Comparative analysis of stress state and fatigue behaviour of two types of welded joints used for a HEM-beams structure

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Abstract. The paper presents the comparative analysis of two types of welded structures used in railway bridges. The differences between the two types of structures are given by the configuration of welded joints (HEM profiles are used for both structures). Constructive and technological analysis made for each structure are presented, highlighting the differences of own weight and material consumption. Static and fatigue behaviour analysis are made using finite element method simulations. Static analyses aim to determine the stress and displacement states for limit loading cases, highlighting the areas with maximum stresses and displacements. The results obtained from the static analysis are used in the analysis of fatigue behaviour of the two structures.

1. Introduction
Welded bridges have been developed since the first half of the 20th century (the first fully welded bridge in Romania was made in Resita in 1931 and is still in use). Welded railway bridges are complex structures that were subjected to a continuous process of optimization in the last century. The main goal followed in the process of optimization of railway bridges is to design bridges with slight structure using simple manufacturing process. This goal can be achieved by optimizing the superstructure of the bridge so that the stresses and deformations are evenly distributed and do not exceed the admissible values [12].

The development of monitoring and control systems and the emergence of FEM (finite element method) simulation software facilitated high advances in the design and monitoring of railway bridges [14]. The monitoring systems of deformations allow a precise diagnosis of structure behaviour under real operating conditions [6,7]. Static analyses, modal analyses, or aerodynamic flow analyses can be performed on bridge structure using CAE software. By static analysis of the bridge superstructure can be identified areas with maximum stresses and large deformations [10,11]. By modal analysis are computed the bridge own frequencies and the structure's response to the external factors that can generate vibrations [16]. By numerical simulations it can also be defined the fatigue behaviour of bridges [1,9,13,15]. Related to fatigue behaviour of structures it should be noted also the development of experimental testing methods [2]. However, considering the diversity of applications and working conditions of railway bridges, it can be concluded that many research directions are still open.

The paper is focused on the comparative analysis of two constructive layouts for the welded joints from a railway bridge structure. The welded joints submitted to analysis connect the stringers and the struts of the bridge superstructure. The stringers and the struts are made of HEM beams (HEM 160 for stringers and HEM 320 for struts). For the first welded joint geometry (existing railway bridge [4,5])
the upper surfaces of the stringers and the struts are located in same plane and the stringers are divided by the struts. In the new proposed welded joint geometry the stringers and the struts are placed one above the other.

2. The analysis of first constructive solution

2.1. The geometry
The geometry of first constructive solution (figure 1) is designed in SolidWorks software in the following configuration: stringers made of HEM 160 beams (\( h_1=180 \text{ mm}, b_1=166 \text{ mm} \)), struts made of HEM 320 beams (\( h_1=359 \text{ mm}, b_1=309 \text{ mm} \)), concrete plate with 150 mm height positioned over the struts and two lateral beams of 1720 mm x 400 mm (dimensions of the soles: 400 mm x 40 mm; dimensions of the heart 1640mm x 20 mm). The layout of the profiles is presented in figure 2. The total mass of the assembly is 91802 kg.

![Figure 1](image1.png)

**Figure 1.** The bridge superstructure for first constructive solution.

![Figure 2](image2.png)

**Figure 2.** The geometry of welded joint for first constructive solution.

For this constructive solution the stringers upper surfaces are placed in the same plane as the struts upper surfaces. Two lateral ribs are used in each welded joint between the two components. The manufacturing and the assembly process of the bridge deck impose to cut the stringers at lengths equal
to the distances between the struts. The stringer end geometry is correlated with the HEM profile of the struts, requiring a complex cutting technology.

2.2. The static analysis
The static analysis was made based on finite element method simulation. In the static FEM study the loads were applied on the concrete plate on twelve rectangular areas (figure 3). On each of the twelve areas a force of 20833 N was applied, leading to a total prescribed force of 250000 N. Also, the gravity loading was applied. The gravity is calculated by multiplying the specified acceleration of gravity by the mass. The fixture was made on the marginal struts of the bridge (figure 3). The mesh was made with 158897 finite elements of solid types (figure 4). For the HEM-beam structure and for the lateral beams was used the AISI 1020 Steel. The materials characteristics are presented in Table 1.

Table 1. Mechanical properties of the materials used for bridge deck.

| Property                  | Units | Concrete | AISI 1020 Steel, Cold Rolled |
|---------------------------|-------|----------|------------------------------|
| Elastic Modulus           | [N/mm²] | 35000    | 205000                       |
| Poisson's Ratio           | [-]   | 0.2      | 0.29                         |
| Mass Density              | [kg/m³] | 2400    | 7870                         |
| Tensile Strength          | [N/mm²] | 420     |                              |
| Compressive Strength      | [N/mm²] | 40      |                              |
| Yield Strength            | [N/mm²] | 30      | 350                          |

The results are presented numerically in table 2 and graphically (figures 5, 6 and 7) as the distribution of maximum von Mises stress (for steel components), intensity stress (for concrete plate) and displacement. Figure 5 shows the stress distribution on the superstructure of HEM 160 & 320 beams. The maximum value (local stress) of 188.4 MPa occurs in the fixture area near the marginal struts supports. Figure 6 shows the stress intensity distribution on the concrete plate with a maximum value of 7,624 MPa. The maximum displacement 8.80 mm occurs at the middle of span distance (figure 9). The resultant reaction force was 1151300 N.

