Research Article

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Effect of notch on static and fatigue properties of T800 fabric reinforced composites

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Abstract: To investigate the effect of notches on static and fatigue properties of T800 fabric carbon fibre reinforced epoxy, comparative tests were conducted between specimens of three depths of notches and un-notched specimens. Results demonstrate that the residual tensile strength of specimens is linearly decreased with the increasing depth of notches from 2mm to 4mm. The tensile strength on notched specimens dropped 31.5% comparing with no-damaged laminate. Due to the effect of notches, the fatigue limit was reduced to 55% of UTS and the slope of the *S-N* curve tends to be horizontal. In-situ damage expansion process was observed and the shape of proposed normalized *S-N* curves could be explained and concluded as two stages: the first stage accounts for 20% of the fatigue life, showing a dramatic decrease of fatigue strength; the remaining stage takes up the rest of the total life span, representing a steady decline in strength. It shows that no-damaged and notched laminates exhibit different behaviours in terms of damage evolution.

Keywords: T800 fabric CFRP; double-edge notch; tensile strength; fatigue properties; *S-N* curve; In-situ damage expansion

1 Introduction

Compared to metals, the nature of CFRP (Carbon Fibre Reinforced Plastic) allow better fatigue resistance and higher strength to weight ratios, thus CFRP is moving into 'Primary structure' on aircraft [1, 2]. The tension-tension fatigue limit of CFRP can exceed 40% of its tensile strength, and even reach up to 90%. For most metallic materials, the fatigue limit is lower than 50% of the UTS and only 30% for aluminum [3]. However, what appears to be 'minor damage' in metals can be 'major damage' in CFRP and results in a dramatic decrease in load-capacity of structures. Thus it is significant to understand the effects of defects and damage on the structural integrity of composites.

During the manufacture, processing and service of composite structures, defects or damage are often found, such as matrix defects, micro-cracking, delamination, debonding scratches, notches and impact, etc. [4]. Many of these damages can result in a significant reduction in the residual strength of components. Cantwell *et al.* [5–7] found that even a small impact energy can reduce more than 50% of the load-carrying capacity of carbon fibre composite structures. Gary [8] pointed out that undiscovered flaws during the manufacturing process can cause catastrophic failure of composite structures as well. Huang [9] proved that manufacturing defects lead to a sharp drop in the strength and stiffness of composites, and that the decrease in residual strength and stiffness is related to the form and size of defects or damage. Shams [10] studied the effect of three scratch depths on the tensile strength of laminates and found that the position of the scratched tip and the depth of scratches are the key factors to the load capacity of composites. In addition, this resulted in unexpected compression and torsional deformation of the laminate. To investigate the effect of flaws and damage on the fatigue properties of composite materials, Zhu and Xu [11] conducted low-speed impact and compression-compression fatigue studies on T300/QY8911 composite laminates. The fatigue failure process was divided into two stages: a stable period and an expansion period with the former period accounting for 60% of the total life. The fatigue strength (under 10^6 cycles) is about 55% of the tensile strength of the test specimens with impact damage. Shahkhosravi, N.A. [12] studied the impact of high speed drilled holes on static and fatigue properties of Glass Fibre Reinforced Polymer (GFRP), and they found that drilling parameters

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had a significant effect on specimen fatigue life: for unidirectional specimens, a fatigue life variation (increase) of 160% was found; and, for woven specimens this variation was much more (unlimited).

The impact of notching, which refers to injuries that are common in manufacturing or machining processes such as incorrect drilling or milling, has been studied by many scholars due to its importance to designers. Unlike no-damaged components, notches result in a stress concentration and exaggerate the complexity of damage and failure mechanisms [13, 14]. Harris [15] concluded that the fatigue limit is between the UTS and the residual static strength in tension-tension cyclic loading for notched materials, while the fatigue limit is clearly less than the residual compressive strength if it is compressive loaded. For researches on comparison between notched and no-damaged materials, Reifsnider [16] analysed the fatigue strength, residual strength, and damage characteristics of composite materials with no-damaged and notched specimens, and concluded that the residual strength of no-damaged specimens decreased monotonously and the regulation of residual strength of notched specimens was first increased and then decreased under the fatigue loading. Sims and Gladman [17] also studied different types of notches and examined the effects of centre-holed and double-edge notches on glass-fibre fabric epoxy; the result shows that the normalized *S-N* curves of no-damaged, holed and notched specimens are shown to be consistent. Other than the initial ultimate strength reduction, there is no additional deterioration of the fatigue properties of composites due to notches or holes.

However, effects of notches on fatigue properties of composite laminates, especially on T800 level CFRP have not been examined completely from previous studies, and the damage mechanism of notched laminates was not concerned. In addition, with the application of high performance T800 level CFRP laminates, researches of its sensitivity to notches or damages are of great value. Therefore, effects of notches on mechanical properties of laminates are studied in the present work. Based on a previous study [10], as for the tensile or fatigue test of single-edge notch laminates can cause additional torque which might results in the deterioration of mechanical properties, double-edge notches were selected, so as to balance the effect of torque on mechanical properties. Both static and fatigue test were carried out to determine the effects of double-edge notch on mechanical performance.

