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CURRENT STATUS OF PERFORMANCE VERIFICATION FOR LARGE AND/OR SPECIAL CIVIL STRUCTURES

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Abstract

Recently, the heights and volumes of constructed buildings have been increasing. Similarly, bridges are being constructed with larger spans and lengths. The damage to structures such as huge buildings, bridges, or nuclear power plants can result in a substantial social impact; therefore, these structures should be designed such that they are safer than conventional structures. In particular, it is essential to verify the performance of such structures under earthquakes in earthquake-prone countries such as Japan. However, experimental verification based on a real-size structure as a test specimen under the reproduced ground motion of a real earthquake is almost impossible. As a result, analytical verifications should be conducted.

A structural design does not require the true values of stress and deformation. It only requires proof that the stress and deformation generated by external forces are within the acceptable criteria. However, to design safer structures, we must evaluate the response to a larger external force with higher reliability and improve the accuracy of the evaluation. Therefore, the evaluation methods involved in the current structural design paradigms are reviewed in this study, which will facilitate the design of safer structures in the future.

A few full-scale specimens were tested using a shaking table; however, there were limited to those for small structures such as a wooden structure of a building or at most a five-story reinforced concrete or steel building. The response evaluation of large structures was conducted based only on analytical simulations. Some of the analytical structural models were validated via experiments employing full-scale specimens; however, a majority of the implemented experiments used reduced scale specimens. The columns of the tallest building in Japan use concrete-filled tubes with steel and concrete of high strengths. The structural design has been validated based on tests using 1/4 scaled specimens. A large, scaled reinforced concrete beam was tested using seven similarity test specimens, whose depth varied from 100 mm to 3000 mm. The tests were conducted to observe scale effects; the results indicated that the rapture patterns depend on the scale of the specimen, and that the shear strength is inversely proportional to the 1/4th power of length.

Earthquake observation is the only solution to verify the performance of a real large structure as a whole under an earthquake. A finite element analytical model of the No.2 nuclear power plant in the Onagawa site, Japan, was verified in detail using observation records of the ground and structure obtained during the 2011 Tohoku earthquake. A blind analysis is a useful and effective method to directly prove the accuracy of the analysis. In the blind analysis, the response is evaluated prior to the verification test. In an example for the limit state pressure test on a 1/4 scaled pre-stressed concrete containment vessel of a pressurized water reactor type nuclear power plant, which was conducted after the analysis, the stiffness and strength were accurately evaluated prior to the tests. As for a blind analysis of the dynamic response analysis, the response of a four-story steel frame under earthquakes was calculated without knowing test results and verified using the test results.

Although a large structure cannot be tested as a whole, the members of the structure should be tested to validate its analytical model. Currently, these members are mainly tested using a scaled model, in one direction, and in quasi-statically. For future structural designs, the tests should employ full-scale specimens and dynamic loadings and also consider multiple direction.

Keywords: review paper, structural design, performance verification, large structure, full-scale test

1. Introduction

Recently, the heights and volumes of constructed buildings have been increasing. Similarly, bridges are being constructed with larger spans and lengths. However, damage to structures such as huge buildings, bridges, or nuclear power plants can result in a substantial social impact; therefore, these structures should be designed to ensure that they are safer than conventional structures. In particular, it is essential to verify the performance of such structures under earthquakes in earthquake-prone countries such as Japan. However, experimental verification based on a real-size structure as a test specimen under the reproduced ground motion of a real earthquake is almost impossible. As a result, analytical verifications should be conducted. For the design of safer structures, it is necessary to evaluate the response to a larger external force with higher reliability and also improve the accuracy of this evaluation. Therefore, the evaluation methods involved in the current structural design paradigms are reviewed in this study, which is expected to facilitate the design of safer structures in the future.

2. Classification of verification

The methods to verify and validate structural designs consist of a combination of loading tests of specimens and simulation analyses. These methods are classified into five categories, as shown in Table 1.

