

The Fatigue Behavior of Fastener Joints

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ABSTRACT

The fatigue behavior of Hilok fastener joints under constant amplitude loading has been investigated experimentally. The effects of load transfer in an unbalanced joint configuration was characterized in terms of a stress severity factor relative to the open-hole configuration. The experimental data indicates that the clamp-up forces dominate the performance of fastener joints with the open-hole fatigue life being the lower bound at the stress levels investigated. The failure modes were observed to transition from a net-section type failure across the minimum section to a fretting induced failure at some distance from the hole. The experimental data has been used to develop stress severity factors to be used as a measure of the fatigue quality of the fastener joints.

INTRODUCTION

The fatigue behavior of fastener joints has received widespread attention for several years due to their extensive use in metallic airframe structures. The fastener joints serve the primary purpose of transferring loads across structural members through bearing and by clamp-up induced friction in some instances. The stress and displacement fields arising due to load transfer by fasteners has been studied in detail by Barrios[1]. The increase in stress concentration due to the combined effects of load bypassing a hole and the hoop-stress due to bearing load transfer have been shown to decrease the fatigue life of the joint[1-4].

The fatigue behavior of fastener joints with different levels of load transfer was studied by Lee [3]. The behavior of 7075-T7351 aluminum fastened by traditional (nut-bolt) fastener under constant amplitude fatigue loading ($R=0.05$) was addressed. The authors observed a decrease in both crack initiation life and total fatigue life with increasing levels of load transfer.

The clamp-up loads generated by the fasteners could have a significant effect on the load-transfer mechanism and the resulting failure modes and life under fatigue loading. Starikov [4] reports the influence of frictional forces arising due to fastener clamp-up on load-transfer and fatigue life of fastener joints. Using an instrumented fastener, they measured the load transferred by bearing and due to friction at the faying surfaces. The authors observed fretting fatigue as the major mechanism inducing the initiation of fatigue fracture in the joint.

The current AFS-120-73-2 document [5,6] uses Miner's linear cumulative damage theory [7] to evaluate the fatigue strength of a wing and associated structure of part 23 small airplanes using S-N curves from full-scale tests. The S-N curves contained in AFS-120-73-2 document are based on full-scale wing test results for a single type of wing. Full-scale tests were conducted because they incorporate important variables such as stress concentrations, multiple load paths due to adjacent elements, stress redistribution that occurs as damage propagates, fretting, load transfer rates, and material variability. The main problem with the current methodology is that it does not account for variations in stress concentrations and load transfer that occur from one wing to another. Furthermore, the current methodology does not accurately predict fatigue damage accumulation, especially in older aircraft that are subjected to severe flight conditions. This uncertainty results in high maintenance costs and potential catastrophic consequences and thus is a major concern for operators as well as regulatory agencies around the world. The methodology presented herein provides a direct approach for evaluating fatigue lives of fastener joints. Fatigue test data are used to establish an effective stress concentration factor that takes into account individual structural details. S-N curves are used with this effective stress concentration to evaluate the fatigue life of the structure.

The use of a “Stress Severity Factor (SSF)” to characterize the fatigue quality of fastener joints has been reported by Jarfall [8]. The fatigue quality of fastener joint is expressed in terms of the SSF which is given by [8]

$$SSF = \frac{\sigma_{loc}}{\sigma_{ref}} = \frac{\alpha\beta}{\sigma_{ref}} \left\{ K_{tb} \frac{\Delta P}{dt} \theta + K_{tg} \frac{P}{wt} \right\} \quad (1)$$

where, K_{tb} and K_{tg} are the stress concentration factors associated with bearing and bypass loads [9], ΔP is the load transferred by the fastener/joint. σ_{loc} is the local stress of interest at the joint as illustrated in figure 1 and σ_{ref} is the reference stress and could represent the remote stress in the part(s) being joined. The constant α is the hole preparation factor that accounts for hole surface roughness and residual stresses from cold working, β is the hole filling factor that accounts for the interference between the fastener and the hole, and θ is the bearing distribution factor that accounts for the effect of non-uniformity of bearing stress on the hole surface[8]. For the factors α and β , reference conditions may be chosen arbitrarily. For instance, $\alpha=1$ for a drilled hole of standard quality and $\beta=1$ for an open-hole [8]. In order for the SSF to be used as a measure of fatigue quality, the empirical factors α , β and θ must be developed from fatigue test data and will thus be dependent on the stress levels and the number of stress cycles. This means that the combinations of fasteners and plate materials should be tested at stress levels and number of cycles typical of the intended application.

