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EFFECT OF THE RIVET-HOLE TOLERANCE ON THE STRESS-SEVERITY FACTOR

VPLIV TOLERANCE IZVRTINE ZA KOVICO NA FAKTOR KONCENTRACIJE NAPETOSTI

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This work is focused on a quantitative procedure for estimating the generally unfavourable effects that incorrectly drilled holes, characterized by the initial clearance between a rivet and a hole, have on the fatigue life of riveted joints. The solution is based on an analytical approach using the stress-severity-factor concept. An experimental programme with riveted-joint specimens characterized by low-load transfer factors was realized in the Czech Aerospace Research Centre (VZLU) test lab under constant amplitude loading. The holes for rivet joints with 4-mm diameters were prepared with the clearance in a range of 0.0–0.16 mm. Force-controlled riveting was applied using a constant pressure force to form the driven head. To prevent fretting events between the joined parts, their anodized contact surfaces were lubricated with MOLYKA, plastic grease with molybdenum disulphide and graphite. The experimental data showed that the load-transfer factor and the fatigue life depend on the initial clearance between a rivet and a hole. The presented procedure introduced the hole-filling factor, integrated in the stress-severity-factor concept as a function of the initial clearance between a rivet and a hole.

Keywords: stress-severity factor, rivet load transfer, hole-filling factor, fatigue life

V članku avtorja opisujeta delo, ki je osredotočeno na kvantitativni postopek ocenjevanja, v splošnem, neželenih učinkov, to je nepravilno izvrtanih lukenj (izvrtin), za katere je karakteristično nepopolno prileganje med kovico (zakovico) in izvrtino, kar vpliva na dinamično trajno trdnost oziroma dobo trajanja zakovičenega veznega spoja. Rešitev avtorjev temelji na analitičnem pristopu z uporabo koncepta faktorja koncentracije napetosti. Eksperimentalni program preizkušanja kovičenih spojev, z značilno majhnim faktorjem prenosa obremenitve in pri konstantni amplitudi obremenitve, so izvedli v laboratoriju češkega letalskega raziskovalnega centra (VZLU). Izvrtine za kovičene spoje so imele premer 4 mm s toleranco od 0,0 mm do 0,16 mm. Kovičenje je bilo izvedeno s konstantno tlačno silo za oblikovanje vodilne glavice zakovice. Zato, da so preprečili freting obrabo med vezanima elementoma, so anodizirane kontaktne površine namazali s plastičnim mazivom (MOLYKA), ki vsebuje MoS_2 in grafit. Eksperimentalne ugotovitve kažejo, da sta prenos obremenitve in trajna dinamična trdnost, odvisna od začetnega prileganja med zakovico in izvrtino. V predstavljenem postopku sta avtorja uvedla pojem polnilnega faktorja izvrtine in ga uporabila v konceptu faktorja koncentracije napetosti v odvisnosti od začetnega prileganja med zakovico in izvrtino.

Ključne besede: faktor koncentracije napetosti, prenos obremenitve s kovice, faktor polnitve izvrtine, trajna nihajna (dinamična) trdnost

1 INTRODUCTION

Although the bonding and welding technologies are experiencing a great development, there are some obstacles to applying these technologies to real structures.[1] Therefore, the joining technology that uses mechanical fasteners is still the predominant assembly technology for airframe structures. However, a poorly drilled hole for a rivet or other fastener is a significant manufacturing defect that increases the stress-concentration factor at a given location and, consequently, reduces the fatigue life of the joint.[2] Several factors contribute to the rivet failures in an aircraft: induced stresses during the manufacture, thermal fatigue, vibration, manufacturing defects and corrosion. Several factors in the riveting process contribute to the induced stress. Tolerance stack-ups in the sheet metal, the riveting sequence and other process parameters, such as the squeeze force, rivet geometry, edge margin and pitch can all contribute to increased residual stress concentrations in the assembly, leading to the failure of a joint. The presented paper is focused primarily on the manufacturing imperfection – variation of clearance between a hole and a fastener shank.

