Simulation of fracture tests on notched composite plates

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A report submitted to fulfill the requirements of Additional Graduation Work (CIE5050-09)

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Declaration

I **Sai Kubair Kota** solemnly declare that the project report titled **Simulation of fracture tests on notched composite plates** is based on my own work carried out during the course of our study under the supervision of **Dr.ir. F.P. van der Meer**. The report is being submitted to fulfill the requirements of Additional Graduation Work (CIE5050-09) to the Delft University of Technology, Delft, Netherlands. It is not submitted before for a degree or examination to other Universities. The guidelines provided by the Delft University of Technology are followed for writing the report. The materials such as theoretical analysis, data, and text from other sources used for preparing the report were given due credit by providing their details in the references.

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Abstract

Size effects influence the behavior of composites and have a great effect on their properties such as strength, type of failure, etc. The effects of size of the specimen on the behavior of composite laminates were studied based on numerical analyses of sharp and blunt notched $[45/90/\text{-}45/0]_{4s}$ carbon/epoxy composite laminates. Five different numerical models in each notch case with in-plane dimensions scaled up to a factor 16 were analyzed. The computational framework adopted in the study uses phantom node method for modelling matrix cracks, continuum damage model for fibre failure and interface elements for delamination. The capability of the framework to capture the size effects in the failure load and failure mechanisms of composite laminates with both sharp and blunt notches was assessed. The damage zone properties captured through CT images from interrupted tests were compared with the results obtained from numerical simulations. Parametric studies were carried out on the numerical models to match the simulation and the experimental results. The observations from the study revealed that there is a good correlation between the experimental and simulation results. The computational framework used in the study predicts the strengths of composite laminates, replicates size effects in the laminates and the failure mechanisms accurately.

Acknowledgements

I would sincerely like to thank my supervisor, Dr.ir. F.P. van der Meer, for helping and guiding me with his invaluable knowledge and patience throughout the project. I also thank him for introducing me to the new research field of composites. I would like to offer my special thanks to Dr. M. Pavlovic for taking time out of his busy schedule to examine my work.

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Contents

Chapter 1

Introduction

Composite materials have a wide range of applications in various fields of engineering such as in civil engineering (bridges, roads, buildings, etc), aerospace engineering (wings, bulkheads, fuselages, etc) and also in electrical and marine engineering. The increasing demand for the usage of composite materials is due to their superior performance over other materials in terms of strength and durability.

A major problem in solid mechanics is the effect of size on the strength of the structure [1]. The change in strength of the structure due to change in its size is called size effect [2]. In the design of composite structures, size effects play a crucial role because experiments for evaluating the properties of composite materials are generally conducted on specimens of smaller scale than the actual structures that are designed. [3].

In order to accurately predict the strength of composite laminates especially when size effects are present, it is necessary to be able to simulate the complete failure mechanism which involves different processes that occur and interact [4]. Carins et al. [5], Gonzales et al. [6], Rudraraju et al. [7] & Camanho et al. [8] developed numerical methods to study the effects of size on the strength of composite laminates. But they did not exactly simulate the development of damage at the crack tips [5-8]. To study fractures and damage in composites, different numerical approaches were developed based on eXtended Finite Element Method (XFEM) [9-10], continuum modelling [11-13] and discrete modelling such as cohesive interface methods. The above mentioned numerical methods include techniques developed to simulate delamination and matrix cracking, initiating from notches and free edges [14-16].

The crucial failure mechanisms in composite laminates were found to be discrete transverse cracks and delamination [17]. If delamination is neglected in the numerical models used for the simulations, it might lead to over estimation of predicted strengths and mesh-dependency [18]. The behavior of dispersed ply laminates with sharp notches was not predicted properly by Chen et al. [18] because failure of these specimens does not happen directly at the point where first fibre failure happens but a damage zone develops which consists of delaminations, splits and stable fibre failures at crack tips.

The simulation of damage and its influence on progressive fibre failure at the crack tip is important for predicting the behavior of composite laminates. For accurately predicting the fibre failure, Weibull statistics based fibre failure criterion was used [19]. It supposes that the strength of composite materials which fail in a brittle manner is controlled by defects in the material which follow a Weibull distribution [19].

Size effects in the behavior of carbon/epoxy laminates with sharp and blunt notches were studied by Xu et al. [3]. In this study, centre notched (sharp notch) $[45/90/\text{-}45/0]_{4s}$ laminates with five different in-plane dimensions were considered. In-plane specimen dimensions notch length, gauge width and gauge length were each scaled. Interrupted tests were carried out on the composite laminates in which they were loaded up to 95% of their failure load.

In addition, open-hole (blunt notch) tests were also conducted on the composite laminates with same notch length (hole diameter), material type and ply layup for comparison. The test observations revealed that size effects indeed influence the behavior of composite laminates to a great extent. In case both sharp and blunt notches, the notched tensile strength of laminates decreased with increasing specimen sizes. X-ray computed tomography scanning was conducted on the notched specimens to capture the failure mechanism of different plies and the interfaces in the laminates. It was concluded that the damage zone at crack tip governs the failure of center-notch specimens. The small size center-notched specimens had higher strength when compared with the open-hole specimens of the same dimensions [3].

Van der Meer et al. [9] developed a computational framework for simulating failure mechanisms in composite laminates. In this study, the phantom node method which is based on the eXtended Finite Element Method (XFEM) was used for representing matrix cracks in a mesh-independent way as straight discontinuities in the displacement field. The delamination was modelled with interface elements and fibre failure with a continuum damage model. The computational framework was validated with experimental results (open-hole and compact tension tests) and it was concluded that the framework captured different progressive failure mechanisms in composite laminates realistically.

In the present study, the computational framework developed by Van der Meer et al. [9] was used in simulating the experimental tests carried out by Xu et al. [3]. The capability of the framework to capture the impact of size effects on the failure mechanisms and failure load of composite laminates with both sharp and blunt notches was assessed. The damage zone properties captured through CT images from interrupted tests were compared with the results obtained from numerical simulations. The observations from the study are used to explain the role of size effects in deciding the behavior of sharp and blunt notched composite laminates.

Chapter 2

Methodology & Results

2.1 Test setup details

The stacking configuration of the composite laminates for all specimen sizes, used for experimentation by Xu et al. [3] was quasi-isotropic $[45/90/\text{-}45/0]_{4s}$. The material used for preparing the laminates was Hexcel HexPly IM7/8552 carbon/epoxy pre-peg with nominal ply thickness of 0.125 mm and an overall thickness of 4 mm. The in-plane dimensions of the specimens were scaled up to a factor 8 and in case of last specimen referred to as 'Scale 16' only the width and notch length were doubled. The gauge length of this specimen was same as that of the specimen scaled by a factor 8.

The notches in case of sharp notched (centre-notched) baseline specimens were cut for a distance of 2 mm using a 1 mm end mill and then were extended using a 0.25 mm wide piercing saw blades. The initial cut lengths and the final extended lengths of the scaled up specimens were kept proportional to their widths. The notch radii for all specimen sizes were the same. The in-plane scaled dimensions of all the sharp notched specimens are as given in Table 1. The schematic representation of the centre-notched specimens indicating their attributes is as shown in Figure 1.

Tensile tests were carried out on the specimens under displacement controlled mode with a loading rate of 0.25 mm/min for baseline specimen and rates were scaled up for other specimens based on their gauge length. Interrupted tests were carried out on the specimens by stopping the test at 95 % of the average failure load.

