Full-Scale Shaking Table Test on Furnitures subjected to Long-Period Earthquake Motions

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SUMMARY:
This paper presents an experimental study of the sliding or overturning behaviour of indoor articles in long-period buildings subjected to long-period and long-duration earthquake motions, using the 3-dimensional world-largest full-scale shaking table of E-Defense. The main goal is to reduce the risk due to failure of non-structural building components during an earthquake.
Two experimental studies were conducted: the observation (measurements of displacement and acceleration) of the sliding behaviour using block-type sliding specimens including the case of collision with walls, and the direct measurement of anchoring forces between steel cabinets (furniture) and walls or floors, using newly developed bolt-type load-cells. The anchoring force responses were affected depending on the anchoring conditions (3 cases were studied: fixed connection, elastic fix connection, and loose connection that allow rocking motion of furniture). Pulse-like anchoring force responses or acceleration responses up to 3G were observed in the case of loose connections when rocking motions were suddenly locked. Pulse-like responses were also observed in the time of contents collision with the wall after sliding. The impact force response is expected to be reduced when considering the non-linear characteristics of connected materials or interaction, however, the mass of indoor articles is almost rather small and too rigid to expect plastic deformation, therefore, it is better to include the pulse-like phenomenon in the design of anchorage when subjected to long-period earthquake motions.

Keywords: Full-scale shaking table test, Indoor safety, Long-period earthquake motion, Anchoring force

1. INTRODUCTION

It was widely observed in the great East-Japan Earthquake occurred on Mar.11 2011 that the indoor safety of a high-rise building was deteriorated by the large displacement response of indoor articles, especially the sliding and collision of furniture with casters excited from the long-period and long-duration earthquake motion. The requirement of experimental studies on the behaviour of furniture or equipment that suffered from the long-period and long-duration earthquake excitation was well recognized, however, it was limited because the powerful shaking-table was limited.
This paper presents an experimental study of the sliding or overturning behaviour of indoor articles in long-period buildings subjected to long-period earthquake motions, using the 3-dimensional world-largest full-scale shaking table of E-Defense, and aims to reduce the risk due to failure of Operational and Functional Components (OFC) in a building during an earthquake.

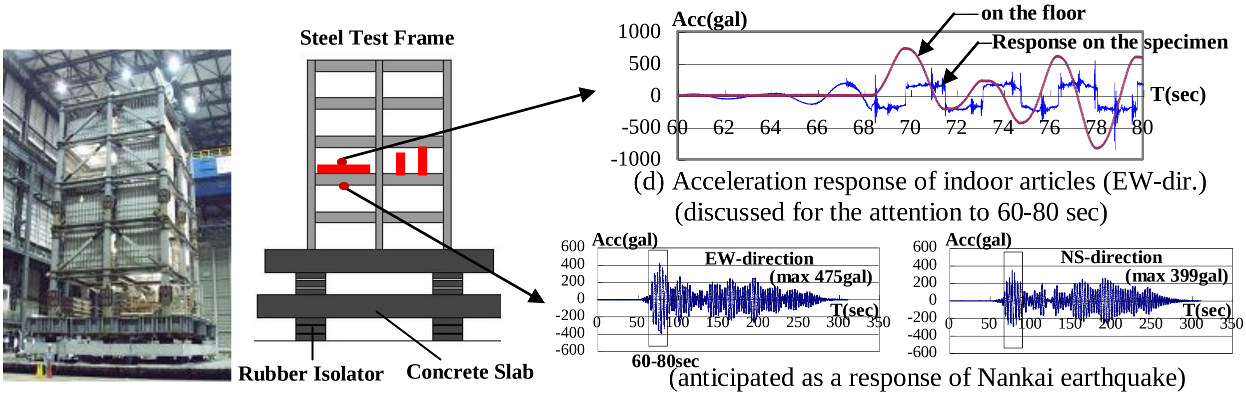
2. EXPERIMENTAL STUDIES

The substructure shaking table test method[*1),*2)] was used to generate the long-period earthquake motion in higher floors of high-rise buildings. A base-isolated full-scale 5 story steel building (the test frame) was set on the shaking table of E-Defense, and the artificial Nankai earthquake[*3)] wave expected at Kobe was input, this was predicted to occur in the near future (a large ocean-ridge earthquake with Magnitude over 8.4, 60% of probability in the next 30 years from Jan. 2012).
Two experimental studies were conducted.

