Dynamic Stability Analysis of High-Speed Trains Moving over Sea-Cross Bridge subjected to Rail Irregularities

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ARTICLE INFO	ABSTRACT
	Dynamic performance of the 3D train–bridge system (TBW model) subjected to different hydrodynamic loads and applying AAR track irregularity is established in this study. By taking a continuous bridge (32 + 48 + 32) m with box girders as a case study, the dynamic responses of the bridge which is under train passing and subjected to several sea hydrodynamic loads are analyzed. The substructure of the bridge includes four concrete solid piers with rectangular sections and piers are fixed at seabed. Piers and decks are designed and analyzed based on dynamic finite elements methods, and hydrodynamic forces are applied on piers according to Morison's theory. Also, car body is modeled by a 27-DoFs dynamic system. Model validation has been performed with another research by considering vessel collision load. Then, the dynamic responses of the bridge and the running safety indices of the train on the bridge under several types of sea wave states when train speed is 300 km/h analyzed. Results of TBW's sensitive analyzes have shown the importance of sea-states conditions for train safe and comfortable running. Also, irregularity has an obvious effect on the dynamic responses of the bridge. It has greater effect on vertical acceleration and displacement than horizontal ones in presence of hydrodynamic load. Combination of these two phenomena (wave and irregularity) jeopardizes the running safety of train when crossing the bridge.

1. Introduction

Today, the use of rail transportation system has been accepted as one of the best transportation modes in the most developed countries. In these countries, high-speed trains play a major role in passenger transportation management and are always in the center of attention. One of the important structures in the railroad are bridges that are constructed with different length and spans over the rail routes and make the traffic of the rail vehicles possible with acceptable quality [1]. Bridges are one of the most important railway structures that may need to be built in challenging locations, one of these is the construction of bridges to cross the waterways safely. River/Sea crossing bridge is one of the common infrastructures for the extension of rail from the mainland to the islands or coastal areas [2]. The behavior of bridges is

affected by different loads and special attention needs to be paid to this. The loads on the railway bridges vary in terms of axle load, running speed and volume of the yearly traffic and affect the behavior of the railway bridges, so extensive studies have been carried out in this regard. Dynamic bridge-train interaction is one of the topics that has attracted the attention of railway engineers over the past thirty years. Train operational parameters are the most important factors affecting the behavior of bridges, consequently many studies have been carried out to resolve the vibration problems and ensure the vehicle–bridge coupling system's performance [1], [3]–[5]. Other Studies on the horizontal displacements in structural frames under vertical forces are discussed [6]. Various studies have been conducted to simulate the behavior of bridges against earthquakes and winds [7], [8]. Further

appropriate research has been done on the lateral dynamic behavior of railway bridges [9]. Other researches on how to model train-bridge interactions using two models of moving load or mass-spring model have been done [10]–[12], and have provided suggestions on how to model the train-bridge interactions, and have presented results about ineffectiveness of modeling all components of bridges with spans greater than 15 m [13], [14]. Other articles have been written about bridge behavior under train moving load with considering bridge's damping ratio, span length and deck materials [15]. Train moving load on bridge is also performed by ANSYS software [16]. A 3D FEM which is employed in Abaqus finite element software to model and analyze the bridge and train while considering the interaction between them using the Hertz theory has been presented [1].

As is clear, bridges are indispensable structures for crossing rivers, bays and other railway or highway lines, while sometimes they also become man-made obstacles against water flow or traffic underneath. With the rapid expansion of the infrastructure network in the past decades, more crossings are generated. They are the cause of many bridge collapse accidents due to vessel, vehicle and other collisions [17], [18]. The factors producing bridge collapses can be divided into two categories: man-made and natural. The man-made factors include design faults, construction mistakes, collisions (by vessels, automobiles and trains), overload, etc. The natural factors include earthquakes, water flow (flood, scouring, etc.), wind, collisions (by floating floes or other objects), environmental deterioration (temperature, corrosion, etc.), etc. Earthquakes and strong crosswinds may jeopardize the running safety of the vehicle, especially when it crossing a viaduct. Many studies carried out regarding the dynamic response of a train-bridge coupling system subjected to crosswinds and earthquakes in the presence of track irregularity levels [19]–[22]. Also according to importance of trains running safety under vessel-bridge or ice-bridge collision, numerical analyzes and experimental tests have been carried out [17], [23], [24].

One of the topics that have not been considered during the study of railway bridges research background is the lack of consideration of coupled high-speed train and bridge system subjected to wave hydrodynamic load. Many structural failures and vehicle accidents due to extreme wave have been reported in previous studies [25]–[27]. Regarding to importance of hydrodynamic failures on coastal bridges, experimental tests for a large-scale bridge superstructure model have been done [28]. Wave hydrodynamic lateral force components and vibration may make troubles to the vehicles running on the deck. Also when train crosses over a bridge, asymmetric loading is applied to the bridge which can laterally move the structure. Train moving load on two-lane bridge can cause lateral displacement

[29]. These displacements and accelerations could be increased with the change in wave load and train speed, and may make trouble in riding comfort and running safety according to domestic or international codes' criteria. Many studies have been conducted to determine the amount of wave force applied to marine structures [30]–[32]. Several analyzes have been carried out in previous studies about coupling hydrodynamic force with other phenomena such as: earthquake, wind, tide level and etc. [32]–[35].

For a bridge, the external load considered in the design may be a vessel collision, an ice-floe collision, a vehicle passing, a train passing, or hydrodynamic loads. However, few of current research studied about considering wave hydrodynamic load on railway bridges. Moreover, sometimes more than one of external loads like train passing and wave hydrodynamic load may occur simultaneously. Since various external loads have different properties, the dynamic responses of the bridge and their effects on the running safety of high-speed trains might be different. In this study, running safety means that acceleration and displacement values are allowed regarding to Chinese and European codes in both vertical and lateral directions, which are introduced in next section as railway bridge safety criteria.

This article presents a 3D train–bridge–wave (TBW) interaction model. A continuous railway bridge with (32 + 48 + 32) m box girders is considered as a case study. This bridge is located in China and some research like vessel and ice-floe collision have been carried out which is proper for validation with TBW model [18], [23]. The train used in the validation is selected based on the passing train in the field test [1], [36].

Most studies carried out in the field of bridge-train interaction are associated with simplifying assumptions like moving load or moving mass. However, considering the importance of high-speed railway bridges, these bridges need a higher precision control. In this paper, a two-lane bridge, a high-speed train and the interactions between them are modeled with considering various speeds of train (V). Moreover, in 3D TBW model, hydrodynamic loads with several wave heights (Hs) and periods (T) have been considered according to Morison equation [31]. When hydrodynamic load acts on bridge piers, it may cause dislocation, uneven deformation, displacement or acceleration, which can affect the bridge's response to train passing.

