Fatigue strength of FRP/metal adhesive joints under low temperature

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Abstract

In this paper we developed the fatigue strength and fatigue life evaluation methods of FRP/Metal adhesive joints under low temperatures. Firstly we present fatigue strength and delamination propagation rate evaluation methods using two stress singularity parameters H and λ which express stress distributions at bonding edge or delamination edges as follows.

$$\tau(r) = H/r^{\lambda}$$

Here $\tau(r)$ is stress (MPa), r is the distance (mm) from the singular point (bonding edge or delamination edge), H is the intensity of stress singularity, and λ is the order of stress singularity. Then the delamination propagation rates of the double lap joints under mechanical cyclic loadings at room temperature were measured. Using the relationship between the measured delamination propagation rates and the analyzed range of stress singularity intensity values we estimated the fatigue strength of embedded adhesive joints. We can confirm that these estimated results coincided well with the experimental results. Then we performed fatigue tests under LN_2 temperatures, and we present thermal effect evaluation methods of fatigue strength and delamination propagation rate by separating the residual stress effect and pure temperature effect independently.

Keywords: adhesive joints, FRP, fatigue strength, stress singularity parameters, thermal stress, delamination propagation rate.

1 Introduction

Fiber reinforced plastics (FRP) have high strength, high rigidity and excellent thermal isolation characteristics so they are used for cryogenic structures such as superconducting magnets. In these cases the FRP structures are ordinary adhesively jointed with metal structures. In these FRP/Metal adhesive joints high

WIT Transactions on The Built Environment, Vol 97, © 2008 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/HPSM080281

thermal residual stresses occur under cryogenic temperatures because of the mismatch of thermal expansion coefficients of the FRP and metal. So, improvement of strength evaluation method of these adhesive joints under low temperature become indispensable to develop high-reliability superconducting magnet systems.

In this paper we developed the fatigue strength and fatigue life evaluation methods of FRP/Metal adhesive joints under low temperatures. The most difficult problem in the strength evaluation methods for adhesively bonded structures is that the stress and displacement fields near the bonding edge, where delamination begins, show singular behaviour [1–7]. In previous papers we presented a new adhesive strength evaluation method using two stress singularity parameters which express stress fields near a bonding edge [5–7]. In this paper we applied these methods to the estimation of delamination propagation behavior. Firstly the delamination propagation rates of the double lap joints under mechanical cyclic loadings at room temperature were measured. Using the relationship between the measured delamination propagation rates and the analyzed range of stress singularity intensity values we estimated the fatigue strength of embedded adhesive joints. And we can confirm that these estimated results coincided well with the experimental results. And then we performed fatigue test under LN_2 temperatures, and present thermal effects evaluation methods of fatigue strength and delamination propagation rate by separating the residual stress effect and pure temperature effect independently.

2 Stress and stress singularity analysis

2.1 Stress singularity parameters

The stress fields near the bonding edges show singular behavior as shown in Fig. 1. In these regions, the maximum stresses calculated by numerical stress analysis, such as the finite element method, depend on the size of the element meshes. Therefore, overall strength evaluation cannot be made using only these calculated maximum stress values.

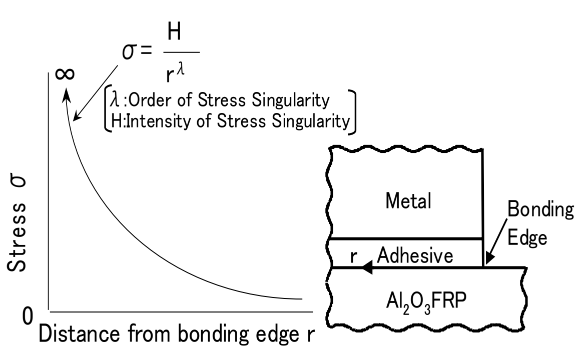

Figure 1: The stress fields near the bonding edge.

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Consequently, a new adhesive strength evaluation method using two stress singularity parameters H and λ has been presented [5–7], which can express stress distribution near a bonding edge as follows [1–7]:

$$\tau(r) = H/r^{\lambda} \tag{1}$$

$\tau(r)$: stress (MPa)
r: distance (mm) from the singular point (bonding edge or delamination edge)
H: intensity of stress singularity
λ: order of stress singularity

2.2 Analytical approach

Figure 2 shows the adhesive joint models used in this study and Fig. 3 shows a quarter-cut FEM model for analyzing stress singularity parameters. The adhesive used was 50µm thick epoxy resin. To evaluate the delamination behavior, delamination elements with various delamination lengths (1mm, 5mm, 10mm, 15mm, 20mm) are used in this model. And mechanical properties of each material are shown in Table 1. Mechanical load is applied to the Al_2O_3FRP on the axial direction, and thermal load is applied to cool this model from room temperature (293K) to LN_2 temperature (77K). Analytical results of stress distributions on adhering interfaces between the Al_2O_3FRP and the adhesive under mechanical loading are shown in Fig. 4. From these results we can see that the stress levels on corner section (B) are higher than those on center section (A). The dependence of the intensity of stress singularity H at (B) section calculated by those procedure on delamination length a is shown in Fig. 5. From these results we can see that the intensity of stress singularity of double lap joints increase continuously in accordance with the increase of delamination length, whereas the intensity of stress singularity of embedded joints decrease slowly and converged to a certain value.

