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Research Article

Composite Bonded Joints' Lifetime for Aircraft under Random Fatigue Loads

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Abstract: In this present study, a lifetime prediction model of composite bonded joint in aircraft is developed based on variation of its elastic modulus under Random Fatigue Loads (RFL) of aircraft and its approach is deduced by Miner linear damage accumulated theory. Considering some assumptions, this prediction model is conservative for aircraft engineering industry. Finally, simulation approach and analysis is developed and done for verification of deduction models. As a precondition, some assumptions are defined for simulation and verification. From simulating results, we can give a conclusion that models are properly accuracy for further study and engineering application.

Keywords: Composite bonded joint, damage, elastic modulus, lifetime, random fatigue

INTRODUCTION

Composites have been widely used in different industrial fields, especially in aircraft industry, for several decades. And thousands of experts had studied the characters and engineering applications of composites by numerous papers. Moreover, joints between composites and metals or those between composites and composites have become a further-studied hot field in recent decades (Ferry *et al*., 2004; Nguyen *et al*., 2012; Banea and Silva, 2009; Stapleton *et al*., 2011; Caleb *et al*., 2007; Julia De Castro, 2005; Zhang, 2010; Roohollah, 2012; Michelle, 1998; Yu *et al*., 2012; Konstantinos, 2012; Post *et al*., 2008; Christophe *et al*., 2013; Bernasconi *et al*., 2012; Fernandez *et al*., 2013a, b; Comer *et al*., 2012; Kimiaeifar *et al*., 2013; Garcia *et al*., 2011; Colombo and Vergani, 2010; Shenoy *et al*., 2010; Mendoza-Navarro *et al*., 2013; Quaresimin and Ricotta, 2006; Yeager *et al*., 2013). In these studies there has some important type of composite joints concluded as T-joint (Ferry *et al*., 2004; Nguyen *et al*., 2012), bolt/bonded joint (Christophe *et al*., 2013), fasten hybrid joint (Comer *et al*., 2012), adhesively bonded joint (Banea and Silva, 2009; Stapleton *et al*., 2011; Caleb *et al*., 2007; Julia De Castro, 2005; Zhang, 2010; Roohollah, 2012; Michelle, 1998; Yu *et al*., 2012; Konstantinos, 2012; Bernasconi *et al*., 2012; Fernandez *et al*., 2013a, b; Kimiaeifar *et al*., 2013; Garcia *et al*., 2011; Colombo and Vergani, 2010; Shenoy *et al*., 2010; Mendoza-Navarro *et al*., 2013; Quaresimin and Ricotta, 2006; Yeager *et al*., 2013).

Furthermore, from number of papers we can give a simple phenomenological opinion that character of adhesively bonded joint is an important topic and grasps thousands of experts' eyes. For requirement of further research and development and engineering application in aircraft industry, FAA (Federal Aviation Administration) of USA has reported and renewed the newly study results of composites and composite joints from all of the world (Federal Aviation Administration, 2011, 2005, 1984, 1996 and 2009), there is a fact that AC20-107A (Advisory Circulars) shown in Ref. (Federal Aviation Administration, 2005) had been renewed by AC20-107B (Federal Aviation Administration, 2009) on 8 Sep. 2009 and AC 146-6 (Federal Aviation Administration, 1996) had been cancelled for its contents has been included in AC20-107B (Federal Aviation Administration, 2009).

Fatigue property, one of the most common mechanics properties of composite bonded joints, are so significant for aircraft structure especially for aircraft composite fuselage that analysis of aircraft composite fuselage has been separated different levels shown in Fig. 1.

In mostly papers, (joggled/splice strap/splice strap) lap joint in aircraft fuselage, shown in Fig. 2, has been simulated by single-lag joint (Mohamer Bak *et al*., 2012; Khalili *et al*., 2013; Pirondi and Nicoletto, 2013; Sahoo *et al*., 2012) or double-lag joint (Accardi and La

