PERMISSIBLE RESIDUAL DEFORMATION LEVELS FOR BUILDING STRUCTURES CONSIDERING BOTH SAFETY AND HUMAN ELEMENTS

Jason McCormick[1], Hiroshi Aburano[2], Masahiro Ikenaga[3], and Masayoshi Nakashima[4]

[1] *Assistant Professor, Department of Civil & Environmental Engineering, University of Michigan, Ann Arbor, MI, USA. Email: jpmccorm@umich.edu*

[2] *Engineer, Takenaka Corporation, Osaka, Japan.*

[3] *Graduate Student, Department of Architecture and Architectural Engineering, Kyoto University, Kyoto, Japan.*

[4] *Professor, Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan.*

ABSTRACT :

A review of permissible residual deformation levels is undertaken in light of the increased interest in performance-based seismic design and self-centering systems. Permissible residual deformation levels are considered based on functionality, construction tolerances, and safety. Values are defined based on a review of past structural engineering research, post-earthquake reconnaissance, current building codes, and research in the field of psychology. The findings show that there are only a limited number of studies that measured residual drift levels of structures after an earthquake and correlated these to actual damage levels. In general, construction tolerances remain at or below 0.003 rad depending on the type of structural system and material being considered. This value is below the residual drift levels at which non-structural systems start to lose functionality. Research in the field of psychology has also shown that the lower limit at which people can sense an inclination is approximately 0.005 rad above which extended periods of inclination can cause headaches and dizziness. In order to verify these findings and provide further quantitative results, floor inclinations and column tilt of an occupied 40 year old structure are investigated. These results combined with those obtained through the extensive literature review suggest that 0.005 rad is an important engineering index in terms of permissible residual deformation levels.

KEYWORDS: Residual deformation, inclination, tilt, performance-based design, self-centering

1. INTRODUCTION

The 1994 Northridge earthquake in the United States and 1995 Hyogoken-Nanbu (Kobe) earthquake in Japan caused significant damage to the infrastructure of these urban areas. Over 6,000 people lost their lives during the Hyogoken-Nanbu event and economic losses due to damage incurred during these earthquakes were upwards of $50 to $100 billion (U.S.) (Comartin et al. 1995; Eguchi et al. 1998). The Hyogoken-Nanbu earthquake also left 240,000 building structures in a state of partial collapse requiring decisions to be made on the feasibility of repair versus demolition (AIJ 1998). As a result of the human, infrastructure, and economic losses sustained during these and other recent events, the academic and structural engineering community focused on a performance-based seismic design methodology to ensure a more reliable and predictable performance of structures during a seismic event. This methodology requires structures to meet specific limit states for design level earthquakes based not only on damage to the lateral force resisting system, but also safety of the occupants and functionality of the structure after an earthquake. This has resulted in the refinement of various structural systems and the development of a number of innovative systems which limit inter-story drifts during an earthquake. Self-centering systems which limit residual deformation also are being studied.

Currently, inter-story drift is used to evaluate the performance of a building under performance-based design. The development of self-centering systems and economic losses associated with partially collapsed structures suggest that residual deformation also needs to be considered as a limit state within performance-based seismic design. Residual deformations lead to inclination of horizontal members and tilt of vertical members which can cause additional and unexpected stresses on members and joints. These deformations must be considered against allowable construction tolerances, manufacturing errors, and long term deterioration effects to determine permissible residual deformation limits. However, very few studies have focused on residual deformation as a limit state for seismic design. Even fewer reconnaissance studies have actually measured residual drift levels in buildings after an earthquake and related them to damage states. In general, collapse prevention has been the main focus and as a result the importance of residual deformation levels has not received a significant amount of effort.

In order to determine the importance of residual deformation and permissible limits an extensive literature review is conducted in light of three categories: building functionality, construction tolerances, and safety. In regards to functionality, the psychological and physiological impact of different inclination levels on the human body is considered. Construction tolerances and errors provide a quantitative value for inclination and tilt which may exist prior to an earthquake. Finally, the effects of residual deformation are considered in regards to impedance of escape routes after an earthquake. Based on these three categories, a permissible residual drift level is suggested. In order to further verify the appropriateness of this value, an investigation of an occupied steel frame building also is conducted.

