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DYNAMIC BEHAVIOR OF RAILWAY BRIDGES UNDER HIGH-SPEED TRAFFIC LOADS

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Abstract

The interest on the dynamic behavior of railway bridges has grown in recent years due to the emergence of high-speed trains that induce a significant dynamic effect. A correct understanding of the dynamic behavior of a railway bridge is essential, as an accurate prediction of the structure's response contributes to cost-effective design for new bridges and rational operation of existing ones.

The objective of this study was to investigate the dynamic behavior of an existing single-track railway bridge under dynamic traffic loads. For this study, it was assumed that the bridge is traversed by a high-speed train traffic with different speeds, ranging from a minimum speed of 100 km/h to a maximum of 300 km/h.

Moving vehicles, represented by Eurocode LM 71 and HSLM-A1 models, are simulated using constant intensity forces at the wheel locations, moving across the bridge at a constant speed. Dynamic interactions between the vehicle and the bridge, as well as track irregularities, are not considered.

To illustrate the variation of the dynamic amplification factor during the passage of the convoy at different speeds, a 3D dynamic model of the bridge structure was created, and dynamic analysis was performed using the modal superposition method.

The paper presents variations in displacements, accelerations, and the dynamic amplification factor determined through dynamic analysis for different elements of the bridge structure, depending on the speed of the moving forces. The numerical resonance speed, significantly amplifying the bridge structure's response, was identified.

Keywords: Dynamic Analysis, Railway Bridge, High-Speed Trains

1. INTRODUCTION

The recent expansion of high-speed railway networks in Europe and the Far East has needed a reevaluation of design criteria for high-speed railway bridges. In particular, assessing the dynamic effects associated with vehicle-structure interaction has led to the development of new safety and comfort criteria for passengers, translating into maximum acceleration limits for the structural system interacting with the moving train.

High-speed trains can induce significant vibrations in railway bridge structures, especially in simply supported decks. Moreover, the varied operating speeds of modern trains are sufficient to create resonance situations, representing one of the most critical scenarios in structural design. Therefore, there is a keen interest in developing mathematical models capable of accurately reproducing bridge behavior at resonance with minimal computational cost.

Normative regulations in railway engineering rely on the provisions of Eurocode SR EN 1991-2:2005 [6], where the dynamic nature of loading is considered based on dynamic analysis of the structure's response to a simulated moving force traffic. This analysis involves the direct determination of the structural deformation process and the internal force distribution caused by high-speed trains simulated through High Speed Load Models (HSLM).

The design principles for high-speed railway bridge differ from those for conventional railway bridges. In this context, certain additional checks become mandatory for high-speed routes:

- verification of the maximum acceleration of the bridge deck;
- maximum stresses generated by dynamic loading must not exceed acceptable limits;
- fatigue failure check;
- verification of the maximum acceleration at the level of the train cars for passenger comfort;
- determination of the resonance speed.

Although there are a large number of studies aiming to model the dynamic action of moving vehicles on bridge structures, there are still many unresolved aspects that directly influence the dynamic behavior of the vehicle-bridge system. These aspects are closely related to the spatial variation of the bridge structure, the materials comprising the bridge-track assembly, the vehicles traversing the bridge, and, last but not least, their temporal variation.

The objective of this paper is to develop a simulation model for the dynamic behavior of a railway bridge when crossed by moving forces at different speeds. The study utilizes three-dimensional models created with finite elements.

In the conducted analyses, the assumption of linear elastic behavior of the bridge structure and track elements was adopted, and damping is introduced globally and remains constant. The train crosses the bridge at a constant speed and is represented by the moving forces corresponding to the axles; hence, the interaction between the track and the vehicle is not considered. It is assumed that the moving forces travel on a smooth surface, at different speeds, and are symmetrically placed relative to the longitudinal axis of the bridge. Irregularities in the track are ignored.

The dynamic response primarily considers the vertical direction effect, as time variations of accelerations, displacements, and stress at different points on the structure. Conclusions regarding the bridge's performance during the passage of high-speed trains can be drawn from the presented results. The results are not calibrated with measured data.

In construction practice, it is recommended that the bridge structures with large spans, those built using special solutions or with special materials, and those constructed with new execution technologies to be tested before being put into operation. The tests performed on bridge structures practically validate the correctness of the design and construction. The tests consist of real-time recording of the accelerations, velocities, and displacements of the bridge structure at a certain number of points. By processing these recordings, other dynamic parameters can also be determined, such as the dynamic amplification factor and the critical damping factor. [7], [8], [9].

2. DYNAMIC EFFECTS GENERATED BY MOVING VEHICLES ON BRIDGE STRUCTURE [5], [3]

The magnitude of the dynamic response of bridge structures to the dynamic action of moving vehicles crossing the structure depends on several factors, including the mass and dynamic properties of the moving vehicles, the dynamic characteristics of the bridge structure, and the track surface conditions that provide the interface between the bridge structure and vehicles.