2 Experiment

2.1 Material

T800 level 3238A/CF8652 fabric carbon fibre-reinforced epoxy composite laminates were studied in this work. A typical configuration of $[(45/-45)/(0/90)]_{2s}$ lay-up was selected based on the application in the rotorcraft industry. Prepregs were supplied by Weihai Guangwei Composites Co., LTD; details are presented in Table 1. Laminates were manufactured by AVIC composite corporation then. The maximum temperature for curing of laminates was 120°C and they were kept for 120mins under that condition. A pressure of 0.5MPa was applied during the entire curing cycle. Nominal thickness of laminates investigated is 2.8mm.

Table 1: Information of 3238A/CF8652 prepregs

Material	Fibre area weight of reinforcement, g/m^2	Fibre content, %	Nominal thickness of lamina, mm	T_g, °C
3238A/CF8652	293±8	55±3	0.35	155

2.2 Experimental methodology

Comparative static tensile tests and tension-tension fatigue tests were conducted on specimens with double-edge notched damage and no-damaged so as the application of composites on predominantly tension loading. The test matrix of static tensile and fatigue tests is shown in Table 2.

Table 2: Test matrix of 3238A/CF8652 laminates

Category of damage	Depth of notch	Test content
No-damaged	N/A	Tension, Fatigue (tension-tension)
Double-edge notch	2mm	Tension
	3mm	Tension, Fatigue (tension-tension)
	4mm	Tension

In tensile tests, specimens with three depths of notches were examined and five specimens were tested in each group. According to ASTM D3039 [18], dimension

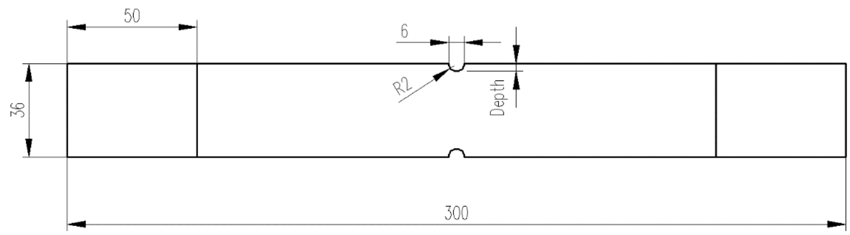


Figure 1: Drawing of double edge notch specimens (Depth: 2mm, 3mm and 4mm)

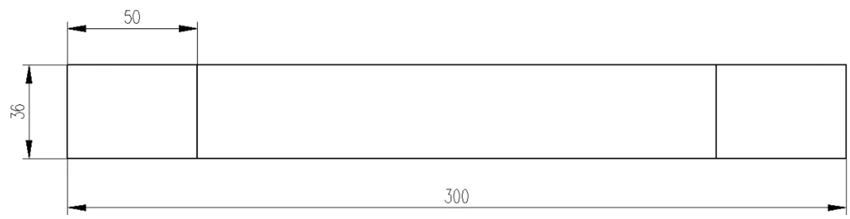


Figure 2: Drawing of no-damaged specimens for fatigue test

of 250 (length) × 25 (width) ×2.8 (thickness) mm was applied for no-damaged specimens. Double-edge notch specimens were designed according to ASTM D5766 [19] and notches were machined by a diamond tool with the radius of 2mm, to match with the application of tools during manufacturing; detailed drawing is shown in Figure 1. When notches were introduced, a sacrificed laminate was applied to avoid the delamination of specimens.

3mm depth of the double-edge notch and un-notched specimens was selected to investigate the tension-tension fatigue behaviour. Drawings of specimens are shown in Figure 1 and Figure 2 separately. In order to obtain a fatigue stress and life (*S*-*N*) curve, 20 specimens were required to conduct the fatigue test.

Static tensile tests were conducted on Zwick/Roell Z100 materials test machine under the mode of displacement control to determine the UTS of laminates, with a displacement speed of 2mm/min applied. Notched and unnotched specimens were tested according to ASTM D5766 and ASTM D3039 separately.

Tension-tension fatigue tests were carried out on a MTS 370 electro-hydraulic servo fatigue tester under load control mode according to ASTM D3479 and ISO 13003 standard [20]. Sinusoidal waveform was applied and a stress ratio $R = 0.05$ were set. Frequency was set to be 8Hz to avoid an excessive rise in the specimen temperature due to self-generated heating. Nominal stress was used for load calculation. Four stress levels which represent the maximum fatigue stress were selected based on some definite percentages of the UTS. The test was terminated once the specimen breaks or the specified number of life cycles has been reached.

3 Experiment results and discussion

3.1 Static tensile test

The result of static tensile tests can be found in Table 3, showing the value and standard deviation of tensile strength. The gross cross-section area of test method was used for the calculation of UTS. The tensile strength is plotted versus the depth of notch in Figure 3, and results of no-damaged specimens are drawn as a horizontal line in the diagram for comparison. It states that the tensile strength and its standard deviation decrease as the depth of double-edge notch increases. Compared to no-damaged specimens, the net section area of 2mm depth notched specimen is decreased by 11.1%, however it did show a 31.5% drop of tensile strength, and a linear relation between strength and notch depth can be observed. This phenomenon is caused by the stress concentration around the notch, and a deeper notch results in a more severe stress concentration.

