ENHANCEMENT OF BLAST RESISTANCE OF SANDWICH PLATES

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Abstract This research examines the effect of design modifications on response of sandwich plates to impulse pressure loads. The objective is to limit damage by delamination of the laminated face sheets and by crushing of the structural foam core that dominates response of conventionally designed sandwich plates. This is achieved by introducing structural elements that store the incident energy and thus reduce damage-related energy dissipation. In particular, ductile interlayers inserted between the outer face sheet and the foam core, can absorb a significant part of the incident energy, and protect the foam core from excessive deformation. These design concepts have been developed in our earlier work on the effect of low and medium velocity impact on sandwich plates, where they enhanced resistance to local deflections of the face sheet, foam crushing and interface delaminations.

Keywords: sandwich plates, blast, dynamic finite element analysis.

1. INTRODUCTION

One standard Design (1) and three modified sandwich plate Designs (2)-(4) have been analyzed and evaluated under blast load. The modified designs included thin, ductile interlayers, which separate the outer face sheet and the foam core. The interlayers were selected as the relatively stiff Isoplast 101 polyurethane manufactured by Dow Plastics, and a fairly compliant elastomeric foam. Two of the new Designs (2) & (3) had a single interlayer inserted between the outer face sheets and the foam core. Most successful was Design (4), where the polyurethane interlayer was combined with another interlayer made of the elastomeric foam. In this combination, the

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stiff polyurethane layer offers good support to the outer face sheet, while the easily compressible elastomeric foam layer protects the inner foam core from damaging contact with the outer face sheet or the polyurethane interlayer. In comparison with the conventional design, Design (4) shows significant reduction in the peak kinetic energy, face sheet deflection and core crushing.

Explicit dynamic finite element solutions were developed with the LS-Dyna software. Contact algorithms were invoked to model intermittent separation and rejoining of the face sheets and the inner core following delamination. Both impulse and explosive pressure loads were applied to the outer facesheet of a section of a continuously supported plate.

The results show almost instant facesheet delamination and permanent crushing of the foam core in all designs. However, the pair of polyurethane and elastomeric foam interlayers reduced the peak kinetic energy and core compression by approximately 50%. The longitudinal strain in the outer facesheet was also reduced in the new sandwich design to magnitudes which fall below the ultimate tensile limit. The deformation mechanisms leading to this enhanced performance under blast loads are mainly the hyperelastic behavior of the polyurethane rubber and the collapse of the low density elastomeric polyethylene foam. Both these effects reduced the amplitude and velocity of the incident compression wave and protected the foam core. As a result, the core compression was both delayed and reduced, and this led to a significant reduction in the plate deflection at mid-span and in curvature at the supports.

2. GEOMETRY, MATERIAL PROPERTIES, LOADS

A sandwich panel, continuously supported by equally spaced rigid stiffeners is considered, with the dimensions indicated in Figs. 1 & 2. The total width, measured in the X_2-direction of Figure 1 is assumed to be sufficiently large, so that the plate can be analyzed in plane strain, with displacements $u_2 = 0$ everywhere. The four structural arrangements of the plate examined in this study are shown in Figure 2. In the standard Design (1), the laminated composite facesheets are bonded to a structural foam core, to form a symmetric sandwich cross-section. Modifications of the standard design were motivated by results of our past studies, of the effect of low and medium velocity impact on stress distribution and damage evolution in such laminates (Dvorak and Suvorov 2005, Suvorov and Dvorak 2005a,b). These studies examined Designs (2) and (3), modified by replacing a part of the foam core by a ductile interlayer, inserted between the loaded or outer face sheet and the remaining part of the foam core. In particular, a relatively stiff polyurethane (PUR) interlayer was used in Design (2); this interlayer

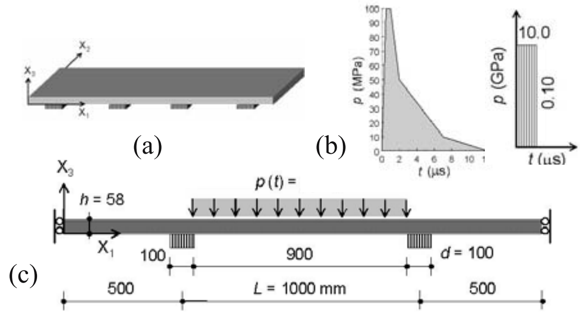

Figure 1. Geometry and loading of a continuous sandwich plate.