One is the observation (measurements of displacement and acceleration) of the sliding behaviour using block-type sliding specimens including the case of collision with walls, and the other is the direct measurement of anchoring forces between steel cabinets (furniture) and walls or floors using newly developed bolt-type load-cells.

2.1. Substructure Shaking Table Test

Figure1 shows the shaking table setup (2-layer mass-damper system) that generates the long-period earthquake motion on the floor of the test frame, where the concrete mass (mat-slab) and rubber bearings were inserted between shaking table and test frame. The maximum amplified floor responses for displacement and velocity were ±1.3m and ±2.4m/sec, respectively.
The target wave (anticipated from Nankai earthquake) was derived from inversed response analysis, which is simulated on the top floor of a high rise building (about 100m height with a fundamental period of 3seconds) in Kobe (the soil condition near the site of Kobe city hall was used).
Two directional horizontal waves (UD component was not input) were generated, and furniture responses are discussed for the attention to 60-80sec (dominant part with the maximum acceleration of 399gal in NS-direction and 475gal in EW-direction on the test floor), which was almost a sine wave with a period of 3seconds and 300-400gal of acceleration amplitude.

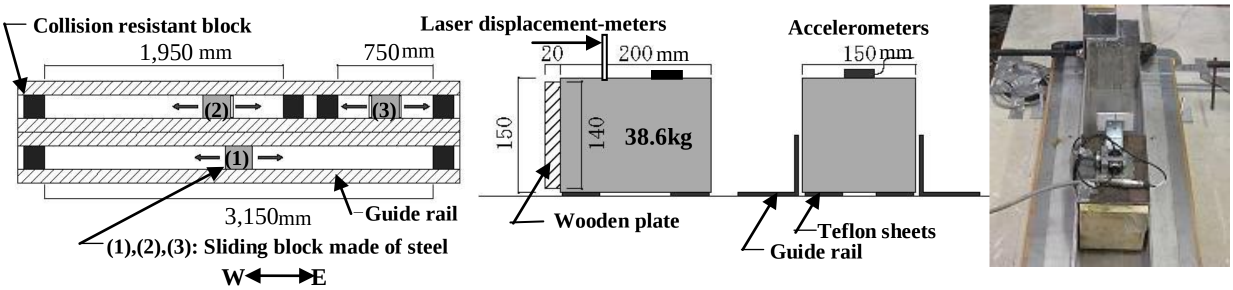


(a) Test frame (b) Test frame on 2-layer rubber isolators (c) Target earthquake motion on the floor

Figure 1. Substructure shaking table test

2.2. Sliding Behaviour

Figure 2(a) shows the 3 sliding steel-blocks with guide rails made of stainless steel and the collision resistant steel blocks arranged on both ends of each guide rails (see Fig.2(d)). The three blocks correspond to the sliding (1) without collision (free sliding), (2) with one time collision, and, (3) with many collisions. Figure 2(b) and (c) show the sliding block made of steel (weight: 38.6kg and dimensions: 150x150x200mm) which was put on each rails, and its collision surface was covered by medium hard wooden plate (t=20mm) to soften the impact effect. Teflon sheets were inserted between rails to reduce the (dynamic) frictional coefficient μ (=0.18-0.21, average 0.2).



(a) Sliding blocks with guide rails (b) Sliding block (c) Sliding block on the guide rail (d) Testing set up

Figure 2. Experimental apparatus for sliding behaviour

2.3. Anchoring Force

The anchoring forces to the floor were measured by the cabinet A (the height to breadth ratio (H/B)=4), and the anchoring forces to the wall by the cabinet B (H/B=5).

2.3.1. Experiment on Anchoring Force to Floor (Cabinet A)

As shown in Fig.3(a), the steel cabinet was fixed to the concrete floor slab using 4 bolt-type load cells (NE, NW, SE, and SW), which can measure the UD directional anchoring forces (zero-setting in initial value, therefore, the additional overturning moment caused by the horizontal load can be calculated), and the horizontal movements of the cabinet base in both directions were restrained by steel jigs, as shown in photo.1. Contents in the cabinet were paper wrapped concrete-blocks and books (32.7kg, 200mm width) in each steel shelves (4 shelves in the cabinet, each 400mm width), which can move about ±100mm in the EW direction (short direction of the cabinet, H/B=4) and almost does not move in the NS direction (long direction of the cabinet, H/B=2). The total weight was 176.4kg, in which 45.6kg was fixed mass (cabinet) and 130.8kg was movable mass (contents, 75% of total mass). Two directional (NS and EW) excitations were input.

