XVIII SCIENTIFIC-EXPERT CONFERENCE ON RAILWAYS RAILCON '18

# COMPARATIVE ANALYSIS OF FATIGUE STRENGTH OF AN Y25LS-K BOGIE FRAME BY METHODS OF UIC AND DVS 1612

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***Abstract*** *– This paper contains the results of the fatigue analysis of the Y25Ls-K bogie frame. Fatigue analysis have been made using the Finite Elements Method in the Department of Railway Engineering at the Technical University – Sofia and the fatigue tests of the bogie frame have been carried out in the Testing laboratory VUZ in Czech Republic. The software product SolidWorks has been used. The comparative analysis is based on the EN 12663, ERRI B12/Rp 17 and 60, DVS 1612-2014 standards. The assessment is made by different methods: Moore-Kommers-Jasper (MKJ) diagram, Goodman-Smith diagram and the method proposed in DVS 1612.*

***Keywords – bogie, FEM, calculations, fatigue.***

## 1. INTRODUCTION

In the present work, a comparative analysis of different methods for estimating the probability of the occurrence of cracks in the welds caused by fatigue of the material in metal constructions (MKJ diagram, Goodman - Smith diagram, ERRI and DVS 1612-2014 [1-5] ) is presented. The object of the study is a Y25Ls-K bogie designed for freight wagons developed by Transvagon AD. The strength analysis of the object was done in the Department of Railway Engineering at the Technical University of Sofia, taking into consideration the normative documents [6-8]. Based on these, 19 load cases describing the behavior of the structure during operation were determined.

## 2. ANALYSIS OF NORMATIVE DOCUMENTS

Modern methods for simulation and modeling (including the Finite Element Method) allow theoretically with great precision to create complex mechanical products with parameters close to the optimal ones. One of the serious problems in the field of railway wagon bogies is the presence of failures due to insufficient dynamic strength. The main regulatory documents related to the railway equipment [9] are: UIC - ERRI B 12 / RP 17 and ERRI B 12 / RP 60 [1. 2]; EN 12663-1, EN 12663-2 [3, 4] - for wagons; EN 13749: 2011 [6] - design of bogies. Standards EN 1993-1-1: 2005, EN 1993-1-9: 2005 and EN 1999-1-3: 2007 [10-12], provide general rules for designing and testing the fatigue of steel structures. DVS 1612 - national standard in Germany. ERRI B 12 / RP 17 addresses issues related to static and dynamic tests as well as a static fatigue test of the material. Goodman-Smith and MKJ diagrams are used [1,2,5,9].

When working with the MKJ diagram (Fig.1.a), the permissible stresses are a function of the asymmetry coefficient of the cycle R (1) and depend on the material characteristics: $R_p$ - yield limit; $R_m$ - tensile strength; and the area where the calculated stress is located [1,2,5,9,13].

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \qquad (1)$$

if $R>1$ or $R<-1$, then the reciprocal value of the coefficient obtained is taken into account when determining the permissible stresses.

When evaluating fatigue using the Goodman-Smith diagrams (Fig.1.b), permissible stresses $\sigma_{lim}$ are a function of the mean stresses $\sigma_m$ [1,2,3,9,13,14,15, 16]:

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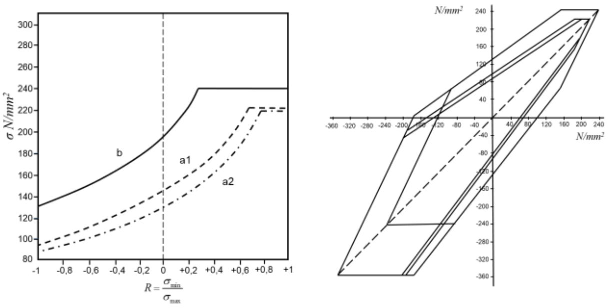


a) b)

*Fig.1. a) MKJ-diagram. b) Goodman-Smith diagram.*

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2}, \quad (2), \quad \sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2}, \quad (3)$$

where: $\sigma_a$ is a stress amplitude [1,2,3,9,14,15, 16, 17].

