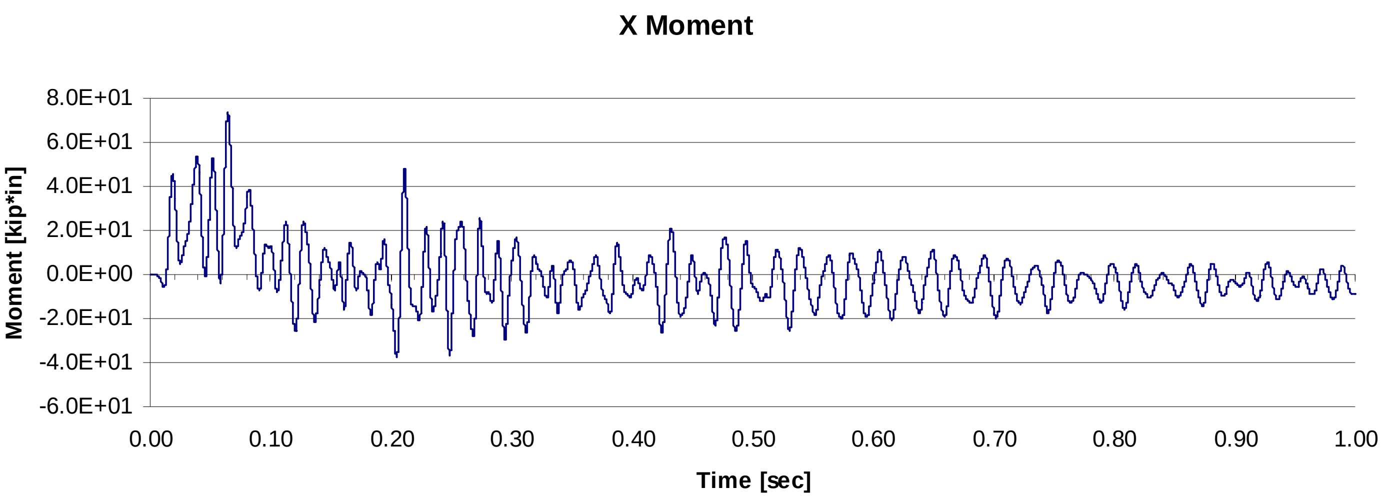
Moments

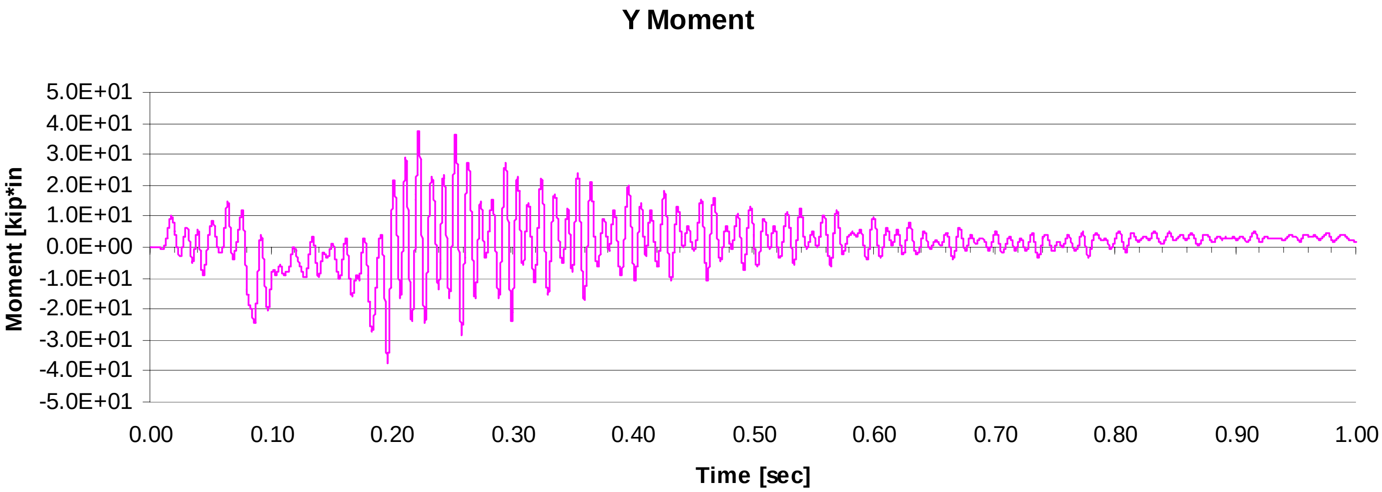
The maximum and minimum values for each of three moment components for the Post-Baseplate connection are shown respectively in Table 22.

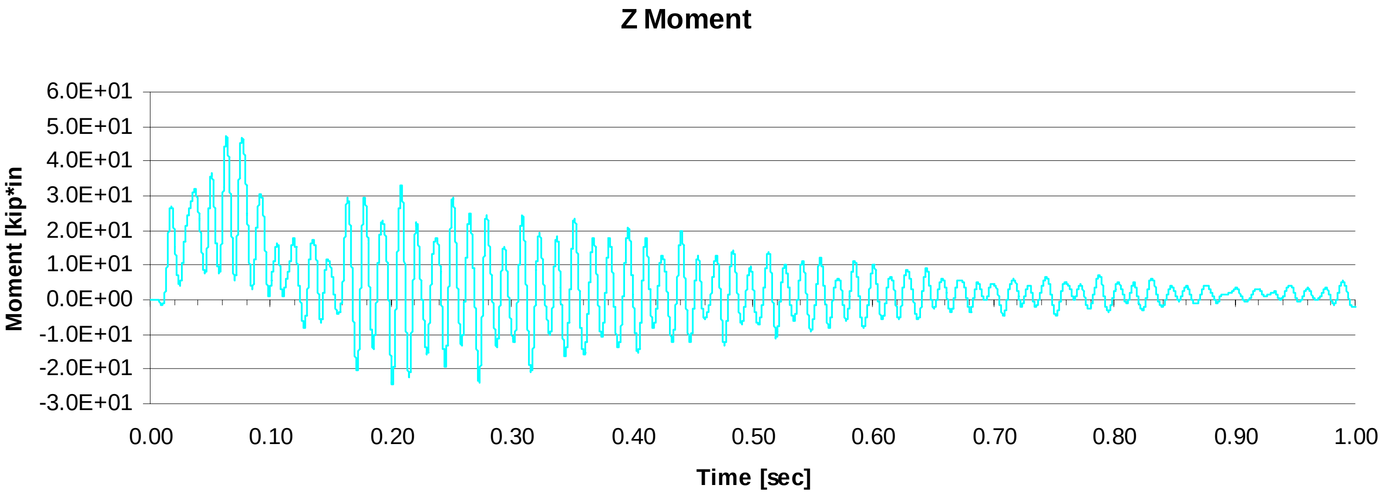
Table 22. Maximum and minimum values of the moments acting along the Post-Baseplate connection.

	X component [kip*in]		**Y component [kip*in]**		**Z component [kip*in]**	
	min	**Max**	**min**	**Max**	**min**	**Max**
Post #4	-3.71E+01	2.57E+01	-7.78E+01	2.62E+01	-1.89E+01	2.80E+01
Post #5	-5.29E+01	5.80E+01	-1.17E+02	1.32E+01	-4.75E+01	2.41E+01
Post #6	-5.20E+00	1.98E+02	-9.79E+01	4.07E+01	-9.25E+01	9.49E+01
Post #7	-5.86E+01	2.42E+02	-3.74E+01	4.83E+01	-3.89E+01	4.55E+01
Post #8	-3.73E+01	7.37E+01	-3.77E+01	3.76E+01	-2.47E+01	4.72E+01

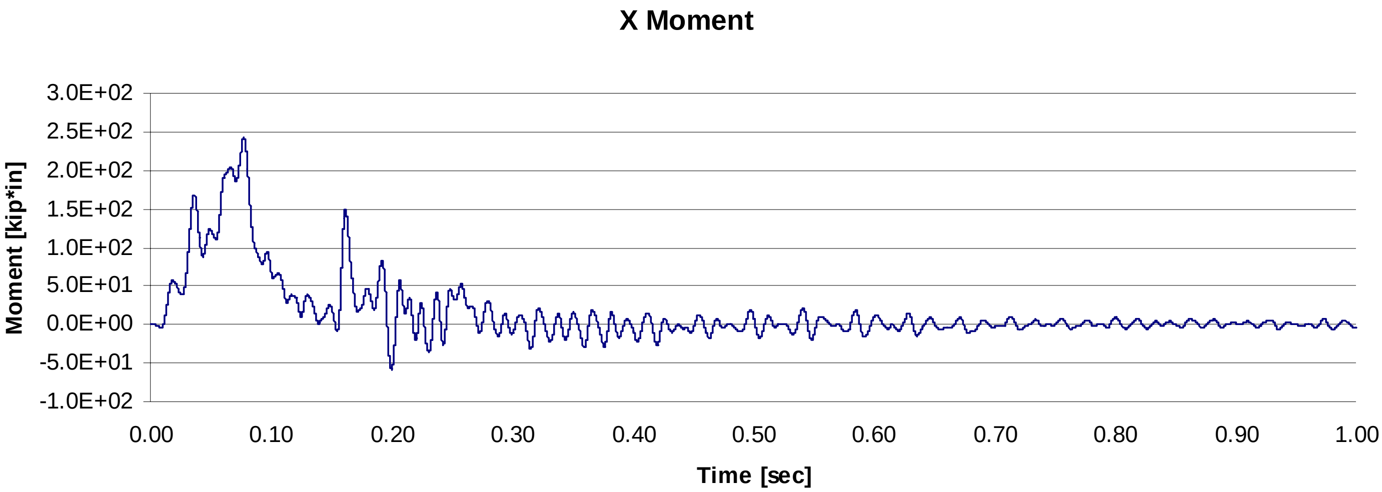
Post #8 (Post-Baseplate connection)

