A comparative study on nonlinear damping behaviors of precast and cast-in-situ recycled aggregate concrete frames

Authors: **Jianzhuang Xiao**, Chunhui Wang, Changqing Wang, Tao Ding, Amardeep Singh

Department of Structural Engineering, Tongji University, Shanghai, China

State Key Lab. for Disaster Reduction in Civil Eng., Tongji University, Shanghai, China

再生混凝土结构与建造研究室
Research Group for Recycled Concrete Structures and Construction

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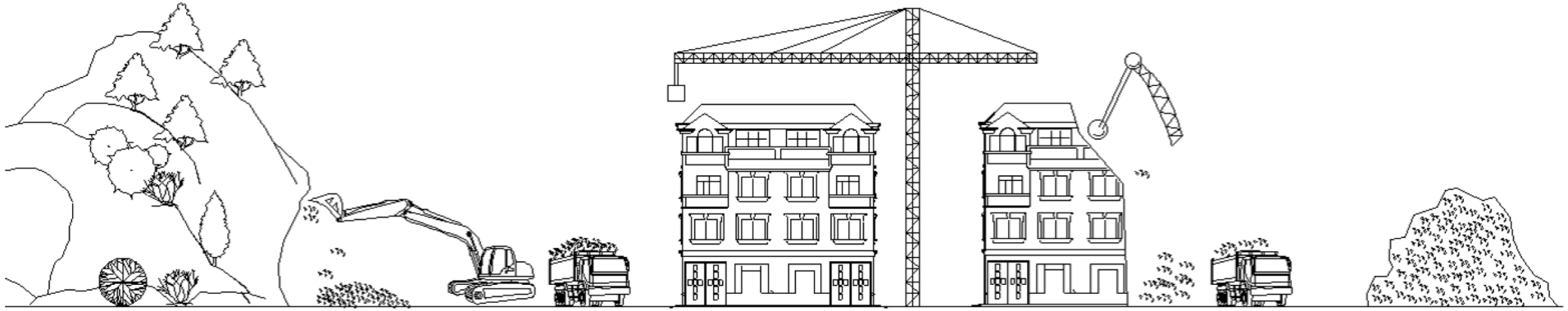
Background

Resource and environment crisis

➢ It is predicted that 52 billion tons of aggregates will be exploited in 2019 worldwide, resulting in significant environmental and ecological crisis.

➢ It is estimated that C&D wastes take up over 4300 acres at a depth of 50 feet, resulting in over 3 billion square yards of landfill each year.

http://fenxiang.siyuefeng.com/gallery/19012
Freedonia. World construction aggregates-Demand and sales forecasts, market share, market size, market leaders. Industry Study No. 3389. Cleveland, Ohio, USA: The Freedonia group, 2016. 390. Pages.
https://www.rubiconglobal.com/blog-construction-demolition-waste-facts/

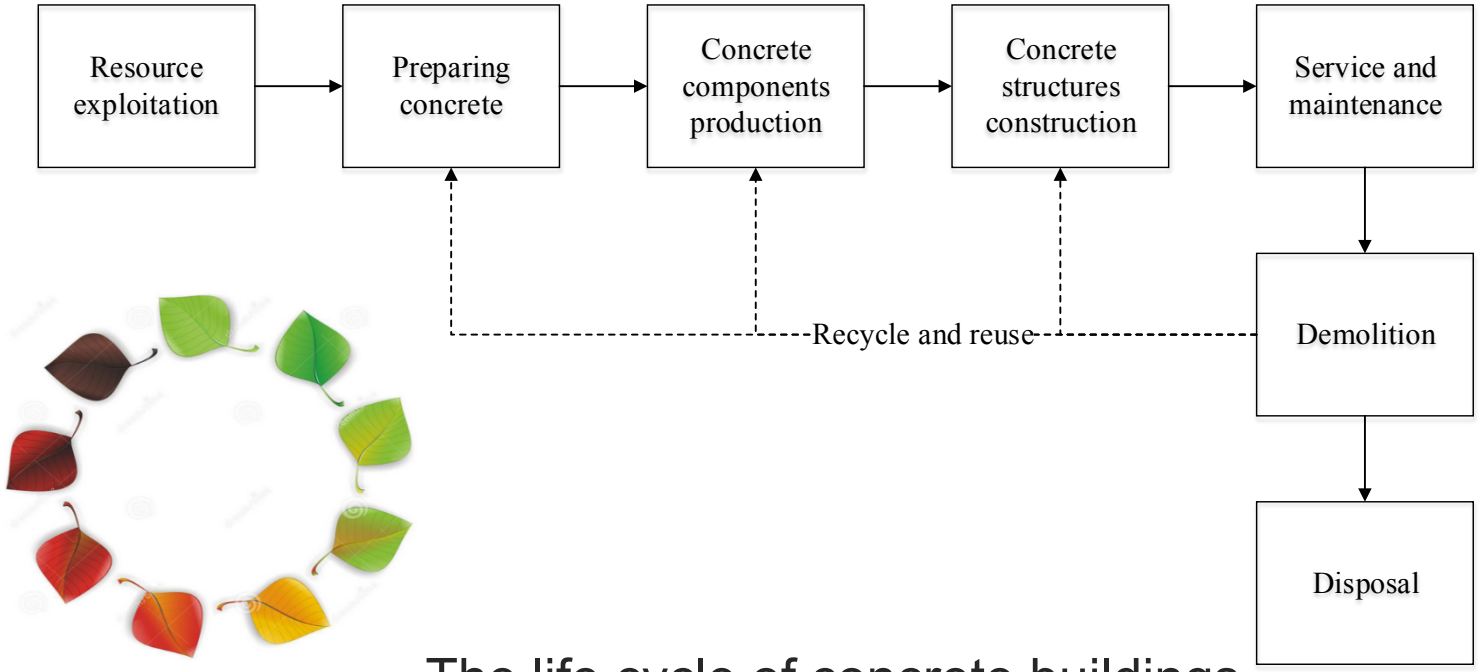


Traditional pattern of building industry

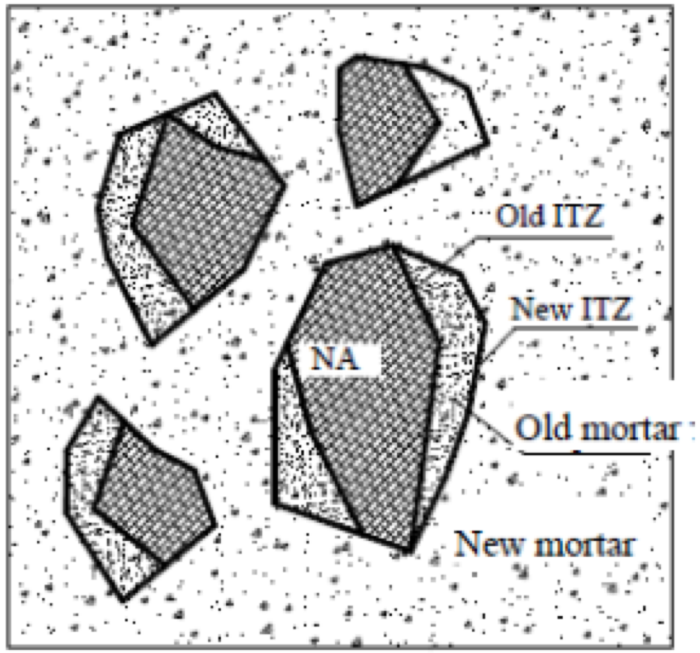
Traditional pattern of building industry generally contains exploitation and processing the raw materials, construction, maintenance, and finally demolition. Most of the C&D waste is directly discharged to the natural world, and the whole process rarely considers the negative effects on the environment.

