Study on characteristics of fatigue strength of ARALL composite in constructive elements

L Adegova¹², V Frolova³ and S Losev¹

¹Department of Structural mechanics, Novosibirsk state University of architecture and civil engineering (Sibstrin), Novosibirsk, Novosibirsk Oblast 630008, Russia
²Department of Structural mechanics, Siberian Transport University, Novosibirsk, Novosibirsk Oblast 630049, Russia
³Chaplygin Siberian Scientific Research Institute of Aviation (SIBNIA), Novosibirsk, Novosibirsk Oblast 630051, Russia

E-mail: adegova@mail.ru

Abstract. Due to Fatigue Testing fatigue life of specimens made of various materials and with various flange types was estimated. Specimens with dish-shaped and ring-shape flanges were tested. Specimens were made of aluminum alloy D16chATV sheets (thickness 1.2 mm) and of ARALL with a thickness of 1.2 mm based on aluminum layers of 0.5 mm thickness. Specimens were tested under 3 levels of cyclic stress: \(\sigma_{\text{max}}=120, 100, 80\) MPa with minimum stress of \(\sigma_{\text{min}}=20\) MPa. Some of ARALL specimens were tested only under \(\sigma_{\text{max}}=100\) MPa stress level. Under each stress level were tested 5 – 6 specimens. According to the results of all specimen tests the authors plotted plotted fatigue curves. Using the Finite Element Method the stress state of specimens during cyclic stress tests was analyzed. Calculations of fatigue life of specimens were made on the basis of the offered method. Full-element and numerical experiments revealed that fatigue resistance of monolithic alloy specimens with dish-shaped flange under all stress levels is higher than of specimens with a ring-shaped flange. ARALL specimens with dish-shaped and ring-shaped flanges both according to test results have a higher fatigue resistance than monolithic alloy specimens.

1. Introduction

In modern constructions it is important to use composite materials that have high fatigue resistance and cyclic crack resistance characteristics in comparison with monolithic alloys, moreover composite materials have low density and high resistance. This type of materials includes hybrid laminated composites such as ARALL [1] and Glass laminate aluminum reinforced epoxy (GLARE) [2-7] designed by Federal State Unitary Enterprise "All-Russian Scientific Research Institute Of Aviation Materials" (VIAM). ARALL is a laminate material composed of aluminum alloy layers and Lavsan (Polyethylene terephthalate brand name in Russia)/epoxy resin layers (GLARE consists of aluminum layers and glass fibre/epoxy prepreg layers). Aluminum layer ensures a better stress-strain behavior of the composite. Glass fiber/epoxy prepreg layer ensures a better bearing strength and restrain fatigue crack opening.
2. Main part

Below are presented constructive element specimens fatigue test results. Specimen flange types differ: dish-shaped and ring-shaped flanges (Figure 1). Specimens were made of aluminum alloy D16chATV sheets with a thickness of 1.2 mm and of ARALL with a thickness of 1.2 mm with aluminum layers of 0.5 mm thickness.

![Figure 1. Specimens with different flange types.](image)

Aluminum alloy and ARALL samples were made by forging.

Some of ARALL specimens with ring-shaped flange were made separately: flanges were formed in aluminum sheet and later they were bonded with other layers during pressure process.

The test program included:

- Fatigue life of specimens was estimated on basis of full-element experiment (fatigue test). Specimens had different flange types (dish-shaped and ring-shaped) and were made of D16chATV alloy and ARALL containing 3 layers, specimen forming method also differ;
- Specimen fatigue properties were estimated on basis of numerical experiment. Specimens had different flange types (dish-shaped and ring-shaped) and were made of D16chATV alloy and ARALL containing 3 layers.

Specimens with flanges were tested under 3 levels of cyclic stress: \( \sigma_{\text{max}} = 120, 100, 80 \) MPa with minimum stress of \( \sigma_{\text{min}} = 20 \) MPa and under frequency of 11 Hz. During evaluating some of ARALL fabrication way tests were conducted only under one stress level \( \sigma_{\text{max}} = 100 \) MPa. Under each stress level were tested 5 – 6 specimens.

Test results were statistically analyzed with commonly used methods [8]. Number of cycles was \( N = 5 \times 10^6 \) cycles. Specimens that did not failure after \( N \) cycles, in statistics were considered as failure. Test results of specimens with dish-shaped and ring-shaped flanges are presented in table 1, fatigue curves are presented in figure 2.

