

Static, dynamic and fatigue analysis of a railway bridge with pedestrian area

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Abstract. The paper presents a constructive solution for the metallic structure of a city railway bridge, with pedestrian area. The structure made of HEM beams has a modular design in order to facilitate the transport and in-situ assembling. The results obtained from static, dynamic and fatigue analyses are presented. Static analysis highlights areas with maximum stresses and displacements. Dynamic analysis aims to determine the own frequencies of the structure. Analysis of fatigue behaviour aims to compute the fatigue safety factors. The methodology presented in the paper is part of a unitary approach in the design of optimised bridge structures.

1. Introduction

The metallic structures of railway bridges are subjected to complex, static and dynamic loads. The accurate characterization of the operating behaviour of these structures is imposed by the intended use and by the extreme impact of a potential occurrence of failure. The software developed in the last 40 years, as well as state-of-the-art monitoring equipment [4,11] allow the testing and diagnosis of existing bridges as well as the design of optimized structures.

Considering the wide variety of constructive solutions, the literature is very rich in articles that deal with aspects regarding the analysis, the monitoring and the optimization of the mechanical structure of the railway bridges. There are several main research directions: the diagnosis of the existing structures and the estimation of the remaining lifetime [1,10,13], the static analysis of the structures under the operating conditions foreseen in standards [6,7,12,14], the analysis of the fatigue behaviour [3,9], dynamic analysis applied on unloaded structures, on structures loaded under normal conditions [8] or on structures exposed to extreme external factors (high running speeds, extreme environmental conditions, etc.) [2,5,15]. The urban railway bridges require a number of additional design conditions: decrease of running noise, pedestrian safety, etc. Due to the development of composite structures as well as the improvement of computer aided design tools, the research directions in the field are expanding, providing important challenges for civil engineers, mechanical engineers, architects, etc.

The paper presents the analysis of the superstructure of a railway bridge from an urban passage (road or river crossing) with a 12-meter span. The metallic structure is made of HEM 160 beams for the elements of the deck (struts and stringers), HEM 100 and P60x4 beams for deck sides and pedestrian areas. In the basic constructive solution, the stringers are positioned on two levels and the struts are positioned between the stringers (Figure 1). This layout of the stringers aims to obtain a lighter and rigid structure under similar loading conditions.



The pedestrian area, conceived as box pattern frame, takes the role of the marginal beams (classic full-hearted beams) and is lighter in relation to them. This constructive solution allows the set-up of flexible photovoltaic panels (upper side) and acoustic insulating panels with urban architecture (sides).

The metallic structure can be modularly manufactured in order to facilitate the transport to emplacement site. The lateral modules (the sides of the deck and the pedestrian areas) can be assembled with the central module used hinged joints disposed on stringers. These joints allow accurate positioning and welding of the modules. The modularly solution can also be applied to larger span bridges where the total length is ensured by the use of multiple central modules. In this case, the joints will be placed on the struts (on the width of the bridge).

The constructive solution shown in figure 2 was also studied in order to further increase the rigidity of the metallic structure and to obtain an evenly distribution of the stresses for entire deck. This new structure contains a reinforcing grid made of two bonded U40x20 beams disposed on two levels (parallel to the struts) and two bonded U50 beams disposed parallel to the stringers. This grid is applied in each rectangular area delimited by stringers and struts. In the central area of the structure the grid is disposed on two levels. The grid is suitable for incorporation in concrete or in a composite material (organic matrix and fiberglass reinforcement). The metal - concrete structure (or composite material) will have superior mechanical properties compared to the basic metal structure. In this study only the metallic structures were analysed, without calculating the effect of the filling material.

