OFF-AXIS NOTCHED FATIGUE BEHAVIOR OF FIBER METAL LAMINATE GLARE-3

M. Kawai*, T. Sato

Department of Engineering Mechanics and Energy, University of Tsukuba, Tsukuba 305-8573, Japan
**mkawai@kz.tsukuba.ac.jp*

Keywords: fiber metal laminate; off-axis fatigue; notched strength; fiber orientation dependence; fatigue strength model

Abstract
The effects of notch size and fiber orientation on the off-axis fatigue strength of the notched fiber metal laminate GLARE-3 are examined. Off-axis fatigue tests are performed on notched (center open hole) specimens with different fiber orientations. It is clearly observed that the fatigue strength of notched GLARE-3 specimens exhibits not only notch size dependence but also fiber orientation dependence. A new criterion for the fatigue failure of notched orthotropic materials is developed which allows predicting their fatigue lives for any notch size and for any multiaxial state of stress. A major advantage of the proposed method is to allow efficient prediction of the S-N curves of notched GLARE-3 laminates using only a limited amount of test data: the S-N curves for unnotched specimens and the notch sensitivity of GLARE-3. It is demonstrated that the off-axis S-N relationship for notched GLARE-3 laminates can accurately be predicted by means of the proposed fatigue failure criterion, regardless of the notch size and fiber orientation.

1 Introduction
Fiber Metal Laminates (FMLs) which consist of alternating layers of unidirectional fiber reinforced plastic (UD FRP) laminae and thin metal sheets have potential advantages over monolithic metal alloys not only in weight saving in the design of structural components but also in its damage tolerance [1]. Within the FML family, GLARE composed of UD GFRP laminae and thin sheets of aluminum alloy has proved to be superior to monolithic aluminum alloys, especially in resistance to the growth of cracks in the aluminum alloy layers under tensile fatigue loading conditions owing to the fiber-bridging effect from the GFRP layers [2]. The fatigue crack propagation in the aluminum alloy layers was found to be 10-100 times slower than in the monolithic aluminum alloy [1]. It has also been confirmed that GLARE exhibits higher impact resistance as well as excellent fatigue resistance [1]. The mechanical properties of a unidirectional GLARE-2 laminate in the fiber direction contribute to weight saving over the aluminum alloy by 6% in the design based on bending stiffness and by 17% in the design based on yield strength. Because of its optimized performance, GLARE has now been applied to the fuselage skin structures of commercial aircrafts.
Structural components in aircraft and general transportation applications often contain different kinds of stress risers, such as holes at riveted and bolted joints, grooves and corners. This suggests that the materials applied to those structural members should be shown to exhibit excellent fatigue resistance and damage tolerance in notched configurations as well.

Therefore, more extensive application of GLARE not only to aircraft structures but also to components for general transportation requires more detailed understanding of the fatigue resistance and damage tolerance of notched GLARE laminates for different configurations of GFRP and Al alloy layers and for different orientations of GFRP layers.

For efficiently designing the structural components made of GLARE which contain blunt notches on the basis of a limited number of tests, furthermore, it is an essential prerequisite to develop and establish an engineering method for accurately and efficiently predicting the notched strength of GLARE for any notch size and fiber orientation. Recently, Kawai and Arai [3] have conducted experimental and theoretical studies of the effects of notch size and fiber orientation on the off-axis notched static strength of GLARE-3. They examined the off-axis notch sensitivity in GLARE-3 for different fiber orientations, and showed that off-axis notch sensitivity moderately depends on fiber orientation and it is higher than the notch sensitivity of a monolithic aluminum alloy. They also established an engineering method for accurately and efficiently predicting the anisotropic size effect in GLARE-3. On the fatigue resistance of notched GLARE laminate for different fiber orientations that is of the utmost importance in the practical design of various shapes of structural member, however, little information has been available. The fatigue resistance of GLARE in notched configuration for different fiber orientations, therefore, has not been understood, and a method for efficiently predicting the S-N curves for notched GLARE laminates for different fatigue loading conditions has not been established yet.

