Vulnerability of Bridge Piers to Impact by Heavy Vehicles

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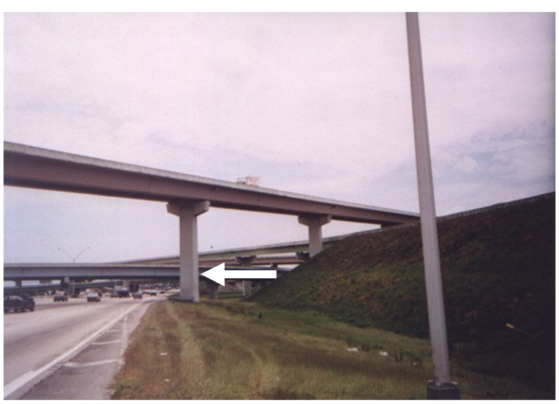
Abstract

My talk presents work undertaken to investigate the effects of vehicle collision on bridge piers. Inelastic transient finite element simulations are used to investigate the structural demands on bridge piers generated during such events, which have occurred in the past, sometimes with catastrophic consequences. Two different types of trucks and two different bridge/pier systems are used in the simulations. The approach speeds for the trucks range from 55 to 135 kph. Various quantities of interest are extracted from the finite element results and used to develop a better understanding of the vehicle/pier crash process and to critique current specifications addressing such events.

Introduction

Imagine the following scenario. The driver of heavy truck loses control of his rig and it veers to impact one of the columns supporting an overhead bridge (as in Figure 1, for example), bringing down the superstructure. Such an event can have serious implications in terms of loss of human lives and damage to the transportation system and economy. While relatively rare, catastrophic vehicle/pier collisions have actually occurred several times already. One such incident took place on 1:35 a.m. on May 19th, 1993 on Interstate 65 in Evergreen, Alabama. A tractor with a bulk-cement-tank semitrailer was driving south on I-65 when it left the paved road, traveled over the embankment, overran a guardrail, and collided with a supporting bridge column of the County Road 22 overpass. Two spans of the overpass collapsed onto the semitrailer and southbound lanes of the interstate. An automobile and another tractor-semitrailer then collided with the collapsed bridge spans killing both drivers. Other similar accidents happened just recently. For example, at 9:00 pm on May 23rd, 2003, a semitrailer crashed into the median support of a bridge crossing I-80 near Big Springs, Nebraska, causing the overpass to collapse. Figure 2 shows the collapsed bridge shortly after impact. One person was killed in the incident, and Memorial Day traffic was severely disrupted on the busy I-80 route



(a) Box girder bridge near Miami, Florida

(b) I-girder bridge in Texas

Figure 1: Bridge piers vulnerable to impact by heavy vehicles.

The parameters influencing vehicle versus structure collisions are at present not well understood, and existing design provisions are deficient. The current AASHTO-LRFD [1] code specifies that bridge piers should be designed for a collision force - represented by a 1800-kN static force if they are unprotected and located within a distance of 10-m to the edge of a roadway. The force is applied in a horizontal plane located 1.35-m above ground and should be applied to the pier in the most critical direction. The provisions suffer from a number of drawbacks including: 1) the design collision force is not specified as a function of the design speed of the adjacent roadway nor the vehicle characteristics, 2) the dynamic interaction between the colliding vehicle and bridge structure is not recognized, nor indeed, even mentioned, and 3) There are no guidelines on how to detail a vulnerable member to ensure that it will perform well in the event of a crash.

This paper discusses work undertaken to investigate the effects of vehicle collision with bridge piers. Both the pier and impacting vehicle are represented using finite element models, and the analyses are conducted using LS-DYNA [2].

Figure 2: Collapse of I-80, Nebraska, bridge after being struck by tractor trailer (courtesy of NDOR)

Analytical Study

Publicly available finite element models of an 11.25-kN Chevy truck and a 66-kN Ford truck are used as the impacting vehicles (models available from http://www.ncac.gwu.edu). These vehicle models and others like them were developed and validated by the Federal Government to be used in crashworthiness exercises and studies such as the one presented herein. Vehicle impact speed is assumed to range from 60-kph to 140-kph, with the 140-kph representing a maximum realistic speed for the vehicles.

