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The influence of gas mixture detonation loads on large plastic deformation of thin quadrangular plates: Experimental investigation and empirical modelling

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ABSTRACT

The investigation leading to the present study is motivated by the fact that dimensional analysis, as well as empirical modelling, are valuable methods for scholars to find the relationships between effective parameters in every process. By suggesting new dimensionless numbers based on the dimensionless governing equations and using a new mathematical method, namely, singular value decomposition method, significant improvements have been made in preparing a wide range predictions of maximum permanent transverse deflections of thin quadrangular metallic plates due to impulsive loads, especially, gas mixture detonation loading. The dimensionless numbers are based on important and effective parameters such as inertia of applied loads, mechanical properties of materials, structural geometry and strain rate sensitivity. The accuracy and benefits of present empirical models have been investigated by validating the obtained results with gas mixture detonation loading experiments and those in the literature for impulsively loaded plates. Experimental data have been obtained by single staged gas detonation apparatus for aluminum alloy and mild steel plates with different thicknesses. A comparative study revealed that when the material coefficients in Cowper-Symonds constitutive equation have been considered as functions of plate thickness, the present empirical models predict the ratio of midpoint deflection to the thickness more accurately than well-known Jones' theoretical equation.

1. Introduction

Over the last decade, the study of the influences of ballistic and blast loads on the dynamic performance of structures has been increased worldwide due to terrorist attacks, accidental explosions and military assaults and also broad applications in the high technology domain like nuclear and railway industries, aerospace, automobile and shipbuilding. With regard to aforementioned points, the mechanical behaviors of different materials such as mild steel, aluminum alloys, and also sandwich structures subjected to dynamic loading have been caused the great attentions of countless scholars in the academic circles [1–5].

Up to now, analyses of the dynamic plastic response of different structures such as circular and rectangular plates due to all types of impulsive loads have been intensively investigated which includes experimental works, numerical approaches and theoretical modelling researches [4–14]. In most investigations on high energy rate sheet forming against impulsive loading, the specimens have been formed by using ballistic pendulum method with the aid of plastic explosive charges. Because of high budgets and safety concerns, application of the blast experiment is not accessible without difficulty. Hence, in order to replicate blast loading, different experimental techniques such as impact experiments with projectile [15], shock tube apparatus [3] and pressure blow down device have been conducted to the materials depending on the specifications of blast conditions. During recent years, gas mixture detonation technique has been applied as an alternative method instead of explosive detonations for tube and sheet forming. Generally speaking, gas detonation forming process can be more beneficial in the commercial applications because of a clean combustion, little requirement for external devices, an easy automation which results in easily repeat the operations, higher safety in comparison with using plastic explosive charges that leads to apply this process in factories, and also good formability for different materials.

Examples about the forming of different structures by using gas detonation phenomenon are less and can be found in [16–22]. In this field, early experiments on the metal plates backs to Honda and Suzuki's [16] investigations. They used free stretching and shear forming methods for production of different products. They also noted that this process can be used as alternative technique for forming of different metal plates instead of conventional processes. The investigations have been continued by numerical and experimental studies on the die

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forming of aluminum cylindrical cups by Yasar and his co-workers [17,23]. They used a double staged gas mixture detonation forming apparatus so that in this series of experiments, Oxygen and Acetylene were mixed together into the combustion chamber in an equal volume ratio. Two and three-dimensional computational models were simulated by LS-DYNA commercial software and also numerical results for thickness strain distribution, geometry of cups deformation, and die design parameters were compared with those experimental ones. The results illustrated approximately 80–90% similarities in desired shape formability. Later on, a German academic group [18] applied gas mixture detonation technique for free expansion of tubes made of medium strength alloy AlMgSi1 and pure aluminum Al99.5. They concluded that this technique can be used for hydroforming parts such as exhaust elements or car body in the automotive industry. The investigations have been experimentally and numerically developed on the die forming fully clamped circular plates by considering the effects of different mix ratios of Oxyhydrogen on the dynamic plastic performance of mild steel specimens [19]. The main result of this investigation was that the best forming process occurs when nearly 32% Oxygen and 68% Hydrogen are applied in the combustion chamber. In recent years, experimental and theoretical investigations have been conducted on the free forming of gas detonation loaded circular mild steel plates that were fully clamped around the entire boundary. By equating the plastic work deformation to the kinetic energy and using Cowper-Symonds constitutive equation for considering the effect of strain rate sensitivity of materials, a theoretical model was proposed based on zero-order Bessel function of the first kind in order to predict permanent deflection of specimens [20,21]. The theoretical model was a nonlinear relationship between the plate geometry, impulse of applied load, material properties, strain-rate sensitivity of material and central deflection.

