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Response of clamped sandwich beams subjected to high-velocity impact by sand slugs

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A B S T R A C T

The dynamic response of end-clamped sandwich and monolithic beams of equal areal mass subjected to loading via high-velocity slugs of dry and water-saturated sand is measured using a novel laboratory-based method. The sandwich beams comprise aluminium face sheets and an aluminium honeycomb core: the effect of sandwich core strength and beam thickness on the dynamic beam deflection is investigated by varying the orientation and height of the anisotropic aluminium honeycomb core material. High-speed imaging is used to measure the transient transverse deflection of the beams and to record the dynamic modes of deformation. The measurements show that sandwich beams with thick, strong cores are optimal and that these beams significantly outperform monolithic beams of equal mass. The water-saturated sand slugs cause significantly higher deflections compared to the dry sand slugs having the same mean slug velocity and we demonstrate that this enhanced deflection is due to the larger mass of the water-saturated slugs. Finally, we show that the impact of sand slugs is equivalent to the impact of a crushable foam projectile. The experiments using foam projectiles are significantly simpler to perform and thus represent a more convenient laboratory technique.

1. Introduction

In recent years, much attention has been devoted to the dynamic response of above-ground structures subjected to blast from shallow-buried explosives [1]. Experimental and numerical studies have shown that compared to surface-laid explosives, shallow-buried explosives result in higher impulse transmission and larger deflections of the afflicted structure [2,3]. It is widely hypothesised that the increased severity of the loading is generated by the impact of soil that is ejected by the expansion of detonation products [4].

It is extremely difficult to characterise the expanding cloud that contains both soil and detonation products because of the opaqueness of the cloud, the short time scale of the event, and the high-intensity loading that typically damages instrumentation. Despite these difficulties, experiments have established that only a small portion of the ground shock associated with the detonation of a shallow-buried explosive will be transmitted into the surrounding air [5,6] – this is primarily a result of the large mismatch in acoustic impedance between soil and air [7]. Instead, most of the explosive energy goes into the creation of soil ejecta and the expansion of detonation products. This finding corroborates what simulations suggest: the loading of the afflicted structure is dominated by the impact of soil rather than the air shock.

The design of lightweight structures that can resist such loading is a topic of considerable interest. Following the work on water blasts [8,9] and air blasts [10,11], a number of recent experimental studies [12,13] suggest that sandwich structures outperform monolithic structures of equal mass when subjected to high-velocity soil loading that is representative of a landmine explosion. However, the precise nature of the explosive sand loading within these studies is unknown due to experimental difficulties alluded to above. A consequence of this is that such experimental studies cannot be used to validate numerical modelling methods nor used to fully understand the reasons behind the superior performance of sandwich structures. Concurrently with these experimental studies, a range of new numerical techniques have been developed to simulate the response of structures subject to high-velocity soil loading. The most successful strategy involves modelling the soil as an aggregate of discrete particles [14,15]. Such a strategy has been used to model the response of monolithic [14] and sandwich [13] plates subject to the impact of spherically expanding shells of sand particles. However, as the sand shells were not fully characterised in these experiments, their results require

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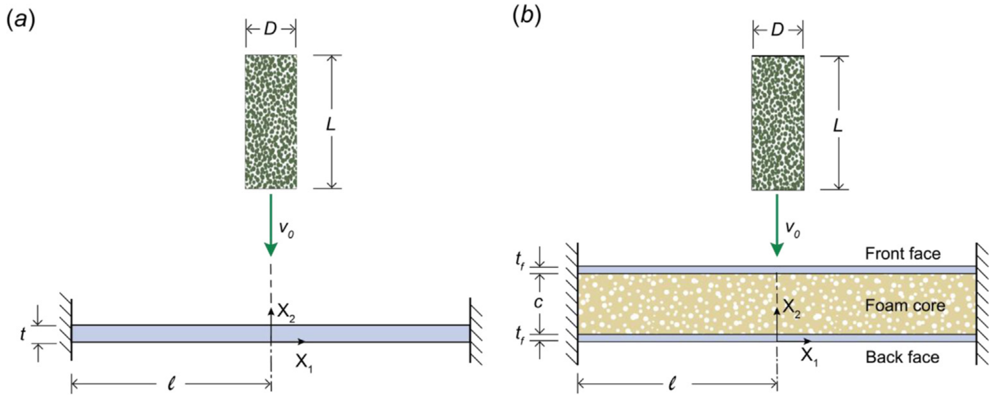

Fig. 1. Sketches of the loading of clamped (a) monolithic and (b) sandwich beams by cylindrical slugs of sand. The leading components are labelled on the figures and the co-ordinate system indicated.

considerable interpretation that is not fully backed by measurements. Moreover, the experiments referred to above only investigate one specific sandwich geometry, and hence do not give insight into the effect of sandwich geometry on performance.

