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Dynamic numerical analysis of single-support modular bridge expansion joints

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Abstract. Severe fatigue and noise problems of modular bridge expansion joints (MBEJs) are often induced by vehicle loads. However, the dynamic characteristics of single-support MBEJs have yet to be further investigated. To better understand the vibration mechanism of single-support MBEJs under vehicle loads, a 3D finite element model of single-support MBEJ with five center beams is built. Successive vehicle loads are given out and the vertical dynamic responses of each center beams are analyzed under the successive loads. Dynamic amplification factors (DAFs) are also calculated along with increasing vehicle velocities from 20 km/h to 120 km/h with an interval 20 km/h. The research reveals the vibration mechanism of the single-support MBEJs considering coupled center beam resonance, which shows that dynamic responses of a given center beam will be influenced by the neighboring center beams due to their rebound after the vehicle wheels depart. Maximal DAF 1.5 appears at 120 km/h on the second center beam. The research results can be utilized for reference in the design, operation and maintenance of single-support MBEJs.

Keywords: single-support modular bridge expansion joints; vehicle loads; coupled center beam resonance; dynamic amplification factors; finite element model

1. Introduction

Modular bridge expansion joints (MBEJs) are commonly installed in large span bridges. There are two major types of MBEJs, namely the multi-support modular expansion joints and the single-support modular expansion joints. The main discrepancy of the two types of MBEJs is the supporting system. In the single-support MBEJs, all the center beams (perpendicular to the direction of bridge axis) are supported on a common set of crossbeams (parallel to the bridge axis) with elastomeric bearings; while in the multi-support system each center beam is disparately welded on a corresponding set of crossbeams. Fig. 1 shows the two different types of MBEJs. The movement system of MBEJs is mainly comprised of steel center and cross beams, which make them capable to accommodate large movements and support heavy dynamic vehicle loads. Besides, the gaps between center beams are sealed to resist the penetration of water and trash into the inside structure, thus reducing corrosion of steel components. Therefore, MBEJs are generally recognized to have advantageous structural performance in service life because of the merits mentioned above.

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However, function failures of MBEJs still can be caused due to anomalous vibration induced by heavy traffic loads. Roeder (1998) investigated the fatigue problems of one particular joint in numerical simulation and field experiment methods, pointing out that large horizontal force caused by the acceleration and braking of vehicles could be a primary contributor to the fatigue cracking of center beams. Meanwhile, the numerous complaints about the expansion joint noise induced by the loose elastomeric bearings used to cushion the vehicle impact are also mentioned. Ravshanovich *et al*. (2007) investigated the noise generation mechanism of a single-support modular expansion joint in a bridge under vehicle passage, and experimented on a full scale model. The acoustic and dynamic characteristics of this joint were determined by experimental modal analysis through the car-running experiments as well as by modal analysis of finite element modeling. Ghimire *et al*. (2009) investigated the dynamic characteristics and acoustic characteristics of a single-support modular expansion joint installed in an expressway bridge. Dynamic analysis of the joint was carried out by FEM and the fields inside the cavity located beneath the joint and outside of the cavity were analyzed by BEM. Steenbergen (2004) studied the dynamic behavior of multi-support joints under vehicle loads with constant speeds in detail, mainly focusing on the vertical dynamic characteristics of the joints. A simplified mathematical model was established numerically, which included the middle center beam and its corresponding set of crossbeams. Then a half-cycle sine pulse was deployed on the upper flange of the middle center beam, representing the impact between the tyres and the center beam when wheels ran over. The dynamic characteristics of multi-support MBEJs with a different number of center beams were studied, including the frequency response functions and DAFs for design.

The existing numerical researches mainly focused on vertical dynamic characteristics of MBEJs under vehicle loads at a constant speed, when the horizontal forces could be ignorable (Roeder 1998, Steenbergen 2003). Ancich *et al*. (2006) referred to coupled center beam resonance as the basis of the dynamic behavior of single-support MBEJs. However, either for the multi-support joints or the single-support joints, a generally simplified numerical model was utilized which was only comprised of a given center beam (usually the middle center beam) and its corresponding set of crossbeams. The wheel loads were only deployed on the selected center beam, without considering the influence of the coupled center beam resonance. In fact, the simplified numerical model is reasonable for the multi-support joints because the center beams of multi-support joints are disparately supported by different sets of crossbeams, thus the dynamic interactions between different center beams can be inconsequential. But for the single-support

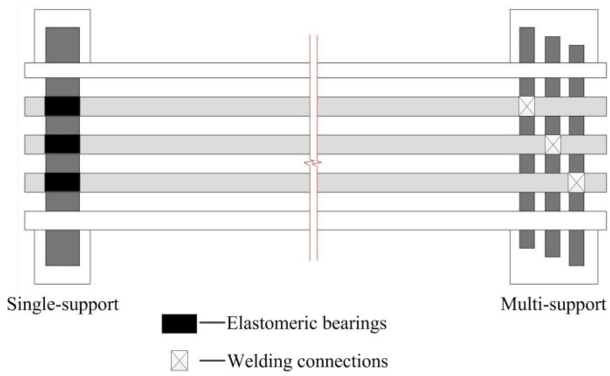

Fig. 1 Discrepancy of supporting systems of single-support MBEJs and multi-support MBEJs

joints, all the center beams are supported by a common set of crossbeams and the dynamic response of a given center beam will be affected dramatically by its neighboring center beams when the wheels run over the full-scale joint. Therefore, in this research, a full-scale finite element model of a typical single-support modular expansion joint with five center beams is established and a successive vehicle load form is given out to simulate the transient impact of wheel loads. Then the dynamic response of each center beam is analyzed with considering coupled center beam resonance. Besides, dynamic amplification factors of all center beams are also calculated to understand the variation along with the increasing vehicle velocities.

