Shaking Table Test of Long-span Connected Structure under Multi-supported Excitation

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SUMMARY: (10 pt)
The shaking table test of a long-span connected structure is conducted on a triple earthquake simulation shake table system which is just set up in Fuzhou University. This experiment is performed to examine the seismic behaviour of connected structure under multi-dimensional earthquake excitation while considering wave passage effect. it is found that wave-passage effect has diverse influence on different elements, and special attentions should be paid to those elements near connections between the main tower and the corridor which inertial forces may change a lot when subjected to travelling wave excitation with different apparent velocities. Moreover, the vertical acceleration responses of the corridor can be increased significantly by wave passage effect.

Keywords: long-span connected structure, wave-passage effect, multi-dimensional earthquake, shake table experiement

1. INTRODUCTION

The development of urban structure has led to more and more construction of irregular building, most of which do not follow the traditional structural design concepts completely. Connected high-rise structure, which is characterized by its corridor connected to main towers, has an obvious stiffness irregularity in the connection area (Zhou et al., 2009). As the span of the corridor becomes larger, attentions should be paid to the safety of this kind of structures under strong earthquakes.

It is well known that when perform seismic analysis on a long-span structure, it is necessary to account for the wave passage effect, which is proved to have significant influences on its seismic behaviour (Wang et al., 2009, Zhang et al., 2005, Ohsaki, 2001). Although compared to long-span bridges and distributed structures like stadium, the span of the corridor in connected structure is rather small, but some evidence has shown that for certain kind of structure, non-uniform earthquake excitation can cause unexpected torsional responses (Heredia-Zavoni et al., 2003). In 1969, Newmark found that wave passage effect will generate torsional responses in regular building structure. Hahn and Liu (1994) also investigated the torsional effect caused by non-uniform excitation, coupling with the unexpected eccentric problem. For long-span connected structure, it is believed that the unsymmetrical vibration in main towers may excite torsional vibration of the corridor, which may easily cause collapse.

A triple shaking table test system is just set up in Fuzhou University, Fuzhou, China. An experiment was performed on a 1:35 model of Eastcity building using this test system. During this experiment, the influence of multi-component earthquake excitation and wave passage effect on the seismic behavior of the connected structure is analyzed.

2. DESCRIPTION OF THE CONNECTED STRUCTURE

The Eastern City is a shopping center located at Fuzhou city. The CD block of the building is designed as a two-tower building (C# and D# blocks) connected by a long-span corridor at its top. The symmetric two towers are Frame-shear wall structures, which contain 15 floors with the height of 60.2m. The corridor is a steel structure which connected rigidly from height 40.7m to 56.7m; it has a span of 63.3m. The finite element model of the prototype structure is shown in Fig. 1. The scaled model used in this experiment is shown in Fig. 2.

