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Performance of bridge piers under vehicle collision

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ABSTRACT

Both the peak dynamic force (PDF) and the equivalent static force (ESF) of a vehicle collision with reinforced concrete bridge columns were examined as part of an extensive finite element (FE) analyses study. An extensive parametric study of 13 parameters, including the concrete material model, the unconfined concrete compressive strength (f'_c), the material strain rate, the percentage of longitudinal reinforcement, the hoop reinforcement, the column span-to-depth ratio, the column diameter, the top boundary conditions, the axial load level, the vehicle's velocity, the vehicle's mass, the roadside distance between errant vehicle and unshielded bridge column, and the soil depth above the top of the column footing was conducted. Three approaches were used to investigate the ESF. The ESF in the first (stiffness-based) approach was defined as the static force producing the same maximum displacement that is produced by a vehicle collision at the point of impact. The ESF examined in the second approach was calculated according to the Eurocode. The ESF studied in the third approach was defined as the Peak of the Twenty-five Milli Second moving Average (PTMSA). The different ESFs were compared to the ESF in the American Association of State Highway and Transportation Officials-Load and Resistance Factor Design (AASHTO-LRFD; 2670 kN [600 kips]). In general, the ESF calculated according to the Eurocode presented the lower bound while those from the stiffness-based approach presented the upper bound. Furthermore, the recommended ESF of the AASHTO-LRFD was found to be non-conservative for heavy and/or high speed vehicle impacts; it was found to be too conservative for light and/or slow vehicle impacts. Hence, rather than a constant design impact force, a variable design impact force should be used. An equation was developed to calculate a design impact force, which is the function in the vehicle's mass and velocity. A simplified equation based on the Eurocode equation of the ESF was proposed. These equations, however, do not require cumbersome FE analyses.

1. Introduction

Vehicle collision with bridges can have serious repercussions with regard to both human life and transportation systems. Collisions often result in either a complete or partial bridge collapse. Many vehicle collision events involving bridge piers were reported throughout the U.S. Surveys concluded that vehicle collision caused approximately 15% of bridge failures in the U.S. making it the highest third cause of bridge failures in the U.S. [1,2]. In 2008, for example, a vehicle weighs 39 tons (80 kips) and moving at a high speed collided with a bridge pier on IH-30 near Mount Pleasant, Texas leading to failure of the bridge [3]. In July of 1994, a tractor-trailer truck carrying liquid propane hit a guardrail, and the cargo tank collided into a column of the Grant Avenue overpass over Interstate 287 in White Plains, New York [4]. Twenty-three people were injured, the driver was killed, and the crash fire extended over a radius of approximately 122 m (400 ft).

2. Background and research significance

The American Association of State Highway and Transportation Officials-Load and Resistance Factor *Bridge Design Specifications 5th edition* (AASHTO-LRFD [5]) mandates that abutments and piers located within a distance of 9.1 m (30 ft) from the roadway edge be designed to allow for a collision load using equivalent static force (ESF) of 1800 kN (400 kips) at a distance of 1200 mm (4.0 ft) above ground. Both the peak dynamic force (PDF) which is the maximum contact force of the vehicle collision with a bridge column and the ESF were evaluated in the literature. The AASHTO-LRFD *5th edition* was found non-conservative in some cases [6,7]. Hence, the ESF was increased to 2670 kN (600 kips) in the latest AASHTO-LRFD *6th edition* [8] at a distance of 1500 mm (5.0 ft) above ground. While the increase in the impact load and moments were very well justified, the quantification of the increase was not.

