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Evaluation of Redesigned Slipbase Sign Support Using Crash Simulation

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ABSTRACT

Improvement in computer hardware and Finite Element (FE) software have made it possible to simulate complex phenomenon such as the behavior of automobiles and roadside hardware during crashes. In this paper, the performance of a modified 3"x3" slipbase sign support system is evaluated using Finite Element simulations. The first task of the study consisted of developing an accurate finite element model of the new 3"x3" slipbase. This is achieved by using full-scale tests that were conducted on an 8"x8" slipbase at 32 and 96 km/hr (20 and 60 mph) to validate an 8"x8" slipbase FE model. Once an accurate model of the 8"x8" slipbase is obtained, the exact modeling techniques used in developing this slipbase are used to construct a FE model of the 3"x3" slipbase. The second task of this study involved using the 3"x3" slipbase model to predict its behavior in a 32 and 96 km/hr (20 and 60 mph) impacts. The predictions showed that modified 3"x3" slipbase passes the NCHRP 350 safety criteria. These predictions were compared to full-scale tests that were conducted subsequent to the simulations. It was found that the FE model accurately predicted the full-scale test results. The final task of this study consisted of conducting a parametric FE analysis to determine the maximum clamping force that can be applied to the 3"x3" slipbase without causing it to fail the NCHRP 350 safety criteria. The computer simulation parametric study revealed that the bolts can be clamped up to their yielding point and the slipbase will still pass the safety criteria of acceptable vehicle velocity change.

Evaluation of a Redesigned Slipbase Sign Support System Using Finite Element Simulations

INTRODUCTION

The Federal Highway Administration, state departments of transportation, and roadside hardware manufacturers are conducting extensive research to improve the safety of roadside hardware and therefore minimize the deaths and injuries to highway travelers. Through these efforts, roadside hardware structures are continuously evaluated and if necessary redesigned to keep up with the constantly changing shape and size of the vehicle fleet. Safety criteria and regulations are updated to accommodate these changes and to further improve the safety of highway roadside appurtenances. The methods used in evaluating and analyzing roadside hardware has been mainly based on full-scale crash testing through trial and error. These methods are not always cost effective and do not lead to the most efficient and optimum design.

In recent years, computer technology and finite element codes have seen significant progress. Through the use of Shared Memory Processing (SMP) and Massively Parallel Processing (MPP) architectures, computers are becoming much faster and less expansive. Similarly, finite element codes today are more efficient, accurate, and reliable. These advances in computers and finite element codes have made it possible to accurately simulate complex crash phenomena such as vehicles impacting roadside hardware structures.

The goal of this study is to use finite element simulations to predict the behavior of a modified 3"x3" slipbase design and conduct parametric studies to evaluate the performance of the model by simulation. All simulations in this study used LS-DYNA explicit non-linear FE code [1,2]. Slipbase systems are simple and very effective designs for supporting signs and luminares in highways. A safety mechanism at the base allows separation of flanges which causes the pole (e.g. sign or luminare post) to move away (break away) from the impacting vehicle. This reduces the vehicle velocity change in a crash and hence minimizes the risk of injury to the occupant. The slipbase mechanism has to be "strong" enough to withstand the sign-pole weight and wind forces but designed in a manner that would breakaway upon impact with vehicles with sufficient momentum. The details of the selected slip-base designs are described in more details later.

MODELING AND VALIDATION APPROACH

The procedure followed to achieve the goal of the study consisted of first developing a methodology for modeling the slipbase design in general. This methodology was verified by using previously conducted full-scale crash tests. Three crash tests were selected for validating this methodology. The first test was that of a surrogate test vehicle (Bogie) impacting a rigid pole at an impact speed of 36 km/hr (20 mph). This test was used to develop and validate a finite element model of Bogie, which is the impactor used in the other two tests. The second test was on Bogie impacting an 8"x8" Oregon slipbase sign support system at 36 km/hr (20 mph). This test was used to validate the 8"x8" slipbase model, hence ensuring the accuracy of the FE modeling methodology. The third test consisted of the 8"x8" slipbase impacted with Bogie at 96 km/hr (60 mph). This test was used to check the validity of the slipbase and Bogie models. It should be mentioned here that the 96 km/hr (60 mph) impact of Bogie into a rigid pole is construed as a destructive test for the Bogie and has never been conducted. Therefore, the third test above is used to validate Bogie's 96 km/hr flexible nose, realizing that this nose is different from the 36 km/hr bogie nose.