According to DVS 1612 [5] evaluation of the fatigue strength is done using MKJ-diagrams. Relative to ERRI B 12/R17 [1,2] diference is in the number of permissible stress curves (Fig.2.), which are defined by formula (4).

$$\sigma_{zul}(R_\sigma) = 150\left(1,04^{-x}\right)\left[\frac{2(1-0,3R_\sigma)}{1,3(1-R_\sigma)}\right] \quad (4)$$

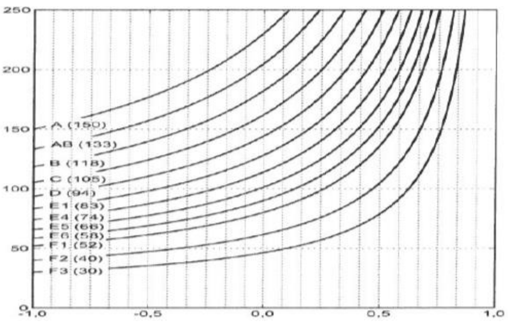


*Fig.2. MKJ-diagrams for steel S355 in DVS 1612 [5]*

The fatigue strength evaluation in DVS 1612 [5] for complex mechanical structures shall be subject to the following conditions:

- for stress components

$$\frac{\sigma_{\parallel}}{\sigma_{\parallel,zul}} \le 1 \quad (5), \quad \frac{\sigma_{\perp}}{\sigma_{\perp,zul}} \le 1 \quad (6), \quad \frac{\tau}{\tau_{zul}} \le 1 \quad (7)$$

- for comlpex stresses

$$\left(\frac{\sigma_{\parallel}}{\sigma_{\parallel,zul}}\right)^2 + \left(\frac{\sigma_{\perp}}{\sigma_{\perp,zul}}\right)^2 - \frac{\sigma_{\parallel}\sigma_{\perp}}{\left|\sigma_{\parallel,zul}\sigma_{\perp,zul}\right|} + \left(\frac{\tau}{\tau_{zul}}\right)^2 \le 1,1 \quad (8)$$

## 3. METHODOLOGY FOR FATIGUE STRENGTH ANALYSIS

In this study the following methodology for fatigue strength analysis was used [18]:

1. Load cases are determined.
2. Design documentation (drawings) is analysed.
3. Structure elements are classified into „n" groups according to the material used.
4. Material properties $R_p$ and $R_m$ are determined for all materials used according to European or national standards.
5. Determine "m" number of groups depending on the design features of the node under consideration (type of welds).
6. A computational model for stress-strain analysis is developed.
7. Verification calculations are performed.
8. The results obtained for stresses are generally selected in $m_x n$ databases obtained according to:
   - structure features –"m" databases;
   - the types of materials used – "n" databases.
9. A standard and method to be used is selected.
10. For each database the asymmetry factor according to formula (1) or the mean stresses according to (2) are determined depending on the chosen method;
11. The permitted stress $\sigma_{lim}$ is determined depending on asymmetry factor (9) or the mean stress (10) depending on the chosen method.
    - using MKJ-diagrams

    $\sigma_{lim} = f(R)$ (9);

    - using Goodman-Smith diagram.

    $\sigma_{lim} = f(\sigma_m)$ (10);
12. Safety factors S are calculated according to (11) for all stress values obtained:

$$S = \frac{\sigma_{zul}}{\sigma_u} \quad (11)$$

13. The evaluation criterion is given with the condition (12):

$$S = \frac{\sigma_{zul}}{\sigma_u} \ge 1 \quad (12).$$

If the safety factor is less than one, the test area is of insufficient strength and it is advisable to take constructive measures for local or radical strengthening.