Background

Waste concrete recycling



The life cycle of concrete buildings



Concrete recycling reduces the need for extraction of natural aggregates (NAs) and the amount of waste ending at landfills. Concrete recycling also finds strategic importance in regions with lack of natural reserves of aggregates or with remote quarries such as Singapore and Shanghai, respectively.

Background

Waste concrete recycling

Waste concrete

Recycle

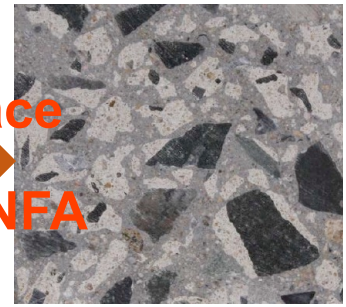
RB/>40mm

RCA/5-40mm

RFA/0.075-5mm

RP/<0.075mm

Replace NCA/NFA



RAC

- **Recycled aggregate concrete (RAC)** is produced through a partial or complete replacement of NAs with recycled aggregates (RAs).
- Due to its environmental benefits and comparable properties to natural aggregate concrete (NAC), RAC is accepted as an alternative to NAC.

RAC structures

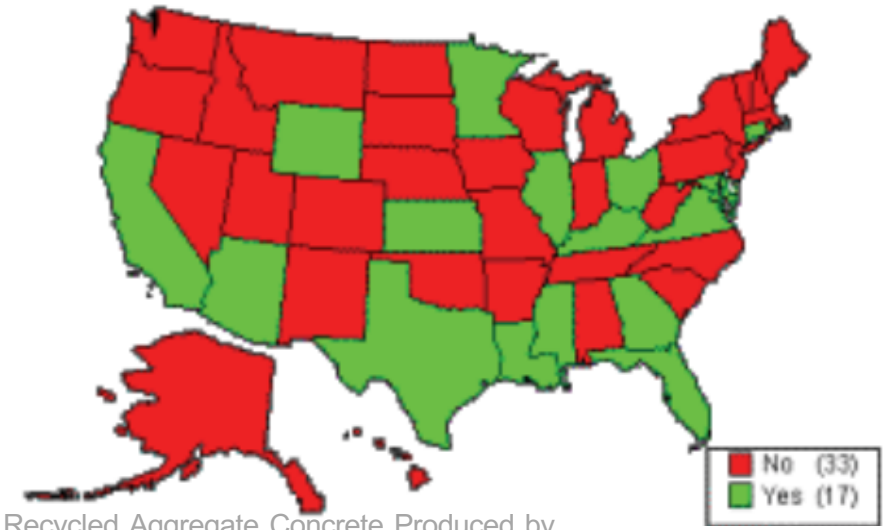
Background

Waste concrete recycling




- The research on the properties of the RAC, dates back to 1919.
- RAC is currently limited to use as granular base or sub-base applications for embankment construction, earth construction works, and low rise buildings.

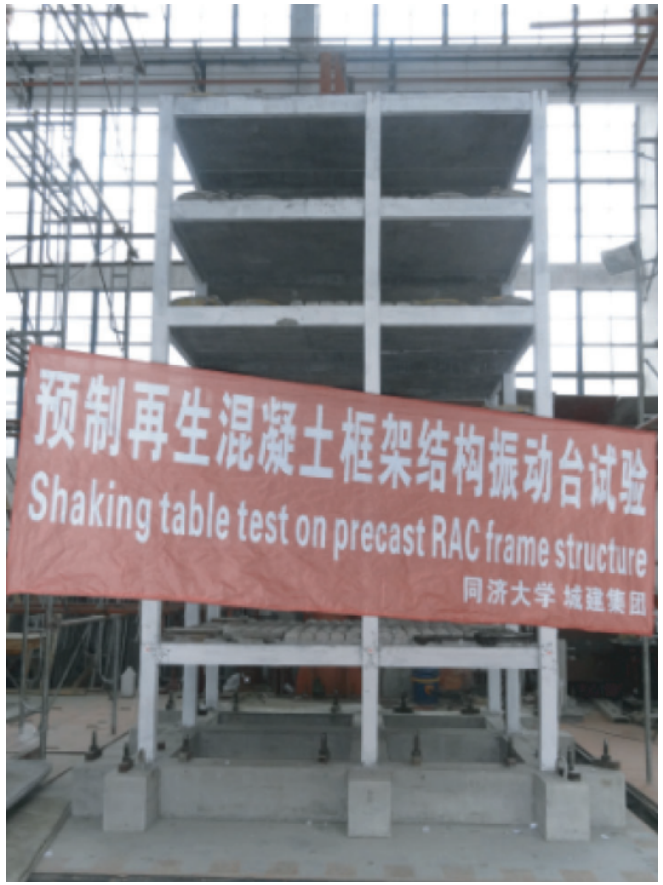
The growing interest in adopting RAC in practice as a sustainable construction material in higher grade applications calls for a comprehensive study to investigate the durability improvement and seismic resistance of RAC structures.

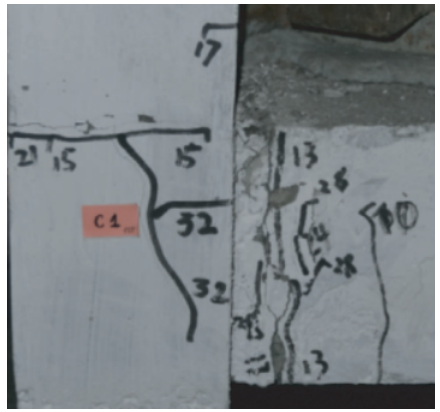


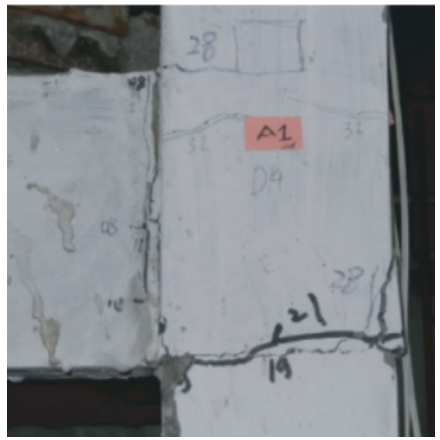
[1] Yasuhiro D. Development of a Sustainable Concrete Waste Recycling System -Application of Recycled Aggregate Concrete Produced by Aggregate Replacing Method[J]. Journal of Advanced Concrete Technology, 2007, 5(1):27-42.
[2] Jin R, Chen Q. Investigation of concrete recycling in the U.S. construction industry. Procedia Engineering, 2015, 118: 894-901.

