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Dynamic performance of girder bridges with explosion-proof and aseismic system

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Abstract. Recently, the transportation of dangerous explosive goods is increasing, which makes vehicle blasting accidents a potential threat for the safety of bridge structures. In addition, blasting accidents happen more easily when earthquake occurs. Excessive dynamic response of bridges under extreme loads may cause local member damage, serviceability issues, or even failure of the whole structure. In this paper, a new explosion-proof and aseismic system is proposed including cable support damping bearing and steel-fiber reinforced concrete based on the existing researches. Then, considering one 40m-span simply supported concrete T-bridge as the prototype, through scale model test and numerical simulation, the dynamic response of the bridge under three conditions including only earthquake, only blast load and the combination of the two extreme loads is obtained and the applicability of this explosion-proof and aseismic system is explored. Results of the study show that this explosion-proof and aseismic system has good adaptability to seism and blast load at different level. The reducing vibration isolation efficiency of cable support damping bearing is pretty high. Increasing cables does not affect the good shock-absorption performance of the original bearing. The new system is good at shock absorption and displacement limitation. It works well in reducing the vertical dynamic response of beam body, and could limit the relative displacement between main girder and capping beam in different orientation so as to solve the problem of beam falling. The study also shows that the enhancement of steel fibers in concrete could significantly improve the blast resistance of main beam. Results of this paper can be used in the process of antiknock design, and provide strong theoretical basis for comprehensive protection and support of girder bridges.

Keywords: blast impact; earthquake; scale model test; cable support bearing; fiber reinforced concrete

1. Introduction

Since the 1990s, the bridge construction in China is in the rapid development. By the end of 2011, as one of the biggest country in bridge construction, the number of bridges in China is up to 689 thousand. However, bridges will inevitably suffer from many potential threats such as natural disaster, terrorist attacks in the process of operation.

In recent years, the transportation of dangerous explosive goods is increasing, which makes frequent vehicle blasting accidents become a potential threat for the safety of bridge structures (Zhang 2013). However, the antiknock research of the bridges in China is in the primary stage. The effect of blast impact is not considered in the load code for the design of bridge structures, nor the specific antiknock construction requirements is put forward at present. By contrast, the aseismic design based on the real reaction of bridges is basically mature. Thus, whether bridge structures based on the aseismic design could bear the impact effect from blast load needs to be further researched. In addition, China is an earthquake-prone country. When earthquake occurs, it’s highly possible that trucks loaded with dangerous explosive goods will explode due to crashes. And this could result in structural damage with a greater degree and larger scope. Nevertheless, the research on security capability of bridges under the extreme load combination of earthquake and explosion is insufficient. Considering the large number of bridges in China and their utmost significance in our nation’s transportation infrastructure, bridge safety has become a major public concern and greater attention is paid to the dynamic effects of bridge structures subjected to blast load and earthquake.

To improve the antiknock ability and minimize the damage, studies have been undertaken to understand the effects of blast load on bridges. Experimental, analytical, and numerical researches have been directed to investigate the vulnerabilities and failure modes of bridge girders, columns, beams, and whole bridge structures subjected to different levels of blast load (Yi *et al.* 2014). Based on the Timoshenko beam theory, Fang (2003) proposes a finite difference prediction method which depicts the failure pattern of the reinforced concrete beam, and applies the method to analyze the influence of the load loading rate, height of cross section and concrete strength to the failure pattern of the reinforced concrete beam. Hacıefendioğlu *et al.* (2015) investigates the effects of ground shocks due to

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explosive loads on the dynamic response of historical masonry bridges by using the multi-point shock response spectrum method. Zhou (2015) establishes a general simulation platform to investigate the dynamic performance of the bridge-traffic system under multiple service and extreme loads. Based on the orthotropic steel bridge, Son (2011) puts forward the concept--”insurance system”, this method can effectively limit the impact of the explosion shock scope. Recently, some efforts have been put forth on using high strength material to improve the antiknock ability of concrete. And steel fibers (Burrell and Aoude 2015, Zhou and Kuznetsov 2008), organic synthetic fiber materials (Foglar 2013), carbon fiber cloth (Hao 2010), aluminum foam (Schenker 2008) have already been applied to the practice.

As for the aseismic design of bridges, the fact that damage such as bearing failure, collision and beam falling resulted from large relative displacement between upper and lower structure happens quite often could be discovered after studying different forms of damage appeared on the bridge in earthquake. Currently, the most widely used subtraction isolation measures are reducing vibration isolation technology and ductility seismic design. A new type of damping bearing comes up in the literature (Yuan 2011). By adding limit cables to the tub bearing to effectively limit the bearing displacement and dissipate the earthquake energy transferred from the lower structure through friction.