Two pier models with different geometric characteristics and heights are used. Pier dimensions were obtained from structural plans of existing vulnerable bridges in Florida. The first pier, hereafter referred to as Pier I, is a reinforced concrete column that has a 1.5-m x 1.58-m cross-section and is 16.30-m high. The pier is attached to a reinforced concrete pile cap with dimensions 5-m x 4-m x 1.67-m that is embedded 2.16-m underground. The superstructure, pier, and cap are supported by twelve 0.45-m diameter prestressed concrete piles of 10-m length. Pier II is also a reinforced concrete pier. It has a circular cross-section of 1.17-m diameter and a height of 9.92-m. It is attached to a reinforced concrete pile cap that is 3.30-m x 2.30-m x 1.17-m in dimension and embedded 0.83-m into the ground. The pile cap is supported on six 0.45-m diameter prestressed concrete piles of 10-m length. Concrete in both piers has a nominal strength of 23 MPa.

The pier and pile cap are represented using fully integrated 8-node brick elements with elastic properties representing uncracked concrete. The superstructure is modeled using beam elements, and is attached to the pier through a spring element, which has the structural properties of elastomeric bearings. The piles rest against the soil through compression-only springs that cannot accept tension forces. The pier/bridge model is comprised of about 25,000 elements.

The truck models are allowed to impact the pier in a head-on manner, transverse to the longitudinal axis of the superstructure. The impact event is simulated for a period of 200 ms, and various quantities of interest are extracted from the finite element results including: impact force versus time relationship, stress and strain values and rates at key points, pier deformations, pile forces, pile cap deformations. The total energy in the system was conserved to within a reasonable tolerance (about 10%), implying that numerical problems were not dominant. Figure 3 shows various views of the model and impact event between the Chevy truck and Pier I.