The next step in the study was to predict the behavior of the 3"x3" slipbase system in crashes. For this part of the study a finite element model of the 3"x3" slipbase was built using the same methodology. The model was then impacted by Bogie in two crashes at speeds of 36 km/hr (20 mph) and 96 km/hr (60 mph). The results from the two simulations were compared to full-scale tests that were performed at a later time and were proved successful predictions.

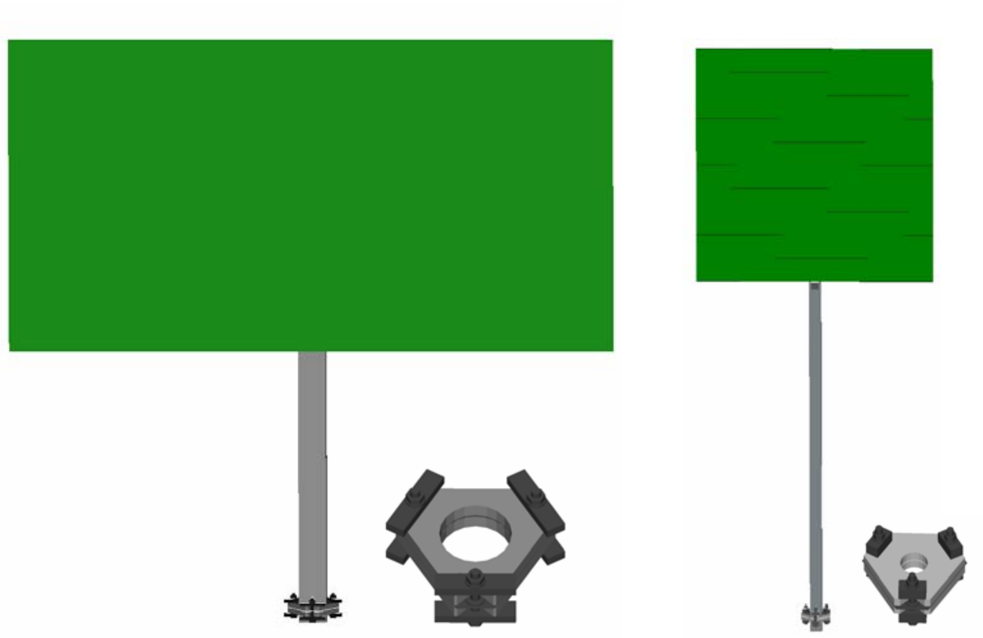
The final step in this study was to use the 3"x3" slipbase model to conduct parametric studies and determine the optimum clamping force that can be applied to the slipbase without causing it to fail the safety criteria. Simulations were performed at different clamping force levels and the change in velocity was monitored. The parametric study showed that this modified 3x3" slipbase is less sensitive to the clamping force than the previous designs. Even when high clamping forces, i.e., forces that would cause almost yielding of the clamping bolts, the performance of the 3"x3" slipbase still passes the safety criteria of the NCHRP 350 report.

The results of this study are shown in this paper. The first section describes the slipbase design. In the second section the Bogie model development and validation are presented. The validation of the 8"x8" slipbase system is shown in the third section. The predictions of the 3"x3" slipbase performance are shown in the fourth section. The parametric study to determine the optimum clamping force is shown in the fifth section. The sixth and final section lists some of the conclusions of this study.

SLIPBASE DESCRIPTION

Figure 1 shows the two slipbase systems that are modeled in this study: the Oregon 8"x8" slipbase system and the 3"x3" modified slipbase system. The 8"x8" and 3"x3" designations are attributed to the size of the posts (203mmx203mm and 76mmx76mm). Close up views of the slipbase mechanisms are shown in the figure as well. The two slipbase systems differ in size but they have the same design. The bottom portion of the slipbase consists of a square tube (the stub) which is usually embedded in the ground in a concrete foundation. This stub is welded to a triangular flange (the lower flange). A similar flange (the upper flange) is welded to the square tube (the post) which holds the sign or the luminare. The upper and lower flanges have 90o notch openings in three corners. The flanges are clamped together by three steel bolts at the three notches. The purpose of the bolts is to clamp the base flanges together to support for gravity, wind, and other normal environmental loading conditions. A thin plate (keeper plate) is placed between the two flanges. The keeper plate is made of galvanized steel and its main function is to maintain the position of the bolts during and after installation and to reduce the friction between the two flanges. Large size washers are placed between the upper/lower flanges and bolts/nuts. The purpose of using these large washers is to increase contact areas between the flanges and the bolts/nuts. With this increased contact area, higher clamping forces can be obtained without causing the bolts to tilt and slide out of their respective notches.

