Feasibility of increasing train speed in existing railway concrete slab deck bridges

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Abstract. Increasing train speed in railway networks is one of the most important factors in attracting more passengers and cargo. The construction of new railway tracks and structures with the aim of increasing the speed of trains requires a lot of costs. Therefore, the aim of this study is to investigate the possibility of increasing the train speed using a low-cost method, such as changing the conditions of bridge bearings in existing railway concrete slab deck bridges. First, a 3D finite element model of the bridge and train was created by considering their interaction and it was validated based on the results of a valid field test. Then, the effect of train speed increasing on the bridge and train displacement and acceleration is investigated. The obtained results indicated that when the stiffness of the bridge bearing was reduced by 50%, the maximum values of the vertical displacement of the bridge deck increased by 5-10%, and the maximum values of the vertical acceleration of the bridge deck increased by 10-20% for the 2 and 4 m bridge, and 30-50% for the 6 and 8 m bridge, but the vertical acceleration of the train passenger wagon body was reduced by 10-20%.

Key words: Finite Element Model, Train-Track Interaction, Existing Railway Concrete Slab Deck Bridge, Speed Increase, Model Validation

1. Introduction

One of the main and most important factors in increasing the efficiency and attractiveness of any mode of transportation is its speed and travel time, which have a tremendous effect on attracting passengers or cargo owners. In this regard, one of the main and most challenging parts of the route is the existing structures on railway tracks, especially bridges. No defects in their performance are acceptable, and the occurrence of any problems can lead to complete blockage of the path for a long time. Considering that the bridges on the route are under service, the main priority in improving the speed of the train is to increase the efficiency of the existing bridges by making low-cost technical changes, such as improvement of the conditions of the bridge bearings that can be performed in a short time. According to information from the Islamic Republic of Iran Railway Company, the average travel speed in the country's railway network is low at approximately 60 km/h [1]. To increase train speed, bridges are considered as one of the most important points of the railway network. The investigation of the speed increase on bridges is in same way and a part of the investigation of the speed increase on railway lines. Based on the statistical information provided by the Islamic Republic of Iran Railway Company, until the end of 2020, railway bridges with a concrete slab deck have a frequency of 57% of the total bridges, with dimensional specifications, as well as the number of different spans [1]. Tables 1 and 2 show the number of this type of bridge according to the number and length of spans [1]. As can be seen in the aforementioned tables, these types of bridges are mostly single-span bridges, and their span length is less than 4 m in most cases. The thickness of the deck of these types of bridges has different values in the range of 25–100 cm, according to different conditions, such as the length and number of spans and the thickness of the pavement [1].

In recent decades, bridge–train dynamic interaction has drawn the attention of structural and railway engineering specialists and experts [2]. The most important parameters that are effective in this regard are the frequency characteristics of the bridge structure, frequency characteristics of vehicles, damping coefficients of bridges and vehicles, speed of vehicles, and road irregularities [3]. During the construction of the first railway track in England in the first half of the 19th century, engineers had two different ideas about the interaction between the track and train. The first group considered that when the train passed along the bridge, the dynamic effect of movement was added to the static load of the vehicle. The second group believed that the structure did not have sufficient time to change shape and did not understand the effect of movement. For this reason, during the same period, experiments were carried out by Willis [4] and theoretical studies by Stokes [5]. These studies showed that the actual effect of a train moving on a bridge was between these two ideas. Since then, the dynamics of railway bridges have attracted the attention of researchers worldwide. To model the loads passing over a railway bridge, there are three general methods: the moving load method, moving mass method, and moving suspended mass method [6,7]. In the method of moving loads, the amount of vertical force transferred from each wagon or locomotive to the axle location is applied as a single force, and the effects of the interaction between the track and vehicle cannot be checked [8,9]. In the moving mass method, the device is modeled as a discrete mass and volumetric forces or weights are applied to its mass. However, because of the absence and consideration of stiffness and damping effects, and the relationship between different masses, effective effects can be considered [10]. Dynamic interactions were not correctly provided. However, in the third method, the vehicle is modeled with full accuracy and in the form of discrete masses concentrated in the mass centers of different parts of the wagon, including the axles, bogies, and body of the wagon, and the connections between these masses are established using springs and dampers. This can be a very good representative of the behavior of a real example of a wagon [11,12]. Yang and Wu suggested a versatile element for analyzing vehicle–bridge interaction response that is capable of treating various vehicle–bridge interaction (VBI) effects is derived [13]. Hajiani Boushehrian et al [14] modeled two loads moving in different directions on a simple bridge span in their research project. Liu et al [15] investigated the interaction between the bridge and passing trains. In their study, they used two-dimensional finite element modeling and considered the bridge to be a simple double-headed beam. Examining the vibrations caused by train passage and the solutions and factors affecting vibrations in railway tracks or technical buildings became more important and widespread in China with the studies of Fryba [16] and Xia and Zhang [17]. Sadeghi and Esmaeili [18] stated that the main method for reducing vibrations is to reduce track stiffness. This is the most basic method used for new and existing rail routes [19,20,21]. Some researchers [22,23,24] reduced vibration in high-speed railway bridges by using PTMD (Passive Tuned Mass Dampers) and the results show that the proposed PTMD is a useful tool for controlling vibrations and also for reducing bridge accelerations. Martínez-Rodrigo et al. [25] proposed a possible solution to reduce the unacceptable level of vertical acceleration of the deck, which is based on retrofitting the bridge with viscous dampers connected to the slab and auxiliary structure. Moliner et al. [26,27] in studies aimed at strengthening existing railway bridges with a span of 10 to 25 meters for the passage of high-speed trains using viscoelastic dampers and evaluating the effect of the flexibility of elastomeric bearings to reduce the vibrations of the bridges. Jahangiri and Zakeri [28] have studied the dynamics of concrete bridges with one-lane and two-lane railway box sections against increasing train speed. They modeled the bridge and train as a three-dimensional finite element in ABAQUS software and examined the vertical and horizontal acceleration of the bridge as criteria for evaluating the behavior of the bridge against the increase in train speed. In the study of Erduran et al. [29] on a bridge with a 50 meters span in three modes of single-span, double-span, and three-span, the effect of several types of stiffness of the bridge bearing on the vibrations of the bridge caused by the passage of a train at speeds of 50 km/h, 80 km/h, and 130 km/h was checked. In the results of this study, it can be seen that in different parts of the length of the bridge, the effect of reducing or increasing the stiffness of the bridge bearing is different; however, in general, the acceleration of the bridge deck decreases with an increase in the stiffness of the bridge bearing. In a study on a 32-meter bridge with a box section, Zhang et al. [30] investigated the effect of the stiffness of the bridge bearing on the vibration damping of a bridge caused by the passage of a train. Their study results showed that in different frequency ranges and at different train speeds, the impact of the bridge bearing stiffness can be different. Therefore, for example, in one frequency range, the behavior and effect of the stiffness of the bridge bearing are completely opposite to the behavior and effect of the same stiffness of the bridge bearing in another frequency range. Li et al. [31] have conducted a field and numerical study of the effect of using elastic bridge bearings in reducing the vibrations caused by the train passing around the railway track and around the railway bridge. In their study, four types of stiffnesses of elastic bridge bearings were investigated to reduce vibrations. In their study, after conducting a field test to validate the numerical model made in ABAQUS finite element software, the vibrations, vertical acceleration, and forces created in the elastic bearings of the bridge, ground around the bridge, and passing train at a speed of 350 km/h were investigated at different distances up to 25 m from the bridge. The railway bridge studied by these researchers was a concrete bridge with a concrete box deck. According to previous studies, various solutions have been used to improve the behavior of bridges and reduce vibrations in railway lines. In this study, a detailed investigation of this issue was conducted for existing bridges with concrete slab decks, especially bridges with a span of less than 10 m, in order to increase the speed of trains, taking into account the least damage to the bridge and the least duration of obstruction in the traffic passing through the bridge and track.