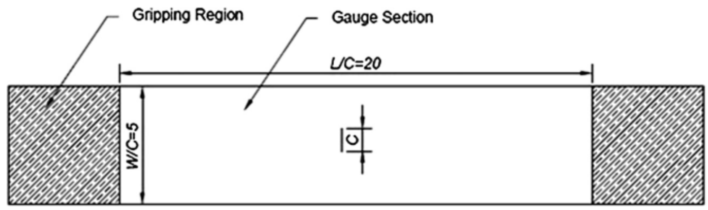


Figure 1: Experimental setup of the sharp-notched specimens

Table 1: In-plane scaled dimensions of sharp notched specimens

Specimen	Notch Length (mm)	Gauge Width (mm)	Gauge Length (mm)
Baseline	3.2	15.9	63.5
Scale 2	6.4	31.8	127.0
Scale 4	12.7	63.5	254.0
Scale 8	25.4	127.0	508.0
Scale 16	50.8	254.0	508.0

For comparison, blunt notch (open-hole) specimens with hole diameter same as the notch length of sharp notch specimens were tested. The experimental strengths of sharp and blunt notched composite laminates found by Xu et al. [3] are as given in Table 2. Finally, the specimens after carrying out the interrupted tests were studied for their damage state using the CT (Computed Tomography) scanning technology.

Table 2: Experimental strengths of sharp & blunt notched specimens

Specimen	Sharp Notch Strength (MPa)	Blunt Notch Strength (MPa)
Baseline	582	478
Scale 2	519	433
Scale 4	456	374
Scale 8	349	331
Scale 16	261	323

2.2 FE model details

The composite laminates were modelled assuming a 2D plane stress situation for the plies as proposed by [9]. The FE models were developed using the constant strain triangular (CST) elements. One side of all the specimens along the length direction was fixed and a uniform displacement was applied on the opposite edge. Only half width of each specimen was modelled and symmetry boundary conditions were applied along the nodes which pass through the plane of symmetry. Furthermore, periodic boundary conditions were applied to the model in the through-thickness direction for simplification. This means that only four plies are modelled in the entire laminate. The last ply of the laminate is assumed to be connected to the top ply in a periodic manner. This assumption has a drawback: It can't simulate the central double 0°ply failure in the experiments.

The typical FE meshes used for analyzing the sharp and blunt notched baseline specimens are as shown in Figures 2 to 5. The length of the refined zone in both sharp and blunt notched baseline specimens was 10 mm and their width was equal to width of the FE model. The shape of notch tip in case of sharp notched specimen was modelled as

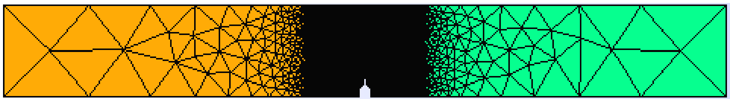


Figure 2: Typical FE mesh used for analyzing the sharp notched baseline specimen

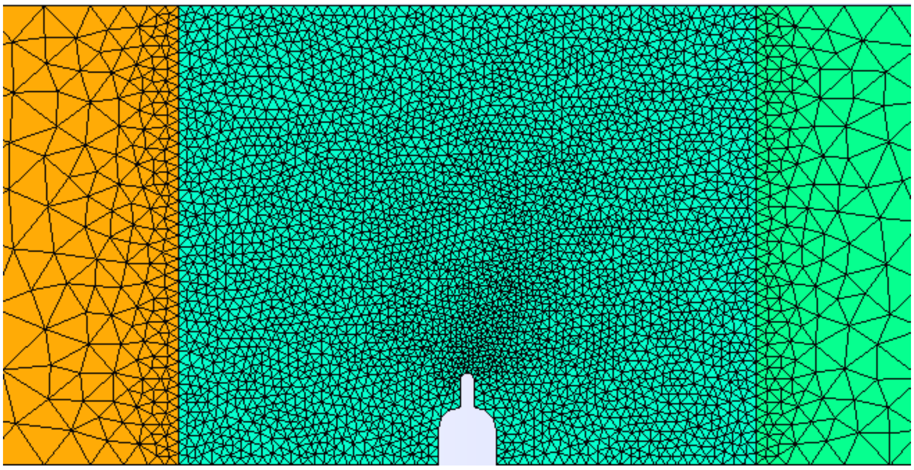


Figure 3: FE Mesh used in the refined zone of sharp notched baseline specimen

detailed in experimental investigation by Xu et al. [3]. From the experimental CT images, it can be observed that the damage is mostly concentrated in the $\pm 45°$region from the tip of notch. So in the FE model, a region with refined mesh was constructed. Inside this region, plies were modelled separately, matrix cracking & delamination (presence of interface elements) were allowed. Outside the refined mesh region, delamination and matrix cracking were prevented and the plies were tied with elastic interface elements.

The thickness of each ply in the composite laminate was 0.125 mm and the overall laminate thickness was modelled as 0.5 mm. This was because of the periodic boundary condition used in the simulation due to which only 4 plies could be modelled. For calculating the peak load of the complete laminate as specified in experiments, the simulation peak loads were multiplied by a factor 16. This was to account for two effects: 1. only half width of the specimen was modelled and 2. accounting for presence of 32 plies in the complete laminate in which only 4 were modelled.

2.3 About the computational framework

The computational framework used in this study was developed by Van der Meer et al. [9]. In this framework, matrix cracking in composite laminates was modelled using phantom node method (a variation in XFEM). Delamination was modelled using interface elements and fibre failure with continuum damage model. The dissipation based arc-length method was used for following the quasi-static equilibrium path with a Newton-Raphson iterative

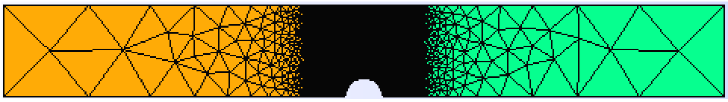


Figure 4: Typical FE mesh used for analyzing the blunt notched baseline specimen

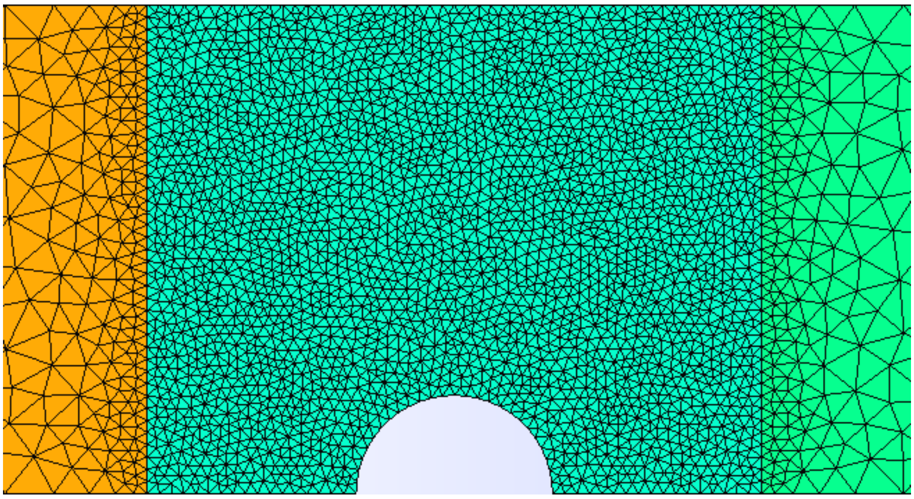


Figure 5: FE Mesh used in the refined zone of blunt notched baseline specimen

method. More detailed information regarding the computational framework adopted in this study can be found in Van der Meer et al. [9,20]. This framework involves material parameters to be given as an input that govern the failure behavior of the composite laminate. The parameters used for simulations in this study are as given in Table 3. The material parameters used in this study were same as the ones used by Van der Meer et al. [9] because in both the studies, same composite material IM7/8552 carbon/epoxy was used for preparing the composite laminates.

