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

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Abstract. It has been well accepted that applying recycled aggregate concrete (RAC) into structural engineering is a sustainable method to solve the problem of construction and building waste (CDW) accumulation meanwhile to save natural resources exploitation. Precast RAC members in factories is beneficial to improve their qualities and will extend the RAC application. This study presents nonlinear damping behaviors of precast and cast-in-situ RAC frames after simulated earthquakes, as a reference of quality control of precast RAC members, and of damage detection under ambient vibration. The nonlinear damping of precast RAC slabs with different damage degrees was studied to validate the feasibility of applying the quadratic damping coefficient as a sensitive damage factor without any requirement of undamaged baseline. Meanwhile a comparative study on nonlinear damping behaviors of a precast and a cast-in-situ RAC frames was conducted. Results highlight a change of nonlinear damping mechanism for both precast and cast-in-situ RAC frames from a viscous damping into a nonlinear damping. The precast RAC frame had a comparatively larger quadratic damping coefficient before and after earthquake hitting, indicating it had more severe initial damage and damage developed more significantly compared with the cast-in-situ frame. A unified damage classification was proposed for both precast and cast-in-situ RAC frames based on quadratic damping coefficient and observation.

1. Introduction
The use of construction and demolition (C&D) wastes as building materials has been gradually common in recent decades. Both the growing scarcity of raw materials and the gradual accumulated C&D wastes encourage the application of recycled materials in new built structures. Concrete recycling, crushing waste concrete into recycled concrete aggregates (RCAs), is considered as one of the most widely adopted strategies around the world, mostly due to its ease of implementation and the availability of market for the recycled products, such as recycled aggregate concrete (RAC). For extending the application of RAC to consume more C&D wastes, many reliable researches have been reported in terms of mechanical properties, durability, workability and seismicity of RAC structures \([1-4]\). It is generally accepted that the durability of RAC is inferior to that of natural aggregate concrete (NAC), which significantly limit the application of RAC in engineering, especially those exposed in corrosive environment \([5]\). Precast RAC members in factories might be a solution to this problem, considering its superior qualities of concrete members to the cast-in-situ ones \([6]\).
Furthermore, prefabrication in factories has the benefits of higher opportunity for standardization of concrete structures, processing large waste concrete for on-site activities, and saving cost and construction time [7].

For proving the feasibility of precast RAC structures, the authors carried on the first shaking table test of a precast RAC frame model [6]. The result demonstrated that the precast RAC frame had a comparable seismic performance under minor earthquakes to the corresponding cast-in-site one; the displacement ductility of the precast RAC frame was adequate to resist moderate earthquakes; however, a more significant damage occurred in the joint area of the precast RAC frame lead to an inferior stiffness deterioration and energy dissipation performance under stronger earthquakes.

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. In this study, the nonlinear damping mechanism was identified of precast RAC slabs and frames based on their vibration responses, as a reference of quality control of precast RAC members, and of damage detection under ambient vibration as well.

2. Nonlinear damping and damage detection method

Normally, the linear damping mechanism was generally applied in dynamic calculation for the sake of simplification and adequate accuracy when the structural members were undamaged. However, it has been clearly expressed by Franchetti and Modena [8] that the damaged concrete members generally behaved nonlinearily, not only considering the stiffness softening behavior, but also a nonlinear damping behavior. Researchers have proposed manifolds of models to describe the nonlinearity of damping under damage [8-11]. Among these, the viscous-quadratic combined damping model firstly proposed by Franchetti and Modena [8] could properly estimate the nonlinearity of damping with comparatively small vibration amplitudes. This model assumed that the undamaged concrete behaved following a viscous damping mechanism, while the damaged part in concrete members behaved nonlinearily. The pure viscous damping was combined with a polynomial damping, as illustrated in Eq.(1) [8]:

\[ F_D = c\dot{x} + d\dot{x}\dot{x}\ldots(1) \]

where \( F_D \) represents the damping force; \( c\dot{x} \) represents the viscous damping force; and \( d\dot{x}\dot{x} \) represents a quadratic damping force, in which \( d \) was a constant coefficient.

