DISSCUSSION ON SEISMIC PERFORMANCE INDEXES OF ARCHITECTURAL CURTAIN WALLS

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ABSTRACT:

Based on the test results of structural models of high-rise buildings and architectural curtain wall specimens on shaking table test methodology, the evaluation indexes for seismic performance of architectural curtain walls were put forward, i.e. indexes of acceleration magnification coefficients and inter story drift angles. Furthermore, the indexes distribution characteristics along the height of high-rise building were analyzed, the appraising methodology for seismic performance of architectural curtain walls were also investigated. Finally, the application of the method in the curtain wall design and the experimental study were discussed. Shaking table tests of curtain walls were executed with improved experimental methodology, the seismic performance of the specimens were estimated with the new indexes and proved its efficiency.

KEYWORDS: architectural curtain wall, seismic performance, inter story drift angle, acceleration magnification coefficient

1. INTRODUCTION

Architectural curtain walls, e.g. glass curtain walls and stone curtain walls as primary envelope members for high-rise buildings, have been widely used in China for about three decades. At present, however, the safety performance especially the seismic performance of curtain walls are not properly assessed due to the limitation of safety knowledge, various design and installation measures, lifelong maintenance and the earthquake disaster by the characteristics of chanciness, paroxysmalness and severity. Fortunately, there were few serious earthquake damages to curtain walls in mainland of China, and their seismic performances were not adequately studied and qualified. It is necessary to study the seismic mechanism and the proper evaluation indexes on the seismic performance of curtain walls, which might be helpful to seismic test researches, design and construction of the curtain wall structures.

Earthquake simulation shake table test could realize the earthquake wave reoccurrence and investigate the seismic performance of the curtain wall specimen and the main structure which the curtain wall anchored on. The seismic performance requirements such as the acceleration magnification coefficient index (β) and the inter story drift angle index (θ) of the nonstructural members especially the curtain wall could be got by analyzing the inter story deformation and the acceleration variation of the main structure. In this paper, the seismic performance evaluation indexes (β and θ) were discussed on the base of the model structure shake table tests, curtain wall shake table tests and their research results.

2. THE DEFICIENCY OF THE CURRENT EVALUATION INDEXES

The β and θ has been used to evaluate the seismic performance of the architectural curtain walls in current codes [1]-[5]. This paper tries to investigate more ideal indexes, considering the site conditions, seismic intensities, structural styles and heights of high-rise buildings.

2.1. Acceleration Index (β)

The β is the ratio of floor peak acceleration value at a level to PGA, which is utilized in seismic design to estimate the earthquake action of the curtain wall system. For example, β =3.0 in *Technical Code for Glass Curtain Wall Engineering (JGJ 102-96)*, but it was supposed to be relatively smaller and not safe enough after about 5 years practice. In current curtain wall design codes[3]-[5], β is increased to 5.0. However, the common value of β has two disadvantages:

1) The exemplification effect is various along the height of the main structure, commonly, it increase along the height. Smaller β might be of insufficient to the earthquake actions on the top or other special location of main structure. According to the research results of high-rise structure models on shake table, many structure models are exceeding $\beta = 5.0$, some are even achieving about 10.0. It might be unsafe to adopt the common value $\beta = 5.0$.

2) Frequency, time histories and peak values are the characteristics of the earthquake waves. The β could only exhibit the effect of the peak acceleration value to the curtain wall structure. The factors such as the frequency distribution and the times the peak value achieve are not considered yet.

2.2. Inter Story Drift Angle Index (θ)

There are direct relationships between the seismic performance of the curtain wall and its deformation capacity. Curtain structure was installed on the main structure; it has to bear the deformation action which the main structure acts on it. It means that the curtain wall should have enough deformation capacity to accommodate the deformation between itself and the main structure. The deformation performance was frequently described by the inter story drift angle (θ). In current codes [3]-[5], a determinate θ of the curtain wall was set and it should not exceed the three times of the determinate plastic θ of the main structure according to the relative codes. The determinate θ of the curtain wall have two insufficiencies:

1) During serious earthquake action, the plasto-elastic deformation of the main structure might exceed 3 times the elastic deformation. Shake table test results showed that the peak θ of many structural models exceeded 3 times the main structure, i.e. the deformation capacity of the curtain wall structure might not be enough.