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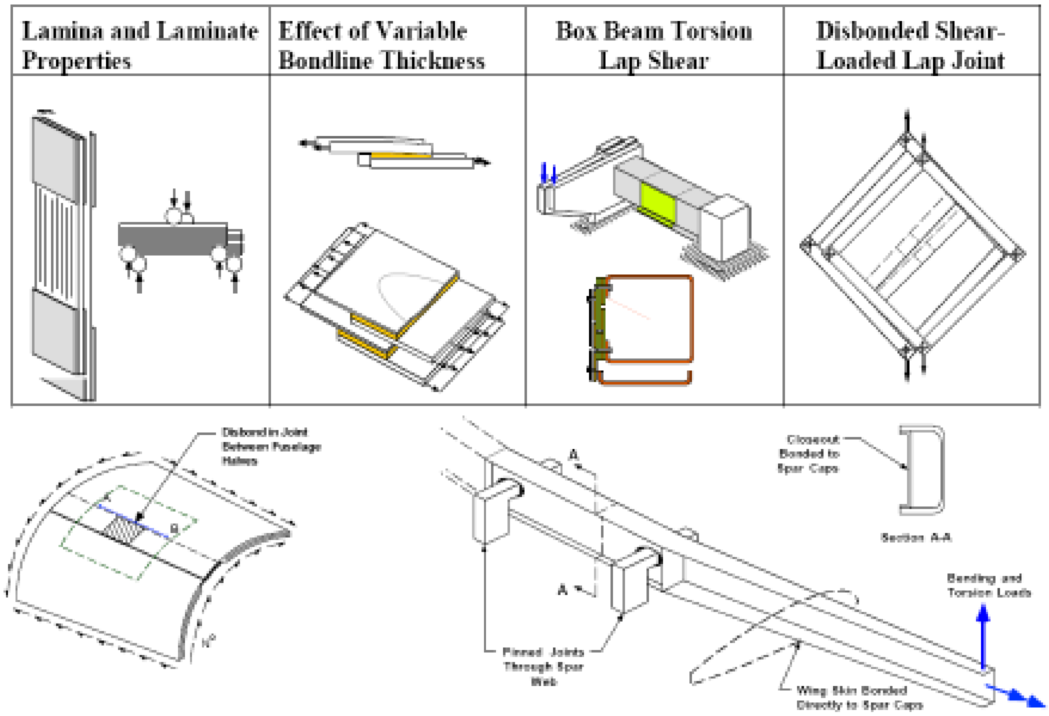

Fig. 1: Different-level tests of aircraft composite fuselage (Hoyt and Ward, 2004)

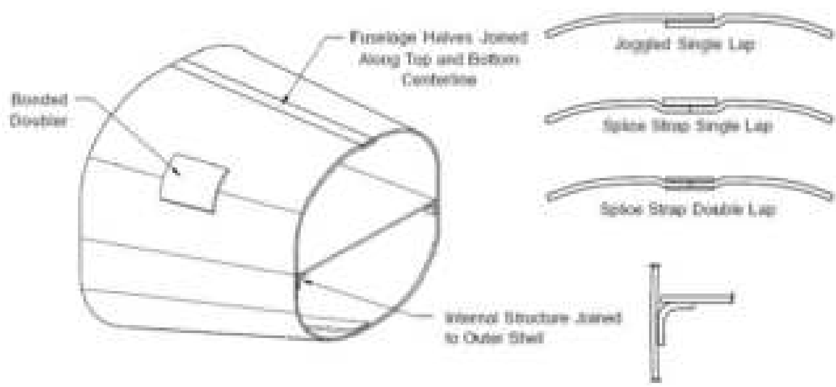

Fig. 2: Schematic diagram of bonded joint using in aircraft structural component (Mohamer Bak *et al*., 2012)

Mendola, 2013; Abdel Wahaba *et al*., 2004) or composite/tape pipe joint (Knox *et al*., 2001).

And the fatigue analysis of these simulated joints has been divided into Mode I (open) (Nguyen *et al*., 2012), Mode II (shear) (Zhang, 2010; Roohollah, 2012; Bernasconi *et al*., 2012; Fernandez *et al*., 2013a), Mode III (tearing) (Shenoy *et al*., 2010) and mixed mode (Fernandez *et al*., 2013b). And some affected factors and characters have been further studied such as geometry and material models (Ferry *et al*., 2004; Banea and Silva, 2009; Garcia *et al*., 2011; Mohamer Bak *et al*., 2012; Khalili *et al*., 2013), material strength (Christophe *et al*., 2013; Zuo *et al*., 2007; Xiaoxun *et al*., 1995), crack and fatigue (Bernasconi *et al*., 2012; Fernandez *et al*., 2013a; Sahoo *et al*., 2012; Abdel Wahaba *et al*., 2004; Knox *et al*., 2001; Hwang and Han, 1986), thermal (Comer *et al*., 2012; Boccaccini and Pearce, 1997), reliability (Kimiaeifar *et al*., 2013; Chao, 2004), Fracture (Shenoy *et al*., 2010), microstructure (Mendoza-Navarro *et al*., 2013), damage (Pirondi and Nicoletto, 2013), interface (Accardi and La Mendola, 2013), elastic modulus (Shuangming and Shengru, 2012), statistical character (Zuo *et al*., 2007; Xiaoxun *et al*., 1995) etc.