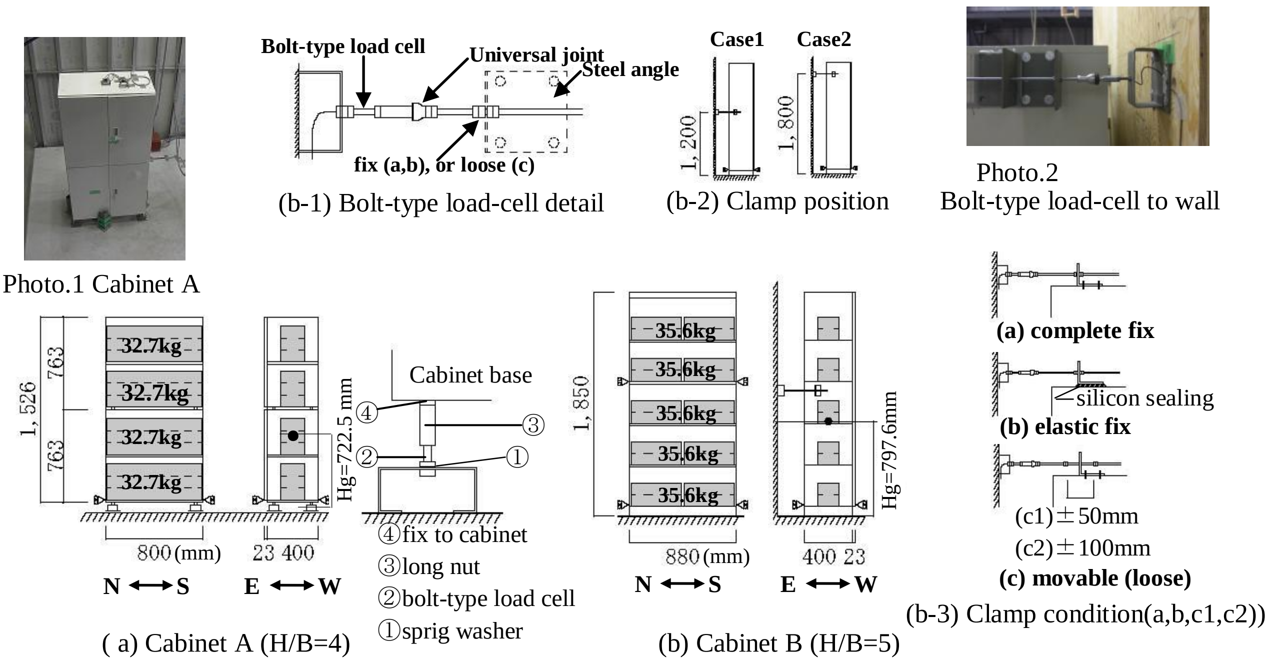


Figure 3. Experimental apparatus for measuring anchoring forces

2.3.2. *Experiment on Anchoring Force to Wall (Cabinet B)*

As sown in Fig.3(b), the steel cabinet was set to vibrate only in EW direction (the movement of NS direction was restrained by side bars, and the both directional horizontal movements in the cabinet base were restrained by steel jigs). Therefore, an overturning in EW (short) direction may easily occur when the horizontal acceleration is over (1/5)G, because of H/B = 5, where, G is the acceleration of gravity. Contents in the cabinet were paper wrapped concrete-blocks (35.6kg, 200mm width) in each steel shelves (5 shelves in the cabinet, each 400mm width), which can move about ±100mm in EW direction. The total weight was 221kg, in which 43kg was fixed mass (cabinet) and 178kg was movable mass (contents, 80% of total mass). The anchoring force was measured by 2 bolt-type load-cells (shown in Fig.3(b-1)) arranged on the both sides (N and S sides) of the cabinet. Experimental parameters were the clamp position (case1 and 2) and conditions (a, b, c1, and c2). The case1 is the middle height clamped, and case2 is the top height clamped, as shown in Fig.3(b-2). Clamp conditions are (a) complete fix connection, (b) elastic fix connection, (c1) loose connection to allow±50mm movable, (c2) loose connection to allow±100mm movable, which was attained, as shown in Fig.3(b-3), by (a) nut clamped steel angle and bolt setting, (b) 10mm thickness of silicon sealing inserted between steel angle and cabinet, (c) nut position adjusting, respectively.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Sliding Behaviour

