THE EFFECT OF ANGLE OF INCIDENCE ON THE IMPACT RESPONSE OF COMPOSITES AND SANDWICH STRUCTURES

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Abstract
This paper presents a study on the low-velocity impact response of glass-fibre reinforced epoxy laminates and sandwich foam structures at three impact angles including 0°, 10° and 20° over a range of impact energies. Also, based on the conservation of energy, predictions of the maximum contact force at varying impact angles were carried out using an energy-balance model. An effect of varying the angle of obliquity is that damage initiation differs for the GFRP laminate structures at different impact angles. In terms of the damage pattern, oblique impact resulted in a more elliptical shape of damage, particularly for the samples impacted at 20°, in comparison to the typical oblong or "peanut" shape damage mode induced at normal impact angles. Overall, normal impact loading resulted in more severe forms of damage in the glass-fibre reinforced epoxy laminate as well as in the sandwich foam structures. In addition, using an energy balance model for a circular plate, there is a good agreement between the predicted maximum contact force and the experimental findings for both the composites and the sandwich structures. This indicates that it is possible to predict the maximum contact force of laminates as well as sandwich foam structures at oblique angles.

1.0 Introduction
Extensive research have focused on foreign object since this phenomenon could affect the mechanical performance of the composite material, potentially causing significant reductions in the strength of the structure, which can sometimes lead to severe damage over time. At low impact energies, damage is usually barely visible and often cannot even be detected by non-destructive testing (NDT). Typically, impact events can occur during the manufacturing process, in-service operation as well as during maintenance of a structure or component [1-3, 5].In general, normal impact is considered to be the most unfavourable dynamic loading condition; however the possibility of oblique impact occurring must also be considered. In addition, depending on the angle of incidence of the projectile with respect to the target, rebounding or ricocheting can occur [4]. To date, a limited number of studies have focused on the oblique impact response of composites, although most of these works are dedicated to ballistic impact.

Among these is the experimental investigation by Madjidi *et al.* [5] on normal and oblique impact response of chopped strand mat reinforced polyester laminates at varying impact angles. They reported that CSM (Chopped Strand Mat) reinforced polyester laminates suffered much greater damage under normal angle in comparison to obliquely impacted laminates, at impact velocities in the range of 0 to 5.4 m/s. It was also observed that the damaged area reduced with increase in the inclination angle.

The aim of this study is to investigate the low-velocity oblique impact response of fibre-reinforced composites and sandwich structures. Also, an energy-balance model is used to predict the maximum contact force at varying angles.

2.0 Experimental Procedure

The 8-plies glass-fibre reinforced laminates were fabricated using the unidirectional fibre reinforced epoxy prepreg laminate supplied by the Advanced Composites Group with lay-up sequence of $[0/90/0/90]_s$. The sandwich foam panels were fabricated using 4-plies of the UD GFRP laminate with lay-up sequence of [0/90/0/90] as the facings in between the linear PVC foam core, supplied by Alcan Composites with the commercial name of AIREX®R63.80, with nominal density of 102.4 kg/m^3. The test panels were cured in the hot press. The nominal cured thickness of the GFRP laminate is 2.0 ± 0.5 mm, whilst the total thickness of the sandwich panel is 21 ± 0.5 mm, with final dimensions of 150 mm x 150 mm.

Using the drop hammer rig, the test panels were impacted at the centre using a 5.6 kg carriage using a 12-mm hemispherical steel indentor at a release height between 0.28 m to 0.55m to study the impact response from 2 J up to 31 J. A jig was fabricated to study impact events at both 10° and 20° impact angles. All the test panels were fully-clamped between a circular steel ring supports, with the inner diameter of 100 mm.

Analytical model via Energy-balance model

Based on the conservation of energy, predictions of the maximum contact force at varying impact angles were made. Using the energy-balance model [6], the impact response of the laminated composites was modelled, where it is assumed that the kinetic energy of the target is absorbed in bending, shear and contact effect deformations, using equation (1) as follows:

$$\frac{1}{2}mv^2 = E_{b/s} + E_m + E_c \tag{1}$$

Where m is the impactor mass, v is the velocity of the impactor, $E_{b/s}$ is the energy absorbed in bending and shear deformations, E_m is the energy absorbed in membrane deformations and E_c is the energy absorbed in contact deformations. Therefore, the energy-balance for the centrally-loaded composites can be expressed as shown in Equation (2) below:-

$$\frac{1}{2}mv^2 = \frac{1}{2}K_{b/s}\delta^2 + \frac{1}{4}\ K_m\delta^4 + \frac{C\left(\frac{P_{max}}{C}\right)^{\frac{n+1}{1}}}{n+1} \tag{2}$$

Where C is the contact stiffness and n is the contact parameter, which was determined experimentally for each impact angle considered in the study.