For the purposes of this study, following load cases were determined (Tab.1.) [6, 7, 8, 19]:

*Tab. 1. Load cases*

| Load case | Load | | | | | | Twist | Brake force | |
|---|---|---|---|---|---|---|---|---|---|
| | Vertical | | | Transverse | Longitudinal | | | | |
| [kN] | sidebearer $F_{z2}$ | pivot $F_{zc}$ | sidebearer $F_{z1}$ | $F_y$ | | | $g^+$ | Fbz | Fbx |
| 1 | - | $F_z$ | - | - | - | - | - | - | - |
| 2 | - | $(1+\beta)F_z$ | - | - | - | - | - | - | - |
| 3 | - | $(1-\beta)F_z$ | - | - | - | - | - | - | - |
| 4 | - | $(1-\alpha)(1+\beta)F_z$ | $\alpha(1+\beta)F_z$ | $0,1(F_z+m^+g)$ | - | - | - | - | - |
| 5 | $\alpha(1+\beta)F_z$ | $(1-\alpha)(1+\beta)F_z$ | - | $-0,1(F_z+m^+g)$ | - | - | - | - | - |
| 6 | - | $(1-\alpha)(1+\beta)F_z$ | $\alpha(1+\beta)F_z$ | $0,1(F_z+m^+g)$ | - | - | +5 ⁰/₀₀ | - | - |
| 7 | - | $(1-\alpha)(1+\beta)F_z$ | $\alpha(1+\beta)F_z$ | $0,1(F_z+m^+g)$ | - | - | -5 ⁰/₀₀ | - | - |
| 8 | $\alpha(1+\beta)F_z$ | $(1-\alpha)(1+\beta)F_z$ | - | $-0,1(F_z+m^+g)$ | - | - | +5 ⁰/₀₀ | - | - |
| 9 | $\alpha(1+\beta)F_z$ | $(1-\alpha)(1+\beta)F_z$ | - | $-0,1(F_z+m^+g)$ | - | - | -5 ⁰/₀₀ | - | - |
| 10 | - | $(1-\alpha)(1-\beta)F_z$ | $\alpha(1-\beta)F_z$ | $0,1(F_z+m^+g)$ | - | - | - | - | - |
| 11 | $\alpha(1-\beta)F_z$ | $(1-\alpha)(1-\beta)F_z$ | - | $-0,1(F_z+m^+g)$ | - | - | - | - | - |
| 12 | - | $(1-\alpha)(1-\beta)F_z$ | $\alpha(1-\beta)F_z$ | $0,1(F_z+m^+g)$ | - | - | +5 ⁰/₀₀ | - | - |
| 13 | - | $(1-\alpha)(1-\beta)F_z$ | $\alpha(1-\beta)F_z$ | $0,1(F_z+m^+g)$ | - | - | -5 ⁰/₀₀ | - | - |
| 14 | $\alpha(1-\beta)F_z$ | $(1-\alpha)(1-\beta)F_z$ | - | $-0,1(F_z+m^+g)$ | - | - | +5 ⁰/₀₀ | - | - |
| 15 | $\alpha(1-\beta)F_z$ | $(1-\alpha)(1-\beta)F_z$ | - | $-0,1(F_z+m^+g)$ | - | - | -5 ⁰/₀₀ | - | - |
| 16 | - | Fz | - | - | $0,05x(F_z+m^+g)$ | $-0,05x(F_z+m^+g)$ | - | - | - |
| 17 | - | Fz | - | - | $-0,05x(F_z+m^+g)$ | $0,05x(F_z+m^+g)$ | - | - | - |
| 18 | - | $1,2F_z$ | - | - | - | - | - | $F_{bz}$ | $F_{bx}$ |
| 19 | - | $1,2F_z$ | - | - | - | - | - | $-F_{bz}$ | $-F_{bx}$ |

Materials used have following properties: steel S355J2, thickness $3 \le t \le 16$ mm, $\boldsymbol{R_p}$= 355 MPa, $\boldsymbol{R_m}$= 470 MPa. Steel S355J2, thickness $16 \le t \le 40$ mm, $\boldsymbol{R_p}$= 345 MPa, $\boldsymbol{R_m}$= 470 MPa. Material GE240, $\boldsymbol{R_p}$= 240 MPa, $\boldsymbol{R_m}$= 450 MPa.