It seems that previous studies are mainly focused on the seismic response analyses or explosive response analyses of bridges separately without considering the combination of the two extreme loads. Similarly, protective measures are proposed only for the prevention of blast accidents or earthquake respectively. Comprehensive and protective measures are not put forward. Therefore, in this study, it is intended to put forward a new comprehensive protection system comparing with the existing aseismic measures, and carry out 3D dynamic analysis and corresponding scale model test of girder bridges with the above protective system under the loading conditions including blast load, earthquake, and the combination of the two loads.

2. Design of scale model

Referring to the existing researches of seismic and antiknock measures (Zhang 2016), available explosion-proof and anti-seismic measures are proposed to constitute a new resistant system: (1) Considering the large relative displacement between main girders and piers caused by earthquake and blast load, cable support damping bearing is utilized; (2) For the punching shear damage or bending failure of structural elements subjected to the blast load, steel-fiber reinforced concrete is used to improve the bearing capacity. In brief, the new seismic and antiknock system appears and contains two essential parts: cable support damping bearing and steel-fiber reinforced concrete.

Regarding a pre-stressed simply supported concrete T-bridge as the prototype, specific scale model test is carried out. In the production process of the model, organic glass is being used to simulate the fiber reinforced concrete, and lead is increased to meet the requirements of the similar weight. Based on the principle of equivalent stiffness, the vertical and horizontal bending stiffness remain equivalent between the prototype and model, and the influence of axial stiffness and torsional stiffness are ignored. Considering the material specifications of organic glass, by assuming one certain quantity of geometrical section, other geometrical sizes of the cross section could be obtained after ceaseless trials. Model bearing is obtained from the bearing factory based on the design drawings. Considering the performance parameters of the shake table and the maneuverability of the experiment, the similarity relation between model and the prototype is attained by dimension analysis. (Table 1)

The physical properties of the organic glass are not very stable, and its elastic modulus will change with the environmental temperature. Organic glass is used to simulate the stiffness of the section in this test. In order to guarantee the stability of material performance for the organic glass, test is carried out in the thermostatic chamber which has a constant temperature of 20 degrees Celsius. In the experiment, two specimens with different specifications are made to measure the real-time elastic modulus as the experiment goes on.

3. Simulation of blast load

The most important question needed to be dealt with in this test is how to simulate the blast load. According to the

Table 1 Similarity relation between model and the prototype

Item	Physical quantity	Relation	Ratio of similitude	Remark
Material property	Strain ε	$S_\varepsilon=1$	1	Model design control
	Stress σ	$S_\sigma=S_E$	0.0699	
	Modulus of elasticity E	S_E	0.0699	
	Poisson's ratio μ	$S_\mu=1$	1	Model design control
	Density ρ	$S_\rho= S_E/S_a S_l$	2.237	
Geometric features	Length l	S_l	1/80	Model design control
	Area S	$S_s= S_l^2$	1/6400	
	Displacement δ	$S_\delta=S_l$	1/80	
	Rotation θ	$S_\theta=1$	1	
Load and internal force	Force F	$S_F=S_E S_l^2$	1.092e-05	
	Bending moment M	$S_M=S_E S_l^3$	1.365e-07	
Dynamic character	Mass m	$S_m=S_\rho S_l^3$	4.368e-06	Dynamic loading control
	Stiffness k	$S_k=S_E S_l$	8.737e-4	
	Time t	$S_t=(S_m/S_k)^{0.5}$	7.071e-2	Dynamic loading control
	Frequency f	$S_f=1/S_t$	14.142	
	Damp c	$S_c=S_m/S_t$	6.178e-05	
	Velocity v	$S_v=S_l/S_t$	0.177	
	Acceleration a	$S_a=S_l / S_l^2$	2.5	Dynamic loading control

literature (Yang 2010), under the impact of solid projectile and static charge contact explosion, the reinforced concrete target boards of different thickness will both appear four kinds of typical failure forms including pit, damaged, throughout and cutting. Similar and corresponding relations are existed between these two. Whether the projectile impact or contact explosion, the reinforced concrete plates are both under an instantaneous high-pressure pulse load rendering the similar brittle failure characters, and their failure mechanisms are the same. Therefore, the equivalent relationship between the projectile impact damage effect and contact explosion damage effect can be used to solve the problem of contact explosion.

