Effect of intense impulsive loading on performance of multi-layered plates

T. Mirzababaie Mostofi[1], M. Rezasefat[1], M. Sayah Badkhor[1], H. Babaei[2,*]

[1] Faculty of Mechanical Engineering, University of Eyvanekey, Eyvanekey, Iran
[2] Faculty of Mechanical Engineering, University of Guilan, Rasht, Iran

ABSTRACT: This paper dealing with an experimental study, numerical simulation, and mathematical modeling of the dynamic response of single-layered and double-layered circular plates under localized impulsive loading. In the experimental section, six experiments were conducted on double-layered configurations made of copper-aluminum plates (2mm+2mm) under different loading conditions. ABAQUS commercial software via a user-defined FORTRAN subroutine was used to develop a numerical model. The Johnson-Cook thermo-viscoplastic constitutive law, as well as the Johnson-Cook damage model, was used in the model. The numerical simulations were verified using the conducted experiments in this study and those in the literature. It has been shown that simulations correctly reproduce the deformation mechanisms of structures during the loading process. Furthermore, a rigorous parametric study was conducted on double-layered metallic plates made of five different layering configurations including aluminum-aluminum, steel-steel, steel-aluminum, copper-aluminum, and copper-steel plates. Two and four different plate radiuses and charge diameters were considered. After conducting the parametric study, an empirical model based on new dimensionless numbers was developed to predict the maximum transverse deflection of plates. Very good overall agreement was obtained between the results of numerical simulations and empirical predictions.

1- Introduction

In the present study, besides a short experimental study on the dynamic plastic response of double-layered circular metallic plates due to locally distributed impulsive loading, simple empirical design expressions have been developed to predict the central deflection of plates. Numerical simulations have been validated using published experimental data available in Ahmad's study [1], and then, rigorous parametric investigations have been conducted for analyzing the effects of different geometrical aspects of structure and explosive charge, impulse magnitudes, material characterizations, and strain rate sensitivity of materials on the blast resistance and dynamic response of the structures. Based on the suggested dimensionless numbers in literature as well as numerical results of the parametric study, new empirical design expressions have been derived by using the novel mathematical method, namely the singular value decomposition approach.

2- Methodology

The Finite Element (FE) model of the structure has been generated using a three-dimensional (3D) quarter symmetry model in the ABAQUS/CAE. Plates with different thicknesses have been modeled as deformable solids. For modeling one-quarter of the specimen, the problem symmetry was employed by using symmetry boundary conditions. Two clamping frames were modeled as 3D rigid bodies to house the plates and simulate the boundary conditions of the specimen. An extra 100 mm radius has been employed as a clamping area. In the last step, the plates have been meshed using solid tetrahedral linear elements (C3D4). The assembly of the numerical model has been illustrated in Fig. 1.

A mesh sensitivity study in the plates was carried out and the results demonstrated that the dynamic plastic response was considerably affected by changing element size. The dynamic plastic response and failure mode of the structure were found in good agreement with experiments when the size of the element was $2\times2\times1$ mm³. Therefore, the element size was determined to be $2\times2\times1$ mm³ in all numerical simulations. However, for the regions away from the loading area (clamping area), the mesh size was slightly increased. The contact between the clamping frames and plates has been modeled by employing the surface to surface contact algorithm according to the penalty method. In the normal direction, hard contact has been determined and in the tangential direction, the friction parameter between the surfaces of the layered plates and also between the surfaces and clamps were assumed to be 0.3 and 0.9, respectively [2-7].

For the impact and blast phenomenon, the material model quality plays an important role and affects the accuracy of numerical simulation results. Generally speaking, two different

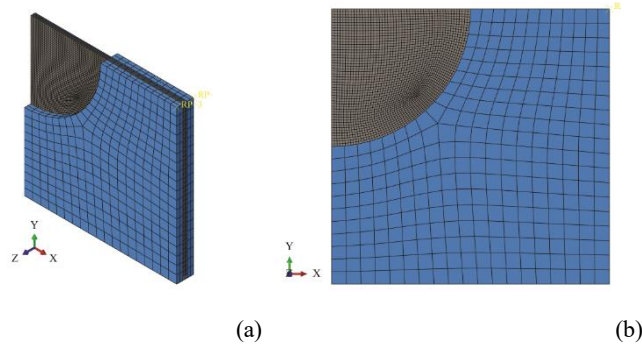*Corresponding author's email: ghbabaei@guilan.ac.ir

(a) (b)
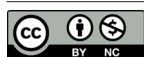
Fig. 1. Full-scale 3D numerical model for single- and multi-layered circular plates; (a) 3D model (b) FE mesh
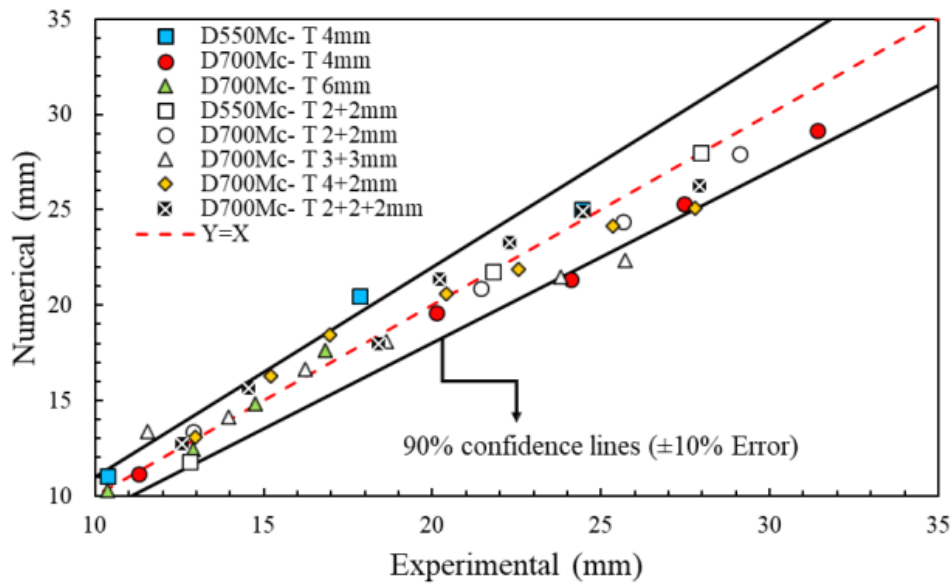

