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Effective initial stiffness and deformation of recycled aggregate concrete columns under seismic loads

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Abstract

This paper deals with the effective initial stiffness and lateral deformation capacity of recycled aggregate concrete (RAC) columns under seismic loads based on existing experimental database. The characteristic of these existing studies and main research results regarding the seismic behavior of RAC columns were reviewed shortly. Based on this database, the effects of main structural factors on effective initial stiffness (EIS) and maximum drift ratio (MDR) which corresponding to maximum lateral resisting force of RAC columns were analyzed, respectively. According to the comparative results reported in this study, effective initial stiffness and maximum drift capacity of RAC columns were discussed and modeled simply considering the effects of several structural factors on seismic performance of RAC columns. To evaluation the accuracy and reasonability of the two proposed models, existing evaluation models for predicting EIS and MDR of reinforced concrete (RC) columns were collected and compared with the proposed two models using the database. Comparative results implied that the two proposed models both evaluate the experimental results with a good agreement.

Keywords: Seismic assessment, Ductility, Sustainable concrete, Replacement ratio of aggregate;

1. Introduction

Every year, earthquake disasters attract so many concerns from all the world communities, not only for they bring numerous dead and injured and property loss, but also produce numerous building waste caused by the collapse of various structures such as concrete buildings. For example, it was reported the loss ratios of residential buildings and public buildings (school and hospital etc.) are 27.4% and 20.4% of the total loss of Wenchuan earthquake, respectively [1]. Among these buildings, 6,945,000 buildings have completely collapsed and 5,932,500 buildings were seriously destroyed [2]. Similarly, in the 2011 Great East Japan earthquake, Japan government reported that 127,290 buildings had been totally collapsed, while further 272,788 buildings were assessed as 'half collapse', and another 747,989 buildings are partially damaged [3]. Besides, during the earthquake, a number of structural damages have been confirmed as the results of the strong ground vibration and tsunami, including heavy damage to transportation system such as roads and railways as well as fire disasters and collapse of dam structure[4, 5]. All these damage draw a new research hotspot for civil engineering, i.e., how to reuse effectively the materials from the damage concrete structures.

Until now, the handling method of the building wastes obtained from earthquake hazards is landfill or burning in most of country. It is obvious that this kind of treatment methods is not favorable for our soil and atmosphere environment. In addition, this also wastes a number of valuable materials which can be used in new concrete structures with good economic benefits. On the other hand, the demolitions of existing dangerous old buildings and other damaged structures also are a considerable resource of these valuable building wastes. Therefore, the concrete containing the wastes produced by earthquake disasters is being concerned by the researchers in worldwide who try to reuse the wastes to reduce their negative effects on environment and realize their new utilization value. RAC is an important representative of these concretes using waste and has been widely applied and researched in civil engineering.

Although a number of previous studies indicated that most of the mechanical properties of RAC are less than the ones of normal aggregate concrete (NAC) [e.g. 6-8], as long as controlling carefully the replacement ratio of recycled aggregate (RA) and use properly, RACs are still proposed to apply in RC structures by many researchers [e.g. 9-12]. The application of RACs using the wastes obtained from earthquake in new RC structures is very significant to the fast-restoration post-earthquake because of fast-waste treatment and good economic benefits. Because these new buildings are built and used in an earthquake prone zone, their seismic behavior becomes a very important concern, in particularly their basic mechanical properties are lower than NAC's. As two important evaluation indexes to assess the seismic response of RC building structures, the stiffness development and deformation capacity of RC columns have been studied by a number of researchers. Therefore, as a starting, to clearly understand the stiffness and deformation behaviors of RAC columns subjected seismic loads, this study will try to model the two evaluation indexes using existing test database.

2. Shortly review on stiffness and deformation

The reasonable assessment of the stiffness development and deformation capacity of RC structural elements is important to evaluate the seismic preformation of whole RC structures. The experimental results investigated by existing studies with regard to the two properties can be summarized mainly in the terms of the main characteristic deformation/ductility development such as the displacements at cracking load, maximum load, ultimate load and failure of RC members, and the stiffness degradation with lateral deformation at later stage.