2. Material and methods

In this study, to model and analyze the bridge and train system, a 3D finite element model was developed using ABAQUS (a finite element software). The interaction between the bridge and the train was created using the Hertz theory [32]. Then, the created model was validated by comparing the values of the vertical displacement, mode frequency, and vertical acceleration of the bridge deck obtained from the analytical model and field test. Then, a sensitivity analysis is conducted.

2.1. Assumptions considered in this study

The train and bridge were modeled using the finite element method. The train was modeled in three dimensions, and 33 degrees of freedom were considered for each vehicle with six axles. The bridge is a single-lane, simple span, and concrete slab deck system. Subsequently, the pavement was ballasted. Rails, springs, and dampers related to the pads and stiffeners were modeled. The lengths of the selected bridge spans for the analysis were 2, 4, 6, and 8 m. The train crossed the bridge at different speeds (from 20 to 260 km/h in increments of 20 km/h).

2.2. Objectives of the study

- Investigating the current condition of existing railway concrete slab deck bridges in terms of bridge operation levels, including the vertical displacement of the span, vertical acceleration of the deck, and vibration frequency of the bridge span against the increase in train speed along the selected span.

- Determine the optimal maximum crossing speed based on the current conditions of bridges.

- Investigating the possibility of increasing the speed of the train on the existing concrete slab deck bridge by changing the conditions of the bridge bearings (from simple seating to neoprene)

According to the assumptions and intended goals, the review process was in accordance with Figure 1.

2.3. Bridge and train characteristics

The accuracy of the results of the finite element model was validated and controlled by comparing the results with the results of the field test of the bridge located at km 168+100 of the old Tehran-Qom track between Nudej and Garmanuri stations [33]. The total length of the proposed bridge is 5.8 m with a free span length of 4 m, width of 4 m, and thickness of the bridge deck is 50 cm [33]. The deck was placed in the form of a simple double-headed beam on the foundation, and the height of the middle of the bridge span was 3 m from the ground level (Figure 2) [33]. The rail used in this track was U33, and its sleepers were metal type with a distance of 50 cm [33]. The thickness of the ballast on the deck was 40 cm and the width of the ballast on the bridge deck was 3.2 m [33].

2.4. Loading conditions

Two GT26 locomotives connected to each other crossed the track at speeds of 20 and 50 km/h [33]. The axial load and distance between the axles and bogies are shown in Figures 3 and 4.

2.5. Vehicle modeling

The finite element model of the train includes a set of point masses, including the body, bogie, axles, springs, and dampers that exist in the connections of the body to the bogie and the bogie to the axles of the wheels. The general model of a traditional six-axle wagon is shown in Figure 5. The wagon includes a primary suspension system with stiffness and damping K_p and C_p, secondary suspension system with stiffness and damping K_s and C_s, mass of wheels M_w, mass of bogie M_b and J_b, and mass of wagon bodies M and J. The model considered to solve the problem in this study is based on the details shown in Figure 5. The technical specifications of the GT26 locomotive used in the selected field tests are listed in Table 3. In the train finite element model, the wagon, bogies, and axles are modeled as a rigid body with rotational inertia and are connected to each other by springs and viscous dampers. Figure 6 shows an image of the locomotive model, and Figure 7 shows the Hertz spring model with spring elements.