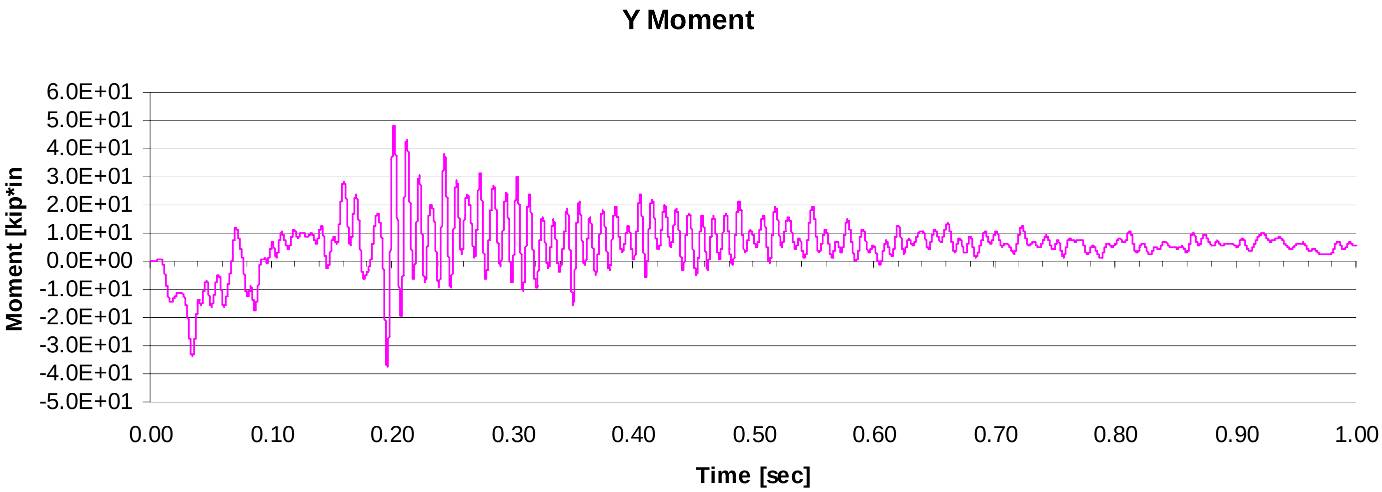


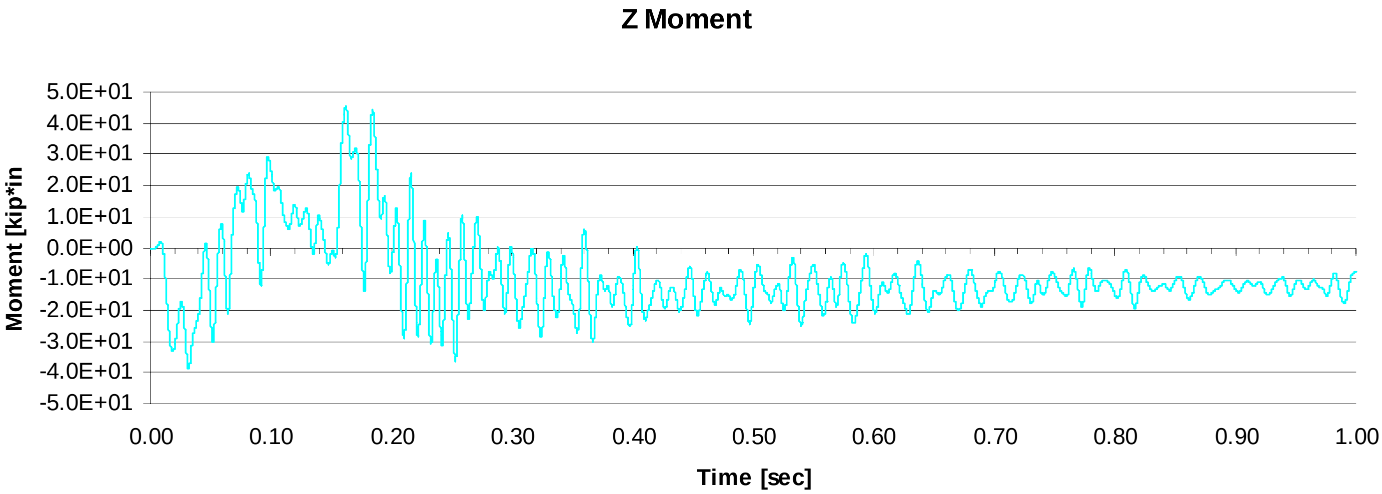




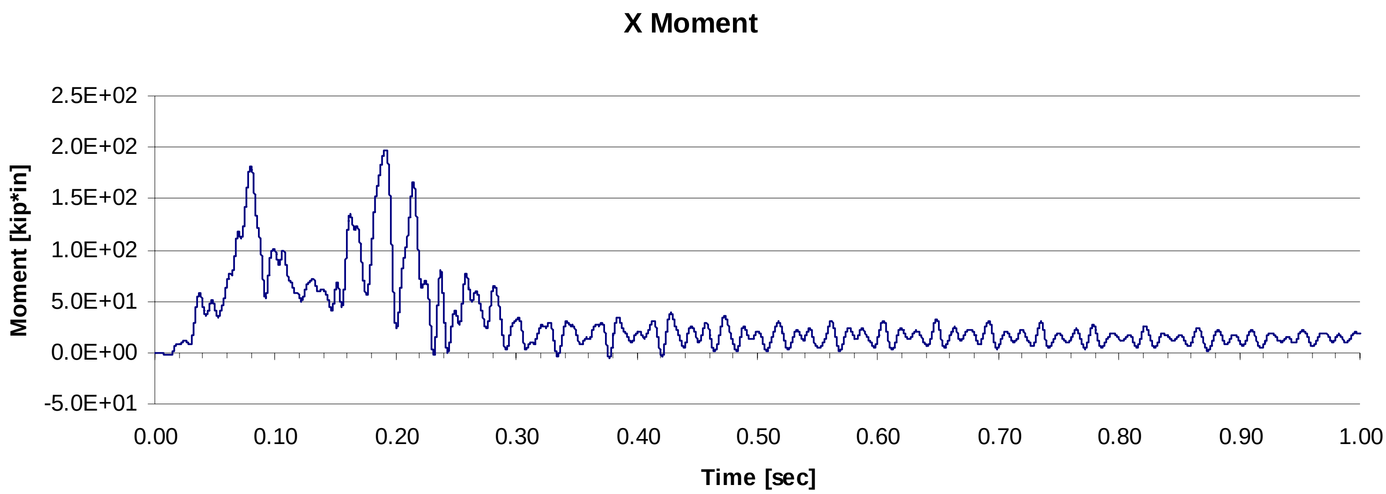
Post #7 (Post-Baseplate connection)

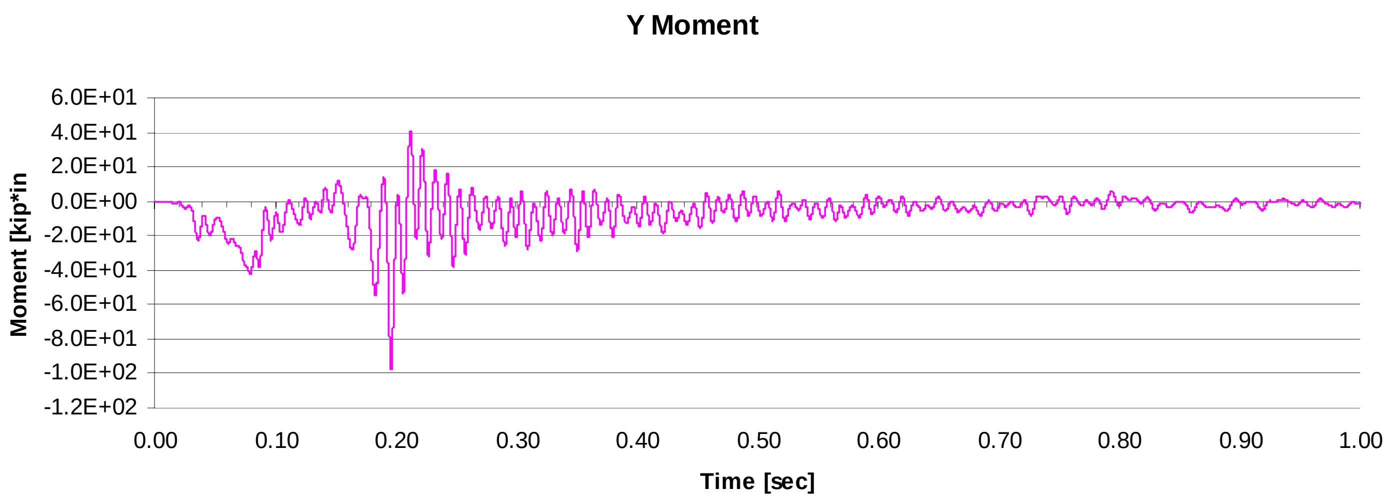


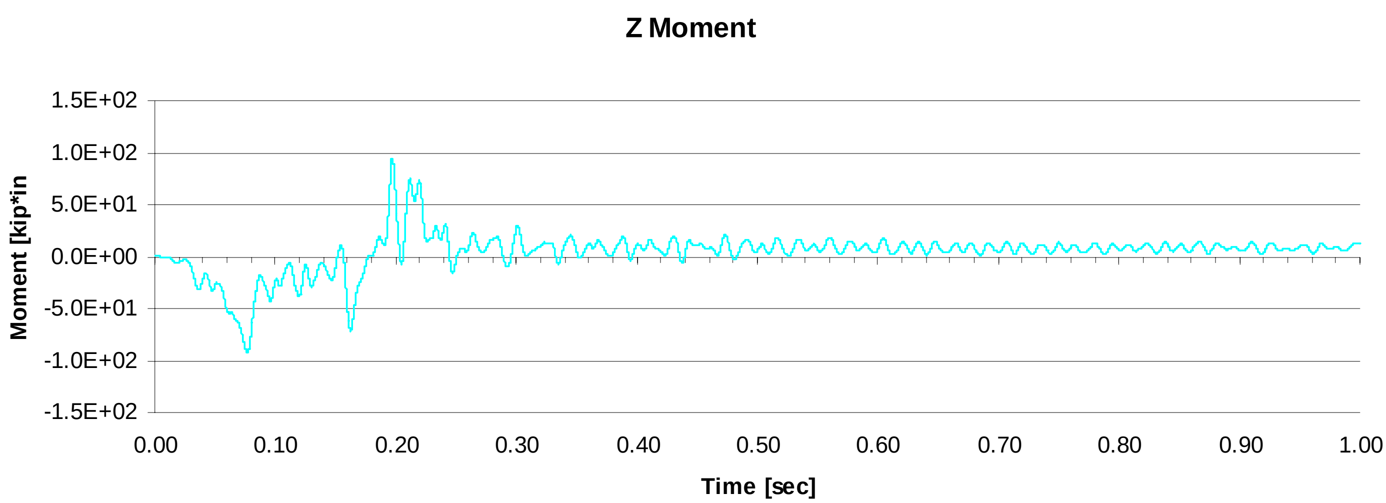




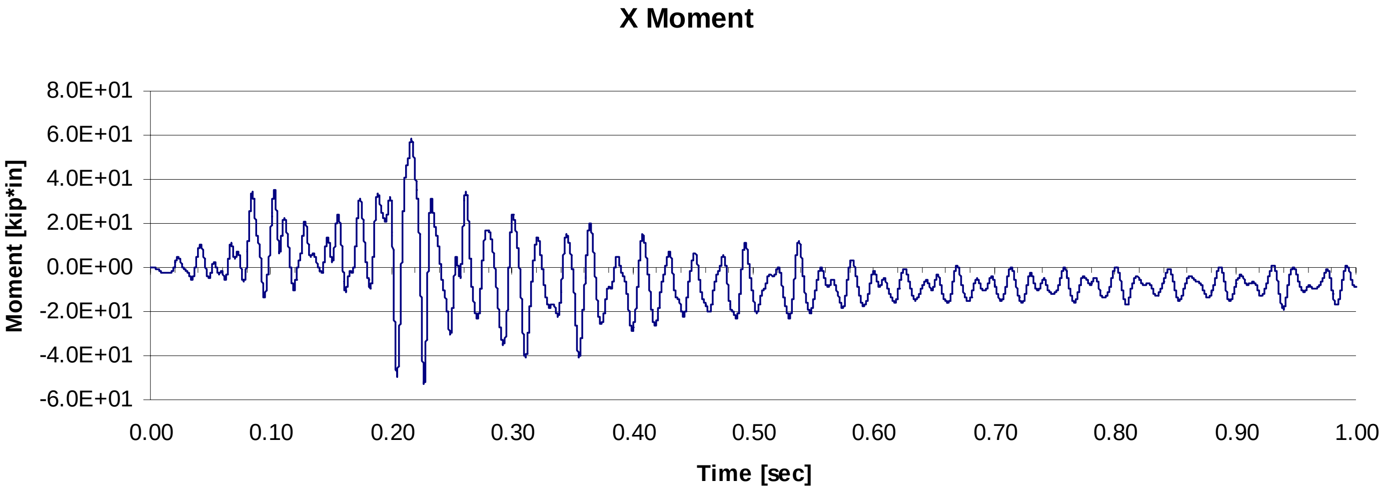
Post #6 (Post-Baseplate connection)