Fig. 2. Comparison between simulated and measured maximum permanent transverse deflections of back layers

types of material models are applied in numerical simulations, in which the first one represents plastic flow and the second one shows a material fracture. Simpler material models are generally preferred due to difficulties in the calculation of the material coefficients from the results of material tests. In the current numerical simulations, the Johnson-Cook plasticity model has been used as a phenomenological model which considers linear thermoelasticity, the von Mises yield criterion, the associated flow rule, strain-rate sensitivity, isotropic strain hardening, and thermal softening of material due to adiabatic heating and damage [2]. By taking into account the influence of strain rate, strain path, and temperature on the stress triaxiality as well as the fracture strain expression, Johnson and Cook developed the failure criterion which was proposed by Hancock and Mackenzie in 1976. In this study, the fracture behavior has been modeled by a combination of a damage evolution rule and a damage initiation criterion based on the Johnson-Cook (JC) dynamic failure criterion. It is based on an equivalent plastic strain value at element integration points and is assumed to happen when the damage factor D reaches unity [2]. During the numerical analysis, the pressure load has been implemented into the ABAQUS/Explicit by employing a user-defined FORTRAN subroutine (VDLOAD) [2].

3- Discussion and Results

Experimental results of the locally impulsive loaded monolithic and multi-layered circular plates for maximum permanent transverse deflections have been compared with numerical simulations in Fig. 2. In this Figure, the red dashed line illustrates fits of numerical simulation results to experimental data reported by Ahmad [1]. The turquoise band between two black solid lines represents the ±10% error at a 90% confidence level which has been plotted to evaluate the accuracy of the numerical model.

Good agreement between the experimental results and simulation ones was observed for different layering configurations. For this series of experiments, a slight underestimation and overestimation of 10% (4/39) were obtained. These under and overestimations may be attributed to the material parameters of the Johnson-Cook plasticity model, the approximate value of the exponential decay parameter, etc. However, by considering the problem complexity and the limitations of constitutive relation and failure criterion, the difference between experimental results and predictions are acceptable and can be used with confidence to analyze the dynamic plastic response of monolithic and multi-layered plates under localized blast loading.

4- Conclusions

The most important and useful findings of the parametric study are as follows:

a) In the same condition, when the targets were made of a combination of the same materials (DWW and DAA), the double-layered 2+4 mm configurations have the best blast performance. This issue is also true for the case when the density of the front and back layers is close to each other (DCW). However, for the double-layered mixed targets that the density of front and back layers is not close to each other, 2+4 mm configuration has the poorest performance.

b) The target blast resistance increased by the increase of charge radius for all layering configurations in a determined impulse value.

c) There was an obvious qualitative distinction between the deformation profiles of back and front layers when the target configuration was made of a combination of the same or different materials. For double-layered mixed configurations, a slight difference at the maximum permanent transverse deflection was observed between the front and back layers. For the case of DCW and DCA configurations, the maximum deflections of front layers were slightly more than that of back layers because the first layer has lower strength and less resistance to deformation.

d) The blast resistance of DWW conFigurations was superior to the other ones when compared to similar impulse values.

e) Although DCW configuration had the highest areal density of 54.37 kg/m², in this case, the deflections of front and back plates were larger than that of DWW configuration .

References

[1] M.S. Ahmad, Study of dynamic behaviour of multi-layered structures subjected to blast loading, University of Cape Town, 2012.

[2] T.M. Mostofi, H. Babaei, M. Alitavoli, G. Lu, D. Ruan, Large transverse deformation of double-layered rectangular plates subjected to gas mixture detonation load, International Journal of Impact Engineering, 125 (2019) 93-106.

[3] Rezasefat M, Mirzababaie Mostofi T, Babaei H, Ziya-Shamami M, Alitavoli M. Dynamic plastic response of double-layered circular metallic plates due to localized impulsive loading. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications. 233(7) (2019) 1449-71.

[4] Mostofi TM, Sayah-Badkhor M, Rezasefat M, Ozbakkaloglu T, Babaei H. Gas mixture detonation load on polyurea-coated aluminum plates. Thin-Walled Structures. 155 (2020) 106851.

[5] M. Rezasefat, T.M. Mostofi, T. Ozbakkaloglu. Repeated localized impulsive loading on monolithic and multi-layered metallic plates. Thin-Walled Structures, 144 (2019) 106332.

[6] H. Babaei, T. Mirzababaie Mostofi, E. Armoudli, On dimensionless numbers for the dynamic plastic response of quadrangular mild steel plates subjected to localized and uniform impulsive loading, Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 231(5) (2017) 939-950.

[7] Babaei H, Mirzababaie Mostofi T, Alitavoli M. Experimental and theoretical study of large deformation of rectangular plates subjected to water hammer shock loading. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering. 231(3) (2017) 490-6.