Seismic Behavior of Long-span Connected Structures under Multi-supported and Multi-dimensional Earthquake excitations

W. Lin, G. M. Zhang, A. Qi
School of Civil Engineering, Fuzhou university, Fuzhou, P. R. China

SUMMARY:
More and more connected structures with long-span corridors have been constructed during these years. As the span of corridor increases, it is necessary to consider their earthquake behaviour and insure aseismic safety. Seismic response of long-span connected structure under multi-dimensional and multi-support excitation is investigated. Algorithms for seismic analysis of long-span connected structure under multi-dimensional and multi-support excitations are firstly established. Then, numerical simulation of a newly constructed connected structure with a span of 110m is performed. The influences of different earthquake components are compared and also the coupling effect is investigated under multi-dimensional earthquake excitation. Further, the influence of travelling-wave effect is analysed by comparing the seismic responses of the structure under multi-supported excitation with different apparent velocities. The results show that seismic responses will be increased if multi-dimensional earthquake excitation is considered, and wave-passage effect will greatly amplify the seismic responses of vertical earthquake components.

Keywords: long-span connected structure, wave-passage effect, multi-dimensional earthquake excitation, multi-supported earthquake excitation

1. INTRODUCTION

The architectural design of modern high-rise building has become increasingly integrated, and multi-functional. Connected high-rise structures, which comprise of main towers and corridor in between, have received much attention for their great aesthetic value. Besides, newly constructed structure continues breaking the records of the span. Earthquake has always been a major hazard to human being, as these structures are generally important facilities, their aseismic capabilities are highly relevant to public safety (Lin et al. 2008). Unlike traditional high-rise building, this type of structures has features from both high-rise structures and long-span structures. From past experience, spatial variability of the ground motion may greatly affect the seismic behavior of long-span structure (Wang et al., 2009; Zhang et al., 2005).

Although the spans of connected structures are rather small compared to long-span bridges and even long-span spatial structure, earthquake spatial variability may still cause torsional responses of the structure (Hahn and Lin, 1994; Heredia-Zavoni and Leyva, 2003; Newmark, 1969), which will result in safety problem of corridor.

In this paper, algorithms for seismic analysis of long-span connected structure under multi-dimensional and multi-support excitation are first established, and then seismic behavior of long-span connected structure is studied under both uniform and travelling wave excitation.

2. GOVERNING EQUATIONS OF MOTION

Consider a long-span connected structure discretized by the finite-element method. The total degrees of freedom (DOFs) of the internal nodes and supports are divided into unconstrained DOFs (UDOFs) and support DOFs (SDOFs). The stiffness matrix, mass matrix and damping matrix, denoted by ***K***, ***M*** and ***C***, respectively, are divided into the components corresponding to UDOFs and SDOFs as indicated by the subscripts s and b, The equation of motion can then be written as (Ohsaki 2001)

$$\begin{bmatrix} \boldsymbol{M}_{\mathrm{ss}} & \boldsymbol{M}_{\mathrm{sb}} \\ \boldsymbol{M}_{\mathrm{bs}} & \boldsymbol{M}_{\mathrm{bb}} \end{bmatrix} \begin{Bmatrix} \ddot{\boldsymbol{X}}_{\mathrm{s}} \\ \ddot{\boldsymbol{X}}_{\mathrm{b}} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{C}_{\mathrm{ss}} & \boldsymbol{C}_{\mathrm{sb}} \\ \boldsymbol{C}_{\mathrm{bs}} & \boldsymbol{C}_{\mathrm{bb}} \end{bmatrix} \begin{Bmatrix} \dot{\boldsymbol{X}}_{\mathrm{s}} \\ \dot{\boldsymbol{X}}_{\mathrm{b}} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{K}_{\mathrm{ss}} & \boldsymbol{K}_{\mathrm{sb}} \\ \boldsymbol{K}_{\mathrm{bs}} & \boldsymbol{K}_{\mathrm{bb}} \end{bmatrix} \begin{Bmatrix} \boldsymbol{X}_{\mathrm{s}} \\ \boldsymbol{X}_{\mathrm{b}} \end{Bmatrix} = \begin{Bmatrix} 0 \\ \boldsymbol{F}_{\mathrm{b}} \end{Bmatrix} \tag{2.1}$$

where $\boldsymbol{X}$ 、 $\dot{\boldsymbol{X}}$ and $\ddot{\boldsymbol{X}}$ are the displacement, velocity and acceleration vectors, $\mathbf{F_b}$ is the seismic excitation vector. Expanding the first line of Eqn. 2.1, the following equation can be obtained

