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# ESTIMATION OF VEHICULAR COLLISION FORCE FOR BRIDGE COLUMNS USING COMPUTATIONAL MODELS

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Although not commonly occurring, collisions of heavy vehicles with highway overpass bridge columns have happened in the past and resulted in catastrophic structural failures that paralyze traffic on both the overpass and the highway below. A study that was conducted at South Dakota State University performed risk assessment and developed mitigation strategy for vehicular collision with bridge columns on South Dakota interstate highways. Since the collision force is dependent upon the stiffness of the structure and the approach speed of the crashing truck, a finite element (FE) dynamic analysis was performed in the study to evaluate the collision forces resulting from two different truck sizes crashing into a prototype bridge bent at three different approach speeds (55 mph, 65 mph, 75 mph). This paper covers the FE simulation that was performed using computer software. The results indicate that the 600-kip vehicular collision force specified by AASHTO is a reasonable estimate for the load demand induced by an 80,000 lb. tractor-trailer crashing into a bridge column at an approach speed not exceeding 55 mph.

*Keywords*: Bridge piers, Extreme loads, Tractor-trailer, Finite element model.

## 1 INTRODUCTION

AASHTO-LRFD Bridge Design Specifications (AASHTO 2012) require unprotected bridge columns to be designed for 600-kip lateral collision force applied at 5 feet above the road surface. The collision force represents the impact resulting from a run-off-the-road heavy vehicle. The majority of overpass bridges on South Dakota interstates and other major highways were designed and constructed prior to the development of the design requirements for collision load. In a study conducted at South Dakota State University, a risk assessment was performed and a mitigation strategy was developed for vehicular collision with bridge columns on South Dakota interstate highways (Xiao *et al.* 2016, Wehbe and Tigges 2014). The study included laboratory testing of one as-built and one retrofitted 1/3-scale specimens of a prototype bridge bent. The as-built specimen failed at less than one-half the design collision force while the retrofitted specimen was capable of resisting 1.5 times the design collision force (Wehbe and Tigges 2014).

The 600-kip vehicular collision force specified by AASHTO (2012) is based on recommendations by Buth *et al.* (2010, 2011) who performed finite element (FE) simulation and full-scale testing of an 80-kip tractor-trailer crashing into a concrete column. Many researchers have used finite element (FE) simulation to determine collision forces on bridge piers and crash barriers resulting from truck crashes (Buth *et al.* 2010, El-Tawil *et al.* 2005).

## 2 OBJECTIVE AND SCOPE

Since the collision force is dependent upon the stiffness of the structure and the approach speed of the crashing truck, FE analysis was performed to assess the suitability of the AASHTO collision force to bridges in South Dakota. The analysis was performed to determine the collision forces resulting from two different truck sizes (15,000 lb. and 80,000 lb.) crashing into a prototype bridge bent (described below) at three different approach speeds (55 mph, 65 mph, 75 mph). The FE simulation was performed using the computer software LS-DYNA (LSTC 2013).

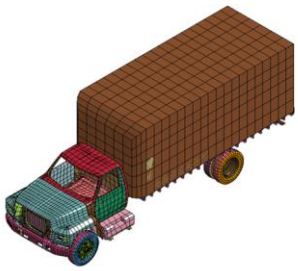
## 3 THE PROTOTYPE BRIDGE BENT

The prioritization analysis (Xiao *et al*. 2016) indicated that the two-circular column bent type represented the vast majority of the structurally inadequate bents in the high-risk collision pool. The research team selected one of the high-risk two-circular column bents as the prototype structure for experimental investigation (Wehbe and Tigges 2014). A view of the prototype bridge is shown in Figure 1. The bridge superstructure consisted of a concrete deck supported by four steel plate girders. The girders were supported at the bent cap by roller supports, with two girders located between the columns and one girder located at each bent cap overhang. Each column was 27 in. in diameter and was reinforced with ten #11 longitudinal bars and #4 spiral at 2 in. pitch. The bent cap was 36 in. deep, 30 in. wide, and 372 in. long, and was reinforced with six #11 top and six #11 bottom bars. The shear reinforcement consisted of two #5 overlapping ties spaced at 9 in. in the column region and at 12 in. elsewhere. The clear cover for the columns and the bent cap was 2 in. Each column was supported by a 36 in. deep by 99 in. square footing that was supported by nine piles. The footing was reinforced with eight #8 bottom bars in each direction. The specified yield strength of the steel reinforcement was 50 ksi and the specified concrete strength was 4.0 ksi.

