Comparative Experimental Study on the Seismic Performance of Reinforced Totally-Recycled Concrete Frame and Semi-recycled Concrete Frame

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SUMMARY:
With the development of the environmental and recycle concept in China, recycled concrete attracts more and more attention from engineers to researchers. After the 2008 Wenchuan earthquake, there are a lot of damaged buildings. How to dispose and even use the building wastes is a problem to be solved. In order to take the waste to reconstruct the new buildings, it is necessary to study the seismic performance of the recycled and semi-recycled concrete structures. Therefore two comparative shaking table tests of concrete frames have been conducted in the State Key Laboratory of Disaster Reduction in Civil Engineering at Tongji University. One model is constructed in totally recycled concrete. The other model is constructed in semi-recycled concrete. The definition of the totally-recycled concrete is that the coarse aggregates and fine aggregates come from the broken building waste. Whereas the definition of the semi-concrete is that only the coarse aggregates come from the building waste, the fine aggregates is the common sand used in the concrete. In this test, the earthquake waves are selected critically according to the design response spectrum in *Code for seismic design of buildings GB 50011-2010*, which is important to evaluate the seismic performance of the recycled reinforced concrete frame. Besides, the structural dynamic characteristics, responses such as acceleration and displacement, and failure patterns were studied. Meanwhile, the numerical models are built using the software of CANNY, and elasto-plastic time history analysis was done. The comparative results between test and analysis show the numerical model can effectively simulate the behaviour of the test model. The test results show that the performance of the semi-recycled reinforced concrete frame is better than the totally-recycled reinforced concrete frame. Both of the two models basically meet the requirement of the *Code for seismic design of buildings GB 50011-2010*.

Keywords: totally-recycled concrete, semi-recycled concrete, seismic performance evaluation, shaking table test, reinforced concrete frame, elasto-plastic time history analysis

1. INTRODUCTION

It is a main way to use shaking table test to study the seismic performance and failure mechanism of the structures. In shaking table test, the scaled model designed through similarity theory is excited by a series of selected waves at different levels to demonstrate some extent degree nonlinear behavior which is used to study the structural seismic behaviour (Lu Xilin. 2007). This paper mainly introduce the shaking table tests on the semi-recycled concrete frame and totally recycled concrete frame as well as the comparison between the experiment results and analytical results to evaluate the seismic performance of recycled concrete frame.

The research results on the recycled concrete include three main aspects. The first phase is the constitutive relationship research phase. In this phase, some researchers (Xiao Jianzhuang , Du Jiangtao, Liu Qiong. 2009;Xiao Jianzhuang, Li Wengui &Liu Qiong. 2011; Xiao Jianzhuang. 2007; Xiao Jianzhuang, Li Jiabin, Sun Zhenping *et al*. 2004; M.Chakradhara Rao, S.K. Bhattacharyya, S.V. Barai. 2011;) had done a lot of research to study the constitutive relationship of recycled concrete. The agreed basic conclusion is that compared with the common concrete, the elastic modulus of the recycled concrete is less than common concrete modulus, the strain corresponding to the peak stress is larger than common concrete's strain, the peak stress is less than that of common concrete, the ultimate strain is less than common concrete's strain. In sum, the mechanical property behaves low-ductility and low-strength. At the second phase, some researchers (Cao Wanlin, Liu Qiang, Zhang Jianwei *et al*. 2009; Zhang Yaqi, Cao Wanlin, Zhang Jianwei *et al*.2010; Cao Wanlin, Xu Taiguang, Liu Qiang *et al*. 2009; Yin Haipeng, Cao Wanlin *et al*. 2010; Xuping Li. 2009; Xiao Jianzhuang, Zhu Xiaohui. 2005) had conducted a lot of experiments on recycled concrete members including shear walls, beams, columns and joints. At the third phase, with the research (Sun Yuedong, Xiao Jianzhuang, Zhou Deyuan *et al*.2005) furthering, some researchers had done some research on the sub structure, such as one plane frame pseudo dynamic test. These experiments' disadvantage is that they can not simulate the boundary condition as well as the much range of the frequency of earthquake wave and the effect of time-duration to the structure. Therefore, it is necessary to conduct a shaking table test to evaluate the seismic performance of this kind of structure.

2. DESIGN OF THE PROTOTYPE

In order to get a general result, the prototype is designed to a regular 8-story reinforced concrete frame as shown in Fig.2. The plan layout is given in the Fig. 1.