2. DETERMINATION OF PERMISSIBLE RESIDUAL DEFORMATION LEVELS

Due to the small amount of quantitative data relating residual deformation levels to sustained damage, permissible residual deformation levels have not been considered in a systematic manner previously. Often, collapse prevention is the primary objective with consideration of residual deformation secondary. Only minimal effort during past reconnaissance missions has focused on the residual deformation of a structure and often it is approached in a more qualitative manner. For example, residual displacements of a 17-story moment frame deemed functional after the Northridge earthquake were not found until the elevators failed to operate properly after re-occupancy due to the building being out-of-plumb (Anderson and Filippou 1995). In order to better define permissible residual deformation levels, an extensive literature review is undertaken with the available data being arranged into three categories: building functionality, construction tolerances, and safety. Residual deformation of the vertical members is referred to as “column tilt” and residual deformation of horizontal members is defined as “inclination” as shown in Figure 1.

2.1. Permissible Residual Deformation Based on Building Functionality

For the purpose of this study, functionality is based on the psychological and physiological discomfort that residual deformation has on the occupant and not specific damage to the structural system. If the occupants experience dizziness, headaches, and nausea while occupying a building, then that building is considered nonfunctional and inhabitable. To consider permissible residual deformation levels with respect to building functionality, the inclination or tilt which people can perceive and that which qualifies a structure as inhabitable needs to be determined.

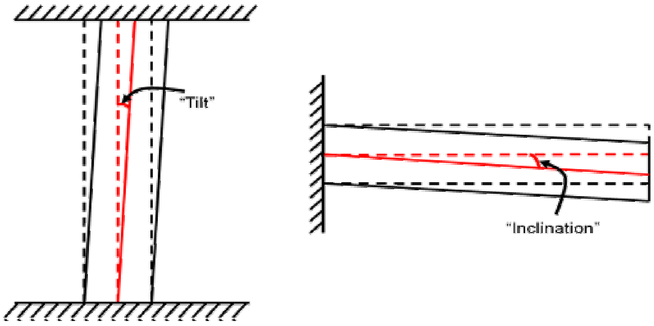

Figure 1 Schematic for definition of residual deformation in vertical and horizontal members

2.1.1 Minimum Perceptible Inclination Angle

Studies in the field of psychology have considered the ability of people to perceive floor inclinations when their eyes are closed. A recent experiment conducted with 22 subjects used a platform for which the inclination to the left and right could be controlled in units of 0.1° (0.002 rad) (Kaga et al. 2005). At the start of the experiment, the platform was inclined 5° (0.087 rad) to one side and the subject standing on the platform with their eyes closed was asked to change the inclination through the use of a remote control until they perceived it to be horizontal. When the platform was initially inclined to the right, on average the subjects returned the table to an inclination of 0.57° (0.01 rad) at which point they assumed it was horizontal. Alternatively, when the initial incline was to the left, the subjects returned the table to an inclination of 0.14° (0.0024 rad). The difference in the results may partially be attributed to the fact that all of the subjects in the study were right handed. A second study found that people tended to recognize when their vertical axis was tilted at 0.2° (0.0034 rad) or greater (Seto et al. 1996). Both of these studies suggested that the minimum inclination angle which people can perceive is approximately 0.3° (0.0052 rad).

2.1.2 Correlation between Physical Ailments and Inclination Angle

The West Tottori Prefecture earthquake of 2000 caused significant liquefaction resulting in damage to many residential structures (Yasuda and Hashimoto 2002). The maximum measured residual deformation was 0.0375 rad. Based on a survey of 169 homes, the residual inclination and/or tilt angles due to settlement were greater than 0.015 rad in 47 homes, between 0.015 rad and 0.01 rad in 30 homes, between 0.01 rad and 0.005 rad in 39 homes, and less than 0.005 rad in 53 homes. Occupants of those residences with residual deformations greater than 0.01 rad reported experiencing headaches and other hindrances to their daily lives. As a result, it was suggested that leveling of these homes was necessary in order for them to maintain functionality.

