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Simplified FE vehicle model for assessing the vulnerability of axially compressed steel columns against vehicle frontal impact

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ABSTRACT

The main objective of this study is to present and validate a simplified numerical vehicle model that can be used to simulate the effects of vehicle frontal impact on steel columns by using the commercial finite element code ABAQUS/Explicit. The simplified numerical vehicle model treats the vehicle as a spring–mass system. This model has in fact already been exploited by other researchers in the preliminary stages of vehicle design and occupant safety assessment. The proposed model consists of three parts: an indeformable body representing the total vehicle mass; a spring or connector with nonlinear force–deformation relationship to represent the dynamic stiffness of the vehicle; and a rigid but weightless plate to generate the contact between the spring–mass system and the impacted column. The dynamic load–deformation characteristic of the spring is assumed to be bilinear: the initial linear elastic part simulating the vehicle deformation until it has reached the vehicle engine box, followed by a near rigid relationship. This concept has been validated by comparison against simulation results of steel columns under different impact velocities, axial load ratios, boundary conditions, and slenderness ratios using the full-scale vehicle model and using the proposed simplified spring–mass model. Having validated the proposed model, this study presents the derivations and validations of an equation to predict the equivalent linear stiffness of the vehicle that can be used either in a future numerical simulation model or in an energy based analytical model.

1. Introduction

Many researchers have used finite element method to simulate vehicle impact on structures. In some of these studies, the vehicle impact was simulated using a time-varying load with an assumed maximum amplitude [1,2]. This approach involves many approximations and uncertainties which affect the level of accuracy achieved in the analysis. For example the impact force time history of the vehicle impact on column cannot be accurately predicted because it depends on a large number of variables including the impact velocity, the impact mass, and the column size. In addition, this approach cannot account for local deformations at the impact point as a result of the contact between the vehicle and the column. Furthermore, the effect of kinetic impact energy on the column behaviour and failure cannot be considered if the vehicle impact is input as an impulsive load.

On the other hand, full-scale finite element models of vehicles have been frequently used to simulate vehicle impact under different impact scenarios to assess vehicle integrity. Full-scale vehicle modelling is necessary because the focus is on vehicle crashworthiness. However, the simulation is demanding, involving a very large number of elements, material nonlinearity, strain rate dependency and very large strains and deformations. For structural engineering applications of vehicle impact on structural members such as the columns of buildings, it is doubtful whether full-scale vehicle modelling is necessary when the focus of the study is on the structural member, not the vehicle. Nevertheless, some numerical studies have been attempted using full-scale numerical vehicle models to assess the design approaches and equations used to investigate vehicle impact on columns and bridge piers under vehicle impact. For example, these studies include numerical study of vehicle impact on concrete bridge piers conducted by El-Tawil [3], numerical study of vehicle impact on light steel pole by Elmarakbi [4] and the numerical study conducted by Ferrer [5] to simulate vehicle impact on underground park steel column. In all these studies, some limitations had to be applied to reduce the simulation effort and time. For example, in these studies, the effects of material nonlinearity and failure of the structure were neglected. These limitations severely restrict applications of such investigations. Furthermore, in many situations, obtaining full-scale model of a particular vehicle type is either not available yet or not accessible to engineers.

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The above discussion leads to the conclusion that there is a need to develop a simplified numerical vehicle model which can be utilized for studying behaviour and failure of structures under vehicle impact. This has already been recognized by others and the following section reviews work already done in this area to identify a method for further development.

Based on experimental study of vehicle frontal collision on rigid barrier, Emori [6] suggested that the undamaged or intact portion of the impacting vehicle may be considered as a rigid body while the crushed portion of the vehicle absorbs all the kinetic energy of the impacting vehicle just before the impact. Therefore, the vehicle impact processes may be modelled by a spring–mass system in which the rigid mass represents the vehicle total mass and the one-way linear spring represents the vehicle resistance. Tani [7] proposed a more sophisticated mathematical model having three masses and three springs simulating the three parts of a vehicle: the engine box, the structure in front of the engine and the frontal structure. The load-deflection characteristics of each spring were determined based on experimental observations. Kamal [8] and Lin [9] proposed further refinements to the previous two models by using eight nonlinear springs with three masses to simulate frontal impact [8] and seven nonlinear springs to simulate rear barrier impact [9].

In the above-mentioned studies, the vehicle impact was against a wide, flat and rigid barrier rather than a deformable structure with limited width such as a column considered in the present study. Nevertheless, the concept of simplifying the vehicle using a spring–mass system is still applicable as long as the spring can capture the dynamic and stiffness characteristics of the impacting vehicle.

