ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/01.3001.0012.2465

FATIGUE STRENGTH ANALYSIS OF WELDED ALUMINIUM STAIRS

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Abstract

The article presents numerical analyses and results of experimental fatigue tests of the welded stairs made from prefabricated EN-AW 6063-T66 aluminium alloy thin-walled profiles. Fatigue life analysis of welded thin-walled structures is a complicated and demanding task. Fatigue analysis of stairs was carried out according to the concept of a weak link, which was verified experimentally. The FEM method was applied in strength analysis. The conducted research allowed identifying the weak link of the structure at the welded joint. The samples stairs were subjected to fatigue tests. The fatigue tests have been conducted using specially designed set up. The experiments confirmed the numerical analysis. The cracks occurred at welded joints before expected fatigue life to fracture. Then the stairs structure was modified by changing the weld joints arrangement. The fatigue tests were carried out again and showed further weaknesses of their structure – cracking of the step profile. To precisely capture this problem, detail finite element calculations for the analysed stairs have been conducted. Applying the nominal stress method, this problem was solved changing the treads profile of the stairs step. The last improvement in the construction was sufficient to satisfy fatigue strength requirement of the analysed structure. The weak link approach and nominal stress method proved to be an effective tool in fatigue analysis of the examined structure.

Keywords: *fatigue tests, welded joints, aluminium thin-walled constructions*

1. Introduction

Many constructional welded elements are subjected to varying loads in time during operation, which can cause fatigue damage to the material [1-6]. It often occurs at maximum stresses significantly lower than the ultimate strength R_m, or even from the yield strength R_e or $R_{0.2}$ [3].

Depending on the material of structure, the geometry of elements and working conditions, fatigue cracks have the character of plastic-brittle cracks [2]. Brittle cracks are particularly dangerous because the fatigue crack is often left unnoticed, and develops with high intensity, usually leading to dangerous disasters. Statistical studies of the causes showed that about 80% of all cracks in structures are caused by material fatigue, and only about 20% – exceeding the permissible stresses at static load.

A variety of fatigue life assessment methods have been proposed in the literature [5-10]. Generally, the methods used for fatigue life estimating are based on strains, stresses, or stress intensity factors. We can distinguish four common assessment methods applied for the fatigue life estimation of metal structures. These methods may be divided into two groups: the global and local methods. The most often used, also categorized as a global method is the nominal stress method [3, 7, 8]. In the group of local methods, are the hot spot stress method, the effective notch stress method and the crack propagation approach [2, 5, 6, 10]. A common characteristic factor for these approaches is the need to find a weak link in the structure, which characterizes in high stress/strain concentration [11-13]. To get this information, the analytical methods based on the linear elastic theory are applied. For structures that are more complex numerical methods such as the finite element method (FEM) or the boundary element method (BEM) [14-16] are commonly used.

The accurate FEM application for obtaining the design stress/strain information is essential to perform further fatigue life analysis. Researchers have been making a lot of effort in developing methods and procedures for the accurate determination of stress concentrations and fatigue life of welded components. Their efforts resulted in the development of many strategies.

The article presents numerical FEM analyses and results of experimental fatigue tests of the welded aluminium structure such as stairs. The construction was fabricated from thin-walled prefabricated EN-AW 6063-T66 aluminium alloy profiles. Strength and fatigue analysis of stairs were carried out according to the concept of a weak link, which were verified experimentally. Considering whole structure the nominal stress method was used generally.

2. FEM analysis of the structure

The analysed structure was stairs made of welded thin-walled prefabricated EN-AW 6063--T66 aluminium alloy profiles. EN-AW 6063-T66 aluminium is a type of 6063 aluminium alloys. It is furnished in the T66 temper. To get this temper, the alloy is solution heat-treated and artificially aged. The chemical composition and the mechanical properties of the alloy are listed in the Tab. 1 and 2.

