14th International Conference on Structural Safety and Reliability - ICOSSAR'25
1-6 June, 2025 - Los Angeles California, USA
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THE SHAKE TABLE TEST STUDY ON HIGH-RISE SHEAR WALLS CONSIDERING THE SPATIAL VARIABILITY OF CONCRETE MECHANICAL PROPERTIES

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Key words: Shake Table Test; Spatial Variability; Concrete Mechanical Properties; Nonlinear Response.

Abstract. *Concrete materials in concrete structures exhibit significant randomness and spatial variability, which have considerable impact on the random responses and global reliability of these structures under seismic and other disastrous loads. To quantitatively assess the influence of uncertainty, particularly spatial variability, in mechanical properties of concrete on the seismic responses of structures, a large-scale shake table test was conducted. In this study, four single-span, 9-story reinforced concrete shear wall structures were simultaneously cast and cured. These structures were subjected to identical seismic input on the same shake table to obtain corresponding seismic responses. The experimental design aimed to keep the structural models simple while ensuring a large similarity ratio, allowing the effects of spatial variability of concrete to be reflected in the structural damage and seismic response. The study also ensured that the four structures were synchronized in casting, curing, and seismic input, with the loading process avoiding cumulative damage in the structures. Based on the experimental data, key results, including natural frequencies, damage distribution, and seismic responses, were analyzed and discussed. Preliminary results indicate that: (1) Concrete uncertainty leads to different forms of structural damage and failure; (2) Significant differences in both the fundamental frequency and higher-order natural frequencies are observed; (3) The relative ranges of inter-story displacement angles—defined as the difference between the maximum and minimum values divided by the mean—generally reach 30%, with certain floors under specific tests significantly exceeding this value. This comprehensive experimental dataset provides valuable reference data for the quantification of spatial variability, and the validation and* *improvement of numerical simulation methods, and demonstrate the necessity of involving spatial variability in the performance and reliability evaluation of concrete structures.*

1 INTRODUCTION

In structural analysis, the inherent randomness and nonlinearity of concrete are tightly coupled, as they stem from the complex physical processes governing structural damage and failure. Variability in concrete properties arises from factors such as raw material inconsistencies, environmental conditions, and construction practices [1-3]. As such, neglecting material uncertainty in nonlinear analysis of reinforced concrete structures can lead to unreliable predictions or even misleading conclusions.

Numerous studies have underscored the stochastic nature and spatial variability of concrete constitutive parameters [4,5]. Recognizing this, the design codes require the consideration of material randomness [6-9]. Spatial variability, in particular, is driven by heterogeneous composition, curing conditions, and local defects. For instance, Tao and Chen [10] observed significant fluctuations in compressive strength across a large-scale concrete slab, while Geyer et al. [11] adopted a hierarchical Bayesian approach to identify the correlation length of compressive strength, highlighting the need to incorporate spatial variability into structural models.

Actually, numerous researchers have examined the spatial correlation of the physical and mechanical properties of concrete using destructive and non-destructive testing methods. For instance, the correlation length of rebound values obtained by using the rebound hammer method was reported as 0.80 m [12] and 0.74 m [13]. The correlation length of ultrasonic pulse velocity, measured using the ultrasonic method, was found to be 0.40 m [12] and 1.24 m [14]. Similarly, the correlation length of moisture content, assessed via electrical resistivity measurements, ranged from 0.9 to 1.02 m [15]. These findings indicate that different concrete properties exhibit varying degrees of spatial correlation. Given these limited correlation lengths, accounting for spatial variability remains essential for practical structural applications. Tao [16] incorporated the spatial variability of concrete compressive parameters into a hysteretic performance simulation of shear walls, which identified multiple failure modes, further underscoring the necessity of integrating spatial variability into predictive models. Concrete randomness also influences structural reliability and failure mechanisms. Li et al. [17] conducted static pushover tests on eight geometrically identical reinforced concrete frames and observed notable differences in cracking and plastic hinge development, driven by material variability. These findings underscore the limitations of deterministic models and the necessity of probabilistic approaches.

Although dynamic tests on shear walls have been widely conducted [18-21], material randomness has often been overlooked. A notable exception is the work by He et al. [22], who integrated concrete property randomness into shaking table tests on two nine-story shear wall structures by using the Bayesian compressive sensing [23] and the Karhunen-Loève (K-L) expansion [24,25]. His experimental work primarily demonstrated the critical importance of constitutive models, indicating that inaccurate constitutive relationships can lead to erroneous results in nonlinear structural analysis.