2.6. Bridge modeling

The technical characteristics of the bridge and track parameters as shown in Table 4 were obtained by Esmaeili et al. [33]. An overview of the bridge, track, and vehicle models is shown in Figure 8.

2.7. Modal analysis and optimal mesh size determination

An effective parameter in the finite element analysis results is the model meshing dimension. In general, the smaller the elements, the more accurate the results of the model, but on the other hand, more time is spent on analysis. Therefore, in the first step, modal analysis with different meshing dimensions was performed on the bridge model, and the results of different modes were compared with each other, as shown in Table 5.

According to the results in Table 5, the values of the natural frequencies of the first to fourth modes did not change with the reduction in the mesh dimensions from 15 to 10 cm and were completely convergent. Therefore, in further stages of the analysis, 15 cm meshing dimensions were considered as optimal meshing dimensions. Figure 9 shows the shapes of the first to fourth modes of the bridge with 15 cm mesh dimensions.

2.8. Boundary conditions

In research projects [35,36], to simplify the calculations and assumptions, the entrance and exit of the spans are considered rigid and without displacement relative to the bridge; however, in this study, to consider the effects of the entrance and outlet in the studied main span by considering the equivalent hardness of the soil on the sides of the bridge by modeling it as a spring element in two spans before and after the main span. The main spans and springs of the side spans are shown in Figure 10. To eliminate calculation errors, the translational degrees of freedom of the rail were closed in the transverse direction. The finite element model of the concrete slab deck bridge in mesh shape is shown in Figure 11.

2.9. Validation of the model

In this section, the finite element model is validated based on the results of the field test. For this purpose, the results of the modal analysis and the results of the time history of the displacement and acceleration of the middle of the bridge span under the passage of the GT26 train at speeds of 20 and 50 km/h were considered. The frequency of the first vibration mode of the FE model of the bridge is equal to 20.42 Hz, which is in good agreement with the results obtained in the field test [33] (i.e., 20.03 Hz). In addition, a comparison of the displacement and vertical acceleration values in the middle of the span in the finite element model and the field test is shown in Figure 12. As shown in Figure 12, the results of the finite element model in this section are completely consistent with the results of the field test and indicate the correctness of the behavior of the finite element model.

3. Results and Discussion

After ensuring the accuracy of the behavior and the results of the finite element model, the results of the sensitivity analysis are presented and reviewed in this section. In this section, the values of the dynamic responses of a bridge under the passage of a train at different speeds are presented. The displacement and acceleration values at different points of the bridge in the midspan and a quarter of the bridge span are recorded according to Figure 13, and their maximum values are presented in the graphs of the results.

3.1. Changing the condition of the bridge bearing

To investigate and analyze the results of the bridge with a concrete slab deck to increase the speed of the train, four span lengths frequently used in the Iranian railway, including spans of 2, 4, 6, and 8 m, were considered for analysis. The current bearing conditions of the bridge with the concrete slab deck selected in this study as well as the bearing conditions of most bridges of this type are such that the flat concrete slab of the bridge is placed as a simple bearing without separate seating on the concrete foundations of the bridge. has taken. To increase the speed of a train passing over a bridge, changing the conditions of the bridge bearing was evaluated as a solution. For this purpose, elastic cushions (neoprene) were used according to the technical specifications of Gumba [37]. Owing to the number of metal and rubber layers used in their construction, neoprenes have a high hardness. Three types of neoprene with a circular cross-section, a diameter of 35 cm, and three different vertical hardnesses were considered. According to the technical specifications of the neoprenes in the Gumba catalog [37], the vertical hardnesses of these neoprenes were 2900, 4450, and 7250 kN/m, respectively. Parametric analyses of the speed and length of the spans were performed according to the changes in the stiffness of the bearing, and the results are presented in the form of graphs of maximum displacement values (Figure 14), vertical acceleration of the bridge (Figure 15), and train body (Figure 16) in different spans, which are offered at different speeds. In these graphs, the bridge bearing is shown at four different modes: simple seating (N= without neoprene), hard neoprene (HN=7250 kN/m), medium neoprene (MN=4450 kN/m), and soft neoprene (SN=2900 kN/m). According to the results of the maximum values of the vertical displacement of the bridge (Figure 14), it can be seen that the bridge with simple sitting bearing conditions (without neoprene) has the lowest maximum values of the vertical displacement of the deck among other bearing conditions. In addition, in the state of bearing with soft neoprene, the maximum vertical displacement values of the bridge deck were the highest. In all the selected spans and according to the types of bridge bearing conditions and at all train speeds, the maximum amount of vertical displacement of the bridge span in the most possible state reached approximately 1.5 mm and According to the UIC code [38] and EN 1990 [39], from the point of view of the vertical displacement of the bridge span, there will be no problem for the bridges in question against increasing the speed of the train.