Tab. 1. The chemical composition of EN-AW 6063-T66 in AW %

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Inclusions	Al
0.20-0.6	0.35	0.10	0.1	0.45-0.90	0.1	0.1	0.1	0.15	Balance

Tab. 2. Mechanical properties of EN-AW 6063-T66

Aluminium alloy	Temper	Wall thickness of the profile	Young's modulus	Yield strength	Tensile strength	Fatigue strength	Elongation
		t [mm]	E [MPa]	$R_{0.2}$ [MPa]	R_m [MPa]	Z [MPa]	A [%]
EN AW 6063	T66	$t \leq 10$	68	200	245	95	9

The whole stairs construction consists of 9 steps and the platform on the top. External dimensions of stairs were high 2000 mm, with 610 mm and depth 3000 mm. In the numerical and further experimental analysis, the three steps stairs samples have been designed, manufactured and used in experiments (Fig. 1). Detailed test procedures regarding strength tests for the stairs has been taken from the following normative acts [17, 18].

The shape of used aluminium elements and are shown in Fig. 2. In this figure, the initial weld connections have been also depicted.

According to the standard [17], durability testing does not have to be carried out for individual components, joints and configurations of scaffolding systems. However, welded aluminium steps of stair steps should be checked for durability, both computationally and by static and fatigue testing. For fatigue procedure, a cyclic load value of 1.5 kN should be applied to the surface of the stair tread, measuring 100 mm × 100 mm. The step should be checked for two applied load positions:

a) in the middle of the stair tread (Fig. 1),

b) in such a position that the load is situated in distant by no more than 100 mm from the tread centre.

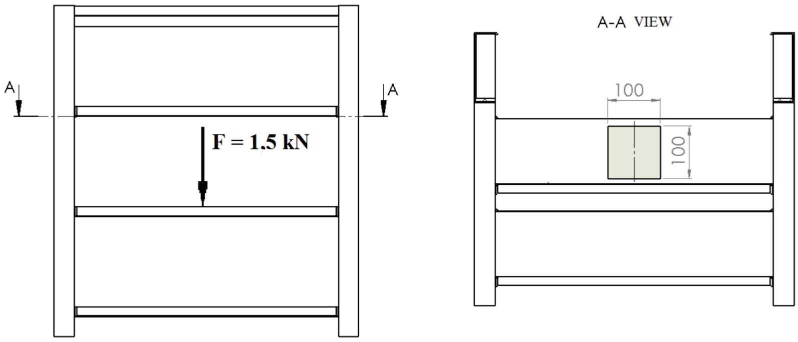

Fig. 1. Examined stairs sample – load in the middle of the staircase

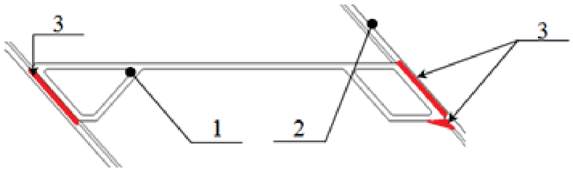

Fig. 2. Scheme arrangement of welds for the examined aluminium stair-step: 1 – tread, 2 – stringer (side member), 3 – continuous fillet weld

A single test of a stair tread should be considered as a confirmation of compliance if the structural integrity is maintained and there are no signs of damage due to fatigue at the end of the test. The tested stair samples are to be carefully checked after each test. Special attention should be paid to the welded areas. For the test to be successful, three stair samples tested must meet the criteria set for them.

Strength analyses using finite element method (FEM) were carried out for the designed welded aluminium stairs sample. Fig. 3 and 4 show a solid mesh model made for a stairs sample and the results of strength calculations using the FEM.

