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Residual strength of stiffened panels with multiple site damage

H.J. ten Hoeve, H.H. Ottens, L. Schra and H. Vlieger

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ABSTRACT
Residual strength tests on stiffened panels with multiple site damage were done. The main purpose was to generate experimental data to be used to verify predictions of the residual strength. Flat sheets without lap joints but with sawcuts were fatigued to get sharp cracks. Next, flat strip stiffeners were riveted to both sides of the sheets, which were then tension loaded to failure.

Contents

(8 pages in total)

RESIDUAL STRENGTH OF STIFFENED PANELS WITH MULTIPLE SITE DAMAGE

H.J. ten Hoeve*, H.H. Ottens*, L. Schra* and H. Vlieger*

Residual strength tests on stiffened panels with multiple site damage were done. The main purpose was to generate experimental data to be used to verify predictions of the residual strength. Flat sheets without lap joints but with sawcuts were fatigued to get sharp cracks. Next, flat strip stiffeners were riveted to both sides of the sheets, which were then tension loaded to failure.

INTRODUCTION

After the Aloha accident in 1988 the significance of multiple site damage (MSD) became generally recognised. Several working groups were formed to develop means to maintain safety in ageing aircraft showing MSD. One of the key topics is the residual strength of riveted fuselage lap joints showing MSD. Different computer codes are being developed to analyse these joints. In order to validate these codes, tests on stiffened panels with MSD have been performed.

EXPERIMENTAL

Three panel configurations were chosen namely:

- Configuration I — A skin crack extending between two stiffeners
- Configuration II — A skin crack extending under an intact stiffener
- Configuration III — As configuration II, but extending under a broken stiffener.

The width of the panels was 1200 mm. To allow a configuration of a lead crack with a number of MSD cracks in the same stiffener bay, a stiffener spacing of 340 mm was chosen. four stiffeners

* National Aerospace Laboratory NLR, the Netherlands

were used for configuration I panels and three stiffeners were used for configuration II and III panels (Fig. 1). To avoid load eccentricities in the clamping areas, strip stiffeners were riveted to either side of the skin. A nominal skin thickness of 1.27 mm (0.05") was chosen. The stiffeners were 2.06 mm (0.08") thick and had a width of 45 mm (resulting in a representative stiffening ratio of 0.7). The material of the skin was 2024-T3 and that of the stiffeners 7075-T6.

The stiffeners were connected to the skin by means of 4.0 mm DD-rivets (protruding head type). The rivet patterns are given in figure 1. The stiffeners on either side of the skin were made from 1200 mm wide sheets by milling away the material between the stiffeners. At the panel ends the stiffeners were left interconnected (see Fig. 1) to ensure a uniform load introduction.

Figure 2 gives an overview of the crack configurations. Secondary cracks had a length of 25 mm. The main objective in testing panel configuration I was to investigate the residual strength behaviour for a central lead crack and secondary cracks before the inner stiffeners, after the inner stiffeners, and both before and after the inner stiffeners. Panel IIa had an intact central stiffener crossing a central crack with the same length as in panel IIIa1. Testing these panels will show the effect on the residual strength of a broken central stiffener. Testing panels of configuration II with secondary cracks was not considered useful. The main objective in testing panel configuration III was to investigate the effect of link-up on the residual strength of the central lead crack and two or four secondary cracks, all before the outer stiffeners.

For all panels a load (stress) - crack length relationship was determined until failure of the panel. In addition, panel Ia1 was strain gauged to measure the strain distribution in the panel. Further, the strain in the central stiffeners of panel IIa was measured during growth of the central crack.]-beams with a height of 10 cm were used on both sides of the panels to restrain buckling. However, during testing rather severe buckling occurred. The strain gage measurements and buckling are reported in reference 1. A cut-out with a length of 70 cm and a width of 4 cm was made in the web of the]-beam at the front side of a panel to enable crack length reading.