According to the results obtained in Figure 15 for bridges with spans of 2 and 4 m, the response of each bridge is critical at travel speeds of 240 and 180 km/h, respectively. In addition, according to the results of the bridge with a 6-meter span, it can be seen that the response of the bridge is critical at speeds of 120, 200, and 220 km/h (in medium neoprene, soft neoprene, and medium neoprene bearing, respectively). The results of the bridge with an 8-meter span also show that the response of the bridge is critical at speeds of 80, 180, and 220 km/h (in hard neoprene, medium neoprene, and hard neoprene bearing, respectively). Generally, the maximum vertical acceleration of the bridge deck increases at most speeds by reducing the stiffness of the bridge bearing. According to the results obtained in this section, it is clear that the vertical acceleration of the bridge deck is critical in bridges with shorter spans (2 and 4 m) compared to bridges with longer spans (6 and 8 m). According to the UIC code [38] and EN 1990 [39], if the vertical acceleration of the bridge deck is greater than 3.5 m/s^2, it is considered unacceptable. According to the results of the vertical acceleration to the vehicle body (Figure 16), it can be seen that, in general, in all four conditions of the bridge span length and at most of the travel speeds, with a reduction in the stiffness of the bridge bearing, the maximum vertical acceleration to the vehicle body The vehicle is reduced. This trend is prominent in bridges with spans of 2 and 6 m at a speed of 80 km/h, 4 m at a speed of 140 km/h, and 8 m at a speed of 120 km/h. According to EN 1990 [38], if the vertical acceleration on the body of the vehicle wagon is greater than 2 m/s^2, the comfort of the passenger is unacceptable.

3.2. Dynamic amplification analysis

In bridge design, the dynamic amplification factor is generally used to consider the dynamic effect of a train on a bridge structure, and it is defined as the ratio of the maximum dynamic response to the maximum static response. Dynamic amplification factor is the most widely used parameter because it shows how much the static load should be increased to cover additional dynamic effect [16]. According to EN 1990 [39] the dynamic factor can be calculated by Equation (1):

$$\varnothing = \frac{1.44}{\sqrt{L} - 0.2} + 0.82 \qquad (1)$$

Where L denotes the bridge span length. For L = 2, 4, 6, and 8 m, the dynamic amplification factors are 2, 1.62, 1.46, and 1.37, respectively. In this section the measured vertical displacements of bridge deck are being compared with the static calculated vertical displacements in order to get the real dynamic factor. Figure 17 shows the real dynamic factor which are actually the proportion of the experimentally determined vertical displacement to the static calculated ones in each bridge span length. The results showed that the real dynamic amplification factor of the vertical displacement of the bridges is lower than the values obtained from Equation 1, which shows that the results of the finite element modeling are acceptable.

4. Conclusion

- This study investigates the effect of changing the bearing conditions of existing bridges with concrete slab decks as a solution to improve existing bridges under railway service by increasing the train speed in the country's rail network. In this study, the response of existing concrete slab deck bridges with short spans on railway tracks under different bearing conditions and travel speeds was investigated.
- The bearing conditions of the bridges were investigated in four different modes: simple sitting (without neoprene) (N), with hard neoprene (HN), medium neoprene (MN), and soft neoprene (SN), which conform to simple sitting positions (without neoprene); neoprene

with a hardness of 7250 kN/m; neoprene with a hardness of 4450 kN/m; and neoprene with a hardness of 2900 kN/m.

- The speed of trains is considered to range from 20 km/h to 260 km/h. In this study, the three-dimensional finite element method was used to model the bridge, train system, and interaction between them, and valid field test results were used to validate the model. Examining the responses of the bridge, train, and the interaction between them includes an examination of the results of the vertical displacement and vertical acceleration of the bridge deck, as well as an examination of the results of the vertical acceleration to the body of the train wagon while passing over the bridge.
- The results of the study revealed that decreasing the stiffness of the bridge bearing (from simple sitting mode to HN mode, from HN mode to MN mode, and from MN mode to SN mode) resulted in an increase in the maximum values of vertical displacement of the bridge deck by 5% to 10%, and an increase in the maximum values of vertical acceleration of the bridge deck by 10% to 20% for 2- and 4-meter bridges, and by 30% to 50% for 6- and 8-meter bridges. Additionally, the vertical acceleration of the train passenger wagon body was reduced by approximately 10% to 20%.
- In addition, according to the results, it is clear that the vertical acceleration of the bridge deck is critical in bridges with shorter spans (2 and 4 meters) compared to bridges with longer spans (6 and 8 meters) and at speeds higher than 120 km/h, it enters the unacceptable vertical acceleration range according to the UIC and EN 1990 codes.

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Figure and Table Captions List:

Table 1. Number of bridges according to the number of spans [1]

Table 2. Number of bridges according to the span length [1]

Figure 1. Schematic of the research methodology

Figure 2. Field test bridge and placement of sensors

Figure 3. Distance between axles in meters in the locomotives used in the field test

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Figure 12. Bridge deck response in the middle of the span in the field test and FEM model:
Vertical displacement (a): Train speed 20 km/h, (b): Train speed 50 km/h
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Figure 13. Target points for recording results on bridge deck

Figure 14. Maximum displacement of bridge deck:

(a): 2 m span, (b): 4 m span, (c): 6 m span and (d): 8 m span

Figure 15. Maximum acceleration of bridge deck:

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Figure 16. Maximum vertical acceleration of passenger wagon body in bridges:

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Figure 17. Dynamic amplification factor of displacement of bridge deck:

(a): 2 m span, (b): 4 m span, (c): 6 m span and (d): 8 m span

Figures and Tables:

Table 1. Number of bridges according to the number of spans (adopted from [1])

span	1	2	3	4	5	6	7	8	9	10
Bridges	10383	788	496	109	110	39	30	9	9	8

Table 2. Number of bridges according to the span length (adopted from [1])