*Fig.3. Finite elements mesh of calculation model*

A computational model for stress-strain analysis has been developed. In this model the finite elements mesh is compressed (1 374 520 nodes and 843 616 elements), maximum size of finite elements is 15 mm (Fig.3), which shows a very good mesh density of the analysed structure.

## 4. RESULTS ANALYSIS

The results obtained for the stresses $\sigma_u$ are selected by choosing the nodes of the welds. Various databases were obtained depending on the type of welding and the material used.

During the work with MKJ and Goodman-Smith diagrams, we identified a problem with respect to the determination of the minimum and maximum stresses, which determine the asymmetry factor R (1) or the mean stresses $\sigma_m$ (2) depending on the selected evaluation method. For the purpose of objectivity and comprehensiveness of the study, the following approach is applied to each node of the welds: The principal stresses ($\sigma_1$, $\sigma_2$, $\sigma_3$) [20] are determined under all load cases; the stress with maximum value ($\sigma_{max}$) is selected; all normal stresses from the stress tensors ($\sigma_x$, $\sigma_y$, $\sigma_z$ from formula (13)) are projected in the direction of the highest main stresses; the minimum stress ($\sigma_{min}$) is then selected for all load cases [1, 2, 3, 14]. The procedure is repeated for each of the nodes in the welding area.

$$\sigma_{ij} = \begin{bmatrix} \sigma_x & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & \sigma_y & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \sigma_z \end{bmatrix} \qquad (13)$$

When working with german standard DVS 1612, the stress tensors (13), obtained for different load cases, should be projected in the weld plane [21]. The highest stresses are then taken for assessment: perpendicular $\sigma_{\perp}$, parallel $\sigma_{\parallel}$ and tangential $\tau$ to the weld. The evaluation criterion is given with conditions (5,6,7,8).

The analysis of the obtained results shows that in all evaluation methods the same areas with insufficient dynamic strength are obtained.

In evaluation with MKJ-diagrams from DVS 1612 [5], because of welds type, two curves (line C- and line D) were used. In this case 21 nodes have safety factor less than one. (Fig.4., tab. 2.).

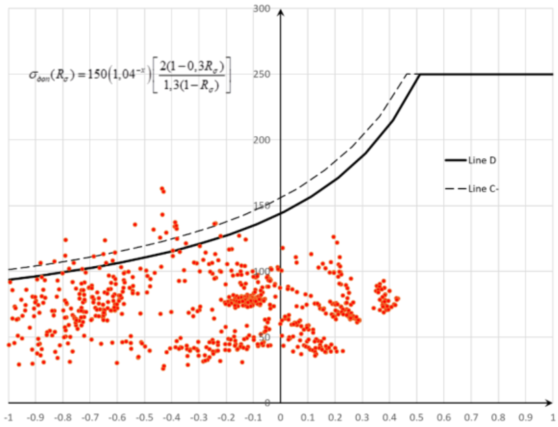


*Fig.4. Results by MKJ-diagrams DVS 1612-2014 [5]*

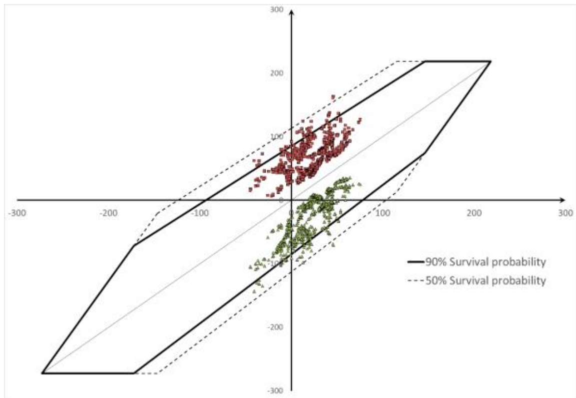


*Fig.5 Results by Goodman-Smith diagram*

In evaluation with Goodman-Smith diagram 37 nodes have safety factor lower than one (Fig. 5, tab. 2.), with 90% reliability. When reliability value is 50%, only two nodes (No 1012625 and 1012153) have safety factor less than one (tab.2.).

