Journal of Constructional Steel Research 92 (2014) 136–149

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

A simplified analytical method for predicting the critical velocity of vehicle impact on steel columns

Haitham Al-Thairy [a], Y.C. Wang [b,*]

[a] Civil Engineering Department, College of Engineering, University of Al-Qadissiya, Iraq
[b] School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, UK

ARTICLE INFO

Article history:
Received 28 May 2013
Accepted 19 October 2013
Available online 10 November 2013

Keywords:
Vehicle impact
Critical impact velocity
Steel column
Simplified method
Axial loads
Transverse static resistance

ABSTRACT

This research develops a simplified analytical method to predict the critical velocity for vehicle impact on steel columns under axial compressive load. The method is based on the energy balance principle with a quasi-static approximation of the column behaviour. The energy terms for the column include energy absorption through both elastic and plastic deformations and the work done by the axial compression load through shortening of the column. The vehicle response under impact is represented by a linear spring until the frontal structure of the vehicle has deformed to the engine box and rigid thereafter. This paper will present a comprehensive set of numerical simulation results, using ABAQUS/Explicit, to check validation of the simplified analytical method for the various energy terms and the final result of column critical velocity.

1. Introduction

Resistance to accidental loading such as vehicle impact is an important consideration to many structures. However, the current design methods offer only rudimentary rules. For example, in Eurocode EN 1991-1-7 [1], vehicle impact is represented either by a static force or by an impulse. The authors [2] have recently carried out an assessment of this simplified design method and found that the equivalent static force approach may be unsafe when the column size is large and is impacted by a vehicle travelling at high speed. In the impulse approach, the impact is either soft or hard and this approach only considers the elastic stiffness of either the vehicle or the structure. Whilst the authors' paper [2] has suggested a method to improve the accuracy of the impulse approach, there is still large inaccuracy in some cases. Furthermore, using an impulse to represent the impact action, it is still necessary to use sophisticated finite element models such as LS-Dyna or ABAQUS to obtain the required structural performance data, which requires significant effort and expertise. This is particularly true if nonlinear dynamic analysis and material nonlinearity are included. Therefore, it is desirable to develop a simplified analytical method to handle the aforementioned problem. This is the aim of the study reported in this paper.

The development in this paper will be based on the principle of energy conservation and the assumption that the deformation process of the column is quasi-static. The authors have validated this assumption for columns subject to rigid body impact [3]. In fact, the quasi-static approach has been adopted by many researchers in the development of analytical methods to predict the behaviour of beams subjected to transverse dynamic impact [4–6]. Furthermore, the experimental and numerical studies of Zeinoddini et al. [7–9] have indicated that the quasi-static assumption can be used for axially compressed steel columns under low velocity transverse rigid impact.

For the impacting vehicle, its effect on the column can be represented by a spring with a non-linear load–deformation relationship. This model has been shown to be valid by a number of researchers, including Al-Thairy [10], Milner [11], Campbell [12], and Jiang et al. [13]. Furthermore Jiang et al. [13], based on the work of Campbell [12], presented a method to evaluate the initial linear stiffness of the vehicle. By comparing simulation results using a full-scale vehicle model and a spring model, Al-Thairy [10] has found that this method gives accurate results for predicting the column behaviour. Furthermore, Al-Thairy [10] has proposed that the spring behaviour should be considered rigid after the frontal deformation of the vehicle has reached the position of the engine box of the vehicle. A similar approach was developed by Milner et al. [11] who presented a simplified theoretical model for vehicle impacting on wooden poles. In their analytical model, the vehicle was modelled by a mass representing the vehicle total mass and a bi-linear stiffness representing the vehicle stiffness characteristics before and after deforming to the engine location. Their results suggested the validity of the bilinear stiffness assumption.

Tsang and Lam [14] also employed a similar approach to determine the frontal impact velocity of the vehicle to cause global instability of reinforced concrete columns subject to road vehicle impact at the column mid-height. The energy absorbed by the vehicle at column failure was calculated by assuming a linear relationship between the impact force

* Corresponding author.
E-mail address: yong.wang@manchester.ac.uk (Y.C. Wang).