For damage of composite bonded joints, the common developing route of damage for bonded joint in fatigue interaction loads is shown in Fig. 3. And for fatigue composite bonded joints, there are so many experts for development of classical stress-fatigue cycle (S-N) curve, $SN^b = C$, the newly modified S-N model

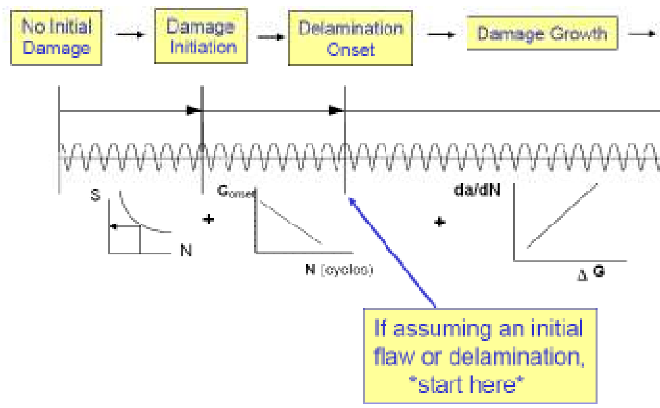

Fig. 3: Developing route of damage for FRP bonded joint in fatigue interaction loads (Pirondi and Nicoletto, 2013)

for fatigue model of bonded joints, (Roohollah, 2012), is a hybrid S-N model shown in the following Eq. (1):

$$s = CN^{D} + \left[\frac{1}{1+\left(\frac{N}{N_{trans}}\right)^{2}}\right]\left[A + B\log(N) - CN^{D}\right] \quad (1)$$

where, A, B, C, D are constant, respectively.

Random Fatigue Loads (RFL) is important in aircraft flight profile. According to aircraft flight feature, in one flight profile composite bonded joints of aircraft is under low-cycle random fatigue load and damage of it will create and develop and after several flight profiles the damage will be accumulated to fatigue destruction, which is different from damage induced by constant-amplitude fatigue loads or various-amplitude fatigue loads recorded in Bernasconi *et al.* (2012), Fernandez *et al.* (2013b), Sahoo *et al.* (2012), Abdel Wahaba *et al.* (2004), Knox *et al.* (2001) and Hwang and Han (1986). Till now, although mostly present papers have studied composite bonded joints' fatigue character; there has little paper to record character of composite bonded joints' random fatigue under RFL of aircraft.

In this present study, first, a novel fatigue lifetime model of composite bonded joints is established based on variation of elastic modulus to simulate damage induced by RFL of aircraft and then an approach/flowchart to assess damage and fatigue of composite bonded joints is developed. And finally ANSYS® 12.0, together with MATLAB®, is chosen for simulation and verification of models' deduction.

METHODOLOGY

Model and approach:

Assumptions: The fatigue model and approach in this present study are developed by some assumptions in the following:

- Law of composite is similar as that of composites, only if composite materials are same; from FAA (Federal Aviation Administration)' view, this assumption can be ok in aircraft industry.
- The margin between each aircraft profile, there is assumed no damage for composite bonded joints; which means there is no aged effect.
- For damage accumulated in *n* aircraft profiles, same as accumulated in one aircraft profile, there is no sequence effect of fatigue loads.

Variation of elastic modulus under RFL: For testing samples of fiber-reinforced glass matrix composites, its elastic modulus can be obtained by (Hwang and Han, 1986):

$$E = 0.9464\times10^{-9}\left(\frac{L}{h}\right)\frac{M}{b}f^{2}T \quad (2)$$

where, E is elastic modulus of composite sample, f stands by inherent frequency, M, L, h, b means quality, length, thickness, width of this composite sample, respectively; and T shows a constant for error. Moreover, in advance of assumption that there have no changes of quality, length, thickness, width of this composite sample after RFL, (Shuangming and Shengru, 2012) deducts an equation in the following based on Eq. (2):

$$\frac{E_n}{E_0} = \left(\frac{f_n}{f_0}\right)^{2} \quad (3)$$

where,

E_0, f_0 : Initial elastic modulus and initial inherent frequency of this composite sample

E_n, f_n : Elastic modulus and inherent frequency of this composite sample after nth random fatigue loads

So, elastic modulus of this composite sample can be calculated by inherent frequency of that by destructive/non-destructive test (Caleb *et al.*, 2007), numerical simulation or other methods.