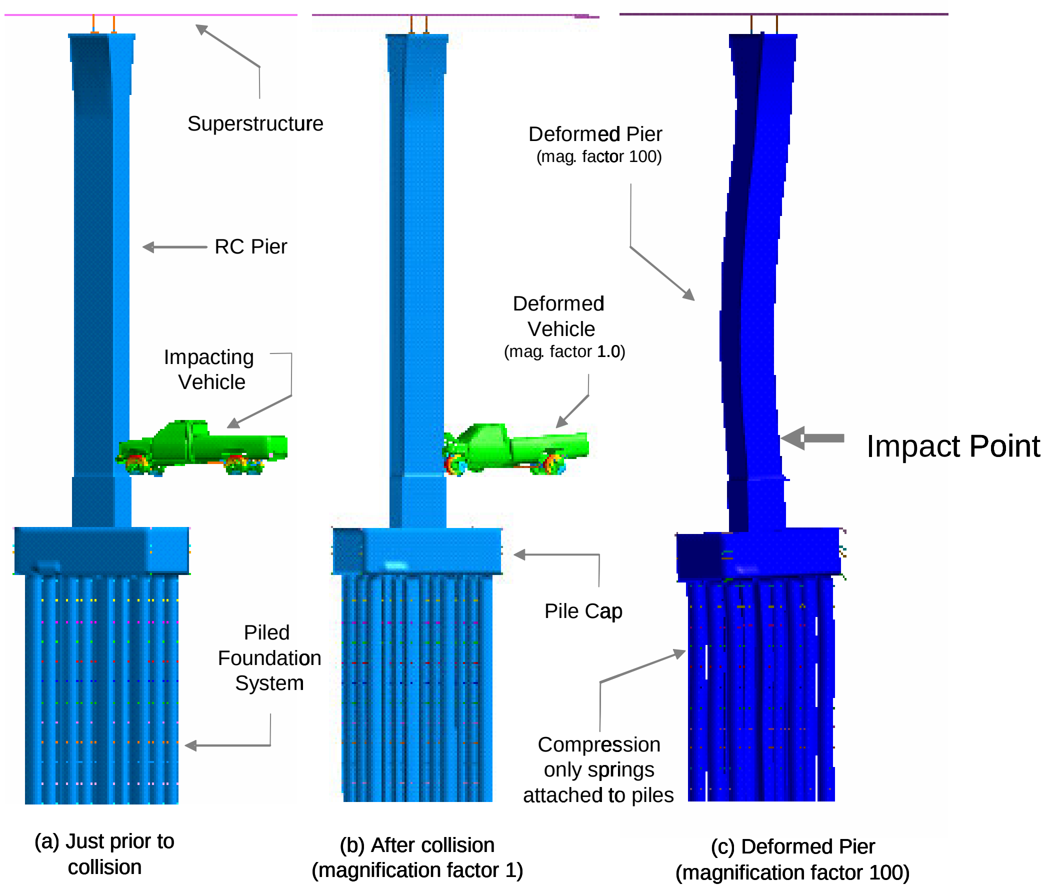
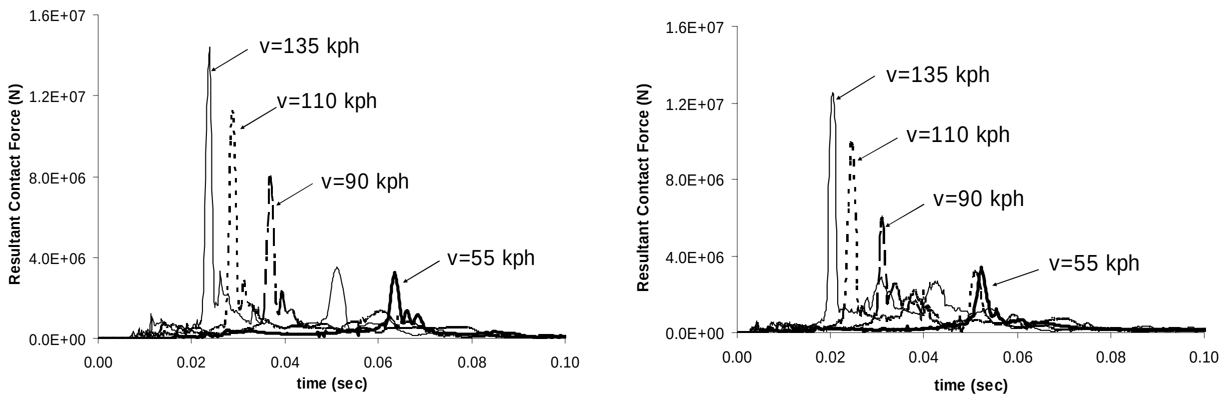


Figure 3: Model representing impact simulation between the Chevy truck and Pier I.

Structural Demands

The force versus time responses generated by transverse impact of the Chevy truck for various approach speeds are shown in Figures 4a and 4b for Piers I and II respectively. Several observations are evident from the figures. The impact force versus time function appears to be comprised of a relatively low force level that is sustained over the duration of the impact event combined with several large spikes. The sharp spikes occur when stiff or heavy components of the vehicle, such as the chassis or engine block, reach the pier and interact with it. As the approach speed increases (Figure 4), the first significant spike occurs earlier in time compared to slower approach speeds, which is expected.



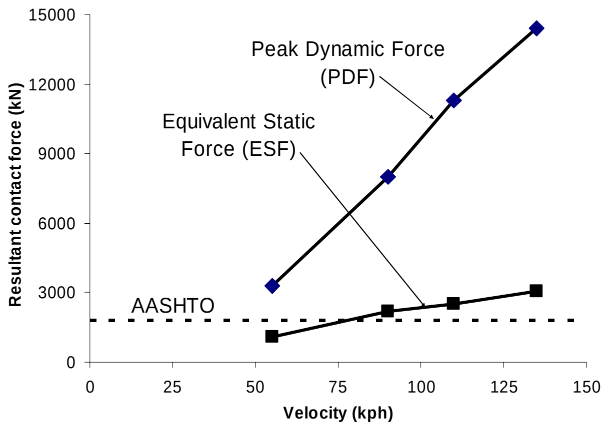
(a) Pier I (b) Pier II

Figure 4: Impact force versus time for Chevy truck at various speeds approaching in transverse direction.

