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Experimental study on the response of thin aluminium and steel plates subjected to airblast loading

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ABSTRACT

This work presents results from an experimental investigation on the influence of stand-off distance on the dynamic response of thin ductile plates subjected to airblast loading. The square plates had an exposed area of $0.3 \times 0.3\,m^2$ and were manufactured from two different materials, i.e., medium-strength steel and low-strength aluminium. The airblast loading was generated by detonating spherical charges of plastic explosive at various stand-off distances relative to the centre of the plates. Piezoelectric pressure sensors were used for pressure recordings, and synchronized with two high-speed cameras in a stereoscopic setup to capture the response of the targets. The 0.8 mm thick plates were painted with a speckle pattern to measure the transient deformation fields using a three-dimensional digital image correlation (3D-DIC) technique. The tests covered the entire range of structural response from complete failure at the support to a more counter-intuitive behaviour where the permanent mid-point deflection was in the opposite direction to the incident blast wave due to reversed snap buckling. The synchronization of the pressure and displacement measurements enabled a thorough examination of the entire experiment. The trend in all tests was that the maximum response is driven by the positive impulse from the airblast, as it occurred after the positive duration of the pressure pulse. However, depending on the intensity of the blast load and the structural characteristics, elastic effects and the negative phase could play an important role in the final configuration of the plate. Comparison of the permanent deflection and the measurements from digital image correlation confirmed that this technique is capable of accurately measuring the structural response at high loading rates.

1. Introduction

Protection of industrial, military and civilian engineering structures against blast loading has received a lot of attention in recent years (see e.g. Hanssen et al. [1] and Børvik et al. [2,3]). Such structures are often made of steel or aluminium plates. Steel is often preferred due to its combination of high strength, high ductility and good formability, resulting in an effective load carrying capability at a relatively low cost compared to many other materials. During the last decades, aluminium alloys have become increasingly more attractive for structural applications, particularly due to its relatively high strength to weight ratio. Since thin plates are frequently being used in engineering structures, it has become necessary to evaluate the structural response of such components exposed to blast loading.

Nurick and Martin [4,5] presented a comprehensive literature review of thin plates subjected to blast loading. These studies included theoretical considerations, experimental techniques and experimental results for relatively large permanent displacements. Nurick and Martin [5] also suggested a non-dimensional empirical analysis in an attempt to compare experimental results from various studies using different loading parameters, plate dimensions and materials. This approach has proven to be a useful guideline to predict the maximum deflection of impulsively loaded plates.

Menkes and Opat [6] reported failure modes on clamped aluminium beams subjected to blast loading using sheet explosives. By monotonically increasing the impulse, they identified three different damage modes, i.e., large inelastic deformation (mode I), tensile tearing at supports (mode II) and transverse shear at supports (mode III). Teeling-Smith and Nurick [7] found the same failure modes for clamped circular plates subjected to impulsive loading, and reported that the magnitude and shape of the deformed plates depend on the intensity of the loading. These failure modes were also observed for blast loaded square plates by Olson et al. [8]. However, a slight change in the interpretation was needed to account

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for tensile tearing at the supports as failure was first observed at the centre of the boundary before progressing towards the corners with increasing impulse. Subsequent work by Nurick et al. [9,10] extended these failure modes by including necking at the boundary for mode I, and some geometric additions to mode II by including the amount of tearing at the boundary (called mode II* in the literature). Thus, experimental evidence was used to show a significant effect of the boundary conditions when predicting tearing. Similar results were also reported by Wierzbicki and Nurick [11].

The dynamic elasto-plastic structural response under pulse loading may be divided into three categories depending on the intensity of the loading and the permanent mid-point deflection (see e.g. References 12 and 13). If the structural component oscillates on both sides of its original configuration with a positive final deflection, this is called Type I. However, if the pulse is more intense, the structural component will oscillate only on the positive side of the original configuration (Type II). Finally, the structural component may first deform in the positive direction and then rebound to the negative side of the original configuration (Type III). The two first types of response are intuitive as the final deflection is positive (i.e., in the same direction as the external loading), while the latter type confounds intuition as the final deflection is negative (i.e., in the direction opposite to the external loading). This phenomenon was first reported during numerical studies by Symonds and Yu [14] and called counter-intuitive behaviour (CIB). They noted that this behaviour was extremely sensitive to the structural and loading parameters, and concluded that the response pattern was strongly dependent on the peak deflection or the release angle at which reverse motion starts. That is, CIB only occurred within some narrow range of structural and loading conditions during the transition from elastic to moderate plastic deformations, and that this behaviour could be related to the phenomenon of reversed snap buckling. The unexpected nature of this behaviour has received much attention during the years [15–17], and is still a topic of interest in the literature [18]. Theoretical and numerical investigations have managed to associate the phenomenon with chaotic and complex vibrations [17,19], and this insight has motivated experiments to confirm both theoretical and numerical investigations [13,20,21].