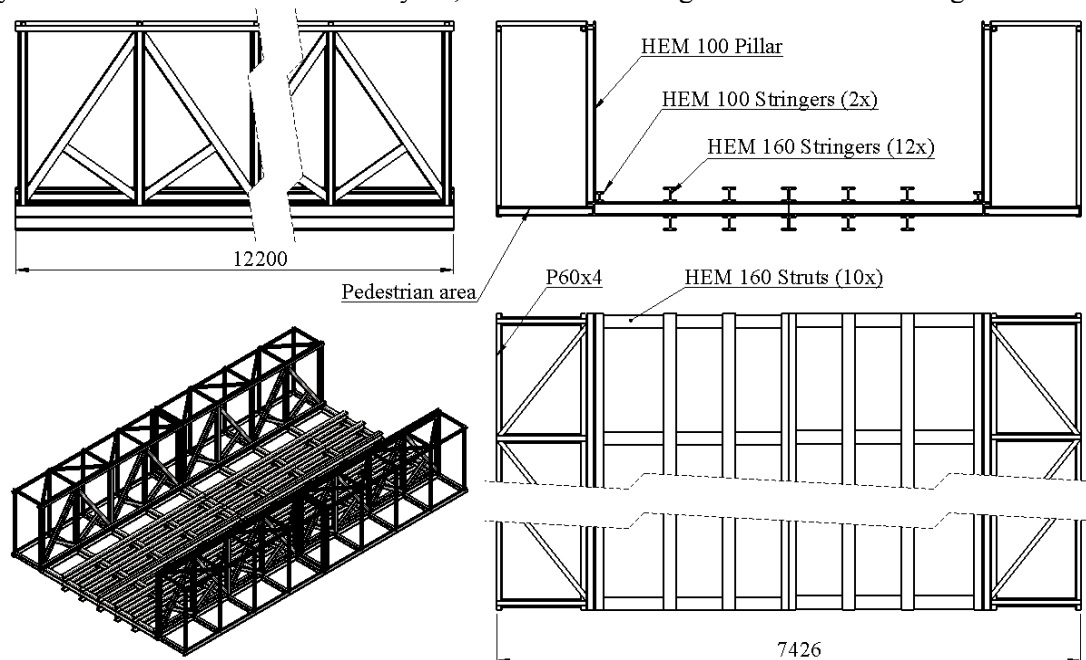


Figure 1. 3D model of the railway bridge superstructure.

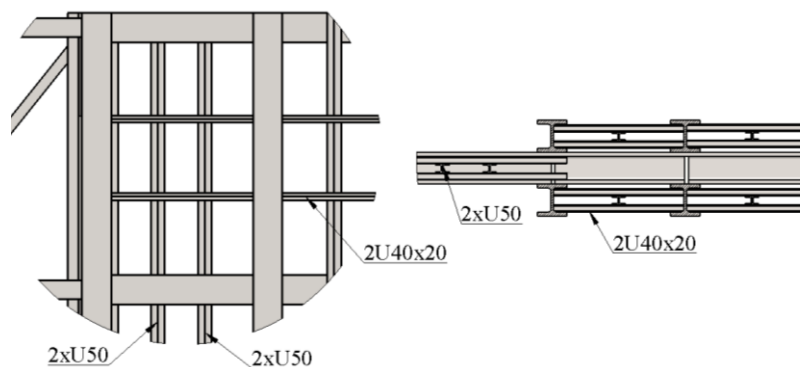


Figure 2. The constructive solution of bridge deck with reinforcing grid.

2. Methodology

The structure of the railway bridge presented in the paper was subjected to static, fatigue and dynamic analysis. The FEM simulations were made on real dimensions 3D models. The material used for all components of the structure was the steel S355JR, with the yield strength $\sigma_c = 355$ MPa, tensile strength $R_m = 470\text{--}630$ MPa and fatigue limit $\sigma_{-1} = 275$ MPa (at 10^6 fully-reversible bending loads). The total weight of the first constructive solution is 23957 kg and for the second solution is 27087 kg.

