Tensile Property Evaluation of Stepped Scarf Joint Repair for Wind Turbine Trailing-Edge Laminate

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Abstract: A solid model of the trailing-edge laminate with a stepped scarf joint repair is created and calculated by non-linear time-domain analysis method to analyse the structural strength of the entire model and the shear stress of the bondline. Experimental test of samples of the model was carried out to determine the influences of joint type, repair ply number and joint number on the failure load of stepped scarf joint repair. The results showed double-joint repair can be used for the repair of the trailing edge UD; reinforcement ply can be used for strength recovery of damaged trailing-edge UD laminate; the N-joint repair can be reinforced by N-ply reinforcement, and failure load of repair sample is 1.2 to 1.3 times of the original failure load. Through structural analysis and experimental test, samples and model, of which the failure mode is mainly the shear failure of the bondline, all deformed compatibly.

1. Introduction

Different forms of damages occur in the vicinity of wind turbine blade trailing edge, which lead to aerodynamic performance reduction, shorten fatigue life span, even threaten the structural safety of wind turbine[1]. Due to alternating cyclic loading, the complex structure and the geometric nonlinearity near bondline, trailing edge has become a main region where damages occur. Failure of wind turbines due to failure of the blades represents 19.4% of a total of 1028 wind turbine failure, while 40% of blade failures are caused by damage of the tailing edge such as cracks, flaws, delamination and wrinkling[2]. The causes of trailing edge failure are extremely complex owing to the special bonding technique. The root cause may be the integration of the complex loading situation, anisotropic material properties, geometric singularity, manufacturing process and nonlinear response[3].Trailing edge needs to be repaired once a damage occurs, and stepped scarf joint repair is usually applied to any composite damage in trailing edge to rebuild the structure. Currently, in absence of common standards and technical norms on repairing of blade trailing edge, most damages are repaired by experience. However, for laminate repair, especially trailing edge UD repair, assessing the strength of the repairs and repair technique are crucial.

The analysis of the trailing edge of blade is usually based on fracture mechanics and damage mechanics: the structural stress parameters and degradation of energy are obtained through different failure criterion and fracture mechanism models to detect the progressive edge damage and the failure of the bondline[4][5]. In this paper, A solid model of the trailing-edge laminate with a stepped scarf joint repair is created and calculated by non-linear time-domain analysis method to analyse the structural characteristics of repaired laminate and bondline. At the same time, experimental test of large dimension samples of the model was carried out to determine the influences of joint type, repair ply number and joint number on the strength recovery ability of stepped scarf joint repair.

2. Stepped Scarf Joint Repair of Laminate

Stepped Scarf Joint Repair is a main repair technique utilized in blade laminate repair, of which

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the principle is to finally restore the stiffness, strength and service performance of the structure by removing damaged material and replacing with new repair plies. While the restored strength of repaired biaxial and triaxial laminate has received much attention, there is barely no paper on the study of strength of repaired unidirectional laminate which is mainly used in trailing-edge part. Considering that trailing edge UD is a vital loading part and is vulnerable to damages, a solid model of the trailing-edge laminate with a stepped scarf joint repair was created in this study(shown in Fig.1) including the original laminate, joint bondline and repair plies, to calculate the tensile strength of the repaired laminate by non-linear time-domain analysis method. Meanwhile, experimental test of the model was carried out to obtain tensile strength, stiffness, and failure mode and determine the strength recovery rate of this repair method. This could possibly provide an effective method to repair blade trailing-edge UD.

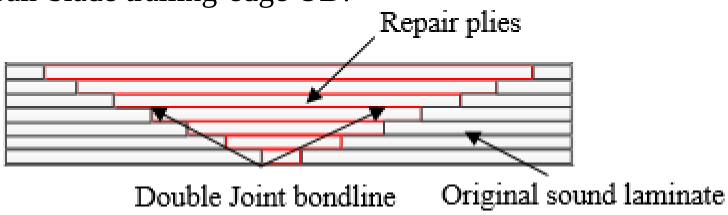

Figure 1 A model of the trailing-edge laminate with a stepped scarf joint repair

3. Finite Element Analysis

The bondline of stepped scarf joint repair is subjected to pure sheer load. In order to simulate the real loading situation, 3D solid element was used to create the model according to the real dimension, shown in Fig.2. Bondline elements were mainly under shear loading, which leads to shear failure of bondline.

