

Failure load prediction of single-lap bonded joints by damage zone method

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ABSTRACT

The failure load of single-lap bonded joints with dissimilar adherend materials was predicted using the damage zone method. A number of six joint configurations with different thicknesses of the adherends were considered. Three-dimensional finite element models were built to represent the behavior of the bonded joints, and the damage zone method was applied to predict the failure loads of the joints. The predictions of failure loads of the joints were achieved, showing a good agreement between the numerical and the corresponding experimental results.

Keywords: Single-lap joint; Composite; Damage zone method; Finite element analysis; Failure load prediction.

1. INTRODUCTION

Composite materials are commonly used in marine and aircraft structures because of their advantages compared to conventional metallic materials, such as high specific strength, high specific modulus, and corrosion resistance [1]. A composite structure is generally assembled by many parts via mechanical or adhesive joints. Mechanical joints using bolts, screws, or rivets for joining are simple, therefore, been widely used in the past. However, this kind of joint is required a fastener hole which induces stress concentrations, leading to a reduction in the strength of the joint.

Another joining method is an adhesive-bonded joint that has been increasingly used in assembling composite structures in recent decades [2]. This bonded joint uses adhesive materials instead of a fastener for joining the parts to form the whole structure. As a result, there is no existence of stress concentration due to the fastener hole in the bonded joint. The typical failure modes of bonded joints are cohesive and adherend failures. The cohesive failure is failure occurring inside the adhesive material or interfacial failure, which locates at the interface between adherend and adhesive components.

The strength of an adhesive bonded joint is generally affected by many factors such as the adhesive and adherend materials themselves, the overlap length, joint geometry as well as the quality of bonding surfaces. Most of the available published studies on the behavior of single-lap joints considered the adherends with the same material, for example, between composite and composite or metal and metal. Harris and Adams [3] performed finite element analysis to predict the failure mode of metallic single-lap bonded joints. Crocombe [4] proposed a method based on the assumption that the failure was assumed to occur as whole adhesive layers become plastic for the prediction of the bond line failure of single-lap bonded joints. The failure of the composite single-lap joint was also studied by many researchers [5-8].

Some authors investigated the failure of the single-lap joint between the two dissimilar adherends [9-11]. Shin and Lee [9] applied two failure criteria, the Ye-delamination and the 3D Tsai-Wu, to predict the failure load of the single-lap and double-lap joints. Owens et al. [10, 11] examined the failure of the joint between composite and aluminum

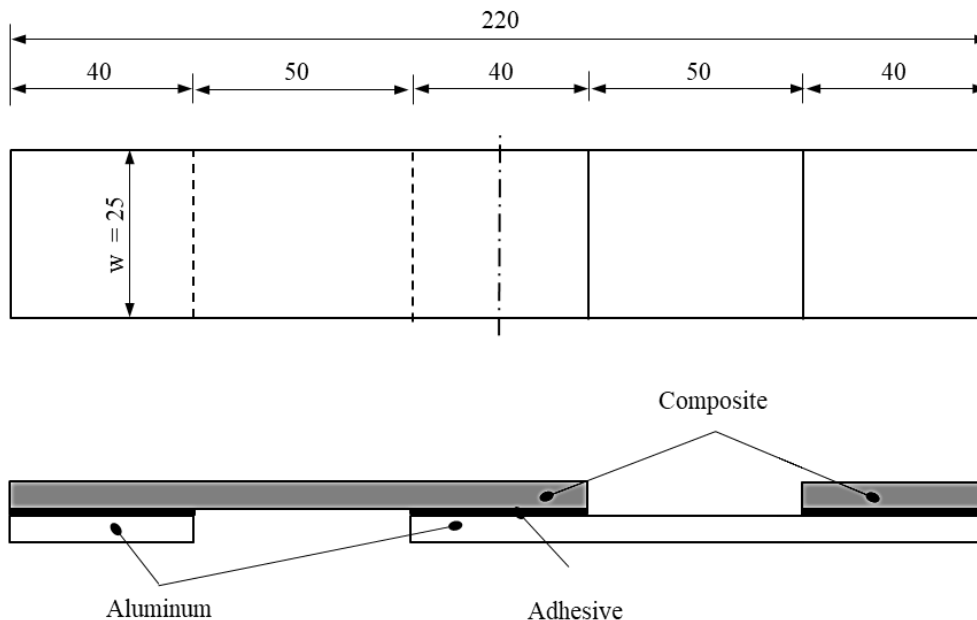
adherends by proposing a theoretical model to predict both the maximum joint stiffness and the rate of stiffness loss with crack growth. Kweon and his colleagues [12-15] conducted a series of numerical and experimental studies on the failure of the single-lap joint between aluminum and laminate composite substrates. The authors [12] investigated the effects of bonding pressure, overlap length, and adherend thickness on the failure of the joint. The effects of temperature and moisture on the strength of the composite bonded joints were also extensively investigated in their work [14].