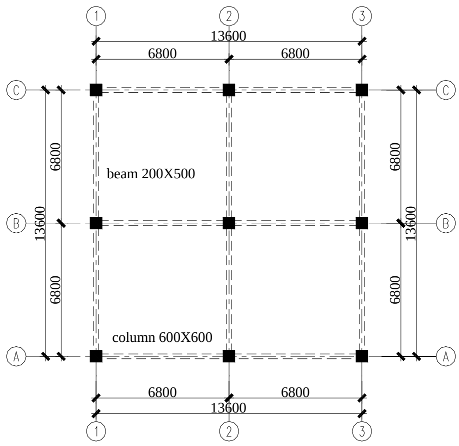


Figure 1 Plane layout of the prototype

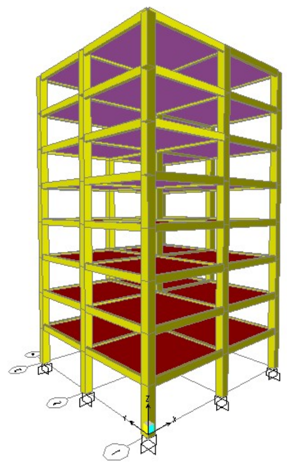


Figure 2 Model of prototype

The seismic intensity of fortification is assumed to be 8. The seismic site design is Group I and the soil classification is II (in China Code). The characteristic period of site is 0.35 s. The dead and live load of the building is 5 kN/m^2 and 2 kN/m^2. C30 concrete is used in the structure. The whole process of design was done by the design software PKPM which was developed by China Academy of Building Research architectural design institute. The dynamic characteristics can be seen in the Tab. 1.

Table 1 Dynamic characteristics of the prototype

Modal No.	Period(s)	Rotation(°)	Factor of translation (X+Y)	Modal participation mass ratio
1	1.379	12.39	1.00 (0.95+0.05)	0.68
2	1.379	102.39	1.00 (0.05+0.95)	0.68
3	1.152	0.00	0.00 (0.00+0.00)	0.27
4	0.408	179.31	1.00 (1.00+0.00)	0.09
5	0.408	89.31	1.00 (0.00+1.00)	0.09
6	0.347	0.00	0.00 (0.00+0.00)	0.04

Rotation：representing the whole structure rotation around the Z axis

3. THE SHAKING TABLE TEST DESIGN

3.1 Selection of material for the model

According to the experimental purpose and similarity theory, the model-used concrete must employ the recycled aggregates to make micro recycled concrete for the model, and the elastic modulus is 1/4 of the prototype elastic modulus. There is an unavailable concrete mix proportion for such recycled concrete in the State Key Laboratory of Disaster Reduction in Civil Engineering. So the recycled concrete mix proportion must be found firstly.

This experiment will use two kinds of recycled concrete, one is semi-recycled concrete, and the other is totally-recycled concrete. The definition of Semi-recycled concrete is that only the coarse aggregate come from building wastes. The definition of the totally-recycled concrete is that the coarse and fine aggregates come from the building waste. There is no difference between the recycled concrete and common concrete except the coarse aggregate and fine aggregate.

In order to find such available mix proportion, the laboratory set up 7 groups of mix proportion for semi-recycled and totally-recycled concrete. The mix proportion can is given in Tab. 2 and Tab. 3. In the tables, the purpose of mixing lime plaster is to reduce the elastic modulus of the micro concrete used for models. The difference between the recycled coarse aggregate and fine recycled aggregate is shown in Fig. 3 and Fig. 4. The model for shaking table test can be seen in the Fig. 5 and Fig. 6.

Table 2 Semi recycled concrete mix proportion

	Cement (kg)	Lime plaster (kg)	Fine recycled aggregate(kg)	Coarse recycled aggregate(kg)	Water (kg)	Stress(N/mm^2)	Elastic modulus(N/mm^2)
Set 1	1.00	0.40	4.58	1.69	0.66	14.59	16217.39
Set 2	1.00	0.00	3.26	1.20	0.75	21.89	20324.48
Set 3	1.00	0.50	4.58	1.69	0.83	9.32	13012.82
Set 4	1.00	0.60	4.58	1.69	0.60	14.34	14608.70
Set 5	1.00	0.75	4.58	1.69	1.00	7.21	9847.47
Set 6	1.00	0.27	4.06	1.50	0.76	13.94	16592.31
Set 7	1.00	0.27	4.06	1.50	0.76	11.50	16584.97