Upon impact with a vehicle with sufficient momentum, the upper flange pushes the opposing bolts out of the notches. During this process the keeper plate shears at the holes. Once the bolts are out of the notches, the breakaway mechanism is open; the clamping forces are reduced to zero and the upper portion of the slipbase system slides over the lower flange and the stub. This breakaway mechanism reduces the resistance forces applied by the slipbase to the impacting vehicle and therefore decreases the severity of the impact.



a- 8"x8" Slipbase System. b- 3"x3" Slipbase System.

Figure 1. Modified Slipbase Sign Support System.

BOGIE MODEL DEVELOPMENT AND VALIDATION

The vehicle used in the full-scale tests is known as Bogie. Bogie is a reusable unpowered four-wheeled structure with a frontal deformable nose (Figure 2). The deformable nose consists of several honeycomb cartridges. The cartridges have different strengths, sizes, and punch holes. Dead weight plates can be added at Bogie's four corners. By varying the arrangements of the honeycomb cartridges and number of dead weight plates, Bogie can be calibrated to replicate the behavior of an actual vehicle. For the tests that were used in this study, the bogie nose and weight was calibrated to represent a VW Rabbit vehicle. Two deformable nose configurations were assembled to replicate the VW Rabbit vehicle behavior at 32 km/hr (20mph) and 96 km/hr (96 km/hr).

A validated finite element model of Bogie was developed to simulate the full-scale crash tests. Figure 2 shows the actual Bogie and its finite element model. The model was validated using a full-scale test of Bogie impacting a rigid pole. Details of the model developments and validations are described in reference [3]. The initial and final deformed plots from the simulation are shown in Figure 3. Figure 4 shows comparisons between simulation results and data measured in the full-scale test results. The Bogie center of gravity accelerations and the rigid pole forces are plotted versus time. The Bogie model is considered validated for 32 km/hr (60 mph) crash simulations.

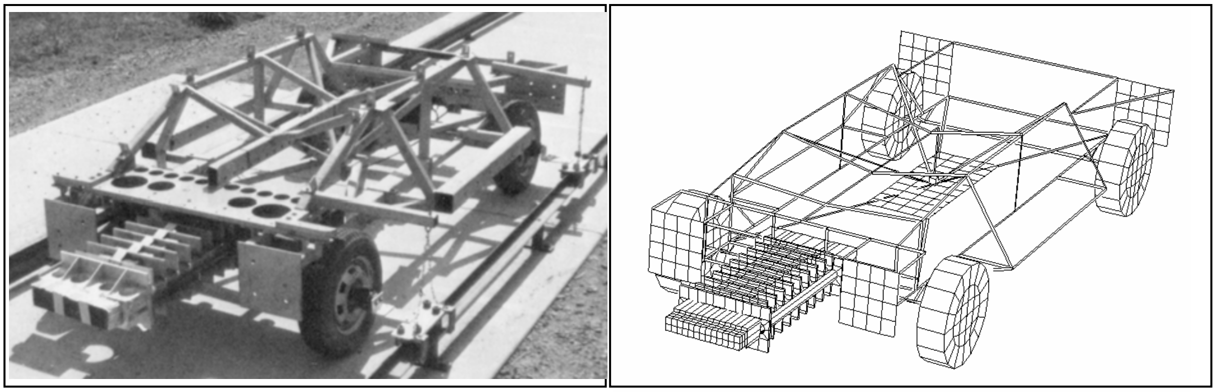


Figure 2. Actual (left) and Finite Element Model (right) of Bogie Vehicle.