For the case of a centrally-loaded sandwich plate, the energy-balance model is as shown in equation (3) below:-

$$\frac{1}{2}mv^2 = \frac{{P_{max}}^2}{2}\left(\frac{1}{K_{bs}}\right) + \frac{C\left(\frac{P_{max}}{C}\right)^{\frac{n+1}{n}}}{n+1} \tag{3}$$

3.0 Results and Discussion

The experimental findings obtained from the low-velocity impact on glass fibre-reinforced epoxy laminates at varying impact angles are presented in Figure 1. From Figure 1(a), damage initiations are marked for the varying angles, where a significant difference is found between the normal impact and a 20° impact, with the damage initiation energies being 2 J, 2.9 J and 4.8 J for the 0°, 10° and 20° angles respectively. In Figure 1(b), the variation of damage area vs. impact energy as a function of impact angles is presented. It can be seen that the damage area does not differ greatly below 20 J, where the panels responded elastically. For both normal and 10° impact angles, there is a continuous increase in the maximum contact force with impact energy up to 28 J. Above this, a sudden drop in load is observed, where full perforation occurred in the laminates, as illustrated in Figure 3(d) to (h).

As for the impact at 20°, there is a linear increase in damage area with impact energy since no perforation occurred in the panels up to 31 J. The damage pattern observed showed a more elliptical shape for oblique impact particularly at 20°, as observed in Figure 3(f), whereas normal and 10° impact resulted in typical oblong or “peanut-like” shape, as depicted in Figures 3 (d) & (e) respectively. This is due to the elliptical contact surfaces at oblique angles which occurred at 20°. Overall, normal impact resulted in the largest damage area and the highest maximum contact force, whilst impact at 20° resulted in the lowest maximum contact force at all impact energies considered. This may be attributed to geometrical effects which induce horizontal forces at an inclined angle, particularly at 20°. Consequently, more kinetic energy is transferred to the guide rods resulting in a reduced force in the vertical component, similar to an earlier finding on oblique impact on CSM laminates [5].

The dynamic response of the linear PVC (R63.80) sandwich foam structures showed similar trends in terms of the maximum contact force and damage area, with a lower maximum contact force and a larger area of damage apparent in the sandwich structures up to 20 J at varying impact angles, as observed in Figure 2. Referring to Figure 2(c), the maximum contact force increased with impact energy at different impact angles, with the normal impact resulting in a highest maximum force. This induced the largest area of damage under normal impact; however, the 20° impact angle produced the smallest area of damage.

Typical load-histories for the sandwich panels with 28 J of impact energy are presented in Figure 4. It can be seen that in Figures 4 (a) & (b), large load-drops are observed from the impact response at normal and 10° impact angles. The load-drops observed correspond to perforation at 15 J and full perforation in the sandwich panels at normal and 10°, which were clearly apparent in the structures, as shown in Figures 4 (d) and (e) respectively. The sandwich panels at normal and 10° impact angles exhibit debonding of the top skin and the core with severe upper skin failure and core rupture. However, the sandwich panels impacted at 20° only incurred a small area of delamination up to 20 J, as observed in Figure 4 (f).

Using the energy balance model, the maximum contact force was accurately predicted for both the glass fibre reinforced epoxy laminates as well as linear PVC (R63.80) sandwich foam panels. Generally, there is good agreement between the predicted maximum contact force and the experimental values for both systems. Referring to Figure 5 (a) to (c), up to 14 J where an elastic response is observed in the panels, good correlation is observed between the predicted and experimental maximum contact forces. Above this energy, where plastic deformation occurs, the maximum contact force was over predicted. This is in agreement with earlier studies, where it has been reported that this model tends to over-estimate the peak force after the onset of damage, since it does not account for the damage initiation and propagation [7].

