COMPARISON OF DAMAGE TOLERANCE OF INTEGRALLY STIFFENED AND RIVETED STRUCTURES

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Abstract

Crack resistance of aluminium alloys used in Russian riveted and integrally stiffened airplane structures is outlined. Experimental data on crack growth duration and residual strength of riveted and integral structures are compared.

1 Introduction

Passenger-carrying and transport aircraft in Russia include riveted and integrally stiffened panels (Fig. 1). Approximately 50 per cent of Russian aircraft have the wings made of integrally stiffened panels. The latter have been introduced in the 1950s for USSR military aircraft and in the 1960s for passenger ones. Almost 35 years of experience in operating airplanes with such wings have been acquired by now. In Russia the integral wing structures are being manufactured mainly of extruded panels. Skins of riveted panels are made in most aircraft of clad sheets. Since the early 1990s heavy-gauge plates are also being utilized as riveted-structure skins. And riveted-panel stringers are made of extruded sections. When selecting between integrally stiffened and riveted panels, the designers first compare damage tolerance of these two structural concepts. Comprehensive test-and-analysis study on damage tolerance of riveted and integrally stiffened structures has been performed at TsAGI to support the design work. Generalized study results are presented below.

2 Materials crack resistance

Crack resistance of extrusions, sheets and rolled plates made of Al-alloys has been determined experimentally by using wide unstiffened plate coupons being tested without eliminating their bulging near the cracks (that is, without guiding laps). Critical stress intensity factors K_{app} have been found in experiments with coupons having the width W = 750 - 1200 mm. The further calculations rely on values of K_{app} for coupons with W = 1200 mm. If the values of K_{app} are from coupons with W < 1200 mm, then these values are referenced to the 1200-mm wide coupon, see [1].

Crack growth rates da/dN were found both for the wide coupons used to find K_{app} and for narrow coupons with W = 160 - 200 mm. Fatigue crack growth rates have been obtained at the cycle stress ratio R = 0 - 0.05. The cyclic load frequency f was 0.1 - 0.2 Hz for wide-coupon tests and 2 - 3 Hz for narrow-coupon tests. The thickness t of the tested coupons was 2 - 5 mm for sheets and 4 - 12 mm for plates and extrusions.

Long operated (aging) aircraft structures include clad sheets of D16ATV alloy and extrusions of D16T alloy. New structures have the improved modifications of this alloy: D16chT, 1163T, and 1161T; the latter contains some zirconium.

Figure 2 presents crack resistance of D16chT alloy, found from coupon tests when the loads were applied along fibers (L-T). Critical stress intensity factors K_{app} correspond to the coupons with W = 1200 mm. The symbol

"a" defines central-crack half-length; the crack growth rate da/dN depends on the stress intensity factor range ΔK.

It follows from the Fig. 2 data that from the view point of crack resistance the extrusions of D16 alloys have the advantage as compared to the sheets and rolled plates.

3 Fatigue crack growth duration

Fatigue crack growth durations were compared by using experimental data from damage tolerance test of large-scale wing/fuselage panels and full-scale aircraft structures. The duration was for growth of cracks from artificial notches in the skin and/or stiffeners of experimental panels, while in the full-scale structures it was measured from the fatigue cracks that emerged during fatigue test of the structure. Crack growth was monitored by visual inspection, special foil gauges, and post-test fractography.

Figures 3 - 5 depict the central crack length $2a$ vs cycle number N for the D16chT panels. Integrally stiffened panels and riveted-panel skins were made of D16chT extrusions. The panels have been tested at maximum stresses σ_{max} = 130 MPa with the cycle stress ratio R = 0. The initial cracks in the Figures are black, and the final cracks are dashed. Test results presented in Figs. 3 and 4 have shown insignificant difference in crack growth durations for the skin of integral and riveted structures in those cases when the initial damage is either the crack beneath the broken stringer or the skin crack between stringers. If the initial damage is the stringer crack (Fig. 5), then the crack growth duration for the riveted structure may be much longer than that for the integral one - due to the delay in crack initiation in the riveted panel skin after stringer failure.

Figures 6 and 7 give examples of simultaneous damage of spar caps and lower wing skin during fatigue tests. The components were fabricated of D16chT alloy. The tests applied blocks of variable loads. One block simulates wing loading during a typical flight. Figures 6 and 7 provide the block (or flight) number N after which the damage was detected.

These examples are demonstrating that, upon long operation of build-up structures where the primary components are riveted or bolted, the fatigue cracks propagate in both the skin and the stiffeners (such as stringers, spar caps, etc.) in many cases simultaneously. Therefore, the design damage criterion for riveted structures should be the simultaneous initiation of cracks in the skin and stiffeners.