For a target board of certain thickness, when a projectile goes forward with a velocity of v and the mass of m, the impulse it has is mv and the kinetic energy is mv^2/2. When it hits the center of the target plate, its speed drops to zero, and the damage effect made to the target board is equivalent to the damage effect made by surface contact explosion with a certain amount of explosives *Qz*. As the projectile impact and impulse is relatively small, the energy equivalence principle could be took advantage of to get the corresponding equivalent amount of TNT.

In the scale model test, the whole structure is always assumed in the linear elastic state without damage. Significant elastic impact to the model bridge made by organic glass is equivalent to the projectile impact with low speed and small impulse. Thus, a high-elastic sphere in the state of free fall or sinusoidal oscillation is used to simulate the blast impact. The principle of energy conservation is applied to get the falling kinetic energy of the elastic sphere, and this energy is exactly the energy released from the explosion happened near the deck which could cause the same damage effect. With the help of data acquisition system, the response of acceleration, displacement and strain from essential position of the model under various blast loads are collected.

4. Scale model test

According to the seismic hazard analysis, site category, structure dynamic characteristics and other related factors, six different seismic waves are selected as the incentives, testing and evaluating the applicability of the explosion-proof and aseismic system under earthquake. After the input of each seismic wave, white noise is used to sweep the model structure and get its natural frequency to estimate whether the stiffness of the structure has been changed. In the process of experiment, response of acceleration, displacement and strain from different parts of the model under each earthquake condition are collected. As mentioned in the above, a high-elastic sphere in the state of free fall or sinusoidal oscillation is used as the blast load impact in order to obtain the dynamic response of the girder bridge under blast load. When earthquake and blast load are applied together through experimental facilities, the dynamic performance under the combination effect could be attained. Laboratory equipment used in this test mainly contains shake table, high-elastic sphere, acceleration sensors, laser displacement sensors, strain gauges and data

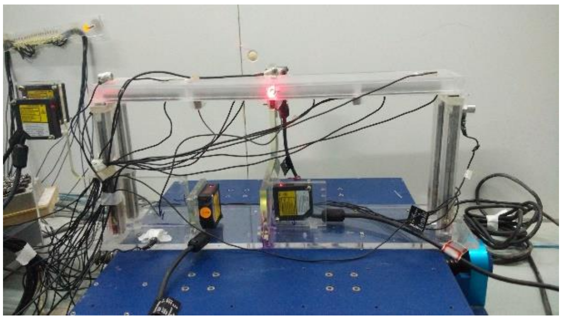


Fig. 1 Assembled test model

Table 2 Loading condition of the scale model test

Serial number	Model	Loading Condition	Waveform	Peak acceleration		Load time
E1			EL-centro	1.5g		2.82s
E2			White noise	0.1g		25s
E3			CHICHI1	0.6g		12.72s
E4			White noise	0.1g		25s
E5			CHICHI2	0.1g		12.72s
E6				0.2g		12.72s
E7		Only earthquake (Longitudinal)	White noise	0.1g		25s
E8			CHICHI3	0.1g		12.72s
E9				0.2g		12.72s
E10			White noise	0.1g		25s
E11			CHICHI4	0.1g		12.72s
E12	Cable support damping bearing system (Non-cable friction damping bearing system)		White noise	0.1g		25s
E13			CHICHI5	0.1g		12.72s
E14				0.2g		12.72s
E15			White noise	0.1g		25s
Serial number			Impact direction	Mass (kg)	Position	Distance (cm)
B1			Above the bridge	0.0526	Mid-span	10
B2			White noise		0.1g	
B3		Only blast load	Along the bridge	0.0526	End of the girder	10
B4			White noise		0.1g	
B5			Cross the bridge	0.0526	Mid-span	10
B6			White noise		0.1g	
CB1~3				E1+B1/B3/B5		
CB4		Combination effect	White noise		0.1g	
CB5~7				E5+B1/B3/B5		
CB8			White noise		0.1g	

acquisition system. Eventually, through model assembling, instruments collecting and equipment calibration, a completed test model is established (see Fig. 1).

For comparative analysis, two different damping bearing systems are tested including cable support damping bearing system and non-cable friction damping bearing system. Three kinds of loading conditions are conducted including simulated seismic shaking table test, simulated blast load test and the combination test. Detailed information is shown in Table 2.