Background

Precast RAC structures







Prefabricating RAC members in factories is a solution to the problem of the inferior durability of RAC members.

Though the advantages of combining the RAC and the prefabrication technique, there are still challenges faced by researchers and engineers. One of them is how to control their qualities of the prefabricated RAC members, and to detect the damage within the RAC structures after extreme events, for example, strong earthquakes.

Xiao J, Thi LP, Ding T. Shake Table Test on Seismic Response of a Precast Frame with Recycled Aggregate Concrete. ADV STRUCT ENG. 2015;18(9): 1517-34.

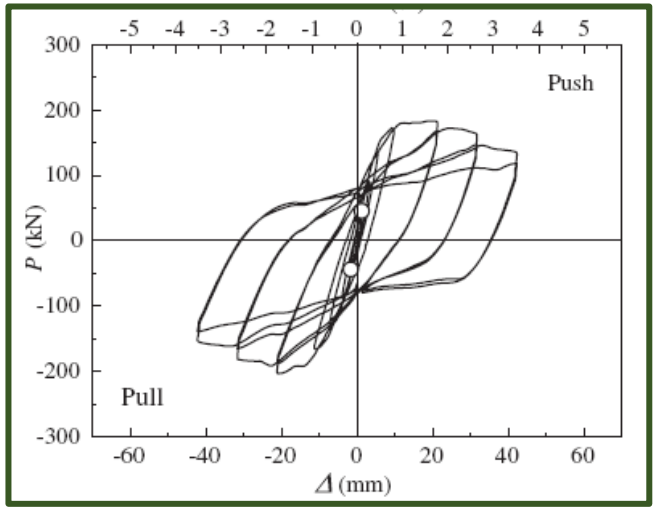
Background

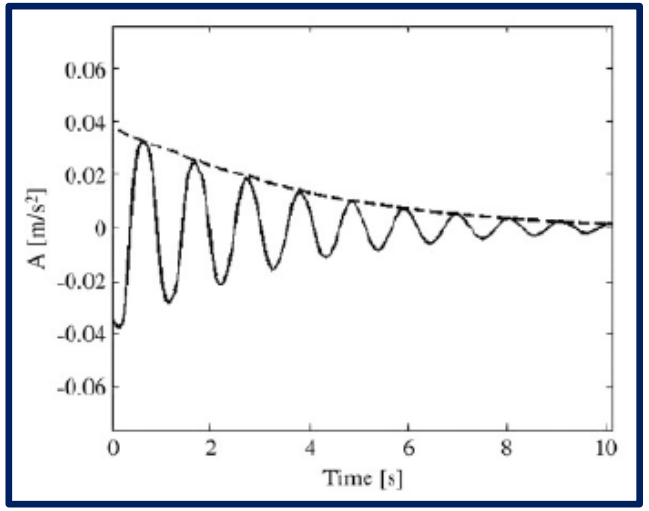
Importance of damping

RAC structures

Wind

Earthquake





Structural responses

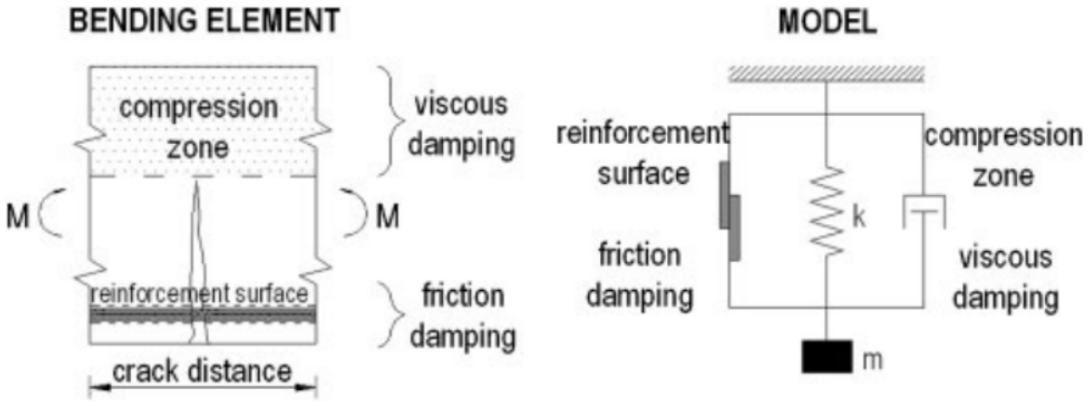
$$m\ddot{x} + D(x,\dot{x})\dot{x} + kx = -m\ddot{x}_g$$

- Structural dynamic response is a function of damping.
- Damping characterizes the energy dissipation mechanism of structures or materials.
- Damping is directly related to the development of damage.

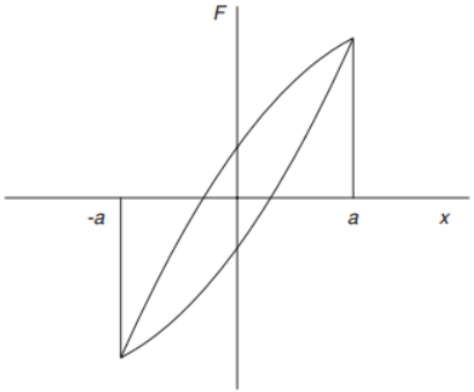
Contents

Method and validation

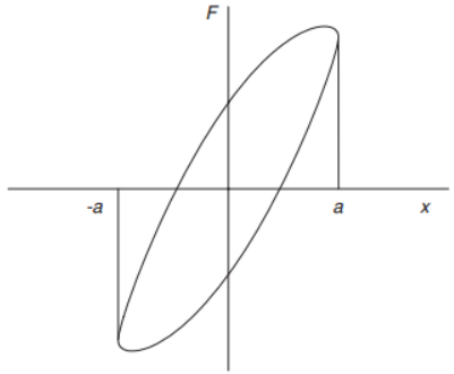
Combined damping model



Cracked bending and corresponding model



Damping force of a quadratic-damped oscillator



Damping force of a viscous-damped oscillator

The combined damping model was introduced by Franchetti and Modena, in which the pure viscous damping was combined with a polynomial damping:

$$F_D = c\dot{x} + d\dot{x}|\dot{x}|$$

The equation of motion of a free oscillator with a quadratic and viscous combined system became:

$$m\ddot{x} + c\dot{x} + d\dot{x}|\dot{x}| + kx = 0$$

Frizzarin M, Feng MQ, Franchetti P, Soyoz S, Modena C. Damage detection based on damping analysis of ambient vibration data. Structural Control and Health Monitoring. 2010;17(4): 368-85.

Franchetti P, Modena C, Feng M. Nonlinear damping identification in precast prestressed reinforced concrete beams. COMPUT-AIDED CIV INF. 2010;8(24): 577-92.

