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A Review on Performance of Circular Reinforced Concrete Bridge Piers Subjected to Vehicular Collisions

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ABSTRACT

The finite element code LS-DYNA is utilized to simulate & analyze the vehicle collisions to obtain accurate & detailed results. The vehicle models offered by the National Crash Analysis Center and the National Transportation Research Center, Inc. are used to conduct this research. The finite element modeling controls & material properties are validated by conducting an impact drop hammer experiment. The bridge pier collision models are validated by compare vehicle damage & impact forces with published research results. Conservation of energy is also checked to oath stability within the impact replication.

Piers with large firmness result in high impact forces, low lateral displacements, & high resistance to shear forces & bending moments. A performance-based analysis shows that bridge piers can be designed using damage ratios associated with particular damage states.

Keyword:-

Collision, vehicle, pier, review, performance-based design

INTRODUCTION

On 22 May 2011 at around 3:00 a.m., a tractor-trailer carrying newspapers and magazines was traveling northbound on I-85 near Gaffney, SC, when it struck the pier of the SC Highway 150 overpass (Kudelka 2011). The force of the collision destroyed the impacted column and half of the bent cap while also damaging the other two columns and resulting in the sagging of the superstructure spans. The destruction caused by the collision is shown in Figure 1.2. I-85 northbound traffic resumed 52 hours following the accident, after the damaged section of the overpass was demolished. Bridge failures due to vehicle collisions have huge economic impacts and can result in the loss of human life. The economic impacts include the cost required to repair or replace the damage to the bridge, vehicles involved, and goods lost. Additional costs are associated with redirecting traffic during the repair work, lost commerce to local businesses due to the disrupted traffic circulation, and remediation due to any environmental damage caused from the accident (Kamaitis 1997). When a bridge is damaged and requires immediate repair, an emergency contract needs to be written up and bids put out with haste to reduce the impact on disrupted traffic. The states departments of transportation finance these projects with states funds that could otherwise be used to improve other government facilities or programs.

LITERATURE REVIEW

Harik et al. (1990) reported the causes of bridge failures in the United States from 1951 to 1988. The 114 failure cases were classified into two categories: complete and partial collapse. Complete collapse consisted of bridges that were no longer able to support their design loads due to loss of a pier, a span, or a major portion of their sub- or superstructure. Partial collapse consisted of bridges that required only partial closure of the bridge. The observed causes of bridge failures were due to vehicle accidents, nature, age of structure, and overweight loading. The majority of the observed vehicle collision failures were due to trucks, ships, and trains.

Wardhana and Hadipriono (2003) repeated the same study as Harik et al. (1990) for the years between 1989 and 2000. Causes of bridge failures during this period included, but were not limited to, hydraulic, collision, overload, deterioration, fire, and earthquake. Of the total 503 bridge failures analyzed during this time period, 59 failures were a result of vehicular collisions; 14 from automobiles and trucks, 10 from barges, ships and tankers, 3 from trains, and 32 from other collision related causes. Vehicular collisions were the third most frequent cause of bridge failure, accounting for nearly 12% of all bridge failures after flood and scour.

Agrawal and Chen (2008) analyzed the causes of over-height vehicle impact events with bridge components for the state of New York from 1998 to 2008. A thorough literature review on the subject was conducted by the authors in order to better understand the key factors that may be implemented to mitigate over-height vehicle collisions with bridge components. It was observed that bridge frames and girders were the most commonly struck element of a structure. Bridge piers accounted for 10% of the 146 observed objects that were struck by vehicles in this study. It was also observed that tractor-trailers and trucks account for 95% of all vehicle impacts with bridges.

Construction equipment has the highest frequency of hitting bridge components. The New York State Department of Transportation assesses the vulnerability of the state's bridges for possible failure modes due to collision through their Bridge Safety Assurance (BSA) program (NYSDOT 1995). According to this program, bridges are classified as having low, medium, or high vulnerability to failure based on the structure having adequate collision protection systems It was observed that bridges with low vulnerability rating accounted for 46% of bridge hit cases. This suggests that even bridges thought to be well protected from vehicle collisions still have a probability of being struck.