3.1.1. Free Sliding without Collision

Figure 4 shows the time history (60-80seconds) of (absolute) acceleration on the floor and on the block, and the (relative) displacement of block in the case of free sliding without collision. The block started to slide when the floor acceleration exceeded the equivalent frictional coefficient (μG≒200gal) at T1 (about 68.5sec), and the reverse movement (relative velocity =0) occurred at T2 (about 69.5sec) when the opposite directional floor acceleration exceeded the equivalent frictional coefficient (≒200gal). A large (relative) displacement (+734 to -828mm) and a large (relative) velocity (over 150cm/sec) at about a period of 3 seconds (same as the floor vibration) were observed. The acceleration response on block consisted of 3 waves, namely, the fundamental long-period step-like oscillation, the small high-frequency vibration caused from the tolerance of frictional surface on the sliding rails, and the pulse-like peaks when start to slide (at T1), the absolute value of the floor acceleration is just under the equivalent frictional coefficient μG (at about 69, 71, 72.5, 74.5, 75.5, 77, and 79sec), and the reverse points (at T2, about 71.5, 73, 75, 76.5, 78, and 79.5sec). The pulse-like peaks (+565 to -835 gal) were 3-4 times of the average (200gal) sliding acceleration.

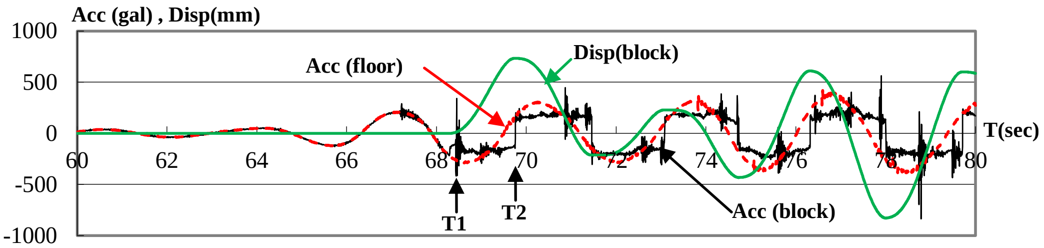
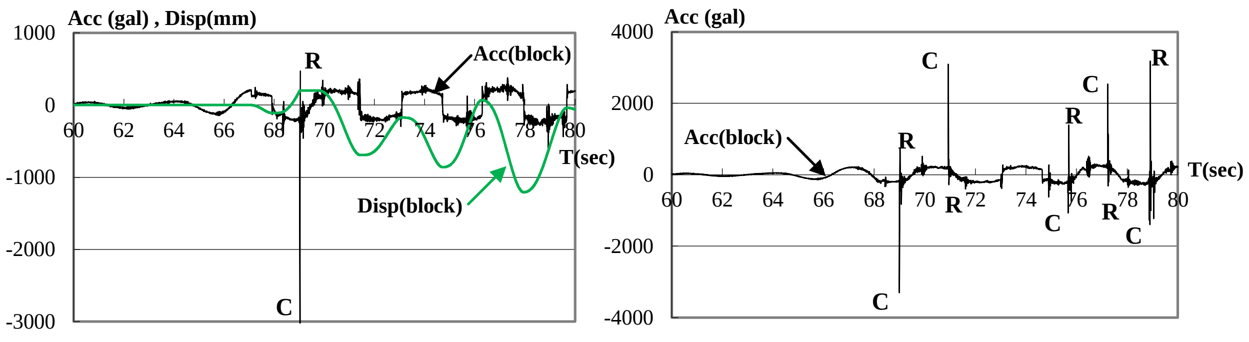


Figure 4. Time history of accelerations (on floor and on block) and relative displacement

3.1.2. Sliding with Collision

Figure 5 shows the effects of collision. Compared to the free sliding (Fig.4), the large acceleration peaks (over 3G) were observed at collision (C) and its reaction (R). As shown in figure 5(a), after the collision and pause (about 69-70sec), the displacement record was the same as in free sliding.