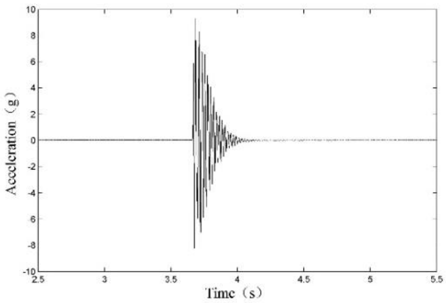
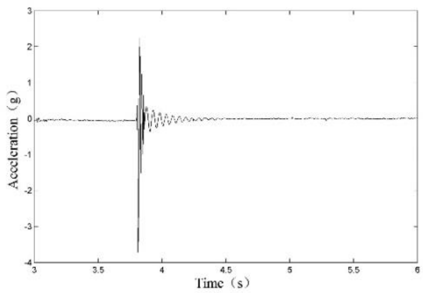
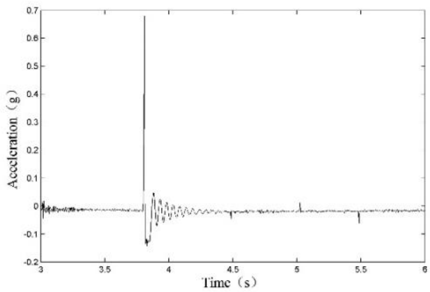


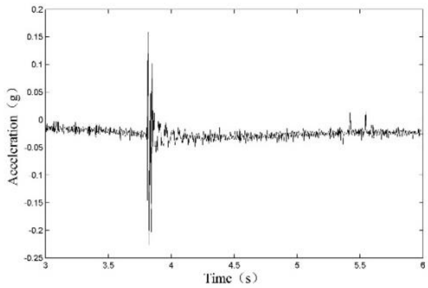
Fig. 2 Mid-span acceleration time-history curve of main girder



(a) End of the main girder



(b) Bent caps



(c) Middle of the piers

Fig. 3 Acceleration time-history curves when impact applied along the bridge at the end of the main girder

5. Discussions

5.1 Dynamic performance of the girder bridge under blast load

5.1.1 Response of acceleration

Under the impact of blast load, acceleration response time-history curve of the main beam at the mid-span is in the damped harmonic vibration form when impact occurs at the middle, and then return to original state after a few seconds. This phenomenon shows that the whole structure is in the elastic state as being assumed (see Fig. 2). The most dramatic response appears at the impact location. When the main beam suffers from the elastic sphere impact along the bridge at the end, the longitudinal acceleration response of the main beam is the most dramatic, and then the dynamic response transfers to the bent caps and piers through friction between main beam and bent caps (bearing support). In such a case, the acceleration response of bent caps is lower than the main girder, and the acceleration response of the piers is lower than bent caps (see Figs. 3(a)-(c)).

5.1.2 Response of displacement

Under the impact of blast load, the displacement time-history curve of the main beam at the mid-span is in the damped harmonic vibration form when impact occurs at the middle and then return to original state after a few seconds. This phenomenon shows that the whole structure is in the elastic state (see Fig. 4). And the longitudinal and horizontal blast impact both make large displacement deviation between main girder and bent caps (see Figs. 5(a)-(b)).

5.2 Dynamic performance of the girder bridge under earthquake

5.2.1 Response of acceleration

As a result of the interference from the working mechanism of shaking table and the environment, the maximum acceleration implemented by the shake table will be slightly above or below the design requirements, but are basically satisfied (see Fig. 6). The acceleration on the top of the piers is larger than the bottom while earthquake occurs along the bridge. This phenomenon shows that piers have considerable amplification effect to ground motion. As the height of piers becomes larger, the amplification effect

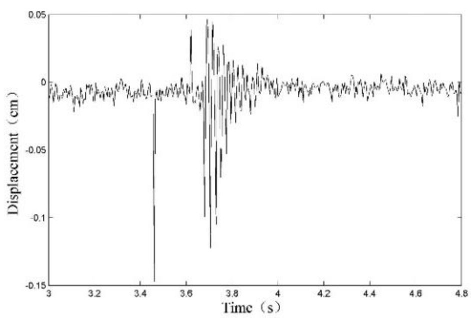
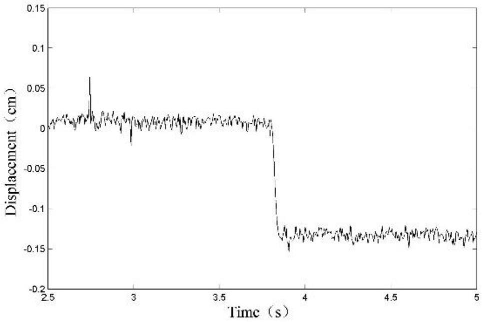
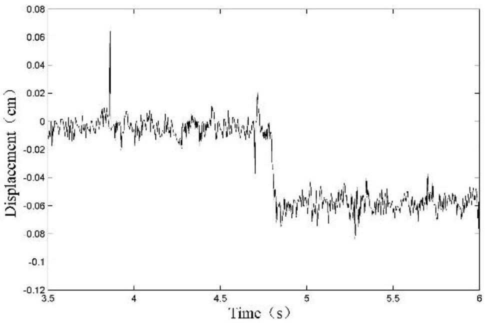


