

# VALIDATION OF FINITE ELEMENT MODELS OF INJURY RISK IN VEHICLE-ROADSIDE BARRIER CRASHES

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## ABSTRACT

Guardrail systems are widely used to reduce the possibility of occupant injury in vehicle roadside crashes. This paper investigates the occupant injury risk in vehicle collisions with the weak post w-beam Test Level 2 guardrail barrier. A finite element model of the weak post w-beam guardrail barrier impacted by a 2000-kg pickup truck at a speed of 70 km/h and an angle of 25 degrees was developed and simulated using LS-DYNA. The simulation results were validated against a full-scale crash test conducted at these same conditions. The maximum dynamic deflection of the guardrail, exit velocity and angle of the vehicle, and occupant injury risk were calculated and compared to the test. Kinematics of the vehicle and guardrail were assessed qualitatively as well as quantitatively. The analysis showed that the vehicle was contained and redirected by the weak post w-beam guardrail barrier. The vehicle remained upright and stable during and after the impact. The occupant impact velocity (OIV) and occupant ridedown acceleration (ORA) calculated from simulation results were in good agreement with test data.

**Keywords:** Injury Risk, Weak Post Guardrail, Finite Element Model

## INTRODUCTION

W-beam guardrail systems have been used for decades in the United States to reduce the number of fatalities and injuries that result from roadside crashes. W-beam guardrail systems prevent vehicles from leaving the roadway and striking a hazard by containing and redirecting the vehicle. Strong post w-beam guardrail system is the most commonly used guardrail in the United States, while weak post w-beam guardrail system is mostly used in the northeast states [1]. The characteristics of weak post w-beam guardrail system in collisions are different from those of strong post guardrail barrier. Larger dynamic and permanent deflections of weak post guardrail were seen in the tests and real world crashes. Consequently, occupant injury potential that involve roadside accidents with weak post guardrail barrier showed differences from strong post system. A study conducted by the New York Department of Transportation found that vehicle crashes involving weak post w-beam guardrail system were less severe than strong post w-beam guardrail crashes [2].

The objective of this study is to develop and validate a finite element model of weak post w-beam (G2) guardrail system. Several finite element models of strong post w-beam guardrail system have been developed. However, no weak post w-beam guardrail Test Level 2 model was found in the National Crash Analysis Center (NCAC) finite element model archive [6]. According to the National Cooperative Highway Research Program (NCHRP) Report 350, Level 2 tests require that longitudinal barriers be subjected to a full-scale vehicle crash test of a 2000-kg pickup truck impacting at a speed of 70 km/h and an angle of 25 degrees. Development of a weak post w-beam guardrail system is helpful in understanding occupant injury risk in vehicle roadside crashes. In addition, minor damage that results from a low speed collision or sideswipe is commonly seen in the guardrail barrier. The effect of this damage on the performance of the barrier system in subsequent crashes is not well understood. Therefore, this weak post w-beam guardrail model will also help the investigation of injury potential of occupants in vehicle roadside accidents that involve damaged guardrail.

## METHODS

The objective of this study is to develop and validate a finite element model of weak post w-beam (G2) guardrail system. The standard weak post guardrail system in a NCHRP Report 350 Test Level 2 test generally consists of at least 9 weak posts and w-beam rails for a total length of 30 m excluding terminals. The spacing between posts is 3810 mm and the rail height is 770 mm. Post was attached to the rail at splices. No weak post w-beam Test Level 2 guardrail models were found in the NCAC finite element model archive [6]. A weak post w-beam Test Level 3 guardrail model developed by Ray [3] was found in the literature. However, the configuration of that model is different from that of Test Level 2 guardrail system. The differences include: 1) the W-beam guardrail was mounted 820-mm above the ground with splices at mid-span 2) the W-beam backup plates were mounted at each post 3) the post was attached to the rail at non-splice location. Therefore, it is necessary for us to develop our own weak post w-beam Test Level 2 guardrail model.

