



Effect of geometry and adhesion on the performance of fiber reinforced thermoplastic composite joints with metal inserts

Muhammad Ridha^{a,*}, Zhoucheng Su^{a,*}, Le Quan Ngoc Tran^b, Wei Ming Albert Yek^c, Sridhar Narayanaswamy^a, Tong-Earn Tay^d

^a Institute of High Performance Computing (IHPC), Agency for Science, Technology and Research (A*STAR), 1 Fusionopolis Way, #16-16 Connexis, Singapore 138632, Singapore

^b Institute for Frontier Materials, Deakin University, 75 Pigdons Road, Waurn Ponds, Victoria 3216, Australia

^c Singapore Institute of Manufacturing Technology, Agency for Science, Technology and Research (A*STAR), 73 Nanyang Drive, Singapore 637662, Singapore

^d Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Blk EA, Singapore 117575, Singapore

ARTICLE INFO

Keywords:

Carbon fiber reinforced thermoplastic composites
Finite element analysis
Progressive damage
Composite joint

ABSTRACT

Joints for laminated composite structures using mechanical fasteners or adhesives often face issues such as reduced strength from fiber breakage in mechanically fastened joints and complex preparation for adhesive joints. Additionally, adhesive joints require compatibility between the adhesive and the composite matrix, limiting their suitability for many thermoplastics. To address these challenges, this study explores a technique that uses metal inserts embedded during the consolidation of laminated thermoplastic composites. It investigates how the geometry of metal inserts and their adhesion to the fiber-reinforced thermoplastic composite affect the joint's performance under out-of-plane loads. Results indicate that while mechanical locking assists in load transfer, the adhesion between the metal insert and the composite is crucial for the joint's failure mechanism and overall performance. Strong adhesion delays final failure by requiring fiber breakage through the composite's entire thickness, while weak adhesion leads to failure through fiber breakage on the bearing side.

1. Introduction

Large and complex structures made of fiber reinforced composite materials often consist of smaller components joined together using mechanical fasteners like bolts or rivets, or alternatively, layers of film adhesive. Mechanical fasteners are preferred for their simplicity in preparation, assembly/disassembly, and inspection [1]; however, joining composite materials with mechanical fasteners is more challenging compared to metallic materials. Laminated composites have shear and bearing strength properties sensitive to fibre orientation, and these properties significantly decrease when defects, such as unwanted delamination and fiber discontinuity around the drilled holes, are present. The mechanical joint strength is also highly dependent on the laminate design. To enhance bolted joint strength in fiber reinforced composite plates, techniques such as adding additional $\pm 45^\circ$ plies, incorporating metallic inserts, or introducing metal layers into the composite have been explored [2].

Alternatively, using adhesives for joining composite materials requires more complex preparations and processes, including machining

and surface treatments for bonding preparation, and heat and pressure application to the joint section to facilitate chemical reactions. Inspecting and repairing damage in adhesive joints is also challenging. Furthermore, the performance of adhesive joints depends not only on the adhesive properties, but also on their compatibility with the adherent material. Thermoplastic resin systems are generally incompatible with thermoset adhesives, such as epoxies, due to differences in reactivity, surface energy and polarity [3]. This means that commonly used epoxy film adhesives approved for joining of high-performance aircraft structures are not suitable for fiber reinforced thermoplastic composites.

Another method of joining laminated fiber reinforced composites involves inserting metallic components during the lamination process and attaching these metallic inserts to other parts using bolts. Several researchers [4–7] have studied the use of metal inserts embedded during the curing or consolidation of laminated composites. This approach utilizes both direct adhesion and mechanical locking between the composite and the metal insert to transfer loads. Unlike bolt/rivet joints, this method does not require post-curing drilling, which can potentially

* Corresponding authors.

E-mail addresses: ridham@ihpc.a-star.edu.sg (M. Ridha), suzc@ihpc.a-star.edu.sg (Z. Su).

<https://doi.org/10.1016/j.compositesa.2024.108482>

Received 13 June 2024; Received in revised form 3 September 2024; Accepted 17 September 2024

Available online 19 September 2024

1359-835X/© 2024 Elsevier Ltd. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

damage the laminated composite. Fiber continuity can also be maintained by steering the fibers around the insert before curing. This method does not rely only on the bonding between the insert and the matrix because mechanical locking also plays a significant role in load transfer. This is especially important when joining thermoplastic composites with metals because the quality of adhesion between the thermoplastic and the metals is not as good as between thermoset composite or adhesive and the metals. The adhesion strength may also degrade during the service life of the joints due to cyclic loading.

Daynes et al. [8] conducted optimization studies on the geometry of metallic inserts in carbon fiber-reinforced polycarbonate composite plies to improve the transfer of out-of-plane (pull-out) loads. They employed static analysis using a first ply failure criterion to assess the load-bearing capacity of the joints. Mechanical properties of the composites were determined from pull-out tests on metallic-insert joints with various geometries, leading to the proposal of optimal geometries for steel and titanium inserts. Although the quasi-static finite element analysis by Daynes et al. [8] provides a quick estimation of the strength of composite-metal insert joints using the first ply failure approach, it fails to capture the progression of damage due to the absence of algorithms for modelling damage propagation or material degradation post-initial failure. The analysis did not account for disbonding between the insert and the composite, a phenomenon observed during experiments. As a result, this method cannot be used to analyse the performance of imperfect joint, such as those arising from imperfect bonding during manufacturing or cyclic loading during operation. Furthermore, the static analysis overlooked compressive failure in the composite, despite compressive damage being observed on the underside of the metal insert joint.

Computational progressive damage simulations provide a detailed analysis of composite structures by accounting for evolving damage under various loads, including mechanisms such as fiber breakage, matrix damage, and delamination. These simulations have been effective in elucidating performance and damage mechanisms at both the coupon level, such as open hole tension (OHT) [9–11], open hole compression (OHC) [11–13], impact tests [14,15], compression after impact [16–18] and bearing tests [19], as well as at the part level, including impact and bending tests for aircraft composite frames [20]. This progressive damage simulation approach can also be applied to composite-metal insert joints. For instance, Cheng et al. [21] utilized progressive damage simulation to analyse composite joints with metal inserts under in-plane loads. Their models included not only the failure in the composite plies but also the failure of the resin between the composite plies and the insert.

This study investigates the influence of geometry and adhesion quality in composite-metal joints under out-of-plane loads using detailed progressive damage finite element simulation. By employing progressive damage simulation, various damage mechanisms can be considered, including:

- Separation or loss of adhesion between the metal insert and the composite material (composite-to-metal disbond).
- Failure modes in the composite plies, such as matrix cracking, fiber failure, compressive failure, and shear deformation.
- Separation or debonding between individual layers of the composite material (delamination within composite plies).

This approach allows for the analysis of the impact of each damage mechanism on the ultimate failure of the joint and explores the interactions between different damage mechanisms. Moreover, parametric studies can be conducted to assess the effect of varying insert geometry and adhesion parameters between the composite and the metal insert. This analysis is particularly important for thermoplastics like nylon, which may exhibit weak adhesion with metals such as steel, or when adhesion is degraded by cyclic loading.

2. Experimental Methodology

2.1. Composite-metal insert joint design

Fig. 1 illustrates a cut view of the composite-metal insert joint. The joint utilizes a conical-shaped insert to transfer out-of-plane loads through mechanical locking between the insert's top side and the composite plate's bearing side, as well as adhesion between the insert and the composite at both the top and bottom surfaces. The composite plate, measuring 150 mm by 150 mm and 4 mm thick, comprises 16 carbon fiber (CF) woven plies. The insert is positioned 1 mm below the top surface of the composite, specifically between the 4th and 5th CF layers from the top, with all fibers aligned in the 0/90 direction.

The laminated fiber-reinforced thermoplastic composite is constructed using a plain weave dry CF fabric (Torayca® CO6343 3 K) with a fabric areal weight of 198 g/m² and polycarbonate (PC) film (100 µm thick) supplied by Glastic CCL+ (Korea). The composite lay-up was created by placing PC films both outside and between the carbon fiber fabrics, requiring two plies of PC film for each ply of carbon fiber to ensure adequate wetting of the CF, resulting in a fiber volume fraction of 55 %. During manufacturing, the steel insert was embedded into the unconsolidated composite by cutting a hole in the PC film and shearing the carbon fibers to accommodate the metal pin, ensuring no fibers were cut. A specialized compression mold ensured the insert was placed at the intended layer position, and the mold pressure formed the final shape of the joint. The composite was then consolidated using a hot-press machine at a maximum pressure of 20 bar and a temperature of 260 °C. No adhesive was applied between the PC film and the metal insert, so the bonding relies entirely on the direct adhesion between the PC matrix and the metal surface. Further details of the manufacturing process can be found in [8].