Fig. 4 Mid-span displacement time-history curve of main girder



(a) Longitudinal direction



(b) Horizontal direction

Fig. 5 Displacement time-history curve between main girder and capping beams when longitudinal and horizontal impact applied to the main girder

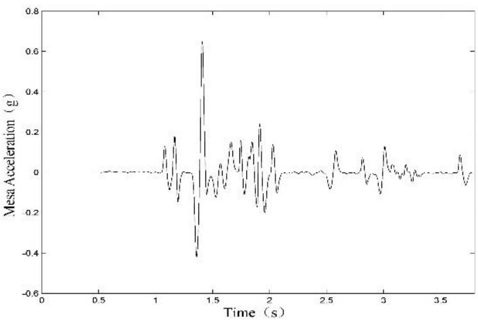


Fig. 6 The output of the mesa acceleration time-history curve (EL-centro1.5 g)

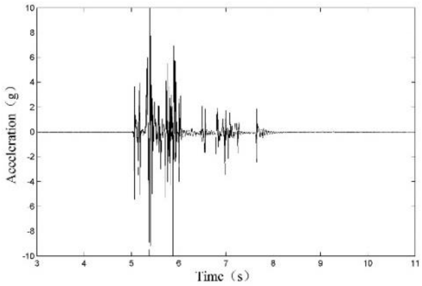
would be more significant. Under the same condition, the longitudinal dynamic acceleration response of main girders is significantly lower than the dynamic response of bent caps. The efficiency on reducing vibration isolation of cable bearing support is very high (see Figs. 7(a)-(c)).

5.2.2 Response of displacement

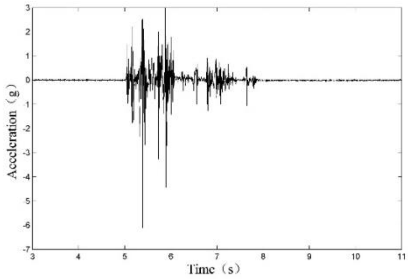
When the earthquake occurs along the bridge, the maximum displacement between main girder and bent caps is up to 3mm, and the response of all the bearing support is consistent. The residual displacement under CHICHI2 earthquake is only 0.3 mm. The residual displacements caused by other seismic waves are larger (see Figs. 8(a)-(b)).

5.2.3 Response of strain

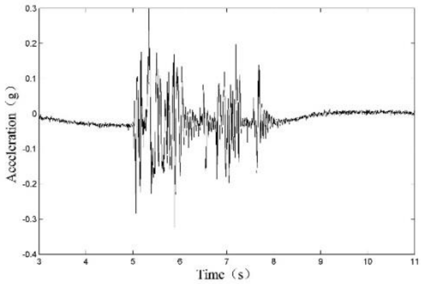
The strain of piers at different height are relatively small



(a) At the bottom of piers

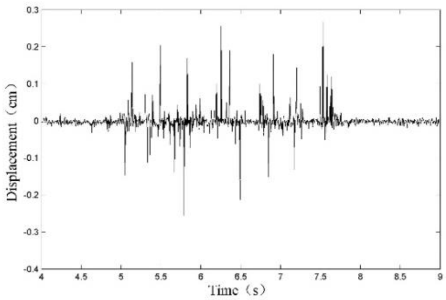


(b) At the middle of bent caps

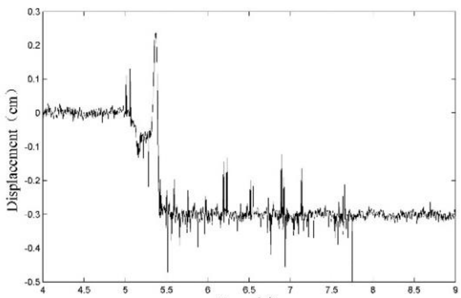


(c) At the end of main girder

Fig. 7 Longitudinal acceleration time-history curve of bridge structures while earthquake occurs along the bridge