The machined-in central lead crack, as well as the secondary cracks in the skin of the panels, were pre-cracked by fatigue under constant amplitude loading. After fatigue pre-cracking the stiffeners were riveted to the skin.

The residual strength tests were done under displacement control. This enabled following static crack growth beyond the point of maximum load. The displacement increase was periodically interrupted for visual reading of the crack length, using a travelling microscope combined with a crack-monitoring device.

RESULTS

During the residual strength tests static crack growth was observed in all panels. Crack length data were obtained as a function of the applied load. From the applied loads the stresses were calculated using the actual gross section (based on actual thickness of skin + stiffeners). The nominal gross section for configuration I is: (1190 x 1.27) + (8 x 45 x 2.06) = 2253 mm^2 and for configurations II and III: (1190 x 1.27) + (6 x 45 x 2.06) = 2068 mm^2. Crack growth was symmetric for all panels, enabling mean values to be reported. Figures 3 and 4 give the mean crack growth, starting from the different crack tips, as a function of the applied load.

Panel configuration I

Crack growth data for the panels with configuration I (4 stiffeners) are given in figure 3. The panels Ia show crack extension until reaching the stiffener, then the stiffeners fail, followed immediately by failure of the panel. Small discontinuities in the crack extension curves are due to skin buckling. The Ib panels show crack extension and crack link-up of the lead crack and the MSD cracks followed by crack extension to the stiffener. Then the stiffener fails, followed immediately by panel failure.

For panel Ib link-up of the central crack and the secondary cracks occurred far below the failure stress of the inner stiffeners (about 70 % of failure stress). After link-up further static crack growth took place and the crack reached the inner stiffeners at a substantially lower stress level compared to panel Ia3. However, failure of the inner stiffeners and panel failure occurred at almost the same stress for both panels. For panel Id, after the first link-up the large central crack grew under the stiffeners and linked-up with the secondary cracks beyond. After some further crack growth the inner stiffeners failed at a lower stress than the second link-up stress. It must be noted that the inner stiffeners would have failed at the second link-up stress if the test had been done under load control. For panel Ic the growth of the central crack was hardly influenced by the secondary cracks. However, failure of the inner stiffeners occurred at a 7 % lower stress than that for the panel with a central crack only (Ia3).

Panel configuration III

Crack growth data for the panels with configuration III are given in figure 4. For panel IIIb growth of the central crack was influenced by the secondary cracks only above 140 MPa. The central crack linked up with the secondary cracks at an 8 % lower stress compared to the maximum stress of panel IIIa2. After link-up the crack grew until the stiffener was reached. Failure occurred at a 2.5 % lower stress then panel IIIa2. Load control would have resulted in unstable crack extension after link-up, and the crack would probably have arrested at the stiffeners. For panel IIIc the growth of the central crack was only slightly influenced by the secondary cracks. The first link-up stress is 11 % below the maximum stress for panel IIIa2, i.e. link-up occurred at a slightly lower stress than for panel IIIb. After the first link-up a second link-up occurred at a lower stress, and the tips of the resulting large crack were close to the stiffeners. Failure occurred after a load increase at a stress comparable to that for panel IIIb. Load control would have resulted in the central crack jumping to the stiffeners at the first link-up stress.

Panel configuration II

Crack growth data for panel IIa is also given in figure 4, in order to compare it with the crack growth curve for panel IIIa. It is seen that a much higher maximum stress is reached with an intact central stiffener. The central stiffener failed at a half crack length of 225 mm. The crack arrested, and after further growth (at a much lower stress) the panel failed. If load control had been applied, failure of the central stiffener would have resulted in failure of the panel. In this case the failure stress of the panel with the unbroken central stiffener would have been 37 % higher than that of the panel with a broken central stiffener.

REFERENCE

(1) Hoeve, H.J. ten, Schra, L., Michielsen, A.L.P.J., Vlieger, H., Residual strength test on stiffened panels with multiple site damage, NLR CR 96792 L.