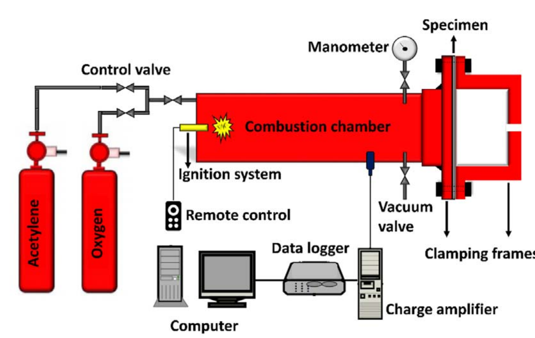
Over the past 27 years, numerous empirical and theoretical models have been developed in the literature for design and evaluation of thin-walled structures against impulsive loads [22,24–29]. The important point is that the theoretical models are mostly based on multiple assumptions regarding the temporal and spatial loading distribution. Previous investigations on the gas mixture detonation loaded circular plates have demonstrated that pre-detonation pressures and properties of applied gasses affect considerably on the dynamic response of structure, particularly in positions involving large plastic deformations [22]. Due to the complexity of considering the direct effects of mentioned parameters on the analytical modelling in [20,21], the velocity of applied dynamic loads has been converted into impulse factor that obtains from pressure-time history and considers all the effects of detonation. The most interesting as well as the most convenient alternative technique that can be helped and applied for analyzing the complex problems in more details is advanced numerical methods like dimensional analysis. Hence, dimensional analysis along with an innovative mathematical approach, namely, singular value decomposition method can contribute to the comprehending of the effect of the gas detonation loads and the resulting plastic structural response in more details. It is noteworthy to mention that those dimensionless numbers extracted from dimensional analysis are helpful for arranging experimental tests program and for measuring purposes and computational calculations in order to keep away from any inessential repetition of the experimental results in the dimensionless space [24]. However, this needs an in-depth comprehension of the governing physics in the gas mixture detonation forming process, because the dynamic plastic response of the structure may become remarkably different depending on the detonation severity. Before using dimensional analysis along with dimensionless numbers, its performance must be accredited by dimensionless governing equations of the structure in terms of effectiveness, robustness, and reliability in assessing the dynamic response and the loading [3]. Hence, for verifying the obtained models, more experimental data are need for realizing the actual physics of the problem and structural response during gas detonation events.

This article firstly commences with a detailed explanation of the single-staged gas mixture detonation forming apparatus preparing all the essential information about the experimental conditions and the materials used during the measuring process. It goes forward with a comprehensive description of the dimensional analysis and effective parameters in predicting the dynamic plastic response of plates by overviewing and describing the literature relevant to the issue. Then, some new dimensionless numbers are proposed in order to predict the maximum permanent deflection of quadrangular plates due to dynamic loads based on dimensional analysis and dimensionless governing equations. These numbers consider the effects of plate geometry, characteristics of materials and gas mixture, inertia of applied load, and strain rate sensitivity on the structural response. Next, a novel mathematical approach, namely, singular value decomposition method is used for finding a nonlinear relationship between the suggested dimensionless numbers and maximum deflection. Furthermore, in order to increase the reliability of the outcomes, the results of suggested empirical models are compared with experimentally obtained data as well as the other existing equations in the literature. Moreover, the influence of material coefficients of Cowper-Symonds constitutive equation on the accuracy of the results is highlighted. Finally, this paper ends with concluding remarks and future improvements.

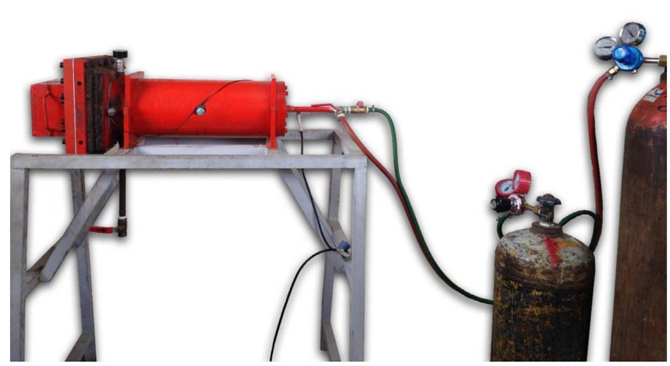
2. Experimental investigation

2.1. Experimental setup and measurement instruments

The authors of the present study have designed and manufactured a single staged gas detonation forming apparatus to carry out some gas mixture detonation tests. These experiments are carried out at Impact and Blast laboratory of University of Guilan (IBLUG) for analyzing large plastic deformations of thin rectangular metallic plates due to gas mixture detonation loading. The schematic and photograph of experimental setup are illustrated in Figs. 1a and b, respectively.



(a)



(b)

Fig. 1. Photos of gas detonation forming apparatus: (a) schematic, (b) global view.