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Protecting Critical Civil Infrastructure Against Impact from Commercial Vehicles - Phase I, Year 2

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16. Abstract
Pier columns are often not adequately designed to resist vehicle collisions and blasts. This research aimed to enhance the durability of bridge piers and columns exposed to both vehicle impacts and air blasts. A prototypical bridge pier, including its foundation, was analyzed. Three-dimensional LS-DYNA models were created for circular reinforced concrete (RC) columns and piers, along with their footings and piles. Vehicle impacts were simulated using a Ford F800 truck, while air blasts of varying intensities were modeled. The models were validated using data from previous impact and blast tests. Parametric studies assessed how design variables affected performance, and damage indices were developed by comparing the residual load-bearing capacity of damaged columns to their original strength. Retrofit methods, such as applying FRP wraps and polyurea coatings, were evaluated for their effectiveness in improving blast and impact resistance. The study also involved coordinating with the Nebraska State Patrol (NSP) to acquire information about explosives (TNT) that could be used to simulate or, potentially, complete future air blast tests of structural materials and components. Appropriate data collection methods were selected, and an enhanced impact testing approach using a beam geometry of 10 x 10 x 30 cm was introduced. In lieu of air blast tests, impact tests were conducted to evaluate material behavior under dynamic loading conditions.

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Disclaimer

Abstract

Pier columns are often not adequately designed to resist vehicle collisions and blasts. This research aimed to enhance the durability of bridge piers and columns exposed to both vehicle impacts and air blasts. A prototypical bridge pier, including its foundation, was analyzed. Three-dimensional LS-DYNA models were created for circular reinforced concrete (RC) columns and piers, along with their footings and piles. Vehicle impacts were simulated using a Ford F800 truck, while air blasts of varying intensities were modeled. The models were validated using data from previous impact and blast tests. Parametric studies assessed how design variables affected performance, and damage indices were developed by comparing the residual load-bearing capacity of damaged columns to their original strength. Retrofit methods, such as applying FRP wraps and polyurea coatings, were evaluated for their effectiveness in improving blast and impact resistance.

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Chapter 1 Introduction and Background

Reinforced concrete (RC) columns commonly serve as bridge piers, forming essential substructure units. These piers, especially when positioned near travel lanes, are susceptible to significant damage from vehicle collisions, whether accidental or intentional. The combination of an impact and an air blast can lead to even greater deterioration, potentially causing the collapse of the pier and the entire bridge. Despite this vulnerability, current American Association of State Highway and Transportation Officials (AASHTO) bridge design codes do not specifically address the scenario of vehicle collisions coupled with air blasts. A significant example of this occurred in 2014 on I-65 in Nashville, Tennessee, where a tanker truck collision, followed by an explosion, caused severe damage to the reinforced concrete bridge, as shown in Figure 1.1, resulting in an unsafe condition.