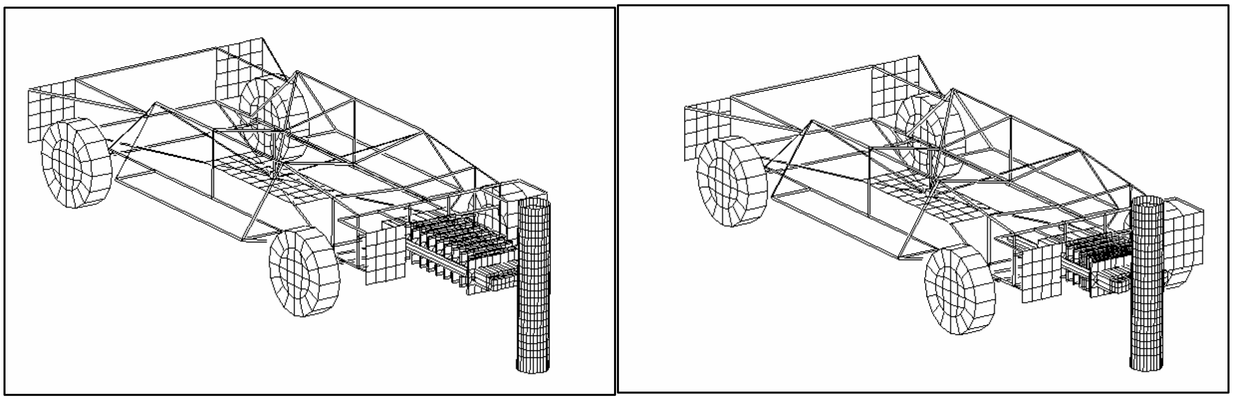


Figure 3. Simulation Initial and Final Deformed Plots.

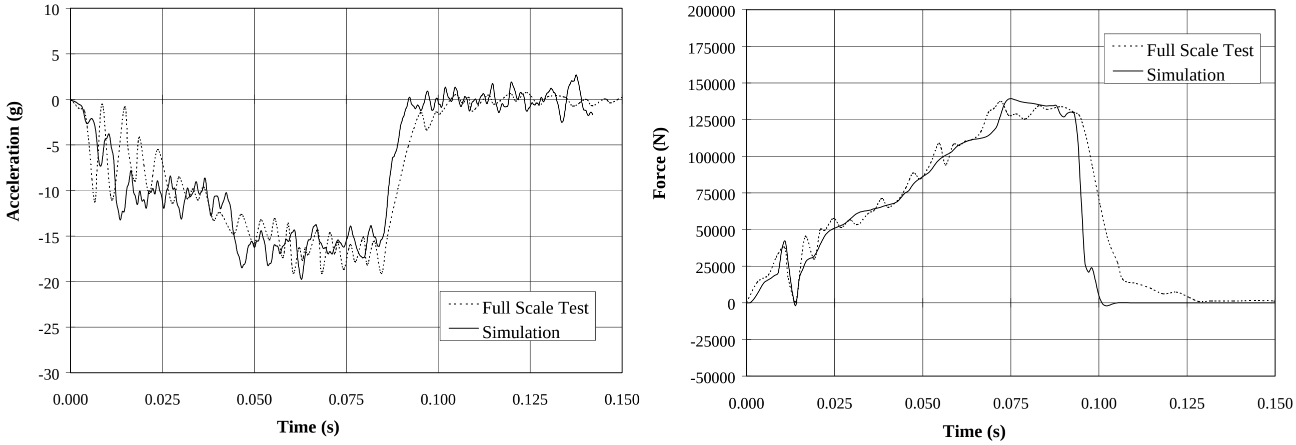


Figure 4. Full-scale Test and Simulation Comparisons: Bogie – Rigid Pole – 32 km/hr.

8"x8" SLIPBASE VALIDATION

To build an accurate model of the 3"x3" slipbase system, a general methodology for creating slipbase models that capture the true behavior of the system was needed. Since no crash tests were performed on the modified 3"x3" slipbase system, a different size (8"x8") system was used to validate this methodology. The two systems have identical designs except for their sizes. Therefore, once a validated model of the 8"x8" slipbase design is created, the same method can be used to create a reliable model of the 3"x3" slipbase system.

The finite element model of the 8"x8" slipbase system is shown in Figure 5. A list of the model composition is presented in Table 1. All components of the slipbase system with the correct geometry were incorporated in the model to ensure accurate mass and inertial properties. Furthermore, since the base of this system has the most influence on the response, special care was taken in developing this section of the model (Close up and exploded views of the base of the system are shown in Figure 5). In the initial simulations, each of the three bolt-washers-nut assemblies was modeled with a simple spring that applies the appropriate clamping force between the two flanges. From these initial simulations, it was found that the correct response of the system could not be fully captured without detailed modeling of bolts, washers, and nuts. The geometry of the bolts and the contact between the flanges and the bolt-washers-nut assemblies have a significant influence on the impact force and could not be neglected. Consequently a detailed bolt-washer-nut assembly was incorporated in the model. This detail improved the behavior of the model at the cost of increased computation time.

