Front. Struct. Civ. Eng. 2013, 7(3): 215–226
DOI 10.1007/s11709-013-0212-z

RESEARCH ARTICLE

Research on recycled concrete and its utilization in building structures in China

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ABSTRACT Large quantities of construction and demolition (C&D) building waste are being generated as a result of rapid urbanization and natural disasters in China. An increasing awareness of environmental protection is escalating C&D waste disposal concerns. This paper presents a brief introduction to current shaking table test research in China on structures built with recycled aggregate concrete (RAC). Test structures include a cast-in situ frame model, a precast frame model and a block masonry building. The test results prove that it is feasible to use RAC as a structural material in seismic areas, with recommended modifications and proper design, especially in low-rise structures. This paper also presents several successful applications of RAC in civil and structural engineering projects in China, which will serve to promote RAC as a global ecological structural material.

KEYWORDS recycled aggregate concrete (RAC), structural material, shaking table tests, building structure

1 Introduction

With rapid urbanization and construction industry growth in China, large quantities of building materials are being consumed, and an increasing quantity of construction and demolition (C&D) waste is being produced. The economic growth in China is being gradually constrained by resource shortages and environmental destruction. According to statistics, China consumes 820 million tons of cement and accounts for 55% of the world's consumption of this material. It is estimated that approximately 300 million tons of waste concrete are being produced annually in mainland China [1]. Furthermore, natural disasters in China, such as the Wenchuan earthquake (2008) and the Yushu earthquake (2010), have also produced tremendous quantities of waste concrete [2]. Additionally, during the construction process of the Shanghai 2010 World Expo, nearly 300 million tons of C&D waste was generated by the demolition work [3]. The handling of the increasing C&D waste has become a difficult problem for cities and municipalities.

During the reconstruction period in Germany immediately after the Second World War, it was necessary to satisfy an enormous demand for building materials. The recycling of C&D waste was handled well during this period. In fact, systematic investigations on the effect of the cement content, water content, and grading of crushed brick aggregates have been conducted since 1928 [4]. Since then, research conducted in several countries has provided sufficient support for the use of construction waste as a constituent in new concrete. The recycled aggregate concrete (RAC) technique provides an effective approach to dealing with C&D waste, while it also conserves resources, protects the environment and enables sustainable development in the building industry.

Realizing the importance of C&D waste, the USA, Japan, and the European Union have established solid waste management regulations to encourage the reuse and recycling of waste materials and to set goals for recycling C&D waste as a substitute for natural resources such as timber, steel and quarry materials [5].

The need to recycle and reuse waste concrete is critical in China. Recycled aggregate concrete (RAC) can be prepared from recycled aggregate as a substitute for natural aggregate, either partially or wholly, in the concrete mixing

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Article history: Received Mar. 19, 2013; Accepted June. 5, 2013

process. However, to establish RAC as an accepted structural material, structures constructed with RAC need to be carefully evaluated. In recent years, related research has been conducted in China. In addition, to better understand the properties of RAC, some pilot construction projects have been completed to demonstrate and promote more widespread application of RAC in practical engineering projects.

This paper will present a review of recent research on the seismic behavior of three-dimensional RAC structures. In addition, several successful RAC structural applications in China are included. The authors hope that the information presented in this paper can be helpful in establishing RAC as a widely accepted structural material.

2 Research on seismic behavior of three-dimensional RAC building structures

Domestic and foreign researchers have recently conducted several investigations on the physical and mechanical properties of RAC [6–8]. A series of experimental studies on the structural performance of RAC components (beams [9,10], columns [11,12], joints [13,14]) and plane frames [15]) have also been conducted. However, to the best of the authors' knowledge, there have been few investigations on the seismic performance of dimensional structures made with RAC. The following describes the authors' recent research on the seismic behavior of three-dimensional RAC structures using shaking table tests.

2.1 Shaking table test on a cast-in situ RAC frame model

Investigations conducted post-earthquake have shown that concrete frame buildings will not collapse if they are properly designed according to the present Chinese Building Design Codes GB-50010 [16] and GB-50011 [17]. However, the seismic behavior of frame structures using RAC structural materials in a seismic area has not been clearly defined and should be researched and evaluated.

To provide a comprehensive understanding on the overall dynamic behavior of the cast-in situ RAC frame structure under earthquake loading, a 1/4-scale model of a two-bay, two-span, six-storey cast-in situ RAC frame structure with 750 mm storey height was tested on a shake table at Tongji University, Shanghai, China in 2011 [18]. This test can offer experimental support for similar cast-in situ RAC frame structures constructed in earthquake prone areas.

