Engineering and Technology Journal

Parametric Study of PEKK Based Fiber Metal Laminates Used in Aerospace Applications

Nassier A. Nassir[a]* , **R. S. Birch**[b] , **A. K. Haldar**[c]

[a] Materials Engineering Dept., University of Technology-Iraq, Alsina'a street, 10066 Baghdad, Iraq.
[b] School of Engineering, University of Liverpool, Liverpool L69 3GQ, UK
[c] Mechanical and Automobile Engineering Dept., Technological University of Shannon, Limerick, V94 EC5T, Ireland.
*Corresponding author Email: 130076@uotechnology.edu.iq

HIGHLIGHTS

- Understanding impact behavior informs design and optimization of FMLs for diverse engineering applications.
- FE models offer cost-effective exploration of structural behavior in FMLs under varying impact conditions.
- FE modeling reduces the requirement for expensive and time-consuming experimental investigations.

ARTICLE INFO

ABSTRACT

Numerical analyses offer a cost-effective and efficient alternative to experimental investigations, and Finite Element (FE) models have become a popular tool to simulate the behavior of Fiber metal laminates (FMLs) under impact loads. This study verified the reliability of the proposed FE models to predict the perforation response of the FMLs investigated under low-velocity impact loadings. The validation of the FE models was assessed through comparison with the corresponding results of the experimental work. The results showed that the proposed simulations are capable of predicting the dynamic response of the laminates investigated with a high degree of success. The parametric studies were conducted on 2/1 titanium FMLs based on 2-ply composite cores and 2/1 aluminum FMLs based on 4-ply composite cores under impact with a variety of loading conditions. The developed FE models were then used to explore the structural behavior of the fiber metal laminates investigated with an extended variation of parameters, i.e., projectile striking angle, impact locations, tgeometry of the projectile, and velocity. The results of the FE models are presented in terms of load-displacement traces, energy absorption, and failure modes. The findings of this study contribute to the understanding of the structural behavior of FMLs under impact loads and can inform the design and optimization of FMLs for various engineering applications. The use of FE models provides a cost-effective and efficient means of exploring the structural behavior of FMLs under different impact conditions, which can reduce the need for costly and time-consuming experimental investigations.

1. Introduction

FMLs are a class of materials widely used in the aerospace, automotive, and marine industries due to their high strength-to-weight ratio and durability. Understanding the structural behavior of FMLs under impact loads is crucial to ensure their safe and reliable performance. However, conducting experimental investigations can be costly, time-consuming, and sometimes challenging. FMLs have received significant attention in aerospace applications and it has been used extensively in the design of specific aircraft such as the upper fuselage of the Airbus A380 due to their outstanding fatigue properties [1,2]. FMLs also offer attractive properties under dynamic loadings, i.e. localized impact tests [3]. FMLs are based on stacking alternative layers of composites and metal sheets. The superior properties of FMLs are relative to their constituents. The static and dynamic responses of ARALL (epoxy-based aramid fiber /aluminum, CARE (epoxy-based carbon fiber /aluminum), and GLARE(epoxy-based glass fiber /aluminum laminates were investigated by Vlot [4]. The results showed that FMLs exhibited a smaller post-impact damage zone than fiber-reinforced composites. Extensive work has been undertaken to investigate the impact properties of epoxy-based fiber–metal laminates [4 –8].

The numerical response of FMLs under impact loading has been developed using finite element models. Lee et al. [9] used explicit finite element code, LS-DYNA3D, to model the penetration and perforation responses of aluminum (6061-T6) and

carbon fiber-reinforced 6061-T6 (MMC) plates under impact loading. Hughes-Liu shell elements were used to model carbon fiber reinforced composites, whereas the projectile, aluminum plate, and aluminum matrix of the composite were modeled using 8-node hexahedron elements. Perforation damage of the plate was found to occur under all the impact conditions investigated. The deformation behavior of the projectile, plate, projectile post-perforation velocity, and projectile's deceleration was significantly dependent on the properties of the plate and impact velocity.

Guan et al. [10] investigated the impact resistance of the FMLs manufactured by stacking woven self-reinforced polypropylene plies with two aluminum types, these being 2024-O and 2024-T3. The plain composite was modeled as an isotropic material with a specific tensile cut-off stress. The failure of the aluminum layers was modeled using shear and tensile failure criteria. Both predicted maximum permanent displacement and failure modes were correlated well with the corresponding experimental results. FE models showed that, at the perforation threshold, the passage of the projectile through the target introduces a significant plastic deformation immediately under the impact location. The failure in the lower plies of the thick panels, (i.e. 5/4 FMLs), is significantly delayed at which the projectile should perforate the upper layers before completely passing the laminates.

FE models were developed by Payeganeh et al. [11] to investigate the impact response of GLARE laminates in terms of contact force history, deflection, in-plane strains, and stresses. The results showed that the parameters such as target stacking configurations, the masses, and the velocities of the impactor are important in determining the impact response of the FMLs. Fan et al. [12] modeled the perforation response of GLARE laminates which includes woven glass fiber reinforced composite and 2024-O aluminum alloy sheets with various stacking sequences, i.e. 2/1, 3/2, and 4/3 subjected to a low-velocity impact loading. The rear surface plies of the perforated panels exhibited petalling around the perforation area. The cross-section of the failed panels shows significant delamination between the aluminum layers and composite plies, plastic deformation in the metal layers, and fiber fracture in the composites. The perforation region of these panels was successfully predicted using the FE analyses. The authors also showed that the FE models are capable of predicting the perforation energy of the FMLs under impact with various projectile diameters. The FE models suggest that the perforation energy increases rapidly with the projectile diameter in a non-linear pattern.

Many researchers suggested a full three-dimensional composite failure criterion to model the response of the composite material under impact loading [13–17]. However, it is worth mentioning that other researchers concluded that continuum shell elements available in ABAQUS/Explicit can be used to successfully model the response of the composite laminates [14],[18–21] under impact loading with good agreement between the numerical and experimental results. Seo et al. [17] developed FE models to predict the dynamic response of GLARE laminates. 2D and 3D failure criteria were used to simulate stiffness degradation in the glass reinforced-fiber composites. The FE models were validated against the experimental results reported by Wu et al. [20]. They observed that the results of both 2D and 3D models correlated well with the experimental data. Finally, it has concluded that the failure mechanisms and energy absorption of the laminated composite structures can be effectively predicted using finite element analysis. ABAQUS/ Explicit is well suited to model the dynamic response of composite structures.

A significant amount of research has been conducted on fiber metal laminates (FMLs) using various techniques such as experiments, numerical modeling, and theoretical analysis to investigate and optimize their properties and design procedures. However, there are still concerns surrounding the damage behavior of FMLs based on novel high-performance thermoplastic polymers under various loading rates, especially for those interested in using these new-generation materials in advanced engineering structures.

Experimental investigations of the damage behavior of these FMLs under different loading conditions can be expensive and time-consuming. Therefore, the objective of this study is to use validated numerical models to investigate the response of the novel FMLs under various loading conditions which are too difficult to conduct experimentally such as the effect of striking angles of impact loadings. The findings of this study can contribute to the development and optimization of novel FMLs for advanced engineering applications.

2. Modeling The Impact Response of The FMLs

The FE analyses on the titanium-based and aluminum-based FMLs were carried out to model their response under a low-velocity impact. Here, titanium layers, (GF/PEKK) composites, and PEKK (i.e. adhesive layers) were stacked together to produce titanium-based FMLs, whereas aluminum-based FMLs were made of aluminum layers, (GF/PEKK) composites, and PEKK layers. The plastic response of these metallic materials (i.e., titanium and aluminum) was modeled using an isotropic hardening. Ductile and shear damage models, which are available in ABAQUS/Explicit, were used to model the damage initiation of the titanium and aluminum layers. Hashin criteria that are available in ABAQUS/Explicit were implemented to model the damage of the composite layers. The cohesive layers on both FML systems were simulated using cohesive elements based on nominal stress and energy conjunction defined in terms of traction separation. A plate size of 72 mm x 72 mm with fully-fixed edges as boundary conditions were considered in the simulations. Only one-half of the specimen was modeled due to geometric and loading symmetries to reduce the CPU time and the associated cost. The finite element models of the fiber metal laminates investigated are fully detailed in references [8, 21- 22].

3. Results and Discussion

3.1 Effect of Angle of Obliquity

The influence of impact loadings at different striking angles, i.e., 60°, 70°, 80°, and 90°, on the 2/1 titanium-based and aluminum-based FMLs, was investigated numerically. Figures 1, 2 show the load-displacement traces generated by the FE models. Here, the impact angle refers to the angle between the target axis and the projectile. It can be seen from the figures that all traces show similar stiffness values, with the force increasing up to maximum values in a roughly linear fashion after the initial plateau stage. The forces then reduce to the lowest values (i.e., depending on the friction between the projectile and targets) when the projectile fully perforates the targets.

