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Fatigue behavior and life prediction of self-piercing riveted joint

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ABSTRACT

The fatigue behavior of self-piercing riveted joints of aluminum alloy AA6111-T4 and steel HSLA340 sheets has been experimentally and numerically investigated in present paper. Fatigue results reveal that the mating sheet stiffness and load ratio have significant impact on the fatigue strength, and the dominant failure mode under tensile–shear loading is eyebrow crack with an approximately semi-elliptical crack front. New stress intensity factor equations are derived for a semi-elliptical surface crack in a finite plate near a rigid cylindrical inclusion with axial shear force and bending moment, including the ratio of crack depth to crack length ranged from 0.2 to 1 and the ratio of crack depth to sheet thickness ranged from 0.2 to 0.8. A new structural load fatigue crack growth model is proposed, and predictions of fatigue lives and final crack aspect ratios show good agreement with experimental results.

1. Introduction

As an alternative of traditional resistance spot welding (RSW), self-piercing riveted (SPR) joint has been widely used in automotive industry for vehicle body manufacture. SPR is a direction dependent mechanical joining technique, by driving a rivet through one or more layers of upper sheets, forms a mechanical interlock without piercing through the lower sheet. It has good static and fatigue strength and can be used to join dissimilar materials such aluminum, steel, magnesium, and composite [1–3].

SPR is widely used in modern light weight vehicle manufacturing and an a typical vehicle body consists of several thousands of SPR joints. Since joint fatigue is the one of the main concerns in body durability, durability analysis of the joints is of great interest in vehicle design. Extensive researches have been performed on SPR, primarily on the riveting simulation [4–10], static strength [1,3,11] and fatigue performance [2,11–16]. Generally, sheet thickness [17], sheet material property [2,13], specimen size [13], joint distribution pattern [12,14], riveting parameters [15] were found as important factors influencing the static and fatigue strength of SPR. Fatigue failure of SPR might occur in the upper or lower sheet, or the rivet itself [18]. Usually, sheet cracks were found to initiate at the faying surface [17], adjacent to the rivet hole where fretting damage was often observed [18,19], which was very similar to the traditional riveted joint [20–22].

Secondary bending, caused by geometric eccentricities when the structural member is loaded in tensile, is detrimental to fatigue strength of joints [23]. Such impact of local bending on fatigue lives of riveted joint has been proved by four different types of specimens with different bending factors [24]. Han [13] studied secondary bending effect on SPR of AA6111 and NG5754 aluminum sheets with different thicknesses. The strain gauge was attached on the sample surface near the rivet head to capture the local bending stress. It was found that the secondary bending is important for fatigue strength of SPR joint, while increasing overlapping length and width of the sample will result in higher static and fatigue strength. Besides secondary bending, it is important to note that the SPR riveting process can lead to significant residual stress due to large local plastic deformation and the cutting of the material [8,10,25]. Residual stress has played an important role in the fatigue analysis of traditional riveted joints, where the fatigue life and the failure location of riveted joints can be affected by the level of residual stresses around joint [26,27].

Fatigue strength of SPR joint could be evaluated by either global or local approach, such as structural stress approach [28], local strain–stress approach [26], and local crack growth approach [29]. Stress intensity factor (SIF), as a similitude parameter for severity of local stress concentration at crack tip, has received great interests in the last several decades for life estimates. Structural stress or finite element method has been adopted to evaluate the SIF along the circumference of welded joint [30–33] or cracked traditional riveted joint [26]. As for structural connectors with natural sharp notch, like RSW, analytical or semi-analytical solutions have

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Nomenclature

a	depth of crack
a'	original crack length
a'_{eff}	effective crack length
A_{ij}	coefficients of boundary correction function at surface point
B_{ij}	coefficients of boundary correction function at deepest point
c	half-length of crack
C	crack growth constant
d	nominal riveted hole diameter
E	Young's modulus
f	boundary correction factor
F	remote load applied on specimen
F_x, F_y, F_z	forces components
G	geometry correction factor
h	distance from crack plane to rivet central axis
I	rotational inertia
k	increment of crack aspect ratio
k'	coefficient of base material
K_{I}	mode I stress intensity factor
K_{II}	mode II stress intensity factor
K_{III}	mode III stress intensity factor
K_{eff}	equivalent stress intensity factor
L	plate length
L_1	effective upper plate length
L_2	effective lower plate length
L_3	average plate thickness
m	crack growth exponent
M_x, M_y, M_z	moment components
N	fatigue cycles
w	plate width
P	magnitude of load
Q	shape factor for elliptical crack
r_y	plastic zone radius
R	load ratio
t	plate thickness
t_1	upper plate thickness
t_2	lower plate thickness
σ_{ys}	yield stress
β	coefficient of mode II sensitivity
γ	coefficient of cyclic plastic zone radius
ν	Poisson's ratio
ϕ	angle of the crack front