Kamaitis (1997) discusses the effects that vehicle collisions with bridges have on society. A major end result of a vehicle-bridge collision is the economic impact that a damaged bridge has on the general public. It is suggested that the main consequences of vehicle bridge collisions are the cost of repairing or replacing the damaged bridge, cost of the damage to the colliding vehicle and any goods that were being carried, cost of injuries or fatalities, cost involved with reorganizing and detouring the traffic during the repair or reconstruction period, local business and social losses due to disruption of the detoured traffic, and the cost of the damage to the surrounding environment. The authors observed that many of the bridges constructed in the 1970's and 1980's no longer met the vertical clearance required by more recent design specifications in 1997; resulting in an increase of over-height vehicle impacts with bridges. It was also suggested that the impacting force caused by the vehicle could be interpreted as a dynamic force as a function of the vehicle mass and speed before and after impact.

Sharma et al. (2012) studied the response of reinforced concrete columns subjected to vehicle collisions and evaluated the amount of damage in them based on the performance of the column after the impact. The behavior of the impacted columns was divided into four damage categories and three performance levels. The damage levels ranged from insignificant damage to total collapse. The performance levels were defined as fully operational with no damage, operational with damage, and collapse prevention. The impact scenarios were ranked as low, moderate, and severe depending on the mass and velocity of the impacting vehicle. The performance-based design aims to improve the behavior of the column to ensure that performance levels are met at varying levels of damage. The finite element code LS-DYNA was used to simulate four different vehicle types impacting a circular reinforced concrete pier.

The dynamic shear force demand on the reinforced concrete column was analyzed, and it was concluded that the dynamic shear force demand increased with vehicle mass and impact velocity. The authors suggest that a hinge is formed at the location of impact when the dynamic shear force velocity exceeds the design shear force capacity, and that the safety of an existing bridge can be evaluated by comparing the design shear force capacity to the calculated dynamic shear force demand that results from an impact.

Murray (2007) developed a concrete material model that could be used during high speed, short duration impact events. The model was a continuous surface cap, elasto-plastic damage material model, with strain rate effects, for concrete that is used with the finite element code LS-DYNA. The material model was developed to represent the concrete in bridge rails and portable barriers subjected to vehicle collisions. The concrete model is capable of modeling strain rate effects, ductile and brittle damage, and stiffness and strength recovery.

Murray et al. (2007) evaluated the elasto-plastic damage material model developed for the finite element code LS-DYNA. The material model was validated by correlating the analysis results with experimental test data. The validation models consisted of drop tower impact of one-third-scale beams, bogie vehicle impact of full- scale reinforced concrete beams, pendulum impact of bridge rails, and quasi-static loading of a safety-shaped barrier. The results of the numerical models accurately matched the results of the experimental tests for most cases and required the adjustment of some of the material parameters in others. The most critical material properties were found to be the facture energies, rate effect on fracture energy, and the maximum principal strain at which erosion occurs. A simplified version of the material model is available that uses default values determined by the mass density, unconfined compressive strength, and maximum aggregate size of the concrete mix. The accuracy of this concrete model was validated by the authors and will be used for conducting research.

Malvar and Crawford (1998) investigated the effect of high strain rates on the yield stress of steel reinforcing bars. It was observed that as the strain rate increases the yield stress of the reinforcing bar increases log-linearly. They proposed a formulation that could be used to determine the dynamic increase factor (DIF), the ratio of dynamic to static yield stress values, for steel reinforcement. The formulation is only valid for bars with yield stress between 290 and 710 MPa and for the range of strain rates between 10^{-4} and 225 s^{-1}. These formulas will be used to model the increase of strength for steel reinforcement bars under dynamic loading.

El-Tawil et al. (2004) investigated the accuracy of using the finite element code LS-DYNA to study vehicle collisions with bridge piers. Two vehicle models were used in this study; the Chevy C-2500 pickup truck and the Ford F800 single-unit truck. These vehicles have been validated for the use of crash analysis simulations and are available through the National Crash Analysis Center (NCAC). The dynamic force time-histories were recorded during the impact simulations with the trucks traveling at impact speeds ranging from 55 to 135 km/h. The results of the impact simulations showed that the computed equivalent static forces generated from the collisions of both vehicles could be greater than the design collision force specified by design standards. This suggests that the design vehicle collision force could have been underestimated substantially by the design specifications.