4 Residual strength

Residual strength values for integrally stiffened and riveted structures have been compared by using the structures made of the plastic alloy D16chT (similar to 2024-T351 alloy) and brittle alloys V95T1 (similar to 7075-T6 alloy) and AK4-1T1. Critical stress intensity factors are K_{app} = 160-198 MPa$\sqrt{\text{m}}$ for the plastic alloy and K_{app} = 60-70 MPa $\sqrt{\text{m}}$ for the brittle alloys.

The comparison is based on experimental data for structures having skin cracks beneath broken stringers or broken spar caps. Results are presented in Figs. 8 through 12: gross stresses versus the ratio of crack length $2a$ to the stringer spacing b. Stable crack growth under a single static load has been observed. The initial and final crack sizes are connected with lines. Experimental points with upward-looking arrows are for the cases when the structures have not been broken by the specified stresses at crack sizes prescribed. The initial cracks are depicted in black, while their growth path is dashed.

The residual strengths of integral and riveted structures fabricated of D16chT alloy were compared after special test of large-scale stiffened panels - see [1, 2] and Figs. 8 and 9. The test data analysis has shown that residual strength values for integral and riveted D16chT structures are almost identical. Residual strength of a structure having a skin crack beneath a broken central stringer decreases greatly if the crack tips propagate beneath stringers in integral structures or protrude from skin holes for attaching the stringers in riveted structures.

Residual strengths of integral and riveted structures fabricated of V95T1 and AK4-1T1 alloys were compared on the basis of full-scale structure tests (Figs. 10 - 12). In the riveted structures the stringers have been fabricated by extrusion, and the skin was sheet. Integral structures of V95T1 have been based on extruded panels, while those of AK4-1T1, on rolled plates.

Test data presented in Figs. 8 through 12 demonstrate that residual strength test of riveted structures reveals significant difference in fracture kinetics for plastic and brittle materials. A riveted structure of the plastic material D16chT, having a skin crack beneath the broken central stringer gets broken ultimately after fracture of side stringers. Residual strength of such structures depends on the stringer strength degraded by holes. In the case of similar damages the riveted structure made of brittle materials V95T1 or AK4-1T1 first shows complete fracture of the skin, while side stringers remain intact. For the riveted structures the stringer strength σf decreased by holes is approximately equal to 500 MPa for V95T1 and 400 MPa for D16chT.

Subjected to static load, the integral structure with a skin crack beneath a broken central stringer features the simultaneous propagation of cracks in both the skin and side stringers. Residual strength of the structure depends on characteristics of the side stringers damaged by the crack. Upon the damage to the stringers strength of brittle V96T1 stringers is less than strength of plastic D16chT stringers. Therefore, residual strength of integral panels made of the statically stronger V95T1 alloy is less than that of integral panels made of the statically weaker D16chT alloy.

Figures 10 and 11 demonstrate that structural fracture is terminated by longitudinal joints, so the latter are effective stoppers of damage in both integral and riveted structures.

The Fig. 13 diagrams illustrate the difference in fracture kinetics for riveted structures with brittle and plastic skins. Fracture diagrams for integrally stiffened structures made of plastic and brittle materials are similar to those for riveted structures of plastic materials (refer to Fig. 13b).

5 Conclusion

Crack resistance of D16 series alloys in extruded semi-products utilized in integrally stiffened structures are better than that of sheets and heavy-gauge plates of the same alloys utilized in riveted structures.

When fatigue damage is growing from an initial crack in a riveted stringer, crack growth may be delayed when the crack propagates from the stringer into the skin. The duration of this delay may be comparable with stringer fracture time. There is no such delay in integrally stiffened structures.

Durations of fatigue damage in integrally stiffened and riveted panels are practically identical when the initial damage is a skin crack beneath a broken central stringer or a skin crack between stringers (provided that the skins of integral and riveted panels are fabricated of the same material).

In full-scale riveted airplane structures affected by long-term variable loading the cracks propagate in many cases almost simultaneously in the skin, spar caps, and stringers. Hence the damage tolerance analysis of riveted structures should consider simultaneous initiation and growth of skin and stiffener cracks.

Differences in residual strength of integral and riveted structures made of D16 alloys and having two-bay skin cracks and broken central stringers have been found to be insignificant.

Residual strength of a stiffened structure having a two-bay skin crack and a broken central stringer decreases drastically if a crack in an integral structure propagates under the stringers or if a crack in a riveted structure propagates from a skin hole for fastening the stringer.

A riveted structure made of plastic D16T materials and having a skin crack beneath the broken central stringer breaks down after failure of side stringers. Residual strength of such structures depends on the stringer strength decreased by the holes. In the case of similar damages the riveted structure made of brittle V95T1 material first undergoes complete fracture of the skin, whereas side stringers remain intact.

