LARGE-SCALE SHAKING TABLE TESTING OF WOOD BUILDINGS - HISTORICAL REVIEW AND RECENT TESTS

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ABSTRACT: This paper will present a historical review and recent shaking tablet tests. It will also give a brief overview of the relationship between Japan's seismic requirements and actual ground shaking to understand why these tests are necessary.

KEYWORDS: timber, shaking table test, CLT, two story house, composite structure

1 – INTRODUCTION

In Japan, severe earthquakes, such as the 1995 Kobe and 2016 Kumamoto earthquakes, caused significant damage to timber structures. Residential timber houses, including newly built ones, collapsed during these earthquakes. The authors have conducted many shake table tests. There are several purposes of shaking table testing. The first objective is to confirm that the performance obtained from the shaking table test is as designed, in this case, the relationship between the load and deformation of the stories. The second is to evaluate the marginal performance. As mentioned above, the observed waves are more significant than the requirement in the seismic design. This means it is important to check the performance against observed waves. Although the observed waves are unknown, it is confirmed that the building will not collapse under the earthquake motion observed so far. All buildings are required not to collapse under the observed seismic motion in design. However, the design of a building must satisfy the design safety limit deformation for the design earthquake. The safety limit is generally much lower than the actual collapse limit, and one of the purposes is to evaluate the actual collapse limit. In addition, experiments are conducted to determine the exact safety limits so that they can be more easily designed. In addition, companies often use shaking table testing to demonstrate how safe the buildings they are constructing are. This article focuses on the results of shaking table tests on modern wooden buildings, not traditional wooden buildings such as private houses, shrines, or pagodas.

2 – SEISMIC DESIGN IN JAPAN

To understand the purpose of shaking table testing, it is necessary to understand the basic issues of seismic design in Japan. Japanese seismic design requires different routes for buildings of different heights and volumes. Several methods are available, e.g., calculation of ultimate performance method and capacity spectrum method, but only the basics are outlined here.

Two levels of seismic design methods are required. One is the elastic design, which is damage control for moderate earthquakes, of which the return period is 30-50 years. The second is non-linear design, which prevents collapse in a severe earthquake. For each of these external forces, a moderate earthquake is considered to have a horizontal force of 20% of the seismic weight of the building, and a severe earthquake has an external force equal to the seismic weight of the building. However, the constant energy law allows the input earthquake motion to be reduced by plasticization. Depending on the type of structure, the capacity of the building against a severe earthquake of 25% to 55% of the building weight is required.

Equations (1) and (2)for elastic design and (3) to (4) for non-linear design show the fundamental seismic force required here. For moderate earthquakes, 0.2 is used for Co, and 1.0 is used for maximum design earthquakes, as mentioned above. The structural reduction factor Ds, which can be considered nonlinearity, varies depending on the type of structure and can be reduced to 0.25 to 0.55 for structures with high ductility.

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$$Q_i = C_i \times \Sigma W_i \quad (1)$$

$$C_i = Z \times R_t \times A_i \times C_0 \quad (2)$$

Where, Q_i ： Shear force for elastic design, W_i : Weight of the i-story assumed at the time of initial design, C_i : Seismic layer shear coefficient of the above-ground portion of a building of a certain height, Z: Value determined by the Minister of Land, Infrastructure, Transport and Tourism within the range between 1.0 and 0.7, according to the degree of earthquake damage based on earthquake records, seismic activity, and other earthquake characteristics in the relevant area, R_t: A value representing the vibration characteristics of a building determined by a calculation method specified by the Minister according to the natural period of the elastic range of the building and the ground, A_i: A value representing the vertical distribution of the seismic layer shear coefficient of the i-th floor according to the vibration characteristics of the building determined by the calculation method specified by the Minister, C_0: Standard shear coefficient

$$Q_{un} = D_s \times F_{es} \times Q_{ud} \quad (3)$$

$$Q_{ud} = Z \times R_t \times A_i \times C_0 \times \Sigma W_i \quad (4)$$

Where Q_{un}: Shear force for no-linear design, Fes: amplification coefficient for modulus of rigidity and eccentricity.