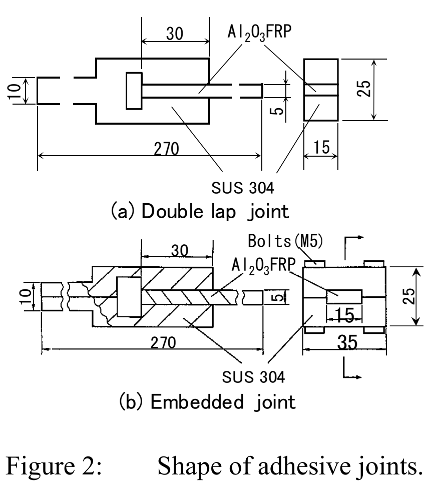

Figure 2: Shape of adhesive joints.

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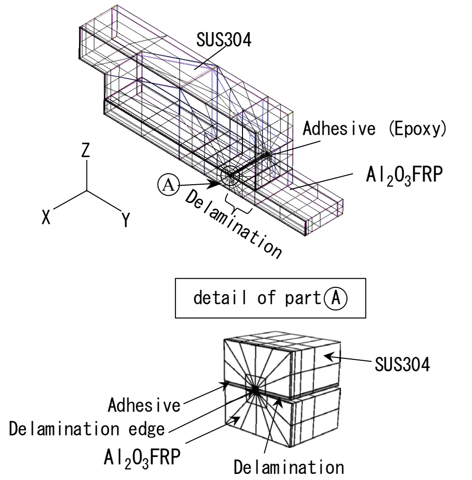

Figure 3: Finite element mesh of double lap joint model (delamination length 5mm).

Table 1: Mechanical properties of materials.

Al_2O_3FRP			
Young's modulus (MPa)	Poisson's ratio	Shearing modulus (MPa)	Thermal expansion coefficient (1/℃)
Ex=33000	ν yx=0.16	Gyx=17000	α x=24×10^{-6}
Ey=67000	ν yz=0.13	Gyz=16000	α y=5×10^{-6}
Ez=30000	ν xz=0.29	Gxz=12000	α z=39×10^{-6}
Steinless Steel			
Young's modulus (MPa)	Poisson's ratio	Shearing modulus (MPa)	Thermal expansion coefficient (1/℃)
210000	0.3	81000	12×10^{-6}
Adhesive			
Young's modulus (MPa)	Poisson's ratio	Shearing modulus (MPa)	Thermal expansion coefficient (1/℃)
7600	0.3	2900	29×10^{-6}

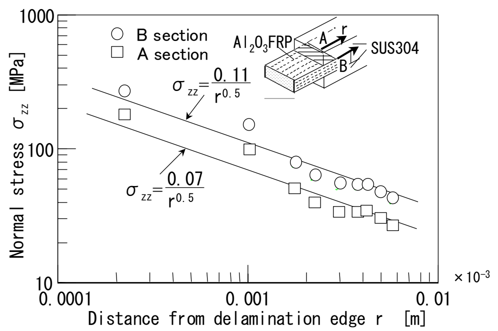

Figure 4: Stress distributions near delamination edge of double lap joint under mechanical loading (delamination 5mm).

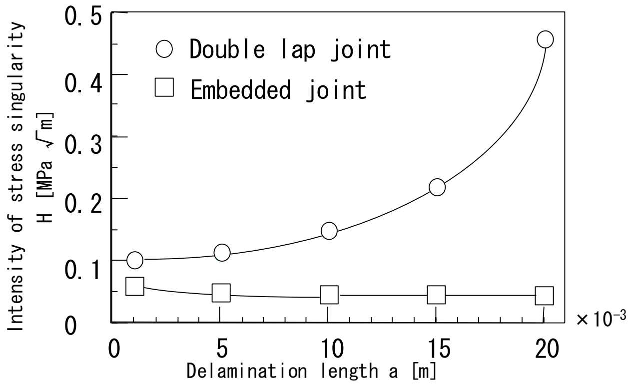

Figure 5: Relation between intensity of stress singularity and delamination length (τn = 2.9MPa).