Residual strength of a riveted structure having the skin of plastic material of D16 series (similar to 2000 series) and the stringers of high-strength V95 alloy (similar to 7000 series) is higher than residual strength of an integral structure made of D16 alloy and having a two-bay skin crack and a broken central stringer.

The longitudinal joints between panels are effective stoppers of damage in both integral and riveted concepts.

6 Acknowledgement

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References

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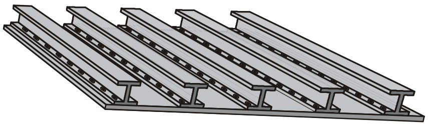
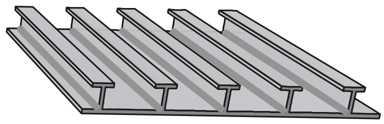


Riveted

Boeing	Douglas	Airbus Industrie	Lockheed	Antonov	Il'ushin	Tupolev	Yakovlev
B-707	DC-8	A300	C-130	AN-10	IL-18	TU-104	YaK-40
B-727	DC-9	A310	L-1011	AN-12	IL-96	TU-134	YaK-42
B-737	DC-10	A320				TU-154	
B-747		A330				TU-204	
B-757		A340					
B-767							
B-777							

Integrally stiffened



Aerospatiale -British Aerospace	Lockheed	Dornier	Vickers	Antonov		Il'ushin	Tupolev
"Concorde"	C-188	Do 228	VC 10	AN-22	AN-70	IL-62	TU-144
	C-141			AN-24	AN-72	IL-76	
	C-5			AN-26	AN-74	IL-86	
				AN-30	AN-124		
				AN-32	AN-225		