Today's research on structural response of plates exposed to airblast loading is often based on the ballistic pendulum approach using a sheet explosive (e.g. References 22–24), or free airblast experiments using an explosive charge at a given stand-off distance from the plate (e.g. References 25–27). All setups are in general interested in the permanent deflection and deformed shape of the plate. However, due to the complex nature of an explosion, the experimental results are evaluated using various methods. Some data are compared to analytical and empirical methods, as those presented by Nurick and Martin [4], while other results are used to validate numerical methods' ability to describe both the loading and the structural response [26,28,29].

Measurement techniques are equally important as the experimental setup since they determine the usefulness, reliability and validity of the experimental data. Until recently it was difficult to measure the deflection-time history of plates exposed to blast loading. However, the recent development of three-dimensional digital image correlation (3D-DIC) techniques has enabled such measurements of the complete deformation history during blast experiments [27,28,30,31]. The two most common techniques are the subset-based local DIC [32] and the finite element-based global DIC [33]. Tiwari et al. [30] and Zhao et al. [31] used subset-based local 3D-DIC to obtain full-field transient deformations of thin aluminium plates during buried blast events to simulate realistic ground conditions and to validate a dimensional analysis, respectively. Spranghers et al. [27,28] used a similar subset-based DIC technique for full-field measurements of aluminium plates under free airblast loading conditions.

The objective of the present study is to investigate the dynamic response of thin ductile plates by performing controllable small-scale airblast experiments. The square plates with dimensions $0.4 \times 0.4\,\text{m}^2$ were made of 0.8 mm thick Docol 600 DL steel and EN AW 1050A-H14 aluminium sheets. The loading, and consequently the structural response, was varied by positioning the explosive charge of C-4 at various stand-off distances relative to the centre point of the plates. Piezoelectric pressure sensors were used for pressure recordings and synchronized with two high-speed cameras to capture the structural response using a finite element-based 3D-DIC technique. Material tests were also performed to determine the materials' behaviour at large plastic strains. The experimental results provide a set of data which can be used to validate the reliability, robustness and effectiveness of available computational methods in predicting the structural response of thin ductile plates exposed to blast loading.

2. Experimental study

2.1. Experimental setup and programme

All experiments were performed at an indoor test facility possessed by the Research and Development Section at the Norwegian Defence Estates Agency. The experimental setup is shown in Fig. 1a and 1b and was inspired by Spranghers et al. [27]. The setup consisted of a steel mounting frame fixed to the concrete floor with outer dimensions $1.0\,\text{m} \times 1.0\,\text{m} \times 0.015\,\text{m}$ and a square opening of $0.3\,\text{m} \times 0.3\,\text{m}$ in the centre. The square plate specimens with dimensions of $0.4\,\text{m} \times 0.4\,\text{m} \times 0.0008\,\text{m}$ were clamped to the rigid frame using bolted connections and a clamping frame in an attempt to achieve fixed boundary conditions. The 16 bolts were tightened using a wrench with a torque M_t of 200 Nm, which is equivalent to a preloading force F_p of 92.6 kN [34] for the M12 bolts used in this study.

Two high-speed cameras in a stereoscopic setup were used to capture the response of the thin plates with a framing rate of 21,000 fps. The plates were painted with a speckle pattern to measure the transient deformation fields using a 3D-DIC technique (Fig. 1c). It was necessary with additional lighting for the speckle pattern to have enough contrast to calculate the transient deformation fields using DIC. The cameras were triggered manually and the trigger mode was centred such that an equal number of frames before and after the explosion were stored. A blast pencil was used to determine when the shock wave arrived at the cameras (Fig. 1a and 1b). From this point on the correlation of the images had reduced accuracy due to possible oscillations of the cameras, resulting in a loss of calibration of the system.

The explosive mass W was positioned at various stand-off distances R relative to the centre point of the plate depending on the material, and the test matrix is given in Table 1. The explosive material was Composition C-4 with a spherical shape, a mass of 30 g (equivalent to 40.2 g of TNT) and a diameter of approximately 34.5 mm. The blast was initiated by an electric detonator of type RP-83 exploding bridgewire (EBW) with a TNT equivalent of 1 g. The explosive charge and detonator were held together using a black electrical insulation tape (Fig. 1d).

Piezoelectric pressure sensors (Kistler 603B), corresponding charge amplifiers (Kistler 5064) and data acquisition systems from National Instruments (NI USB-6356) and Yokogawa (DL850E ScopeCorder) were used to measure the pressure at various locations during the experiments (see Fig. 1c and 1e). These sensors are designed to measure fluctuations of high frequency with short rise time, and are capable of measuring pressures up to 200 bar at temperatures up to 200 °C [35]. The pressure transducers were positioned in threaded adapters which were fastened at the desirable locations. The pressure was recorded using two independently operating