Several scenarios by varying wave parameters such as wave height and wave period (Hs, T) have been carried out in this paper. Finally vertical/lateral acceleration (Ay, Az) and vertical/lateral displacement (Uy, Uz) values of railway bridge deck are compared with the permissible values regarding to Chinese and European codes, and the values of safe and comfort speed

according to environmental conditions (wave parameters) are determined in different scenarios. Moreover, track irregularities are an important source of excitation for both the bridge and the vehicle. The irregularities are deviations of the rail from the design geometry, which is one of the most significant load amplification factors in railway track systems [37]–[39]. As mentioned, train run excites the track through the wheel-rail contact mechanisms. Under certain conditions of track, the load coming from the train could be significantly higher than the static value due to irregularity. In last section of this study, TBW model is developed by applying rail irregularity and additional sensitive analyzes are done to evaluate the performance of high-speed train and bridge system under the excitation of wave hydrodynamic load and rail irregularity. Fourth quality level of Association of American Railroads [39] is applied on TBW model to consider irregularity.

2. Railway Bridge Safety Criteria

Among the restrictive criteria for safe and comfort passage of high-speed railway bridges are vertical and lateral accelerations and displacements of decks, which have been referred in various sources such as Chinese and European codes. So as mentioned, several scenarios by varying wave parameters (Hs, T) and passing train with speed of 300 km/h have been carried out in this paper. Finally vertical/lateral acceleration (Ay, Az) and vertical/lateral displacement (Uy, Uz) values of railway bridge are compared with the permissible values regarding to Chinese and European codes [22], [40]–[43], and the values of safe and comfort speed according to sea states (wave parameters) are determined in these scenarios.

2.1. China's high-speed railway bridges criteria

China's high-speed railway bridges criteria for displacement and acceleration, which have been used to study safe and comfort passing in this study [44], are as follows:

(i) The maximum allowable vertical displacement of the deck is determined by Table 1 for different speeds.

Table 1. Maximum allowable vertical displacement of bridge

Range of Span Designed Speed	L ≤ 40 m	40 m < L ≤ 80 m	L > 80 m
250 km/h	L/1400	L/1400	L/1000
300 km/h	L/1500	L/1600	L/1100
350 km/h	L/1600	L/1900	L/1500

(ii) The maximum allowable lateral displacement of the deck (Uz) is determined by Eq. (2.1) according to length of span (L).

$$U_z \leq \frac{L}{4000} \qquad (2.1)$$

(iii) The maximum vertical and lateral acceleration of the deck (Ay, Az) are determined as 0.13g and 0.1g, respectively.

Also, for better review, other codes such as European codes and ISO criteria have been used to study safe and comfortable passing in this study.

2.2. European's high-speed railway bridges criteria

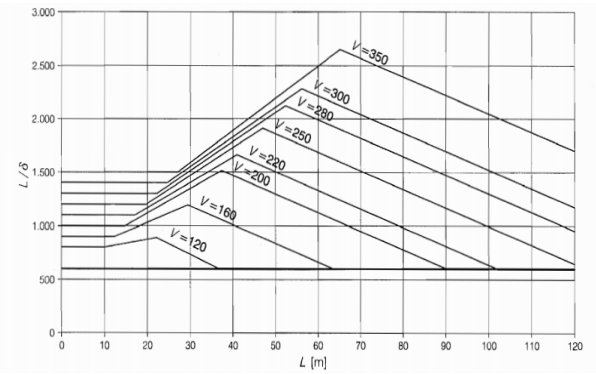(i) According to Euro Codes, the maximum allowable vertical displacement of the deck (δ) is determined by Fig. 1.

Fig 1. Maximum allowable vertical displacement of bridge [15], [40], [41]

(ii) According to Euro Codes, the maximum allowable lateral displacement of the deck (Uz) is determined by Eq. (2.2) according to length of span (L) and maximum allowable horizontal rotation (r) as shown in Table 2.

$$U_z \leq \frac{L^2}{8*r} \qquad (2.2)$$

Table 2. Maximum allowable lateral rotation of bridge [15], [40], [41]

Speed (km/h)	Single Deck	Multi Deck Bridge
V ≤ 120	1700	3500
120 < V ≤ 200	6000	9500
V > 200	14000	17500

(iii) According to Euro Codes and ISO, the maximum vertical and lateral acceleration (Ay, Az) are determined as 1.25 m/s^2 for the good safety and comfortable train passing on bridge [40], [41], [43], [45], [46].

Comparing the two codes with each other, it can be seen that in general, the Chinese code offers more restrictive criteria than the European codes. However, both codes have been used to better

investigate the present research outcomes in the next sections.

3. Interaction Models Development

3.1. Train-bridge interaction model

The China high-speed train and bridge models are used in this study. A 3D FE model is employed in Abaqus finite element software to model and analyze the bridge and train while considering the interaction between them using the Hertz theory [47]. Next, Abaqus model is validated by comparing the lateral acceleration of bridge under vessel collision load which is done by Xia et al.[18]. The 3D Train-Bridge-Wave model (TBW) is then used to assess sensitivity analysis according to wave height (H) variations (when train speed is considered 300 km/h) to monitor train riding comfort and running safety according to code's criteria.

The train model is composed of locomotive and wagon. Each locomotive or wagon consists of a car body, two bogies, four wheel-sets, and the spring and damping connections between the three components. The car body configuration and train's mechanical properties and dimensions are presented according to China high speed train in Fig. 2 and Table 3, respectively. Also, cross section of the concrete box deck is illustrated in Fig. 3.
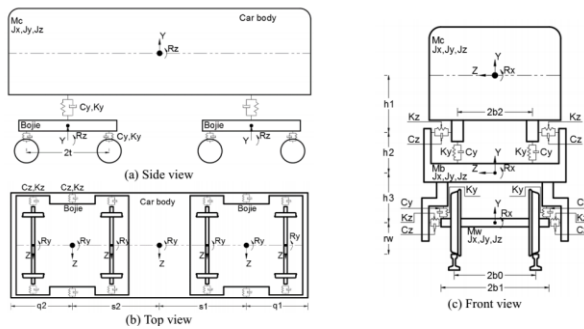

Fig 2. Car body configuration [48]

Table 3. Train's mechanical properties and dimensions

| DESCRIPTION	NAME	UNIT	POWER CAR	PASSENGER CARS
CAR-BODY DIMENSIONS	s1; s2; q1; q2; h1	m	5.73;5.73;6.8;3.75; 0.75	9;3.75;3.75;0.75
MASS OF CAR-BODY	Mc	ton	63.98	43.82
CAR-BODY INERTIA MOMENTS	Jx; Jy; Jz	ton.m2	59.4; 2505.3; 2485.4	23.2; 2100; 2080
MASS OF BOGIE	Mb	ton	3.434	3.04
BOGIE INERTIA MOMENTS	Jx; Jy; Jz	ton.m2	1.766; 2.453; 4.905	1.580; 2.344; 3.934
SECONDARY SUSPENSION STIFFNESS	Kz; Ky	KN/m	297.2; 1245.87	176; 265
SECONDARY SUSPENSION DAMPING	Cz; Cy	KNS/m	98.1; 98.1	39.2; 45.12
SECONDARY SUSPENSION DIMENSIONS	b2; h2	m	1.23; 0.42	1.23; 0.42
PRIMARY SUSPENSION STIFFNESS	Kz; Ky	KN/m	2452.5; 1226.25	2350; 590
PRIMARY SUSPENSION DAMPING	Cz; Cy	KNS/m	98.10; 29.43	58.86; 19.62
MASS OF WHEEL-AXLE	Mw	ton	1.776	1.776
WHEEL-AXLE MOMENT	Jx; Jy; Jz	ton.m2	1.138; 1.138; 0.00785	1.138; 1.138; 0.00785
PRIMARY SUSPENSION & WHEEL	b0; b1; h3; t; rw	m	0.75; 1; 0.2; 1.25; 0.455	0.75;1;0.2;1.25;0.455
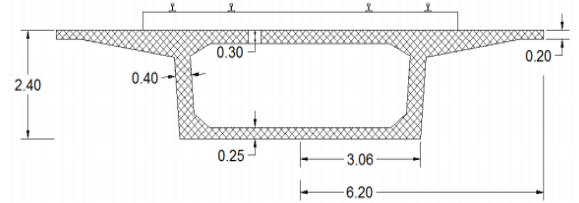
Fig 3. Cross section of the concrete box deck