Table 2. Maximum displacement and von Mises / intensity stress for bridge deck, first constructive solution.

| First constructive solution | Displacement [mm] | Maximum von Mises Stress [MPa] | Stress intensity (P1-P3) [MPa] | Mass [kg]     |
|-----------------------------|-------------------|--------------------------------|-------------------------------|--------------|
| Concrete plate 150 mm       | 8.80              | 17.6                           |                               | 45126        |
| Lateral beams (2x)          | 8.17              | 169.6                          |                               | 11843 (2x)   |
| HEM-beams structure         | 8.78              | 188.4                          |                               | 22990        |

Figure 3. The loads applied to the structure.
Figure 4. The mesh for static analysis of first constructive solution.

Figure 5. Von Mises stress distribution for HEM beams structure (first constructive solution).

Figure 6. Stress intensity (P1-P3) distribution for concrete plate (first constructive solution).

Figure 7. Resultant displacement distribution for deck assembly (first constructive solution).
2.3. The fatigue analysis

In order to perform the fatigue study an event of constant amplitude loading was added in SolidWorks Simulation, with 100000 cycles. The loading ratio of the cycles was R=0 (zero based fatigue study). On a zero-based loading type the stress is varied between zero and the maximum value and SolidWorks sets the alternating stress at each node equal to half of the corresponding stress from the reference static study. The following options of the fatigue study were imposed:

- Computing alternating stress using – Equivalent stress (von Mises);
- Mean stress correction – None;
- Fatigue strength reduction factor \( K_f = 1 \).

Fatigue studies evaluate the consumed life of an object based on fatigue events and S-N curves. The figure 8 shows the S-N curve for the steel used for HEM beam and lateral beam [3]. According to the previous results, the maximum von Mises stress value is 188.4 MPa and the alternating stress value is 94.2 MPa. At the end of the fatigue calculation, the software shows the message “Alternating Stresses everywhere in the model are below the minimum S-N Curve value resulting in no damage”. Hence, the result of the study predicts that the fatigue failure does not occur, because the point (1000000, 94.2) lies below the curve.

In FEM fatigue study could be obtained also the diagram of fatigue safety factors related to fatigue failure. The fatigue safety factor is the calculated as the ratio between the alternating stresses corresponding to the lowest point from the S-N curve and the maximum value of alternating stresses. For this structure the fatigue safety factor is \( LF = \frac{275}{94.2} = 2.91 \);

On a railway with high traffic it can be reach more than \( 10^6 \) cycles and it is required an extension of fatigue curve to \( 10^7-10^8 \) cycles (EN 1993-1-9).

![Figure 8. The material S-N curve.](image)

3. The analysis of the second constructive solution

3.1. The geometry

For the second constructive solution the bridge superstructure is designed only with HEM 160 beams (assigned to the stringer and struts). A concrete plate with 150 mm height is positioned over the beams structure. Lateral beams are placed on both sides of the structure (figure 9). The total mass for this assembly is 82900 kg. The mass decrease relatively to first constructive solution is about 8900 kg. In this variant, the nodes of the welded structure are obtained by simply overlapping the stringers with the struts. The main technological advantage of this solution is that the stringers can be used at lengths close to the length of the supply (is not necessary to cut the stringers according to the profile of the struts).
3.2. The static analysis
The simulation conditions for the static analysis of the second constructive solution were similar to the conditions used for first constructive solution. The results are presented numerically in table 3 and Figure 11 shows the distributions of von Mises stress (for steel components) and stress intensity P1-P3 (for concrete plate). The maximum value of 231.4 MPa occurs in fixture area (local stress) near the marginal struts supports. Figure 12 shows the intensity stress distribution on the concrete plate (maximum values of 14.1 MPa). The maximum displacement 9.67 mm occurs at the middle of span distance (figure 13).

| Second constructive solution | Displacement [mm] | Maximum von Mises Stress [MPa] | Stress intensity (P1-P3) [MPa] | Mass [kg] |
|-----------------------------|-------------------|-------------------------------|-----------------------------|---------|
| Concrete plate 150 mm       | 9.67              | 14.1                          | 231.4                       | 44659   |
| Lateral beams (2x)          | 8.80              | 231.4                         |                             | 11843 (2x) |
| HEM-beams structure         | 9.62              | 231.4                         |                             | 14558   |
3.3. Fatigue analysis
The results of the fatigue study, performed in the same conditions as variant 1, predict that the fatigue failure does not occur. The maximum von Mises stress value is 231.4 MPa and the alternating stress value is 115.7 MPa. The fatigue safety factor is \( LF = \frac{275}{115.7} = 2.377 \).

4. Conclusions
Static and fatigue behaviour analysis were performed for two constructive solutions of a railway bridge superstructure. The analysis of first constructive solution highlights uneven distribution of stress in HEM-beam structure with low stress on the struts. Also the manufacturing technology is expensive, requiring a complex cutting process of stringers segments (correlated with struts cross – section).
The analysis of second constructive solution highlights the next advantages:

- The layout of welded joints obtained by overlapping the stringers over the struts led to a more efficient superstructure manufacturing. The stringers can be used at lengths close to the length of the supply, resulting in lower manufacturing times and costs;
- A decrease of the weight of the deck (8900 kg relatively to first constructive solution) under the conditions of the same mechanical performance.

5. References

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