The coarse aggregates used in this test were recycled coarse aggregates (RCAs) with a particle diameter between 5 and 10 mm. The RAC mixture of nominal strength grade C30 was proportioned with a RCA replacement percentage of 100%. The tested model was a frame structure that was regular in elevation and designed according to the present Chinese Building Standard Code for seismic design of buildings (GB-50011) [17]. The plane layout of the cast-in situ RAC frame model is presented in Fig. 1. Figure 2 shows the general view of the model on the shaking table.

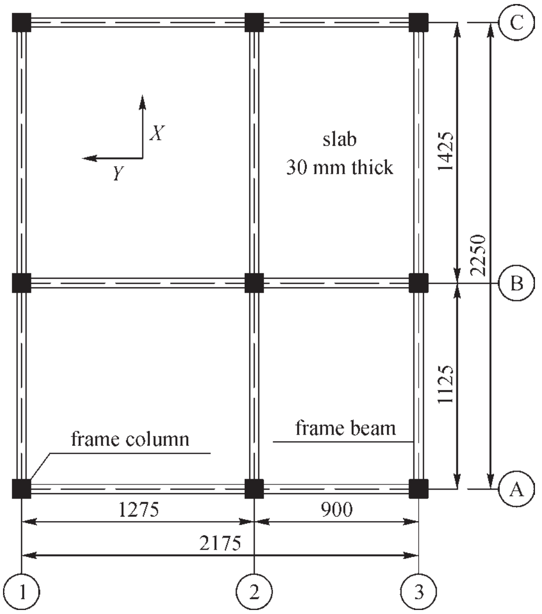

Fig. 1 Plane layout of the cast-in situ RAC model (unit: mm)

Fig. 2 General view of the cast-in situ RAC frame model

The Wenchuan seismic wave (WCW), El Centro wave (ELW), and Shanghai artificial wave (SHW) were selected as the input seismic waves. To evaluate the overall capacity and dynamic response of the cast-in situ RAC frame structure, the test procedure consisted of nine phases using varying peak ground accelerations (PGA): 0.066 g, 0.130 g (frequently occurring earthquake of intensity 8), 0.185 g, 0.264 g, 0.370 g (moderately occurring earthquake of intensity 8), 0.415 g, 0.550 g, 0.750 g (rarely occurring earthquake of intensity 8), and 0.170 g (rarely occurring earthquake of intensity 9).

From intensive analysis of the failure mechanism and the structural elasto-plastic response, the inter-storey drift, seismic force, inter-storey shear, hysteresis curves, capacity curve, ductility coefficient, and stiffness degradation were calculated and analyzed. The overall seismic performance of the cast-in situ RAC frame structure was evaluated, and the following findings are presented:

1) The failure pattern of the cast-in situ RAC frame structure during the shaking table tests is shown in Fig. 3. Failure first occurred at the end of beams and then at the bottom of columns, which can be characterized as: "strongest joints, stronger columns, and weaker beams". The model did not collapse after the 1.170 g test phase even though it sustained very severe damage after the series of earthquakes.

2) From Table 1, which describes the maximum values of inter-storey drift ratios under different test phases, it can be observed that the maximum corresponding inter-storey drift ratios meet the intensity 7 requirements in the current Chinese Code for seismic design of buildings (GB-50011) [17].

3) It can be inferred from the model's capacity curve and stiffness degradation (shown in Figs. 4 and 5, respectively), derived from the shaking table tests, that the cast-in situ RAC frame structure, if properly designed and constructed, has good load-bearing capacity, deformation capacity, energy dissipation capacity and seismic performance to withstand earthquake strikes with a high ductility coefficient of 4.218.

4) Compared to the normal concrete frame structures reported in Refs. [19–21], there is no obvious difference in seismic performance. The cast-in situ RAC frame structure is able to withstand the rare high-magnitude earthquakes of intensity 8. It is thus feasible to use cast-in situ RAC frame buildings of less than six stories in seismic regions and post-earthquake reconstruction areas.

(a) (b)

Fig. 3 Failure pattern of the cast-in situ RAC frame structure. (a) Beam; (b) column

Table 1 Maximum inter-storey drift ratio

PGA/g	floor					
	1	2	3	4	5	6
0.066	1/1114	1/824	1/863	1/957	1/1220	1/2195
0.130	1/405	1/280	1/266	1/292	1/444	1/844
0.185	1/211	1/174	1/198	1/199	1/334	1/733
0.264	1/215	1/170	1/185	1/212	1/319	1/993
0.370	1/89	1/75	1/100	1/116	1/182	1/455
0.415	1/67	1/58	1/82	1/101	1/188	1/426
0.550	1/38	1/34	1/58	1/88	1/164	1/300
0.750	1/29	1/29	1/41	1/61	1/111	1/293
1.170	1/29	1/25	1/41	1/66	1/117	1/276