Combined damping model

Through energy balance, the envelope curve of a free oscillation could be presented as

$$a(t) = \frac{(a_0 c_1)e^{-c_1 t}}{c_1 + a_0 c_2(1 - e^{-c_1 t})}$$

where

$$c_1 = \xi\omega$$

$$c_2 = \frac{4}{3\pi}\delta\omega$$

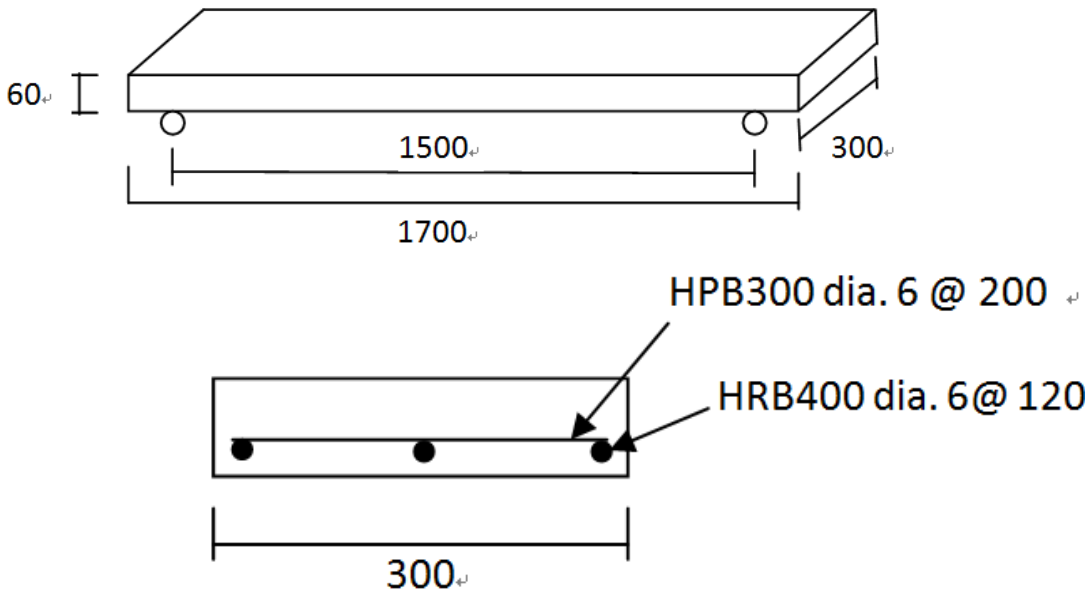
$$\delta = \frac{d}{m}$$

By fitting the envelope curve of the free decay vibration, the viscous damping factor ξ and the quadratic damping factor δ could be estimated and give information about the percentage of the total energy dissipated by each damping mechanism.

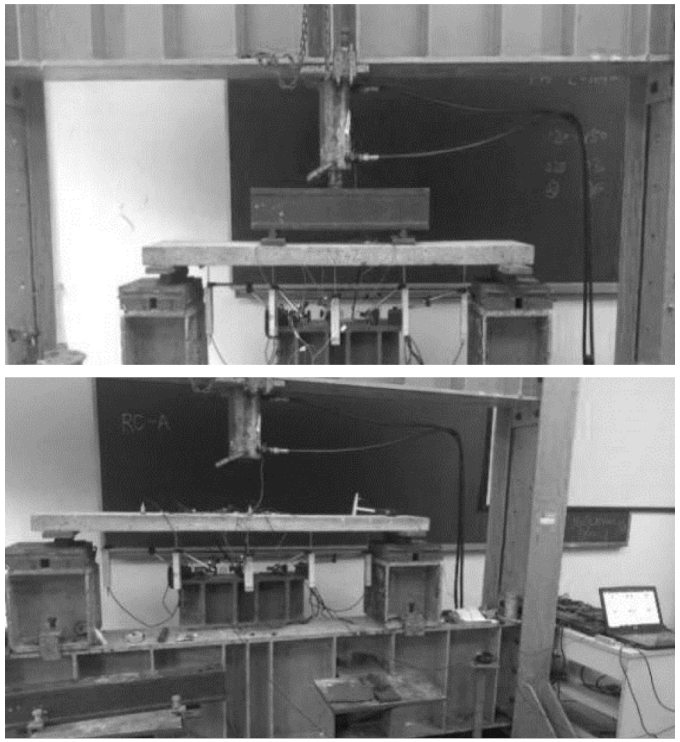
δ=0 means that no nonlinear damping acted on the system, therefore no damage occurred.

δ>0 means a nonlinear dissipation acted on the concrete member.