Appendix Mechanical properties of skin and stiffener material

Tensile tests were done according to ASTM specification E8M-89b to determine the longitudinal mechanical properties of the skin and stiffener materials. Average results for both materials are given in table 1.

TABLE 1 - Mechanical Properties of Sheet and Stiffener Material

Longitudinal mechanical properties					
material	Thickness (mm)	$\sigma_{0.2}$ (MPa)	σ_{ult} (MPa)	δ_{50} (%)	E (MPa)
2024-T3	1.27	366	482	17.3	71100
7075-T6	2.06	525	579	16.0	67000

To obtain the residual strength properties of unstiffened skin material, two residual strength tests were carried out on the 1.28 mm thick, 500 mm wide skin material. Fracture toughness properties as well as an R-curve were determined according to ASTM specification E561-86. Residual strength prediction tools do not always permit the use of an R-curve as function of Δa_{eff}. Hence table 2 gives the measured test results.

TABLE 2 - R-curve Properties of Sheet Material

E = 73000 MPa, $\sigma_{0.2}$ = 366 MPa, W = 500 mm, t = 1.28 mm, η = 0.33, Y = 4.0 mm					
Specimen H100, a_o = 49.8 (mm)			Specimen H156, a_o = 78.0 (mm)		
a_p (mm)	S_{gr} (MPa)	S_{net} (MPa)	a_p (mm)	S_{gr} (MPa)	S_{net} (MPa)
49.78	0.0	0.0	77.98	0.0	0.0
49.87	105.1	131.3	77.98	79.1	115.0
50.21	136.9	171.3	78.71	117.4	171.3
50.96	166.4	209.0	84.31	189.5	285.9
52.25	197.3	249.4	86.95	200.6	307.6
54.98	229.1	293.7	95.67	211.1	342.0
67.00	256.3	350.1	110.90	203.1	365.1
80.71	246.1	363.4	141.45	160.4	369.3
118.31	196.3	372.6			