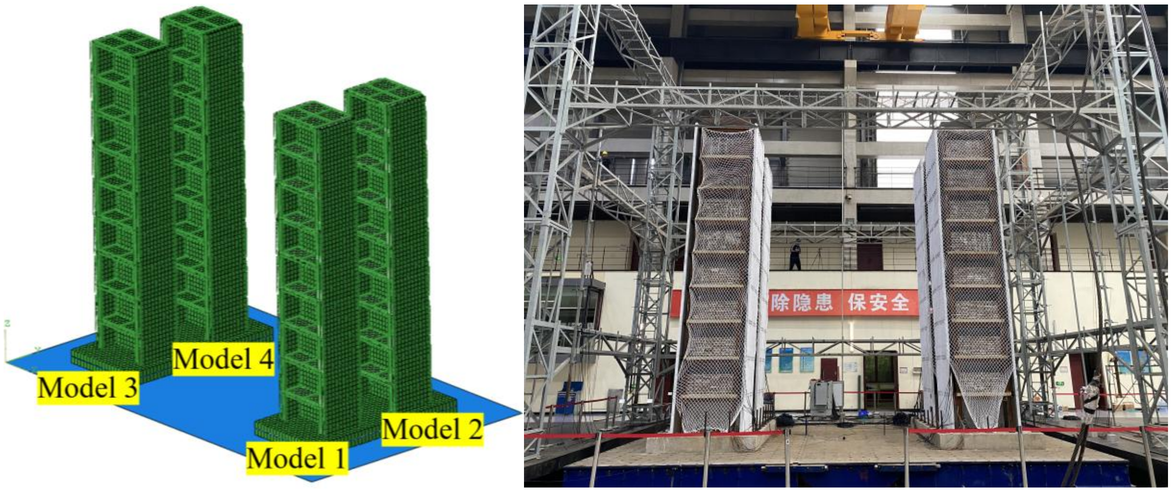
This raises a fundamental question: To what extent does material randomness affect seismic response? Addressing this is vital for improving structural reliability under extreme loads.

To this end, this study presents a large-scale shaking table experiment involving four identically designed, cast, and cured nine-story shear wall structures. All specimens were subjected to identical seismic excitations on the same shaking table. This experimental setup isolates the effect of concrete randomness on seismic response, providing deeper insights into its role in performance-based design and reliability assessment of reinforced concrete structures.

2 TEST SETUP

2.1 The design of experimental structural models

The shake table test models consist of four 9-story shear wall structures, and the geometric dimensions and materials of the four structures are identical. The overall arrangement of the four structures is such that Model 1 and Model 2 share one foundation, while Model 3 and Model 4 share another foundation, as shown in **Figure 1**.



(a) Designed experimental structure (b) Actual experimental structure

Figure 1: Overall diagram of the experimental structure

The structural dimensions are shown in **Figure 2**. The foundation of the structure has a span of 2100 mm in the x-direction and a span of 3940 mm in the y-direction, with a thickness of 300 mm. Two identical structures are placed on each foundation, with a total height of 7540 mm for each structure, consisting of nine stories, each with a floor height of 800 mm. Each structure is arranged with one web wall in the x-direction and two wing walls in the y-direction, with the seismic excitation applied in the x-direction.

