European Journal of Mechanics A/Solids 64 (2017) 46–57

Contents lists available at ScienceDirect

European Journal of Mechanics A/Solids

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

Dynamic response of multibody structure subjected to blast loading

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ARTICLE INFO

Article history:
Received 5 September 2016
Received in revised form
16 January 2017
Accepted 25 January 2017
Available online 30 January 2017

Keywords:
Multibody structure
Blast loading
Plastic hinge
Dynamic response

ABSTRACT

The response of multibody structures with plastic hinges subjected to confined blast loading is investigated through experimental tests, theoretical calculation and numerical simulation in this paper. The time histories of plastic hinges' rotation angles have been obtained using a time-to-digital converter (TDC) in experiments during the deformation process. These tests were simulated using ABAQUS/Explicit, with a strain rate-dependent, critical plastic strain fracture criterion employed to model tearing failure of plastic hinges. Based on the rigid plastic assumption, a dynamics analytical model for blast loaded multibody structures is presented, in which the strain hardening and strain rate effects are considered. The FE models and theoretical method were validated by comparing their predictions against the corresponding experimental results, and were then used to gain insight into the effects of blast loading and thickness of plastic hinges on the deformation processes of the multibody structure.

1. Introduction

Dynamic response of steel structures subjected to blast loading has received much attention over the past few decades. Most of the studies were focusing on structure designs for blast-resistant. For example, a lot of researches were made to investigate the dynamic response of simple structure members such as beams (Jama et al., 2009; Li et al., 2009), single plates (Balden and Nurick, 2005; Cloete et al., 2005; Jacob et al., 2007; Bonorchis and Nurick, 2009; Safari et al., 2011) and sandwich plates (Qin et al., 2014) under uniform or localized blast loading. Several authors such as Sabuwala et al. (2005), Baum et al. (2009), and Borvik et al. (2009) have carried out experimental and numerical studies on response of complex structures such as column connection, steel tower and unprotected container. These studies mainly focused on the pattern and severity of blast damage sustained by the structures. The other studies of structural response under blast loading aimed at engineering uses of explosively driven, such as explosive welding (Akbari-Mousavi et al., 2008; Wang et al., 2011) and fragments propelling in warhead design (Kong et al., 2013; Huang et al., 2015; Lian et al., 2011). These studies paid more attention to the explosively driven mechanisms and focused on the velocity gained of the structure during the driving process.

Completely modeling the elastic and plastic behavior of the material would generally make problems extremely difficult to solve analytically. Hence, most of the theoretical work in the open literature for structural response under extreme loading are based on the rigid-plastic idealization, which neglects the elasticity of materials. This idealization was proved to be appropriate for the rapid assessment of dynamic response of blast loaded structures by many authors (Safari et al., 2011; Lian et al., 2011; Lee and Wierzbicki, 2005). Based on the rigid-plastic assumption, the plastic hinge approach (Li et al., 2009; Bonorchis and Nurick, 2009; Safari et al., 2011) was widely used for large displacement analysis, especially when the deformations are concentrated locally such as notched beams.

Warhead design calls for maximizing the lethality with the payload constraints of the missile. One of the potential payloads for deployment against an air defense missile target is the directional Variable Geometry Warhead (VGW). As can be seen in Fig. 1, the cylindrical warhead is radially segmented into four quarter-cylindrical bodies. These bodies are interlinked with each other by means of plastic hinges to simply be thin metal plates which bend when subjected to blast loading. In the near vicinity of the target, the hinge fartherest from the target is cut off by a linear shaped charge, and the associated thin sheet explosive is detonated simultaneously. Under the confined blast loading, plastic deformations are mostly concentrated at the thin metal plates which turn into plastic hinges due to lack of rigidity. With rotating of the plastic hinges, the device is opened towards the target direction,

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http://dx.doi.org/10.1016/j.euromechsol.2017.01.010

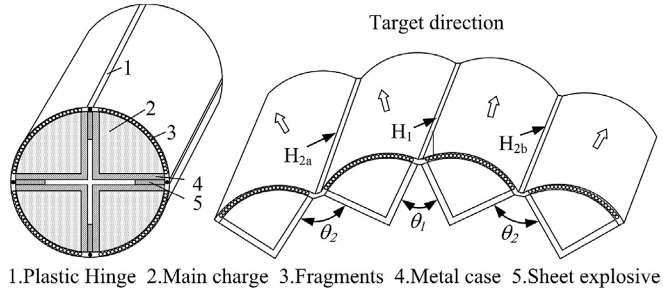

Fig. 1. Diagram of a VGW.

resulting in increase of the proportion of effective kill mechanism. The capability of clustering kill mechanism depends strongly on the deformed shape of the structure, which is quantified by the rotation angles of the plastic hinges. For effective neutralization of the target, it is essential to understand the general deformation process of a simplified blast loaded multibody structure, which consists of four quarter-cylindrical bodies and three plastic hinges.

The objective of this study is to investigate the dynamic behavior of the multibody structure under blast loading and to obtain basal experimental and predicted data on the opening process of a VGW. An experimental research using the simplified VGW configuration was carried out to study the deformation and fracture of the multibody structure. Numerical simulations of experimental procedures for multibody structures under blast loadings were performed using the finite element code ABAQUS/Explicit. A theoretical approach based on the rigid-plastic assumption was presented in order to predict the local deformation of the plastic hinges. The calculations were compared to the test results with respect to deformed shapes as well as the time histories of opening angles.