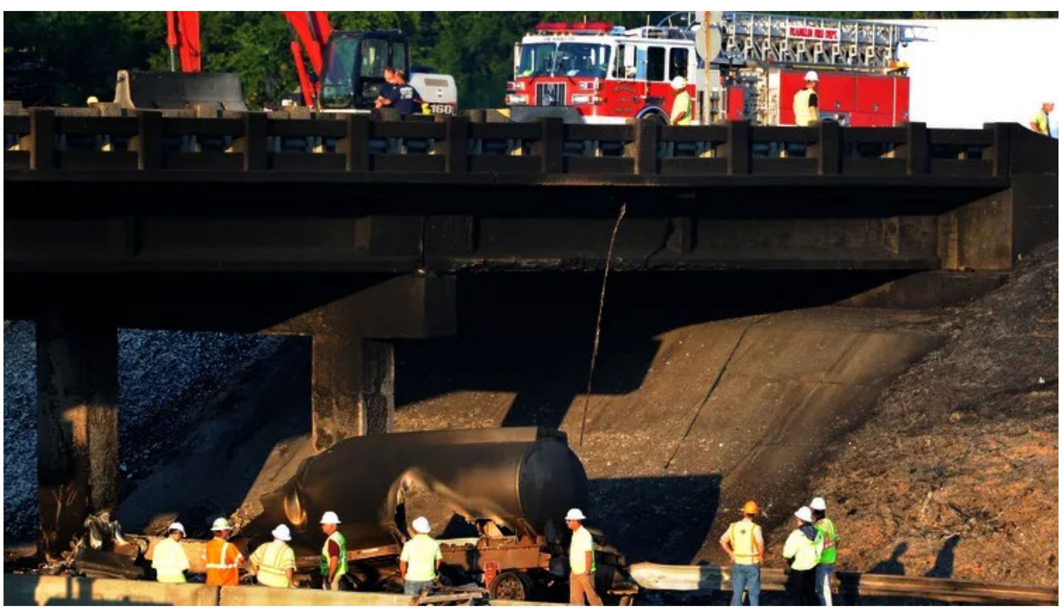

Figure 1.1 Truck explosion on I-65 at the Peytonsville Road bridge [1]

To mitigate the risk of damage from vehicle collisions and air blasts, protective devices like crash barriers, fencing, and bollards are typically employed to prevent direct impact and increase the standoff distance for explosions. However, the placement of these devices around bridge piers is often impractical or economically unfeasible. In such cases, the effectiveness of the protective measures can be severely compromised. Strengthening pier columns and caps with advanced structural detailing and hardening techniques is a potential solution. The current AASHTO LRFD Bridge Design Specifications [2] mandate using an equivalent static force (ESF) to represent vehicle collision loads. However, recent studies suggest that these design loads may inaccurately estimate forces from heavy trucks traveling at high speeds, and multi-hazard scenarios, such as impacts followed by explosions or fires, are not explicitly addressed in the LRFD code.

To address these concerns, research is focused on improving the resilience of bridge piers and columns under extreme dynamic loading conditions, such as vehicle collisions and air blasts. Data will be gathered through simulated blast tests, potentially though actual blast tests, and using impact tests that represent dynamic loading rates that approach those encountered during an air blast to enhance the understanding of the behavior of RC structures under these conditions. Such testing is crucial for ensuring that bridge piers can handle both routine stresses and extraordinary events like collisions and blasts, thereby improving overall infrastructure safety.

1.1 Problem Statement

This research aims to address the following challenges:

1. Research gaps existing in open literature caused by a limited number of published studies that examined bridge pier columns under the combined effects of collision and blast loads, with the goal of parametrizing structural response and damage [3-6].

2. Inadequate resistance of bridge columns to high-speed vehicle collisions combined with air blasts.
3. A lack of valuable data regarding column performance and serviceability during simultaneous collision and blast events, which is crucial for retrofitting existing columns and designing new columns.
4. Inaccurate modeling of the demands on bridge columns subjected to both vehicle collisions and air blasts.
5. A lack of understanding of material response under the effects of air blast loads.

1.2 Objectives

The primary goal of this research is to explore, develop, and recommend retrofitting techniques, as well as analysis and design procedures. Key objectives included:

1. Performing numerical simulations on validated column models for vehicle collisions and air blasts.
2. Conducting parametric studies to assess design and demand parameters affecting pier column response.
3. Developing and evaluating damage mitigation strategies for bridge piers under impact and blast.
4. Testing retrofit methods using CFRP wraps or polyurea coatings to enhance column resistance.
5. Evaluating current AASHTO impact load standards for combined vehicle collisions and air blasts.
6. Better understanding of material response under extreme demands.

Chapter 2 Retrofitting Techniques and Testing Procedures

2.1 Overview

This chapter focuses on developing and recommending retrofitting techniques and design procedures for bridge columns affected by vehicle collisions and air blasts. Key accomplishments included numerical simulations, parametric studies, and damage mitigation evaluations. The research also prepared for potential blast testing with the Nebraska State Patrol (NSP), refined impact testing methods that could be used in lieu of NSP tests, and established data collection procedures.

2.2 Research efforts

2.2.1 Bridge Column Damage Mechanisms and Mitigation

1. Damage mechanisms for bridge columns subjected to combined vehicle collision and air blast were characterized as: (M1) concrete cracking; (M2) concrete spalling; (M3) plastic hinge formation; (M4) shear cracking of the footing; (M5) column shearing; (M6) reinforcing failure; and (M7) shear failure.
2. Damage severity levels for a bridge column subjected to combined vehicle collision were classified in three levels based on the items above: (i) repairable damage; (ii) extensive damage; and (iii) severe damage according to damage effects on column performance.
3. Results from parametric studies, which investigated effects of column diameter, transverse reinforcement spacing, column height, longitudinal reinforcement ratio, and axial load ratio on column response, were examined. Larger and more heavily reinforced columns better resisted the imposed demands subjected to vehicle collision and blast. Column height slightly affected response, and a larger axial load ratio equated to an increased column resistance and capacity to sustain the combined collision-blast load.