The damage zone method developed by Sheppard and Kelly [16] was utilized in several studies [17-19] to predict the failure load of the bonded joint or bonded repair. Truong et al. [17] applied this damage zone method for predicting failure loads of the composite laminates repaired with a scarf-bonded patch. Their predictions [16] were agreed well with the corresponding experimental data. Ban [18] predicted the strength of the bonded joint between metal and composite using a modified damage zone theory. Other researchers [19, 20] conducted their investigation on the failure of a composite structure.

According to the literature survey [9-11, 12-15], the joint geometry, such as joint length and adherend thickness, significantly affects the failure of the single-lap bonded joints. This work aims to numerically investigate the influence of the adherend thickness on the failure load of single-lap joints between composite and aluminum adherends. A number of three-dimensional finite element models were built to represent the behavior of the joints, and the damage zone method was applied to predict the failure loads of the joints. The predictions of failure loads of the joints were achieved, showing a good agreement between the numerical and the corresponding experimental results.

2. SINGLE-LAP JOINT CONFIGURATION

The configuration of the aluminum-to-composite single-lap joint is depicted in Fig. 1.



**All dimensions are not to scale and in mm except scarf angle*

Figure 1. Schematic of single-lap joint.

The overlap length is 40 mm, whereas several thicknesses of the adherends were taken into account. The Aluminum 2024-T3 and the unidirectional carbon-epoxy prepreg USN-125B (SK Chemicals Company, Korea) were selected for the two adherends. Two stacking sequences of [45/90/-45/0]2S and [45/90/-45/0]3S, resulting in the thicknesses of 1.92 and 2.88 mm, were adopted for the composite adherends. Three considered thicknesses of the aluminum were chosen to be 1.6, 2.0, and 2.4 mm. An epoxy film adhesive FM73m, Cytec Industries, USA, was employed as bonding material with its mechanical properties are listed in table 1.

Table 1. Material properties of USN-125B, Aluminum, and FM73m [13, 17].

Property	Symbol	USN-125B	FM73m	Al-T2043
Elastic modulus (GPa)	E_1	142	2.8	73
	E_2	8.4		
	E_3	8.4		
Shear modulus (GPa)	G_{12}	5.34		
	G_{13}	5.34		
	G_{23}	3.06		
Poisson's ratio	ν_{12}	0.3	0.38	0.33
	ν_{13}	0.3		
	ν_{23}	0.47		
Tensile strength (MPa)	X_T	2320		
	Y_T	37.6		
	Z_T	37.6		
Compressive strength (MPa)	X_C	1400		
	Y_C	130		
Shear strength (MPa)	S_{12}	82.3	40	
	S_{13}	82.3		
	S_{23}	40		
Thickness (mm)	t	0.120		

3. FINITE ELEMENT ANALYSIS

3.1. Damage zone method

The DZM is based on the assumption that failure will occur after an appropriate number, area, or volume of elements fails in the finite element model. The following are steps to predict the failure load using the DZM [16]:

(i) Test one or more reference specimens and record the failure loads and failure modes.