Till now, in engineering application field, especially in aircraft industry, almost all character calculation of composite bonded joints can use the studied results of composites directly; this conclusion can be deduced in Documents of FAA. Furthermore, there have no papers to record other law for composite bonded joint. So, in this present study, variation law of composites' elastic modulus can be assumed as that of composite bonded joints.

Number of maximum stress under RFL in one aircraft profile: In one aircraft profile, composite bonded joints is under RFL, Generally, calculating curve of low-cycle fatigue model can be obtained by the relationship between maximum stress σ and cycle number n. In RFL composite bonded joints' response, maximum stress σ, will change by time t, so expectation of RFL cycle number can be defined by the number of crossing zero stress by positive slope. Then expectation of stimulant frequency can be calculated by:

$$f_s = \frac{n_c}{tP(\sigma)d\sigma} \tag{4}$$

where,

n_c : Expectation of number of maximum stress between σ and $\sigma+d\sigma$ in t time

$P(\sigma)\,d\sigma$: The probability of maximum stress between σ and $\sigma+d\sigma$

For common consideration, maximum stress in narrow-band RFL will be described by Rayleigh distribution, that is:

$$P(\sigma) = \left(\frac{\sigma}{\xi^2}\right)\exp\left(-\frac{\sigma^2}{2\xi^2}\right) \tag{5}$$

where, ξ^2 is mean square root; for RFL where $\mu = 0$ there has:

$$\xi^2 = \int_0^\infty G^2(f)df \tag{6}$$

where, G (f) is power spectral density function.

Model under constant-amplitude fatigue loads in n aircraft profile: Damage in t time, D_t, can be defined by Elastic modulus, E, shows:

$$D_t = 1 - \frac{E_t}{E_0} \tag{7}$$

where, E_t, E_0 means elastic modulus in time of t and 0, respectively.

According to Hwang and Han (1986), damage rate of composite (composite bonded joint) in constant amplitude fatigue loads can be done by:

$$\frac{dD}{dn} = A\left(\frac{\sigma^2}{D}\right)^B \tag{8}$$

where,

n = Cycle number (number of aircraft profile)
D = The damage after n^{th} cycle
σ = The maximum stress
A, B = Materials constant

After integral calculation, Eq. (8) can be shown in the following:

$$D = [A(B+1)n]^{\frac{1}{B+1}}(\sigma)^{\frac{2B}{B+1}} \tag{9}$$

It can be shown that the damage will be determined by Eq. (9) in the condition of constant amplitude fatigue loads; while, for a random fatigue loads, maximum stress σ will be various and in different cycle there have different σ whose change affect increment of damage.

So, it is defined that: D_i stands by damage induced by stress level σ_i after n_i th cycle. So there have:

$$D_i = [A(B+1)n_i]^{\frac{1}{B+1}}[\sigma_i]^{\frac{2B}{B+1}} \tag{10}$$

So, for stress level σ_i

Model under RFL in n aircraft profile: While, according to Linear Miner Accumulative Law, when cycle stress is continuous, damage in random fatigue loads can be shown by:

$$D_{total} = \sum_{i=1}^{E(n_s)} D_i \tag{11}$$

Then,

$$D_{total} = [A(B+1)]^{\frac{1}{B+1}} \sum_{i=1}^{E(n_s)} \left\{[n_i]^{\frac{1}{B+1}}(\sigma_i)^{\frac{2B}{B+1}}\right\} \tag{12}$$

where, $E(n_s)$ determined by expectation number of stress peak. And in narrowband random vibration, expectation number of crossing zero stress by positive slope can be regarded as equal to that of maximum stress (Chao, 2004):

$$E(n_c) = E(n_s) \tag{13}$$

So, Eq. (12) can be changed to:

$$D_{total} = [A(B+1)]^{\frac{1}{B+1}} \sum_{i=1}^{E(n_c)} \left\{[n_i]^{\frac{1}{B+1}}(\sigma_i)^{\frac{2B}{B+1}}\right\} \tag{14}$$

Considering Eq. (7) and (12), there has:

$$\frac{E_t}{E_0} = 1 - [A(B+1)]^{\frac{1}{B+1}} \sum_{i=1}^{E(n_c)} \left\{[n_i]^{\frac{1}{B+1}}(\sigma_i)^{\frac{2B}{B+1}}\right\} \tag{15}$$

From Eq. (15), we can obtain the relationship between elastic modulus and time (lifetime) under RFL in n aircraft profile.