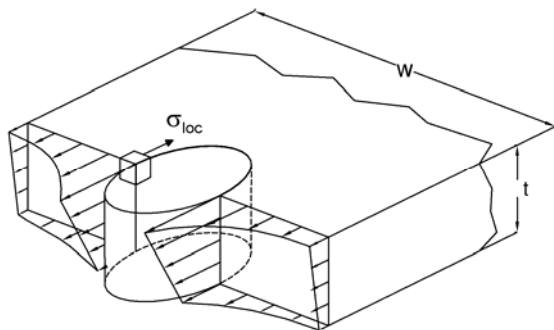


Figure 1. Stress distribution around fastener in a joint.

While the effects of load transfer on the fatigue life of specific fastener joints under constant amplitude[3] and spectrum loading[4] has been reported in literature, no attempts have been made to develop the aforementioned constants based on the data. The development of fatigue based empirical constants will facilitate the use of Miner's damage rule while suitably accounting for the effects of load transfer. In the current study, the constant amplitude fatigue behavior of single-lap fastener joints have been investigated experimentally. The experimental data has been used to generate the empirical factors β and θ as a function of stress levels or fatigue life. The effects load transfer level and interference/clearance fit of the fastener on the

fatigue life has been addressed. The details of the experimental program, results and observations are presented in this paper.

EXPERIMENTS

In the present study empirical factors β and θ were developed using fatigue tests conducted on open-hole (OH), filled-hole(FH) and load-transfer(LT) specimens. The nominal load transfer levels addressed in this study are 30% (Intermediate Load Transfer – ILT) and 50% (Medium Load Transfer – MLT). The details of the materials, specimen geometries, load transfer characterization and fatigue testing are described in this section.

MATERIALS AND SPECIMEN GEOMETRY - The test specimens were fabricated using 2024-T3 clad aluminum with a nominal thickness of 2.286mm. The nominal mechanical properties of the material are listed in table 1.

Table 1. Nominal Mechanical Properties of clad 2024-T3 Aluminum [9]

Young's Modulus, E	72.4 GPa
Poisson's ratio, ν	0.33
Ultimate tensile Strength	427 MPa
Tensile yield strength	324 MPa
Ultimate shear strength	262 MPa
Failure strain	15%
Bearing yield (e/d=1.5)	482 MPa
Bearing yield (e/d=2.0)	579 MPa

The basic test specimen used for the open-hole, filled-hole and load transfer specimens is dogbone shaped as illustrated in figure 2. Test specimen widths of 38.1mm have been used in this study. HI-LOK protruding shear head fastener (HL18 pin and HL70 collar) with nominal diameter of 4.127mm was used in the present study. Thus the fastener diameter to sheet thickness ratio used is 1.82.

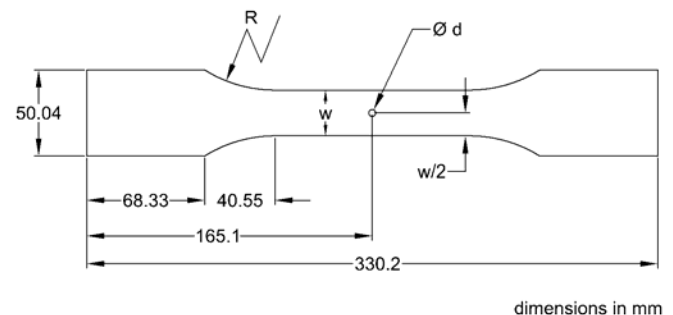


Figure 2. Specimen geometry for open and filled hole tests

The load-transfer specimens used in the current study was a variant of the 1½ dogbone specimen configuration

[2,3] as illustrated in figure 3. The specimen assembly consists of a main (or bypass) part which is the primary member and a load transfer (or secondary) part. The two parts are connected to each other using the fastener (under study) in the gage section and constraint pins in the gripping region. Ensuring compatibility of displacements in the gage region is necessary to force load transfer between the two parts [2]. The far-field loads are introduced into the main part of the assembly. Depending on the relative stiffness of the load transfer part, a specific amount of load is transferred to it via the fastener. The stiffness can be varied by altering the cross-section dimensions and the material itself. The widths of the load-transfer part of the ILT and MLT specimens are listed in table 2. Due to the inherent asymmetry in load transfer, the specimen is prone to bending loads, which is classified as secondary bending [2-4]. The amount of bending will depend on the load transfer levels and the applied load itself [2].