Figure 1. Stiffened wing structures

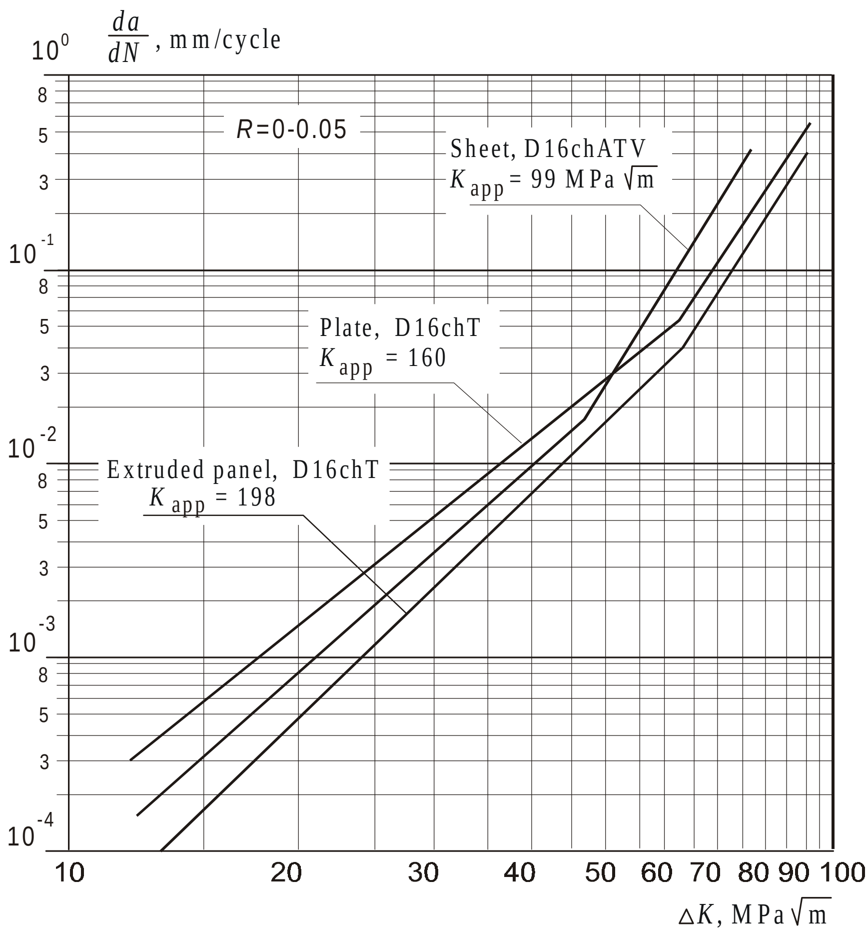


Figure 2. Crack resistance of D16chT alloys

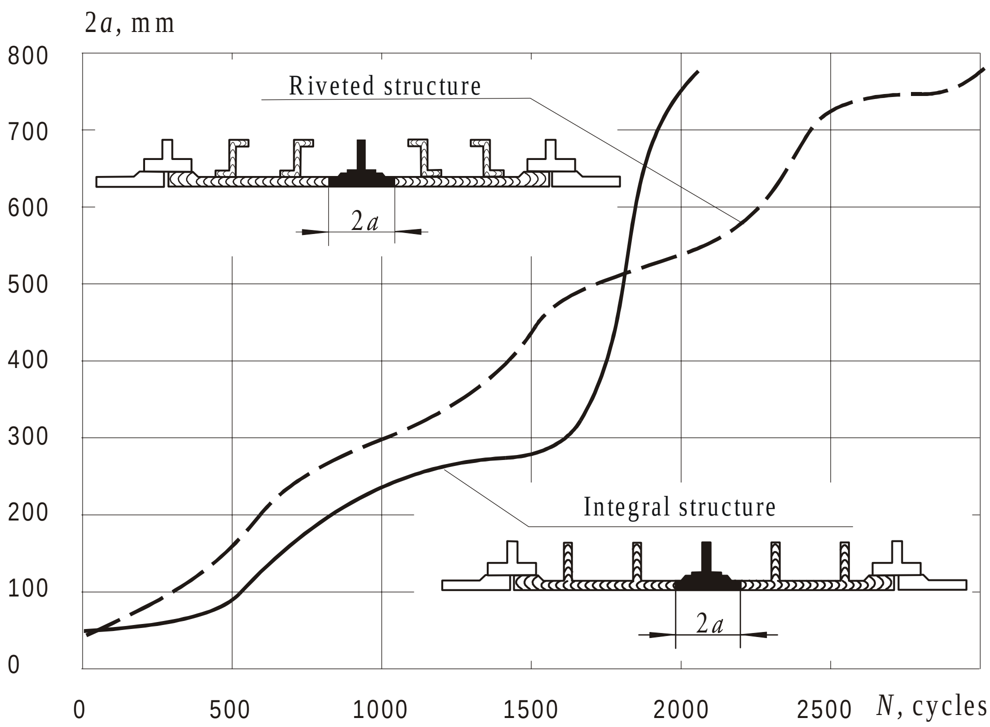


Figure 3. Duration of crack growth in riveted and integral panel skin from initial skin crack beneath broken central stringer

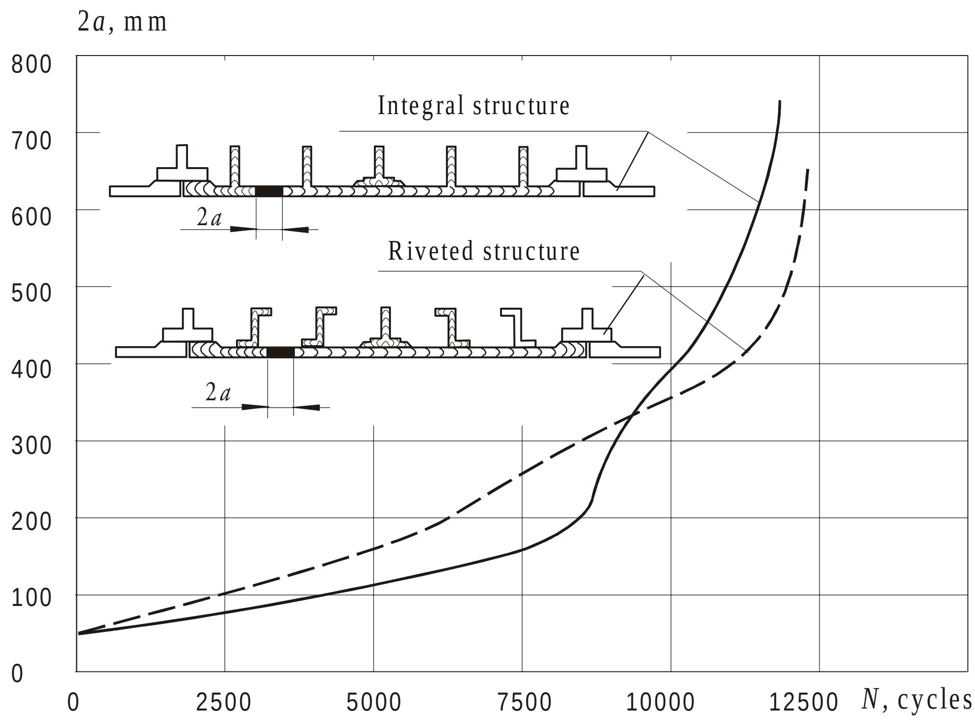


Figure 4. Duration of crack growth in riveted and integral panel skin from initial skin crack between intact stringers

