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VIRTUAL TESTING OF LOW-VELOCITY IMPACT RESPONSE OF A COMPOSITE LAMINATE – FROM ANALYTICAL TO HIGH-FIDELITY MODELLING

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Abstract: The primary strategy to ensure the structural integrity of composite structures for aircraft design, certification, and sustainment is based on costly experimental campaigns. Virtual testing tools are essential to assist with materials screening and design processes. Advanced virtual testing tools offer potential to transform aircraft development and certification towards certification by analysis, and then they can be integrated as a part of digital twin for individual aircraft tracking and management.

Virtual structural testing may include a range of modelling and simulation tools, from analytical, low order to high order numerical tools, to predict structural responses and performance. Lower order tools are often computationally efficient and require less specialized expertise to run the tools. Such tools are often used in preliminary designs allowing extensive trade-off studies and layup optimization. Lower order tools are often well suited for quick decision making to assess the effect of damage on airworthiness. However, such tools come with concerns of their ability to provide adequate prediction for design and maintenance. High-fidelity finite element models are proven to provide accurate, physics-based prediction of composite progressive damage. Although great progress has been made in achieving improved fidelity of composites modelling, there remains challenges in achieving computational efficiency. It can be prohibitively expensive to run high-fidelity modelling of composite structures, thus rendering it impractical for some applications.

This study offers an assessment of modelling strategies to support concession decision making for aircraft designers, operators and maintenance facilities. A trade-off study between the accuracy and the computational costs of modelling methods was conducted based on prediction of damage resistance of IM7/977-3 composite panels subject to low-velocity impact. Simulation was performed using an analytical solution, a continuum mechanics based finite element model (FEM), and a high-fidelity FEM based on an integrated discrete damage and continuum mechanics-based approach. The predicted damage size and impact response were compared with experiments to assess the predictive accuracy and computation costs.

Keywords: Virtual Testing, Composites; Impact damage; Analytical, Finite element analysis;

INTRODUCTION

The usage of lightweight advanced composite materials on aircraft has enabled manufacturers to produce more fuel-efficient aircraft. Nearly 50% of airframe materials by weight on the Boeing 787, Airbus A350 and A220 are composites. The benefits of composites are not limited to their high stiffness and strength to weight ratio, they also include tailorable properties, low part counts, resistance to fatigue and corrosion (except for galvanic corrosion), and high damage tolerance.

As of today, aircraft design, certification and maintenance are largely dependent on physical testing. There has been tremendous effort in aerospace in development of capabilities in virtual testing and digital twinning. Digital engineering is seen as a game changer to transform the future of aerospace, enhancing competitiveness of aircraft industry and speed up adaption of new materials, non-conventional aircraft design and low-emission engine technologies. Major aerospace OEMs, such as Airbus, Boeing and certification authorities including FAA and EASA, have also been acting jointly to develop guidelines and standards for Certification by Analysis (or modelling and simulation) in structures, flight dynamics and other relevant areas with a goal of reducing costly physical testing and speed up time to develop a new aircraft.

The question has been raised regarding the required fidelity of modelling and simulation for the purposes of design, development, certification and maintenance of aircraft structures. Lower order modelling such as an analytical solution offers the benefit of computational efficiency, and requires less specialized knowledge or expertise to run a prediction. High-fidelity modelling tools for composite materials and structures often account for their complex damage mechanisms and their interactions. Specialised knowledge and expertise are often required to develop and run high-fidelity models, and custom user-defined subroutines are often necessary. However, high-fidelity models for composites can be prohibitively expensive in terms of computational costs, which may render the approach impractical for large-scale structural applications.

In this study, a Low Velocity Impact (LVI) event was modelled using three strategies - the analytical solution, continuum 3-D FE model, and a high-fidelity 3-D FE model. The analytical solution was developed by Esrail and Kassapoglou [1] using the energy minimization and Hertzian contact formulation. The low order finite element model (FEM) based on continuum mechanics only, without integration of fracture mechanics. For failure criteria, the enhanced LaRC05 failure criteria with a search algorithm to find the matrix fracture plane and the fibre kink-band angle were applied. The last strategy is a high-fidelity FEM model using integrated continuum and a discrete damage modelling approach, where energy-based fracture mechanics was integrated for damage propagation, along with the enhanced LaRC05 failure criteria. The predicted damage areas, as the key output of the impact simulations, were compared with X-ray CT results. In addition, the predicted peak load, contact duration, maximum displacement, absorbed energy, and also the time that was required to obtain the results from these three models, were compared. This work offered a quantifiable comparison among predictive tools from low to high fidelity to illustrate the trade-off between accuracy and computational costs. The conclusion from this study cannot be generalized for other scenarios of composite failure prediction.

LOW-VELOCITY IMPACT TEST SCENARIO

Impact damage resistance, the ability of a composite material or structure to resist the formation of damage, is one of the key considerations for composite aircraft design and certification. Composite structures are subject to various impact damage sources, such as dropped tools, runway gravel, and hail. Drop tower testing of LVI and Compression After Impact (CAI) are widely used as the base level of a building-block approach for assessing composite impact resistance and damage tolerance. There has been a great interest in replacing physical testing with virtual testing to reduce the number of larger, and more complex test articles. This paper focuses on the study of trade-off of accuracy and computational costs of different virtual testing strategies based on a LVI test scenario of composite laminates.