The present study aims to examine the effects of notch size and fiber orientation on the off-axis fatigue strength of the notched fiber metal laminate GLARE-3. Off-axis fatigue tests are first performed on notched (center open hole) specimens with different fiber orientations. A new criterion for fatigue failure of notched orthotropic materials is then developed which allows prediction of their fatigue lives for any notch size and for any multiaxial state of stress. It is formulated on the basis of the fatigue damage mechanics model for unnotched orthotropic materials [4] and the anisotropic notched strength model for orthotropic materials [3]. Finally, the accuracy of prediction using the proposed notched fatigue model is evaluated by comparing with experimental results in regard to the off-axis S-N relationships for notched GLARE-3 laminates with different fiber orientations.

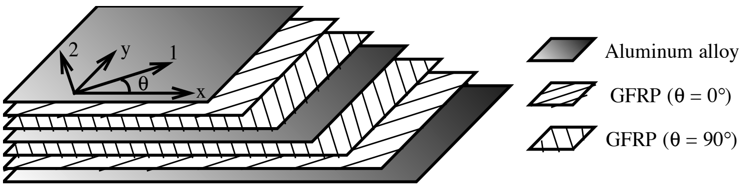


Figure 1. Schematic illustration of GLARE-3 laminate

2 Experimental procedure

2.1 Material and specimens

The material used in this study was GLARE-3, a symmetric fiber-metal laminate that consists of three layers of high strength aluminum alloy (2024-T3) and four layers of GFRP (Vetrotex R-glass/Fibredux 925); the same number of GFRP layers are oriented in two orthogonal directions, and this hybrid system is denoted by a simplified code [0/90]. The GLARE-3 laminate was manufactured using the autoclave method, and its lay-up is schematically illustrated in Fig. 1.

Four kinds of specimens with different fiber orientations (θ = 0, 5, 15, 30 and 45°) were cut from a large GLARE-3 panel. The off-axis angle θ is defined as an angle at which the fiber axis of the GFRP layers just below the surfaces of the specimen inclines, as indicated in the illustration of specimens. The off-axis GLARE-3 specimen is hereafter distinguished by

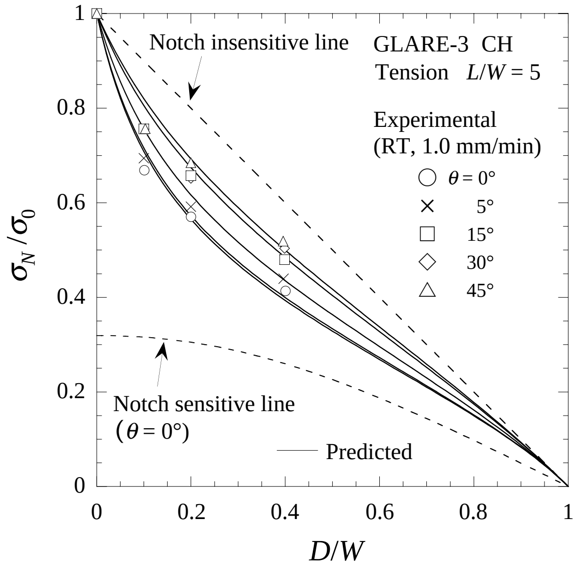


Figure 2. Hole size effect on the off-axis strength of GLARE-3 laminate

the off-axis angle θ or the simplified code with angle $[0/90]_\theta$. The geometry and dimensions of GLARE-3 specimens were determined on the basis of the testing standard JIS K7073 [5]; the dimensions were length L = 200 mm, gauge length L_G = 100 mm, width W = 20 mm and thickness t = 1.44 mm. Rectangular-shaped tabs made of aluminum alloy were glued on both ends of the specimens with epoxy adhesive (Araldite) to protect the gripped portions of the specimens; the thickness of the tabs was 1.0 mm.