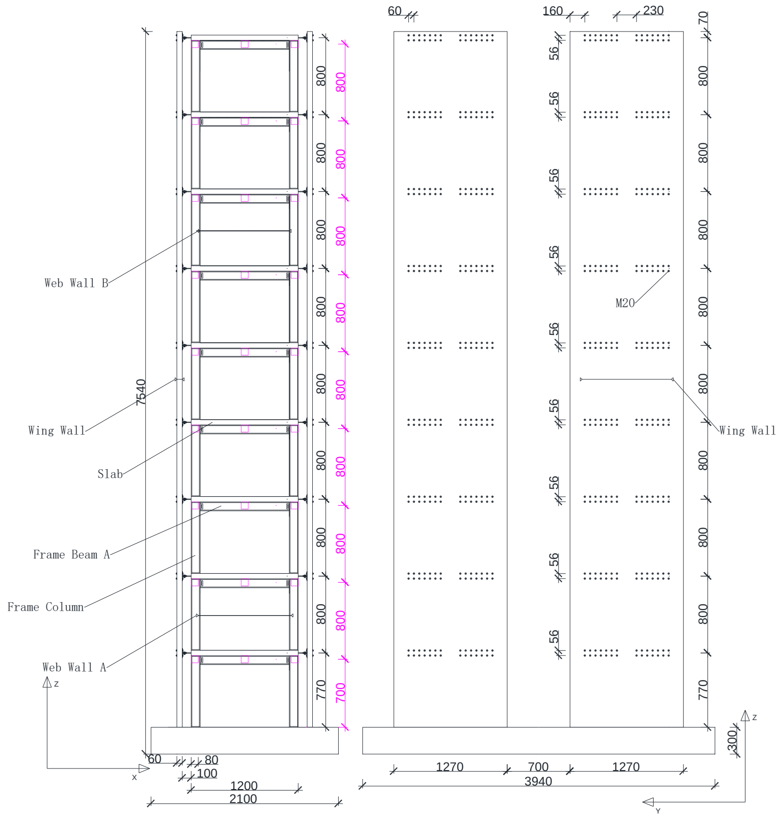


Figure 2: Elevation view of the experimental structure

2.2 Scale ratio

The similarity ratio of the test model length, s_L , is 1:4. Meanwhile, full-scale steel and concrete materials are used for the structure, ensuring that the stress similarity ratio, s_σ , is 1:1 and the acceleration similarity ratio, s_a , is 1:1. Considering the above constraints, the similarity relationships for length, time, and mass are 1:4, 1:2, and 1:16, respectively.

According to the scaled model with this similarity ratio, the total height is 7540 mm, and the total mass should be 29.4 tons. The earthquake simulation shake table array on Tongji University's Jiading Campus consists of multiple shake tables, among which two have a load capacity of 70 tons each and can be combined to form a larger shake table with a total load capacity of 140 tons. This configuration allows for the simultaneous testing of four structures. The self-weight of each structure is 7.88 tons, so an additional mass of 21.52 tons needs to be designed for each structure, with an extra 2391 kg added to each floor.

3 EXPERIMENTAL CONTENTS

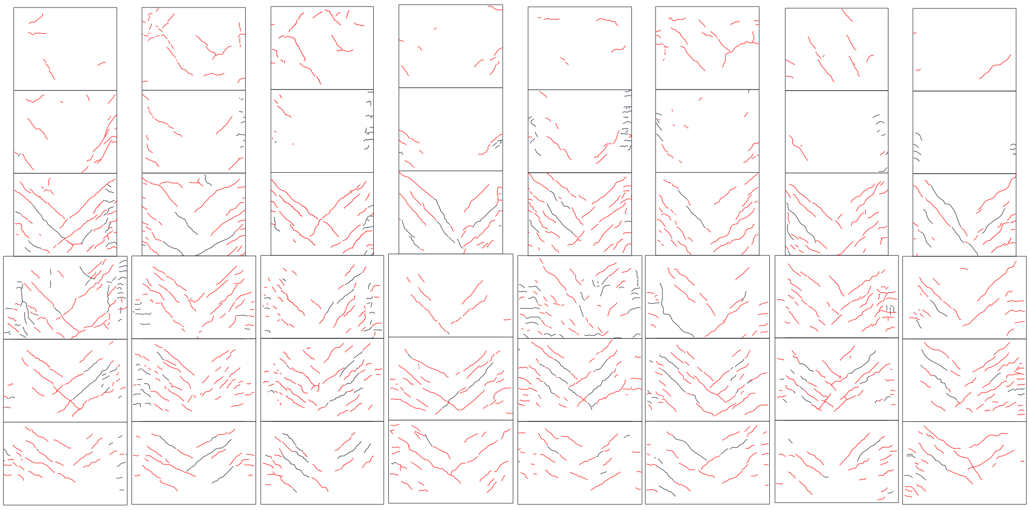
The shake table tests mainly include four categories: white noise scanning (GK1, GK3, GK5, GK7, GK9, GK10, and GK12), small earthquake simulation (GK2, GK4, and GK6), large earthquake simulation (GK8), and aftershock simulation (GK11). Each simulation employs unidirectional loading, with the loading direction in the x-direction. The large earthquake simulation is applied directly after the small earthquake simulation in order to minimize cumulative damage.