4. Numerical studies investigating in-situ FRP and polyurea coating strengthening systems were initiated (see Figure 2.1 and Figure 2.2).

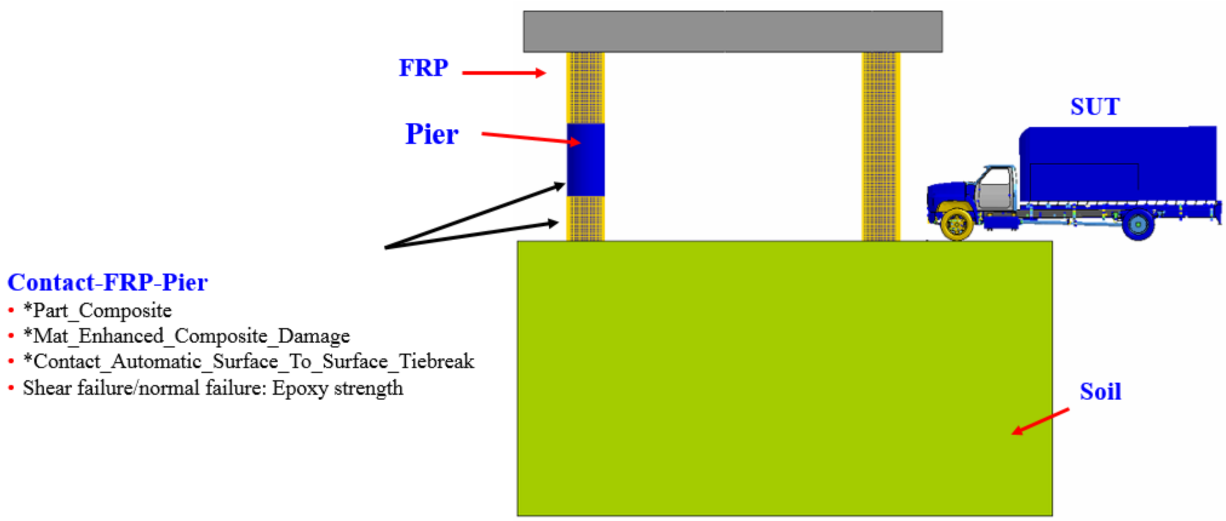

Figure 2.1 FRP-coated pier

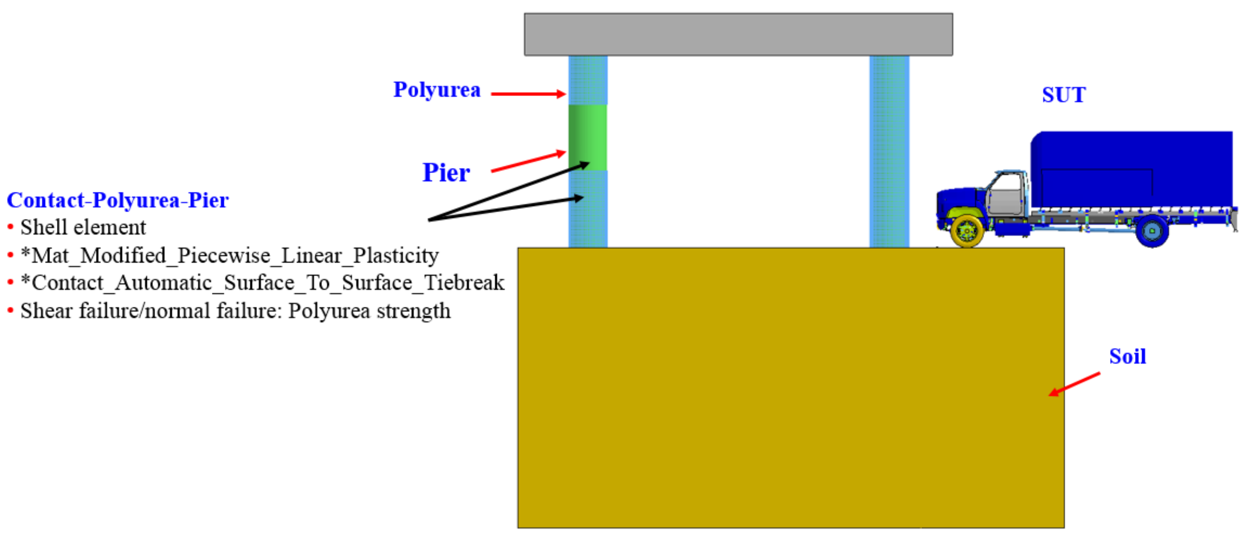

Figure 2.2 Polyurea-coated pier

2.2.2 Blast Testing Protocols and Impact Testing Methodology

1. Initial planning for potential reinforced concrete bare and polyurea coated beam blast testing in collaboration with the NSP was completed and included determining data acquisition methods as follows:
    - Strain gauges on top and bottom reinforcing bars in a representative reinforced concrete structural element will be used.
    - Four gauges for the top and bottom bars (i.e., total eight gauges) will be placed in perpendicular directions (i.e., x-y axis). Originating from the center, the gauges will have a separation distance of 10 cm between them.
    - Two free-field pressure meters will be placed at 15 and 25 meters from the explosion centroid.
