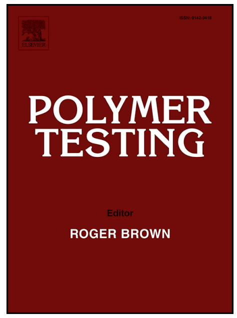
Accepted Manuscript



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PII: S0142-9418(18)31561-7

DOI: https://doi.org/10.1016/j.polymertesting.2018.11.007

Reference: POTE 5683

To appear in: *Polymer Testing*

Received Date: 28 September 2018

Accepted Date: 5 November 2018

Please cite this article as: N. Nassir, R.S. Birch, W.J. Cantwell, Q.Y. Wang, L.Q. Liu, Z.W. Guan, The perforation resistance of glass fibre reinforced PEKK composites, *Polymer Testing* (2018), doi: https://doi.org/10.1016/j.polymertesting.2018.11.007.

Material Properties

The Perforation Resistance of Glass Fibre Reinforced PEKK composites

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Abstract

This paper presents a study focusing on the perforation resistance of glass fibre-reinforced PEKK composites. Woven S-glass fibre (GF) reinforced poly-ether-ketone-ketone (PEKK) thermoplastic prepreg materials were manufactured using a dry powder prepregging method. Prior to impact testing and modelling, the properties of the composites were evaluated by conducting a series of quasi-static tests at room and elevated temperatures.

Quasi-static tensile and perforation tests showed that the optimum weight fraction of PEKK, $w_{f,}$ is approximately 0.4, which gives the peak tensile strength and perforation resistance. Tests at elevated temperatures highlighted the excellent stability of these materials under extreme conditions. As expected, the energy required to perforate the targets increased with projectile diameter. Subsequent tests highlighted the severity of conically-shaped projectiles with the perforation resistance dropping under sharp object impact loading.

A series of finite element models were also developed to predict the response of the glass fibre/PEKK composites to impact by projectiles based on different diameters and shapes. The predictions were validated against the experimental force-displacement traces and failure modes with good agreement.

Keywords: Poly-Ether-Ketone-Ketone (PEKK); woven S-glass fibre; powder prepregging; temperature-dependent behaviour; perforation; finite element.

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1. Introduction

The introduction of high-performance thermoplastic composites has resulted in increasing interest in the aerospace, automotive and marine industries, due to the light-weight characteristics, the ability for integral design, fire/smoke resistance, recyclability, almost unlimited shelf life and superior impact properties [1, 2]. Moreover, thermoplastic composites can be welded at high temperatures, thus making them suitable for high speed production processes such as thermoforming, and allowing the application of novel joining techniques such as ultrasonic and induction welding [3]. Although thermosetting (TS) prepregs, such as epoxy prepregs, are also used widely in automotive, construction and aerospace industries, they have a limited shelf life and need to be stored in a freezer, typically at -18°C [4-7] to prevent polymerisation of the resin.

In the aerospace applications, fibre metal laminates (FMLs) are finding use in fuselage, wing and leading edge tail structures, most of which are based on thermosetting epoxy based prepregs. Low viscosity, a low fabrication temperature and good resin/fibre wettability are the major reasons for the use of epoxy-based composites. However, these kinds of prepregs do exhibit relatively poor hot/wet stability, higher cost of manufacture and low combustibility resulting in smoke and toxic fumes which can pose a serious health hazard [8–12].

Thermoplastic prepregs can be stored in an ambient environment with an infinite shelf-life unless they contain solvent, which may limit their shelf life [13]. Despite the advantages offered by the traditional thermoplastic matrices, their use has been limited due to their low modulus, poor chemical resistance, low glass transition temperature (Tg) and poor thermal stability at elevated temperatures [14]. The development of multi-functional thermoplastic matrices based on an aromatic polymer has potential to address all the above limitations. High-performance thermoplastics, such as poly-ether-ketone-ketone (PEKK), have demonstrated exceptional impact resistance, vibration damping and thermal properties at high temperatures, especially when reinforced with high-performance fibres [15].

Previous work has shown that there are a number of procedures available to combine a thermoplastic matrix with fibres to make prepregs, such as solution dip prepregging [16], hot melt prepregging [17, 18], film calendaring [18], dry powder and aqueous suspension techniques [19, 20]. Differences between these methods relate to the way in which the matrix is deposited on fibres and the bonding force between the matrix and the fibre, which is responsible for adhesion at the microstructural level [21]. There are a number of advantages associated with dry powder prepregging, including a wide range of melt viscosities without the need for a solvent or hot melt problems, thus widening the potential range of available polymers [22]. High-performance thermoplastics, such as PEEK and PEKK [23, 24], are considered to be amongst the most suitable matrix systems for use in the aerospace industry, satisfying the need for light-weight, low cost primary load-bearing structures and high temperature FMLs [25–27]. Extensive work has been carried out on PEEK based composites [28–32] . However, PEKK is expected to become a competitive candidate for aerospace applications given that it is 60% cheaper than PEEK, with a Tg of 165 ^{o}C compared to 145 ^{o}C for PEEK. Moreover, the processing temperature for PEKK is lower than for PEEK, which simplifies the manufacturing process.

A review of the literatures indicates that few researchers have studied the behaviour of PEKK-based composites under various loading conditions. The influence of accelerated aging on the compression strength and interlaminar shear strength of carbon fibre reinforced PEKK composites were investigated by Mazur et al. [32]. Here, laminates were manufactured using hand lay-up and hot compression moulding techniques. The authors showed that hot compression is a suitable technique for producing thermoplastic composites. Bucher and Hinkley [33] studied the flexural strength of PEKK reinforced with different types of unidirectional carbon fibres, these being AS-4, IM-7 and G30-500. The unidirectional towpreg was manufactured via a dry powder prepregging technique using a continuous powder prepregging line. The results showed that composites based on CF/PEKK prepregs behave differently with different carbon fibre types. Sun et al. [34] proposed a model to predict the elasto-plastic behaviour of PEKK composites reinforced with discontinuous (LDF) and continuous carbon fibres (AS-4). The results showed that the model could be used to successfully predict the plastic behaviour of those composites at ambient and elevated temperatures up to 177 ^{o}C.

To date, little work has been undertaken to investigate the perforation resistance of high-performance thermoplastic composites. The current work is primarily to study the perforation resistance of S-glass fibre reinforced PEKK prepregs manufactured using a powder-based prepregging technique. The initial study focuses on developing the composite material, with the identified optimum weight fraction of the polymer for better mechanical behaviour. Other key mechanical properties were evaluated to characterize the composite developed as well as to generate input data for subsequent numerical analyses. Finite element models were then developed to simulate the impact response of GF/PEKK laminates, which were validated against the corresponding test results.