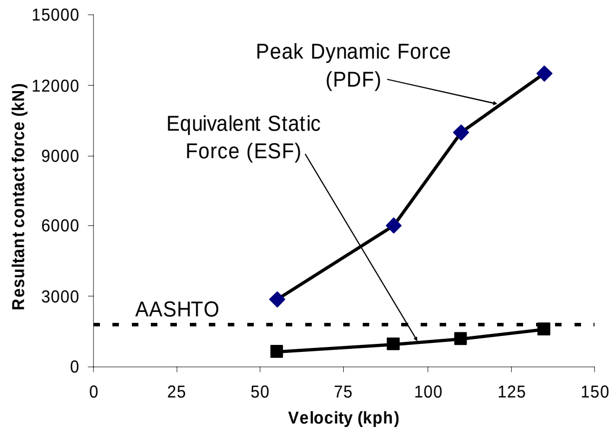
Several force measures are used to characterize each impact event. The peak dynamic force (PDF) is the largest impact force computed during the simulation. The PDF usually occurs early on in a run as shown in Figure 4. The PDF is not representative of the design structural demands that engineers need to consider, because the structure has not had 'time' to respond to the rapid change in loading. According to Chopra (2001), the equivalent static force (ESF) is a more appropriate measure of the design structural demand. The ESF is the static force necessary to produce the same deflection at the point of interest as produced by the dynamic event and is a function of the stiffness of the system and its dynamic characteristics.

It was observed during the research that the PDF is quite dependent on the ratio of hourglass energy to the total energy in the system. In general the PDF grows as the ratio of hourglass energy grows. Hence readers should view the PDF as more of a qualitative number rather than a quantitative measure of demand. Fortunately, the ESF is not as sensitive to this modeling issue.

The PDF and ESF quantities for both trucks are plotted in Figures 5 and 6 along with the AASHTO-LRFD design impact force (1800-kN). Only quantities pertaining to transverse impact (i.e. transverse to the bridge axis) are presented. Parallel impact (i.e. travel parallel to the bridge axis) is an unlikely event, and in any case the forces generated by such a situation do not differ much from transverse impact.

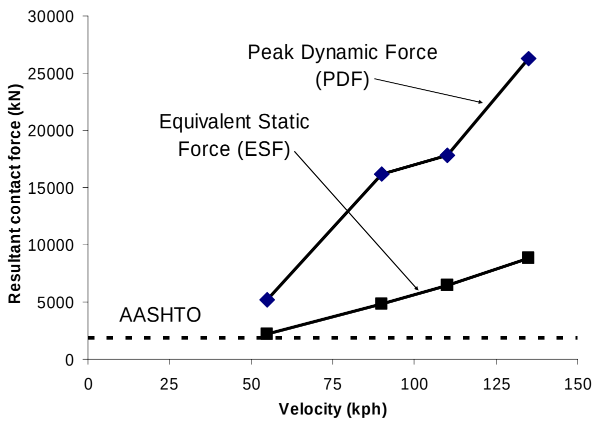


(a) Pier I

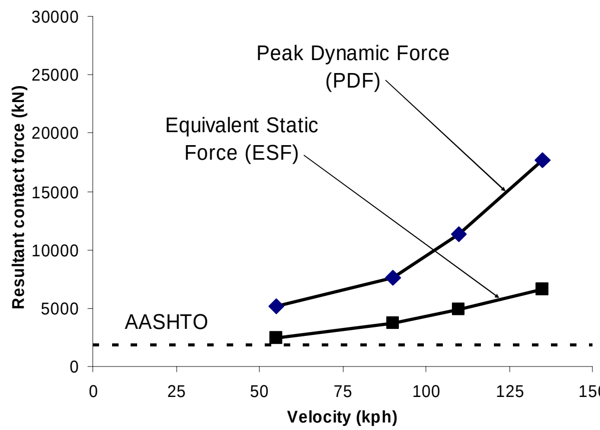


(b) Pier II

Figure 5: Impact force versus approach speed relationship for Chevy truck.



(a) Pier I



(b) Pier II

Figure 6: Impact force versus approach speed relationship for Ford truck.