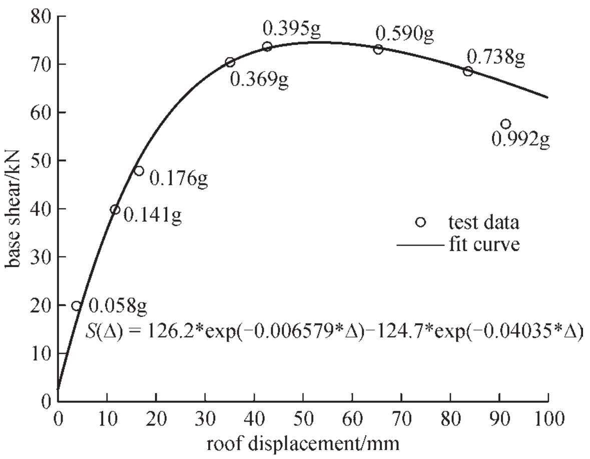

Fig. 4 Capacity curve of the cast-in situ RAC model

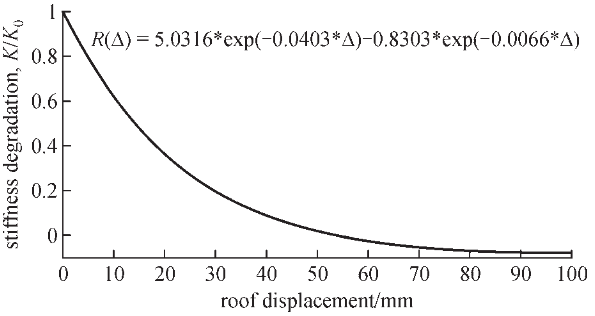

Fig. 5 Stiffness degradation of the cast-in situ RAC model

2.2 Shaking table test on a precast RAC frame model

RAC properties are greatly influenced by mixing conditions [22], and concrete mixing quality is better controlled under factory conditions. Therefore, factory prefabrication of building elements results in inherent advantages over purely site-based construction [23]. The quality of RAC components will be ensured if produced in precast factories. Although prefabrication of building elements in factory conditions is becoming increasingly popular globally, including in China [24], there have been only a few investigations of the complete seismic performance of precast structures, especially precast RAC structures in earthquake-prone areas. To capitalize on the inherent advantages of precast structures and improve RAC structural element quality, the first shaking table test on a precast RAC space frame structure was conducted at Tongji University, Shanghai, China in 2013 [25].

Just as in the above mentioned cast-in situ RAC frame model, the coarse aggregates used in this test were also RCAs with particle diameters between 5 mm and 10 mm, and the recycled concrete mixture of nominal strength grade C30 was proportioned with a RCA replacement percentage of 100%. To best assess the seismic performance of the precast RAC frame structure, the model plan and elevation was the same as that of the previous cast-in situ structure, and the length-scaling parameter was also 1/4, as illustrated in Fig. 1. The joint reinforcement and construction is detailed in Fig. 6; Figure 7 shows the entire precast RAC structure on the shaking table. To accurately compare the seismic performance, the seismic wave selection, loading method, and instrument arrangements were identical to those of the previous cast-in situ test.

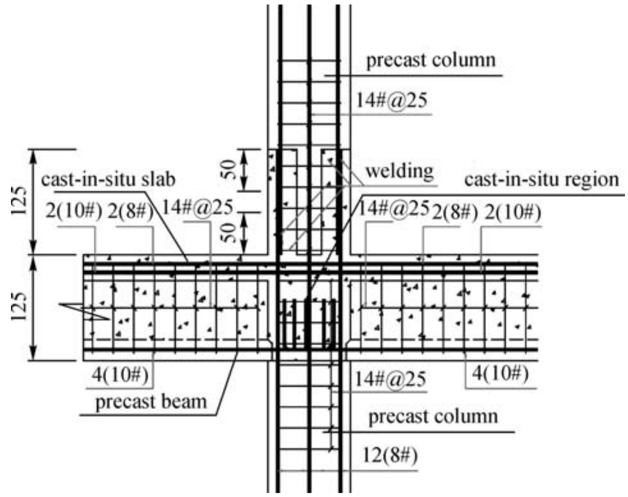

Fig. 6 Details of the precast frame joint (unit: mm)

Fig. 7 General view of the precast RAC frame model

The failure pattern of the precast RAC frame structure is illustrated in Fig. 8. Based on the overall performance evaluation of dynamic characteristics, seismic capacity, and deformability, the following conclusions can be made after analyzing and comparing the seismic behavior of the cast-in situ and precast concrete frame models:

(a) (b)

Fig. 8 Failure pattern of the precast RAC frame structure. (a) Beam; (b) column and joint

1) After analyzing the complete maximum inter-storey drift distribution (Fig. 9) and capacity curves (Fig. 10) of the two frame structures, it can be inferred that the seismic performance of precast RAC frame structure at the elastic stage and early elasto-plastic stage is acceptable and is almost the same as that of the cast-in situ model. However, in the late nonlinear stage, the precast frame joint was damaged relatively rapidly; the structural lateral stiffness degradation occurred more quickly.