Campbell [10] proposed a linear equation to estimate the peak impact force and the energy absorbed by the vehicle in terms of its frontal plastic deformation. A linear force–displacement relationship is proposed based upon full frontal impact on barrier crash at velocities ranging from 24 km/h to 97 km/h. The maximum impact force is given by:

$$F = A + BC \tag{1}$$

Where A and B are the stiffness coefficients of the vehicle and C is the vehicle deformation. Fig. 1 shows an example of impact force–vehicle deformation relationship, in which C_{max} is the maximum deformation of the vehicle. The two main assumptions are that the damage of the vehicle is uniform and the force–deflection relationship does not significantly vary across the vehicle width. A minimum limit of 25% of the vehicle frontal width in contact with the struck object was suggested. Following Campbell's study, many other research studies were conducted to compute the stiffness coefficients A and B in Eq. (1).

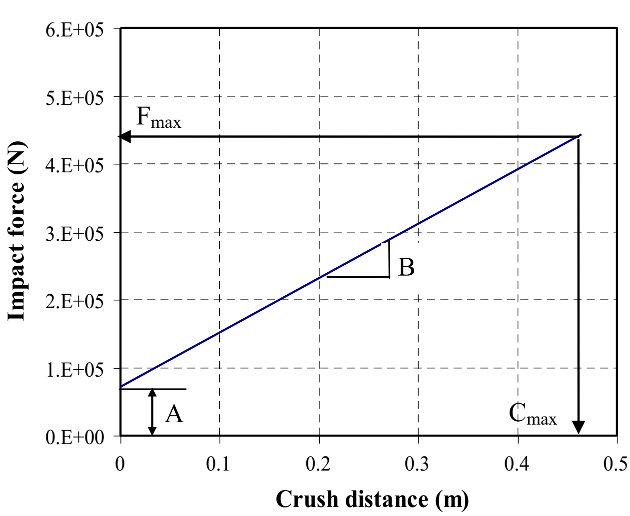

Fig. 1. An example of vehicle impact force–crush distance relationship.

Campbell proposed to relate the coefficients A and B in Eq. (1) to vehicle stiffness per unit width (W_v) of the vehicle, vehicle mass (M), and experimental parameters (b_1 and b_0) as expressed in the following equations:

$$A = \frac{M b_o b_1}{W_v} \tag{2}$$

$$B = \frac{M {b_1}^2}{W_v} \tag{3}$$

Some simplifications were suggested by various researchers to determine the values of A, B, b_0, and b_1 without having to resort to experimental data. For instance it has been assumed by Jiang [11] that the value of b_0 can be taken as 2.2 m/s while b_1 can be determined using the following equation:

$$b_1 = \frac{V - b_o}{C_{max}} \tag{4}$$

Where V is the standard vehicle impact velocity used in crash barrier tests (around 56. km/h for most vehicle crash tests).

Alternatively, Siddall and Day [13] have defined five classes for passenger vehicles and two classes for pick-up, van and multi-purpose vehicles according to the wheelbase range (m), and proposed the A and B values in Table 1. Campbell's equation was also used by Jiang et al. [11] to develop an analytical approach of predicting the peak impact force caused by vehicle crash into frontal and inclined concrete road safety barriers in the direction perpendicular to the barrier. It was assumed that all the impact energy was absorbed by vehicle deformations without any contribution from the impacted concrete barrier. The energy absorbed by vehicle deformation was obtained by integrating Eq. (1) over the damage profile of the vehicle after impact. Wågström [12] proposed a stiffness value of 1000 kN/m for light vehicles (1200 kg) and medium weight vehicles (1600 kg) and 2000 kN/m for heavy vehicles (2000 kg) . The proposed values were validated against full frontal, rigid barrier crash tests conducted by the National Highway Traffic Safety Administration (NHTSA) for different vehicle models, weights and velocities.

In these previous studies, the structure was almost rigid. In the present study, the structure (column) is flexible and will deform and absorb energy during the impact process. Nevertheless, this research will investigate the applicability of this approach.

To achieve the objective of this study, the method of investigation will include the following steps:

a) Identifying the vehicle characteristics affecting vehicle impact on steel columns;
b) Proposing and validating a simplified numerical vehicle model to simulate the effects of vehicle impact on the behaviour and failure of steel columns under axial compressive load using the finite element code ABAQUS/Explicit; and,
c) Suggesting and validating a simplified analytical approach to estimate vehicle linear stiffness to be used in the vehicle model derived in b).