The current test standard D7136/D7136M [1] is based on testing and evaluation of 4” x 6” (101.6 mm x 152.4 mm) composite laminate panels for measuring the damage resistance of a fiber-reinforced polymer matrix composite to a drop-weight impact event. Questions persist about whether or not CAI strengths obtained using this relatively small specimens can be applied to larger aircraft components or more complex geometries. In this study, larger composite test panels of 10” x 12” x 0.171” (or 204.8 mm x 254 mm x 4.3 mm) were fabricated to better represent actual composite structures. The composite laminates were made of 32 plies of IM7/977-3 prepreg, with a layup of $[0/45/90/-45]_{4s}$.

The impact tests were conducted in an INSTRON Dynatup Drop Weight System 8200, as shown in Figure 1. The drop-weight impact system load measurement was calibrated to ± 1 % of the maximum load. The specimen was supported by a modified fixture base to support a 10” x 12” (204.8 mm x 254 mm) panel with a rectangular cut-out of 9” x 9” (228.6 mm x 228.6 mm), as shown in Figure 2. A specimen was held in place using the four rubber-tip clamps (minimal clamping force) and centred relative to the cut-out using three-point corner pins. All drop-tower impact tests were conducted using a hemispherical impactor with a diameter of 15.87 mm and mass of 6.14 kg moving with an initial kinetic energy of 30 J.

The impact test results of seven IM7/977-3 composite laminates are shown in Figure 3, demonstrating exceptional repeatability of impact responses. The impact event lasted approximately 8ms, with a peak load at 10,000N for an impact kinetic energy of 30J. All results exhibited significant but consistent load drops in terms of the magnitude and the time of the events. This suggests that there exists a close linkage between the load responses and damage progression, as a result of failure mechanisms such as fibre kinking, fibre splitting, fibre breakage, interlaminar or intralaminar matrix cracking, or delamination.

Figure 1. Drop weight tower system

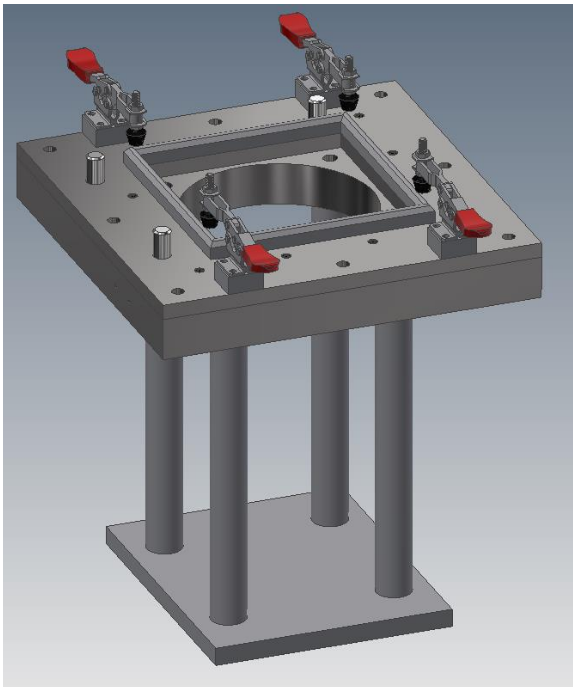

Figure 2. Drop tower fixture with an opening window of 228.6 mm x 228.6 mm to accommodate test panels of 204.8 mm x 254 mm

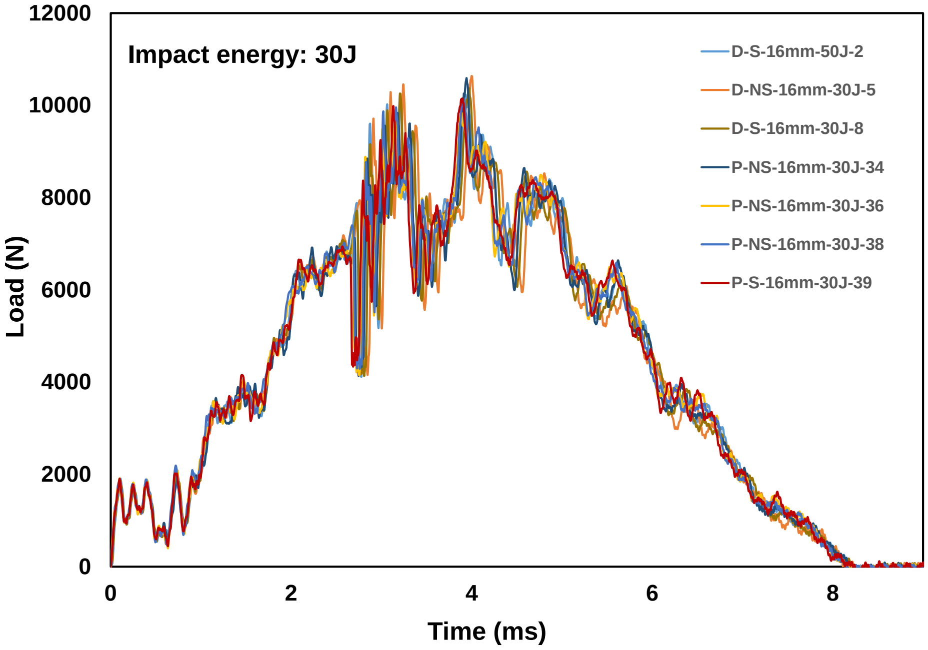

Figure 3. Load response during impact event of a composite panel, with initial kinetic energy of 30J and impactor diameter of 15.87 mm