As normal RC columns, previous studies [13-15] reported that RAC columns can obtain better ductility and rotate capacity under a low axial ratio, *i.e.* subjected to a low axial compression effect. Xiao *et al.* [16] and Yin *et al.* [15,17] pointed out that the ductility of RAC columns is similar to the ones of NACs, which is applicative for short RC columns [18]. When using certain level of axial compression load, Hu and Lu [14] illustrated that the addition of fly ash can improve the ductility of RAC columns subjected to seismic loads. Besides, Xiao *et al.* [16] indicated that the RAC columns with a common axial-compression ratio have excellent elastic–plastic deformation capacities and anti-collapse abilities to resist earthquake effects. Based on their experimental results, the ultimate drift ratio of RAC columns ranges from 1/45-1/28 that meets the design requirement of elastic-plastic story drift ratio (1/50, for middle earthquake) of RC frame system. When using recycled bricks as coarse aggregates in the concrete for columns, however, the ductility of the RAC columns is significantly lower than the ones of normal concrete columns but they still can meet the seismic design requirements of RC structures. To enhance the seismic ductility of RAC columns, the improvement methods proposed by previous researchers have using of fly ash [14] or silica fume [19] or fiber [19]; arrangement of cross X-type reinforcements in hinge region of elements[18] or high transverse confinement [20] etc.

On the other hand, Xiao *et al.* [13] reported that NAC columns have a little higher initial stiffness comparing with RAC columns using RAs to replace 100% normal aggregates, and pointed out that the use of RAs in concrete has no significant influence on the stiffness degradation of RC columns. As the increasing of RAs in concrete, the initial stiffness of RC columns decreases obviously [15, 18], which is similar to the ones of NRCs. At the same time, Yin *et al.* [15, 17] explained that the stiffness of RAC columns degrades fast with the replacement ratio of RA in concrete at early stage. This can be attributed to the fact that the contribution of concrete to the stiffness of whole member is larger than the one from reinforcements at early stage. As the increase of lateral deformation, this degradation becomes tardy since the occurring of a complete crack development of tensile concretes[15, 18]. At the same time, the increase of the replacement ratio of RA in concrete [15, 18] or reinforcement amount, the cracking and yielding stiffnesses of RAC columns both decrease. However, Bai *et al.* [21] considered that the ductility of the RAC columns using 50% RA is lower than the one of 100% RAC columns because of the increase of discreteness of concrete when RA partly replaces the normal aggregates in concretes.

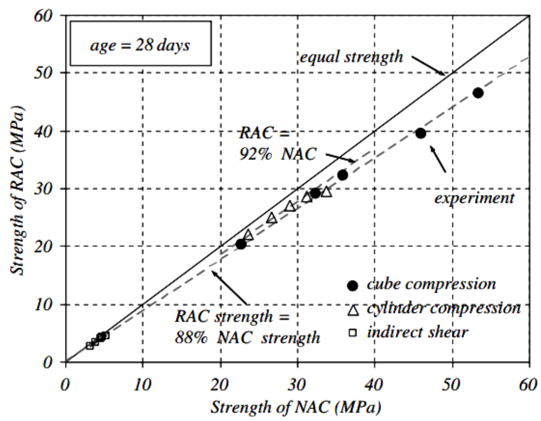

Fig. 1 – Comparison between the compressive strengths of RACs and NACs [9]

3. Database and assessment methods

3.1 Definition of initial stiffness and building of database

There are two common methods to estimate the initial stiffness of RC columns in which reinforcements can reach their yielding strength or not. They both can be defined through a force-displacement envelope curve of RC elements obtained from a simulated seismic test. The first initial stiffness is calculated as a stiffness level corresponding to the first nominal yielding point of RC columns, *i.e.*, certain tensile reinforcement yielded or concrete maximum strain research 0.002 in the sectional compressive zone of columns, as the point ***A*** in the method reported by Elwood and Eberhard [22] or point ***B*** in Vu *et al.* method [23] plotted in Fig.1. This method is based on the widely-accepted assumption that RC members start to yield when their main tensile reinforcement yields or their compressive concrete is crushed. It is accepted for the RC column and beam members, but not for wall type members usually such as shear walls. In addition, a completed monitoring of reinforcement and concrete strains has to be performed for this method. For the second method, the RC members usually are considered to arrive their yielding status when their lateral forces reach 0.75-0.85 times of nominal lateral resistance strength that is usually calculated by current codes/models such as ACI code, as the point ***B*** in Elwood and Eberhard method [22] and point ***A*** in Vu *et al.* [23] method, as shown in Fig.1. In this paper, a combined method is used to calculate the effective initial stiffness of RAC columns. When a detailed yielding situation can be obtained in a research literature, the first method is used, *i.e.* the point ***A*** in Elwood and Eberhard model or point ***B*** in Vu *et al.* method. For the specimens without the detailed descriptions regarding the yielding of reinforcements in columns, the point ***A*** in Vu *et al.* [23] model is used but applying the corresponding measured maximum lateral force not a calculated nominal strength of members V_u in this figure.