The following assumptions are made in modeling the train vehicle:

(i) The car body, bogies and wheel-sets in each vehicle are regarded as rigid components, neglecting their elastic deformation during vibration as shown in Fig. 4.

(ii) The connections between car body, bogies and wheel-sets are represented by linear springs and viscous dashpots (as shown in Figs. 5 and 6).

(iii) Each train body has five degrees-of-freedom (DoFs). They correspond to the lateral displacement, the roll displacement, the yaw displacement, the vertical displacement, and the pitch displacement. Each bogie on the vehicle has five DoFs: the lateral displacement, the roll displacement, the yaw displacement, the vertical displacement, and the pitch displacement. For each wheel under the bogie, three DoFs are considered: the lateral displacement, the roll displacement, and the vertical displacement. Thus, the train is modeled in TBW for each vehicle with 2-bogies and 4-axles can be modeled by a 27-dof dynamic system, as shown in Fig. 6.

(iv) Regarding to other research [14], in longer spans (L >15m) the dynamic response is not sensitive to track stiffness value, so slab track is not modeled separately and merged with deck as an integrated model. Piers and deck are modeled as 3D deformable solid element with considering concrete specification. Rails are modeled as 3D deformable solid element with considering steel specification and tied on deck, also for considering the interaction between wheels and rails the Hertz theory is used (as shown in Figs. 5 and 6).
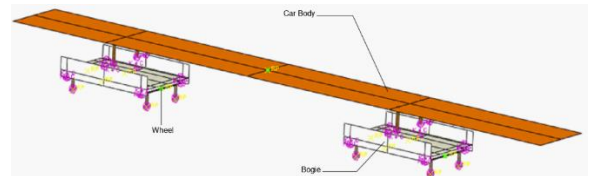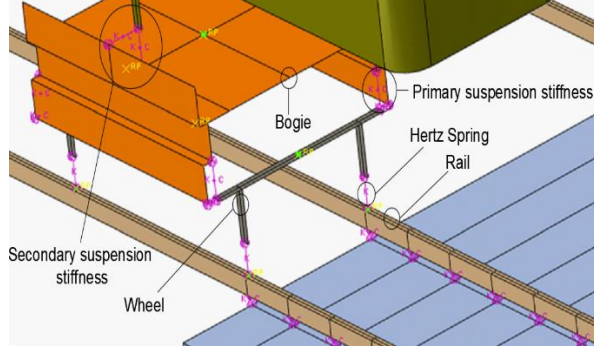

Fig 4. Train 3D model

Fig 5. Modeling wheel-rails interaction by hertz spring

(v) The considered bridge is a two-lane continuous with concrete box (32+48+32) m (as shown in Fig. 6). The substructure of the bridge includes four concrete solid piers with rectangular sections (8m x 4.5m) and piers are fixed at seabed. Deck mounted on piers are fixed pot neoprene bearings and the bearings are modeled according to the design [18]. For the fixed bearings, the rotational angle about the transverse axis z of the girder end is free, while the other 3 translational displacements and 2 rotational angles are connected through master-and-slave relations to the pier-top and the damping ratio of the bridge is taken as 2.5 %. The height of piers are assumed 20 m and sea level which is proposed hydrodynamic force interaction with piers is considered at level +15m.

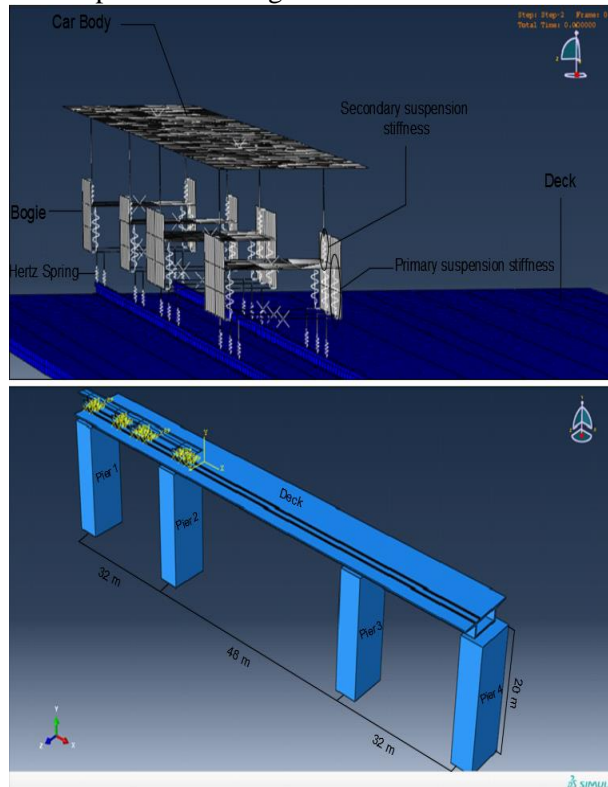(vi) Train passes the bridge with V=300 km/h.

Fig 6. Train-bridge 3D model

Summary of the train modeling method and the definition of its interaction with the bridge is provided in the following steps:

(i) Several 3D models were developed in real dimensions of car-body, bogies and wheels by using 3D discrete rigid shells module in Abaqus.

(ii) Real mass and inertia were assigned for each part of wagon and locomotive according to car-body's specification (which are represented in Table 3).

(iii) Several springs were modeled to connect different parts of car-body to each other by using interaction module of Abaqus. In this model several rigid parts were linked in all directions by primary and secondary springs for considering suspension stiffness and damping (as shown in Figs. 3 and 4).

(iv) All wheels were connected to rails by using interaction module of Abaqus and applying hertz theory.

(v) In addition to define displacement and rotation boundary conditions, velocity boundary condition in x direction was defined to model car-body movement in Abaqus to perform dynamic analysis.

3.2. Hydrodynamic force on pier

Based on the Morison's theory [31], it is assumed that the effect of fluid on the structure is caused by the acceleration field and velocity field, and the effect of structure on the movement of fluid could be ignored. Therefore, the hydrodynamic force (F_{Wave}) acting on the column includes two components (as shown in Equations (3.1)-(3.5)): one is the inertial force (F_I) and the other is the drag force (F_D) on the column due to the effect of viscous and swirl (as shown in Figs. 7).