2.2. Material properties

Material characterization was performed to obtain properties needed in the progressive damage numerical simulation. Fiber direction tensile, fiber direction compression, and 45°/45° tension tests were performed following ASTM D3039, ASTM D6641, and ASTM D3518, to obtain the tensile, compression and shear properties of the woven fabric composite plies; the results of these tests are summarized in Table 1. In addition, double cantilever beam (DCB), edge notched flexure (ENF), and climbing drum peel tests were also performed to obtain the interlaminar fracture toughness between the composite plies and the adhesion toughness between the steel and the composite plies shown in Table 2. The properties marked with asterisk symbol * are not obtained from experiments but are assumed properties needed in the numerical simulation which are obtained based on other properties or references as shown in the tables.

The assumption is made that the out-of-plane shear behavior mirrors the behavior observed in-plane. It is important to highlight that, properties pertaining to out-of-plane behavior, such as E_{33} , G_{13} , G_{23} , ν_{13} , ν_{23} , along with related plasticity behavior, do not significantly impact the behavior of laminated composites. This is because deformation mechanisms are primarily governed by in-plane stress and strains. Additionally, the study will address inter-laminar delamination by employing cohesive elements inserted between the composite ply elements.

Fig. 2 shows that the delamination propagation observed in DCB (Double Cantilever Beam) and ENF (End-Notched Flexure) test specimens used to measure interlaminar fracture toughness is accompanied by additional damage modes. In the DCB specimens, delamination is dispersed, whereas the ENF specimens display compressive failure. As a result, the interlaminar fracture toughness values presented in Table 2 are regarded as conservative estimates.

The base value for the adhesion normal toughness of the composite-insert interface was established using climbing drum peel tests, while the shear toughness was assumed to be 50 % higher than the normal

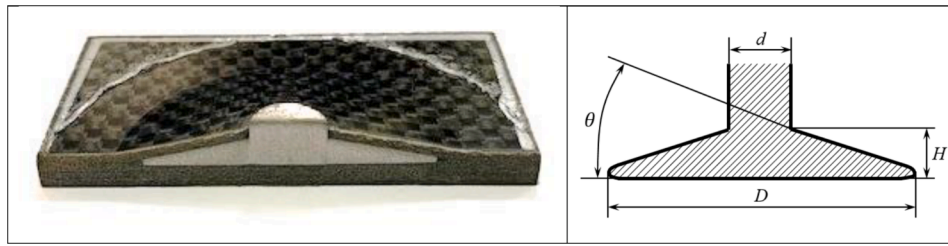


Fig. 1. Composite-metal insert joint.

Table 1
Mechanical properties of composite plies.

Property name	Values
Tensile Young' s modulus E_{11t}	49600 MPa
Compressive Young' s modulus E_{11c}	44400 MPa
Tensile Young' s modulus E_{22t}	49600 MPa
Compressive Young' s modulus E_{22c}	44400 MPa
*Young' s modulus E_{33}	5000 MPa
Shear modulus G_{12}	2300 MPa
*Shear modulus G_{13}	2300 MPa
*Shear modulus G_{23}	2300 MPa
Poisson's ratio ν_{12}	0.1
*Poisson's ratio ν_{13}	0.3
*Poisson's ratio ν_{23}	0.3
Tensile strength S_{11t}	472 MPa
Compressive strength S_{11c}	221 MPa
Tensile strength S_{22t}	472 MPa
Compressive strength S_{22c}	221 MPa
Shear strength S_{12}	84.5 MPa
*Shear strength S_{13}	84.5 MPa
*Shear strength S_{23}	84.5 MPa
*Tensile fracture toughness G_{11st}	50 kJ/m ² [23]
*Tensile fracture toughness G_{22st}	50 kJ/m ² [23]
*Residual compressive strength S_{11rc}	110.5 MPa
*Residual compressive strength S_{22rc}	110.5 MPa
*Thermal expansion coefficient α	$20 \times 10^{-6} / ^\circ\text{C}$ [24]

Table 2
Cohesive properties for interlaminar delamination and metal-composite adhesion.

	Interlaminar	Composite-Insert		
		Base	Weak	Strong
*Mode I (normal) strength N	63 MPa	60 MPa	6 MPa	120 MPa
*Mode II (shear) strength S	72 MPa	60 MPa	6 MPa	120 MPa
Mode I (normal) fracture toughness G_{Nc}	3.15 kJ/m ²	1.33 kJ/m ²	0.133 kJ/m ²	2.66 kJ/m ²
Mode II (shear) fracture toughness G_{Sc}	1.57 kJ/m ²	*2 kJ/m ²	0.2 kJ/m ²	4 kJ/m ²

toughness. The cohesive strength between composite plies and the adhesion strength between the composite and the insert did not significantly influence the simulation results of the composite-metal insert joint. This observation is consistent with the findings of Lu et al. [22], who noted that delamination behavior modeled using cohesive elements is insensitive to their strength parameters when potential delamination sites have pre-existing high stress concentrators or stress singularities. In the composite-metal insert joint, the edge of the metal insert serves as a stress concentrator.

3. Numerical Methodology

3.1. Elements and material model for composite plies

The composite-metal insert joint is vulnerable to various failure

mechanisms, including in-plane fiber or matrix failure and delamination between composite plies and between the composite material and the metal insert. This study utilized the finite element software Abaqus [25] due to its comprehensive element and material libraries necessary for progressive damage simulation and its capability to incorporate user-defined material models.

Abaqus offers several element types for modeling laminated composites, such as 3-dimensional (3D) continuum shell elements (SC6R or SC8R) and 3D solid shell elements (CSS8). These elements can be coupled with Abaqus' material models or user-defined materials to simulate the in-plane behavior of fiber-reinforced composite plies. Both element types can be easily integrated with cohesive elements or interactions to model delamination. The primary distinction between these two types of elements is the number of integration points per plane, with 3D solid shell elements having more (four versus one). Additionally, the 3D solid shell elements use a 3D material model, whereas the 3D continuum shell elements utilize a 2-dimensional (2D) material model.

Abaqus includes a built-in 2D material model specifically designed for modeling woven fabric composites. This material model can simulate in-plane tensile, compressive, and shear damage in composite plies. However, due to its 2D nature and compatibility issues, the model can only be used with Abaqus/Explicit for shell elements or continuum shell elements.

Several problems were encountered while implementing this built-in material model. Firstly, the continuum shell elements tended to distort easily once compressive failure occurred, leading to premature termination of the simulation. Secondly, discrepancies were observed between the simulation results and experimental data when applying the material model to simulate three-point bending (3 PB) tests. These tests were performed on a 3.77 mm thick and 12.55 mm wide plate made of 16 plies of the same material used in the metal-composite joint study, using a 100 mm 3 PB jig. In the simulations, the load-bearing capacity of the model significantly diminished as soon as compressive damage emerged on the compressive side of the plate, just below the middle loading bar. In contrast, experimental 3 PB tests, as shown in Fig. 3, indicated that the composite plies continued to exhibit residual load-carrying capability following damage initiation on the compressed side of the specimen, resulting in a plateau in the load curve. This experimental evidence suggests that the composite plies can withstand a certain amount of compressive stress following the initiation of compressive damage.

Similar plateauing of stress-strain curves was observed by Kyriakides et al. [26] when testing fiber-reinforced plastic composite rods under compression while restricting radial displacement. Successive kinking of fibers in the rod specimens was observed following initial damage, which caused the plateauing of the measured stress-strain curve.

Due to issues with element distortion and the inadequate material models available in Abaqus for modeling the thermoplastic composite, a custom material model was developed using the UMAT subroutine in Abaqus. It was found that 3D solid shell elements exhibited greater stability compared to continuum shell elements when experiencing compressive failure. Therefore, a 3D material subroutine was developed for modeling the thermoplastic composite in this study.

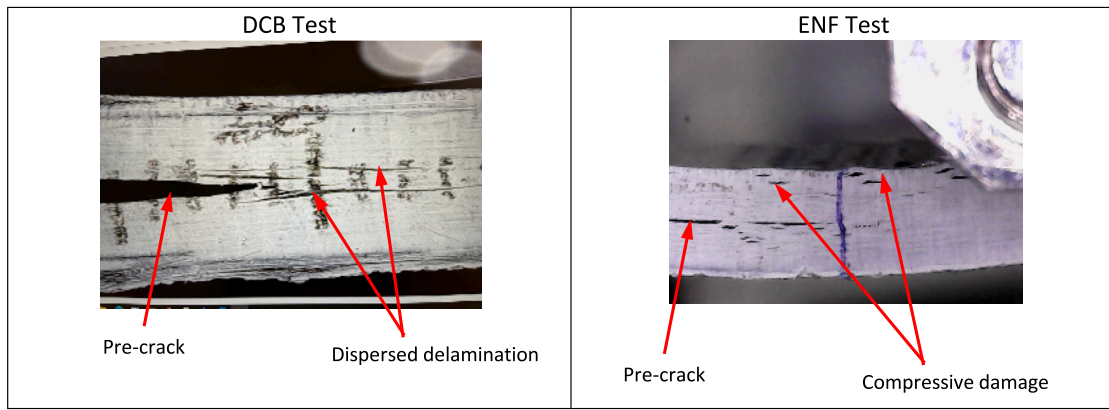


Fig. 2. Damage modes in double cantilever beam (DCB), edge notched flexure (ENF) test specimens.