For the case of sandwich foam panels, in general, the energy-balance model showed good agreement between the predicted and the experimental maximum contact force, up to 10 J. Above this energy, with perforation in the upper skin occurring under normal impact and at an angle of 10°, the model over-predicted the maximum contact force, as presented in Figure 5(d) – (f).

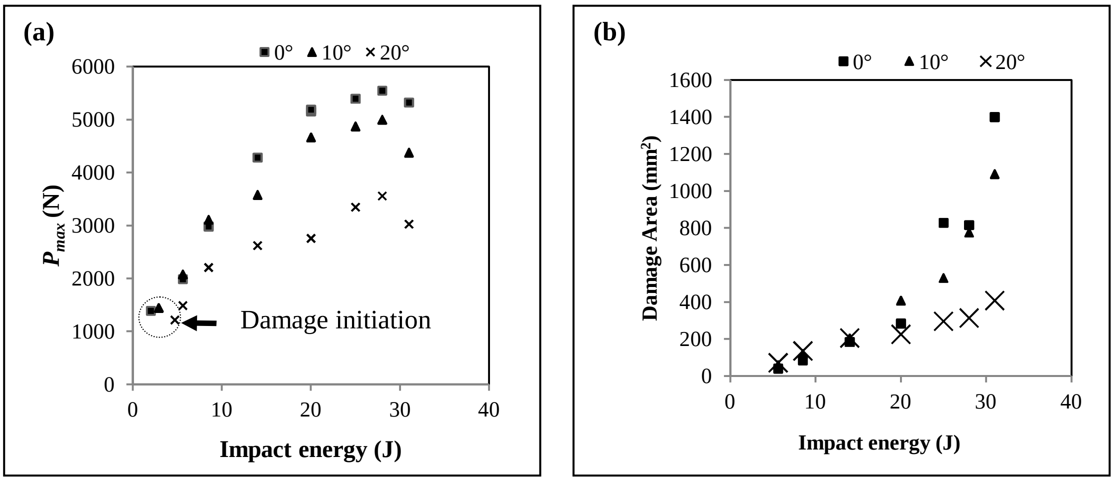

Figure 1. (a) Maximum contact force vs. impact energy and (b) Damage area vs. impact energy at varying angles for laminated composites

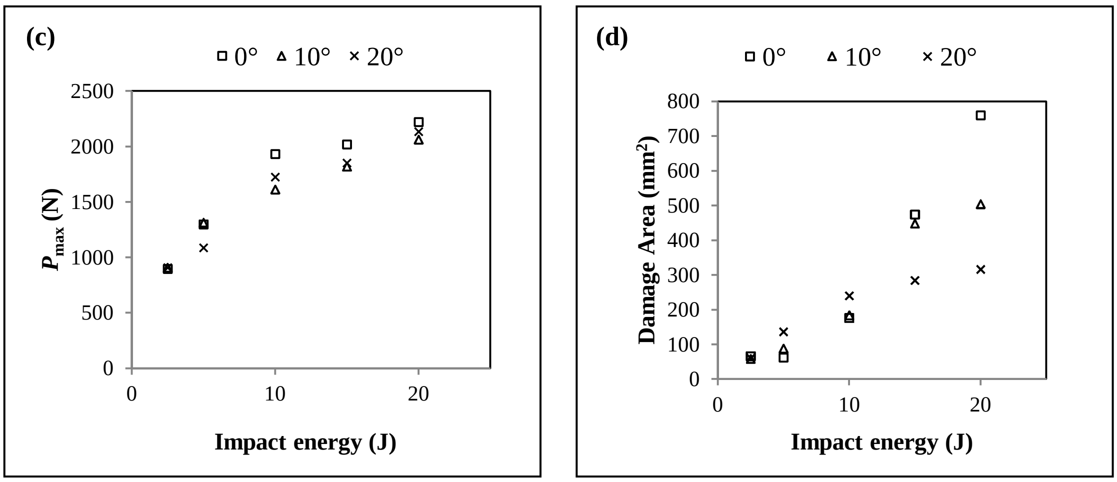

Figure 2. (a) Maximum contact force vs. Impact energy; (b) Damage area vs. Impact energy at varying angle for the linear PVC sandwich foam panels