STRATEGY I: ANALYTICAL SOLUTION FOR IMPACT DAMAGE

The analytical approach [2] was applied to predict the size of the LVI damage in quasi-isotropic composite laminates in the current study to find the delamination area for a 254 mm by 304.8 mm (10 in by 12 in) carbon/epoxy (IM7/977-3) panel. This analytical solution is applicable to symmetric and balanced laminates with a quasi-isotropic stacking sequence and with the simply supported boundary condition. In this closed-form solution, the low energy and high mass situation were assumed, for which the impact event is long enough for the boundary reflections to die out and the response of the panel is dominated by static response characteristics. Thus, the LVI event can be considered to be a quasi-static event. The state of stress in the laminate was found by minimizing the complementary strain energy. In the energy calculations, only the internal energies due to bending and indentation were taken into account, and the other forms of absorbed or dissipated energies, such as damage dissipated energies, were considered negligible.

To determine the stress in the laminate, the Hertzian contact pressure distribution was used. In the first step, the peak force corresponding to the impact energy level was determined using the energy balance. Then, the impacted laminate was divided into two regions, one within the contact area ($0 \leq r \leq R_c$) and the other outside the contact area ($r > R_c$) as shown in Figure 4. For each region, the normal, σ, and shear stresses, τ, were obtained in the cylindrical coordinate system (σ_{rr}, $\sigma_{\theta\theta}$, σ_z and τ_{rz}) for different values of z, r and θ. Because of the quasi-isotropic assumption for the composite laminate, there was no dependence on θ in the stresses and the shear stresses $\tau_{r\theta}$ and $\tau_{\theta z}$ were zero. To determine the delamination areas, τ_{rz} was decomposed to its τ_{xz} and τ_{yz} components at ply interfaces (x was in the fibre direction, y was perpendicular to the fibre direction, and z was out-of-plane) and were compared with the corresponding strengths of both plies sharing the interface. If the average of the τ_{xz} or τ_{yz} stresses exceeded their corresponding allowable for each ply over a characteristic distance [3], the occurrence of delamination was predicted at that location. This procedure was repeated for different z, r, and θ until a complete damage map was obtained.

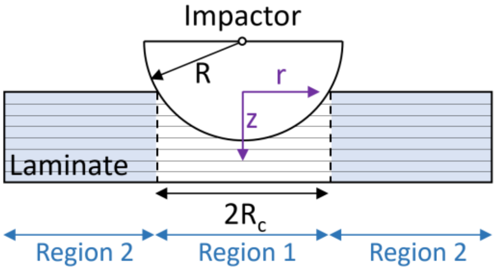

Figure 4. Determination of the contact radius (R_C).

To implement this analytical solution, a MATLAB code was developed. The predicted delamination areas at all interfaces are shown in Figure 5. The largest diameter of the delamination was 18 mm and it was predicted to occur at the interfaces between ply-15 and ply-16 and also between ply-17 and ply-18. Although the stresses were not dependent on θ, the resulting delamination pattern was not axisymmetric because of non-axisymmetric interlaminar strengths in the xz and yz planes. The peak force, maximum displacement (peak deflection of the laminate) and contact duration were also predicted using this analytical solution. The running time to get the total delamination area for the studied composite laminate was about 15 minutes on a personal computer with 1 CPU core. However, this analytical solution did not address the progressive damage nature in composites where stiffness and strength would be changed continuously during the impact event. Additionally, it made no use of fracture mechanics for monitoring the delamination initiation and growth. Therefore, this analytical solution can only provide an approximation of the total delamination area, without the capability to predict damages from other mechanism such as fibre breakage and matrix cracking.

