ON SOME FEATURES OF FAILURE AT MULTIAXIAL CYCLIC LOADING

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ABSTRACT

This paper presents some results of cruciform and tubular specimen testing under uniaxial and multiaxial cyclic loading. It is shown that application of widely used criteria based on invariants of stress state can lead to qualitatively wrong results at out-of-phase loading.

KEYWORDS

Multiaxial fatigue, multiaxial fatigue failure criteria.

INTRODUCTION

At fatigue life estimates of aircraft structures, it is often necessary to determine the fatigue life at biaxial cyclic loading, for example for a wing or fuselage skin, where weight efficiency is one of the main requirements. At the same time, the formal application of widely used failure criteria for biaxial loading by Tresca and Saint-Venant or Huber, Henky and von Mises requires the weight of power elements to be increased by a factor of about 2 at biaxial counter-phase cyclic loading with $\sigma_1 > 0$ and $\sigma_2 < 0$. Obviously such weight increase needs substantation. Some experimental results are considered in this paper to illustrate this problem for bolted joints and failure criteria at biaxial cyclic plane stress state investigated on tubular specimens.

TESTS OF JOINTS

<u>Specimens and Test Equipment.</u> In order to determine the effect of biaxial loading on fatigue life of a bolted joint of alclad aluminium alloy sheet (of thickness of 8 mm) the specimens shown in Fig. 1 were tested. In the middle part of a cruciform specimen there are 2 holes (aligned in the x-axis direction) for attaching steel overlaps to the sheet. These holes are loaded by titanium bolts (8 mm in diameter). The tails of the sheet shortened in x-direction are assembled with overlaps by 3 conical steel studs (about 8 mm in diame-

ter), that load the tails of the specimen in x-direction.

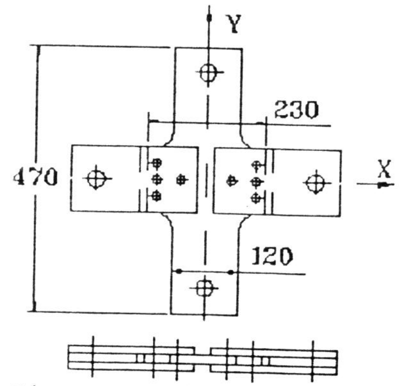


Fig. 1 Cruciform specimen

Such specimen design provides a lesser dependence of the load transferred by the titanium bolt on the load applied to the steel overlaps by hydraulic actuators. This is verified by results of strain gage measurements of overlaps. Because of small deformations of the overlap between the steel studs and the titanium bolt it was necessary to use semiconductor strain gages with the essentially higher gage factor. The measurements have been taken:

- On a completely assembled specimen at loads adopted for fatigue tests;
- On a specimen without titanium bolts at loads reduced by 20% relative to fatigue loads;
- On a specimen with titanium bolts, but without steel studs, at loads equal to 20% of fatigue loads.

Such measurements have estimated separately an effect on gage reading of loads, transferred by the steel stud and by the titanium bolt; that allowed us to estimate more accurately a load transferred by the titanium bolt on a completely assembled specimen. Additionally an effect of sign and value of the load applied along the y-axis of the specimen was also estimated.

The holes for steel studs and titanium bolts were drilled and reamed for neat-fit (an interference is 0 to 0.05% of diameter).

Tests were conducted on a test rig with 4 independent control channels. Each of 4 channels had its hydraulic actuator with servovalve and load cell. In a specimen area under investigation, owing to the specimen being cruciform a two-axial stress state appears at uniaxial loading . Strain measurements in the specimen middle part without holes were used to determine factors A,B,C,D, which relate loads P_x, P_y (applied to tails of specimen along the x and y-directions) to stresses σ_x, σ_y in the middle part of the specimen

$$\sigma_x = A * P_x + B * P_y$$
$$\sigma_y = C * P_x + D * P_y$$

here A= 9.620; B= -1.205; C= -2.589; D= 8.865, if the stress units are MPa and load units are kilonewtons. Different values of A versus D, B versus C may be explained by different lengths of tails in the x and y-directions.