2. Model investigation

2.1 Brief Description of singl-support MBEJs

Single-support MBEJs are mainly comprised of center beams, edge beams, crossbeams and a number of elastomeric bearing components. Center beams and edge beams are perpendicular to the bridge axis. Crossbeams are parallel to the bridge axis. The center beams are supported on a common set of crossbeams through stirrups, with sliding elastomeric bearings at the underside and pre-stress polyurethane bearings at the upside. The gaps between center beams are evenly distributed, which usually range from 0 to 100 mm. Crossbeams are placed in the support boxes with elastomeric sliding bearings underside and pre-stress polyurethane bearings upside as well. The stiffness of the elastomeric bearing ranges from 40000 N/mm to 80000 N/mm and the damping ranges from 0.5 N.s/mm to 12 N.s/mm. Center beams and crossbeams can slide horizontally to accommodate the horizontal movements of bridge superstructures caused by the shrinkage and creep of concrete, the temperature effect and the exterior horizontal forces from vehicles etc. The horizontal movements of center beams are controlled and balanced by the elastomeric control springs fixed between center beams. The stiffness of the control spring ranges from 200 N/mm to 600 N/mm and the damping ranges from 1 to 5 N.s/mm. The whole joint then is built in the ends of the girder bodies. The plane and lateral views of the configuration of a single-support modular expansion joint with five center beams are shown in Fig. 2.

2.2 Finite element model of single-support MBEJs

A 3D finite element model with five centre beams is built by ANSYS 15.0 according to the full-scale structure of a joint manufactured by a Chinese manufacturer. The centre beams, edge beams and crossbeams are modelled by element BEAM188 and the elastomeric bearings are modelled by the 3D linear spring element COMBIN14. Poisson ratio of steel components is determined as 0.25. The stiffness and damping of vertical elastomeric bearings are determined as 60000 N/mm and 5 N.s/mm respectively. The values of horizontal control springs are determined as 400 N/mm and 2 N.s/mm. The five centre beams and two edge beams are equally 14.75 m long and the ten crossbeams are 1.05 m long. The gaps between centre beams are 40 mm wide. The torsional movements of center beams and crossbeams in the finite element model are constrained. The cross section sizes of centre beams, edge beams and crossbeams are shown in Table 1.

Ample modal analyses have been conducted on both single-support joints and multi-support joints in numerical and experimental ways in the existing reseraches. Several dominant vetical mode of a full-scale single-support MBEJ were obtained experimentally and theoretically by