Table 3 Totally recycled concrete mix proportion

	Cement (kg)	Lime plaster (kg)	Fine recycled aggregate(kg)	Coarse recycled aggregate(kg)	Water (kg)	Stress(N/mm2)	Elastic modulus(N/mm2)
Set 1	1.00	0.40	4.58	1.69	0.85	10.47	13334.26
Set 2	1.00	0.00	3.26	1.20	0.75	15.04	13725.93
Set 3	1.00	0.50	4.58	1.69	1.00	8.07	7538.36
Set 4	1.00	0.60	4.58	1.69	0.85	8.31	10939.26
Set 5	1.00	0.75	4.58	1.69	0.89	6.45	7290.81
Set 6	1.00	0.30	4.06	1.50	0.76	9.23	10527.13
Set 7	1.00	0.75	3.14	3.14	0.76	8.41	7127.44

Figure 3 Recycled coarse aggregate

Figure 4 Recycled fine aggregate

Figure 5 The panorama of semi-recycled concrete model

Figure 6 The panorama of totally-recycled concrete model

3.2 Similarity relationship of shaking table test

Similarity relationship is the bridge connecting the two different dimension systems. The essence of the similarity relationship is that the Newton second law is applicable in both of the two different dimension systems. The requirement of the similarity is that similarity coefficient must be equal to each other once the variables' dimensions are the same. Therefore, it is well-known that the shaking table test was conducted on the earth, so the gravity acceleration applied in the model and prototype are the same. So the similarity coefficient of gravity acceleration equals 1. According the rules mentioned above, all of the acceleration's similarity coefficient must be equal to 1. Otherwise, the shaking table test will lose its real similarity relationship in the vertical direction. Consequently, the Eqn.3.1 must be obeyed in the shaking table test, only in this way, can the similarity relationship be completely similar. Otherwise, it is partially similar. According to the material property adjustment, the final similarity relationship can be determined in the Tab. 4.

Table 4 Similarity relationship of both of the two models

Physical Property	Physical parameter	formula	Relationship	Remark
Geometry parameters	Length	S_l	**1/4**	Control the dimension
	Displacement	$S_\delta = S_l$	1/4	
	Angle displacement	$S_\varphi = S_\sigma / S_E$	1.00	
Material property	Strain	$S_\varepsilon = S_\sigma / S_E$	1.00	
	Elastic modulus	$S_E = S_\sigma$	0.30	Control the material
	Stress	S_σ	**0.30**	
	Poisson's Ration	S_υ	1.00	
	Mass instensity	$S_\rho = S_\sigma / (S_a \bullet S_l)$	1.00	
	Mass	$S_m = S_\sigma \bullet S_l^2 / S_a$	1.56×10^{-2}	
Load	Concentrated force	$S_F = S_\sigma \bullet S_l^2$	1.88×10^{-2}	
	Line load	$S_q = S_\sigma \bullet S_l$	0.075	
	Area load	$S_p = S_\sigma$	0.30	
	Moment	$S_M = S_\sigma \bullet S_l^3$	4.69×10^{-3}	
Dynamic performance	Damp	$S_c = S_\sigma \bullet S_l^{1.5} \bullet S_a^{-0.5}$	3.42×10^{-2}	
	Period	$S_T = S_l^{0.5} \bullet S_a^{-0.5}$	0.46	
	Frequency	$S_f = S_l^{-0.5} \bullet S_a^{0.5}$	2.17	
	Velocity	$S_v = (S_l \bullet S_a)^{0.5}$	0.55	
	Acceleration	S_a	**1.20**	Control the shaking table test
	Acceleration of gravity	S_g	1.00	
Height of the model			6.00m	Without the height of bottom
Gross mass of the model			23.56t	With the payload and base

$$\begin{cases} S_g = 1 \\ S_a = \dfrac{S_E}{S_L S_\rho} \\ S_a = S_g \end{cases} \tag{3.1}$$

3.3 Rebar details of model

According to the cross section strength similarity principle (Zhou Ying, Lu Wensheng, Lu Xinlin. 2003), the diameter of the 10#, 12#, 14#, 20# which are 3.50 mm, 2.77 mm, 2.11 mm, 0.90 mm respectively are used to simulate the model cross section rebar, as shown in Fig. 7.

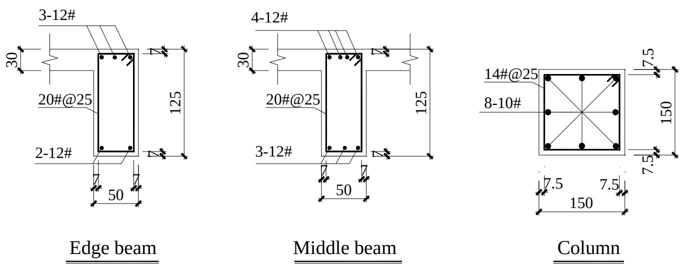


Figure 7 Rebar details of different cross sections

3.4 Ground motion selection and sequence determination

According to the fitting degree between the acceleration response spectrum of ground motions and design response spectrum, four ground motions were selected as the input of the shaking table tests. The input order can be determined by the weighted average value of the acceleration spectrum at the first time period of structure (Zhou Ying, Zhang Cuiqiang, LU Xilin. 2011). The weight factors in X, Y, Z direction are 1:0.85:0.65. The ground motions' acceleration spectrum can be seen in the Fig 8.

