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Experimental investigation on blast response of cellular concrete

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ABSTRACT

A test setup consisting of a shock-tube with an instrumented short rod is developed for investigating the blast response of cellular concrete foams. In the shock tube facility, blast pressure wave is generated by the rupture of a notched aluminum membrane. An instrumented rod is calibrated for measuring transmitted stress from the cellular foam. Experiments are conducted on brittle cellular concrete foam, which exhibits non-linear stress–strain behavior associated with crushing of the cellular structure and subsequent densification. Crushing is initiated when the stress exceeds the crushing strength and continued crushing produces an upward concave stress–strain curve leading to densification of the material. Foams with two different crushing strengths are evaluated. The influence of the length of the foam is investigated. For an applied blast pressure amplitude, which is higher than the crushing strength of foam, the wave structure in the foam consists of an elastic precursor wave followed by a compaction front that produces crushing of the cellular structure of the material. From the experimental investigation, the existence of a critical length for completely attenuating the applied blast pressure wave is established. For a given blast pressure loading, when the length of foam is larger than the critical length, the applied blast pressure wave is transmitted as a rectangular pulse of nominally constant magnitude, which is slightly higher than the crushing strength of the foam. The foam is compacted without significant densification. The critical length depends on the crushing strength of the foam and the blast pressure amplitude and duration. If the length of the foam is smaller than the critical length, there is an enhancement in the transmitted stress amplitude. If the length of foam is significantly smaller than the critical length, the transmitted stress is enhanced to a magnitude higher than the applied blast pressure amplitude and the compaction of foam leads to significant densification of the material.

1. Introduction

Cellular materials possess energy-absorbing properties and are widely used as protective materials in applications such as improving crash worthiness [1]. The successful use of these materials in mitigating impacts has drawn the attention of the structural community toward the development of blast mitigation strategies. Use of sacrificial claddings when placed in the path of an incoming blast pressure wave alter the blast wave characteristics and reduce the stress transferred to the structural element to mitigate the impact of a blast pressure wave have been explored [2]. The available information in the literature is sparse and not very consistent. Some experimental evidence and results from numerical simulations suggest the possibility of stress enhancement, rather than mitigation, in the substrate material when foam is placed in front.

The available experimental evidence indicates that both flexible polymeric and rigid aluminum foams produce pressure enhancement when subjected to shock loading. Shock pressure loading consists of a shock front followed by constant pressure and is associated with a linearly increasing impulse input with time. The pressure enhancement by foams was first shown for flexible porous material; the stress transferred at the back wall due to a planar shock wave reflected off the front face of the foam exceeded the pressure obtained without the porous material [3]. These findings were later confirmed by experimental studies on the interaction of shock waves with very low density flexible polymeric foams; from polyurethane foam [4,5] and using open-celled polymeric foams [6,7]. The polymeric foams used in these experiments had very high porosities (in the range of 90% and higher) and were able to rebound after the loading was removed. The transmitted stress from the head on collision of a planar shock wave to an elastic substrate through an open celled rigid porous material has also been shown to exceed the stress magnitude obtained from direct shock wave incidence on the substrate [8,9]. Experiments with the use of metallic (alumina matrix) and brittle (silicon carbide matrix) foams were confined to studying the response at shock pressure amplitudes, which do not

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produce significant deformation of the solid skeleton. The extension of results for metallic and brittle foams at pressure amplitudes, which would produce irreversible compaction, are not clear.

Loading associated with a blast pressure wave has a decaying pressure profile, which follows the sudden pressure rise produced by the leading shock front. Blast pressure loading is of a short duration and is associated with a finite impulse input. Therefore, extension of the findings from shock loading to the case of transient loadings with finite impulse is not yet clear. Limited results on stress amplification by soft foams for blast loading are available. In a study on the thoracic visceral injury from blast loading, it was found that the transmitted overpressure from air to the anechoic water chamber is enhanced significantly by a soft foam layer [10]. The results indicated that a soft foam layer attached to substrate may produce a higher level of damage in the protected object.

The experimental results on the use of metallic foams obtained from studies involving impact have shown the benefit of using foam in providing energy dissipation [11,12]. It should however be noted that there is a fundamental difference in the nature of loading associated with impact and blast pressures. In an impact, the energy delivered to a solid substrate by a projectile travelling at a given velocity, is a fixed value, but the stress transmitted at the interface can vary depending on the materials in contact. The loading history produced by an incident blast wave at different solid substrates is always the same (neglecting the effect of the fluid solid interaction) but, the energy transferred to the solid substrate varies depending upon the stiffness of the substrate and is larger for softer material [13].