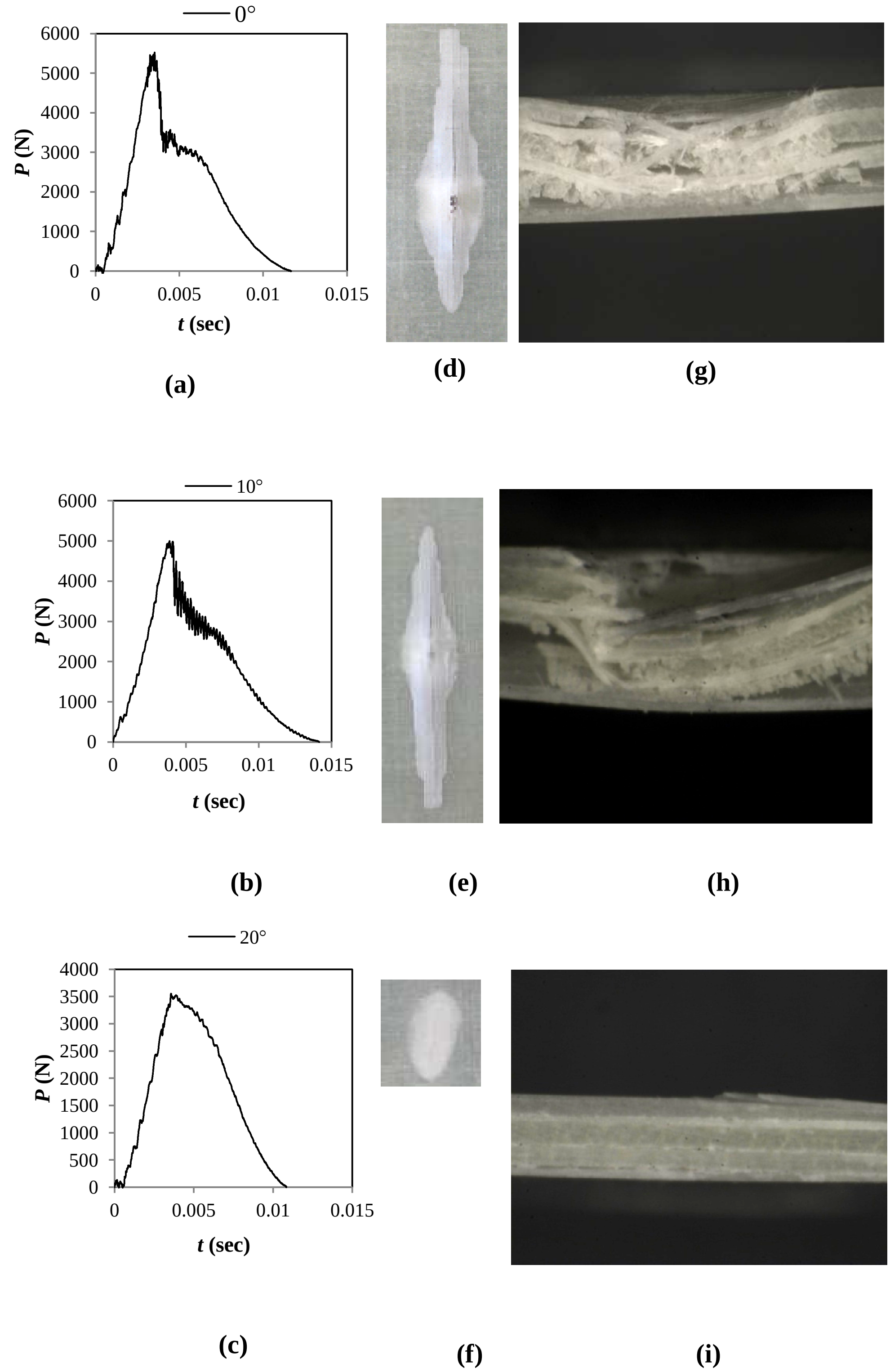

Figure 3. The impact response of the GFRP laminates at 28 J at the respective impact angle showing the load-time histories of (a) 0°, (b) 10° and (c) 20°; (d)- (f) visual image of the back surface of the GFRP laminates;(g) – (i) optical micrographs of the cross-sectional views of the impacted surface.