    - Images of test specimens before and after the testing will be taken to extract cracking patterns and quantify effects of polyurea coating on blast waves.
2. An enhanced impact testing method using beam specimens was developed and tests conducted. An existing drop tower machine was used to accommodate a new specimen geometry (i.e., 10 × 10 × 30 cm) using the fixture shown in Figure 2.3a. Concrete beam samples were fabricated as shown in Figure 2.3b. Figure 2.3 provides details on impact testing specimens and Figure 2.4 shows the test setup.

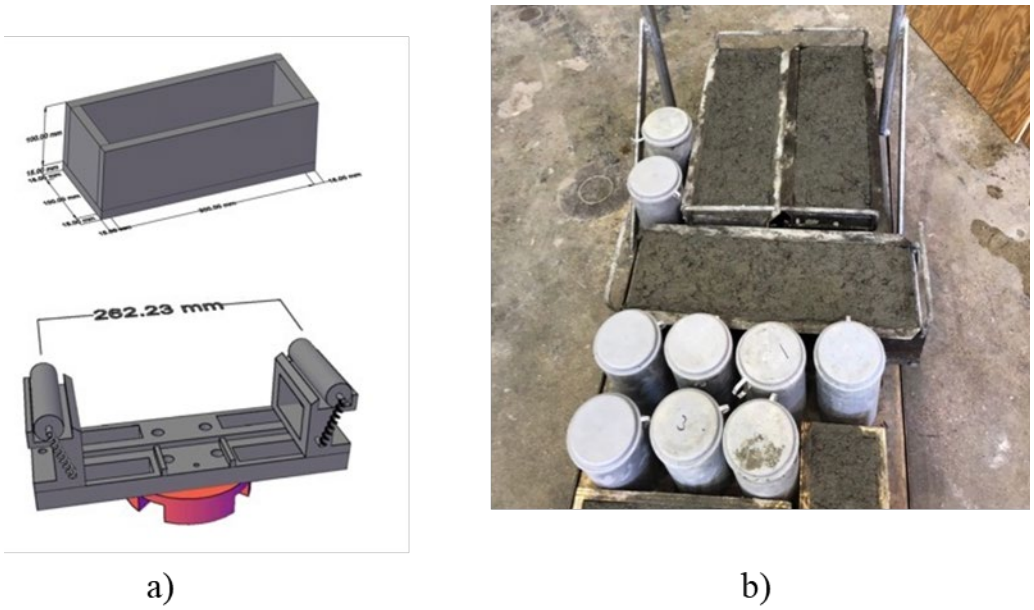

Figure 2.3 Experimental specimens a) mold and b) concrete specimens

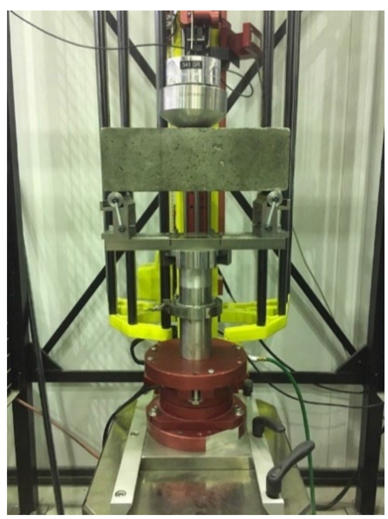

Figure 2.4 Experimental setup

3. Impact testing results (load vs. time) are shown in Figure 2.5. A total of five specimens were tested. Test results were generally quite repeatable, showing similar peak loads and times of failure. It is noted that all tests were conducted using a 4.2 kg mass dropped

from a height of one meter. The span length of the beam testing was set to 26 cm. All specimens fractured at the first impact.