2) As for high-rise building, the θ values are distributed along the height of the main structure. They are obviously bigger in the middle along the height of the main structure. A single envelope value might not approve the security of the overall curtain wall. On the contrary, the value might be conservative on the location where the deformation of the main structure is very small.

3. ACCELERATION INDEX DISCUSSION

It has been discussed that β increase along the height of the main structure, and its distribution characteristic is very interesting. Based on the model structure shake table tests and analysis results, the proper β distributions were summarized and advised.

3.1. Unitary Height and Acceleration Response

Acceleration distribution along the height of the main structure could be described by the Acceleration-Height curve. It is convenient to adopt the unitary height (δ), the ratio of the floor height (h) and the total height of the structure (H).

$$\delta_i = h_i/H \tag{3.1}$$

where, δ=the unitary height, δ=0.0 at the first floor of the structure, δ=1.0 at the top of the structure, δ is between 0.0 and 1.0 at the rest part of the main structure along the height and h_i =the height of the ith floor in meters and H=the total height of the main structure in meters.

Acceleration response under frequently occurred earthquake could be got by shake table tests of the high-rise building structure model. The distribution curve of the β along the height of the building could be got after analyzing the shake table tests results (Figure 1).

3.2. Analysis and Discussion

According to Figure1, it could conclude that 1) β values were all bellow 5.0 in 75% of the total shake table tests, therefore, the relative specification in the current codes [2]-[5] could be reasonable, 2) As $\delta<0.6$, the acceleration responses were smaller and β almost less than 5.0, there were only few structural models with quite uneven stiffness or mass distribution along height with β values larger than 5.0 and 3) Once $\delta>0.6$, acceleration response obviously increased to $\beta = 8.0$, and rare peak values could exceed 10.0.

According to Figure1, it is advised to regulate the curve of β along the height of the main structure, β=5.0 as δ<0.6, β=8.0 as δ>0.6 (refer to the black bold line in Figure 1). At the same time, near the top of the building β could be increased according to the site conditions, height, intensity, structural type and the importance classification of the main structure, the amplitude should be less than 2.0. As for the floors near the ground, β could be reduced, but the amplitude should be less than 3.0.

It is necessary to have detail seismic performance analysis to guide the curtain wall design and construction in local area once the main structure is very complicated and then the earthquake response might be very serious.

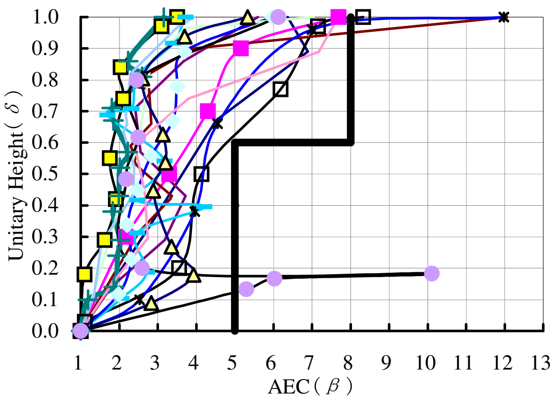

Figure 1 β distribution along the height of the building

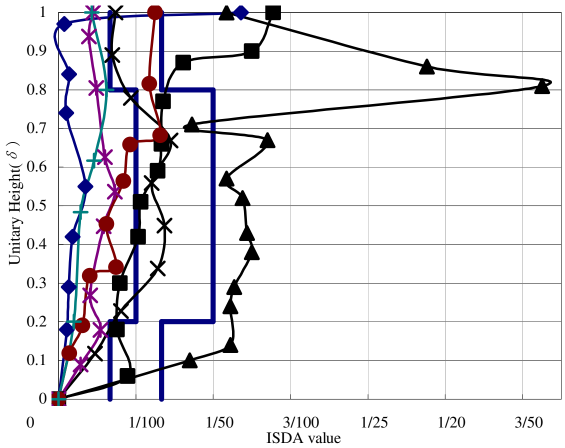

Figure 2 θ distribution along the height of the building

4. INTER STORY DRIFT ANGLE INDEX DISCUSSION

Inter story drift angle index is adopted to estimate the seismic performance of the curtain wall under the elasto-plastic earthquake action. Since the curtain walls were installed on the main structure, they should have enough ability to bear the deformation of the main structure under serious earthquake action. According to a great deal of shake table tests research results and curtain wall shake table tests research results, analysis and discussion were taken on the curtain wall seismic deformation capacity in order to found the reasonable evaluation index of it.