Morison equation is adopted to calculate the wave forces on the columns, of which the structure diameter or width D is smaller than 0.2 times wave length L.

$$F_{Wave} = F_D + F_I \tag{3.1}$$

$$F_D = \frac{C_d}{2} \rho A u^2 \tag{3.2}$$

$$F_I = C_m \rho V \mathring{u} \tag{3.3}$$

$$F_{Wave} = \frac{C_d}{2} \rho A u^2 + C_m \rho V \mathring{u} \tag{3.4}$$

Here, ρ is the density of the fluid, V is the volume of the submerged structure, A is the area of the column section, u and ů are the absolute velocity and acceleration of the fluid respectively, C_m is the inertia coefficient and C_d is the drag force coefficient of the fluid. The total hydrodynamic force on the unit length (ds) of the column along the Z-axis direction can be expressed as:

$$F_{Hydrodynamic} = \frac{F}{ds} = \frac{C_d}{2} \rho D u^2 + C_m \rho \left(\frac{\pi D^2}{4}\right) \mathring{u} \tag{3.5}$$
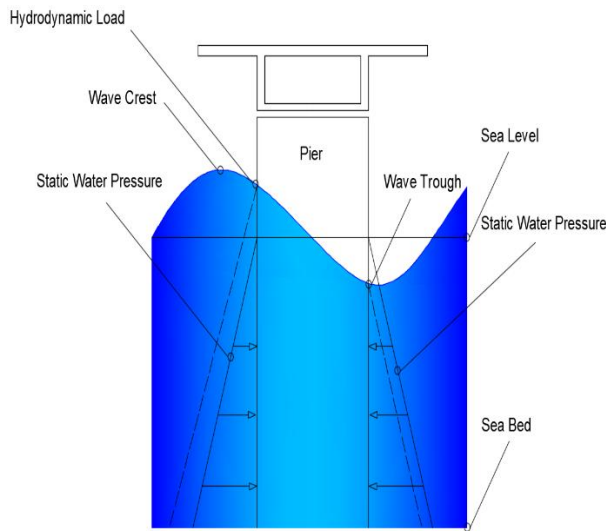
Fig 7. Hydrodynamic force on pier

Table 4. Wave estimation according to wind conditions [49]

Wind Conditions			Wave Size		
Wind Speed in One Direction	Fetch	Wind Duration	Average Height	Average Wavelength	Average Period
56 km/h	518 km	23 h	4.1 m	76.5 m	8.6 sec
74 km/h	1313 km	42 h	8.5 m	136 m	11.4 sec
92 km/h	2627 km	69 h	14.8 m	212.2 m	14.3 sec

Three sea states, sea states I, II, and III, are considered based on three different mean wind speeds U_{Wind} of 56, 74, and 92 km/hr for China Sea area. The characteristics of selected sea states for TBW model are defined in Table 5.

Table 5- Selected sea states for TBW model

Sea States	Hs(m)	Ts(s)
I	4.1	8.6
II	8.5	11.4
III	14.8	14.3

The wave hydrodynamic force is calculated and applied to the Abaqus model as harmonic forces according to the marine conditions as mentioned in Table 5 and Eq. (3.5). The assumed values for the coefficients Cd and Cm are 1 and 2, respectively [30]–[32].

3.3. Train - bridge – wave model

As mentioned previously, wave hydrodynamic lateral force makes troubles to the trains running on the deck. Also when train crosses over a bridge, asymmetric loading is applied to the bridge which can move the structure (as shown in Fig. 8). The wave hydrodynamic force is calculated and applied to the Abaqus train-bridge-wave model (TBW) according to the marine conditions mentioned in Table 5 and using Eq. (3.5). Vertical and lateral displacements and accelerations are increased with the change in wave load and train speed, and may make trouble in riding comfort and running safety according to code's criteria.
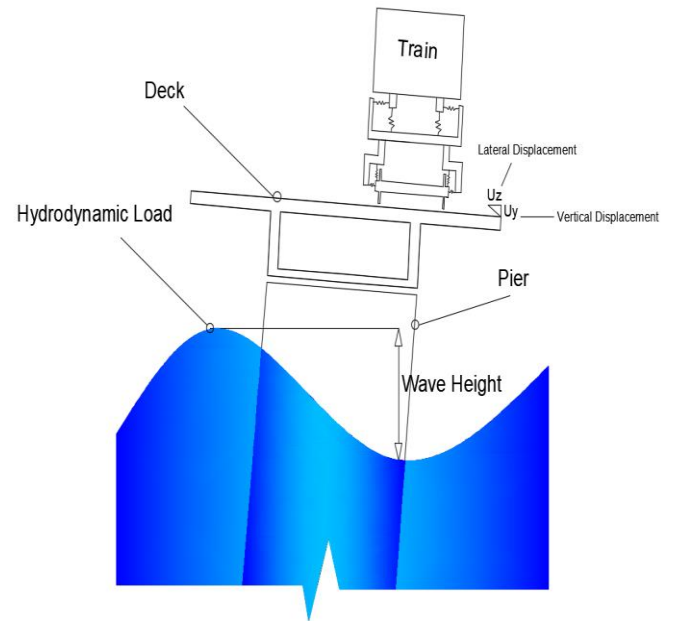

Fig 8. Pier lateral movement due to wave force

Bridge, Train and Hydrodynamic load modeling are performed using the FEM in Abaqus software. Sea states I, II, and III, are applied to assess sensitivity analysis. As mentioned, substructure of the bridge includes four concrete solid piers with rectangular sections (8m x 4.5m) and piers are fixed at seabed. The height of piers are assumed 20 m and sea level which is proposed for hydrodynamic force interaction with piers is considered at level +15m. The wave direction (Z-axis) is assumed to be perpendicular to the train passing direction (X-axis). Also, hydrodynamic load is applied to bridge piers simultaneously and train passes the bridge with speed of 300 km/h to sensitivity analysis. Eight scenarios with wave and track irregularity variation have been applied in this study for considering effect of presence or absence of wave and track irregularity for train running on bridge are performed. Full 3D Train-Bridge-Wave (TBW) model is shown in Fig. 9. As mentioned, China high speed railway code and European code are used for assess riding comfort and running safety. In order to make a good judgment with respect to the importance of wave reaching time to the piers, as the worst scenario each maximum value of hydrodynamic loads are applied on piers at the time when the train arrives middle of deck.
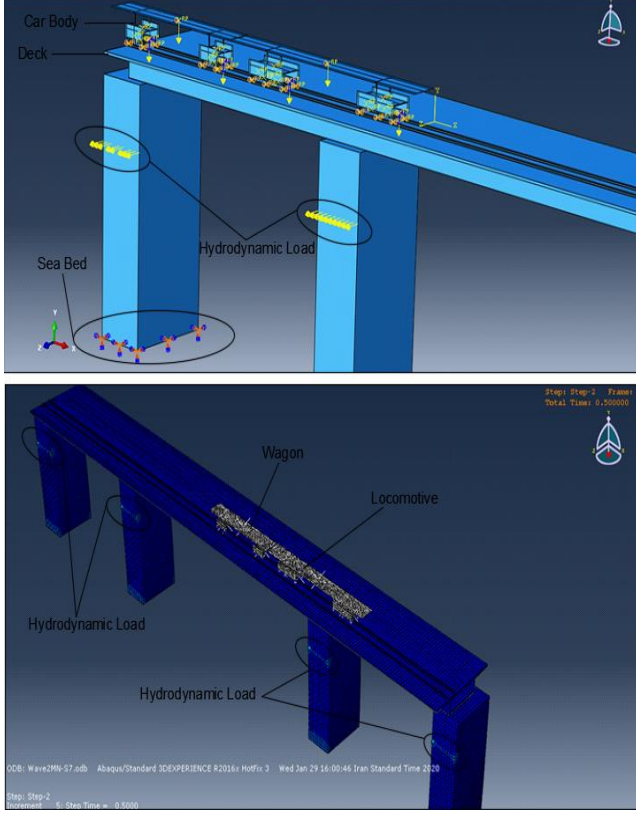
Fig 9. Train-bridge-wave (TBW) 3D model