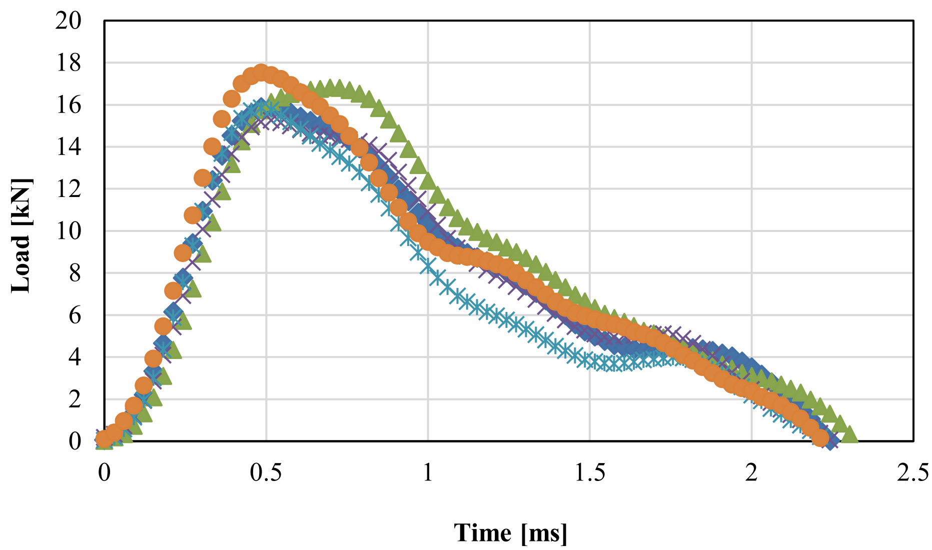

Figure 2.5 Impact test results of five uncoated beam specimens

2.3 Findings

1. Parametric studies showed that larger and more heavily reinforced columns better resisted imposed demands subjected to vehicle collision and blast. Column height slightly affected response, and a larger axial load ratio equated to an increased column resistance against combined collision and blast. Finite element models of fiber reinforced polymer (FRP) wrapped and polyurea coated pier columns in two-column frames were created to evaluate their effectiveness to improve impact and blast resistance.
2. Impact testing on beam specimens can be used to help understand the behavior of bridge piers impacted by heavy vehicles. Relevant properties and constitutive

models, which can provide material inputs for bridge pier modeling, can be determined as a function of impact energy using reduced-scale beam specimens. The effect of polyurea coating to resist and mitigate impact can be characterized by conducting similar tests using polyurea coated specimens.

Chapter 3 Evaluation of CFRP and Polyurea Retrofitting Techniques

3.1 Overview, research efforts

This chapter summaries activities that validated numerical modeling approaches for carbon fiber-reinforced polymer (CFRP) wrapped columns and conducted simulations of multi-column bridge piers retrofitted with CFRP wrap and polyurea coating under vehicle collisions and air blasts. The effectiveness of these retrofitting schemes was evaluated, and key parameters were identified through parametric studies. The accuracy of the AASHTO design impact loads for combined collision and blast scenarios was also initially assessed.

3.2 Findings

1. It was shown that using CFRP wrap and polyurea coating can effectively mitigate the effects of combined vehicle collision and air blast, with effectiveness of each scheme differing as a function of studied geometric and material properties and on imposed demands.
2. For the variables and demands examined, thickness most significantly influenced effectiveness of the CFRP wrap to improve column performance. Limits existed with respect to beneficial effects resulting from a thicker CFRP wrap.
3. The influence of CFRP strength on retrofit effectiveness was largely insignificant for the variable and demands examined.
4. Certain columns retrofitted using CFRP would experience extensive damage at their base due to increased shear demand.
5. For the variables and demands examined, increased polyurea thickness also affected column performance, with the most dramatic benefits being observed for the medium and large thicknesses studied.