The static FEM simulation was performed on a quarter of structure. Two symmetry conditions (figure 3, a-b) were applied. This simplifying hypothesis increases the simulations accuracy. The fixing of the structure was made on the end struts and on the adjacent areas of the stringers (figure 3, c). The own weight (Figure 3, d) and the external forces according to the loading mode 71 of EN 1991/2003 (Figure 3, e-h) were applied to the model. The values of forces were calculated correlated to the symmetrical structure analysis mode. The same static analysis conditions were applied to the second constructive solutions (structure with reinforcing grid).

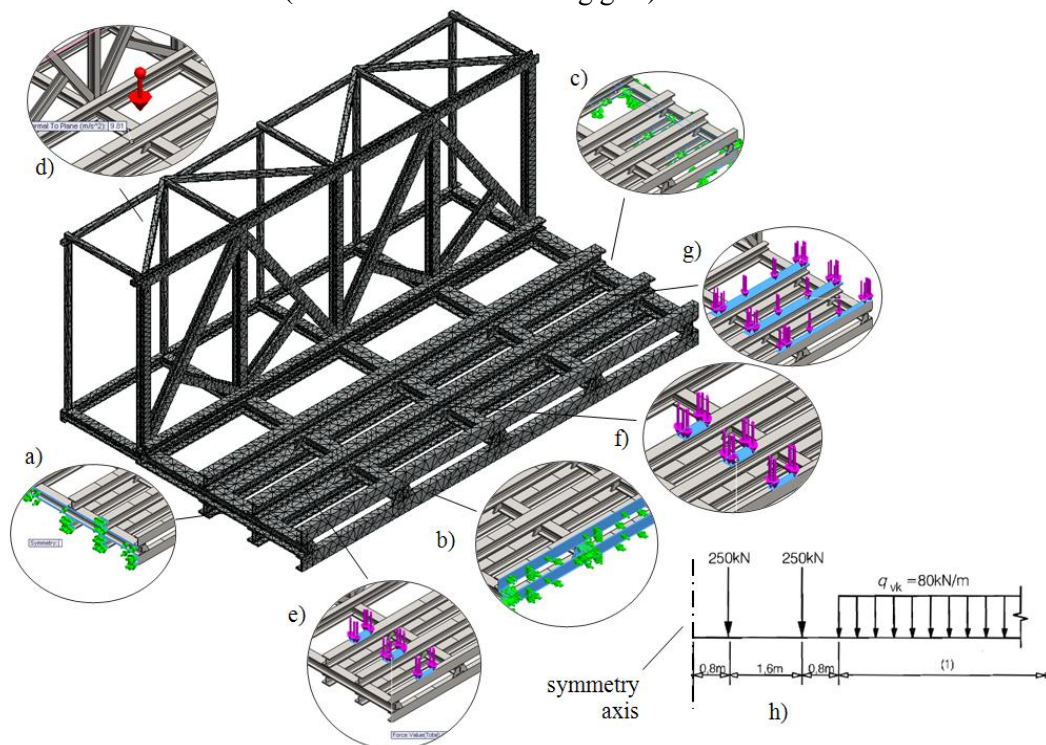


Figure 3. Mesh, loads and fixtures on static study.

The analysis of fatigue behaviour was based on the stress distributions obtained from the static analysis. Zero based loading cycles (asymmetry ratio $R=0$) were used.

The modal analysis aimed to determining the first eigenfrequencies and the mass participation for these frequencies. In the design of the structure must be avoided the overlapping of eigenfrequencies with frequencies induced by external factors. The emergence of vibrations can lead to a high level of acoustic pollution and can endanger the integrity of structure, trains and pedestrians.