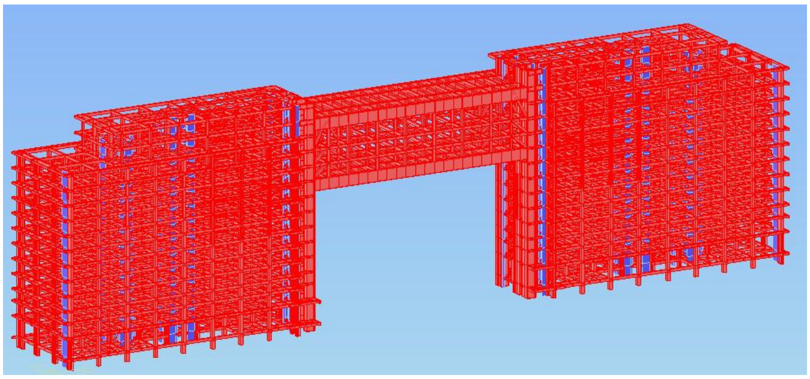

Figure 1 Finite element model

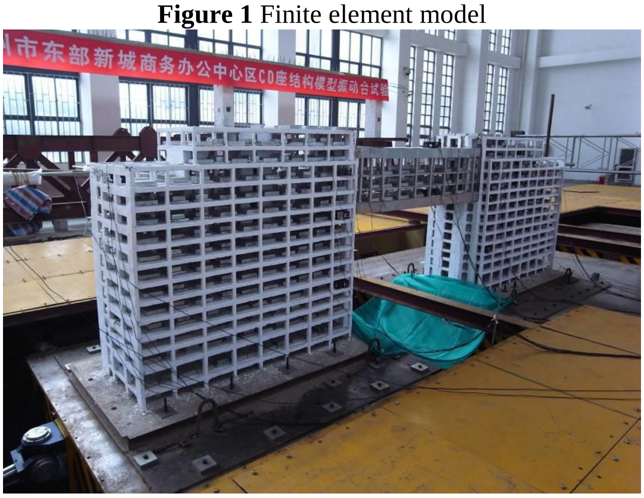

Figure 2 1:35 Scaled model

Because there are obvious stiffness irregularities between the main towers and the corridor, special attention should be paid to the connections. Besides, the corridor is located at over 40m height above, which may potentially induce severe vibration during earthquake excitations. Moreover, unsymmetrical vibration induced by unsynchronized earthquake, which may easily cause torsional vibration of the corridor. Therefore, the aseismic safety of this long-span connected high-rise building should be studied especially when non-uniform earthquake input is considered.

3. EXPERIMENTAL SETUP

3.1 Model design

The dynamic behavior of a structure can be fully identified by means of three basic quantities, i.e., mass, stiffness and restoring force. In this experiment, considering the carrying ability and the size of the shaking table, the scaling factor S_l is chosen to be 1/35. The scaling model is built with a height of 1.72m and the corridor has a span of 1.81m. Second, Microconcrete is used to simulate the concrete of the prototype structure, wire is embedded to simulate the rebar, and aluminum alloy plate is used to simulate the steel corridor. Because the scaling factor of elastic modulus S_E should be determined by two kinds of materials, after examining the material test results, the overall S_E is chosen to be 1/4. Third, since there is a limit effective frequency band of the triple shaking table system, the scaling factor of time S_t is selected to be 1/7. All of other scaling factor can be derived, and some of which are listed in Table 3.1.

Table 3.1 Typical scaling factor

Parameter		Relationship	Scaling factor
Length	S_l	—	1/35
Elastic modulus	S_E	—	1/4
Acceleration	S_a	—	1.4
Mass	S_m	$S_m = S_E S_l^2 / S_a$	1/6860
Time	S_t	$S_t = \sqrt{\frac{S_l}{S_a}}$	1/7
Frequency	S_f	$S_f = 1/S_t$	7
Force	S_F	$S_F = S_E S_l^2$	1/4900

3.2 Instruments and Transducers

A total number of 34 accelerometers were installed at the test model as shown in Fig. 4. In the main towers, the 4th, 9th and 13th floor are selected, and each section of each tower has four uni-axial accelerometers, two for measurement of horizontal vibration along the long-axis (*x*-direction) and two for short-axis (*y*-direction), that is 24 accelerometers on the main towers. The mid-span on the bottom and the upper floors of the corridor are installed with three uni-axial accelerometers, two for measurement of horizontal vibration and the other for vertical vibration. In order to measure the real acceleration input, there are also four uni-axial accelerometers stick to the shaking table. Four displacement meters were equipped on top of the two towers to measure the displacement responses under different excitation cases. Since the behavior of the connections between the corridor and the main towers is one of the most important purposes of this experiment, eight strain gauges were installed on the main beam of the corridor.

3.3 Test program

According to the ground condition of the prototype structure, El Centro and Taft earthquake record were used in this study. The peak ground acceleration is specified from 0.05g to 0.3g. both the uni- and multi-dimensional earthquake excitations were considered. In order to study the influence of non-uniform earthquake excitation, three different apparent velocities (600m/s, 300m/s and 100m/s) were considered. When considering wave passage effect, the wave propagation direction is assumed to be along the *x*-direction. Besides, in order to examine possible damage, white noise signal with peak value 0.05g was used to scan the model after every case.

4 EXPERIMENTAL RESULTS

4.1 Multi-dimensional earthquake excitation results

One of the main purposes of this experiment is to study the influence of multi-dimensional earthquake components, thus earthquake record is generated in *x*-direction, *y*-direction and multi-dimensional with peak value from 0.05g to 0.2g. The ratio of the earthquake amplitudes in the *x*- and *y*- dimensions is taken as 1:0.85. The peak acceleration responses on some typical measurement points on top of the building were compared in Table 4.1. From the table one can see that the *x*- direction's peak acceleration responses on top of both towers can be enlarged by 16% when multi-dimensional earthquake components are considered simultaneously, compared to *x*-direction earthquake excitation cases. When it comes to the corridor substructure, the lateral acceleration responses can be either increased or decreased under multi-dimensional earthquake excitations. While it should be noticed that the vertical acceleration responses on top of the corridor are significantly increased in multi-dimensional earthquake cases, where the peak vertical acceleration responses can reach 1.5 times compared to uni-dimensional excitation.