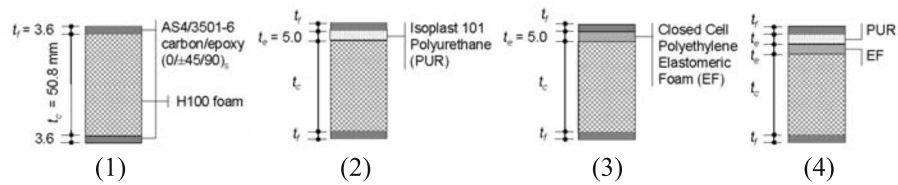

Figure 2. Cross sections of standard and modified designs of sandwich plates.

improves the support of the outer facesheet and does not elevate overall deflection under applied uniform pressure. Design (3) employs a fairly compliant elastomeric foam (EF) interlayer, which offers better protection of the foam core, albeit at the expense of higher local and overall deflections. Design (4) utilizes both PUR and EF interlayers, each 5.0 mm thick, in an effort to combine the described benefits.

The facesheets are made of a AS4/3501-6 carbon/epoxy fibrous composite laminate, and each consists of eight plies arranged in a quasi-isotropic $(0/\pm45/90)_s$ symmetric layup. They are assumed to remain linearly elastic during the loading cycle and are modeled as homogeneous orthotropic material layers, using *LS-Dyna Material Type 2*.

The polyurethane (*PUR*) *interlayer* was selected as Isoplast 101 manufactured by Dow Plastics. It was modeled as an isotropic, nearly incompressible, hyperelastic rubber material, using the formulation of Blatz and Ko (1962). The stress-strain response of polyurethane under uniaxial tension is shown in Figure 3. In the finite element analysis, the PUR interlayer was represented by *LS-Dyna Material Type 7.*

The elastomeric (*EF*) *foam* is a low density, closed-cell polyethylene. The stress-strain response under uniaxial compression is shown in Figure 3. *LS-Dyna Material Type 63* represented the elastomeric foam interlayer.

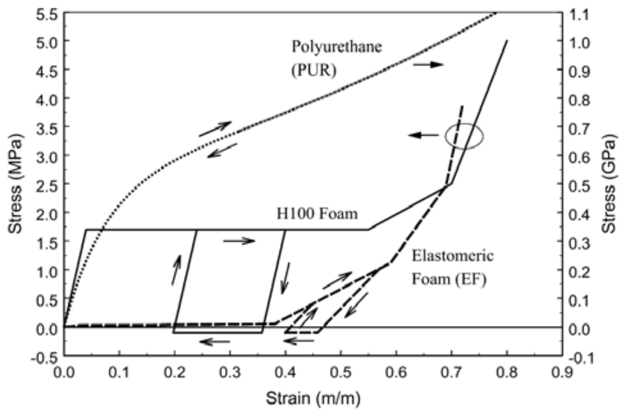

Figure 3. Comparison of stress-strain behavior of elastomeric foam and H100 closed cell foam under compression, and of polyurethane under uniaxial load.

The structural foam core material is H100 Divinycell, an isotropic, closed cell foam. Under uniaxial compression, it deforms as shown Figure 3 (Fleck 2004). In the finite element calculations, the foam was also modeled by LS-Dyna Material Type 63.

Specific material properties of the face sheet laminates, interlayers and foam core are listed in Table 1.

