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# Impact and close-in blast response of auxetic honeycomb-cored sandwich panels: Experimental tests and numerical simulations

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ABSTRACT

Protecting building, critical infrastructure and military vehicles from Improvised Explosive Devices (IEDs) has become a critical task. This study aims to examine the performance of a new protective system utilizing auxetic honeycomb-cored sandwich panels for mitigation of shock loads from close-in and contact detonations of high explosives. Both field blast tests and drop weight tests were performed using the proposed sandwiches as a shield for concrete panels in combination with conventional steel protective plates. The combined shield was found to be effective in protecting reinforced concrete structures against severe impact and close-in blast loadings. The honeycomb core with re-entrant hexagonal cells shows evident auxetic characteristics which contribute substantially to outstanding force mitigation and blast-resistance performances of such sandwich panels. Numerical simulations showed good agreement with the experimental results. The proposed auxetic panels were found to perform better than conventional honeycomb panels of the same size, areal density and material. Both were found to boost the energy absorption of the monolithic steel plate by a factor of 2.5 by changing its deformation pattern under close-in blast loading. In addition, a combination of the steel plate and an auxetic sandwich panel has aerial specific energy absorption (*ASEA*) higher than either of them, showing great potential for the development of lightweight blast protection of civil, mining, military, nuclear infrastructure and vehicles.


## 1. Introduction

Due to the increasing terrorist attacks involving constrained small charges such as a back pack near to the target, near field and contact detonation of high explosives has become a major threat to civil constructions in which the explosive is detonated within a distance 15–20 radii (for an equivalent spherical blast source) from the target [1]. Same threat still exists on the battlefield where armored vehicles and personnel carriers are exposed to close-range explosions of landmines or improvised explosive devices (IEDs). Different from the far-field diffracting blast wave which usually causes global structural responses, close-range detonations often result in severe local structural damages because of the loading being dominated by the impingement of dense, high-pressure, high-temperature detonation products and after burn.

Response of structural systems and elements to far-field blast loading has been thoroughly investigated for decades. Blast-resistant protective structures have been well-developed and designed including layered sacrificial claddings [2,3], metallic sandwich panels with foam [4–6] and honeycomb [7,8] cores, nested tube systems [9] and other high-performance protective solutions. In contrast, research on structural response to contact and close-range blast loads have recently emerged with applications to such structural components as bare steel plates [1], reinforced concrete (RC) frames [10], tubular steel columns with and without concrete infill [11–13], pre-stressed concrete (PSC) panels [14] and cellular concrete foams [15]. However, studies on effective countermeasures and protective structures for these components to survive contact and close-in blasts are still very limited. Raman et al. [16] showed numerically the positive effects of utilizing polymer coating on RC structures against near field blast loads. Remennikov et al. [1] further investigated experimentally the potential damage mitigation technique through additional polyurea protective coatings of steel plate under close-in blast loading conditions. A thick coating of 12 mm to the back surface was found effective in reducing overall damage of the plates, however, no considerable mitigation effect was discovered with a thin polyurea coating of 6 mm applied on the front face [1]. Ackland et al. [17] on the other hand reported a negative outcome of the application of

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polyurea coating on steel plates under localized blast loading. These studies highlight the importance of developing innovative structural solutions for contact and close-in blast protection in civil and military applications. For the latter, the development of lightweight protective structures is critical to ensure high mobility and fast deployment of the protected vehicular units.

Metallic sandwich panel is a typical composite structure extensively used for impact and blast mitigation purposes. Lightweight materials including metal foams and honeycombs are commonly used as the core of a sandwich panel owing to their excellent energy absorption capacity relative to their low mass density. Compared to metal foams whose energy absorption capabilities are dominated by their relatively densities, metallic honeycombs have tunable mesoscale configurations which can be used to tailor for specific functions such as impact mitigation, blast attenuation and ballistic resistance. Mechanical deformation/failure and energy absorption/dissipation mechanisms of metallic honeycomb sandwiches under dynamic loads have been extensively investigated using experimental [8,18], analytical [6,19] and numerical [20–24] methods. Most of the early efforts [18–20,25–27] have focused on the out-of-plane direction in which the honeycomb unit cell axis is perpendicular to the face-sheets. In this arrangement, buckling and crushing of the cell walls and shearing of the plug were found to be the major energy absorbing mechanisms thus resulting in low levels of energy absorption, especially under close-in blast and ballistic loads. Moreover, cell configuration parameters including unit size, wall thickness, expanding angle as well as core thickness have very limited effects on the protective performance of such sandwich panel [19]. In view of this, several recently published works have focused on the in-plane arrangement in which the cell axis is parallel with the face-sheets [21,28,29]. In this arrangement, shape and configuration of the unit cells have been shown to have great effects on the overall performance of the sandwich panel.

