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Honeycomb sandwich panels subjected to combined shock and projectile impact

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Structural response and failure modes of honeycomb sandwich panels subjected to a shock (impulsive pressure) followed by a high velocity projectile impact were investigated using detailed finite element simulations. Performance of sandwich panels was quantified by maximum transverse deflection of the bottom face sheet and core crushing strain along with an investigation of their optimal behavior. Three failure modes were observed in panels – core failure, top face failure, and tearing and detachment from support. Failure maps of honeycomb sandwich panels were constructed to show the failure mode of panels as a function of shock intensity, projectile velocity and panel core relative density. In addition, a limited set of simulations were carried out to study the role of incident angle of projectile on the overall performance of a panel. These simulations showed that maximum deflection occurred for vertically impacting projectiles. However, we found that this did not directly translate to maximum core crushing strain in sandwich panels. The results provide new insight into the performance and failure of sandwich panels under complex dynamic loading conditions, and further highlight the potential of these panels for development of threat-resistant structural systems.

1. Introduction

Sandwich panels with low density core constructions have the potential to significantly enhance the security metrics of structural systems under extreme loading conditions such as impact, blast and thermal shocks [1–15]. In a pioneering study, Xue and Hutchinson [16] simulated the response of tetragonal truss core sandwich panels under blast loading. Their study showed that a well-designed sandwich panel can sustain a higher impulsive load and absorbs more energy prior to failure compared to a counterpart solid plate of same mass. This motivated further studies on performance of lightweight sandwich panels under impulsive loading [17–25]. These studies further highlighted the potential of sandwich panels for enhancing the safety of structures under impulsive loading.

To better assess the potential of these panels for developing robust threat-resistant structural systems, additional investigations into their behavior under more complex loading conditions are required. To this end, computational techniques, especially finite element simulation are widely used in understanding the behavior of sandwich panels especially for the case of impulsive loadings since physical recreation of the conditions being studied can be prohibitively expensive. In a recent computational work, Ebrahimi and Vaziri [26] considered honeycomb and corrugated core sandwich panels subjected to multiple shocks. In addition, further complicated loading scenarios may be envisioned such as: (i) multiple impacts by non-explosive projectiles [21,27–29], (ii) shock or projectile loading followed by an internal fire (e.g. World Trade Center collapse in 2011 [30,31]) and (iii) shock or projectile loading followed by internal explosion (e.g. in pipeline networks and fuel tanks). In addition to these, shock loading followed by projectile impact constitutes an important practical scenario deserving a thorough treatment. This type of loading typically occurs when for example a primary explosion fragments parts of the enclosing or surrounding structure launching a major fragment into the air (like a projectile). Thus, the initial shock wave of the blast is followed by a projectile strike.

This important scenario will be the focus of the current work, which is investigated using detailed finite element based computational models. It's been well shown in the literature that numerical simulation of sandwich panels can capture many of the phenomenological details of deformation of these panels (see for example Refs. 32 and 33). Rizov et al. [34] compared the numerical and experimental results of indentation of a foam core sandwich panel and reported a good match between the results. Validation of finite element models has been examined for different core topologies such as multilayered pyramidal lattice core [35], corrugated [24] and honeycomb sandwich panels [36] under blast loading and good agreement compared to analytical and experimental results has been reported. The present study closely follows the work of Hutchinson and his colleagues [2,37] who studied the performance of square

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honeycomb sandwich panels under shock loading [2] and projectile impact [37] and validated a computational model of these panels in ABAQUS against experimental data and reported that the finite element method predicts displacement of the panel with a very good agreement to the experimental observations and also can capture many details of the core crushing behavior. Our computational model's geometry and meshing in the present study is near-identical to this validated model (except for the core element where we have used hexahedral elements rather than shell elements). In addition, the material models used for both this work and the current work fall broadly under similar class of materials. Thus we have strong reasons to expect realistic predictions especially for deflection and core crushing behavior. For failure of the panels, since we have neglected manufacturing imperfections and assumed joints to be perfect, we admit that our results for failure can overestimate experimental results. In spite of these limitations, the results still retain significance as a comparison tool and design aide for honeycomb panels of different core densities and load intensities. To this end, in this paper, we study the performance and failure behavior of square honeycomb core sandwich panels (known to exhibit superior performance in comparison to many other types of core configurations – [17,18,26,38]) under combined shock and projectile impact. We compare the results with a corresponding solid plate of same mass. Although, for the current study, we do not consider the example of multiple fragment strikes, the framework presented can be readily extended to include such a case.

The rest of the paper is organized as follows – section 2 describes detailed geometry of the panel and the projectile along with the material models employed. In addition, the method for applying shock loading and geometry of the projectile is explained. Response of sandwich panels to combined shock and projectile loading is studied in section 3, including the effect of projectile size and incident angle. In section 4, an optimal core density is sought for honeycomb sandwich panels subjected to combined shock and projectile loading. Finally, failure mechanisms of honeycomb sandwich panels under combined shock and projectile loading are discussed in section 5, and failure diagrams were constructed. The concluding remarks are drawn in section 6.