Method and validation



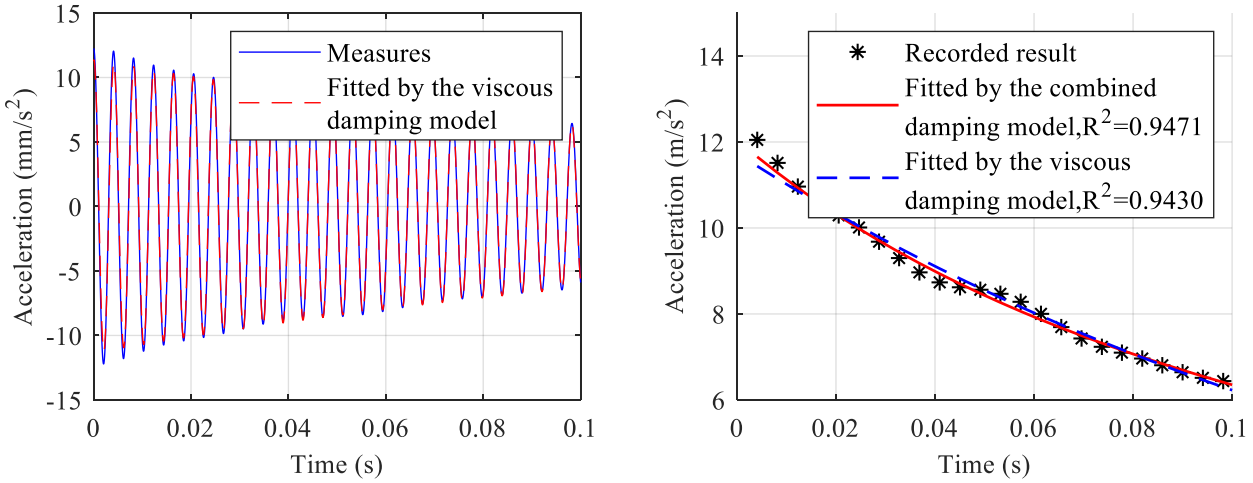
RAC slabs



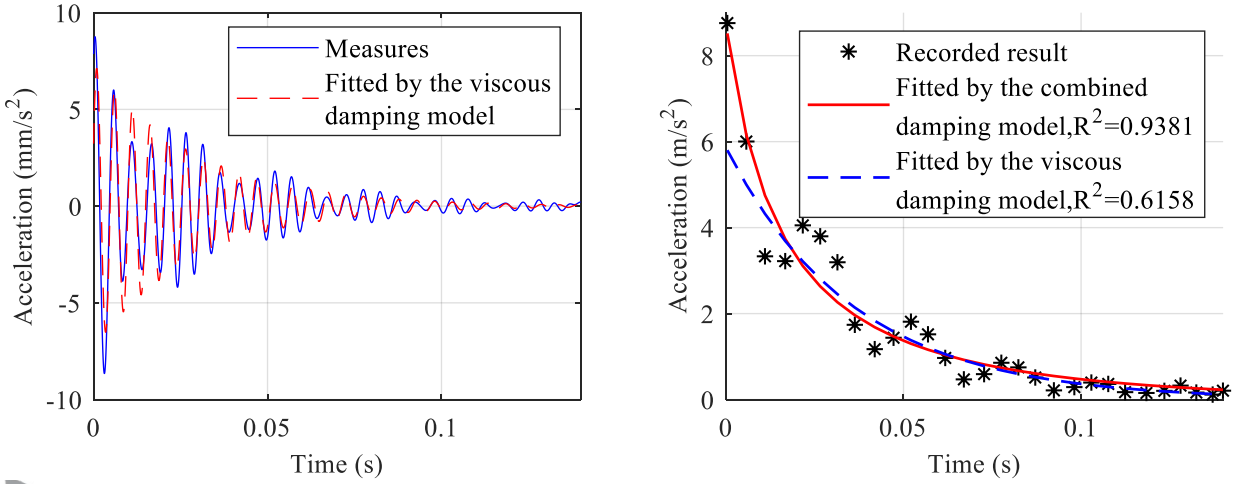
Instruments of applying static loads and impact loads

5 damage phases were subjected by static loads on RAC slabs, i.e. undamaged, cracked, yielding, peak bearing capacity and failure. Impact loads were subjected by a hammer after each static load phase and the free decay vibration responses were recorded by the acceleration gauges.

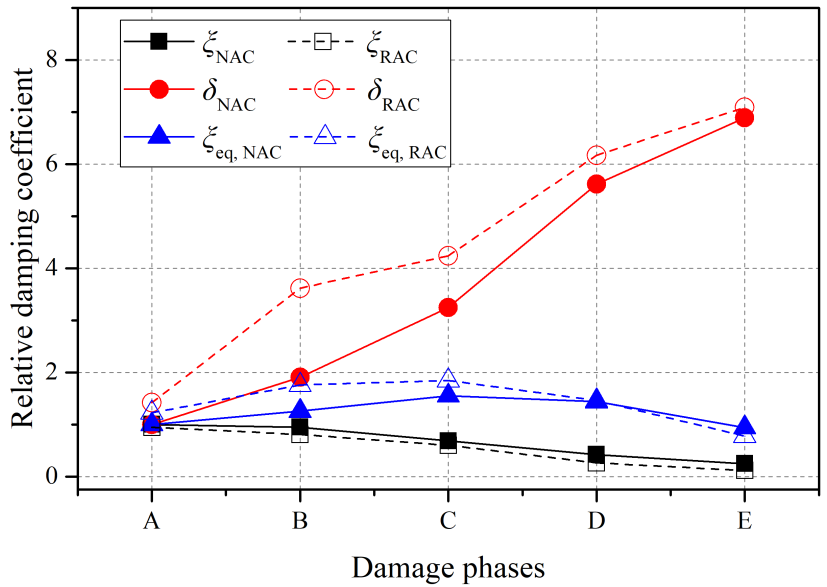
Method and validation



Free decay vibration of the undamaged RAC slab



Free decay vibration of the RAC slab at the failure stage



The method is validated to be accurate to estimate the nonlinear damping characteristics. The quadratic damping factor δ has the potential as a damage indicator.

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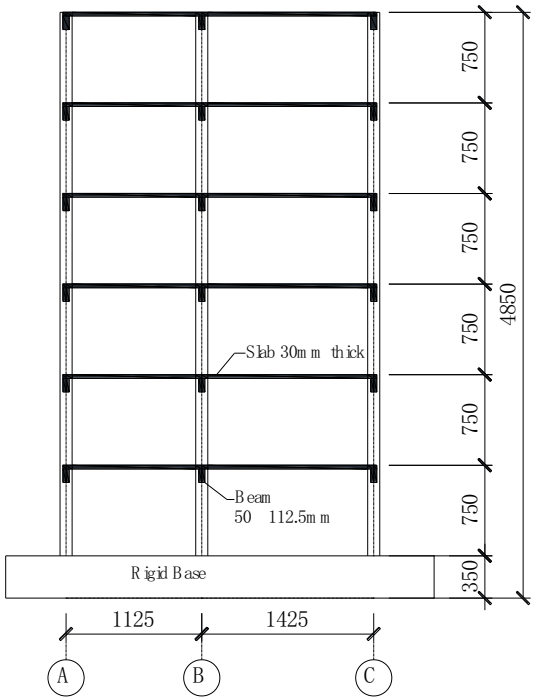
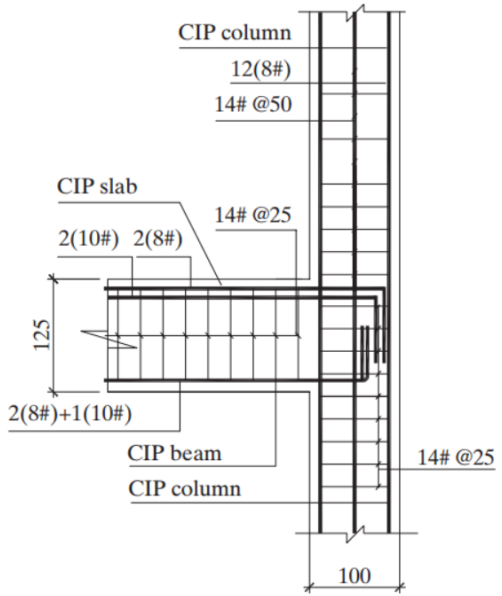
Shake table tests

Description of RAC frames

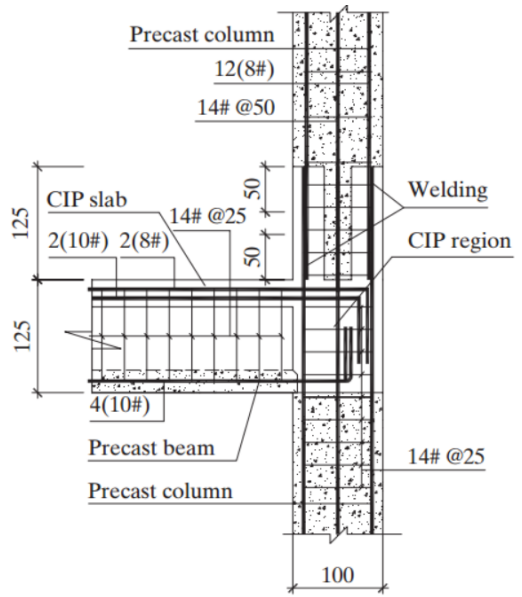


Configuration of the precast and CIS frames

Two 6-floor, 2-span, 2-bay RAC frame structures, one was prefabricated and one was cast in situ, were constructed to conduct the shaking table test.