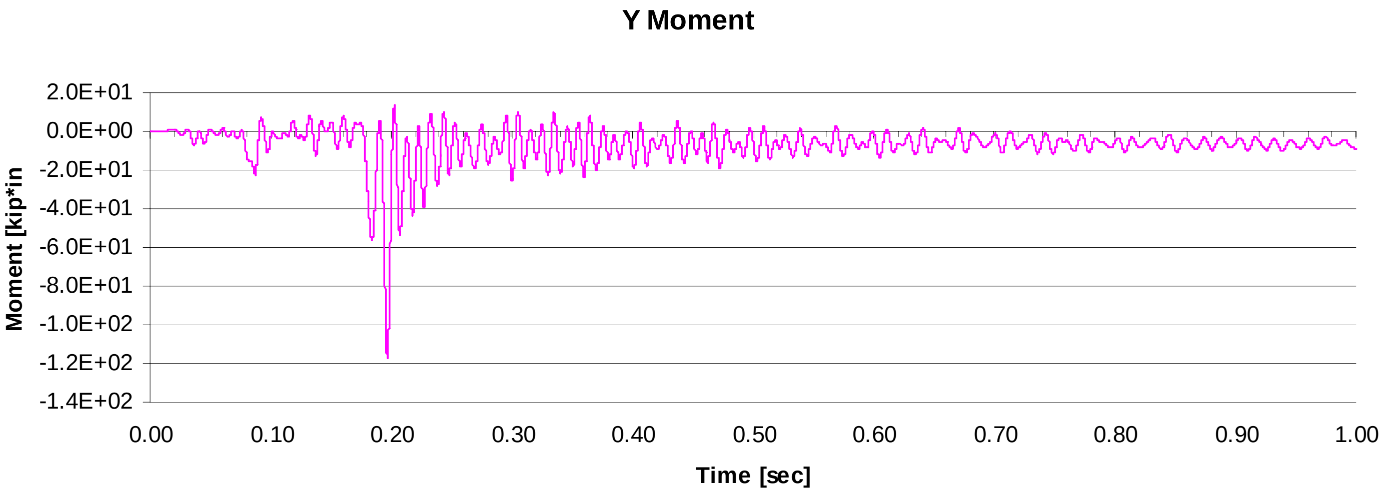


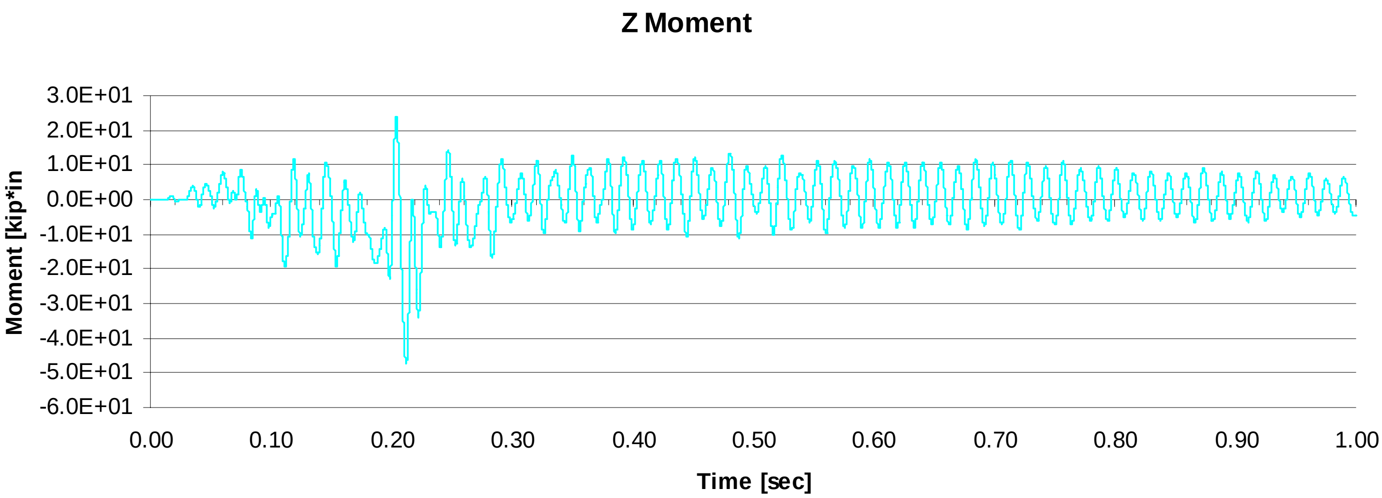




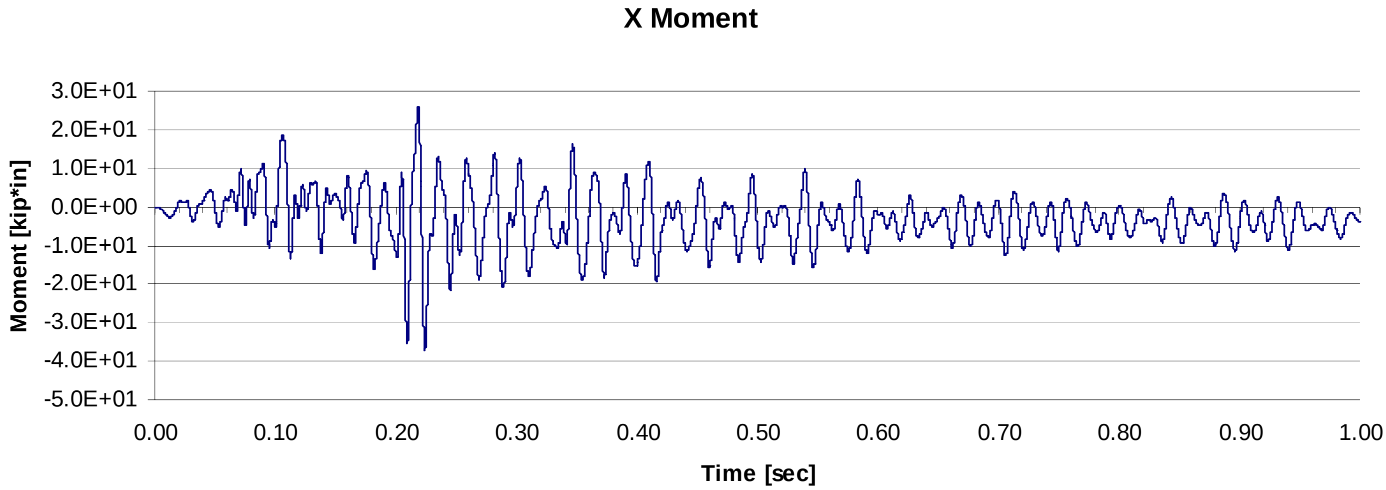
Post #5 (Post-Baseplate connection)

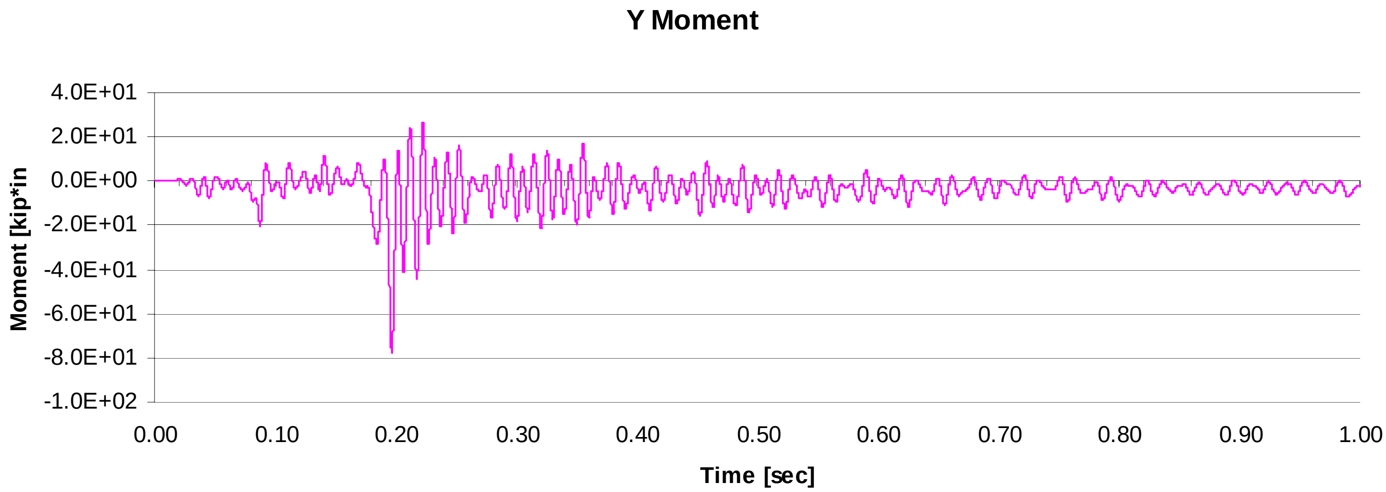


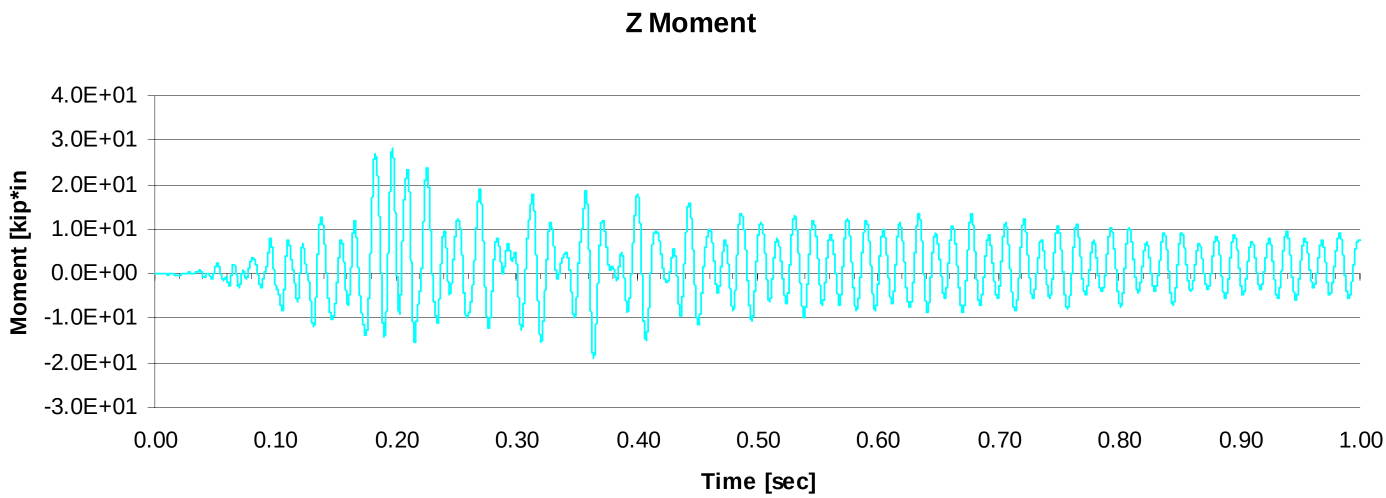




Post #4 (Post-Baseplate connection)







Appendix B: Wall forces

The longitudinal and lateral components of the forces acting on the concrete wall during the impact are herein shown. Figure 53 shows the coordinate system to which the values are referred.

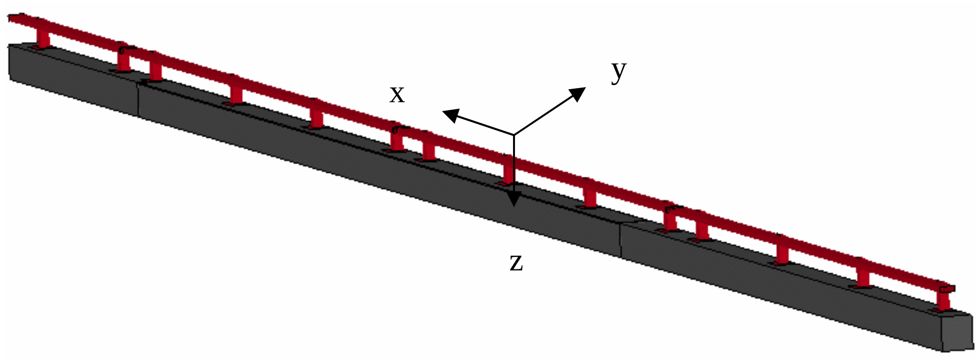


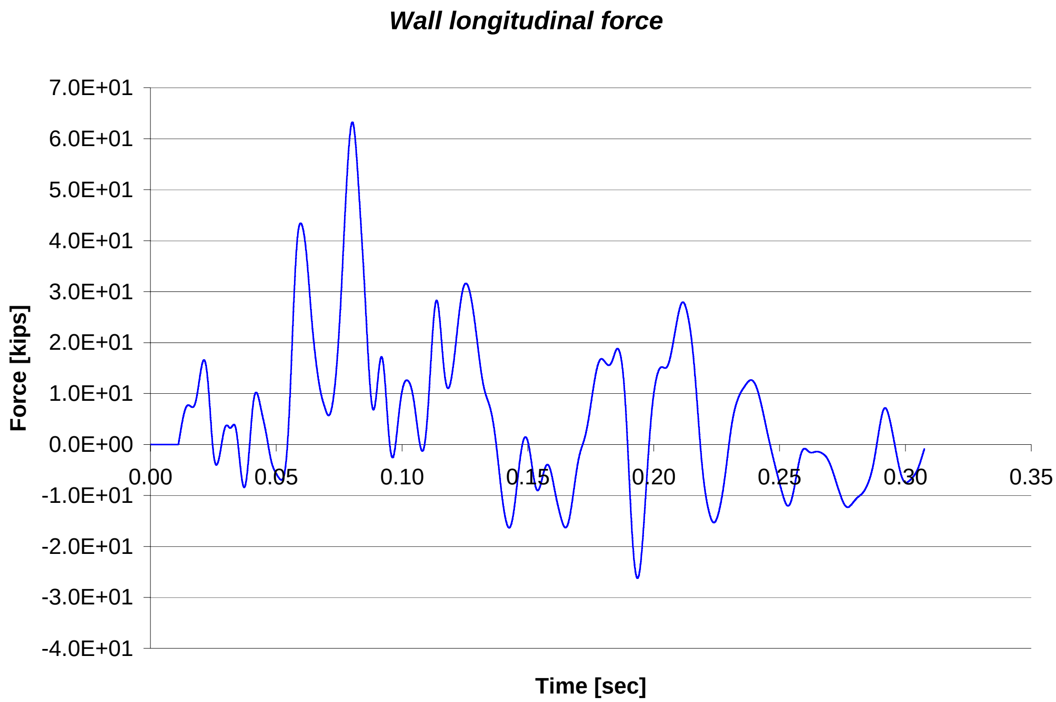
Figure 53. Coordinate system used to plot the forces acting on the wall.