Table 1 – Classification of verification and validation methods

Category	Test		Analysis
	Scale	Model	
I	Full-scale	Whole structure	None
II	Full-scale	A member	Whole structure
III	Reduced-scale	Whole structure	None
IV	Reduced-scale	A member	Whole structure
V	None		Whole structure

If the test is conducted properly and has sufficient accuracy, the method in category I is the optimal method; contrarily, the methods in categories IV and V are the second worst and the worst, respectively. Standard tests consist of appropriate combinations of the specimen, fixing to the test facility, and measurement and excitation. Furthermore, the tests should be conducted with due consideration to effects such as dependency on rate, orthogonal displacement, repeated cycles, temperature etc. These dependencies relate to conditions such as loading speed and direction.

The actual force on a structure during an earthquake is dynamic and has six degrees of freedom. It is difficult or impossible to apply these conditions to a real structure during a test. As a result, earthquake observation is the only method to verify the structural performance of a real structure under the action of an earthquake.

A blind analysis is useful to validate the analysis. These verification and validation methods are introduced in the following sections.

3. Current status of verification

3.1 Category I: Full-scale test of a whole structure

A few studies have tested real-sized structures by employing a shaking table; however, these experiments were limited to small structures such as wooden structures or at most a five-story reinforced concrete building. Examples of these tests are shown in the following subsections. Figure 1 depicts an outline of the specimens used in these tests.

Thus far, full-scale tests have not been conducted for large structures. Consequently, we must wait for the occurrence of a large earthquake, to verify the structural performances of these structures.

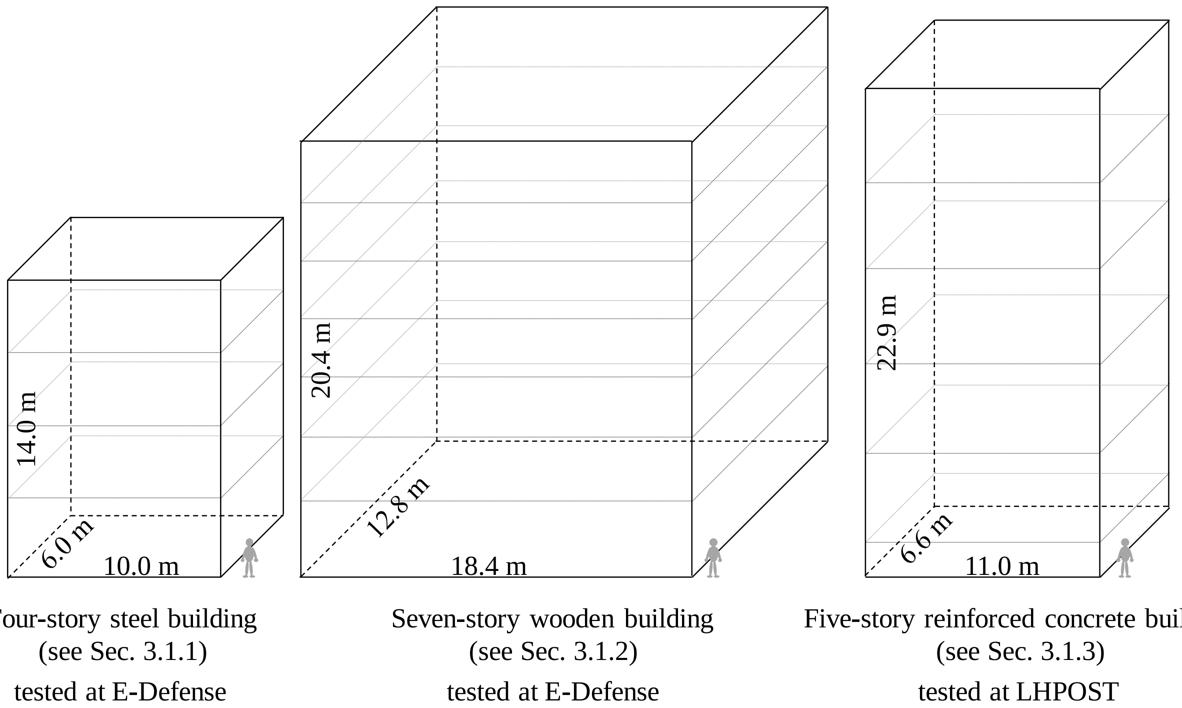


Fig. 1 – Outline of specimens referred in Sec. 3.1 (Category I)

3.1.1 Four-story steel building

Many full-scale shaking-table projects were conducted at E-Defense at the National Research Institute for Earth Science and Disaster Resilience (NIED), Japan [Nakashima et al. (2017)]. The specimen was designed as a whole structure in those projects. Yamada et al. (2008) conducted a full-scale experiment on 4-story steel moment frame. This experiment was planned to evaluate the structural and functional performance of the steel moment frame under design-level ground motions, and to evaluate the safety margin against collapse under exceedingly large ground motions. Therefore, the experiment was continued until the frame collapsed.