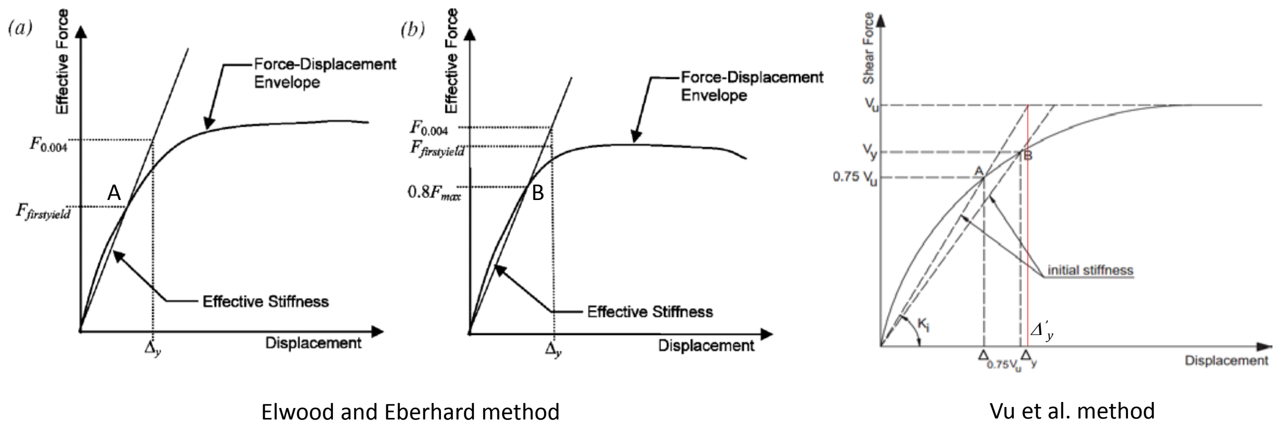

Fig. 2 – Definition of initial stiffness of columns [22, 23]

Based on a comprehensive literature review and using the methods described above, 53 RAC columns have been collected to build a research database focusing on the stiffness and deformation of RAC columns under seismic loads. It should be noted that the test results of RAC frames and beam-column joints have not been included in this database, considering their different failure modes maybe. The detailed studies of these members will be reported elsewhere. Previous studies mainly have focused on understanding the effects of RA replacement, axial load ratio, concrete compressive strength and aspect ratio on seismic behavior of RAC columns. Among them, 7 RAC columns failed as a shear failure mode, while other 45 columns have a flexural dominate failure mode. As shown in Fig.3, the varying ranges of main investigated parameters in the these studies are: axial load ratio ranging from 0.02 to 0.8, concrete compressive strength is 23.6MPa to 50MPa, RA replacement ratio is from 0 to 00% and the aspect ratio of columns is 1.75 to 4.0, respectively. On the other hand, according to Fig.3, in the following cases, RAC columns have a trend to fail as a brittle shear failure mode when subjected to seismic loads: (1) under high level of axial loads and using low strength concrete; (2) under high level of axial loads and having a large aspect ratio; (3) under high level of axial loads and with a small transverse reinforcement ratio; (4) using a small transverse reinforcement ratio and a large aspect ratio. The trend presented in Fig.3 (e) is similar to the results in circular concrete columns [24]. This means the relationships have a potential to make a preliminary judgement for the possible failure mode of RAC columns under seismic action. However, as shown in the figure, more experimental investigations are expected to be performed for further analyses, for example the columns with low aspect ratio and lightly reinforced ones.