A hearing of 100 residents in Ashiya city conducted after the Hyogoken-Nanbu earthquake investigated the affects of settlement in that area (Fujii et al. 2002). It was found that the smallest inclination angle which the residents were conscious of was between 0.005 rad and 0.006 rad. For those homes with residual inclination angles of 0.008 rad, the residents were highly conscious of the inclination and complained of dizziness, headaches, and nausea. These same residents also complained about cracking, rolling objects, and the formation of gaps allowing air to escape which reduced the functionality of the home.

2.1.3 Legal Definition of a Non-Functional (Defective) Residence

The Residential Housing Dispute Processing Handbook in Japan states the definition of a non-functional or defective home as one in which the overall drift or inclination and tilt of any member exceeds 0.006 rad (Japanese Law Publication 2000). This limit is set to ensure construction quality and is obtained based on typical construction tolerances (0.003 rad) and the allowable deformation limit associated with unequal settling (0.003 rad). The selection of this deformation limit is further verified by a study which started in 1962 and extended through 1976 in Hokkaido Japan (Dobashi and Ino 1978). The bending behavior and quality of reinforced concrete floor slabs of residential buildings built by both small-to-medium construction contractors and major construction companies was explored. A total of 1122 floor slabs were studied in 72 homes. The study found that the lowest inclination angle due to defective construction or excessive settlement for which grievances were reported was 0.005 rad. This value compares well the 0.006 rad limit stated in the handbook.

2.2. Permissible Residual Deformation Based on Construction Tolerances

During new construction, specified construction tolerances are required to be met in order to ensure the integrity of the structure. The construction tolerance, typically found in the building codes, set allowable residual deformation levels for new construction by establishing limits for deviations from the established column and beam lines specified in the building plans and are dependent on the structural material being used.

The cost to restore a structure back to its constructed position after a seismic event is also important in the consideration of permissible residual deformation levels as it can often exceed the value of the structure.

2.2.1 Construction Tolerances

Construction tolerances for wood-frame structures in Japan are specified based on whether the lumber is precut or cut in the field (Koyama 1998). Since it is often more difficult to maintain precision and accuracy in the field, tolerances for field cut lumber are larger, 2.72 mm/m, as compared to precut framing, 2.30 mm/m. Even further restrictions are placed on lumber which is both dried and precut, 2.28 mm/m. The construction tolerance for wood-frame structures ensure that the walls and floor of the structure remain plumb and that column tilt and floor inclinations are not greater than approximately 0.003 rad.

The JASS5 (Japanese Architectural Standard Specification) for reinforced concrete construction specifies the construction tolerances for concrete walls and floor systems (AIJ 1997). To ensure that the walls are plumb and floors are even, construction tolerances are set at 10 mm for every 3 meters of height or span. Thus, the approved construction tolerances for reinforced concrete structures in Japan are similar to those of wood-framed structures with a value of 0.0033 rad.

The technical guide specifies two types of tolerances for steel members (AIJ 1996). Manufacturing tolerances refer to the permissible out-of-straightness of a particular member received from the steel manufacturer where at least 95% of a given batch of product must meet these tolerances. The second type of tolerance is the typical construction tolerance. For column members, the manufacturing and construction tolerances are 0.001rad and 0.0014 rad, respectively. Similar tolerances are specified for the maximum inclination of beam members where the manufacturing tolerances are 0.001+(3/span length) rad and the construction tolerances are 0.0014+(5/span length) rad. The results show that the construction tolerances for wood-frame and reinforced concrete structures are approximately 0.003 rad, while much stricter tolerances are in place for steel-frame structures. In general, the construction tolerances for steel-frame structures are approximately half those specified for these other types of construction.

2.2.2 Rehabilitation and Repair of Deformed Structures

Because of the number of buildings that suffered damage or partial collapse during the Hyogoken-Nanbu earthquake, a number of studies focused on the cost to rehabilitate or repair these structures. A study conducted on 12 steel-frame buildings damaged during the earthquake considered the residual deformation in determining whether to repair the structure versus demolish it (Iwata et al. 2005). When direct and indirect repair cost were considered along with losses due to building closure during the repair period, it was no longer financially viable to make repairs when residual deformations were greater than 0.005 rad. This result suggests that self-centering systems may be practical depending on the added initial construction costs.