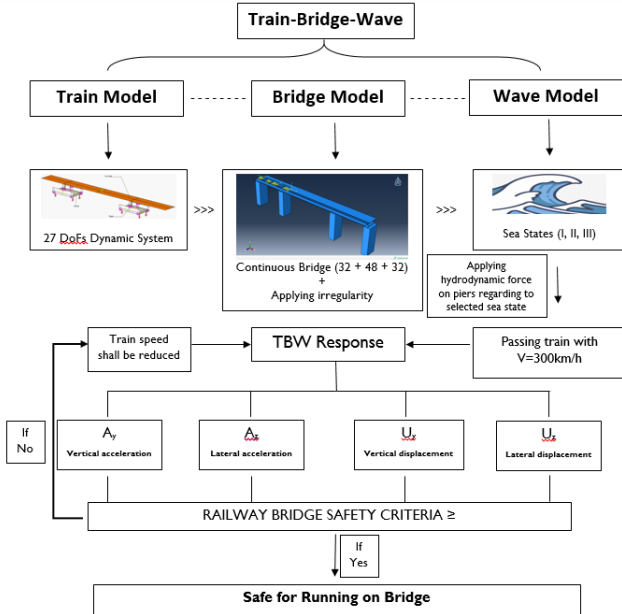Train-bridge-wave modeling is presented by a flowchart as shown in Fig. 10 to show the solving methodology.

Fig 10. Train-bridge-wave-irregularity solving methodology

3.4. Model validation

The 3D finite element model of Train-Bridge-Wave was validated according to numerical simulation results of Train-Bridge model with considering 10 MN vessel collision load which is applied on pier 2 at level +10 m above the seabed. The vessel load is taken from Ref. 19 and represents the collision history by a ship, which is a wide continuous pulse with the total duration of 1.8 s, as shown in Fig. 11.

The equations of motion for the train–bridge system subjected to a collision load can be expressed as:

$$\begin{bmatrix} M_{VV} & 0 \\ 0 & M_{BB} \end{bmatrix} \begin{Bmatrix} \ddot{x}_V \\ \ddot{x}_B \end{Bmatrix} + \begin{bmatrix} C_{VV} & C_{VB} \\ C_{BV} & C_{BB} \end{bmatrix} \begin{Bmatrix} \dot{x}_V \\ \dot{x}_B \end{Bmatrix}$$

$$+ \begin{bmatrix} K_{VV} & K_{VB} \\ K_{BV} & K_{BB} \end{bmatrix} \begin{Bmatrix} x_V \\ x_B \end{Bmatrix} = \begin{Bmatrix} F_{VB} \\ F_{BV} \end{Bmatrix} + \begin{Bmatrix} 0 \\ F_C \end{Bmatrix} \qquad (3.6)$$

Where M, C and K are mass, damping and stiffness matrices of the train–bridge system, x, $\dot{x}$ and $\ddot{x}$ are displacement, velocity and acceleration vectors, respectively; F_{VB} and F_{BV} are interaction forces between vehicle and bridge, and the subscripts V and B represent vehicle and bridge, respectively. The components of these matrices and vectors can be found in Ref. 19. F_C is the generalized vector of the collision load applied on the bridge.

In the validation stage, the train consists of wagons and locomotives with considering vessel collision load is modelled as shown in Fig. 12, and lateral acceleration time histories comparison at the top of pier 2 under vessel collision load for a train speed of 200 km/h is presented as Fig. 13. In the sensitivity analysis, the train consists of one locomotive and one wagon. The axle loads of locomotive and wagon are 19.5 and 14.25 tons, respectively. Dimensions and mechanical properties of the train car (27-DOFs dynamic system) are described in Fig. 2 and Table 3. Vessel impact is modeled as concentrated loads which are distributed on contact level of vessel and pier 2, as shown detailed in Fig. 12. Mesh size is one of the effective parameters in FEM analyses. Mesh configuration can be selected regarding to several conditions. Although smaller elements lead to a higher precision of the model, they require more time to analyze. In this research, several analyses are carried out with various mesh sizes on the bridge model to determine the optimum meshing dimensions. Results did not experience any considerable changes by decreasing the mesh sizes smaller than 0.5 m. Consequently, in this study, optimum mesh size is selected 0.5 m as shown in Fig. 12 to obtain proper train, rail and deck interactions. Moreover, choosing this mesh size is helpful about including rail and deck connection points. The comparison with numerical study demonstrated that the results of the present model were close to collision test results. The accuracy of the results of the two models is higher than 92% for maximum values and 87% for root mean square as shown in Fig. 13. These 8% and 13% differences for maximum and RMS values could be due to some of the simplifications considered in the train-bridge interaction model, input parameters and modeling errors, calculation methods and etc. In this study, time step is taken as 0.005 s. Xia et al.[18] considered this parameter as 0.0001 s in their numerical analysis. This

subject is one of the main reasons for 13% difference between the results of present study and Xia et al.[18] results.
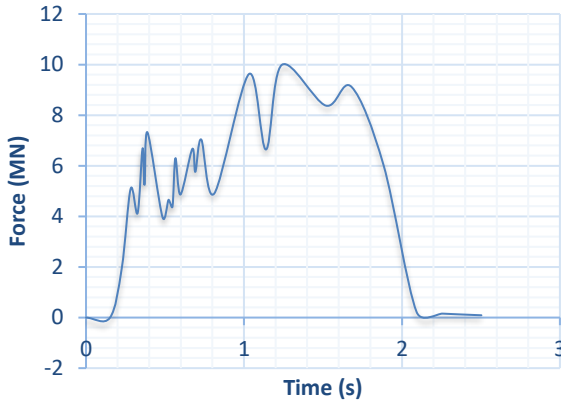