It can be also noted that increasing the striking angle of the impactor for the titanium-based FMLs leads to increasing displacement values at peak load and decreasing maximum load, maximum displacement as well as the corresponding energy absorption, as shown in Table 1. This evidence suggests that the energy absorption capacity of the targets investigated under impacts with obliquity between 70o and 60o is better than those impacted at 90o (i.e., normal impact). The increase in the perforation energy can be attributed to the fact that, at an off-axis angle, a larger material volume should be fractured when the projectile passes through the target. However, for a given striking angle, aluminum-based FMLs did not show any significant dependency on obliquity as shown in Table 2. As shown in Figures 3 (a), (b) and (c), as well as Figures 4 (a), (b) and (c), the cross-sections predicted by the numerical analysis of the FMLs investigated were compared when subjected to impact by a 10 mm hemispherical projectile at different striking angles of 80, 70, and 60, respectively. From the figures, it can be observed that as the angle of obliquity decreases, the cross-shaped fracture occurs further away from the center of the target.
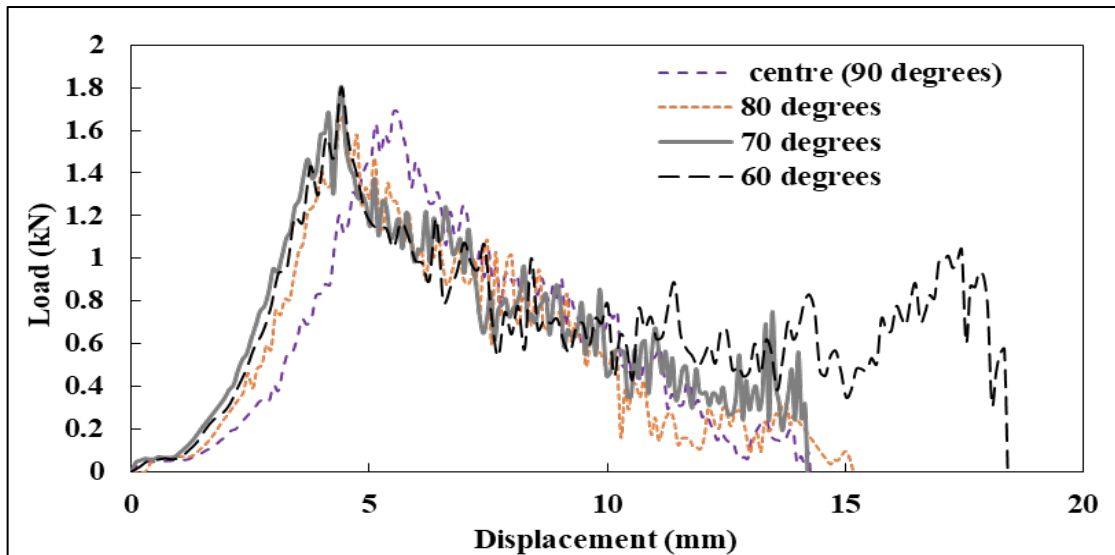

Figure 1: Predicted load-displacement traces for titanium-based FMLs under impact with various striking angles. The impactor mass and velocity were 1.48 kg and 4m/s, respectively
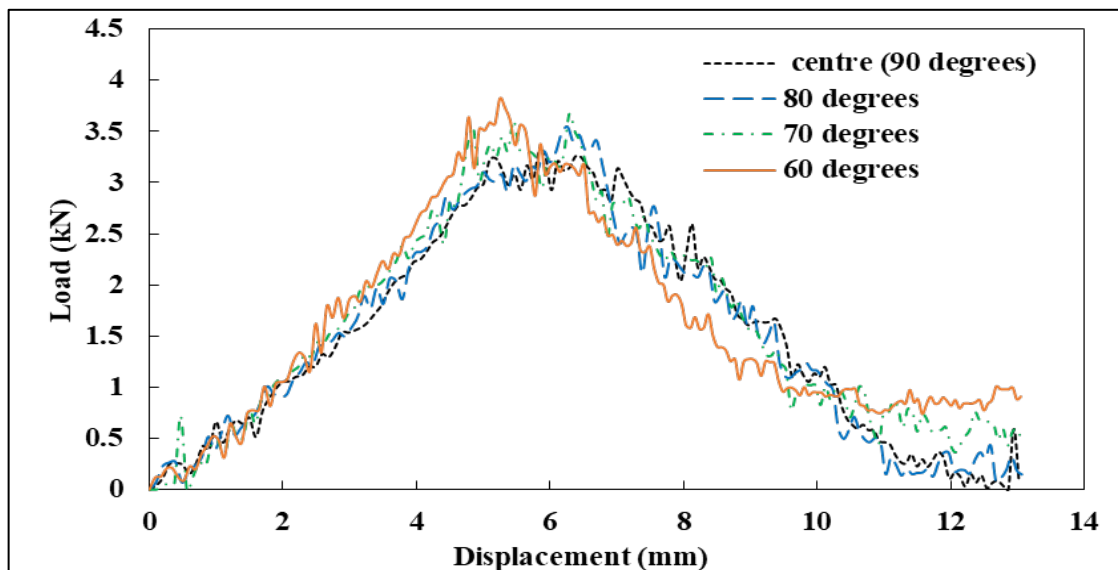

Figure 2: Predicted load-displacement traces for aluminum-based FMLs under impact with various striking angles The impactor mass and velocity were 3.56 kg and 4m/s, respectively

Table 1: Summary of results for 2/1 titanium-based FMLs (0.52 mm thick) impacted at different angles

Striking angle (degrees)	Peak force (N)	Displacement at peak force (mm)	Maximum displacement (mm)	Energy absorption (J)
60	1801	4.41	18.4	13.08
70	1804	4.41	14.2	9.87
80	1666	4.46	15.1	8.69
90	1689	5.51	14.3	8.7

Table 2: Summary of results for 2/1 aluminum-based FMLs (1.48mm thick) impacted at different angles

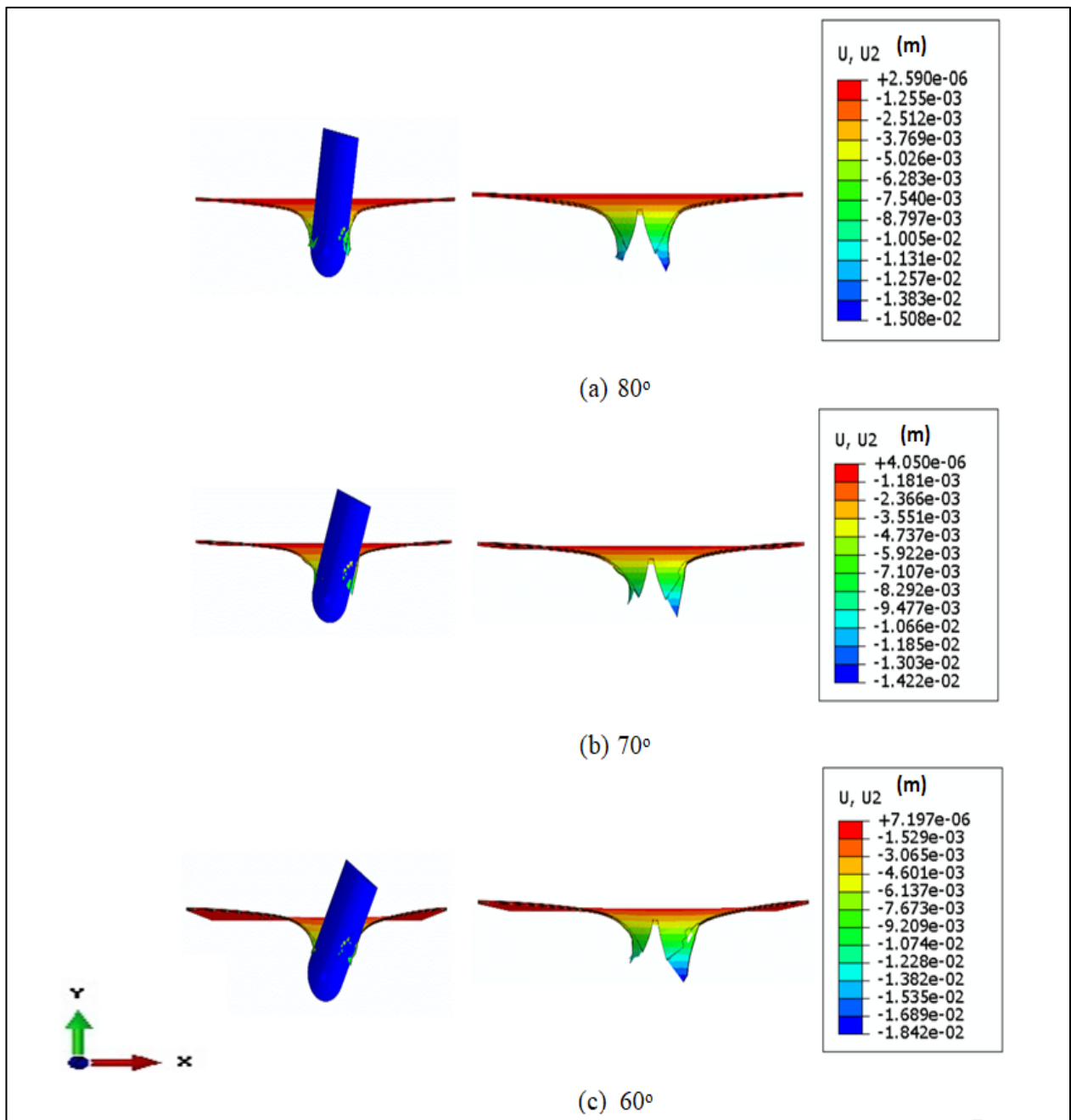| Striking angle (degrees)	Peak force (N)	Displacement at peak force (mm)	Maximum displacement (mm)	Energy absorption (J)
60	3822	5.77	13	21.3
70	3669	6.28	13	23.4
80	3545	6.26	13	20.0
90	3309	5.83	13	20.1