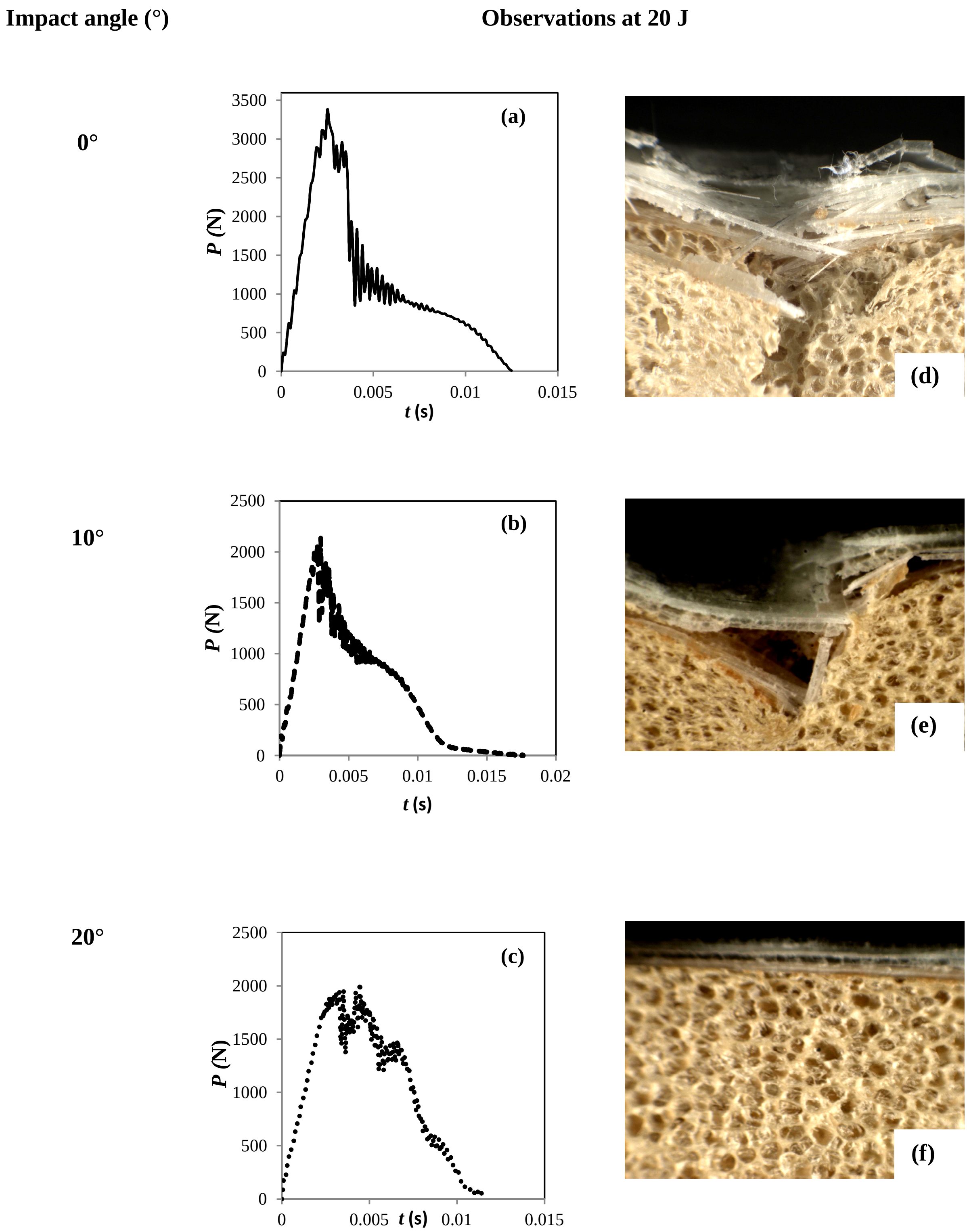

Figure 4. Typical load-histories for sandwich foams impacted at 20 J with impact angle of (a) 0°; (b) 10° and (c) 20°; Optical micrographs of the R63.80 sandwich foams showing cross-sections of the impacted surface at 20 J for (d) normal impact ;(e) 10° impact angle ; (f) 10 J and (f) at 20 impact angle.