With regard to riveted structures, it is primarily the rivet hole itself that forms the stress concentration as a result of structure loading. The loading can be due to the following:

- the bypass load, which causes stress concentration corresponding to the open hole,
- the load transfer through the fastener, which causes local bearing stress concentration and local tension stress since the shaft of the rivet is tilted by the shear force acting between the parts to be joined,
- technological factors, especially the surface quality of the hole and the measure for filling the hole with the shank of the fastener.

Considering the technological factors' impact on the fatigue behaviour of airframe structures is problematic

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even if advanced analytical methods, such as the finite-element analysis (FEA), are applied.[3,4] Additionally, when these methods are applied, creating an FE model is so complicated that its application on a real riveted structure is too expensive and time-consuming. Therefore, there are many works devoted to estimating the rivet-joint service life with analytical methods.[5–7]

The submitted study is focused on the production-quality assurance from the opposite point of view – identifying possible consequences of technological defects occurring during riveting, especially when the initial clearance between a rivet shank and a hole is exceeded. An analytical method proposed by L. Jarfall[8] is applied. The concept is based on the assumption that the fatigue failure originates in the structure location with the highest value of the stress-severity-factor (SSF). The SSF represents the value of stress-concentration factor K_t corrected by other technological effects, which are given below. The SSF thus defines the local stress peak as a result of the components of fastener loads, including the relevant technological factors, such as the overall fatigue-quality index of the structure. Mathematically, the SSF is expressed with the following relation:

$$SSF=\left(\frac{\alpha\beta}{\sigma_{\mathrm{ref}}}\right)\left[\left(K_{\mathrm{tb}}\frac{\Delta P}{Dt}\right)\theta+\left(K_{\mathrm{tg}}\frac{P}{Wt}\right)\right] \tag{1}$$

where:

W, D, t geometric parameters of the structure (width, hole diameter, thickness)

σ_{ref} reference stress of the critical area of the structure

P, ΔP structural and transferred loads

K_{tb}, K_{tg}, θ tension load, secondary bending and bearing stress-concentration factors

α fastener hole condition

β hole-filling factor.

The load redistribution in a riveted joint with a low-level load transfer is shown in **Figure 1**. Stress concentration coefficients K_{tb}, K_{tg} and θ can be assigned according to the stress concentration handbook.[9] The technological influences are then expressed by the specific values of factors α and β.

In terms of the above-mentioned quality of the fastener-hole production, the analysis is focused on the holes with diameters beyond the prescribed tolerance limits, especially when the upper tolerance limits are exceeded.

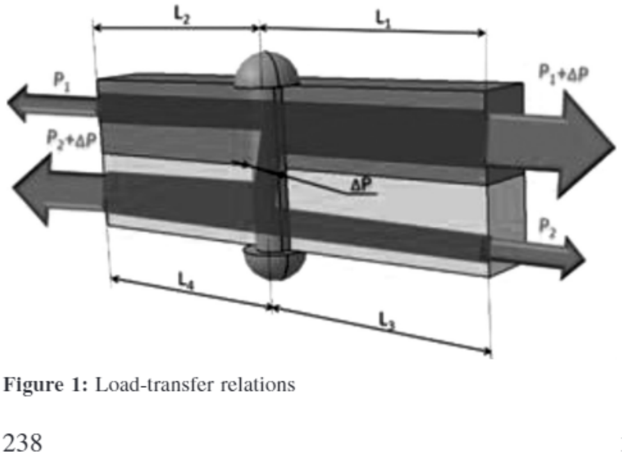

Figure 1: Load-transfer relations

Taking into account a constant squeeze force in combination with exceeding tolerance limits, a hole with a stamped fastener shaft is incompletely filled. Incomplete filling of a hole with a rivet leads to a loose rivet with sealing issues and premature failure of the rivet.

