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FEM analysis of reinforced RAC columns under cyclic loading: preliminary results

Jin-Jun Xu[1),] Xin-Yu Zhao[2)] Cristoforo Demartino[3)] and Zong-Ping Chen[4)]

[1), 3)] *College of Civil Engineering, Nanjing Tech University, Nanjing 211816, P.R. China'*
[4), 1)] *College of Civil Engineering and Architecture, Guangxi University, Nanning 530004, P.R. China*
[2)] *State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou 510640, P.R. China*
[3)] *cristoforo.demartino@me.com*

ABSTRACT

This paper presents the preliminary results of FEM analysis of reinforced aggregate concrete (RAC) columns under cyclic loading. Previous research has demonstrated that RAC can be a feasible and environmentally friendly alternative to conventional concrete for the use in structural applications. Currently, very limited information is available in the literature about the methods to be used for designing RAC columns. A fiber section based nonlinear finite element (FE) model was developed so as to provide in-depth insights into the seismic behavior of RRAC columns. A comparison between simulation results of the seismic behavior of RRAC columns and available experimental results were made to validate the FE model.

1. INTRODUCTION

The use of construction and demolition waste (CDW) as aggregates in the new concrete mixture has been recognized as an attractive approach to preserve natural resources and to reduce the environmental impact of the construction industry (Loo et al. 1987 and Pepe et al. 2016). Significant research efforts that have been made to date have demonstrated that recycled aggregate concrete (RAC), manufactured using crushed concrete obtained from CDW, can be a feasible and environmentally friendly alternative to conventional natural aggregate concrete (NAC) for use in structural applications (Xu et al. (2017) and Xu et al. (2018)). The resulting material can be lead to the construction of "Green Concrete" structures. However, RAC is characterized by

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[1)] Assistant Professor
[2)] Associate Professor
[3)] Post Doc
[4)] Full Professor

generally slightly lower mechanical behaviors and durable properties compared to equivalent NAC.

Reinforced Concrete (RC) structures made of RAC, namely reinforced recycled aggregate concrete (RRAC), can promote the reuse of waste concrete and can be widely used in constructions similarly to conventional RC structures made of NAC. Beams and columns are the main resistance components in frame structures, and their mechanical behaviors need to be accurately determined during the structural analysis and design process.

Han et al. (2001), González-Fonteboa and Martínez-Abella (2007), Choi et al. (2010), Fathifazl et al. (2010), Arezoumandi et al. (2014), Knaack and Kurama (2015), Sadati et al. (2016) and Katkhuda and Shatarat (2016) experimentally investigated the influence of RCA content on the shear failure and behavior of RRAC beams showing that the failure modes of RRAC beams are similar to those of reinforced natural aggregate concrete (RNAC) beams. Generally, these studies demonstrate that the shear capacity of RRAC beams decreases with an increase of RCA content being lower than that of RNAC beams. Xiao et al. (2012) investigated the seismic behavior of semi-precast column with recycled aggregate concrete and concluded that the semi-precast RRAC columns have the similar seismic behavior as that of the fully cast-in situ RNAC columns. Yang (2016) carried out the pseudo-static tests on cast-in-situ RRAC columns to study their seismic performance, and the experimental results showed that the failure patterns of RRAC columns are similar to those of RNAC columns.

The literature review reported herein reveals that the investigation of the seismic behavior of RRAC columns has generally received limited attention. Therefore, studying the seismic behavior of RRAC columns is of crucial importance to gain sufficient confidence to enable large-scale structural applications of this material and to obtain reliable design procedures for the resulting structural members. The objective of this study is to develop and validate a nonlinear finite element (FE) model of RRAC columns under combined axial compression and cyclic lateral loads to emphasize the effect of RCA properties on the behavior of RAC.

2. FE MODELING AND VALIDATION

2.1. FE modeling

The first step of this study was to develop a fiber section based nonlinear FE model capable of predicting the seismic behavior of RRAC columns under combined axial compression and cyclic lateral loads. The modeling and nonlinear analyses of RRAC columns were done by employing SeismoStruct (2014). The “inelastic displacement-based frame element” was used to model the RRAC columns in SeismoStruct. The boundary conditions of the column were set in accordance with the cantilever boundary conditions, which resulted in a fully fixed column footing and a free top end. Fig. 1 illustrates the boundary conditions and the loading scheme for RRAC columns, in which the axial compressive load (*N*) is applied at the end of column top, and meanwhile, the lateral load (*P*) is applied to the point corresponding to *N*. Some failure modes, such as shear failure, compression-shear failure and flexural failure, can be observed in the cyclic loading tests of RC columns. The shear damage component of the failure mode always results in a reduction in the ductility of the column, and the low ductility of the columns is very taboo when employing them in seismic regions. On the other hand, the flexural failure mode of the column exhibits a better ductility when compared with shear failure. In this paper, only the flexural failure is considered in order to meet the ductility demand in seismic regions.