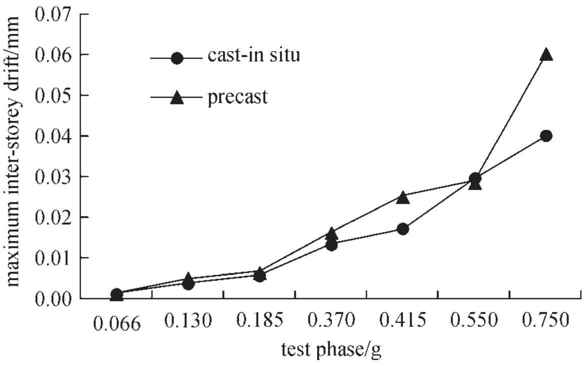

Fig. 9 Distribution of maximum inter-storey drift

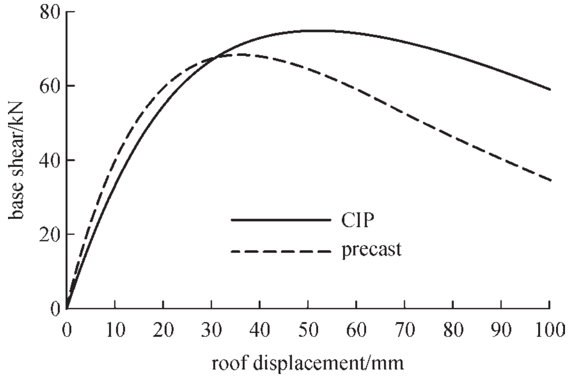

Fig. 10 Capacity curves of the two models

2) The maximum inter-storey displacement of the precast RAC frame structure, shown in Fig. 9, did not meet the specification requirements during the shaking table test, especially during rarely occuring earthquake of intensity 8. Some modifications should be made to improve the energy dissipation of the precast beam-column joint before using in an intensity 8 area.

3) The analysis shows that the precast RAC frame structure has a good energy consumption capability. The hysteresis loops presented in Fig. 11, along with the capacity curve, reveal that the precast RAC frame structure also has good seismic performance with a ductility coefficient of 4.811. The model did not collapse after serious damage occurred, demonstrating that the precast RAC frame building also has good ductility and seismic-resistance capacity.

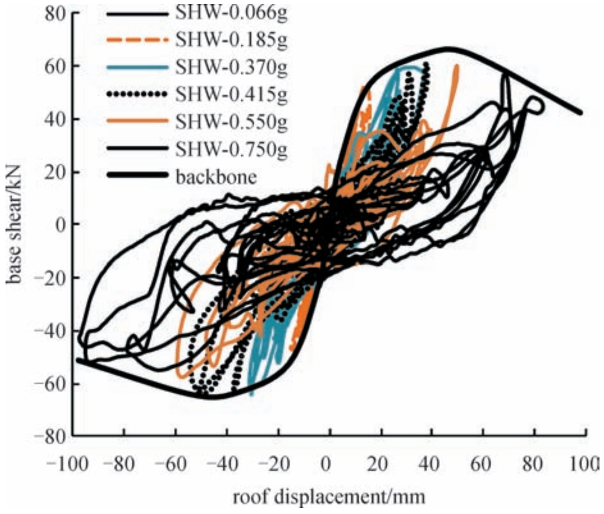

Fig. 11 Hysteresis loops of the precast RAC model

4) The seismic characteristics of precast RAC frame structures are similar to conventional precast concrete frame structures, as published in Refs. [26–28]. Therefore,

a combination of RAC and precast structures is ideal for using and promoting precast RAC frame structures for mid-rise buildings in seismic regions.

2.3 Shaking table test on a RAC block masonry building

To provide some insight into the overall dynamic behavior of recycled aggregate concrete block masonry buildings using tie column, ring beam, and cast-in situ slab structural systems and to gather experimental evidence for the establishment of design guidelines for such RAC block masonry structures, a full scale model of a RAC block masonry building was tested on a shake table at Tongji University, Shanghai, China in 2011 [29].

The recycled concrete hollow block in this test was made of building waste, cement, slag and fly ash. The recycled concrete mix with a nominal strength grade C20, proportioned with a RCA replacement percentage of 100%, was used for the tie columns and ring beams of the block masonry structure. The plane layout, elevation, and connection details of this RAC block masonry structure are displayed in Fig. 12. The model after installation on the shaking table and the experimental set-up can be seen in Fig. 13.