Parametric studies were carried out on the baseline specimens to study the effect of different material properties on the simulation results. The results from these studies proved that reducing the fibre fracture energy ($F_{Ic,f}$) to 50% of its original value recommended by Van der Meer et al. [9] matched the experimental strengths of composite laminates with the simulation strengths. It was even experimentally observed by Xu et al. [3] that the specimens mostly failed due to fibre breakage. The smaller specimens exhibited more pull-out type failure and cleaner fractures in case of larger specimens. So the effect of fibre related parameters on the simulation results seemed logical. Also the tensile strength (F_{2t}) and shear strength (F_{12}) of the matrix were increased to 139 and 153 MPa respectively in order to delay the process of matrix cracking and delamination. These parameters will not have any effect on the peak load and this was also verified from simulations. The parameters obtained from calibrating the baseline FE models to experiments were also used for analysis in case of scaled up specimens.

Table 3: Different parameters used in the framework for simulations

		Elasticity		
E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	ν_{12}	ν_{23}
161	11.38	5.17	0.32	0.4
		Matrix/delamination		
F_{2t} (MPa)	F_{12} (MPa)	$G_{Ic,m}$ (N/mm)	$G_{IIc,m}$ (N/mm)	η
30 (139)	45 (153)	1	1	1
fibre Failure			**Thermal strain**	
F_{1t} (MPa)	$G_{1c,f}$ (N/mm)	α_1 (per°C)	α_2 (per°C)	ΔT (°C)
3131	130 (65)	0	3×10^{-5}	-160
		Shear non-linearity		
C_1	C_2	C_3	C_4	
22	-22	35	-5	

2.4 Mesh dependence

In order to check the dependency of simulation results on the element size used in meshing the refined zone of interest, mesh dependency studies were carried out. The mesh dependency studies were only carried out on the baseline specimens (both sharp and blunt notched) because other specimens consume a lot of time for computations. Five different FE models were constructed for each case of sharp and blunt notched specimens. In these models, the refined zone was meshed with five element sizes starting from 0.1 to 0.5 mm. The size of the refined zone and the element sizes outside the refined zone were same in all the models. The strength of the composite laminate was calculated by dividing the peak load with its un-notched cross sectional area. The results obtained in case of sharp and blunt notched specimens after carrying out the mesh dependence studies are as shown in Figure 6 & 7 respectively.

It can be observed from Figure 6 that the strength of laminate is almost same even with varying mesh sizes in sharp notch baseline specimens. Figure 7 reveals that strength of blunt notch baseline specimens decrease with increase in element size in the refined zone. But the decrease of strength in case of blunt notch baseline specimens is less indicating a weak mesh dependence. The simulation in case of using 0.5 mm element size in the refined zone of blunt notch baseline specimen didn't converge. Hence it can be concluded that sharp notched FE models are almost mesh independent and blunt notched FE models are slightly mesh dependent. Using an element size greater than 0.2 mm in case of sharp notched baseline specimens resulted in a bumpy load-displacement curve. Also using element sizes 0.1 mm and 0.2 mm in the refined zone, resulted in a strength which is close to the experimental strength. Taking all these facts and computational time into account, the refined zone of interest was decided to be meshed with an element size of 0.2 mm in case of sharp notched specimens.

It can also be observed from Figure 7 that upon refining the mesh with an element size of 0.1 mm, the strength of the laminate almost remained same as in case of 0.2 mm element size in blunt notched FE models. So it can be well concluded that the blunt notched FE models become mesh independent from an element size of 0.2 mm. Hence the blunt notched FE models in this study were meshed with an element size of 0.2 mm in the refined zone of interest even though there was a better match with the experimental result obtained through through 0.3 mm element size. The regions outside the refined zone were meshed with element size of 1 mm and 10 mm in case of sharp baseline specimens and 10 mm in case of blunt baseline specimens. For the specimens whose dimensions were scaled up, the element size inside the refined zone was kept same as 0.2 mm but the element sizes outside were scaled up based on the gauge lengths of the specimens. The magnitude of error between the experimental and simulated strengths upon using an element size of 0.2 mm in case of sharp and blunt notched specimens are 1.13 % and 3.88 % respectively.

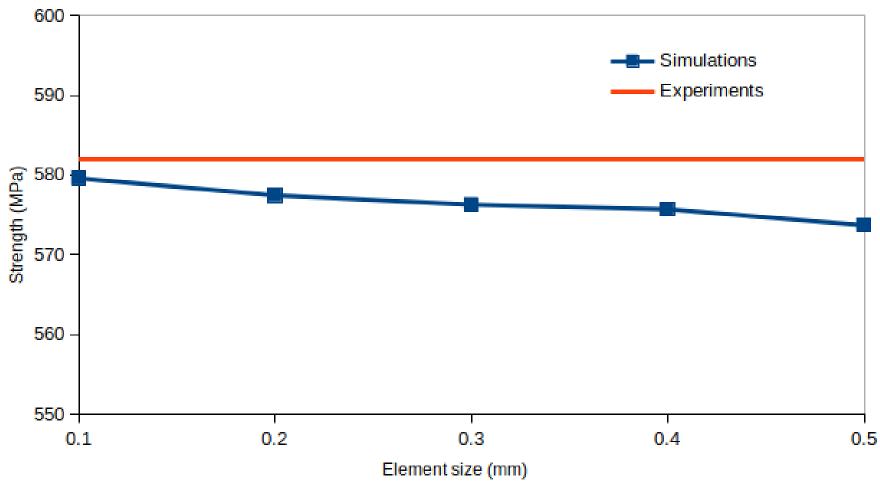


Figure 6: Mesh dependence in sharp notched baseline specimens

The load-deflection plots of the sharp notched baseline specimen obtained from experiment and simulation are as shown in Figure 8. It can be observed from Figure 8 that the experimental and simulation peak loads were close to each other but the maximum deflection predicted through simulations was lesser when compared with experimentally obtained maximum deflection. There is a difference in the stiffness of the laminate obtained experimentally and predicted through simulation. This may be because of the differences in measuring the displacements between experimental test setup and the FE models. This can also happen because of the material parameters considered in the numerical analysis but no such sort of effect was revealed when parametric studies were carried out. It can also be observed that the load-deflection curve obtained through simulations does not go all the way down to zero after the peak load. This is because of the

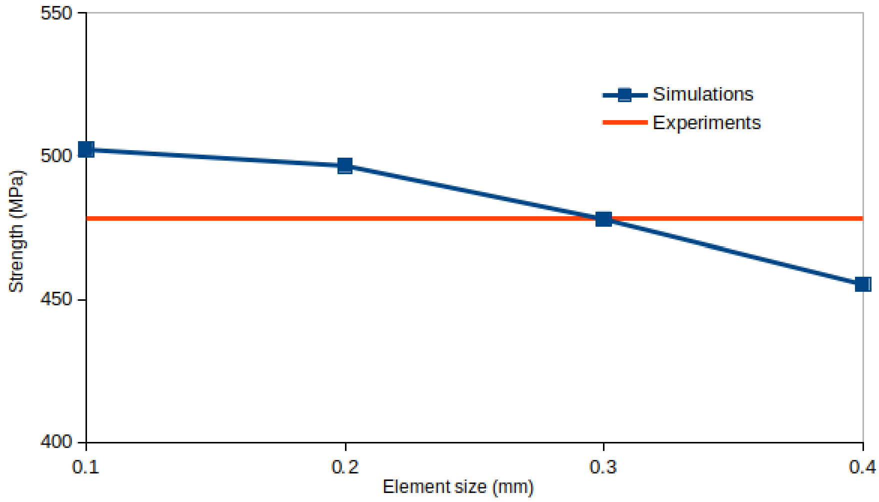


Figure 7: Mesh dependence in blunt notched baseline specimens

convergence problems faced by the computational framework due to drastic reduction in the fibre fracture energy to 50% of its original value. But as the peak loads are primary quantities of interest in this study, the post peak response of the specimens was not given much importance.