Many earthquakes have occurred in Japan, and many seismic motions have been observed. Comparing the strength of these earthquake motions with the performance required by the Building Standard Law, it is clear from the comparison of spectra that the actual earthquake motions act on a building about two to three times as much, as shown in Figure 1. The reason why collapse is prevented despite severe earthquake motion in the design is due to the margin of safety of materials and joints, as well as the margin of deformation, which is not taken into account in the structural design and is assumed to be the limit of collapse as shown Figure 2. In addition to this, there may be input reduction due to soil breaking in low-rise reinforced concrete buildings.

The lateral resistance elements of the seismic resistance elements are calculated as follows. The example of the load-deformation relationship shown in the Figure is used here. However, for some elements, the allowable resistance Pa and ultimate resistance Pu can be calculated without any tests. *Pa* is compared with the *Qi* mentioned above, and *Pu* is compared with *Qu*, and it is assumed that the requirement obtains seismic performance.

Figure 3 shows the backbone curve obtained from the cyclic loading test. Pa, the allowable shear strength, is determined by determining the minimum value of the following three criteria. $P_{1/200}$ can be softened up to $P_{1/120}$ by checking the finish material's conformity.

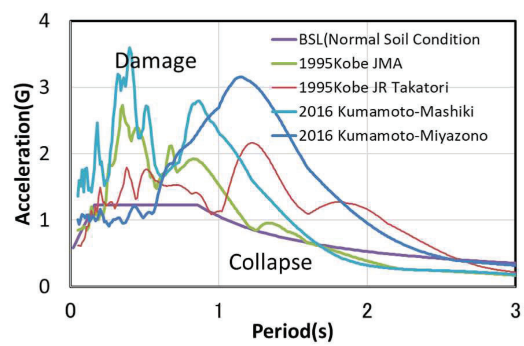

Figure 1 typical observed waves and BSL

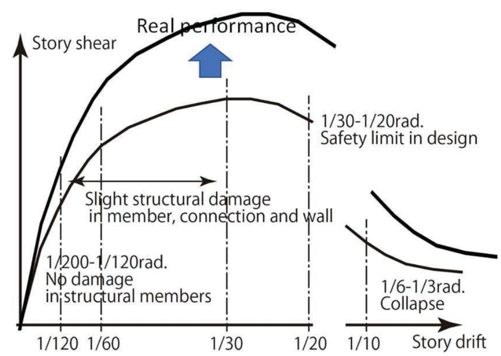

Figure 2 Limit state in design and real performance

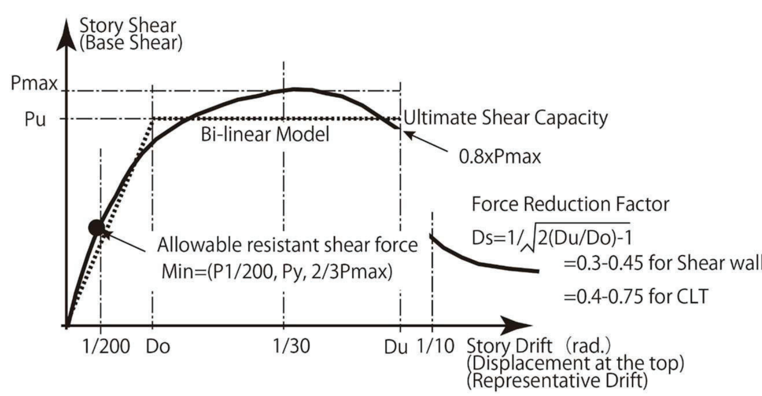

Figure 3 Load-story drift relationship

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$$Pa = minimum \begin{cases} P_{1/200} \\ 2/3 P_{max} \\ P_y \end{cases}$$

Where, $P_{1/200}$ is the load corresponding to the shear deformation of 1/200rad. *Pmax* is the maximum load, P_y is the yield strength calculated from the intersection of line I and III in the Figure, and Pu is the ultimate strength; δ_u and δ_y are pseudo ultimate defamation and pseudo yield, respectively, as shown in the Figure. The value of the wall multiplier is obtained.

In the past, when the number of shear walls was reduced to the minimum requirement shown in Figure 4, and the earthquake motion obtained in the 1995 Kobe earthquake was input to the building, the building almost collapsed. On the other hand, the same tests were conducted with additional finishing materials, which are gypsum hanging and lintel walls and siding, and it was confirmed that they did not lead to collapse. It is well known to Japanese researchers that the design ground motion is too small. If a building is to be designed more like a performance evaluation type, including the performance of finishing materials, the seismic input must also be close to the actual condition.