Derived from conventional hexagonal configuration, the honeycomb comprising in-plane arranged re-entrant shaped units showing auxetic behavior has attracted increasing attentions [21,23,24,28,30–32]. An auxetic material contracts in the transverse direction when compressed longitudinally and expands when stretched out axially. This behavior is characterized by a negative Poisson's ratio (NPR) in contrast to the positive Poisson's ratio of most natural materials. Such a unique property of auxetic honeycombs endows them with some enhancements in physical properties, such as greater yield strength, higher shear modulus, higher fracture toughness [33–35], lower fatigue crack propagation [36], as well as greater vibration and impact energy absorption [37], than conventional foams. As such, lightweight composite structures with auxetic cores have shown a great potential in protective applications involving impact, blast [28,30–32,38,39] and ballistic [23,24,30] loads. Ma et al. [38] developed a functionally-graded NPR material concept for a blast-protective deflector, which can adapt its shape under blast load to improve blast mitigation effects. Grujicic et al. [28] performed numerical simulations of the re-entrant hexagonal honeycombs under blast loading and found that specific fabrication processes do have influence on its dynamic behavior. Schenk et al. [39] proposed a stacked, folded auxetic core in a sandwich beam and demonstrated that the blast response of the sandwich beam can be controlled by altering the fold pattern of the core. Jin et al. [21] numerically investigated the blast response of aluminum alloy sandwich structures with auxetic re-entrant cell honeycomb cores. The numerical approach was validated using the blast test results of square honeycomb panels in out-of-plane direction due to the lack of experimental data on blast response of honeycomb-cored sandwich panel with in-plane configuration. Imbalzano et al. [31] proposed innovative auxetic composite panels (ACPs) composed of 3D re-entrant auxetic cellular cores for blast resistance applications. Numerical simulations demonstrated that 30% reduction in back facet displacement and 50% increase in plastic energy dissipation was achieved by the ACPs compared with equivalent monolithic panels under blast loadings. More recently, they further analyzed and compared the blast-resistance performances of the ACPs with that of the conventional honeycomb cored sandwich panels [32]. It has been shown that the ACPs could dissipate and mitigate the imparted energy more efficiently than the equivalent conventional honeycomb panels. These important findings have demonstrated that the auxetic composite sandwich panels are promising structures for protective applications against blast loadings. For ballistic impact, Yang et al. [23] showed that the auxetic honeycomb-cored sandwich structure has far superior ballistic resistance compared to foam-cored sandwich panels owing to the NPR effect induced material concentration toward the impact zone. Qi et al. [24] further confirmed this finding by comparing the ballistic resistance of rectangular, hexagonal and re-entrant shaped honeycombs. Imbalzano et al. [30] showed that the 3D lattice auxetic sandwich panels are promising for ballistic impact protection. All above-mentioned work, however, were based on numerical and/or analytical methods for evaluating the blast responses of auxetic-cored composite panels. Physical blast tests of these innovative composite structures have not yet been reported in open literatures.

This research is aimed at developing novel lightweight protective structures for civil and military applications against contact and close-in detonations. Full-scale aluminum alloy sandwich panels with the auxetic re-entrant honeycomb cores were manufactured by the authors. To evaluate the effectiveness of the proposed structure as a protective shield for civil and military infrastructures in resisting close-in blast loads, field explosive tests were carried out on a target concrete slab with and without the protective sandwich panels. In addition, drop weight impact testing was performed to better understand the dynamic behavior and impact force mitigation of the auxetic specimens under a relatively low strain rate loading. High-fidelity numerical models corresponding to both drop weight and blast tests were developed using the non-linear explicit finite element (FE) code LS-DYNA [40] making use of the Blast Impact Impulse Model (BIIM) [1]. The numerical modeling techniques were validated using the test results including permanent plastic deformation, deformation and load histories of the sandwich panel and the cover plate as well as the failure mode of the concrete slab. The validated models were subsequently used for simulating the impact force mitigation, material concentration, and bulging effects as well as the Poisson's ratio evolution of the auxetic honeycomb core in detail. Energy conversion in the blast tests were numerically analyzed and the role of the protective auxetic sandwich panel was highlighted. Contributions of the auxetic sandwich panel and the steel cover plate to the overall energy absorption have been quantified and discussed. In addition, the impact and blast protection performance of the auxetic honeycomb core was compared with that of the conventional honeycomb core with the same material and mass density.

## 2. Specimen and experimental set-ups

### 2.1. Specimen

The specimens for the tests were sandwich panels made from AA6061 aluminum alloy. The panels were composed of two aluminum face-sheets and a honeycomb core with the re-entrant hexagonal cells. The geometry and dimensions of the specimens are shown in Fig. 1a. The panel had length $L$ = 500 mm, width $W$ = 550 mm, and height of $H$ = 101 mm. Both face-sheets had a thickness of 1 mm. The honeycomb core consists of eight layers