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ASSESSMENT OF THE FATIGUE BEHAVIOR OF REPAIRED ALUMINUM CARBODY STRUCTURE

Goran SIMIĆ[1]
Dragan MILKOVIĆ[2]
Vojkan LUČANIN[3]
Jovan TANASKOVIĆ[4]
Milan POZNANOVIĆ[5]

Abstract *– Aluminum carbody structures vs. steel structures have an increasing share in rail vehicle passenger fleet. New trams for Belgrade city transport with aluminum carbody structure after approximately three years of service, suffered from cracks. The first repair made by manufacturer was only partially successful. Two years after repair some cracks reappeared. This paper deals with some specificity of the aluminum structures repair process. The issue of the aluminum structures fatigue is compared with the fatigue of common carbody steel structures. Stress measurements in the repaired welding zone after second repair and reinforcement are presented. The test was performed with fully loaded tram under typical service conditions. Assessment of the future fatigue behavior is made based on the analysis of measured data.*

Keywords – carbody, aluminum, cracks, fatigue, repair.

1. INTRODUCTION

The strength of aluminum alloy and steel structures has many important differences. Among them, the significantly lower fatigue strength in the welded zones, in the case of aluminum alloys, requires special attention.

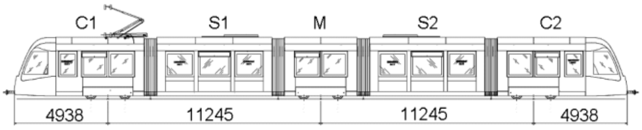


Fig.1. 5- module articulated tram

In the year 2011/2012, the Belgrade City Transportation company has acquired 30 articulated five-module low-floor trams (Fig.1) with aluminum alloy carbody structure. Modules C1, M and C2 rests on the bogies, while modules S1 and S2 are articulated connected between C and M modules. After less than three years of service, in the carbody structure appeared fatigue cracks.

2. MECHANICAL CHARACTERISTICS OF ALUMINUM ALLOYS WELD ZONES

Rail vehicles structures require aluminum alloys suitable for extrusion, eldable, with good mechanical properties after welding and with good corrosion resistance in welding zones. Two groups of alloys dominates in rail vehicle structures: AlMgSi (international alloy designation 6000) and AlMgZn (7000).

Static mechanical characteristics of both groups for base metal (examples are listed in table 1) are comparable to carbon steel S235 or S275. However, immediately after welding, in the heat-treated zones mechanical characteristics significantly drop, and after few months of ageing process partially recover. AlZnMg alloys recover mechanical properties up to 80-90% of the original metal, and AlMgSi alloys only to 50-60%.

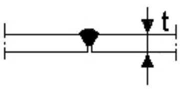
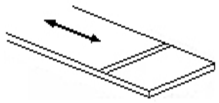
Fatigue characteristics of welded joints of aluminum alloys are also significantly lower than corresponding characteristics of steel welds. Table 2 gives examples for steel and table 3 for corresponding aluminum alloy welding.

[1] University of Belgrade Faculty of Mechancal Engineering, Belgrade, gsimic@mas.bg.ac.rs
[2] University of Belgrade Faculty of Mechancal Engineering, Belgrade, dmilkovic@mas.bg.ac.rs
[3] University of Belgrade Faculty of Mechancal Engineering, Belgrade, vlucanin@mas.bg.ac.rs
[4] University of Belgrade Faculty of Mechancal Engineering, Belgrade, jtanaskovic@mas.bg.ac.rs
[5] University of Belgrade, Faculty of Mechanical Engineering, Belgrade, mn.poznanovic@yahoo.com

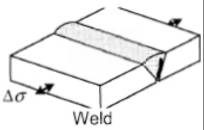
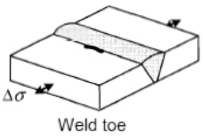
Tab. 1. Mechanical characteristics of representative Al alloys (heat-treated and artificially aged - T6)

Alloy		AlMgSi1 (6082)	AlZn4,5Mg1 (7020)
Base metal	R_{p02} (N/mm^2)	235	270
	R_m (N/mm^2)	275	330
	A_5 min (%)	9	10
Welded zone	R_{p02} (N/mm^2)	50-60% of base metal	80-90% of base metal
	R_m (N/mm^2)		

Tab.2. Fatigue category examples of steel welds [1]