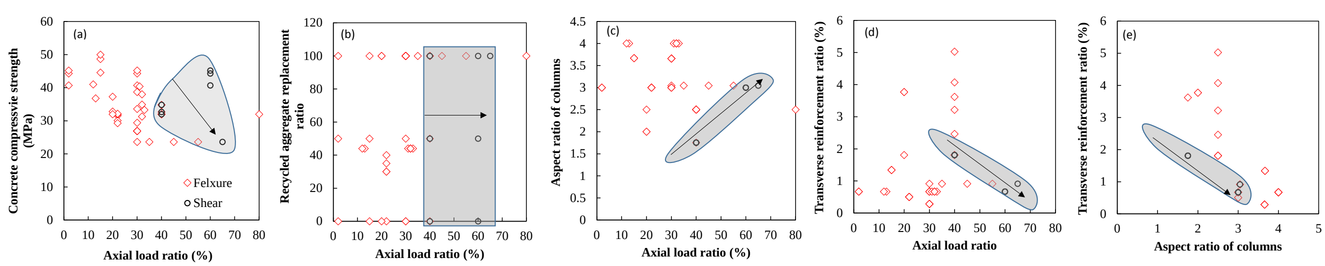

Fig. 3 – Main structural factors in the collected database

3.2 Existing models for assessing the effective stiffness of RC columns

Except for the theory initial stiffness, several simplified initial stiffness models have been proposed including FEMA 356-00[25], ASCE 41-07[26], ACI 318-11[27], Paulay/Priestley[28], Khuntia/Ghosh [29] and

Elwood/Eberhard [22] models, as listed in Table.1. These previous empirical formulae were developed based on the common assumption that the RC columns have a linear variation in curvature over their height and are expressed in a simple form as shown in Fig.4.

The factor *k* in the equations shown in Fig. 4 and Table.1 is termed as initial stiffness effective factor, accounting for the effect of applied axial load level on the initial stiffness of RC columns. Fig. 4 presents the difference in the definitions of the factor *k* in different tested column specimens. As plotted in Fig. 4, most of the listed models presume that the initial stiffness increases with axial compression load level.