3. Results

3.1. Static analysis

The static analysis revealed a maximum value of von Mises equivalent stresses of 224.1 MPa for the first constructive solution and 333.1 MPa for the second constructive solution (Figures 4 and 7). Areas with stresses higher than 100 MPa were highlighted in Figure 5 and Figure 8. The structure with reinforcing grid has stress peaks on the U40 beams ends. The distribution of resulting displacement

reveals a maximum value $U_{res}=12.03$ mm for the first structure (Figures 6) and a maximum value $U_{res}=10.25$ mm for the structure with reinforcing grid (Figure 9). For the second structure, total weight increases by approximately 13%, the maximum displacement decreases by approximately 17% and the maximum equivalent stress increases significantly due to occurrence of local stresses on reinforcing grid.

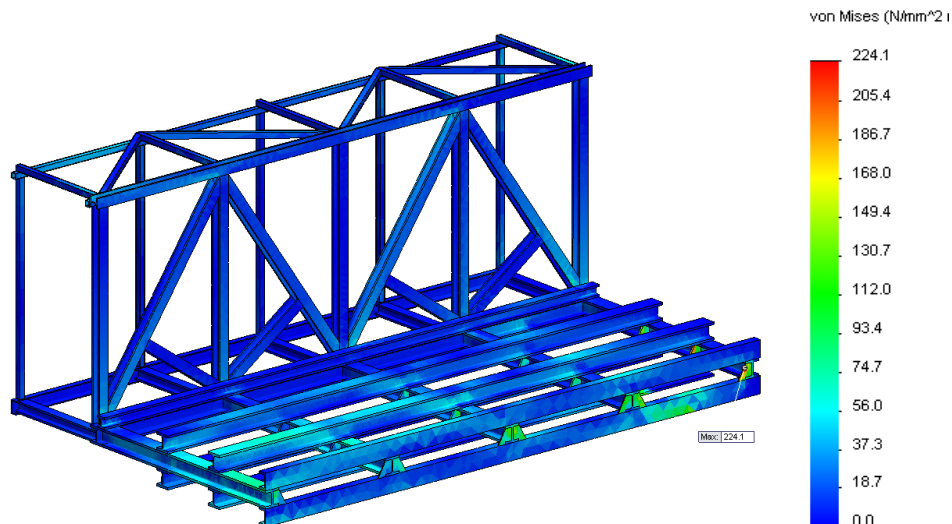


Figure 4. Von Mises stress chart (basic structure).

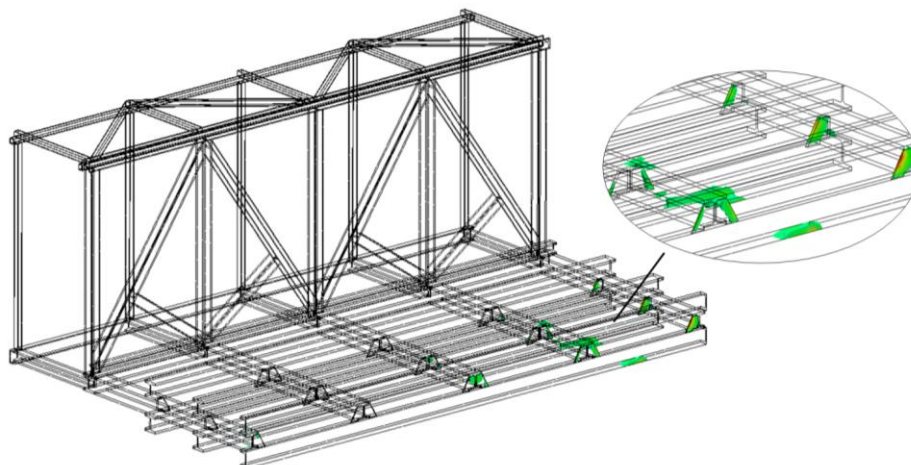


Figure 5. Areas with von Mises stress over 100 MPa (basic structure).