Selection of adhesives and their properties are beyond the present scope, hence the interfaces are assumed to be well bonded. Delamination cracks are expected to occur in the Divinycell structural foam, along a path adjacent to its interface with either one of the face sheets or interlayers. To this end, the foam core was subdivided such that a thin layer of elements was present at such interfaces. The delamination of the foam core from either the laminated face sheets or PUR or EF interlayers is modeled by removing from the mesh the thin foam interface elements, using the material erosion capability of LS-Dyna. Maximum strain failure criteria are utilized to initiate failure of the foam interface elements and their elimination from the mesh when ultimate strains of the H100 foam (Table 1) are exceeded.

Blast loads were idealized by a uniform pressure impulse $p(t) = p_0\delta(t)$ as shown in Figure 1b.

3. FINITE ELEMENT MODELS

Response of the four sandwich plate designs to blast loading was examined using the LS-Dyna software (LSTC 2003). It performs a Lagrangian dynamic analysis using an explicit, central difference integration scheme. The solution domain is selected as a 'unit cell' consisting of a single span that extends over the support on either side, to the middle of the next span, as shown in Figure 1c. Under a uniform load applied as shown in Figure 1c, the plate deformations are symmetric with respect to the X_2X_3-plane located at the center of the middle span. In this case, the solution domain was reduced from that shown in Figure 1c to one which contains half of the loaded span, and half of the adjacent span, Figure 4. The pressure impulse of Figure 1b was applied as a uniform stress, perpendicular to the exterior surfaces of the outer laminated facesheet elements.

The inserts in Figure 4 show details of the mesh for the four Designs (1-4).

Table 1. Elastic properties and dimensions of sandwich plate constituents.

<table>
<tr><th colspan="2">Property (units)</th><th>$(0/\pm45/90)_s$ AS4/3501-6 Carbon/epoxy</th><th>H100 Divinycell foam</th><th>Isoplast 101 Polyurethane Foam (PUR)</th><th>Elastomeric Foam (EF)</th></tr>
<tr><td colspan="2">Material type</td><td>Orthotropic, elastic</td><td>Isotropic, crushable</td><td>Isotropic, hyperelastic</td><td>Isotropic, crushable</td></tr>
<tr><td colspan="2">LS-Dyna material #</td><td>2</td><td>63</td><td>7</td><td>63</td></tr>
<tr><td colspan="2">$E_1 = E_2$ (MPa)</td><td>55022.0</td><td rowspan="2">111.0</td><td rowspan="2">1500.0</td><td rowspan="2">10.0</td></tr>
<tr><td colspan="2">E_3 (MPa)</td><td>10792.0</td></tr>
<tr><td colspan="2">G_{12} (MPa)</td><td>21319.0</td><td rowspan="2">50.45</td><td rowspan="2">513.0</td><td rowspan="2">5.0</td></tr>
<tr><td colspan="2">$G_{13} = G_{23}$ (MPa)</td><td>4953.0</td></tr>
<tr><td colspan="2">ν_{12}</td><td>0.29</td><td rowspan="2">0.1</td><td rowspan="2">0.463</td><td rowspan="2">0.0</td></tr>
<tr><td colspan="2">$\nu_{13} = \nu_{23}$</td><td>0.248</td></tr>
<tr><td colspan="2">ρ (kg/m^3)</td><td>1580</td><td>100</td><td>1200</td><td>148</td></tr>
<tr><td colspan="2">Compressive yield strength (MPa)</td><td>-</td><td>1.7</td><td>-</td><td>0.0264</td></tr>
<tr><td colspan="2">Tensile strength (MPa)</td><td>-</td><td>0.3</td><td>-</td><td>0.1</td></tr>
<tr><td colspan="2">Maximum tensile strain (%)</td><td>-</td><td>0.28</td><td>-</td><td>-</td></tr>
<tr><td colspan="2">Maximum shear strain (%)</td><td>-</td><td>3.5</td><td>-</td><td>-</td></tr>
<tr><td rowspan="4">Thickness (mm)</td><td>Design (1)</td><td rowspan="4">3.6</td><td>50.8</td><td>-</td><td>-</td></tr>
<tr><td>Design (2)</td><td>45.8</td><td>5.0</td><td>-</td></tr>
<tr><td>Design (3)</td><td>45.8</td><td>-</td><td>5.0</td></tr>
<tr><td>Design (4)</td><td>40.8</td><td>5.0</td><td>5.0</td></tr>
</table>