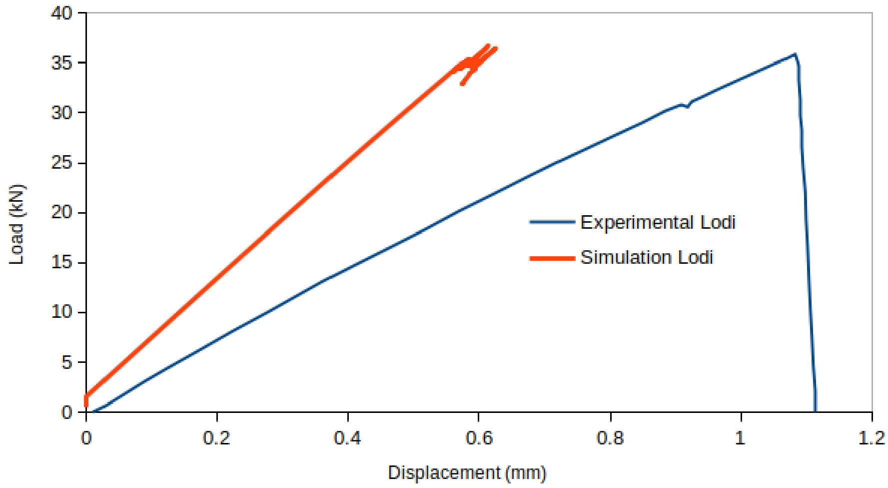


Figure 8: Load-deflection plot of sharp notched baseline specimen from experiment and simulation

To check if the strength values of laminates obtained through simulations are reliable, the delamination damage and fibre failure at peak load step of the computations were assessed. The delamination damage at all interfaces in the sharp and blunt notched baseline specimens with an element size of 0.2 mm are as shown in Figures 9 & 11 respectively. It can be observed from the figures that the delamination failure was well within the refined zone region which means any sort of restriction to the delamination damage growth was not imposed till the peak load was reached. The ply failures in the sharp and blunt notched baseline specimens with an element size of 0.2 mm are as

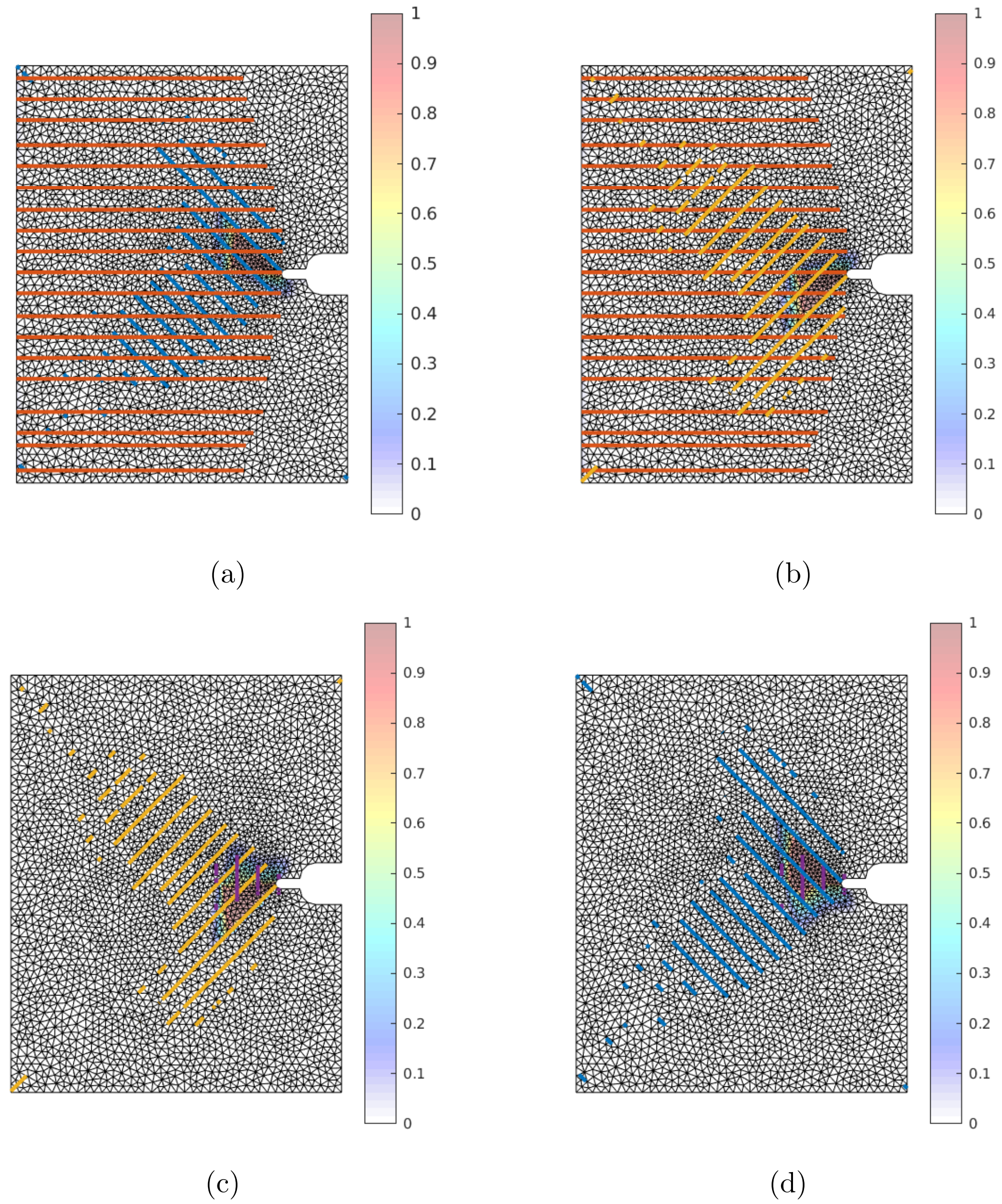
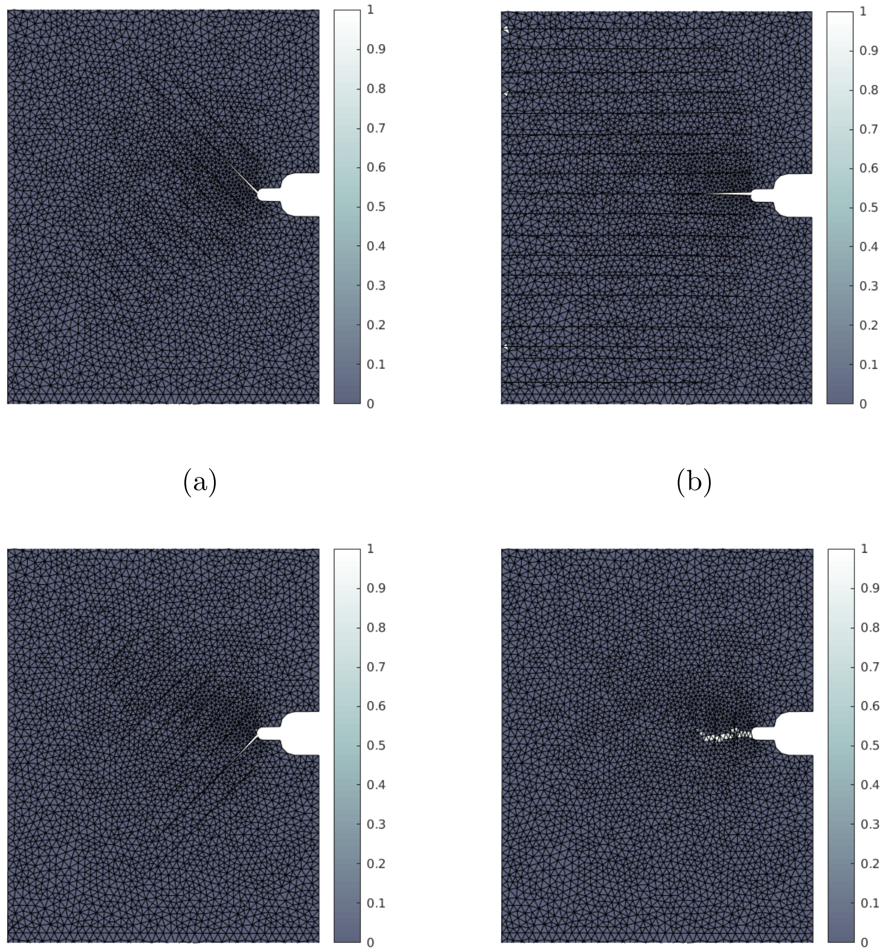