The extent to which a bridge structure exhibits a dynamic response when traversed by a convoy of vehicles at a given speed depends on several factors related to the geometry of the bridge structure, the elastic and damping characteristics of the material, and the inherent vibration characteristics of the bridge. Among these factors are:

- vibration characteristics of the bridge - directly depend on the length and stiffness of the bridge. Bridges with a small span may be more sensitive to dynamic actions, resulting in a higher dynamic amplification factor;

- plan geometry of the bridge - skew and curved bridges, in certain situations, can amplify or reduce the dynamic response;

- damping capacity of the bridge - generally varies between 1-5%, and for higher values, it can significantly attenuate the dynamic response. Accurate consideration of damping is crucial when successive vehicle convoys traverse the bridge;

- support conditions of the bridge structure - directly influence the dynamic response.

Vehicles crossing the bridge structure have their own dynamic characteristics that significantly contribute to the generation of dynamic loads and the dynamic response of the interacting bridge. These include:

- travel speed: a critical travel speed can generate increased dynamic amplification factors. While high vehicle speeds do not automatically result in large dynamic loads, a combination of high speed with an uneven track can lead to increased dynamic loads.
- vehicle mass: theoretical and experimental studies have shown that an increase in vehicle mass can result in reduced dynamic amplification factors.
- suspension type: the vehicle's suspension type can lead to a significant amplification or reduction of dynamic effects.
- wheel configuration and spacing: generally, vehicles with a smaller wheelbase induce more significant dynamic effects on the bridge structure.
- vehicle type: vehicles with higher stiffness induce larger dynamic effects on the bridge structure than articulated vehicles.
- vehicle position on the bridge: the dynamic response of the bridge structure can be significantly influenced by the lateral position of the vehicle on the bridge, with bridges on slabs and girders being the most sensitive.
- presence of a large number of vehicles on the bridge: a high number of vehicles on the bridge across different lanes is associated with a reduction in dynamic effects transmitted to the bridge structure.

The condition of the track on the bridge structure is a significant factor in amplifying dynamic effects on the bridge. A decrease in the quality of the track directly leads to an increase in dynamic loads on the bridge and an increase in its vulnerability. This factor, combined with low values of the elastic and damping characteristics of the vehicle suspension, will accentuate surface imperfections and increase dynamic effects on the bridge.

3. RESONANCE IN RAILWAY BRIDGES

Dynamic analysis of specific bridge structures is necessary in the occurrence of the resonance phenomenon. Resonance is a hazardous phenomenon that arises due to high crossing speeds of the bridge and the existence of nearly equal distances between successive axles forming the train.

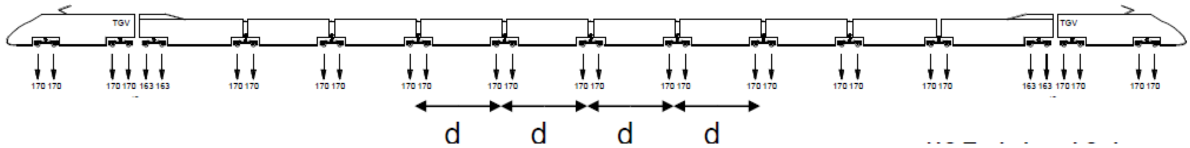


Figure 1. High-speed train configuration [1]

Due to the regular spacing of the train axles, the force exerted by them has a periodic nature with a frequency given by the formula:

$$f = \frac{v}{d} \tag{1}$$

where: d = distance between the axles; v = train speed; f = frequency of the force produced by the train axles.

In the situation where the frequency of the force equals one of the natural frequencies of the bridge structure, the resonance phenomenon occurs:

$$f = n_i \tag{2}$$

where n_i, with i =1,2,3,…, is one of the natural frequencies of the bridge.

In the case of resonance, due to high accelerations and the presence of noticeable irregularities on the track, excessive vibrations of the bridge structure can occur, leading to the loss of contact between the rail and wheel, destabilization of the ballast prism, the formation of cracks in the reinforced concrete deck, and exceeding permissible limits of forces in certain bridge elements.

When resonance occurs, the dynamic response of the structure increases very rapidly. The occurrence of resonance depends on the number of regularly spaced force groups, the damping of the structure, the nature of the loading, and the structural characteristics. The magnitudes of resonance response peaks depend significantly on structural damping. A low value of structural damping can result in high resonance peaks. In such situations, the safety of railway traffic on the bridge is compromised.

4. DYNAMIC AMPLIFICATION FACTOR

In a simplified manner, the dynamic response of a structure can be presented through dynamic amplification factors. These factors indicate how many times the static response of a bridge, subjected to moving traffic, needs to be increased to account for additional effects produced by the dynamic action of the traffic. Most commonly, the dynamic amplification factor is defined as a dimensionless ratio of the absolute value of the dynamic response to the absolute value of the maximum static response.