2. Preparation of the material and samples

The fibre reinforced laminates investigated in this study were based on prepreg sheets manufactured from an S-glass woven fabric and a poly-ether-ketone-ketone **(**PEKK) matrix. PEKK is a high temperature, high performance thermoplastic material that belongs to the poly aryl ether ketone (PAEK) family, in which the resulting polymers differ according to the ratio of ketone-ether groups within the structure. These resins have a semi-crystalline aromatic structure and exhibit low melt viscosity, excellent thermal stability, low moisture absorption, high toughness and tensile modulus, good chemical resistance and good flammability resistance. The glass transition temperature or Tg of PEKK is 165 °C. Table 1 shows the mechanical and physical properties of PEKK and other thermoplastic polymers. In this research, KEPSTAN-6003 PL (Lot # P12S049) PEKK resin (ARKEMA, France), supplied in powder form with a particle size of 50 microns, was used. This polymer was selected since it has a relatively low melting point (~303 °C) coupled with a high Tg and excellent metal bonding characteristics.

S-glass fibres offer a high compressive strength, a superior high temperature performance and a good impact resistance. Here, a plain S-glass woven fabric (124 gsm) from Aerialite (East Coast fibreglass Supplies, UK) was used.

A dry powder prepregging technique was used to manufacture prepregs of PEKK and woven S-glass fabric, in which PEKK polymer in the form of a dry powder was deposited onto the fibres. The GF/PEKK prepregs were manufactured following steps below:

1. The woven S-glass fibre fabric was cut into square sheets (250 mm x 250 mm) and weighed using a precision balance.

2. An adhesive (3M Multipurpose Spray) was sprayed evenly on the fabric and re-weighed. The adhesive served as a temporary binder to hold the PEKK powder in place on the glass fibre fabric.
3. The fabric was then repeatedly dipped into a powder tank and weighed until the target weight fraction of resin was obtained.
4. The glass fibre fabric containing the desired amount of powder was placed between two platens in a Meyer hydraulic press with platen dimensions of 300 mm x 300 mm and heated to 330 ^{o}C. A high temperature release agent (Frekote) was applied to the mould to facilitate removal after consolidation. The processing cycle involved applying a pressure of 6 bars during a holding time of 10 minutes.

The composite laminates were manufactured by stacking the prepreg plies (0.12 mm thick) in a mould. The resulting stack was then heated to a temperature of 330 ^{o}C at a rate of 5 ^{o}C/minute. Laminates, with dimensions (125 mm x 125 mm) and (250 mm x 62.5 mm), were consolidated under a pressure of 3 bars for 30 minutes prior to cooling at a rate of 2 ^{o}C/minute. After cooling, the pressure was released and the laminates were removed from the mould and inspected for defects. The laminates were produced based on different weight percentages of PEKK. Table 2 gives details of the panels investigated in this study. Four thicknesses of plain GF/PEKK laminates were studied, these being 0.47, 0.96, 1.4 and 1.8 mm, which corresponding to 4, 8, 12 and 16 plies.

3. Mechanical tests

A series of mechanical tests on the GF/PEKK laminates (4-ply) were undertaken to evaluate their mechanical response under various loading conditions. Initially, quasi-static tensile tests were conducted according to ASTM D3039/D3039M – 14 [35] using an Instron 3369 testing machine. The length and the width of the tensile specimens were set as 200 mm and 15 mm (with different ply numbers), respectively, which were based on trial tests with various widths. An extensometer, with a gauge length (GL) of 25 mm, was attached to the middle section of the specimen to measure extension. Three repeat tests were undertaken at a constant crosshead speed of 0.5 mm/minute.

Quasi-static perforation tests were also carried out on the GF/PEKK panels clamped in a square steel frame with a 72 mm x 72 mm opening. A hemispherical indentor, with a diameter of 10 mm, was used to perforate the specimens. The specimens were tested on an Instron 4505 testing machine with a maximum loading capacity of 50 kN. A crosshead displacement rate of 1 mm/minute was selected and the load-displacement curve was recorded during each test.

The influence of temperature on the tensile strength of GF/PEKK laminates was investigated by conducting tensile tests on an Instron 3369 testing machine. GF/PEKK samples were tested at temperatures of 25, 50, 150, 200 and 250^{o} C. The samples were heated locally in a small heating chamber. Here, two thermocouples were attached to sample edges to monitor the temperature throughout the test. The temperature was maintained using a temperature controller and the variation of the temperature inside the chamber was approximately within ± 0.5 % of the desired values.

Finally, low velocity impact tests were conducted on 4, 8, 12 and 16-ply laminates using a drop-weight tower. A steel mass was attached to a carriage with a 10 mm diameter hemi-spherical steel indentor to impact the laminated panels centrally. The mass of the impactor was 1.37 kg and the release height of the carriage was varied between 0.29 and 1.09 meters. Further impact tests were undertaken on an 8 ply composite to investigate the influence of the project shape and diameter on the impact response of the thermoplastic laminates. Details of these tests are given in Table 3. The composite plates were clamped in the same frame as that used for quasi-static perforation testing, this being a square steel support with external dimensions of 100 mm x 100 mm and opening of 72 mm x 72 mm. The impact force and displacement were recorded using a piezoelectric load cell and a high speed camera, respectively.

4. Investigation of effects of binder and PEKK content on the mechanical behaviour

Experimental work was initially focused on investigating the effect of a binder between the thermoplastic powder and the fibres on the mechanical properties of the GF/PEKK laminates. Figure 1 shows the average load-displacement traces with the standard deviations following quasi-static perforation tests on panels manufactured with and without the use of a binder. An examination of the figure indicates that both traces exhibit similar initial stiffness characteristics due to the similar initial contact area before the first delamination. However, the maximum force in the modified laminate is roughly double that of its untreated counterpart. Clearly, the higher maximum force for the treated panels is associated with the enhanced level of adhesion between the thermoplastic polymer and the glass fibres. The influence of fibre treatment on the tensile strength of GF/PEKK samples was also studied. Here tensile tests were conducted on a four ply laminate with a thickness of 0.47 mm and typical stress-strain traces are shown in Figure 2. As noted previously, the treated laminates offer strength properties that are more than double those associated with untreated laminates.

Then, work was carried out on studying how PEKK content affects the mechanical behaviour of GF/PEKK laminates. Figure 3 presents load-displacement traces following quasi-static perforation tests on laminates with weight fractions of PEKK between 0.3 and 0.5. All of the traces exhibit similar trends during the perforation process, with the force initially increasing in a non-linear fashion to the maximum force at a displacement of approximately 4 mm, followed by a progressive decrease as the projectile perforates the plate. Clearly, the maximum force increases with PEKK weight fraction, reaching the highest value at 0.4 of PEKK.

The influence of the weight fraction of PEKK on the tensile strength of the GF/PEKK composites is shown in Figure 4. Clearly, the tensile strength increases with PEKK w%, reaching a maximum at 300 MPa, again corresponding to a PEKK weight fraction of 0.4. At higher weight fractions, a noticeable drop in the tensile strength occurs, probably due to the presence of resin-starved regions between the fibres. The above results suggest that, in terms of mechanical properties, the optimum weight fraction of PEEK is close to 0.4.

Prior to undertaking further mechanical tests, a number of specimens were sectioned, polished and examined under an optical microscope to study their microstructure and the distribution of the fibres within their cross-sections. Figure 5 shows a micrograph of a 4 ply-GF/PEKK with the optimum PEKK content (i.e. 0.4 or 40 wt. %) where it can be seen that the glass fibres are fully impregnated by the PEKK polymer. This point is emphasized when examining the high magnification image where it is evident that the thermoplastic resin has flowed between all of the individual glass fibres to give a high quality composite laminate.