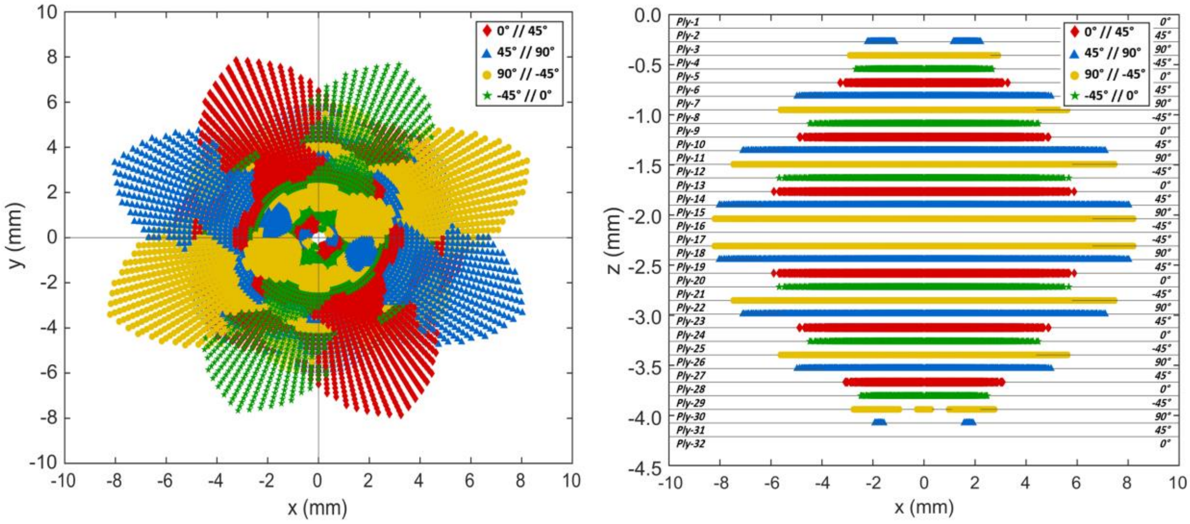

Figure 5. Delamination areas predicted by analytical solution for the quasi-isotropic laminate with a stacking sequence of $[0/45/90/-45]_{4s}$ after a 30 J impact event [4].

STRATEGY II: CONTINUUM FINITE ELEMENT MODEL

The same LVI case of the 254 mm by 304.8 mm IM7/977-3 composite laminate with a stacking sequence of $[0/45/90/-45]_{4s}$ was simulated in Abaqus using a continuum mechanics approach. The mechanical properties of IM7/977-3 that were used can be found in [4]. The assembly of the FE model is shown in Figure 6. The support plate and impactor were considered rigid bodies. Four rubber cylinders were modelled to simulate the clamps, and the rigid body movement of the laminate was constrained in the x and y directions by defining contacts between the edges of the laminate and three pins of the support plate. The composite plies were modelled individually using 3-D 8-node continuum elements with reduced integration (C3D8R). After a mesh sensitivity analysis, the composite laminate was divided into 288,000 finite elements with a higher mesh density in its centre. To predict matrix cracking, fibre breakage, fibre splitting, and fibre kinking failures, a VUMAT user-defined subroutine was developed for Abaqus/Explicit based on the LaRC05 failure criteria [5]. Using the LaRC05 failure criteria, it is possible to predict the fracture plane angle, which is important to predict the consequences of failure in composite laminates. To efficiently identify the matrix fracture plane and the fibre kink band angle in each region of the laminate, the selective range golden section search (SRGSS) algorithm, which efficiency and reliability were verified for Puck’s criteria [6], was employed.

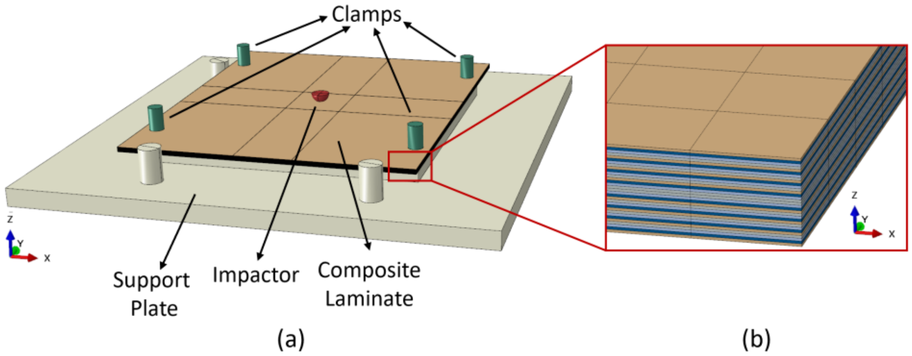

Figure 6. (a) Assembly of the continuum LVI FE model, (b) Layup configuration of the continuum 3-D FE model.

STRATEGY III: HIGH-FIDELITY FINITE ELEMENT MODEL

The assembly of the high-fidelity model is shown in Figure 7(a). To predict delamination and intralaminar matrix cracking, cohesive elements (COH3D8) with a bilinear traction-separation constitutive relationship were employed between each adjacent composite ply and also inside each composite ply as shown in Figure 7(d). The intralaminar cohesive elements were embedded with a 45° angle to the thickness of the laminate according to the experimental observations [7][8][9]. The damage initiation in the cohesive elements was determined by the quadratic stress criterion and the damage evolution was governed by the power law damage evolution criterion. The properties of the cohesive elements were defined similar to those in [4]. To model the composite laminate, 272,000 continuum elements (C3D8R) and 315,000 cohesive elements (COH3D8) were used. Each cohesive layer was tied to its adjacent composite plies due to their non-conforming mesh distribution. The same VUMAT subroutine that was used in the continuum model was used with this high-fidelity model to predict fibre tensile failure, fibre splitting, fibre kinking, and matrix cracking. To avoid excessive distortion of elements after failure, the maximum stiffness degradation of the continuum elements was set to 95% and the “element deletion” option in Abaqus was switched on for the cohesive elements. In order to prevent the penetration of the continuum elements of the adjacent composite plies after the deletion of the cohesive element in between, a set of contacts was defined between each adjacent composite ply.