### Finite Element Modeling of the Weak-Post W-Beam Guardrail System

A detailed finite element model of weak-post w-beam guardrail system was developed. The guardrail system was designed as a Test Level 2 barrier. All barrier components were modeled using Hypermesh 8.0. The crash test was simulated using the LS-DYNA finite element code, and post-processed in LS-PREPOST. The mesh of the w-beam guardrail, soil, and splice bolts and nuts was taken from the NCAC strong post w-beam guardrail model [6]. The weak post, rail-post bolt and nut, guardrail washer, soil plate, and end terminals were modeled and assembled with the guardrail system.

The test installation in the model is similar to a full-scale crash test No. 471470-22 conducted at the Texas Transportation Institute [4]. The top of the rail in the system was located 770 mm above the ground. The mounting height of the center slot of the guardrail was 610 mm from the ground. The soil plate with the dimension of 600 mm in length, 200 mm in width, and 6 mm in thickness was mounted on the post and located 124 mm below the ground. Simplification was made such that the nodes at the end terminals were only constrained in three translational directions.

All posts, rails, and soil plates were modeled using quadrilateral shell elements. \*MAT\_PIECEWISE\_LINEAR\_PLASTICITY was used for the posts, rails, and soil plates. The material property of the guardrail was taken from the guardrail model developed by Ray [3]. The same material property was assigned to the end terminals. The rail-post bolt and nut (Designator No. FBX08a) was modeled and used to connect the w-beam to the post. The rail-post bolts and nuts and washers were modeled using quadrilateral shell elements. The material selected for the rail-post bolt and nut was rigid material. This assumption was made to reduce the computational time. A spring was placed between the bolt head and the nut to represent the force and stiffness of the bolt. The failure force for the spring was set to 16 kN [3]. The material model \*MAT\_SPRING\_NONLINEAR\_ELASTIC was selected for the springs. The finite element model and material properties of the soil was taken from the NCAC strong post w-beam guardrail model. \*CONTACT\_AUTOMATIC\_SURFACE\_TO\_SURFACE was defined between the outer surfaces of the post and inner surfaces of the soil block to simulate the contact between the post and the soil. Friction coefficients between the post and the soil were also taken from the NCAC strong post guardrail model.

A reduced finite element model of a Chevrolet C2500 pickup truck developed at the NCAC was used in the simulation. The simulation setup is shown in Figure 1. \*CONTACT\_AUTOMATIC\_SURFACE\_

TO\_SURFACE was defined between the vehicle and the guardrail system. The vehicle model was assigned an initial velocity of 71.0 km/h at an angle of 25 degrees to impact the midspan between posts 4 and 5 of the barrier system.

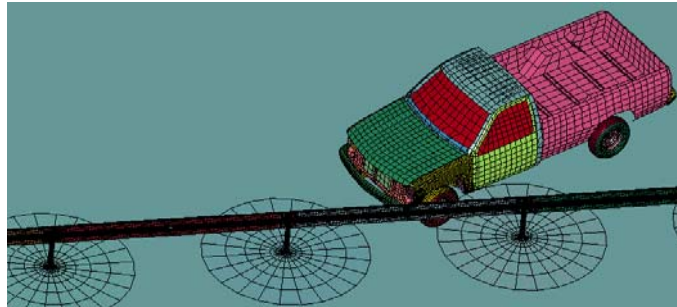


Figure 1. Simulation setup of the weak-post w-beam guardrail impact test.