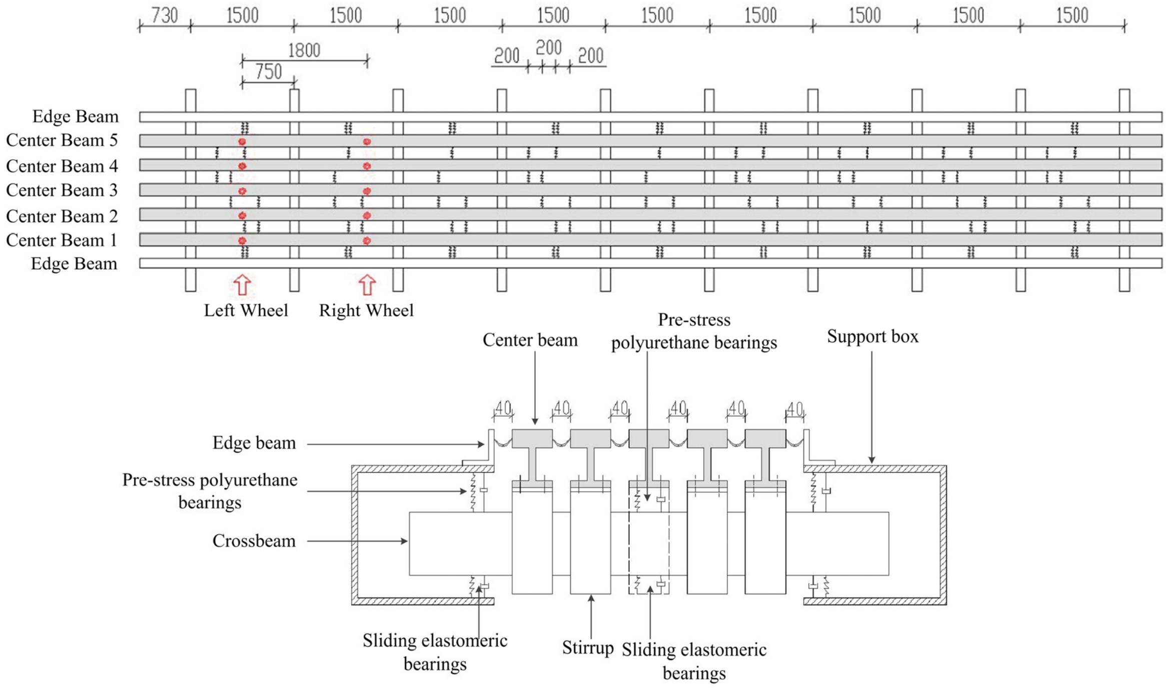

Fig. 2 Plane and lateral views of single-support MBEJs

Table 1 Cross-section properties of edge beams, center beams and crossbeams

Section type	Center beam	Edge beam	Crossbeam
	I-shaped	L-shaped	Rectangular
Cross section area (m^2)	6.224×10^{-3}	1.656×10^{-3}	9.800×10^{-3}
Moment of inertia-strong (m^4)	4.803×10^{-5}	2.081×10^{-6}	6.403×10^{-5}
Moment of inertia-weak (m^4)	1.603×10^{-5}	1.411×10^{-6}	1.601×10^{-5}
Product of inertia (m^4)	2.116×10^{-5}	-4.020×10^{-7}	1.401×10^{-5}
Young modulus (MPa)	2.050×10^{5}	2.050×10^{5}	2.050×10^{5}

Ravshanovich *et al*. (2007), of which the correspongding natrual frequencies are around 82 Hz, 113 Hz and 152 Hz. The frequency of first mode of vibration of a single center beam and its corresponding set of crossbeams obtained numerically by Steenbergen (2004) is 110 Hz, which is related to a center beam vibration (pinned-pinned vibration), and the second mode is 150 Hz, which is related to some mixed motion of crossbeams and the center beam. Another full-scale experimental model analysis was conducted on a hybrid designed modular expansion joint by Ancich *et al*. (2006), of which the first vertical mode at 71 Hz is characterized by the whole body bounce of all center beams, the second vertical mode at 85 Hz is the first bending of center beams and the third vertical mode at 91 Hz is the second bending of the center beams, etc. The vertical model analysis is also conducted in this study and the first 3 modes are given in Fig. 3. The frequency of the first vertical mode 75.6 Hz. The discrepancy of natural frequencies existing in different researches is primarily caused by the structural differences of the analyzed MBEJs.

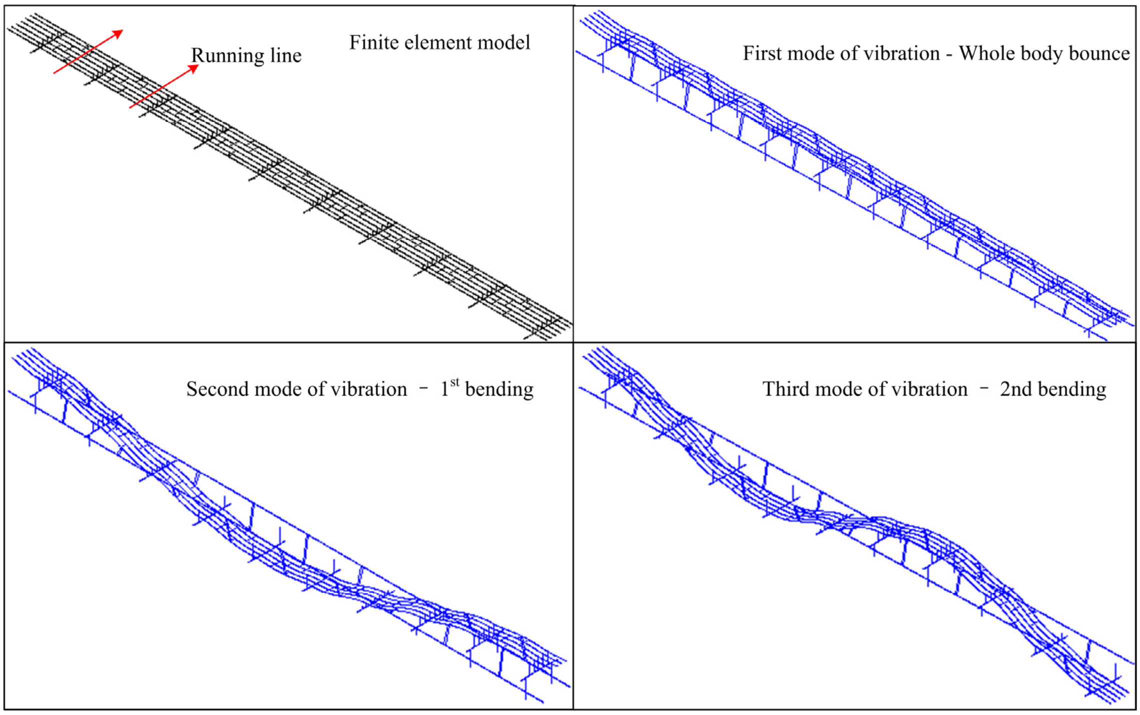

Fig. 3 Finite element model of MBEJs and the first three modes of vibration

3. Vehicle load investigation

When vehicles pass over MBEJs, the vertical, horizontal and torsional forces are acted on the center beams. Simple ramp load and half sine load with minor accuracy and energy loss were adopted to simulate the wheel load in analyzing the dynamic characteristics of MBEJs (Ramberger and Robra 2003, Goangseup and Zhu 2014). Steenbergen (2004) investigated the three forces extensively and meticulously and gave a more precise vertical wheel load considering the dynamic effects