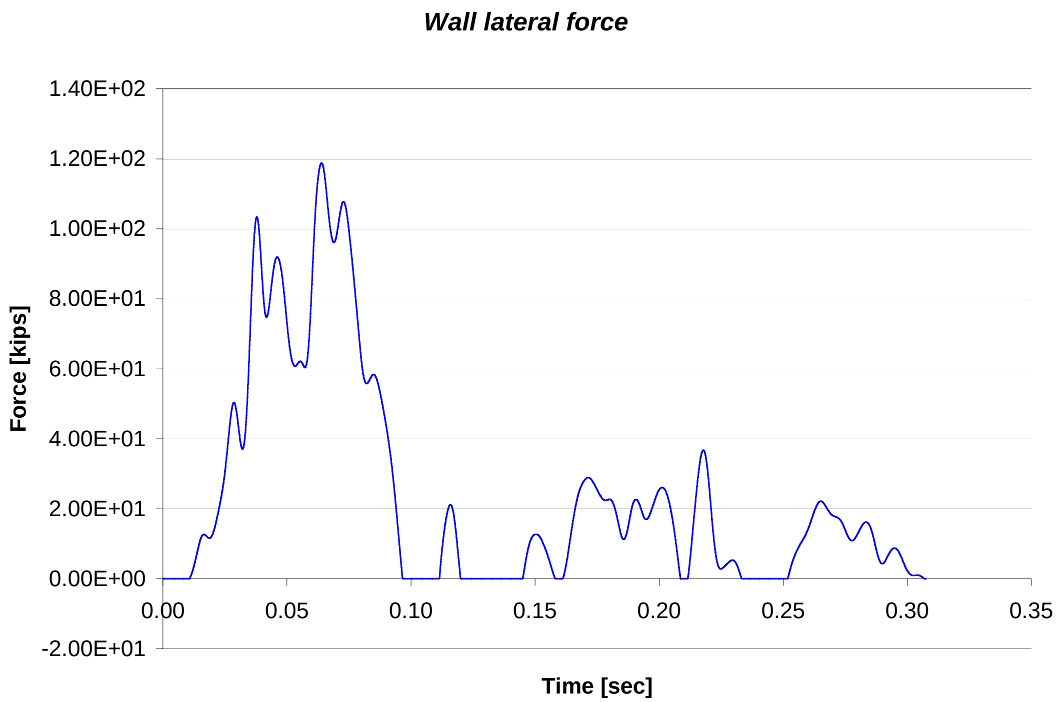
All the forces and moment components obtained from the finite element simulations were filtered using a SAE 60 filter.

The maximum and minimum values for both the lateral (x-axis) and longitudinal (y-axis) forces are shown respectively in Table 23.

Table 23. Maximum and minimum values of the longitudinal and lateral forces acting along the railing.

	Force [kips]	
	min	**Max**
Longitudinal	-26.2	63.2
Lateral	0	118.8


Wall longitudinal force
7.0E+01
6.0E+01
5.0E+01
4.0E+01
3.0E+01
2.0E+01
1.0E+01
0.0E+00
-1.0E+01
-2.0E+01
-3.0E+01
-4.0E+01
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
Force [kips]
Time [sec]


Wall lateral force
1.40E+02
1.20E+02
1.00E+02
8.00E+01
6.00E+01
4.00E+01
2.00E+01
0.00E+00
-2.00E+01
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
Force [kips]
Time [sec]

Appendix C: AASHTO LRFD Bridge Guide calculations for Designs #5 and Design #6

This appendix describes the hand calculations performed to check the AASTHO LRFD Bridge Guide specifications for both Designs #5 and Design #6.

According to AASHTO LRFD Bridge Guide, the nominal resistance to transverse load, R_W, may be determined using a yield line approach,

$$R_W = \left(\frac{2}{2L_c - L_t}\right)\left(8M_B + 8M_W H + \frac{M_C L_C^2}{H}\right)$$

where,

$$L_C = \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{8H\left(M_B + M_W H\right)}{M_C}}$$

M_W, M_C *and* M_B are respectively the Flexural Resistance of a wall, the Flexural Resistance of a cantilevered wall and the additional flexural resistance of a steel beam (in addition to M_W).

To evaluate the Flexural Resistances of the concrete wall, the following approximations were made:

1. The stress distribution of the concrete is supposed to be uniform and equal to the 85% of the ultimate compressive stress of the concrete.
2. Steel rebars reach the yield point.
3. Steel rebars can bear tensile forces only.

Evaluation of the Flexural Resistance M_W

Figure 54 shows a sketch of the wall cross section.

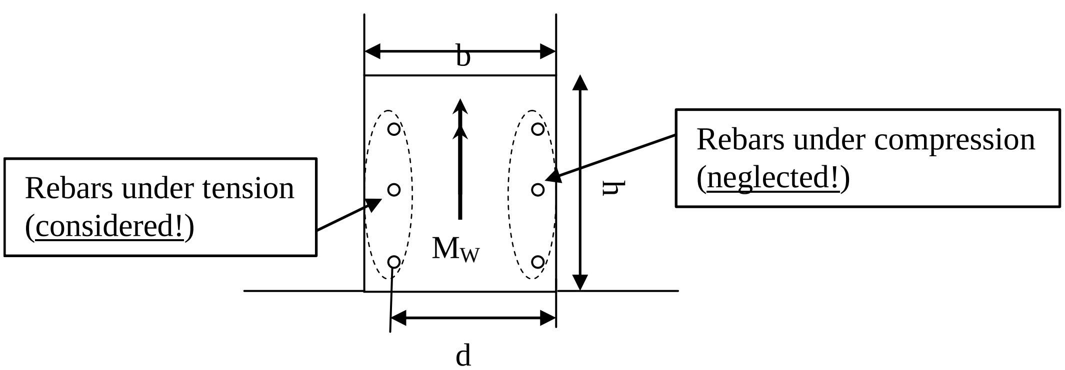


Figure 54. Sketch of the concrete cross section.

Following are the cross section and concrete properties

$d = 14"$

$b = 16"$

$h = 17"$

$\sigma_{Y\,steel} = 40\,ksi$

$A_{BAR} = 0.31\,in^2 \quad \rightarrow \quad A_{BAR\,S} = 3 \cdot 0 \cdot 31 = 0.93 in^2$

$f_c^{'} = 3 ksi$

Figure 55 shows the typical stress distribution in the concrete due to the application of a vertical moment $M_{W.}$

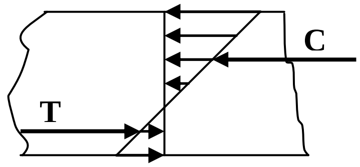


Figure 55. Typical stress distribution due to the application of a vertical moment (T and C are the forces equivalent to the applied moment).

The stress distribution in the concrete can be approximated as uniform along a certain width *a* (Figure 56). Hence the equivalent compressive force, C, can be considered as applied in the middle of this width.

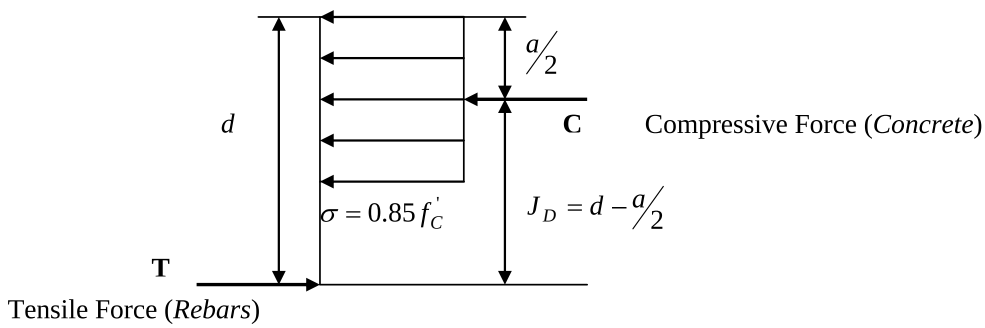


Figure 56. Approximated homogeneous stress distribution in the concrete under a vertical moment.

In this way, applying the body equilibrium, it is possible to calculate the value of the distance between T and C (the two forces equivalent to the stress distribution on the wall cross section).

$$\begin{cases} C = 0.85 \cdot f_C^{'} \cdot a \cdot h \\ T = A_{BARS} \cdot \sigma_{Y\,steel} \end{cases}$$

$$C = T$$
$$\Downarrow$$
$$0.85 \cdot f_C^{'} \cdot a \cdot h = A_{BARS} \cdot \sigma_{Y\,steel}$$
$$\Downarrow$$
$$a = \frac{A_{BARS} \cdot \sigma_{Y\,steel}}{0.85 \cdot f_C^{'} \cdot h}$$

Substituting the numerical values,

$$a = \frac{0.93 \cdot 40 \cdot 10^3}{0.85 \cdot 3 \cdot 10^3 \cdot 17} = 0.858\, in$$

Once we know the value of this distance (arm), we can evaluate the value of the ultimate vertical moment by simply multiplying the value of the tensile force in the steel rebars by the arm. As the steel rebars were supposed to yield, the force of the steel rebar is the area of their cross section multiplied by the steel yield stress,

$$M_W = A_{BARS} \cdot \sigma_{Y\,steel} \cdot \left(d - a/2\right)$$

Substituting the numerical values,

$$M_W = 0.93 \cdot 40 \cdot 10^3 \cdot \left(14 - 0.858/2\right) = 504.8\, kip \cdot in = 42\, kip \cdot ft$$

Evaluation of the Flexural Resistance M_C

In the case a horizontal moment is applied, vertical rebars (stirrups) bear the loads being under compression or tension (Figure 57). Considering the same approximation already applied in the previous case, only rebars under tension were considered.