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Nomenclature

A_c	cross sectional area of the concrete column
A_s	cross-sectional area of the longitudinal steel reinforcements of column
D	column diameter
DIF	dynamic increase factor
DIF_c	compressive strength dynamic increase factor
DIF_t	tensile strength dynamic increase factor
DR_d	dynamic damage ratio
d_s	soil depth above column footing
E	modulus of elasticity
EC_{ESF}	Eurocode equivalent static force
ESF	equivalent static force
FEA	finite element analysis
FE	finite element
f'_c	standard concrete cylindrical compressive strength at 28 days
f_c	concrete dynamic compressive strength at $\dot{\varepsilon}_c$
f_{cs}	concrete static compressive strength at $\dot{\varepsilon}_{sc}$
f_t	concrete dynamic tensile strength at $\dot{\varepsilon}_t$
f_{ts}	concrete static tensile strength at $\dot{\varepsilon}_{st}$
f_y	static yield stress of the longitudinal steel reinforcements
f_{yd}	dynamic steel yield stress
k_s	soil modulus of subgrade reaction
KE	vehicle's kinetic energy
KEB_{ESF}	kinetic energy-based equivalent static force
L_c	roadside distance between errant vehicle and unshielded bridge column
m	vehicle's mass
MB_{ESF}	momentum-based equivalent static force
P	applied axial compressive load on the column
P_m	momentum of the vehicle
P_o	column nominal axial compressive capacity
PDF	peak dynamic force
PTMSA	peak of the twenty-five milli second moving average
SB_{ESF}	stiffness-based equivalent static force
S/D	column span-to-depth ratio
SR	strain rate
SUT	single unit truck
v_r	vehicle's velocity
$\dot{\varepsilon}$	strain rate value s^{-1}
$\dot{\varepsilon}_c$	strain rate of concrete in compression in the range of 30×10^{-6} to $300\ s^{-1}$
$\dot{\varepsilon}_{sc}$	static strain rate of concrete in compression of $30 \times 10^{-6}\ s^{-1}$
$\dot{\varepsilon}_t$	strain rate of concrete in tension in the range of 10^{-6} to $160\ s^{-1}$
$\dot{\varepsilon}_{st}$	static strain rate of concrete in tension of $10^{-6}\ s^{-1}$
ρ_s	column longitudinal reinforcement ratio
ω	fractional dilation parameter of material model Mat72RIII
δ_c	vehicle deformation
δ_d	column deformation

Hence, more research is required to determine vehicle impact load on columns. However, experiments conducted on vehicle collisions with bridge columns are both difficult and expensive. Hence, determining the vehicle impact is quite a challenge. Another option to investigate vehicle collision with bridge columns is to use finite element models. Finite element analysis (FEA) is considered an attractive approach because it is relatively economical, and reliable. However, the development of high fidelity FEA of a collision event requires a combination of vehicle and concrete structure modeling.

Several vehicle models were developed by the National Crash Analysis Center (NCAC) of The George Washington University under a contract with both the Federal Highway Administration (FHWA) and the National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation (DOT). These models were calibrated and readily available to be downloaded and used for crash and impact analysis.

Finite element models for bridge columns under extreme loads such as earthquakes and vehicle impact have been developed [9,14–18]. In such models, a structure response is function in loading time and structure natural period. If the loading duration is lower than a quarter of the structure's natural period, the loading is considered as an impact load. However if the loading duration is larger than four times the structure's natural period, the applied load is considered quasi-static [10].

While developing finite element models, material response is significantly influenced by the applied strain rate. The strain rate is the change in a material's strain with regard to time. A static load typically occurs within a time duration that is greater than 10^4-10^6 s and a strain rate that is less than 10^{-8}–$10^{-6}\ s^{-1}$ [10]. However, the impact load typically occurs within a time duration that is between 10^{-6} and 10^{-4} and a strain rate that is between 10^2 and $10^4\ s^{-1}$.

While experimental work and/or finite element can be used to determine the PDF, another challenge is to deduce the ESF based on PDF. ESF is essential for design of bridge columns. Several approaches have been developed in the literature to deduce ESF based on PDF; however, still no consensus exists among researchers on the best approach to deduce ESF. Three different approaches, developed in the literature, were used during the present study to determine ESF. The ESF in the first approach (stiffness-based ESF: SB_{ESF}) was defined as the static force needed to produce displacement equal to that of the maximum displacement by a collision vehicle at the point of impact [6]. The second approach (Eurocode ESF: EC_{ESF}) is the one recommended by Eurocode-1 [12] to calculate the ESF using the following equations:

$$EC_{ESF} = \frac{KE}{\delta_c + \delta_d} \tag{1}$$

$$KE = \frac{1}{2} m\ v_r^2 \tag{2}$$

where KE is the vehicle's kinetic energy, m is the vehicle's mass, v_r is the vehicle's velocity, δ_c is the vehicle deformation, and δ_d is the column deformation. The δ_c of each vehicle was calculated as the change in length between the vehicle nose and the center of mass according to NCHRP 350 [13]. The center of mass of a vehicle changes when the vehicle's mass changes. The δ_d of each column was calculated as the lateral displacement of the column at the point of impact load. The ESF in the third approach was defined as the Peak of the Twenty-five Milli Second moving Average (PTMSA) of the time-dynamic force relation of the impact load. This approach was referenced from the 50 ms moving average frequently used in automotive crash analyses [7].

In an analogy to the performance based design in earthquake engineering, a damage factor of 2, 5, or >5 for minor, moderate,