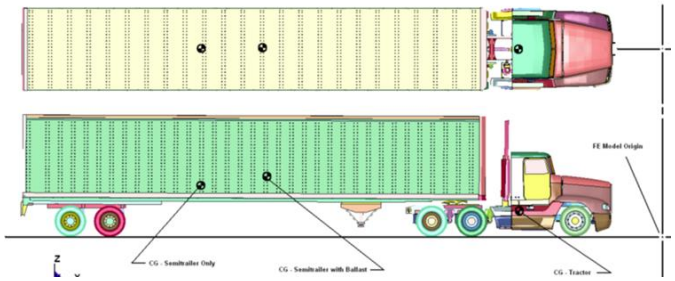
Figure 1. The prototype bridge.

## 4 THE FINITE ELEMENT MODEL

Two vehicle models were used in the FE analysis, the 15,000 lb. Single Unit Truck (SUT) and the 80,000 lb. Tractor-Trailer (TT). The FE models for the two vehicles were developed at George Washington University and were downloaded from the National Crash Analysis Center website (www.ncac.gwu.edu). Figure 2 shows the FE models for the SUT and the TT vehicles. The models take into account the stiffness of the engine block and drive train parts. The SUT model represents a medium-weight vehicle, while the TT model corresponds to the truck size for which the AASHTO vehicle collision force was developed.



(a) 15,000 lb SUT




(b) 80,000 lb TT

Figure 2. Vehicle FE models.

In this study, MAT_CSCM_CONC (MAT 159 in LS-DYNA) was selected to model the concrete material since it factors in the effect of strain rate on the performance of the concrete and can model concrete in tension and compression based on strain limits. The failure criteria were set to erode the concrete at 6% compressive strain. The unconfined compressive strength was set at 4.0 ksi. The strain at concrete strength and the crushing strain were set at 0.0022 in/in and 0.0047 in/in, respectively. The reinforcing steel material was modeled using MAT_PIECEWISE_LINEAR_PLASTICITY (MAT 24 in LS-DYNA). This material incorporates the effects of the strain rate and can model the inelastic behavior of steel after yielding. Steel Grade 50 with modulus of elasticity of 29,000 ksi and ultimate stress of 64 ksi was used to model the material for all of steel reinforcement. The strain at the beginning of strain hardening and at ultimate strain were set at 0.0017 in/in and 0.17 in/in, respectively.

Fully integrated solid elements were used to model all concrete members. An AUTOMATIC_SURFACE_TO_SURFACE contact was assigned between all of the concrete elements. The Lagrangian coupling method was used to model the contact between the steel bars and the concrete. The translational and rotational degrees of freedom at the footings were restrained since the footings were supported by piles.

## 5 SIMULATION CASES AND RESULTS

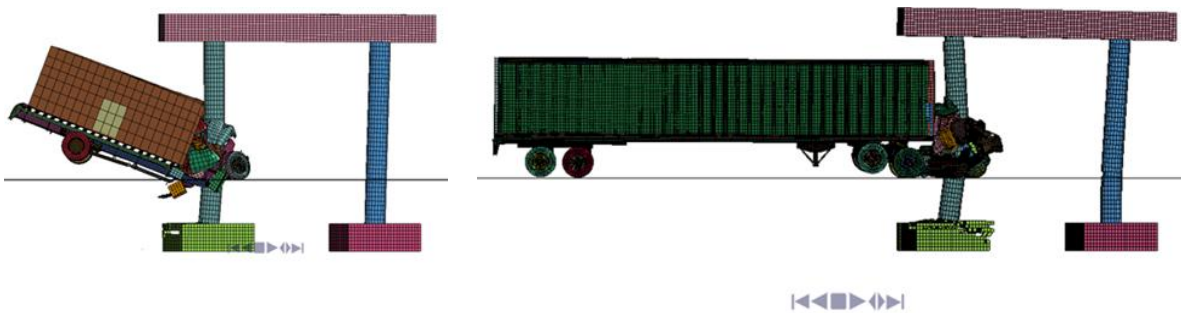
Finite element dynamic analysis was performed for the SUT and the TT truck models. AASHTO (2012) specifies an approach angle between 0° and 15° to the direction of traffic. The approach angle was set at 15° since it resulted in the most critical loading condition. The truck placement was configured such that the impact with the column was at 5 feet above ground level. For each truck, dynamic analysis was conducted at speeds of 55 mph, 65 mph, and 75 mph. The total simulation time was set to 200 ms and 300 ms for the SUT model and the TT model, respectively, in order to capture the significant collision events and optimize the computer program run time. Figure 3 shows computer-generated images of the trucks after impact at 55 mph.

For each run, the collision dynamic force was plotted versus the time after initial contact. The collision dynamic force is defined as the force corresponding to 1 ms moving average. Figure 4 show the collision dynamic force at approach speeds of 55 mph, 65 mph, and 75 mph versus time after initial impact for the SUT and the TT models, respectively.

