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Mechanics Research Communications 33 (2006) 771–774
MECHANICS
RESEARCH COMMUNICATIONS
www.elsevier.com/locate/mechrescom

Limit states of elastic–viscoplastic plate deformations caused by repeated shock wave-loadings. Part 1: Experimental observation

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Available online 5 April 2006

Abstract

In the present work, the evolution of the inelastic centre deflections of shock wave-loaded circular metal plates due to repeated loadings is studied experimentally and numerically. These displacements are compared to those of quasi-statically deformed plates loaded by a pressure equal to the peak pressure of the impulsive loading. Thereby three types of permanent centre deflections are observed: (1) The quasi-statically obtained deflection is exceeded by the middle point displacement of a dynamically loaded structure already after the first impulse and tends towards a limit state after repeated shock wave-loadings. (2) The centre deflection of the impulsively loaded plate exceeds also the quasi-statically caused deflection and does not increase after repeated impulsive loadings any more. (3) The permanent middle point displacement of a dynamically loaded plate is smaller than the deflection of a quasi-statically loaded one and tends towards the middle point displacement of the quasi-static counterpart after repeated shock wave loadings. This phenomenon is known in the literature as 'Pseudo-shakedown'.

In Part 1 of this study the experimental observation is described, followed by a theoretical study in Part 2.

Keywords: Shock waves; Plates; Dynamics; Viscoplasticity; Finite element method

1. Introduction

The development of permanent deflections of circular metal plates after repeated impulsive loadings can lead to different final deformations depending on the material and on the magnitude of displacements. However, in engineering applications it is important to predict deformations for all loading conditions which can appear. Here, not only loading histories are regarded which occur only once, but also repeated loadings are taken into account. The deformation history of repeatedly loaded plates is traced until a limit state occurs. In the following, evolutions of permanent centre deflections are studied as well as their connection to quasi-statically caused inelastic middle point displacements.

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0093-6413/$ - see front matter
doi:10.1016/j.mechrescom.2006.03.004

In the present study, aluminium, steel and copper plates are used, taking elastic and viscoplastic material properties into account. Damage effects are not considered. In the literature, the development of permanent displacements of repeated impulsively loaded structures and a comparison to the inelastic deformations of quasi-statically deformed plates, loaded with the same peak pressure as in the dynamic case, was first introduced by Jones (1973) and later considered by Jones (1989), Yuhara (1975), and Shen and Jones (1992).

In studies of Jones (1989), Shen and Jones (1992) two situations were observed:

A. For a sufficiently small impulse duration, the middle point deflection of a quasi-statically loaded plate was not exceeded by that of an impulsively loaded one and after each repeated impulsive loading the inelastic deflection increased and tended towards the displacement of the quasi-statically loaded plate. This effect was called 'Pseudo-shakedown'.

B. If the impulse duration was sufficiently long, than the inelastic middle point displacement of a circular plate, subjected to an impulsive loading, was greater than that of a quasi-statically deformed one loaded with an identical peak pressure. In this case, the displacement did not increase any more, if the dynamically deformed plate was loaded again by the same impulse.

From the above mentioned studies it follows, that the permanent deflections of the impulsively loaded plates depend on the impulse duration. But in the present study two additional observations were made:

C. In contrast to case A, it was measured that even after arbitrary long impulse durations the inelastic middle point displacements of impulsively loaded steel plates did not exceed those of quasi-statically loaded ones. But after further repeated impulsive loadings the deflection tended towards the quasi-statically caused displacement.

D. The observation described in case B was also made here. But depending on the magnitude of plate deflection it was also possible that the deflection (which is greater than the quasi-static one) can also increase after further impulsive loadings and tends towards a limit state.

These observations should not be treated as a contradiction to the above mentioned studies in the literature, but it is investigated how the described results A, B and C, D can be connected with each other.

In order to measure time-deflection and time-load histories of structures under impulsive loading conditions, two shock tubes are used for investigating circular metal plates. In the literature, an overview about studies of structures subjected to impact, explosions or shock wave-loadings can be found in Stronge and Yu (1993) and Jones (1989). In the following, the experimental observations about inelastic plate deformations under repeated shock wave loading conditions are presented.

2. Experimental observation

In the experiments steel and copper plates with diameters of 138 mm and aluminium plates with 553 mm diameter are loaded by shock waves. All plates are 2 mm thick. Due to the plane pressure waves, the loading history can be measured by pressure sensors located in a mounting ring next to the plate without changing the structural properties of the plate. Here, piezoelectric pressure sensors are used which are suitable for fast pressure changes. The plate deflection is recorded by a capacitor located in front of the plate. A calibration of the sensor before the experiment allows an accuracy of 1/100 mm. In many studies in the literature only final displacements of impulsively loaded structures were measured. In the present work both values, displacement and pressure, are measured during the impulse period. This experimental technique was applied in Stoffel et al. (2001) and Stoffel (2005) where it is described in detail.

In Fig. 1 measurements of shock wave-loaded and quasi-statically loaded plates (138 mm diameter) are presented. Each point in the diagram indicates the inelastic middle point displacement after an impulsive loading. The used material and pressure peaks are indicated in the legend. The horizontal lines in the diagram denote the total deflections after unloading caused by quasi-static loadings. It is written next to the lines to which material and pressure they belong. Experiments were carried out with two different peak pressures of 8 and 14.5 bar in the dynamic and quasi-static case, respectively. Pressure evolutions and vibrations of the plates, caused by shock waves, can be found in the mentioned earlier studies. As it is presented in Fig. 1, the permanent deflections of the dynamically loaded steel plates tend towards the quasi-statically caused deformations, where they reach a limit or stabilized state. The inelastic deformations of quasi-statically loaded copper plates, however, are exceeded by the permanent displacements of the impulsively loaded counterparts already after