$$\boldsymbol{M}_{\mathrm{ss}}\ddot{\boldsymbol{X}}_{\mathrm{s}} + \boldsymbol{M}_{\mathrm{sb}}\ddot{\boldsymbol{X}}_{\mathrm{b}} + \boldsymbol{C}_{\mathrm{ss}}\dot{\boldsymbol{X}}_{\mathrm{s}} + \boldsymbol{C}_{\mathrm{sb}}\dot{\boldsymbol{X}}_{\mathrm{b}} + \boldsymbol{K}_{\mathrm{ss}}\boldsymbol{X}_{\mathrm{s}} + \boldsymbol{K}_{\mathrm{sb}}\boldsymbol{X}_{\mathrm{b}} = 0 \tag{2.2}$$

In order to solve Eqn. 2.1, $\boldsymbol{X}$ is decomposed into two parts

$$\begin{Bmatrix} \boldsymbol{X}_{\mathrm{s}} \\ \boldsymbol{X}_{\mathrm{b}} \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{Y}_{\mathrm{s}} \\ \boldsymbol{X}_{\mathrm{b}} \end{Bmatrix} + \begin{Bmatrix} \boldsymbol{Y}_{\mathrm{d}} \\ 0 \end{Bmatrix} \tag{2.3}$$

Where $\boldsymbol{Y}_{\mathrm{s}}$ and $\boldsymbol{Y}_{\mathrm{d}}$ are pseudo-static displacement and relative dynamic displacement, respectively. The pseudo-static displacement $\boldsymbol{Y}_{\mathrm{s}}$ can be solved by neglecting all the dynamic terms in Eqn. 2.2

$$\boldsymbol{Y}_{\mathrm{s}} = -\boldsymbol{K}_{\mathrm{ss}}{}^{-1}\boldsymbol{K}_{\mathrm{sb}}\boldsymbol{X}_{\mathrm{b}} = \boldsymbol{\alpha}\boldsymbol{X}_{\mathrm{b}} \tag{2.4}$$

Where $\boldsymbol{\alpha} = -\boldsymbol{K}_{\mathrm{ss}}{}^{-1}\boldsymbol{K}_{\mathrm{sb}}$ is the pseudo-static displacement matrix, it denotes the pseudo-static displacement of the structure induced by unit displacement of the support nodes. Substitute Eqn. 2.4 into Eqn. 2.2

$$\boldsymbol{M}_{\mathrm{ss}}\ddot{\boldsymbol{Y}}_{\mathrm{d}} + \boldsymbol{C}_{\mathrm{ss}}\dot{\boldsymbol{Y}}_{\mathrm{d}} + \boldsymbol{K}_{\mathrm{ss}}\boldsymbol{Y}_{\mathrm{d}} = -\boldsymbol{M}_{\mathrm{ss}}\ddot{\boldsymbol{Y}}_{\mathrm{s}} - \boldsymbol{C}_{\mathrm{ss}}\dot{\boldsymbol{Y}}_{\mathrm{s}} - \boldsymbol{M}_{\mathrm{sb}}\ddot{\boldsymbol{X}}_{\mathrm{b}} - \boldsymbol{C}_{\mathrm{sb}}\dot{\boldsymbol{X}}_{\mathrm{b}} \tag{2.5}$$

Assuming that the damping force is only related to the relative velocity, and thus in Eqn. 2.1, $\begin{Bmatrix} \dot{\boldsymbol{X}}_{\mathrm{s}} \\ \dot{\boldsymbol{X}}_{\mathrm{b}} \end{Bmatrix}$ can be replaced by $\begin{Bmatrix} \dot{\boldsymbol{Y}}_{\mathrm{d}} \\ 0 \end{Bmatrix}$, which yields

$$\boldsymbol{M}_{\mathrm{ss}}\ddot{\boldsymbol{Y}}_{\mathrm{d}} + \boldsymbol{C}_{\mathrm{ss}}\dot{\boldsymbol{Y}}_{\mathrm{d}} + \boldsymbol{K}_{\mathrm{ss}}\boldsymbol{Y}_{\mathrm{d}} = -\boldsymbol{M}_{\mathrm{ss}}\ddot{\boldsymbol{Y}}_{\mathrm{s}} - \boldsymbol{M}_{\mathrm{sb}}\ddot{\boldsymbol{X}}_{\mathrm{b}} \tag{2.6}$$