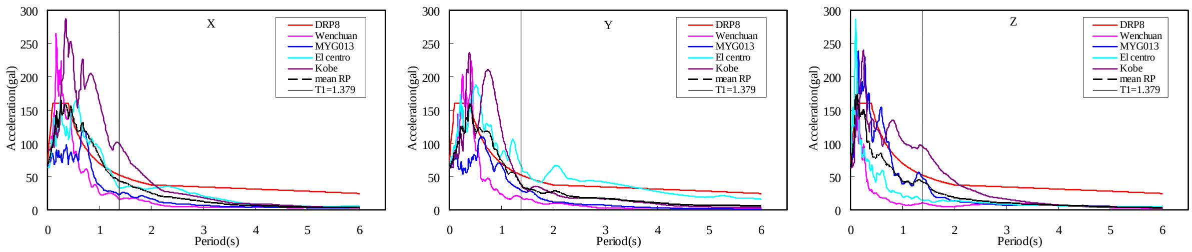


Figure 8 The response spectra of input ground motions and designed response spectrum

3.5 The loading case of shaking table tests

The purpose of this shaking table tests is to evaluate the seismic performance of the recycled concrete frame and to compare the difference between the semi-recycled concrete frame and totally-recycled concrete frame. So four levels were set up to test the model, such as frequently occurred intensity 8, basic intensity 8, rarely occurred intensity 8, as well as rarely occurred intensity 8.5, including two direction input simultaneously and three direction input simultaneously.

3.6 The configuration of transducers on the model

Based on the structural characteristics, accelerometers were put at the base, 2nd floor, 4th floor, 6th floor, 8th floor respectively. The displacement transducers were placed on the base, 4th floor, and 8th floor to calibrate the data from accelerometer.

4. THE RESULTS OF SHAKING TABLE TESTS

4.1 The failure phenomena of shaking table tests

The failure state of semi-recycled concrete frame can be seen in the Tab. 5. The failure state of totally recycled concrete frame was display in Tab. 6. the column and joint in the table refer to the model column, beam column joints. The typical failure mode of semi-recycled concrete frame can be seen from Fig. 9 to Fig. 12. The ones of totally-recycled concrete frame can be observed from Fig. 13 to Fig. 16.

Table 5 The failure state of semi-recycled concrete frame

Earthquake levels	beam	column	Beam-column joint
frequently occurred intensity of 8	1st-3rd floor	0	0
basic intensity of 8	1st-8th floor	2	8
rarely occurred intensity of 8	1st-8th floor	7	more than 8
rarely occurred intensity of 8.5	1st-8th floor	9	63

Table 6 The failure state of totally-recycled concrete frame

Earthquake levels	beam	column	Beam-column joint
frequently occurred intensity of 8	1st-4th floor	2	0
basic intensity of 8	1st-8th floor	5	1
rarely occurred intensity of 8	1st-8th floor	7	more than 8
rarely occurred intensity of 8.5	1st-8th floor	9	72

Figure 9 Cracking at the end of a beam at 2nd floor

Figure 10 Cross cracking at the end of a beam at 1st floor

Figure 11 Horizontal cracking at the bottom end of a column at 1st floor

Figure 12 Damage of the joint at 8th floor

Figure 13 Cracking at the end of a beam at 1st floor

Figure 14 Cracking at the bottom end of a column at 6th floor

Figure 15 Cracking at the top end of a column at 7th floor

Figure 16 Damage of the joint at 7th floor

4.2 The characteristics of the model

The semi-recycled concrete frame and totally recycled concrete frame went through five times of white noise to observe the frequency changing. The semi-recycled concrete frame's frequency changing was displayed in the Fig. 17, the damping ratio changing can be observed in the Fig. 18.

Similarly to this, the ones of totally-recycled concrete frame are shown in Fig. 19~20. From the comparison of the changing of frequency and damping ratio, the totally-recycled concrete frame has suffered more severe inner damages than the semi-recycled concrete frame.