Experiments involving blast loading with the use of metallic and brittle foams have been confined to studying the interaction at blast pressure amplitudes that do not produce any significant change in the structure of the foam and deformations of the solid skeleton are limited to elastic deformations [4,14,15]. These studies were limited to understanding the change in the characteristics of the pressure wave upon transmission through the porous matrix. Experimental results on the blast response of aluminum foam panels, which undergo compaction showed that the addition of the foam panels increased the energy and impulse transferred to a structure [16]. The blast pressure wave obtained from an explosive charge was used. While the predictions of transmitted stress considering irreversible compaction of the material indicated a decrease in transmitted pressure to the face of the pendulum, these could not be verified since the applied blast pressure and the pressure transmitted to the substrate were not measured in the experiments. The increase in transmitted impulse was attributed to the geometric effect associated with the continuous change in the shape of the initially plane panel surface into a double-curved shape.

The available information consisting of successful use in mitigating impact using foams that undergo irreversible compaction do not provide sufficient indication about the application of foam in mitigating blast loading. The blast test results available in the literature [10,16] are also not helpful since the stress transmitted from the foam to the solid substrate, which is critical in order to understand the behavior of foam in blast mitigation, were not measured. Careful experiments on blast response of foams obtained from experiments with well-defined input blast pressure waves, which would lead to a fundamental understanding of the behavior of foam, are currently not available.

In this study, an experimental investigation of the one-dimensional dynamic response of cellular concrete foams subjected to blast pressure loading was conducted. Cellular concrete is a class of brittle matrix foam, which exhibits compaction associated with crushing of structure. A shock tube was used to generate controlled blast pressure loading of different amplitudes and durations. Instrumentations for measuring the blast pressure history applied at the front end (loaded end) of the foam and the stress transmitted to a solid substrate through the foam (transmitted stresses) were developed. Cement foams of different densities and different lengths were evaluated for different blast pressure loadings. The deformation of the cement foam bars after application of the blast pressure loading was also recorded.

2. Cellular concrete foam

The cellular concrete foam has a cementitious matrix and a cellular structure consisting of large entrained porosity in the form of uniformly distributed air cells. The air cells are introduced by mixing a stable, voluminous, micro-bubbled foam into cement paste. The porosity of the mix is varied by controlling the volume of foam mixed into the cement paste. After setting, when the cement paste gains strength, the cementitious matrix develops a cellular structure. The bubbles in the foam form disconnected pore space.

The cellular concrete foams used in this study were made using cement paste with a water to cement ratio (by mass) equal to 0.55. The cement paste was prepared by mixing cement and water in a paddle mixer. Polypropylene fibers (Stealth® e3 micro-reinforcement, classification D700/800) were also added to the cement paste. Approximately, 10 grams of fibers was used for each 5 kg of cement paste. The foam was generated with a foam generator (shown in Fig. 5.5) using a commercially available foaming agent. MEARLCRETE® FOAM LIQUID produced by Cellular Concrete LLC, which is an aqueous concentrate of a surface-active polypeptide-alkylene polyol condensate, specially formulated to yield tough, stable, voluminous micro bubbled foam. The foaming agent was diluted in water at the recommended dosage and mixed with air in the foam generator. The foam was then hand mixed with the cement paste and cement foams with two different wet cast densities equal to 432 kg/m^3 and 528 kg/m^3 were produced by varying the volume of foam added to the cement paste. Cylindrical samples with diameter equal to 44 mm were prepared using acrylic molds. The inner surface of the mold was lined with a Teflon paper. The paste with the entrained foam was poured into the mold in layers and gently tapped on the sides to ensure proper placement. After 7 days, the foams were demolded and left to dry in the laboratory environment (maintained at 23 °C and 50% RH). The dry densities of the foam after 7 days were equal to 384 kg/m^3 and 480 kg/m^3. The porosity of the cellular solid was determined using the relationship between the bulk density of the cellular material (ρ_{bulk}) and the density of the solid matrix (ρ_s) using the relationship, porosity = $(1 - \rho_{bulk}/\rho_s)$. The ρ_s of the cementitious matrix was taken as 1400 kg/m^3 and the porosities of the foams with dry densities equal to 384 kg/m^3 and 480 kg/m^3 were estimated to be 73% and 65%, respectively.

A photograph of the cellular microstructure of a typical cement foam sample showing the dispersion of air cells is shown in Fig. 1. A closed-cell foam structure with disconnected porosity can be identified. The walls of the porous network consist of hardened cementitious material. There was no moisture in the large pores of the cellular network. After 28 days of age (following casting) the quasi-static load response of the foams were obtained. Tests were performed by placing the foams inside an acrylic tube with inner and outer diameters equal to 44.5 and 50.8 mm, respectively. The acrylic tube was used to confine the material during compaction and to prevent the spalling of the material due to disintegration. The acrylic tube also allowed for viewing the deformation of the specimen during the test. The acrylic tube was instrumented with a strain gage to measure circumferential strains. To minimize the influence of friction in the relative motion between the foam and the tube during compaction, the cement foam was wrapped with two sheets of Teflon and a low viscosity oil was placed in the gap between the Teflon sheet and the inner wall of the acrylic tube. Load was applied to the foam using a steel cylinder, which could slide