### Table 1. Fatigue life of flanged specimens made of D16chATV sheet and ARALL containing 3 layers.

| Stress level \( \sigma_{\text{max}} \), MPa | Flange fabrication method | Fatigue life \( N_{\text{lg}} \) cycle |
|------------------------------------------|---------------------------|----------------------------------|
|                                         | Forging \( \sigma_{\text{min}} = 20 \) MPa, \( f = 11 \) Hz | Pressure bonding method |
|                                         | D16chATV sheet 1,2 mm     | ARALL sheet 1,2 mm                |
| Dish-shaped flange                      | 185 910                   | 493 430                          |
| Ring-shaped flange                      | 156 800                   | 2 444 815                        |
| 120                                      |                           |                                  |
| 100                                      |                           |                                  |
| 80                                       |                           |                                  |

For ARALL sheet 1,2 mm:

- Dish-shaped flange:
  - 185 910 cycles
- Ring-shaped flange:
  - 156 800 cycles

For ARALL sheet 1,2 mm:

- Dish-shaped flange:
  - 2 444 815 cycles
- Ring-shaped flange:
  - 435 100 cycles
Figure 2. Fatigue life of specimens with flanges.

Fatigue life of ARALL specimen with dish-shaped flange is 2 times higher than of D16chATV alloy specimens under $\sigma_{max}=120$, 100 MPa, under $\sigma_{max} = 80$ MPa during N cycles all ARALL specimens did not failure and did not crack.

Results of tests of ARALL specimens made by forging with dish-shaped flange revealed increase of fatigue life in 10 times ($\sigma_{max}=$100 MPa; $\sigma_{min}=20$ MPa) and fatigue life specimens with flange produced by pressure bonding method increased in 1.8 times in comparison with monolithic specimens. It was noticed that fatigue life of ARALL specimen fabricated by pressure bonding method significantly decreased in comparison with flanged specimens fabricated by forging (table 1, figure 2).

Fractographic analysis of fracture surface revealed that fatigue cracks initiated in wall and flange boundary zone in aluminum layer of the composite (through strained fibers). The crack was growing symmetrically to flange and perpendicular to tensile stress oriented to the specimen border. Cracks generally were first initiated in one of outer metal layers and later in other metal layer. During crack flatter out started failure in fiber layer in crimp zone radius and the crack propagation continued up to specimen failure.

It should be noticed that in ARALL specimens fatigue crack propagated slowly. The propagation stage of fatigue (crack could be observed after it reached half length $a = 5…10$ mm) occupied 20…25% of the fatigue crack total length.

When a crack initiation in aluminum layer fibers slowed the crack propagation down metal layers were unloaded. That is why fatigue failure the second stage (propagation stage of fatigue) for laminates is more important and determinant and ARALL has a higher fatigue life in comparison with monolithic alloys. During the composite delamination in the crack growth zone and in flange contour, holes were not revealed. Wall and flange boundary zone surface microanalysis revealed microcracks in all tested specimens in both stretched and compressed fibers. Cracks initiation reason is flange
forming method. This factor caused fatigue crack initiation uniformity in both ARALL and monolithic alloy specimens.

In order to estimate fatigue life of specimens (figure 1) were designed Finite Element Models (figure 3). A half of specimens was analyzed under symmetry condition for unit movement that lie on mirror plane. In order to design a model of aluminum alloy specimen were used two-dimensional PLATE elements [9-11] that consider membrane, shear, transverse, flexibility factors. In order to design a model of ARALL specimen were used LAMINATE elements [9 – 11]. Specimens were tested using three-stages loading program (figure 4): $\sigma_{\text{max}}=150, 130 \text{ и } 110 \text{ MPa}$. The highest load of $\sigma_{\text{max}}=150 \text{ MPa}$ repeated after each 120000 cycles that included 20000 cycles with load $\sigma_{\text{max}}=130 \text{ MPa}$ and 100000 of load $\sigma_{\text{max}}=110 \text{ MPa}$. Load was applied to the model upper face end and was spread through cross-section surface.

Figure 3. Finite Element Model of the specimen.

Figure 4. Loading program.