(a) At the top of piers



(b) Displacement between the main girder and bent caps

Fig. 8 Longitudinal displacement time-history curve of bridge structures while earthquake occurs along the bridge

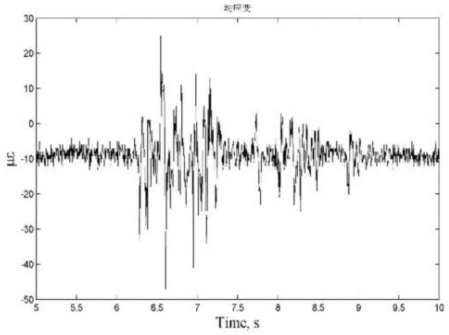
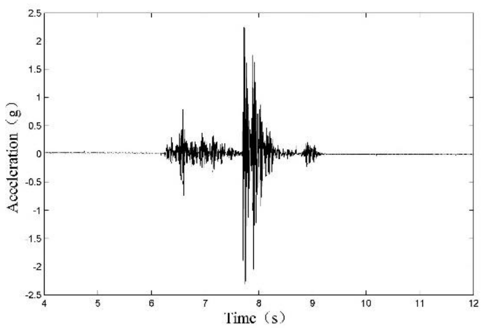
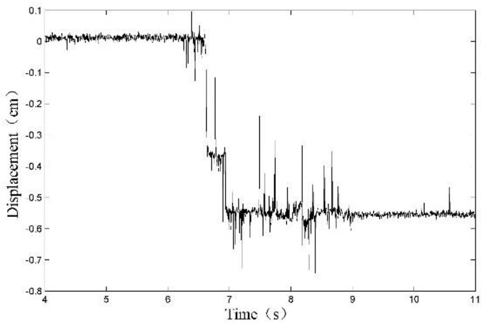


Fig. 9 Longitudinal strain time-history curve of the piers at the bottom



(a) Acceleration time-history curve of main girder at the mid-span



(b) Displacement time-history curve between main beam and bent caps

Fig. 10 Time-history curve of bridge structures under composite effect

under the earthquake along the bridge, and is at the level of the parts per million. All piers have the same trend, and return to the original state after the earthquake. This indicates that all the piers are in elastic range, and the internal force of the piers is small. Most of the inertial forces are cut off in the bearing support and the isolation measure (cable bearing support) is effective (see in Fig. 9).

5.3 Dynamic performance of the girder bridge under composite effect

The simulated blast load applied to the bridge structure when longitudinal earthquake happens would cause instantaneous effect to the acceleration response on different part of the bridge. The overall dynamic response of the structure is more intense just like what is shown in Fig. 10(a).

By analyzing the combination loading condition CB5, when impact load exerted, the end of the main girder bounce and the friction between main beam and capping beam is reduced. A larger relative displacement appears between main beam and capping beam (see Fig. 10(b)).

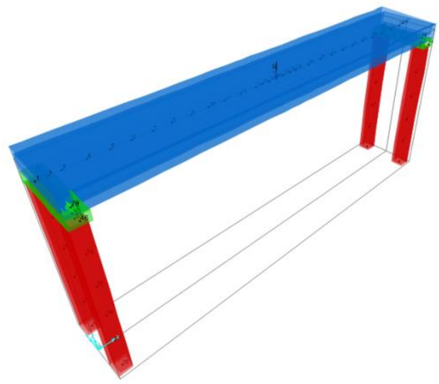


Fig. 11 The 3D finite element model of 40m-span simply supported concrete T-bridge (SAP 2000)

Table 3 Modal characteristics of the target bridge

Order	Frequency(Hz)	Period(s)
1	1.4037	0.712
2	1.4056	0.711
3	2.3597	0.424
4	42.333	0.0236
5	42.333	0.0236
6	45.723	0.0219
7	57.969	0.0173
8	58.039	0.0172
9	110.02	0.00910
10	110.02	0.00910

6. Numerical simulation

6.1 Finite element model

Considering the above 40m-span simply supported concrete T-bridge used in the scale model test as the prototype, a three dimensional trussing finite element model is being built by using general finite element software SAP2000 (see Fig. 11). Through modal analysis, the natural dynamic character of this modal bridge is obtained in Table 3.