Due to its simplicity, the expressions for the dynamic amplification factor specified in bridge design codes cannot characterize the effect of all parameters influencing the dynamic response. To obtain a more accurate representation of dynamic effects, additional dynamic loads must be determined more precisely. In this context, it is recommended that for the design of high-speed railway bridges, the dynamic response should be analyzed using specialized calculation programs that can consider resonance phenomenon and other vibration effects in the bridge structure.

5. LOADS FROM MOBILE TRAFFIC AND THEIR COMBINATIONS

Studying the interaction between a bridge structure and a convoy of vehicles moving on it at a given speed is a typical problem of dynamic interaction between the vehicle and structure. Most theoretical and experimental studies often focus on the response of the bridge structure, resonance studies, and the analysis of track irregularities.

In cases where the study focuses solely on the response of the bridge structure, vehicles are represented by a set of mobile forces whose magnitude remains constant during their movement on the bridge structure. When studying the combined response of both the bridge structure and vehicles, calculation models are used that take into account the interaction of the two systems. In this case, the bridge and vehicles are considered two different structures interacting through forces or displacements developed at the contact points between the wheel and the track.

According to SR EN 1991-2:2005 [6], dynamic analyses should be performed using the HSLM calculation convoy for bridge structures located on European International Lines where interoperability criteria for high speeds apply. The HSLM convoy includes two different universal trains, HSLM-A and HSLM-B, with variable lengths of the wagons. The composition of the HSLM-A convoy is presented in Figure 2.

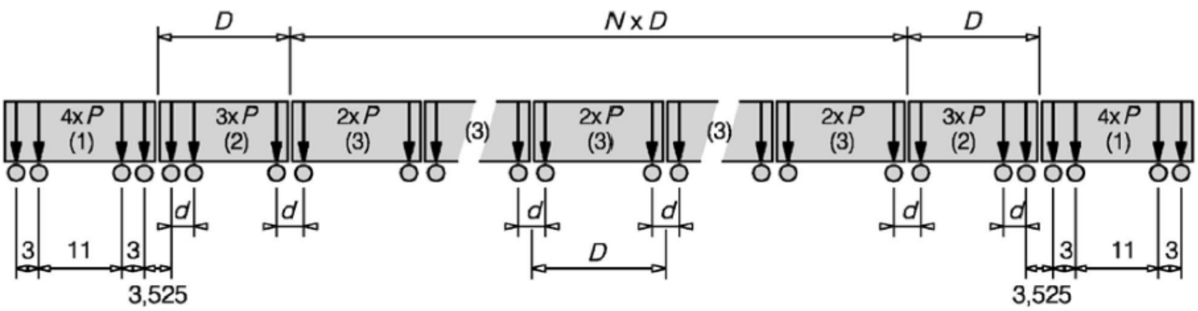


Figure 2. Composition of the HSLM-A convoy [6]
(1) Engine, (2) Last wagons, and (3) Intermediate wagons

In dynamic analyses, a series of speeds below the maximum design speed must be considered for each real train and for the HSLM loading model. The maximum design speed is generally established as 1.2 times the maximum speed at the location. Calculations are performed for speeds ranging from 40 m/s up to the maximum design speed. Near the resonance speed, the increments in speed are smaller.

6. DYNAMIC MODEL PARAMETERS OF RAILWAY BRIDGES CROSSING BY MOBILE TRAFFIC

6.1. Bridge stiffness

Similar to damping and mass, the stiffness of the bridge structure has a direct influence on dynamic effects. Any overestimation of bridge stiffness will overestimate the natural frequency of the structure and the traffic speed at which resonance occurs. It is advisable to use lower values of stiffness estimated for bridge structure elements, as specified by design codes.

6.2. Bridge mass

The loading from moving traffic produces the maximum dynamic effect at resonance when the loading frequency equals the natural frequency of the structure. Consequently, any underestimation of the structure's mass leads to an overestimation of the structure's natural frequency and the traffic speed at which resonance occurs. At resonance, the maximum acceleration of the structure is inversely proportional to the mass of the structure. To determine the mass of the structure, two specific cases must be considered, including the ballast and the track:

- estimate the minimum value of the structure's mass to evaluate maximum accelerations at the track level using the dry density of the ballast and its minimum thickness. The minimum density of the ballast can be considered as 1700 kg/m^3.
- estimate the maximum value of the structure's mass to evaluate the lowest speeds at which resonance effects may occur, using the saturated maximum density of the dirty ballast and an increase in its thickness in case of potential future track lifts.

6.3. Estimating structural damping

Damping is a highly complex phenomenon. The energy induced by the passage of vehicles is irreversibly dissipated, either through plastic deformations of the material or transformed into other forms of energy during the vibrations of the bridge.