The results of insufficient dynamic strength for a part of the welds obtained in theoretical study were not confirmed in the actual tests of the bogie frame [22]. The main reasons for this are:

- The theoretical studies were made taking into account the most unfavorable tension combinations $\sigma_{max}$ and $\sigma_{min}$.
- The bogie frame test is carried out in accordance with [6-8], and there is a constant alternation of each of the load cases from a table 1.

## 5. CONCLUSION

The analysis of the results shows that all theoretical methods used for evaluation give the same areas of insufficient dynamic strength. This indicates that if the frame is tested at the worst stress combinations $\sigma_{max}$ and $\sigma_{min}$ ($10^7$ cycles), it would likely show insufficient dynamic strength. There is, therefore, a discrepancy between the theoretical methods and the test method for bogies. This requires the development of a new methodology for the theoretical analysis of material fatigue in the welding area, which corresponds exactly to the test method for bogie frames.

*Tab. 2. Results of the analysis*

| Node | case up | up | down | case down | R | zul (MKJ) | S (MKJ) | σa | σm | zul (G-S) | S (G-S) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1012625 | 17 | 62.1 | -143.2 | 16 | -0.43 | 122.9 | 0.86 | 102.7 | -40.5 | 48.1 | 0.77 |
| 1012153 | 17 | 72.5 | -135.5 | 16 | -0.54 | 117.9 | 0.87 | 104.0 | -31.5 | 56.3 | 0.78 |
| 1013670 | 18 | 163.1 | -71.1 | 19 | -0.44 | 113.5 | 0.70 | 117.1 | 46.0 | 126.9 | 0.78 |
| 1012491 | 17 | 124.0 | -97.9 | 16 | -0.79 | 107.7 | 0.87 | 110.9 | 13.0 | 96.9 | 0.78 |
| 1013412 | 18 | 160.6 | -69.0 | 19 | -0.43 | 113.8 | 0.71 | 114.8 | 45.8 | 126.7 | 0.79 |
| 1012627 | 16 | 123.8 | -80.0 | 17 | -0.65 | 113.1 | 0.91 | 101.9 | 21.9 | 105.0 | 0.85 |
| 1012492 | 17 | 106.5 | -93.9 | 16 | -0.88 | 104.8 | 0.98 | 100.2 | 6.3 | 90.7 | 0.85 |
| 966824 | 17 | 112.0 | -88.7 | 16 | -0.79 | 107.7 | 0.96 | 100.4 | 11.7 | 95.6 | 0.85 |
| 966940 | 17 | 61.5 | -131.8 | 16 | -0.47 | 121.2 | 0.92 | 96.7 | -35.1 | 53.0 | 0.86 |
| 966823 | 17 | 107.7 | -89.5 | 16 | -0.83 | 106.4 | 0.99 | 98.6 | 9.1 | 93.3 | 0.87 |
| 1012885 | 19 | 137.4 | -53.2 | 18 | -0.39 | 116.0 | 0.84 | 95.3 | 42.1 | 123.3 | 0.90 |