Span length (m)	Up to 2 m	Up to 4 m	Up to 6 m	Up to 8 m	More than 8 m
Bridges	3448	2370	1076	751	688
Percentage	42%	28%	13%	9%	8%

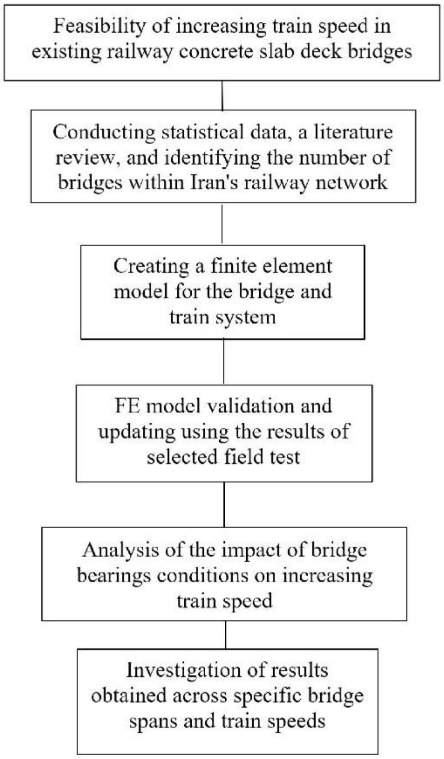


Figure 1. Schematic of the research methodology

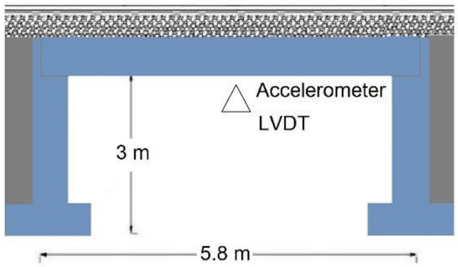


Figure 2. Field test bridge and placement of sensors

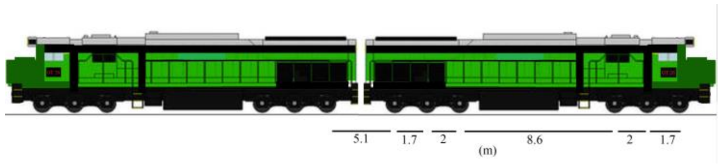


Figure 3. Distance between axles in meters in the locomotives used in the field test

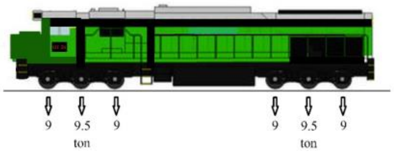


Figure 4. Axle load (ton) of the GT 26 locomotive used in the field test

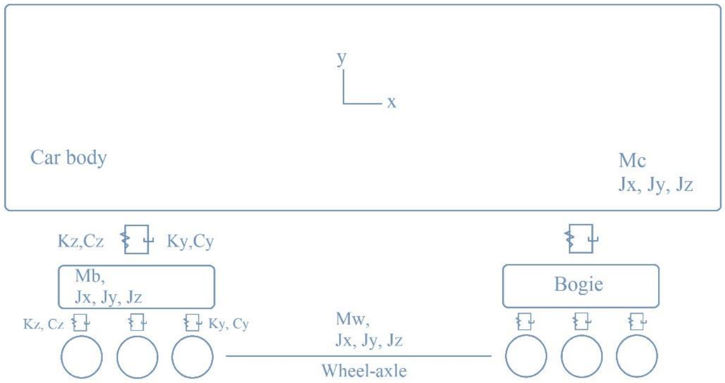


Figure 5. 3D vehicle model

Table 3. Technical specifications of the field test locomotive (adopted from [34])

Description	Name	Unit	Power car	Passenger cars
Mass of car-body	Mc	ton	68	59
Car-body inertia moments	Jx; Jy; Jz	ton. m^2	180;3500;3500	85;2900;2870
Mass of bogie	Mb	ton	3.4	3
Bogie inertia moments	Jx; Jy; Jz	ton. m^2	1.76;2.5;5	1.55;2.4;4.6
Second suspension stiffness	Kz; Ky	KN/m	220;1040	105;810
Second suspension damping	Cz; Cy	KNS/m	95;120	40;45
Primary suspension stiffness	Kz; Ky	KN/m	2890;1683	2350;970

Primary suspension damping	Cz; Cy	KNS/m	80;35	62;25
Mass of wheel-axle	Mw	ton	1.8	1.8
Wheel-axle moment	Jx; Jy; Jz	ton. m^2	2.1;2.1;0.043	2.1;2.1;0.043

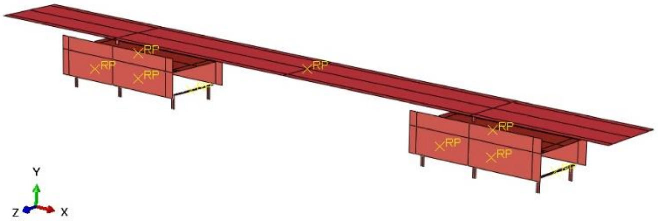


Figure 6. Train locomotive body model

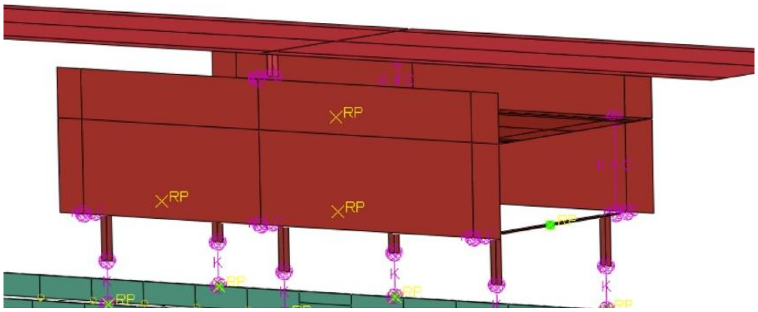


Figure 7. Hertz spring modeling with spring elements

Table 4. Technical specifications of modeling materials in ABAQUS software (adopted from [33])