5. Finite element modelling

ABAQUS/Explicit [38] was used to develop numerical simulations to predict the response of the GF/PEKK laminates under low velocity impact loading. The woven glass fibre reinforced PEKK laminates were modelled as an orthotropic elastic material prior to the onset of damage. Table 4 shows the material properties of the laminates used in this study.

Hashin failure criteria [39, 40] were used to model damage initiation in the laminates, involving four failure initiation mechanisms, namely fibre tension, fibre compression, matrix tension and matrix compression. The criteria based on effective stress tensor components ($\hat{\sigma}_{11}, \hat{\sigma}_{12}, \hat{\sigma}_{22}$) and strengths of woven composites ($X^T, X^C, Y^T, Y^C, S^L, S^T$) are expressed in equations [38] below.

Fibre in tension:

$$F_f^t - \left[\left(\frac{\hat{\sigma}_{11}}{X^T}\right)^2 + \alpha\left(\frac{\hat{\sigma}_{12}}{S^L}\right)^2\right] = 0,\ \hat{\sigma}_{11} \geq 0 \quad (1)$$

Fibre in compression:

$$F_f^c - \left(\frac{\hat{\sigma}_{11}}{X^C}\right)^2 = 0,\ \hat{\sigma}_{11} \leq 0 \quad (2)$$

Matrix in tension:

$$F_m^t - \left[\left(\frac{\hat{\sigma}_{22}}{Y^T}\right)^2 + \left(\frac{\hat{\sigma}_{12}}{S^L}\right)^2\right] = 0,\ \hat{\sigma}_{22} \geq 0 \quad (3)$$

Matrix in compression:

$$F_m^c - \left[\left(\frac{\hat{\sigma}_{22}}{2S^T}\right)^2 + \left[\left(\frac{Y^C}{2S^T}\right)^2 - 1\right]\frac{\hat{\sigma}_{22}}{Y^C} + \left(\frac{\hat{\sigma}_{12}}{S^L}\right)^2\right] = 0,\ \hat{\sigma}_{22} \leq 0 \quad (4)$$

An element removal procedure was employed to remove elements following matrix and fibre failure. Table 5 gives the damage initiation properties used in this investigation. The values for the fracture energies in the longitudinal and transverse directions of the woven laminates under tension and compression were based on previous work on glass fibre reinforced composites [41] and taken to be 50 kJ/m^2 and 60 kJ/m^2, respectively. One half of the panel was modelled, as shown in Figure 6, to reduce the CPU time and associated costs.

Surface-based tie constrains were employed between adjacent plies in the composite, and surface to surface contact interaction was imposed between the projectile surface and the node set over the central region (20 x 20 mm x thickness) of the target. A penalty friction coefficient of 0.15 was used to simulate the tangential contact behaviour. Linear pressure-overclosure, with a contact stiffness of 0.5 MPa, was assumed for all interaction surfaces. The composite plies were meshed using eight-noded linear brick elements with reduced integration and hourglass control (SC8R), and the projectile was meshed as a rigid body using four–noded bilinear quadrilateral rigid elements (R3D4). A mesh-sensitivity study was conducted to obtain the optimized mesh size for which a suitable balance between the accurate modelling results and the CPU time was achieved. As a result, a mesh size of 1.1 mm x 1.1 mm over a central area of 20 mm x 20 mm was employed. The contact force was calculated by summing the contact force between the projectile and the individual composite plies.

6. Results and discussion

In order to assess the effect of specimen thickness on the tensile strength of GF/PEKK laminates, samples were manufactured with different thicknesses, being based on 4, 8, 12 and 16 ply samples. The resulting experimental data showed that the tensile strength of GF/PEKK panels is not significantly affected by the sample thickness or ply number, with the tensile strength being approximately 300 MPa.

The load-displacement traces following quasi-static perforation tests on GF/PEKK laminates with different ply number (thickness) are shown in Figure 7. Here, it is evident that the initial stiffness and the maximum force values increase with the ply number (so (thickness) of the sample.

Figure 8 shows the variation of the tensile strength of the 4 ply GF/PEKK composite with temperature. As expected, the figure shows that the tensile strength of the laminate decreases with the temperature. At 250 ^{o}C, the tensile strength had dropped by approximately 35% relative to room temperature. It is interesting to note that there was hardly any change in the tensile strength when the composite was heated to 100 ^{o}C. There is a 10 % reduction in tensile strength at 150 ^{o}C. a temperature that is close to the glass transition temperature of the PEKK matrix (165 ^{o}C) It is worth noting that, even at a temperature of 250 ^{o}C, the GF/PEKK still exhibits a tensile strength of approximately 200 MPa.

Figure 9 shows a comparison between the predicted load-displacement traces and the corresponding experimental data for the GF/PEKK composite laminates under low velocity impact loading. An examination of the figure indicates that, for the range of sample thicknesses (number of plies) considered here, good agreement was observed in terms of the initial stiffness, maximum load and maximum displacement. From the figure, it can also be noted that the traces are highly oscillatory, due to the dynamic nature of the test, associated with ringing in the load cell. The trends in the traces under impact loading are similar to those observed following quasi-static perforation tests, with higher maximum forces being observed during dynamic testing, highlighting the strain-rate sensitivity of the glass fibres, as observed by other research [42, 43]. It is encouraging to note that the FE model predicts the impact perforation resistance of the laminates. As a result, the fundamental features of impact event were successfully captured by the numerical model.

Figure 10 shows a comparison of the experimental and predicted rear surfaces of the perforated 4-ply of GF/PEKK composites following impact. Here, the experimental failure mode was captured after removing the projectile from the damaged panel, whereas the predicted cross-section was taken without unloading the panel (i.e. removing the projectile). Clearly, the FE simulation shows a good degree of agreement with the experimental damage pattern in terms of the local deformation at the target centre and the cross-cracks on the rear surface of the panel. This evidence suggests that the FE model captures the failure modes in the perforated GF/PEKK composite reasonably successfully.

The impact perforation resistance of the 8-ply laminates involving projectiles with various diameters of 5, 10, 15 and 20 mm was investigated both experimentally and numerically. Figure 11 compares the load-displacement curves, where a high level of correlation is observed between the experimental and experimental traces. As expected, the maximum impact force increases with projectile diameter. For example, the panel impacted by a 20 mm indentor results in a much higher impact force of 1710 N than the value of 815 N resulting from impact by a 5 mm projectile. This is due to the larger volume of sheared material in the panel impacted by the large diameter projectiles.

Load-displacement traces following impact tests on the GF/PEKK laminates by flat (flattened area/overall area = 0.55), hemispherical and conical projectiles are shown in Figure 12. Clearly, the panels impacted by the flat and hemispherical projectiles exhibit similar initial stiffness values, due to the fact that they have a similar initial contact area. In contrast, the trace associated with impact using a conically shape projectile results in a much lower stiffness. The figure also shows that the panel impacted by the flat projectile exhibits a higher impact force (approximately 2100 N) than the value (1070 N) generated by the hemispherical projectile. The conically shaped projectile resulted in the lowest impact force of 870 N [44]. Figure 13 compares the predicted and experimental load-displacement traces of 8-ply GF/PEKK panels resulting from impact by flat and conical projectiles where good agreement between the predicted and measured traces is apparent. The simulated results capture the experimental features from the beginning to the full perforation stages.