Figure 9: Delamination failure at all the interfaces in sharp notched baseline specimen: (a) delamination in 45/90 interface; (b) delamination in 90/-45 interface; (c) delamination in -45/0 interface; (d) delamination in 0/45 interface

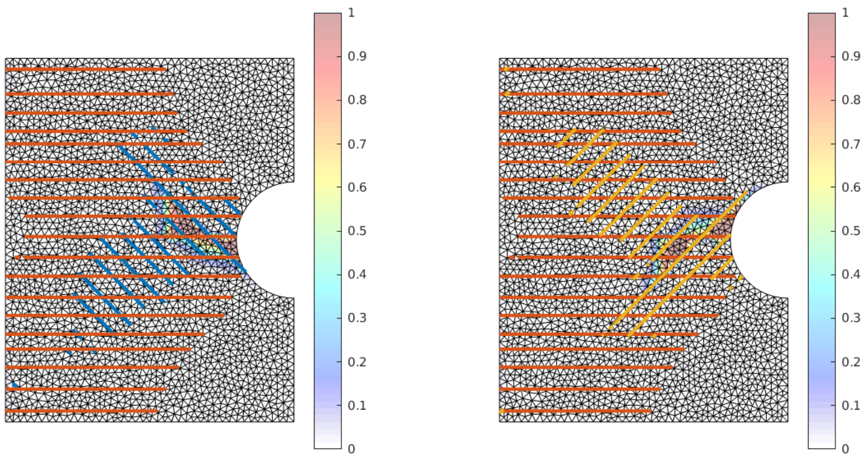
shown in Figures 10 & 12 respectively. It can also be observed from the figures that fibre failure was observed only in the 0°ply and matrix cracking in the other plies. These observations match the findings obtained experimentally by Xu et al. [3]. Also the fibre failure in the 0°ply did not reach beyond the refined zone region. From experiments, pull-out type failure was observed in baseline specimens but that could not be exactly simulated due to computational limitations. Nevertheless, the specimens exhibited fibre dominated failures experimentally. From all these observations, it can be concluded that the peak load obtained through simulations is reliable.



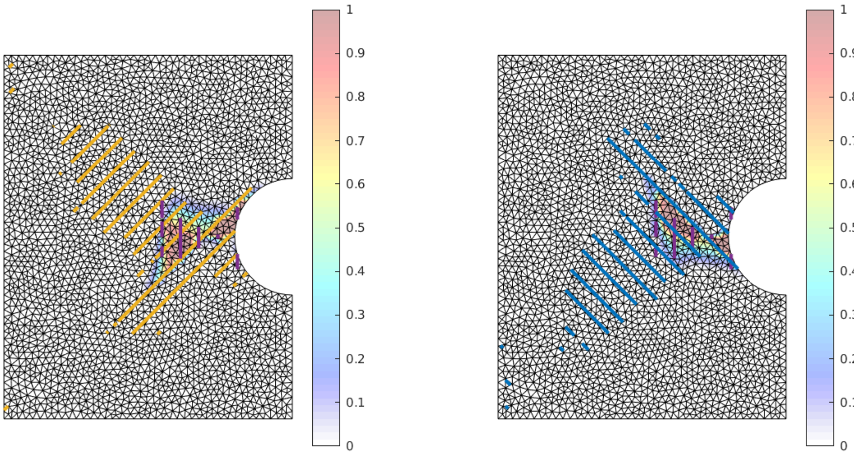
(a) (b)

(c) (d)

Figure 10: Matrix cracking & fibre damage in all the plies of sharp nocthed baseline specimen: (a) Matrix cracks in 45°interface; (b) Matrix cracks in 90°interface; (c) Matrix cracks in -45°interface; (d) Matrix cracking & fibre damage in 0°interface

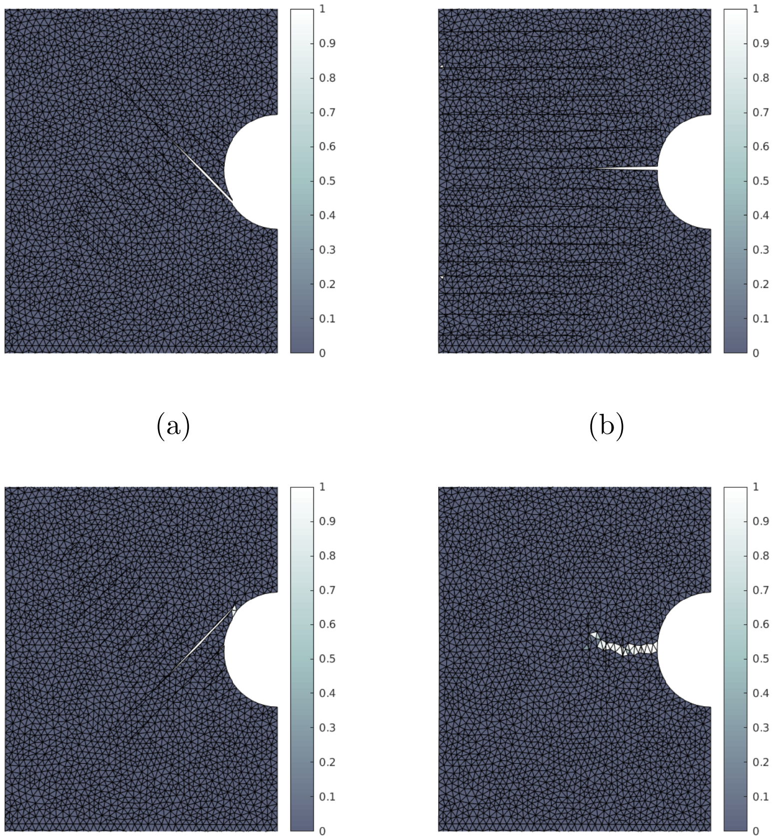


(a) (b)



(c) (d)

Figure 11: Delamination failure at all the interfaces in blunt notched baseline specimen: (a) delamination in 45/90 interface; (b) delamination in 90/-45 interface; (c) delamination in -45/0 interface; (d) delamination in 0/45 interface



(a) (b)

(c) (d)

Figure 12: Matrix cracking & fibre damage in all the plies of blunt notched baseline specimen: (a) Matrix cracks in 45°interface; (b) Matrix cracks in 90°interface; (c) Matrix cracks in -45°interface; (d) Matrix cracking & fibre damage in 0°interface

2.5 Size effects

To study the influence of size of the specimen on the strength of the laminate, size effect analyses were performed on both sharp and blunt-notched laminates. The in-plane dimensions of the baseline specimens were scaled up to a factor 8 to obtain the scale 8 specimens. In scale 16 specimens, only the width and notch length were scaled up but the length was same as in case of scale 8 specimens. The details regarding the dimensions of scaled up specimens are given in Table 1.