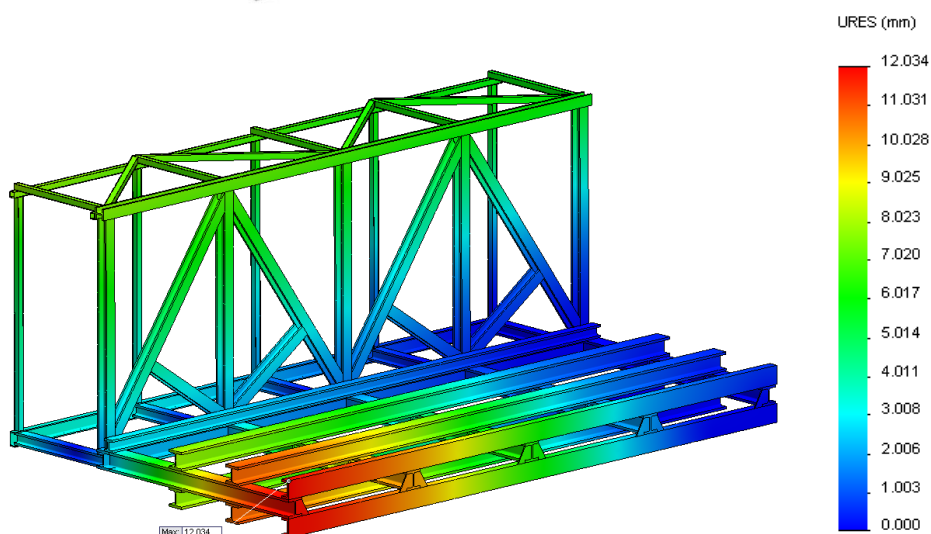


Figure 6. Resultant displacement chart (basic structure).

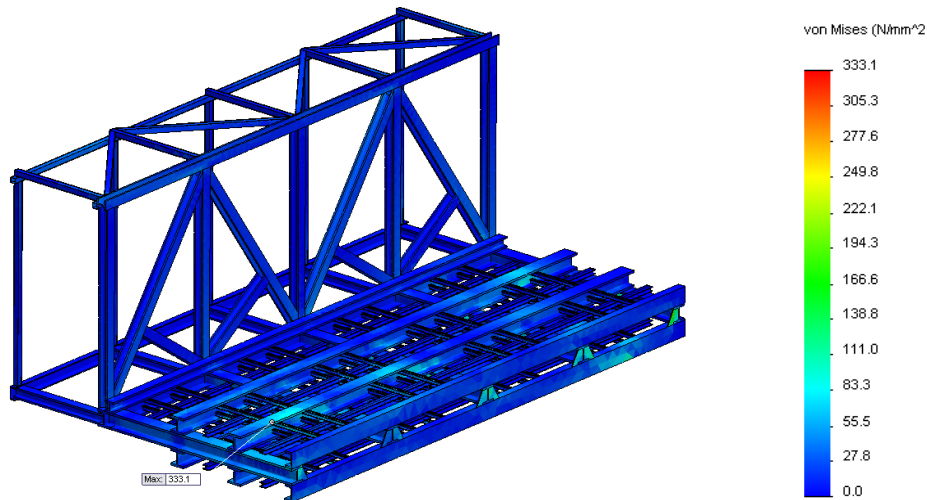


Figure 7. Von Mises stress chart (reinforced grid structure).