The influence of the projectile diameter on the perforation energy for the 8-ply GF/PEKK laminates is shown in Figure 14. The solid line represents the predictions from the FE analyses. Clearly, the perforation energy increased rapidly with the projectile diameter in a non-linear fashion. Good agreement between the predicted and the measured perforation energies was obtained. The influence of the projectile shape on the perforation energy was also investigated. Figure 15 shows the variation of the perforation resistance of 8-ply GF/PEKK laminates subjected to impact by different projectile head shapes. From the figure, it is clear that the perforation energies associated with panels impacted with hemi-spherical, conical and partial flat projectiles are following an uptrend almost linearly. Again, reasonably good agreement between the measured data and the predicted results is obtained over the relatively narrow range of the projectile shapes.

7. Conclusions

The mechanical properties of a high temperature thermoplastic composite based on S-glass fibre reinforced poly-ether-ketone-ketone (PEKK) were investigated. A dry powder prepregging technique was employed to manufacture the GF/PEKK prepregs. The wettability of the resin was investigated by examining polished sections removed from the as-manufactured laminates. Experimental tests showed that the maximum perforation force and the tensile strength of laminates are observed at a weight fraction of fibres of approximately

0.4. The GF/PEKK laminates offer attractive residual strength characteristics at high temperatures, highlighting the potential of such thermoplastic-matrix composites for use in aerospace applications. The perforation response of the GF/PEKK laminates was subsequently modelled using finite element analysis techniques, and the predictions were compared with the experimental data where good agreement was observed in all cases. The FE models yielded accurate predictions of the load-displacement traces and the associated perforation threshold energy. The perforation energy increased with increasing panel thickness in a linear fashion, whereas the variation of perforation energy with projectile diameter followed a more non-linear relationship.

Acknowledgements

The authors would like to thank the Committee for Education Development (HCED) in Iraq for supporting this work.

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Table 1: Comparison of the properties of PEKK with other thermoplastic polymers [13].

Property	unit	PEI	PPS	PEEK	PEKK
Density	kg/m^3	1270	1330	1320	1290
Tensile strength	MPa	105	90	100	90
Tensile Modulus	GPa	3.0	3.8	3.5	3.4
Elongation at Failure	%	60	3	60	80
Flexural Modulus	GPa	3.3	3.8	4.0	3.3
Flexural Strength	MPa	152	96	170	138
Notched Izod Impact Strength	J/m	53	16	60	48

Table 2: Summary of the laminates investigated in this study.

No. of plies	Thickness (mm)	Weight fraction of fibres (wt. %)
4	0.47	60
8	0.96	60
12	1.4	60
16	1.8	60

Table 3: Details of the impact tests involving various projectile shapes and diameters.

Indentor shape	Indentor diameter	Impactor mass (kg)
Hemi-spherical	5	3.02
Hemi-spherical	10	3.02
Hemi-spherical	15	3.19
Hemi-spherical	20	3.22
Semi-flat	10	3.02
conical	10	3.02

Table 4 Material properties for the glass fibre reinforced PEKK laminates used in this programme.

E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	ν_{12}	ν_{13}	ν_{23}	G_{12} (GPa)	G_{13} (GPa)	G_{23} (GPa)
26	26	2.6	0.15	0.15	0.15	2.6	2.6	2.6

Table 5: Strength data for the glass fibre reinforced PEKK laminates.

X_T (MPa)	X_C (MPa)	Y_T (MPa)	Y_C (MPa)	S_L (MPa)	S_L (MPa)
304	200	304	200	50.4	50.4

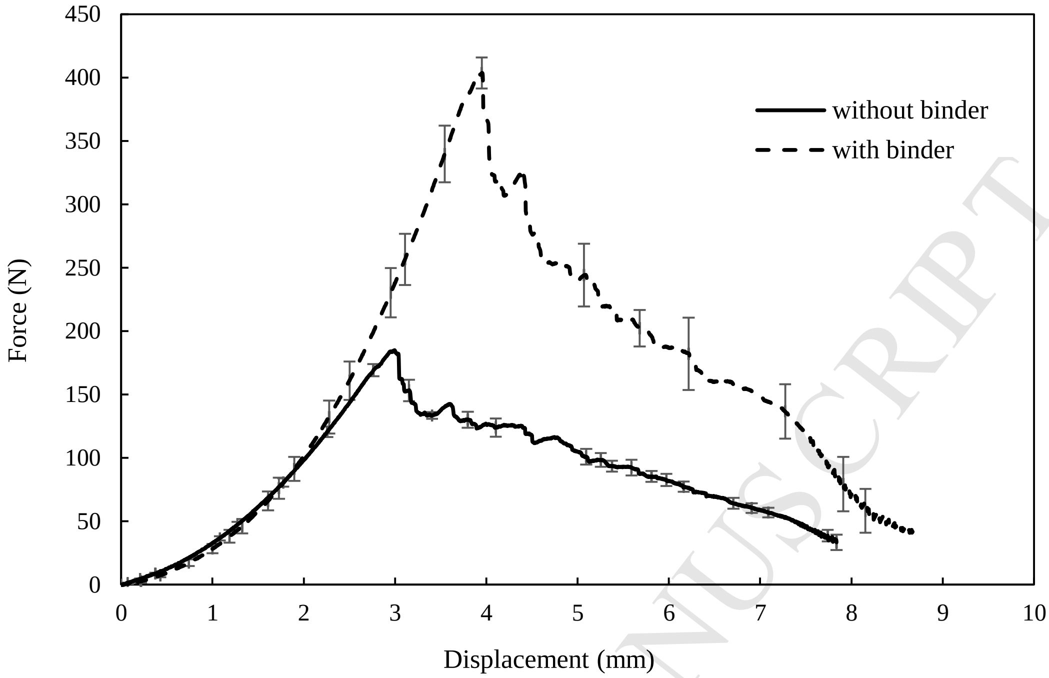


Figure 1. Load-displacement traces following perforation tests on the 4 ply PEKK/GF composite with binder (solid line) and without binder (dashed line) applied to the fibres.