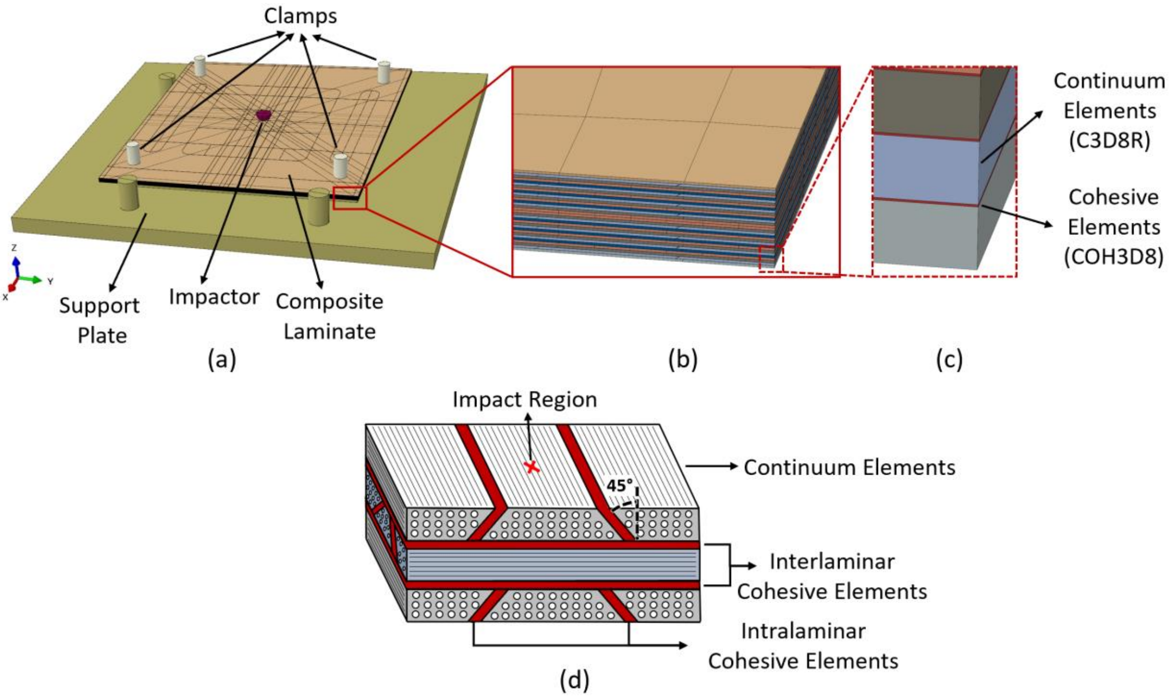

Figure 7. (a) Assembly of the high-fidelity LVI FE model, (b) Layup configuration of the high-fidelity 3-D FE model, (c) Continuum and cohesive elements used in the FE model, (d) Schematic of the inter- and intra-laminar cohesive elements.

RESULTS AND DISCUSSIONS

The computational time and the predicted damage areas obtained with the FE models and the analytical solution are compared in Table 1. With the MATLAB code written based on the Esrail and Kassapoglou [2] analytical solution, the delamination area at each interface of the 32-ply quasi-isotropic laminate was obtained in 15 minutes on a single CPU core. This time is for the data point density that are shown in Figure 5, and by changing the number of the data points, the required time would change. The continuum FE model took 19.5 hours on a high-performance computer (HPC) with 32 CPU cores, and the high-fidelity FE model took 58.8 hours on the same HPC with 32 CPU cores. The continuum FE model had 288,000 continuum elements and the high-fidelity FE model had 272,000 continuum and 315,000 cohesive elements. As compared to continuum model, more constraints were employed in the high fidelity models, including 62 additional tie constraints to tie each cohesive layer to its adjacent composite plies, and 31 additional contacts to prevent penetration of the continuum elements after deletion of the cohesive element between them. Another reason for the higher computational time of the high-fidelity model compared to the continuum model was its smaller stable time increment (STI). In the high-fidelity model, cohesive elements were kept small (0.5 mm × 0.5 mm × 0.005 mm) in order to provide accurate results [4]. The STI in the high-fidelity model was controlled by the smallest cohesive element, which was 5.8×10^{-9} s at the beginning of the simulation. Whereas, in the continuum model the STI was controlled by the smallest continuum element and it was 1.6×10^{-8} s, which was 2.75 times higher than that in the high-fidelity model.