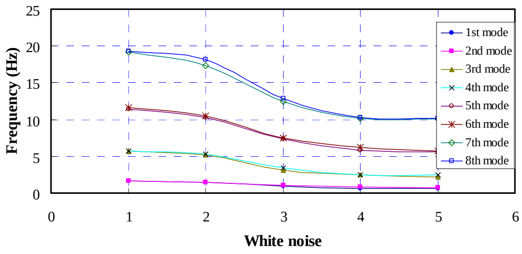


Figure 17 The changing of mode frequencies of semi-recycled concrete frame model

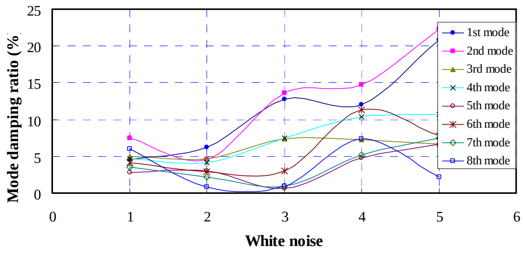


Figure 18 The changing of mode damping ratio of semi-recycled concrete frame model

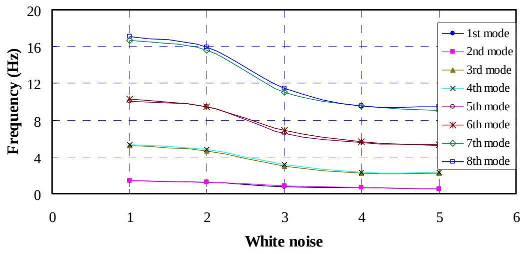


Figure 19 The changes of frequencies of totally-recycled concrete frame model

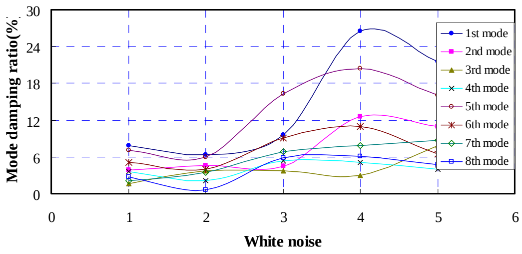


Figure 20 The changes of damping ratio of totally-recycled concrete frame model

4.3 The amplification coefficient of acceleration

The amplification coefficient of acceleration on semi-recycled concrete model is displayed in the Fig. 21. The one of totally recycled concrete model can be seen in the Fig. 22.

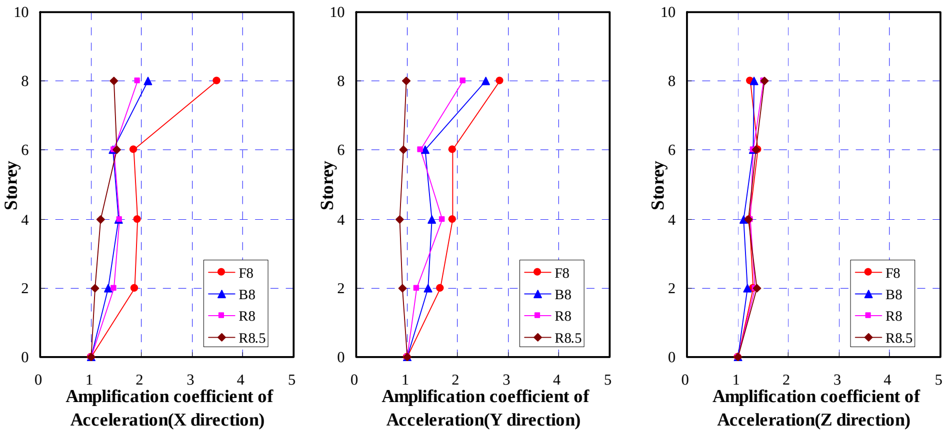


Figure 21 The amplification coefficient of acceleration at different levels of intensity of degree (SRC)

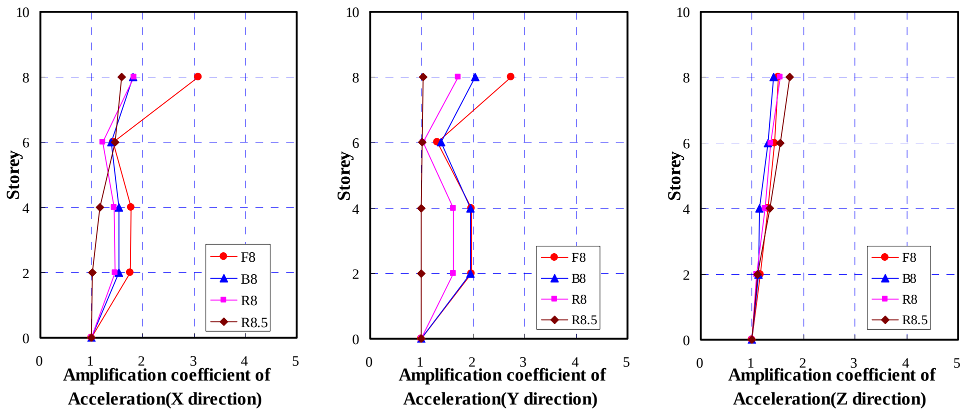


Figure 22 The amplification coefficient of acceleration at different levels of intensity of degree (TRC)

4.4 The displacement envelope of model

The semi-recycled concrete frame model and totally-recycled concrete model's displacement envelope are depicted in the Fig. 23~24.