Bridge and Track parameters	Young's modulus (MN/m)	Specific weight (kg/m^3)	Poisson's ratio	Damping ratio (ξ)	α	β
Concrete slab deck	11105	2400	0.18	0.05	11.44	0.00105
Ballast	150	1800	0.1	0.11	5.8	0.000327
Steel Sleeper	210071	6186	0.3			

U33 Rail	210071	6186	0.3			

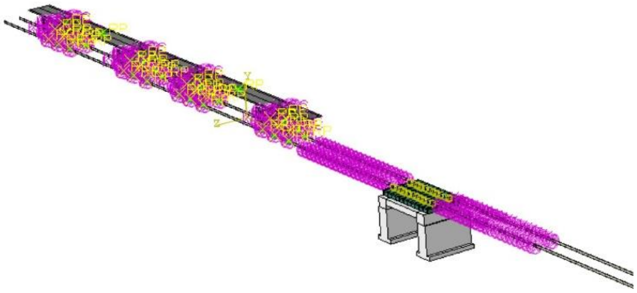
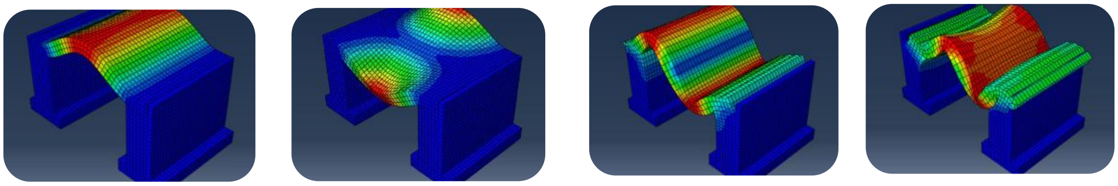


Figure 8. Bridge–track and vehicle model

Table 5. Mode frequency results

	Frequency (1/sec)				
Max Mesh size (cm) Mode Num	30	25	20	15	10
1	26.77	24.23	22.51	20.42	20.18
2	33.82	31.46	29.17	28.19	27.79
3	69.12	67.56	64.38	62.76	61.61
4	79.28	77.35	73.44	71.77	70.91



a. 1st Mode b. 2nd Mode c. 3rd Mode d. 4th Mode

Figure 9. Mode shapes of bridge

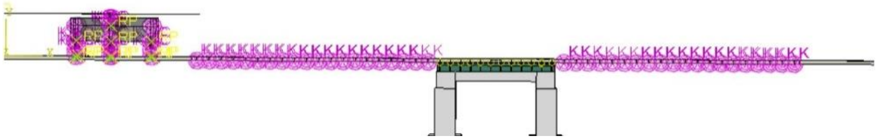


Figure 10. Modeling of the main and side spans

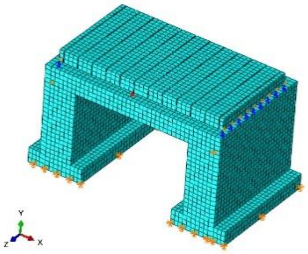
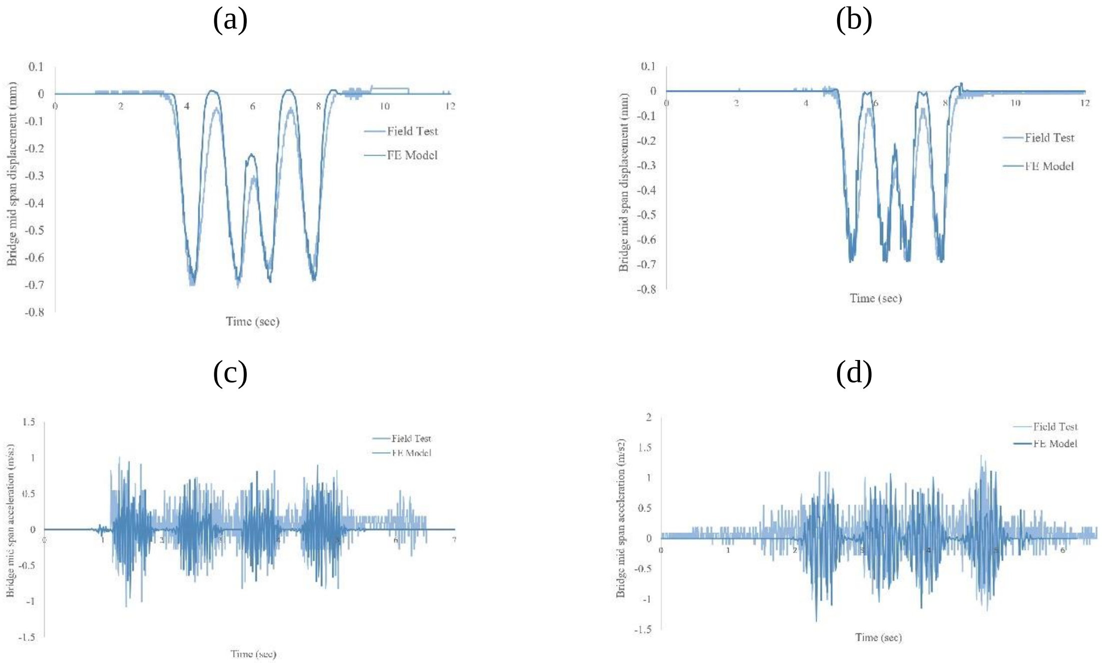


