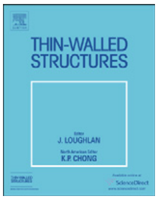
Thin-Walled Structures 62 (2013) 169–178

Contents lists available at SciVerse ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws



Transverse blast loading of hollow beams with square cross-sections

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A R T I C L E I N F O

Article history:
Received 24 July 2012
Received in revised form
12 September 2012
Accepted 12 September 2012
Available online 12 October 2012

Keywords:
Hollow beam section
Blast load
Energy absorption
Analytical model
Rigid-plastic analysis

A B S T R A C T

A model of deformation of a metal hollow section beam under a uniform blast loading is developed in order to reveal the characteristic features of deformation and energy absorption of hollow section beams under such loading. It is established that as a typical structural component a hollow section distinguishes itself from its solid counterpart with two characteristic features of the response. First, a considerably larger kinetic energy is generated in the hollow section beam as the impulsive load is imparted on the upper flange of the beam having a significantly lower mass than the member. Second, a considerable proportion of the blast energy can be absorbed by the local collapse of the section. A two-phase analytical model is proposed. In the first phase, the local collapse of the thin-walled cross-section is determined by using an upper bound approach; and in the subsequent second phase, the global bending of the beam with the distorted section is analyzed by taking into account the effect of axial force. It is demonstrated that mass distribution in the hollow section is an important factor in determining the energy partitioning between the local deformation phase and global bending of the hollow beam. Reasonable agreement is obtained with the experimental data published in the literature [*Jama HH, Nurick GN, Bambach MR, Grzebieta RH, Zhao XL, Steel square hollow sections subjected to transverse blast loads, Thin-Walled Structures 2012;53:109–122*].

1. Introduction

The analysis of various structural members subjected to blast loads are of an interest due to increased security demands in the urban environment as a result of the occurrence of accidental or intended explosions. Thin-walled members with various cross-sections including hollow sections are used extensively in the construction, offshore and mining. The responses of these structural members to blast loading can include unacceptably large permanent deformations and even total failure.

Although the numerical analysis can provide valuable information on the details of the response of structural members with more complex material properties, the analytical models, which retain the characteristic features of the structural response, can reveal important relationships between the structural parameters. Analytical models of the response of metal beams with solid sections subjected to transverse blast loads have become classical guidelines to analyze the influence of different factors on the behavior of these members. Due to the large plastic deformations involved often the elastic deformations are neglected and a rigid plastic material model is employed. Depending on the geometry and material characteristics different factors may become important under intensive dynamic load. It has been recognized that similarly to the influence of the geometry changes on the behavior of statically loaded structural elements [1], the finite displacements play an important role for structural elements loaded dynamically [2]. Among the analytical studies on the axial membrane and bending response of rigid-plastic beams subjected to transverse impulsive loads the notable work include that by Symonds and Mentel [3] on pinned and clamped beams, Jones [4] on beams and plates, Symonds and Jones [5] on the combined effect of finite deflections and strain rate. These studies have shown the importance of retaining the axial membrane force in the yield condition and the beam response, particularly for beams with large length/depth ratios that respond with finite transverse deflections greater than the beam depth.

The developed analytical models are predominantly focused on solid metal cross-sections and the investigations of impulsively loaded beams of other sections are limited to sandwich beams with different core configurations. As metal foams become available, sandwich beams and plates using metal foam as core have received much attention and their response to blast has been investigated extensively [6,7]. Sandwich beams with cellular materials/structures as core such as honeycomb, lattice, "Y" frame or corrugated plates have been analyzed. Blast

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http://dx.doi.org/10.1016/j.tws.2012.09.004

response of circular and square sandwich panels with foam core has been studied [8,9] and experiments with sandwich shells were conducted [10]. Most recently, the behavior of a circular sandwich cylinder with internal blast loading has been investigated [11]. See Ref. [12] for a review of the recent studies on the response of sandwich structures and Ref. [13] on the impact dynamics and its applications.

Despite some similarities in the response of hollow section beams and sandwich beams, the response of thin-walled beams to blast loading is less studied. The behavior of an impulsively loaded simply supported steel beams with a hollow section was studied by Wegener and Martin [14]. A semi-empirical analytical solution was derived with a partial use of a numerical analysis to determine the deformation modes of the beam. More recently, experimental work on steel hollow and steel concrete filled sections was reported by Bambach et al. [15] and on aluminium hollow section beams by Bambach [16]. An extensive experimental program on the blast impact of clamped hollow beams with square sections was carried out by Jama [17] and the major results from this study were published in [18].

In addition to the experimental studies reported in [16–18], a semi-empirical analysis gave bounded solutions for the observed transverse plastic deformation of hollow members using the assumption that the local collapse of the beam section and the global bending of the beam develop sequentially. This assumption is confirmed to a large extent by the experiments and numerical analysis of the hollow section in [19].