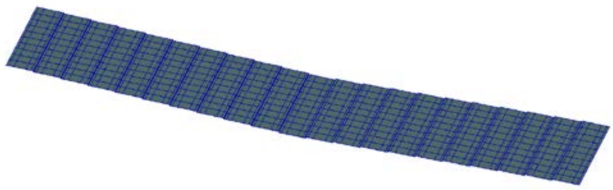

Figure 2 Bondline elements in model of trailing-edge UD with stepped scarf joint repair

Materials of original laminate and repair plies were both unidirectional fabric UD 1150, and bondline was a layer of 5mm structural adhesive, material properties of UD and structural adhesive is shown in Table 1.

Table 1 Material properties of UD and structural adhesive

Name	**Unit**	**UD1150**	**structural adhesive**
E_11	Mpa	40000	3200
E_22	Mpa	15000	
G_12	Mpa	4500	
G_23	Mpa	3000	
G_31	Mpa	3000	
μ_12	-	0.29	0.3
μ_23	-	0.29	
μ_31	-	0.29	
t	mm	0.87	5
Density	kg/mm3	1.90E-06	1.35E-06

The whole model was loaded with displacement in the direction of tension. The simulation time was 600 seconds and the calculation time steps were 30. Fig.3 shows the uniform stress distribution of the whole model after calculation. The failure modes of the original laminate are mainly matrix failure and fiber failure, and the main failure mode of the bondline is shear failure.

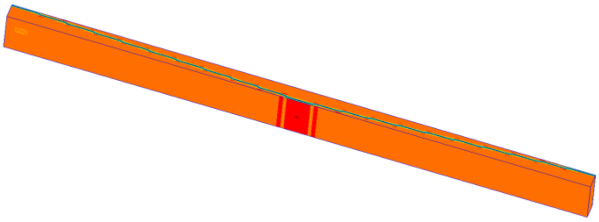

Figure 3 Stress in fiber direction of the whole model of trailing-edge UD with stepped scarf joint repair

As shown in Fig.4, the stress distributes uniformly in the whole bondline. The maximum stress is in the joint corner, which is also the main failure position relating to the geometric singularity of the corner. So, it is crucial to ensure the continuity of bondline and reduce the stress in joint corners for a joint repair, and especial attention should be paid to the repair quality in joint corners.

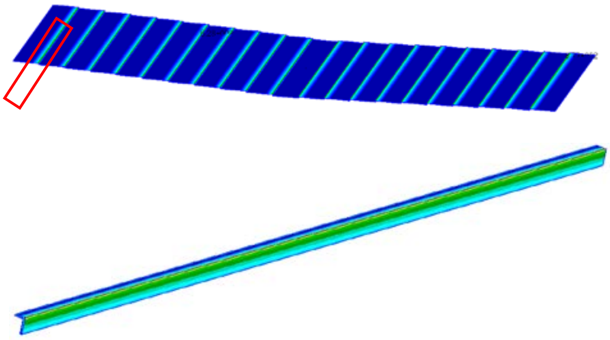

Figure 4 Stress distribution of bondline and joint corner

The midpoint of the outermost layer of the whole model is extracted as a characteristic point. The stress-strain curve of this characteristic point is linearly distributed, as shown in Fig5, because of the linearity of material and no periodic variation of displacement load.