Figure 3: Cross-sections of 2/1 titanium-based FMLs impacted by a 10 mm hemispherical projectile at different striking angles. The impactor mass and velocity were 1.48 kg and 4m/s, respectively
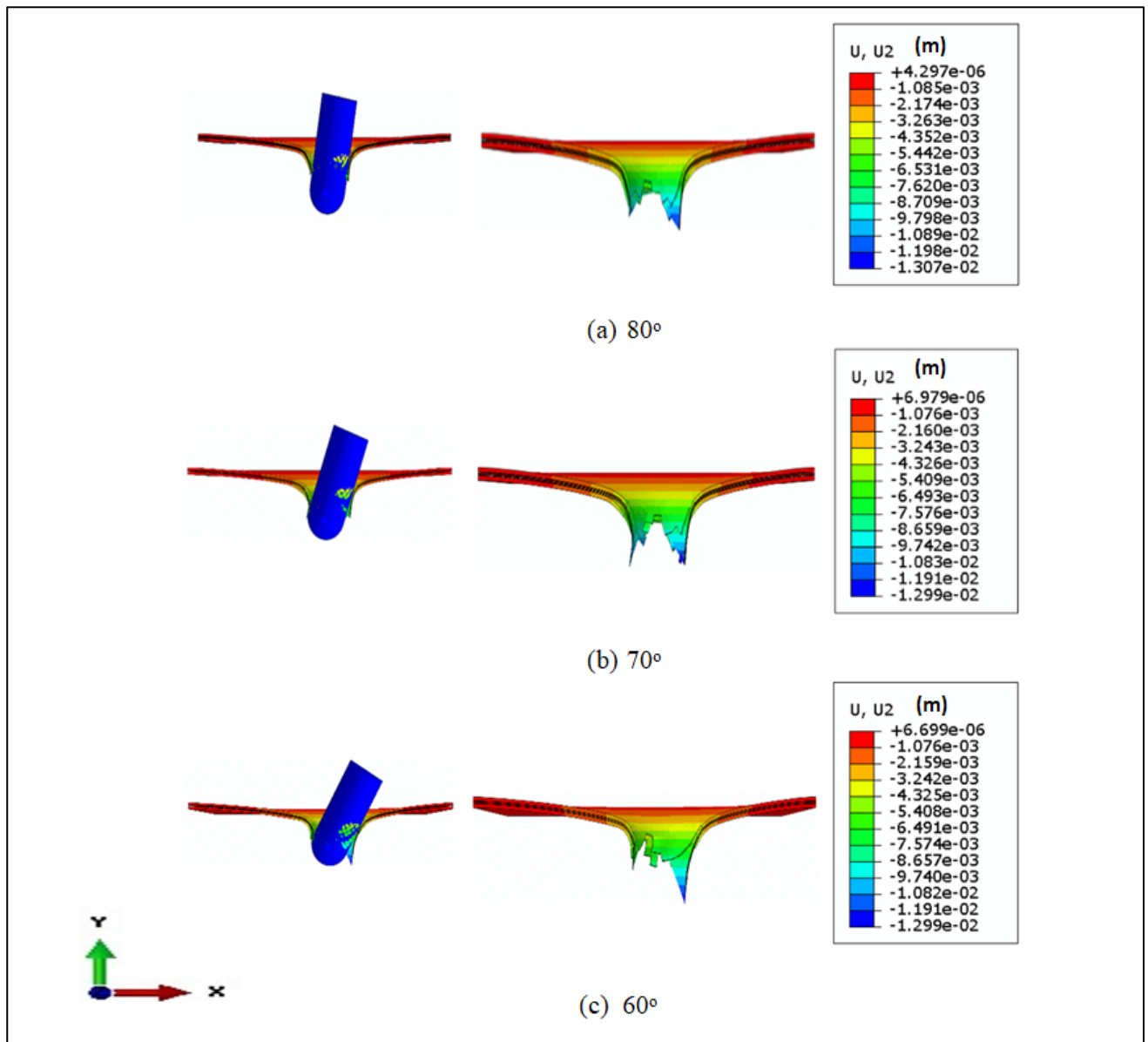
Figure 4: Cross-sections of 2/1 aluminum-based FMLs impacted by a 10 mm hemispherical projectile at different striking angles. The impactor mass and velocity were 3.56 kg and 4m/s, respectively

3.2 Effect of Impactor Mass and Velocity

Initially, an impactor with a mass of 1.48 kg and velocity of 4 m/s was used to generate an impact energy of 11.8 J on the 2/1 titanium FMLs based on 2-ply composite cores. In contrast, another impactor with a mass of 3.56 kg and velocity of 4 m/s was used to produce a constant energy of 28.4 J on the 2/1 aluminum FMLs based on 4-ply composite cores. Clearly, the impact energy generated is directly related to the mass and the initial velocity of the impactor according to the following formula:

$$E = \frac{1}{2}MV_e^{\,2} \tag{1}$$

where M and V_e are the impactor mass and velocity, respectively.

Here, the investigation focused on the effect of changing the impactor velocity and mass to generate a similar impact energy. Three numerical tests were conducted on each FML system, varying the velocities and masses. Figures 5 (a) and (b) depict the load-displacement traces of the investigated FMLs subjected to impact loads using a 10mm hemispherical projectile at velocities of 4, 2, and 1m/s. The peak load, maximum displacement, and corresponding energy values are presented in Table 3 and 4. The numerical results demonstrate that increasing the impactor velocity and decreasing the impactor mass resulted in higher peak forces for the fiber metal laminates under investigation. This suggests that, within the range of velocities tested, both FML systems exhibit improved resistance to perforation under high-velocity impact. This enhancement can be attributed to the strain rate effect, where the material strength increases at higher impact velocities. All the relevant testing variables are presented in Tables 3 and 4, respectively.
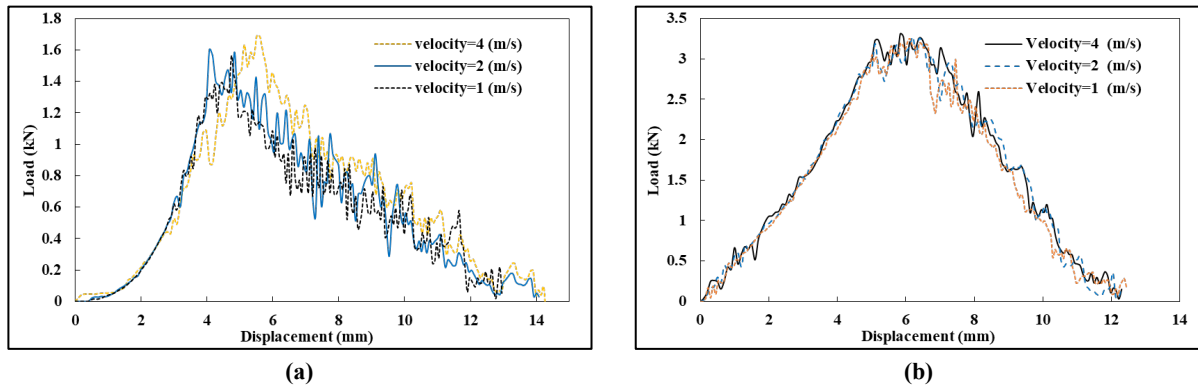
(a)

(b)

Figure 5: Load-displacement traces for 2/1 titanium-based FMLs (a), and 2/1 aluminum-based FMLs (b) impacted by a hemispherical indenter at different velocities.