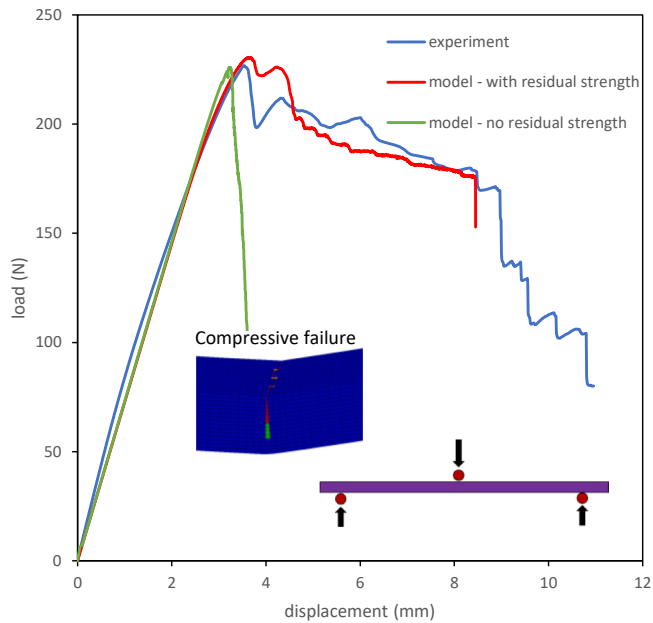


Fig. 3. Load-displacement response of 3-point bend experiment and models.

Fig. 4 illustrates the stress-strain curve of the material model, which exhibits different responses under various loading conditions as outlined below:

- Under in-plane tensile load, the material demonstrates linear elastic behavior with brittle failure. This failure is modeled using linear softening, defined by the fracture energy required for material failure. Here we assume that the critical fracture energy for this material is similar to the material tested by Laffan et al. [23] When subjected to compressive load, the stress reduces to a certain stress value (a plateau) after the onset of damage to mimic the residual load-bearing capacity post-damage. As shown in Fig. 3, we found that setting the residual stress to half of the maximum compression strength adequately replicates the response of the composite plate in 3 PB tests. This model is in line with the stress-strain plateauing observed by Kyriakides et al. [26] in their compression tests of fiber reinforced composite rods. It is important to note that the tensile and compressive stiffness can be defined independently in general.
- Under in-plane shear load, the material undergoes a linear elastic response followed by plasticity and failure. The plastic response is defined using a tabulated plastic-strain-stress format, while the elastic stiffness is assumed to be retained prior to the onset of failure.
- The same model is employed for out-of-plane shear loading; however, in the current model, plasticity and failure are not defined for this case due to the lack of available data. Out-of-plane shear failure is captured by the cohesive elements between the plies.
- Out-of-plane tensile and compressive responses are assumed to be linear elastic. This simplification is sufficient since any out-of-plane

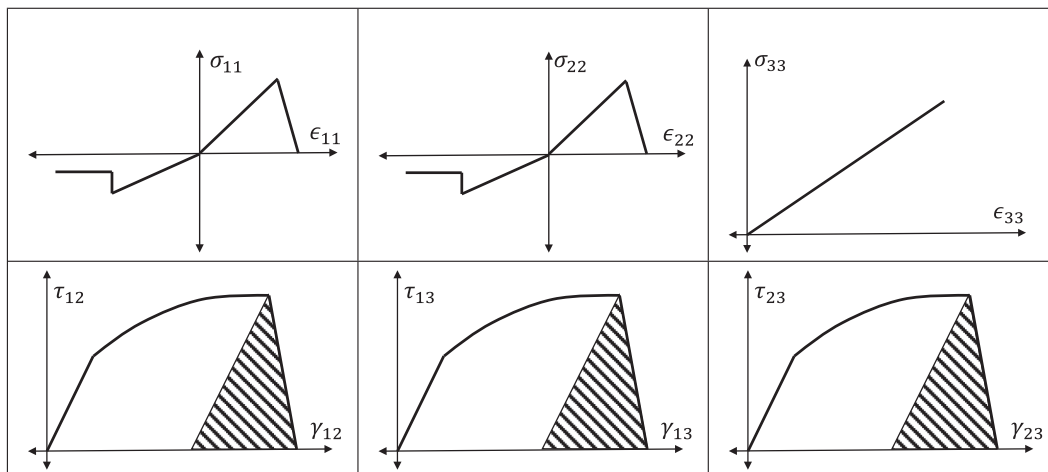


Fig. 4. Material model for woven fabric reinforced composites.

tensile failure will be modeled by the cohesive elements between the plies.

3.2. Model setup

Fig. 5 illustrates the geometry of the finite element model employed in this study. Following the experiment, the composite plate was clamped between two 10 mm thick steel plate with 100 mm diameter hole at the top. The steel insert was pulled upwards while the bottom plate was held by a circular pin. A quarter model was created by leveraging the symmetry of both the test specimen and the test jig. The inclusion of the test jig in the model was found to be essential as early simulations demonstrated an underprediction of displacement when the jig was replaced by idealized boundary conditions. Notably, the jig itself, particularly the top plate, undergoes bending when subjected to the load. The simulation incorporated thermal shrinkage effects during manufacturing by conducting a thermo-mechanical procedure before applying the pull-out loading. It was assumed that the PC matrix becomes completely solid at the glass transition temperature (T_g), necessitating thermo-mechanical analysis from T_g at 150 °C [27] down to room temperature at 25 °C.

The composite plate is modelled layer by layer using solid shell elements (CSS8) while the steel inserts and jigs/plates were modelled using solid elements (C3D8R). The mechanical properties of the laminated composite are assumed to remain uniform, even though local fiber distortions occur due to the insertion of the steel insert. Contact interactions were implemented between the composite plate and the jig, as well as between the bolts and the top plate of the jig. To account for the possible adhesion disbond between the plate and the insert, a surface-to-surface cohesive interaction model was employed. Additionally, cohesive elements were introduced between the plies above and below the insert to simulate the anticipated delamination at this interface, as shown in Fig. 5. The characteristics of the composite layers, including adhesion cohesive interactions and cohesive elements, are detailed in Table 1 and Table 2. The steels are modelled as elastic material with a Young's modulus of 210000 MPa, a Poisson's ratio of 0.33, and a thermal expansion coefficient of $17 \times 10^{-6}/^{\circ}\text{C}$ [28], while the resin rich zone is represented as elastic-plastic material, characterized by a Young's modulus of 2100 MPa and a Poisson's ratio of 0.37, and a yield strength of 60 MPa [29,30].

4. Results and discussions

4.1. Simulation results for base design

The metallic insert's base design features a 30 mm diameter cone

with a 3 mm height, as illustrated in Fig. 6. In the experiment, the final failure of the joint is characterized by a combination of fiber failure around the outer edge of the insert (circumferential) and emanating from the center of the insert towards its edge (radial). The measured strength is 14153 N with a standard deviation of 335 N.

The progressive damage simulation predicts a strength of 12842 N, around 9 % lower than average experimental values. The simulation results in the form of postmortem fiber damage and composite-metal disbond are depicted in Fig. 6. In these figures, the colors in the simulation results represent degrees of damage/degradation in the adhesion and composite plies; dark blue (0) represents pristine condition while red (1) represents total damage. The simulation results reveal that the thermal shrinkage mismatch between the steel insert and composite plies during consolidation leads to stress concentration at the interface and the outer edge of the composite plies. However, this stress is insufficient to induce disbonding. The model suggests that disbonding remains minimal, and no delamination between composite plies is observed until the final failure, even though the conservative inter-laminar fracture toughness values in Table 2 were used. The final failure is primarily marked by circumferential fracture of fibers in the composite plies above and surrounding the insert, along with some radial fracture of fibers emanating from the center of the insert, similar to the experiments. Compressive damages, characterized by fiber kinks at the bottom of the specimens, are experimentally observed and accurately predicted by the simulation. These compressive damages occur well before the final failure of the joint in the simulation, yet they do not result in a significant drop in the load.

To gain deeper insights into the impact of various parameters on the failure mechanism and overall strength of the joint, a parametric study was conducted on both the insert geometry and adhesion parameters. The findings are detailed in the subsequent subsections.