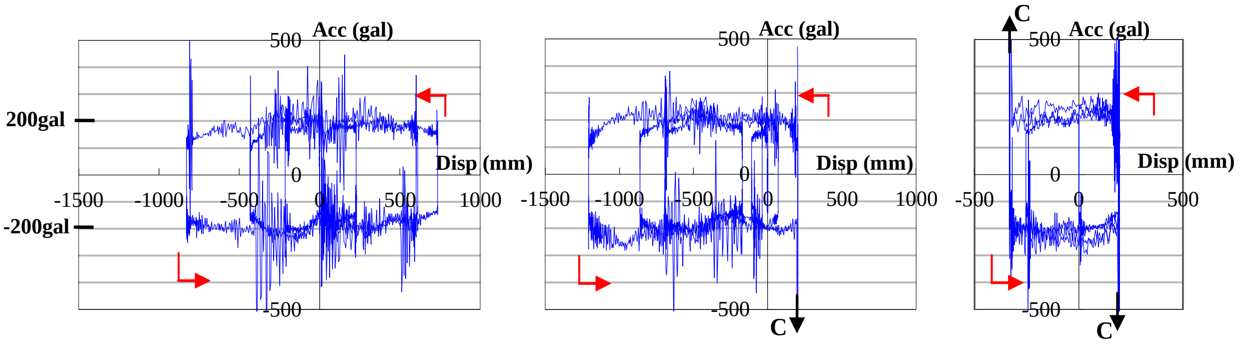


(a) with one time collision (acceleration and displacement) (b) with many collisions

Figure 5. Sliding with collision (time history of acceleration on the block)

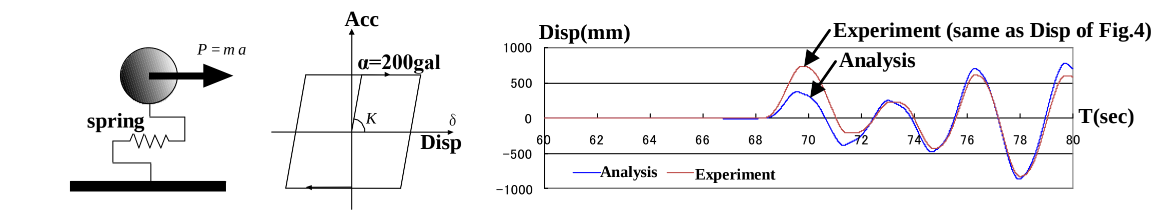
3.1.3. Acceleration and Displacement Relationship (Hysteresis Loop)

Figure 6 shows the relation between (absolute) acceleration to (relative) displacement of blocks. Fig.6 (a), (b), (c) correspond to sliding without collision (a), with one time collision (b), and with many collisions (c), respectively. The hysteresis loop is considered as a perfect rigid bi-linear type (between $\pm\mu$G, corresponding to the equivalent frictional coefficient), except pulse-like peaks. Figure 7 shows the result of analytical study when the restoring-force characteristic is assumed to be simple perfect bi-linear, the displacement time history is good-trace of the experimental results.



(a) without collision (b) with one time collision (c) with many collisions

Figure 6. Acceleration and displacement relationship (sliding behaviour)



(a) One mass system (b) Hysteresis loop of spring (c) Results

Figure 7. Time history of displacement (experimental and analytical results)

3.2. Anchor to the Floor (Cabinet A)

3.2.1. Time history of Acceleration (on the Floor and on the Cabinet)

Figure 8 shows the time history of accelerations on the floor and on the top of cabinet, and both were almost same before T0 (about 67sec, the floor acceleration is less than 200gal), in other words, the cabinet performed as a rigid body. After T0, the high-frequency wave started to contain in the cabinet acceleration record, which is corresponding to the movement of the contents. Pulses up to 1.5 times of floor acceleration caused from sliding and collision of the contents were observed at 70.5, 72, 74, 75.5, 77, and 78.5sec, which were almost same the maximum timing of floor acceleration.

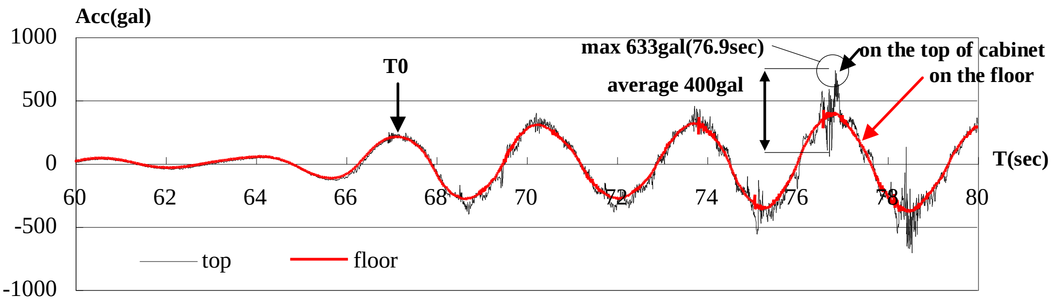


Figure 8. Time history of accelerations (on the floor and on the top of cabinet A)