Table 3: Details and results of 2/1 titanium-based FMLs impacted with different masses and velocities

Impactor mass (kg)	Impact energy (J)	Velocity (m/s)	Peak force (N)	Maximum displacement (mm)	Energy absorption (J)
1.48	11.84	4	1689	14.3	8.7
5.94	11.84	2	1600	14.0	7.4
23.68	11.84	1	1561	13.9	7.5

**Table 4:** Details and results of 2/1 aluminum-based FMLs impacted with different masses and velocities

| Impactor mass (kg)	Impact energy (J)	Velocity (m/s)	Peak force (N)	Maximum displacement (mm)	Energy absorption (J)
3.56	28.48	4	3309	13.0	20.1
14.24	28.48	2	3273	14.0	20.0
56.96	28.48	1	3251	13.4	18.7

3.3 Effect of The Projectile Size

It has been shown in this study that the projectile geometry has a significant effect on the perforation resistance of the plain GF/PEKK composites. Hence, it will be beneficial to employ the validated FE models to predict the perforation response of the dynamically-loaded FMLs under different projectile diameters. This section considers the influence of projectile size on the impact response of 2/1 titanium FMLs based on 2-ply composite cores and 2/1 aluminum FMLs based on 4-ply composite cores. Four hemispherical projectiles with diameters of 5, 10, 15, and 20mm were employed in this study. Figure 6 (a) illustrates the predicted load-displacement traces obtained from the FE models of 2/1 titanium laminates subjected to impact loading. Whereas Figure 6 (b) depicts the load-displacement traces of 2/1 aluminum-based laminates. It is evident that the impacted specimens exhibit a similar initial stiffness for both types of laminates under impact with different projectile sizes. . It can also be noted that the specimens show similar trends, i.e., the load increases with displacement up to maximum value before dropping when the projectile starts to perforate the targets.

The variation of the peak force and energy absorption with respect to the projectile diameter is inshown in Figure 7 (a) and (b), for both 2/1 titanium-based and aluminum-based FML systems, respectively. It is evident that as the projectile diameter increases, both the peak force and energy absorption increase. For example, when impacted with a 20 mm projectile diameter, the titanium-based FML (0.51 mm thick) experiences a peak force of 2500 Newtons, while the aluminum-based FML (1.51 mm thick) experiences a peak force of 5779 Newtons. Relative to the corresponding results of those impacted with a 5 mm projectile of 1291 and 2227 Newtons, they are 48 and 61 % higher, respectively. The energy absorption values of the titanium-based and aluminum-based FMLs impacted with a 20 mm projectile diameter were 61 and 71 %, respectively, higher than the corresponding values obtained using a 5 mm projectile diameter, due to a larger contact area.

Figure 8 (a), (b), (c) and (d) show the cross-sections of the 2/1 titanium-based FMLs impacted with projectile diameters of 5 mm, 10 mm, 15 mm, and 20 mm, respectively, as predicted by the FE analyses. Similarly, Figure 9 (a), (b), (c) and (d) depict the numerical cross-sections and failure modes of the 2/1 aluminum-based FMLs impacted with various projectile diameters of 5 mm, 10 mm, 15 mm, and 20 mm, respectively. A closer examination of the figures indicates that the panels show local plastic deformation and fracture at the center of the impacted area, including a combination of tensile and shear failure. As expected, the increase in the projectile diameter leads to an increase in the damaged area. Delamination can be clearly observed between the metal sheets (i.e., titanium and aluminum alloys) and the GF/PEKK layers. The delamination becomes more severe with increasing projectile diameter. The reason can be attributed to the impact time effect, that is, a larger projectile i.e., 20 mm diameter would take more time to perforate the specimen, which causes more damage as well as more delamination between the layers.
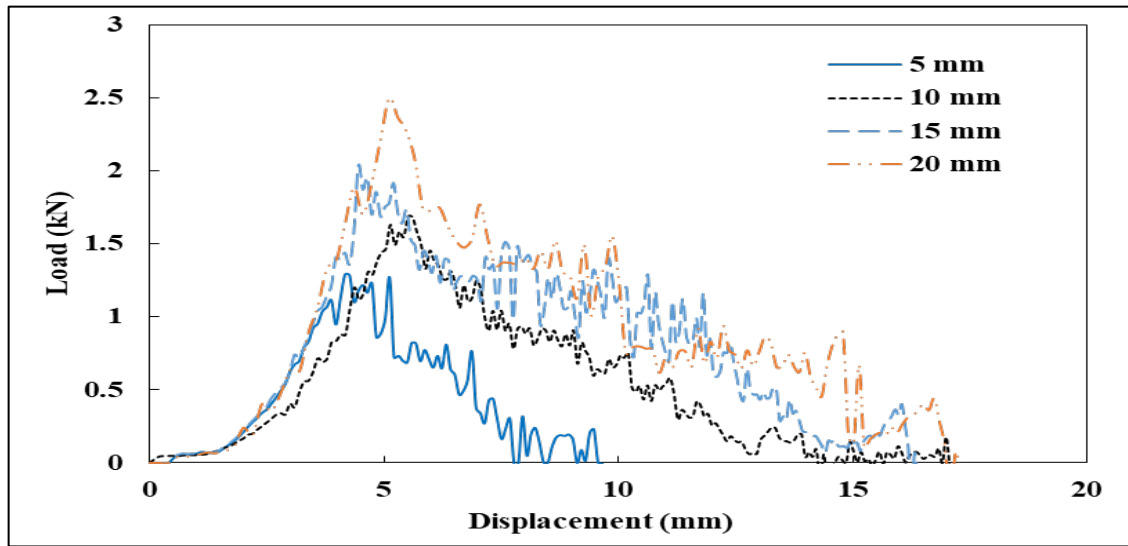
(a)   2/1 titanium (0.51 mm thick) FMLs based on 2-ply composite cores. The impactor mass and velocity were 1.48 kg and 4m/s, respectively
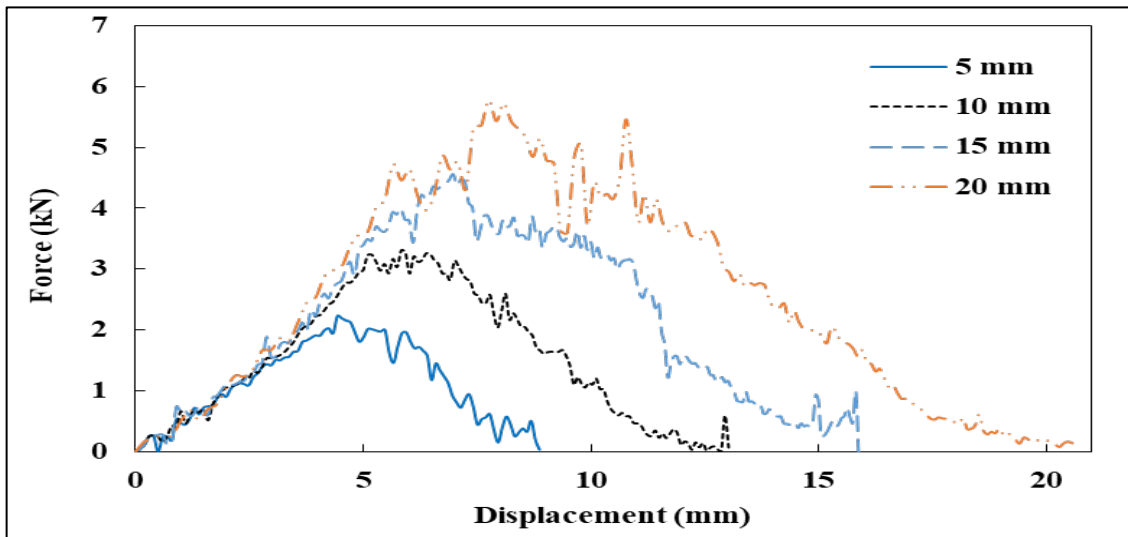
(b)   2/1 aluminum (1.51 mm thick) FMLs based on 4-ply composite cores. The impactor mass and velocity were 3.56 kg and 4m/s, respectively