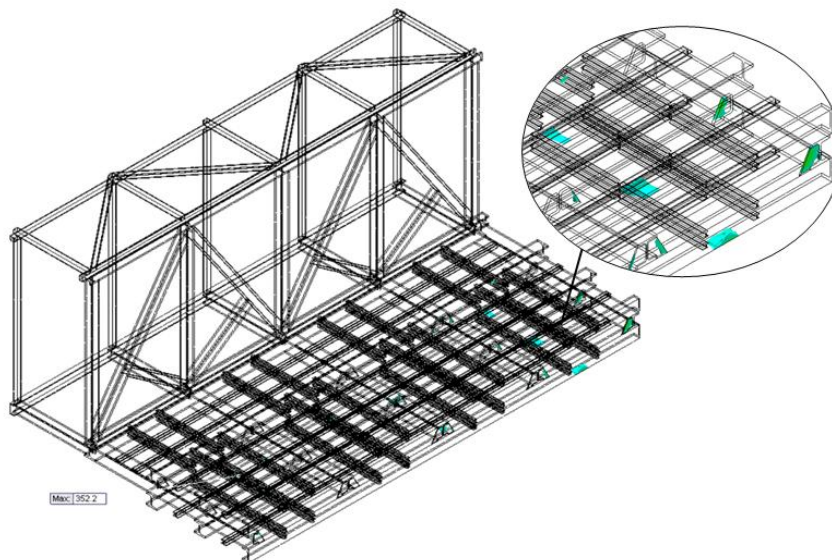


Figure 8. Areas with von Mises stress over 100 MPa (reinforced grid structure).

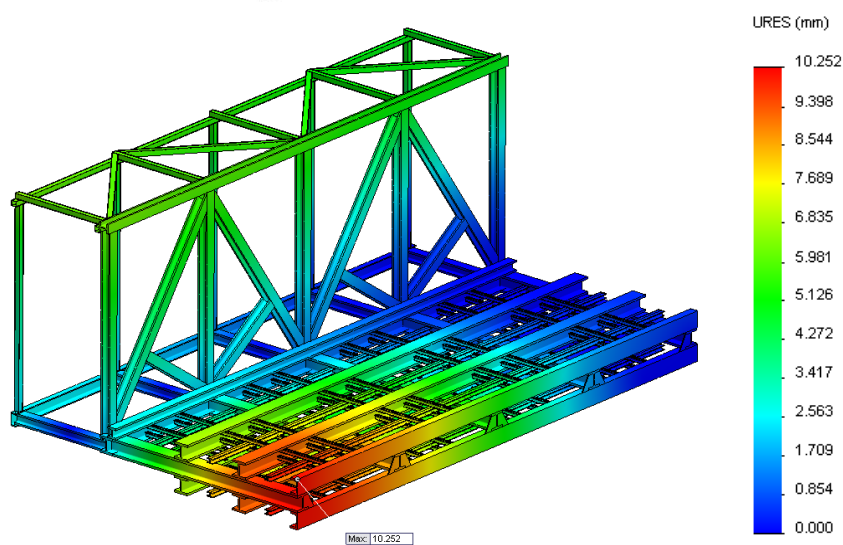


Figure 9. Resultant displacement chart (reinforced grid structure).

3.2. Fatigue analysis

The distribution of fatigue safety factors (Figure 10) calculated for 10^6 zero based cycles indicates a minimum value of 2.05. This value corresponds to the areas with maximum stresses from the static analysis (ribs, central struts and central stringers). On a railway line with heavy traffic it can be reach more than 10^6 cycles. In this case, according to “Eurocode 3: Design of steel structures - Part 1-9: Fatigue” (EN 1993-1-9) the fatigue strength should be based on the extended fatigue strength curves. An extension of the material S-N curve to 10^7 - 10^8 cycles is therefore required.