4 EXPERIMENTAL OBSERVATIONS

To observe the crack development in the web walls, the crack distribution maps were drawn for the eight surfaces across four specimens following the mainshock and subsequent aftershock, as shown in **Figure 3**. In the figures, black lines represent cracks formed after the mainshock, while red lines indicate additional cracks that developed after the aftershock. Considering the consistency of boundary conditions and the geometrical symmetry of the specimens, the eight surfaces were categorized into two groups for comparison. The first group, denoted as the O (outside) group, includes the external faces of the web walls of the four specimens. The second group, referred to as the I (inside) group, includes the internal faces of the web walls. By inspection, the following conclusions can be drawn:

(1) After the mainshock, relatively few cracks were observed. The direction and distribution density of the cracks varied significantly among the four specimens, highlighting the considerable influence of concrete material randomness on the structural response under strong seismic excitation.

(2) After the aftershock, cracks developed substantially in all four specimens. Overall, diagonal cracks predominated. While the overall crack densities became more consistent, notable local differences remained, indicating that material randomness in concrete must still be considered in refined structural analysis.



(a)1-O (b)2-O (c)3-O (d)4-O (e)1-I (f)2-I (g)3-I (h)4-I

Figure 3: Crack distribution on all faces after the aftershock

5 ANALYSIS OF EXPERIMENTAL RESULTS

5.1 White noise tests

The following analysis is conducted based on the results under the white noise tests. The modulus of the acceleration frequency response function (FRF) is used to describe the structure's inherent characteristics in the frequency domain. In this study, the poly-reference Least Squares Complex Frequency domain method (p-LSCF, aka. PolyMAX) is applied to obtain the FRF of the system [26]. This method is known for the capability of generating a clear stability diagram [27-29].

The following conclusions can be made:

(1) The structural fundamental frequencies exhibit no significant change after the minor earthquake excitations (GK2, GK4, GK6), indicating that the structures remained within the linear range. However, after the major earthquake (GK8) and the aftershock (GK11), the fundamental frequencies decreased notably, suggesting that the structures had entered the nonlinear range under these stronger excitations.

(2) Distinct differences were observed among the four models in the initial state, after the minor earthquakes, and after the major earthquake, which indicates that the randomness of concrete properties has a considerable influence on the structural seismic response in both the linear and nonlinear phases.

5.2 Seismic tests

Under seismic tests, structural seismic response analysis primarily focuses on inter-story drift angles and dynamic amplification factors. To compare the seismic response differences among the four models, **Figure 4** and **Figure 5** present the inter-story displacement angles and dynamic amplification factors of the four models under major earthquake test (GK8). To quantify the difference of the inter-story displacement angles, the relative ranges are provided in **Table 1**. Based on the comparison, the following conclusions can be drawn:

(1) Under the same excitation, the locations of the maximum inter-story drift ratios differ among the four models. This indicates that the inherent randomness of concrete material properties can alter the structural failure pattern, thereby affecting the location of the weak story.

(2) Under various seismic tests, the relative ranges of inter-story displacement angles generally reach 30%. Under major earthquake test (GK8), the relative ranges of inter-story displacement angles for the third and fourth stories exceed 100%. Moreover, under major earthquake test (GK8), the dynamic amplification factor at the seventh story shows notable variations among the four models. These results clearly demonstrate the significant impact of concrete material randomness on the seismic response of the structure.

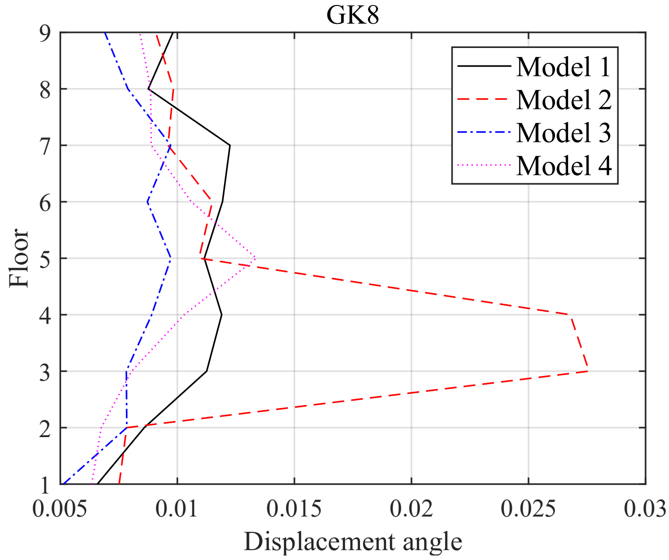


Figure 4: Interlayer drift angles of each model under major earthquake test (GK8)