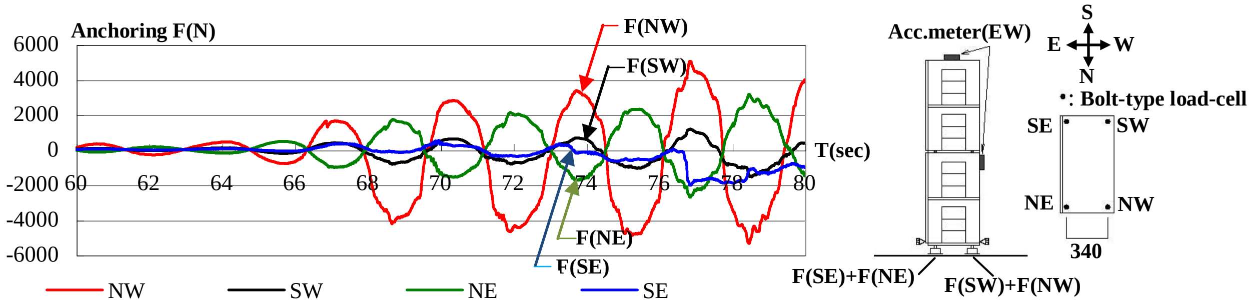


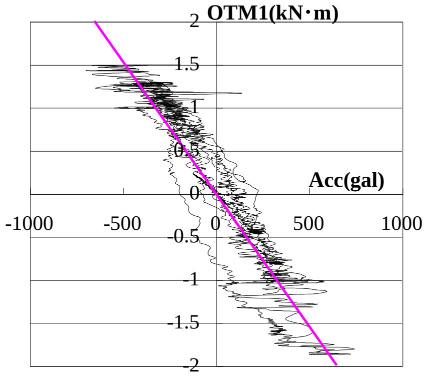
Figure 9. Time history of the anchoring forces in the load cells (SE, NE, SW, and NW)

3.2.2. Time history of Anchoring Forces

Figure 9 shows the time history of anchoring forces to the floor, which vibrates as a sine curve with about a period of 3 seconds, however, its peaks were changed to triangular shape at 77, 78.5sec, corresponding to the acceleration pulses in Fig.8.

3.2.3 Overturning Moment

Figure 10 shows the simultaneous relationship of the cabinet acceleration and the overturning moment (OTM1) derived from Eq. (1). OTM1 was proportional to the average acceleration value and rather stable (the effect of high frequency waves was disappeared) in spite of the large acceleration change. Comparing to the overturning moment (OTM2) derived from Eq.(2), OTM1was 2-3 times of OTM2, which was considered as a dynamic response effect.



$OTM1 = (B/2) \times \{[F(SE)+F(NE)]-[F(SW)+F(NW)]\}$ ---Eq.(1)

F(SE): anchoring force data of SE load-cell, so on

B: breadth of cabinet

$OTM2 = M \times Hg \times \alpha$ ---Eq.(2)

α : floor acceleration/G

Hg: height of mass center

M: mass of cabinet with contents

OTM1: derived from anchoring forces

OTM2: derived from floor acceleration

Figure 10. Overturning moment (OTM1 derived from load cell data) and acceleration (cabinet) relationship

3.3. Anchor to the Wall (Cabinet B)

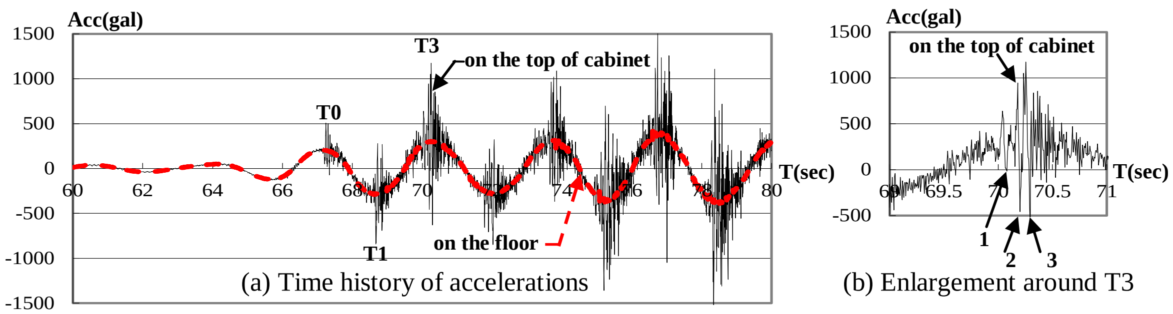


Figure 11. Time history of accelerations (on the floor and on the top of cabinet B)