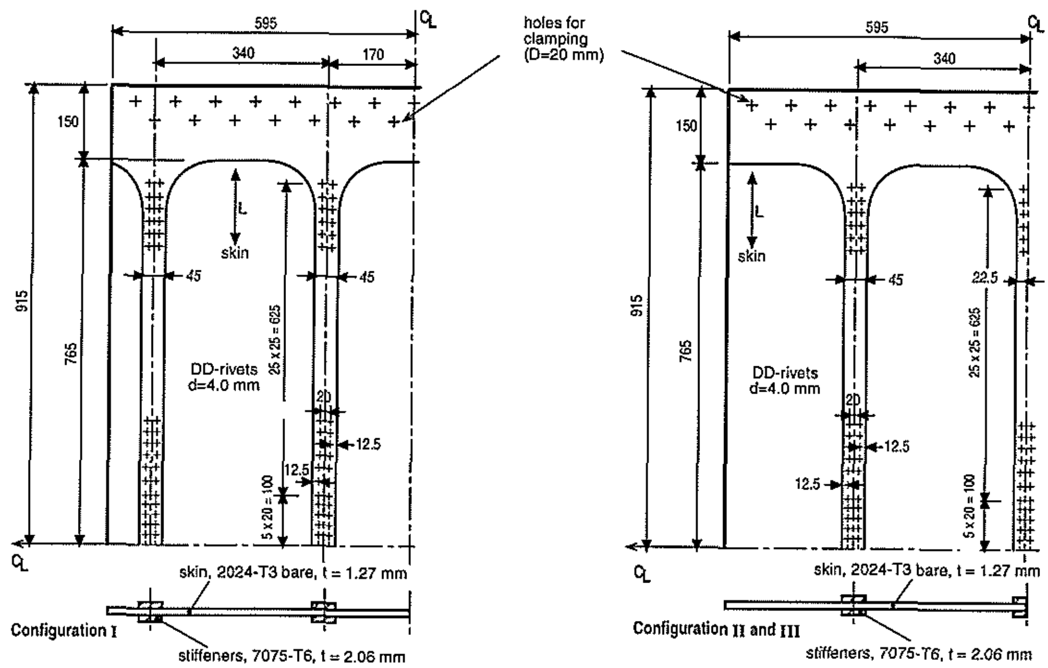

Figure 1 Panel design uncracked

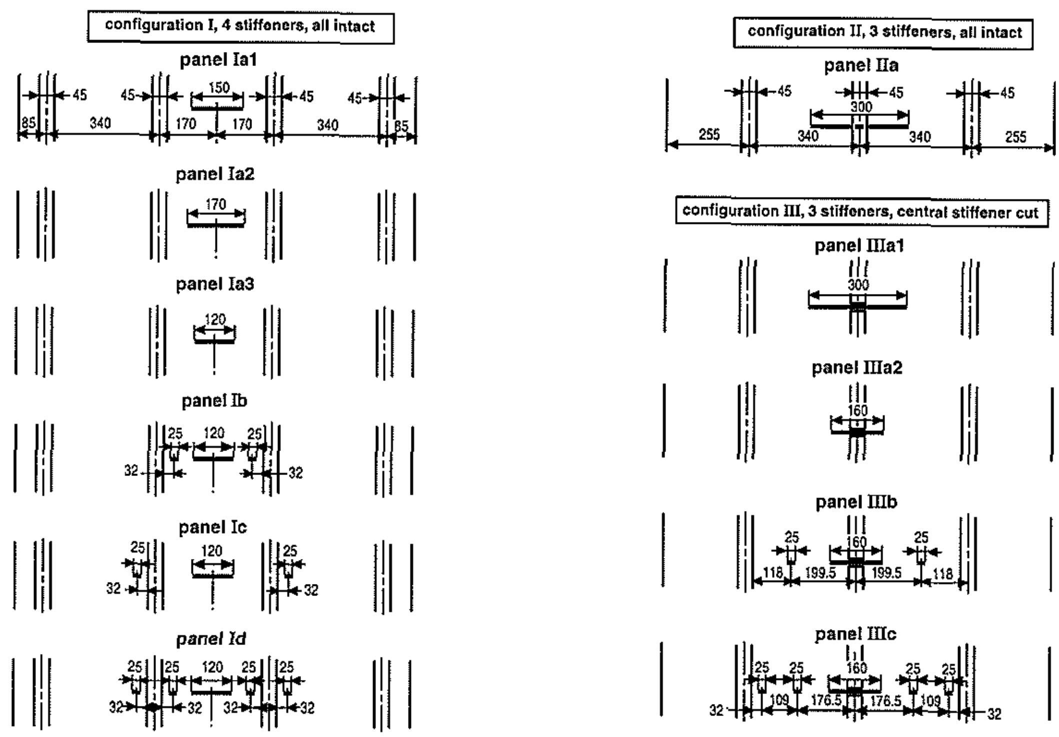

Figure 2 Crack configurations as machined

