THE OBLIQUE IMPACT RESPONSE
OF COMPOSITES AND SANDWICH
STRUCTURES

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ABSTRACT

This research project focussed on the low-velocity oblique impact response of glass fibre-reinforced epoxy laminates and sandwich structures with a range of polymeric cores of linear PVC and PET with nominal densities in the range of 90-140 kg/m$^3$, conducted at normal ($0^\circ$), $10^\circ$ and $20^\circ$ inclination angles, at energies up to 40 J. For the laminated composites and the linear PVC sandwich structures, at maximum impact energies, the damage area reduced whilst the energy absorbed increased with increasing inclination angle. Damage took the form of matrix cracking, due to bending and shear, combining with fibre fracture due to tensile loading. In the case of the higher density foam-core sandwich structures (PVC and PET), the maximum damage area occurs at $10^\circ$ and less severe damage occurs at $20^\circ$, suggesting an effect of the combination of tensile, compression and shear occurred at $10^\circ$. Interestingly, the absorbed energy reduced with increasing inclination angle for these structures. The threshold energy in which visible damage occurs was observed at 14 J and 10 J for the laminated composites and sandwich structures, respectively. At higher energy levels (40 J), full perforation occurred. Contrary to the observations at relatively low energies, the PET-based sandwich structures showed increased damage with increasing inclination angle. An energy-balance model was established and used to successfully predict the maximum impact force ($P_{\text{max}}$) values, showing good agreement with the experimental results up to the threshold energy. In addition, these findings also showed that core density has a great influence on the impact response of the sandwich structures, whereby the contact stiffness, $C$, and the maximum impact force ($P_{\text{max}}$), increased with an increase in core density.
NOMENCLATURES

Symbols

\( t \) \quad \text{Impact duration}

\( h_c \) \quad \text{Thickness of the core}

\( E \) \quad \text{Young’s modulus of the composite}

\( \rho \) \quad \text{Density of the composite}

\( R_p \) \quad \text{Support span}

\( \rho_1 \) \quad \text{Density of the facesheet}

\( M \) \quad \text{Target mass}

\( m \) \quad \text{Mass of the indenter}

\( k \) \quad \text{Constant stiffness; static force required to produce unit transverse deflection}

\( V_o \) \quad \text{Velocity of the indenter immediately before impact}

\( U_o \) \quad \text{Energy of the indenter before impact}

\( U_i \) \quad \text{Energy of the indenter at time, } t

\( U_p \) \quad \text{Strain energy stored by the plate at time, } t

\( F, P \) \quad \text{Contact force}

\( F_{\text{max}} \) \quad \text{Maximum load (force)}

\( V \) \quad \text{Velocity of the indenter}

\( E_b \) \quad \text{Energy absorbed in bending effects}

\( E_s \) \quad \text{Energy absorbed in shear effects}

\( E_m \) \quad \text{Energy stored due to membrane stiffness}

\( E_c \) \quad \text{Energy stored in the contact region during indentation}
$K_{bs}$ Linear stiffness including bending and transverse shear deformation effects

$K_m$ Membrane stiffness

$\omega$ Overall deformation of the plate (target)

$\omega_o$ Maximum deflection of the plate

$\alpha_o$ Maximum indentation of the plate

$G$ Shear modulus of the foam core

$L$ Span

$D$ Flexural rigidity of the skins

$A$ Geometrical parameter that depends on the thickness of the core and skin materials, as well as the beam width.

$\delta_{\text{max}}$ Maximum displacement

$P_{\text{max}}$ Maximum contact force

$C$ Contact stiffness

$\alpha$ Indentation

$E$ Young’s modulus

$E_1$ Young’s Modulus of the indenter

$E_2$ Young’s Modulus of the target

$R$ Radius of the indenter

$\nu$ Poisson’s ratio

$\delta$ Displacement

$n$ Indentation exponent

$P_{\text{crit}}$ The critical impact load or threshold value

$t$ Laminate thickness

$E$ Flexural modulus
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<tr>
<td>$G_{IIc}$</td>
<td>Critical value of the energy release rate for Mode II fracture</td>
</tr>
<tr>
<td>$P_f$</td>
<td>Indentation load at shear failure</td>
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<tr>
<td>$K_c$</td>
<td>Constraint factor</td>
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<tr>
<td>$F_f$</td>
<td>Maximum impact force</td>
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<tr>
<td>$\tau_{13d}$</td>
<td>Dynamic transverse shear strength of the facesheet</td>
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<tr>
<td>$q_d$</td>
<td>Dynamic crushing strength</td>
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<td>$\varepsilon_{cr}$</td>
<td>Tensile fracture strain</td>
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<td>$N_{cr}$</td>
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<tr>
<td>$P_f$</td>
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<tr>
<td>$d$</td>
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<tr>
<td>$R_e$</td>
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<td>$\gamma_f$</td>
<td>Transverse shear fracture strain</td>
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<td>$G_{13}$</td>
<td>Transverse shear modulus of the honeycomb</td>
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<td>$E_l$</td>
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<tr>
<td>$V_S$</td>
<td>Striking velocity</td>
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<tr>
<td>$V_R$</td>
<td>Rebound velocity</td>
</tr>
<tr>
<td>$U_R$</td>
<td>Strain energy due to the deflection of the guide rods</td>
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<tr>
<td>$K$</td>
<td>Transverse stiffness of the indenter and the guide rod assembly</td>
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<tr>
<td>$F_H$</td>
<td>Horizontal force in the guide rod assembly</td>
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<tr>
<td>$F_N$</td>
<td>Normal or reaction force</td>
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<tr>
<td>$F_s$</td>
<td>Striking force (measured by the force transducer during an impact test)</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Plate inclination angle</td>
</tr>
<tr>
<td>$k$</td>
<td>Indenter unit stiffness in horizontal direction</td>
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\( \delta x \)  Displacement in horizontal direction

\( F_T \)  Friction or tangential force

\( \mu \)  Coefficient of friction

\( r \)  Radius of the right cylinder

\( R \)  Long radius of the elliptical oblique cylinder

\( I \)  Angle between the right cylinder and the elliptical oblique cylinder

\( D \)  Diameter of the damage

**Abbreviations**

- SDOF  Single-degree of freedom
- TDOF  Two degree of freedom
- ILSS  Interlaminar shear strength
- CSM   Chopped strand mat
- ACG   Advanced Composites Group
- UD    unidirectional
- PVC   poly (vinyl chloride)
- PET   poly (ethylene terephthalate)
- BVID  barely visible impact damage
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