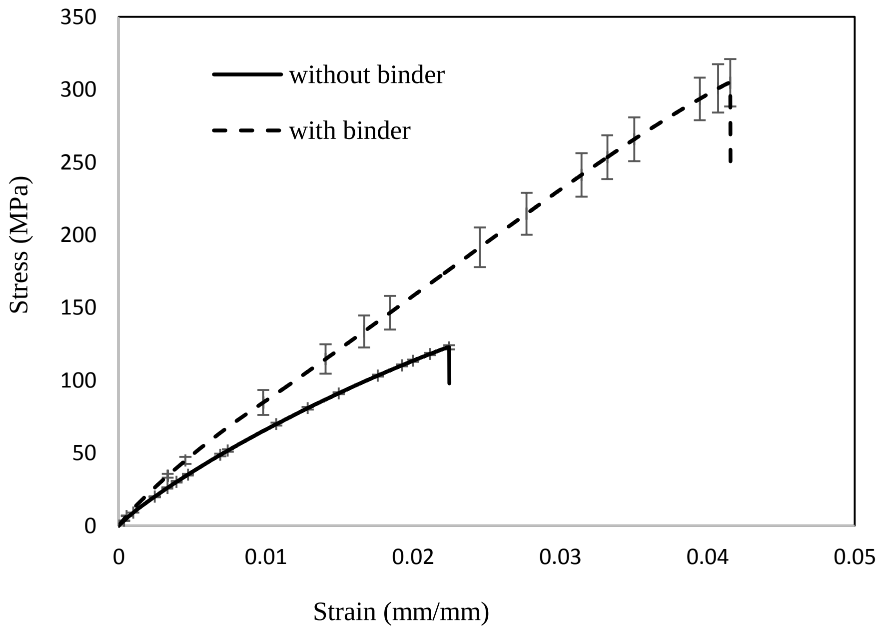


Figure 2. Tensile stress-strain curves for the 4 ply PEKK/GF composites with binder and without binder applied to the fibres.

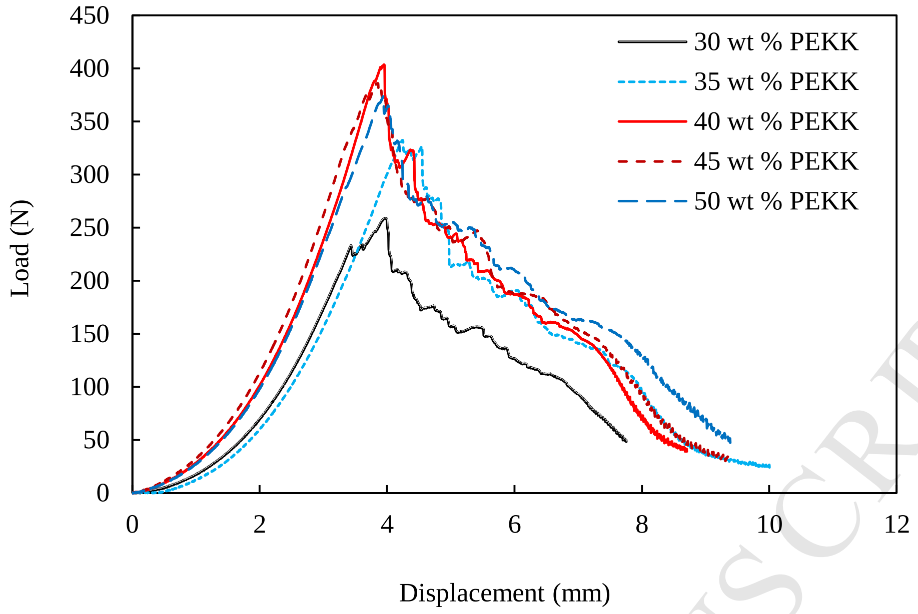


Figure 3. Load-displacement traces following quasi-static perforation tests on the 4-ply panels based on different weight fractions of PEKK.

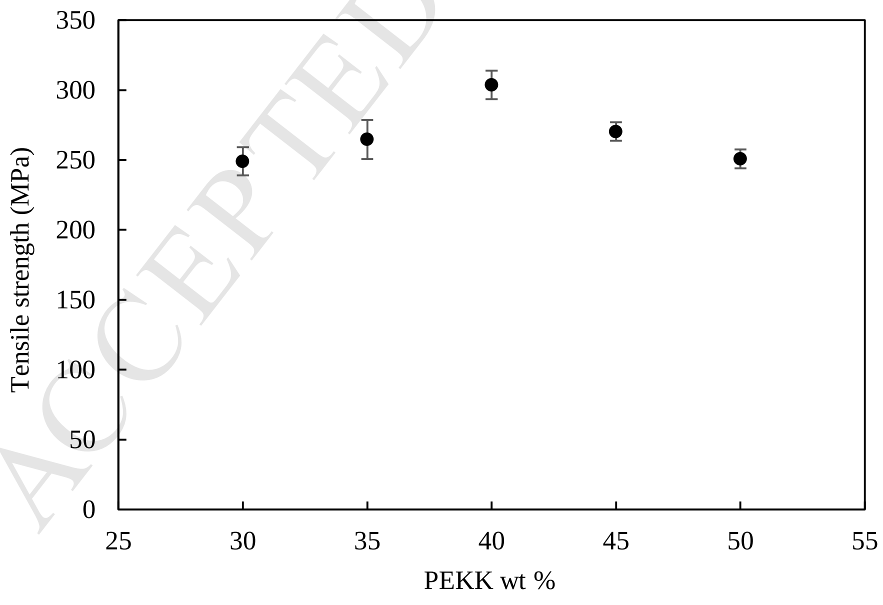


Figure 4. Tensile strength versus weight percentage of PEKK.

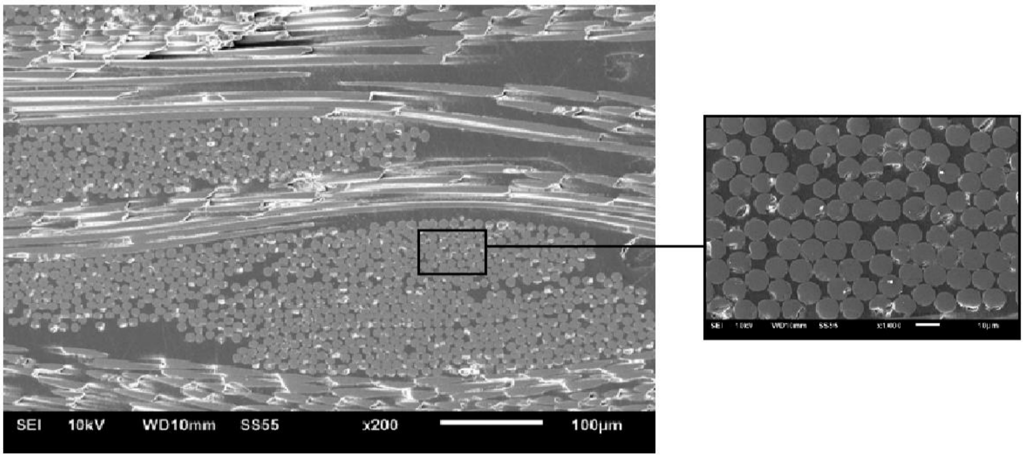


Figure 5. Micrographs of the 4-ply GF/PEKK at magnification factor of (a) 200 and (b) 1000.