$$F_{vert}(\mathrm{t}) = \frac{R + nk_{tyre}u_0}{2ni}(1 - \cos\frac{2\pi t}{T}) \quad 0 \le t \le T \tag{1}$$

Where 'R' is the load of vehicle axle, 'n' is the number of wheels per vehicle axle, 'k_{tyre}' is the radial tyre stiffness of vehicle, 'u_0' is the vertical unevenness in road surface, 'i' is the number of loaded center beams per wheel, 'T' is the contact time between wheels and a center beam. The contact time 'T' can be calculated by

$$T = \frac{b_g + l_c}{v} \tag{2}$$

Where 'b_g' is the width of gaps between center beams (here b_g is 40 mm), 'l_c' is the tyre contact length and 'v' is the vehicle velocity.

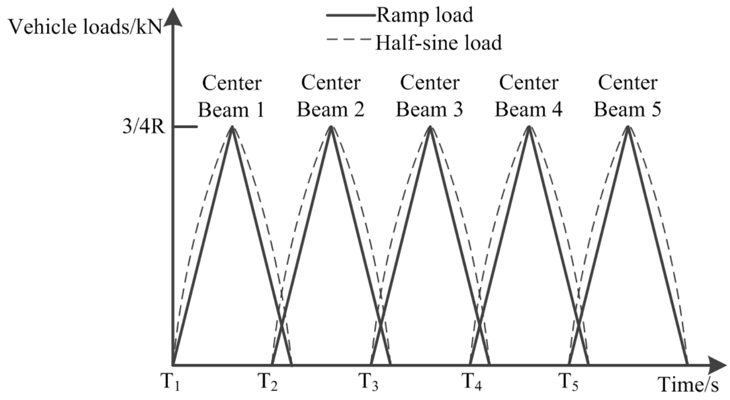

Fig. 4 Time-dependent wheel loads on each center beam

According to Eq. (1), the vertical force of vehicle load is sinusoidal. The tyre contact length 'l_c' is 200 mm, and the axle load 'R' is 140 kN (Technical Standard of Highway Engineering 2005). Here, 'R' is discounted as 0.75 R since the contact length is greater than the sum of the gap width 40mm and the center beam width 90 mm, thus the wheels are always running on at least two center beams (Sun 2013). Unevenness u_0 is considered to be zero in this study. The wheel load on each center beam stays zero before the tyres contact the center beam. Then it increases after the tyre-beam contact and reaches its maximum value when the wheel is rightly centered on the center beam. Afterwards the wheel load decreases to zero when the tyres depart the center beam. In this study the wheel loads are still approximated as a ramp load, considering the advantage of wheel load input in ANSYS despite of the negligible energy loss. A successive vehicle load form deployed on each center beam is shown in Fig. 4. When the vehicle runs over the MBEJs at the constant speed 80 km/h, for example, the time of wheel load arriving on each center beam T_1, T_2, T_3, T_4, and $T5$ corresponds successively to 0, 0.00585 s, 0.0117 s, 0.0175 s, and 0.0234 s. The contact time T between wheels and each center beam is 0.01305 s.

4. Dynamic analysis of single-support MBEJs under vehicle loads

The vehicle loads run straight over the joint and the most unfavorable positions of wheel loads are selected on each center beam to analyze the dynamic responses. Here the most unfavorable positions on each center beam are under the left wheel because it runs over the midspan between two crossbeams, shown in Fig, 2. The dynamic vertical displacements of these positions are recorded and analyzed. Many factors can affect the dynamic characteristics of MBEJs such as the velocity, the number of center beams, the width of gaps between center beams and the elastomeric bearings, etc. This paper mainly studies the dynamic effect of vehicle loads along with increasing velocities, compares the dynamic displacements of center beams which considering the interaction among center beams to those which not considering the interaction, reveals the coupled center beam resonance mechanism of the neighboring center beams, and obtains the DAFs curves of each center beam along with increasing velocities. More extensive and deeper investigation of other factors which influence the dynamic characteristics of MBEJs will be conducted in the future theoretical and experimental research.