The maximum dynamic response of the bridge structure due to the traffic speed corresponding to resonance largely depends on the damping of the structure. The recommended characteristic values of damping to be used in dynamic analysis depend on the type and span of the bridge. For the analyzed bridge case, according to SR EN 1991-2:2005 [6], a fraction of critical damping of 5% was considered. The recommendation is to use the smallest possible estimated damping value.

7. DYNAMIC RESPONSE ANALYSIS TO THE ACTION OF MOVING LOADS

To perform the dynamic response analysis of a structure due to the passage of a traffic of mobile forces with different speeds, the modal analysis procedure was employed. This involves decoupling the equations of motion and superimposing the effects resulting from integrating the decoupled equations of motion. It is essential to conduct a prior analysis of eigenvalues and eigenvectors to select the significant natural modes for the dynamic response.

The size and geometric configuration of the moving train remain constant throughout the analysis. Data related to frequency-dependent equivalent loads are applied to each vibration mode separately, and the total response at any point in the structure is obtained by summing individual responses through superposition techniques. The assumption of linear elastic structural behavior allows the use of linear superposition techniques. All results are determined in the time domain. The adoption of modal analysis results in reduced computational effort compared to traditional step-by-step direct integration of the coupled equation system.

8. CASE STUDY

The object of the study consists of determining the influence of the moving speed of an HSLM-type traffic when crossing a railway bridge with a truss system and determining the first resonance speed.

The structure of the bridge is presented in Figure 3. and consists of a superstructure made up of two metal truss girders, stringers, cross braces, sway braces, a reinforced concrete box, a ballast prism, and reinforced concrete sleepers to which the rails are attached.

The analyzed model of the bridge includes only the superstructure, with the influence of the infrastructures being negligible. The support is achieved using neoprene bearings, one for each metal girder.

8.1. Finite elements used in modelling the bridge structure

Several types of 3D finite elements were used in modeling the analyzed structure, depending on the structural element to be modeled. The components of the structure were modeled as follows:

- thick shell elements were used for the concrete box;
- beam-type BTS3 elements were used for lines (rails, sleepers, girders, cross braces, stringers, trusses, sway braces);
- volume elements were used for the ballast.