2.3. Permissible Residual Deformation Based on Safety

Occupant safety directly after an earthquake is paramount whether the danger is related to damage to the load bearing system or to non-structural elements limiting egress from the building. The Bureau of Residential Construction in Japan defines a “level A” structure as safe after an earthquake (JBDPA 1991). For wood-frame, reinforced concrete, and steel-frame structures, a “level A” structure is one in which the first floor residual drifts are less than 0.017 rad, 0.01 rad, and 0.01 rad, respectively. However, these values do exceed the drift levels which could be perceived by the occupants.

The ability to evacuate a structure after an earthquake also falls under the category of safety as residual drift levels can have a significant impact on the functionality of non-structural elements. Studies of non-structural systems through both uni-directional testing of wall systems (Kato et al. 2007) and shake table studies

(McCormick et al. 2008) have shown significant damage to door systems when the vertical tilt of the door frame and surrounding members is greater than 0.005 rad. As a result, the permissible residual deformation for vertical members based on safety can be taken as 0.005 rad.

2.4. Summary of Permissible Residual Deformation Based on Past Studies

With the limited number of past studies on residual deformation levels, a general understanding of permissible inclination and tilt angles has been achieved considering functionality, construction tolerances, and safety.

1) With respect to building functionality, it was found that people can perceive horizontal inclinations between 0.005 rad to 0.006 rad while inclinations of 0.008 rad or greater can lead to headaches, dizziness, and an overall hindrance to daily life. Current Japanese guidelines also state that a home is non-functional when inclination levels are greater than 0.006 rad.
2) With respect to construction tolerances, the most stringent tolerances are for steel frame structures. The tolerances for vertical and horizontal members are 0.0014 rad and 0.0014+(5/span length) rad, respectively. Based on a survey of structures damaged during past earthquakes, it was shown that repair of steel frame buildings with residual drift levels greater than 0.005 rad was not economically feasible.
3) With respect to safety, buildings with residual drifts (column tilt) less than 0.01 rad after an earthquake are considered safe. However, studies of non-structural systems have shown that residual deformations of 0.005 rad may impede egress from a structure in the event of a large aftershock.

The above findings suggest that for all three categories a single standard permissible residual drift level of 0.005 rad can be defined for both column tilt and beam inclination. This value can be used as a starting point to considering residual deformation in the context of performance-based seismic design along with acting as a reference in the development of self-centering systems.

3. OCCUPIED BUILDING INVESTIGATION

3.1. Building Details

In order to further verify the 0.005 rad residual deformation index, an investigation of the residual deformations found in an occupied building located on the Uji campus of Kyoto University was completed. The building was constructed in 1970 and is a 5-story steel moment frame. The structure consists of 43 spans in the long direction and 20 spans in the short direction. The span lengths are 3750 mm and the floor heights are 3300 mm. Figure 2 provides the plan and elevation views of the building. On the east side of the structure, there are two, 2-span by 2-span openings for emergency vehicle access, while the openings on all other sides are only one bay by one bay for conventional vehicle access.

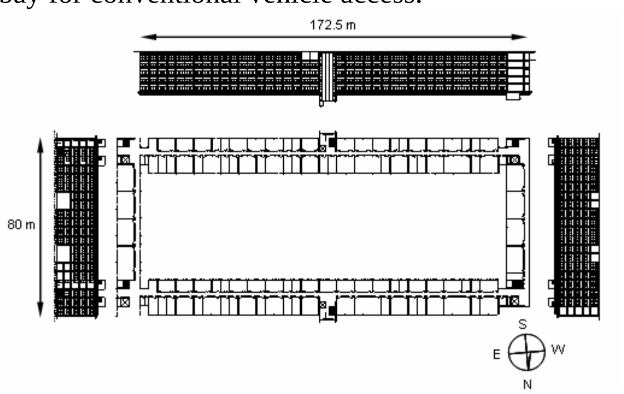

Figure 2 Plan and elevations for the target structure

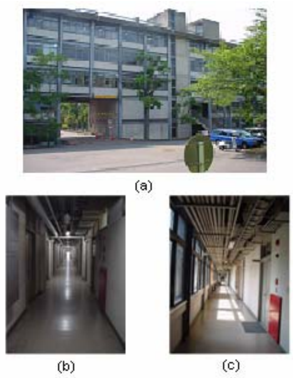

Figure 3 Target Structure: (a) East side, (b) South corridor, and (c) East corridor