#### Validation of the Finite Element Model of Weak Post Guardrail Model

For the W-beam weak-post roadside barrier system, Test No. 471470-22 [4] was selected for finite element model development and validation. The test setup was based on the NCHRP Report 350 Test Level 2 configuration. The spacing between posts is 3810 mm and the rail height is 770 mm. Post was attached to the rail at splices. In the test performed by the Texas Transportation Institute, 17 posts with 3810 mm spacing between posts were used to support the guardrail barrier system. The total test installation was 76.2 m with a 7.62 m turned-down terminal at each of the two ends. The top of the rail in this system was located 762 mm above the ground. A 1985 Chevrolet Custom 20 pickup truck, which had a test weight of 2076 kg, was used for the crash test. The vehicle impacted the guardrail system at midspan between posts 4 and 5 at a speed of 71.0 km/h and an angle of 26.1 degrees. The test vehicle separated from the guardrail at approximately 1.08 s after impact with an estimated exit speed and angle of 25.7 km/h and 9.5 degrees. The guardrail had a maximum dynamic deflection of 1.4 m at 0.372 s after impact. The maximum permanent deflection of the guardrail was 1.3 m. The longitudinal occupant impact velocity was 4.6 m/s at 0.3 s; the highest 0.01 s average ridedown acceleration was -4.8 g's between 0.384 and 0.394 s. In the lateral direction, the occupant impact velocity was 3.3 m/s at 0.228 s; the highest 0.01 average ridedown acceleration was 3.1 g's between 0.386 and 0.396 s.

#### Flail-Space Injury Risk Model

A flail-space model was utilized to evaluate occupant injury risk during roadside crashes by calculating the velocity at which the unrestrained occupant impacts the vehicle interior and the acceleration that the occupant experiences by contacting the vehicle interior [5]. The assumptions made in the flail-space model were: 1) Occupant was located at the center of mass of the vehicle. 2) Yaw motions of the vehicle were ignored, and the lateral movement of the occupant is independent of the motion in the longitudinal direction. 3) Motion of the vehicle and the occupant is in the x-y plane. 4) Occupant was allowed 0.3 m of motion in the lateral direction before impact with the vehicle side structure, and occupant was allowed 0.6 m of motion in the longitudinal direction before impact with the vehicle dashboard.

#### Injury Risk Calculation Procedures

The flail-space injury risk model assumed that occupant was allowed to travel in the vehicle compartment 0.6 m in the longitudinal direction and 0.3 m in the lateral direction. The time ( $t^*$ ) when occupant contacted the vehicle interior was determined by the double integration of acceleration.

$$X, Y = \int_0^{t^*} \int_0^{t^*} a_{x,y} dt^2 \quad (\text{eq.1})$$

where  $a_{x,y}$  is the vehicle acceleration in the longitudinal or lateral directions,  $X = 0.6$  m and  $Y = 0.3$  m. Acceleration in the longitudinal direction is integrated twice with respect to time to find the value of time,  $t_x^*$ , at which the double integration equals 0.6 m. Acceleration in the lateral direction is integrated twice with respect to time to find the value of time,  $t_y^*$ , at which the double integration equals 0.3 m. Time  $t^*$  is the smaller of  $t_x^*$  and  $t_y^*$ . The equation for the occupant impact velocity (OIV) is:

$$V_{l_{x,y}} = \int_0^{t^*} a_{x,y} dt \quad (\text{eq.2})$$

where  $V_{l_{x,y}}$  is the velocity at which the occupant impacts the vehicle interior in the longitudinal or lateral directions.

For the occupant ridedown acceleration (ORA), an arbitrary duration of 10 ms was selected as a time base to calculate average accelerations for occupant risk assessment. The ORA was obtained by finding the highest 10 ms average vehicle accelerations after time  $t^*$  in the longitudinal and lateral directions.

The calculated occupant impact velocity and occupant ridedown acceleration were compared to the recommended values [5]. Two limits are given for each injury risk parameter, as listed in Table 1. It is desirable that computed values be below the “preferred” limits, and it is recommended that the computed values be below the “maximum” values. It should be noted that the recommended limits were absolute values.

Table 1. Occupant injury risk limits

Occupant Impact Velocity Limits (m/s)			Occupant Ridedown Acceleration Limits (G's)		
Component	Preferred	Maximum	Component	Preferred	Maximum
Longitudinal	9	12	Longitudinal and Lateral	15	20

## RESULTS

The comparisons of guardrail deflections, vehicle exit velocity and angle, occupant impact velocity, and occupant ridedown acceleration are listed in Table 2, 3, and 4. Data from the accelerometer located at the center of gravity of the vehicle were extracted for evaluation of occupant risk. The occupant impact velocity in the longitudinal direction was 5.96 m/s at 0.267 s; the highest 0.01 s average ridedown acceleration in the longitudinal direction was -3.15 g's between 0.279 and 0.289 s. In the lateral direction, the occupant impact velocity was 3.26 m/s at 0.233 s; the highest 0.01 average ridedown acceleration was 5.08 g's between 0.375 and 0.385 s.