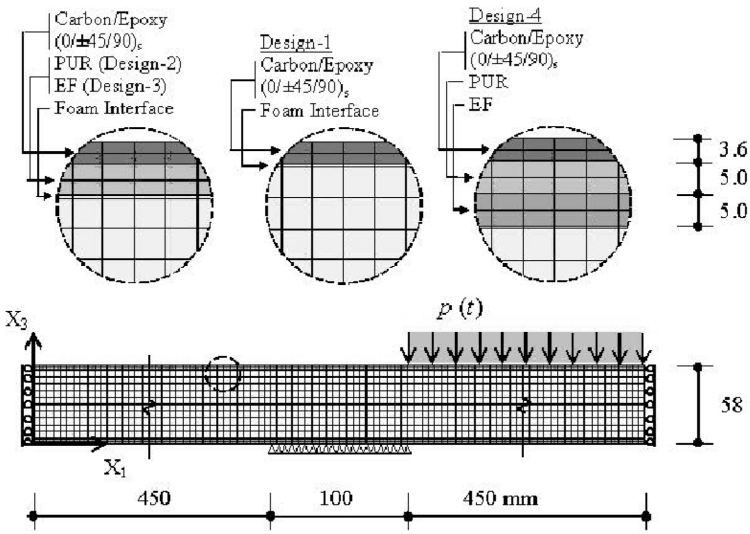

Figure 4. Finite element solution domain and mesh.

Surface to surface contact conditions were introduced to prevent the face sheet and core parts from interpenetrating each other upon erosion of the thin foam surface layers. Finally, to prevent element deformations into negative volumes, particularly in the crushable H100 foam elements, LS-Dyna's interior contact capability was activated.

4. RESPONSE TO A FULL-SPAN PRESSURE IMPULSE

When the pressure impulse of Figure 1b is applied to the entire middle span of the sandwich plate, Figure 1c, each of the four designs of Figure 2 undergoes a particular deformation history, which determines the distribution of the kinetic and strain energy absorbed by the different layers of the sandwich structure.

The extent of delamination and compression of the foam core, and the overall deformation of the standard sandwich plate Design (1) and the enhanced Design (4) is illustrated in Figure 5 at t = 0.1, 0.2 ms, which are well beyond the transient response loading period. The foam core undergoes large compressive or crushing deformation in the top half of the core layer, resulting in substantial reduction of the core thickness. Under the uniformly applied pressure, the foam compression is largest in center of the span, and then decreases in sections that are located closer to supports. During loading,

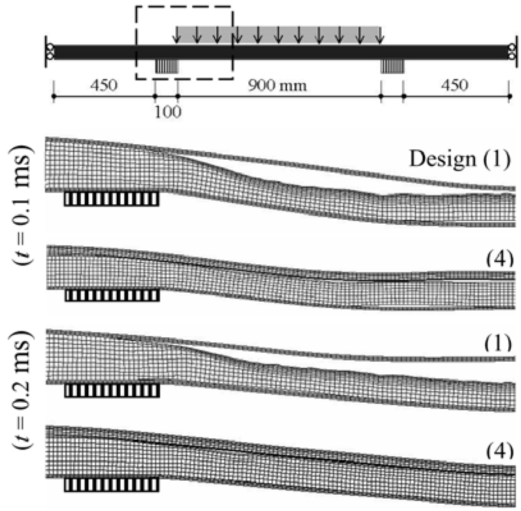

Figure 5. Deformed geometry of a sandwich plate with a standard Design (1) and modified Design (4).