4.1. Unitary Height and Inter Story Displacement Response

The relationship between the θ and the unitary height were discussed according to the building structure model shake table tests research results. The θ under rarely occurred earthquake was analyzed because θ achieves peak value on above condition. The curve of θ distribution along the height of the building could be got after analyzing the shake table tests results (Figure 2).

4.2. Analysis and Discussion

According to Figure2, it could be concluded that 1) the θ values were almost below 1/50, and many θ values were about 1/100, 2) generally, θ distributions along the height of the main structure were various as various main structure types. As for the shearing deformation leading structures, θ values were near the lower storeies, as for the moment deformation leading structures, the peak θ values might move to the mid-height of structures. As for the moment-shearing deformation leading structures, however, the peak θ values might occur along lower stories and the mid-height of structures. As for the structures with slender higher stories, the θ values could increase abruptly.

The moment-shearing deformation is the primary deformation style as for many high-rise buildings. According to Figure2, it could be found that 1) near the first floor of the structure, where δ is between 1.00 and 0.20, θ is increasing along the height of the structure, 2) as δ is between 0.20 and 0.80, θ is relatively bigger and 3) as δ exceeds 0.80, θ decrease.

As for the same the building structure, the deformation of the mid-height of the structure is bigger, thereby, the curtain wall installing in this area should have enough deformation capacity to adopt the plastic deformation requirement. According to Code for Seismic Design of Buildings (GB 50011-2001) [6]-[7], parameters of the drift angles of the curtain wall could be referenced. Near the base and the top of the structure, where δ>0.80 and δ<0.20, θ is the 2/3 of the plastic deformation capacity of the main structure, as shown in table 4.1.

Table 4.1 Parameters of the drift angle

Structure Type	0.20<δ<0.80	δ<0.20 or δ>0.80
R.C frame	1/50	1/50
R.C frame-shear wall or Slab column–shear wall or Frame-tube	1/100	1/150
R.C. shear wall or tube system	1/100	1/150
Steel structure	1/50	1/75

Note: 1. the content of the table is applied to bending-shearing leading building structure, as for other structures, this table could be referenced according to experience and experiment.
2. As for R.C frame supported story, θ should be selected according to its location, θ =1/120 is adopted.

5. EVALUATION INDEXES APPLICATION

The new evaluation indexes provide a clear requirement of the seismic performance of the curtain wall and they could improve the seismic design level and seismic test methodology efficiently.

5.1. Architectural Curtain Wall Design

5.1.1 Seismic calculation of the curtain walls

According to the specific characteristics of the curtain wall, including the structural type, height, site conditions, intensity and current codes [1]-[5], the seismic design could then be started. Select the typical curtain wall unit to calculate the earthquake force, shown in equation (5.1) as following,

$$q_E = \frac{\beta_\delta \cdot \alpha_{\max} \cdot G}{A} \qquad (5.1)$$

where, q_E =earthquake force perpendicular to the curtain wall surface (kN/m^2) and G=the weight of the curtain wall member (including the panel and/or the frame)(kN) and A=the surface area of the curtain wall panel (m^2) and α_{max} =horizontal earthquake parameters, α_{max} =0.04 as the fortification intensity is 6, α_{max} =0.08 as the fortification intensity is 7, α_{max} =0.16 as the fortification intensity is 8 and β_δ reference to 3.2 of this paper.

According to the calculation results of equation (2), check the seismic performance of the panel, anchorage, structural clue and support system (poles, beams, frames or cables) and so on to ensure the bearing capacity of the specific members under earthquake action.

5.1.2 Deformation calculation

Deflection calculation of the curtain wall panel is the main deformation calculation form but the deflection calculation of the curtain wall unit or system and the deformation parallel to its surface were all ignored in current codes [3]-[5]. Curtain wall criterion [10] classified the deformation performance parallel to its surface and no equations were mentioned.