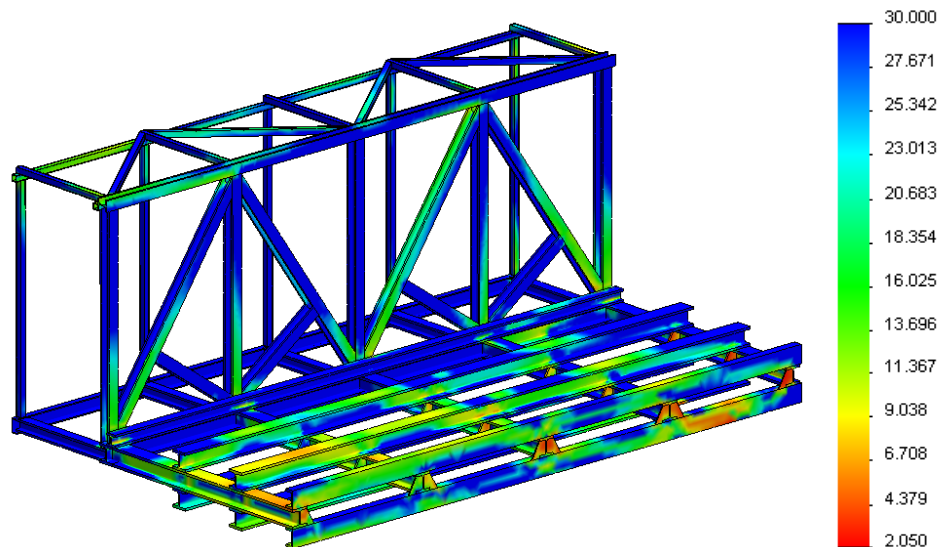


Figure 10.
Fatigue factor of
safety chart.

3.3. Modal analysis

The analysis of the structure's eigenfrequencies must be correlated with the characterization of vibrations that can be induced to the structure by external factors (dynamic loads and environmental factors). FEM modal analysis applications allow the determination of a large number of eigenfrequencies. However, the computing resource and processing times are directly proportional to the number of frequencies determined. In practice, the first modes of vibration and the frequencies associated with these modes are determined, or the frequencies around a certain value (frequency determined by external factors) are determined.

In the study presented in the paper, the first eight frequencies were determined on the basic structure (without the stiffening grid). Mass participation on X, Y and Z directions was highlighted for each of these frequencies (Table 1). In the analysis of vibration modes and related frequencies, those modes where the mass participation is over 20% (participation coefficient higher than 0.2) are considered significant. The shapes of the first eight modes are shown in Figure 11. It is noticed that modes with a mass participation of over 20% (modes 1 and 6) generate displacements both on the side modules of the bridge (including pedestrian areas) and on the central module. Modes that cause displacements in particular on the side modules have a low mass participation (the mass of the lateral modules is much smaller than the mass of the central module).

Table 1. Natural frequencies and mass participation

Mode no.	Frequency [Hz]	Mass participation ratio [-]			Mode no.	Frequency [Hz]	Mass participation ratio [-]		
		X	Y	Z			X	Y	Z
1	5.458	0.77	0.00	0.00	5	15.304	0.01	0.00	0.00
2	11.394	0.00	0.03	0.00	6	18.136	0.00	0.62	0.00
3	13.266	0.03	0.00	0.00	7	19.645	0.02	0.00	0.00
4	15.183	0.03	0.00	0.00	8	23.706	0.00	0.00	0.00