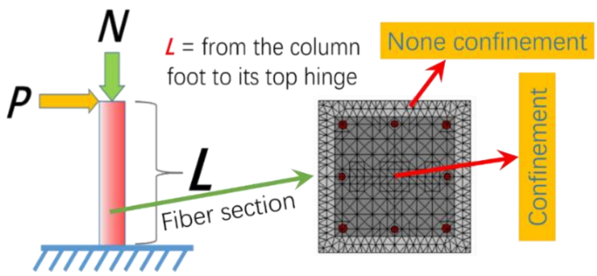

Fig. 1 Loading scheme and fiber section regions for RRAC columns

2.1.1 Stress–strain relationship of RAC

The concrete model of "*con_ma*" was used in SeismoStruct and its stress-strain relationship is based on the confinement effect provided by the transverse stirrups. Concrete was modeled using the uniaxial nonlinear constant confinement model, initially developed by Madas (1993), which follows the constitutive relationship proposed by Mander et al. (1998) and the cyclic rules proposed by Martinez-Rueda and Elnashai (1997). In SeismoStruct, the cylinder compressive strength (f_c), elastic modulus (E_c) and peak strain (ε_{co}) are the parameters to determine the concrete stress-strain relationship, and the confinement factor can be automatically computed based on the geometrical and material characteristics (i.e. cross-sectional size, concrete strength, volumetric ratio and yield strength of transverse steel reinforcement, number of transverse steel reinforcement legs, and total area of longitudinal steel reinforcement). In addition, it should be noted that the tensile strength of RAC was neglected in the stress-strain relationship.

Based on the available database of the compressive behavior of RAC, Gholampour et al. (2017) respectively proposed a prediction model of the cylinder compressive strength (f_c) and the elastic modulus (E_c) of RAC using gene expression programming:

$$f_c\left(\mathrm{MPa}\right)=\frac{23.5\times0.998^{r}\times\left(w_{\mathrm{eff}}/c+0.09\right)}{w_{\mathrm{eff}}/c^{1.7}} \tag{1}$$

$$E_c\left(\mathrm{MPa}\right)=16\times\left(6.1-0.015r\right)\times\left(5.3-1.7w_{\mathrm{eff}}/c\right)^{3.9} \tag{2}$$

where r is the RCA content (%), $0<r<100\%$; w_{eff}/c is the effective ratio of water-to-cement, $0.3<w_{eff}/c<0.8$.

Xiao et al. (2005) undertook the compressive tests on RAC and suggested the following prediction model of the peak strain of RAC ($\varepsilon_{co}{}^{r}$):

$$\varepsilon_{co}^{r}=\varepsilon_{co}^{n}\left(1+\frac{r}{65.715r^{2}-109.43r+48.989}\right) \tag{3}$$

where $\varepsilon_{co}{}^{r}$ is the peak strain of RAC, $\varepsilon_{co}{}^{n}$ is the peak strain of NAC. It should be noted that Eqs. (1)-(3) have the same parametric range of application.

Lim and Ozbakkaloglu (2014) put forward a prediction model of $\varepsilon_{co}{}^{n}$ as follows:

$$\varepsilon_{co}^{n}=\frac{f_{c}^{0.225k_{d}}}{1000}k_{s}k_{a}\ ;\ \ k_{d}=\left(\frac{2400}{\rho_{c,f}}\right)^{0.45}\ ;\ \ k_{s}=\left(\frac{152}{D}\right)^{0.1}\ ;\ \ k_{a}=\left(\frac{2D}{H}\right)^{0.13} \tag{4}$$

where f_c is the cylinder compressive strength (MPa), $\rho_{c,f}$ is the concrete density (kg/m^3) and D and H are the diameter and height of concrete cylinder specimens (mm), respectively, in which, 2250 kg/m^3<$\rho_{c,f}$<2550 kg/m^3, 50 mm<D<400 mm, 100 mm<H<850 mm. k_d, k_s, and k_a, respectively, are coefficients accounting for the concrete density and specimen aspect ratios. It is worth noting that the coefficients of kd, ks, and ka are equal to 1.0 when considering common cylindrical NAC specimens, i.e. $\rho_{c,f}$=2400 kg/m^3, D=152 mm and H/D=2.0.

2.1.2 Stress-strain relationship of steel reinforcement

The steel model of "*stl_mp*" was used in SeismoStruct and its stress-strain relationship was modeled using the uniaxial steel model initially proposed by Yassin (1994) based on a simple, yet efficient, stress-strain relationship proposed by Menegotto-Pinto (1973), coupled with the isotropic hardening rules proposed by Filippou et al. (1983). The current implementation follows that carried out by Monti et al. (1996).