Figure 6: Load-displacement traces of the FMLs investigated subjected to impact loading with various hemispherical projectile diameters
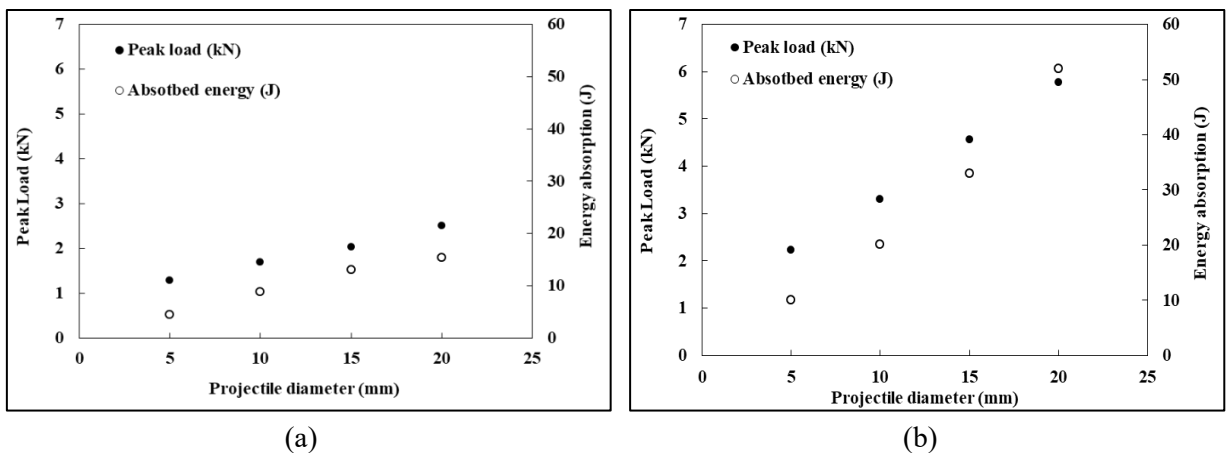

(a)

(b)

Figure 7: Variation of the peak load and perforation energy with projectile diameter for 2/1 titanium-based FMLs (a) and aluminum-based FMLs (b).
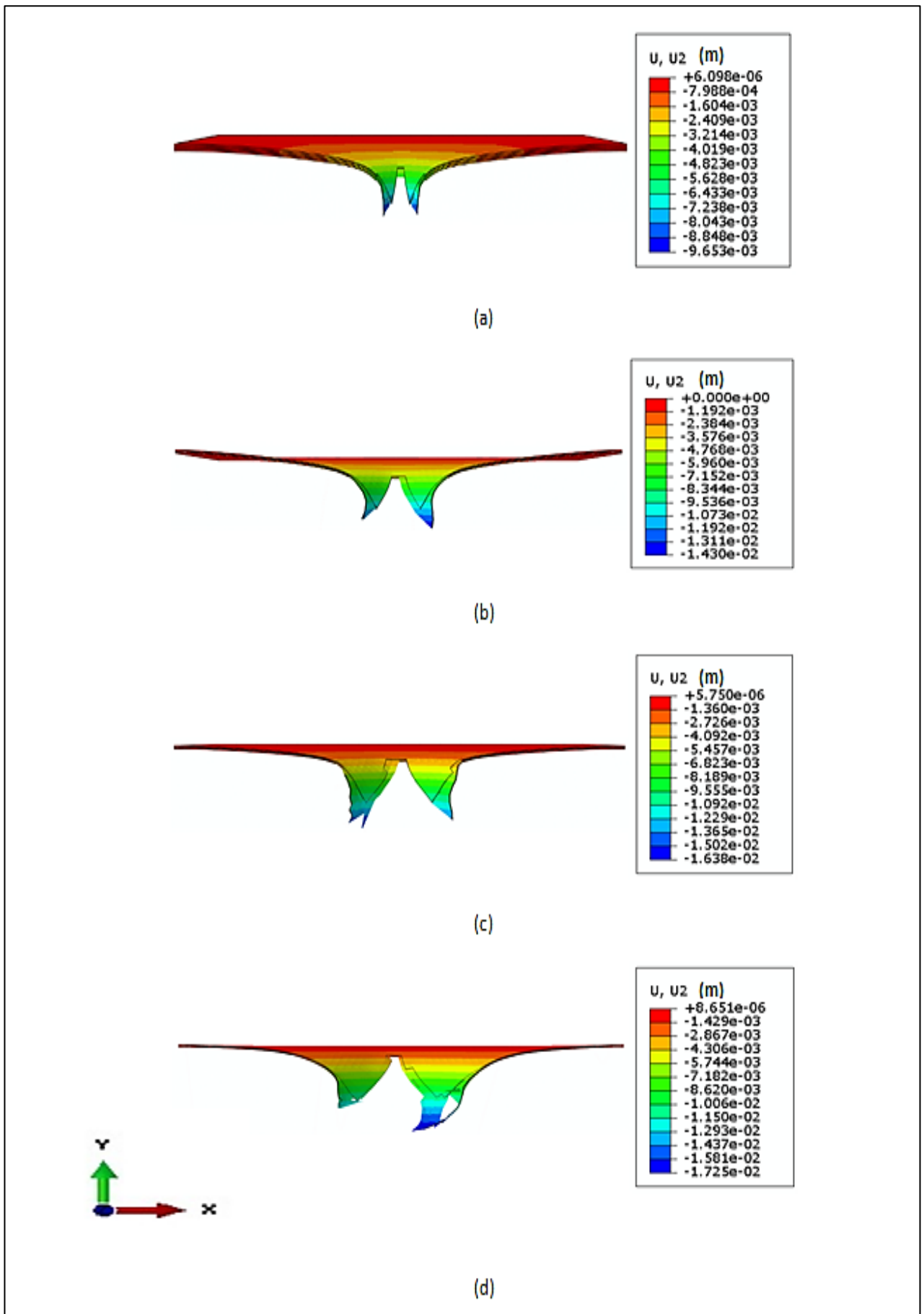
Figure 8: Predicted cross-sections of the 2/1 titanium-based FMLs impacted with different projectile diameters: (a) 5mm; (b) 10mm; (c) 15mm; (d) 20mm
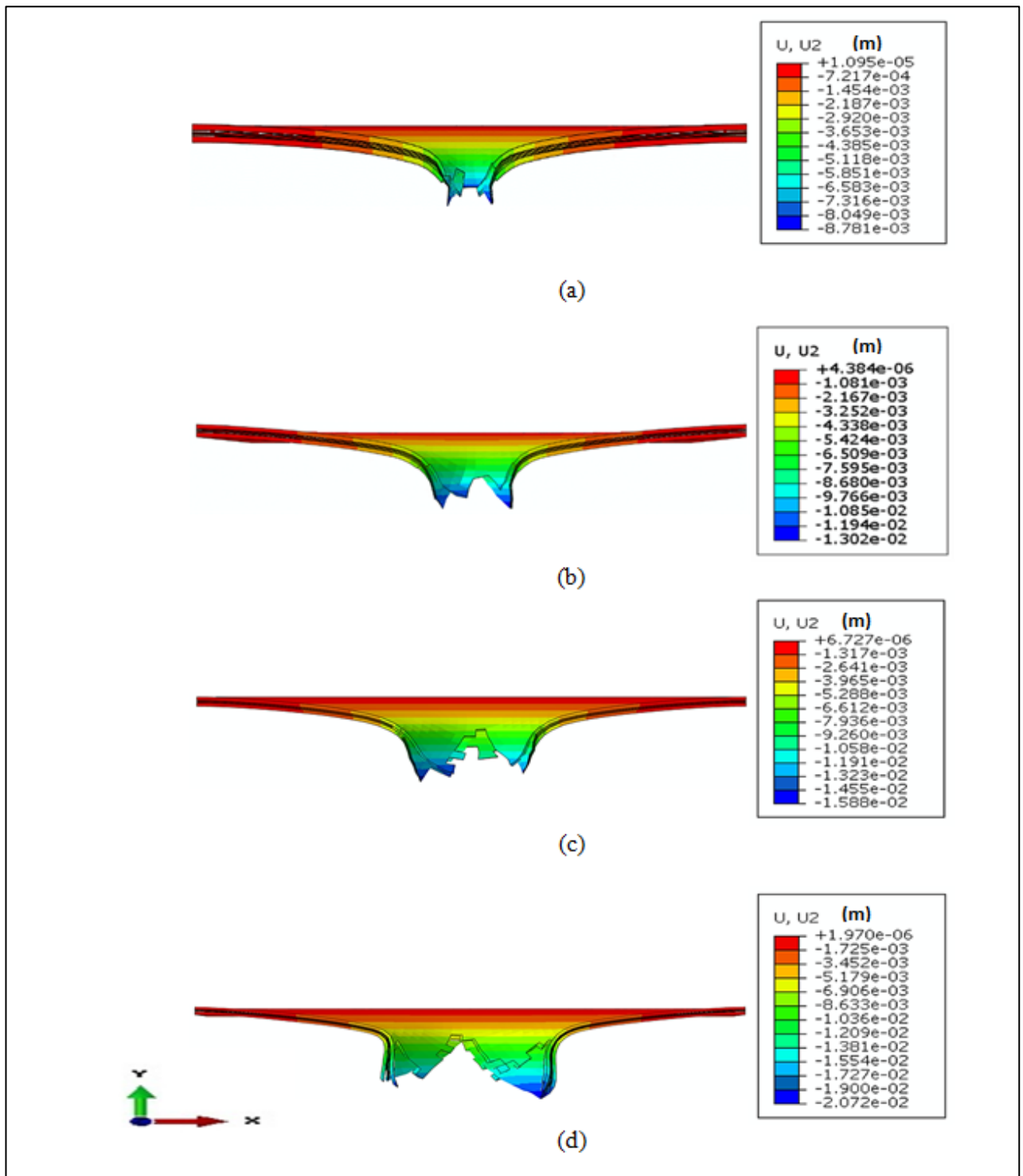
Figure 9: Numerical cross-sections failure modes of the 2/1 aluminum-based FMLs impacted with various projectile diameters: (a) 5mm; (b) 10mm; (c) 15mm; (d) 20mm