The specimen building has plan dimensions of 10 m (two-bay) in the longitudinal direction (Y) and 6.0 m (one-bay) in the transverse direction (X). Each story has a height of 3.5 m, resulting in an overall story height of 14 m. The structure was designed according to the most common design considerations exercised in Japan for steel moment frames following the 1995 Kobe earthquake. The designed natural periods of the specimen in the Y-direction are 0.90 s in the 1st mode and 0.29 s in the 2nd mode. The total weight of the specimen is 2113 kN.

The JR Takatori station record [Nakamura et al. (1996)], which was obtained during the Kobe earthquake, was used as the input wave. The NS, EW, and UD components were considered for the Y-, X-, and Z-directions, respectively. Suita et al. (2008) summarized the results of this experiment especially for collapse behavior. The input motion was applied repeatedly with increasing scale factors from 0.05, 0.2, 0.4, 0.6, to 1.0. The design basis earthquake was equivalent to the input motion with a scale factor of 0.4. The collapse occurred at 1.0 times the Takatori records, with a peak ground velocity of 1.28 m/s, which was 2.5 times greater than the design basis earthquake [Suita et al. (2008)].

3.1.2 Seven-story wooden building

A shaking table test of a full-scale seven-story wooden (steel-wood) apartment building that would be constructed in the United States was also conducted using E-Defense, to verify its seismic performance under a large earthquake ground motion [van de Lindt et al. (2011)]. The specimen was a single-story steel moment frame with six stories of wood on top. The specimen had an approximate length of 12.8 m, breadth of 18.4 m, and height of 20.4 m.

Van de Lindt et al. (2011) concluded that the building was found to perform excellently, with significantly low damage following an event that was slightly larger (×1.16) than the design-level event for the city of Los Angeles, California. The peak global drift at the roof level was 166 mm, and the peak inter-story drifts were approximately 1.3%.

3.1.3 Five-story reinforced concrete building

Chen et al. (2016) conducted a full-scale test of a five-story reinforced concrete (RC) building by using the Network for Earthquake Engineering Simulation unidirectional Large High-Performance Outdoor Shake Table (LHPOST) at the University of California, San Diego. The test building had a plan dimension of 6.6 m by 11.0 m at its base and a total height of 22.9 m above the shake table platen.

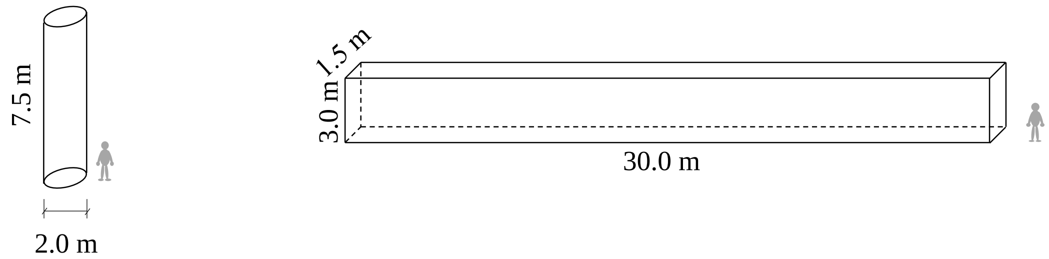
This experiment focused on investigating the interaction between structural and nonstructural component systems (NCSs) during earthquakes. Therefore, the building was equipped with a large variety of essential NCSs including a passenger elevator. The building was subjected to a suite of earthquake motions of increasing intensity while base-isolated, and then fixed to the shake table platen. Post-earthquake live fire tests within select earthquake damaged compartments were also conducted to evaluate the performance of fire protection systems.