Table 4.1 Peak responses under uni- and multi-dimensional earthquake excitations

Cases	C# *x*-	C# *y*-	D# *x*-	D# *y*-	Corridor *x*-	Corridor *y*-	Corridor *z*-
El Centro (*x*- 0.05g)	1.262	0.189	1.264	0.168	1.378	0.378	0.342
El Centro (*y*- 0.05g)	0.263	0.848	0.258	0.850	0.473	1.780	0.569
El Centro (multi 0.05g)	1.464	0.709	1.262	0.748	1.441	1.566	0.633
Taft (*x*- 0.05g)	1.318	0.269	1.184	0.331	1.461	0.508	0.398
Taft (*y*- 0.05g)	0.276	1.327	0.286	1.292	0.548	2.060	0.894
Taft (multi 0.05g)	1.330	1.203	1.209	1.130	1.290	1.906	0.959
El Centro (*x*- 0.1g)	2.447	0.416	2.278	0.372	2.847	0.746	0.519
El Centro (*y*- 0.1g)	0.405	2.016	0.425	1.769	0.835	3.844	1.127
El Centro (multi 0.1g)	2.509	1.535	2.181	1.490	2.635	3.538	1.326
Taft (*x*- 0.1g)	2.108	0.460	1.955	0.528	2.296	0.864	0.719
Taft (*y*- 0.1g)	0.521	2.255	0.513	2.374	1.108	4.277	1.697
Taft (multi 0.1g)	2.240	2.154	2.103	2.315	2.230	3.862	1.756
El Centro (*x*- 0.2g)	6.253	1.105	5.345	1.059	6.331	1.519	2.128
El Centro (*y*- 0.2g)	2.128	6.212	2.368	4.850	4.913	16.672	7.792
El Centro (multi 0.2g)	4.468	3.791	4.948	3.679	5.158	6.729	2.845
El Centro (*x*- 0.3g)	6.075	0.895	7.134	1.233	8.708	1.574	1.881
El Centro (*y*- 0.3g)	1.650	5.083	1.228	5.955	3.641	11.736	3.654
El Centro (multi 0.3g)	6.463	5.086	7.465	5.466	7.433	11.155	4.313

4.2 Traveling-wave earthquake excitation results

It is believed that when spatial effect is taken into account, which means the supports will move unsynchronized during earthquake, unfavorable responses may be excited especially for such symmetrical building. In this experiment, El Centro earthquake record was used to excite the structure with apparent velocities of 100m/s, 300m/s and 600m/s, respectively. The earthquake wave propagates along *x* direction. Then the acceleration and displacement response of the main towers and the corridor, as well as the stress responses of the main beams around connections between the corridor and the main towers were studied. Fig. 3 compares the acceleration responses on top of the main towers under different travelling-wave excitations. The figure clearly shows that the responses can be rather different when wave passage effect is considered. It can be seen that the acceleration responses can either be increased or decreased with different apparent velocities, and there is no evidence that the wave-passage effect will definitely enlarge the acceleration responses of this model. However, there is a trend from these results that the influence of wave passage effect increases as the apparent velocity decreases.