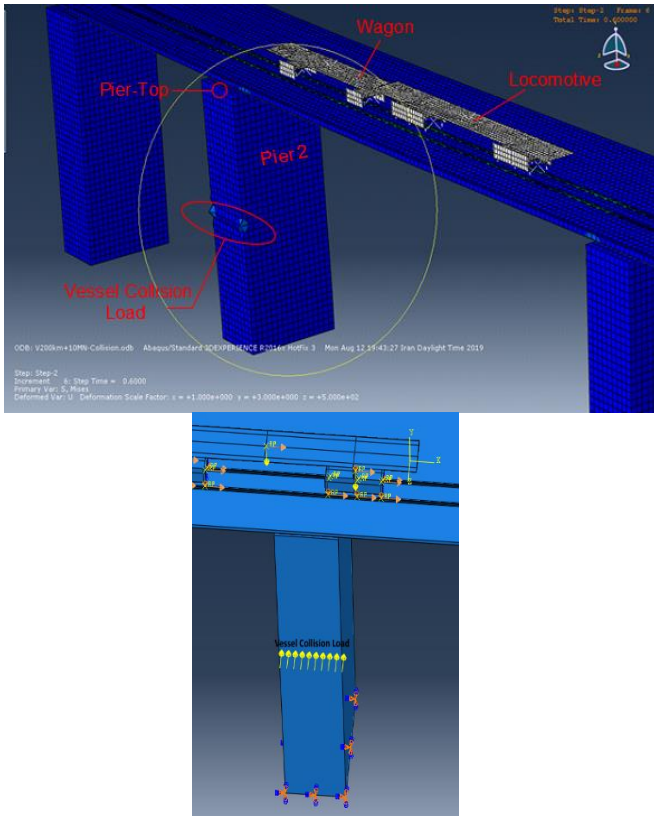**Fig 11. Time histories of vessel collision load**

Fig 12. 3D validation model for considering vessel collision load
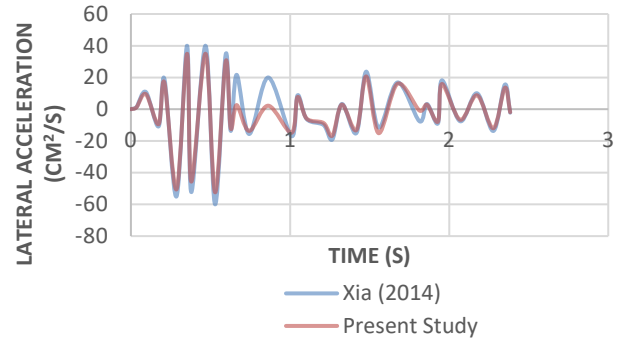

Fig 13. Comparing lateral acceleration time histories at the top of pier 2 under vessel collision load for a train speed of 200 km/h

4. Sensitivity Analyses

By using this 3D validated model, the effects of some important parameters on the running safety of high-speed train on a bridge subjected to hydrodynamic load can be assessed. In this study, eight scenarios as shown in Table 6 are applied according to assuming various conditions for sea states and track irregularity. In all cases with hydrodynamic force, the time history of the sea states are applied on piers at level +15 m above the seabed.

Table 6. Scenarios for wave and irregularity variation (V=300 km/h)

Scenario	Irregularity	Hs(m)	Ts(s)
1	NA	0	0
2	NA	4.1	8.6
3	NA	8.5	11.4
4	NA	14.8	14.3
5	Applied	0	0
6	Applied	4.1	8.6
7	Applied	8.5	11.4
8	Applied	14.8	14.3

5. Sensitivity Analyses of TBW Model under Several Conditions

This section investigates the dynamic response of bridge during the train passes with speed of 300 km/h through the bridge under several sea states by time history analyses. Structural dynamic response discussed in this study includes the lateral displacement (Uz), vertical displacement (Uy), lateral and vertical acceleration (Az, Ay) response at the middle point of span. The performance of bridge structure and train (TBW model) under different sea states is carefully discussed.

5.1. The effect of hydrodynamic load on railway bridge

First, to study the effect of the waves on the safety of the bridge to train passing, analyzes are simulated with

and without hydrodynamic loads. And the bridge's behavior, such as: vertical and lateral displacements and accelerations are compared when the train passes at a speed of 300 km / h.

As shown in Fig. 14, when train is passing on bridge without hydrodynamic force (wave height=0), the amount of lateral displacement under train passing (which is less than 1 mm) is less than the permissible value. In the following, by applying hydrodynamic loads on piers and increasing the height of the wave, the lateral displacement of the deck increases and exceeds the permissible values of the European and Chinese codes.

Lateral displacement response of the bridge subjected to stormy hydrodynamic load (H = 14.8 m) could be up to 26 times higher than the ones without hydrodynamic load.
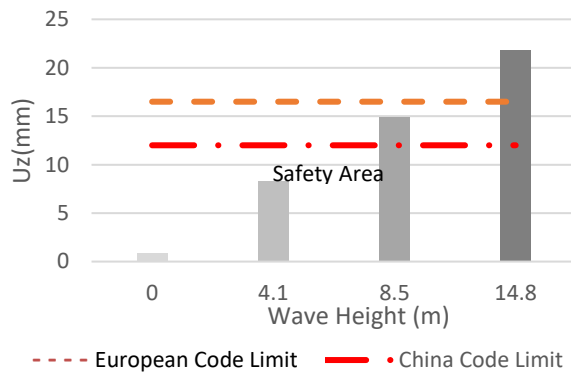
Fig 14. Lateral displacement of the bridge deck against several sea states

As shown in Fig. 15, by applying hydrodynamic loads on piers and increasing the height of the wave, the vertical displacement of the deck increases but do not exceed the permissible values of the codes. However, due to the increasing trend of displacement with increasing wave height, the displacement will be approached to critical values. (Negative value indicates downward vertical displacement)

Vertical displacement response of the bridge subjected to stormy hydrodynamic load (H = 14.8 m) is 40% higher than the ones without hydrodynamic load.
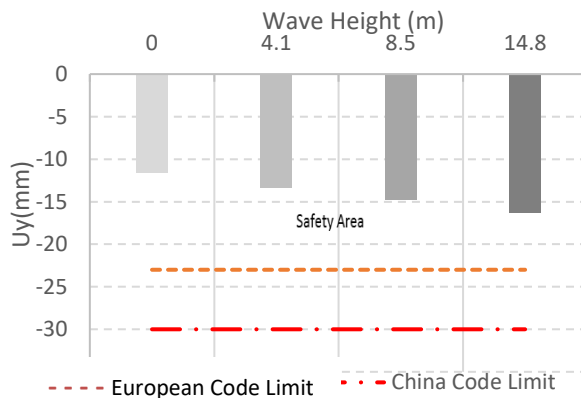

Fig 15. Vertical displacement of the bridge deck against several sea states

When train is passing on bridge without hydrodynamic force (wave height=0), the amount of lateral acceleration under train passing is less than the permissible value (which is negligible). By applying hydrodynamic loads on piers and increasing the height of the wave, the lateral acceleration of the deck increases and exceeds the permissible values of the European and Chinese codes (as shown in Fig. 16).
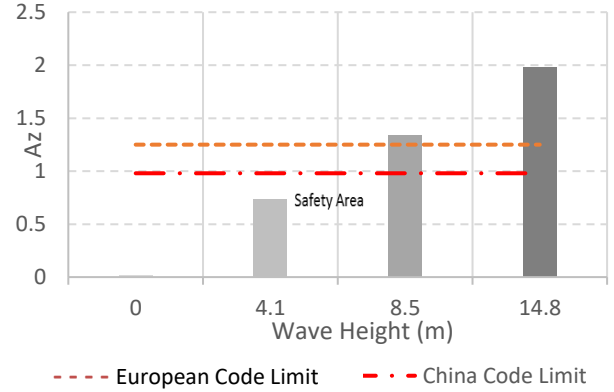