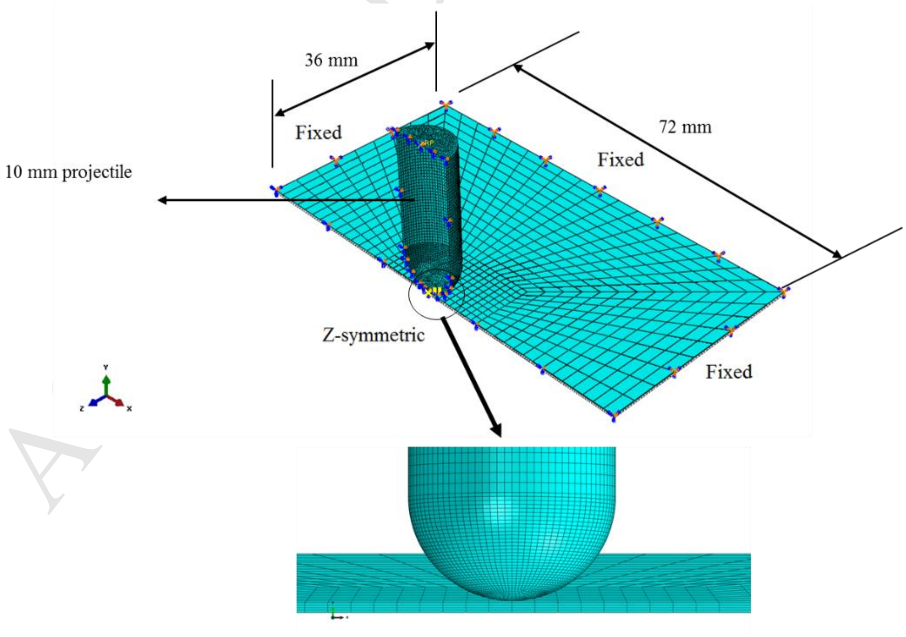


Figure 6. Geometrical, boundary and conditions as well as mesh generation of a half model of 8-ply GF/PEKK composite panel.

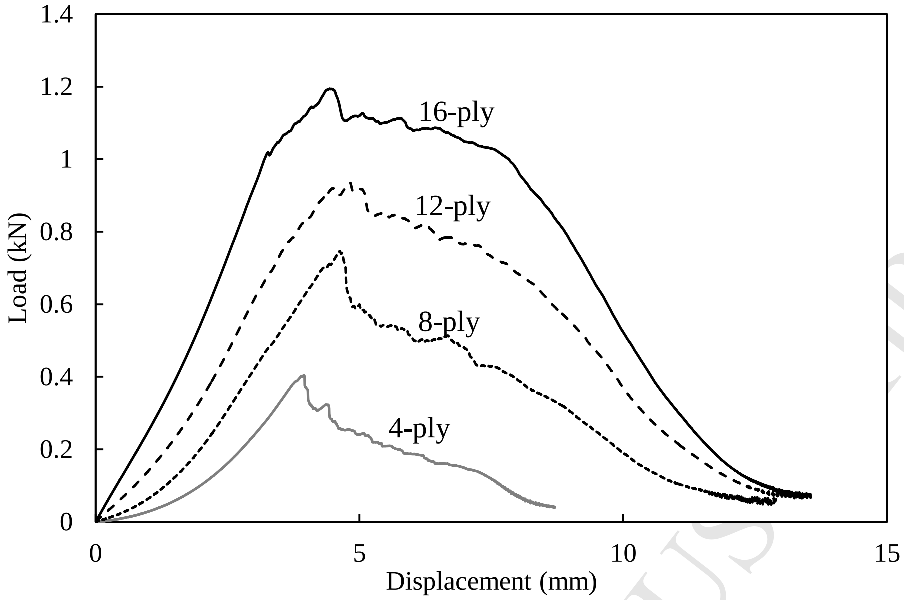


Figure 7. Load-displacement traces following quasi-static perforation tests on the 4, 8, 12 and 16 ply GF/PEKK laminates with differing thicknesses.

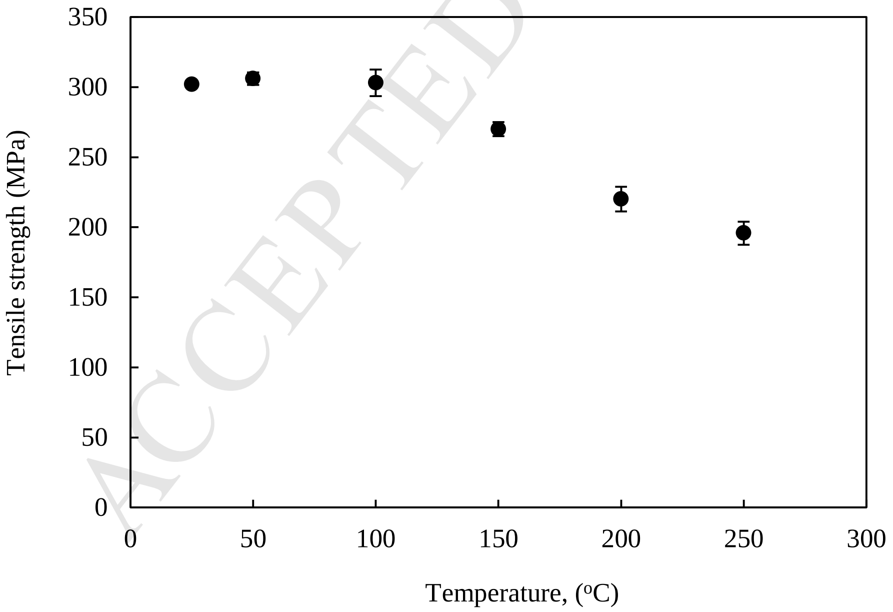


Figure 8. Tensile strength of the 4-ply GF/PEKK panels as a function of temperature.

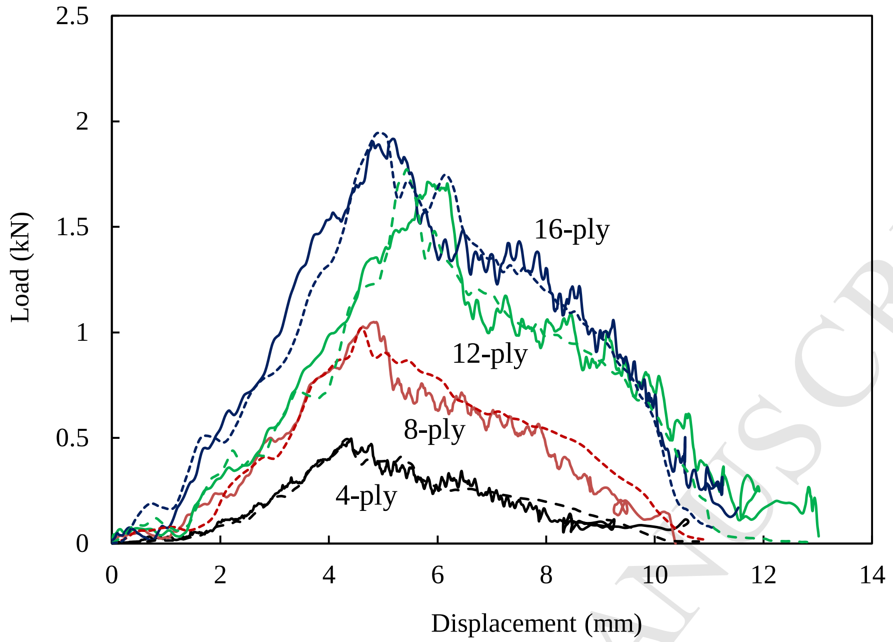


Figure 9. Load-displacement traces for 4, 8, 12 and 16-Ply GF/PEKK laminates subjected to low velocity impact loading. The solids line corresponds to experimental traces and the dashed line to numerical predictions.