As in the previous two tests, WCW, ELW and SHW were selected as the input seismic waves. The test procedure consisted of six phases with the following PGAs: 0.071 g (frequently occurring earthquake for fortification intensity 8), 0.136 g, 0.200 g (basic occurrence for fortification intensity 8), 0.310 g, 0.410 g (rarely occurring earthquake for fortification intensity 8), and 0.630 g (rarely occurring earthquake for fortification intensity 9). The damage exhibited during the different shakings is shown schematically in Fig. 14.

After analyzing the natural frequency, the equivalent stiffness of the structure, the structural damping ratio, the acceleration response, the seismic force response, the displacement response, the base shear response and the structural fragility of this test building, the following conclusions can be made:

1) It can be inferred from the maximum displacement values and the ratio of the displacement at the roof level to the overall structural height (summarized in Table 2) that the displacement response during the test is consistent with the ordinary assumption that RAC masonry buildings will not collapse if subjected to major earthquakes, which would otherwise endanger human lives.

2) Based on Table 3, which characterizes the level of damage for the tested masonry building, Figure 15 illustrates the generated fragility curves for a typical RAC block masonry building with tie column, ring beam, and cast-in-place slab systems in an intensity 8 area and indicates that in a major earthquake, approximately 80% of the RAC masonry buildings are likely to suffer minor damage or be repairable.

3) The seismic behavior of the RAC block masonry structure is similar to that of a traditional masonry structure [30,31]; thus, it is feasible to utilize RAC block masonry buildings in the seismic regions.

From the three experimental shaking table investigations of the seismic performance of three-dimensional RAC building structures, it can be observed that, although the mechanical behavior of RAC may generally be less than that of a normal concrete, the seismic performance of the RAC structure is not inferior to that of normal concrete structure. RAC is still feasible for practical applications in civil engineering. These three studies will contribute to an increased confidence in the application of RAC and eventually lead to the development of standard specifications enabling widespread utilization of RAC.

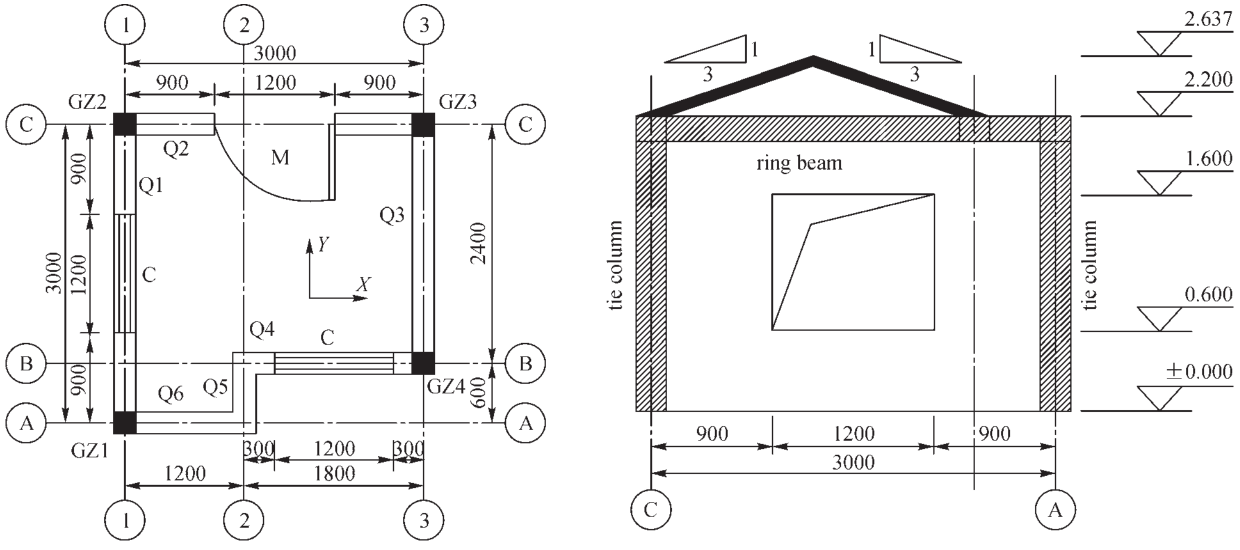

Fig. 12 Plane layout and elevation of the RAC block masonry structure (unit: mm). (a) Plane layout; (b) elevation

Fig. 13 General view of the RAC block masonry structure

3 Three applications of RAC in building structures in China

There have been comprehensive investigations on the physical and mechanical properties, as well as the structural behavior, of RAC [32–34]. However, the RAC technique is still in the research stage, and application is limited. The results obtained during extensive research at Tongji University and other institutions have demonstrated that RAC can be used in buildings if proper design and construction techniques are implemented. Clearly, this information should encourage clients and demolition contractors to recycle C&D waste for production of RAC, which will also reduce disposal demands on landfill sites.