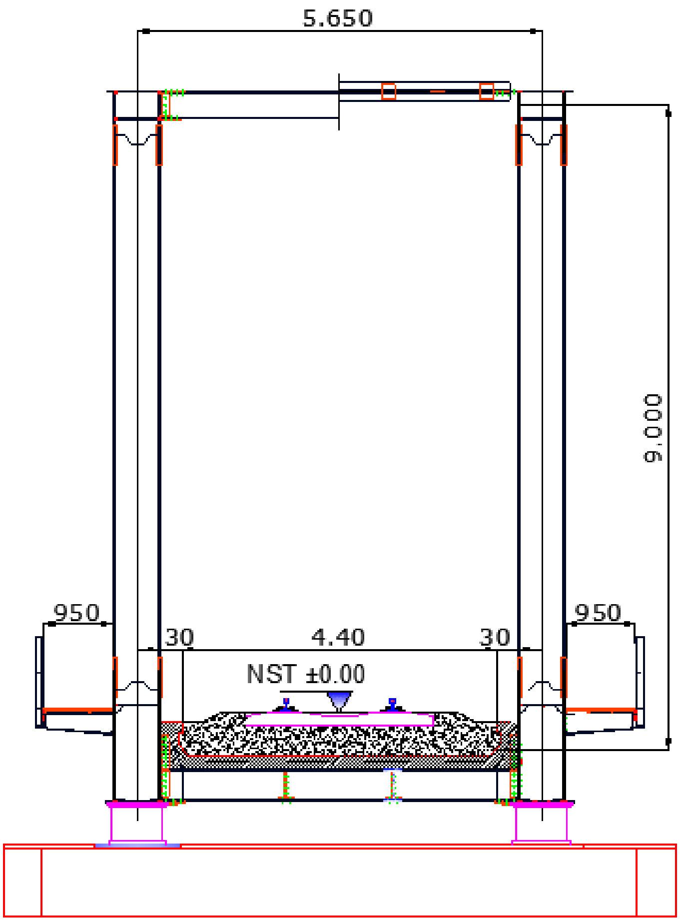


Figure 3. The bridge structure (cross section) – Case Study

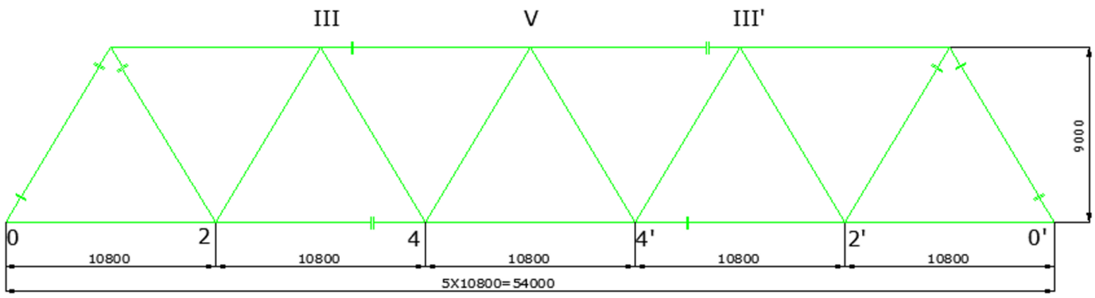


Figure 4. The bridge structure (deck general arrangement - Elevation)

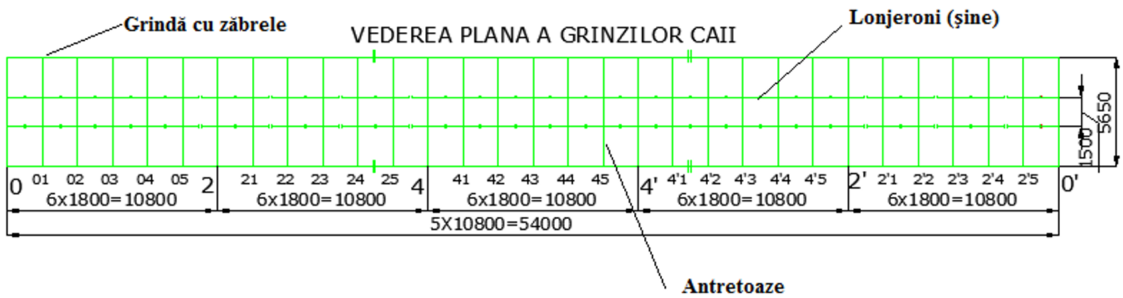


Figure 5. The bridge structure (plan view of the track beams) – Case Study

8.2. Variable parameters considered and analyses assumptions

In the dynamic analyses conducted, only two types of railway traffic were considered: LM 71 Convoy representing the static effect of vertical loads due to normal railway traffic and HSLM-A Convoy representing the dynamic effect of loads from high-speed conventional vehicles for passenger traffic. Only the results obtained for the HSLM-A Convoy are presented in this study.

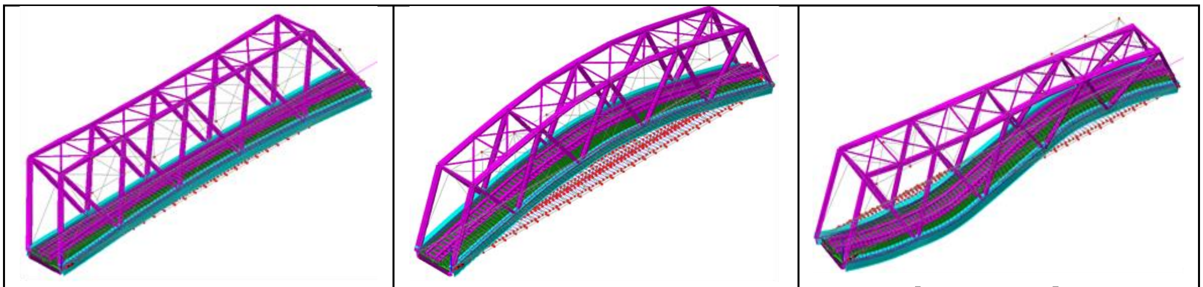
The speed of the considered mobile force traffic ranges between 100 km/h and 300 km/h when crossing the bridge. The train speed is an important parameter, directly influencing the dynamic responses of railway bridges.

The dynamic analysis of the structure, when different traffic models pass at varying speeds, was carried out through modal analysis. The rail condition was considered to be very good, thus neglecting interactions between the vehicle-bridge and track irregularities.

8.3. Analyses of dynamic characteristics of the bridge structure. Natural modes of vibration

The calculation of natural frequencies was performed using the subspace iteration method, considering 20 natural modes of vibration for the structural response. These modes account for 90% - 98% mass participation in the modal response, with natural frequencies ranging between 2,625 and 15,704 Hz.

Figure 6. illustrates some of the significant natural modes of vibration for vertical displacement of the entire bridge structure and track.



Shape mode 1 f = 2.625 Hz	Shape mode 2 f = 3.441 Hz	Shape mode 7 f = 7.894 Hz

Figure 6. Significant modes shape for vertical displacement of the railway bridge structure and track

8.4. Dynamic analysis of the traffic speed effect on the railway bridge

The dynamic analysis was conducted using a specialized module of the LUSAS [4] finite element structural analysis software. This module, named IMDPlus, allows for the definition of the spatial and temporal configuration of the moving train, generation of its displacement history on the track based on speed, determination of modal equivalent forces for each position of the train, and calculation of the bridge structure's response to the train's movement for a set of given speeds.