The aim of the present analysis is to develop a model, which adequately describes the deformation phases of a hollow section beam subjected to an impulsive loading, considering the temporal development of the deflections of the beam. A two-phase analytical model is proposed in this paper. In the first phase, the local collapse of the thin-walled cross-section is determined by using an upper bound approach; and in the subsequent second phase, the global bending of the beam with the distorted section is analyzed by taking into account the effect of axial force. The model allows an estimation of the absorbed energy during the response. The details of the proposed model are presented in Sections 3 and 4 where the essential influence of the strain rate is taken into account. The energy partitioning between the local and global deformations depends on the load intensity and it is analyzed for different mass distributions of the hollow sections when retaining the total mass of the beam constant.

2. Blast loading of a hollow section beam

An analysis is carried out of the response of an impulsively loaded metal hollow section beam with square or rectangular shape, which is an idealization of the behavior of hollow sections subjected to a uniform blast. Experimental results of blast loading on square steel hollow beam reported in the literature [17,18] are used to verify the proposed model.

The structural members studied in [17,18] were approximately uniformly loaded using PE4 plastic explosive placed in one, two or three equally spaced strips on a polystyrene path on the upper flange (face) of the hollow section. The predictions of the proposed model are compared with the results from the experiments with two and three explosive strips as these loading conditions led to a more uniform loading. Therefore, it is anticipated that the load is uniformly distributed across the full width of the upper flange of a clamped hollow beam (Fig. 1(a)) and can be idealized as an impulsive loading due to the very short pulse duration resulting from the detonation of the explosive.

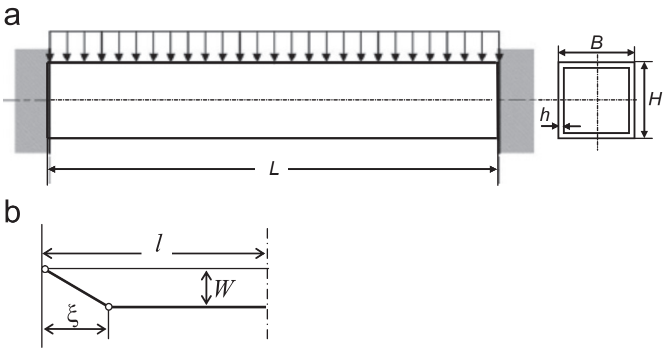

Fig. 1. A hollow beam under blast loading; (a) geometry and loading configuration and (b) mechanism of global bending.

Based on the experimental observations [17,18] and the conclusion from the numerical simulations of the behavior of hollow beams reported in [19] it is anticipated that a phase of a local collapse of the cross-section precedes the global bending of the beam. For that reason, the model of the beam response is developed by assuming that there is no coupling between the two phases of deformation. As used in the experiments [17,18] hollow beams with section dimensions 35 × 35, 40 × 40 and 50 × 50 mm, all with wall thickness of 1.6 mm, are utilized for the model verification.

3. Local deformation phase

3.1. Mechanism of deformation

Based on the experimentally observed pattern of deformation (Fig. A1(a), see Appendix) a model for the local collapse of the beam section is proposed to evaluate the energy absorbed during this deformation phase. The cross-section is characterized by width B, height H and wall thickness h. The construction of the geometrical profile of the deformed section due to the vertical displacement, u, is shown in Fig. A1(b). It is assumed that the section collapses due to the plastic bending of segments CD and MF with curvatures κ_1 and κ_2, respectively, and a stationary hinge at the corner F of the section. The elastic deformations of the beam are neglected and rigid, perfectly plastic property is assumed for the base material. The deformation energy per unit length of the hollow beam is equal to the plastic bending energy and is calculated as

$$E_L(u)/L=2M_0\left\{\beta(u)+\int_{\mathrm{CD}}\Delta\kappa_1(u)ds+\int_{\mathrm{MF}}\Delta\kappa_2(u)ds\right\} \tag{1}$$

where $M_0=\sigma_0 h^2/4$ is the fully plastic bending moment per unit length of the section wall, and σ_0 is the material flow stress. L is the length of the beam. $\beta(u)$ is the change of angle at plastic hinge F, which varies with displacement u. From the geometric relationships (see Appendix) the energy can be obtained as a function of the section dimensions B, H, h and the radii of segments CD and FM, R_1 and R_2. Since the energy is not uniquely defined, a minimum is sought with respect to R_1 to obtain the values for the model parameters and this process leads to $R_1=0$ for all the displacements. However, due to the finite thickness of the wall and relatively large slenderness ratio B/h of the analyzed section it can be assumed that R_1 should be larger than zero. Because of the very large curvature at the centre of the upper flange it is reasonable to assume that $R_1 \geq 2h$. A constant length of the rigid link $\overline{DF}$ (Fig. A1(b)) can be obtained from the