Substituting Eqn. 2.4 into Eqn. 2.6

$$\boldsymbol{M}_{\mathrm{ss}}\ddot{\boldsymbol{Y}}_{\mathrm{d}} + \boldsymbol{C}_{\mathrm{ss}}\dot{\boldsymbol{Y}}_{\mathrm{d}} + \boldsymbol{K}_{\mathrm{ss}}\boldsymbol{Y}_{\mathrm{d}} = -(\boldsymbol{M}_{\mathrm{ss}}\alpha + \boldsymbol{M}_{\mathrm{sb}})\ddot{\boldsymbol{X}}_{\mathrm{b}} \tag{2.7}$$

In which $\boldsymbol{M}_{\mathrm{sb}}$ is zero matrix when lumped mass matrix is applied, then

$$\boldsymbol{M}_{\mathrm{ss}}\ddot{\boldsymbol{Y}}_{\mathrm{d}} + \boldsymbol{C}_{\mathrm{ss}}\dot{\boldsymbol{Y}}_{\mathrm{d}} + \boldsymbol{K}_{\mathrm{ss}}\boldsymbol{Y}_{\mathrm{d}} = -\boldsymbol{M}_{\mathrm{ss}}\alpha\ddot{\boldsymbol{X}}_{\mathrm{b}} \tag{2.8}$$

where $\ddot{\boldsymbol{X}}_{\mathrm{b}}$ can be obtained from the acceleration time-history of each support, relative dynamic displacement $\boldsymbol{Y}_{\mathrm{d}}$ can then be solved from Eqn. 2.8.

3. NUMERICAL SIMULATIONS

3.1 Finite Element Model

A newly constructed long-span connected structure is selected. This symmetric building is composed of two main towers and a corridor in between. The main towers are concrete frame-shear wall structure, and the corridor is a steel structure which is connected between 39.85m and 55.85m height with a span of 105.00m. As shown in Fig. 1, a finite element model was first built using ANSYS software. Tianjin earthquake record (1976, NS) was used to excite the structure. In this numerical example, when considering non-uniform earthquake excitation, it is assumed that the seismic wave propagates along the long-axis of the structure.

Modal analysis was carried out using the ANSYS. The first 10 natural frequencies are listed in Table 3.1, and Fig. 2 shows the first 6 mode shapes. It is observed from Fig. 2 that unlike normal high-rise structure, the long-span connected structure is characterized by its antisymmetric mode shapes of the main towers which will easily result in torsional response of the corridor. Thus, this numerical study will focus on the seismic responses of elements around the connection area.

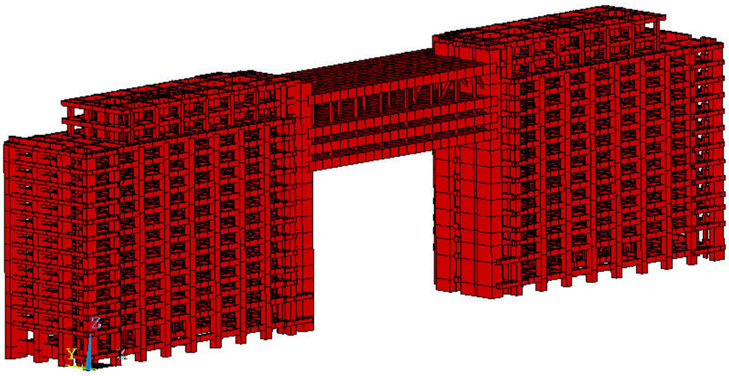


Figure 1 Finite element model

Table 3.1 The first 10 natural frequencies

Mode	1	2	3	4	5
Frequency (Hz)	0.790	0.831	1.015	1.158	1.306
Mode	6	7	8	9	10
Frequency (Hz)	1.631	1.668	2.135	2.236	2.756

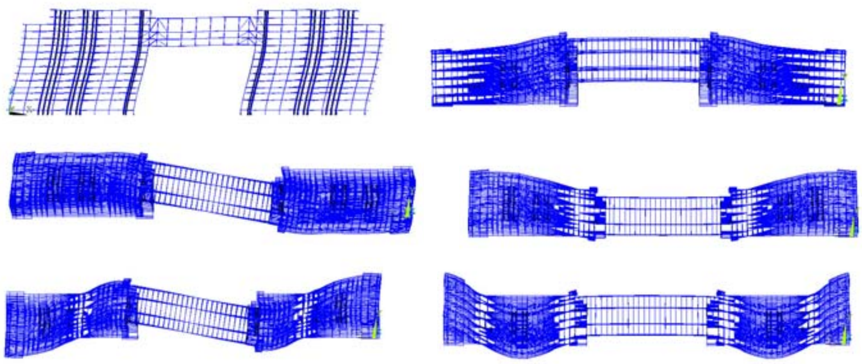
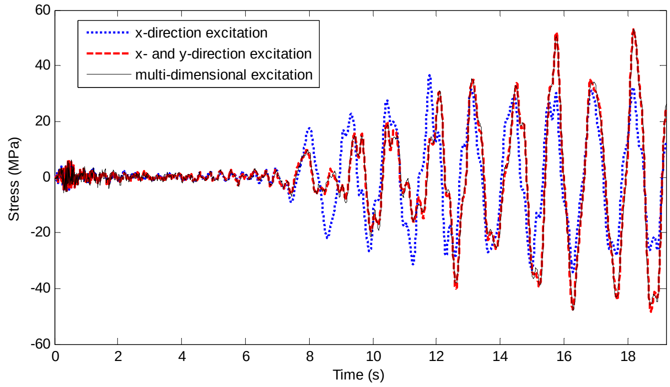