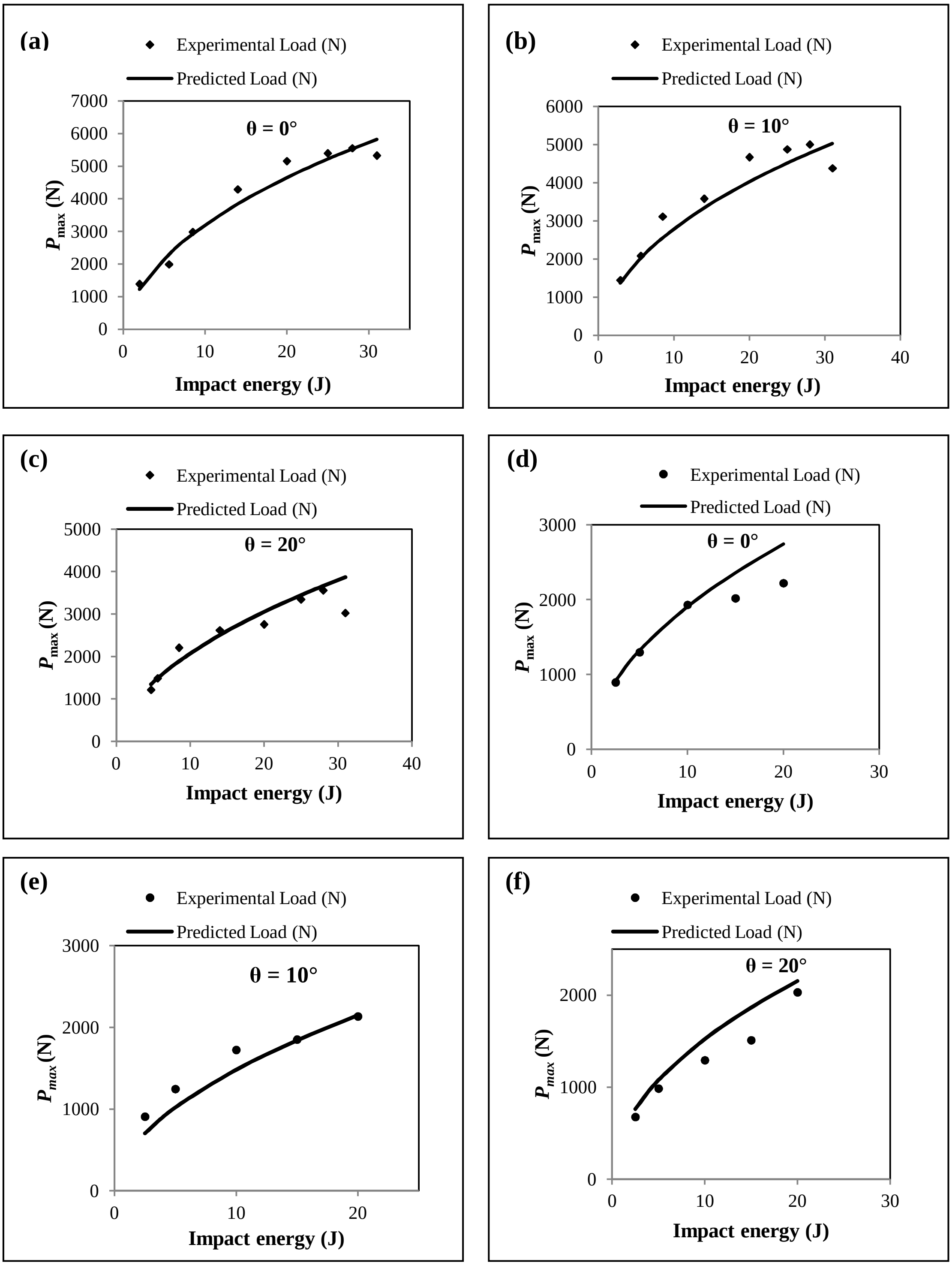

Figure 5.Predicted maximum contact force vs. impact energy at (a) normal impact angle, (b) 10° impact angle and (c) 20° impact angle for laminated composites; (d) normal impact angle, (f) 10° impact angle and (f) 20° impact angle for R63.80 sandwich foam panels.

3.0 Conclusions

From this study, it can be concluded that for low-velocity impact loading, normal impact results in higher contact forces relative to 10° and 20° impact angle. This result in more severe forms of damage, in which the normal and 10° impacts showed a typical oblong or "peanut-like" damage, whilst impact at 20° resulted in a more elliptical shape due to the change in contact surface, which is in agreement with an earlier work. In addition, an energy-balance model showed good agreement between the predicted and the experimental maximum contact forces up to the onset of damage. Above this energy, the model tends to over-estimate the maximum contact force.

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