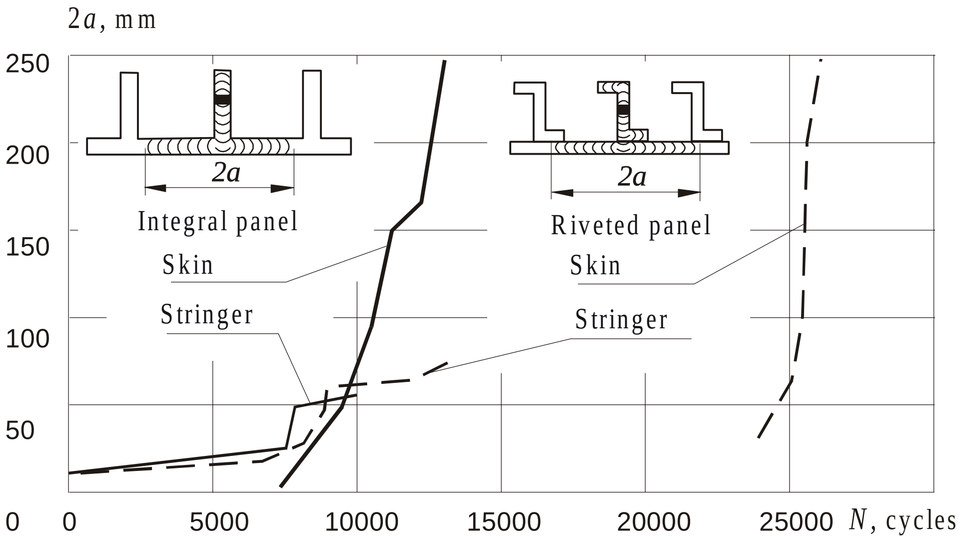


Figure 5. Duration of stringer and skin destruction in riveted and integral panels