The peaks in Figure 4 correspond to the impact of the engine block with the column. For the SUT simulation, the peak collision dynamic forces were 1,229 kips, 1,988 kips, and 2,312 kips at approach speeds of 55 mph, 65 mph, and 75 mph, respectively. For the TT simulation, the peak collision dynamic forces were 2,359 kips, 3,384 kips, and 3,433 kips at approach speeds of 55 mph, 65 mph, and 75 mph, respectively. The results indicate that higher approach speeds result

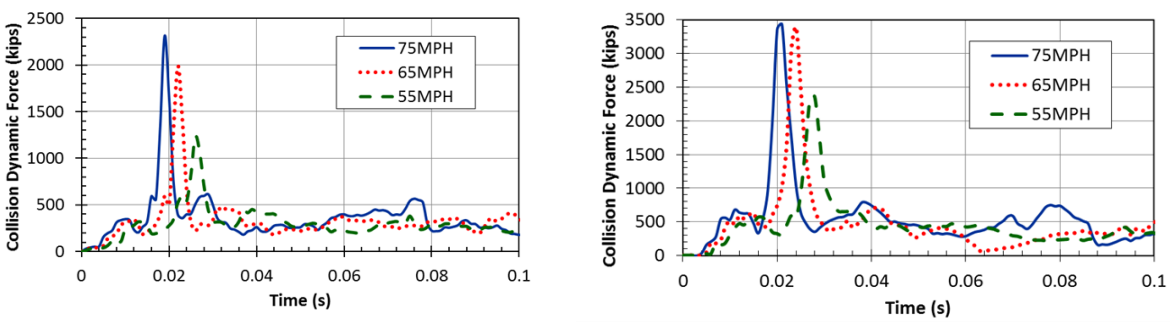
in higher peak collision dynamic forces but the rate of increase in the peak collision dynamic force reduces with increased speed. The results also indicate that the TT vehicle induced significantly higher peak collision dynamic forces than the SUT vehicle. At 55 mph approach speed, the peak dynamic collision force induced by the TT vehicle was almost twice that of the SUT vehicle.

The peak collision dynamic force is a short-duration event that does not allow sufficient time for the structure to respond in proportion to the applied force magnitude. Thus, the peak collision dynamic force should not be used for determining the load demand on a structure. In this study the collision force was determined at 1 ms, 10 ms, and 50 ms moving averages. Figure 5 shows the results for the SUT and TT vehicles.



(a) SUT after Impact (b) TT after Impact

Figure 3. Trucks after impact – approach speed = 55 mph.




(a) SUT Simulation (b) TT Simulation

Figure 4. Collision dynamic force.

The 50 ms moving average method has been considered by researchers for determining equivalent static collision forces on bridge piers (Buth *et al.* 2010, El-Tawil *et al.* 2005). For comparison, the peak forces at 1 ms and 50 ms moving averages are plotted in Figure 6. Also shown on the plots are lines representing the AASHTO 600-kip vehicle collision force and the lateral load capacity obtained from the experimental work (Wehbe and Tigges 2014). Based on the 50 ms peak force, the results indicate that the AASHTO 600-kip design force would be adequate for the SUT vehicle at all approach speeds, but would be adequate for the TT vehicle only at or below an approach speed of 55 mph. At 55 mph, the 50 ms peak force for the TT case is 585 kips, or 97.5% of the AASHTO vehicular collision force. For speeds higher than 55 mph, the 50 ms peak load exceeds the AASHTO vehicular collision force. Since the AASHTO vehicular collision force was based on the load imparted by an 80,000 lb. truck-trailer traveling at

an approach speed of 50 mph, it can be concluded that a collision static design load of 600 kips is reasonable for the prototype bent considered in this study.