This building was selected as the target structure because at the time of construction fire-proofing of the steel members was not required. The steel framing throughout the structure is exposed and the corridors of the building are straight and run the length of each side allowing for an easy means to measure residual deformations as can be seen in Figure 3. It should be noted that after the completion of this survey, a previously planned earthquake retrofit of the structure began.

3.2. Investigation Plan

Two studies of the target building were conducted. The first study concentrated on the inclination of the 4th story corridor floors in all four sides of the building and the column tilt of the 4th story columns in the east and west sides. A laser level with a precision of ±1 mm over 5 m was used as the datum from which inclination changes were measured at 41 points along the north and south side corridors and 16 points along the west and east side corridors. In order to reduce errors from lack of precision, the laser level was placed at the center of each column to column span when taking measurements. The laser level was also used as a vertical datum for measuring the column tilt. The change in distance from the column flange edge to the datum was measured at the floor and ceiling level. The tilt angle of 14 columns in each of the east and west corridors was measured.

The second study focused on residual deformations within an occupied office space located on the second floor of the south corridor. The room had plan dimensions of 3600 mm by 7550 mm. As with the previous study, the laser level was used to provide a datum for the floor inclination measurements. The laser level was placed 2400 mm from the outside wall and 1800 mm from the two side walls. A total of 107 measurements were taken as can be seen in Figure 4. The choice of measurement points was dictated by permanent furniture present in the office space. This particular office space was chosen because the occupant felt that the floor was inclined, but did not experience dizziness or headaches as a result of it.

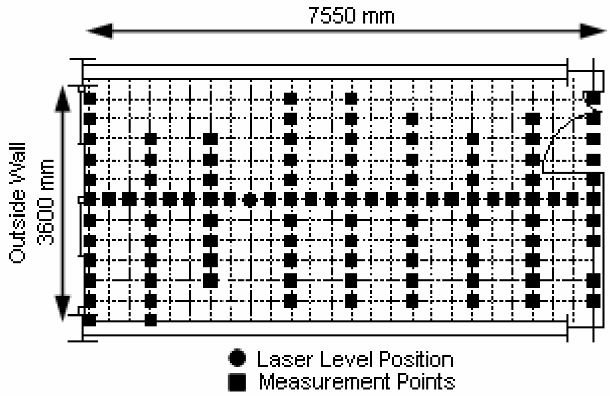

Figure 4 Plan view of the occupied office space and the measurement points

3.3. Investigation Results

3.3.1 Corridor Study Results

Figure 5(a) and (b) provide the change in floor height along the corridor for each side of the building with respect to the initial measurement point (0 mm). The shaded area indicates those spans which are above vehicle openings at the lower levels. Both the north and south corridors sloped downward to the west, while the east and west corridors sloped downward to the north. The resulting inclination angles were 0.00014 rad, 0.0002 rad, 0.00016 rad, and 0.00019 rad for the north, south, east, and west corridors, respectively. All of these values were within the construction tolerances for steel structures. The maximum local change in floor height occurred in the north corridor where the floor height decreased by 20 mm over a single span. This decrease resulted in a local inclination angle of 0.0053 rad which exceeds the permissible residual deformation obtained previously and suggests that the inclination over this span would be perceivable to the occupants.