Liu et al. [16] employed the particle-based simulation technique to investigate the response of end-clamped beams subjected to central and normal loading via high-velocity sand slugs, as sketched in Fig. 1. These simulations provide insight into the physics of the dynamic deformation processes and the main conclusions of this work are:

- Sandwich beams with thick and strong core outperform monolithic beams of equal mass. The reduced deflection is primarily due to the higher bending strength of the sandwich beam.
- The response of the beams is primarily sensitive to only two loading parameters, namely the momentum of the incoming sand slug and the loading time.
- An equivalent foam projectile can simulate the response of the beams subjected to sand slug impact.

The experimental validation of the predictions of Liu et al. [16] would represent a significant advance in understanding of the response of structures subject to high-velocity particle/soil loading. McShane et al. [17] developed a laboratory-based buried charge simulator that produces a high-velocity sand cloud similar to that created by the detonation of shallow-buried explosives, as reported in Ref. [6]. Similarly, Taylor et al. [18] have developed small-scale experiments using shallow-buried explosives. These laboratory-based techniques all have the drawback that the cloud of high-velocity particles impacting the structures is not well characterised and hence cannot be used to directly characterise the response in terms of the two loading parameters identified by Liu et al. [16].

Park et al. [19] have recently proposed a technique to generate a high-velocity sand slug within a laboratory setting and without the need for the detonation of an explosive. A key feature of this technique is that it generates a circular cylindrical sand slug similar to that analysed by Liu et al. [16]. Moreover, since this technique generates a slug rather than an expanding cloud of sand, high-speed photography can be readily used to fully characterise the spatial velocity and density distribution within the slug as it traverses through air (before it impacts the structure). Furthermore, high-speed photography can also be used to observe the transient response of the impacted structures rather than just measure the permanent deformations as done in all the experimental studies referred to above.

1.1. Scope of study

We report experimental measurements for the dynamic response of monolithic and sandwich beams of equal areal mass subjected to impact by high-velocity slugs of dry and water-saturated sand, as sketched in Fig. 1. These experiments are designed to mimic loading modelled in Ref. [16] and thereby experimentally investigate the fidelity of their predictions. Thus, the primary aims of the investigation are:

- To develop an understanding of mechanisms of the interaction of high-velocity dry and water-saturated sand slugs with structures.
- Compare and contrast the response of sandwich and monolithic beams of equal mass.
- Investigate the effect of sandwich design (e.g. core thickness and core properties, such as compressive and shear strength) on the dynamic response of sandwich beams.
- Experimentally demonstrate that the impact of sand slugs is equivalent to the impact of crushable foam projectiles.

The outline of the paper is as follows. First, we describe the sandwich and monolithic beam configurations and specimen manufacture. Second, we describe the sand slug impact experiments and summarise the results. Finally, we discuss the design of equivalent foam impact experiments and compare the dynamic responses of the beams subjected to both foam and sand slug impacts.

2. Specimen configuration and manufacture

Sandwich beams comprising a hexagonal honeycomb core and two identical face sheets were manufactured to a net areal mass $m = 4$ kg m^{-2}. The beams of span $2l = 100$ mm comprise face sheets of 99.5% pure aluminium (grade EN AW1050A-H14[1]) of thickness t_f and an aerospace grade aluminium honeycomb core (grade 3.1-1/8-07N-5052[2]) of thickness c and density $\rho_c = 50$ kg m^{-3}. The equal mass monolithic beams were made from the same material as the face sheets of the sandwich beam and had a thickness $t = 1.5$ mm. Both sandwich and monolithic beams had a width $B = 21.3$ mm. We proceed to describe the geometry and construction of the sandwich beams.

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