0143-974X/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jcsr.2013.10.014

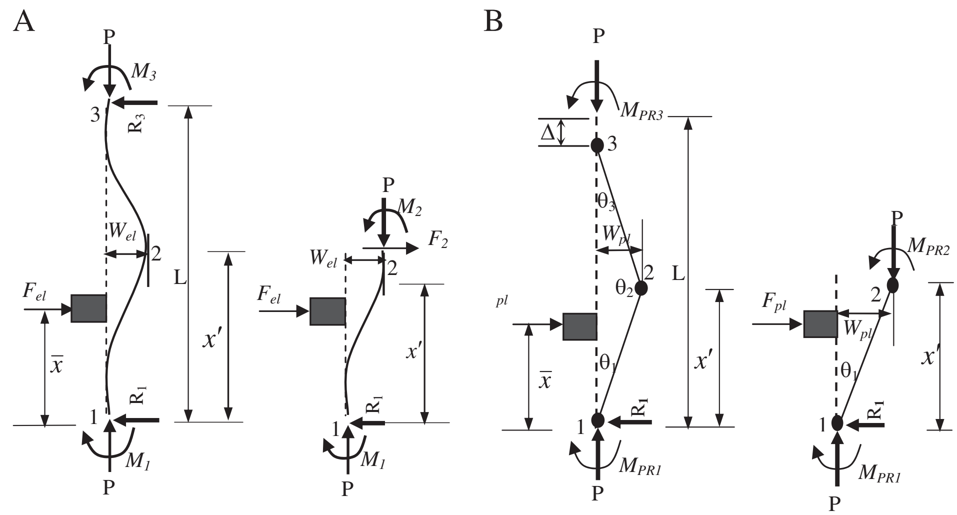

Fig. 1. Column model used in the simplified analysis. A: Elastic phase, B: Plastic phase.

and uniform shortening of the vehicle frontal. However their comparison with non-linear dynamic simulation results showed that the suggested method considerably underestimates the column resistance. This underestimation of column resistance was as a result of neglecting the contribution of the inertia force on the column resistance [14]. However, for steel columns that are much lighter in weight than RC columns, the effects of the inertial force will be small.

This paper will present detailed analytical derivations based on the above assumptions for axially loaded steel columns under vehicle impact and numerical simulation results for validation of the analytical method.

2. Energy balance equation

The general energy balance equation for the structural system under dynamic impact can be expressed as:

$$IE + VD + KE + FD - WK = ETOTAL = Energy\ \ Balance = CONSTANT \quad (1)$$

where *IE* is the internal energy (consisting of both the recoverable or elastic strain energy, *SE*, and the plastic strain energy, *PD*), *VD* the viscous dissipation energy, *KE* the residual kinetic energy, *FD* the frictional dissipation energy at the contact zone, *WK* the work done by the external forces, and *ETOTAL* the total conserved energy of the system (the energy balance of the system).

For the critical situation, the column and the impactor are at rest, therefore $KE = 0$. Due to the short duration of the impact, the viscous dissipation energy at the critical condition is negligible compared to the initial impact energy, making $VD = 0$. Assuming there is no friction under direct impact, then $FD = 0$.

Hence, Eq. (1) becomes:

$$IE - WK = ETOTAL = Total\ \ conserved\ \ energy = Total\ \ impact\ \ energy \quad (2)$$

or

$$IE = Total\ \ impact\ \ energy + WK. \quad (3)$$

For the case of rigid impact which does not absorb any energy, the *IE* is that of the column (i.e. $IE = IE_{col}$). Under vehicle impact, this term also includes the energy absorbed by the vehicle deformation (i.e.

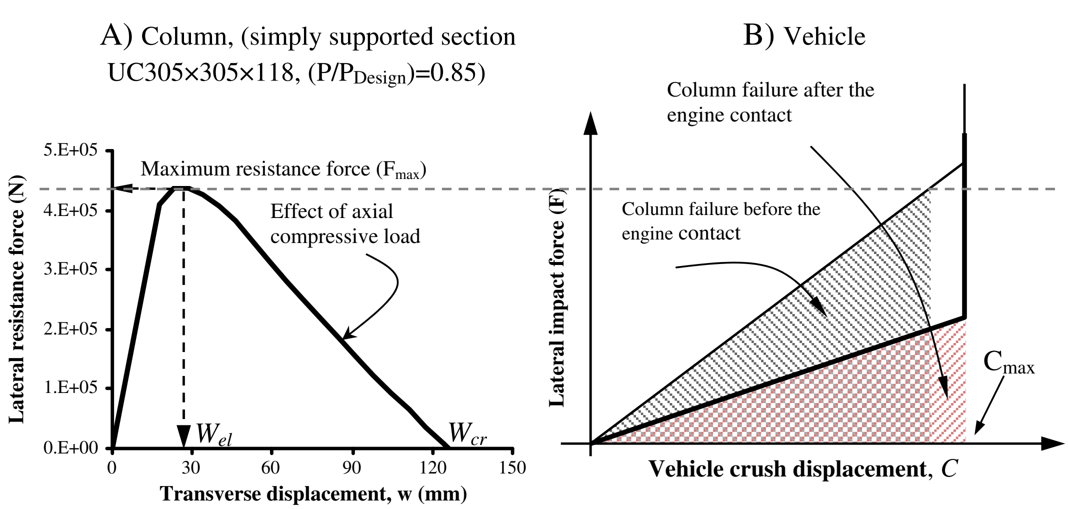

Fig. 2. Determination of the maximum vehicle deformation at column global failure: A) energy absorbed by the vehicle; and B) energy absorbed by the column.