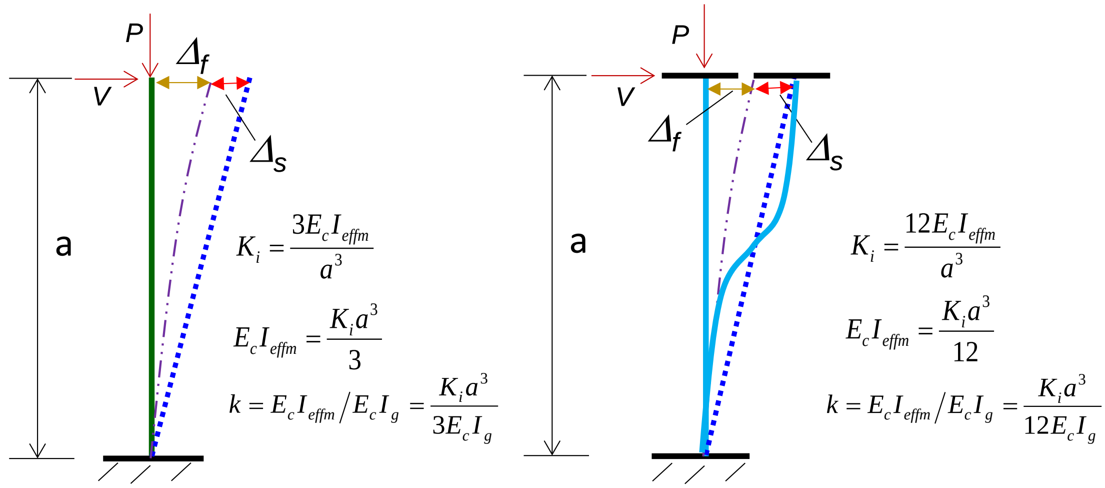

Fig. 4 – Definition of effective stiffness ratio *k*

Table. 1 Existing models for predicting the effective stiffness of RC column

Models	**Stiffness ratio $k=E_cI_{effm}/(E_cI_g)$**	
ACI 318-11*	(a) 0.35, (when n<0.1), 0.7, (when n≥0.1); or (b) 0.5 for the all columns.	
AFEMA 356*	0.5, (when $n \leq 0.3$); 0.7, (when $n \geq 0.3$)	
ASCE 41*	0.3, (when n≤0.1); 0.7, (when n≥0.5);	
Paulay and priestley*	0.4, (when $n \leq -0.05$); 0.7, (when $n \geq 0.5$)	
Khumntia and ghosh	$k_1 = (0.1+25\rho_l)/(1.2-0.2b/d) \leq 0.5$	$f_c' \leq 40$MPa
	$k_2 = (1.15-0.0004f_c')k_1$	$f_c' \geq 40$MPa
Elwood and Eberhard	$0.2 \leq (0.45+2.5n)/(1+110d_b/a) \leq 1.0$	

where, *a* is shear span of RC column, *b* and *d* are the web width and effective depth of RC column; I_{effm} and I_g are measured effective and gross moment of inertia; ρ_l is tensile longitudinal steel ratio.

Khuntia and Ghosh [29] have studied the effect of concrete compressive strength and suggested that the effective factor *k* should not be greater than 0.6 based on a series of parametric studies and presents different calculation equations when concrete compressive strength is over 40MPa or not, as shows,

$$k = \begin{cases} (0.1+25\rho)\times\left(1.2-0.2\times\frac{b}{d}\right) & (f_c' \leq 40MPa) \\ (0.1+25\rho)\times\left(1.2-0.2\times\frac{b}{d}\right)(1.15-0.0004f_c') & (f_c' > 40MPa) \end{cases} \tag{1}$$

In 2009, Elwood and Eberhard [22] proposed a model to predict the factor k taking into account of the effects of shear span ratio and axial load level simultaneously, which is expressed in form of

$$0.2 \le k = \frac{0.45 + 2.5n}{1 + 110\frac{d_b}{h} \times \frac{h}{a}} \le 1.0 \tag{2}$$

4. Results and discussions

4.1 Comparison between calculation models and experimental results

To investigate the feasibility and applicability of the aforementioned empirical formulae to predict the effective initial stiffness factor k of RAC columns, Fig. 5 compares the experimental initial stiffness ratios and their calculated results. When using the above models to calculate these effective stiffnesses, the Young's modulus of RACs are obtained through the following equation recommended by Xiao *et al.* [30], which is given by,

$$E_c = \frac{10^5}{2.8 + \frac{40.1}{f_{cu}}} \tag{3}$$

The results plotted in Fig.5 show that the existing models present bad feasibility and accuracy when used in RAC columns with flexural failure mode. Relatively, ASCE 41 and Elwood/Eberhard models present a better prediction result than other models. However, the accuracies of these two models still are not enough for the practical design work. Therefore, further analyses are expected for the predication improvement of this factor.