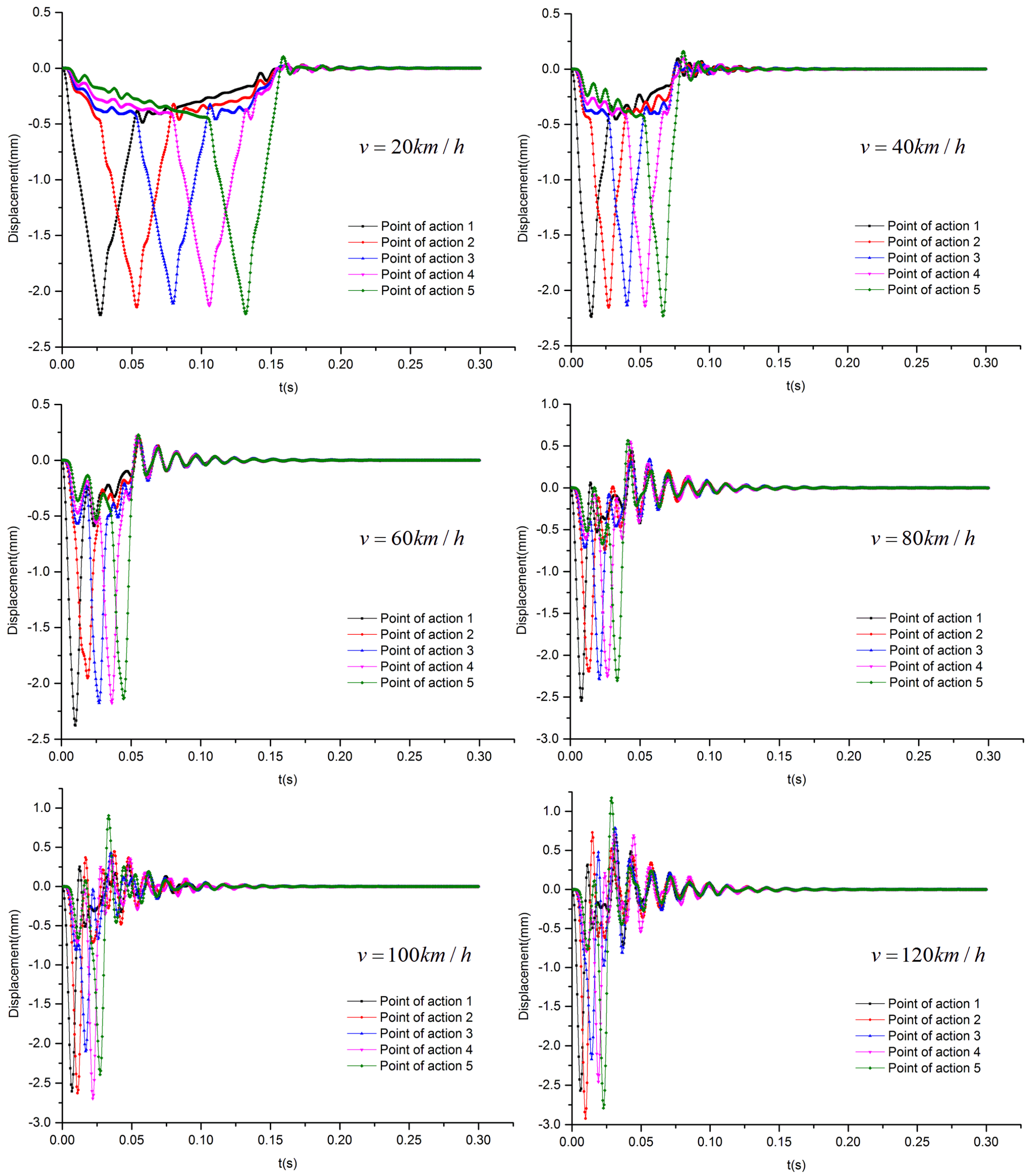

Fig. 5 Dynamic displacements of points of action under left wheel with increasing velocities

4.1 Dynamic displacements of center beams under different vehicle velocities

According to Eq. (2), the contact time between tyres and center beams are partially determined by vehicle velocities. When the traffics run over the joint at a low speed, the dynamic effect is believed to be inconsequential. However, when traffics run over the joint at a high speed, the dynamic effect of vehicle loads is expected to dramatical. Hence the dynamic displacements of all five center beams are studied considering a wide range of velocities from 20 km/h to 120 km/h with an interval 20 km/h.

The time-dependent dynamic displacemet responses of center beams are shown in Fig. 5. Dynamic responses of center beams show a quasi-static feature under vehicle velocities below 40 km/h, in which the maximal vertical displacement is around 2.25 mm. When the velocities exceed 60 km/h, however, the dynamic responses of center beams become more and more dramatical and the maximal displacement reaches to 3.0 mm on Center Beam 2 at 120 km/h. Besides, dramatical rebound displacements also appers on the center beams after the tyres depart the center beams. Obviously when traffics pass over MBEJs at high speeds greater than 60 km/h, the dynamic amplification of vehicle impacts to MBEJs does harms to the structural components of MBEJs.