3 – SHAKING TABLE TESTS

3.1 TWO STORY RESIDENCIAL HOUSE

Isao Sakamoto provides an overview of the shake table tests conducted immediately after the Great Hanshin-Awaji Earthquake[1]. Based on this article, the outline is introduced below.

Since the Great Hanshin-Awaji Earthquake of 1995, the Tadotsu Engineering Research Center has carried out a series of experiments on wooden houses, and since then, experimental research on wooden buildings using shaking tables has been vigorously pursued. In the ten years since Kobe, if the reports on shaking table experiments on full-scale buildings are organized based on the proceedings of the Architectural Institute of Japan, the number of test buildings is about 30, and the number of published papers is over 80.

A few researchers researched the seismic performance of wooden houses before the Great Hanshin Earthquake. Although the vulnerability of wooden houses was reported with each earthquake, it did not become a social issue. This situation changed completely with the Great Hanshin Earthquake. Immediately after the earthquake, six shaking table tests were conducted at the Tadotsu Engineering Research Center, and these tests are regarded as the first to have dealt with the dynamic seismic performance of full-scale wooden houses profoundly and systematically. The test aimed to prove the seismic resistance of newly-built wooden houses at the time, in other words, to confirm the seismic resistance of wooden houses that met the required wall volume of the Building Standards Law at the time. In addition to the idealized test specimen, which was a two-story building with a square layout, there was also a two-story external wall mortar specification with an eccentricity of around 0.15, which is considered to be a typical building and a two-story house built by a private company that supported the primary purpose of the test. The input waves used were the waves observed at the Kobe Marine Meteorological Observatory during the Hyogo-ken Nanbu Earthquake, and the original waveforms were used without normalization from slight acceleration. In addition, the waves observed at El Centro in 1940, which are often used in earthquake response calculations, were used. This experiment confirmed that houses with wall volumes of around 1.5 times would not collapse due to these seismic waves.

Figure 4 Minimum requirement of BSL

After a series of experiments to confirm the seismic performance of full-scale houses, dynamic research was actively conducted to understand the effects of eccentricity and floor rigidity on the behavior of each part and design methods, as well as the effects of load speed. These are the main factors causing damage in earthquakes. In the study of eccentricity, experiments were conducted on box-shaped test bodies, taking into account the effects of the reduction in rigidity due to the use of exterior materials and vibration, with the primary objective of clarifying the differences in the effects of static and dynamic eccentricity and the effects of orthogonal walls and floor rigidity. In addition, analytical studies are also being carried out. In full-scale vibration tests of two-story frame wall construction, the effects of the layout of bearing walls, eccentricity, and floor

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openings are determined, and three-dimensional elastoplastic analysis and elastoplastic dynamic analysis are carried out and compared with the test results. At the same time, shake table tests were also being carried out on houses built using the frame wall construction method and wooden panel construction method, as well as on houses with seismic isolation devices added to these. These were aimed at performance-oriented design that responded to customer needs.

As detached houses with seismic isolation systems became commercially available and attracted attention, full-scale testing began to occur again. The purpose of the experiments has returned to the period immediately after the Great Hanshin Earthquake. While there have been cases in the past where shake table tests were conducted as part of product development by housing manufacturers, in recent years, there have been many cases where the aim was to achieve publicity effects. One of the keywords of recent times is "high seismic resistance," experiments have been conducted to prove that there is no damage even when the input doubles the observed wave of the Great Hanshin Earthquake or when the input is repeated several times.

The article introduces the high-seismic-performance housing with which the authors are involved. In Japan, high-performance damping buildings and houses are required to improve seismic safety and minimize damage because of many occurrences of severe earthquakes. On the other hand, Japanese wooden houses do not have enough shear walls to keep them large, and many openings and semi-rigid timber portal frames have been developed and increased. However, the semi-rigid timber frame structure is relatively soft. This study uses full-size shaking table tests to introduce the seismic performance of a semi-rigid timber frame structure with a damper, as shown in Figure 5. Response deformations during moderate and severe ground motions were compared among only frame, frame with oil damper, and frame with shear wall to verify the damping effect of oil damper.