The predicted impact damage areas and the X-Ray CT results of the quasi-isotropic $[0/45/90/-45]_{4s}$ composite laminate after a 30 J impact event are tabulated in Figure 8. The overall delamination and matrix cracking areas were measured to be an average of 841 mm^2 and 894 mm^2, respectively. With the analytical solution, the delamination area was predicted at each ply interface. The predicted damage areas could be surrounded by a circle with an 18 mm diameter, which was smaller than what was obtained from X-Ray CT scanning. With the continuum FE model, a matrix cracking area of 591 mm^2 and a fibre failure area of 398 mm^2 were predicted. The total damage area obtained from the continuum

FE model was 33.2% smaller than that of the experiment. The high-fidelity model provided more accurate predictions for the damage areas. The predicted delamination size was 693 mm^2, the matrix cracking size was 976 mm^2, and the fibre failure area was 113 mm^2. The total damage area obtained from the high-fidelity model was 9.8% larger than that of the experiment.

Table 1. Computational time and the predicted damage areas after the 30 J LVI event.

Modelling approach	Predicted/Inspected damage modes	Simulation time (h)	Projected damage areas (mm^2)			
			Delamination	Fibre failure	Matrix cracking	Total‡
Analytical	• Delamination	0.25†	254	-	-	254
Continuum	• Fibre failures (breakage/splitting/kinking) • Transverse matrix cracking	19.5§	-	398	591	603
Continuum and Discrete	• Fibre failures (breakage/splitting/kinking) • Transverse matrix cracking • Delamination • Delamination and intralaminar matrix crack interactions	58.8§	693	113	976	992
Experiment (X-Ray CT)	• Delamination • Matrix cracking	-	841	-	894	903

† On a personal computer with 1 CPU core

§ On a high-performance computer with 32 CPU cores

‡ The outline of all damage modes was considered to be the total damage area

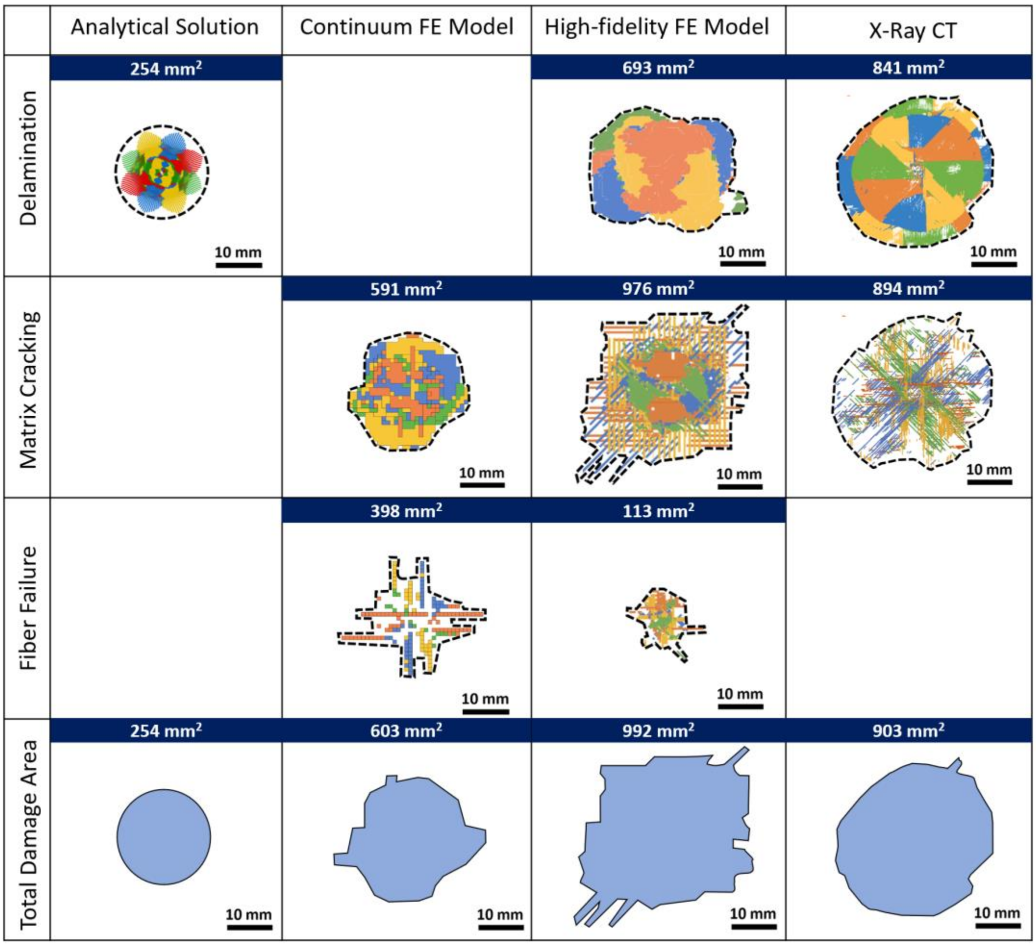

Figure 8. A comparison between the predicted damage areas and the X-Ray CT results.