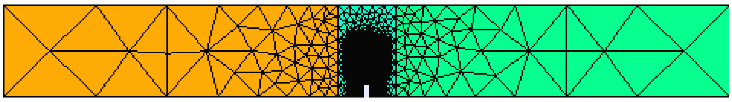


Figure 13: Typical FE mesh used for analyzing the scaled-up sharp notched specimens

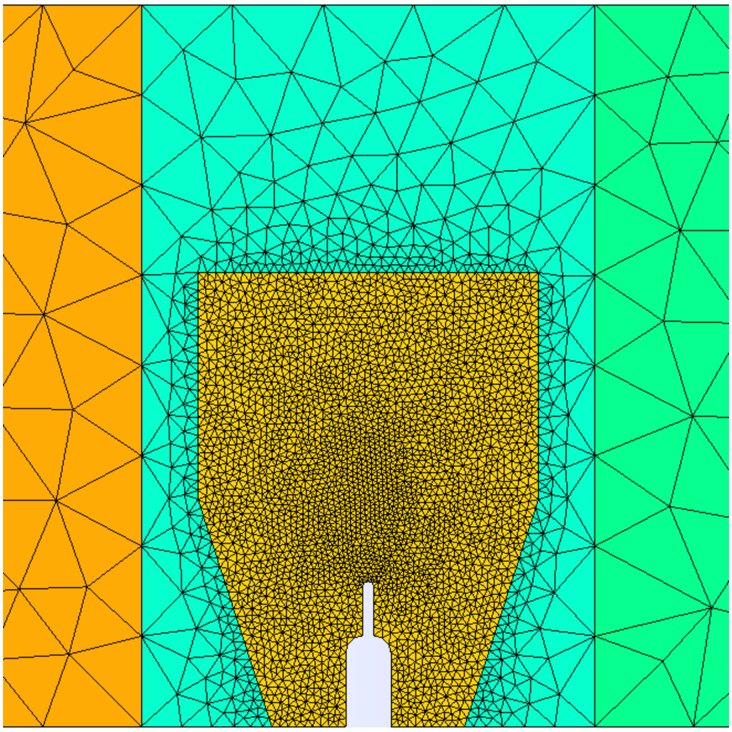


Figure 14: FE Mesh used in the refined zone of the scaled-up sharp notched specimens

The typical FE meshes used for analyzing the sharp and blunt notched scaled up specimens are as shown in Figures 13 to 16. In sharp notched scaled specimens, the width of inner fine zone of the FE mesh was kept as a constant equal to 10 mm as in case of baseline specimens because the failure of most of these specimens is fibre dominated and the stress accumulation is mostly in a small area around the sharp notch. Also the refined zone was further reduced by concentrating it around the notch to reduce the computational time. The height of refined zone in sharp notched specimens was varied depending on the notch length in each scaled up case. In case of blunt notched specimens, the area of stress concentration is located around the notch and large when compared with the sharp notched specimens. So the width of the refined zone in case of each scaled up specimen was equal to half the width of the specimen. This specific refined zone size was chosen after a lot of trials performed to reduce the computational time and obtain an accurate solution. In case of sharp notched scale 4, scale 8 & scale 16 specimens, the FE mesh around the refined zone was not proper as the elements were distorted. But these meshes were still accepted for performing the analysis because they were constructed based on the optimized mesh dimensions through which good accuracy of solution can be obtained with a decent amount of computational time. Also this region was outside the zone of interest and that is why much emphasis was not put on these distorted elements.

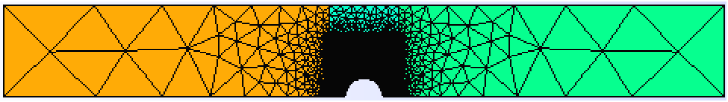


Figure 15: Typical FE mesh used for analyzing the scaled-up blunt notched specimens

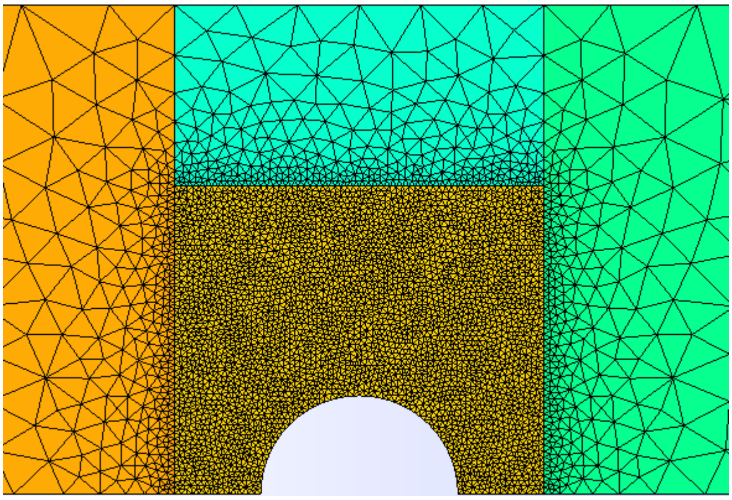


Figure 16: FE Mesh used in the refined zone of the scaled-up blunt notched specimens

The mesh size in the refined zone of both sharp and blunt notched scaled up specimens was equal to 0.2 mm as obtained from mesh dependence studies on the baseline specimens. The mesh sizes outside the refined zone were scaled up in each case based on the size of the specimen. In both sharp and blunt notched scale 2 specimens, the region just outside the refined zone were meshed with 2 mm element size and remaining parts were meshed with 20 mm element size. The mesh sizes outside the refined zone were scaled up in scale 4, scale 8 & scale 16 with the same scaling factor as used for their size. Same computational framework parameters used in case of baseline specimens were also used in case of scaled up specimens.

The strengths of sharp and blunt notched scaled up specimens along with strengths of baseline specimens are as shown in Figures 17 & 18 respectively. The strengths obtained in case of both sharp and blunt notched baseline specimens are reliable, as the matrix cracking, delamination failure and fibre breakage were well within the refined zone region. It can be observed from Figure 17 that the computational framework used in this study gives a good approximation of the strengths of the sharp notched specimens as the difference between the experimental and simulation results in specimens is less than 5%. In case of sharp notched scale 16 specimen, the difference was around 10% and the simulation suffered with convergence issues. Also in case of sharp notched scale 8 specimen, there is no post peak response obtained.