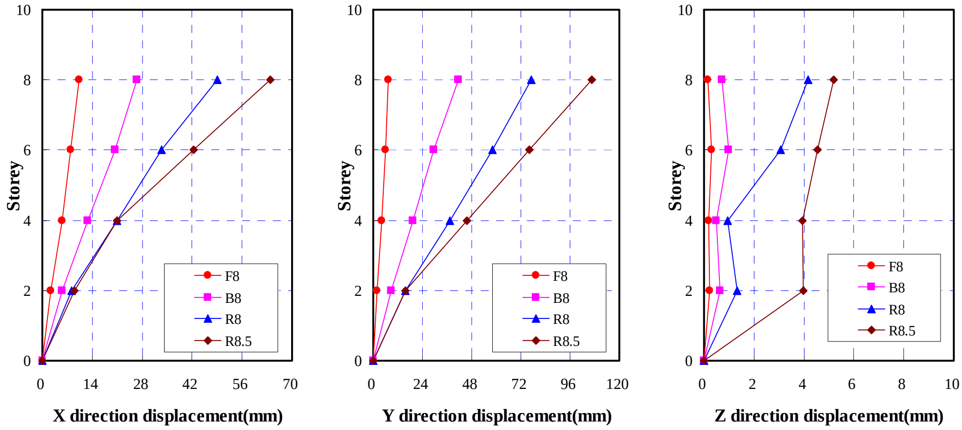


Figure 23 The storey displacement envelope at different levels of intensity (STRC)

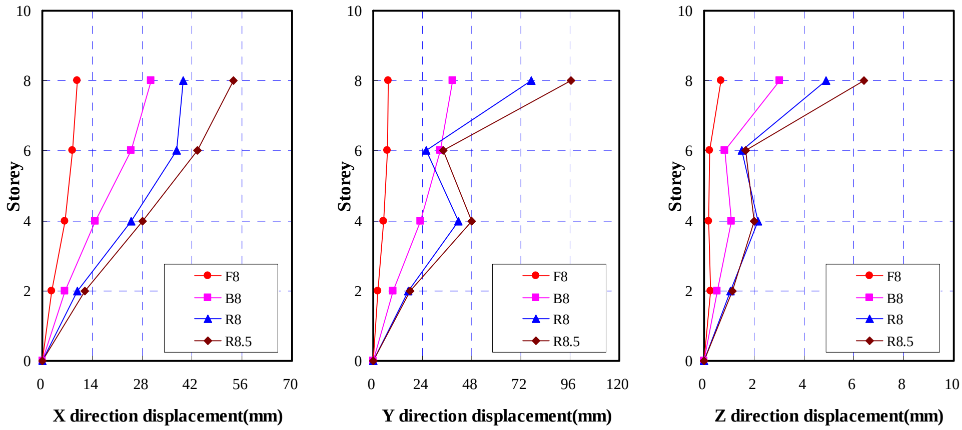
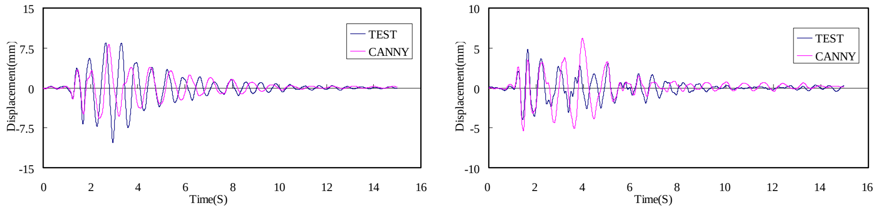


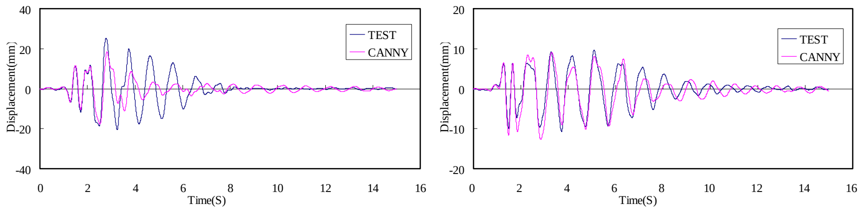
Figure 24 The storey displacement envelope at different level of intensity (TRC)