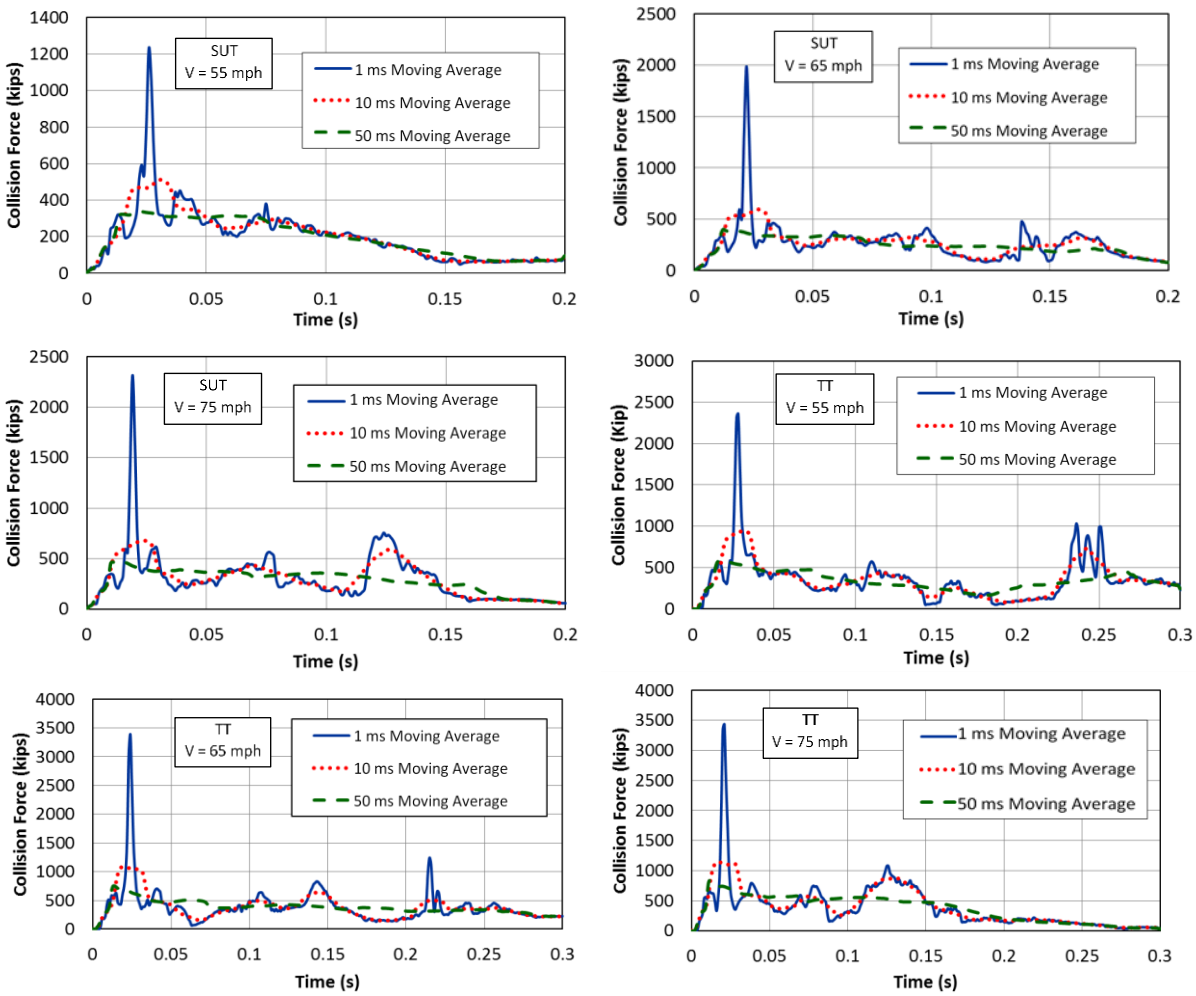
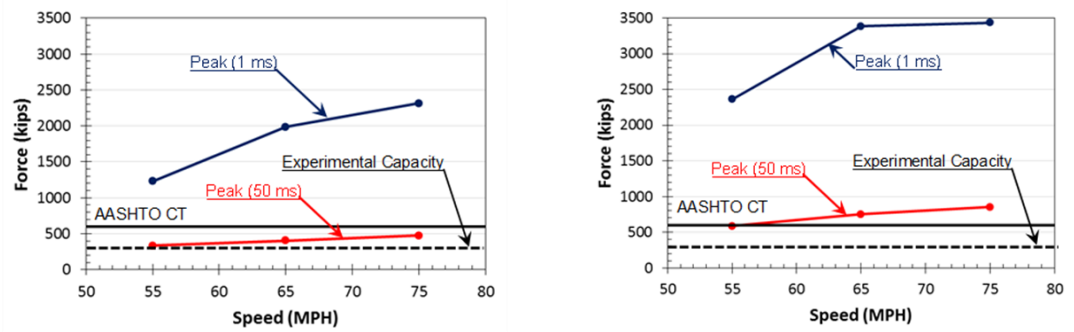



Figure 5. 1 ms, 10 ms, and 50 ms Moving average collision force.




(a) SUT Simulation (b) TT Simulation

Figure 6. Bond failure in a horizontal skew specimen.

## 6 CONCLUSIONS

The finite element dynamic analysis performed in this study showed that for the prototype bridge considered in the analysis, the 600-kip vehicle collision force specified by AASHTO is a reasonable estimate for the load demand induced by the collision with the bridge column of an 80,000 lb. tractor-trailer travelling at 55 mph. At higher approach speeds, the computed collision force exceeded the AASHTO-specified collision force.

**Acknowledgments**

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