Chen et al. (2016) concluded that base-isolation is a highly effective method for attenuating acceleration demands and minimizing inter-story drift ratios. The building remained quasi-linear-elastic throughout the base-isolated testing phase. While fixed at its base, peak inter-story drift ratios reached about 6% during the maximum intensity earthquake.

3.2 Category II: Full-scale test of a member and analysis of the whole structure

Experimental testing of large structures as a whole is not realistic. Instead, a full-scale principal member is experimentally tested to constitute an analytical model of the member and/or to confirm its strength. The whole structure is analytically evaluated by implementing the model into the analytical model of the whole structure.

Examples of full-scale model tests of a member are shown in the following subsections. Figure 2 shows the outline of specimens used in the tests.



Reinforced concrete bridge column (see Sec. 3.2.1) tested at E-Defense

Large reinforced concrete beam (see Sec. 3.2.2) tested at a field

Fig. 2 – Outline of specimens referred in Sec. 3.2 (Category II)

3.2.1 Reinforced concrete bridge column

A full-scale RC bridge column was tested using E-Defense [Kawashima et al. (2009), Ukon et al. (2012)]. The purpose of the test was to clarify the failure mechanism of a single RC column. Kawashima et al. (2009) used specimens C1-1 and C1-5 that were designed based on the 1964 and 2002 design code in Japan, respectively. Specimen C1-1 represented typical columns built in the 1970s that collapsed during the 1995 Kobe earthquake. Specimens C1-1 and C1-5 were 7.5 m tall, 1.8 m, and 2.0 m diameter, respectively. The specimen was anchored to the shake table by a 1.8 m thick square footing and supported a 302 t mass on the top. The JR Takatori station record was used in this experiment again.

Ukon et al. (2012) conducted an analytical simulation of this experiment using a fiber element model which consisted of 635 nodes and 1,226 elements. Each element was assigned a non-linear characteristic that precisely simulated steel or concrete based on the best knowledge available. They concluded that their dynamic analysis had an excellent accuracy for a response with low-plastic range; however, the accuracy was insufficient when the plastic response was dominant.

They also pointed out that the core concrete of the column had crashed and came out of the constrain bars in the full-scale test. This failure mode was different from that from a conventional small-scale testing.

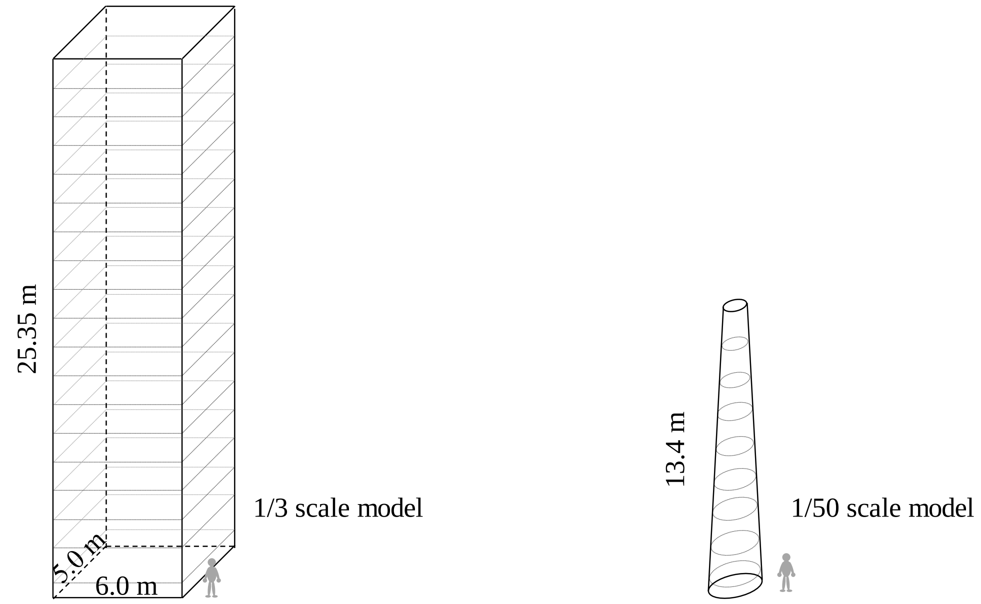
3.2.2 Large reinforced concrete beam

Iguro et al. (1984) tested large RC beams using seven similarity test specimens whose depth varied from 100 mm to 3000 mm. The width was half of the depth. The tests were intended to observe the scale effect of shear strength; therefore, the specimens were designed to not have shear reinforcing bars. The span of the specimens was fixed to 12 times their depth to induce diagonal tension failure. Therefore, the span of the largest specimen was 36 m.