6. Wrapping or coating the entire height of columns can effectively mitigate the effects of combined collision and blast. Retrofitting half of a column height offers similar performance if the collision aligned with a pier long axis.
7. For the multi-column piers examined in this study, the effectiveness of a 3 mm thick CFRP wrap was equivalent to 9mm polyurea.
8. Numerical results identified that the peak dynamic forces (PDF) were significantly larger than the AASHTO-LRFD collision design load and could not be used to appropriately predict the demands for bridge column subjected to combined collision and blast. The equivalent static force (ESF) determined from the peak of the 25 ms moving average force was a more acceptable measure of the demand for bridge column during the collision and blast combination.

3.3 Summary

The effectiveness of in-situ retrofit schemes using either CFRP wrap or polyurea coating to improve isolated column performance was examined analytically. CFRP wrap and polyurea coating can effectively mitigate the combined vehicle effects of collision and air blast on bridge columns, with effectiveness of each scheme differing as a function of studied geometric or material properties and on column demand. For the column variables and the demands examined, thickness most significantly influenced the effectiveness of the CFRP wrap or polyurea coating with respect to improving performance. A limit to effectiveness existed, however. For the smaller and medium diameter columns analytically examined (750 mm and 900 mm), the CFRP wrap was shown to be a preferred retrofit scheme. For the large diameter column analytically studied (1050 mm), the CFRP wrap and polyurea coating were shown to have similar effectiveness.

Chapter 4 Impact Load Modeling and Analysis

4.1 Overview, research efforts

This chapter summarizes research that focused on validating numerical models for predicting impact load time histories from combined vehicle collisions and air blasts. The research included simulations of bridge columns under these conditions to obtain impact load time histories, and parametric studies to assess the effects of vehicle velocity, air blast scaled distance, and column dimensions on impact loads. Additionally, peak dynamic and equivalent static forces and evaluated the efficacy of AASHTO design impact loads for bridge columns subjected to these combined events were analyzed.

4.2 Findings

1. Numerical results indicated that impact load time histories included two primary peaks, one from engine block collision and the other from the blast wave. The peak dynamic force (PDF) and equivalent static force (ESF) were controlled by column geometry, vehicle impact velocity, and scaled distance.
2. Peak dynamic forces were significantly larger than the AASHTO-LRFD collision design load for the isolated columns analytically studied.

4.3 Summary

Two load peaks, one for engine block impact into the column and a second for air blast wave impingement onto the column, were observed for the conducted parametric analyses. The applicability of the AASHTO-LRFD design impact load to a combined vehicle collision and air blast event was also examined. An equivalent static force obtained using a 25 ms moving average best represented bridge column impact demand. PDF and ESF differed as a function of column geometry, vehicle velocity, and scaled distance. ESFs were shown to be higher than the AASHTO-

LRFD design collision load for several simulations involving high-speed vehicle collisions and bridge column diameters larger than 1050 mm.

References

1. Tennessean News. *Tennessean News Archive*. 2014 [cited 2012 August 15th]; Available at: https://www.tennessean.com/story/news/local/williamson/2014/08/15/franklin-tanker-explosion-65/14097717/.

2. AASHTO, "*AASHTO LRFD bridge design specifications, eighth edition*." 2017: Washington, DC.

3. Abdelkarim, O.I. and M.A. ElGawady. 2017. "*Performance of bridge piers under vehicle collision.*" Engineering Structures. 140: pp. 337-352.

4. AuYeung, S. and A. Alipour. 2016. "*Evaluation of AASHTO Suggested Design Values for Reinforced Concrete Bridge Piers Under Vehicle Collisions.*" Transportation Research Record: Journal of the Transportation Research Board.(2592): pp. 1-8.

5. Buth, E.C., M.S. Brackin, W.F. Williams, and G.T. Fry, "*Collision loads on bridge piers: phase 2, report of guidelines for designing bridge piers and abutments for vehicle collisions*." 2011, Texas Transportation Institute.

6. Buth, E.C., W.F. Williams, M.S. Brackin, D. Lord, S.R. Geedipally, and A.Y. Abu-Odeh. 2010. "*Analysis of large truck collisions with bridge piers: phase 1. Report of guidelines for designing bridge piers and abutments for vehicle collisions.*" Texas: Texas Transportation Institute.