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PROGRESSIVE DAMAGE ANALYSIS ON YIELDING OF BONDED PATCH REPAIRED COMPOSITE LAMINATES UNDER COMPRESSIVE LOADING

Jian Deng [1, 2], *Guangming Zhou[1], Pierre Kerfriden[2], Stéphane Bordas[2, 3], Qiaozhi Yin [1]
[1] State Key Laboratory of Mechanics and Control of Mechanical Structures,
Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
[2] 1 Institute of Mechanics and Advanced Materials, Cardiff School of Engineering, Cardiff University, UK,
[3] Université du Luxembourg, Faculté des Sciences, de la Technologie et de la Communication, Research Unit in Engineering Science, Campus Kirchberg, 6, rue Richard Coudenhove-Kalergi, L-1359 Luxembourg

*zhougm@nuaa.edu.cn

ABSTRACT

In this paper, a progressive damage model for single-side bonded repaired composites laminates under compressive loading is introduced. Continuum damage model and cohesive zone model including stiffness degradation schemes are employed in the nonlinear FEM to predict the initiation and evolution of damage in the repaired structures. In proposed model, solid elements are applied for composite layers and cohesive elements for the adhesive. The numerical results of failure loads under compression shows consistency with experimental ones. The damage evolution is studied with analysis of loading process and failure propagation in adhesive. It indicates buckling deformation initiates the damage in plate and finally make the repaired structure crush.

Keywords: *bonded repair; composite laminates; compression; buckling; progressive damage*

1. Introduction

Composite laminates are widely applied in high performance industries such as aerospace and other industries like automobile and civil construction due to its traits in weight loss, low energy cost and well developed mechanical behaviours. However, damage varying from production, appliance to maintenance cannot be totally removed, which could reduce the safety and reliability of structures. Considering the replacement costs of the damaged composite parts would be quite high, effective repair techniques have increasingly drew engineers' attention. Bonded patch repair, through removing the damaged material and adhesively bonding several patches on outfaces of damaged structures, surmount the shortcomings of mechanical repair (e.g. reverting and fastening). Specifically, it can be divided into single bond (SB) on one side and double bonds (DB) on both sides. Since the peel stress on the boundary of bonded patches is quite high, it is generally applied as temporary repair in highly loaded structures and a permanent method for lightly loaded and slightly damaged parts.

Considering composites structures are generally thin walled with modes of failure caused by compression, the compressive behaviour should not be ignored in designing process. This paper establishes a progressive damage model for SB repaired laminates under compressive loading. Continuum damage model and cohesive zone model are employed in the nonlinear FEM to predict the initiation and evolution of damage in the repaired structures. The finite element model is discretized by solid elements accounting for composite layers and cohesive elements for the adhesive. All the material softening laws and failure modes are implemented with ABAQUS UMAT code. The failure strengths are predicted comparing with experimental outcomes from Campilho [1]. Damage propagation of one typical specimen is also studied.

2. Damage Model

Fibre failure, matrix failure and delamination failure in composites are all considered here with Hashin criteria [2] for the damage initiation under a three-dimensional state of stress in composites. The relations between failure modes are illustrated in Table 1.

Table 1: Failure indexes corresponding to different failure modes

Fibre failure in tension ($\sigma_{11} \geq 0$)	$(\frac{\sigma_{11}}{X_T})^2 + (\frac{\sigma_{12}}{S_{12}})^2 + (\frac{\sigma_{13}}{S_{13}})^2 = e_1^2$
Fibere failure in compression ($\sigma_{11} < 0$)	$(\frac{\sigma_{11}}{X_C})^2 = e_1^2$
Matrix cracking in tension ($\sigma_{22} \geq 0$)	$(\frac{\sigma_{22}}{Y_T})^2 + (\frac{\sigma_{12}}{S_{12}})^2 + (\frac{\sigma_{23}}{S_{23}})^2 = e_2^2$
Matrix cracking in compression ($\sigma_{22} < 0$)	$(\frac{\sigma_{22}}{Y_C})^2 + (\frac{\sigma_{12}}{S_{12}})^2 + (\frac{\sigma_{23}}{S_{23}})^2 = e_2^2$
Delamination in tension ($\sigma_{33} \geq 0$)	$(\frac{\sigma_{33}}{Z_T})^2 + (\frac{\sigma_{13}}{S_{13}})^2 + (\frac{\sigma_{23}}{S_{23}})^2 = e_3^2$
Delamination in compression ($\sigma_{33} < 0$)	$(\frac{\sigma_{33}}{Z_C})^2 + (\frac{\sigma_{13}}{S_{13}})^2 + (\frac{\sigma_{23}}{S_{23}})^2 = e_3^2$