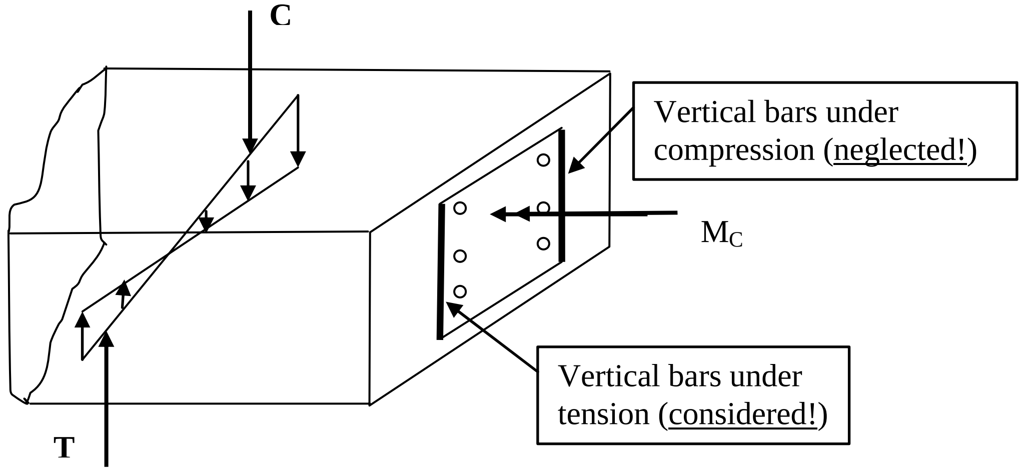


Figure 57. Sketch of the wall cross section with the typical stress behavior due to a horizontal bending moment.

In a way similar to that followed in the previous case for the ultimate vertical moment, the ultimate horizontal moment can be evaluated considering the stress distribution in the concrete as uniform along a certain width *a* (Figure 58).

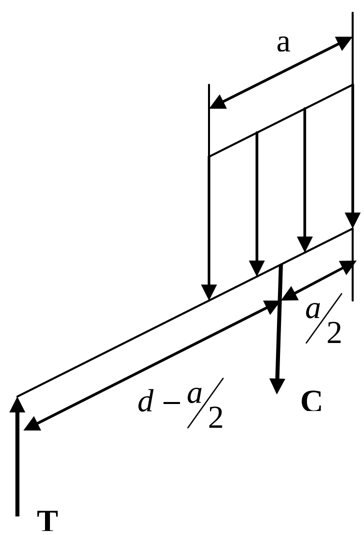


Figure 58. Approximated homogeneous stress distribution in the concrete under a vertical moment.

Appling the body equilibrium, it is possible to evaluate the length *a* along which the approximated stress distribution acts.

$$\begin{cases} C = 0.85 \cdot f_C^{'} \cdot a \cdot 12 \quad \textbf{\textit{(Considering one stirrup every foot, i.e. 12 inches)}} \\ T = A_{BARS} \cdot \sigma_{Y\,steel} \end{cases}$$

Appling the body equilibrium,

$$C = T$$
$$\Downarrow$$
$$0.85 \cdot f_C^{'} \cdot a \cdot 12 = A_{BARS} \cdot \sigma_{Y\,steel}$$
$$\Downarrow$$
$$a = \frac{A_{BARS} \cdot \sigma_{Y\,steel}}{0.85 \cdot f_C^{'} \cdot 12}$$

Substituting the numerical values,

$$a = \frac{0.31 \cdot 40 \cdot 10^3}{0.85 \cdot 3 \cdot 10^3 \cdot 12} = 0.4\,in$$

Hence, the ultimate horizontal moment can be evaluated as,

$$M_C = A_{BARS} \cdot \sigma_{Y\,steel} \cdot \left(d - \frac{a}{2}\right)$$

Substituting the numerical values,

$$M_C = 0.31 \cdot 40 \cdot 10^3 \cdot \left(14 - \frac{0.4}{2}\right) = 171.1\,kip \cdot in = 14.3\,kip \cdot ft$$

Evaluation of the additional Flexural Resistance of the steel rail M_B

Figure 59 shows a sketch of the steel rail cross section for the Design #5.

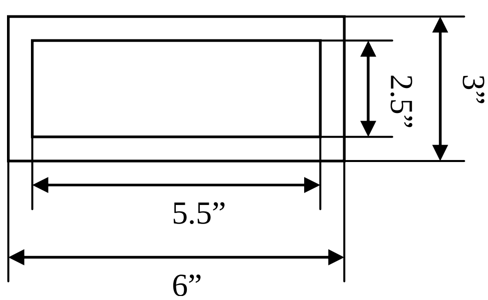


Figure 59. Sketch of the steel rail cross section for Design #5 (rectangular tube).

For sake of safety, the ultimate flexural resistance of the steel railing, M_B, can be considered when the section starts yielding,

$$M_B = \sigma_{Yeld} \cdot \frac{I}{y}$$

Where,

$$I = \frac{1}{12}\left(6^3 \cdot 3 - 5.5^3 \cdot 2.5\right) = 19.3\,in^4 \quad \textbf{(Design \#5)}$$
$$I = \frac{1}{12}\left(8^3 \cdot 3 - 7.5^3 \cdot 2.5\right) = 40\,in^4 \quad \textbf{(Design \#6)}$$

$\sigma_{Yeld} = 50\,ksi$
$y = 3''$

Substituting the numerical values,

$$M_B = 50 \cdot 10^3 \cdot \frac{19.3}{3} = 321.6\,kip \cdot in = 26.8\,kip \cdot ft \quad \textbf{(Design \#5)}$$
$$M_B = 50 \cdot 10^3 \cdot \frac{40}{4} = 500\,kip \cdot in = 41.6\,kip \cdot ft \quad \textbf{(Design \#6)}$$

Now M_W, M_C *and* M_B are known, it is possible to evaluate the critical wall length, L_C, and eventually, the nominal railing resistance, R_W,

$h = 1.42\,ft$
$L_t = 4\,ft$

$$\begin{cases} M_B = 41.6\,k \cdot ft \\ M_W = 42\,k \cdot ft/ft \quad (Design\#5) \\ M_C = 14.3k \cdot ft/ft \end{cases} \qquad \begin{cases} M_B = 26.8\,k \cdot ft \\ M_W = 42\,k \cdot ft/ft \quad (Design\#6) \\ M_C = 14.3k \cdot ft/ft \end{cases}$$

$$\Downarrow$$

$$\begin{cases} Design\#5 \\ \\ L_C = 10.5\,ft \\ \quad\Downarrow \\ R_W = 212\,kip \end{cases} \qquad \begin{cases} Design\#6 \\ \\ L_C = 11.2\,ft \\ \quad\Downarrow \\ R_W = 225\,kip \end{cases}$$

According to the AASHTO LRFD Bridge Guide specifications, the typical value for the transverse load, Ft, for a TL-3 bridge railing is 54 kips. The nominal railing resistance, R_W, for both the Design #5 and Design #6 is much higher than this value. Hence, both Design #5 and Design #6 could be considered strong enough to bear the typical loads of a TL-3 railing.

Appendix D: acceleration data plots

The acceleration data obtained from the finite element simulations were filtered using a SAE 60 filter. For both the small car and the pick-up truck tests, the data were collected close to the vehicle center of gravity.
The coordinate reference system used is the one proposed by the Report 350 (Figure 60)

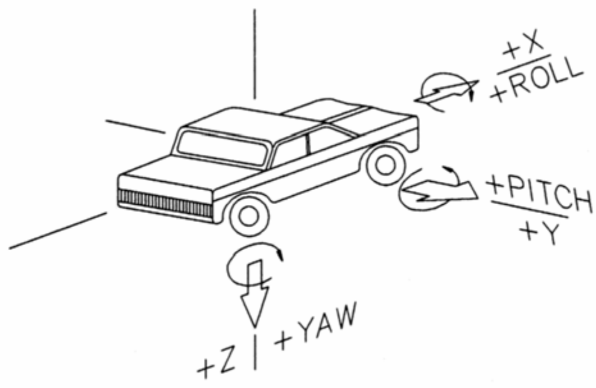
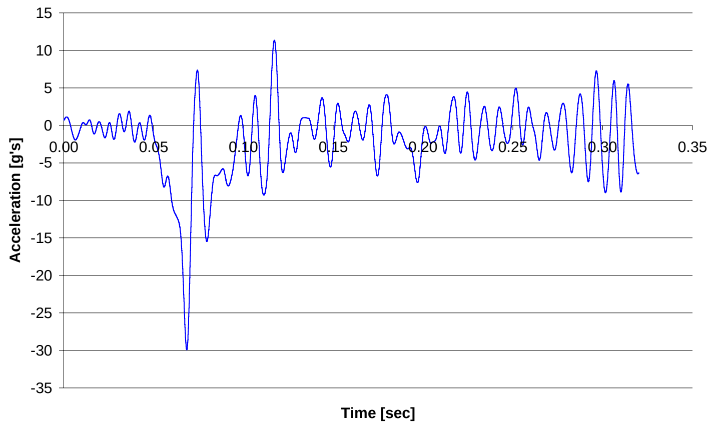


Figure 60 Local coordinate reference system used to collect acceleration time histories.

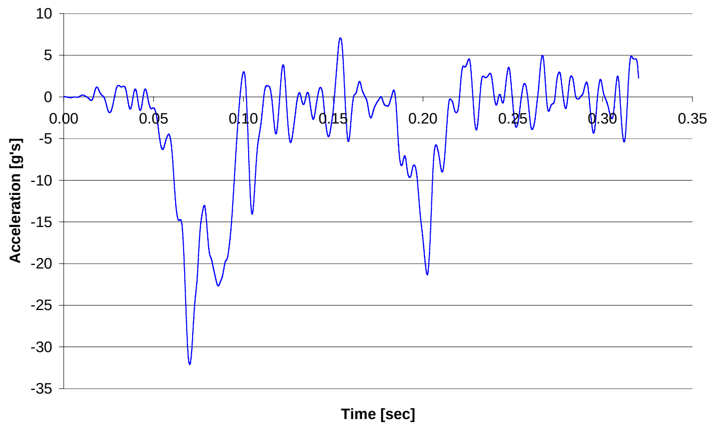
In the following graphs, the longitudinal direction is X, the lateral direction is Y and the vertical direction is Z.