The impact responses predicted with the FE models are compared with the drop-weight impact test results in Figure 9. With the continuum FE model, the contact duration and the maximum deflection of the laminate were predicted with high accuracy. However, the peak load was 19.5% lower than that in the experiment. The lower peak load might be the reason for the smaller predicted damage area with the continuum model. With the high-fidelity model, the contact duration and the maximum deflection were predicted with higher accuracy. The predicted peak load was also more accurate than the result from the continuum model and it was 8% lower than the experiment. The high-fidelity model also captured the load drops better than the continuum model.

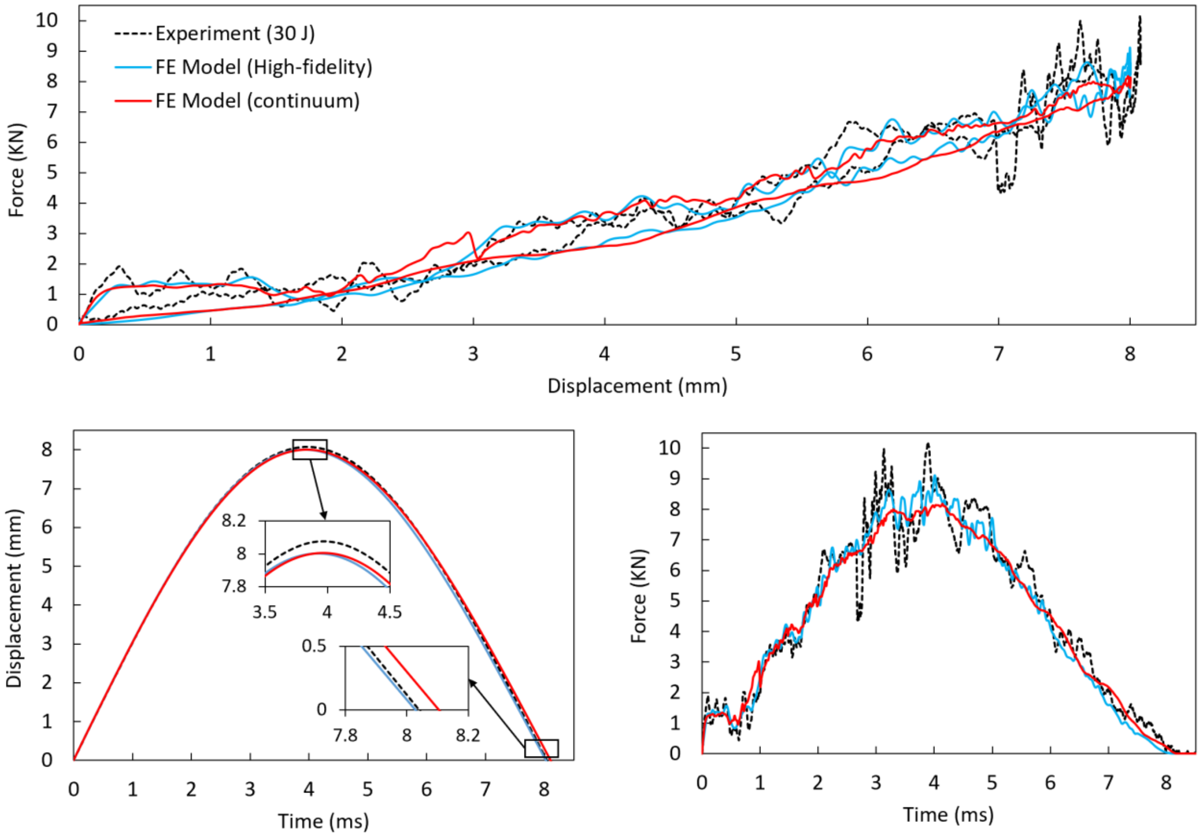

Figure 9. Comparisons of the predicted impact responses and the drop-weight test results.

In Figure 10, the key outputs of the impact models are compared with the experimental results. The detailed values of these parameters are also summarized in Table 2. The analytical solution predicted the maximum deflection and the contact duration with less than a 15% error. However, the peak load was lower and the total damage area was smaller than in the experiment. The smaller damage area might be due to the failure criterion that was used to predict the delamination. Instead of using fracture mechanics, a physics-based approach for predicting delamination initiation and evolution, the shear stresses (τ_{xz} and τ_{yz}) at the interface of two plies were compared with the shear strength of the plies that share the interface. The calculated absorbed energy in the analytical solution was only due to the work done to indent the laminate, whereas dissipated energy due to damage was not considered. For this reason, the absorbed energy was lower than what was obtained in the experiment.

The prediction of the continuum FE model for force and displacement during the impact event matches reasonably well with the experiment. However, the predicted peak load and the total damage area, although much improved, were still underestimated, respectively by 19.5% and 33.2%, compared to the experiments. The high-fidelity FE model predicted the peak load and total damage areas with higher accuracy. The peak load was 8% lower and the total damage area was 9.8% larger than the experiment. The reason for the higher absorbed energy in the FE models was the use of artificial and viscous energies that were dissipated to help the convergence of the explicit solver. By calculating and adding up the dissipated energies due to different damage modes, a more accurate prediction can be put forward for the absorbed energy [4].