The hole-filling effect is introduced into the SSF analysis by factor β. The β value recommended for Equation (1) is β = 1.0 for a free hole, β = 0.75 for a classic rivet, and up to β = 0.5 for fasteners with interference fits. For example, the Taper-Lok fastener can be considered according to M. C. Y. Niu.[10]

The relationships between the load transferred by a fastener ΔP and the load transferred by structural parts P_1 and P_2 are defined by load-transfer factor p_i as a ratio, as follows:

$$p_1=\frac{\Delta P}{P_1+\Delta P} \tag{2}$$

and

$$p_2=\frac{\Delta P}{P_2+\Delta P} \tag{3}$$

While the effect of the mean stress of the load cycle on the fatigue life is normally included in the fatigue-curve equation (Equation (10)), the effect of the stress-concentration factor is expressed with discrete values of K_t, see, for example, the fatigue curves of any alloy published in the MMPDS.[11] The interpolation of the fatigue curve for a specific value of K_t = SSF is, therefore, a relatively complex matter.

The solution published by R. B. Heywood[12] is one of the best approaches that unifies individual fatigue curves. It is valid for a given material and different K_t values through the notched-material sensitivity q_a, as follows:

$$q_{\mathrm{a}}=\frac{K_{\mathrm{a}}-K_{\mathrm{s}}}{K_{\mathrm{A}}-K_{\mathrm{s}}} \tag{4}$$

whereas the notched-material sensitivity can be described by the following general function:

$$q_{\mathrm{a}}=\frac{\lg N_{\mathrm{f}}^{4}}{b+\lg N_{\mathrm{f}}^{4}} \tag{5}$$

where b is the valid constant for the tested material, K_{S} is the rate of the static strength of smooth and notched material specimens and K_{a} is the rate of the fatigue strength of smooth and notched material specimens at a given number of loading cycles up to the specimen failure, N_{f}. K_{A} is the same rate at the material fatigue limit. At the beginning of cyclic loading, $N_{\mathrm{f}} = 1$; thus, $q_{\mathrm{a}} = 0$ and $K_{\mathrm{a}} = K_{\mathrm{S}}$ during the loading at the fatigue limit; when N_{f} approaches infinity, the notched-material sensitivity $q_{\mathrm{a}} = 1$ and the stress-concentration factor $K_{\mathrm{a}} = K_{\mathrm{A}}$.

The solution should be performed for alternating loadings, i.e., at stress ratio $R = -1$, to prevent cyclic hardening/softening of the material hysteresis loop.

2 EXPERIMENTAL PART

2.1 Material, specimen and joining procedure

A double dog-bone specimen with a riveted joint and 10-% load transfer was designed, see **Figure 2.**

The test specimens were made from sheets of the D16Č-ATV aluminium alloy, which can be considered an alternative to the 2124-T3 alloy. The nominal thickness of the parts to be joined was 3 mm and an actual sheet thickness of 2.94 mm was determined with a measurement. This is a typical thickness in the critical area of an L-610 airframe structure (turboprop aircraft with a seating capacity of 40 passengers). The sheet surface was anodized. Parts of the test specimen were riveted with a rivet of 4 mm in diameter and 11 mm in length in accordance with the LeN 3366.5 specification, which defines dimensions of solid rivets with the d11 shank tolerance, a countersunk head angle of 95° and the H12 hole tolerance.

An occurrence of fretting events is a typical fault of joints that usually leads to a shortened fatigue life. Due to small relative movements of the surfaces under a high contact pressure, a large amount of heat is generated in the vicinity of a rivet, sufficient to melt the material in the surface layers being in contact. Breaking the fatigue test, the molten material cools down and, as proved with a fractographic analysis, spot welds can occur. During the next step of the fatigue test, the load transfer is distributed also to these spot welds, which leads to an increase in the fatigue life of the joint. To prevent the formation of fretting events between the joined tested parts, which cannot be defined in advance, an anti-friction layer (plastic grease with molybdenum disulphide and graphite MOLYKA) was applied on the anodized contact surfaces in the region of the riveted joint.