Table 3: Tensile result of 3238A/CF8652 laminate

Category of damage	Depth of notch	Tensile Strength /MPa	Standard Deviation /MPa
No-damaged	N/A	627	42.4
Double-edge notch	2mm	429	31.9
	3mm	385	11.4
	4mm	346	7.6

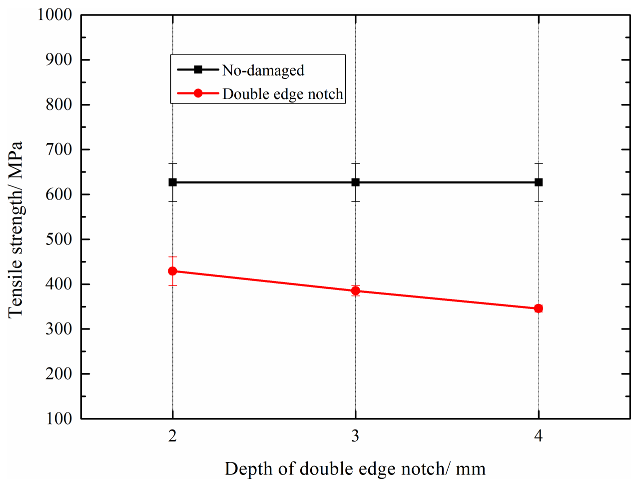


Figure 3: Comparison of static testing result on specimens with different depth of double-edge notch

Figure 4: View of specimens after tensile test (a) No damage (b) 2mm depth of notch (c) 3mm depth of notch (d) 4mm depth of notch

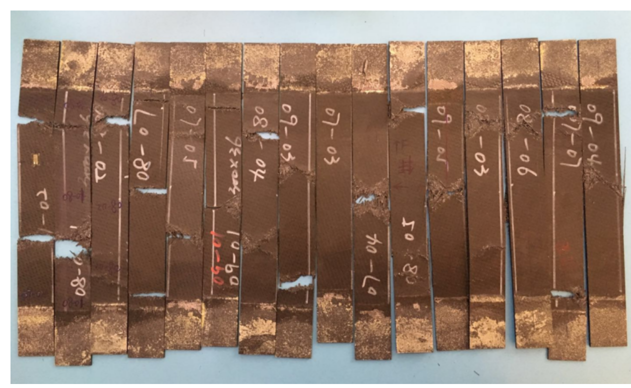
Specimens after tensile tests are shown in Figure 4, demonstrating the failure mode of no-damaged, 2mm, 3mm and 4mm depth of notch specimens. As can be seen in Figure 4(a), two specimens broke into three parts as a strong rebound of laminates was occurred at the time of fracture, while failure modes of all specimens meet requirements of the testing standard. Figure 4(b)–(d) illustrates that all notched specimens are failed at the region of notching. This can be concluded that the size of damage has an obvious influence on the failure mode of specimens.

3.2 Fatigue test

The results of fatigue tests on no-damaged and 3mm depth notched specimens were shown in Table 4, including the information of stress ratio (R), stress level, maximum stress and life cycle, of which four valid data were finally obtained from each stress level of test.

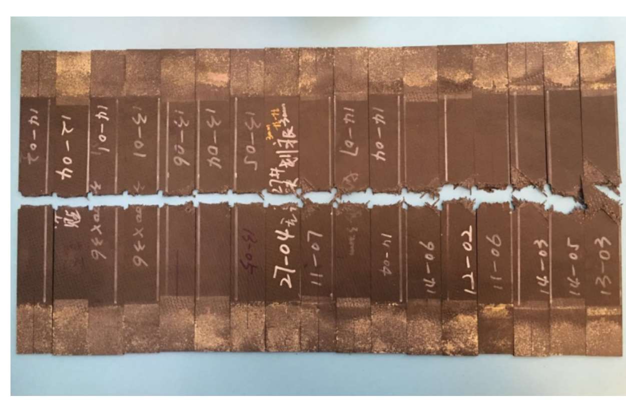
Failure modes of no-damaged specimens after testing are demonstrated in Figure 5. It is observed that almost half of specimens broke into three or more parts as found in static tensile tests, where the cause has been explained above. Fractures along ±45° direction are found in specimens with the lay-up in ±45° direction taking up 50% of fibres.

The picture which shows the failure mode of 3mm depth double-edge notched specimens after fatigue test can be found in Figure 6. Unlike no-damaged specimens,



Note: Tensile test was conducted on specimens with ‘No failure’ after specific cycles to obtain the residual tensile strength.

Figure 5: View of no-damaged specimens after tension-tension fatigue test (R=0.05)



Note: Tensile test was conducted on specimens with ‘No failure’ after specific cycles to obtain the residual tensile strength

Figure 6: View of 3mm depth notched specimens after tension-tension fatigue test (R=0.05)

Table 4: Fatigue results of 3238A/CF8652 laminate

Category and size of damage	Stress ratio	Stress level	Maximum stress/MPa	Cycle/N
None	Tension-tension R=0.05	80%	501.60	49808, 52989, 77981, 32905
		75%	470.25	182256, 70671, 132115, 115147
		70%	438.90	521040, 450006, 168113, 327217
		65%	407.55	802169, 1000000→, 1000000→, 1000000→
3mm depth of double-edge notch	Tension-tension R=0.05	100%	385.20	20, 4, 7
		97%	373.64	9295, 733, 100000→, 100000→
		95%	365.94	761987, 143433, 500000→, 500000→,
		90%	346.68	1000000→, 1000000→, 1000000→, 1000000→

Note: Stress level means the value of maximum fatigue stress divided by the residual strength of specimens with specific flaws/damage. '→' represents No failure when a specific number of cycles is reached.

all notched specimens fractured at the region of notching, which is consistent with what happened after the tensile test.