4.5 The calculation of the model

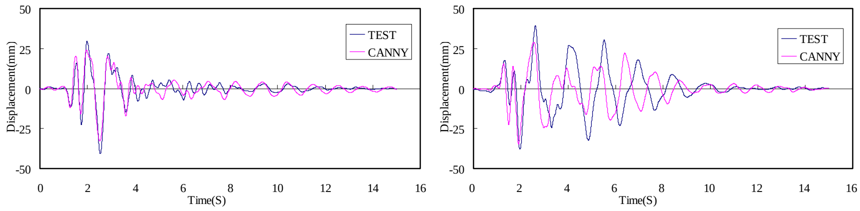
This paper used software CANNY to simulate the time history at different earthquake levels. The comparison between the test and analysis can be seen as following figures.



(a) Frequently occurred intensity 8

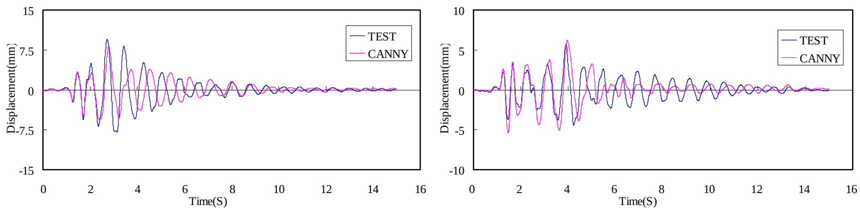


(b) Basic intensity 8

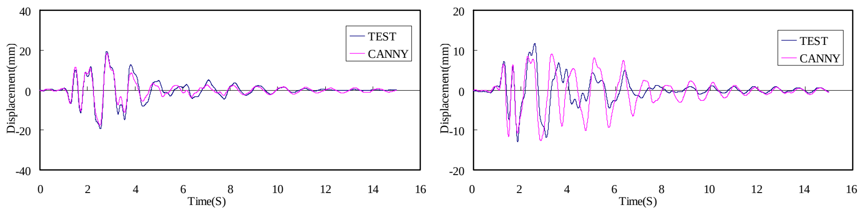


(c) Rarely occurred intensity 8

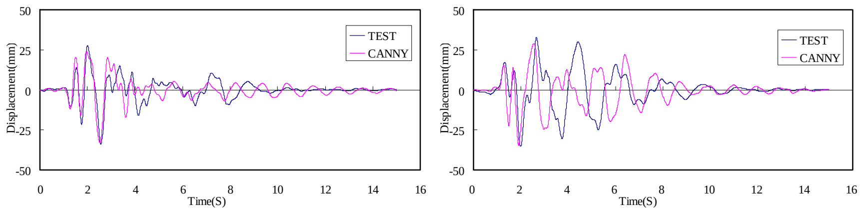
Figure 25 The comparison between the test and analysis (Kobe) (semi-recycled concrete frame)



(a) frequently occurred intensity 8



(b) basic intensity 8



(c) rarely occurred intensity 8

Figure 26 The comparison between the test and analysis (Kobe) (totally-recycled concrete frame)

5 THE SEISMIC PERFORMANCE OF PROTOTYPE

The seismic performance of recycled concrete frame prototype can be evaluated by the results derived from the shaking table tests and numerical analysis.

5.1 The experimental results derived from the shaking table tests

According to similarity relationship, the seismic performance of prototype can be derived from the model test results. The inter-story drift is a very important indicator to evaluate the seismic performance of recycled concrete frame. The inter-story drift is depicted in the Fig.27~28. The conclusion can be draw from the following figures. Semi-recycled concrete frame structure can meet the requirement at the fortification intensity 8 in the *Code for seismic design of buildings GB 50011-2010*. The totally-recycled concrete frame structure basically meets the requirement in Code for seismic design of buildings GB 50011-2010, but at the top floor, the inter-story drift is 1/44, exceeding the specified value 1/50 in *Code for seismic design of buildings GB 50011-2010*. The seismic performance of semi-recycled concrete frame is better than the totally recycled concrete frame.