Table 1: The relative ranges of inter-story displacement angles for different tests

	1	2	3	4	5	6	7	8	9
GK2	72.8%	59.3%	39.4%	56.0%	52.4%	47.4%	66.0%	23.4%	28.0%
GK4	55.8%	25.9%	23.0%	31.2%	58.4%	48.0%	24.6%	36.9%	61.9%
GK6	35.7%	31.3%	61.3%	45.4%	47.8%	56.3%	59.3%	30.7%	36.2%
GK8	37.3%	23.7%	144.5%	123.6%	32.3%	30.1%	33.2%	22.0%	34.2%
GK11	33.3%	44.0%	27.9%	19.8%	16.0%	13.1%	14.1%	10.5%	13.9%

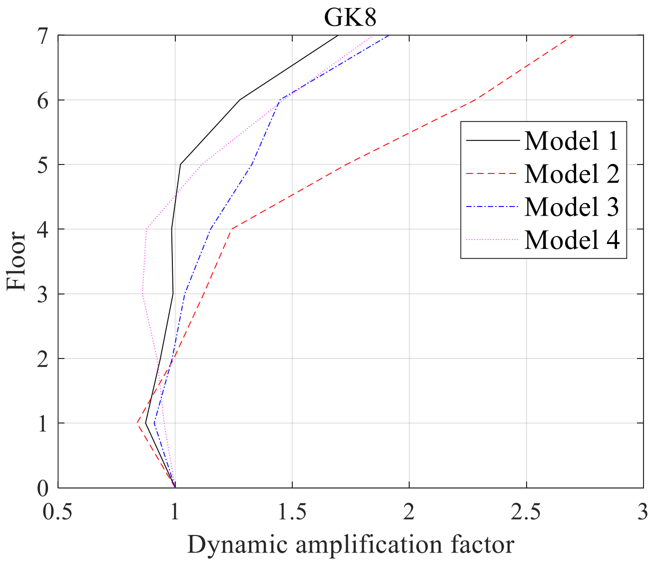


Figure 5: Dynamic amplification factors of each model under major earthquake test (GK8)

6 CONCLUSIONS

Based on the above analysis, the following conclusions can be drawn:

(1) The randomness of concrete properties has significant influence on the distribution and development of cracks in the structure under seismic loading.

(2) The presence of concrete randomness has a non-negligible effect on the fundamental frequency of the structure.

(3) Due to the stochastic nature of concrete, the relative ranges of inter-story displacement angles generally reach 30%, with certain floors under specific tests significantly exceeding this value.

ACKNOWLEDGEMENTS

Financial supports from the National Natural Science Foundation of China (Grant Nos. 52494962 and 12472029) and the Chinesisch-Deutsches Zentrum für Wissenschaftsförderung (Grant No. M-0737), and the Fundamental Research Funds for the Central Universities (Grant No. 22120230524) are highly appreciated. Additionally, Professor Xiaodan Ren and Associate Professor Suzhen Li provided valuable suggestions. I would also like to express my sincere appreciation to Professor Decheng Feng from Southeast University, Associate Professor Jingran He from Guangdong University of Technology, and Lecturer Jinju Tao from Nanjing University of Technology for their significant support. Special thanks go to Assistant

Researcher Jiaxu Shen from Beijing University of Technology for his specific guidance in generating artificial aftershock waves. I am also grateful to our research group members, Mr. Jiankang Xie, Ms. Yangyi Liu, Mr. Disheng Liang, Mr. Yuanxie Shen, Ms. Meifang Hu, Ms. Xin Huang, Mr. Wenwei Ye, Mr. Yongfeng Zhou, Ms. Tingting Sun, and Ms. Xiaofei Lyu, for their assistance!

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