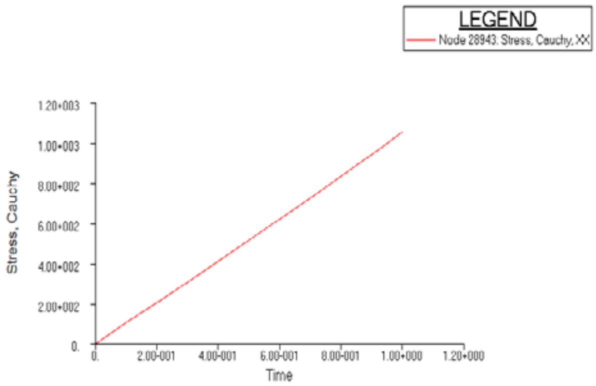

Figure 5 Stress-strain curve of the characteristic point

4. Experimental Test

The influences of joint mode, repair ply number and reinforcement form on the failure load of the test sample are verified by experiments. The test sample is cut by hand, so it is difficult to achieve the consistency of samples' width. In the test results, load per unit width (i.e. failure load/sample width) is introduced to determine the load loss rate, and then to determine whether the strength requirements can be met.

4.1 Sample Preparation and Experimental Setup

Grip area of the samples were abraded with #80 mesh abrasive paper until the whole area was abraded and the roughness met requirements. The end tabs were cut out and bonded to the samples. Fig.6 gives the dimensions of each sample. The size and the joint lap width of each group of samples are shown in Table2. H is the length of test area. The test samples were cut to be symmetrical to ensure that the joint positions were in H area.

Table 2 Dimensions of samples with different joint width

Dimensions of samples, joint lap width 100mm					
Dimensions	b	h	H	T	L
Unit (mm)	25	3.3	180	50	300
Dimensions of samples, joint lap width 120mm					
Dimensions	b	h	H	T	L
Unit (mm)	25	3.3	230	50	350
Dimensions of samples, joint lap width 120mm					
Dimensions	b	h	H	T	L
Unit (mm)	25	3.3	280	50	400

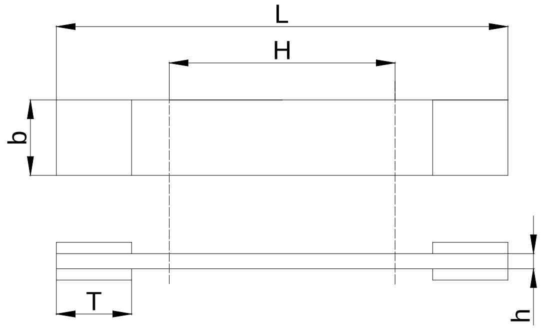

Figure 6 A schematic of test samples

Test samples were prepared by RTM technique. End tabs were bonded to the grip area with structural adhesive. The test samples were shown in Fig.7.

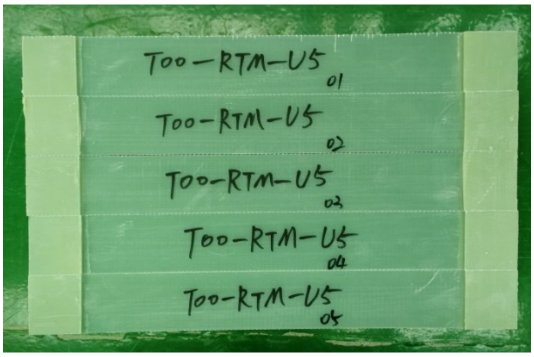

Figure 7 Test sampes

Figure 8 Experimental setup

Fig.8 shows the experimental setup of tensile test, test speed was 2mm/min. The dynamic strain gauges were used to measure the strain changes at key points of the samples. The test points were distributed in joint areas, non-repair areas and repair ply aeras.

4.2 Joint Type Test

A group of samples without reinforcement ply were tested to evaluate the influences of joint type on the repair strength. The basic information is in Table 3. A total of 9 types (A, B…., I) of samples were prepared according to the maximum stroke of test machine. Every type contained 4 samples, the results of which were averaged to minimize data dispersion

Table 3 Basic information of the first group of samples

No	Length	Width	Joint type	Joint lap Width	Joint number	Effective samples
A	600	50	Double	80	3	4
B	600	50	Non	Non	3	4
C	600	50	Single	80	3	3
D	520	50	Double	100	2	4
E	520	50	Single	100	2	4
F	520	50	Non	Non	2	2
G	320	25	Single	100	1	4
H	320	25	Non	Non	1	3
I	320	25	Double	100	1	3
J	300	25	Non	Non	2	3
K	300	25	Non	Non	3	3

The load loss rate per unit width of samples with single-joint should be the same with that with double-joint theoretically. Practically, due to the influences of manufacturing process, the load loss rate per unit width of single-joint samples were less. However, as the number of laminate ply increases, the failure load loss rates of single-joint repair and double-joint repair are tend to be the same. Considering the actual operation, double-joint repair can be used for the repair of the trailing edge UD.