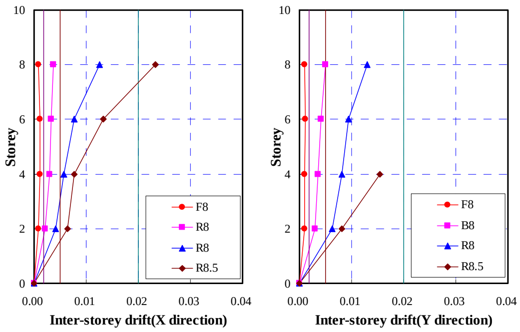


Figure 27 The inter-storey drift of STRC prototype

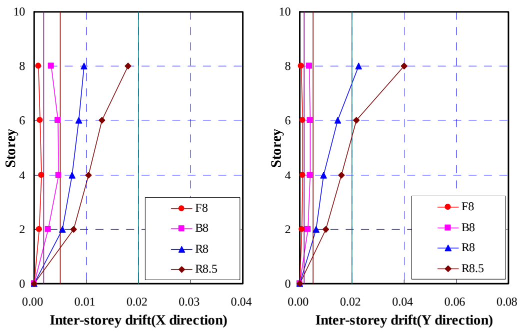


Figure 28 The inter-storey drift of TRC prototype

5.2 The calculating result of prototype

According to the available research (Xiao Jianzhuang. 2008), the semi-recycled concrete mechanic property mainly focuses on the two aspects. One aspect is the elastic modulus, which is 0.55 times of that of common concrete. The other aspect is the ductility, which is defined as the ratio of ultimate strain to peak strain, the ductility of recycled concrete is 1.29, smaller than the common concrete ductility value 1.65. Totally-recycled concrete have the analogy property with the semi-recycled concrete except the lower peak stress. Because of considering the comparison between the two kind of material and the same concrete designed strength used in the prototype, so the same tress-strain relationship is used in the following analysis. The dynamic characteristics comparison is shown in the table 7.

Table 7 Comparison of dynamic characteristics

model	Model in PKPM	Model No.1 in CANNY		Model No.2 in CANNY		Model No.3 in CANNY	
Mode No	EC=30000	EC=30000	error	EC=30000	error	EC=30000*0.55	error
	——	ES=30000		ES=210000		ES=210000	
1	1.379	1.391	0.9%	1.251	-9.3%	1.544	12.0%
2	1.379	1.391	0.9%	1.251	-9.3%	1.544	12.0%
3	1.152	1.196	3.9%	1.075	-6.7%	1.328	15.3%
4	0.408	0.414	1.4%	0.376	-8.0%	0.466	14.0%
5	0.408	0.414	1.4%	0.376	-8.0%	0.466	14.0%
6	0.347	0.356	2.8%	0.324	-6.7%	0.401	15.7%

The numerical inter-story drift is shown in the following figures.

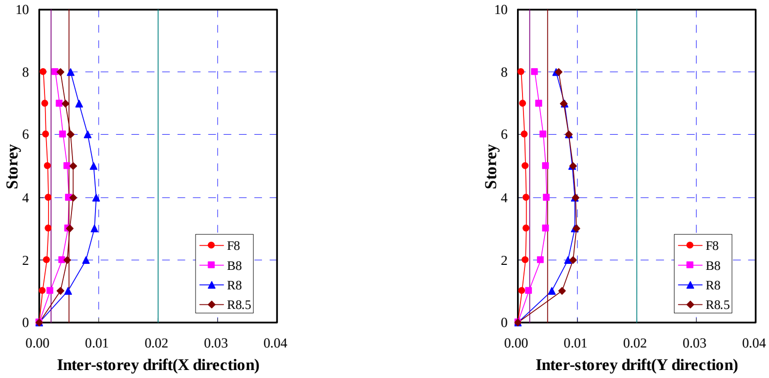


Figure 23 The calculation result of the inter-storey drift of TRC prototype

6 THE CONCLUSIONS

Shaking table tests on the semi-recycled concrete frame and totally-recycled concrete frame was discussed in this paper. And the design of prototype, similarity relationship, mix proportion of the model material, as well as the loading case was introduced in the paper. In addition, elasto-plastic time history analysis was done to study the performance of totally-recycled concrete frame. Finally, according to the experimental results and numerical calculation, this paper discussed the seismic performance difference between the semi-recycled concrete frame and totally-recycled concrete frame.
(1) According to the shaking table tests, through reasonable design, the semi-recycled concrete frame can meet the requirement of *Code for seismic design of buildings GB 50011-2010*. The totally-recycled concrete frame can meet the requirement of the first two phases of fortification, but at the top floor, the inter-story drift is 1/44, exceeding the specified value 1/50 in *Code for seismic design of buildings GB 50011-2010* under the rarely-occurred earthquake.
(2) Based on the elasto-plastic time history analysis, 8-story totally-recycled concrete frame can meet the requirement of *Code for seismic design of buildings GB 50011-2010*.
(3) By the comparison, semi-recycled concrete frame behaved better than the totally recycled concrete frame.

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