3.4 Effect of Impact Location

In practice, during routine maintenance and service conditions, composite structures may be exposed to impact at different locations, i.e. near or on the edge of the composite structure. Limited research work has been conducted to investigate the impact response of composite structures under various locations. Breen et al. [23] considered the effect of central and near-edge impacts on the residual strength of carbon fiber-reinforced plastic laminates. Their results showed that near-edge impacts caused a greater reduction in the residual compressive strength than those under central impacts. This evidence suggests that the commonly-adopted test scenario in which panels are subjected to impact at a central location may yield a non-conservative damage outlook. This may have great importance in the aerospace industry, where impact loading on composite aircraft structures rarely occurs at mid-bay locations, i.e. structures based on thin skins connected to stringers, spars, and ribs. Therefore, consideration should be given to more realistic loading conditions.

The validated finite element (FE) models were employed to investigate the effect of impact locations on the perforation response of fiber metal laminates (FMLs). The targets were subjected to impacts at various off-center locations, specifically 10 mm, 20 mm, and 30 mm. Figure 10 (a) and (b) present load-displacement traces for the 2/1 titanium-based FML (with an impactor mass of 1.48 kg and velocity of 4 m/s) and the 2/1 aluminum-based FML (with an impactor mass of 3.56 kg and velocity of 4 m/s), respectively. These load-displacement traces depict the predicted response of the laminates after impact tests involving a hemispherical projectile with a diameter of 10 mm at different impact locations. It can be seen that off-setting the impact location serves to increase the effective slope of the traces, highlighting the increased stiffness associated with such loading conditions [24].

The finite element (FE) analysis was conducted to evaluate the peak load and energy absorption of composite materials, as presented by Haldar et al. [25-27]. Similar to their study, Figure 11(a) and (b) show the variation of the peak load and energy absorption of the fiber metal laminates investigated with the striking positions. An examination of the figure indicates that off-setting the impact location from the center has no significant effect on the peak load. This may be due to the size of the specimens with a fully fixed boundary condition in which there is not a great scope to significantly change the positions of the impact within the relatively small target, i.e., 72mm x 72mm. From the figure, it can also be noted that the perforation energies of both systems are higher at the center of the target, decreasing to what appears to be a constant value as the boundary condition is approached. Interestingly, the perforation energy values at 30 off-center impact locations of the titanium-, and aluminum-based FMLs are approximately 20 and 18 %, respectively, lower than those obtained under central impact indicating that off-center impacts are more serious than the commonly-investigated central impact scenario.
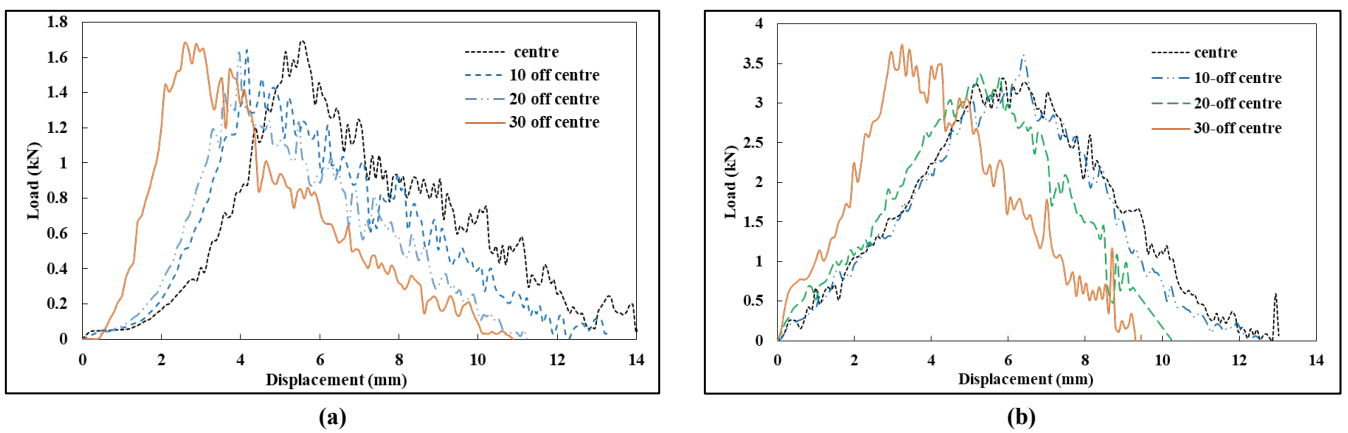

(a)   **(b)**

Figure 10: Load-displacement traces for the 2/1 titanium-based FML (the impactor mass and velocity were 1.48 kg and 4 m/s, respectively) (a) and 2/1 aluminum-based FML (the impactor mass and velocity were 3.56 kg and 4m/s, respectively). (b) following impact tests with a hemispherical projectile (10mm diameter) at different impact locations
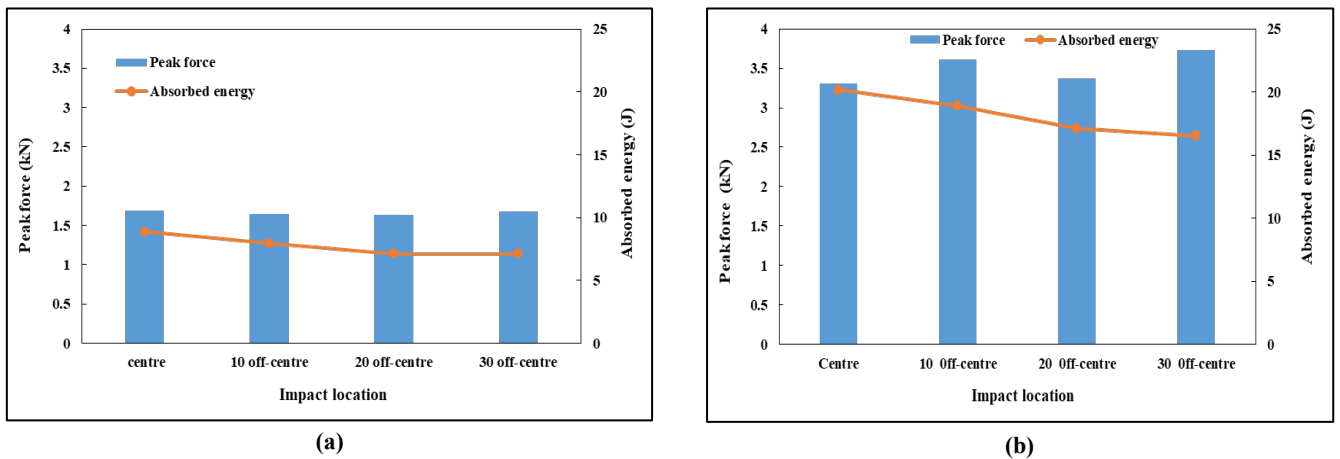

(a)   **(b)**

Figure 11: Variation of the peak force and the absorbed energy with the impact location for the 2/1 titanium-based (a) and 2/1 aluminum-based (b) FMLs impacted with a hemispherical projectile (10mm). The bar charts are the peak forces and the line is the energy