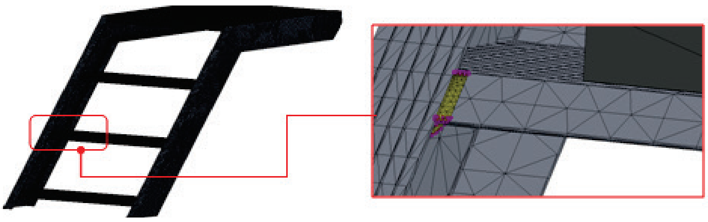

Fig. 3. A solid mesh model made for a sample of stairs

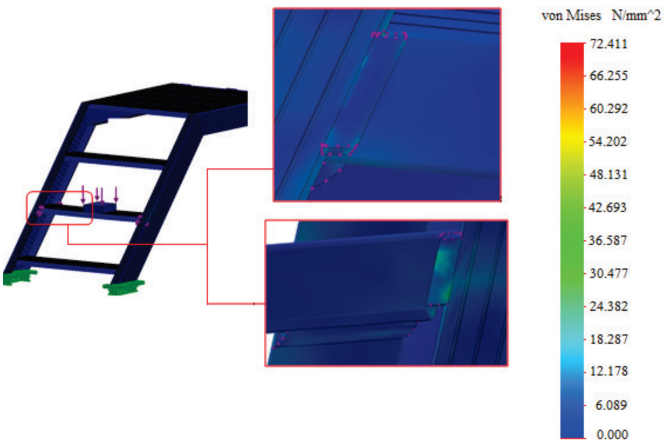

Fig. 4. Reduced stresses according to the Huber-Mises-Hencky hypothesis for a model of a stairs sample – load applied in the middle of the tread

On the basis of the conducted strength analyses (FEM), a critical construction node (weak link) was selected for further analysis [19]. As it was expected, the high-stress areas have been found in the left filled weld. However, this maximum stress level has not exceeded available stress. Imperfections due to welding may have negative effects on fabrication accuracies and result in low strength of structures that can lead to premature failures. Detail analysis of node geometry and stress concentration in weld connection has not been done. Quality of welds was not perfect and it was extremely difficult to model it. Therefore, to check the durability the experimental fatigue tests have been suggested.

3. Experiments

Tests of fatigue strength were carried out for the same samples as analysed numerically. Experiments were performed according to the following program: the load applied in the centre of the stair tread, value of the of the force (load) in a sinusoidal cycle – $F = 1.5$ kN. In the initial experiments, two stairs samples were used.

The fatigue strength tests were carried out in the Institute of Mechanized Construction and Rock Mining Laboratory (Fig. 5). The loading system was designed to satisfy test requirements. Tests have been conducted under stress control mode, at a frequency of $f = 0.2$ Hz, in a sinusoidal mode, and stress ratio $R = 0$.

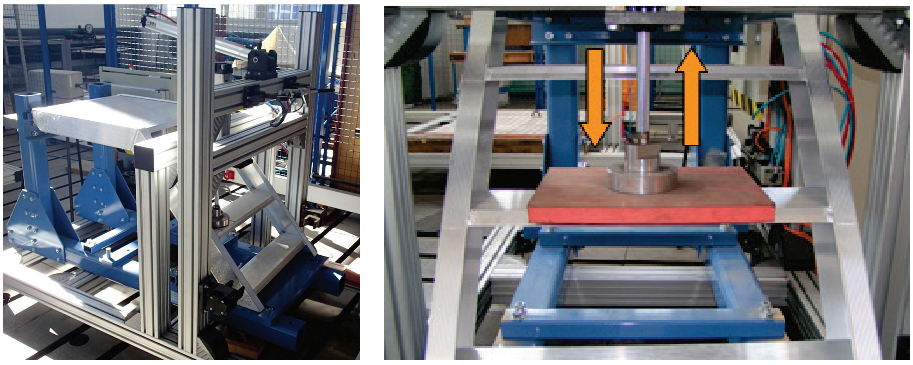

Fig. 5. Stand for fatigue testing

The tests have confirmed FEM calculations, that the welded joint is the weakest element of the tested stairs. In the structure due to high-stress, concentration in the welded node first long crack (~1 mm) appeared after about 7,500 cycles of the applied load for one sample and nearly 15,000 cycles for the second, respectively [19]. The significant scatters of fatigue life to crack initiation are mainly due to high geometrical imperfections in welds. In Fig. 6, the relation between measured crack length and number of cycles for sample 1 is depicted.