Design #1 *(Test 3-10)*

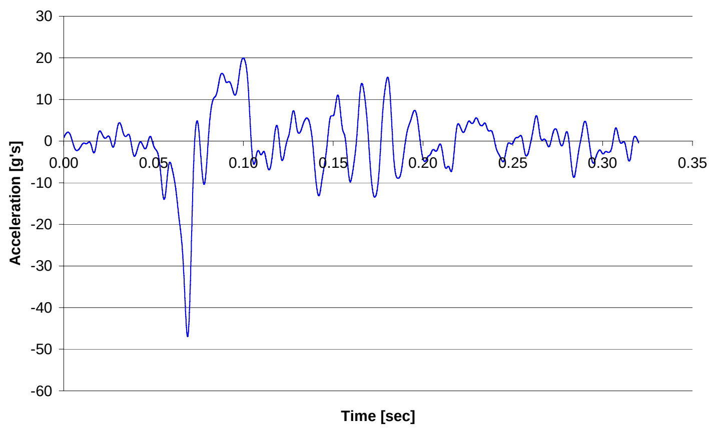
Longitudinal acceleration



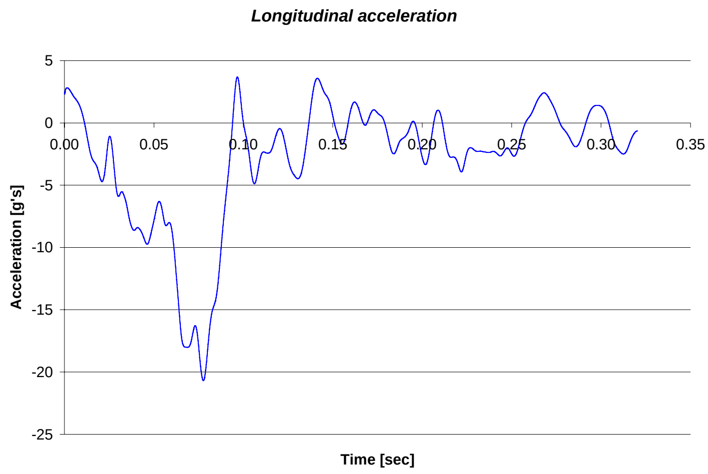
Lateral acceleration

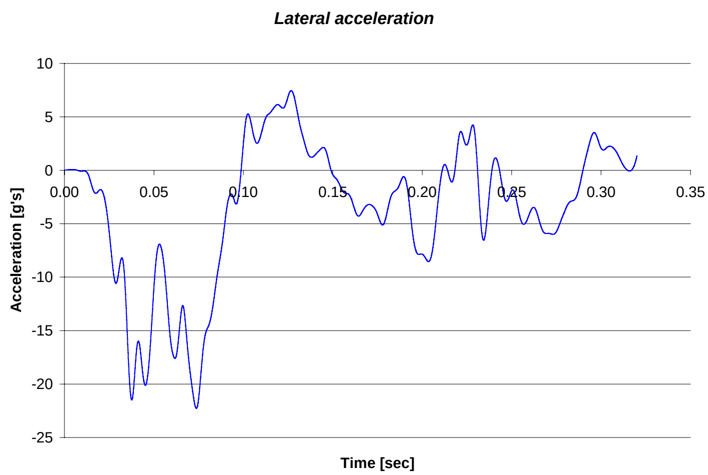


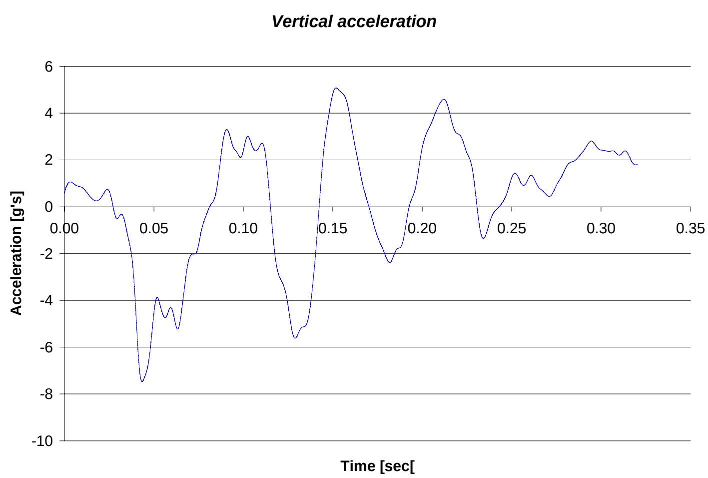
Vertical acceleration



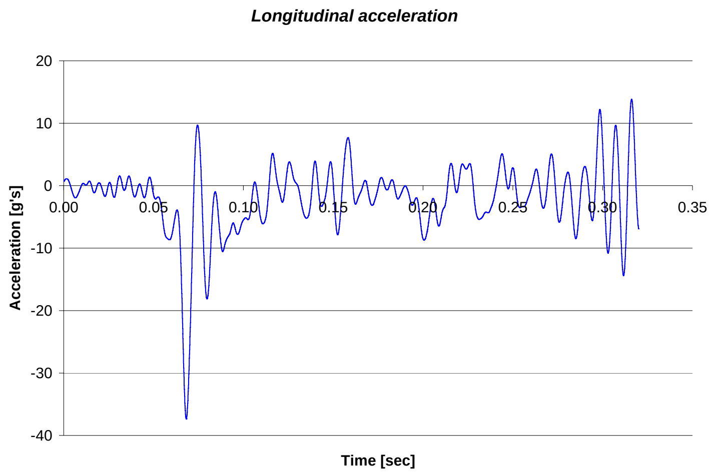
***Design #1* (Test 3-11)**

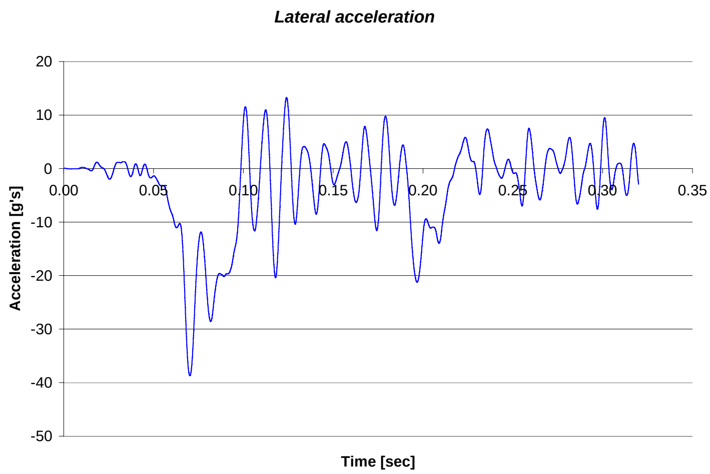


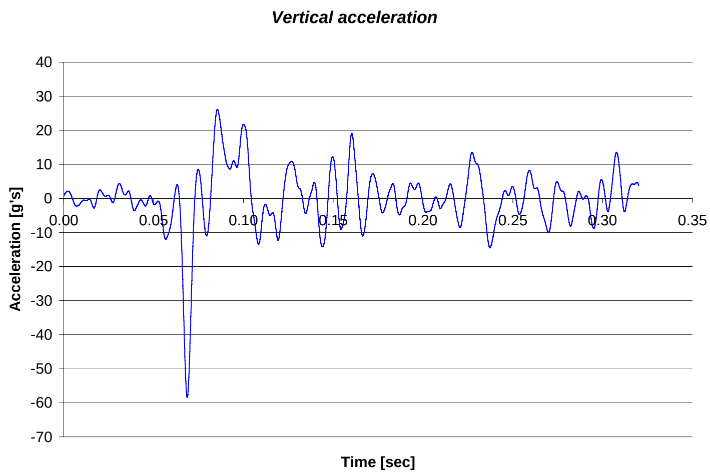




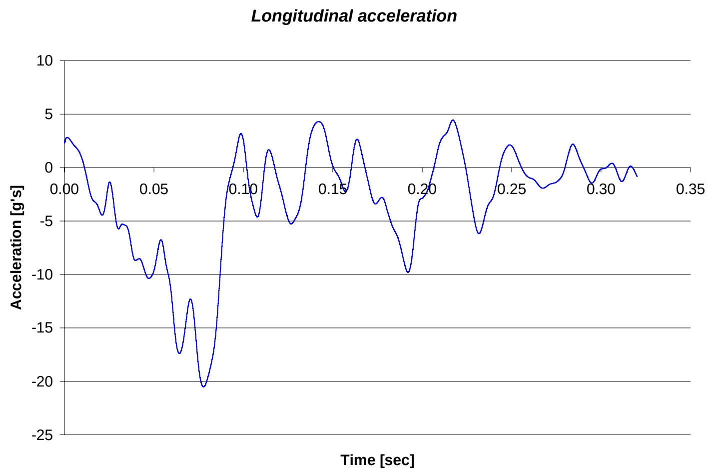
Design #2 ***(Test 3-10)***

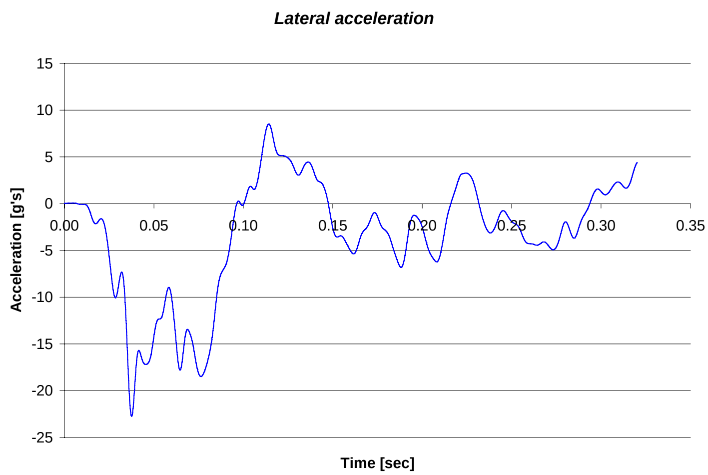


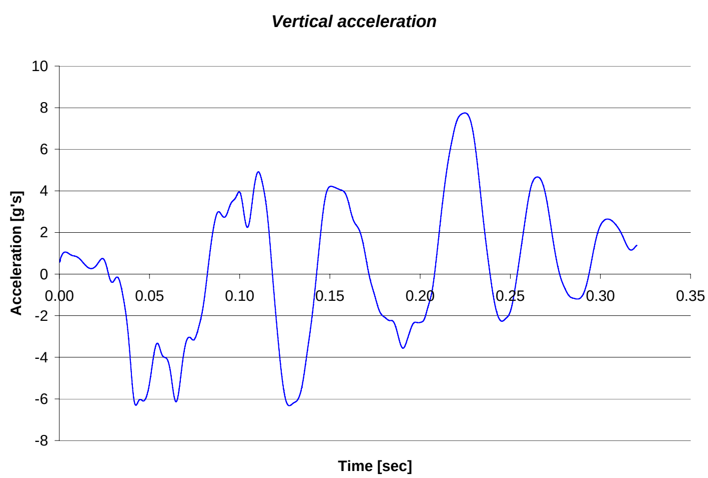




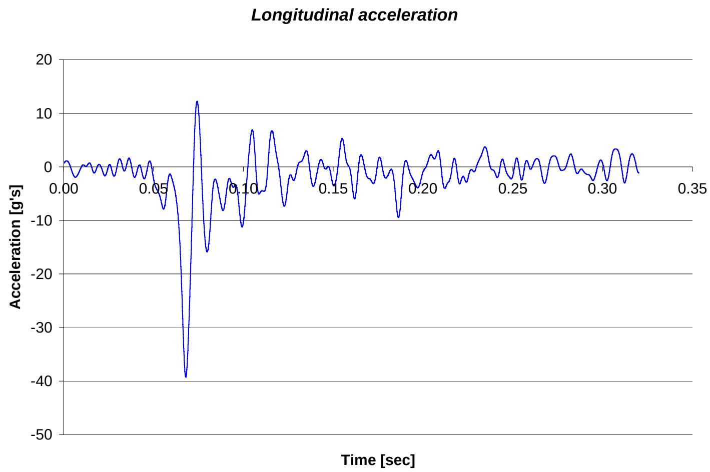
***Design #2* (Test 3-11)**

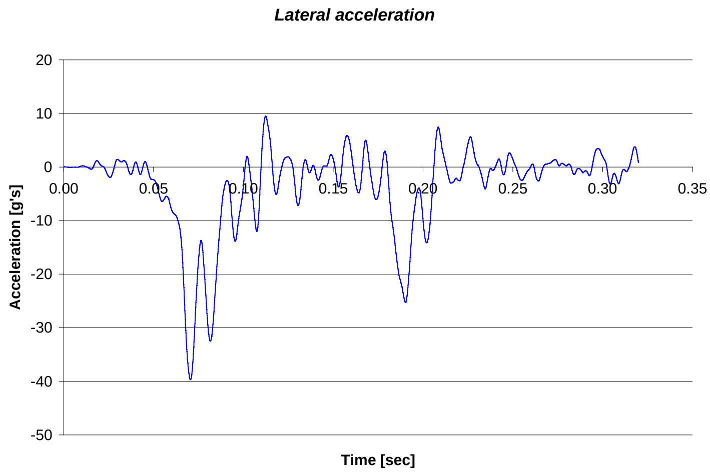


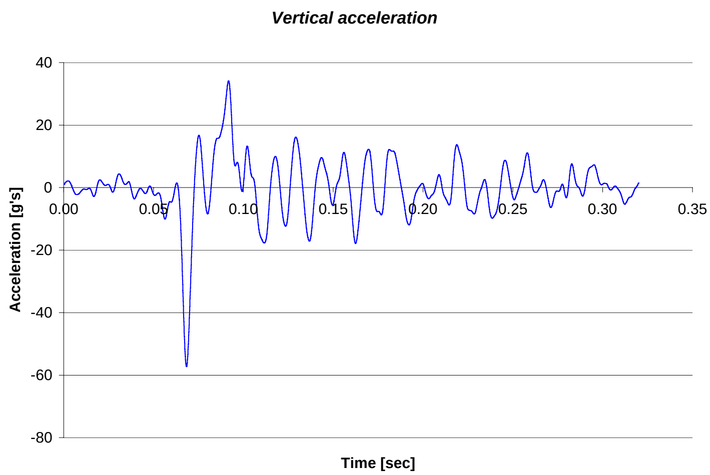




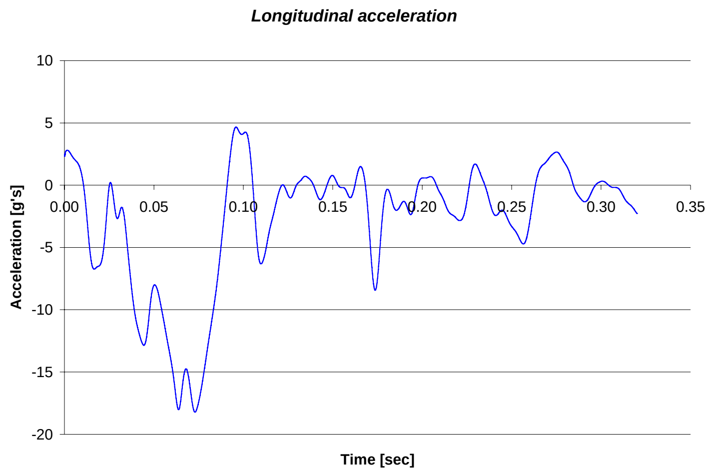
***Design #3* (Test 3-10)**

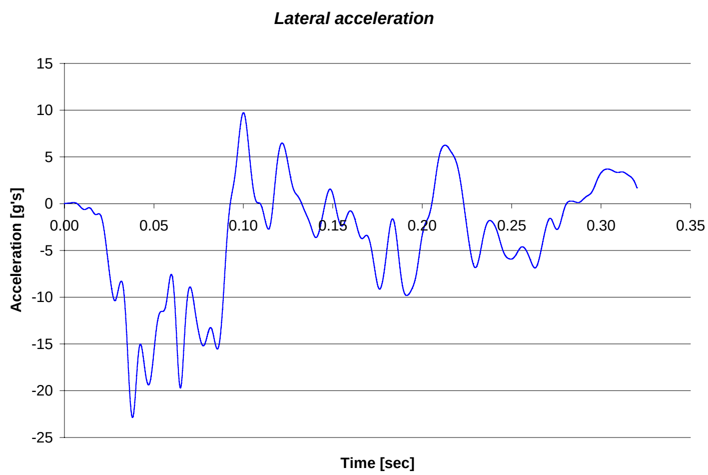


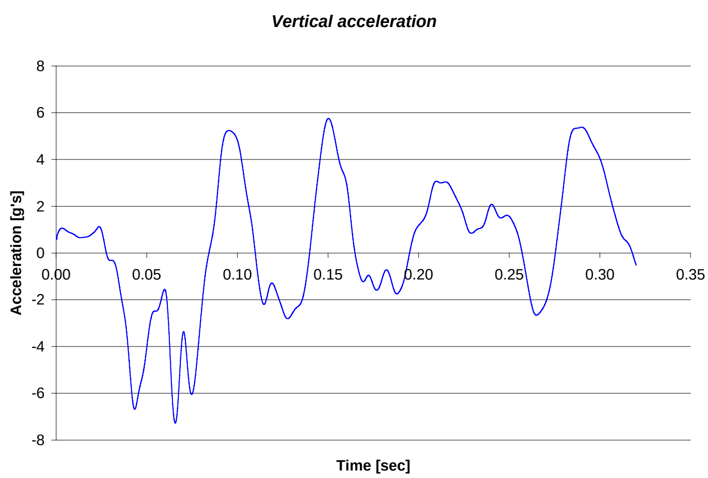




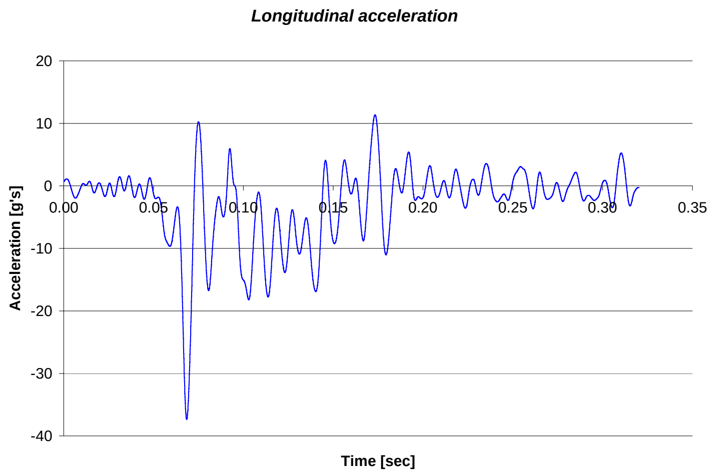
<u>Design #3</u> (Test 3-11)