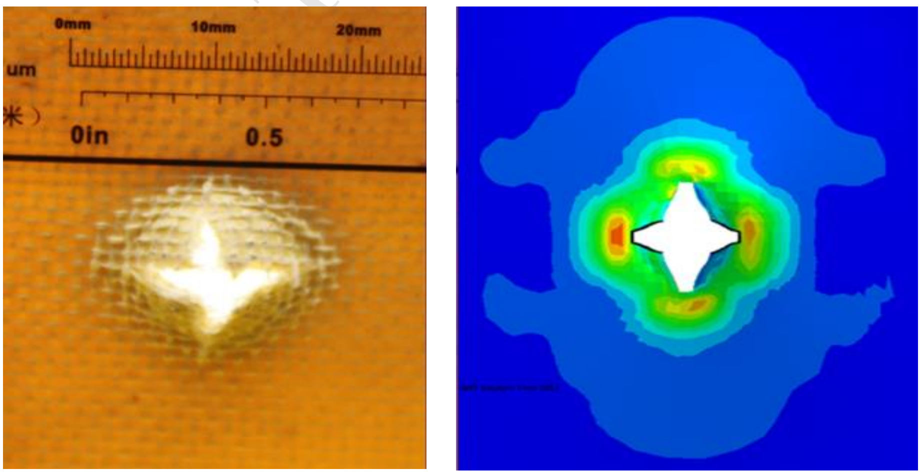
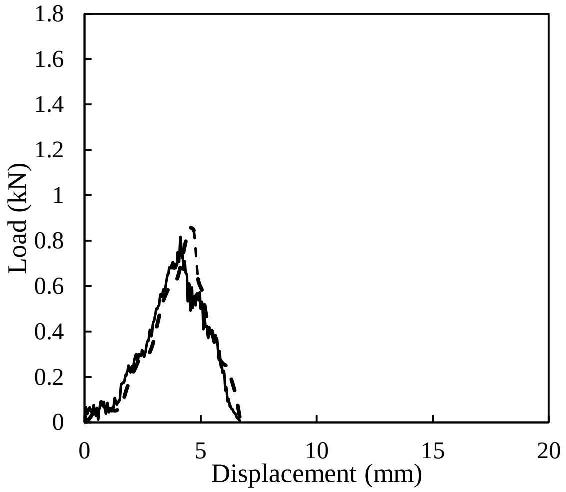
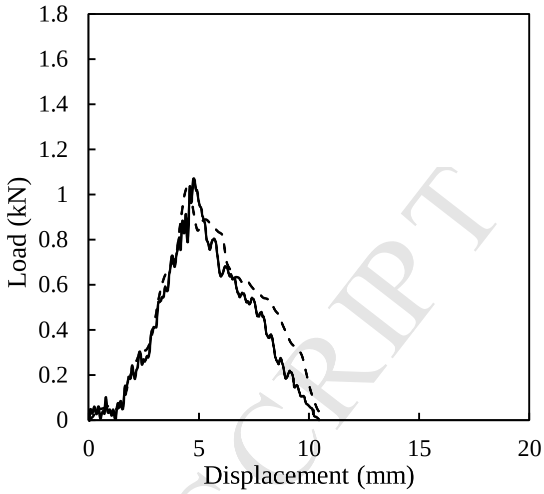


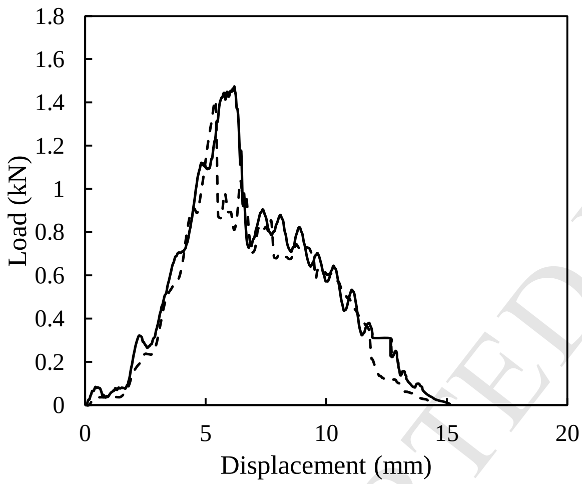
Figure 10. Comparison of the predicted and experimental failure modes following impact test for the 4-ply GF/PEKK panel.



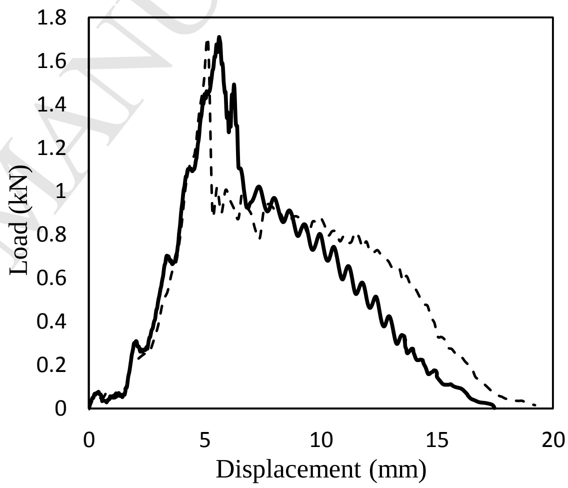
(a) Projectile diameter = 5 mm



(b) Projectile diameter = 10 mm



(c) Projectile diameter = 15 mm



(d) Projectile diameter = 20 mm

Figure 11. Load-displacement traces following impact tests on 8 ply laminates with various projectile diameters. The solid lines are the experimental traces and the dashed lines the numerical predictions.

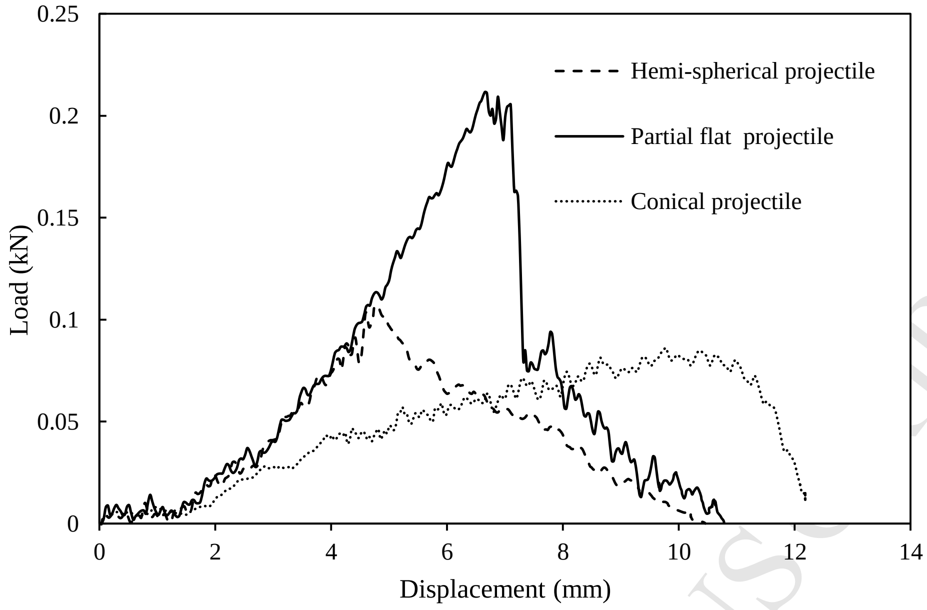


Figure 12. Load -displacement relationship for 8-ply panels impacted with projectiles with different shapes.