3.3 *S-N* curve

The *S-N* curve, also known as the Wöhler curve, is obtained after a number of fatigue tests at different stress levels. In this paper, the three-parameter non-linear model is applied [21]. The fatigue maximum stress S_{max} and fatigue life N is usually plotted on a logarithmic scale. The mathematical expression is shown in the following equation.

$$\log N = A_1 + A_2 \log(S_{\max} - S_0) \tag{1}$$

Where A_1 and A_2 are constants of *S-N* curve of a material under certain stress concentration factor and stress ratio; S_0 represents the fatigue limit when N tends to be gigantic.

Let and $Y = S_{\max} - S_0$, then equation (1) can be rewritten as follows:

$$X = A_1 + A_2 Y \tag{2}$$

$$A_1 = \overline{X} - A_2 \overline{Y} \tag{3}$$

$$A_2 = \frac{L_{YX}}{L_{YY}} \tag{4}$$

$$r = \frac{L_{YX}}{\sqrt{L_{YY} L_{XX}}} \tag{5}$$

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i, \quad \overline{Y} = \frac{1}{n}\sum_{i=1}^{n} Y_i \tag{6}$$

$$\left.\begin{aligned} L_{XX} &= \sum_{i=1}^{n} X_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} X_i\right)^2 \\ L_{YY} &= \sum_{i=1}^{n} Y_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} Y_i\right)^2 \\ L_{YX} &= \sum_{i=1}^{n} X_i Y_i - \frac{1}{n}\left(\sum_{i=1}^{n} X_i\right)\left(\sum_{i=1}^{n} Y_i\right) \end{aligned}\right\} \tag{7}$$

Parameters of $\overline{Y}$, L_{YY}, L_{YX} in equations above are the function of S_0, thus A_1, A_2 and r are also the function of S_0. To obtain S_0, it is required to take the maximum value of $|r(S_0)|$, shown in equation.

$$\frac{d\,|r(S_0)|}{dS_0} = 0 \quad \text{or} \quad \frac{dr^2(S_0)}{dS_0} = 0 \tag{8}$$

As $\frac{dr^2(S_0)}{dS_0} = 2r^2(S_0)\left(\frac{1}{L_{YX}}\frac{dL_{YX}}{dS_0} - \frac{1}{2L_{YY}}\frac{dL_{YY}}{dS_0}\right)$, thus

$$\frac{1}{L_{YX}}\frac{dL_{YX}}{dS_0} = \frac{1}{2L_{YY}}\frac{dL_{YY}}{dS_0} \tag{9}$$

It is assumed that,

$$\begin{aligned} L_{X0} &= -\log\frac{dL_{YX}}{dS_0} \\ &= \sum_{i=1}^{n}\frac{X_i}{S_i - S_0} - \frac{1}{n}\left(\sum_{i=1}^{n} X_i\right)\left(\sum_{i=1}^{n}\frac{1}{S_i - S_0}\right) \end{aligned} \tag{10}$$

$$\begin{aligned} L_{Y0} &= -\frac{1}{2}\log\left(\frac{dL_{YY}}{dS_0}\right) \\ &= \sum_{i=1}^{n}\frac{Y_i}{S_i - S_0} - \frac{1}{n}\left(\sum_{i=1}^{n} Y_i\right)\left(\sum_{i=1}^{n}\frac{1}{S_i - S_0}\right) \end{aligned} \tag{11}$$

Substituting equations and into equation, thus

$$\frac{L_{Y0}}{L_{YY}} - \frac{L_{X0}}{L_{YX}} = 0 \tag{12}$$

It is assumed that,

$$H(S_0) = \frac{L_{Y0}}{L_{YY}} - \frac{L_{X0}}{L_{YX}} \tag{13}$$

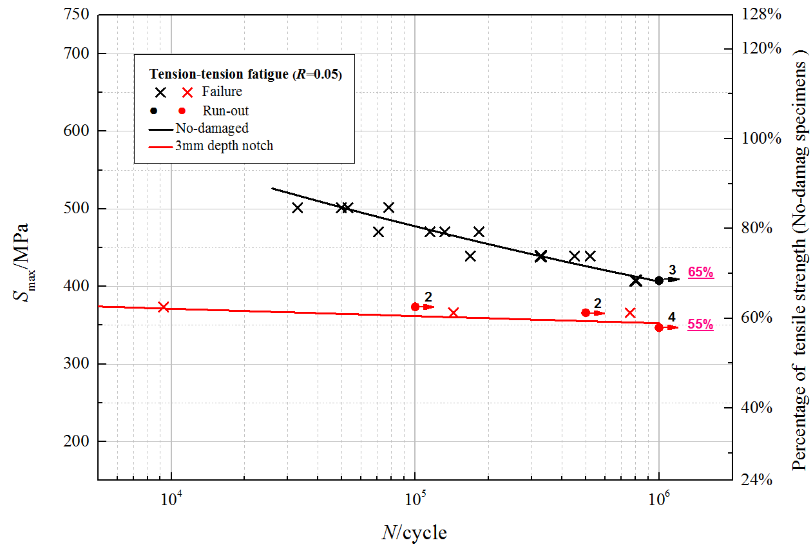


Figure 7: Tension-tension fatigue *S-N* curve of specimens with no-damaged and 3mm depth double-edge notches damage