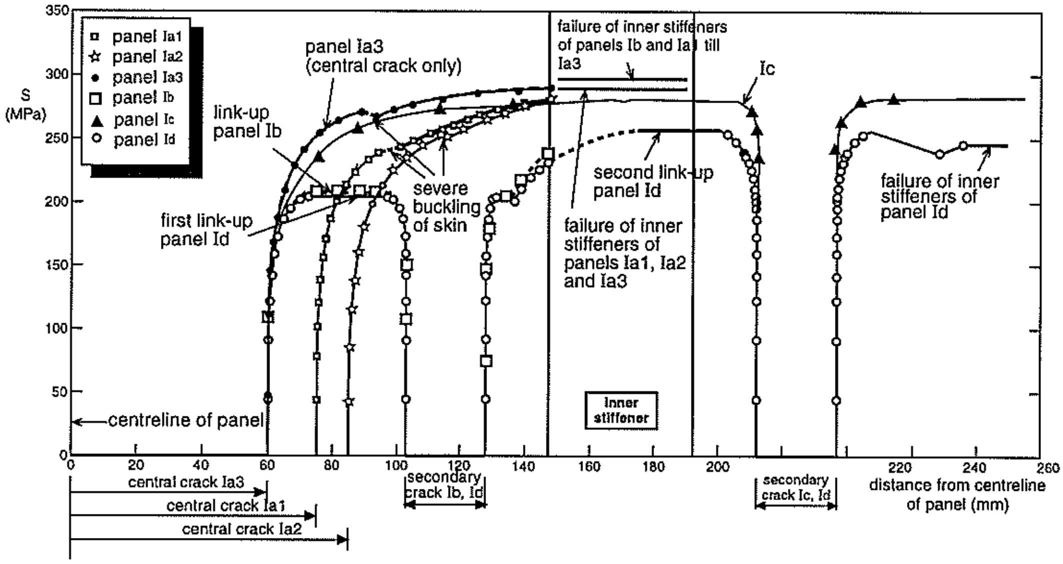

Figure 3 Crack growth curve for panels I

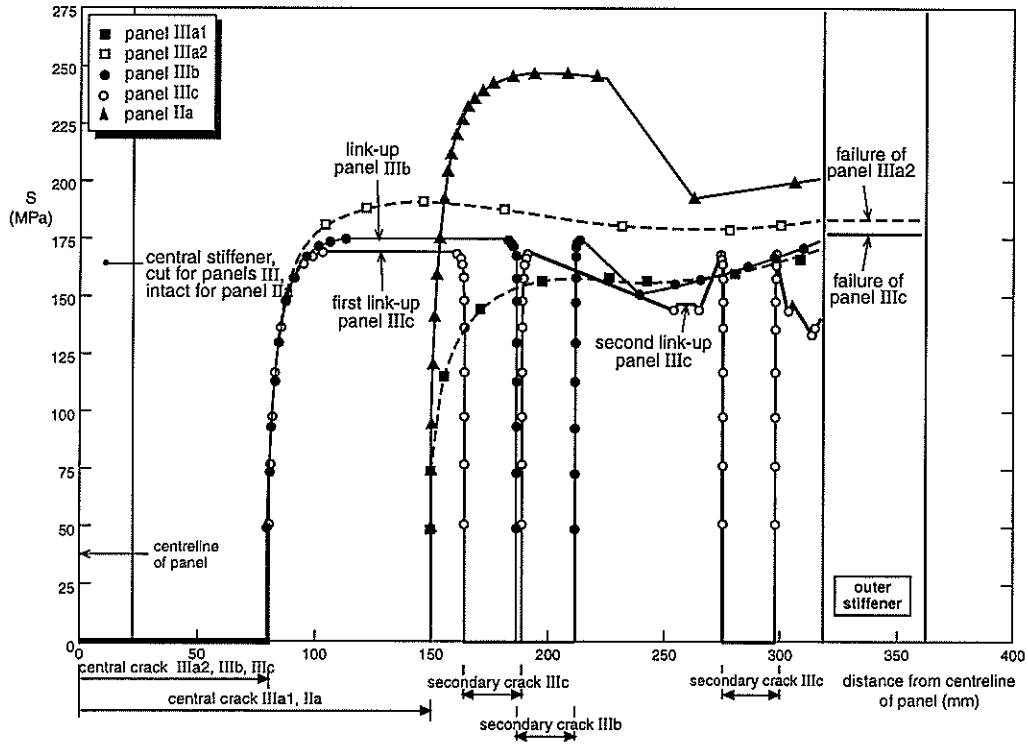

Figure 4 Crack growth curve for panel types II and III