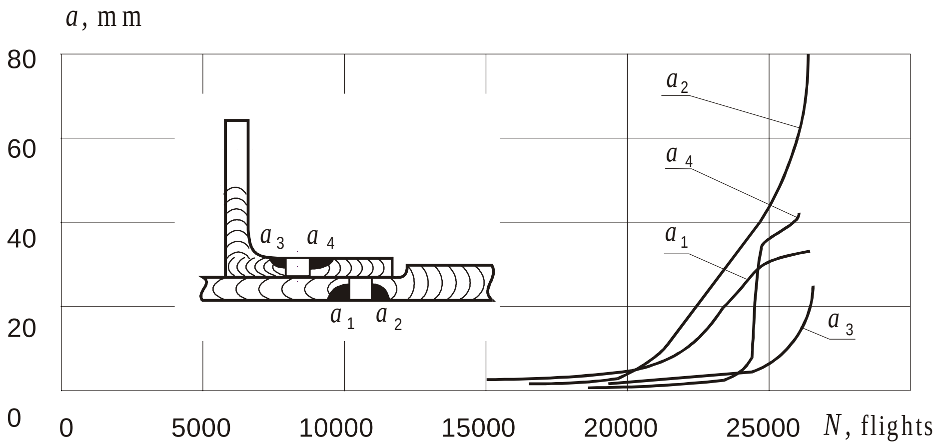


Figure 6. Simultaneous crack growth in lower wing spar and skin

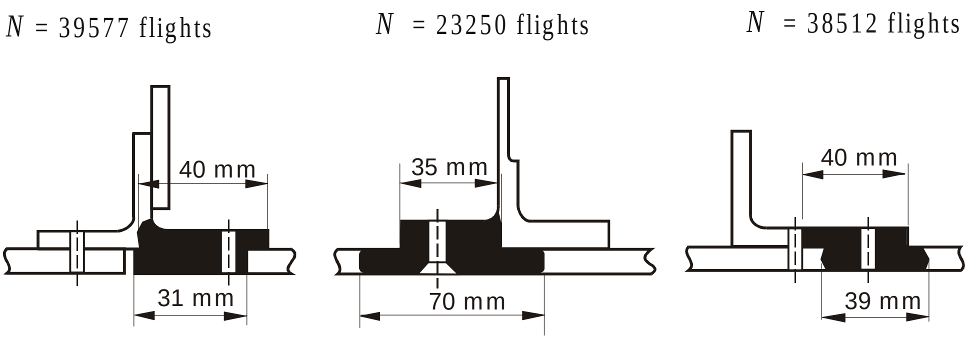


Figure 7. Simultaneous fatigue damage of lower wing spars and skin

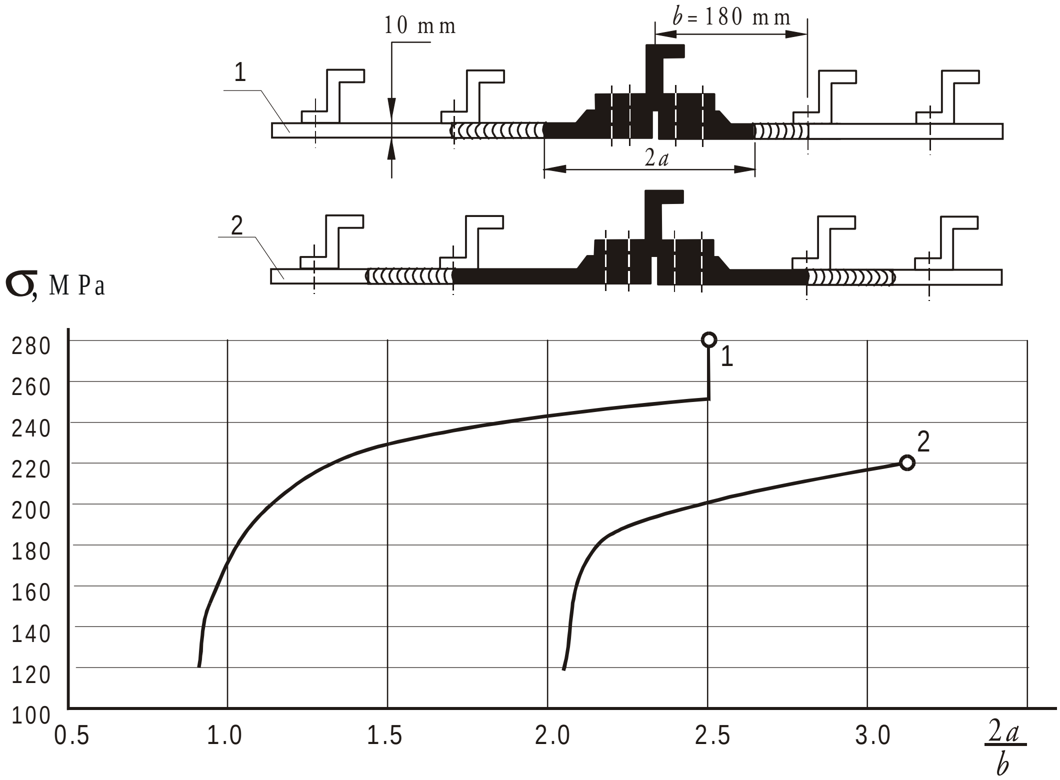


Figure 8. Residual strength of riveted D16chT panel having skin crack under broken stringer

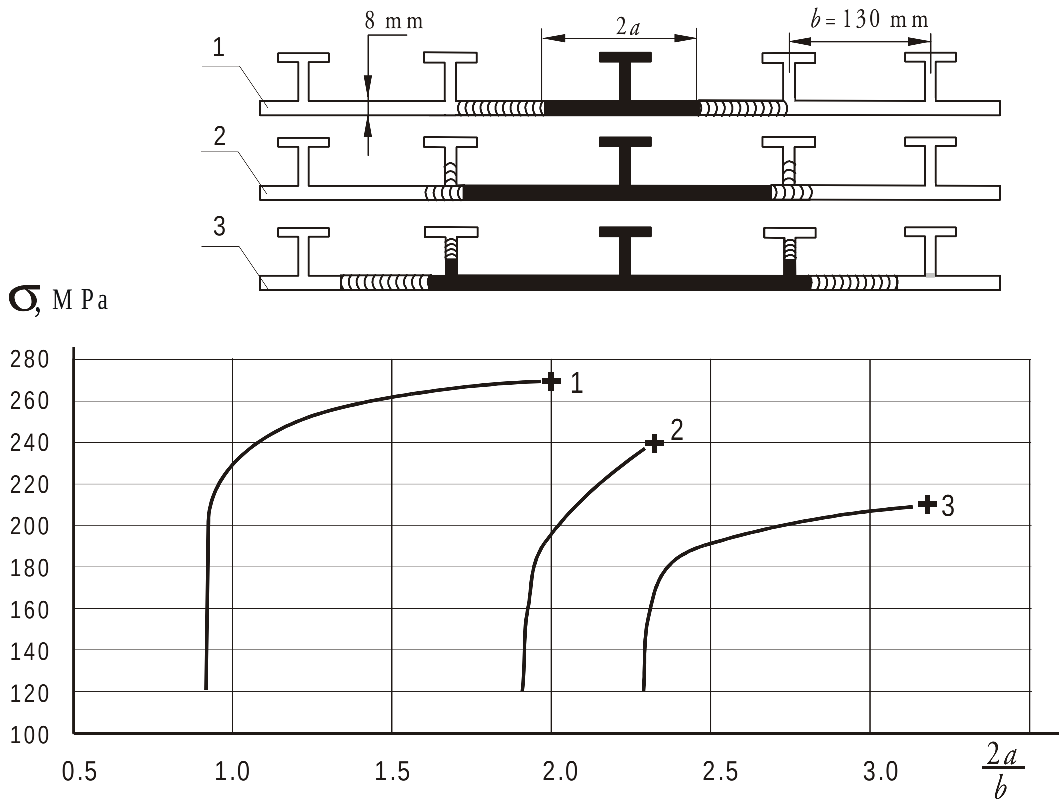


Figure. 9. Residual strength of integral D16chT panel having skin crack under broken stringer