(ii) Apply the tested failure load of the reference specimens to the finite element model and evaluate the critical damage zone corresponding to the tested failure load.

(iii) Use the critical damage zone calculated in the previous step to predict the failure load of other specimens.

In this study, the DZM was applied to predict the failure load of a repaired laminate with scarf bonded joints. This method is based on the assumption that the specimen fails when the damaged area/volume inside it exceeds that critical value [13, 16]. In other words, the specimen fails when Eq. (1) is met:

$$DA = CDA \tag{1}$$

in which,

$$DA = DV/L \tag{2}$$

where DA, CDA, DV, and L are damage zone, critical damage zone, and volume of the damaged elements in the model and overlap length, respectively. In this study, the maximum shear stress criterion was applied to determine the failure of the elements representing the adhesive layer. Herein, the specimen ID FM40 and its experimental failure load conducted by Nguyen [13] were chosen to be the reference specimen.

It means that we created a three-dimensional finite element model representing the behavior of the specimen ID FM40 under the tensile loading condition. The tensile load is the tested failure load of 16.5kN [13]. It is noted that the region selected to apply the damage zone method is the whole region of adhesive materials at the bonding site, which is a rectangular parallelepiped of 40-mm length, 10-mm wide, and 0.14-mm thick. The damage zone area of the FM73m adhesive specimen ID FM40 was then calculated using the maximum shear stress criterion for the adhesive. Finally, the achieved damage area was then used as a critical damage zone value to predict failure loads of all six single-lap joints noted from 1 to 6 in this study.

3.2. Finite element analysis

Figure 2 depicts the boundary conditions where only a 10-mm-wide single-lap joint was modeled to save time.

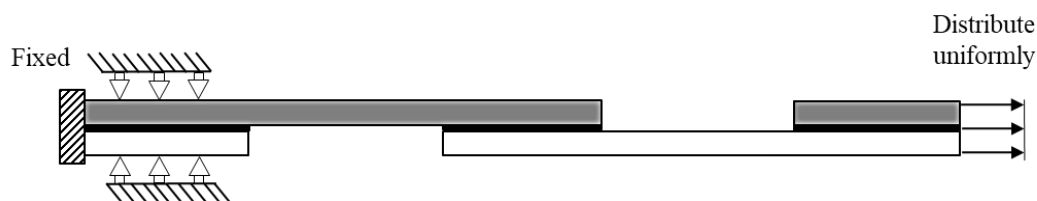


Figure 2. Boundary conditions.

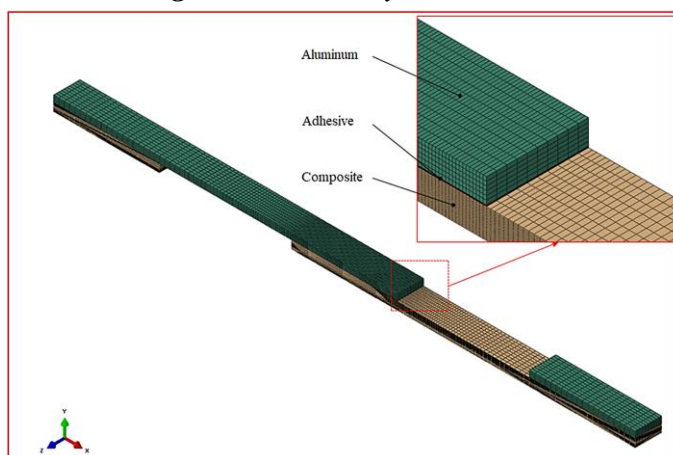


Figure 3. Finite element model.