The equation of motion of a free oscillation with small vibration amplitudes for a quadratic and viscous combined system became:

\[ m\ddot{x} + c\dot{x} + d\dot{x}\dot{x} + kx = 0 \ldots(2) \]

Through energy balance, the envelope curve of a free oscillation could be presented as Eq.(3):

\[ a(t) = \frac{(a_0c_2)}{c_1 + a_0c_2(1 - e^{-c_1t})}\ldots(3) \]

where

\[ c_1 = \bar{\xi}\omega\ldots(4) \]
\[ c_2 = \frac{4}{3\pi}\delta\omega\ldots(5) \]
\[ \delta = \frac{d}{m}\ldots(6) \]

By fitting the envelope curve of the free decay vibration, the viscous damping factor \( \bar{\xi} \) and the quadratic damping factor \( \delta \) could be estimated and give information about the percentage of the total energy dissipated by each damping mechanism. \( \delta=0 \) means that no nonlinear damping acted on the system, therefore no damage occurred. On the contrary, a positive value of \( \delta \) means a nonlinear dissipation acted on the concrete member. Therefore, the quadratic damping factor \( \delta \) could be directly correlated to the presence of damage in the considered concrete structure. This damage detection method has the benefit of baseline free, which is especially suitable for application in detection initial
imperfections in precast members in factories, as well as structures survived after earthquakes. For RAC members and structures, this benefit was even more valuable due to the fact that the essential difference between RAC and NAC was the initial imperfections introduced by pores and weak interfacial transition zones (ITZs) and damage development during extreme events.

3. **Nonlinear damping behaviors of the precast NAC and RAC slabs**

Two precast slabs, one made with NAC and the other with RAC whose aggregates were 100% replaced by RCA, were damaged to different levels by static loads and subjected to impact loads by a hammer, to extract the damage information in the free delay vibration signal of acceleration through the aforementioned damage detection method. The NAC and the RAC slabs shared the same geomatic sizes and reinforcements, as shown in Figure 1.

![Figure 1. Geometric sizes of precast NAC and RAC slabs.](image)

5 damage phases were subjected by static loads on slabs, i.e. undamaged, cracked, yielding, peak bearing capacity and failure, judged by strains on the surface of concrete and reinforcement, and deflections of the slabs as well. Then, impact loads were subjected by a hammer after each phase and the free delay vibration responses were recorded by the acceleration gauges. A typical acceleration record is shown in Figure 2. And a comparison between fitting results by the combined damping model and the viscous damping model is shown in Figure 3. It is easily to find that the acceleration responses showed significant features of nonlinearity that the combined damping model achieved a better fitting result compared to the viscous damping model.

Development of damping coefficients, namely, viscous damping coefficient $\zeta$ and quadratic damping coefficient $\delta$ for the combined damping model, and the equivalent viscous damping ratio for the viscous damping model, correspondingly, are demonstrated in Figure 4. For the sake of convenient discussion, only relative values to the initial corresponding damping coefficient of the NAC slab was presented. A comparatively high value of equivalent viscous damping ratio of the RAC slab was observed at different damage stages in Figure 4, which agreed well with the other reliable experimental observations [12]. However, the viscous constituent of the dissipated energy somehow decreased with the increasing damage, for both NAC and RAC slabs. The viscous damping coefficient $\zeta$ decreased to 0.246 and 0.115 at failure stage correspondingly for the NAC slab and the RAC slab compared to the undamaged conditions. While the higher quadratic damping coefficient of the RAC slab than that of the NAC slab accounted for the higher equivalent damping ratio of the RAC member caused by the more energy dissipated by the nonlinear channel. The initial quadratic damping coefficient of the RAC slab was slightly higher than that of the NAC slab, demonstrating a severer initial damage within the RAC slab. The differences between the quadratic damping coefficients of the RAC slab and the NAC slab increased at first, then tend to decrease when the slabs suffered severe damages. However, the quadratic damping coefficient had an increasing trend along with the damage accumulation for both RAC and NAC, which increased to 6.885 and 7.087 times higher at failure stage than beginning for the NAC and RAC slabs correspondingly. The decrease of the viscous damping coefficient and the increase of the quadratic damping coefficient illustrate a shift of the energy dissipation mechanism. It is generally accepted that the nature of the viscous damping mechanism was molecular forces within materials, while the nonlinear damping mechanism might be caused by the friction between imperfections and cracks [13]. This phenomenon confirmed the fact that the undamaged precast RAC slab contained more imperfections, i.e. pores or weak ITZs compared to the NAC slab, besides a more significant damage development. Meanwhile, the increasing trend of the quadratic damping coefficient $\delta$ with cumulative damage highlighted the
feasibility of using as a unified baseline free reference of damage detection for both precast RAC and NAC members and structures.

Figure 2. A free decay acceleration response.

Figure 3. Comparison between fitting results by combined damping model and viscous damping model.