It has proven necessary to also build several prototype projects in order to guide the development and application of RAC techniques. A number of projects have recently been completed to research and promote RAC techniques. The following is a brief introduction to some of the pilot engineering applications of RAC in China.

3.1 The RAC cast-in situ frame structure case

The building presented in Fig. 16 is the Shanghai ecological house, which is located in the 2010 Shanghai World Expo Park. As a prototype ecological green building, numerous green construction technologies are


(a) (b)

Fig. 14 Failure pattern of precast RAC block masonry structure. (a) Tie column; (b) masonry wall

Table 2 Maximum value of the roof displacement and the total displacement/height

PGA/g	roof displacement/mm		total displacement/height	
	X-direction	*Y*-direction	*X*-direction	*Y*-direction
0.071	0.611	0.612	1/3599	1/3594
0.136	1.568	0.645	1/1402	1/3411
0.200	1.838	0.891	1/1197	1/2468
0.310	3.457	1.344	1/636	1/1637
0.410	4.111	1.498	1/535	1/1469

Table 3 Structural performance levels and drift ratio limits

damage-state	1-2	2-3	3-4	4-5
performance level	normal occupancy (NO)	immediate occupancy (IO)	life-safety (LF)	collapse prevention (CP)
demand	no damage or slight damage for structural and non-structural elements	need a small amount of restoration for structural and non-structural elements	The structure remains stable and has enough bearing capacity	buildings neither collapse nor suffer damage that would endanger human lives
drift ratio limit *LSi* /%	0.1	0.5	0.9	1.3

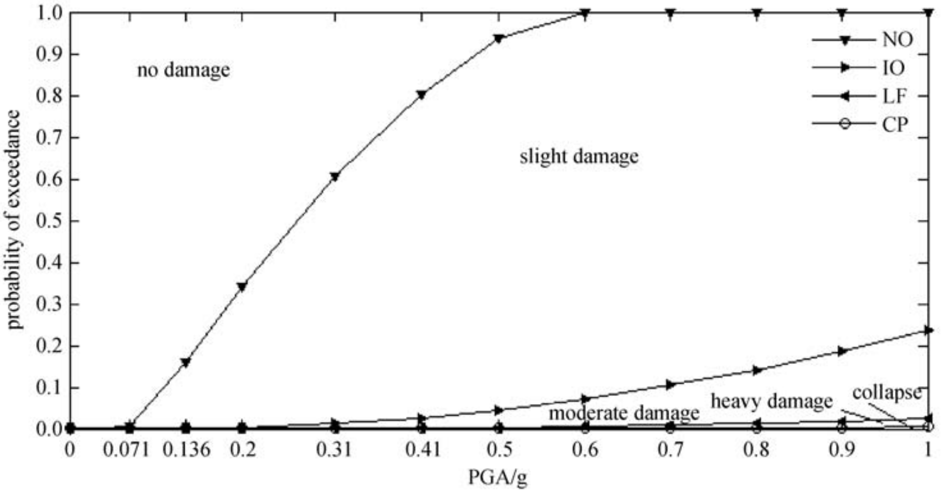

Fig. 15 Fragility curves for qualifying the performance of the RCA masonry building

applied and exhibited. It also represents the first ‘zero energy consumption’ ecological housing in China.

The building is a reinforced concrete frame structure and its total construction area is 3000 m^2, including four floors and one underground floor. It is worth noting that the entire structure is made with RAC. The mass ratio of RCA to the whole coarse aggregate in this building is 100% of the grade C30 and 50% of the grade C40. The field sampling inspections show that the strength, durability and construction performance of RAC can completely meet the design requirements during the construction process.

This building is a typical application of RAC as a structural material in cast-in situ reinforced concrete frame structures.

3.2 The RAC precast frame structure case

The Shanghai Urban Construction No. 2 prototype building shown in Fig. 17 incorporates the full precast frame structure system. Experimental studies are being carried out on this project, focusing on the further development of precast concrete (PC), including precast RAC, technology.

This three-storey building is an assembled monolithic reinforced concrete frame structure with 3.60 m high stories. RAC with a 100% RCA replacement is used in the eastern half of the building. The frame columns used in this test building were prefabricated in a factory, and grout sleeve technology was used to connect the longitudinal reinforcement of the columns. Meanwhile, the frame beams are composite beams, and the slabs are composite slabs. The PC rate was greater than 70%, while the energy-saving rate has been 75% in this test building. Because of the inclusion of RAC, this project not only provides environmental and ecological benefits but also brings economic benefit for the contractor. In addition, because this test building uses both RAC and normal concrete structural materials, a clear comparison can be made to increase the residents’ confidence in the precast RAC structure.

This test building is another typical application of RAC precast reinforced concrete frame structure, in contrast to the cast-in situ structure.