The tilt of the individual columns along the east and west corridor of the 4th story is shown in Figure 5(c). A negative tilt angle specifies that the column leans to the south while a positive tilt angle specifies that the column leans to the north. The shaded areas represent those columns which border or lie above vehicle opening at the lower levels. A total of 8 columns along the east corridor and 0 columns along the west corridor have tilt angles which surpass the construction tolerance (0.0014 rad) designated for steel structures. However, none of these 8 columns are above the permissible residual deformation level of 0.005 rad. The results also show that the 11th span column in both corridors had the maximum tilt angle. The maximum tilt angle for the east and west corridor was 0.003 rad and 0.0013 rad, respectively. As a result, the maximum column tilt for the east corridor was 2.3 times that of the west corridor which may be associated with the fact that vehicle openings are larger in the east corridor versus those in the west corridor (see Figure 3).

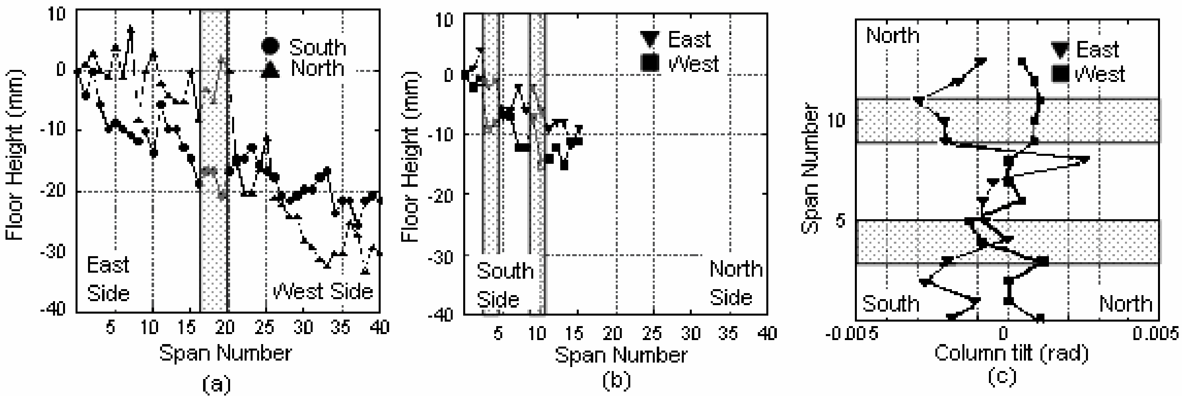

Figure 5 Fourth story (a, b) floor inclination results and (c) column tilt results

3.3.1 Occupied Office Space Study Results

Figure 7 provides the results from the study of the occupied office space. The vertical axis represents the floor settlement with respect to the height of the floor at the back left corner of the room (0 mm, 0mm, 0mm). The results show that the majority of the settlement occurred between 1800 mm and 6600 mm from the outside wall where the inclination angles ranged from 0.0056 rad to 0.0067 rad. The maximum inclinations occurred 3900 mm from the outside wall where the floor settled approximately 13 mm. In the area near the outside wall (0mm and 900 mm) and by the doorway (7550 mm), the local inclination angles were between 0.002 rad and 0.0038 rad. The study shows that residual deformations in this office exceed the permissible residual deformation limit and the perception of the occupant that the floor was inclined further verifies the literature review findings.

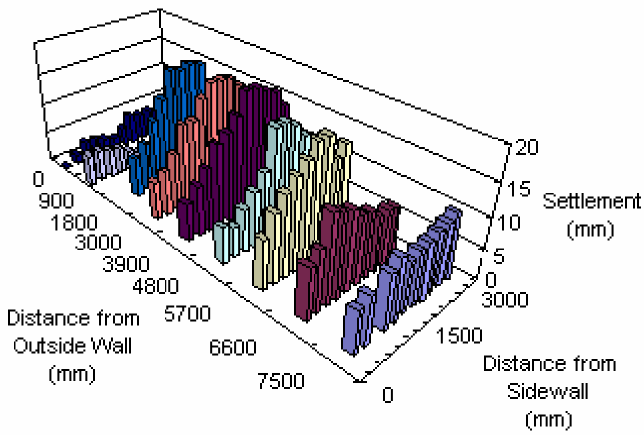

Figure 6 Settlement with respect to position within the occupied office space

4. CONCLUSION

The results of this paper with respect to permissible residual deformation limits are summarized below and provide an initial means of incorporating residual deformation into performance-based seismic design.