Joint of CIS frame



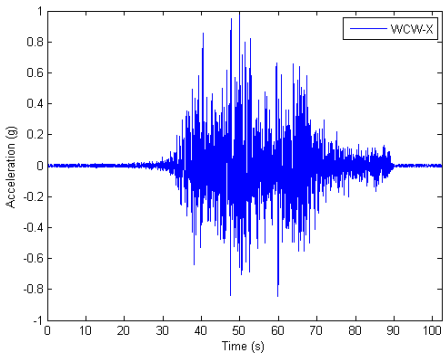
Joint of precast frame

Construction of the precast RAC frame

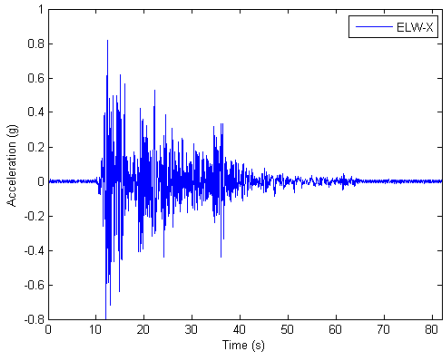
Xiao J, Ding T, Wang C. Seismic behavior of cast-in-place and precast recycled aggregate concrete frames: A comparative study. STRUCT ENG INT. 2016(25): 300-7.

Shake table tests

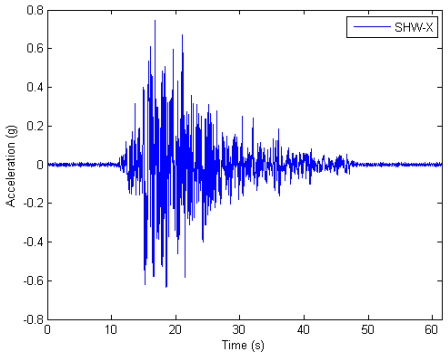
Dynamic excitations



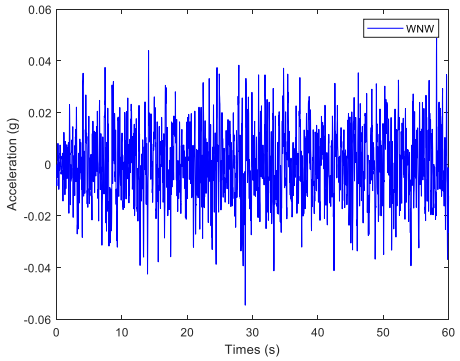
Wenchuan wave



El Centro wave



Shanghai artificial wave



White noise excitation

Series No.	Level	RMS (g)	PGA (g)
1	White noise	0.014	
2	Frequently occurring earthquake of intensity 7		0.066
3	White noise	0.015	
4	Frequently occurring earthquake of intensity 8		0.130
5	White noise	0.014	
6	Basically occurring earthquake of intensity 7		0.185
7	White noise	0.013	
8	Frequently occurring earthquake of intensity 9		0.264
9	White noise	0.012	
10	Basically occurring earthquake of intensity 8		0.37
11	White noise	0.013	
12	Rarely occurring earthquake of intensity 7		0.415
13	White noise	0.013	
14	Rarely occurring earthquake of intensity 8		0.550
15	White noise	0.013	
16	Rarely occurring earthquake of intensity 8		0.750
17	White noise	0.013	

Xiao J, Ding T, Wang C. Seismic behavior of cast-in-place and precast recycled aggregate concrete frames: A comparative study. STRUCT ENG INT. 2016(25): 300-7.

Shake table tests

Dynamic excitations

Typical crack modes of the CIS RAC frame

Typical crack modes of the precast RAC frame

Xiao J, Ding T, Wang C. Seismic behavior of cast-in-place and precast recycled aggregate concrete frames: A comparative study. STRUCT ENG INT. 2016(25): 300-7.

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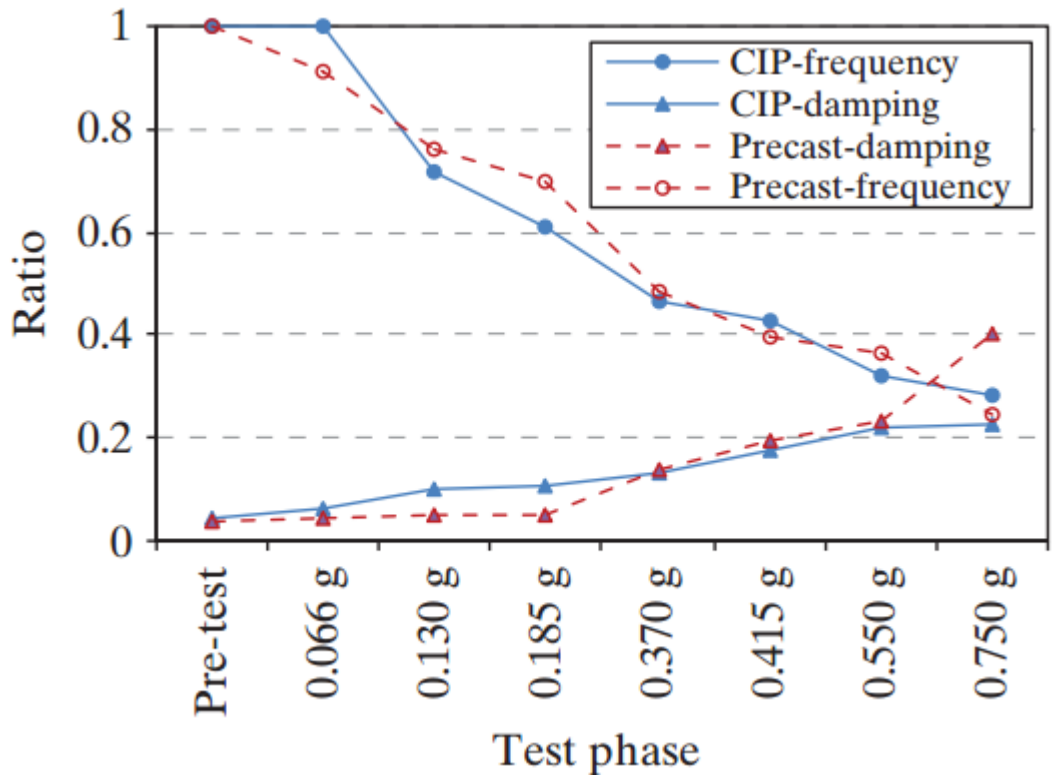
Nonlinear damping and damage detection

Equivalent viscous damping



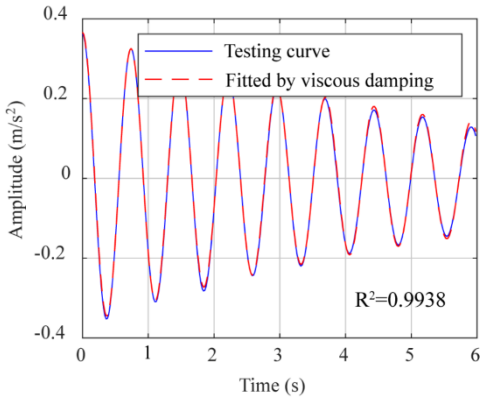
Variation of frequency and damping ratio

- The decrease trend of the fundamental frequency for precast and CIS RAC frames were similar.
- The equivalent viscous damping ratio of the precast RAC frame was smaller than the CIS one after suffering the low-intensity excitations. After the strong earthquakes this trend was inversed.
- Neither variation in frequency nor in damping ratios can characterize the damage accumulation.