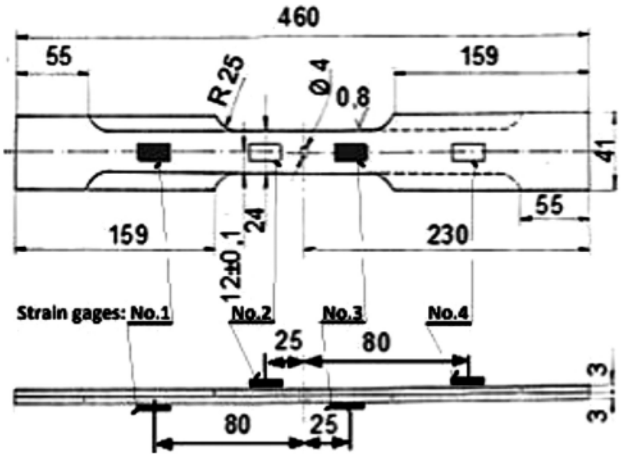

Figure 2: Specimen dimensions for the 10-% load transfer between the parts and strain-gauge positions

An automatic PRECA300S riveting machine was used to make the specimens, which guaranteed constant squeezing forces for each joint during the head formation. The intention was to produce 4 sets of specimens belonging to 4 classes of the initial clearance between the rivet and the hole with clearance values of (0.02, 0.05, 0.10 and 0.15) mm, using suitable drilling tools. Due to a slight dispersion of the production, a range of clearance of 0–0.16 mm was then covered reasonably evenly.

2.2 Test procedure

The experimental programme with the riveted-joint specimens was realized in the VZLU test lab on the SCHENCK hydraulic testing equipment under harmonic loading with a constant amplitude force and a load ratio $R = P_{\text{min}}/P_{\text{max}} \approx 0.005$. The upper stress limit of the loading cycle was $\sigma_{\text{max}} = 160.7$ MPa. The fatigue tests were performed at an operating frequency of $f = 1$ Hz at room temperature in a normal laboratory environment. No guidance plates were used to prevent secondary bending.

The ΔP load transferred by a rivet was measured using strain gauges. The gauges were placed in the areas where a uniform stress distribution in the cross-section of each test part was assumed (**Figure 2**). Therefore, the secondary bending of the joined parts in the joint area was not measured.

3 RESULTS

3.1 Load transferred by a rivet

Prior to the fatigue test of each specimen, the rivet load transfer was measured with the strain gauges. After clamping a specimen into the jaws of the test machine, the specimen was preloaded to a level near the maximum fatigue load P_{max} and the strain on the joined parts was measured. To increase the accuracy of the load-transfer-factor evaluation, the measurements of each specimen were repeated three times.

An overview of the evaluated load-transfer factors of individual specimens at $P_{\text{max}} = 22$ kN is shown in **Figure 3**.

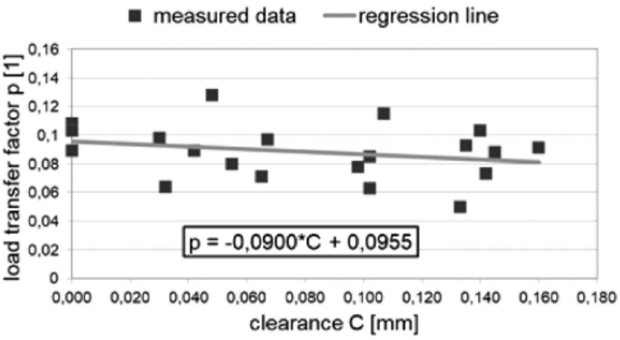

Figure 3: Load-transfer factors measured with strain gauges on individual specimens

Table 1: F-test of linear regression acceptance

Tested factor	Sum of squares			Degrees of freedom		Variance		F-test results	
	(S)	(X1)	(E)	$n_{(X1)}$	$n_{(E)}$	$s_{(X1)}^2$	$s_{(E)}^2$	F_{krit}	α_{krit}
p	0.00672	0.00043	0.00629	1	18	0.00043	0.00035	1.236	0.283
N_{it}	0.46674	0.12187	0.34486	1	18	0.12187	0.01915	6.361	0.021

Due to a great variance of the measured values of the load transfer, only linear regression is used to express the dependence of the load-transfer factor on the initial clearance between a rivet and a hole. The limited validity extrapolation to the possible clearance values outside the measured interval must be taken into account.