DAFs are important in the design of MBEJs for they can reveal the degree of dynamic responses of each center beam under vehicle loads. If DAFs are not considered or underestimated in the design, then MBEJs will soon be damaged and suffer the function failure under the impact of traffic loads (Chang and Lee 2002). Generally, DAFs can be obtained via Eq. (3)

$$DAF = \frac{d_{dyn}}{d_{stat}} \tag{3}$$

Where 'd_{dyn}' is the dynamic displacement of center beams under mobile vehicle loads, and 'd_{stat}' is the displacement of center beams under static vehicle loads. DAFs of center beams are obtained with increasing vehicle loads and the DAF curves are shown in Fig. 6. It is noted that the DAFs are generally amplified along with the increasing velocities. The maximal DAF is found to reach 1.5 on Center Beam 2 at 120 km/h. Besides, the dynamic responses of different center beams of a full-scale joint are different to the traffic impact, which can be apparently found in Figs. 5 and 6. The dynamic characteristics of center beams should be considered disparately in the design of single-support MBEJs to improve the performance and the life service of the single-support MBEJs.

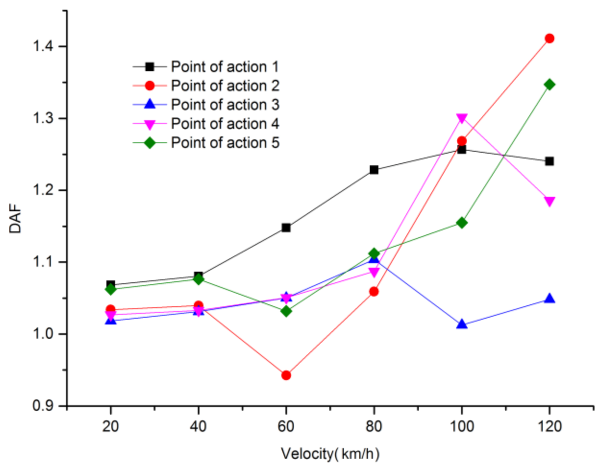

Fig. 6 DAFs of each center beam with increasing velocities

4.2 Coupled center beam resonance analysis

In existing researches a single center beam and its correspongding set of crossbeams are chosen from the full-scale MBEJs to establish the finite element model and conduct the dynamic analysis, which do not consider the coupled resonance of center beams. In this section, the dynamic responses of Center Beam 2 and Center Beam 3 considering the interaction of neibouring center beams are compared with the results when they are analyzed singly. The comparison results of Center Beam 2 and Center Beam 3 are shown in Figs. 7 and 8 repectively, only considering the velocities greater than or equal to 60 km/h, at which the dynamic effects are conspicuous. Case 1 is the results of single center beam investigation and Case 2 is the results of full-scale MBEJ investigation. From Fig. 7 we can see that the maximal displacements of Center Beam 2 when analyzed in full scale are found to be slightly smaller than the results when analyzed singly at 60 km/h and 80 km/h. However, the opposite happens when the velocities exceed 80 km/h. Meanwhile, from Fig. 8 we can see the maximal displacements of Center Beam 3 when analyzed in full scale are consistently found to be smaller than those when analyzed singly under all the chosen velocities. Besides, the rebounds peaks of these two center beams in full-scale analysis are also found to be smaller than those in single analysis. All these results indicate that the full-scale