Figure 12 (a), (b) and (c) display numerical cross-sections of 2/1 titanium-based fiber metal laminates (FMLs) subjected to impacts from a hemispherical projectile with a diameter of 10mm. The impacts occurred at off-center locations of 10 mm, 20 mm, and 30 mm, respectively. Similarly, Figure 13 (a), (b) and (c) show numerical cross-sections of 2/1 aluminum-based FMLs that experienced impacts from a hemispherical projectile with a diameter of 10 mm. The impacts occurred at off-center locations of 10 mm, 20 mm, and 30 mm, respectively. These figures provide simulated visual representations illustrating the

extent and type of damage sustained by the titanium and aluminum FMLs as a result of the impacts. The simulations show that when the impact location is shifted away from the center of the FMLs, towards the boundary condition, the severity of the damage increases. Specifically, the simulations indicate that both titanium and aluminum-based FMLs experience significant delamination and fracture when subjected to off-center perforation impact. However, Figure 13 suggests that aluminum-based FMLs are more susceptible to damage than titanium-based FMLs. The aluminum-based FMLs exhibit more extensive and severe delamination and fracture compared to their titanium-based counterparts, indicating that this could be associated with several factors. For instance, aluminum is a softer material than titanium and has a lower melting point, which may lead to more significant deformation, melting, and separation of the layers in the aluminum-based FMLs upon impact. Additionally, the bonding between the aluminum layers and the fiber layers may be weaker than that in titanium-based FMLs, further contributing to the greater susceptibility of aluminum-based FMLs to damage.
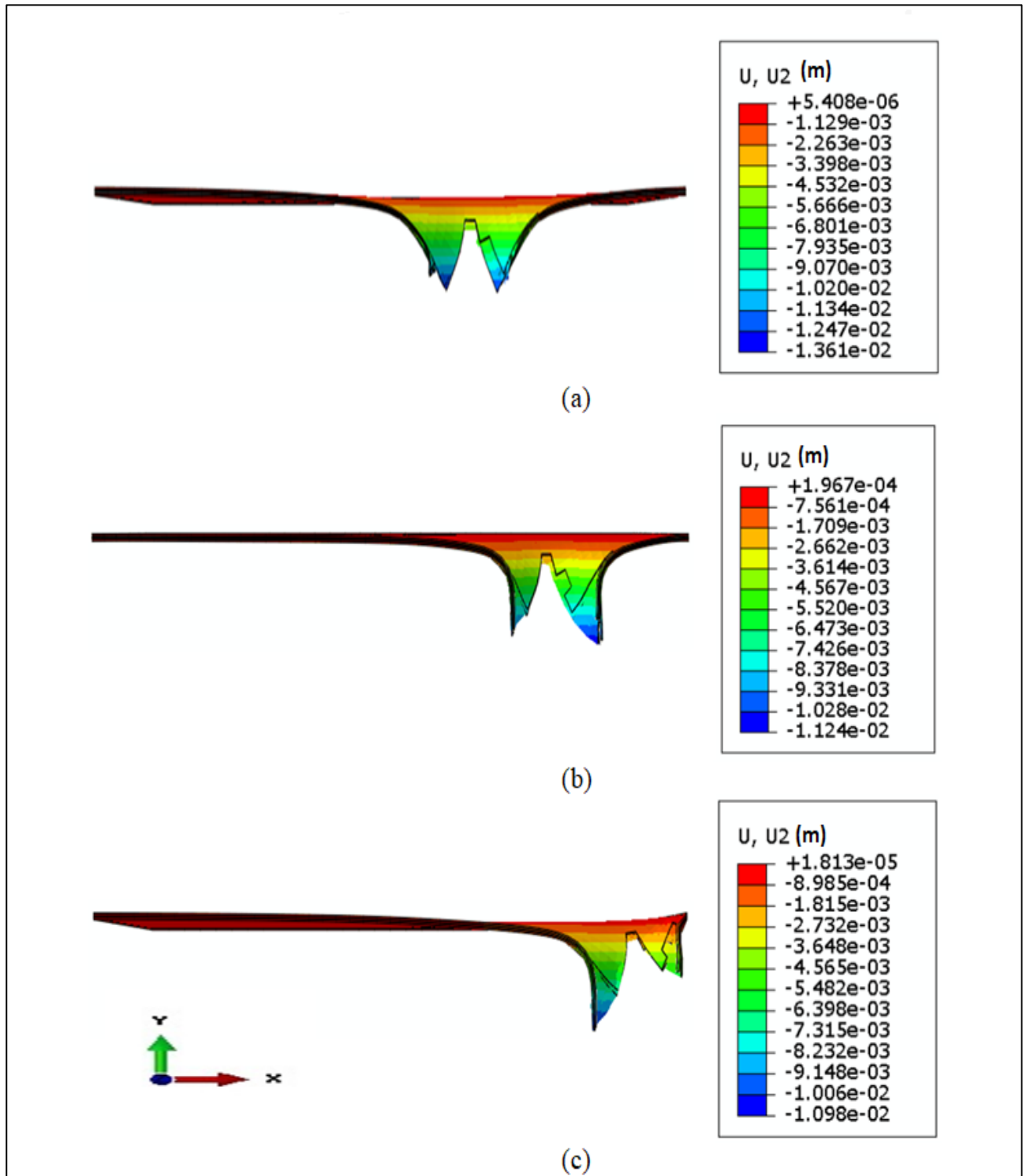

Figure 12: Numerical cross-sections of the 2/1 titanium-based FMLs impacted with a hemispherical projectile (10mm diameter) at different locations of 10 mm off-center (a) 20mm off-center (b) 30mm off-center (c)

Figure 13: Numerical cross-sections of the 2/1 aluminum-based FMLs impacted with a hemispherical projectile (10 mm diameter) at different locations of 10mm off-center (a) 20mm off-center (b) 30mm off-center (c)
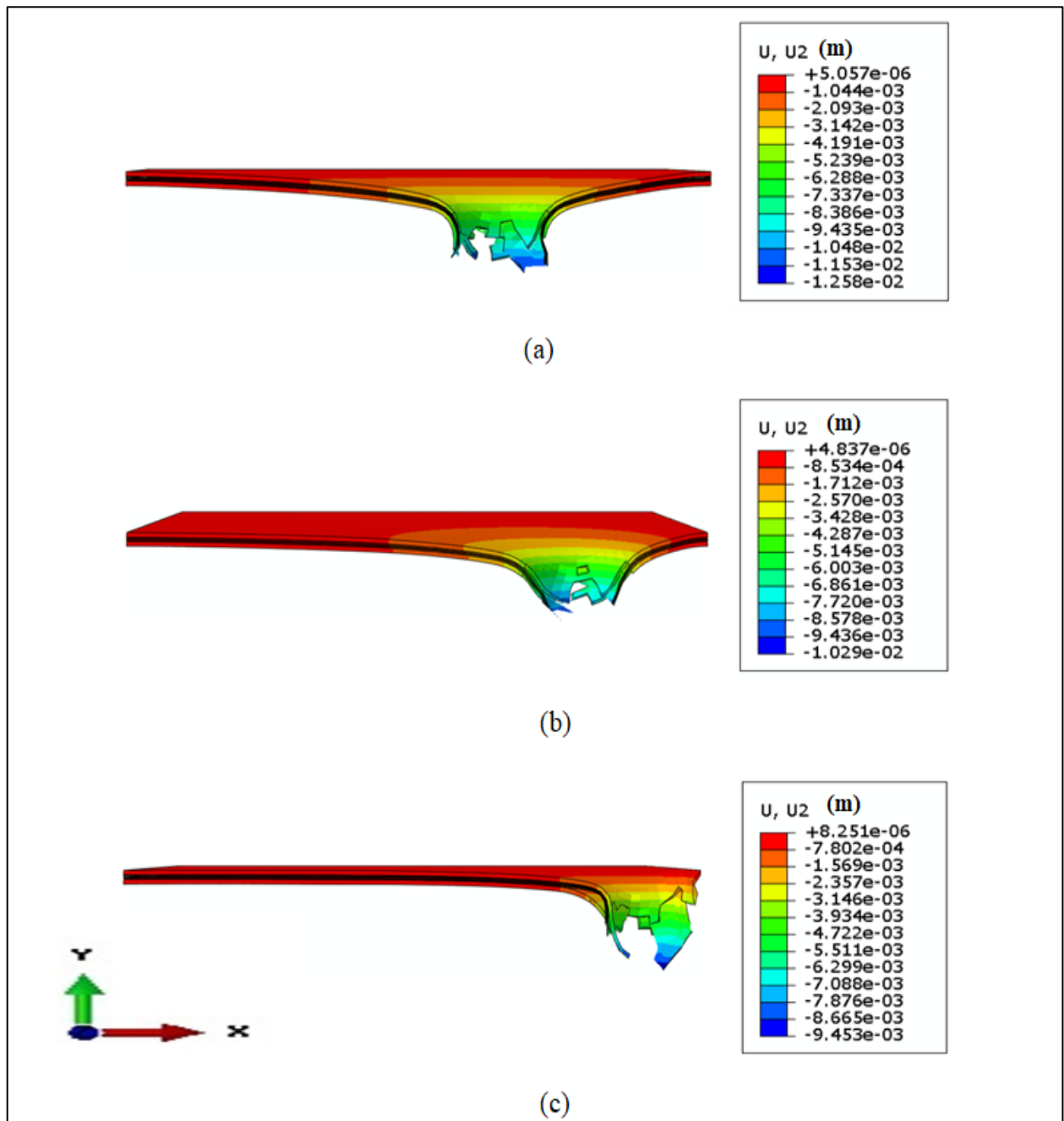
4. Conclusion

The present study employed an explicit dynamic solver, ABAQUS/Explicit, to predict the perforation resistance of GF/PEKK composites, and titanium- and aluminum-based FMLs. The validated FE models were further used to conduct parametric studies to explore the structural behavior of the novel FMLs under a variety of impact conditions. The findings indicated that both FMLs exhibited better energy absorption under oblique impacts than under normal impacts (i.e., 90°). Moreover, both FML systems demonstrated higher perforation resistance under high-velocity impacts, owing to the strain-rate effect on material strength. The peak force and energy absorption of the FMLs also increased with increasing projectile diameter.