Figure 5 Post and beam construction with damper

A law was enacted in 2000 to evaluate houses with high seismic performance. In addition, based on the idea of building good buildings and using them for a long time, the evaluation of long-term excellent houses began and came to be built widely. Four three-story shake table tests were conducted to verify their performances. Figure 6 shows a shake table test of a house designed in compliance with the law and a house with insufficient performance at the joints compared to the horizontal resistance capacity of the shear walls. As a result of inputting seismic motion over that assumed in the building standards, the house that complied with the law collapsed in the story, and the house with insufficient joints escaped collapse due to rocking behavior by the detached column base joint. Although the performance assumed by the standard law was demonstrated, the results made it necessary to consider preparing for unexpected motions.

Seismic retrofitting of existing homes remains an issue that needs to be solved, and unless this is resolved, major earthquakes will continue to cause damage. Shaking table tests, as shown in Figure 7, have been conducted to demonstrate the effectiveness of seismic retrofitting by comparing the results of tests on homes that have been retrofitted with those on homes that have not.

Figure 6 Three story long-term excellent quality houses

Figure 7 Existing house with/without reinforcement

4.2 HYBRID STRUCTURES

Since 1999, a research and development project on timber-based hybrid structures has been promoted in Japan as a five-year national project. The objectives of this project are to develop high-performance timber-based hybrid members and timber-based hybrid structures, which consist of timber and other materials, to develop the evaluation methods of structural performance and fireproof performance for these structures, and to develop the design method for some typical timber-based hybrid structures in this project. Some hybrid systems are proposed, and shaking table tests from one of the proposed types, a reinforced concrete core system with timber post and beam construction, were conducted, as shown in Figure 8. The key point of this system is the transfer of horizontal force through the floor system, and failure eventually occurred at the joint between the wood and R/C

Figure 8 Post and beam construction with R/C corer

4.3 CLT BUILDINGS

As the trend of medium- and high-rise wooden buildings gradually increases, cross-laminated timber, CLT, is one of the engineering woods attracting attention. With the advantages of high rigidity and load capacity, it has become a preferable material for construction purposes. In 2016, Japan promulgated its first structure design criteria according to CLT construction (Notification No. 611 [2]), including CLT in the Building Standards Law. Design and Construction Manual for CLT Buildings (the CLT Manual [3]) was published afterward, offering guidelines for structural design and construction for CLT buildings.

Figure 9 Three story specimen with wide panels

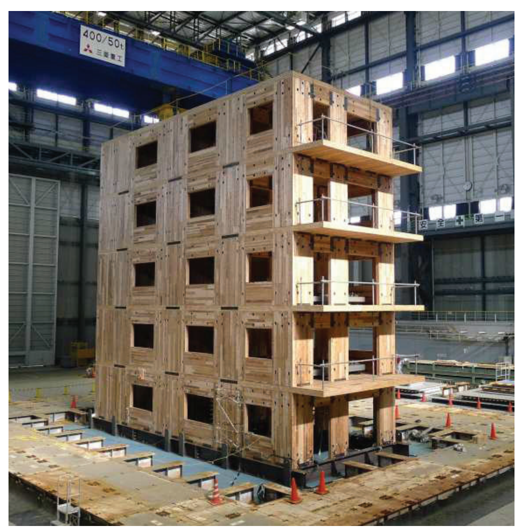

Figure10 Five story specimen with narrow panel

A great deal of analytical and experimental research was carried out in drafting these standards and manuals. In a series of studies, five shake table tests were conducted. The first was a three-story test with wide panels in Figure 9, and the second was a five-story test of Figure 10 with narrow panels and lintel and spandrel walls[4]. These tests aimed to verify the accuracy of the analytical model made based on the element tests, such as the moment-resistant test at the bottom of shear walls with and without lintel and spandrel walls. The three-story specimen consisted of three-ply and three layers CLT, and as the result of the test, the shear walls reached their ultimate state caused by shearing failure. The five-story experiment reached its ultimate state when the narrow panel shear walls, which are also vertical supports, buckled due to the overall rocking of the building. Both of these phenomena were confirmed because they were experiments on dynamic effects and the overall behavior of the building. After that, basic specifications were formulated for wide panels, narrow panels, and joint performance and positions, and three tests were conducted on three-story buildings to confirm their behavior. The behavior was as expected, but to accurately trace the actual behavior, it was found that friction, lintel walls, and spandrel walls needed to be accurately modeled.