been successfully derived and applied as a global representation for local stress concentration [29,34] or considered as a local crack growth parameter for life prediction of kinked crack emanated from joints [35]. As for riveted joints, crack growth lives and crack front patterns have been predicted on various types of lap joints by assuming the crack as quarter-elliptical or semi-elliptical surface flaw [26,36,37]. SIF equations for common flaws [38] have already been generated and implemented in some commercial software packages such as NASGRO and AFGROW. However, limited work has been conducted on fatigue life estimation of SPR joints. Agrawal et al. [39] proposed to use nominal radial stress near the riveted hole to directly fit the fatigue data of Tensile–Shear (TS) and Coach–Peel (CP) specimens in the structural stress model, and validated the model with a *T*-box structure. Similar concept was adopted by Lim [40]. Iyer et al. [17] built a three dimensional finite element model to mimic the mechanical behavior of SPR under cyclic tensile loading, and stress concentration point was found on the upper sheet near the periphery of riveted hole, where most fatigue cracks initiated. Su et al. [41] studied the fatigue and fracture behavior of SPR joined with AA6111-T4 aluminum sheets. The equivalent stress at crack initiation location, based on closed-form structural stress solution near a rigid inclusion, was used as fatigue damage parameter, and good agreement was achieved.

In this paper, the fatigue behavior of SPR joined with aluminum alloy AA6111T4 and HSLA340 steel sheets are experimentally investigated. A structural load and crack growth model is proposed to predict the fatigue life and crack shape evolution. In this model, the TS specimen is simplified as two girders with a rigid connection that closed-form solutions of reaction forces and moments at joint are derived. By assuming that the fatigue crack front is semi-elliptical, new SIF equations are derived for a surface crack in a finite plate near a rigid cylindrical inclusion with axial shear force or bending moment. Residual stress and plastic zone correction is considered by introducing an equivalent SIF. Finally, mean stress modified SIF range is used to predict the fatigue crack aspect ratio and fatigue life with Paris law. Good agreement is found between predictions and fatigue test results.

2. Fatigue experiment

All SPR specimens for fatigue testing were constructed of aluminum alloy AA6111-T4 sheet joined to HSLA340GI steel sheet (with hot dip galvanized zinc coating) with 36MnB4 countersunk rivets by using a HENROB servo-electric riveting gun. A paint bake heat treatment was given after riveting. All the base materials were cut along the rolling direction, and each specimen was made by using two 95.2 mm × 25.4 mm metal strips with 25.4 mm × 25.4 mm overlapped area shown in Fig. 1. More details could be found in Ref. [42].

Load controlled fatigue tests were performed using an MTS servo hydraulic testing machine at 40 Hz with a sinusoidal waveform in tension–tension loading. The load ratio, R, which is defined under fatigue loading conditions as the minimum applied load divided by the maximum applied load for any given loading cycle, was held at 0.1 or 0.5 for different configurations, as listed in Table 1. Early results under load ratio $R = 0.1$ and test setup has been thoroughly discussed by the author [42].

2.1. Failure modes and fatigue performance

Fig. 2(a) and (b) summarizes the fatigue testing results with different thickness of aluminum sheets. Specimens fail either in upper aluminum sheet or through the rivet shank. The sheet cracking, termed as "eyebrow crack," initiates in aluminum substrate near the rivet hole, at the faying interface with mating steel sheet, as shown in Fig. 3(a). The crack then grows both through thickness and across the width of the aluminum sheet in a direction approximately perpendicular to the loading axis. Usually the eyebrow crack plane is observed located near the rivet head, which is about 4 mm away from the center of rivet head. It was believed the combination of tangential stress induced by friction due to fretting and stresses by applied loading could reach a maximum value near the periphery of rivet hole [13], at a distance away from rivet axis and close to the edge of the fretting zone, as illustrated in Fig. 4. The black striped area is the fretting zone. More details about fretting