Then the analytical results of stress distributions near delamination edge under thermal loading are shown in Fig. 6 and 7 for double lap joint and embedded joint respectively. From these results we can see that the thermal normal stress of embedded joint is about 2.6 times higher as double lap joint.

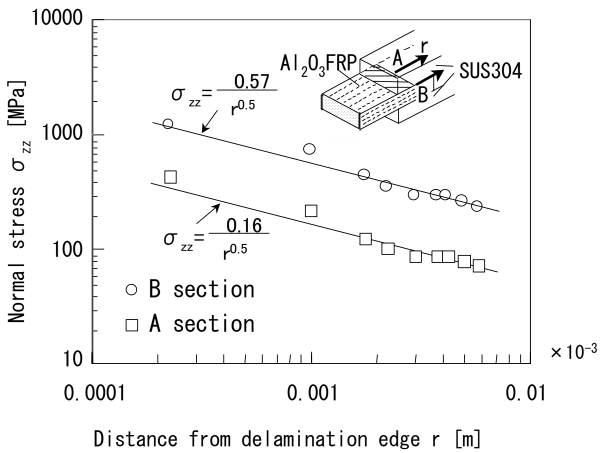

Figure 6: Stress distributions near delamination near delamination edge of double lap joint under thermal loading (delamination 5mm).

3 Fatigue tests

3.1 Fatigue test methods

Double lap or embedded adhesive joint specimens were made by bonding Al_2O_3FRPand SUS304 after brushing and removing grease of both surfaces. And these bonded specimens were after-cured by keeping these specimens at 340K for 2 hours in furnace. The fatigue tests are performed using electric-hydraulic fatigue test machine under room and LN_2 temperature. The cyclic loading speed was 5Hz.

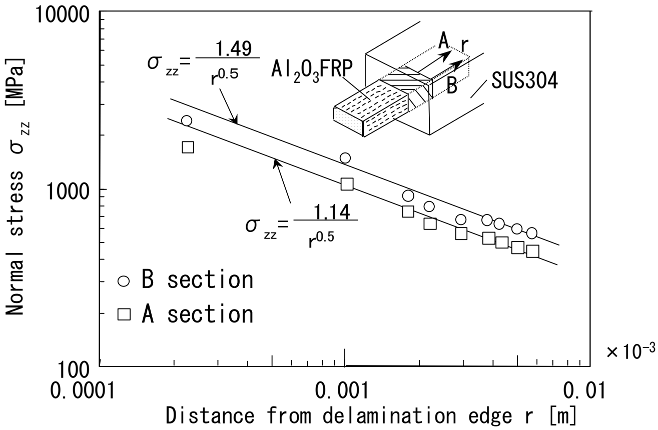

Figure 7: Stress distributions near delamination edge of embedded joint under thermal loading (delamination 5mm).

3.2 Fatigue test results

Fatigue test results of two types of adhesive joints are shown in Fig. 8. In this figure the shear stress amplitude τa was calculated by dividing load amplitude by whole adhering area. From these results we can see that the fatigue strength of embedded joints are higher than that of double lap joints. And by using the measured results of delamination behavior of double lap joints the relation between delamination propagation rate da/dN and range of stress singularity intensity ΔH can be obtained as Fig. 9. From this we can see that the threshold range of stress singularity intensityΔHth is 0.11MPa√m, and delamination toughness H_C is 0.26 MPa√m. And the delamination propagation rate can be expressed as follows:

$$= 0.36(\Delta H)^{8.5} \qquad (2)$$

We can estimate the adhesive fatigue limit of embedded joint using threshold range of stress singularity intensity ΔH_{th} and intensity of stress singularity of embedded joint shown in Fig. 7. And this estimated fatigue limit of embedded joint τ_W = 3.5MPa coincided well with the experimental fatigue limit of embedded joint τ_W = 3.7MPa as shown in Fig. 8.

Both fatigue strength of embedded joint at room temperature and at LN_2 temperature are almost same as shown in Fig. 9. On the other hand fatigue strength of double lap joint at LN_2 temperature is higher than that at room temperature. We consider these complex thermal effects by separating the residual stress effect and pure temperature effect independently as shown in Fig. 10. In this figure we can see that the thermal residual load acting on the embedded joint at LN2 temperature become 13 times higher compare with that corresponding to the ΔH_{th}, on the other hand the thermal residual load acting on the double lap joint at LN2 temperature become 4 times higher compare with that corresponding to the ΔH_{th}. From these results we can separate the following two thermal effects, thermal residual stress effect and temperature dependence of adhesive strength, as shown Fig. 11. From this we can see that the fatigue strength of embedded joint at LN_2 temperature become almost same with that of room temperature as a results of the coupling of improvement of pure adhesive strength by the degradation of temperature and the reduction of joint strength by the increase of thermal residual stress at LN_2 temperature.