Table 2. Comparisons of maximum dynamic and permanent guardrail deflection.

	Test No. 471470-22	Simulation
Maximum Dynamic Deflection (m)	1.4	1.417
Maximum Permanent Deflection (m)	1.3	0.948

Table 3. Comparisons of vehicle exit velocity and angle.

	Test No. 471470-22	Simulation
Vehicle Exit Speed (km/h)	25.7	36.6
Vehicle Exit Angle (degree)	9.5	10.5

Table 4. Comparisons of occupant impact velocity and ridedown acceleration from Test No. 471470-22 and simulation.

	Test No. 471470-22	Simulation	Preferred Limit	Maximum Limit
Longitudinal OIV (m/s)	4.6	5.96	9	12
Lateral OIV (m/s)	3.3	3.26	9	12
Longitudinal ORA (G's)	-4.8	-3.15	15	20
Lateral ORA (G's)	3.1	5.08	15	20

Sequential photographs for Test No. 471470-22 [4] and corresponding overhead view snapshots taken from the simulation were compared in Figure 2. It was observed that the overall vehicle kinematics in the test and the simulation were similar. Small variations were found in the time at which different impact events occurred and the corresponding velocity of the vehicle. In the test, the vehicle was traveling parallel to the guardrail barrier at 0.533s, while the vehicle model was traveling parallel to the installation at 0.51 s in the simulation. The vehicle model separated from the guardrail at approximately 0.92 s after impact with an estimated exit speed of 36.6 km/h at an angle of 10.5 degrees. The guardrail had a maximum dynamic deflection of 1.417 m at 0.280 s after impact.

