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Blast dynamics of beam-columns via analytical approach

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ABSTRACT

Problems involving forced transverse vibrations of beam-columns have many applications in different fields of engineering. This paper presents an analytical procedure allowing the prediction of the blast dynamic response of a beam-column to a combined action of axial and transverse loads. The solution is based on the continuous formulation and the Euler–Bernoulli beam theory. The response of the beam-column in the quasi-static, dynamic and impulsive regimes is analysed using the developed analytical model. The analysis shows that the number of modes of vibration needed to produce an accurate estimate of the beam-column behaviour may vary depending on the loading regime. Various types of spatial load distributions and time histories of transverse loads commonly used in engineering practice for modelling of extreme loads are discussed. The significance of the axial force and the shape of the transverse load time history for the beam-column response is shown using the response spectrum and pressure–impulse diagram methods. The initial imperfections in the beam-column geometry and applied loads are introduced into the analysis and their effects are also examined. The results obtained by the analytical model are compared to the results of a nonlinear finite element analysis performed in ABAQUS. Certain discrepancies between the beam-column response yielded by the analytical solution and the finite element model were observed at high levels of axial force and quasi-static transverse loading conditions.

1. Introduction

Performance of beam-like structural elements and mechanical components subjected to blast and impact loads is a practical problem in a wide range of civil, mechanical and aerospace engineering applications. In many cases, these elements/components carry static axial loads while responding to dynamic and impulsive transverse loads. Axially loaded steel tubes [1], steel columns [2], reinforced concrete columns [3], reinforced concrete building frames [4], etc. that may be a subject of accidental or deliberate impact or explosion are among the most common civil engineering examples. Drilling strings in borehole drilling systems subjected to longitudinal thrust [5–7] are often exposed to various impact loads. Explosive loads have to be considered in the design of aircraft components that are affected by temperature changes. The temperature change can alter the dynamic behaviour of a structural element or a mechanical component by introducing thermal stress resulting in destabilising axial loads [8,9]. Rotating shafts of various machine components are exposed to axial forces and fast moving transverse loads [10]. Offshore pipelines that are subjected to axial forces generated by thermal expansion and differences in material properties of the pipe materials, corrosion resistant liners and claddings [11,12], can suffer from impacts induced by trawl gear, anchoring, vessels and dropped objects [13,14].

Despite the obvious importance of the engineering applications, limited analytical work on the blast dynamics of axially loaded beams or so-called beam-columns can be found in the scientific literature. Although numerical models, in particular finite element analysis, are the main tools used for assessment of structures subjected to explosive loads (e.g. [2,3,15–18]), the analytical methods remain essential tools that provide a comprehensive insight into the physical behaviour of a structural element. These methods offer fast and reliable solutions especially suitable for the preliminary design and post-blast loading assessment. In addition, they are often utilised as a sound benchmark for the verification of the numerical methods and for the development of new computational models.

Detailed analytical solutions for free transverse vibrations of axially loaded beams and for forced transverse vibrations of elastic beams without the axial load are covered in multiple research papers [19–33] and textbooks [34–46]. At the same time, the

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solution for the combination of these two problems has attracted only limited attention. A notable analytical work on this topic was published by Virgin and Plaut [47], where the authors investigated the steady state linear response of elastic beam-columns subjected to a static axial force and a distributed harmonically varying transverse load.

The impulsive loads generated by blasts are non-harmonic in nature and therefore require special treatment. This paper presents a complete analytical solution for an elastic beam-column subjected to a static axial force (representing, for example, the dead load) and a transverse blast loading. The solution utilises the continuous formulation and the Euler–Bernoulli beam theory. The response of the beam-column to different loading conditions including the transverse loads with various time histories and different levels of axial load is studied using the response spectrum and the pressure–impulse diagram methods. The high sensitivity of both the methods to the loading conditions is thoroughly examined and discussed.

Adequate formulation of both spatial distribution and temporal variation (time history) of a load is important for the modelling of extreme loads. In engineering practice, various simplifications are often applied to these distributions. A number of different shapes of spatial distributions and corresponding expressions are considered in the presented beam-column model. The behaviour of a structure is also strongly influenced by the load time history. Depending on the load duration, the structure responds in one of three regimes: (quasi-)static, dynamic or impulsive regime, as shown in Fig. 1. The structure is in the (quasi-)static regime when the load duration (t_0) is considerably longer than the time of the maximum structural response (t_m), thus the load can be assumed as constant (see Fig. 1a). Note that the regime is considered as static when the load has sufficiently long rise time resulting in the absence of the inertia forces. On the other hand, the quasi-static (or 'almost' static) regime is characterised by the presence of inertia forces due to zero or comparably short load rise time [48–50]. To include both regimes the notation '(quasi-)static' is used where it is appropriate in the text. In the impulsive regime t_0 is much shorter than t_m (see Fig. 1b), while in the dynamic regime t_0 and t_m are comparable (see Fig. 1c). In this paper, the duration of the transverse load is varied allowing for the analysis of the beam-column response in all three regimes.