1) Permissible residual deformation levels with respect to floor inclination and column tilt were explored through an extensive literature review based on functionality, construction tolerances, and safety. The findings suggest that 0.005 rad can be used as an index level for permissible residual deformation.
2) The 4th story corridor study of the target structure revealed that only at local points did the floor inclination (0.0053 rad) exceed the permissible residual deformation level. Meanwhile, none of the measured column tilt values along the east and west corridors were above the permissible limit. As a whole, the building did not show a significant amount of residual deformation.
3) Local floor inclinations of 0.0067 rad were measured in the occupied office space. These measurements were above the permissible residual deformation level. The results confirm the literature review findings given the fact that the occupant had mentioned being inconvenienced by the feeling of the floor not being level.

REFERENCES

Anderson, J.C. and Filippou, F.C. (1995). Dynamic Response Analysis of the 17-Story Canoga Building. *SAC Technical Report* **95-04**, 12-1 – 12-53.

Architectural Institute of Japan, AIJ (1996). Technical Guideline on Steel Construction, On-Site Construction. *Architectural Institute of Japan*, Japan. (in Japanese)

Architectural Institute of Japan, AIJ (1997). Standard Specifications and Commentary on Building Construction, Reinforced Concrete. *JASS5*, Japan. (in Japanese)

Architectural Institute of Japan, AIJ (1998). Recommendation for enhancement of disaster mitigation in buildings and urban areas – Based on damage observed in 1995 Hyogoken-Nanbu earthquake. *Building Science* **113:1418**, 9-24. (in Japanese)

Comartin, C., Green, M., and Tubbesing, S. (1995). The Hyogoken-Nanbu Earthquake. *Preliminary Reconnaissance Report*, Earthquake Engineering Research Institute, Oakland CA.

Dobashi, Y. and Ino, S. (1978). Survey on RC floor slabs with large deformations and repair methods. *Journal of the Architectural Institute of Japan* **272**, 41-51. (in Japanese)

Eguchi, R.T., et al. (1998). Direct Economic Losses in the Northridge Earthquake: A Three-Year Post-Event Perspective. *Earthquake Spectra* **14: 2**, 245-6.

Fujii, M. et al. (2002). Damage to an repair of foundations of residential buildings in liquefied areas in Hygoken-Nanbu earthquake. *Soil and Foundations* **46**, 9-12. (in Japanese)

Iwata, Y., Sugimioto, K., Kuwamura, H. (2005). Reparability limit of steel structural buildings: Study on performance-based design of steel structural buildings Part 2. *Journal of Structural and Construction Engineering*, **588**, 165-172. (in Japanese)

Japan Building Disaster Prevention Association (1991). Technical Guideline for Damage Diagnosis of Buildings Suffered from Earthquakes, Japan. (in Japanese)

Japanese Law Publication (2000). Residential Dispute Processing Technical Handbook. Japan. (in Japanese)

Kaga, K., et al. (2005). Vestibular sensitivity and sense of inclination. *Journal of Cognitive Science* **7:1**, 16-22. (in Japanese)

Kato, M., et al. (2007). Seismic performance and damage evaluation of drywall partitions. *Journal of Structural and Construction Engineering (AIJ)* **614**, 139-146. (in Japanese)

Koyama, Y. (1998). Research on construction of wood houses using frame systems. *Journal of Housing Research Foundation* **7**. (in Japanese)

McCormick, J., Matsuoka, Y., Pan, P., Nakashima, M. (2008) Evaluation of Non-Structural Partition Walls and Suspended Ceiling Systems through a Shake Table Study. *Proc. of the 2008 ASCE Structures Congress*.

Seto. M., et al. (1996). Sensitivity and memory of body inclination (part 1) – Ability to restore to vertical position. *Equilibrium Research* **55:5**, 204. (in Japanese)

Yasuda, S. and Hashimoto, T. (2002). Differential settlement caused by liquefaction in Tottori-Seibu earthquake. *Annual Meeting of Japanese Society of Civil Engineers*, 1029-1030. (in Japanese)