Analysis of Results

For the Chevy truck (Figure 5), the peak dynamic forces (PDF) for both piers appear to increase almost linearly with increasing vehicle speed. This suggests that the impact process can be basically represented as an impulse. In impulse situations, assuming that the shape of the force versus time relationship remains constant, the peak impact force is a linear function of the momentum of the impacting body. However, the relationship is not as simple for the Ford truck because the PDF versus speed relation is not linear (Figure 6).

The ESF values for both trucks and both piers appear to have a linear relationship to the approach speed. The ESFs and PDFs are smaller for Pier II compared to Pier I. There are two reasons for this. First, Pier I is significantly stiffer at the point of impact compared to Pier II, and hence would attract greater force. Second, the large rectangular cross-section of Pier I (1450 x 1375 mm) mobilizes more of the structural system of the impacting vehicle leading to greater collision forces than the smaller circular section (1075 mm diameter) of Pier II.

The ESFs and PDFs for the Chevy truck are significantly less than the corresponding values for the Ford truck. This is expected given that the latter is about 5 times heavier than the former. However, it is interesting that the PDFs and ESFs for the Ford truck are less than 5 times their counterpart values for the Chevy truck, implying that differences in the relative strength and stiffness of the structural system of both trucks are significant. In other words, the Ford truck is not able to deliver impact forces 'as efficiently' as the Chevy truck.

Concluding Remarks and Ongoing Work

An investigation into the impact behavior of bridge piers has been presented. Two publicly available truck models were considered, a 14-kN Chevy truck (representing lights trucks) and a 66-kN Ford truck (representing medium weight trucks). The truck models were crashed into finite element models of two different bridge piers, and the peak dynamic forces and corresponding equivalent static forces were calculated. Although physical vehicle-pier impact tests were not carried out to verify the accuracy of the simulations, a variety of exercises were conducted to provide confidence in the analysis results. These exercises included: reviewing previously published verification studies involving the 14-kN truck, mesh refinement studies, energy balance audits, monitoring of hourglass control energy during the simulations, and comparison of pertinent results to data from truck/bollard collision tests.

The results of the simulations showed that, in general, the peak transient forces are very high, much higher than the AASHTO-LRFD collision design force. However, since the peak forces act for a short duration, equivalent static forces were computed to serve as a measure of 'design' structural demands during collision. The computed equivalent static forces turned out to be significantly higher than the AASHTO-LRFD design force for a number of simulations.

These results imply that the AASHTO-LRFD design provisions could be unconservative for feasible crash scenarios such as those considered herein. This is disturbing because heavier trucks, such as tractor trailers, could generate even higher demands. It is furthermore troublesome that there are no guidelines on how to detail a vulnerable member to ensure that it will survive (with a specific structural performance in mind) a catastrophic impact situation.

The simulations presented in this paper demonstrate that numerical modeling of this sort could serve as a powerful tool to investigate the vulnerability of specific bridges or to improve general design criteria. The author is currently continuing this research by refining some of the assumptions involved, e.g. modeling the inelastic behavior of the concrete and reinforcement in the piers, using various other vehicles as impactors, and developing design oriented criteria suitable for implementation in specifications.

Acknowledgements

Financial support for this research was provided in part by the Florida Department of Transportation (Project BC-355-6), the National Science Foundation (Project 0334364), and the University of Michigan. The opinions stated here are those of the authors and do not necessarily reflect the views of the sponsors or the individuals mentioned above.

References

AASHTO-LRFD. LRFD Bridge Design Specifications – Second Edition, 1998, American Association of State Highway and Transportation Officials. Washington, DC.

LS-DYNA. Theory Manual. Livermore Software Technology Corporation, 1999.

Chopra, AK. Dynamic of Structures: Theory and Applications to Earthquake Engineering, 2nd Edition, Prentice Hall, 2001.

Zaouk, AK, Bedewi, NE, Kan, CD, Marzoughi, D. Validation of a Non-Linear Finite Element Vehicle Model Using Multiple Impact Data. Crashworthiness and Occupant Protection in Transportation Systems, ASME, 1996, AMD-Vol. 218, pp. 91-106.