There are many kinds of curtain wall, and their structure type are various therefore, it is difficult to found an omnipotent equation to guide the design. Framed glass curtain wall for example, calculate its deformation parallel to its surface according to shearing Hook's law, shown in equation (5.2) as following,

$$\tau_{eqeq} = G \cdot \gamma \qquad (5.2)$$

where, τ_{eq}=equivalent shearing strength of the framed glass curtain wall parallel to its surface (N/mm^2) and G_{eq}= equivalent shearing modulus of the framed glass curtain wall parallel to its surface (N/mm^2) and γ=shear strain of the framed glass curtain wall parallel to its surface also called displacement angle.

Equation (3) is very simple in form; it is very convenient to be put into practice if the curtain wall manufactory provides information such as shearing strength and equivalent modulus and so on.

American Architectural Manufacturers Association (AAMA) [8] provides an equation to calculate the deformation performance of framed glass curtain wall under earthquake action. Glass in glazed curtain walls, glazed storefronts and glazed partitions shall meet the relative displacement requirement of equation (5.3).

$$\Delta_{fallout} \geq \max(1.25\ I \times D_p,\ 13\ \text{mm}) \qquad (5.3)$$

where, $\Delta_{fallout}$ = the relative seismic displacement (drift) causing glass fallout from the curtain wall, storefront wall or partition and D_p = the relative seismic displacement that the component must be designed to accommodate. D_p shall be applied over the height of the glass component under consideration. I = the occupancy importance factor.

As the result of the kind of the curtain walls are various, and their environment is different, the technical details should be distinguished from each other. Seismic test to the curtain wall is necessary to ensure its deformation performance and the correctness of the equations.

5.2. Seismic Test of the Curtain Wall

There are no efficient equations to calculate the deformation performance of the curtain wall at present. The only effective method is to have seismic test to the curtain wall to ensure its deformation ability by the action of the main structure. It includes *dynamic racking crescendo test* and *earthquake simulation shake table test*. Many scholars home and abroad believed that the deformation capacities of the curtain walls took the primary roles during earthquakes and the above-mentioned test methods were widely used.

5.2.1 Dynamic racking crescendo test

Dynamic racking crescendo test [9]-[10] is widely used to investigate the deformation capacity in USA, Japan and Europe. China also established criterion [11] referenced to the codes of abroad. The curtain wall specimen could be a single glass panel or the metal framed glass panel or a real unit. Investigation could be done in the experimental room or on site, as shown in Figure 3 and Figure 4.

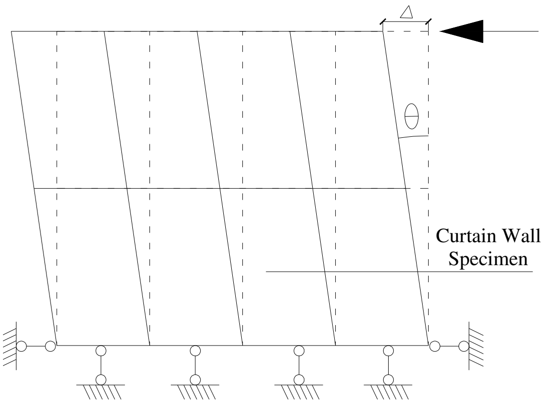

Figure 3 Layout of the dynamic racking crescendo test

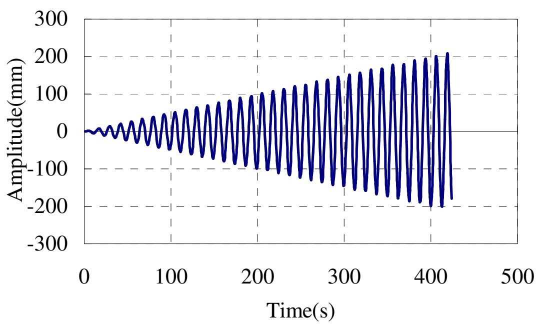

Figure 4 Drift in time history in crescendo test

A curtain wall unit of the under construction Dubai Tower in Arab was tested to estimate its seismic performance. The bottom of the unit was installed on the fixed base in the laboratory and a sinusoidal horizontal force parallel to the panel surface with increasing amplitude was put on the top of the specimen. Once the deformation of the specimen achieve the index of the requirement (table 1), according to the phenomenon of the test decision could be made whether or not the specimen satisfy the design requirements.

Deformation capacity parallel to the curtain wall surface could be investigated by dynamic racking crescendo test, but the test result could not get its dynamic characteristics which are important during earthquake. So the method should take further research and discussion. To overcome this embarrassment, earthquake simulation shake table test is ideal.