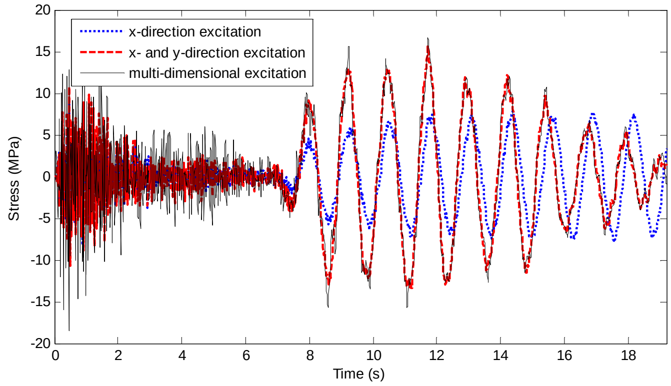
Figure 2 The first 6 mode shapes

3.2 Multi-dimensional Excitations

Seismic behavior of the model under single- and multi-dimensional uniform earthquake excitation is examined. In single-dimensional excitation case, the peak acceleration is set to 0.15g. While in multi-dimensional cases, the proportion of the peak acceleration of the three dimensions is 1:0.85:0.65. Fig. 3 shows the time-history stress of horizontal bar 50001 and tilted bracing 60048 under single- and multi-dimensional earthquake excitations. One can see that from these results, the peak stress responses are increased by 43.7% and 69.5% respectively when subjected two horizontal earthquake excitations. The seismic responses change little when vertical component is also considered.



(a) Horizontal bar No. 50001

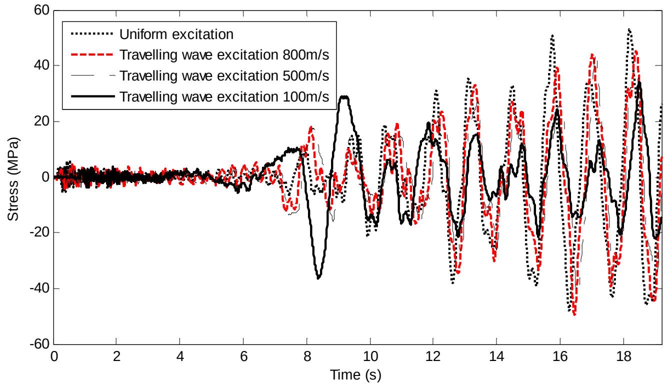


(b) Bracing No. 60048

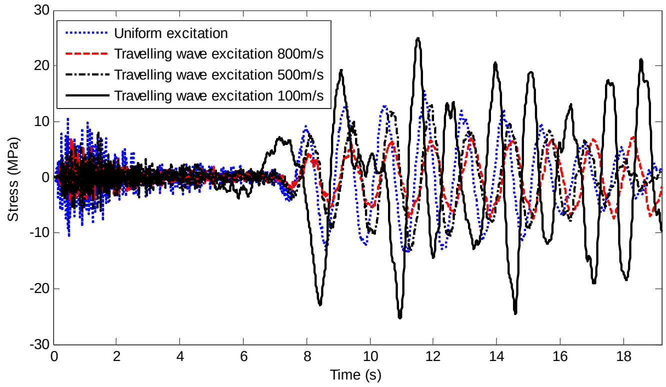
Figure 3 Time-history of stress responses under single- and multi-dimensional excitation

3.3 Multi-dimensional and Multi-supported Excitations

The seismic behaviors of the structure under multi-dimensional and multi-supported earthquake excitations are further studied. Three typical apparent velocities, 100m/s, 500m/s, 800m/s are considered. Fig. 4 shows the comparison of time-history stress responses subjected to uniform and travelling wave excitations with different apparent velocities, and the peak responses are further compared in Table 3.2. It is conclude that the peak responses might be increased or decreased when different apparent velocity is applied. For example, the peak stress of the horizontal bar 50001 is decreased by 31.3% under 100m/s travelling-wave excitation, while the peak stress of bracing 60048 is increased by 37.4%.