The projectile diameter = 10 mm.

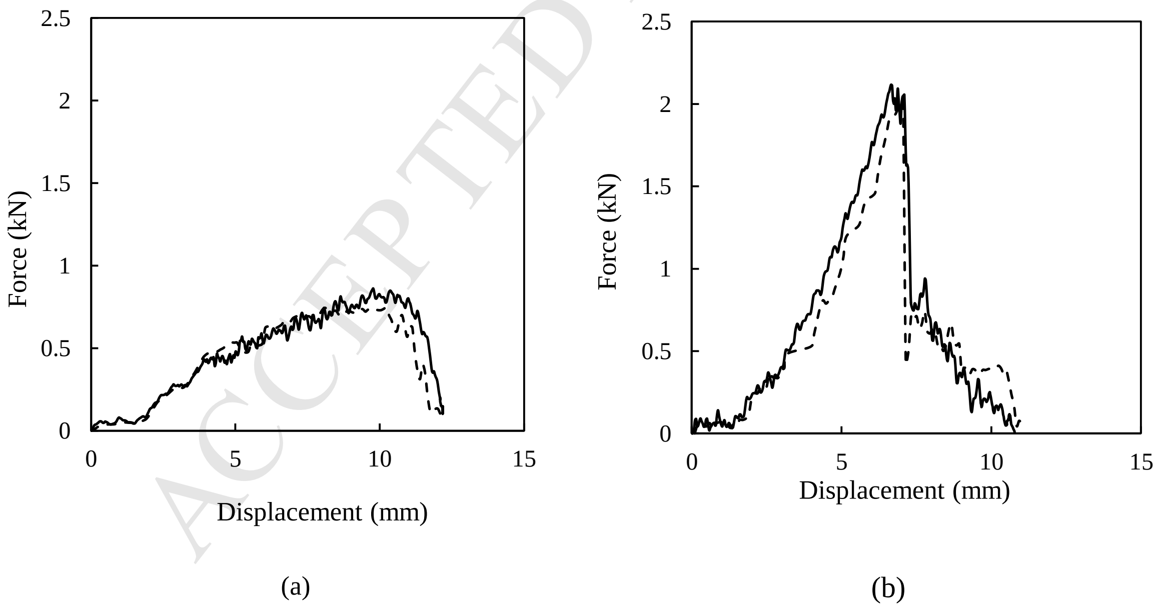


Figure 13. Predicted and experimental load-displacement traces for 8-ply GF/PEKK panels following low velocity impact by different projectile shapes: (a) conical; (b) partially-flat.

The solid lines are the experimental traces and the dashed lines the numerical predictions.

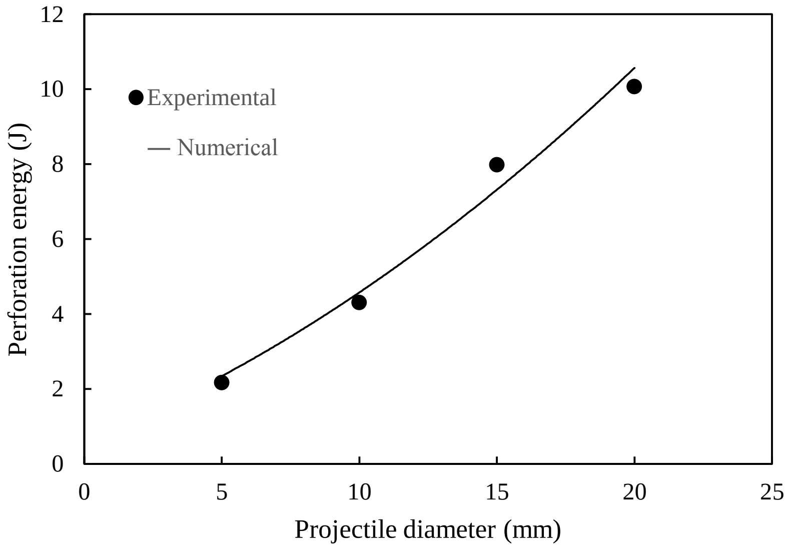


Figure 14. Variation of perforation energy with projectile diameter for 8-ply GF/PEKK panels impacted by projectile with diameters of 5, 10, 15 and 20 mm respectively.

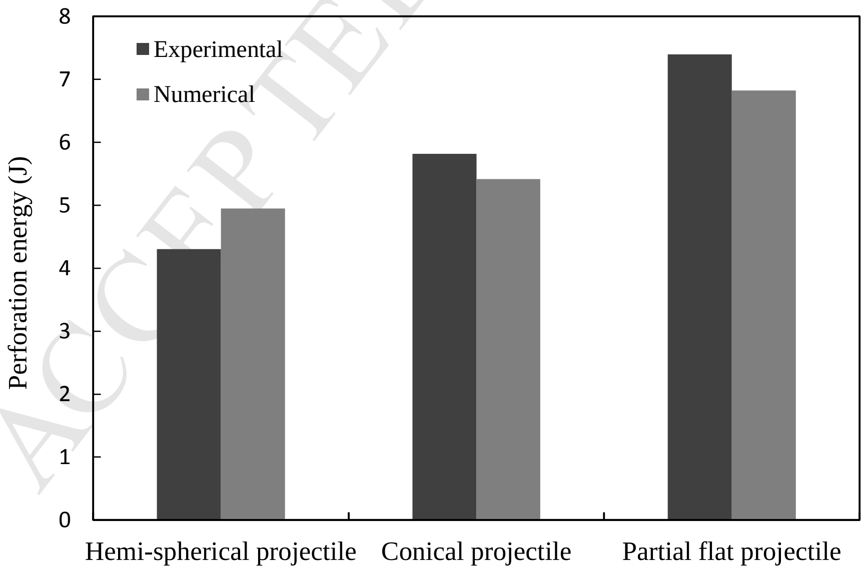


Figure 15. Variation of perforation energy with projectile head shapes for 8-ply GF/PEKK panels.

Highlights

- Manufacture S-glass fibre/PEKK prepreg materials using a dry powder prepregging method;
- The optimum weight fraction of PEKK is approximately 0.4 to offer high mechanical behaviour;
- There is no tensile strength reduction at 100 ^{o}C and only 10 % reduction at 200 ^{o}C;
- Perforation resistance was studies with projectiles in various sizes and shapes;
- The finite element modelling outputs show good correlation with the related test results;