3.3 The RAC masonry case and another frame case

After the devastating earthquake struck the Sichuan Province of China in 2008, a prototype RAC project was erected in Dujiangyan city. Three residential buildings were constructed using RAC in the earthquake reconstruction area. Figure 18 shows that the building on the left is a typical two storey RAC frame structure; the building in the center is a single storey recycled aggregate brick masonry structure, and the building on the right is a two-storey masonry row-style building made with recycled aggregate bricks.

The project was started in October 2008 and completed in April 2009. During this time, the RAC buildings experienced more than ten aftershocks with magnitudes of 4.0 to 5.1 on the Richter scale. There was no damage, even to the appearance of the buildings, demonstrating that both structural systems had good seismic performance [2].

3.4 The RAC frame-shear wall structure case

The No. 6 test building at the Beijing University of Civil Engineering and Architecture, as shown in Fig. 19, utilizes RAC as its structural material. This building is a frame-shear structure with 1200 m^2 of construction area, a maximum span of 12 m, a maximum column height of 4.2 m, and a shear-wall thickness of 190 mm. The concrete design level of this building is C30, and all slabs, columns, beams and shear walls are made with RAC.

The actual results prove that RAC can meet the

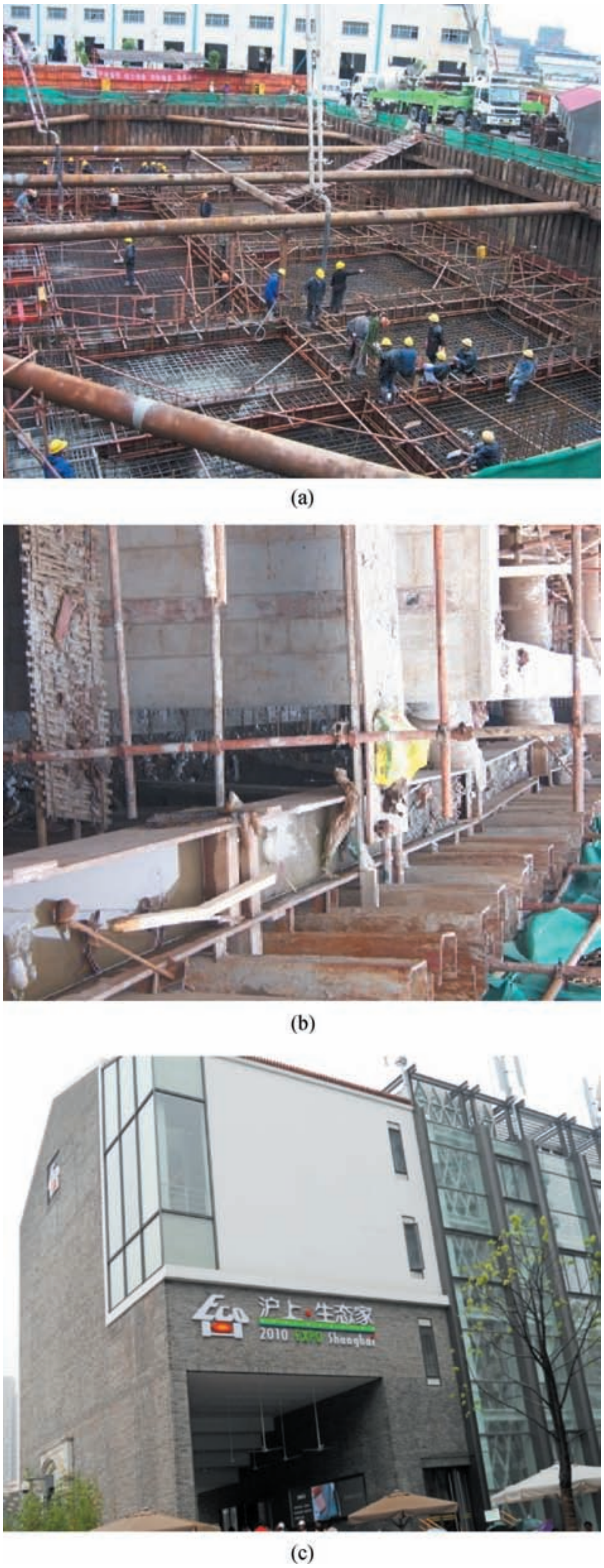

Fig. 16 Shanghai ecological house located in the 2010 Shanghai World Expo Park. (a) Construction on lower part of Shanghai ecological house; (b) construction on upper part of Shanghai ecological house; (c) general view of the Shanghai ecological house

standards required by engineering construction work in the field. RAC demonstrated good performance during the construction process, exhibiting favorable fluidity, water retention and cohesiveness. The appearance quality is good, with no obvious surface cracks after the building was completed. The building has been used for teaching and testing for more than three years now, without any quality problems caused by the application of RAC [35].