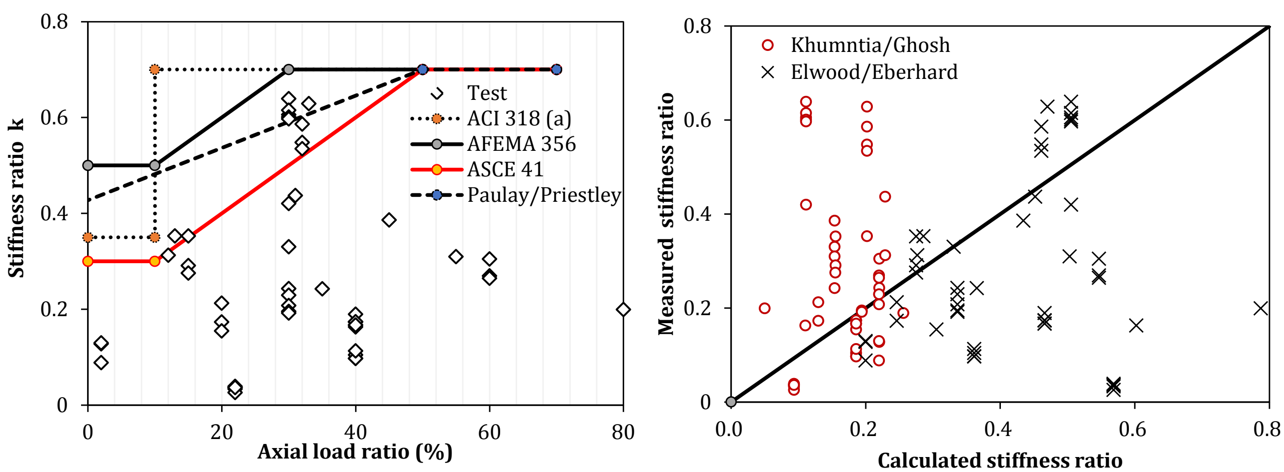

Fig. 5 – Comparison between existing models and experimental results

There are many factors which may affect the initial stiffness of RAC columns. Fig.6 re-examines the relationship between the experimental initial stiffness and several structural factors. The results of 45 RAC columns having flexural failure mode are included in these figures. Result shows that the aspect ratio of columns exhibits much higher correlations with their initial stiffnesses than other factors. This can be explained by that the contribution ratio of the flexural to shear deformation of these RAC columns at early stage is the most important affecting factor of the initial stiffness development. In theory, the aspect ratio of RC columns does reflect this key determination factor. Therefore, the factor can be applied to model its effect on the initial stiffness ratio k. According to above analyses, the effective initial stiffness of RAC columns is expressed in the form of,