In the present study, the load-transfer and main parts were manufactured from the same material. The displacement compatibility in the gripping region was achieved satisfactorily by using four 6.35mm diameter steel pins as illustrated in figure 3. This combination was arrived at by limited experimentation with different configurations.

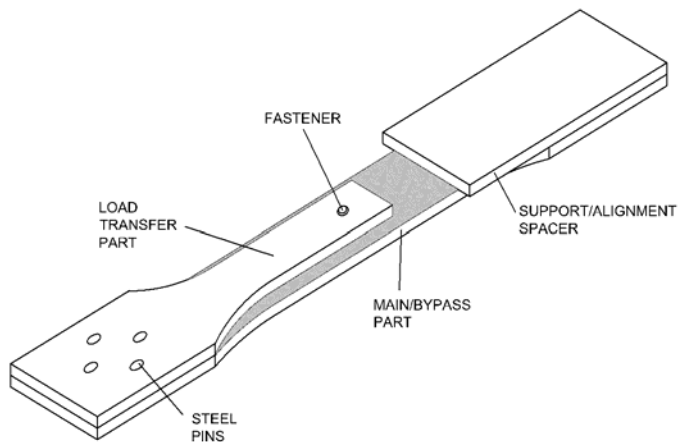


Figure 3. Load transfer specimen

Table 2. Nominal dimensions of test specimens

Specimen Type	Width of main part w_m (mm)	Width of load transfer part w_{LT} (mm)	Nominal Load transfer level
OH/FH	38.10	-	-
ILT	38.10	26.67	30%
MLT	38.10	38.10	50%

LOAD TRANSFER – The load transfer in the 1½ dogbone specimen occurs due to the enforced displacement compatibility between the main part and

the load transfer part. If the fastener is assumed to be rigid and the bearing deformations are negligible, the amount of load transferred is purely a function of the relative longitudinal stiffnesses of the main part and the load transfer part. However, owing to the deformation of the hole, bending of fastener and rotation of the joint itself, the load transfer level will vary as a function of applied loading[2]. The presence of fastener clamp-up loads and hole clearance will further complicate the load transfer process due to the participation of the frictional load transfer at the faying surfaces.

In the present study, the load transfer was characterized by conducting static tests on instrumented specimens. Since the far-field strains are elastic, they were used as a measure of load in the specimen. As the joint is unbalanced (single shear), secondary bending occurs and the strains are not uniform across the thickness of the two parts. Thus, back-to-back strain gages were used as shown in the figure 4.

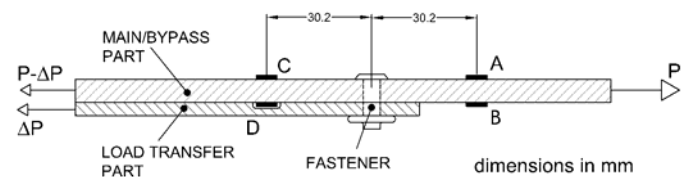


Figure 4. Details of load transfer specimen and location of strain gages along longitudinal plane of symmetry

The variation of load-transfer in the ILT test specimen subjected to a tension-compression loading cycle is shown in figure 5. Anti-buckling restraint supports were used to prevent buckling during the compression phase of the test. The load transfer in the specimen was computed by using the following equation

$$\% \text{ Load Transfer} = \left[1 - \frac{\varepsilon_C + \varepsilon_D}{\varepsilon_A + \varepsilon_B} \right] \times 100 \quad (2)$$

The load transfer computed using the above equation does not resolve the bearing and frictional components of the load transfer. The load transfer was observed to vary with the applied loading with a conspicuous initial drop in the load transferred. This can be attributed to the clearance hole used in the specimen. The friction at the faying surface dominates the initial load transfer process and bearing load transfer takes over when the frictional load transfer ceases and the fastener engages the hole surface. The maximum load transfer level achieved under tensile loading is about 26%. However, the load transfer under subsequent compression loading does not reach the levels achieved under tensile loading. The bearing stress corresponding to the applied tensile loading was higher than the nominal bearing yield stress listed in table 1. Thus the hole is enlarged due to plastic deformation, and in addition to the originally existing clearance results in poor load transfer response during