A circular open hole was machined in the center of specimens with carbide end mill. Three different values (D = 2, 4 and 8 mm) of circular hole diameter, which correspond to the hole-diameter to specimen-width ratios of D/W = 0.1, 0.2 and 0.4 (nominal values) respectively, were considered for each of the four fiber orientations θ = 0, 15, 30 and 45°. Only the specimens with no significant visible damage detected on the surfaces of holes were tested.

2.2 Testing procedure

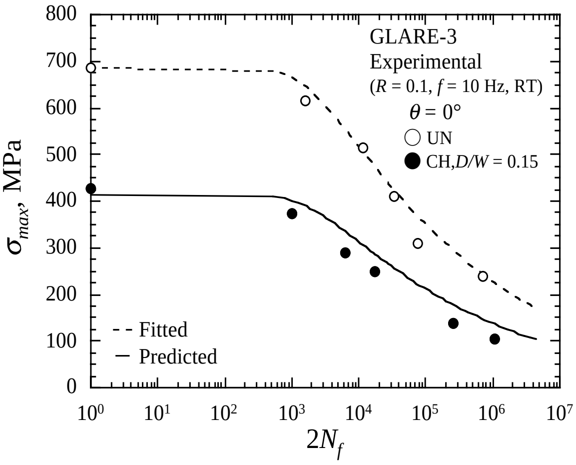
Tension-tension fatigue tests were performed at room temperature. Fatigue load was applied in a sinusoidal waveform with a frequency of 10 Hz. The stress ratio of fatigue loading was kept at a constant value R = 0.1. Most specimens were fatigue tested for up to 10^6 cycles. The tensile fatigue tests in this study were carried out using a servo hydraulic testing machine. The specimens were clamped by the hydraulic wedge grips fitted on the testing machine.

To evaluate the stress levels for fatigue testing, the off-axis static tensile strengths for notched specimens at room temperature are required. They have already been obtained from the off-axis static tension tests for unnotched and notched coupon specimens of the same GLARE-3 in the previous study [3]. Some static tension tests were additionally performed in this study to confirm the results.