Detail category	36	71
Construction detail		
Description	But welds made from one side only	But welds made from one side only when full penetration checked by appropriate NDT

Tab.3. Fatigue category examples of Al-alloy welds [2]

Detail category Δσ–m₁	18-3,4	45-4,3 / 40-4,3
Construction detail Initiation site		
Type of weld	Partial penetration	Welded one side only, full penetration without backing
Joint part		Flats, solids
Quality level acc. to EN ISO 10042		
Internal	D	B / C
Surface and geometric	D	B / C

First number of detail category denotes reference fatigue strength (at $2 \cdot 10^6$ cycles). Welded joints of aluminum alloys have reference fatigue strength 50 to 60% of the corresponding steel welded joints. This makes aluminum alloy carbody structures more susceptible to fatigue cracks, which requires a special care in construction design.

3. CRACK APPEARANCE HISTORY

Figure 2 shows the carbody structure of first tram module C1.

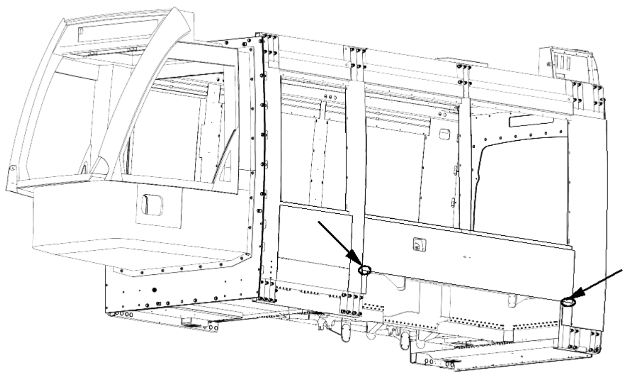


Fig.2. Carbody structure of the module C1 with initial crack positions

The first cracks arise in the corners of the cuts for bogies, along horizontal welds, marked in the figure 2 with arrows. In some units initial cracks appeared after only 20.000 service kilometers. In the next phase, the cracks propagated along vertical weld connecting vertical posts with horizontal profiles (figure 3).

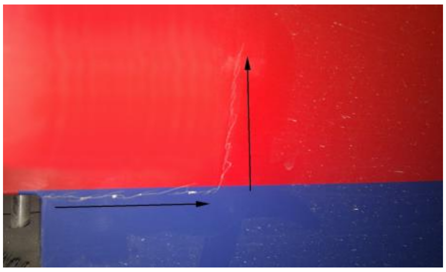


Fig.3. Crack propagation from bogie space corner

Later, some cracks appeared in the lower corners of the windows and in some cases along horizontal welding connecting small post between windows with horizontal profiles (figure 4).

Fig.4. Cracks along window welds

The manufacturer made analysis of all three types of cracks. Analysis suspected following causes of the crack appearance:

- high vibrations as consequence of the bad infrastructure,
- welding quality failures and
- lower weld thickness caused by esthetical outside weld grinding.

It can be remarked that new trams circulates mainly on renewed tracks along with other old steel structure trams that do not have problems with cracks.

First reparation performed by manufacturer included corrective action consisting of:

- corrective welding at all places where vertical cracks appeared and all places where window post horizontal cracks appeared, including added backing,
- in the corners of the bogie space, in the whole fleet the 4 mm plates were replaced with 6 mm plates. A rib supporting a plate was added,

Less than two years after first reparation, cracks in the corners of the bogie space as well as few in other locations reappeared.

In order to better understand the causes of this and some other problems, manufacturer performed test ride with measurements of different accelerations, strokes in primary and secondary suspension etc.

Based on the test results, manufacturer blamed absence of transition curves, which causes occasional impacts on rotational stoppers between carbody and bogie frame, important crack appearance cause.

However, the number of the hard curve entrance impacts is too low to provoke typical fatigue cracks.

The manufacturer increased the stroke of the longitudinal stoppers of the rotary movement of the carbody and made repair of repeated cracked welded joints. In the bogie opening corners this time were used plates with 10 mm thickness with prepared shaped overlap in order to achieve full penetration. The proposal to round the shape of plates in the corners and to make repair in the whole fleet, not only on affected places, was from manufacturer rejected.