Table 4 Results of the first group of samples

No.	Elongation at break	Failure load	Tensile strength	Tensile strain	Unit width load	Load loss rate
	‰	kN	MPa	%	kN/mm	%
A	17.0	71.6	465.4	1.50	1.5	0.26
B	27.8	97.7	850.8	2.28	2.0	
C	19.0	73.8	491.0	1.60	1.5	0.25
D	17.8	53.0	506.5	1.50	1.1	0.27
E	17.4	54.7	466.5	1.35	1.1	0.23
F	23.5	71.2	923.9	1.90	1.5	
G	7.9	13.3	364.4	0.83	0.6	0.31
H	15.3	20.1	1013.8	1.17	0.8	
I	8.7	12.6	318.6	0.87	0.5	0.34
J	22.8	67.8	528.9	1.33	2.9	
K	23.2	66.2	469.5	1.40	2.9	

4.3 Reinforcement Type Test

The test results of the first group shows that the load loss rate per unit width of sample with one joint is the maximum. If a sample with one joint can be reinforced to achieve the same load per unit width with laminate of one UD ply, the reinforcement method can be proved. It can restore the safe operation of the trailing edge beam, and Table5 gives the basic information of the second groups of samples.

Table 5 Basic information of the sceond group of samples

No.	Length	Width	Joint type	Joint lap Width	Joint number	Reinforcement Type	Effective samples
A	420	50	Single	100	1	A ply on one side	4
B	420	50	Single	100	1	A ply on both sides	4
C	600	50	Single	100	1	Two plies on one side	4
D	520	50	Double	100	1	A ply on one side	3
E	520	50	Double	100	1	A ply on both sides	
F	620	50	Double	100	1	Two plies on one side	4

Table 6 shows the results of the sceond group of samples. The minimum load per unit width is 0.95, which is greater than 0.81. So a reinforcement ply is enough for strength recovery of a damaged laminate.

Table 6 Results of the sceond group of samples

No.	Elongation at break	Failure load	Tensile strength	Elastic modulus	Tensile strain	Unit width load
	‰	kN	MPa	MPa	%	kN/mm
A	14.13	47.43	370.20	29856	1.28	0.95
B	14.00	53.95	299.23	25303	1.20	1.10
C		58.07	347.78			1.20
D		51.25	420.27			1.04
F		50.08	302.58			1.01

4.4 Joint Number Test

The above tests verify the strength recovery of samples with one joint. Here, samples with two joints were studied verify the load recovery rate of multi-joint samples. The test results are shown in Table 7, in which model A is reinforced by one ply inside and one ply outside, and model B is reinforced by one ply inside and two plies outside. The test results show that the load per unit width of model A is 1.93, and that of model B is 1.88, both greater than 1.48. It means that the multi-joint repair can be reinforced by multi-ply reinforcement, and failure load of repair sample is 1.2 to 1.3 times of the original failure load.

Table 7 Results of the third group of samples

No.	dimensions	Joint type	Joint lap Width	Failure load	Sample width	Unit width load
	mm			kN	mm	kN/mm
A	620×50	Single	100	95.11	49.35	1.93
B	620×50	Single	100	90.62	48.86	1.88

4.5 Study on tensile shear failure

Three UD laminate samples with double-joint repair (joint lap length is 30mm) were made by

RTM. Strain gauges are fixed in the joint area and in the middle of repair ply. The specific strain gauge positions are shown in Fig. 9.