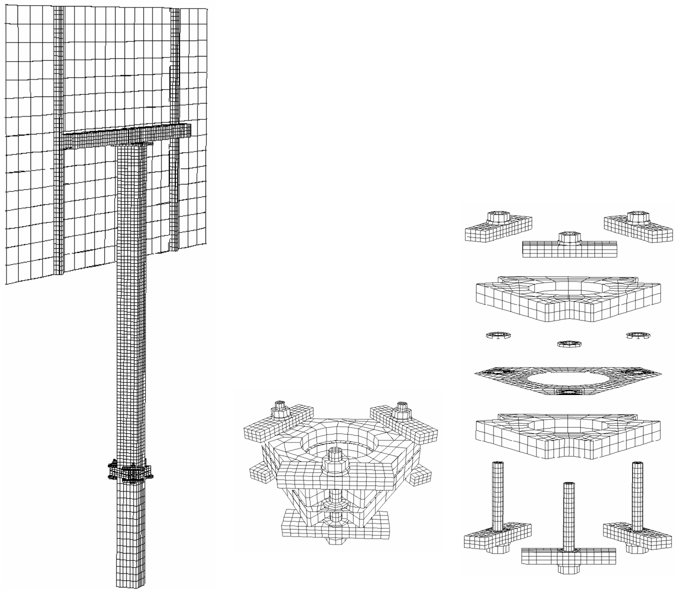


Figure 5. Finite Element Model of the 8"x8" Slipbase Model.

Table 1. The 8"x8" Slipbase Model Information.

Number of Parts	25
Number of Nodes	11,043
Number of Beam Elements	332
Number of Shell Elements	5,573
Number of Solid Elements	3,156

To reduce the computation time without sacrificing the accuracy of the model, some of the small components in the base of the slipbase system were assigned rigid material properties. Using rigid materials for these components reduces their solution time since the calculation of their stresses and strains are avoided. Furthermore, larger time step can be used for the simulation, since these small components would control the time step of the model. A disadvantage that can arise when using rigid materials is contact instability. When two rigid components come in contact, high forces are developed between these components and can lead to unrealistic behavior. This problem is avoided in this model by ensuring that no two rigid parts come in contact. This is achieved by setting the bolt shafts, the flanges, and the keeper plate as flexible components.

An important feature in the slipbase system is the clamping force between the upper and lower flanges, which is applied through three corner bolts. The clamping force primarily controls the impact response of the slipbase system hence it has to be represented very accurately in the model. Since it is not practical to model the threads in the bolts and nuts, their effects are represented by nonlinear springs. The bolts and nuts in the model are created with the correct geometry but without the threads (the bolt slides freely inside the nut). The nonlinear springs are connected between the bolt heads and the nuts. The properties of the nonlinear springs are defined such that their tensile/compression behaviors reproduce that of the actual bolts. For each of the three bolts, four springs were used to ensure symmetry of the applied forces. The initial clamping force in the bolts is achieved by pre-tensioning the nonlinear springs; i.e. giving each of the four springs one fourth of the clamping force at the start of the simulation. To ensure that the system is in equilibrium at the start of the simulation, a process known as dynamic relaxation is utilized.

The contacts between the different components in the slipbase system are modeled using two types of sliding interfaces: surface to surface and nodes to surface interfaces. The surface to surface interface is used for the majority of the contacts. This interface is based on a penalty method. When two surfaces come in contact, equal and opposite forces are applied to the two surfaces to keep them from penetrating each other. Coulomb friction can be used with this interface by defining the static and dynamic coefficients of friction. The second type of interface used in this model is a node impacting surface interface. This is used between the keeper plate and the bolt shafts. This interface is similar to the surface to surface interface except that only the nodes of the slave side (in this case the keeper plate) are checked against the master surface (the bolts).

