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The effect of inclination and stand-off on the dynamic response of beams impacted by slugs of a granular material

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ABSTRACT

The dynamic response of end-clamped sandwich and monolithic beams to impact by high-velocity tungsten carbide (WC) particle columns (slugs) has been measured with the aim of developing an understanding of the interaction of ejecta from a shallow-buried explosion with structures. The monolithic beams were made from stainless steel, while the sandwich beams of equal areal mass comprised stainless steel face sheets and an aluminium honeycomb core. High-speed imaging was used to measure the transient transverse deflection of the beams, to record the dynamic modes of deformation, and to observe the flow of the WC particles upon impact. The experiments show that sandwich beams deflect less than the monolithic beams both in normal and inclined impact situations. Moreover, the deflections of all beams in the inclined orientation were less than their respective deflections in the normal orientation at the same slug velocity. Intriguingly, the ratio of the deflection of the sandwich to monolithic beams remains approximately constant with increasing slug velocity for inclined impact but increases for normal impact; i.e. inclined sandwich beams retain their advantage over monolithic beams with increasing slug velocity. Dynamic force measurements reveal that (i) the momentum transferred from the impacting slug to both monolithic and sandwich beams is the same, and (ii) the interaction between the impacting particles and the dynamic deformation of the inclined monolithic and sandwich beams results in a momentum transfer into these beams that is equal to or greater than the momentum of the slug. These experimental findings demonstrate that contrary to intuition and widespread belief, the performance enhancement obtained from employing beam inclination is not due to a reduction in transferred momentum. Finally, we show that increasing the stand-off distance decreases beam deflections. This is because the slugs lengthen as they traverse towards their target and thus the duration of loading is extended with increasing stand-off. However, combining increased stand-off with sandwich construction does not yield the synergistic benefits of sandwich construction combined with beam inclination.

1. Introduction

The design of vehicle underbody structures that can survive the impact of soil ejected by shallow-buried explosives has been a topic of considerable interest for many years. Several strategies have been recently investigated to improve the blast resistance of these underbody structures without increasing the overall weight of the vehicles. These include: (i) replacing the monolithic underbody by a sandwich panel (Dharmasena et al., 2013; Liu et al., 2013; Rimoli et al., 2011; Wadley et al., 2013), (ii) increasing the so-called stand-off of the vehicle floor from the ground (Børvik et al., 2011; Dharmasena et al., 2013; Hlady, 2004; Pickering et al., 2012), and (iii) inclining the underbody with respect to the ground by making use of a V-shaped hull design (Anderson et al., 2011; Bergeron and Tremblay, 2000; Follett, 2011; Fox et al., 2011) as sketched in Fig. 1. The purpose of this experimental study is to examine the relative efficacies of each of these concepts both independently and in combination using a novel laboratory-based approach.

The phenomena leading to dynamic loading of a structure following detonation of nearby shallow-buried explosives are very complex, but can be separated into three sequential phases: (i) transfer of impulse from the explosive to the surrounding soil, leading to the formation of a dispersion of high-velocity soil particles; (ii) propagation and expansion of the soil ejecta; and (iii) impact of the soil ejecta against the structure with attendant momentum transfer (Deshpande et al., 2009). Experimental

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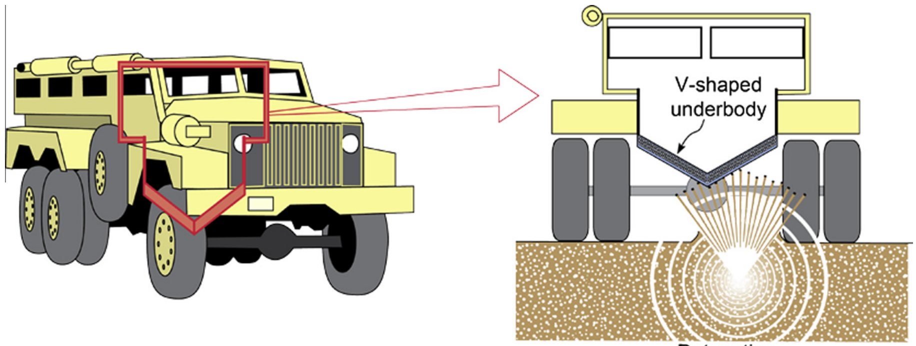

Fig. 1. Schematic illustration of a vehicle with V-shaped underbody designed to protect against the soil ejecta generated by the detonation of a shallow-buried explosive.

(Bergeron and Tremblay, 2000; Reichenbach et al., 1991) and numerical (Børvik et al., 2011; Fairlie and Bergeron, 2002) studies have shown that soil impact is responsible for a substantial fraction of the blast load applied to a target structure. Moreover, empirical models that predict the impulsive loads imposed by soil ejecta (Westine et al., 1985) as well as to structural design codes such as the one proposed by Morris (1993) have helped inform more recent experimental characterizations of buried explosive events (Bergeron et al., 1998; Neuberger et al., 2007).