2. Theoretical analysis

2.1. Problem statement

The main objective of this section is to obtain a complete solution describing the dynamic changing process of the opening angles without hinge fracture. The theoretical solutions are developed using a rigid-plastic idealization with strain hardening and strain rate effects through multi-hinge deformation mechanisms. The four quarter-cylindrical segments are treated as rigid bodies because their deformations in the rotating process of plastic hinges are negligible, as will be explained in Section 5.2. Due to plane symmetry of both the geometry and loading, it is further assumed that the structural response is also plane symmetric. Thus, the geometry can be simplified as a planar two-body system and the opening extent is determined by the rotation angles φ_1, φ_2 and displacement r of hinge H_1 (see Fig. 2). It should be noted that the initial rigid motion of the whole system has no effect on the following opening process, so the initial translation and rotation velocities are neglected in order to simplify the analysis.

It was shown by many authors, for example Lee and Wierzbicki (2005), that for short duration of pressure pulses such as blast loading, the suddenly applied pressure is imparting to the structure an initial velocity $\boldsymbol{v_0}$. Therefore, in this study the initial condition of the deployment dynamics is given by six initial variables as ($\varphi_1(0)$ $\varphi_2(0)$ $r(0)$ $\dot{\varphi}_1(0)$ $\dot{\varphi}_2(0)$ $\dot{r}(0)$). The values of initial opening angles $\varphi_1(0)$ and $\varphi_2(0)$ are assumed zero because of the extremely short duration of pressure pulse. In addition, the initial displacement $r(0)$ and translation velocity $\dot{r}(0)$ are both zero as well, based on the assumption of neglecting initial rigid motion as mentioned above.

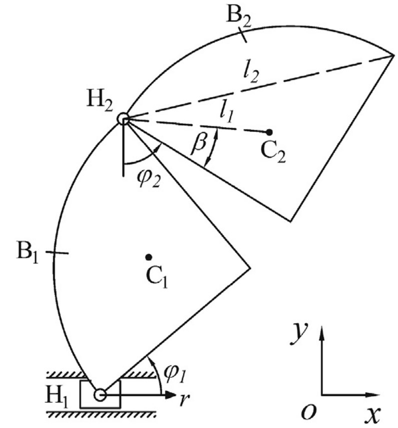

Fig. 2. Configuration of simplified multibody geometry.

Thus, the remaining two initial variables can be obtained based on the momentum conservation theorem as

$$\begin{bmatrix} -ml_1\sin\beta - ml_2\sin\frac{\pi}{4} & ml_1\cos\beta \\ ml_1\cos\beta + ml_2\cos\frac{\pi}{4} & ml_1\sin\beta \end{bmatrix} \cdot \begin{pmatrix} \dot{\varphi}_1(0) \\ \dot{\varphi}_2(0) \end{pmatrix} = \begin{pmatrix} 0 \\ I \end{pmatrix} \quad (1)$$

where I is the total impulse produced by the blast loading applied on body B_2, and m being the mass of each body.

2.2. First phase of motion

If $\dot{\varphi}_2 > \dot{\varphi}_1 > 0$ then the system possesses three degrees of freedom (DOFs) and the generalized coordinates are defined by

$$\mathbf{q} = [q_1 \quad q_2 \quad q_3]^T = [\varphi_1 \quad \varphi_2 \quad r]^T \quad (2)$$

For the obtained three DOFs holonomic system, the general nonlinear differential equations of motion were easily to be deduced by using the Lagrange's equations of the second kind, which is given by

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = Q_i \quad ; i = 1, 2, 3 \quad (3)$$

where $L = T - V$ is the Lagrangian function, Q_i is generalized forces.

Ignoring the effect of gravity, the Lagrangian takes the form

$$L = \frac{1}{2}R_1\dot{\varphi}_1^2 + \frac{1}{2}R_2\dot{\varphi}_2^2 + m\dot{r}^2 + m\dot{\varphi}_1\dot{\varphi}_2 l_1 l_2 \sin\phi - m\dot{r}\dot{\varphi}_1\xi_1 + m\dot{r}\dot{\varphi}_2 l_1\cos(\varphi_2 + \beta) \quad (4)$$

where $R_1 = J + ml_1^2 + ml_2^2$, $R_2 = J + ml_1^2$, $\phi = \varphi_2 + \beta - \varphi_1 - \pi/4$ and $\xi_1 = l_1\sin(\varphi_1 + \beta) + l_2\sin(\varphi_1 + \pi/4)$. J denotes the rotational inertia of each body, with respect to z axis through the center of mass. By means of the virtual work method, the generalized forces are obtained as

$$Q_i = \begin{cases} M_2 - M_1 & i = 1 \\ -M_2 & i = 2 \\ 0 & i = 3 \end{cases} \quad (5)$$

where M_1 and M_2 stand for the dynamic fully plastic bending moments of plastic hinges H_1 and H_2, respectively.

Substituting Eqs. (4) and (5) into Eq. (3) gives the dynamic differential equations