Through time history analysis, displacement and acceleration time-history curves of the essential structural nodes on modal structure are obtained under different types of loading conditions including earthquake effect, blast load effect and the combination effect.

6.2 The consistency validation

In order to validate the effectiveness of scale model test and theoretical analysis, the consistency between the results

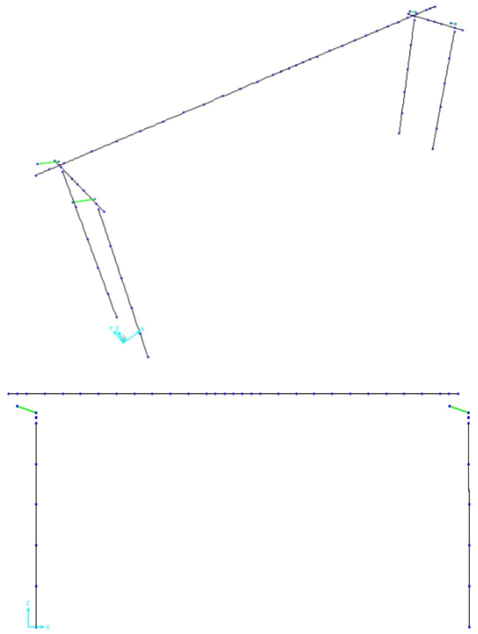


Fig. 12 The first order of the finite element model

of numerical simulation analysis (NSA) and scale model test (SMT) is checked.

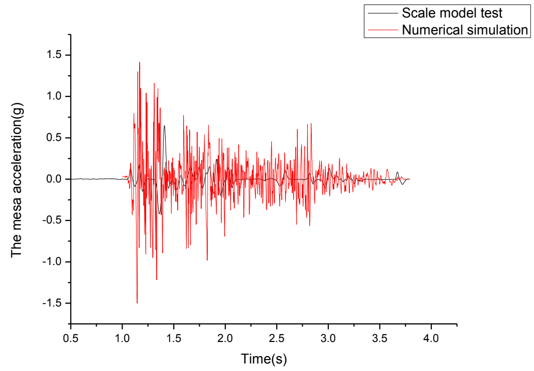
By comparing natural dynamic characteristics, the response of acceleration and displacement, results show that the first longitudinal period and frequency of the modal bridge are separately 0.712s and1.403 Hz, which are basically the same with the test results (see Fig. 12).

Through the comparison of acceleration and displacement response, results suggest that the results of NSA and SMT are in good agreement with each other on the trend (see Figs. 13(a)-(c)). Peaks and troughs appear almost at the same time. The deviation between data is in the acceptable range, which means both the numerical simulation analysis and scale model test are effective and reliable.

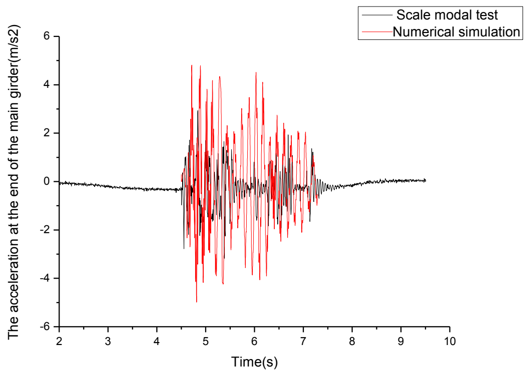
7. Conclusions

Based on the theory of structural dynamics, this paper presents various methods including numerical simulation and experimental test to explore the dynamic response of the 40m-span simply supported concrete T-bridge subjected to earthquake, blast load and the combination effect. A 3D trussing finite element model and a simplified scale modal are established to verify the applicability of the new explosion-proof and aseismic system and explore the real reaction of bridge structures. It was found that the scale model test could reproduce many of the dynamic response identified in previous numerical studies:

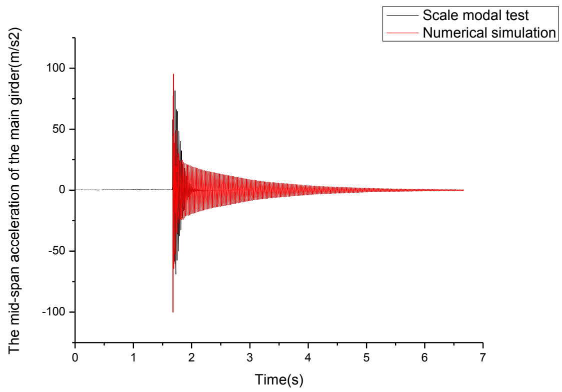
- The explosion-proof and aseismic system has good adaptability to seismic effects at different level. The reducing vibration isolation efficiency of cable support damping bearing is pretty high. Increasing cables does not affect the good shock-absorption performance of the original bearing.