All material properties used in the model are obtained from the literature. An isotropic piecewise elastic-plastic material was used for most of the slipbase components. This material model is well suited for most structural steel materials. The parameters needed for this material are the elastic properties (Young's modulus and Poisson's ratio), the yield stress, and the stress-strain relation beyond the yield point. Even though failure can be incorporated in this material model, it has not been used for any of the components of the slipbase except for the keeper plate which is the only component that is expected to fail (rupture or shear) in the system.

The 8"x8" slipbase model was validated against two full-scale tests: a 32 km/hr (20 mph) and a 96 km/hr (60 mph) impacts with the Bogie vehicle [4]. The bolt torque used for these crash tests is 102 N.m (75 lb-ft) resulting in a bolt pre-tension force of 26,700 N (6,000 lb). The same clamping force is used in the simulations. Figure 6 show the comparison between the simulation results and the full-scale test data for the 32 km/hr (20 mph) impacts. Figure 7 shows the simulation and cash test comparisons for the 96 km/hr (60 mph) impact. The Figures include the acceleration, velocity, and displacement time histories of the center of gravity of Bogie. The Figures indicate that the FE model exhibited the correct response of the slipbase system in both impact speeds and therefore the model is valid.

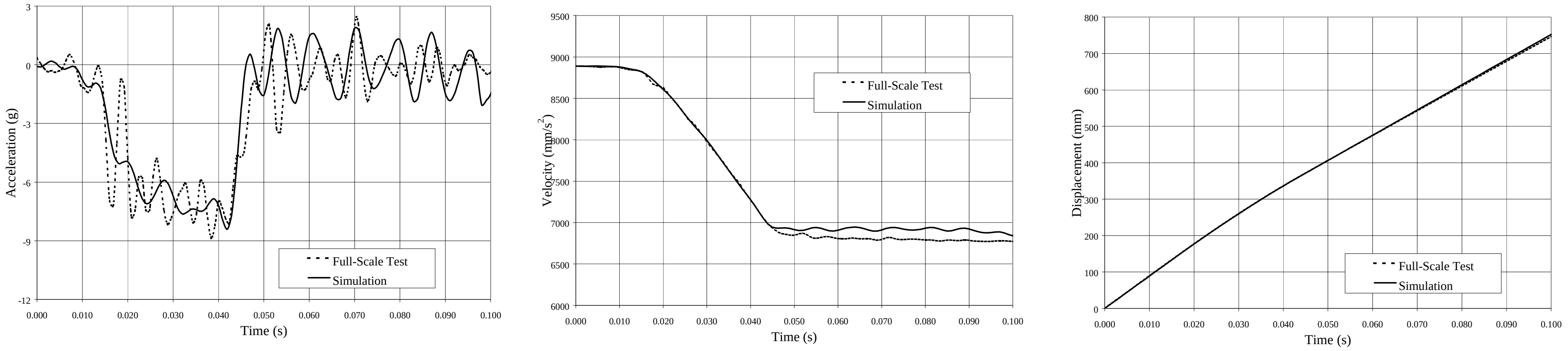


Figure 6. Full-scale Test and Simulation Comparisons: Bogie – 8"x8" Slipbase – 32 km/hr.

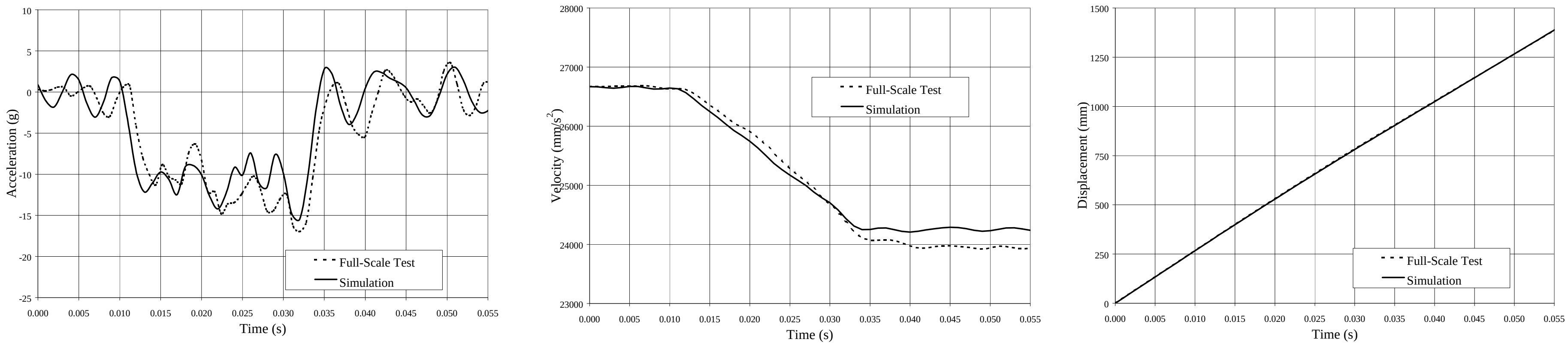


Figure 7. Full-scale Test and Simulation Comparisons: Bogie – 8"x8" Slipbase – 96 km/hr.