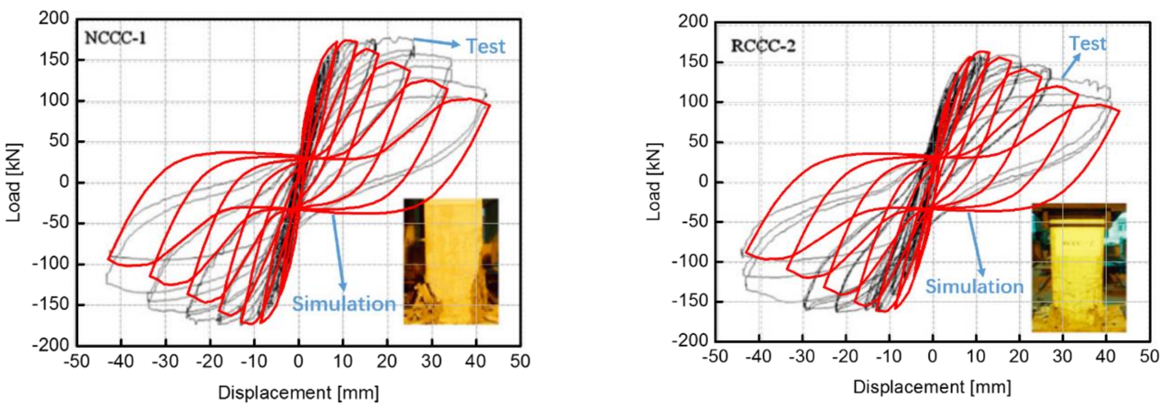

Fig. 2 Comparison of hysteretic curves between experimental and numerical results: Experimental specimens reported in Xiao et al. (2012)

2.2 Validation and discussion

As presented in Section 1, Xiao et al. (2012) and Yang (2016) carried out a series of pseudo-static tests on the seismic behavior of RRAC columns under combined axial compression and cyclic lateral loads. Only the RCAs reported in Yang (2016) were presaturated before manufacturing RRAC columns. The final damage modes of all specimens were the flexural failure. In all of the experiments, three cycles were carried out at the same displacement amplitude, and the loading end in the descent stage of hysteretic curves was almost at the point corresponding to 80% ultimate lateral load. In FE analysis, one cycle at a certain displacement amplitude was executed merely to obtain the hysteretic characteristics and pivotal seismic performance (e.g. hysteretic curves, lateral load capacity and ductility) of RRAC columns. Comparisons in terms of lateral load-displacement hysteretic curves, lateral load capacity and ductility between the measurement and simulation are illustrated in Figs. 2 and 4. The quantitative outcomes, such as the experimental ultimate lateral load ($P_{u,t}$), the numerical ultimate lateral load ($P_{u,s}$), the ratio of $P_{u,t}/P_{u,s}$, the experimental ductility coefficient (μ_t), the numerical ductility coefficient (μ_s) and the ratio of μ_t/μ_s, need to be addressed in details. The ductility coefficient with respect to the load-displacement skeleton curve is usually obtained as:

$$\mu = \frac{\Delta_{0.85}}{\Delta_y} \tag{8}$$

where $\Delta_{0.85}$ is the failure displacement corresponding to the lateral load no less than 85% P_u; Δ_y is the yield displacement determined as explained in Fig. 3, which is presented in Xiao et al. (2012).

It can be seen from Figs. 2 and 4 that the numerical lateral load-displacement hysteretic curves agree well with the experimental curves. This is confirmed by the ratios of $P_{u,t}/P_{u,s}$ and μ_t/μ_s that assume values near the unity for all the tests: (1) the mean value of $P_{u,t}/P_{u,s}$ equal to 1.00 and a coefficient of variation of 0.06; (2) the mean value of μ_t/μ_s equal to 0.92 and a coefficient of variation of 0.13.