A uniformly distributed load was applied quasi statically using a rubber bag with hydro pressure. Iguro et al. (1984) observed almost the same number of cracks in spite of the specimen's depth. This implied that the crack width was proportional to the depth; hence, shear strength reduced according to the depth. They concluded that the scale effect of shear strength is inversely proportional to 1/4th power of length for beams whose depth is more than 1 m.

3.3 Category III: Reduced-scale test of a whole structure

Large structures cannot be tested as a whole because of their size, weight etc. When a large structure is tested as a whole, the specimen must be a scaled model. Examples of these tests are shown in the following subsections. Figure 3 shows the outline of specimens used in the tests.



Eighteen story steel building (see Sec. 3.3.1) tested at E-Defense

Shanghai Tower (see Sec. 3.3.2) tested at State Key Lab. of Disaster Reduction in Civil Eng., Tongji University

Fig. 3 – Sizes of specimens referred in Sec. 3.3 (Category III)

3.3.1 Eighteen-story steel building

Suita et al. (2015) conducted a shaking table test of a scaled model of a steel high-rise building using the E-Defense test facility to investigate the collapse behavior under exceedingly large ground motions. The building specimen was a one-third scale model of an 18-story steel moment frame. The width, depth and height of the specimen were 6 m, 5 m, and, 25.35 m, respectively. The total weight of the specimen was 3800 kN without including its foundation. The steel frame was designed according to the design specifications and practices in date from the 1980s to 1990s. Dampers were not installed, because the use of dampers was uncommon in this period.

The specimen finally collapsed after repeated loadings of long-period and long-duration ground motion. The input ground motion was gradually increased up to maximum pseudo velocity of 4.2 m/s under a damping factor of 5%. Suita et al. (2015) examined the test results precisely and understood the collapse process. The beams of the lower stories yielded followed by fracture of the bottom flange. Hence, the flexure length of columns elongated to multiple stories followed by plastic hinges in the elongated columns.

3.3.2 Shaking table model test of Shanghai Tower

Chinese seismic design guidelines request buildings that are designed beyond related codes to first be studied through the experiment on seismic behavior. Lu et al. (2013) conducted a shaking table test of Shanghai Tower that is a super tall building whose height is 632 m. The height is far beyond the design code in which maximum applicable height is regulated as 190 m for RC core wall. The structural system of the building is also irregular and beyond the design code.

The test specimen was a 1/50 scaled model and was 13.04 m high in total with the inclusion of the base beam. The whole mass of the specimen was approximately 25 t including a rigid base of 4.1 t. The test was carried out at the State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China. Based on the test results, Lu et al. (2013) suggested improvement to the stiffness of the shear walls at the top stories and the modification of the cross-section size of vertical elements at particular stories.

3.4 Category IV: Reduced-scale test of a member and analysis of the whole structure

A member of a large structure is still of large size, stiffness and of high capacity to test in full-scale. Therefore, tests of scaled models of a member are often carried out.

3.4.1 Concrete-filled steel tube column

Yamada et al. (2010) designed columns of a 300 m tall building in Japan by using a concrete-filled steel tube (CFT) with high strength steel and high strength concrete. The strengths of steel and concrete were 150 N/mm^2 and 590 N/mm^2, respectively. They were beyond the conventional design guideline; therefore, an experiment was conducted to validate the structural design. The test specimens were square columns of 0.25 m with a height of 1.25 m which were 1/4 scaled models of the building column. The thickness of the steel tube is 9 mm. They simultaneously applied a quasi-static compression force of 8,846 kN and a shearing force of 332 kN. The specimen was scaled; however, the applied force was large.

Based on the test results, Yamada et al. (2010) found that the conventional design guideline, which is not applicable to this CFT column, overestimates the strength of the CFT column. They also found that the guideline gives a safety-side evaluation of the strength by reducing the concrete strength to 0.7 times.