3"x3" SLIPBASE PREDICTION

Once the 8"x8" slipbase model was validated, a model of the 3"x3" slipbase system was developed using the same methodology. Figure 8 shows the finite element model of the 3"x3" slipbase system. A list of the model composition is presented in Table 2. This model was used to predict the behavior of the system when impacted with Bogie at 32 km/hr (20 mph) and 96 km/hr (60 mph). The results from the simulation were compared to full-scale tests that were performed after the simulations. The comparisons are shown in Figure 9 and Figure 10. The Figures show that the simulation results correlate well with the full-scale test. It can be concluded from these comparisons that the model correctly predicted the behavior of the modified slipbase model in different speed crashes. This adds fidelity and trust to the methodology used in developing the slipbase models.

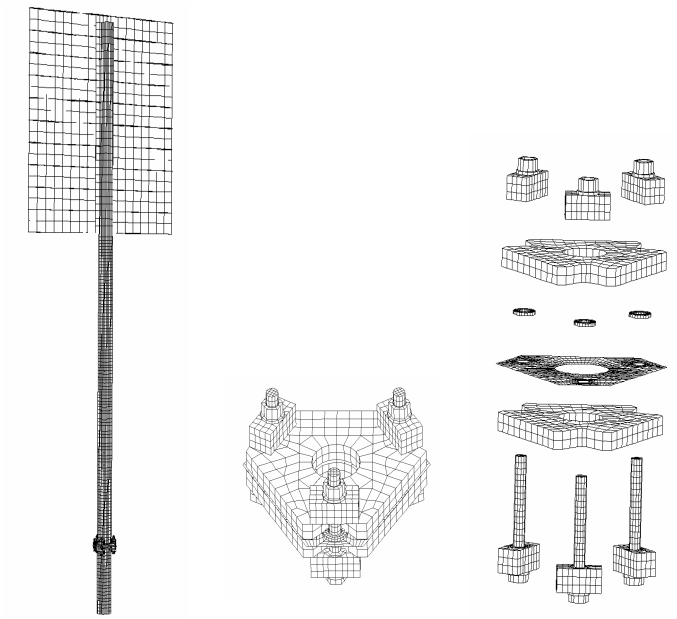


Figure 8. Finite Element Model of the 8"x8" Slipbase Model.

Table 2. The 3"x3" Slipbase Model Information.

Number of Parts	21
Number of Nodes	9,096
Number of Beam Elements	111
Number of Shell Elements	4,645
Number of Solid Elements	2,680