4.2. Effect of insert geometry

Similar to the experiments by Daynes et al [8], insert geometry was varied in the progressive damage simulation. In addition to the base design (30 mm diameter insert with 3 mm cone height), other variations featuring 20 mm and 40 mm diameter insert with various cone height and angle, as presented in Table 3, were examined. Note that the name suffix FA refers to the fixed angle, i.e. the angle of the cone is the same as the one in the base insert design (12.6°), while the name suffix FH refers to fixed height, i.e. the height of the cone is the same as the one in the base insert design (3 mm).

The load displacement curve obtained from both the simulation and experiments of the insert joint with varying insert geometry is depicted in Fig. 7. It is evident that the joint with a larger diameter insert exhibits

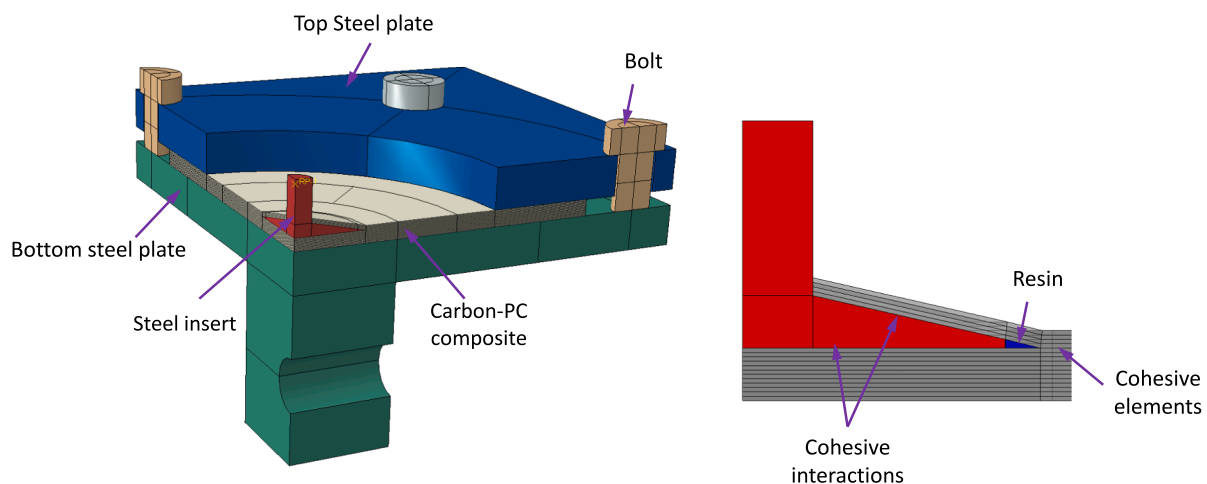


Fig. 5. Finite element model.

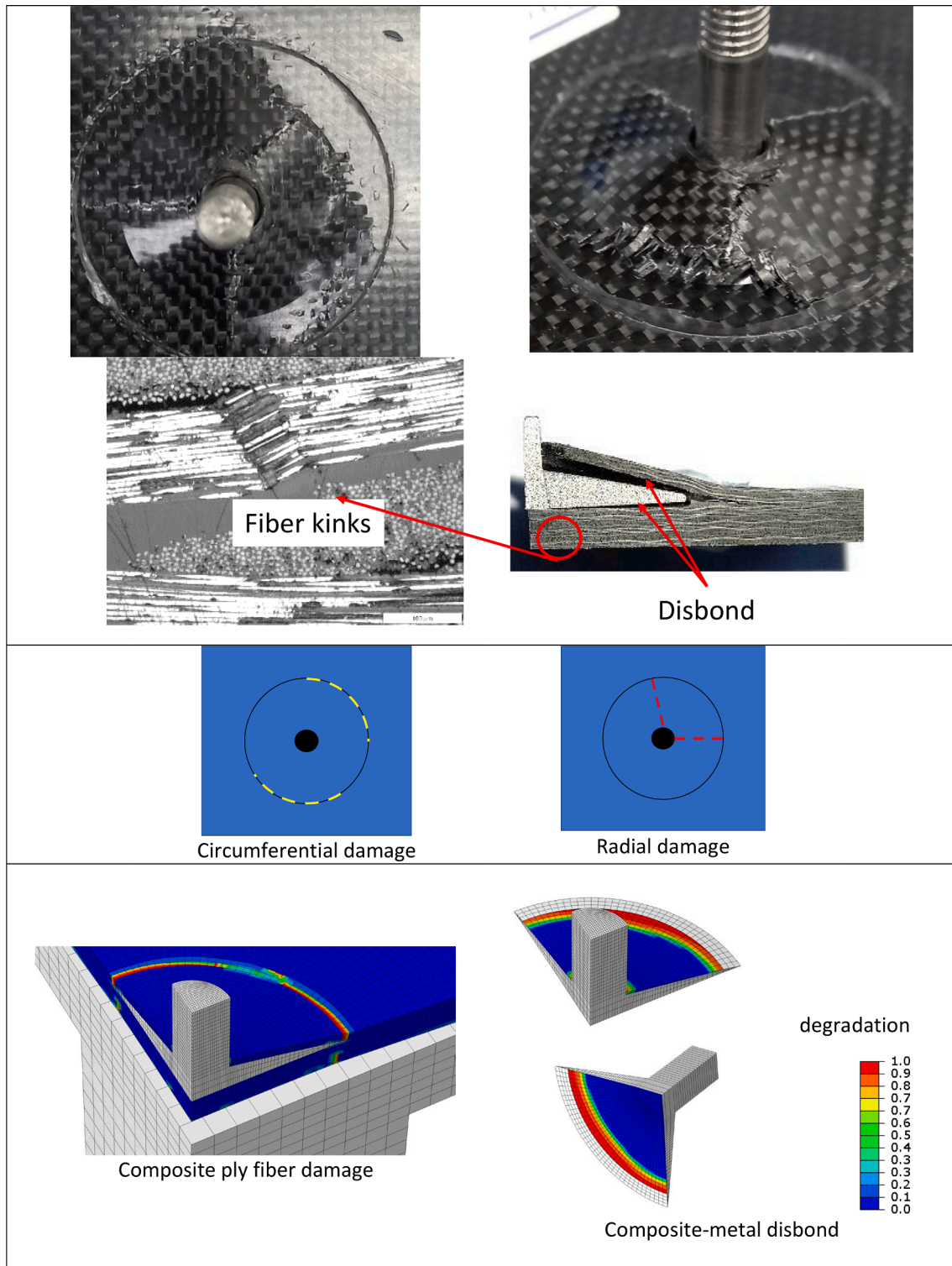


Fig. 6. Postmortem observation of 30 mm diameter composite-metal insert joint.

Table 3
Variation of insert geometry.

Sample name	Diameter (mm)	Cone height (mm)	Cone angle (°)
D20_FA	20	1.9	12.6
D20_FH	20	3	22.6
D30	30	3	12.6
D40_FH	40	3	8.7
D40_FA	40	4.1	12.6

a higher pull-out strength. Interestingly, unlike the experimental results, the simulation results show that the cone height angle does not appear to have a significant impact on the pull-out strength. The strengths of the D20_FH and D20_FA models are almost identical, while the D40_FA model only slightly surpasses the strength of the D40_FH model. The reason for the higher strength and stiffness of the D40_FA can be attributed to its slightly thicker and stiffer insert due to the higher cone angle, resulting in also a slightly larger adhesion area. However, these