Figure 4. Development of relative damping coefficients with damage.

4. Nonlinear damping behavior of precast and cast-in-situ RAC frames

4.1. Description of the RAC 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. These two frames had totally same configuration, as shown in Figure 5, as well as the reinforcement distributions. These two frames utilized the identical target strength RAC, whose replacement percentages of RCA were 100%. For the sake of convenient discussion, the precast RAC frame was represented as RAC-PRE, well the cast-in-site RAC frame was represented as RAC-CIS.
The process of constructing the precast RAC frame included three steps: (1) fabricated beams and columns in a factory, and (2) transported the members to the lab and (3) constructed the frame. 9 columns and 12 beams were erected on each floor level. The beams were seated on the head of columns. For assuring rigid beam-column connections between beams and columns, the longitudinal reinforcements were welded within the joint, as shown in Figure 6. Following that the molds were erected and RAC in joints and slabs was casted, as shown in Figure 7.

4.2. Shaking table tests

The Wenchuan wave (WCW), El Centro wave (ELW) and the artificial Shanghai wave (SHW) as a group with increasing peak ground accelerations (PGAs) of 0.066g, 0.130g, 0.185g, 0.264g, 0.370g, 0.415g, 0.550g and 0.750g were inputted into the frame from the rigid ground of the shaking table. Before and after each group of earthquakes, low-intensity white noise waves (WNW) were inputted to extract dynamic characteristics and to detect damage.

The displacement and acceleration responses were recorded by the displacement linear variable differential transducers (LVDTs) and acceleration gauges, respectively, on the rigid table and each floor of the frames. Meanwhile, strain gauges were fixed on the surface of concrete and reinforcement to analyze the failure procedures of these two RAC frames under earthquakes.

4.3. Nonlinear damping behaviors and damage detection

The aforementioned method of damage detection was proposed for the members or structures behaved harmonically without any load. However, in this study, the structures were excited by the earthquake waves and WNWs, and the nonlinear fitting method could not be applied directly. The random
decrement technique (RDT) [14] was applied to extend the application of this damage detection method from free decay vibration into vibration excited by WNWs. WNW is the most accessible vibration that can be easily acquired from a real structure in the ambient environment, since the measurement requires neither the structure being taken out of service, nor expensive exogenous excitations. The RDT enables the resulting signature from the ensemble averaging of segments of the response to extract damping characteristics from free vibration signature.

The detailed comparison of failure pattern and seismic performances of these two models was elaborately discussed in reference [15]. It could be found in this comparative study that the precast RAC frame suffered a more significant damage under the same dynamic loads than the cast-in-situ one. The relatively severe damage level of a post-cast joint was the main reason for the overall inferior seismic performance of the precast structure, during an earthquake of high-level intensity. Compared to the cast-in-situ RAC frame, it was observed that the precast frame suffered more serious damage under the shear action of the earthquakes.

The quadratic damping coefficient \( \delta \) and viscous damping coefficient \( \zeta \) by nonlinear fitting with the combined damping model are shown in Figure 8. It is worth to mentioning that these coefficients were extracted from the acceleration responses recorded by the acceleration gauges fixed on the roofs of both precast and cast-in-situ RAC frames. In Figure 8, it could be observed that the viscous damping coefficients increased at first and then decreased, while the quadratic damping coefficient increased with the cumulative damage for both precast and cast-in-situ RAC frames. Based on the assumptions of the combined damping model that the undamaged part of structure behaved viscously, while the damaged part behaved nonlinearly, the energy dissipation mechanism changed from the viscous damping mechanism into a viscous-nonlinear damping mechanism, demonstrating a damage development process with the increasing PGA. It could be deduced that the friction and sliding between the two sides of cracks absorbed the inputted energy and accounted for the nonlinear damping mechanism.

![Figure 8. Variations of quadratic and viscous damping coefficient with the increasing PGA.](image)

Furthermore, due to the advantage of baseline free feature, the initial damage within the precast and the cast-in-situ RAC frames were detected. Before excited by earthquakes, the precast RAC frame presented a much higher quadratic damping coefficient than that of the cast-in-situ one. This fact might be caused by the initial cracks between the precast members and the post-cast joints. This difference kept constant after suffered the earthquakes with 0.066g and 0.130g PGA, demonstrating that under low-intensity earthquakes, the precast RAC frame presented a similar seismic resistance compared to the cast-in-situ frame. However, the difference between the quadratic damping
coefficients of these two frames became significant under 0.185g PGA earthquakes. It demonstrated the inferior seismic performance of the precast RAC frame to the cast-in-situ one.