Regarding the output data, in this study the time history of displacements, accelerations, and the dynamic amplification factor for several nodes and elements of the structure was considered significant. For the variation in train speed, an increment of 10 m/s was chosen, starting from the minimum speed of 30 m/s and reaching 90 m/s. To compare the static-dynamic response, the structure's response at a speed of 3 m/s, equivalent to 10 km/h, was analyzed.

The following it is presented the results of the displacement, acceleration, and dynamic amplification factor variation for node 66, located at the midpoint of the bridge span on the lower truss beam, depending on the speed of the HSLM-A1 vehicle crossing the bridge.

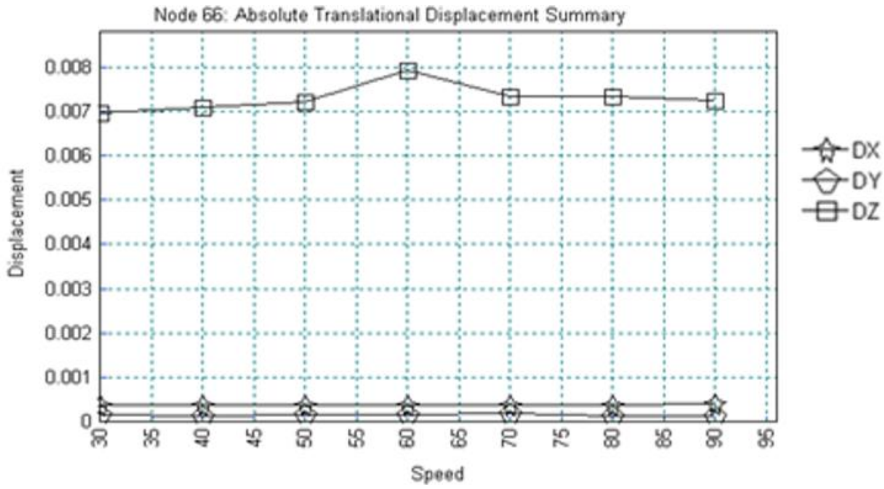


Figure 7. Node 66 – Maximum displacements Dz vs Speed, HSLM-A1 vehicle

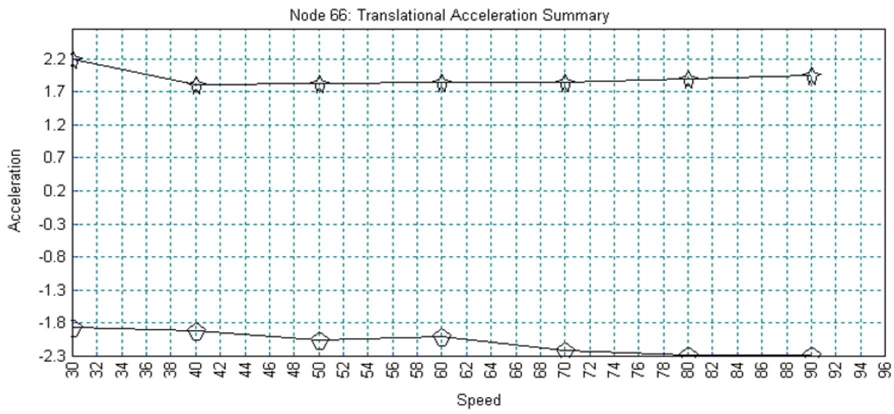


Figure 8. Node 66 – Maximum accelerations Az vs Speed, HSLM-A1 vehicle

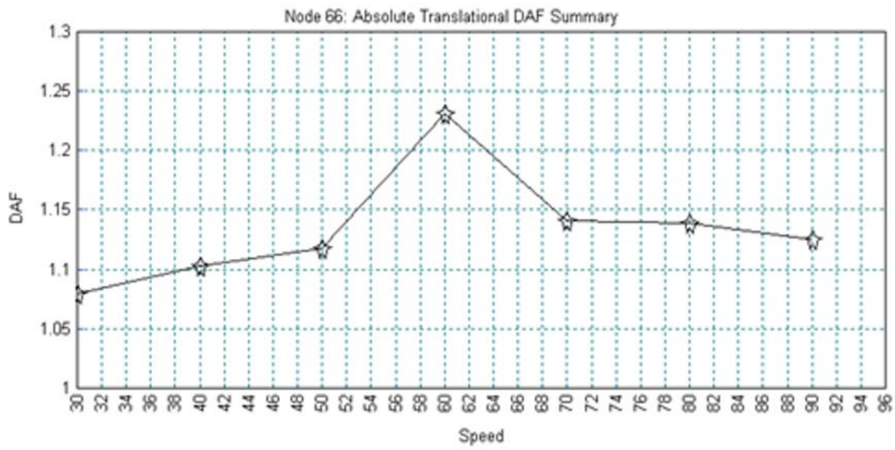


Figure 9. Node 66 – Maximum Dynamic Amplification Factor (DAF) vs speed

Table 1. Node 66 – Displacements/Accelerations/Dynamic Amplification Factor (DAF) as a function of speed. Convoy HSLM-A1

