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A modified single degree of freedom method for the analysis of building steel columns subjected to explosion induced blast load

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ABSTRACT

In this paper, a modified approach to the single degree of freedom (SDOF) analysis method of axially loaded steel columns under blast load is presented and validated. The suggested method utilizes a new non-linear resistance function of steel columns under transverse blast load. The new resistance function was derived based on a quasi-static approximation of column behaviour taking into consideration the reduction in the column transverse resistance caused by the axial compressive load. The derived resistance function has been implemented in a single degree of freedom analysis procedure to trace the full response of the steel column up to global instability failure taking into account the strain rate effects. The developed resistance functions and the SDOF method have been validated against numerical simulation results using two steel columns sections with two boundary conditions subjected to different values of the blast impulse and under different levels of axial compressive loads taken as a percentage of the column design static compressive load. The validation results have indicated the capability and feasibility of the suggested method to predict the response and failure of steel columns under transverse blast load.

1. Introduction

Explosions caused by terrorist attacks during the last three decades have left behind many destroyed buildings and structural members near to the explosion points. As such explosion occurrences have increased at considerable rate; the awareness of the engineering community has risen regarding the importance of developing standards and strategies for the blast protection of building structures that are prone to such extreme loading conditions. For example, sections 3 and 5 of the Eurocode 1 part 7 [1] put forward general strategies that are intended to mitigate the risk of accidental actions, including the occurrence of explosions on the structure. One of these strategies is that, for structures with medium or high consequences of failure, a key element may be designed to withstand the blast load following an explosion. This key element is defined by EC1 as a specific structural member upon which the stability of the whole structure depends, such as an internal ground floor column. Section 3 of EC1 part 7, has suggested selecting materials for such a structure (that may be prone to explosion) that have sufficient ductility to absorb significant strain energy without rupture. Another approach has been presented by part 7-section 3 of EC1 by which an alternative load path may be enabled by providing sufficient redundancy in the structure, following the failure of one or more of the structural members, to resist the progressive collapse resulting from the explosion.

Annex D of part 7 of EC1 [1] has proposed replacing the blast pressure by an equivalent static pressure to be used in the design of a structure prone to explosion. For a structural building subjected to a natural gas explosion, Annex D has provided equations to calculate the design nominal equivalent static pressure. However, for other explosive materials, no guidance has been given about how to determine the equivalent static force.

Chapter five of The Unified Facilities Criteria [2] has suggested the following interaction equations to be used in the design of steel columns subjected to blast load that causes bending about both the major and minor axes under axial compressive loads greater than or equal to 15% of the column yield load [2]:

$$P/P_u + \frac{C_{mx}M_x}{\left(1-{P}/{P_{ex}}\right)M_{mx}} + \frac{C_{my}M_y}{\left(1-{P}/{P_{ey}}\right)M_{my}} \le 1.0 \quad (1)$$

$$P/P_p + \frac{M_x}{1.18M_{px}} + \frac{M_y}{1.18M_{py}} \le 1.0 \quad (2)$$

where M_x, M_y are the maximum applied moments about the column's major and minor axes, respectively; P is the applied axial load; P_{ex}, P_{ey} are the Euler elastic buckling load with respect to the x-axis and y-axis, respectively. P_P is the yield load of the steel column.

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Table 1
Resistance functions of beams under uniform distributed blast pressure as suggested by the UFC [7].

Support condition	Elastic–plastic (ultimate) resistance, r_p	Equation no.
Simply supported beam	$r_p = \frac{8M_P}{L^2}$	(3)
Fixed supported beam	$r_P = \frac{8(M_N + M_P)}{L^2}$	(4)
Fixed-pinned beam	$r_P = \frac{4(M_N + 2M_P)}{L^2}$	(5)

Where M_p and M_N are the maximum positive and negative plastic moment capacities of the member, respectively.

C_{mx}, C_{my} are coefficients dependent upon the column curvature caused by the applied moments [3]; M_{px}, M_{py} are the plastic bending capacities about the major and minor axes of the beam-column, respectively; M_{mx}, M_{my} are the bending moment strength of the beam-column in the absence of axial load about the major and minor axes, respectively. P_u is the ultimate design axial strength of the axially loaded compression [2]. However, Nassr [4] has shown that Eqs. (1) and (2) may give overestimated predictions on the column design capacities for high pressure ranges with considerable values for the axial compression load.

The ASCE [5] has also suggested procedures to calculate the blast load to be used in the design of buildings in petrochemical facilities. The blast load was given for front walls, side walls, the roof, rear walls and frames. However, all the suggested procedures of blast load calculation are based on empirical equations that do not consider the dynamic characteristics of the blast pressure and the interaction between the blast pressure and the structure.