Damage assessment approach: For above mathematic deduction, there should be a concluded approach for further analysis and application. The procedure of approach is:

- To find variation law of elastic modulus of composite bonded joints based on that law of composite, seen in Eq. (3). It's easy to simulation or test
- To find the number of maximum stress of composite bonded joint under RFL in one aircraft profile by stat. theory, seen in Eq. (4)
- According to constant amplitude fatigue model (Hwang and Han, 1986), to find the relationship equation between damage and lifetime under constant-amplitude fatigue loads in *n* aircraft profiles, seen in Eq. (10)
- To find the relationship equation between damage and lifetime under RFL fatigue loads in *n* aircraft profiles, seen in Eq. (15)

And all of above procedures can be calculated and achieved by computer program easily.

NUMERICAL SIMULATIONS

The model of composite bonded joints is shown in Fig. 4. And the materials prosperities are defined in Table 1. Figure of mesh model for FEA is seen in Fig. 5.

In this present study, random fatigue loads in one aircraft profile, whose accelerated PSD (Power Spectrum Density) of RFL (Meng and Hu, 2012) shown in Fig. 6, can be defined by simplifying the loads to composite bonded joints in aircraft fuselages. Also, it can be defined that the time of a typical aircraft profile is 1.5 h. Critical damage value of 3D-C/SiC composites is 0.28 (Shuangming and Shengru, 2012), so it is assumed that mean value of critical damage of all fiber reinforce matrix composite is 0.28 in this present study.

Then, after calculation following the approach of above section in this present, fatigue life of the sample in Fig. 3 is 15435 (cycle, which is also known as numbers of aircraft profiles). So, it can be shown as 23152.5 h according to 1.5 h per aircraft profile. This means that, as for a certain airline, one aircraft containing this composite bonded joint sample can flight 15 years providing this aircraft flight 2 times/day. It can be shown obviously that this result is available and can be accepted by airlines.

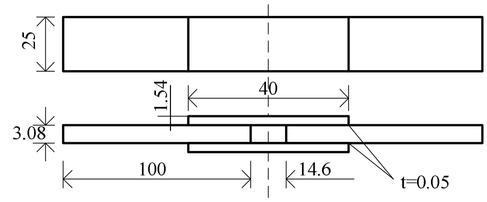

Fig. 4: Dimensions of the double lap joint

Fig. 5: Mesh model for FEA

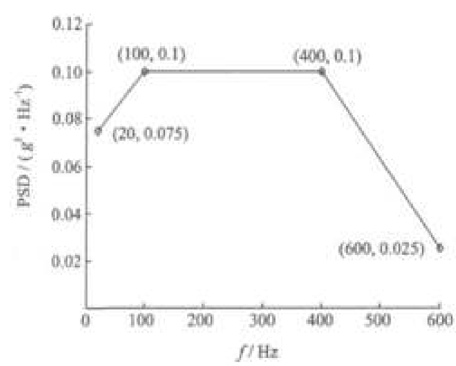

Fig. 6: Accelerated PSD of loads (Meng and Hu, 2012)

Table 1: Materials prosperities

Materials	Elastic modulus (Gpa) Mean value	Elastic modulus (Gpa) Variance	Poisson's ratio
Composite	6.5*	0.06**	0.2*
Adhesive	1.1*	0.01**	0.3*

*: Data comes from Abdel Wahaba *et al.* (2004); **: Data is defined in this present study

CONCLUSION

For composite bonded joints, although there has many paper to study its constant/various amplitude fatigue character, there has little deduce to consider the random fatigue of aircraft. Here is a deduction of fatigue model for composite bonded joints under aircraft random fatigue loads. From the deduction and simulation above, the fatigue models of composite bonded joints under RFL is available and simulation results can be accepted in engineering application. Also, this model can be used in another way for inspecting reliability of composite bonded joint by the way of inspecting elastic modulus of composite bonded joint.

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