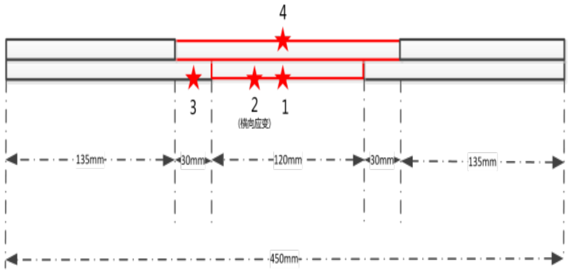

Figure 9 A schematic of test samples

As can be seen in Fig.10, failure of every sample occurred in the same position, i.e. position 3 as shown in Fig.9. This is a typical shear failure of adhesive layer in joint area.

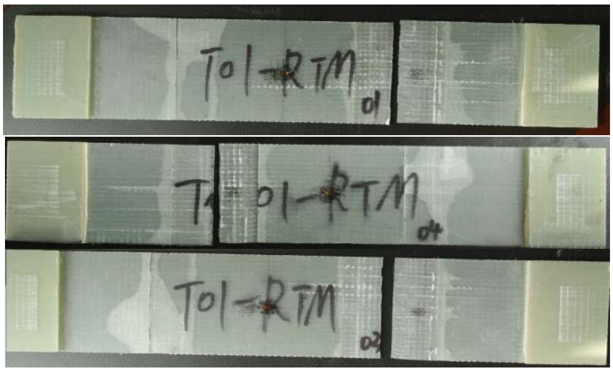

Figure 10 Failure samples after tensile test

Time-stress cures of the three samples are shown in Fig.11. 40 seconds after loading, the shear failure of sample 1 occurred, and the failure stress was 233MPa. 105 seconds after loading, the shear failure of sample 2 occurred, and the failure stress was 237MPa.308 seconds after loading, the shear failure of the sample 3 occurred, and the failure stress was 260MPa.

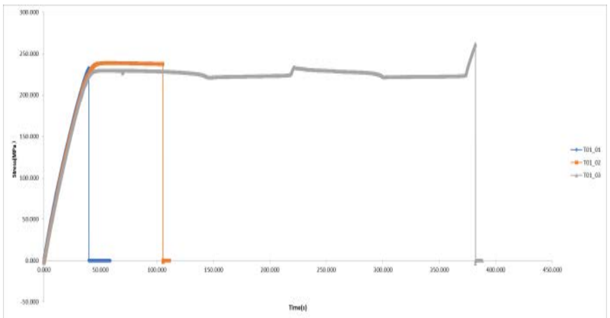

Figure 11 Time-stress cures of the three samples

Take sample 2 as an example, Fig.12 shows the displacement-strain curves of position 1, 3 and 4 shown in Fig.9. The whole sample has compatible strain.

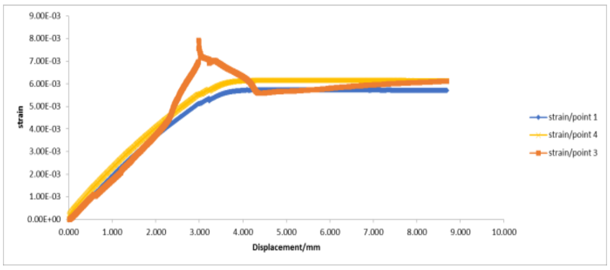

Figure 12 the displacement-strain curves of position 1, 3 and 4 of sample 2

5. Conclusions

Through FEM analysis and experimental test of the trailing-edge laminate with a stepped scarf joint repair, conclusions are as follows:

1) 3D solid element was used to create the FE model, the stress distributes uniformly in the whole bondline. The maximum stress is in the joint corner.

2) As the number of laminate ply increases, the failure load loss rates of single-joint repair and double-joint repair are tend to be the same. Considering the actual operation, double-joint repair can be used for the repair of the trailing edge UD.

3) Reinforcement ply can be used for strength recovery of damaged laminate.

4) The N-joint repair can be reinforced by N-ply reinforcement, and failure load of repair sample is 1.2 to 1.3 times of the original failure load.

5) Failure mode of laminate with stepped scarf joint repair under tensile load is mainly the shear failure of the bondline. Tested samples all deformed compatibly.

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