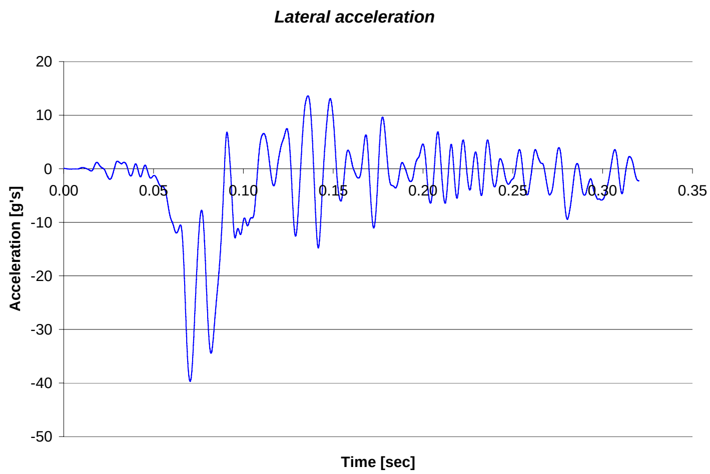


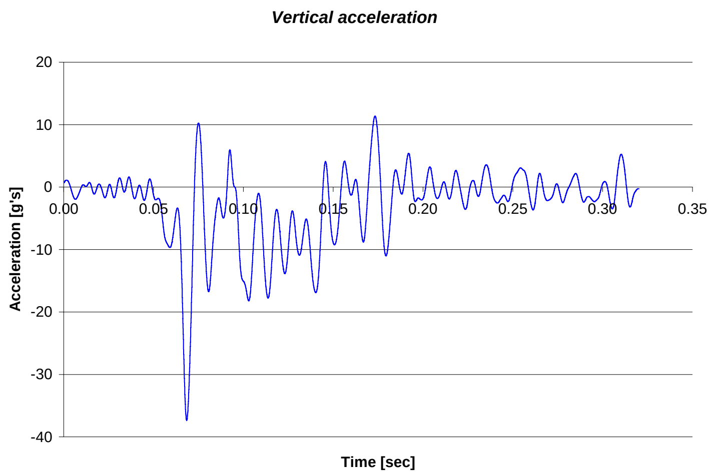




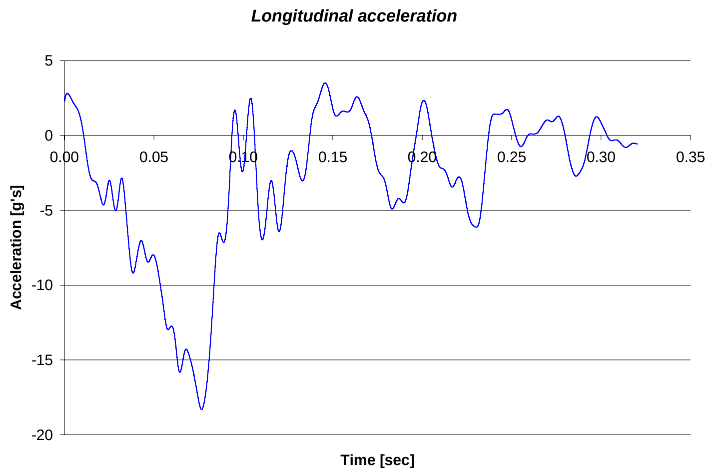
Design #4 *(Test 3-10)*

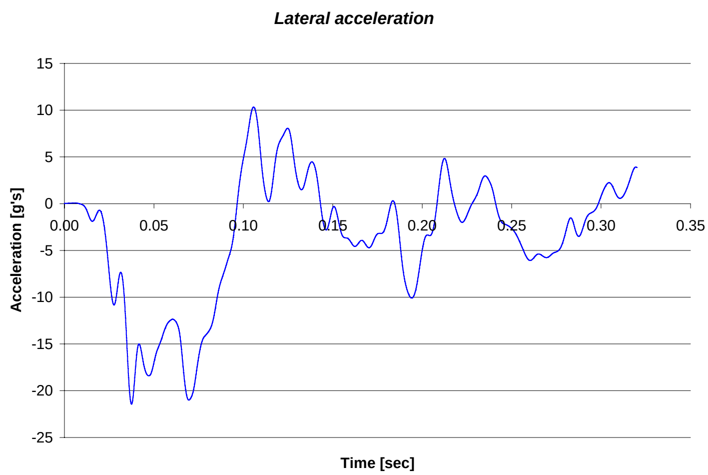


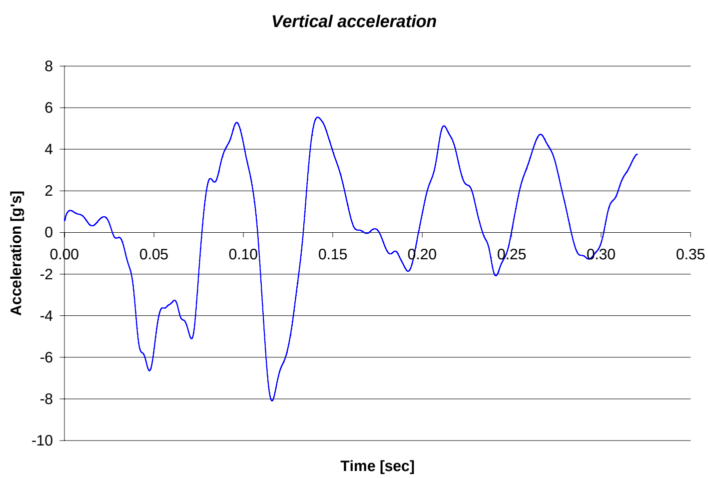




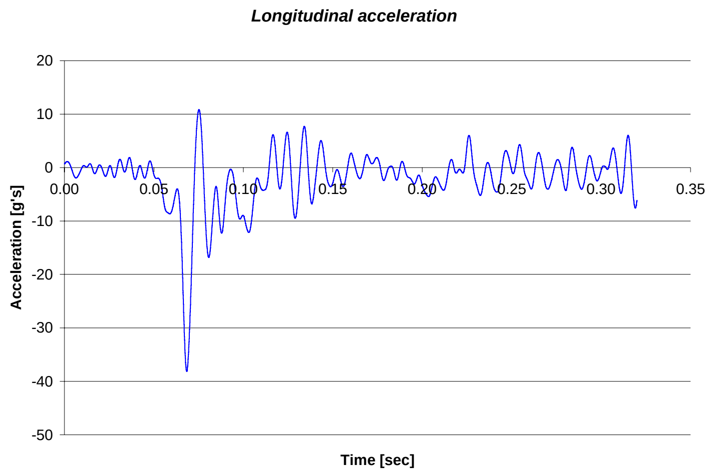
***Design #4* (Test 3-11)**

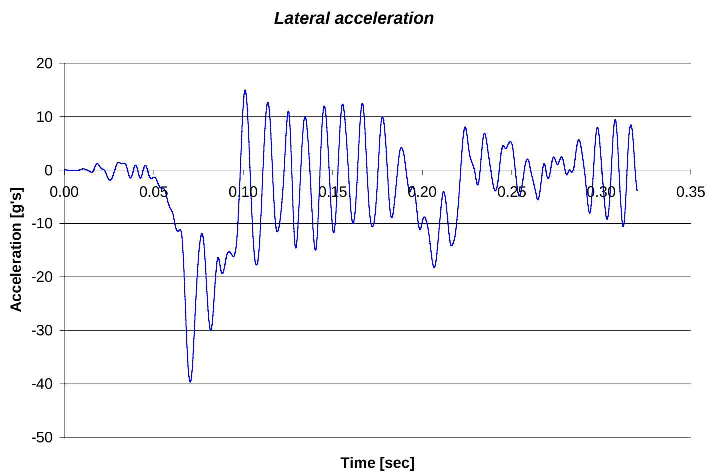


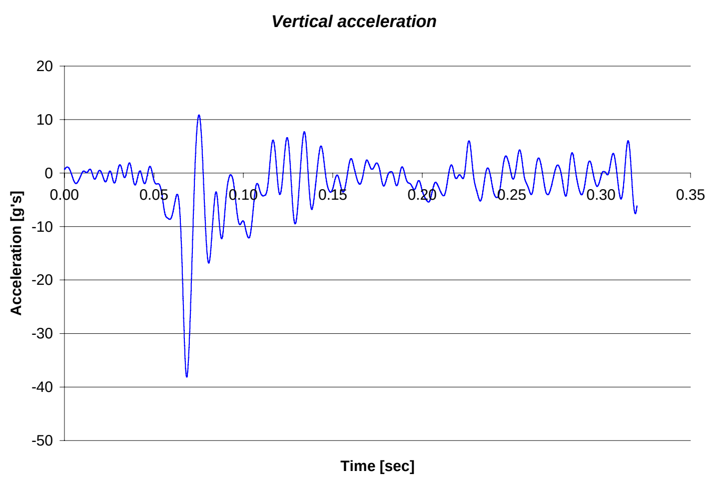




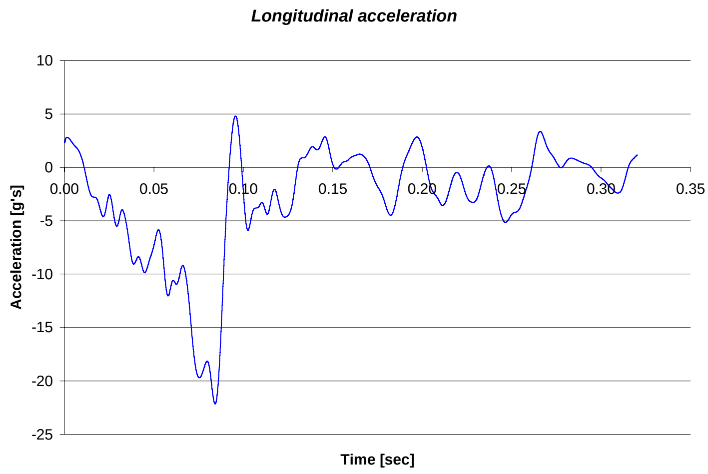
Design #5 ***(Test 3-10)***

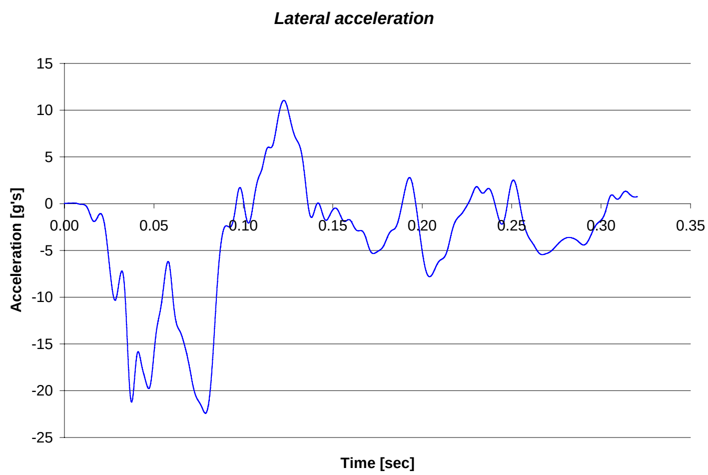


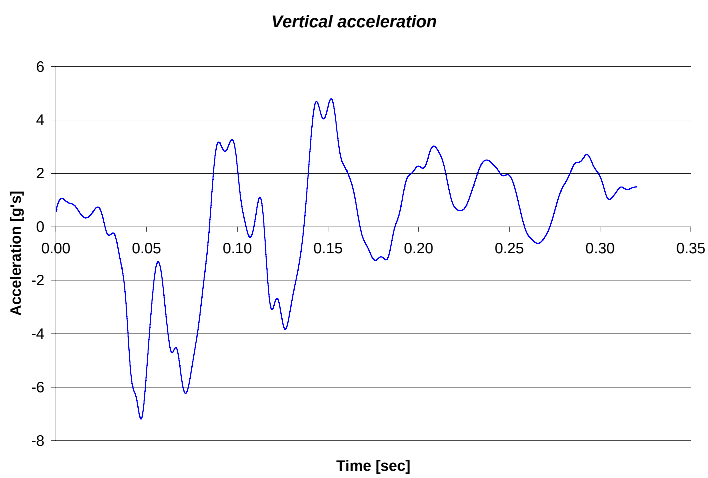




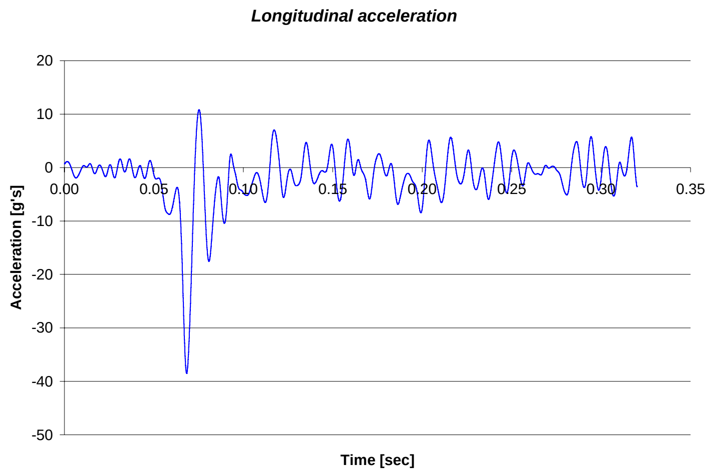
***Design #5* (Test 3-11)**

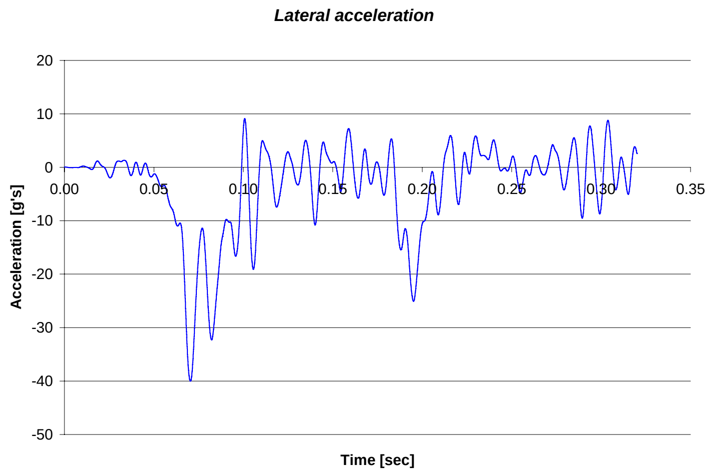


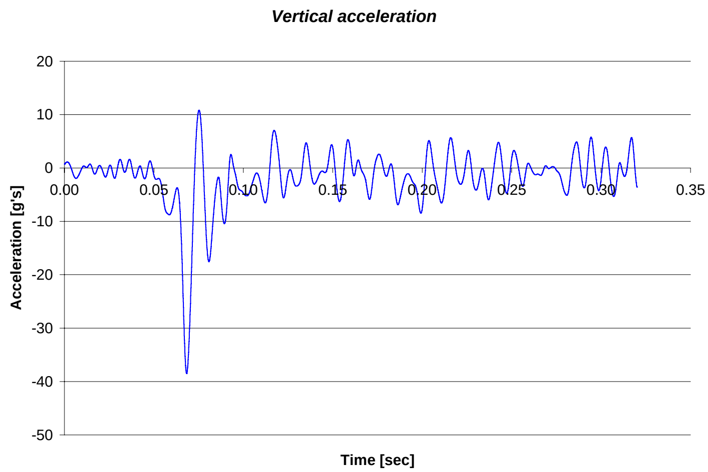




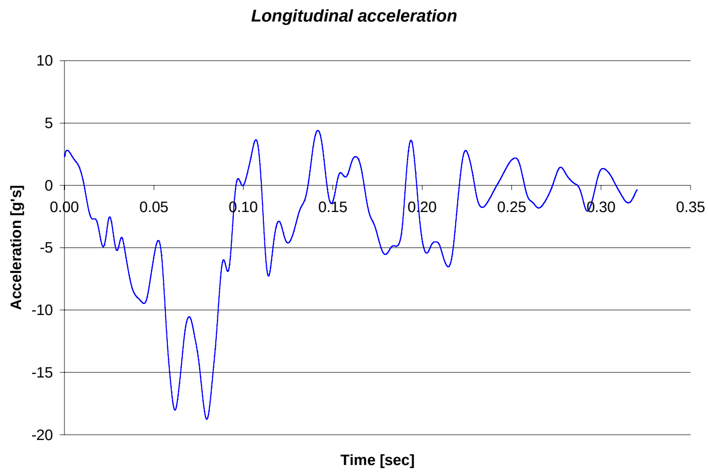
Design #6 *(Test 3-10)*

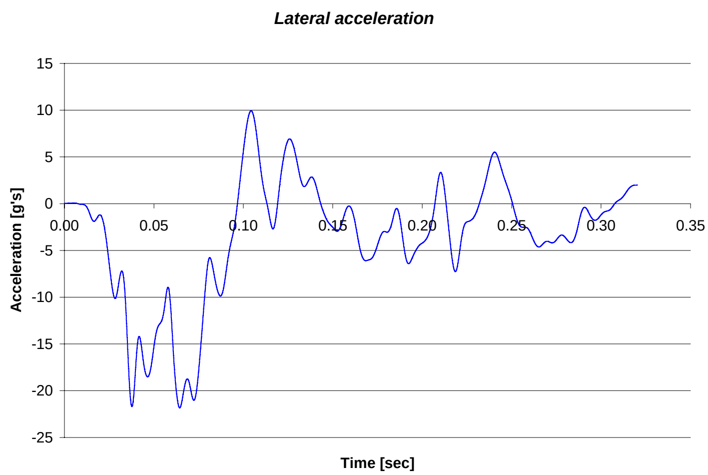