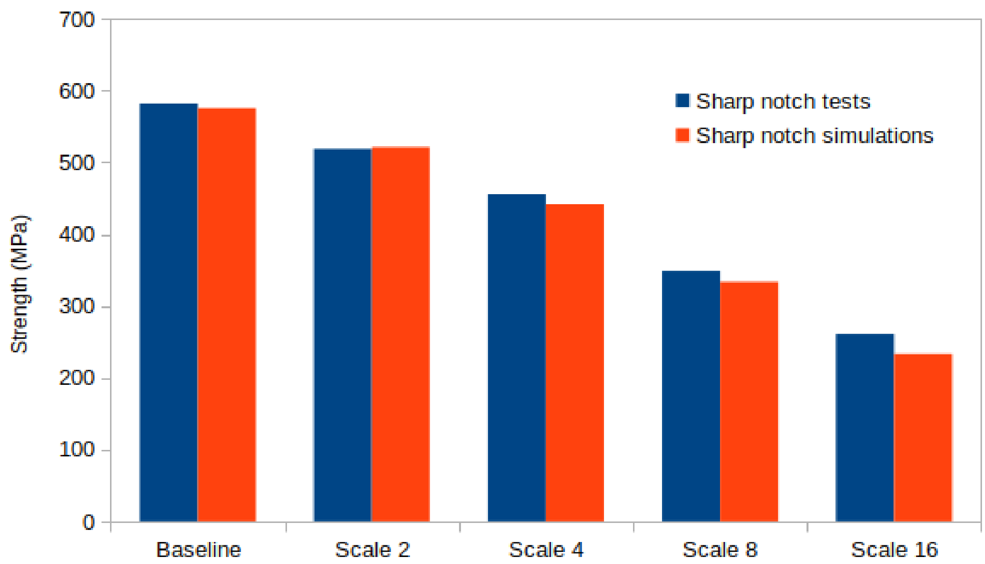


Figure 17: Strengths of sharp notched specimens from experiments and simulations

It was assumed that the load at which non-convergence occurs corresponds to the peak load. These problems are due to reduction in the fibre fracture energy and also due to different competing failure mechanisms that occur especially in the damage zone of scale 8 & scale 16 specimens. This phenomena can well be accepted because with an increase in size of specimen, the damage zone size increases and consequently different failure mechanisms take part in the failure of the laminate [3]. Also the reason behind not obtaining convergence in large scale specimens may also be due to problems in the computational framework used in this study. The size effect observed in experiments in the sharp notched specimens was replicated by the computational framework used in this study. The computational framework under predicted the strengths of sharp notched specimens.

From Figure 18, it can be observed that the computational framework gives a good estimate of the strengths of blunt notched specimens as the difference between the strengths obtained from experiments and simulations in all specimens was less than 10%. In all the

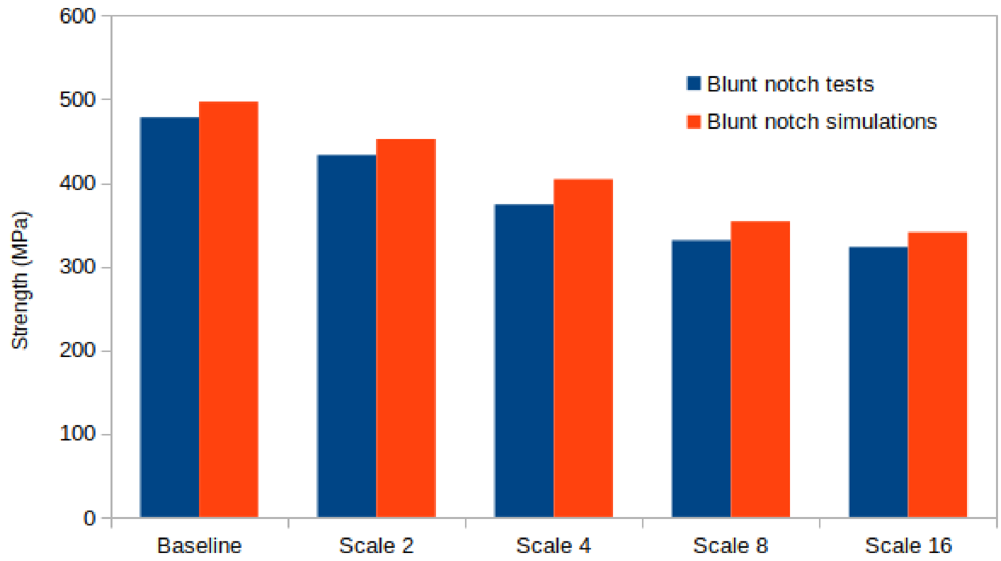


Figure 18: Strengths of blunt notched specimens from experiments and simulations

blunt notched specimens, post peak response was obtained but scale 8 and scale 16 specimens suffered with convergence issues due to reduced fibre fracture energy. The size effect observed in experiments in the blunt notched specimens was also replicated by the computational framework used in this study. The computational framework over predicted the strengths of blunt notched specimens. It can be observed from Figures 17 & 18 that the simulation strengths of sharp notched specimens are higher than their corresponding blunt notched counterparts in case of Baseline, scale 2, scale 4 & scale 8 specimens. But the simulation strength of scale 16 sharp notched specimen was less than that of blunt notched specimen with same scale. These observations are in line with the conclusions made by Xu et al. [3].

Figure 19 shows the size effect curves of sharp notched and blunt notched specimens. It can be observed from Figure 19 that the simulation results in case of both sharp notched and blunt notched specimens follow a similar trend as in experimental results. Only sharp notched scale 16 specimen deviates from this trend due to convergence problems. It can also be observed that none among fracture mechanics and Weibull theory can alone fit the simulation results as observed in case of experimental results by Xu et al. [3].

The failure patterns in the 0°ply observed from experiments and simulations at 95% of failure load in all the sharp notched specimens are as shown in Table 4. It can be observed from Table 4 that the delamination failure and fibre breakage in the 0°ply obtained from the computational framework are close to the failure patterns obtained from experiments. In all the sharp notched specimens, similar 0°splits and fibre breakage pattern can be observed in both experiments and simulation results. The extent and pattern of delamination failure are also similar in experiments and simulations. The extent of progression of the delamination failure in all specimens was less when compared with fibre breakage.

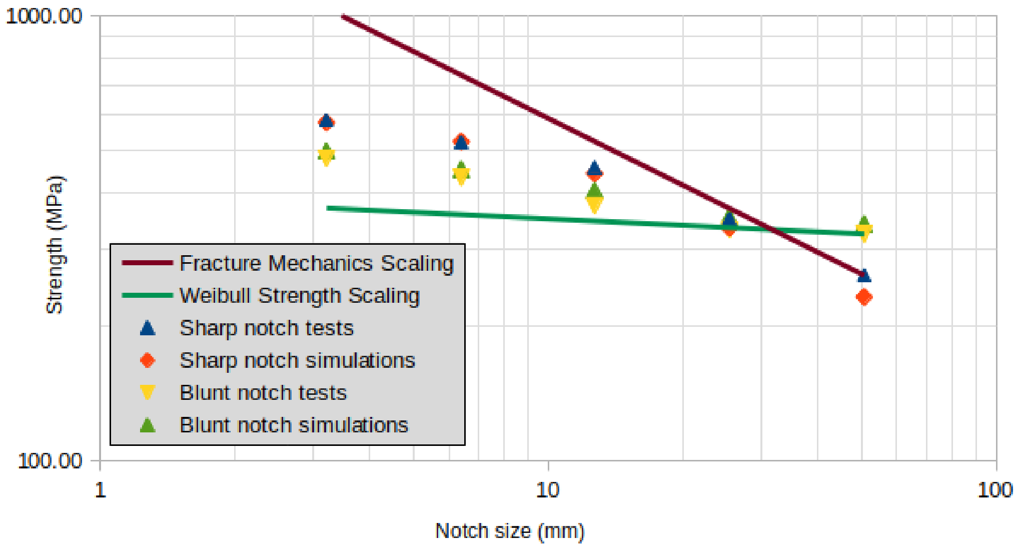


Figure 19: Size effect curves of sharp notched and blunt notched specimens

This is inline with the observation from experiments that the sharp notched specimens exhibited a fibre dominated failure. From all these observations, it can be concluded that the computational framework not only replicates the strengths of sharp notched composite laminates but also their failure patterns.