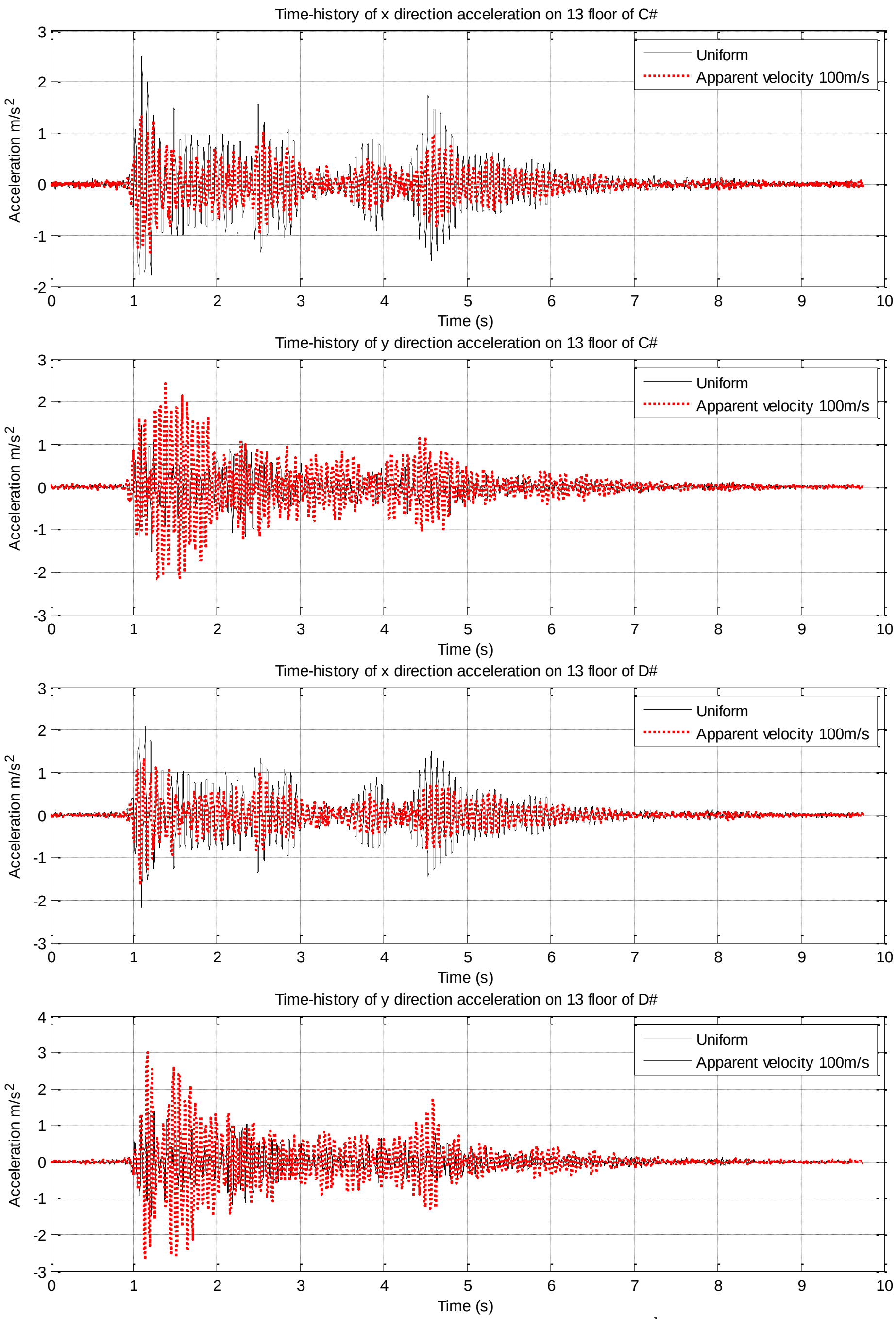

Figure 3 Time-history of acceleration responses on 13th floor of two towers

In order to further investigate the influence of wave passage effect on this structure, the peak acceleration responses of the two main towers and the corridor are compared in Table 4.2.One can see that from these comparison, the peak accelerations along *x*-direction on top of Block C, at which the earthquake wave is assumed to be arrived first, are mostly dropped compared to uniform excitations. However, the peak *y*-direction's accelerations on top of Block D are mostly enlarged by wave-passage effect; the increment can reach 40%~50%. As it comes to the corridor under travelling-wave excitation cases, the peak lateral acceleration is reduced slightly. But special attention should be paid that the vertical acceleration responses of the corridor are significant increased; the increment can reach to 70% when apparent velocity is 100m/s.

Table 4.3 further compared the peak value of stress and displacement responses under different cases. It is shown in the table that the displacement responses has similar rule as the acceleration responses. Most of the peak *x*-direction's displacement responses are decreased, up to 21%, but most of the peak *y*-direction's responses are increased and the maximum increment can be 58%. Conclusions can also be drawn from the table that the wave passage effect has considerable influence on the stress responses of the main beams around the connections. It may result in 40% increment in main beams' stress responses.