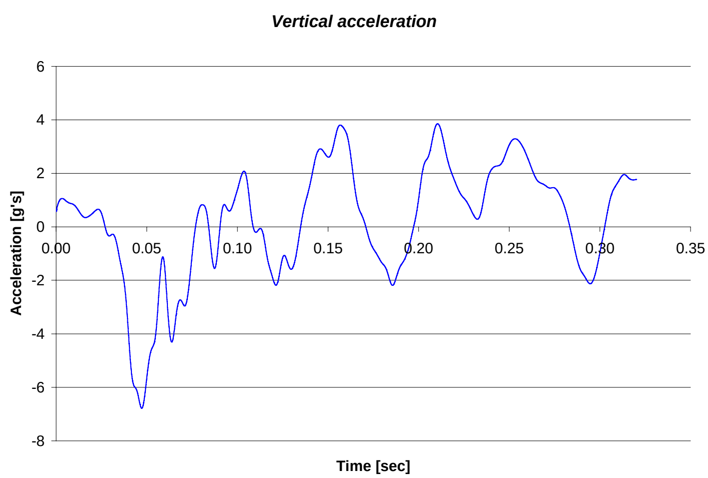




***Design #6* (Test 3-11)**







Appendix E: SI CONVERSIONS

To convert from	*to*	*Multiply by*
	ACCELERATION	
Meter per second squared (m/s^2)	foot per second squared (ft/s^2)	3.280 840 E 00
	AREA	
square meter (m^2)	square foot (ft^2)	1.076 391 E 01
	ENERGY	
Joule (J)	foot-pound ($ft\text{-}lb_f$)	7.375 621 E-01
	FORCE	
Newton (N)	pound-force (lb_f)	2.248 089 E-01
	LENGTH	
meter (m)	foot (ft)	3.280 840 E 00
meter (m)	inch (in)	3.937 008 E 01
millimeter (mm)	inch (in)	3.937 008 E-02
	MASS	
kilogram (kg)	pound-mass (lb_m)	2.204 623 E 00
	PRESSURE OR STRESS	
Pascal (Pa)	pound per square inch (psi)	1.450 377 E-04
	VELOCITY	
kilometer per hour (km/h)	mile per hour (mi/hr)	6.213 712 E-01
Meter per second (m/s)	foot per second (ft/s)	3.280 840 E 00