Three-dimensional finite element models were built using the Abaqus/Standard commercial software. The hexahedral elements (C3D8I) were adopted to represent the behavior of the composite, aluminum, and adhesive materials [17] as well (Fig. 3). A convergence of simulation was conducted as in our previous study [17] to determine an appropriate element size for the FEM model. In such a way, a number of 16 and 24 elements along with the thickness direction corresponding to the 1.92-, and 2.88-mm-thick adherends, respectively, were chosen to represent the behavior of each lamina with different fiber orientations, as shown in Fig. 3. Aluminum is an isotropic material; therefore, only 4, 5, and 6 elements [17] were adopted through the aluminum adherend thicknesses to represent its behavior for the 1.6, 2.4, and 2.4 mm, respectively.

4. RESULTS AND DISCUSSION

Figure 4 presents the deformed shape of the single-lap joint under tensile loading. The maximum Vonmises stress reached a value of 1231 MPa and was located at the 0°-layer in the composite adherend, as shown in Fig. 4. This numerical result agreed well with our previous study [17].

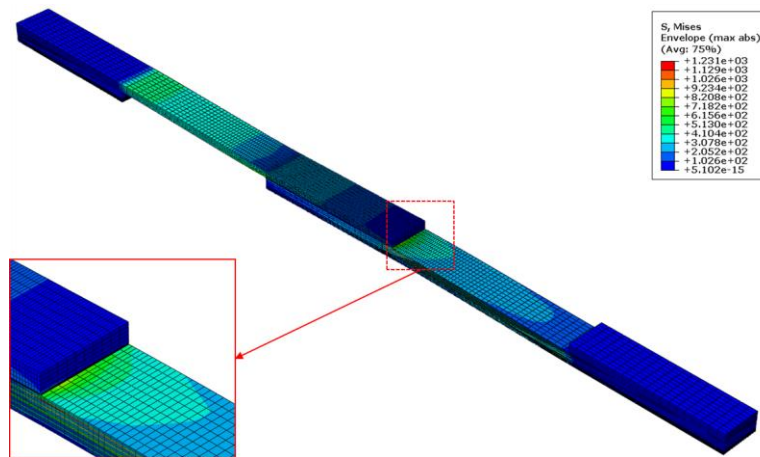


Figure 4. Deformed shape of the joint under tensile load.

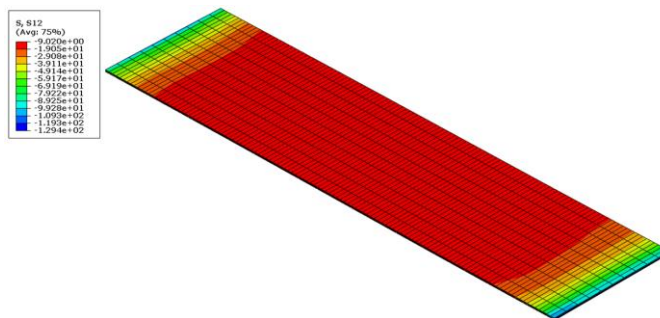


Figure 5. Distribution of shear stress in the adhesive layer.

Failure of a single-lap joint under tensile load is strongly affected by the shear strength of the adhesive layer. Figure 5 indicates the distribution of shear stress in the

adhesive layer, with the maximum stress at the two ends of the layer. The prediction of failure loads of the six joint configurations was obtained using the damage zone method with the chosen reference specimen FM 40 and its tested results in [13].

The DV and DA were calculated to be 0.3733 mm^3 and 0.0093 mm^2 , respectively. These values were then used to predict loads of all six joints. In such a way, the predicted failure loads were achieved, as listed in table 2 and described in Fig. 6. The failure loads of configurations A16C192, A20C192, and A24C192 were predicted to be 16.6, 16.5, and 16.1 kN, respectively. The result indicated that the failure loads decreased with the increase of the thicknesses of the aluminum adherend. Whereas the predicted loads of the joints A16C288, A20C288, and A24C288 were not much different, ranging between 16.1 and 16.2 kN. It allows us to conclude that this range of adherend thickness has a slight effect on the failure load, and the prediction agreed well with our previous study [13, 17].