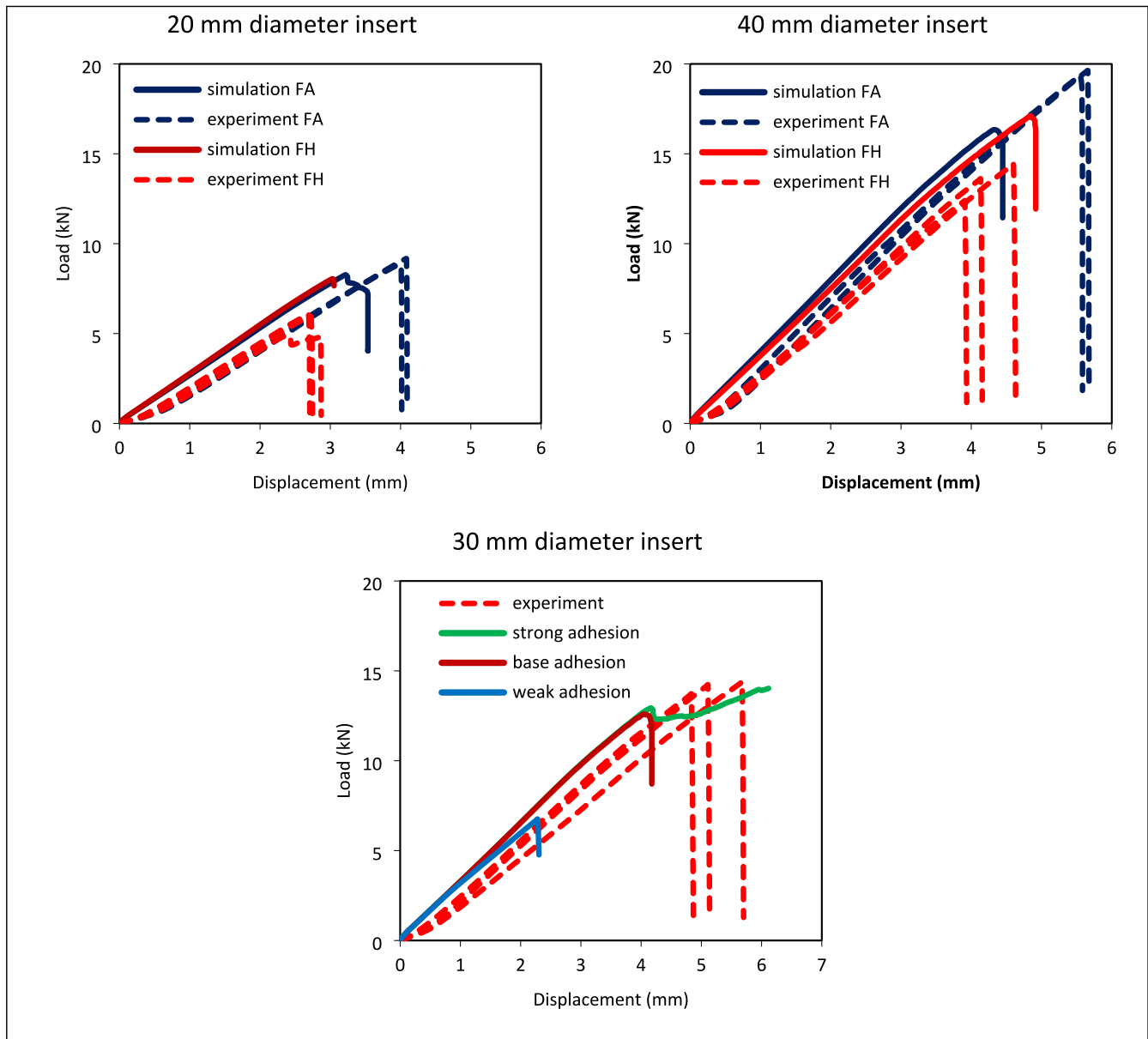


Fig. 7. Load displacement curve for various diameter geometry.

geometric differences alone are not able to explain the 30 % disparity in strength observed between the two joints in the experiments. This observation suggests other variations like adhesion strength may play a role, which will be further explored in the subsequent section focusing on the adhesion parametric study.

4.3. Effect of adhesion between the insert and the composite plies

Because the observed significant difference in strength between the FA and FH specimens in the experiments cannot be explained by the geometric variations alone, a more extensive numerical investigation was conducted into a parameter that is challenging to control in experiments: the adhesion between the steel insert and the composite plies. As shown in Table 2, we varied the adhesion properties ranging from base adhesion, which was obtained from experiments to weak adhesion (10 % of base toughness) and strong adhesion (200 % of base toughness). This study of adhesion parameters is also important because the performance of the adhesion may be degraded during the service life of the joints due to environmental or cyclic load.

The load displacement curves presented in Fig. 7 for the 30 mm diameter joint and Fig. 8 for the 20 mm and 40 mm diameter joints clearly demonstrate the critical role of adhesion in determining the load carrying capacity of the joint. While some load transfer occurs through mechanical locking, the effectiveness of the joint is influenced by adhesion strength. To gain further insight, we conducted a detailed analysis of the damage progression to elucidate how adhesion interacts with other damage mechanisms and ultimately leads to final failure. It's worth noting that the initial stiffness of the experimental load-displacement curves is lower due to imperfect contact among the various components in the testing jig.

The failure patterns observed in the 30 mm diameter insert joint models with different adhesion parameters are depicted in Fig. 9. For this 30 mm diameter insert joint models, higher adhesion does not lead to an increase in pull-out strength, while low adhesion significantly decreases the pull-out strength (Fig. 8). This can be attributed to the fact that, in the 30 mm diameter joint, the fibers in the composite plies in the model with base adhesion already starts to fail when disbond occurs. Consequently, as shown in Fig. 7, increasing the adhesion strength only

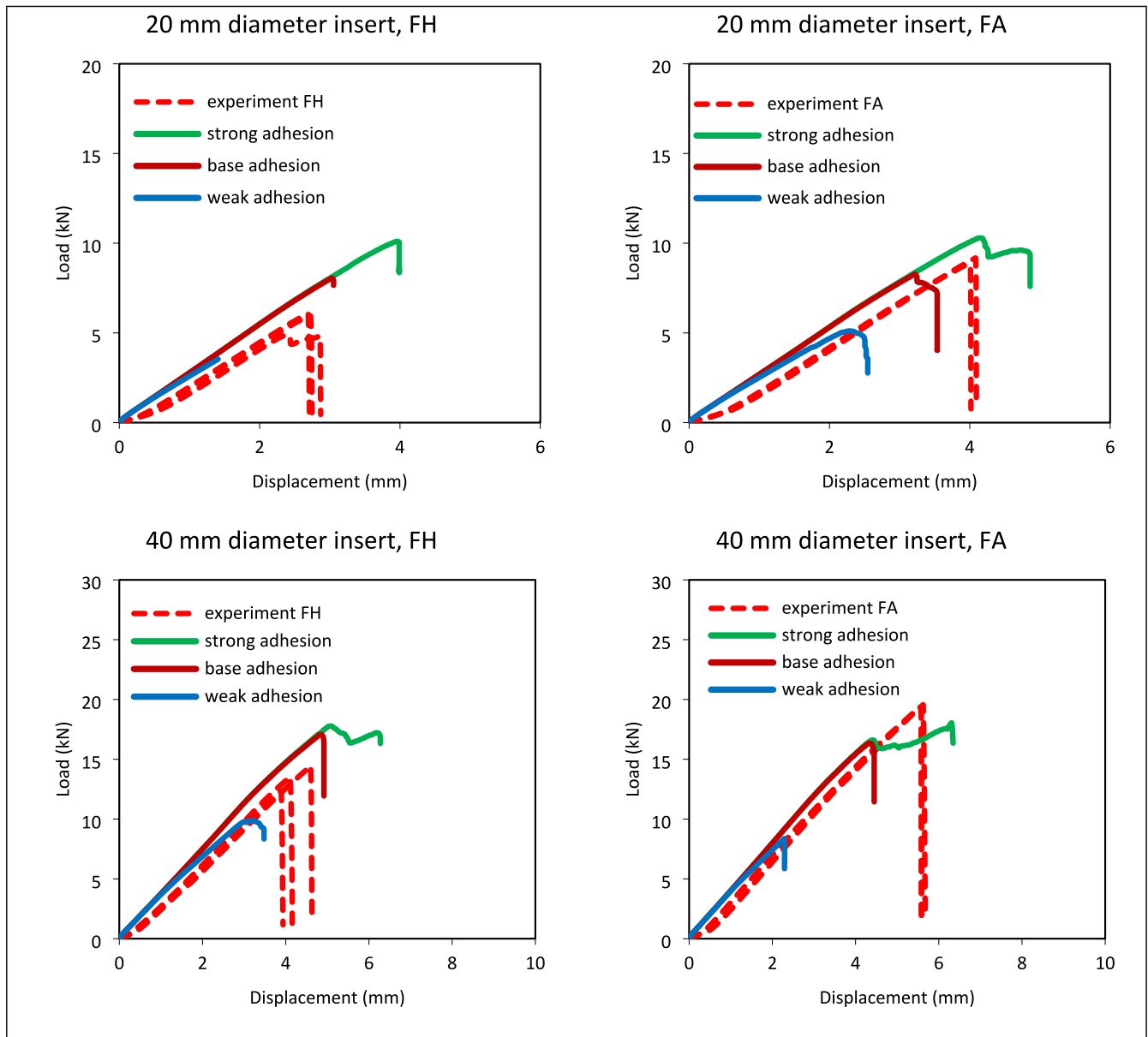


Fig. 8. Load-displacement curves of insert joint with different adhesion parameters.

delays the final joint failure, marked by the major load drop, without significantly enhancing the peak pull-out strength, which is controlled by the breakage of the fibers in the composite plies. In the case of the strong adhesion model, the delayed disbond forces the damage to extend not only to the plies above the insert but also to the plies below it before reaching final breakage.