Test program. Tests were carried-out at regular sinusoidal loading at 1Hz. The research has been done for 4 loading conditions: 1) uniaxial loading with no load along the y-direction; 2) bi-axial in-phase loading with pulsating tensile stress cycle;3) bi-axial counter-phase loading with tension along the x-direction and compression along the y-direction; 4) like case 3 but with reversed signs of load along the x and y-axes, with the tensile load along the y-axis being twice that for case 3.

Test Results and Analysis. Test results are given in table 1. The probable points of fatigue macrocrack initiation determined according to superposition of el.stic stresses at the contour of the hole with a titanium bolt are on the hole diameter perpendicular to the x-axis at uniaxial loading and histories 2 and 3. The similar points for history 4 (biaxial loading) are on the diameter perpendicular to the y-axis. Taking into account the vector of load transferred by titanium bolt and acting additionally along the x-axis it could be shown, that the most dangerous among the two points is the point subjected to the vector of the bolt load. At this point the compressive stresses acting along the x-axis add to tensile stress in the y-direction and make the fracture at this point the most probable (from the point of view of von Mises (or similar to it) criterion).

With the first three load histories, fatigue test results showed that fatigue cracks in both holes with titanium bolts initiated and propagated almost symmetrically in the expected direction, but with the 4-th history the cracks propagated from the points opposed to the points loaded by the vector of the bolt load. In the last case there were no cracks at the side subjected to the vector of bolt load, even at 20 mm crack length in the opposite side.

These tests have been supplemented by tests on tubular specimens to clear the question, if this phenomenon can be related to contact interaction at the point, where the bolt load vector is applied. Relationships between loads applied to tubular specimens were evaluated by superposition of elastic solutions.

TUBULAR SPECIMEN TEST

Specimens and Test Equipment. The tests were carried out using the electrohydraulic test rig, where a specimen could be subjected to the axial load, the torsional moment and the internal pressure. The specimen is shown in Fig.2. The specimen material is a D16T aluminum alloy (similar to 2024-T3). The generation of load program and the monitoring of test parameters were provided by a control computer.

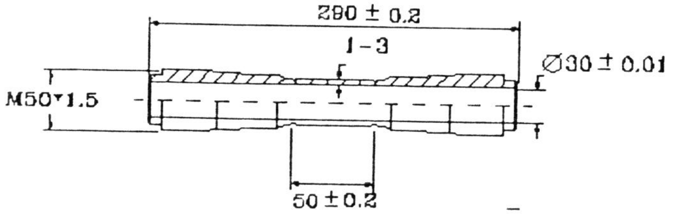


Fig.2 Tubular specimen

Test Program.The tests were carried out under uniaxial loading along both axes to provide a data base for comparison with test results obtained at uniaxial loading of a cylidrical specimen, to evaluate anisotropy and to compare with the results of multiaxial tests. The multiaxial loading tests were carried out to simulate local elastic stress relationships in the joint (see above) and to provide the basis for qualitative and quantitative verification of criteria. It is easy to be convinced that the module of principal stresses would be constant and equal to

$$\sigma_1 = \sigma_m + \sigma_a \ ; \ \sigma_2 = 0 \ ; \ \sigma_3 = \sigma_m - \sigma_a$$

at the stress history

$$\sigma_x = \sigma_m + \sigma_a * \sin \omega t$$
$$\sigma_y = \sigma_m + \sigma_a * \sin(\omega t + \pi) = \sigma_m - \sigma_a * \sin \omega t$$
$$\tau_{xy} = \sigma_a * (\sin \omega t + \pi/2) = \sigma_a * \cos \omega t,$$

where σ_a, σ_m are constants, ω is the frequency, t is time.

Test Results and Analysis. Results of the tests carried by I. V. Gusak are given in table 2. It is seen that the results obtained by simulating the local elastic stress state of the joint are qualitatively the same as the results of the joint tests: the fracture in both cases happened at greater fatigue life than that predicted by criteria using invariants of stress state, that means that an addition of compressive stress along the other axis increases the fatigue life instead of decreasing it.