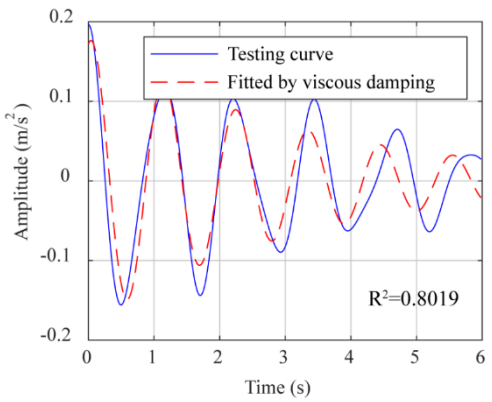
Xiao J, Ding T, Wang C. Seismic behavior of cast-in-place and precast recycled aggregate concrete frames: A comparative study. STRUCT ENG INT. 2016(25): 300-7.

Nonlinear damping and damage detection

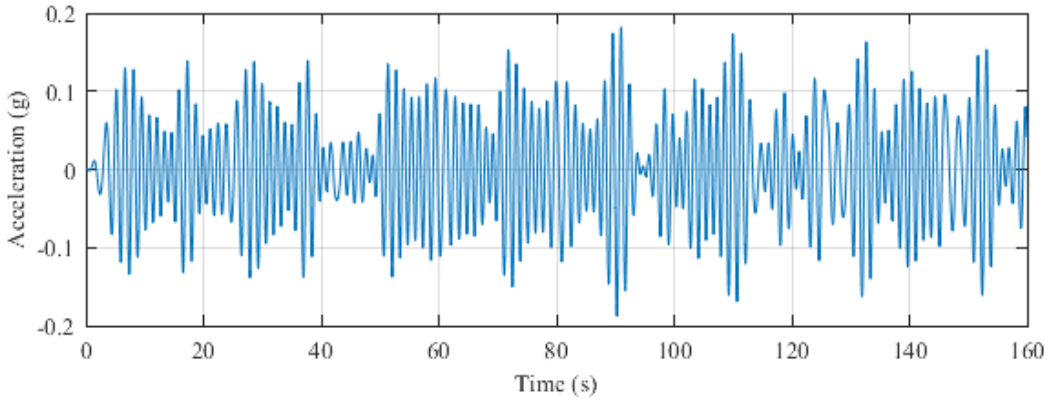
Data process



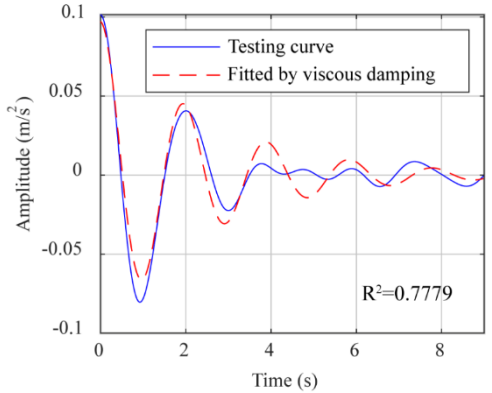
Series No.1 (Undamaged)



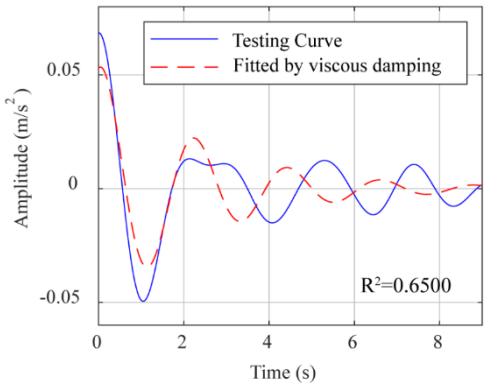
Series No.7 (0.185g)



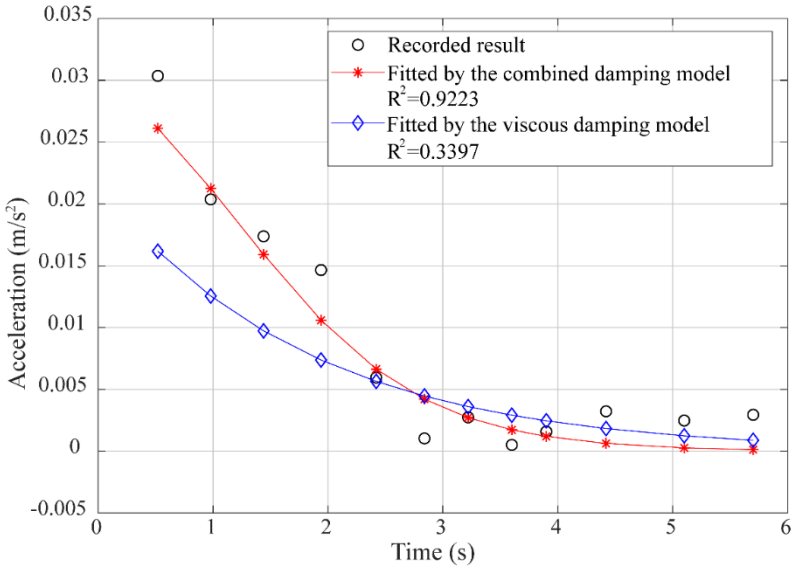
Acceleration responses



Series No.15 (0.550g)