This building is a typical application of RAC as a structural material in frame-shear wall structures, proving that RAC can be successfully used in this type of structure.

3.5 The steel frame filled with recycled aggregate bricks

Figure 20 presents an office building located in Pudong, Shanghai, China. This two-storey office building was built in 2010, with an area of 1200 m^2. This office building is a steel frame structure with filled walls built of recycled aggregate bricks.

This project demonstrates that a building using recycled aggregate bricks exhibits good fire-resistance properties, structural performance, and workability, performance on par with normal aggregate bricks in practical applications. In addition, the cost and the environmental impact of this building are less than in traditional construction.

This prototype office building is a typical application of recycled aggregate bricks as the frame structural material for non-bearing walls, serving to demonstrate the successful application of recycled aggregate bricks.

There is enough evidence from the cases cited and other case study projects to show that RAC can be successfully used in cast-in situ or precast frame structures, masonry structures, frame-shear wall structures, non-bearing walls, etc.

4 Discussion

Previous research has shown that the RCA replacement percentage has a significant influence on the RAC stress–strain curves. As the RCA replacement ratio increases, the compressive strength and elastic modulus decreases, while the peak strain increases [7]. To maximize structural safety if RAC is used as the structural material in civil engineering, the following modifications should be made:

1) Due to the known RAC mechanical property deficiencies, special design considerations may be required before proposing RAC as a structural material. Tight production control is required to appropriately adjust both the composition and the distribution of the particle sizes. In addition, some new approaches in mixing concrete, such as the “two-stage mixing approach (TSMA)” [36], could be introduced to improve the compressive strength for the recycled aggregate concrete and hence decrease its strength variability. The RAC quality should be the top priority.


(a) (b)

Fig. 17 Shanghai Urban Construction test building half made of RAC. (a) Cast-in situ RAC joint of this building; (b) Shanghai Urban Construction No. 2 building in construction process

Fig. 18 Demonstration project with RAC in Dujiangyan

(a) (b)

Fig. 19 No. 6 building in Beijing University of Civil Engineering and Architecture. (a) Construction of No. 6 building with RAC in Beijing, China; (b) completed No. 6 building with RAC in Beijing, China

Fig. 20 Office building using recycled aggregate bricks

2) From the authors' view, it is not recommended that coarse and fine recycled aggregates be used together to replace all of the coarse and fine natural aggregate in concrete mixes in a real project, as the strength and durability of the concrete would be greatly affected.

3) At present, some valuable specifications, such as the "code for recycling of construction & demolition waste" [37] and the "technical code for applications of recycled concrete" [38] proposed and drafted by the first author, have been implemented by national and local governments. RAC can be used in practical engineering projects if the properties of the recycled aggregates and the mixed RAC meet these standards. RAC specific standards will facilitate its utilization in the future. It is recommended that existing standards be revised and new standards be introduced as a result of extensive research and more experience with RAC.

5 Conclusions

This paper presents a state-of-the-art review of the relevant research on seismic performance of three-dimensional RAC structures using shaking table tests and an analysis of several successful building applications in China using RAC as a structural material. The main conclusions and recommendations can be summarized as follows:

1) The rapid growth of the construction industry in China in recent years and the occurrence of several natural disasters have resulted in an increased production of waste concrete. It is necessary to reuse the waste concrete for both environmental preservation and sustainable development. Significant effort has been made in China recently to investigate the seismic performance of RAC structures and the feasibility of RAC applications in practical engineering, especially in earthquake-prone areas.

2) The three shaking tests measuring the seismic performance of RAC structures prove that it is feasible to construct and recommend cast-in situ structures, precast RAC frame buildings of less than six stories and RAC block masonry buildings in seismic regions and post-earthquake reconstruction areas. In addition, modifications should be made to enhance the energy dissipation of the precast beam-column joint if the precast frame structure is used.

3) It can been concluded from the number of existing RAC building structures that with the development of RAC techniques, RAC is increasingly being used in practical engineering projects. The RAC technique has proven to be an effective approach to the disposal of C&D waste.

4) Recycling concrete waste is not only a technical problem but also a management task, requiring global attention. Numerous important advancements in the study and application of RAC have been achieved in China to date. However, due to a lack of appropriate technology, proper standards, support from the government and public understanding, some aspects of RAC utilization still need to be studied further.

5) It is possible to use RAC as an ecological structural material with proper building design and construction. The utilization of RAC is environmentally friendly; it reduces natural aggregate waste and recycles C&D waste.

Acknowledgements The authors wish to acknowledge the financial support from the National Natural Science Foundation of China (Grant No. 51178340) and the Ministry of Education (No. NCET-06-0383). The authors acknowledge other members of the research group who have been engaged in these research projects.

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