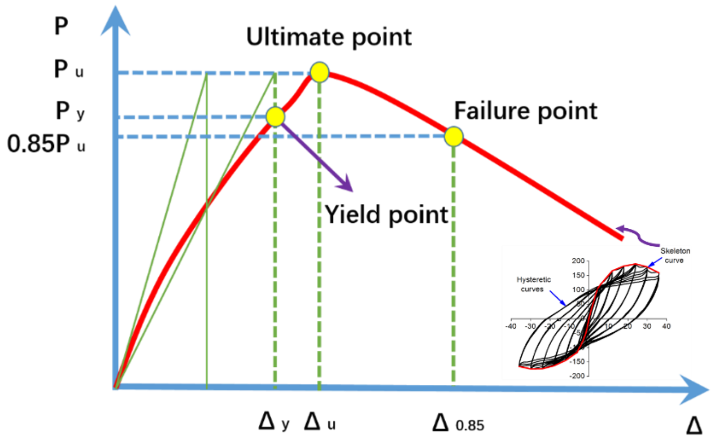

Fig. 3 Load-displacement skeleton curve encompassing hysteretic curves

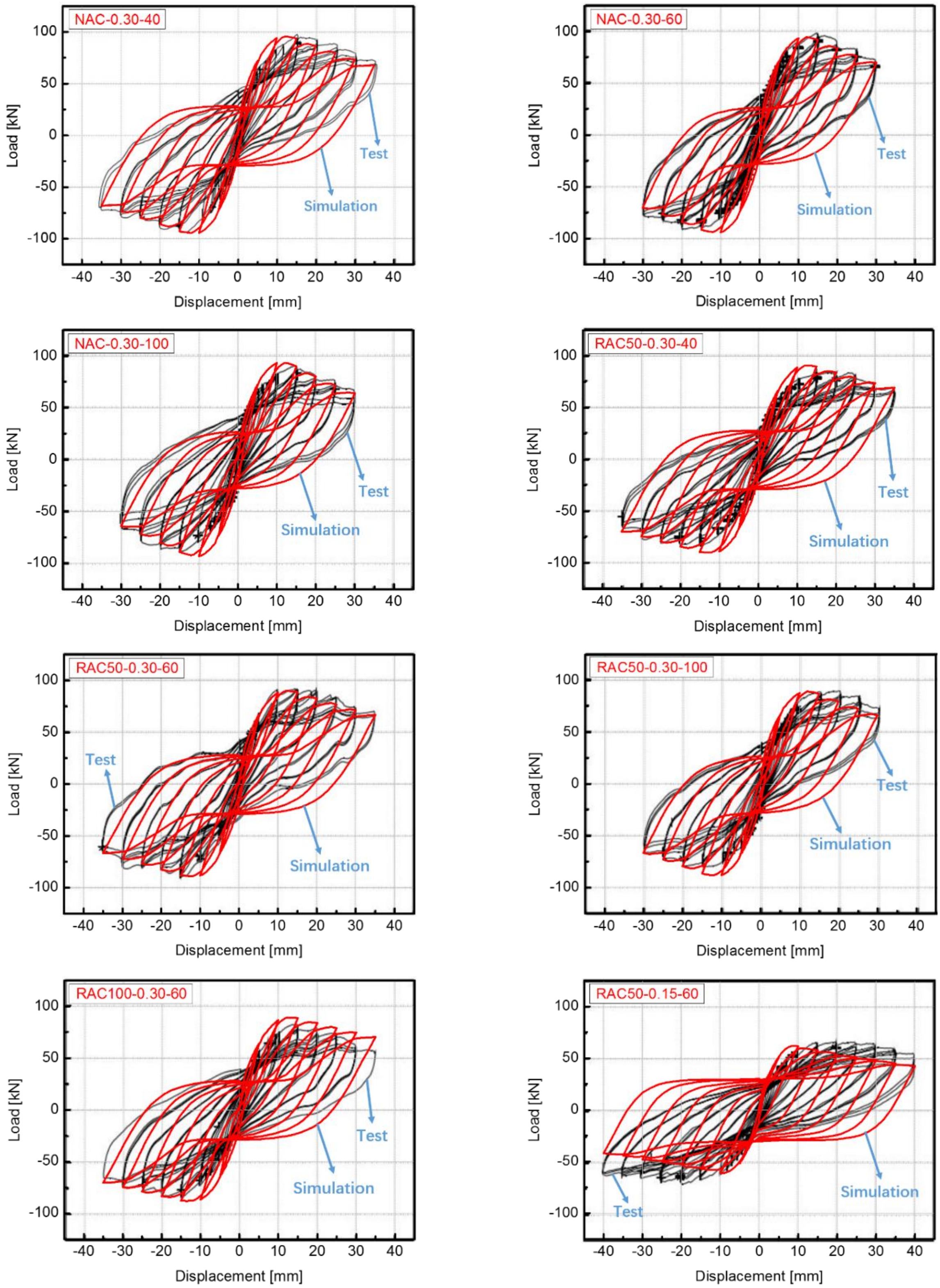

Fig. 4 Comparison of hysteretic curves between experimental and numerical results: Experimental specimens reported in Yang (2016)

3. CONCLUSIONS

A preliminary assessment of the seismic behavior of reinforced recycled aggregate concrete columns has been presented. The study was motivated by the fact that very limited information is currently available in the literature about the methods to be used for designing RC columns manufactured with RCAs. The developed FE model can accurately predict the hysteretic curves and seismic behavior of RRAC columns under combined axial compression and cyclic lateral loads.

ACKNOWLEGMENTS

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