Combining the description of the failure procedures and the quadratic damping coefficients for these two frames, it can be concluded that the precast RAC frame suffered a severe damage under 0.185g with a $\delta$ of 140.1, and was completely damaged under 0.550g with a $\delta$ of 307.7; while the cast-in-situ RAC frame suffered a severe damage under 0.415g with a $\delta$ of 123.3, and was completely damaged under 0.750g with a $\delta$ of 384.1. This result highlighted a better seismic performance of the cast-in-situ RAC frame under strong earthquakes. And the quadratic damping coefficient could be used as a reference to guide the retrofit of precast and cast-in-situ RAC structures after earthquakes.

5. Conclusions

In this study, nonlinear damping behaviors of precast and cast-in-situ 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 under ambient vibration. The nonlinear damping of both the precast NAC and RAC slabs with different damage degrees was studied to validate the feasibility of applying the quadratic damping coefficient as a sensitive damage factor without any requirement of undamaged baseline. By analyzing the experimental results, a shift of the damping mechanism was confirmed from a viscous damping mechanism into a viscous-quadratic combined damping mechanism. Meanwhile a comparative study on nonlinear damping behaviors of a precast and a cast-in-situ RAC frames was conducted. The precast RAC frame had a comparatively larger quadratic damping coefficient before and after earthquake hitting, indicating it had more severe initial damage and more significant damage developed compared to the cast-in-situ frame. The friction and sliding between cracks were deduced to explain the increase of quadratic damping coefficient. A unified damage classification was proposed for both precast and cast-in-situ RAC frames based on quadratic damping coefficient and experimental observation.

References:

[1] Etxeberria M, Vázquez E, Mari A and Barra M Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete 2007 CEMENT CONCRETE RES. 37(5) 735

[2] Silva RV, de Brito J, Evangelista L and Dhir RK Design of reinforced recycled aggregate concrete elements in conformity with Eurocode 2 2016 Constr. Build. Mater. 105 144

[3] Silva RV, Neves R, de Brito J, Dhir RK Carbonation behaviour of recycled aggregate concrete 2015 CEMENT CONCRETE COMPOSITES 62 22

[4] Fan Y, Wang S, Zhao J and Huo X Bi-directional analog shaking table test on performance-enhanced recycled aggregate concrete frame structure model 2015 J. China Civ. Eng. 48(12) 50

[5] Levy SM and Helene P Durability of recycled aggregates concrete: a safe way to sustainable development 2004 CEMENT CONCRETE RES. 34(11) 1975

[6] Xiao J, Thi LP and Ding T Shake Table Test on Seismic Response of a Precast Frame with Recycled Aggregate Concrete 2015 Adv. Struct. Eng. 18(9) 1517

[7] Holden T, Restrepo J and Mander JB Seismic Performance of Precast Reinforced and Prestressed Concrete Walls 2003 J. Struct. Eng. 129(3) 286

[8] Franchetti P, Modena C and Feng M Nonlinear Damping Identification in Precast Prestressed Reinforced Concrete Beams 2010 Comput. Aided. Civ. Inf. 8(24) 577

[9] Demarie GV and Sabia D Non-linear Damping and Frequency Identification in a Progressively Damaged R.C. Element 2011 Exp. Mech. 51(2) 229

[10] Elmenshawi A and Brown T Hysteretic energy and damping capacity of flexural elements constructed with different concrete strengths 2010 Eng. Struct. 32(1) 297

[11] Spence SM and Kareem A Tall Buildings and Damping: A Concept-Based Data-Driven Model 2014 J. Struct. Eng. 140 040140055

[12] Xiao J, Wang C, Li J and Tawana MM Shake-Table Model Tests on Recycled Aggregate Concrete Frame Structure 2012 ACI Struct. J. 6(109) 777
[13] Jeary AP Damping in structures 1997 *J. WIND ENG. IND. AEROD.* **72** 345

[14] Mikael A, Gueguen P, Bard PY, Roux P and Langlais M The Analysis of Long–Term Frequency and Damping Wandering in Buildings Using the Random Decrement Technique 2013 *Bulletin Seis. Soc. Amer.* **103**(1) 236

[15] Xiao J, Ding T and Wang C Seismic behavior of cast-in-place and precast recycled aggregate concrete frames: A comparative study 2016 *Struct. Eng. Inter.* **25** 300