**Note:1- and 2- axis are parallel and transverse to the fibres, respectively, while the 3-axis represents the normal direction, σ_{ij} (i = 1, 2, 3; j=1,2,3) are the stress components in ij directions, X_T、Y_T、Z_T are relative material strengths in tension, X_C、Y_C、Z_C are strengths in compression and S_{ij} stand for shear strengths, and e_i^2(i = 1,2,3) are relative damage indexes.*

After the initiation of damage in composites, damage variables are introduced in the continuum damage model to simulate its decreasing load capacity.

$$d_i = \min\{1, \frac{\langle e_i^2 - \varepsilon \rangle}{1-\varepsilon}\},\ i = 1,\ 2,\ 3 \tag{1}$$

Where $\langle \cdot \rangle$ is the McCauley operator defined as $\langle a \rangle = (|a| + a)/2$, ε is the fitting parameter adjacent to 1, and e_i^2 are attained from equation in Table 1. Therefore, the reduced stiffness matrix in damaged configuration is expressed as follows.

$$\boldsymbol{C}^{\mathbf{d}} = \begin{bmatrix} (1-d_1)C_{11} & (1-d_1)(1-d_2)C_{12} & (1-d_1)(1-d_3)C_{13} & 0 & 0 & 0 \\ & (1-d_2)C_{22} & (1-d_2)(1-d_3)C_{23} & 0 & 0 & 0 \\ & & (1-d_3)C_{33} & 0 & 0 & 0 \\ & \text{sym} & & (1-d_1)(1-d_2)C_{44} & 0 & 0 \\ & & & & (1-d_1)(1-d_3)C_{55} & 0 \\ & & & & & (1-d_2)(1-d_3)C_{66} \end{bmatrix}$$

A bilinear cohesive zone model [3] is applied to model the mechanical behaviour in the adhesive between the plate and bonded patch. The damage initiation law is the following quadratic equation.

$$\left(\frac{\langle t_{\mathrm{n}} \rangle}{T_{\mathrm{n}}}\right)^2 + \left(\frac{t_{\mathrm{s}}}{T_{\mathrm{s}}}\right)^2 + \left(\frac{t_{\mathrm{t}}}{T_{\mathrm{t}}}\right)^2 = 1 \tag{2}$$

where t_i (i=n,s,t) are the normal and shear tractions, and T_i (i=n,s,t) are the corresponding strengths.

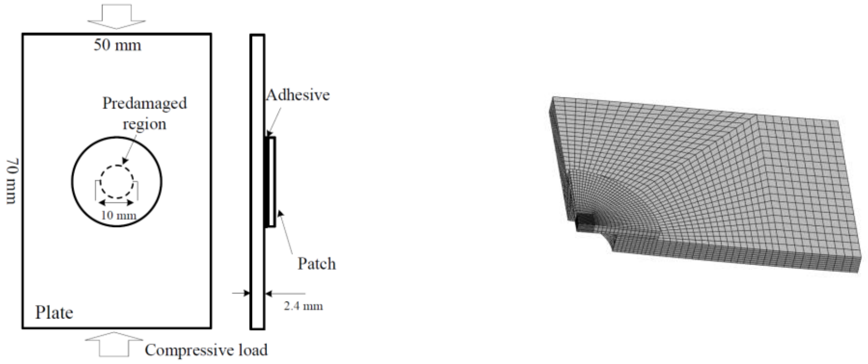
Damage evolution is modelled by quadratic fracture energetic criterion.

$$\left(\frac{G_{\mathrm{n}}}{G_{\mathrm{n}}^{\mathrm{C}}}\right)^2 + \left(\frac{G_{\mathrm{s}}}{G_{\mathrm{s}}^{\mathrm{C}}}\right)^2 + \left(\frac{G_{\mathrm{t}}}{G_{\mathrm{t}}^{\mathrm{C}}}\right)^2 = 1 \tag{3}$$

where G_i (i=n,s,t) are the current strain energy release rate and G_i^C are the corresponding critical energy release rate. When Eq.(3) satisfied, damage development occurs and stresses are released.

3. Numerical models based on FEM

To validate the efficiency of the proposed failure model, numerical studies based on FEM are established referring to the single bonded specimens tested by Campilho in experiments [1]. The geometrical dimension of the bonded repair laminates is shown in Figure 1(a). The stacking sequence of plate is $[0_2/90_2/0_2/90_2]_s$. The thickness of adhesive is 0.2mm.