Where $\hat{S}_0$ is the estimation of S_0, when $\hat{S}_0 < S_0$, then $H\left(\hat{S}_0\right) > 0$; while $\hat{S}_0 > S_0$, $H\left(\hat{S}_0\right) < 0$. Since S_0 must be within the interval $[0, S_0')$, S_0' is the minimum value of the S_i (i=1,2,...,n) for the data point stress, thus S_0 can be easily obtained by the dichotomy method. After obtaining a, b, and S_0, constants of A_1 and A_2 can be found by equation. Therefore *S-N* curve is obtained.

S-N curves of no-damaged and 3mm depth notched laminate are plotted in Figure 7. In this diagram, 'run-out' represents specimens remain no-failure when specific life cycles are reached. It finds that three-parameter non-linear model fits well with the experimental data. Fatigue limit of no-damaged laminate is about 65% of UTS, obtained from the tensile test. This result is consistent with the result from reference. Due to the effects of notches, the fatigue limit of notched specimens is reduced to 55% of UTS (no-damage) and the slope of the *S-N* curve tends to be horizontal. Comparing Tables 2 and 3, it is not hard to find that the fatigue limit decreases very little compared to static UTS, since fatigue is insensitive to the stress concentration factor. Thus the static stress concentration factor is 1.62, and the fatigue stress concentration factor is 1.18.

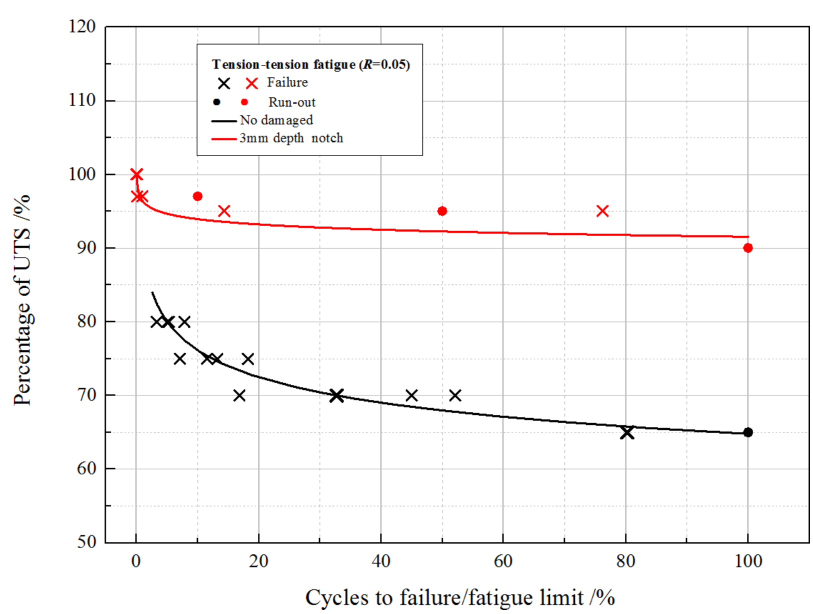


Figure 8: Normalized fatigue data for no-damaged, 3mm depth of double-edge notched specimens

3.4 Normalized *S-N* curve

Normalized *S-N* curves can be obtained by applying normalized fatigue data with respect to relevant tensile strength [15]. In this paper, number of cycles to failure *N* was also normalized by introducing a parameter of 10^6 cycles (cycles for fatigue limit). In this way, the modified normalized *S-N* curve gives the fatigue strength for different life stages.

The pattern of normalized *S-N* curve in this paper differs slightly from Reifsnider's mode. Reifsnider claims, that the residual strength of a laminate remains relatively unchanged until quite near the end of life [16]. However, for the 3238A/CF8652 normalized *S-N* curve, fatigue strength of both notched and undamaged laminate decreases dramatically at the beginning of the fatigue cycles, which is shown in Figure 8. It is found that the curve of notched 3238A/CF8652 laminate does not agree with that of no-damaged one, which differs from the reference [16]. The fatigue limit of notched laminates is more than 90% of UTS, which is much higher than that of no-damaged specimens (65%).

In addition, the fatigue process can be divided into 2 stages according to the normalized *S-N* curve. The first stage accounts for 20% of the fatigue life, appearing in a dramatic decrease of fatigue strength. The remaining stage takes up the rest of fatigue life. During this stage, the fatigue strength exhibits a steady decline with the overall decline being less than 10% of UTS.