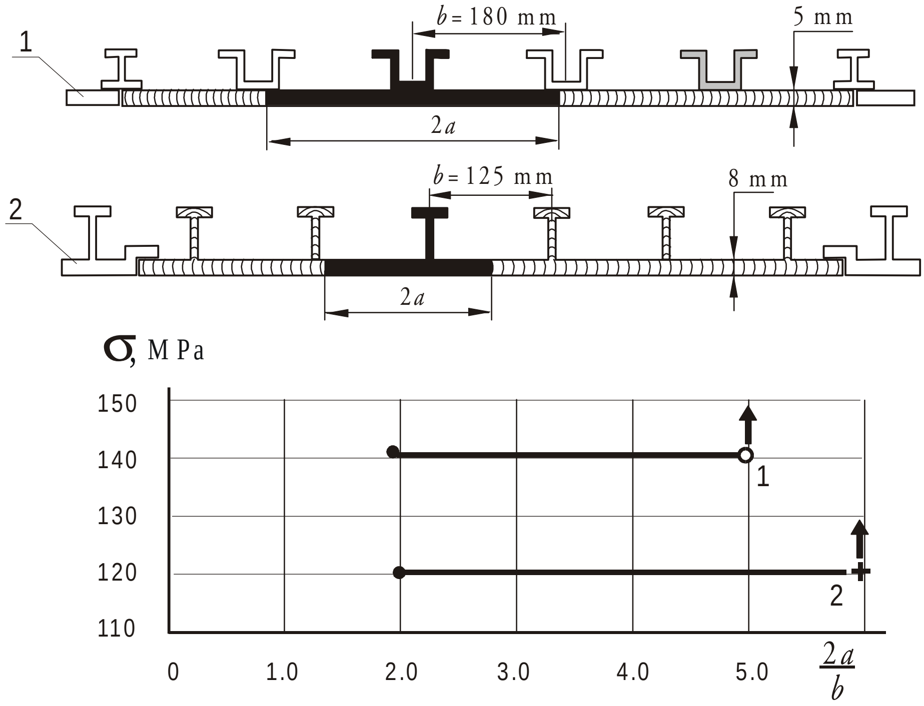


Figure. 10. Residual strength of integral and riveted wing structures having initial skin crack under broken stringer in lower wing surface; V95T1 alloy.

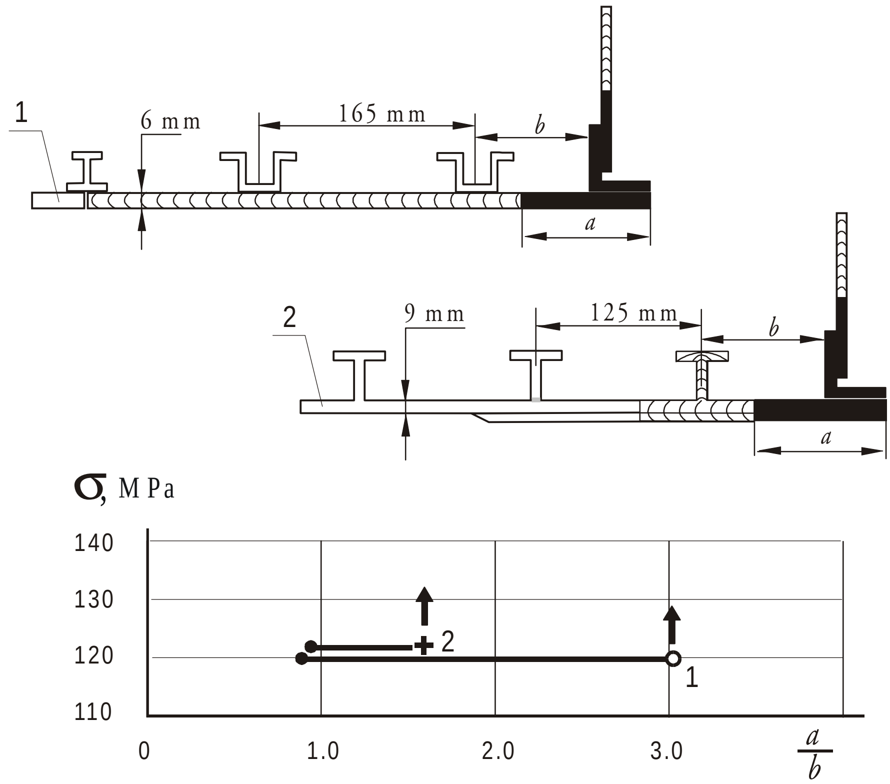


Figure. 11. Residual strength of integral and riveted wing structures having damages in rear spar and lower wing surface skin; V95T1 alloy