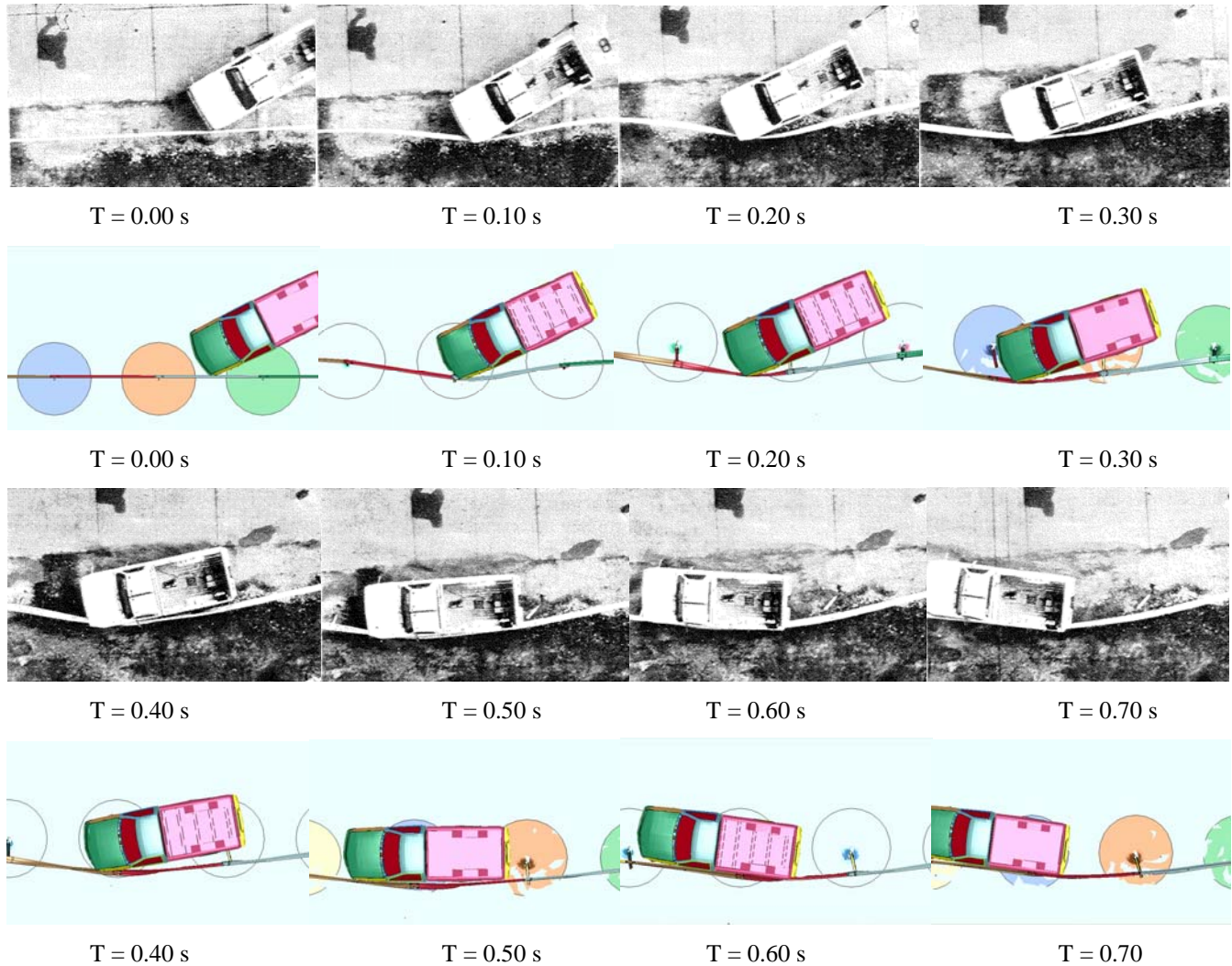


Figure 2. Comparisons of sequential photographs from Test No. 471470-22 and simulation

## DISCUSSION

The numerical model of weak post w-beam guardrail impact was compared to Test No. 471470-22. It was observed that the maximum dynamic deflection of the guardrail obtained from the simulation was very comparable to that in the test. The maximum permanent deflection of the guardrail in the simulation was smaller than that in the crash test. Due to the fact that maximum permanent deflection was measured at the end of the simulation duration (1.2 s); this value may not reflect the true permanent guardrail deflection. The impacted guardrail section may be in the middle of oscillatory motion, and further movement of guardrail is expected after the impact. The recorded vehicle exit velocity in the simulation was relatively higher than test vehicle exit speed. The differences in friction conditions between the vehicle and the guardrail barrier as well as the soil condition could account for this discrepancy. To closely duplicate Test No. 471470-22, more detailed information about the soil and friction conditions need to be investigated. Occupant impact velocity and ridedown acceleration were calculated from the simulation results. The longitudinal OIV values in the test as well as in the simulation were under the preferred and recommended limit. The lateral OIV values obtained from the simulation and the test were very comparable to each other. Both values were below the preferred and maximum limits. Analysis of the ORA showed that the absolute values of the longitudinal and lateral ORA from the numerical model were similar to the test data. All ORA values were considerably lower than the preferred and recommended limits.

## CONCLUSIONS

A finite element model of weak post w-beam guardrail was developed. A 2000 kg pickup truck impacting the weak post guardrail barrier at a speed of 70 km/h and an angle of 25 degrees was simulated using LS-DYNA. The occupant injury risk during the impact was investigated by computing occupant impact velocity and occupant ridedown acceleration. The simulation results were validated against NCHRP Report 350 Test Level 2 Test No. 471470-22. Kinematics of the vehicle and guardrail in the simulation were very similar to the test. The analysis showed that the vehicle was contained and redirected by the weak post w-beam guardrail barrier. The OIV and ORA calculated from simulation results were in good agreement with test data. It was concluded that the model is suitable for conducting studies of injury risk from vehicle collision with weak post guardrail.

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