(a) Horizontal bar No. 50001



(b) Bracing No. 60048

Figure 4 Time-history of stress responses under different travelling wave excitations

Table 3.2 Peak stress responses under different earthquake excitations (Unit： MPa)

	Cases	Uniform excitation （∞）	Travelling-wave excitation (800m/s)	Travelling-wave excitation (500m/s)	travelling-wave excitation (100m/s)
Horizontal bar No. 50001	*x*-direction excitation	12.1283	11.5569	9.9232	10.1421
	x- and *y*-directions excitation	17.6514	13.2651	14.6781	10.2178
	Three dimensional excitation	17.6618	16.5394	15.0370	12.1204
Bracing No. 60048	*x*-direction excitation	3.0643	2.4761	2.0757	3.1640
	x- and *y*-directions excitation	5.1931	4.8930	4.9908	3.9359
	Three dimensional excitation	6.1464	5.6714	4.4080	8.4459

The position and peak stress responses of the dominant element in different cases are list in Table 3.3. The results show that both the dominant element and the peak value are changing with apparent velocities, and dominant internal force of the corridor structure may be increased by 14.69% when subjected to travelling-wave excitations.

Table 3.3 Dominant element and peak stress responses

Cases	Distance from the nearest connection（m）	Peak value（Mpa）	Increase (%)
Uniform （∞）	12.30	28.9315	-
Travelling-wave excitation (800m/s)	12.30	29.4620	1.83
Travelling-wave excitation (500m/s)	5.40	26.2510	-9.26
Travelling-wave excitation (100m/s)	2.70	33.1828	14.69

5 CONCLUSIONS

Seismic response of long-span connected structure under multi-dimensional and multi-supported earthquake excitation is investigated. The comparative performance is studied through a numerical example, and the influence of wave-passage effect is investigated when different apparent velocities are applied. The following conclusion can be drawn from the numerical results.

(i) Under uniform excitation, will increase the seismic responses will be increased greatly when taking into account the multi-dimensional earthquake components;
(ii) Wave-passage effect will amplify the influence of vertical component; the internal force can either be increased or decreased when different apparent velocities are considered. Different element will be suffered from wave-passage effect differently, the impact of wave-passage effect on the seismic response of bracings around the connection between main towers and corridor is particular significant.
(iii) The dominant internal force of the corridor structure may be increased by 14.69% under travelling wave excitation. Therefore, it is necessary for aseismic design of long-span connected structure to take into account multi-dimensional and multi-support earthquake excitations.

AKCNOWLEDGEMENT
The authors are grateful for financial support by National Natural Science Foundation of China (No. 51108089) and National Natural Science Foundation of Fujian Province (No. 2011J05128).

REFERENCES

Hahn G. D., Liu X. (1994). Torsional response of unsymmetrical buildings to incoherent ground motions. *Journal of Structural Engineering* 120: 4, 1158 - 1181.

Heredia-Zavoni E and Leyva A. (2003). Torsional response of symmetric buildings to incoherent and phase delayed earthquake ground motion. *Earthquake Engineering and Structural Dynamics* 32: 1021- 1038.

Li B., Chan K., Chouw N. and Butterworth J. W. (2010). Seismic response of two-span scale bridge model due to non-uniform ground excitation and varying subsoil conditions. *Proceedings of 2010 NZSEE Conference*.

LIN W.，LI Z. X, DING Y. (2008). Trust-region based Instantaneous Optimal Semi-active Control on Long-span Spatial Structure with MRF-04K Damper. *Journal of Earthquake Engineering and Engineering Vibration*. 7 : 4, 447-464.

Newmark N. M. (1969). Torsion in symmetrical buildings. *Proceedings 4th World Conference Earthquake Engineering*. Santiago, Chile: 19-32.

Ohsaki M. (2001). Sensitivity of Optimum Designs for Spatially Varying Ground Motions. *Journal of Structural Engineering* 127 : 11, 1324-1329.

Wang J., Cooke N., Moss P. J. (2009). The response of a 344 m long bridge to non-uniform earthquake ground motions. *Engineering Structures* 31: 11, 2554-2567.

Zhang Y. H., Lin J.H., Williams F.W., Li Q.S. (2005). Wave passage effect of seismic ground motions on the response of multiply supported structures. *Structural Engineering and Mechanics* 20: 6, 655-672.