Fig 16. Lateral acceleration (m/s^2) of the bridge deck against several sea states

As shown in Fig. 17, when train is passing on bridge without hydrodynamic force (wave height=0), the amount of vertical acceleration under train passing is 0.8 m/s2, which is less than the permissible value. In the following, by applying hydrodynamic loads on piers and increasing the height of the wave, the vertical acceleration of the deck increases and exceeds the permissible values when wave height exceeds 8 m. Also, the intensity of the acceleration has increased after the 4.1-meter wave, which indicates that after this wave height, the bridge will be more sensitive to changes.
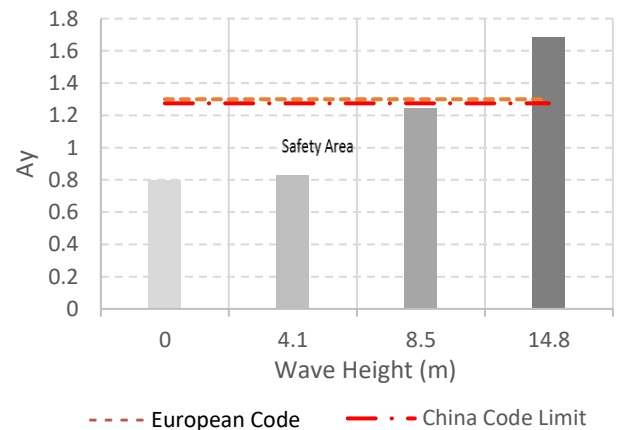

Fig 17. Vertical acceleration (m/s^2) of the bridge deck against several sea states

5.2. Effect of irregularity on TBW model

As mentioned, track irregularities are an important source of excitation for both the bridge and the vehicle. To study the effect of irregularity on TBW model and safety of the bridge to train passing, 4th quality level of

Association of American Railroads [39] is applied on TBW model (as shown in Fig 18). The bridge's behavior, such as: vertical and lateral displacements and accelerations are compared when the train passes at a speed of 300 km / h.
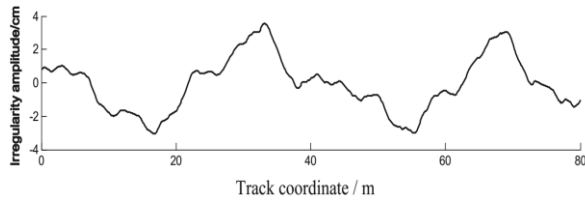

Fig 18. The track profile irregularity for line level 4[39]

As shown in Figs. 19-22, when train is passing on bridge, the amount of lateral and vertical displacements and accelerations under train passing are increased by applying track profile irregularity.
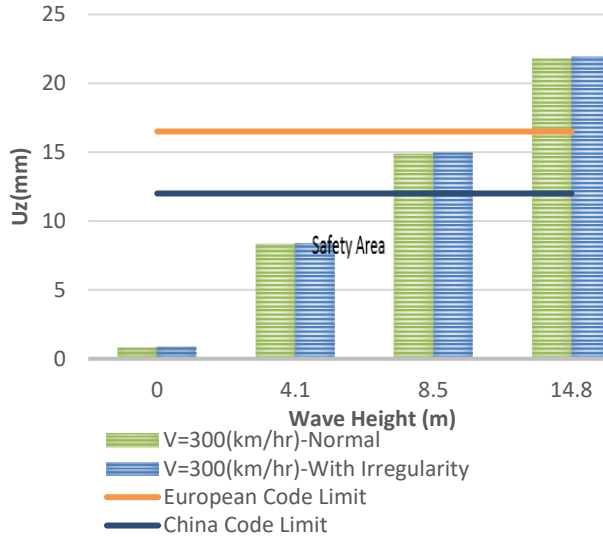

Fig 19. Lateral displacement of the bridge deck with and without irregularity against several sea states
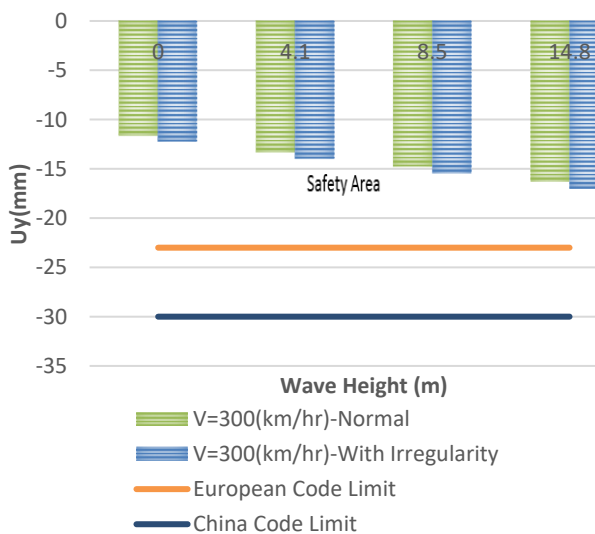

Fig 20. Vertical displacement of the bridge deck with and without irregularity against several sea states
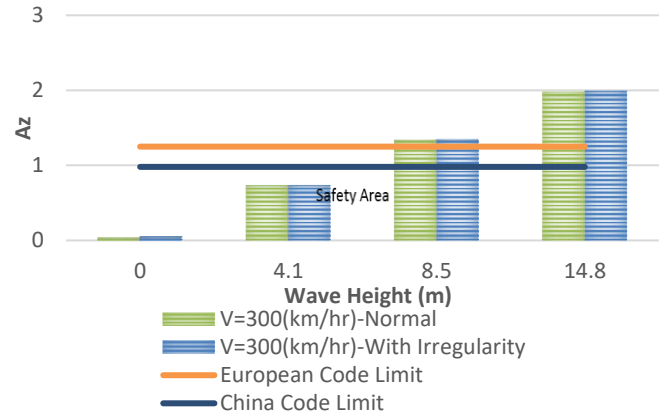

Fig 21. Lateral acceleration (m/s²) of the bridge deck with and without irregularity against several sea states
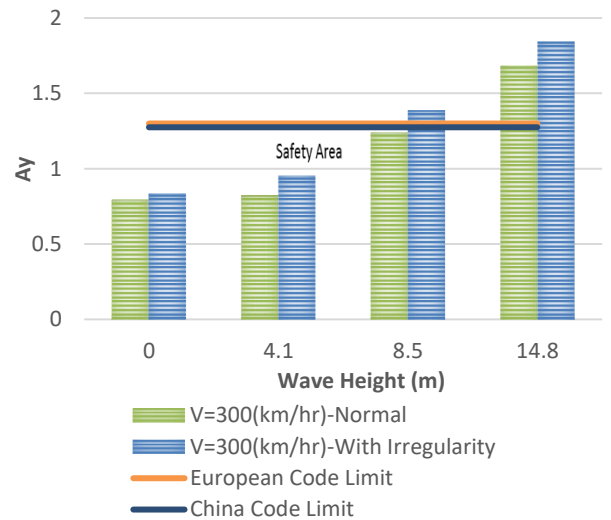

Fig 22. Vertical acceleration (m/s²) of the bridge deck with and without irregularity against several sea states

Figs. 23-26 show variation of TBW's responses when irregularity applies on the model.