Speed	Dz	Az	DAF - Dz
3 m/s	6.54307E-3	2.29699	
30 m/s	6.95429E-3	2.18786	1.07955
40 m/s	7.10346E-3	1.91187	1.10274
50 m/s	7.20062E-3	2.05863	1.11783
60 m/s	***7.93049E-3***	2.00753	***1.23113***
70 m/s	7.35043E-3	2.21476	1.14108
80 m/s	7.33369E-3	***2.28812***	1.13848
90 m/s	7.24418E-3	2.28025	1.12459

From the presented results, it can be observed that the maximum dynamic amplification factor is obtained at the resonance speed of 210 km/h (60 m/s) and has a value of 1.23113.

The time history of the vertical displacement at node 66, located in the middle of the bridge span on the lower deck, for vehicle HSLM-A1 speeds of 3 m/s (quasi-static action) and 60 m/s (resonance speed) is shown in Figures 10. and 11. In both situations, the harmonic variation of the displacement around the elastic equilibrium position marked by a displacement of 0.004 m can be easily seen.

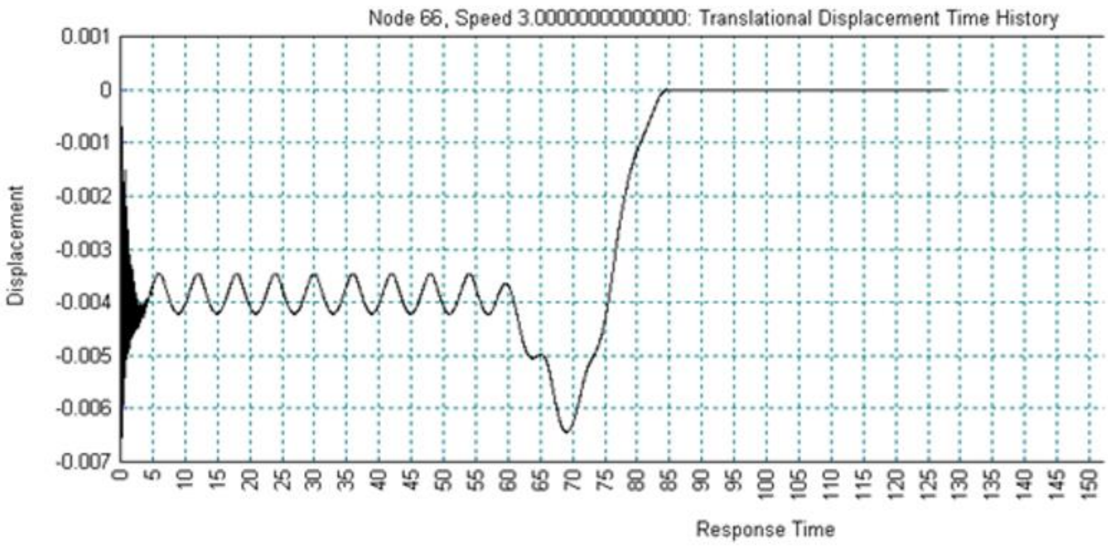


Figure 10. Node 66 - Time history of displacement Dz - speed 3 m/s, HSLM-A1

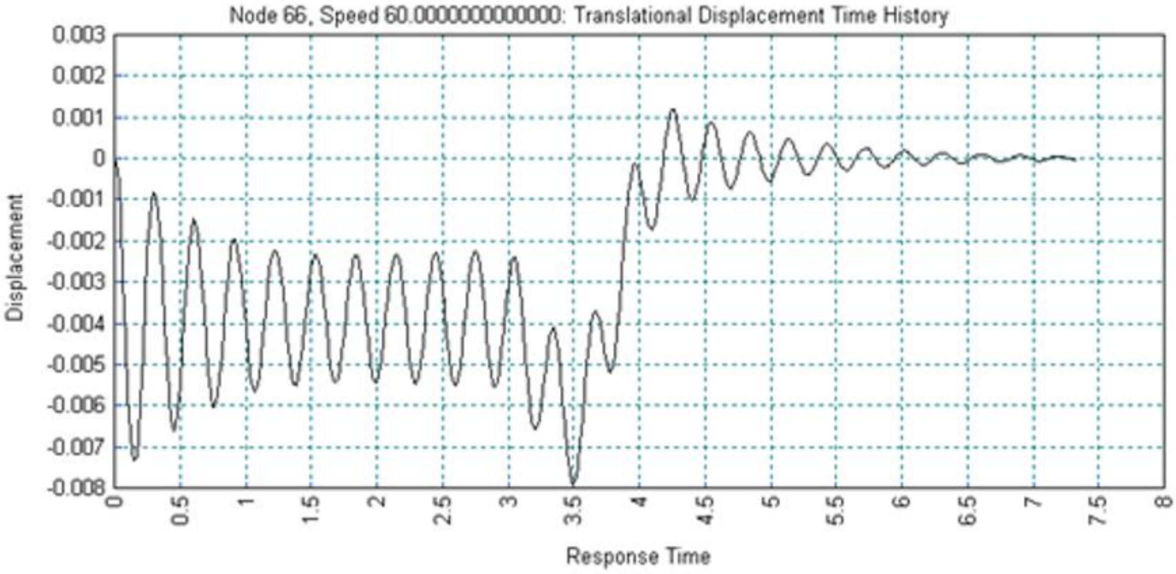


Figure 11. Node 66 - Time history of displacement Dz - speed 60 m/s, HSLM-A1

The influence of the mobile force speed can be achieved by considering, instead of displacements, the stresses generated in the bridge structure due to the traffic action. A significant example is presented in Figure 12. for a lower chord element of the truss located at the middle of the bridge span, element 61.

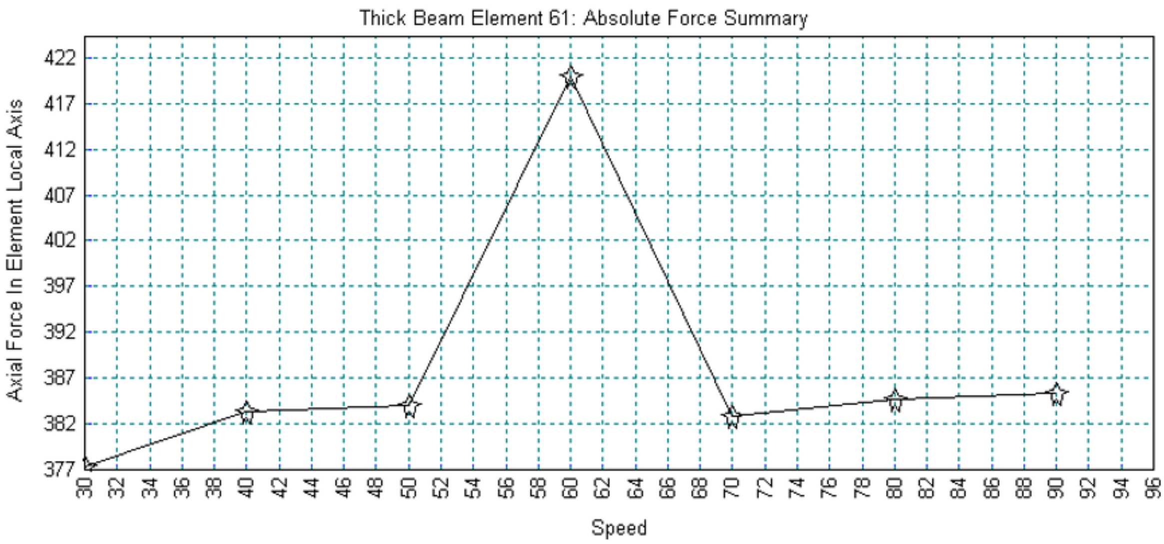


Figure 12. Element 61 – Variation of axial force in the beam element with speed - HSLM-A1

8. CONCLUSIONS

This study analyzed the dynamic behavior of high-speed railway bridge structures subjected to high-speed trains, and the conclusions are as follows:

- the vehicle speed is an important parameter directly influencing the dynamic response of the bridge. Generally, the dynamic response increases with the speed;
- the dynamic response of the bridge reaches the resonance speed at train speeds between 200 and 300 km/h. The degree of displacement multiplication at resonance depends on the bridge type and the model adopted for vehicles;
- sufficiently accurate results are obtained by superimposing vibration modes with frequencies not exceeding 30 Hz, and a time step of 0.01 seconds is small enough to determine the peak value of the resonance speed;
- dynamic amplification factors (DAF) determined for displacements are higher than those obtained for forces. The maximum values are obtained at the midpoint of the bridge span;
- the value of bridge damping significantly influences its response amplitude. However, it has been seen that peak values determined for a specific speed do not depend on the damping coefficient considered;
- the study investigated the influence of increasing axle load for a given train speed. It is noted that bridge accelerations increase proportionally with the increase in axle load, while dynamic amplification factors remain unchanged;
- a higher structural stiffness of the bridge results in the maximum resonance value occurring at higher train speeds. However, the maximum resonance value is independent of the bridge stiffness.

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