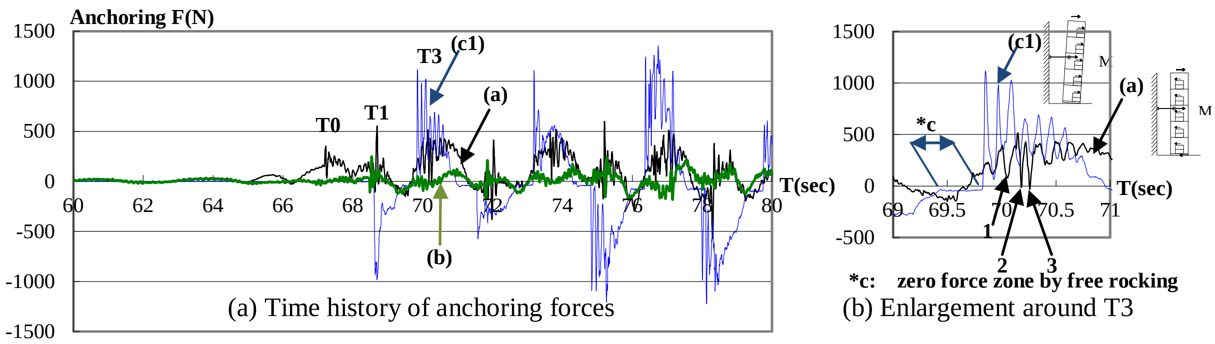


Figure 12. Time history of anchoring forces according to clamp conditions ((a), (b), and (c1))

3.3.1. Time-History of Acceleration (on the Floor and on the Cabinet)

Figure 11shows the time history of acceleration on the floor and on the top of cabinet in case1 (a), where, the cabinet is completely fixed to the wall at the middle of its height.

The contents started to slide at T0 (about 67sec, the floor acceleration over 200gal, and the high-frequency wave started to appear in the cabinet acceleration record).

The contents collisions to the cabinet wall occurred around T1 (about 68.5sec, corresponding to pulse-like peaks), which are similar to the experimental results of sliding (mentioned at **3.1**). High-frequency waves caused by the contents sliding continue until T3 (about 70.5sec), where pulse-like peaks caused by collision (2-3 times of average value) occurred, and these were repeated afterwards. As shown in the enlarged figure (Fig.11(b)), several peaks were observed, which were corresponding to 5 contents in 5shelves colliding in short time differences.

3.3.2. Time-History of Anchoring Forces (according to Clamp Conditions)

Figure 12 shows the time history of anchoring forces to the wall according to clamp conditions (a, b, and c1) in case 1.

(a) Complete fix condition ((a) of Fig.12)

The anchoring force was proportional to the floor acceleration before sliding of the contents (T0, about 67sec). The high frequency wave was corresponding to the contents sliding, and the pulse-like peaks (observed at about 68.5 (T1), 70.5 (T3), 72, 74, 75.5, 77, 78.5sec) were caused by the collision of contents, which were compatible with the acceleration records. However, as shown in Fig.12(b), the anchoring force was firstly decreased and secondly increased by collision and its reaction (the maximum over 500N), which occurs when the contents were sliding to the reverse direction against cabinet and collides to the rear wall of cabinet (corresponding to Fig.11(b)).

This phenomenon is similar to the tuned-mass-damper (TMD) effect by the movable mass (contents).

(b) Elastic fix condition ((b) of Fig.12)

The connecting angles and bolts have the allowance of a slightly different movement against the cabinet and floor by inserting an elastic material (10mm thickness of silicon sealing), therefore, the anchoring forces were decreased comparing to the complete fix condition ((a) of Fig.12). Pulse-like peaks caused from collision were not clearly observed, however the reduction of anchoring force by the TMD effect caused by the reverse motion of contents against cabinet was also observed.

(c) ±50mm movable condition with cabinet rocking ((c1) of Fig.12)

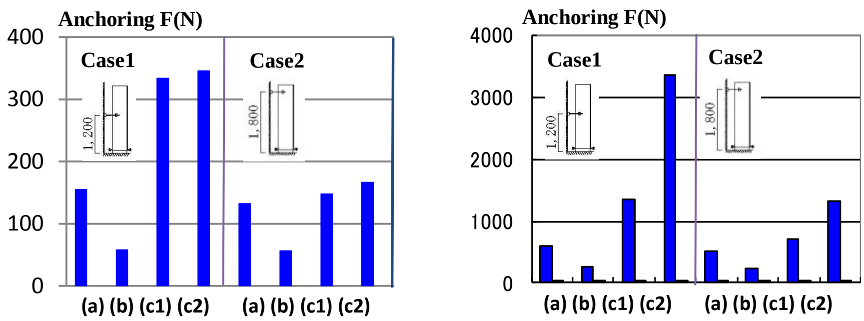
The pulse-like anchoring force responses were observed after zero value (as shown in *c of the enlarged figure, Fig.12(b)) when the free rocking motion was suddenly restrained by connecting bolts, and the severe collisions of contents occurred simultaneously after sliding.