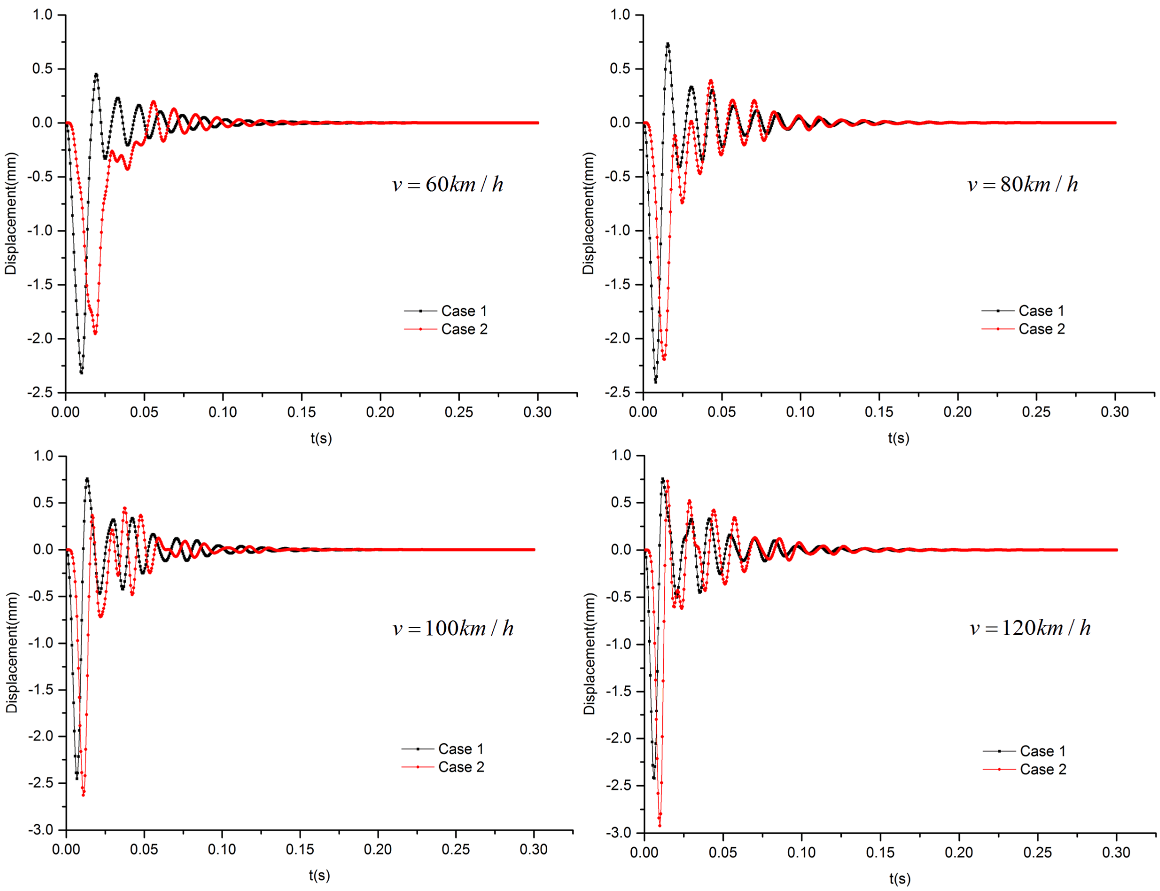

Fig. 7 Comparison of Center Beam 2 under Case 1 and Case 2

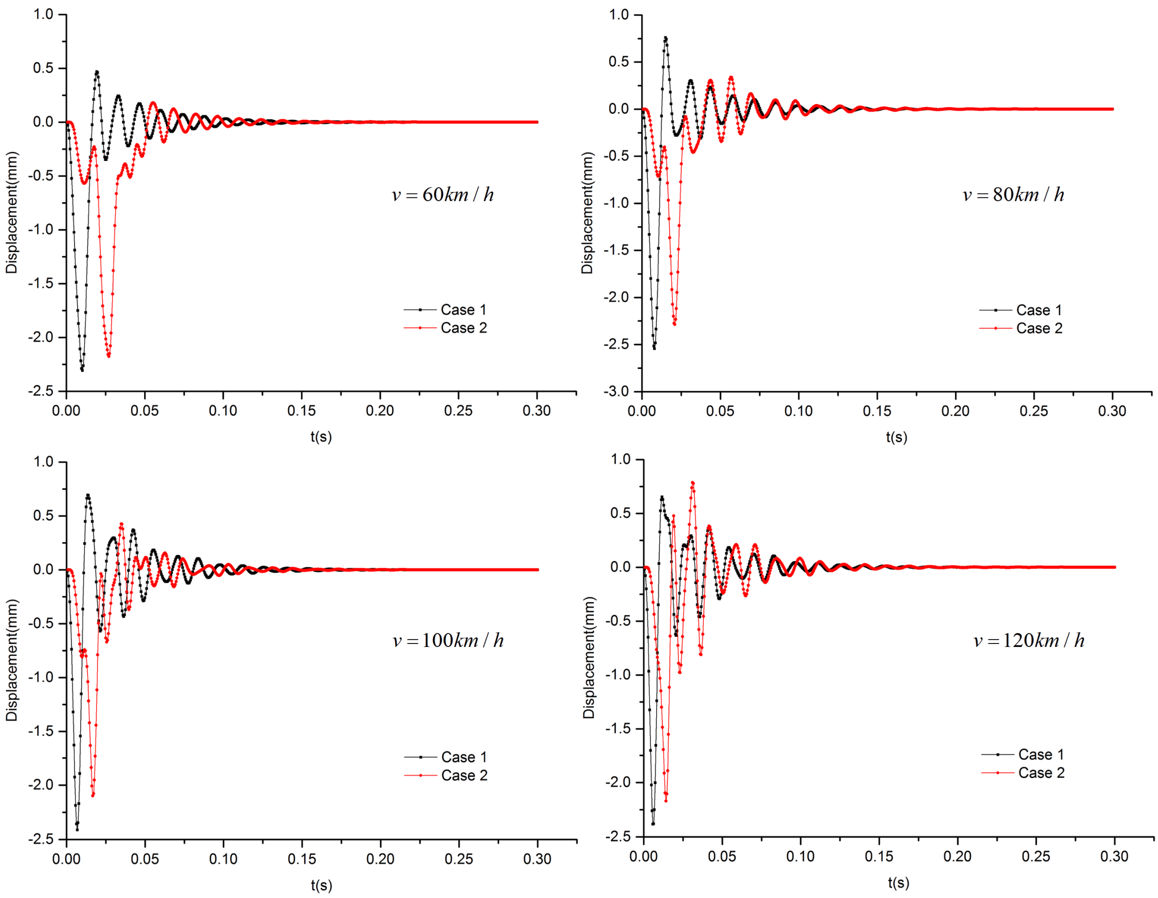

Fig. 8 Comparison of Center Beam 3 under Case 1 and Case 2

dynamic analysis of single-supported MBEJs reveals the real vibration mechanism of center beams than the single center-beam system, since the coupled center beam resonance is considered in full-scale analysis.