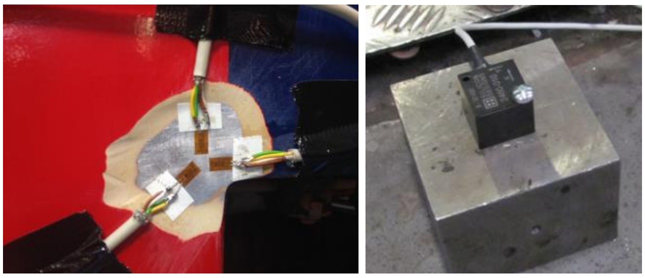
After that, a new test was carried out with a maximum loaded tram. Measurements of different accelerations and relative movements in primary and secondary suspension were done, focused on curve transition performance.

The authors of the paper used this opportunity to make measurement of the stresses in the primary crack appearance zone (corners of the bogie space).

4. STRESS MEASUREMENTS IN THE CRACK APPEARANCE ZONE

At one corner of bogie cut in the lateral side of carbody, in the immediate vicinity of the repaired weld, was performed measurement with strain gauges in 0/45°/90° rosette arrangement (Figure 5a). At two other corners the measurement was made with strain gauges placed perpendicular to weld. The strain gauges HBM 6/120LY13 for aluminum measurement with 6 mm base were used.

Three–axial acceleration measurements were performed with SD2460-010 pickup placed on the floor with the aim to correlate the appearance of high stresses to acceleration amplitudes. In this way, stress causes like curve passing, acceleration, braking, vertical or lateral track irregularities could be identified.



a) strain – gauges b) accelerometer

Fig.5. Measurement sensors

The aquisition was performed using HBM Quantumx MX840a device and Catman DAQ software.

For the test ride the tram was loaded with sacs filled with sand, simulating maximum design load. Test was performed along all parts of Belgrade tram network where new trams circulate: depot "Sava" – Blok 45 - Banovo brdo – Ustanička - depot "Sava". The total length of the tracks where the test were performed was 34 km. Test run included accelerating, driving with normal service speed, braking and stopping on all stops, to obtain stress history under normal service conditions.

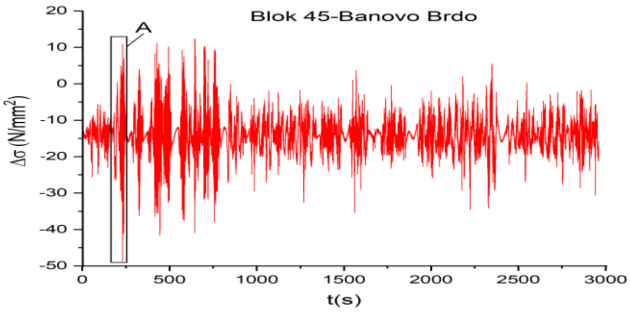


Fig.6. Measured stress, worse track

Figure 6 shows the example of stress measurements between stops Blok 45 and Banovo Brdo. It can seen that the first part of the track is in a worse state, giving larger stress spans.

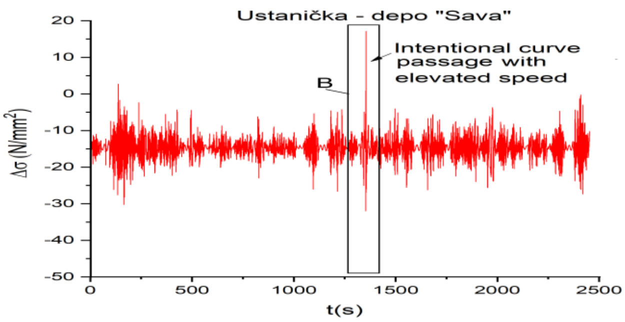


Fig.7. Measured stress, better track

Figure 7 shows the example of the stress measured between stops Ustanička and depot "Sava". The smaller average stress spans are consequence of better track quality. There is one exception. In order to test effect of longer stroke to rotational stoppers of carbody, intentionally passing of the curve to Resavska street was at speed of approximately 18 km/h instead of regular 10-12 km/h (detail B).

Figure 8 shows the detail B of the curve passing, where on the exit from the curve the singular stress span reached 50 N/mm^2.