3.2 Results of the fatigue tests

Generally, standard regression procedures require the residuals from a regression model to be normally distributed. Regarding the fatigue-life data, logarithmic transformation should be used.[11] Due to the increasing initial clearance, the hole will be less filled in during the driving head formation up to the limit state, which can be compared with the free hole behaviour.

Because the data were measured in a relatively small interval of clearances, a linear regression model with parameters u and v was applied to approximate the function between the logarithmic transformed fatigue-life data and the initial clearances despite the mentioned fatigue limit, as follows:

$$\lg N_{\mathrm{f,\,reg}} = uC + v \tag{6}$$

A summary of the numbers of cycles to failure depending on the clearance of all the tested specimens is shown in the diagram in **Figure 4**, using the following relation:

$$N_{\mathrm{f,\,reg}} = 10^{uC+v} \tag{7}$$

4 DISCUSSION

Several other factors (surface roughness of the hole, clamping force, fretting between joined parts, etc.) accompany the analysed effect of the clearance between a rivet and a hole on the fatigue life. Even if these additional factors are kept at a constant level during the specimen manufacturing, their effect on the scatter of the analysed factors is evident, see **Figures 3** and **4**. The F-test was applied to verify the hypothesis that a proposed regression model fits the data well, **Table 1**, where (S) stands for the sums of squares, (X1) for the sum explained with regression and (E) for the unexplained sum of squares, whereby numbers of degrees of freedom and variances are indexed in accordance with the sums.

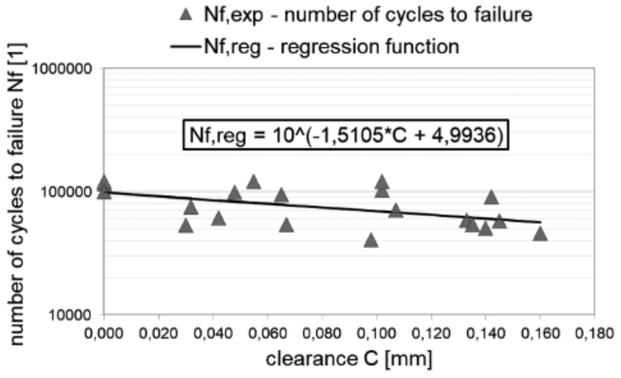

Figure 4: Effect of the initial clearance between the rivet with the LeN 3366.5 specification and the hole on the fatigue-test results and its approximation with a linear-logarithmic regression function

It can be stated that the effect of the clearance between a rivet and a hole on the transfer-load factor can be accepted with a risk of 28 % and the effect of the clearance between a rivet and a hole on the fatigue life can be accepted with a very low risk of 2 %.

To consider the influence of the initial clearance between a rivet shank and a hole on the fatigue life of the joint, factor β in Equation (1) cannot be a constant but has to be a function of the clearance.

It is therefore necessary, due to the nature of the SSF application in fatigue-life calculations, to find dependence, as follows:

$$K_t = SSF = f(\beta) \tag{8}$$

where the size of the initial clearance C between a rivet and a hole is treated as a function:

$$\beta = g(C) \tag{9}$$

Under the condition that the fatigue life is evaluated from the material fatigue curve:

$$\lg N_{\mathrm{f,eval}} = [A_1 - A_2 \lg(\sigma_{\max}(1-R)^{A_3} - A_4)]_{kt=SSF} \tag{10}$$

it will be the same as the mean value of fatigue life from the experimental data:

$$N_{\mathrm{f,eval}} = N_{\mathrm{f,exp}} \tag{11}$$

Due to the strongly non-linear dependence of the system of Equations (8), (9) and (10) regarding parameter K_t, an interpolation procedure was used to ensure the equality in Equation (11).