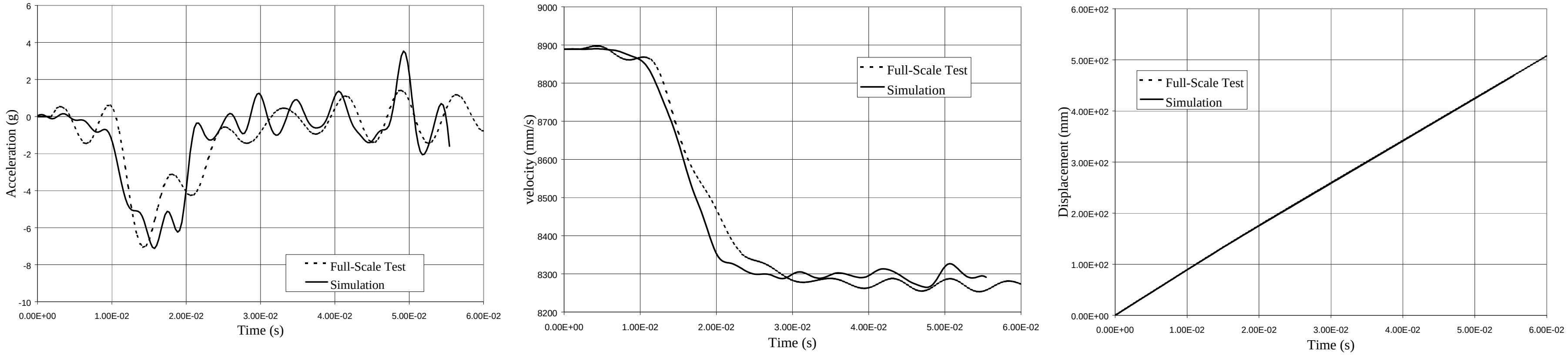


Figure 9. Full-scale Test and Simulation Comparisons: Bogie – 3"x3" Slipbase – 32 km/hr.

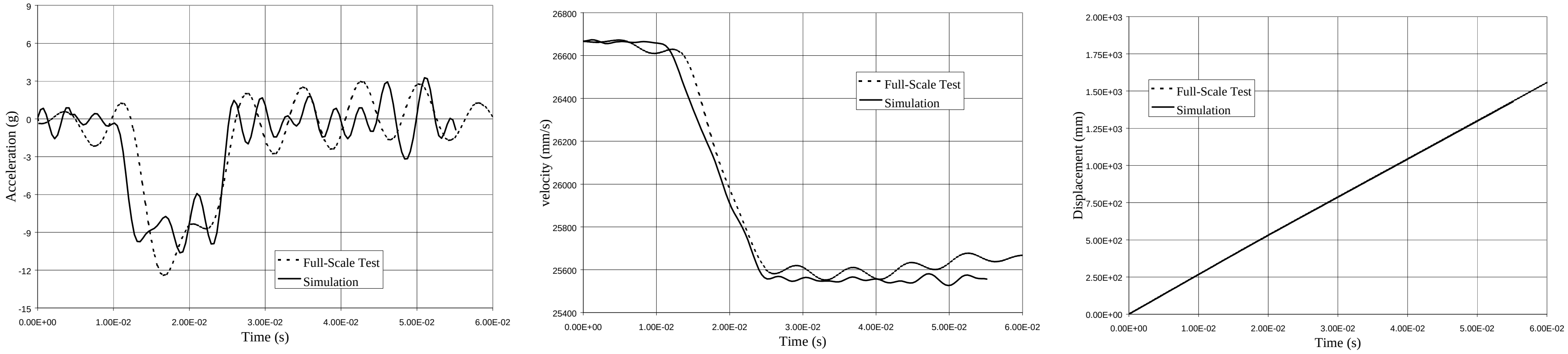


Figure 10. Full-scale Test and Simulation Comparisons: Bogie – 3"x3" Slipbase – 96 km/hr.

PARAMETRIC STUDY

A simple parametric study was conducted to evaluate the performance of the 3"x3" slipbase system. The objective of this study was to determine the maximum clamping force that can be applied to the slipbase system without causing it to fail the NCHRP 350 safety criteria. The 3"x3" slipbase finite element model was used for the study. The clamping force was varied and the velocity of Bogie was monitored. The results showed that an increase in clamping force leads to a higher change in velocity (lower exit speed), which was expected. However, this change in velocity was small as compared to previous slipbase designs. It was found that even if the clamping force was increased to a value that would cause the slipbase bolts to yield it would still pass the safety criteria. Also, the necessary force to cause the 3"x3" slipbase to fail the safety criteria is ten times higher than the recommended clamping force.

Further research is being conducted to analyze other parameters in the slipbase system to investigate other impact scenarios. These parameters include the impact angle and impact location. The possibility of slipbase system lock-up as a result of variation of these parameters will be investigated.

CONCLUSIONS

A finite element model of an 8"x8" slipbase design was developed and validated against full-scale crash tests. After validation, the method used in creating this slipbase model was used to develop a modified 3"x3" slipbase model. The new model was used to predict the behavior of the 3"x3" slipbase system in an impact with the bogie vehicle. Subsequently conducted full-sale tests on the 3"x3" slipbase system were compared to the predicted response. The comparison showed that the model correctly predicted the behavior of the actual system. The model was then used to perform some parametric studies to evaluate the effect of the clamping force on the new slipbase design. It was found that the new design is less sensitive to the clamping forces. High clamping forces can be applied to the system without causing it to fail the safety criteria. Further research is being conducted to evaluate the design in different crash scenarios.

ACKNOWLEDGEMENT

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