As for the CFT columns, those larger than that of the above building were used in the China Zun Tower. The Zun Tower has a total height of 528 m and 108 floors above the ground. The building is supported by four polygonal mega multi-cell CFT columns. The column has thirteen cells, each of which forms a CFT. Dong et al. (2018) examined the rectangular CFT at both ends along the long axis of the mega-column that bore a load larger than any CFT formed by other cells. Six 1/4 scale CFT column specimens were designed to investigate the effect of stiffeners, tie bars, welding studs, internal diaphragms and steel bar cages. All the columns had the same cross-section of 0.51 m by 0.64 m and a length of 2 m. The thickness of the steel tube was 16 mm. The average standard compressive cube strength of the tested concrete samples was 46.0 N/mm^2 on the day of column testing. Q345, which has a yield strength of 345 N/mm^2, was used for all the steel plates.

The tests were carried out at the Key Laboratory of Urban Security and Disaster Engineering at Beijing University of Technology. The specimens were tested under repeated axial compression loading using a hydraulic jack with a capacity of 40,000 kN. The maximum applied compression force was approximately 30,000 kN. Based on the test results, Dong et al. (2018) proposed a method of calculating the ultimate bearing capacities for the six tested specimens.

3.4.2 Pile foundation

A pile used along with a raft foundation in a high-rise building bears a large force during construction. Watanabe et al. (2017) estimated the maximum force to be 60,000 kN for a 220-m high-rise building in Japan. The diameter of the pile was 2.7 m at the axial portion and 4.7 m at the enlarged portion at the end. The bearing capacity of a pile depends on the soil where the pile is constructed. Watanabe et al. (2017) conducted an on-site loading test of a pile to obtain the design parameters—the maximum skin friction coefficient and maximum end bearing stress—of the pile. They constructed a specimen pile with a diameter of 1.1 m at the site. The pile end reached firm soil 76.1 m below the ground surface. The length of the pile was 40 m; therefore, except the lower 40 m part of the pile was isolated from the soil to cut the friction.

The loading apparatus included a pull jack that was connected from the top of the pile to the reacting piles through a reacting beam and a push jack that was installed in the pile end. They used the push jack and/or pull jack depending on the part of pile that was to be investigated. For example, they pushed up to 10,900 kN at the pile end and pulled up to 25,100 kN to investigate total skin friction. Watanabe et al. (2017) decided the design parameters based on the results of this test.

3.5 Category V: Analysis of a whole structure

Due to the developments in computer technology, precise analyses of a whole building has been attempted using the finite element method. Miyamura et al. (2015) precisely modeled a super-high-rise steel frame, mat slab, and soil region using hexahedral solid elements and generating a large-scale finite element mesh of the frame on the soil region. A preliminary seismic response simulation using the mesh was performed on the K computer [Oinaga et al. (2012)], which was one of the fastest supercomputers in the world, using the parallel finite element analysis code E-Simulator [Hori et al. (2017)] developed at NIED.

The steel frame in the model was a super-high-rise office building whose total height, width, and depth were 129.7 m, 50.4 m, and 36.0 m, respectively. The building was built on a mat slab whose height, width, and depth were 3.9 m, 51.0 m, and 36.9 m, respectively. The mat slab was placed on a soil region whose height, width and depth were 100.0 m, 1000.0 m and 1000.0 m, respectively. The mesh had 28,363,862 elements, 37,311,413 nodes, and 111,934,239 DOFs. The computation time for 17 s of the preliminary seismic response analysis was approximately 18 days using 256 nodes (2,048 cores), on the K computer.

Miyamura et al. (2015) concluded that the results of the preliminary simulation demonstrated the feasibility of a large-scale parallel finite element analysis using solid elements for the seismic response analysis of building structures, considering soil-structure interactions.

4. Comments on verification schemes

4.1 Earthquake observation

Earthquake observation is the only solution to verify the performance of a real, large structure as a whole under the action of an earthquake. An earthquake is not controllable; therefore, this method cannot be used always. Furthermore, this method can be applied to a completed building, not for a building in the design stage. Because of this, we do not list the earthquake observation method in Table 1.