Table 2. Predicted failure loads of the joints.

Joint ID	Adherend thickness		Damage zone size		Predicted failure load (kN)
	Aluminum (mm)	Composite (mm)	DV (mm^3)	DA (mm^2)	
REF* FM40[13]	1.58	1.68	0.3733	0.0093	16.5*
A16C192	1.6	1.92	0.3663	0.0092	16.6
A16C288	1.6	2.88	0.3675	0.0092	16.1
A20C192	2.0	1.92	0.3838	0.0096	16.5
A20C288	2.0	2.88	0.3827	0.0096	16.1
A24C192	2.4	1.92	0.3757	0.0094	16.1
A24C288	2.4	2.88	0.3733	0.0093	16.2

Note: * Reference specimen.

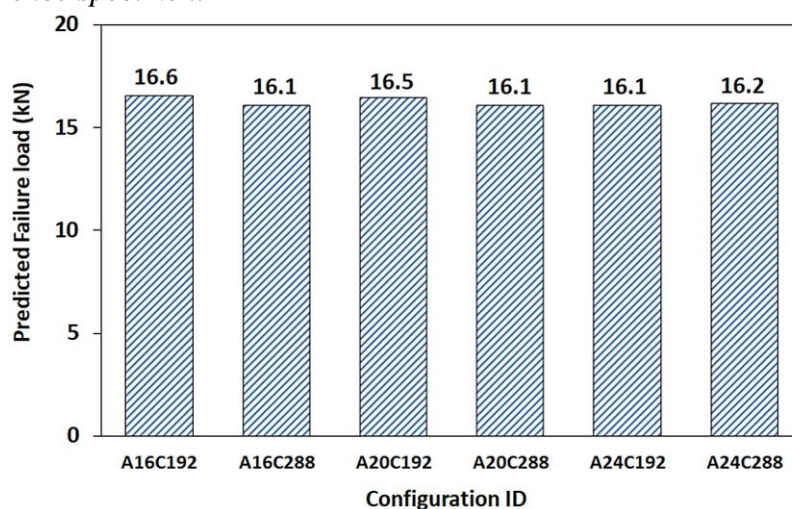


Figure 6. Prediction of failure load.

5. CONCLUSIONS

The failure of the different single-lap bonded joint configurations between aluminum and composite adherends were numerically investigated. The failure loads of the joints

were predicted using the damage zone method, in which the critical damage zone was determined based on the experimental results from the specimen ID FM40 in Nguyen's work [13]. Six three-dimensional finite element models were built, and the corresponding analyses were performed. The maximum shear stress failure criteria were applied to determine the failure of the elements in the adhesive layer. This prediction results can be used in estimating failure loads of the bonded joints such as single-lap, double-lap as well scarf joints without conducting the real test that sometimes is costly and difficult to perform.