Table 4.2 Peak acceleration responses under uniform and traveling-wave excitations (El Centro earthquake record) (unit: m/s^2)

Cases	C# *x*-	C# *y*-	D# *x*-	D# *y*-	Corridor *x*-	Corridor *y*-	Corridor *z*-
x- 0.2g (uniform)	6.253	1.105	5.345	1.059	6.331	1.519	2.128
x- 0.2g (600m/s)	5.095	1.312	4.171	1.264	4.259	1.009	2.137
x- 0.2g (300m/s)	2.469	0.743	2.307	0.603	2.569	0.629	1.912
x- 0.2g (100m/s)	4.194	1.142	3.774	1.068	4.623	1.056	2.366
x- and *y*- 0.2g (uniform)	4.468	3.791	4.948	3.679	5.158	6.729	2.845
x- and *y*- 0.2g (600m/s)	4.774	4.538	3.967	3.573	4.366	5.426	3.395
x- and *y*- 0.2g (300m/s)	2.525	4.385	2.380	5.088	2.602	2.523	2.792
x- and *y*- 0.2g (100m/s)	4.278	4.163	3.592	6.402	5.181	5.442	4.521
x- 0.3g (uniform)	6.075	0.895	7.134	1.233	8.708	1.574	1.881
x- 0.3g (300m/s)	3.600	1.728	4.746	1.612	5.992	1.207	2.664
x- 0.3g (100m/s)	6.154	2.268	6.583	2.202	6.518	1.540	3.211
x- and *y*- 0.3g (uniform)	6.463	5.086	7.465	5.466	7.433	11.155	4.313
x- and *y*- 0.3g (300m/s)	3.988	7.196	4.313	8.252	6.643	5.999	5.905
x- and *y*- 0.3g (100m/s)	5.774	6.297	5.310	7.128	7.462	8.926	5.853

Table 4.3 Peak stress and displacement responses under uniform and traveling-wave excitations (El Centro earthquake record)

Cases	Stress				Displacement （mm）			
	Beam 1#	Beam 2#	Beam 3#	Beam 4#	C# *x*-	C# *y*-	D# *x*-	D# *y*-
x- 0.2g (uniform)	4448.2	984.9	1733.3	785.5	3.069	0.558	2.169	0.414
x- 0.2g (600m/s)	4481.8	728.6	1922.5	709.2	2.967	0.802	2.256	0.444
x- 0.2g (300m/s)	4741.2	878.1	2069.0	742.8	2.397	0.650	1.799	0.431
x- 0.2g (100m/s)	3853.1	1103.9	2261.2	852.7	2.397	0.721	2.084	0.526
x- and *y*- 0.2g (uniform)	3187.8	1119.2	2154.4	846.6	2.886	1.009	2.501	1.601
x- and *y*- 0.2g (600m/s)	2858.3	1183.3	2358.9	846.6	3.333	1.456	2.145	2.109
x- and *y*- 0.2g (300m/s)	3956.9	1213.8	2291.8	913.7	2.418	1.446	1.951	2.292
x- and *y*- 0.2g (100m/s)	3572.4	954.4	2514.5	864.9	2.296	1.402	2.175	2.760
x- 0.3g (uniform)	3011.0	666.9	825.7	413.1	6.004	0.892	5.145	22.258
x- 0.3g (300m/s)	2391.5	355.6	755.5	284.9	5.108	0.923	4.250	22.441
x- 0.3g (100m/s)	1201.3	511.2	1008.8	519.9	5.861	0.648	4.423	22.349

x- and *y*- 0.3g (uniform)	1231.9	560.1	972.2	422.3	5.800	2.357	5.125	23.692
x- and *y*- 0.3g (300m/s)	1726.2	349.5	1240.7	428.4	5.332	3.730	4.372	26.133
x- and *y*- 0.3g (100m/s)	1289.8	505.1	1472.7	556.5	5.739	3.161	4.281	25.940

5 CONCLUSIONS

The seismic responses of a long-span connected structure are investigated through a shaking table experiment. The influence of multi-dimensional components and wave passage effect are studied. Conclusions can be drawn from the experimental results that: (i) when multi-dimensional earthquake is considered, the lateral acceleration responses of the main towers are increased, and the vertical acceleration responses can be amplified significantly. Hence, it is suggested that the aseismic design of this kind of connected structure should take multi-dimensional earthquake components into consideration. (ii) The influence of wave passage effect can either be beneficial or unfavorable for different element. And its influence increases as the apparent velocity drops. (iii) Wave passage effect tend to reduce the *x*-direction's acceleration and displacement responses of one of the main tower while enlarge the *y*-direction's acceleration and displacement responses, the responses can be increased by 40% to 50%. Moreover, the strain of the main beams around the connections between the corridor and main towers will also be increased if wave passage effect is taken into account. Thus it cannot be ignored during aseismic design. (iv) The wave passage effect has little influence on the lateral responses of the corridor. However, its vertical acceleration responses can be increased significantly. Since the limitation of the shaking table, the vertical earthquake component cannot be excited; numerical analysis should be performed to see whether the vertical earthquake component would play an important role in its seismic behavior.

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