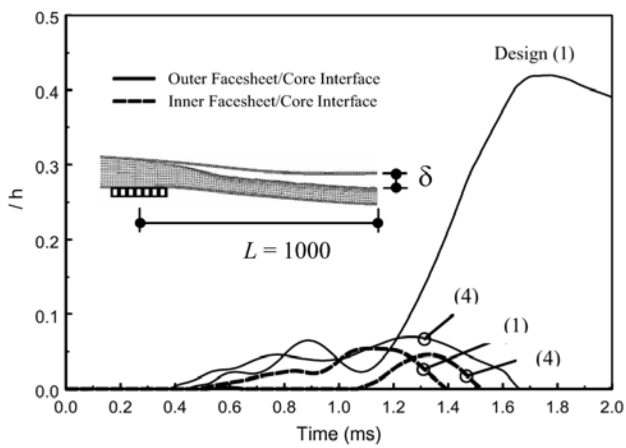

Figure 6. Comparison of facesheet/core interface opening displacement of a sandwich plate with a standard Design (1) and modified Design (4).

large displacement gradients are present in both the outer and inner facesheets. In the outer facesheet, these are associated with the significant deflections of its surface under the applied pressure. On the other hand, the displacement gradient in the inner facesheet is caused by the deflection constraints imposed by the supports.

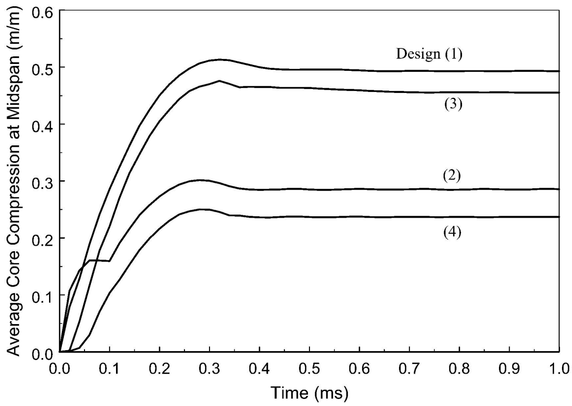

Figure 7. Comparison of average core compression of a sandwich plate with a standard Design (1) and modified Designs (2-4).

Delamination of both outer and inner facesheets from the core was detected, in the form of displacement jumps in both normal and tangential directions to the initially bonded interface. The latter, sliding separation mode is marked by the misalignment of the finite element mesh at certain closed parts of the facesheet/core interface, as seen in Figure 5. Both normal and sliding modes may materialize and interact at a particular interface point during the response time period. An illustration of the evolution of facesheet delamination in the standard Design (1), and the modified Design (4) of Figure 2, is shown in Figure 6 where the normal displacement jump across the facesheet/core interface is plotted as a function of time for the mid-span plate section. The results show a rapid growth of the opening displacement at the debonded outer interface for the standard Design (1). The peak displacement was reduced by a factor of 5.0 in the modified Design (4). Facesheet delamination also occurs at the inner interface with similar opening displacement histories for Designs (1,4).

Averaged core compression at midspan, computed as the ratio $\Delta t_c / t_c$, where t_c is thickness of the foam core and Δt_c is the change in its magnitude, is plotted in Figure 7 as a function of time. Both fully bonded and gradually debonding face sheets are considered. A steady state is reached within about 0.2 ms, after a rapid rise to average strains of 0.3-0.5. However, much larger local compressive or crushing strains are present in the foam core. The stiff PUR interlayer found in Design (2) appears to absorb the induced shockwave, and thus better protect the inner foam core from crushing, which is reduced to about 60% of that in Design (1). On the other hand, the compressible elastomeric foam (EF) interlayer found in Design (3) does not offer a significant improvement in protecting core crushing over the standard sandwich design. However, utilizing a pair of