In addition, a special phenomenon is noticed in Fig. 6 that the dynamic amplification factors of Center beam 3 maintain around 1.05 under the increasing velocities while other center beams change dramatically along with the changing vehicle velocities. Existing researches analyzing the dynamics of a single center beam generally are conducted on the middle center beam (in this study Center Beam 3) of MBEJs, because the dynamic responses of the middle center beam are assumed to be most unfavorable (Coelho *et al*. 2013). DAFs of Center Beam 3 in Fig. 6 shows the opposite. A preliminary interpretation of this phenomenon is that the interaction of rebounds of Center Beam 1 and Center Beam 3 shown in Fig. 9. The elliptical areas show that the displacement of Center Beam 3 is reduced by the rebounds of Center Beam 1 and Center Beam 2 after the wheels depart them, because all the center beams of single-support MBEJs are supported on a common set of crossbeams via elastomeric bearings, thus the rebounds of Center Beam 1 and Center Beam 2 can reduce the dynamic responses of Center Beam 3 via the common set of crossbeams. When vehicles pass over the joint at a low speed below 40 km/h, under which the bounces of center beams are inconsequential, the reduction effect of neighbouring center beams is also

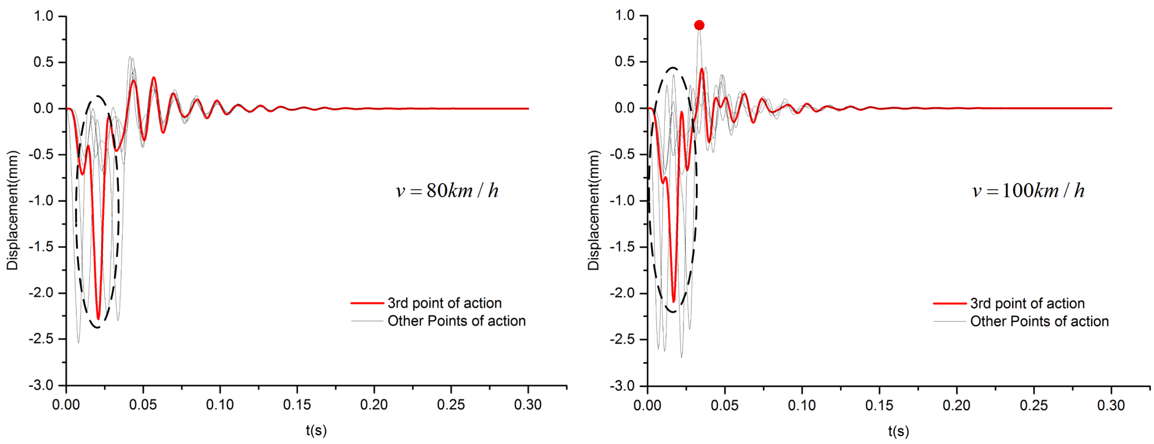

Fig. 9 Dynamic displacements of the third point of action on Center Beam 3 at 80 km/h and 100 km/h

unconspicuous. However, when vehicles pass over the joint at a high velocity exceeding 60 km/h, the reduction effect of bounces of previous center beams becomes dramatical, which can be found in Figs. 5 and 9. Of course, the number of center beams and the width of gaps between center beams may change the dynamic characteristics single-support MEBJs. The dynamic analysis of crossbeams will also help to better understand the interaction mechanism of center beams. More extensive researches including dynamic analysis of different types of single-support MBEJs and the dynamic vibration of crossbeams will be conducted in the future investigation.

5. Conclusions

A full-scale finite element model of single-support MBEJ with five center beams is established and the dynamic characteristics of the MBEJ under successive vehicle loads are investigated theoretically. Several conclusions obtained in this study are summarized as follows:

(1) Responses of the MBEJ in this research show a quasi-static feature when vehicle velocities are below 40 km/h. However, dramatic dynamic responses arise along with the increasing velocities greater than 60 km/h. Besides, more drastic rebounds of center beams are excited when vehicles depart the center beam at a high speed. The rebound peak of Center Beam 5 reaches more than 1.0 mm under the impact of vehicles at 120 km/h. Therefore, when MBEJs are installed in expressway bridges, the dynamic effect should be considered sufficiently in the design of applicable and durable MBEJs.

(2) Coupled center beam resonance is investigated in this research. The interaction of neighboring center beams of single-support MBEJs can reduce or amplify the dynamic responses of the given center beam. In this research, of which the studied MBEJ is comprised of five center beams, dynamic responses of Center Beam 3 are reduced while those of other center beams are amplified to varying degrees. DAFs of different center beams indicate the different dynamic responses of each center beam to the vehicle loads. DAF of the most unfavorable position of Center Beam 2 at 120 km/h reaches 1.5, which does harm to the MBEJ structure.

(3) The coupled center beam resonance is related to the rebounds of neighboring center beams.

Because all the center beams are supported on a common set of crossbeams, the rebounds of neighboring center beams can influence the given center beam drastically via the common crossbeams, reducing or amplifying its dynamic responses.

The dynamic characteristics of single-support MBEJs can be influenced by the number of center beams, the gap size between center beams, and the stiffness of elastomeric bearings etc as well. More extensive and complete dynamic investigation about single-support MBEJs under vehicle loads will be conducted in the future. The results can be utilized for reference in the design, operation and maintenance of single-support MBEJs.

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