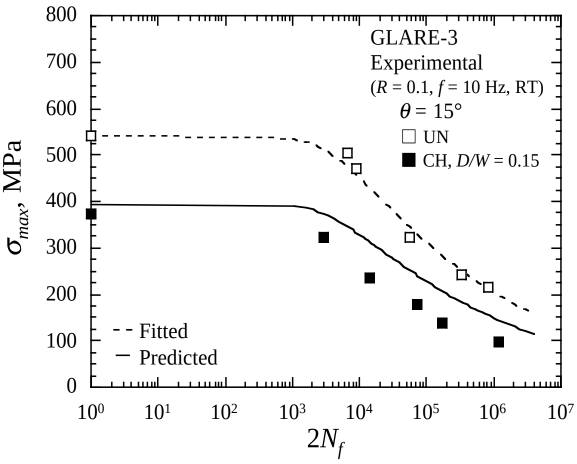
3 Experimental results and discussion

3.1 Off-axis notch sensitivity

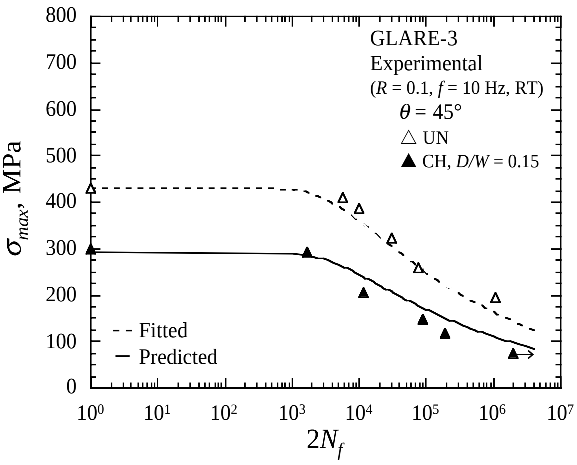
Figure 2 shows comparison between the notch sensitivity data on GLARE-3 for all fiber orientations. The normalized notched strength data are distributed in a narrow range. Nevertheless, we can clearly observe the fiber orientation dependence of the off-axis notch sensitivity of GLARE-3. The notch sensitivity of GLARE-3 is highest in the fiber direction (θ = 0°), while it is lowest in the bias direction (θ = 45°). But the latter is still higher than that of the monolithic aluminum alloy. Overall, the off-axis notch sensitivity data are distributed in order of fiber orientation angle; the data for larger off-axis angle are closer to the notch insensitive limit. These facts suggest that the notch sensitivity in the constituent GFRP layers is responsible for the notch sensitivity in GLARE-3. The lowest notch sensitivity of GLARE-3 in the 45° direction is consistent with its highest elongation (ductility) in that direction.



(a) $\theta = 0°$



(b) $\theta = 15°$



(c) $\theta = 45°$

Figure 3. Off-axis S-N relationships for unnotched and notched specimens

The solid lines in Fig. 2 indicate the predictions using the proposed notched failure criterion [3]. From these comparisons, it is seen that the notch size and fiber orientation dependence of the off-axis notched strength of GLARE-3 are accurately predicted using the proposed failure criterion for notched orthotropic fiber composites.

3.2 Off-axis notched fatigue strength

The S-N data on unnotched GLARE-3 specimens are shown in Figs. 3 (a), (b) and (c) by open symbols as plots of $\sigma_{\max}$ against $\log N_f$ for the representative fiber orientations θ = 0, 15 and 45°, respectively. The open symbols on the vertical axis indicate the tensile strengths for respective fiber orientations. The tensile fatigue strength becomes smaller as the off-axis angle increases. The S-N relationship is almost linear in the fatigue life range $10^2 < N_f < 10^6$, regardless of fiber orientation. The slope of the S-N relationship in this range becomes steeper for smaller off-axis angle. In either shorter or longer fatigue life ranges, i.e., $N_f < 10^2$ or $N_f > 10^6$, the slope of the S-N relationship is much slighter compared with that in the intermediate range. These features clearly exhibit the static strength dependence of the S-N relationship and the tendency of appearance of a fatigue endurance limit.

The solid symbols in these figures indicate the S-N data for notched GLARE-3 specimens. The off-axis static strength of GLARE-3 is reduced by notch. Accordingly, the S-N data on notched specimens are distributed below the data on unnotched specimens, regardless of fiber orientation. Nevertheless, we can see that the shape and fiber orientation dependence of the off-axis S-N relationship for notched GLARE-3 specimens is similar to that for unnotched specimens over the range of fatigue life considered in this study. These features observed in the off-axis S-N relationship for GLARE-3 suggest that it could be predicted if the notch size dependence of the off-axis static strength and the off-axis S-N curve for unnotched specimens can be predicted.

4 A fatigue life prediction method for notched GLARE

A fatigue model for off-axis notched GLARE-3 is formulated by modifying the fatigue model developed for unnotched orthotropic composites [4]. The base fatigue model that allows predicting the S-N relationship for unnotched materials is first reviewed. Then, it is extended to a model for notched materials by taking into account the notch sensitivity in the fatigue strength parameter involved.

4.1 A fatigue model for unnotched GLARE

It is assumed that a state of the fatigue damage in GLARE-3 can be described by a single scalar variable ω, and its growth rate is prescribed by the following equation:

$$\frac{d\omega}{dN} = K\Phi^n \left(\frac{1}{1-\omega} \right)^k \frac{1}{\left(1-\Phi\right)^a} \tag{1}$$

where Φ is a fatigue strength parameter. The coefficients K, k, n, and a are material constants. Imposing the initial condition that $\omega = 0$ when $N = 0$, and the ultimate fatigue failure condition that $\omega = 1$ when $N = N_f$, Eq. (1) can be integrated to obtain the analytic expression of fatigue life:

$$2N_f = \frac{2}{(1+k)K\Phi^n}\left(1-\Phi\right)^a \tag{2}$$

The master S-N relationship for unnotched that is independent of fiber orientation can be described by Eq. (2) in conjunction with the fatigue strength parameter that is identified with the fatigue strength ratio:

$$\Phi = \frac{\sigma_{\max}}{\sigma_0} \tag{3}$$

where σ_0 stands for the ultimate tensile strength of the material.
The material constants involved by the master S-N relation given by Eq. (2) can be identified by fitting Eq. (2) to the plots of the normalized maximum fatigue stress ($\Phi = \sigma_{\max} / \sigma_0$) against the number of cycles to failure (N_f) on logarithmic scales. The S-N curve predictions using the fatigue model described above are indicated by dashed lines in Figs. 3 (a), (b) and (c) for different fiber orientations, respectively, showing good agreements with the experimental S-N data.

4.2 A fatigue model for notched GLARE

The fatigue model develop for unnotched materials is extended to allow predicting the S-N curves for notched materials. For this purpose, we introduce the notched fatigue strength parameter defined as

$$\Phi_N = \frac{\sigma_{\max}}{\sigma_N} \tag{4}$$

where Φ_N stands for the notched fatigue strength ratio for a given material, and σ_N is the theoretical notched strength of the material that is predicted using the anisotropic notch size effect law developed in an earlier study [3]. As a result, the modified fatigue life equation proposed in this study can be expressed as

$$2N_f = \frac{2}{(1+k)K{\Phi_N}^n}\left(1-\Phi_N\right)^a \tag{5}$$

It is assumed that the same material constants involved by Eq. (2) for unnotched materials can be used for the modified fatigue life equation for notched materials. Note that the modified fatigue equation given by Eq. (5) allows us to predict the off-axis S-N curves for notched materials using only the notched static strength of the material and the S-N relationships for unnotched specimens. The off-axis S-N curves for notched specimens that were predicted by the proposed method are shown in solid lines in Figs. 3 (a), (b) and (c). It is seen that good correlations have been obtained. More accurate predictions can be obtained by further considering a notch induced fatigue damage effect in the fatigue model.

5 Conclusions

The effects of notch size and fiber orientation on the off-axis fatigue strength of the notched fiber metal laminate GLARE-3 are examined. It was clearly observed that the fatigue strength of notched GLARE-3 exhibits not only notch size dependence but also fiber orientation dependence. A new criterion for the fatigue failure of notched orthotropic materials was developed that allows prediction of their fatigue lives for any notch size and for any multiaxial state of stress. The proposed fatigue failure criterion is an extension of the fatigue damage mechanics model that was earlier developed for unnotched orthotropic materials. It was demonstrated that the off-axis S-N relationship for notched GLARE-3 can favorably be predicted by the proposed fatigue model, regardless of notch size and fiber orientation.

References

[1] Vogelesang L.B., Vlot A. Development of fibre metal laminates for advanced aerospace structures. *Journal of Materials Processing Technology*, **103**, pp. 1-5 (2000).

[2] Sinke J. Development of fibre metal laminates: concurrent multi-scale modeling and testing. *Journal of Materials Science*, **41**, pp. 6777-6788 (2006).

[3] Kawai M., Arai Y. Off-axis notched strength of fiber metal laminates and a formula for predicting anisotropic size effect. *Composites Part A*, **40**, pp. 1900-1910 (2009).

[4] Kawai M., Hachinohe A., Takumida K., Kawase Y. Off-axis fatigue behaviour and its damage mechanics modeling for fibre-metal hybrid composite GLARE 2. *Composites Part A*, **32**, pp. 13-23 (2001).

[5] JIS K7073. *Testing method for tensile properties of carbon fiber-reinforced plastics*. Japanese Industrial Standard, Japanese Standards Association, (1988).