The single degree of freedom (SDOF) analysis method has widely been used in the analysis and design of structural members subjected to blast pressure. It has been proven to be a simple and powerful tool for predicting the dynamic response of structural members under blast load with reasonably accurate results provided that the equivalent SDOF system parameters have been defined and quantified adequately to represent the accurate behaviour of the structure. One of the major parameters that an equivalent single degree of freedom system relies upon is the resistance function of the structural member [6]. The resistance function must accurately represent the resistance-deflection behaviour of the selected degree of freedom for the actual system. However, for an axially loaded steel column under blast load, no such accurate resistance function has yet been developed.

Chapter three of the UFC [7] has suggested single and multi-degree of freedom analysis methods as acceptable methods that can be utilized for the design and analysis of either simple or complex structures subjected to blast pressures. The UFC manual [7] has also suggested equations to calculate the elastic-plastic (ultimate) resistance functions of one-way and two-way structural members to be used for a single degree of freedom system as shown in Table 1. However, as will be shown in this study, the suggested equations do not consider the reduction in the column resistance caused by the axial compressive load resulting in overestimated strength especially for columns under considerable values of the axial compressive load.

On the other hand, much research has been published on how to characterize the single degree of freedom parameters of beams under blast pressure [6,8] accounting for the strain rate effects [9,10], developing a numerical technique to determining the structural response [11] and using the SDOF analysis to draw the pressure impulse diagrams [4,12,13].

Carta and Stochino [9,10] have recently presented studies in which a SDOF method was used to assess the dynamic response of RC beams subjected to uniformly distributed blast load. The elastic and plastic resistance functions were derived from the static equilibrium equations in conjunction with the linear elastic bending theory. The strain rate effect was incorporated into the analysis by calculating the differentiation of the elastic and plastic strain–curvature relationships with respect to time [9,10]. However, since Carta and Stochino have only considered the concrete beam in their study, the axial load effects have not been accounted for in deriving the resistance function.

The behaviour and failure of beam-columns subjected to blast loads is different from that of beams with no axial load. For the beam-columns' problem, the analysis must be able to capture all possible failure modes including global plastic buckling failure. However, very few studies have included the effects of axial compressive load on the SDOF analysis of beam-column members subjected to blast loads. Among these studies, Shope [14] used the energy conservation principle with quasi-static approximation to develop a simplified analytical and design model for a steel column under static axial force subjected to a blast load. It has been assumed by Shope [14] that the dynamic system behaves as a single degree of freedom model in an elastic perfectly plastic manner. The resistance function of the axially load steel column has been derived taking into account the reduction of the stiffness caused by the axial load. However, the suggested method has not been validated against experimental or numerical results. Nassr et al. [4] have also used SDOF analysis to investigate the effect of the axial compression force on the response of a steel column under blast loads. The suggested model was intended to account for the P-δ and strain rate effects on the column's strength and stability. However, the effect of the axial load has not directly been accounted for in calculating the column resistance [4]. The effect of the axial load has been considered in calculating the reduced plastic moment capacity of the column section and in the dynamic equation of motion by accounting for the second moment caused by the applied axial load [4].

Astarlioglua et al. [15] also employed a single degree of freedom (SDOF) model to study the effect of axial compressive load on the resistance function of reinforced concrete (RC) columns subjected to axial load and blast induced transverse loads. The effects of flexural, diagonal shear, and tension membrane behaviours were also included in the column behaviour. It has been shown that the level of axial compressive load has a significant influence on the behaviour of RC columns when subjected to transverse blast-induced loads.

This paper aims to develop a modified single degree of freedom analysis method for an axially loaded steel column under transverse blast load. The development focuses on deriving a new nonlinear transverse resistance function of the steel column based on a quasi-static approximation of the column behaviour. Subsequently, the developed analysis method will be validated against the experimental test results of Nassr [4] and the numerical simulations results for two steel columns with two boundary conditions, with different values of the transverse blast impulse, two directions of the column, and under different levels of axial compressive loads.

2. Modified single degree of freedom (SDOF) method

The dynamic response of axially loaded columns subjected to blast pressure can be traced and evaluated up to failure using one physical degree of freedom, usually taken as the maximum transverse displacement based on the assumed deformation shape. The best advantages that are achieved from this model are the rapid and simple assessment of the structural response and the intuitive transition from static to dynamic model [6,15]. The following sections present the assumptions and derivations used in developing a SDOF method.