On the other hand, early disbonding in the weak adhesion model results in the load being fully transferred through mechanical locking. The early disbond at the top side of the insert in the weak adhesion model allows the insert to stretch the top composite plies outwards, generating radial damages. Limited radial damage is also observed in the base adhesion case; however, this fracture mode competes with the circumferential fracture surrounding the insert. These findings align well with the experimental observations, where the 30 mm diameter joint specimens exhibited both the circumferential and radial damage. It is important to mention that in both base and strong adhesion scenarios, the composite plies located at the bottom of the metal insert experience compressive damage before the top plies undergo radial tensile damage. Nevertheless, this compressive damage does not result in a significant

reduction in load since the material model is designed to be able to withstand a 50 % of the maximum compressive strength after it fails under compression, as described in section 3.1 and Fig. 4 in the form of plateau of the stress-strain curve under compression. These compressive damages in the form of fiber kinks at the bottom plies are also found in the experiments (Fig. 6).

The FA 40 mm metal insert joint, shown in Fig. 10, with base adhesion fails mainly by simultaneous disbond and composite damage at the circumference of the insert. Only limited radial fracture occurred at the middle of the top composite plies because of the limited disbond at the top side of the insert. Similar to the 30 mm diameter joint with weak adhesion, the load in the 40 mm diameter joint with weak adhesion is carried by mechanical locking after the early disbond and the final failure is mainly by the radial damage of the top plies. In the FA 40 mm metal insert model with strong adhesion, minimal disbonding was observed, and complete joint failure necessitated full through-thickness circumferential damage to the composite plies.

Fig. 11 shows the failure pattern in the FA 20 mm diameter joint. It is noted that insert-composite adhesion area, which comprises of the top

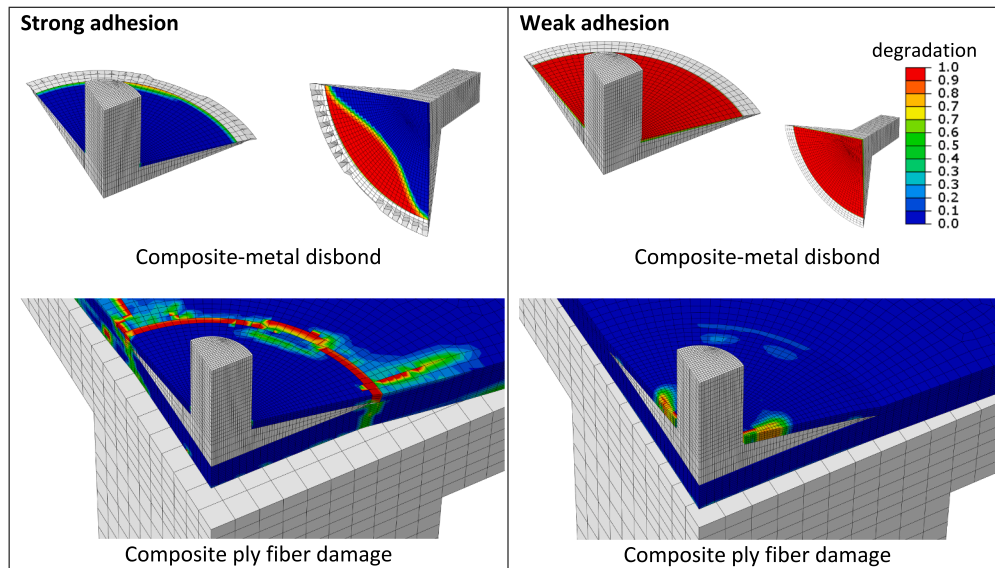


Fig. 9. Failure pattern in 30 mm diameter composite-metal insert joint.

and bottom surface of the cone, increases quadratically with the insert diameter while the potential circumferential fracture surface of the composite plies above the insert (i.e. circumference of the insert multiplied by the ply thickness) increases linearly with the insert diameter. Therefore, the adhesion fails much earlier than the composite plies when the diameter of joint is reduced to 20 mm, leaving only mechanical locking to bear the load, even when the base adhesion parameters are used. The fibers in the composite plies then fractures radially because of the outward stretching by the insert. The damage pattern in the strong adhesion model shows extensive disbond at the bottom side of the insert and limited delamination at the top side, and therefore, the final failure tends to be circumferential type, surrounding the insert instead of the radial damage. The pull-out test conducted on the 20 mm FA specimen predominantly exhibits circumferential failure, indicating a stronger adhesion compared to the model with base adhesion parameters. This finding helps explain why the FA type demonstrates significantly higher strength than the FH type observed in the experiment.

Fig. 12 provides an overview of how insert diameter and the toughness of metal-composite adhesion influence the failure mode and pull-out strength of FA joints in the simulations. In the figure, distinct colors of bullets denote varying insert diameters, while different bullet shapes indicate distinct failure mechanisms—triangular and round symbols represent radial and circumferential fractures, respectively. As both diameter and adhesion toughness increase, the strength also rises. Instances of higher strength are characterized by minimal disbonding between the insert and the composite lamina, leading to eventual failure in the form of circumferential fiber fractures in the composite plies surrounding the insert. The dashed line signifies the transition from radial to circumferential failure. This transition occurs at lower adhesion toughness when a larger insert diameter is employed, and conversely when a smaller diameter is used.

5. Conclusion

The composite-metal insert joint offers an alternative for connecting composite structures with metallic or other composite parts, particularly for thermoplastic composites. This method involves embedding a metallic insert within the carbon fiber thermoplastic plies during the manufacturing process, enabling the insert to transfer loads through a combination of mechanical interlocking and adhesion. Experimental studies provide direct measurements of the joint's strength, while progressive damage modeling delivers deeper insights into the joint's

failure mechanisms and the impact of various variables on its performance. This understanding is crucial for optimizing design, given the variability of parameters that are difficult to control and may degrade over time. In this study, the influence of geometry and adhesion on the performance of a composite-metal insert joint was investigated. It was discovered that while the final failure involves the breakage of fibers in the composite plies, the adhesion strength determines the location and manner of fiber breakage, ultimately affecting the joint's overall performance.

For the joint to be effective, it is desirable for damage to primarily occur at the circumference of the metal insert, with minimal disbonding. This ensures that the ultimate failure of the joint takes place by cutting through the entire thickness of the composite plies, including both the plies above and below the insert. Achieving this outcome relies on having a strong adhesion between the insert and the composite material and/or using a larger insert diameter. In cases where adhesion is not optimal, the following issues may arise:

- If disbonding occurs early between the bottom part of the insert and the bottom composite plies, the load will only be transferred through the top layer. Consequently, the strength of the joint becomes limited by the strength of the top plies.
- After the adhesion between the top plies and the metal insert fails near the metal pin, the conical shape of the insert begins to stretch the composite plies outward. This leads to the development of radial damage, which subsequently triggers premature joint failure.

In summary, our study highlights the critical role of adhesion in the performance of composite-metal insert joints. Strong adhesion between the composite plies and the insert is essential to ensure that the failure mechanism primarily involves cutting through the composite plies surrounding the insert, rather than premature disbonding followed by radial damages of the composite plies. The consideration of adhesion strength becomes more pronounced if the adhesion is degraded by cyclic thermal or mechanical load that may occur during the service life of the joint. A combination of using larger insert diameter, plastic matrix which is compatible with the metal insert, and surface treatment on the insert may be used to delay the disbond and therefore increases the pull-out strength of the joint.