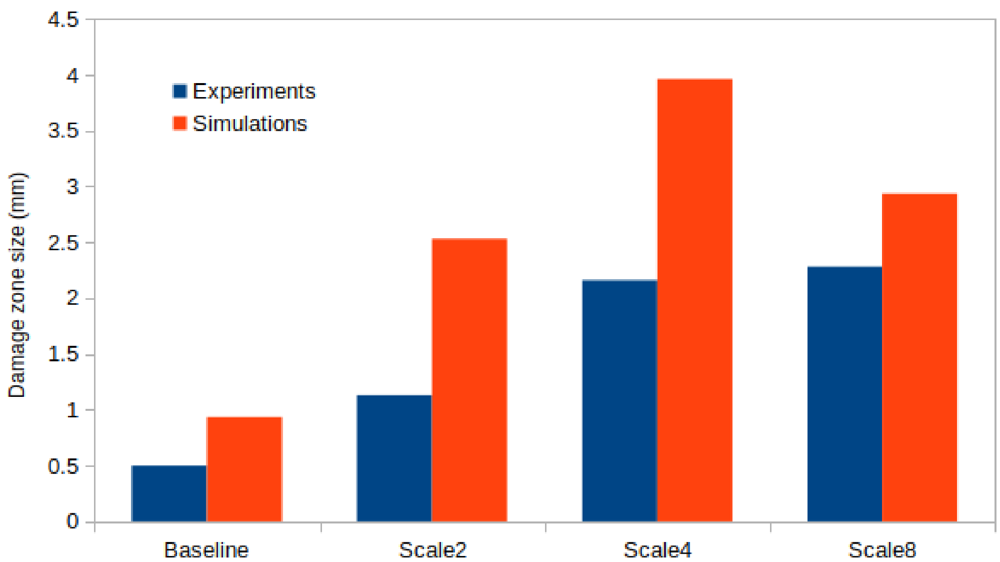
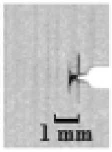
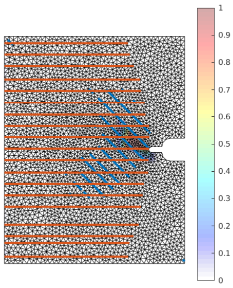
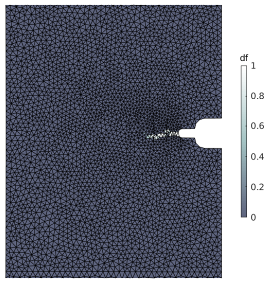
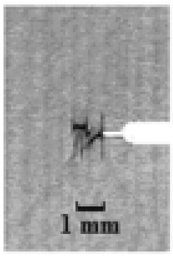
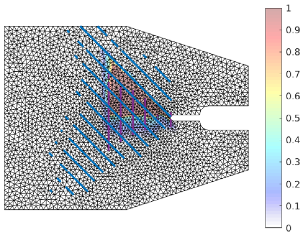
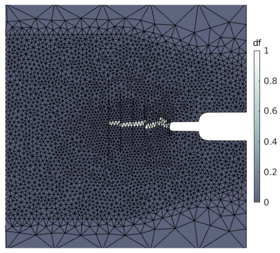
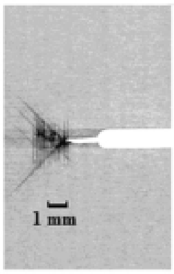
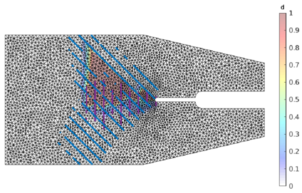
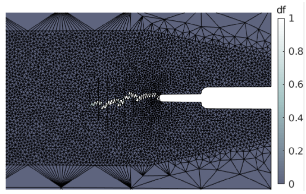
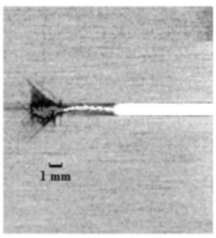
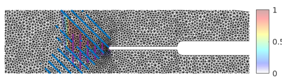
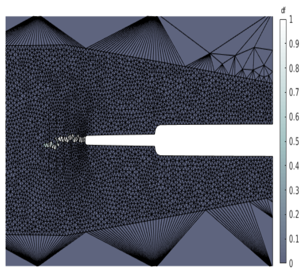


Figure 20: Damage zone sizes in sharp notched specimens

2.6 Damage Zone Sizes

Damage Zone Sizes (DZS) was defined by Xu et al. [3] as the size of damaged zone ahead of the crack tip in which fibre failure occurs in some 0°plies before an unstable failure of

Table 4: Failure patterns in the 0°ply at 95% of failure load observed in experiments and simulations

Specimen	Experiments	Delamination	Fibre failure
Baseline			
Scale 2			
Scale 4			
Scale 8			

the laminate. In this study, the crack tip as mentioned by Xu et al. [3] from which DZS are measured was assumed as notch tip of that particular specimen. DZS are determined by measuring the average distance between the last split and the crack tip in all the 0°plies in the laminate. DZS were only defined in the sharp notched specimens. The DZS were obtained from the FE models by calculating the length of fibre failure zone ahead of the crack tip in the 0°ply at the peak load step. The DZS obtained through experiments and simulations are as shown in Figure 20. From Figure 20, it can be observed that the DZS predicted from simulations are higher than the ones obtained from experiments. This difference may be due to the absence of central-double 0°plies in the FE models which generally require more energy for crack propagation than the out-board 0°plies. As these fibre failure zone sizes are not considered in calculating DZS in the simulations, the values might be higher than actual results. Also there is no particular trend that is followed by the DZS obtained from simulations. The DZS steadily increase from baseline to scale 4 specimens and then suddenly decrease in case of scale 8 specimen. The sudden drop in damage zone size observed in case of scale 8 specimen may be due to poor convergence because of reduced fibre fracture energy.

Chapter 3

Conclusions

In this study, computational framework developed by Van der Meer et al. [9] was used in simulating the size effect based experimental tests. The capability of the framework to capture the impact of size effects on the failure mechanisms and failure load of composite laminates with both sharp and blunt notches was assessed.The damage zone properties obtained from experiments were compared with the results obtained from numerical simulations. The main observations from the study are detailed below.

The parameters used in the computational framework developed by Van der Meer et al. [9] are altered in this study by performing parametric analyses to match the experimental and simulation results. The fibre fracture energy was reduced to 50% of its original value. This change in fibre fracture energy reduced the peak loads of the composite laminates. The tensile and shear strength of matrix were also increased which did not affect the strength of the laminate but just delayed the failure process.

The sharp notched baseline specimens showed almost no mesh dependence but the blunt notched specimens did show some mesh dependence. Based on these observations, an element size of 0.2 mm was decided to be used in the refined zone of sharp and blunt notched specimens.

The peak load obtained from experiment and simulation were close to each other in sharp notched baseline specimen but the displacement predicted by simulations was lower than the one from experiments. This may be due to differences in measuring the displacements between experimental test setup and the FE models. There was very less/no post peak responses obtained in all the specimens because of poor convergence of the simulation. These convergence problems are due to reduction of the fibre fracture energy. As the matrix cracking, delamination failure & fibre breakage in the simulations were well within the refined zone region, the strengths of the laminates obtained are reliable.

The computational framework used in this study gives a good approximation of the strengths of the laminates as the difference between the experimental and simulation results in specimens is less than 10%. Some large scale specimens suffered with convergence issues due to low fibre fracture energy. The size effect observed in experiments in both sharp and blunt notched specimens was also replicated by the computational framework used in this study. The computational framework under predicted the strengths of sharp notched specimens and over predicted the strengths of blunt notched specimens. The strengths of sharp notched specimens obtained from simulations were higher when compared with blunt notched specimens which is also observed from experiments.

Observing the failure patterns in the 0°ply at 95% of the failure load in experiments and simulations revealed that the computational framework is effective in predicting the failure patterns of the sharp notched specimens such as 0°splits, fibre breakage & delamination failure.

The damage zone size measurements obtained from simulations were not close to the ones obtained from experiments. Also there is no particular trend in the DZS obtained from simulations. These may be due to exclusion of central-double 0°plies or convergence problems in large scale specimens.

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