Fatigue life was estimated using traditional methods [12-20]. Figure 5 shows maximum principal stress spreading in specimens. Fatigue curve equations and fatigue life values of specimens are presented in table 2.
Table 2. Calculated fatigue life of flanged specimens made of D16chATV sheet and ARALL containing 3 layers.

| Flange fabrication method | Fatigue curve | Calculated fatigue life Np, cycles |
|---------------------------|---------------|----------------------------------|
| Forging                   |               |                                  |
| Dish-shaped flange        | D16chATV      | $N\sigma_{br}^{5.45} = 1.4767 \times 10^{16}$ | 205 229 |
|                           | ARALL         | $N\sigma_{br}^{6.16} = 1.0309 \times 10^{14}$ | 597 253 |
| Ring-shaped flange        | D16chATV      | $N\sigma_{br}^{2.62} = 2.7248 \times 10^{10}$ | 151 408 |
|                           | ARALL         | $N\sigma_{br}^{5.21} = 2.7115 \times 10^{16}$ | 1 918 667 |
| Pressure bonding method   | Dish-shaped flange | ARALL $N\sigma_{br}^{4.36} = 2.4930 \times 10^{14}$ | 354 727 |

It was calculated that fatigue life D16chATV specimens with dish-shaped flange is 1.35 times higher than of specimen with ring-shaped flange. Fatigue resistance of ARALL specimens both with dish-shaped flange and ring-shaped flange is higher in comparison with D16chATV aluminum alloy (dish-shaped flange in 2.91 times and ring-shaped flange in 12.67 times). Fatigue life of ARALL specimen with ring-shaped flange made by forging is higher than of specimen made by pressure bonding method in 5.4 times.

3. Conclusion

Thus, it can be concluded that to obtain a higher fatigue life value in monolithic alloy it is preferable to use dish-shaped flange and for ARALL it is preferable to use ring-shaped flange. For the both materials forming factor is determinant.

References

[1] Marissen R 1984 *J. Engnr. Fracture Mech.* 19 261
[2] Antipov V, Lavro N, Sukhoivanenko V and Senatorova O 2013 *J. Non-fer. Met.* pp 46–50
[3] Antipov V, Serebryakova N and Shestov V 2017 *J. Avia. Mater. and Tech.* 212
[4] Serebryakova N, Antipov V, Senatorova O, Erasov V and Kashirin V 2016 *J. Avia. Mater. and Tech.* pp 3–7
[5] Stolyankov Y, Antyufeena N, Raskutin A and Karimova S 2014 *J. Comp. and Nanostrut.* 6 25–30
[6] Senatorova O, Glushko O, Tkachenko E, Molostova I, Sidelnikov V and Legoshina S 2007 *J. Tech. of Light Alloys* 12–24
[7] Kablov E, Antipov V, Senatorova O and Lukina N 2016 *Herald of the Bauman MSTU Series Mechanical Engineering* pp 174–182
[8] Stepnov M and Shavrin A 2005 *Statistics Methods of Mechanical Test Results Analysis* (Moscow: Hand-book. Mechanical Engineering) p 344
[9] Shimkovich D 2003 *Construction Design in MSC.Visual NASTRAN for Windows* (Moscow: DMK Press) p 448
[10] Rychkov S 2013 *Construction Modeling in Femap with NX Nastran* (Moscow: DMK Press) p 784
[11] Rydakov K 2011 FEMAP 10.2.0. *Geometry and Finite Element Modeling of Constructions* (Kyiv: Igor Sikorsky Kyiv Polytechnic Institute Press) p 317
[12] Belov V and Adegova L 2009 *J. All-Russian J. Polyot* pp 19–26
[13] Belov V, Rudzei G, Kaluta A and Adegova L 2011 *J. All-Russian J. Polyot* pp 42–46
[14] Rudzei G and Adegova L 2011 *Sibnia 70-Anniversary Scientific and Technical Conf.* (Novosibirsk) (Novosibirsk: Sibnia) pp 285–288
[15] Rudzei G and Adegova L 2014 Construction Design Issues: 3rd All-Russian Conf. reports (Novosibirsk) (Novosibirsk: Novosibirsk state University of architecture and civil engineering) pp 17–24

[16] Rudzei G and Adegova L 2014 J. of Transsib Railway Studies 2 86–94

[17] Belov V, Rudzei G, Kaluta A and Adegova L 2014 J. All-Russian J. Polyot 8 24–30

[18] Adegova L 2014 J. Sci. Bulletin of NSTU 3 160

[19] Adegova L 2015 J. Sib. Transport Univ. Herald pp 49–53

[20] Adegova L 2015 J. News of Higher Educational inst. Construction 3 92–98