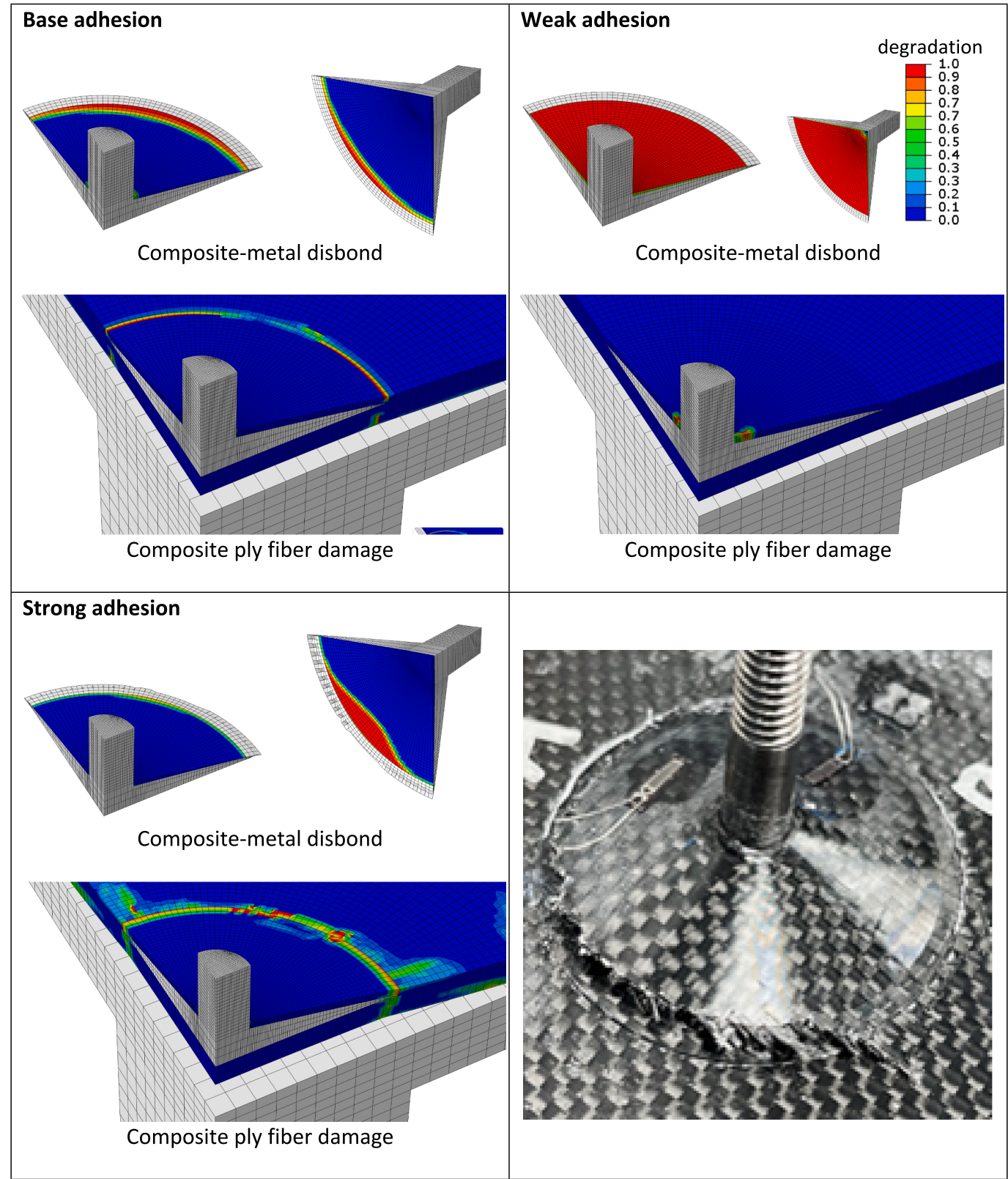


Fig. 10. Failure pattern in 40 mm diameter metal insert joint, FA.

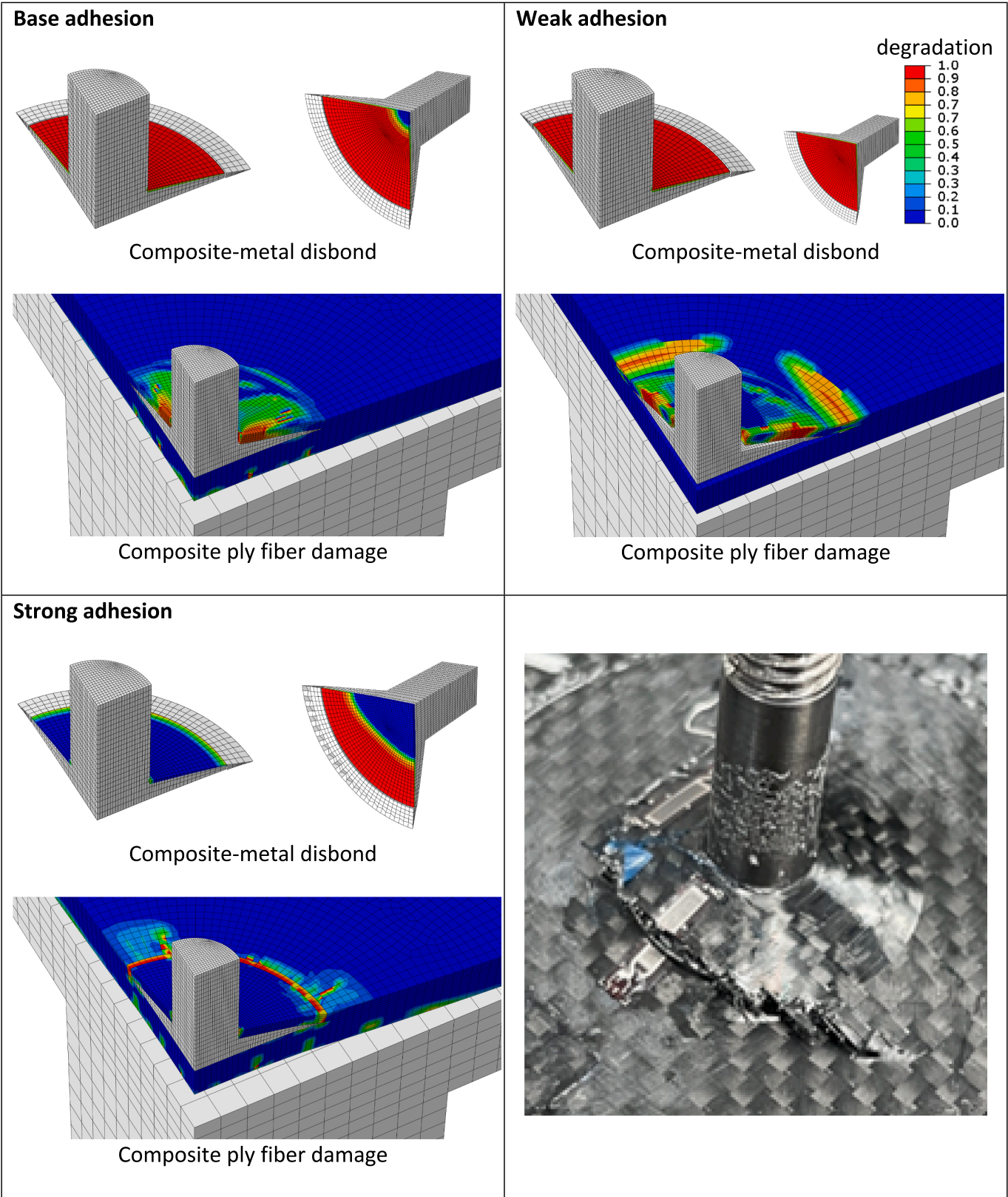


Fig. 11. Failure pattern in 20 mm diameter metal insert joint, FA.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve readability and language. After using this tool/service,

the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

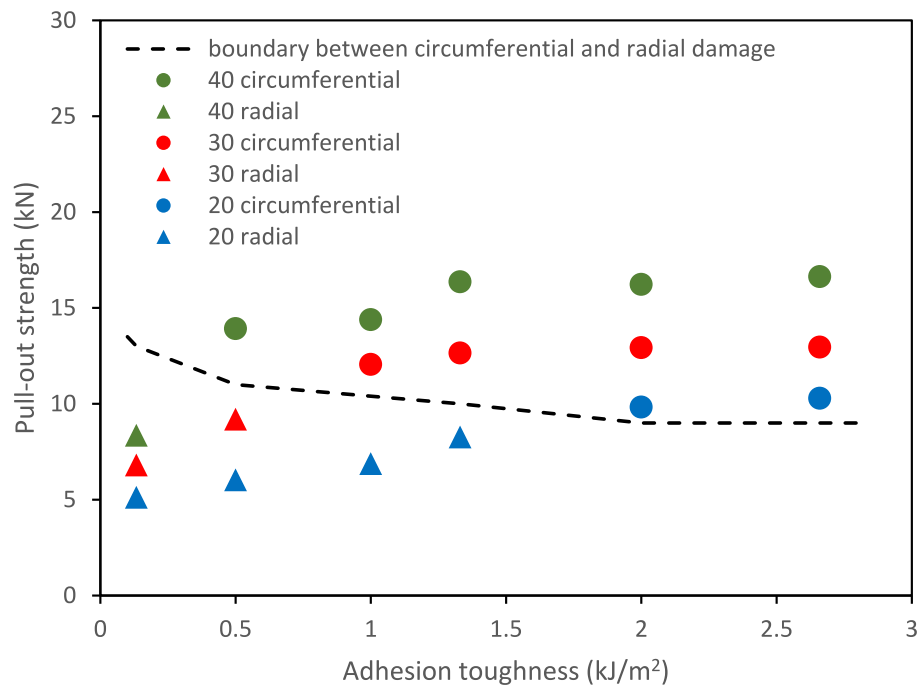


Fig. 12. Joint pull-out strength as a function of insert diameter and metal-composite adhesion toughness.