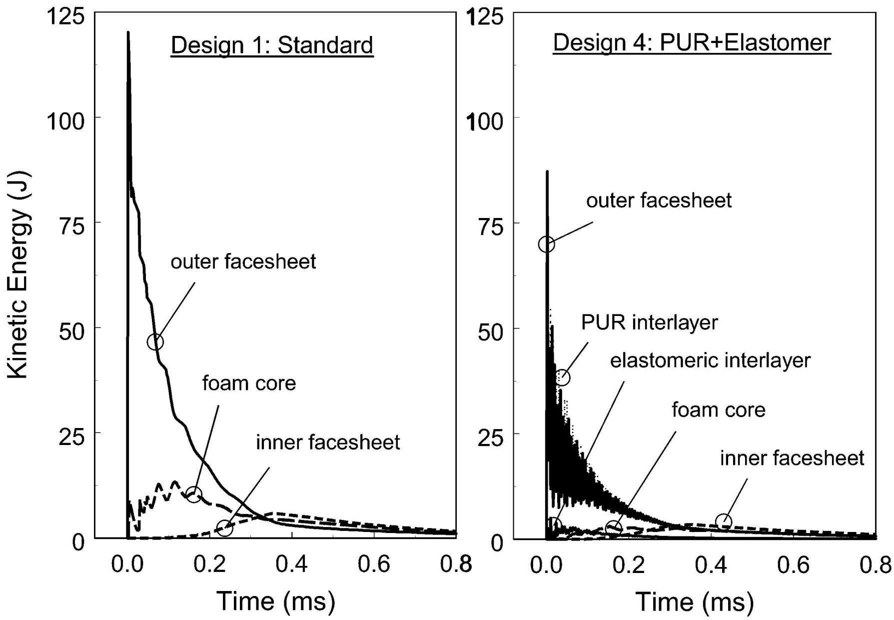

Figure 8. Comparison of kinetic energy distribution in standard Design (1) and Design (4) with polyurethane and elastomeric foam interlayers.

PUR and EF interlayers in Design (4) provides the best protection for the foam core. In this case, the average compressive strain in the core thickness is reduced to about 50% of that in Design (1), Figure 7.

The total energy imparted by the applied pressure impulse is converted, in part, in the strain energy stored in the elastic materials parts of the structure, the energy dissipated by structural and EF foam crushing and face sheet delamination, and the kinetic energy of the moving parts of the sandwich structure. The elastic strain energy is stored primarily in the outer face sheet, and its amount is not much affected by the underlying materials. It is also stored in the PUR and EF interlayers. The inner face sheet stores a relatively small amount. Distribution of the kinetic energy among the structural components of each of the four designs is presented in Figure 8. A comparison of Designs (1) and (4) shows that the kinetic energy of the latter is reduced by about 40%.

5. DICUSSION AND CONCLUSIONS

The work presented has demonstrated the role of the interlayers in enhancing structural performance of sandwich plates under blast loads.

Compared to conventional sandwich plate designs, the benefits gained from the modified designs can be enumerated as follows:

1. The imparted kinetic energy is reduced by almost a factor of two.
2. Energy absorption is increased due to protection of the foam core.
3. Compression of the crushable core is reduced by more than 50%.
4. Opening displacement at debonded facesheet/core interfaces is reduced by a factor of five.
5. Longitudinal strain in the facesheets is reduced by more than 50%.
6. Plate deflection is reduced by 15%.
7. Curvature of the inner facesheet at the supports is substantially lowered.

The results suggest that even better enhancement of blast and impact resistance of sandwich plates could be achieved by more extensive or total replacement of the crushable foam core. A polyurethane core, or one made of a similar material capable of large elastic deformations at high strain rates appear to be suitable candidates. Delaminations could be reduced if the new core would serve as a matrix in the facesheets. For example, Kevlar fiber layers could be inserted in the surface layers of both inner and outer faces of the core, and even inside the core to support high tensile stresses, using advanced fiber architectures and available tire making technology.

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