5.2.2 Earthquake simulation shake table test
The Code about the shake table test of curtain walls was published [12], which could help and guide the seismic researches in this field. According to the experiences, the seismic performance indexes of β and θ could not be reproduced in the shake table test simultaneously. As the increasing of the peak values of the input earthquake waves, the β increase quickly and achieve the requirement (3.2) while θ have not yet achieve the requirement (Table 1). It is necessary to deal with the earthquake waves to avoid the undesirable damage or even destroy of the curtain wall specimen, therefore, the experimental process might be complicated and the results of the test might be inadequate.

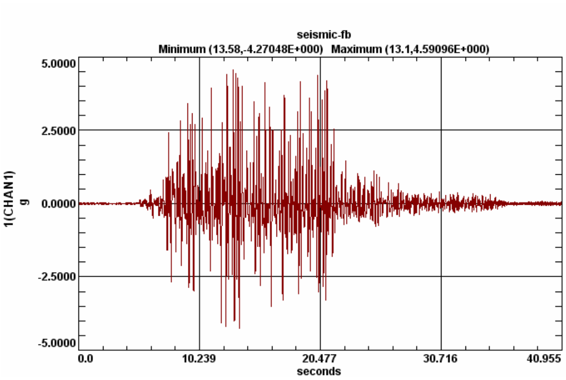

Figure 5 Floor acceleration time history for curtain walls


Figure 6 Shake table tests of curtain walls

Floor response spectrum, including floor acceleration response spectrum and floor displacement response spectrum are suggested to check β and θ of the specimen. In order to get the desirable floor spectrum, earthquake wave calculation and iterative operation are usually performed. Figure 5 is a sample of earthquake wave, which meet with the desired floor spectrum.

Shake table tests were accomplished to investigate the seismic performance of a special stone curtain wall in Tongji University. The building structural style is frame-shear wall, with height of 78.4m. Two kinds of curtain wall specimen were adopted and installed on the experimental frame, and the experimental frame was fixed on the shake table (refer to Figure 6). Sensors such as displacement transducers and the accelerometers were distributed to the key location of the specimen to get the displacement responses and acceleration responses during the process of the tests. The displacement responses and acceleration responses during the process of the test were obtained after input the earthquake wave (refer to table 5.1). The index requirements of the specimen are suggested as shown in table 5.2.

Until the last case of the tests, the earthquake responses was obviously serious and the deformations were visible, evident damages occurred in local area. The tested specimen kept their global structural entirety, without any collapse or component falling down. However, the β and θ of the specimen showed that two tested specimen had different seismic performance, i.e. specimen 1 was safe and satisfied under earthquake of 7 intensity, while specimen 2 was opposite.

Table 5.1 a) Test results of specimen 1

Acceleration (g)	7 FI/β	8 FI/β	θ
0.04	1.1	0.5	1/273
0.07	2.0	0.9	1/162
0.15	4.3	1.9	1/103
0.29	8.3	3.6	1/72
0.56	16.0	7.0	1/49

Note: FI=fortification intensity.

Table 5.1 b) Test results of specimen 2

Acceleration (g)	7 FI/β	8 FI/β	θ
0.03	0.9	0.4	1/1092
0.06	1.6	0.7	1/407
0.11	3.1	1.4	1/252
0.22	6.3	2.8	1/170
0.43	12.1	5.3	1/117

Table 5.2 Evaluation indexes of the tested curtain wall

δ	β	θ
$\delta < 0.20$	5.0	1/150
$0.20 < \delta < 0.60$		1/100
$0.60 < \delta < 0.80$	8.0	
$\delta > 0.80$		1/150

6. CONCLUSIONS

The earthquake simulation shake table test research results were discussed and analyzed, the new seismic performance evaluation index includes β and θ and their distribution along the height of the main structure were put forward. The unitary height-evaluation index system is the founded and its application and analysis were discussed. It might be helpful or referenced for the curtain wall seismic research, design and the real curtain wall engineering.

7. ACKNOWLEDGEMENT

The financial and technical supports in part from the National Key Technology R&D Program (Grant No. 2006BAJ13B01 & 2006BAJ03A03) and SLDRCE are gracefully acknowledged.

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