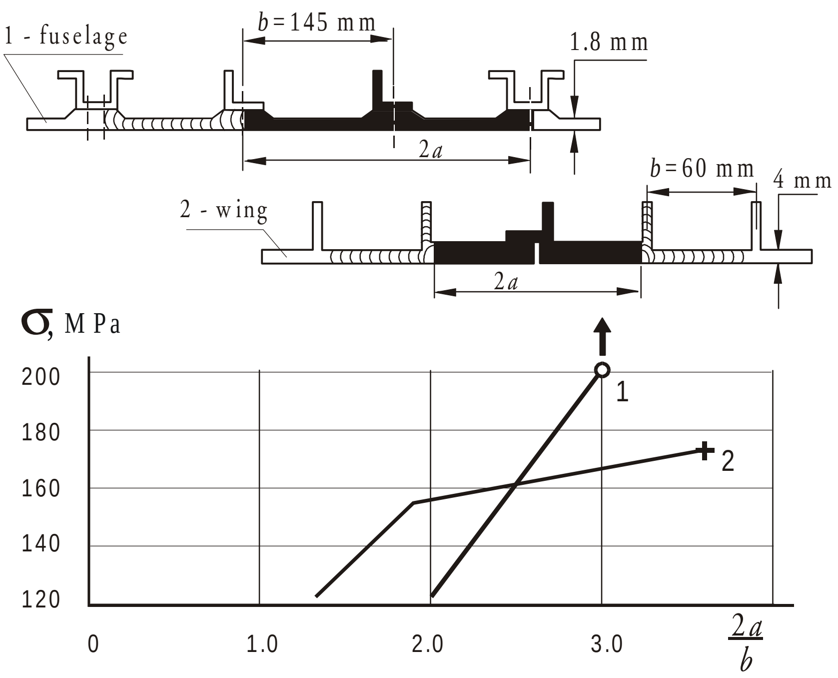


Figure 12. Residual strength of integral and riveted structure having initial skin crack under broken stringer; AK4-1T1 alloy

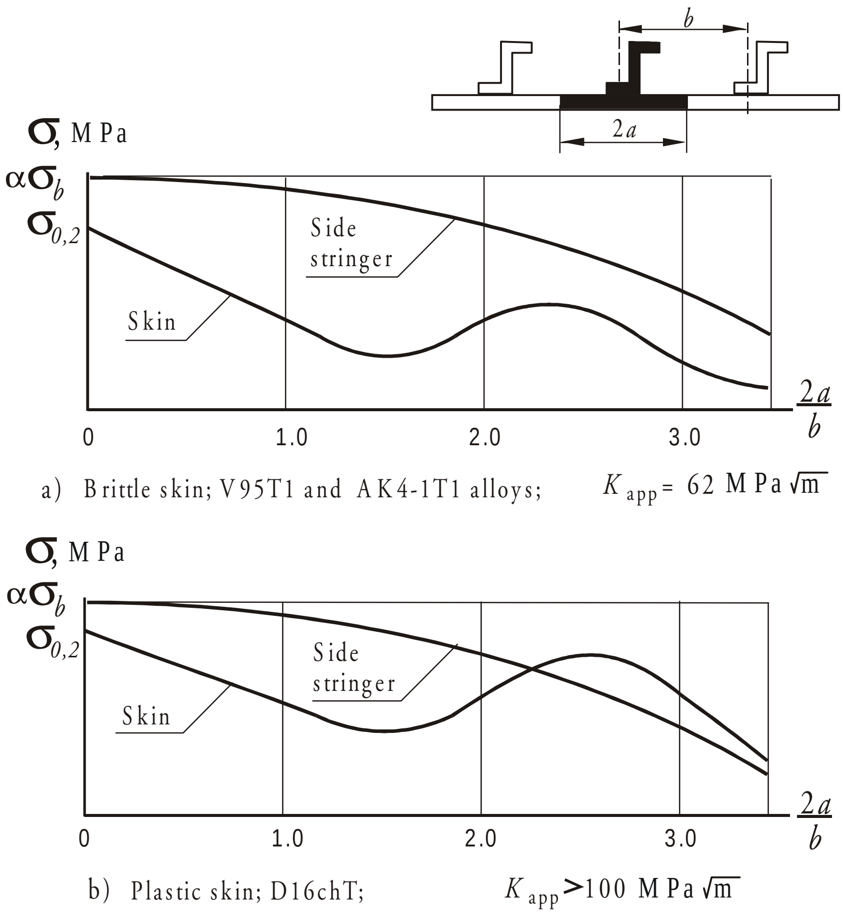


Figure 13. Residual strength diagram for riveted structure having skin crack under broken central stringer