A step-by-step solution for the β factor calculation had to be made, including several selected clearance values:

- the measured values of load-transfer factor p and fatigue life N_f and their regression relationships are shown in **Figures 3** and **4**;
- technological factor β was set to obtain equality (11) using Equations (10) and (1).

Nonlinear multi-parametric interpolation based on the Marquardt-Levenberg algorithm[13] was used to solve Equations (5) and (10). A software utility using the Oc-

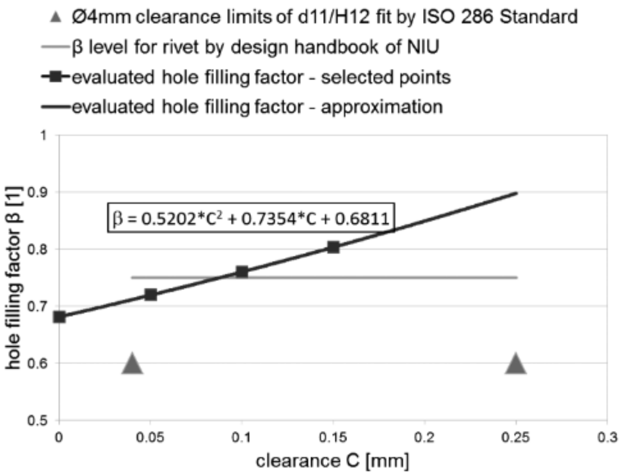

Figure 5: Hole-filling factor evaluated with the fatigue test with regard to clearance fits in comparison to the design handbook recommendation.[10] The clearance interval of the rivet fitting the hole in accordance with the ISO 286 standard is marked.

tave code was developed in accordance with the examples[13] to simplify the interpolation.

The required dependence of technological factor β, characterizing the degree of the filling of a hole with a rivet, on the initial clearance between the rivet and the hole, is shown in the diagram in **Figure 5**.

In general, the fit of the rivet in the hole before riveting is characterized by d11/H12 tolerances in accordance with the ISO 286 standard.[14]

This fit allows a clearance of 0.04–0.25 mm for a rivet with a 4-mm diameter. For the test conditions discussed, it is therefore necessary to assume a change in the mean fatigue life in a range of approximately 41000–85000 loading cycles (**Figure 4**).

The clearance was measured before the rivet was placed into the specimen as the real dimension of the hole filling cannot be evaluated without the specimen cutting. Equation (1) is based on the stress-concentration factor of a free hole and the measurement of the hole filling involves factor β. Therefore, solving the regression function from **Figure 5** for $\beta = 1$, we can evaluate the critical clearance when the rivet shank does not fully fill the hole. Using the given jointing technology, the critical value is 0.34 mm.

5 CONCLUSIONS

The effects of riveted-joint defects on the fatigue life is generally covered by the Damage Tolerance Design Philosophy. The fatigue life of a structure depends both on the manufacturing quality of the joints (initial defects) and on the overall service conditions, which can significantly influence the fatigue crack propagation from manufacturing defects. The quality of a structural joining procedure is important mainly for structural joints, such as transverse joints of wing panels, where the fatigue crack propagation causes their lifetime to be relatively short. The initial defects cannot be completely avoided and then the initiation period of a fatigue crack consumes a substantial part of the life of the structure; thus, it may be appropriate to manage the characteristics of the structures designed under the Safe Life Design Philosophy. The harmful effect of scrapped rivet holes on the fatigue life is generally known.

The paper discusses the procedure for quantitatively estimating the harmful effect of incorrectly drilled holes. The imperfections are characterized by the initial clearance between a rivet and a hole. The influence of imperfections on the fatigue life of riveted joints with low load transfer is documented. An analytical solution based on the stress-severity-factor concept was applied. The aims of the presented solution were to quantify this effect, at least for an example of a typical rivet joint, and show the methodology of setting up the production and control procedures so that the fatigue-life reduction of the riveted joints of an airframe structure with a safe-life design does not exceed the acceptable limits.

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