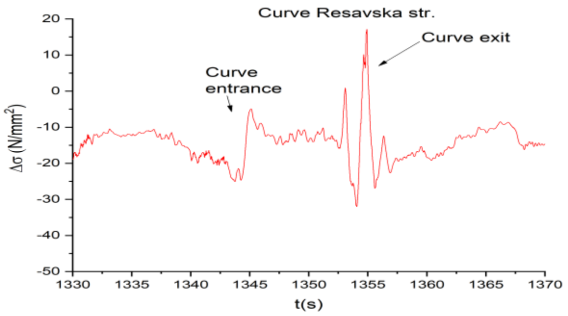


Fig.8. Detail B (curve Resavska str.)

In the same scale figure 9 shows detail A from figure 6 corresponding to straight track passing in Jurija Gagarina street. It can be seen that stress continuosly pulsate with spans from 30 to 60 N/mm^2. Correlation with acceleration measurements shows that these stress alterations origin from roll movement caused by track twist i.e by carbody torsion.

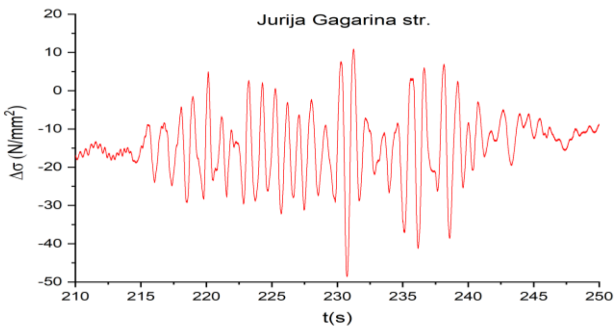


Fig.9. Detail A (J. Gagarina street)

5. CRACK FREE LIFE PERIOD ASSESSMENT

In order to assess fail free life period, expecting after repair of weld cracks, the stress span evaluation was performed. First step was to select one of the different methods of cycle counting that can be applied.

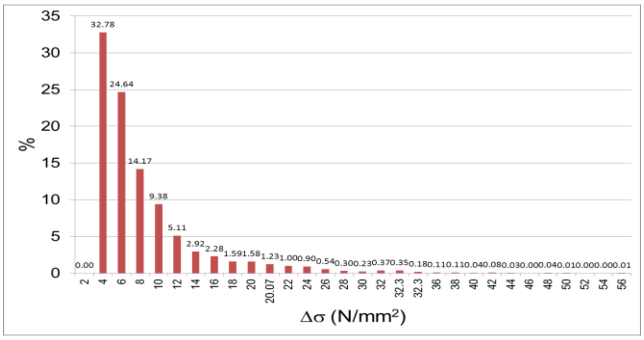


Fig.10. Stress distribution hystogram

In the cases of long stress histories obtained from measured strains in actual structures in [2] is recommended to use Rain-flow method. This method [3] was applied to analyze measured stresses.

Figure 10 shows resulting distribution histogram of the stress ranges. The data are extrapolated on 30-year service life and presented in S-N diagram in figure 11. Calculation of accumulated damage according to Palmgren-Miner damage hypothesis gave value 3.3.

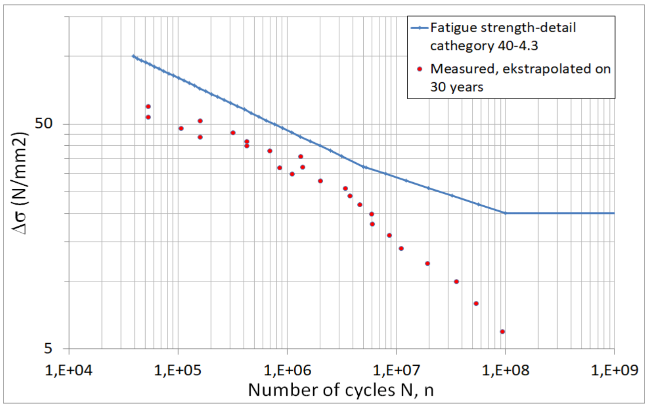


Fig.11. Extrapolated S-N diagram basd on test

6. CONCLUSION

Stress analysis made using results obtained from service like test revealed that the majority of high stress ranges originate from roll movement i.e. from carbody torsion. Result of calculation of accumulated damage based on Rain-flow method cycle count and Palmgren-Miner linear damage hypothesis indicates possible repetition of cracks after estimated mean service time of approximately nine years. However, several parameters can influence this estimation. Having in mind that the test was performed with full load, under average load a longer period to new crack initiation can be expected. Deterioration or renovation of tracks in such a long period is also parameter that shall be additionally taken in account. Supposed welding quality is also an influencing parameter, etc.

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