Additionally, it was observed that off-setting the impact location from the center to the boundary condition resulted in a more severe damage response for the laminates, with significant delamination observed. These results emphasize the importance of careful selection and positioning of impact locations when designing FMLs for high-performance engineering applications. Overall, the validated FE models used in this study proved to be a valuable tool in investigating the impact response of novel FMLs under various loading conditions, providing important insights for the design and optimization of such materials.

Author contribution

Conceptualization, N. Nassir; contributed to the study conception and design, performed the measurements, verified the numerical results and writing the drafted manuscript. R. Birch; involved in planning and supervision of the work. A. Haldar; conducted the analysis and interpretation of the results. All authors reviewed the results and approved the final version of the manuscript.

Funding

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

References

[1] L. B. Vogelesang , A. Vlot, Development of fibre metal laminates for advanced aerospace structures, J. Mater. Process. Technol., 103 (2000) 1–5. https://doi.org/10.1016/S0924-0136(00)00411-8

[2] P. Cortes, W. J. Cantwell, The tensile and fatigue properties of carbon fiber-reinforced PEEK-Titanium fiber-metal laminates, J. Reinf. Plast. Compos., 23 (2004) 1615–1623. https://doi.org/10.1177/0731684404039796

[3] J. Zhou, Z. W. Guan, and W. J. Cantwell, The influence of strain-rate on the perforation resistance of fiber metal laminates, Compos. Struct., 125 (2015) 247–255. https://doi.org/10.1016/j.compstruct.2015.02.034

[4] A. Vlot, Impact loading on fibre metal laminates, Int. J. Impact Eng., 18 (1996) 291–307. https://doi.org/10.1016/0734-743X(96)89050-6

[5] G. R. Rajkumar, M. Krishna, H. N. N. Murthy, S. C. Sharma, and K. R. V. Mahesh, Experimental investigation of low-velocity repeated impacts on glass fiber metal composites, J. Mater. Eng. Perform., 21 (2012) 1485–1490. https://doi.org/10.1007/s11665-011-0038-6

[6] X. Li, X. Zhang, H. Zhang, J. Yang, A. B. Nia, and G. B. Chai, Mechanical behaviors of Ti/CFRP/Ti laminates with different surface treatments of titanium sheets, Compos. Struct., 163 (2017) 21–31. https://doi.org/10.1016/j.compstruct.2016.12.033

[7] S. Bernhardt, M. Ramulu, and a. S. Kobayashi, Low-velocity impact response characterization of a hybrid titanium composite laminate, J. Eng. Mater. Technol., 129 (2007) 220-226. https://doi.org/10.1115/1.2400272

[8] N. A. Nassir, R. S. Birch, W. J. Cantwell, M. Al Teneiji, and Z. W. Guan, The Perforation Resistance of Aluminum-Based Thermoplastic FMLs, Appl. Compos. Mater., 28 (2021) 587–605. https://doi.org/10.1007/s10443-021-09873-3

[9] W.-S. Lee, C.-H. La, and S.-T. Chi, Simulation of perforation behaviour of carbon fiber reinforced 6061-T6 aluminum metal matrix composite by a tungsten projectile, Struct. under Shock Impact VI, 48 (2000)185–194. https://doi.org/10.2495/SU000171

[10] Z. W. Guan, W. J. Cantwell, and R. Abdullah, Numerical modeling of the impact response of fiber–metal laminates, Polym. Compos., 30 (2009) 603–611. https://doi.org/10.1002/pc.20594

[11] G. H. Payeganeh, F. Ashenai Ghasemi, and K. Malekzadeh, Dynamic response of fiber-metal laminates (FMLs) subjected to low-velocity impact, Thin-Walled Struct., 48 (2010) 62–70. https://doi.org/10.1016/j.tws.2009.07.005

[12] J. Fan, Z. W. Guan, and W. J. Cantwell, Numerical modelling of perforation failure in fibre metal laminates subjected to low velocity impact loading, Compos. Struct., 93 (2011) 2430–2436. https://doi.org/10.1016/j.compstruct.2011.04.008

[13] E. Sitnikova, Z. W. Guan, G. K. Schleyer, and W. J. Cantwell, Modelling of perforation failure in fibre metal laminates subjected to high impulsive blast loading, Int. J. Solids Struct., 51 (2014) 3135–3146. https://doi.org/10.1016/j.ijsolstr.2014.05.010

[14] T. P. Vo, Z. W. Guan, W. J. Cantwell, and G. K. Schleyer, Low-impulse blast behaviour of fibre-metal laminates, Compos. Struct., 94 (2012) 954–965. https://doi.org/10.1016/j.compstruct.2011.10.027

[15] T. P. Vo, Z. W. Guan, W. J. Cantwell, and G. K. Schleyer, Modelling of the low-impulse blast behaviour of fibre-metal laminates based on different aluminium alloys, Compos. Part B Eng., 44 (2013) 141–151. https://doi.org/10.1016/j.compositesb.2012.06.013

[16] J. Zhou, Z. W. Guan, and W. J. Cantwell, The perforation resistance of sandwich structures subjected to Low velocity projectile impact loading, Aeronaut. J., 116 (2012) 1247–1262. https://doi.org/10.1017/S0001924000007624

[17] H. Seo, J. Hundley, H. T. Hahn, and J.-M. Yang, Numerical simulation of glass-fiber-reinforced aluminum laminates with diverse impact damage, AIAA J., 48 (2010) 676–687. https://doi.org/10.2514/1.45551

[18] H. Nakatani, T. Kosaka, K. Osaka, and Y. Sawada, Damage characterization of titanium/GFRP hybrid laminates subjected to low-velocity impact, Compos. Part A Appl. Sci. Manuf., 42 (2011) 772–781. https://doi.org/10.1016/j.compositesa.2011.03.005

[19] S. H. Song, Y. S. Byun, T. W. Ku, W. J. Song, J. Kim, and B. S. Kang, Experimental and numerical investigation on impact performance of carbon reinforced aluminum laminates, J. Mater. Sci. Technol., 26 (2010) 327–332. https://doi.org/10.1016/S1005-0302(10)60053-9

[20] G. Wu, J. M. Yang, and H. T. Hahn, The impact properties and damage tolerance and of bi-directionally reinforced fiber metal laminates, J. Mater. Sci., 42 (2007) 948–957. https://doi.org/10.1007/s10853-006-0014-y

[21] N. A. Nassir, R. S. Birch, W. J. Cantwell, Q. Y. Wang, L. Q. Liu, and Z. W. Guan, The perforation resistance of glass fibre reinforced PEKK composites, Polym. Test., 72 (2018) 423–431. https://doi.org/10.1016/j.polymertesting.2018.11.007

[22] N. A. Nassir, R. S. Birch, W. J. Cantwell, D. R. Sierra, S. P. Edwardson, and G. Dearden, Experimental and numerical characterization of titanium-based fibre metal laminates, Compos. Struct., 245 (2020) 112398. https://doi.org/10.1016/j.compstruct.2020.112398

[23] C. Breen, F. Guild, and M. Pavier, Impact damage to thick carbon fibre reinforced plastic composite laminates, J. Mater. Sci., 41 (2006) 6718–6724. https://doi.org/10.1007/s10853-006-0208-3

[24] N. A. Nassir, Z. W. Guan, R. S. Birch, and W. J. Cantwell, Damage initiation in composite materials under off-centre impact loading, Polym. Test., 69 (2018) 456–461. https://doi.org/10.1016/j.polymertesting.2018.06.006

[25] A. K. Haldar, Z. W. Guan, W. J. Cantwell, and Q. Y. Wang, The compressive properties of sandwich structures based on an egg-box core design, Compos. B. Eng., 144 (2018) 143-152. https://doi.org/10.1016/j.compositesb.2018.03.007

[26] A.K. Haldar, J. Zhou, and Z. Guan, Energy absorbing characteristics of the composite contoured-core sandwich panels, Mater. Today Commun., 8 (2016) 156-164. https://doi.org/10.1016/j.mtcomm.2016.08.002

[27] A.K. Haldar, W.J. Cantwell, G. Langdon, Q.Y. Wang, and Z.W. Guan, 2019. The mechanical behaviour of spherical egg-box sandwich structures, Polym. Test., 78 (2019) 105954. https://doi.org/10.1016/j.polymertesting.2019.105954