CRediT authorship contribution statement

Muhammad Ridha: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Zhoucheng Su:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Le Quan Ngoc Tran:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Wei Ming Albert Yek:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Sridhar Narayanaswamy:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Tong Earn Tay:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

The support from Singapore Agency for Science, Technology and Research (A*STAR) through the Polymer Matrix Composite Program (A19C9a0044) is greatly appreciated.

References

- [1] Niu M-C-Y, Niu M. *Composite Airframe Structures*. Hong Kong: Hong Kong Commilit Press Ltd.; 2010.
- [2] Kolesnikov B, Herbeck L, Fink A. CFRP/titanium hybrid material for improving composite bolted joints. *Compos Struct* 2008;83(4):368–80. <https://doi.org/10.1016/j.compstruct.2007.05.010>.
- [3] Deng S, Djukic L, Paton R, Ye L. Thermoplastic–epoxy interactions and their potential applications in joining composite structures – a review. *Compos A Appl Sci Manuf* 2015;68:121–32. <https://doi.org/10.1016/j.compositesa.2014.09.027>.
- [4] Pottmeyer F, Muth M, Weidenmann KA. Research of the load bearing capacity of shape-optimized metal inserts embedded in CFRP under different types of stresses. *KEM* 2017;742:636–43. <https://doi.org/10.4028/www.scientific.net/KEM.742.636>.
- [5] Pottmeyer F, Bittner J, Pinter P, Weidenmann KA. In-Situ CT damage analysis of metal inserts embedded in carbon fiber-reinforced plastics. *Exp Mech* 2017;57(9):1411–22. <https://doi.org/10.1007/s11340-017-0312-0>.
- [6] Muth M, Pottmeyer F, Weidenmann KA. Failure behaviour of metal inserts embedded in CFRP subsequent to thermal, mechanical and cyclic pre-damage. *Compos Struct* 2020;236:111877. <https://doi.org/10.1016/j.compstruct.2020.111877>.
- [7] Muth M, Schwennen J, Bernath A, Seuffert J, Weidenmann KA, Fleischer J, et al. Numerical and experimental investigation of manufacturing and performance of metal inserts embedded in CFRP. *Prod Eng Res Devel* 2018;12(2):141–52. <https://doi.org/10.1007/s11740-018-0829-9>.
- [8] Daynes S, Tran LQN, Ming AYW, Canturri C, Feih S. Design and strength optimisation of inserts embedded into fibre reinforced laminates. *Compos Struct* 2022;294:115744. <https://doi.org/10.1016/j.compstruct.2022.115744>.
- [9] Ridha M, Wang CH, Chen BY, Tay TE. Modelling complex progressive failure in notched composite laminates with varying sizes and stacking sequences. *Compos A Appl Sci Manuf* 2014;58:16–23. <https://doi.org/10.1016/j.compositesa.2013.11.012>.
- [10] Chen BY, Tay TE, Baiz PM, Pinho ST. Numerical analysis of size effects on open-hole tensile composite laminates. *Compos A Appl Sci Manuf* 2013;47:52–62. <https://doi.org/10.1016/j.compositesa.2012.12.001>.
- [11] Shirasu K, Tsuyuki J, Higuchi R, Onodera S, Okabe T. Experimental and numerical study on open-hole tension/compression properties of carbon-fiber-reinforced thermoplastic laminates. *J Compos Mater* 2022;56(14):2211–25. <https://doi.org/10.1177/00219983221096880>.
- [12] Su ZC, Tay TE, Ridha M, Chen BY. Progressive damage modeling of open-hole composite laminates under compression. *Compos Struct* 2015;122:507–17. <https://doi.org/10.1016/j.compstruct.2014.12.022>.
- [13] Liu H, Falzon BG, Li S, Tan W, Liu J, Chai H, et al. Compressive failure of woven fabric reinforced thermoplastic composites with an open-hole: an experimental and numerical study. *Compos Struct* 2019;213:108–17. <https://doi.org/10.1016/j.compstruct.2019.01.070>.
- [14] Liu H, Liu J, Ding Y, Zheng J, Kong X, Zhou J, et al. The behaviour of thermoplastic and thermoset carbon fibre composites subjected to low-velocity and high-velocity impact. *J Mater Sci* 2020;55(33):15741–68. <https://doi.org/10.1007/s10853-020-05133-0>.
- [15] Tan W, Falzon BG. Modelling the crush behaviour of thermoplastic composites. *Compos Sci Technol* 2016;134:57–71. <https://doi.org/10.1016/j.compscitech.2016.07.015>.
- [16] Abir MR, Tay TE, Ridha M, Lee HP. Modelling damage growth in composites subjected to impact and compression after impact. *Compos Struct* 2017;168:13–25. <https://doi.org/10.1016/j.compstruct.2017.02.018>.

- [17] Abir MR, Tay TE, Ridha M, Lee HP. On the relationship between failure mechanism and compression after impact (CAI) strength in composites. *Compos Struct* 2017; 182:242–50. <https://doi.org/10.1016/j.compstruct.2017.09.038>.
- [18] Nagumo Y, Hamanaka M, Shirasu K, Ryuzono K, Yoshimura A, Tohmyoh H, et al. Fracture mechanism of carbon fiber-reinforced thermoplastic composite laminates under compression after impact. *J Compos Mater* 2024;58(11):1377–90. <https://doi.org/10.1177/00219983241240622>.
- [19] Hu XF, Haris A, Ridha M, Tan VBC, Tay TE. Progressive failure of bolted single-lap joints of woven fibre-reinforced composites. *Compos Struct* 2018;189:443–54. <https://doi.org/10.1016/j.compstruct.2018.01.104>.
- [20] Ridha M, Tay T-E, Werner S, Joern P, Tan VBC. Analysis of composite stiffener under successive impact and bending test. *J Reinf Plast Compos* 2017;36(17): 1225–38. <https://doi.org/10.1177/0731684417704076>.
- [21] Cheng X, Li X, Zhang J, Zhang Q, Cheng Y, Zeng B. Evaluation of tensile properties of a composite-metal joint with a novel metal insert design by experimental and numerical methods. *Chin J Aeronaut* 2017;30(3):1004–11. <https://doi.org/10.1016/j.cja.2017.03.016>.
- [22] Lu X, Ridha M, Chen BY, Tan VBC, Tay TE. On cohesive element parameters and delamination modelling. *Eng Fract Mech* 2019;206:278–96. <https://doi.org/10.1016/j.engfracmech.2018.12.009>.
- [23] Laffan MJ, Pinho ST, Robinson P, Iannucci L. Measurement of the in situ ply fracture toughness associated with mode I fibre tensile failure in FRP. Part I: data reduction. *Compos Sci Technol* 2010;70(4):606–13. <https://doi.org/10.1016/j.compscitech.2009.12.016>.
- [24] Daniel IM, Ishai O. *Engineering Mechanics of Composite Materials*. New York, NY: Oxford University Press; 2005.
- [25] “Abaqus - SIMULIA User Assistance 2020.” [Online]. Available: https://help.3ds.com/2020/English/DSSIMULIA_Established/SIMULIA_Established_Frontmatter/Map/sim-r-DSDocAbaqus.htm?contextscope=all. [Accessed: 20-Feb-2023].
- [26] Kyriakides S, Arseculeratne R, Perry EJ, Liechti KM. On the compressive failure of fiber reinforced composites. *Int J Solids Struct* 1995;32(6):689–738. [https://doi.org/10.1016/0020-7683\(94\)00157-R](https://doi.org/10.1016/0020-7683(94)00157-R).
- [27] Pye, A., 2021, “Polycarbonate – an Overview,” Prospector Knowledge Center. [Online]. Available: <https://www.ulprospector.com/knowledge/11442/pe-polycarbonate-an-overview/>. [Accessed: 14-May-2024].
- [28] www.NEWPAGES.com.my, “2316 Plastic Mould Steel | Pre-Hardened Steel Plastic Mould Steel Malaysia, Selangor, Kuala Lumpur (KL), Klang Supplier, Suppliers, Supply, Supplies | E STEEL SDN. BHD.” [Online]. Available: https://m.ecarbonssteel.com/index.php?ws=showproducts&products_id=3173336&cat=Plastic-Mould-Steel. [Accessed: 20-Aug-2024].
- [29] Mu Q. Experimental data for creep and dynamic mechanical properties of polycarbonate and polycarbonate/acrylonitrile-butadiene-styrene. *Data Brief* 2022;42:108264. <https://doi.org/10.1016/j.dib.2022.108264>.
- [30] “Overview of Materials for Polycarbonate, Extruded.” [Online]. Available: <https://www.matweb.com/search/DataSheet.aspx?MatGUID=501acbb63cbc4f748faa7490884cdbc&ckck=1>. [Accessed: 20-Aug-2024].