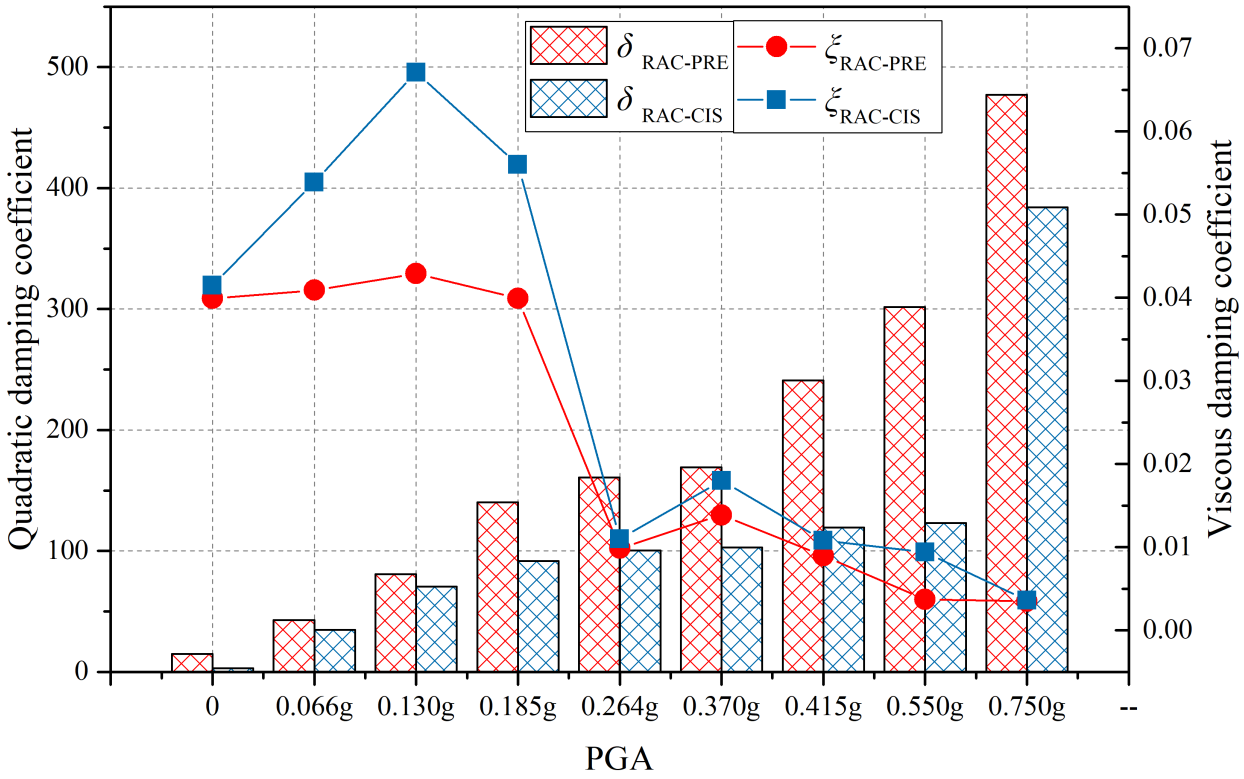


Series No.17 (0.750g)



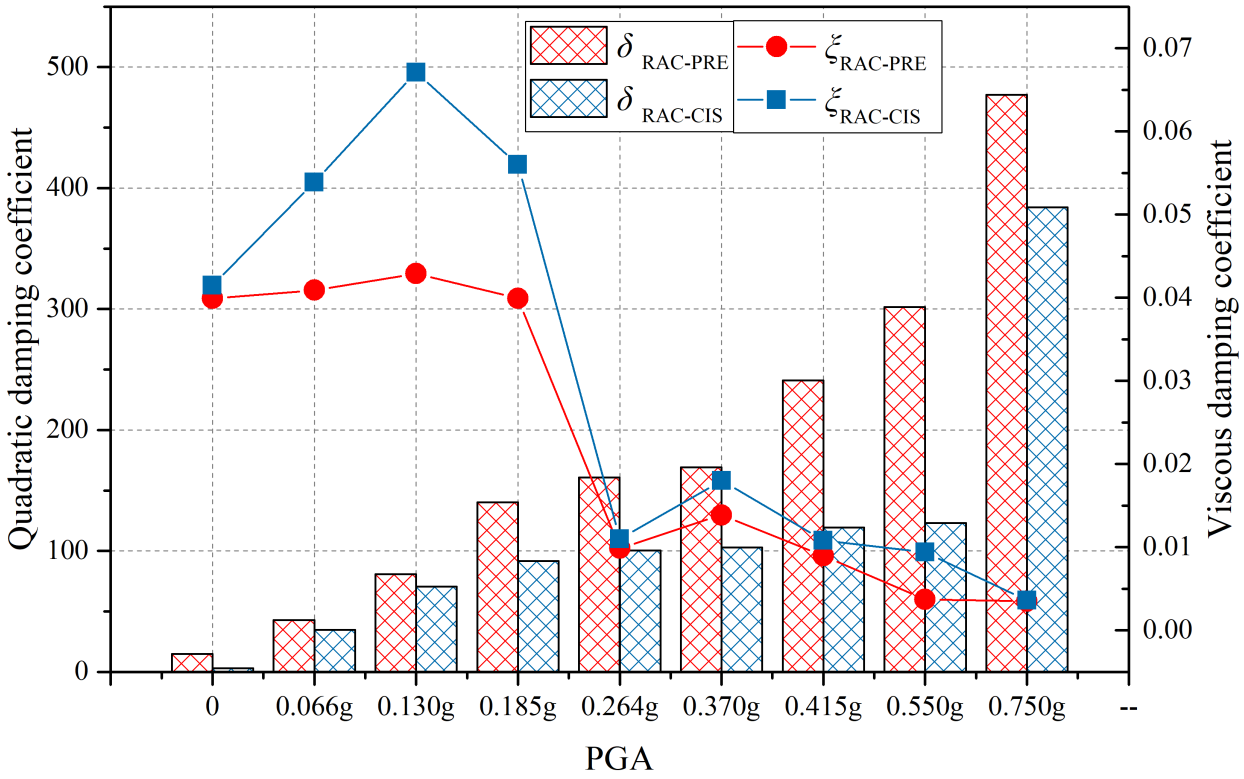
Prediction results

Nonlinear damping and damage detection



- The viscous damping factors increased at first and then decreased.
- The quadratic damping factor increased with the cumulative damage for both precast and CIS RAC frames.
- The energy dissipation mechanism changed from the viscous damping mechanism into a nonlinear damping mechanism.
- The friction and sliding between the cracks absorbed the inputted energy leading to the nonlinear damping mechanism.

Nonlinear damping and damage detection



- The precast RAC frame had a higher quadratic damping factor than that of the CIS one before earthquakes.
- The increase of the damage degree of the precast frame is nearly the same as the CIS one under minor earthquakes.
- Under moderate and strong earthquakes, the quadratic damping factor of the precast frame increased significantly, demonstrating that the seismic resistance of the precast frame is inferior to the CIS frame.

Contents

Conclusions

In this study, nonlinear damping behaviors of precast and CIS RAC frames after simulated earthquakes were analyzed, aiming to provide a reference of quality control of precast RAC members, as well as of damage detection in the ambient environment.

- A shift of the damping mechanism was confirmed from a viscous damping mechanism into a viscous-quadratic combined damping mechanism with damage accumulation.
- The precast RAC frame had a comparatively larger quadratic damping factor before and after earthquake hitting, indicating it had a more severe initial damage and more significant damage developed compared to the CIS frame.
- The friction and sliding between cracks were deduced to explain the increase of the quadratic damping factor.

Thank you for your attentions !

Corresponding author: Prof. Jianzhuang Xiao

Email: jzx@tongji.edu.cn

Presenting author: Chunhui Wang