3.5 In-situ damage expansion

A wide range microscope, shown in Figure 9 was applied to track the in-situ damage expansion on the sides of specimens during different stages of life cycles. The movement of the microscope is accurate to 0.02mm and a maximum magnification of 90X can be achieved. A no-damaged specimen under 70% of UTS fatigue loading was investigated, edge views of the specimen at 7523, 42182, 124371 and 164969 cycles were recorded, which can be observed in Figure 10. It was observed that damage occurred as the inter-ply laminate delaminated between the middle [0/90] and [90/0] plies, which corresponds to a slender crack on the image. This accounts for this dramatic decrease of fatigue strength at the very beginning of its normalized fatigue residual strength- life curve. As the life cycle increased, oblique cracks developed between two plies. Individual cracks were then connected and formed a big crack. Transverse cracks were observed at the same time, and specimens fractured finally with the propagation of transverse cracks and severe delamination of inter-ply laminates.

① Controller
② Height-adjustable tripod
③ Scale reading table
④ Lifting platform in Z direction
⑤ Translation platform in X direction
⑥ Translation platform in Y direction
⑦ Microscopy system

Figure 9: Schematic diagram of JCXE-DF wide range microscope

The 3mm depth notched specimen under 90% of UTS fatigue loading were further examined and used for comparison with no-damaged specimens. Damage expansion of notched laminates was found in Figure 11. In the figure, dash lines mark the approximate position of each ply. The examined specimen did not fracture when 10^6 life cycles were reached. At the very beginning of the test, no damage was found at 1106 cycles as illustrated in Figure 11(a); this evidence verifies that there is no additional damage caused by the preparation of notches. Unlike the no-damaged specimen, the initial damage took place between [45/−45] and [0/90] layers near two sides of the notch. With the number of cycles increasing, transverse cracks appeared, and the intra-layer stratification became more pronounced. The delamination between adjacent plies was then connected, ultimately resulting in the separation of different plies.

To sum up, it was observed that no-damaged and notched laminates perform different behaviours in terms of damage evolution. The differences can be concluded as follows:1) position of crack initiation; 2) sequence of dam-

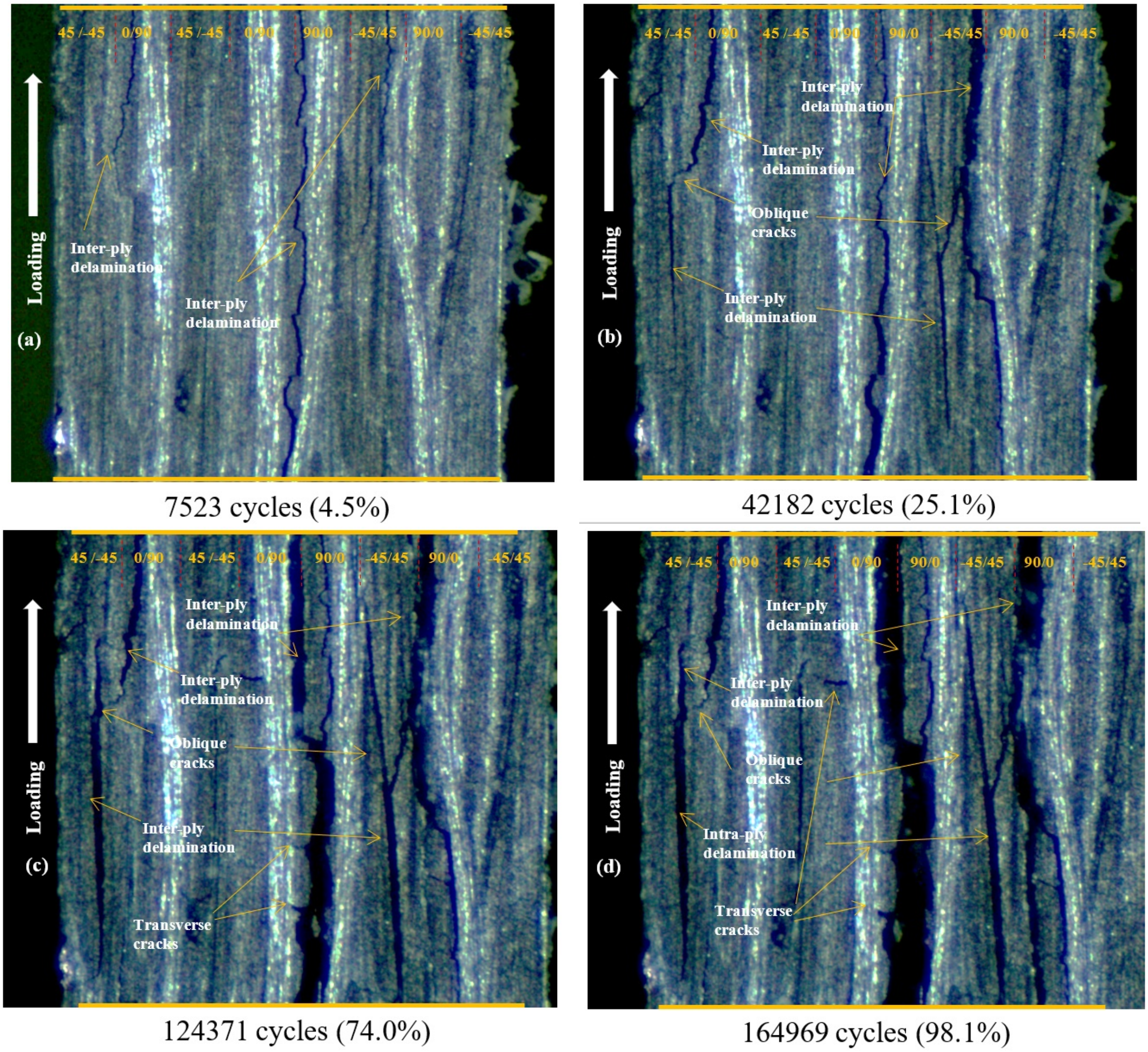


Figure 10: View of the tension-tension fatigue of no-damaged specimens under 70%UTS (a) at 7523 cycles (4.5% of the life); (b) at 42182 cycles (25.1% of the life); (c) at 124371 cycles (74.0% of the life); (d) at 164969 cycles (98.1% of the life)