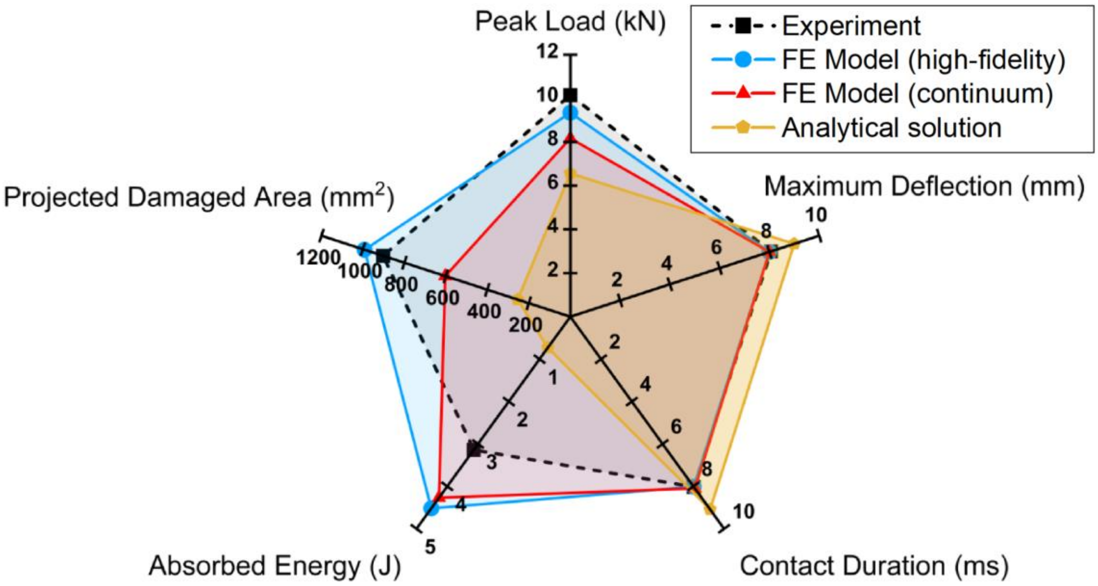

Figure 10. Comparisons of the key outputs of the impact simulation with the experimental results.

Table 2. Comparisons of the key parameters of the predicted impact responses with the experimental results.

	Maximum deflection (mm)	Peak force (kN)	Contact duration (ms)	Absorbed energy (J)	Projected damage area (mm^2)
FE Model (high-fidelity)	8.00 (-0.9%)	9.34 (-8%)	8.02 (-0.1%)	4.52 (+43.95)	992 (+9.8%)
FE Model (continuum)	8.00 (-0.9%)	8.17 (-19.5%)	8.1 (+0.8%)	4.27 (+35.9%)	603 (-33.2%)
Analytical solution	9.00 (+11.5%)	6.56 (-35.3%)	9.09 (+13.2%)	0.73 (-76.7%)[†]	254 (-71.8%)
Experiment	8.07	10.15	8.03	3.14	903

[†] Only the work done indenting the laminate was considered in this analytical solution

CONCLUSIONS

The efficient analytical solution and the FE models with different fidelities can be employed in different stages of the design of composite structures depending on the required accuracy and the number of design possibilities. In this study, a range of virtual testing strategies, including analytical, 3D continuum only, and 3D high-order finite element modelling, were studied and compared in terms of their ability to predict damage areas, damage response and time required to complete a simulation of low-velocity impact scenario. The LaRC5 code with an enhanced search algorithm to enhance computational efficiency was used for the FEM modelling. The trade-off of the computational accuracy and costs were compared against experimental results.

This study demonstrated that all three methods can offers reasonably good prediction in terms of absorbed energy, maximum deflection, peak force and contact duration, with discrepancies within10% of the values obtained from impact testing. The analytical solution was able to predict the impact damage area in a few minutes, while FEMs took up to 1 and 2.5 days to conduct FEM simulation using continuum only and integrated discrete and continuum approaches, respectively. The study shows that in spite of the speed, analytical solution can significantly underestimate the delamination area by 72%, as compared to the X-ray CT result. In order to achieve higher predictive accuracies in damage area, a high-fidelity FE model is required by taking into account all typical fibre and matrix impact damage modes and their interactions in the composite laminates under impact loading. As compared to the experiments, a substantial discrepancy of 33% in damage area was predicted using continuum mechanics only FEM. This prediction was much improved when an integrated discrete damage and continuum approach was used, with a 10% difference in total damage area.

It is worth nothing that the analytical solution can be a useful tool to enhance FEM computational efficiency by using the predicted damage areas to help determine the areas with refined mesh. Additionally, since damage would occur up until reaching the peak load [4], the contact duration predicted by the analytical solution, which can be predicted with satisfactory accuracy, can be used in the FE model to simulate only half of the impact event and predict the damage area as the key output of the impact damage simulation in a shorter simulation time.

In summary, the selection of virtual testing strategies depends on the intended application. It is paramount to establish an understanding of the advantages and limitations of each virtual testing strategy. This study offers, for a specific LVI case, a quantified study of the trade-off among computational time, complexity and accuracy for aircraft designers and maintenance facility for decision making.

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