Maximum forces over 1000N were observed on about 68.5, 70, 73.5, 75, 76.5, 78sec, which were about 0.5sec prior to the maximum timing of the floor acceleration.

Contrary to the case of complete fix condition ((a) of Fig.12), the TMD effect was not observed, because the movement direction of contents was the same as of cabinet, as shown in Fig.12(b).

3.3.3. Average and Maximum Anchoring Forces

Figure 13 shows the average and maximum anchoring forces according to the clamp position and condition, where the average anchoring forces were derived from the root-square-means of the 60-80sec data. Comparing to case1 and 2, the anchoring forces in case2 (top height clamp) were smaller than in case1 (middle height clamp), because of the effective overturning resistance. Comparing with the complete fix condition (a), the average and maximum force was decreasing about 40% in the elastic fixed condition (b), and was increasing 3-6 times in the rocking allowable condition (c1, and c2, where, c2 is larger as the rocking motion is larger).



(a) Average (RMS) anchoring force (b) Maximum anchoring force

Figure13. The average and maximum anchoring forces according to clamp conditions

4. CONCLUSION

The behavior of furniture in high-rise buildings subjected to long-period earthquake motion was experimentally investigated for maintaining an indoor safety, where, a large displacement response including collision is scary for indoor articles with low-frictional coefficient. A strong (±2.4m/s of velocity and±1.3m of displacement) and long-period (about 3 sec) earthquake motion, which is anticipated in higher floors of high-rise buildings by artificial Nankai earthquake (the large ocean-ridge earthquake with Magnitude over 8.4), was well generated using the world-largest shaking table of E-Defense through the sub-structure shaking table test method.

Conclusions are as follows.

(1) Free Sliding of Block (without collision)

Indoor articles (blocks) started to slide when the floor acceleration exceeded the corresponding frictional coefficient μG. In the case that the frictional coefficient μ was 0.2, large displacement (1.4m, sum of plus and minus) and velocity (1.5m/sec) response were observed. The acceleration responses consisted of 3 waves, namely, the fundamental long-period step-like oscillation with the acceleration of corresponding frictional coefficient, the small high-frequency vibration, and the large pulse-like peaks when sliding starts, the absolute value of floor acceleration just under the equivalent frictional coefficient, and the reverse points.

The analytical result using simple perfect bi-linear restoring-force characteristics traced well the experimental result, in spite of pulses or high-frequency waves.

(2) Sliding with Collision

The large acceleration pulses (over 3G) were observed when collision and its reaction occurred, although the maximum floor acceleration was about 0.5G.

(3) Anchor to the Floor (Cabinet A, H/B=4, in the complete fix condition)

The acceleration time history of indoor articles (complete fix to the floor) was almost the same as of the floor (indoor articles were considered as rigid bodies). However, the pulses with high-frequency vibrations due to sliding and collision of the contents made amplification about 1.5 times of the floor acceleration. The responses of anchoring forces did not contain high-frequency waves, however, there observed 2-3 times amplification in the overturning moment.

(4) Anchor to the Wall (Cabinet B, H/B=5, in the complete fix, elastic fix, and loose fix conditions)

Comparing to the complete fix condition (a), the maximum force decreased about 40% in the elastic fix condition (b), and increased 3-6 times in the rocking allowable condition (c). In the case of complete fix and elastic fix conditions, responses were reduced due to the reverse directional sliding of contents against the movement of floor or cabinet, which is similar to the tuned-mass damper (TMD) effect. Pulse-like responses of anchoring forces were observed in the condition of loose fix connection (c1 and c2), when the free rocking motion was suddenly restrained by connecting bolts, and the TMD effect was not observed.

(5) Impact Force Responses of Indoor Articles subjected to Long-period Earthquake Motions

An impact force response is expected to be reduced by non-linear characteristics of connected materials or interaction, however, the mass of indoor articles is almost rather small (and, the movable mass is almost heavier than the fixed mass) and too rigid to expect plastic deformation, therefore, the pulse-like phenomenon is recommended to be included in the design of an anchorage.

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