Tsang and Lam (2008) studied the effects of vehicle impacts with structural reinforced concrete columns and investigated the velocity required for a vehicle of a known mass and type to cause a particular amount of damage in a column. Instead of the traditional strength and strain-based failure criteria, the authors suggest using displacement-based criteria that can be used to estimate the velocity required for a vehicle to cause damage. According to this study, the vehicle acts as a spring by absorbing and defusing the impact energy through crushing and undergoing inelastic deformations. If the vehicle were to act more rigidly, the column would be subject to shear failure characteristics. But since the vehicle is not rigid, the column is susceptible to bending deformations and flexural failure. The study utilizes the law of conservation of energy where the kinetic energy of the moving vehicle is absorbed and dissipated partly through the parts of the vehicle that undergo damage and partly through the flexural bending and formation of a plastic hinge in the column. The total kinetic energy is equal to the amount of energy absorbed through the crushing of the vehicle and deformation of the column.

Mohammed (2011) studied reinforced concrete members under impact loading and how carbon fiber reinforced polymers could be used to rehabilitate aging structures. The finite element code LS-DYNA was utilized to study the response behavior of vehicle collisions with bridge piers and reinforced concrete beams subjected to impact loads. The Chevy C2500 pickup truck and Ford

F800 single-unit truck were used to impact a single hammerhead type pier in the simulations. The impact simulations were validated by comparing the analytical results with rigid wall impact experiment data published by the NCAC to validate the C1500 vehicle model.

Sha and Hao (2013) studied barge impact forces with circular reinforced concrete bridge piers through experimental tests and numerical simulations. The finite element code LS-DYNA was used to create a model of a barge colliding with a single-column bridge pier with a lumped mass on top to represent the mass of the superstructure. A parametric study was conducted to observe the effects of the pier support conditions, barge impact velocity, barge mass, pier diameter, superstructure mass supported by the pier, pier height, and location of impact. The pier support conditions were modeled in three ways: (1) fixed, (2) supported on a rigid pile foundation, and (3) supported on an elastic pile foundation. For the pile-soil-foundation models, the steel piles and soil-pile interactions were represented with beam elements and nonlinear discrete spring elements, respectively. The soil springs were applied in pairs equally spaced along the length and perpendicular to the pile shaft. It was observed that the impact force throughout the collision did not vary based on the support conditions, but the displacement response of the pier was dependent on the support conditions. The authors suggest using a detailed model of the pile foundation to accurately capture the displacement response of the pier subjected to an impact load. The study showed that, as the impact velocity increased, the impact forces and displacements of the pier also increased. It was observed that as the mass of the barge increased the duration of the impact increased, but it did not significantly affect the peak impact force. The diameter of the circular piers had almost no effect on the peak impact force because the area of impact hardly changes with an increase in diameter. This observation does not hold true for rectangular piers due to the increase of contact area with an increase in the cross-sectional area. An increase in the mass of the superstructure was observed to decrease the displacements at the top of the pier and at the location of impact. As the location of the impact moved up along the pier, the bending moment and peak displacement increased.

Conclusion

Overall, the preceding study lays the foundation for future research to be conducted on bridge piers subjected to vehicle collisions. The finite element code LS- DYNA was used to conduct this research. The finite element controls, material properties, and vehicle models have been validated and used with confidence to draw conclusions from the simulations results. The sensitivity analysis showed how increasing structural stiffness causes an increase in peak dynamic impact force, decrease in the lateral displacement of the pier, and an increase in the amount of shear and moment that can be absorbed in the pier. The impact velocity of the vehicle was observed to increase the amount of kinetic energy that had to be absorbed in the pier and vehicle. The higher the impact velocity, the larger the amount of damage caused throughout the pier. A performance-based design approach to constructing bridge piers would allow engineers to design piers to resist a particular amount of damage based on specific impact forces and shear resistance. This design approach had the potential to be more conservative than the design specifications, and can allow for safer and more economical bridge piers.

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