Following the work on water blast (Fleck and Deshpande, 2004; Wadley et al., 2008; Wei et al., 2008; Xue and Hutchinson, 2004) and air blast (Dharmasena et al., 2008, 2011; Kambouchev et al., 2007), a number of recent experimental and numerical studies (Dharmasena et al., 2013; Liu et al., 2013; Rimoli et al., 2011; Wadley et al., 2013) suggest that some sandwich structures outperform monolithic structures of equal mass when subjected to high-velocity soil loading representative of a landmine explosion. Numerical calculations (Dharmasena et al., 2013; Liu et al., 2013) have shown that this performance benefit is not related to a fluid–structure interaction effect as in the water blast problem, but arises from the higher bending stiffness and strength of sandwich structures compared to monolithic counterparts of equal mass per unit area. Experimental studies have also shown that increasing the stand-off distance between the target and the explosive/ground decreases the deflections of monolithic plates (Børvik et al., 2011; Fourney et al., 2005; Pickering et al., 2012) and sandwich panels (Dharmasena et al., 2013). Traditionally, this decrease has been attributed to a reduction in the momentum transfer from the ejected soil and detonation products to the target due to the spherical expansion of the ejecta; see experiments of Hlady (2004) for rigid targets and Pickering et al. (2012) for deformable plates. However, there is an additional factor that leads to reduced deflections with increasing stand-off. Measurements by Taylor et al. (2010) and McShane et al. (2013) have shown that velocity gradients within the soil ejecta tend to spread out the ejecta in the radial direction with increasing stand-off, thereby increasing the loading time and reducing the pressure imposed by the ejecta on the targets. Numerical calculations of Liu et al. (2013) and Dharmasena et al. (2013) have shown that for a given impulse, the plate deflections decrease with increasing loading time and thus Dharmasena et al. (2013) have argued that these radial velocity gradients are an additional factor leading to the observed reduction in plate deflections with increasing stand-off.

Armoured vehicles often employ V-shaped hull designs (Fig. 1) because there is considerable evidence that such constructions significantly enhance the survivability of vehicles subjected to blast from buried explosives. However, there is a paucity of data in the open literature, with most such studies restricted to rigid targets. These experiments (Genson et al., 2008; Anderson et al., 2011; Fox et al., 2011) suggest that the momentum transferred from the ejecta into an inclined rigid target is less than that transferred into a normally oriented target. Benedetti (2008) and Follett (2011) have reported measurements for the performance of V-hulls made from aluminium sheets and composite materials, respectively. However, to date, no systematic studies on the effect of inclination and the origins of the observed benefits of V-hull construction have been reported for deformable targets. Moreover, any potential benefits that might be accrued by the combination of sandwich construction with V-hull design remain scientifically unexplored.

The data in the literature suggests that the key factor contributing to the superior performance of V-shaped hulls is the reduction in the momentum transferred into such structures. Non-cohesive granular materials impinging on an inclined rigid plane generate flow patterns similar to those observed for fluid jet impacts (Cheng et al., 2007; Johnson and Gray, 2011). Implicitly using this analogy, Tremblay (1998) predicted a dramatic reduction of the momentum transferred to a rigid target with increasing obliquity. However, the dynamic deformation of non-rigid targets subjected to liquid-jet impact can result in significant enhancements of the momentum transfer, as shown recently by Uth and Deshpande (2013). Moreover, no measurements of the momentum transfer have been reported to confirm the fidelity of the analogy between the impact of a liquid jet and that of granular material. Measurements of momentum transfer into deformable inclined targets combined with dynamic visualisation of the deformations from well-characterised granular column impacts will aid our fundamental understanding of the response of V-shaped hull structures to such loadings.

1.1. Scope of study

The study investigates the two key concepts currently employed to enhance the survivability of underbody vehicle structures to landmine explosions, viz. inclination of the structure with respect to the incoming granular spray and enhanced stand-off between underbody and ground. In addition, we also investigate whether the use of sandwich structures in combination with these two concepts would give further improvements in performance. We emphasise that the main aim of this paper is to present detailed measurements, which are not possible under field conditions, of the interaction of high velocity granular media with structures. Hence the loading conditions, structures etc. used in this laboratory investigation do not reflect field conditions, e.g. the experiments here use granular media comprising particles of density 16 g cm^{-3} impacting targets at velocities in the range 60–100 m s^{-1} while in typical field conditions the soil particles of density approximately 3 g cm^{-3} impact structures at velocities of about 600 m s^{-1}. However, the results are intended to give insight