(a) Geometric dimension (b) Finite element model (quarter)

Figure 1: Dimension and finite element model of SB specimen

The material system of composites applied in simulation is TEXIPREG HS 160 RM, and the adhesive material is Araldite®2015. All the properties are given in Table 2.

Table 2: Mechanical Properties

TEXIPREG HS 160 RM										
E_{11}/GPa	$E_{22}=E_{33}$/GPa	$\nu_{12}=\nu_{13}$	ν_{23}	$G_{12}=G_{13}$/GPa	G_{23}/GPa	X_T/MPa	X_C/MPa	$Y_T=Z_T$/MPa	$Y_C=Z_C$/MPa	S/MPa
109	8.819	0.342	0.380	4.315	3.2	1401	1132	59	211	54

Araldite®2015						
E/GPa	ν	G/MPa	t_n/MPa	$t_s=t_t$/MPa	G_n/J ·mm-1	$G_s=G_t$/J ·mm-1
1.85	0.3	650	23	22.8	0.43	4.70

Composite materials in the plate and patch are simulated with C3D8R solid elements in ABAQUS while COH3D8 cohesive elements are employed for adhesive layer. All the material softening law and failure modes are implemented with ABAQUS UMAT code. A typical finite quarter model is shown in Figure 1(b) to illustrate the discretization scheme. To ensure the accuracy of simulation, the repair area in the center is refined with smaller element size, and the constraints as well as loading patterns are consistent with experiments from Campilho [1].

4. Results

Table 3 shows the comparison between the simulation results of failure loads under compression and experimental ones differing in patch parameters. It is noticed that the predictions of strengths agree well with experiments. It indicates the damage model proposed is effective. Comparing the failure loads of these specimens, it should be noted that the repair improves the mechanical performance of damaged structures.

A typical load-displacement curve and damage evolution for specimen C are demonstrated in Figure 2 and Figure 3, respectively. Damage firstly initiate in the adhesive layer along with the loading direction (Figure 3(a)). It is due to the stress concentration at the edge of the damaged hole and stiffness difference between the plate and patch. Since the damage is developing in adhesive, its capacity of transferring loads from plate to patch is decreased. It indicates the patch support less for the loading and loads are distributed more on the plate. Then, the specimen is experiencing buckling as the displacement loading increased. It should be noted that stiffness reduction occurs when the structure start buckling in Figure 2. And as shown in Figure 3(c), the damage in adhesive develops perpendicular to the loading direction due to the buckling deformation. Afterwards, with continuously increased compressive loading, deformation caused by buckling of the structure becomes serious and the failure initiates in the plate. It is clearly seen significant stiffness reduction of the structure in Figure 2. The maximum load is taken at the point “Failure load” and then the repaired structure begins to collapse.

Table 3: Failure loads of single bonded specimens

	Diameter/mm	Thickness/mm	Stacking Sequence	Numerical Results / KN	Experimental Results / KN	Error / %
A		Without Repair		20.1	21.2	5.19%
B	20	1.2	$[0_2/90_2]$s	21.6	23.9	9.62%
C	30	1.2	$[0_2/90_2]$s	24.9	25.7	3.11%
D	20	0.6	[0/90]s	22.4	23.7	5.49%
E	30	1.8	$[0_2/90_2/0_2]$s	26.2	24.6	6.50%
F	20	2.4	$[0_2/90_2/0_2/90_2]$s	24.5	25.4	3.54%

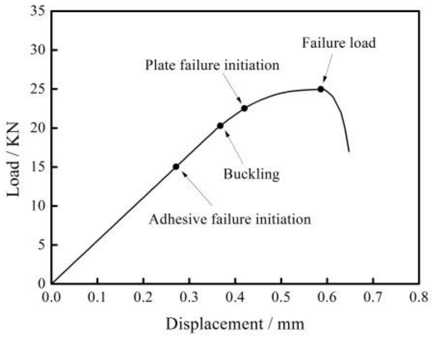


Figure 2: Load-Displacement curve

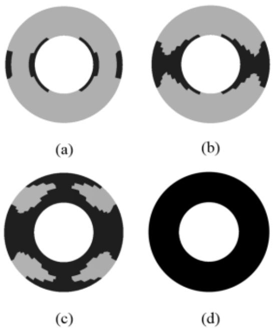


Figure 3: Adhesive failure propagation process

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