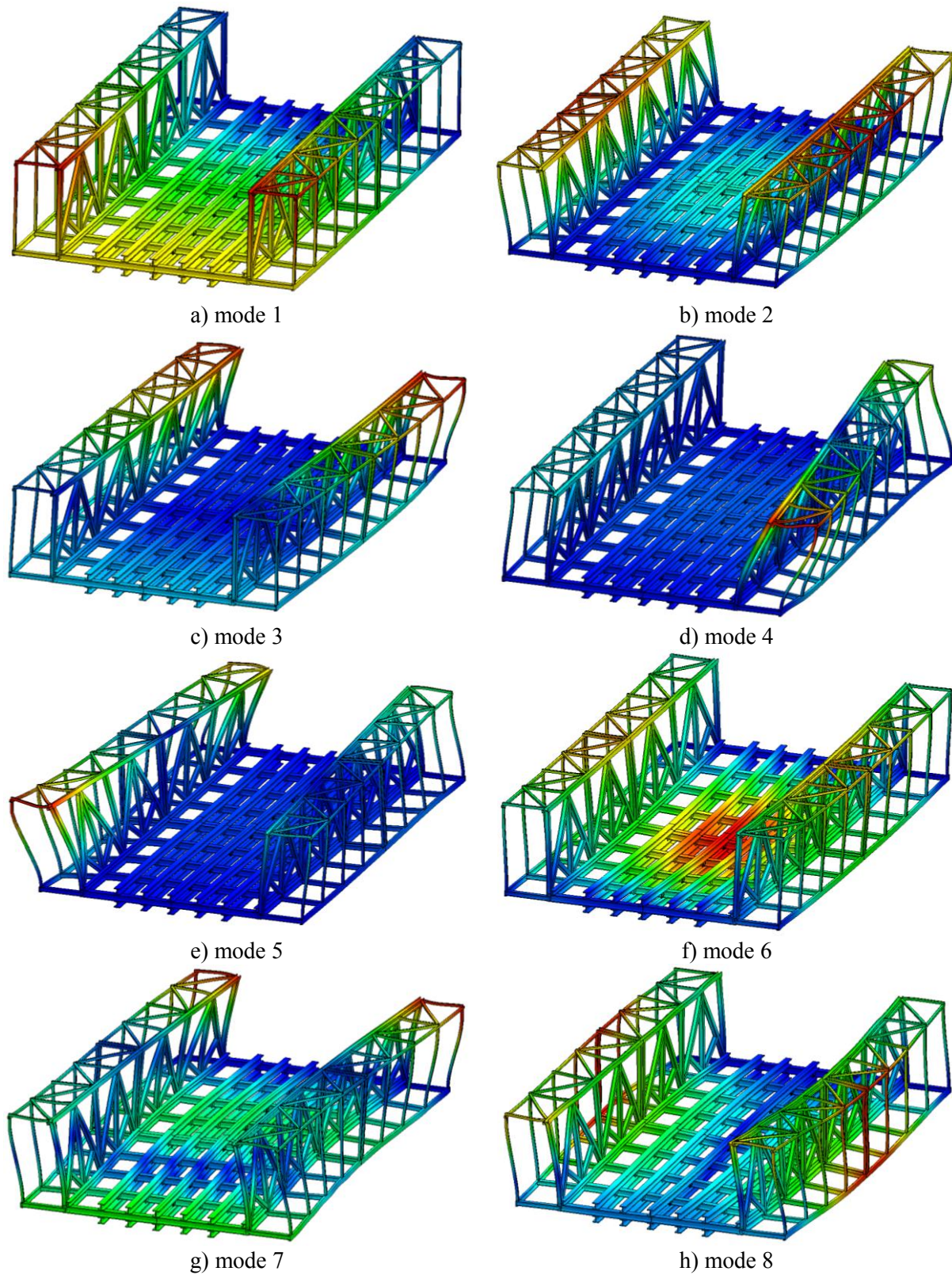


Figure 11. Basic structure mode shapes.

4. Conclusions

The paper presents the static, fatigue and modal analysis of a metallic structure from a 12-meter span railway bridge. The three types of analysis are part of unitary process of optimizing the constructive solution of an urban railway bridge with pedestrian areas.

The static analysis was performed on a basic constructive solution and on a modified constructive solution. The basic structure is made of HEM 160 beams, disposed on three levels (two levels of stringers and an intermediate level of struts). This configuration allows obtaining a lighter structure with high mechanical performance. The modified constructive solution use a reinforcement grid made of U40 and U50 beams. The results obtained for the modified solution show a decrease of the maximum displacement, but also show the occurrence of local stresses (on the reinforcement grid beams). These local stresses were significantly higher in relation to the basic structure.

Analysis of fatigue behaviour shows a safety factor of 2.05 in relation to fatigue limit at 10^6 cycles. On a railway line with heavy traffic it is required an extension of S-N curve to 10^7 - 10^8 cycles.

The modal analysis indicated that two of the first eight modes of vibration have a mass participation higher than 20%. These modes cause displacements both on the side and on the central part of the structure.

5. References

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