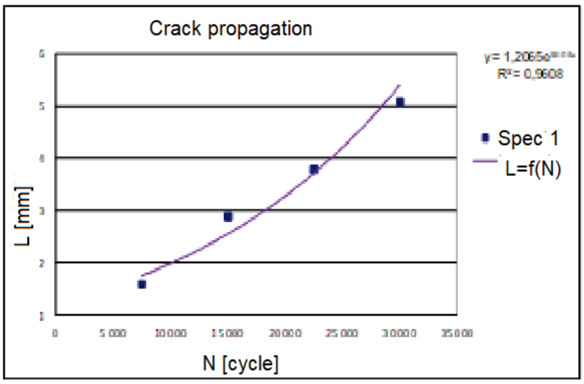

Fig. 6. Crack length vs a number of cycles

In order to eliminate this problem, changes have been made in the tested construction node of the stairs. The location of the welds was not decisive from the constructional point. The applied changes consisted in the modification of the weld connection system. The modified system of weld connections is shown in Fig. 7.

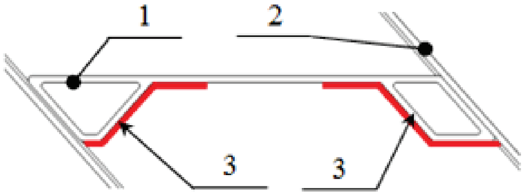

Fig. 7. Modified scheme of the arrangement of welds for the examined aluminium stair-step: 1 – tread, 2 – stringer (side member), 3 – continuous fillet weld

The conducted FEM analysis for this modified stairs sample has shown a great reduction of stress concentration in the welded areas, but the next high-stress area (hot spot) was found in the centre of the tread. For calculated equivalent stress according to the Huber-Mises-Hencky hypothesis, expected fatigue life of the structure $N_f = 10^5\text{-}1.5\cdot 10^5$ cycles based on the nominal stress method has been estimated.

Then, the tests of fatigue strength of the structure of stairs in a real size were done. Two pieces of stairs were used. These tests were carried out for the same loading conditions, i.e. a load of vertical sinusoidal variable force with an amplitude $F = 1.5$ kN applied in the centre of the stair tread. The setup and designed stairs during fatigue tests are shown in Fig. 8.

Fig. 8. The set up for fatigue tests

During the tests, a number of cycles and the degree of deflection of the tread were recorded (Fig. 9). The condition of welded joints in the tested node was monitored.

As a result of the tests, it was observed that the stair tread pattern of the stairs has been damaged (broken) in the middle of the step after 87 934 cycles. The second stairs sample has shown similar fatigue life, i.e. 91 912 cycles. The scatters of the experimental results, for such constructions can be considered as small.

In Tab. 3 measured total treads deflection values at the end of each test have been presented. In Tab. 4, the results of measurements of the final crack length of the stair tread are presented (Fig. 10).

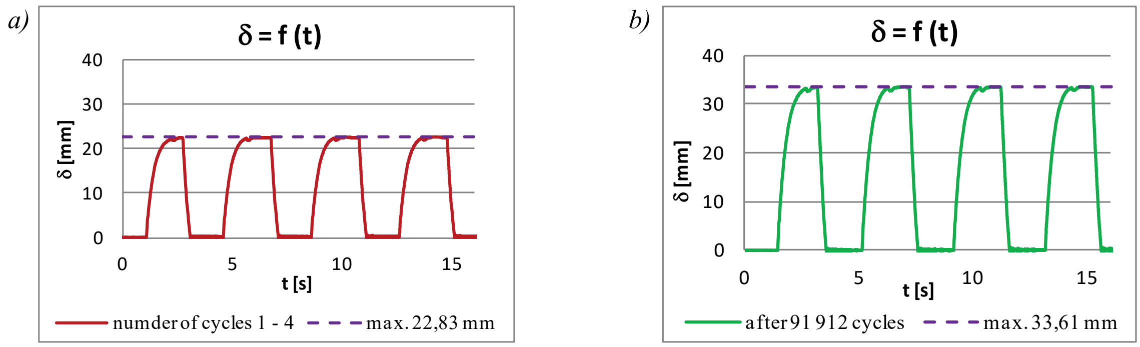

Fig. 9. Diagram of deflection of the stair structure (sample No. 1) as a function of time: a) value for cycles N from 1 to 4, b) value for cycles N from 91 912 to 91 916