Test at the constant module of principal stress have shown that specimens fail and the fracture is of fatigue nature. From these results it can be concluded:
- The usage of modules of principal stresses derived from instantaneous values of stresses to reduce any multiaxial stress state to a uniaxial one, equal in fatigue damage, can give qualitatively wrong results. In the given example the cyclic loading will be replaced by static one. The statement is also valid for some functions of principal stresses (intensity, maximum shear stress etc.).
- Òhe usage of some criteria, based on the largest possible differences of instantaneous values of stress (strain) components (see, for example, (Fuchs, 1979)), underestimates the fatigue damage produced by this type of out-of-phase loading and are not acceptable for random loading. (The damage evaluation has been done after determination of equivalent amplitude according to criteria given in Fuchs (1979) using the fatigue life curve got at uniaxial loading).

CONCLUSIONS

For a general case of a random multiaxial loading there is a strong demand to develop methods for representating multiaxial load history and damage estimation, since the usage of modules of principal stresses gives qualitatively wrong results, and the usage of the largest possible differences can only be done effectively for out-of-phase loading with constant amplitude and phase shift.

R E F E R E N C E S

1. Fuchs, H.O. (1979) Fatigue research with discriminating specimens. Fatigue of engineering materials and structures, v.2, No. 2, pp. 207-215.

Table 1

Results of joint specimen tests

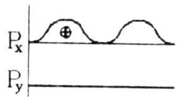
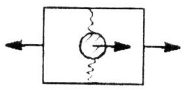
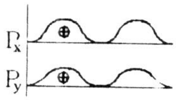
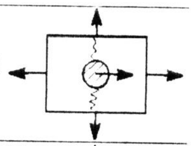
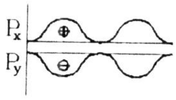
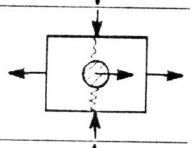
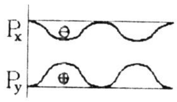
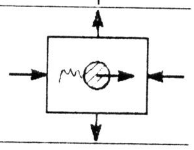
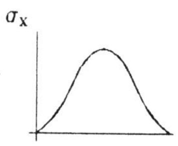
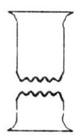
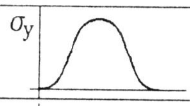
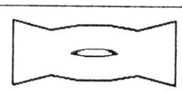
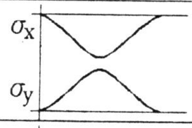
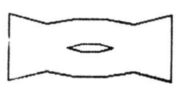
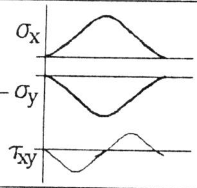
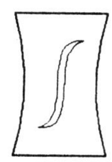
No	P_x	P_y	P_b	Loading diagram	σ_x	σ_y	σ_{sm}	N_i	$\overline{N}$	Fracture mode
	kN				MPa			Cycles		
1	63,74	0	11,66		.50,99	−13,79	182,4	115390 105890 120640	113800	
2	63,74	31,87	11,21		47,61	14,71	175,5	168420 144220 161230	157600	
3	63,74	−63,74	12,13		58,83	−71,58	193,2	74000 69570 79890	74367	
4	−63,74	127,53	−13,20		−65,70	128,6	205,9	84950 53860 57250	63984	

Table 2

Results of tubular specimen tests of D16T alloy

No.	Stress' component	Loading diagram	$\sigma_a(\tau_a)$	$\sigma_m(\tau_m)$	R_f	$\overline{R}_f$	Fracture mode
			MPa		Reversals		
1	σ_x		176,5	176,5	55355 61466 44878	53898	
	σ_x		147,1	147,1	100000 139378 112110	117162	
2	σ_y		117,7	117,7	46779 34696 99308	60261	
3	σ_x σ_y		−68,6 127,5	−68,6 127,5	173294 149172 90430	137632	
4	σ_x σ_y τ_{xy}		117,7 117,7 117,7	117,7 117,7 0,0	13700 15910 13696	14435	
	σ_x σ_y τ_{xy}		78,4 78,4 78,4	78,4 78,4 0,0	132763 148995 80589	120782	