Figure 11. Finite element model of the bridge in mesh shape



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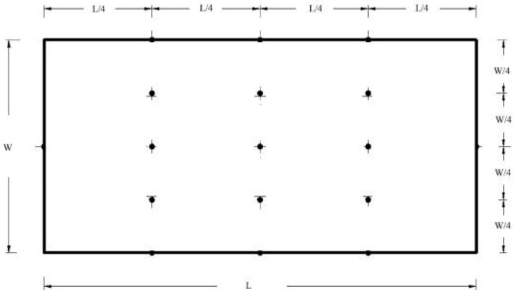
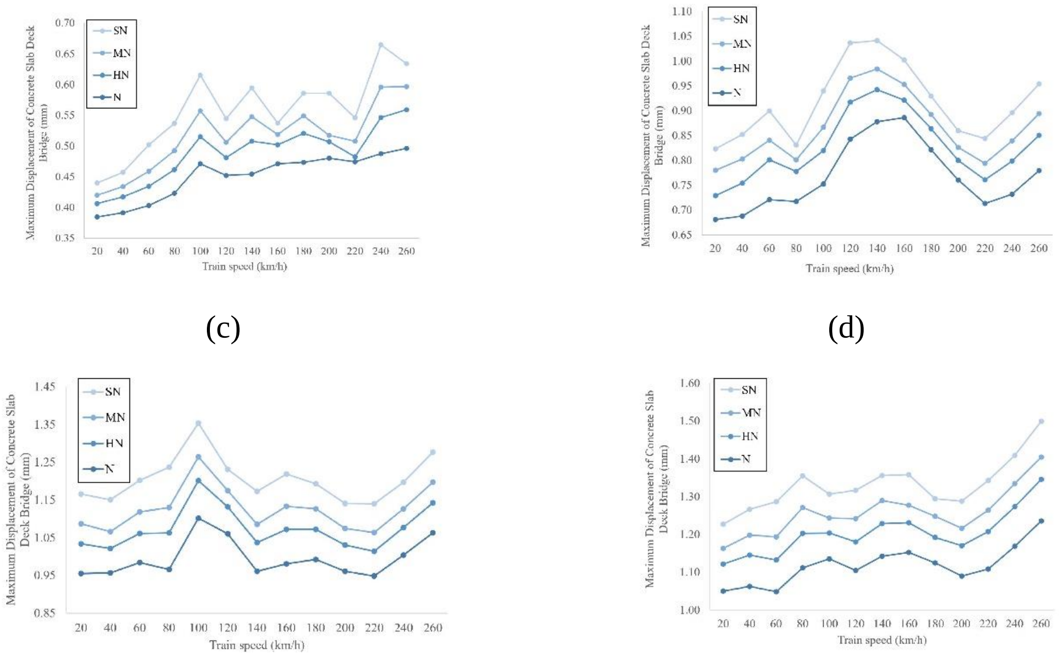


Figure 13. Target points for recording results on bridge deck


(a)

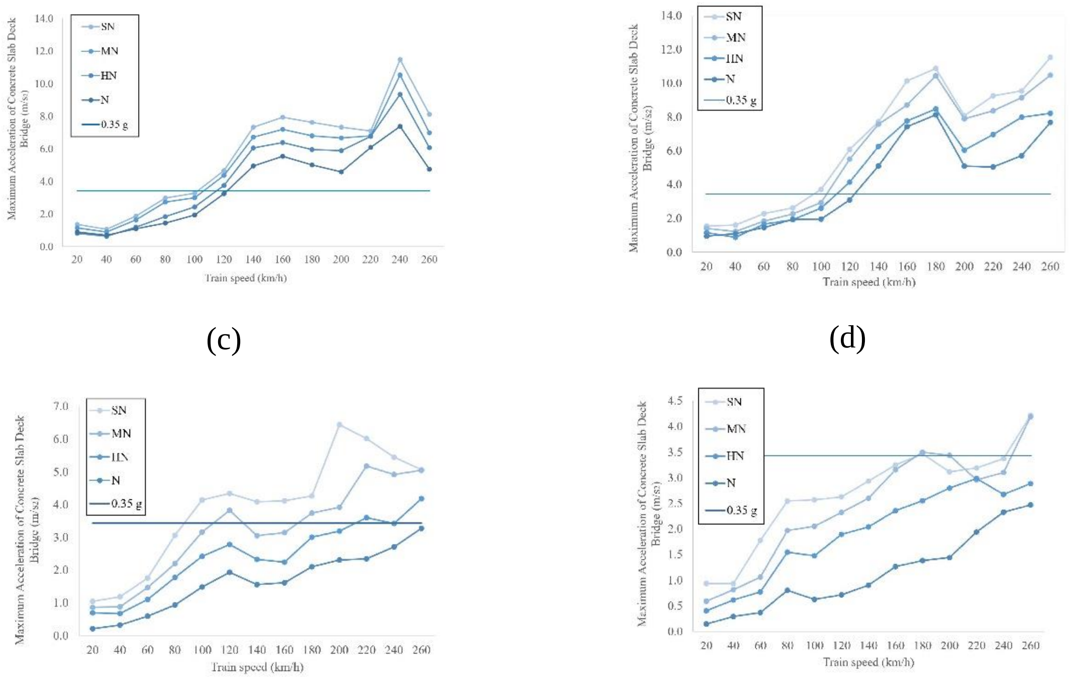
b)