A novel approach for modelling blast loads that reliably captures the major physics of the explosion phenomenon is based on the use of solid particle hydrodynamics (SPH) [51]. The SPH method combines adaptive, mesh-free formulation with Lagrangian nature of the particles and an explicit algorithm. All these make the SPH method very attractive in treating highly dynamic phenomena with large deformations and large non-homogeneities such as explosions. The SPH method provides very good predictions for the distribution of pressure, the magnitude and the form of the blast wave, and also allows to incorporate the effects of the charge shape and the detonation ignition model. However, this method is computationally expensive due to the large number of discrete particles needed to achieve adequate accuracy.

Since in real structures certain imperfections in the geometry and application of loads are unavoidable, additional attention is to be paid to the analysis of the beam-columns with initial imperfections. In this study, two most common types of the initial imperfections are considered, namely, axial force eccentricity and initial deflections.

The developed analytical solution is compared to a nonlinear finite element model simulated in ABAQUS [52]. The applicability of the complex numerical algorithms implemented in ABAQUS to the solution of dynamic problems incorporating geometrical nonlinearity (also known as the P-delta effect [53]) is discussed.

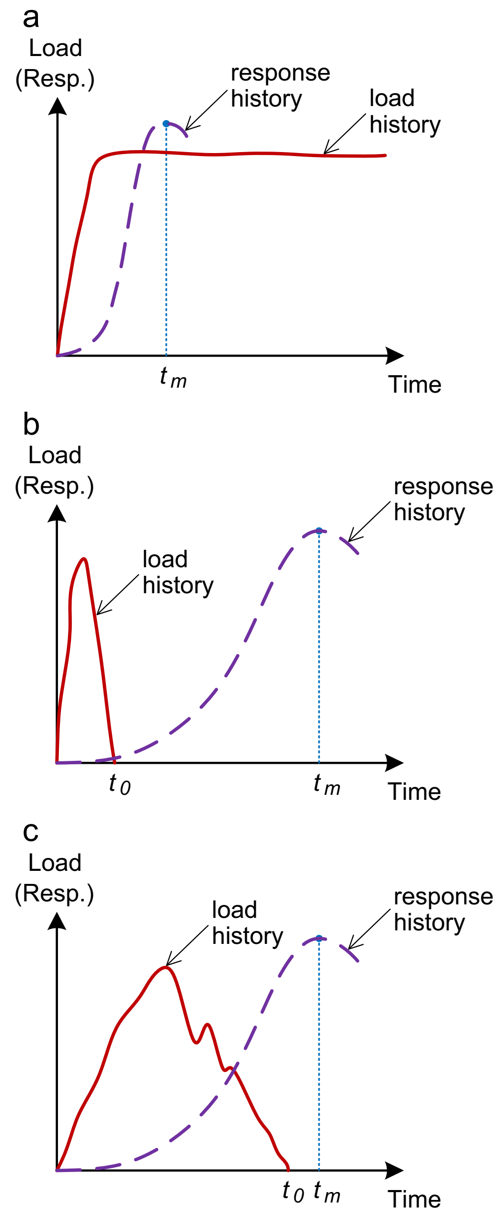

Fig. 1. Load-response regimes: (a) quasi-static, (b) impulsive and (c) dynamic.

It should be emphasised that amongst other applications the analytical model presented in this paper can be efficiently used as a supplementary tool in the elastic design recommended by various design codes (e.g. Eurocodes [54], DNV [14,55], ISO [56,57]) for the design of axially loaded structural elements such as masts, poles, struts, columns, pipelines, etc.

2. Elastic beam-column subjected to a transverse blast load and a static axial force

Consider an elastic beam-column with a uniform cross-section subjected to a transverse blast load and an axial force. It is assumed that the axial force is static, while the transverse load could be either a distributed pressure load or a point force with a non-harmonic time history. A number of simplified time histories shown in Fig. 2, which are commonly used in the analysis and design of structures under blast and impact loads, are discussed in detail. Each shape of the considered load time histories is characterised by a peak load P_0, a load rise time t_{P0}, a load end time t_0