2. Panel geometry, loading and materials

For the purpose of numerical simulations of the response, we base our computation on the model of one unit cell of the sandwich panel with a periodic boundary condition (as depicted in Fig. 1) using commercial finite element code ABAQUS/Explicit (SIMULIA, Providence, RI). Full three-dimensional models were constructed and fully meshed with 8 node three dimensional elements [20,39,40]. Core and face sheets were bonded together with "Tie" option available in ABAQUS which couples degrees of freedoms in associate nodes on the two surface. Fig. 1A shows a schematic diagram of square honeycomb sandwich panel geometry and the corresponding computational model of the unit cell. The panels were considered to have infinite width and finite length of *2L*. Fully clamped boundary condition along the infinite edges was applied for the computational model. At least four 8-node hexahedral elements with reduced integration were employed through the thickness of each face sheet, which can capture early stages of necking with acceptable fidelity [39]. As shown in Fig. 1A, the core has height and web spacing of *H* and *B*, respectively. Also h_f and *t* denote thickness of face sheets and core webs. Core relative density, ρ_c, and mass/area of panels can be calculated based on these geometrical parameters as follows:

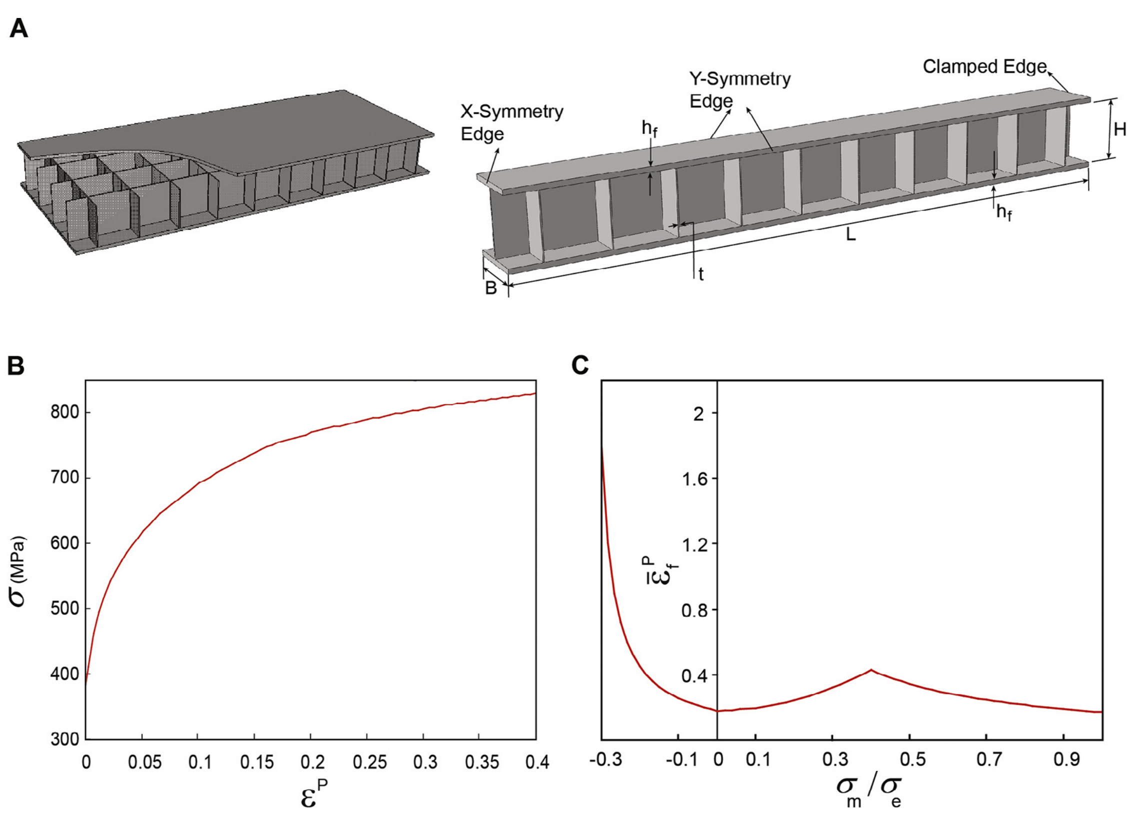

Fig. 1. (A) Schematic diagrams of honeycomb core metallic sandwich panel configurations and the corresponding computational model of the sandwich panel unit cells. The width of the panel is 2L and only half of the panel's unit cell was modeled, while symmetry conditions were applied in both in-plane directions. (B) True stress–true plastic strain response of the AH36 steel considered in this study. (C) Failure locus of AH36 steel.