Baba et al. (2015) modeled a super-structure above the operating floor by finite elements where the wall and roof slab were modeled by layered shell elements, and where columns, beams and trusses were modeled by linear elements. Layered shell elements had seven layers that were modeled as rebars and concretes corresponding to their locations. They used earthquake observation records at the operating floor during the Tohoku earthquake on March 11, 2011 and the aftershock on April 7, 2011. The earthquake records were sequentially input to the analytical model.

The results of the response spectra had good agreement with those from the earthquake observation data. Baba et al. (2015) estimated that the rebar in the wall remained in the elastic range.

4.2 Blind analysis

A blind analysis is a useful and effective method to directly determine the accuracy of an analysis. In the blind analysis, the response is evaluated prior to its verification test. Contrarily, in a round robin analysis, a number of participants conduct analyses based on the same given information. The subject of this analysis is often the prediction of future testing results. Therefore, the blind analysis is a part of the round robin analysis.

4.2.1 Four-story steel building

The testing described in section 3.1.1 was used as a problem of an international blind analysis contest sponsored by NEID in 2007 [Ohsaki et al. (2008a)]. The purpose of the contest was to stimulate the development of computational methods and efficient modeling techniques for collapse analysis.

The actual motion of the table was not known before the test; therefore, the contest had two parts: pre-test analysis based on anticipated seismic motions, and post-test analysis using the actual table acceleration. The building model and the analysis procedure for the post-test analysis were required to be identical to those for the pre-test analysis except for the properties of the concrete material and input accelerations. There were four categories depending on whether the analysis was 2-D or 3-D, and whether the participants were researchers or practicing engineers [Ohsaki et al. (2008a)].

The first author of this paper, who was one of the winners of the contest, conducted a 2-D analysis using a non-linear model which consisted of line elements, hinge elements, and panel-zone elements considering P-Δ effect due to an overturning moment and a vertical response, negative stiffness caused by local buckling, and asymmetrical hysteresis for beams with reinforced concrete slabs. The analysis results simulated the experimental ones well except for the residual story drift angle of the first story [Ohsaki et al. (2008b)].

4.2.2 Pre-stressed concrete containment vessel

Limit state pressure tests on a 1/4 scale pre-stressed concrete containment vessel of a pressurized water reactor type nuclear power plant were conducted in September 2000, in Albuquerque, USA. A round robin analysis was also held as an international contest before and after this test. Yonezawa et al. (2003), who was the winner of the contest, described that the analysis results of participants varied, especially with regard to the displacement at the top of the dome. Yonezawa et al. (2003) predicted the test results well using a 3-D finite element model; however, they were not able to predict the leakage due to liner break. They suggested that the break was caused by insufficient welding.

The purpose of the post-test analysis of this contest differed from that mentioned in the previous section. In this contest, the participants knew the test results and improved their analysis accordingly. Yonezawa et al. (2003) observed the test results and found that extreme drying shrinkage due to the weather in Albuquerque reduced the initial stiffness of the vessel; consequently, they modified their model by considering this effect of drying shrinkage.

5. Conclusion

In this review paper, we have categorized methods to verify and validate structural design into five categories. The first four methods are categorized based on whether an experiment is conducted in full or in scale and whether the specimen is a whole structure or a member. The last method is based on a verification method only based on an analysis. We presented examples according to these categories.

Finite element analysis enables a precise estimation of the results; however, it has been pointed out that its accuracy is insufficient when the nonlinearity is increased. Furthermore, a blind analysis revealed that the analysis results varied significantly among participants. It also suggested that the response in fracture state is hard to predict by simulation analysis. Therefore, we believe that validation based on experiments is inevitable.

Examples of full-scale tests on a whole structure are those conducted for relatively small structures. Although a large structure cannot be tested as a whole, members of the structure should be tested to validate its analytical model. Although there are examples of full-scale experiments of members of large structures, these members are currently mainly tested using a scaled model, in one direction, and in quasi-statically.

The results from these experiments only evaluate the design in extrapolation. However, an interpolative evaluation is essential to validate the structural design. In future structural designs, these tests should employ full-scale specimens and dynamic loadings and also consider multiple direction.

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