Table 5: Differences in damage evolution behaviour between no-damaged and notched laminates

Specimen	Position of crack initiation	Sequence of damage occurrence
No-damaged specimen	Middle of the specimen	1. Inter/intra-ply delamination 2. Oblique cracks 3. Transverse cracks 4. Severe delamination of inter-ply laminate
Notched specimen	Two sides of the specimen	1. Inter-ply delamination 2. Transverse cracks 3. Severe delamination of several inter-plies

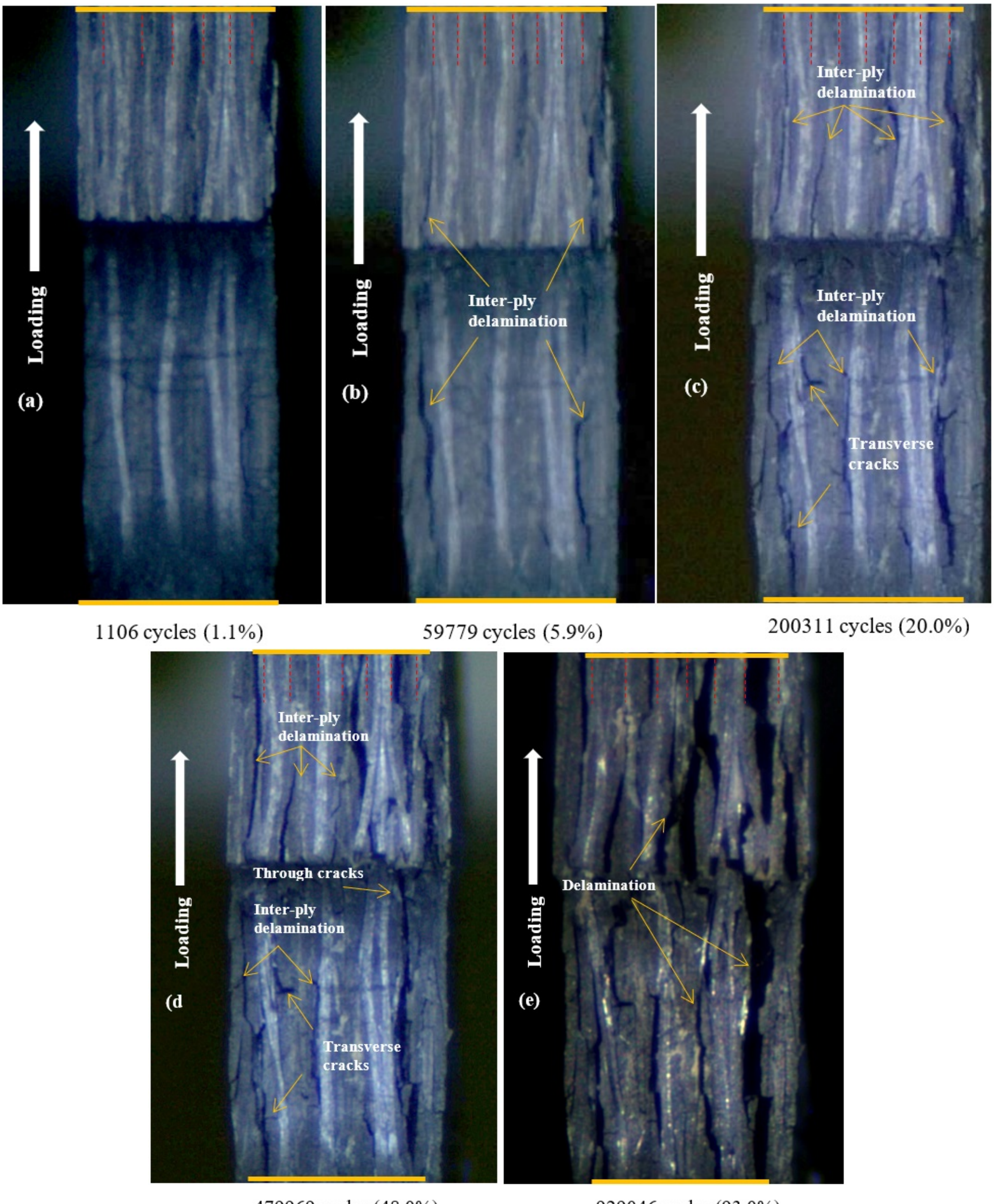


Figure 11: View of the tension-tension fatigue of 3mm depth notched specimen under 90%UTS (a) at 1106 cycles (1.1% of the life); (b) at 59779 cycles (5.9% of the life); (c) at 200311 cycles (20.0% of the life); (d) at 479969 cycles (48.0% of the life); (d) at 929046 cycles (93.0% of the life)

age occurrence. Details are presented in Table 5. Position of crack initiation may play the major role and it could explain the different shapes of the normalized *S-N* curve between no-damaged and notched laminates. In addition, the first occurrence of inter-ply delamination results in a dramatic decrease in fatigue strength on that curve.