| 1012628 | 16 | 111.3 | -76.5 | 17 | -0.69 | 111.5 | 1.00 | 93.9 | 17.4 | 100.9 | 0.91 |
| 1012490 | 17 | 106.6 | -80.9 | 16 | -0.76 | 108.8 | 1.02 | 93.7 | 12.8 | 96.7 | 0.91 |
| 1012156 | 16 | 113.3 | -73.7 | 17 | -0.65 | 112.9 | 1.00 | 93.5 | 19.8 | 103.0 | 0.91 |
| 967184 | 19 | 134.8 | -51.7 | 18 | -0.38 | 116.2 | 0.86 | 93.2 | 41.5 | 122.8 | 0.91 |
| 1013413 | 18 | 134.2 | -52.3 | 19 | -0.39 | 115.9 | 0.86 | 93.2 | 41.0 | 122.3 | 0.91 |
| 1012291 | 17 | 114.3 | -69.6 | 16 | -0.61 | 114.6 | 1.00 | 91.9 | 22.4 | 105.4 | 0.92 |
| 1013669 | 18 | 132.6 | -50.7 | 19 | -0.38 | 116.2 | 0.88 | 91.6 | 41.0 | 122.3 | 0.92 |
| 966847 | 16 | 91.9 | -91.4 | 17 | -0.99 | 101.5 | 1.10 | 91.7 | 0.3 | 85.2 | 0.93 |
| 1012289 | 16 | 54.5 | -129.6 | 17 | -0.42 | 123.6 | 0.95 | 92.0 | -37.5 | 50.8 | 0.93 |
| 1012191 | 17 | 79.4 | -102.2 | 16 | -0.78 | 108.2 | 1.06 | 90.8 | -11.4 | 74.6 | 0.94 |
| 1012465 | 17 | 84.0 | -95.7 | 16 | -0.88 | 104.9 | 1.10 | 89.9 | -5.8 | 79.7 | 0.95 |
| 1012589 | 16 | 55.7 | -125.8 | 17 | -0.44 | 122.4 | 0.97 | 90.8 | -35.1 | 53.0 | 0.95 |
| 1012193 | 13 | 84.0 | -94.0 | 16 | -0.89 | 104.4 | 1.11 | 89.0 | -5.0 | 80.5 | 0.96 |
| 1012556 | 17 | 101.9 | -74.3 | 16 | -0.73 | 109.9 | 1.08 | 88.1 | 13.8 | 97.6 | 0.96 |
| 1012626 | 16 | 108.3 | -66.8 | 17 | -0.62 | 114.3 | 1.05 | 87.6 | 20.7 | 103.9 | 0.96 |
| 966942 | 16 | 106.5 | -68.4 | 17 | -0.64 | 113.2 | 1.06 | 87.4 | 19.1 | 102.4 | 0.96 |
| 1012306 | 16 | 79.1 | -98.7 | 17 | -0.80 | 107.4 | 1.09 | 88.9 | -9.8 | 76.1 | 0.96 |
| 967686 | 18 | 124.9 | -47.5 | 19 | -0.38 | 116.3 | 0.93 | 86.2 | 38.7 | 120.3 | 0.96 |
| 1012851 | 18 | 136.2 | -33.1 | 19 | -0.24 | 134.5 | 0.99 | 84.6 | 51.5 | 131.9 | 0.97 |
| 1013703 | 19 | 136.4 | -32.6 | 18 | -0.24 | 134.9 | 0.99 | 84.5 | 51.9 | 132.3 | 0.97 |
| 966941 | 16 | 102.9 | -68.4 | 17 | -0.66 | 112.3 | 1.09 | 85.6 | 17.3 | 100.7 | 0.98 |
| 1012305 | 6 | 81.0 | -93.5 | 17 | -0.87 | 105.3 | 1.13 | 87.2 | -6.3 | 79.3 | 0.98 |
| 1012557 | 17 | 99.2 | -71.0 | 16 | -0.72 | 110.4 | 1.11 | 85.1 | 14.1 | 97.8 | 0.99 |
| 967912 | 18 | 121.4 | -42.3 | 19 | -0.35 | 118.1 | 0.97 | 81.8 | 39.5 | 121.0 | 1.00 |

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