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The collapse of CLT buildings is least understood, as limited research and experiments were conducted to investigate the limit state performance. In recent years, incremental shake table tests were conducted on two full-scale two-story platform-type narrow-panel CLT buildings, W1 and W2, to investigate the collapse limit state[5]. W1 featured two 1 m wide CLT shear walls per story, while W2 had a single 2 m wide CLT shear wall per story. The response of W1 was governed by rocking walls, whereas W2 was dominated by sliding at higher seismic intensities. The photo of W1 is shown in Figure 11. W1 and W2 did not collapse at the seismic excitation of JMA Kobe NS 140%, where the maximum inter-story drift ratios of 8.8% and 5.9% were achieved. The system has sufficient energy dissipation mechanisms, but the need for an overall system-level design that considers innovative connections is apparent.

In recent years, the post-tensioned CLT shear wall system has been attracting attention worldwide. It is a shaking table test with a three-story wooden building using CLT as two types of multi-layer shear walls, as shown in Figure 12. In addition, dampers were installed between the walls and side columns. One was connected drift-pin to inserted steel plates at both ends of the wall legs as a cantilever; the connection strength showed higher than expected, and brittle failure occurred. Therefore, it was confirmed that the control of the yield strength is important. The other was connected to the foundation using a pre-stressing steel bar in the vertical direction; seismic performance was higher than expected. The compression failure only occurred at the wall legs.

4.4 POST AND BEAM CONSTRUCTION

CLT is a building material that can be used to build high-rise timber structures, but in Japan, the post-and-beam construction method has been developed since early times. Even with the post-and-beam construction method, there have been attempts to achieve medium- and high-rise timber structures. Shaking table tests have been conducted on medium- and high-rise post-and-beam structures.

The target specimen was a full-scale of a five-story wooden building. Figure 13 shows an overview of the specimen. For med- to high-rise buildings, keeping a system that allows for overall collapse rather than shear collapse in a story is preferable. Even in post-beam construction, the seismic-resistant elements are shear walls, not post-beam moment connections; as a result, the ultimate state is assumed to be the story's collapse. In this test, a shear wall system with sufficient ductility and adequate location in each story can prevent the collapse of the story. It was confirmed that even with shear walls, it is possible to prevent extreme deformation from concentrating on any one floor, even for a building with about five stories.

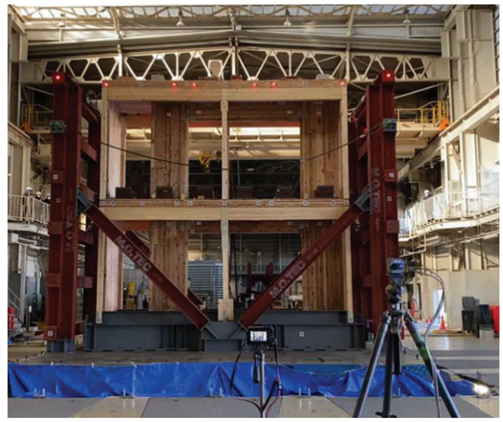

Figure 11 Two-story CLT construction to evaluate collapse limit

Figure 12 Rocking shear wall system

Figure 13 Five-story post-beam construction

5 – CONCLUSION

The authors have conducted many shaking table tests to date with the aim of earthquake disaster prevention. Full-scale structure shake table tests are expensive and sometimes conducted more as demonstrations than research. They provide data. Most of the introductions in this section are papers that have not been translated into English. The authors did not list them as a reference. If you use translation software, you can understand the content. If you have any questions, please contact us.

6– ACKNOWLEDGMENT

The test in Figure 4 was conducted as part of the Shaking Table Experimental Research Committee of the Building Materials Testing Centre. The test in Figure 6 was a collaboration research program with the NIED. The test in Figure 10 is a project supported by the Forestry Agency, with Nihon System Design and Architects as co-proposers. A Grant-in-Aid for Scientific Research supported Figure 11. Figure 12 was conducted as collaboration research with the Acura Group.

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