4 Conclusion

In this paper, effects of double-edge notches on static and fatigue properties of T800 fabric carbon fibre reinforced epoxy were investigated; three notch depths were selected for tension tests. One typical depth was chosen to conduct the tension-tension fatigue test. Comparative tests with no-damaged specimens were carried out to examine the effects of notches on static and fatigue properties. Major results of this paper can be concluded as following:

1) The residual tensile strength of specimens is linearly decreased with the increasing depth of notches from 2mm to 4mm. Compared to no-damaged laminate, the tensile strength of notched specimens decreased by 31.5%.
2) The fatigue limit of notched specimen was reduced to 55% of UTS and the slope of the *S-N* curve tends to be more horizontal, due to the introduction of notches.
3) The fatigue limit of notched laminate is greater than 90% of UTS, which is much higher than that of no-damaged specimen (65%) since fatigue loading is less sensitive to stress concentration factors than static loading.
4) The In-situ damage expansion process explained the pattern of normalized *S-N* curves which can be summarized in two stages: the first stage accounts for 20% of the fatigue life, showing a dramatic decrease in fatigue strength, and the remaining stage takes up the rest of total life span. During the latter stage, the strength exhibits a steady drop with the overall decline being less than 10% of UTS.
5) No-damaged and notched laminates perform different damage evolution behaviours. Position of crack initiation and the sequence of damage occurrence are the two major factors controlling the shape of normalized *S-N* curves.

References

[1] Freeman W. The use of composites in aircraft primary structure. Composites Engineering. 1993;3(7-8):767–75.
[2] Soutis C. Fibre reinforced composites in aircraft construction. Prog Aerosp Sci. 2005;41(2):143–51.
[3] Ashby M, Brechet Y, Cebon D, Salvo L. Selection strategies for materials and processes. Mater Des. 2004;25(1):51–67.
[4] Donald F. Adams—CMH-17, composite materials handbook, Experimental characterization of advanced composite materials, vol. 1, 1982.
[5] Cantwell W, Curtis P, Morton J. Post-impact fatigue performance of carbon fibre laminates with non-fabric and mixed-fabric layers. Composites. 1983;14(3):301–5.
[6] Cantwell W, Curtis P, Morton J. An assessment of the impact performance of CFRP reinforced with high-strain carbon fibres. Compos Sci Technol. 1986;25(2):133–48.
[7] Dorey G. Impact and crashworthiness of composite structures. Elsevier Science Publishing Co, Inc; 1984. pp. 155–92.
[8] Gary P, Riskalla M. Development of probabilistic design methodology for composite structures. VOUGHT AIRCRAFT CO DALLAS TX; 1997.
[9] Huang H, Talreja R. Effects of void geometry on elastic properties of unidirectional fiber reinforced composites. Compos Sci Technol. 2005;65(13):1964–81.
[10] Shams SS, El-Hajjar RF. Effects of scratch damage on progressive failure of laminated carbon fiber/epoxy composites. Int J Mech Sci. 2013;67:70–7.
[11] Zhu W, Xu X. Experiment research and fatigue life prediction of low-velocity-impacted laminate under compressive-compressive fatigue load. Engineering Mechanics. 2013;30:412–4.
[12] Shahkhosravi NA, Yousefi J, Najafabadi MA, Burvill C, Minak G. Fatigue life reduction of GFRP composites due to delamination associated with the introduction of functional discontinuities [J]. Compos, Part B Eng. 2019;163:536–47.
[13] Green BG, Wisnom MR, Hallett SR. An experimental investigation into the tensile strength scaling of notched composites. Compos, Part A Appl Sci Manuf. 2007;38(3):867–78.
[14] Muc A, Romanowicz P. Effect of notch on static and fatigue performance of multilayered composite structures under tensile loads. Compos Struct. 2017;178:27–36.
[15] Harris B. Fatigue in composites: science and technology of the fatigue response of fibre-reinforced plastics. Woodhead Publishing; 2003.
[16] Reifsnider K, Henneke E, Stinchcomb W, Duke J. Damage mechanics and NDE of composite laminates, Mechanics of composite materials: Recent advances, ed: Elsevier, (1983) 399-420.
[17] Sims G, Gladman D. Effect of test conditions on the fatigue strength of a glass±fabric laminate: part B±specimen condition. Plast Rubber Mater Appl. 1980;8:122–8.
[18] ASTM D3039 / D3039M-17, Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials, ASTM International, West Conshohocken, PA, 2017.
[19] ASTM D5766 / D5766M-11(2018), Standard Test Method for Open-Hole Tensile Strength of Polymer Matrix Composite Laminates, ASTM International, West Conshohocken, PA, 2018.
[20] ASTM D3479 / D3479M-12, Standard Test Method for Tension-Tension Fatigue of Polymer Matrix Composite Materials, ASTM International, West Conshohocken, PA, 2012.

[21] Spindel J, Haibach E. Some considerations in the statistical determination of the slope of SN curves, Statistical analysis of fatigue data, ed: ASTM International, 1981.