Tab. 3. The results of measurements of the maximum deflection of the analysed aluminium structure

Number of cycles		N_f [cycle]	0	87 934	91 912
Max. deflection	Sample No. 1	f [mm]	22.83	–	33.61
	Sample No. 2		23.21	32.12	–

Tab. 4. Results of measurements of the final crack length of the stair tread

Number of cycles		N_f [cycle]	0	87 934	91 912
Crack length	Sample No. 1	L [mm]	0	–	29.00
	Sample No. 2		0	23.40	–

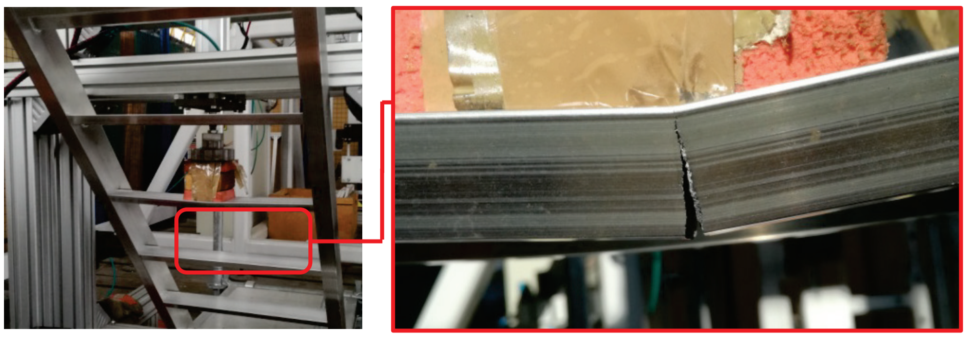

Fig. 10. View of stairs sample after damage due to fatigue load.

The obtained fatigue life of construction was approximately 50% smaller than expected. It was surprised since the initial FEM calculations have not indicated such a discrepancy. Whoever, the FEM calculations of this structure are quite complicated and it appeared that probably analysis has been not enough accurate [15, 16]. Therefore, more detail FEM calculations have been conducted. The new calculations have shown about 6% higher stress level in the hot spot that was primarily calculated. This increase level of stress was the reason for underestimating the fatigue life. The obtained higher stress level was approximately corresponding to the obtained fatigue life of the structure. Because the required fatigue life of designed stairs structure was at least $N_f = 3 \cdot 10^5$ cycles, based on the results, applying nominal stress method a new more rigid cross-section profile of stairs tread has been proposed. The final experimental tests confirm the effectiveness of the applied procedure.

4. Conclusions

In the strength and fatigue analysis of the stairs construction manufactured from prefabricated EN-AW 6063-T66 aluminium alloy profiles, the concept of a weak link was used. In the initial analysis, stair samples consist of three steps and platform has been used. On the basis of strength analysis of the structure using the finite element method (FEM), the areas of occurrence of significant stress concentrations in welded joints were determined. However, the maximum stress level does not exceed available stress, but due to the low quality of welds, the detail FEM calculations were difficult to conduct. Therefore, new weld connections have been proposed for stairs construction. On the basis of the experimental results, the welding system was optimized in the tested welded joint. Repetitive tests for the modified construction of stairs have revealed a new source of crack initiation - in the stair tread profile. To precisely capture this problem detail finite element calculations for the analysed stairs have been conducted. The new calculations have indicated about 6% higher stress level in the hot spot that was primarily calculated. Based on the nominal stress method this problem was solved by changing the stiffness – treads profile of the step. The last improvement in the construction was sufficient to satisfy fatigue strength of the analysed welded stairs. In complex structures, it is essential that the accuracy of the fatigue life predictions based on analytical or/end numerical methods, for example, FEM, if it is possible should be verified experimentally. The weak link approach and the nominal stress method used in the analysis proved to be an effective tool in fatigue analysis of the examined construction.

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Manuscript received 11 December 2017; approved for printing 15 March 2018