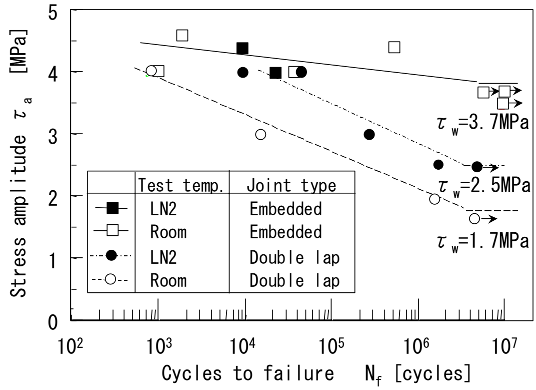

Figure 8: Fatigue test results of adhesive joints (R = 0).

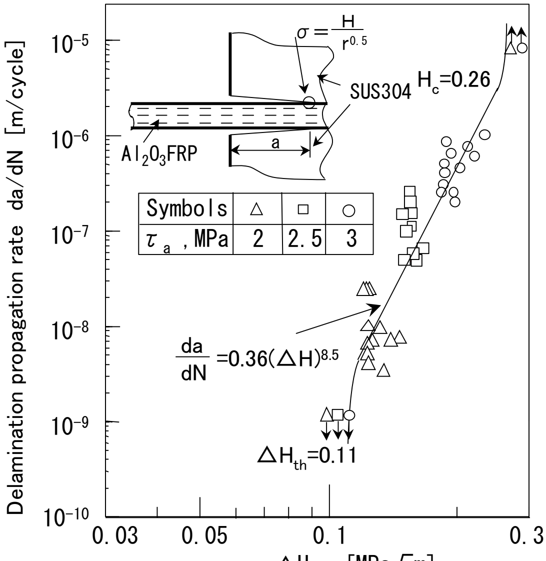

Figure 9: Relation between delamination propagation rate and range of stress singularity (R = 0, at RT).

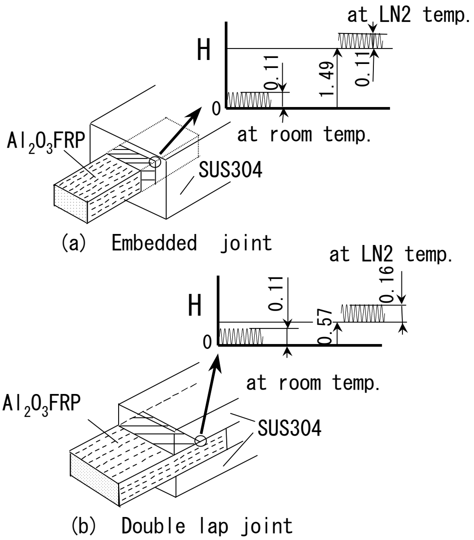

Figure 10: Thermal effect evaluation using stress singularity parameters.

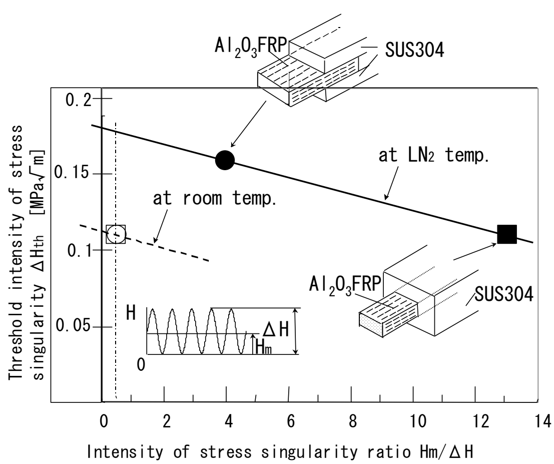

Figure 11: Thermal effect of adhesive fatigue strength.

4 Conclusions

(1) The delamination propagation behavior can be expressed by using two stress singularity parameters H and λ. Using these parameters we can estimate the fatigue limit of embedded joints, and confirm that these estimated results coincided well with the experimental results.

(2) We present low temperature fatigue strength and delamination propagation rate estimation methods by separating the residual stress effect and pure temperature effect independently.

Acknowledgement

This work is supported in part by a grant from the Research & Development Institute of Metals and Composites for Future Industries (RIMCOF), Japan, on the basis of Application of Advanced Composites for Transportation Systems proposed by the Ministry of Economy, Trade and Industry (METI) of Japan.

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