By applying irregularity on the model without hydrodynamic load (wave height=0), and train is passing on bridge, the amount of lateral acceleration increases more than 30% as shown in Fig. 23. (About 32% for RMS and 35% for maximum value)

But as shown in Figs 24-26, by applying irregularity on the model with applying hydrodynamic load (wave height=4.1, 8.5, 14.8m), variation of lateral acceleration and displacement are not increased considerable. This is because of hydrodynamic load greater impact than track irregularity in these cases.

Variation of vertical acceleration and displacement are increased considerable by applying irregularity (about 10% for acceleration and 5% for displacement). But amount of variation is decreased when hydrodynamic load is increased, as shown in Figs. 24-26.

Generally, irregularity has greater effect on vertical acceleration and displacement than horizontal ones in presence of hydrodynamic load. Combination of these two phenomena (wave and irregularity) jeopardizes the running safety of train when it is crossing the bridge.
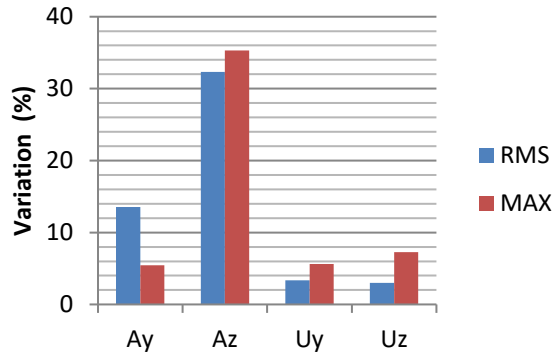
Fig 23. Variation of TBW's responses when excited by irregularity (wave height=0)
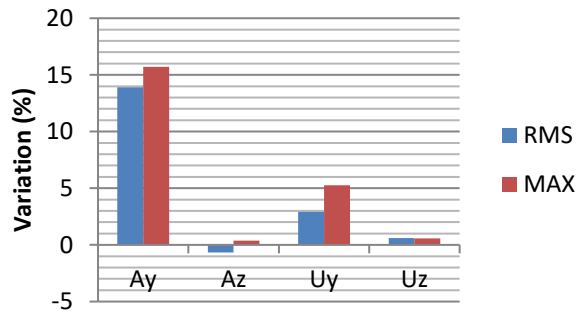

Fig 24. Variation of TBW's responses when excited by irregularity (wave height=4.1 m)
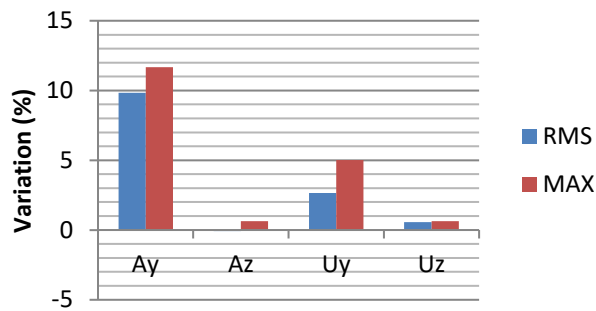

Fig 25. Variation of TBW's responses when excited by irregularity (wave height=8.5 m)
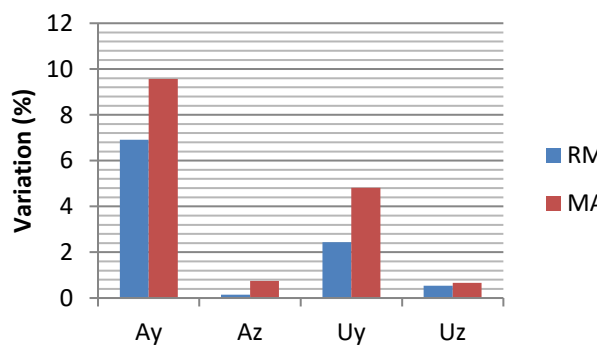

Fig 26. Variation of TBW's responses when excited by irregularity (wave height=14.8 m)

6. Conclusion

The dynamic analysis of coupled train–bridge systems subjected to hydrodynamic loads is a rather complex problem, which is related to the running speed of the train, specification of car-body, train axle loads, specification of bridge, wave height, wave periods and length, the application position and the direction of the hydrodynamic load, and many other factors.

In this study, the dynamic behavior of the 3D train–bridge system subjected to different hydrodynamic loads (TBW model) is carried out. Also additional analyses are done by applying AAR irregularity [39] to the model. By taking a continuous bridge with (32 + 48 + 32) m box girders as a case study, the dynamic responses of the bridge in mid-span of bridge which is under train passing and subjected to several hydrodynamic loads are analyzed. An assessment procedure for the running safety of high-speed train on a bridge subjected to hydrodynamic load is proposed.

The following conclusions can be drawn from sensitivity analyzes of TBW model under several sea-states and track irregularity:

(i) Hydrodynamic load has an obvious effect on the dynamic responses of the bridge. Both lateral and vertical displacements and accelerations responses of the bridge subjected to hydrodynamic load are much greater than the ones without hydrodynamic load.

(ii) Vertical displacement and acceleration responses of the bridge subjected to stormy hydrodynamic load are 40% and 100% higher than the ones without hydrodynamic load, respectively.

(iii) The lateral displacement and acceleration of the bridge are more influenced by hydrodynamic load. By applying hydrodynamic loads on piers and increasing the height of the wave, the lateral displacement and acceleration of the deck increase and exceed the permissible values of the European and Chinese codes.

(iv) Lateral displacement response of the bridge subjected to stormy hydrodynamic load could be up to 26 times higher than the ones without hydrodynamic load.

(v) Vibrations induced by hydrodynamic load have a great effect on the dynamic responses of railway bridge and train running safety. The running safety of the train is affected by both the type of sea-state and track irregularity. Strong waves may threaten the running safety of high-speed trains.

(vi) Results of TBW's sensitivity analyses have shown the importance of sea-states conditions for train safe and comfortable running.

(vii) In very stormy conditions like sea state III (H = 14.8 m), it is not safe for train running.

(viii) The effect of irregularity on the dynamic responses of the bridge is obvious. By applying irregularity on the model without hydrodynamic load (wave height=0), and train passing on bridge, the amount of lateral acceleration is increased more than 30%.

(ix) By applying irregularity to the model with hydrodynamic load, variation of lateral acceleration and displacement are not increased

considerable. Because hydrodynamic load has greater impact than track irregularity in these cases.

(x) Irregularity has greater effect on vertical acceleration and displacement than horizontal ones in presence of hydrodynamic load. Combination of these two phenomena (wave and irregularity) jeopardizes the running safety of train when it is crossing the bridge.

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