REFERENCES

- [1]. *"An Introduction to Composite Materials"*, Cambridge University Press, Cambridge; 1981.
- [2]. Da Silva LFM, Ochsner A. *"Modeling of adhesive bonded joints"*. Berlin: Springer; 2008.
- [3]. Harris, J.A. and Adams, R.D. (1984). *"Strength Prediction of Bonded Single-lap Joints by Nonlinear Finite Element Methods"*, International Journal of Adhesion & Adhesives, 4(2): 65-78.
- [4]. Crocombe, A.D. (1989). *"Global Yielding as a Failure Criterion for Bonded Joints"*, International Journal of Adhesion & Adhesives, 9(3): 145-153.
- [5]. Mazumdar SK, Mallick PK. *"Static and fatigue behavior of adhesive joints in SMC-SMC composites"*. Polymer Compos 1998;19(2):139-46.
- [6]. Li G, Lee-Sullivan P, Thring RW. *"Nonlinear finite element analysis of stress and strain distributions across the adhesive thickness in composite single-lap joints"*. Compos Struct 1999; 46:395-403.
- [7]. Kairouz KC, Matthews FL. *"Strength and failure modes of bonded single-lap joints between cross-ply adherends"*. Composites 1993;24(6):475-84.
- [8]. Kim KS, Yoo JS, Yi YM, Kim CG. *"Failure mode and strength of uni-directional composite single-lap bonded joints with different bonding methods"*. Compos Struct 2006; 72:477-85.
- [9]. Shin, K.C. and Lee, J.J. (2000). *"Prediction of the Tensile Load-bearing Capacity of a Cured Single-lap Joint Considering Residual Thermal Stresses"*, Journal of Adhesion Science and Technology, 14(13): 1691-1704
- [10]. Owens JFP, Lee-Sullivan P. *"Stiffness behavior due to fracture in adhesively bonded composite-to-aluminum joints I. Theoretical model"*. Int J Adhes Adhes 2000; 20:39-45.
- [11]. Owens JFP, Lee-Sullivan P. *"Stiffness behavior due to fracture in adhesively bonded composite-to-aluminum joints II. Experimental"*. Int J Adhes Adhes 2000; 20:47-58.
- [12]. Seong MS, Kim TH, Nguyen KH, Kweon JH, Choi JH. *"A parametric study on the failure of bonded single-lap joints of carbon composite and aluminium"*. Compos Struct 2008; 86:135-45.
- [13]. Nguyen KH, Kweon JH, Choi JH. *"Failure load prediction by damage zone method for single lap bonded joints of carbon composite and aluminium"*. J. Compos. Mater. 2009;43: 3031-3056.
- [14]. Park YB, Song MG, Kim JJ, et al. *"Strength of carbon/epoxy composite single-lap bonded joints in various environmental conditions"*. Compos Struct. 2010; 92:2173-2180.
- [15]. Song MG, Kweon JH, Choi JH, Byun JH, Song MH. *"Effect of manufacturing methods on the shear strength of composite single-lap bonded joints"*. Compos Struct 2010; 92:2194-2202.
- [16]. Sheppard, A., Tong, L. and Kelly, D. (1998). *"A Damage Zone Model for the Failure Analysis of Adhesively Bonded Joints"*, International Journal of Adhesion & Adhesives, 18(6): 385-400.
- [17]. Truong, V. et al. *"Failure load prediction of laminates repaired with a scarf-bonded patch using the damage zone method"*. Adv Compos Mater 26(2), 115-133, 2017.

- [18].Ban CS, Lee YH, Choi JH, Kweon JH. “Strength prediction of adhesive joints using the modified damage zone theory”. *Compos Struct* 2008; 86:96–100.
- [19].Li F et al. “Deformation and failure of hybrid composite sandwich beams with a metal foam core under quasi-static load and low-velocity impact”. *Engineering Failure Analysis* 2020;118.
- [20].Dharmavarapu P et al. “Failure Analysis of Silane-Treated Kevlar-Reinforced Nano-silica-Toughened Epoxy Composite in Laminar Shear Strength, Drop Load Impact and Drilling Process”. *Journal of Failure Analysis and Prevention* 2020.

TÓM TẮT

Dự đoán lực phá hủy của mối ghép dính bám một lớp bằng phương pháp vùng phá hủy

Tải phá hủy của mối ghép dính một lớp với các vật liệu khác nhau được dự đoán bằng phương pháp vùng phá hủy. Sáu dạng mẫu ghép với các chiều dày của vật liệu khác nhau đã được xem xét. Mô hình phân tử hữu hạn ba chiều được xây dựng để mô tả đặc trưng của mối ghép dính và phương pháp vùng phá hủy được áp dụng để dự đoán tải phá hủy của các mối ghép. Kết quả dự đoán tải phá hủy của mối ghép cho thấy sự trùng khớp giữa kết quả mô phỏng số và thực nghiệm tương ứng.

Từ khoá: Mối ghép một lớp; Composite; Phương pháp vùng phá hủy; Phân tích phần tử hữu hạn; Dự đoán lực phá hủy.