(a) The mesa acceleration at the condition of ground motion



(b) Acceleration at the end of the main girder under earthquake



(c) Acceleration of the main girder at the mid-span under blast load

Fig. 13 Comparison of the acceleration between SMT and NSA under different conditions

- In addition, the new system is good at shock absorption and displacement limitation. It works well in reducing the vertical dynamic response of beam body such as lowering the acceleration and displacement response, and could dramatically limit the relative displacement between main girder and capping beam in different orientation including vertical, horizontal and longitudinal direction, and could solve the problem of beam falling effectively.
- The enhancement of steel fibers in concrete could

improve the blast resistance for main beam significantly. However, a quantitative increase could not be given at this stage and is one of the subjects of further studies by authors.

Some improvements need to be considered in the future research. It is advisable to explore the vulnerable reliable ability and demand curve for specific bridge elements and the whole system under the combination of earthquake and blast load by applying the knowledge of probability and statistics into use. And more accurate and quantitative blast load form such as high-speed airflow ejected from air cannon is expected in the future study in order to get high-fidelity experimental results.

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References

Burrell, R.P., Aoude, H. and Saatcioglu, M. (2015), "Response of SFRC columns under blast loads", *J. Struct. Eng.*, **141**(9), 04014209.

Fang, Q. and Wu, P. (2003), "The analysis of the main factors which affect the failure pattern of the RC beams subjected to blast loads", *J. Comput. Mech.*, **20**(1), 39-48.

Foglar, M. and Kovar, M. (2013), "Conclusions from experimental testing of blast resistance of FRC and RC bridge decks", *Int. J. Impact Eng.*, **59**, 18-28.

Hacıefendioğlu, K., Banerjee, S., Soyluk, K. and Köksal, O. (2015), "Multi-point response spectrum analysis of a historical bridge to blast ground motion", *Struct. Eng. Mech.*, **53**(5), 897-919.

Hao, H. and Tang, E.K.C. (2010), "Numerical simulation of a cable-stayed bridge response to blast loads, Part II:Damage prediction and FRP strengthening", *Eng. Struct.*, **32**(10), 3193-3205.

Schenker, A., Anteby, I., Gal, E., Kivity, Y., Nizri, E., Sadot, O. and *et al*. (2008), "Full-scale field tests of concrete slabs subjected to blast loads", *Int. J. Impact Eng.*, **35**(3), 184-198.

Son, J. and Astaneh-Asl, A. (2011), "Blast resistance of steel orthotropic bridge decks", *J. Bridge Eng.*, **17**(4), 589-598.

Yang, X. (2010), *The Numerical Simulation of Explosive Shock Phenomenon*, Press of University of Science and Technology, He Fei, China.

Yi, Z., Agrawal, A.K., Ettouney, M. and Alampalli, S. (2014), "Blast load effects on highway bridges. II: Failure modes and multihazard correlations", *J. Bridge Eng.*, **19**(4), 04013024.

Yi, Z., Agrawal, A.K., Ettouney, M. and Alampalli, S. (2014), "Blast load effects on highway bridges. I: Modeling and blast load effects", *J. Bridge Eng.*, **19**(4), 04013023.

Yuan, W., Wei, Z., Cao, X. and *et al*. (2011), "Cable damping bearing and the research on the application of seimic design of bridges", *Eng.Mech.*, **28**(S2), 204-209.

Zhang, F. (2013), *The World's First Explosion-proof Special Truck for the Transportation Safety of Fireworks*, Hunan Safety and Disaster Prevention.

Zhang, Y., Li, G., Chen, K. and *et al*. (2016), "Research advances of safety assessment of bridges under blast load", *Explos. Shock Wav.*, **36**(1), 135-144.

Zhou, X. Q., Kuznetsov, V. A., Hao, H. and Waschl, J. (2008), "Numerical prediction of concrete slab response to blast loads", *Int. J. Impact Eng.*, **35**(10), 1186-1200.

Zhou, Y. and Chen, S. (2015), "Dynamic simulation of a long-span bridge-traffic system subjected to combined service and extreme loads", *J. Struct. Eng.*, **141**(9), 04014215.

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