(c)

(d)

Figure 14. Maximum displacement of bridge deck:

(a): 2 m span, (b): 4 m span, (c): 6 m span and (d): 8 m span



(a)

(b)

(c)

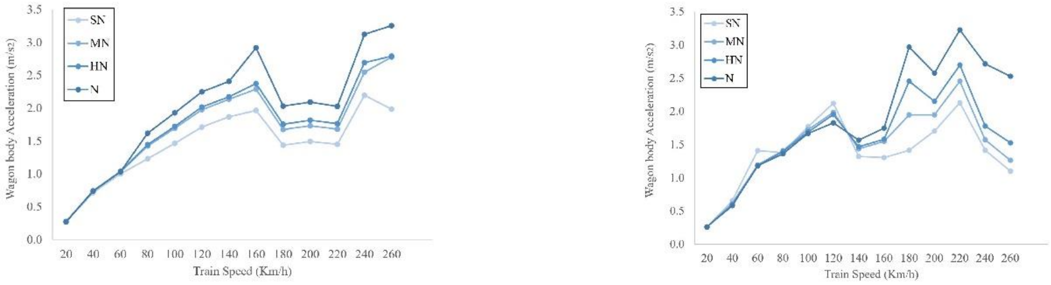
(d)

Figure 15. Maximum acceleration of bridge deck:

(a): 2 m span, (b): 4 m span, (c): 6 m span and (d): 8 m span

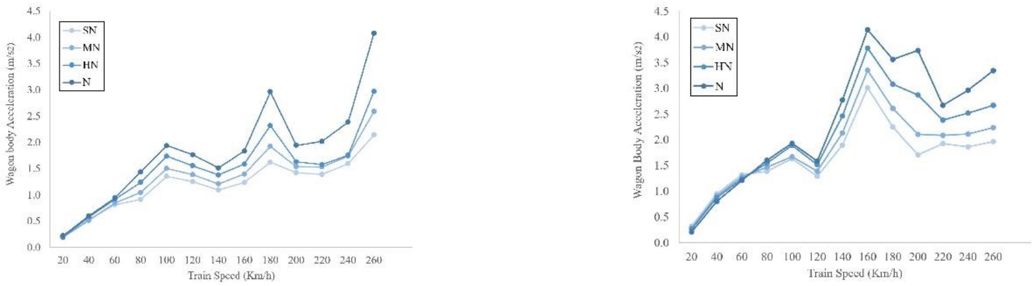
(a)

(b)



(c)

(d)



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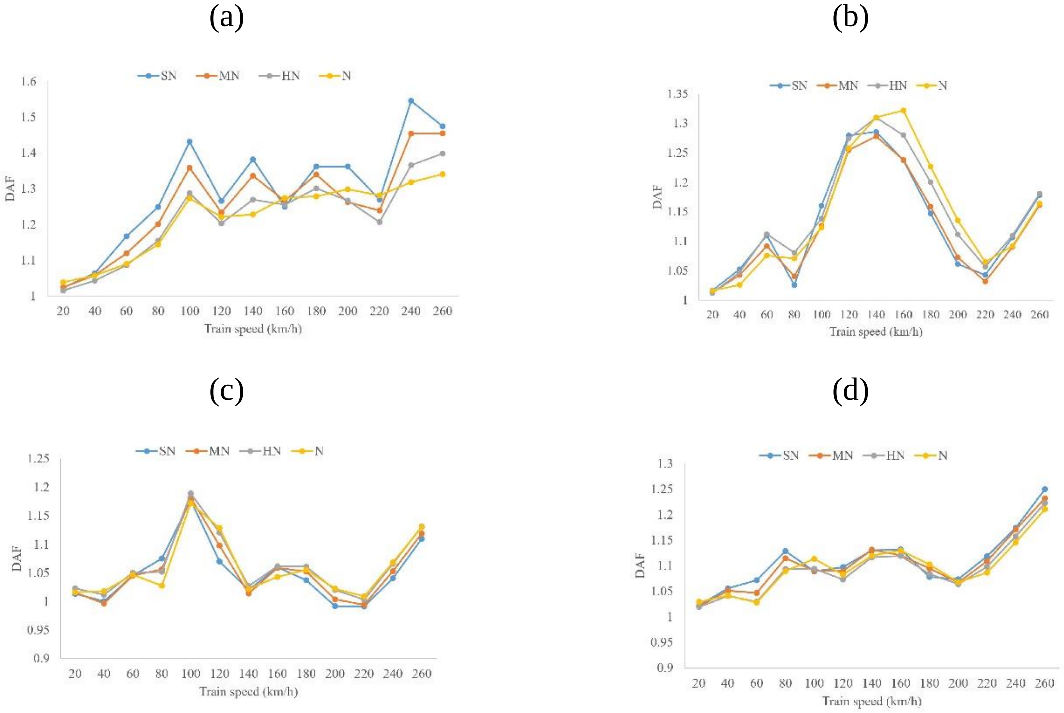

(a)

(b)

(c)

(d)

Figure 17. Dynamic amplification factor of displacement of bridge deck:

(a): 2 m span, (b): 4 m span, (c): 6 m span and (d): 8 m span

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