$$k_{c1} = 0.2a - 0.3 \tag{4}$$

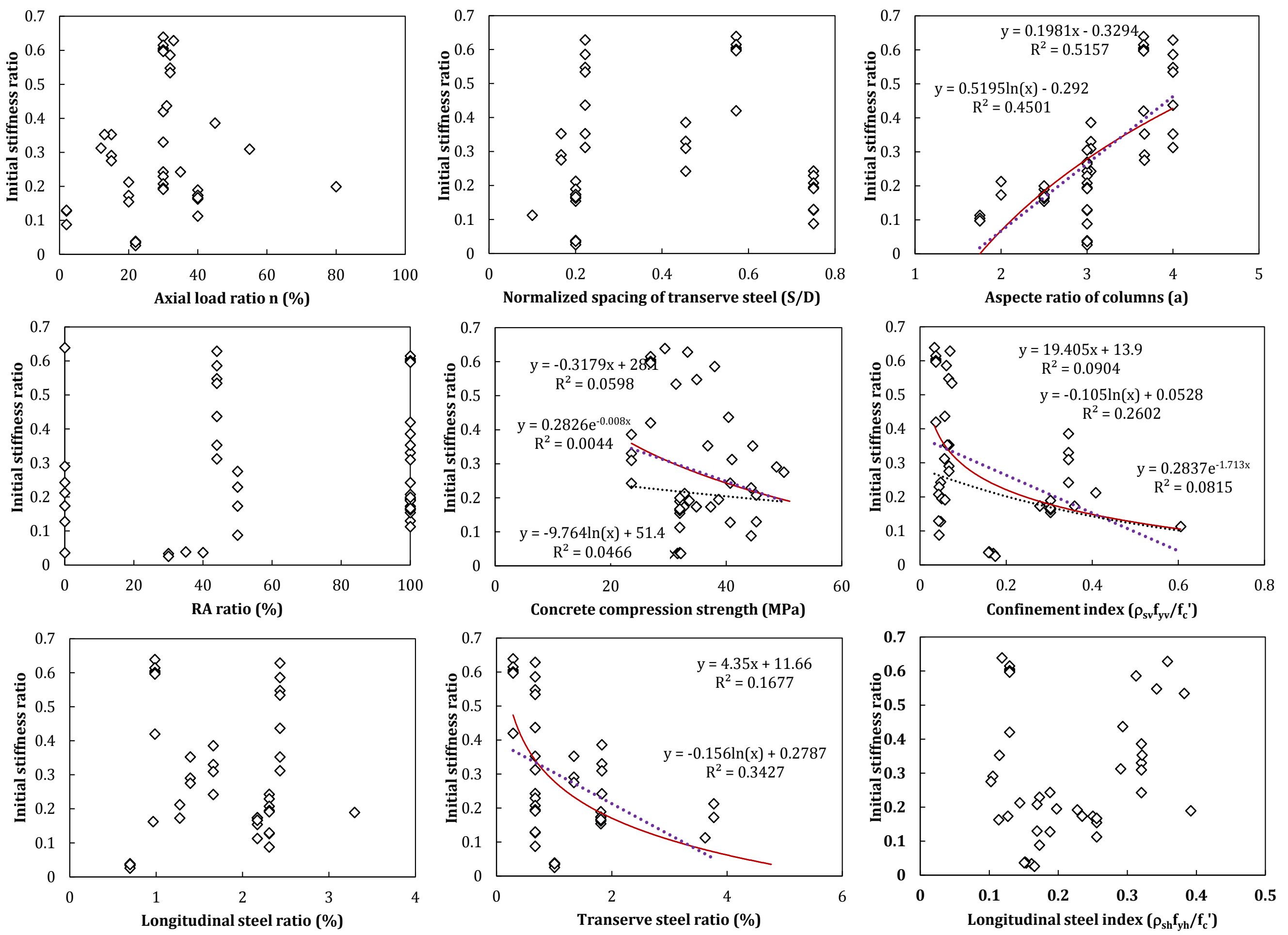

Fig. 6 – Main parameters vs. initial stiffness ratio

On the other hand, the weakened mechanical properties of RACs, due to RA replaces totally or practically normal aggregate in concrete, will influence the whole behavior of concrete columns in theory. However, the relationship plotted in Fig.6 does not show the negative effect of RA. It is possibly affected by other factors such as axial load ratio, aspect ratio of columns and concrete compressive strength etc. In addition, according to existing models listed in Table.1, the applied axial load has a significant influence on the initial stiffness of RAC columns at early stage. The effect of this factor on initial stiffness presented in Fig.6 also is obstructed by other factors, *e.g.* RA replacement ratio, concrete strength etc. Therefore, Fig.7 shows a further examination for the relationship between RA replacement ratio or axial ratio and the initial stiffness ratio k. The comparative results indicate that RA replacement ratio has not significant effect of initial stiffness ratio, which means the factor is not main affecting factor for the initial stiffness or lateral deformation at the early stage. The reason of the result is the self-stiffness of RA does not significantly affect the lateral elastic flexural deformation of columns at the initial stage, which focus on flexural and compressive behavior. With regards to the effect of axial load, however, axial load ratio presents a similar effect trend and an approximate correlation coefficient between different series of columns, as shown in Fig.7. Therefore, the study suggests to use axial load to revise the relationship between the aspect ratio of columns and the initial stiffness ratio. Fig.8 shows the development of the deference ratio between the predications obtained from Eq.(4) and experimental results with different axial load ratio. According the results, to simplify the calculation, an average line is used to fit the development of evaluation differences, as the red dashed line in Fig.8.

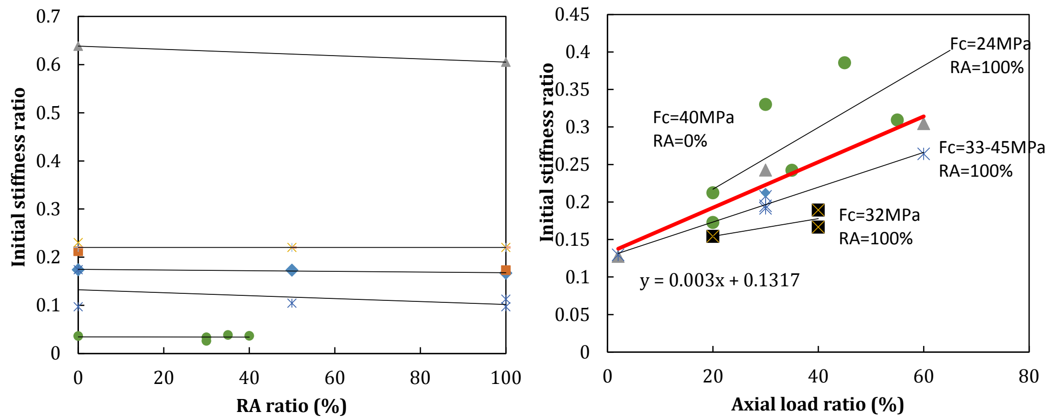

Fig. 7 – RA replacement ratio and axial ratio vs. initial stiffness ratio

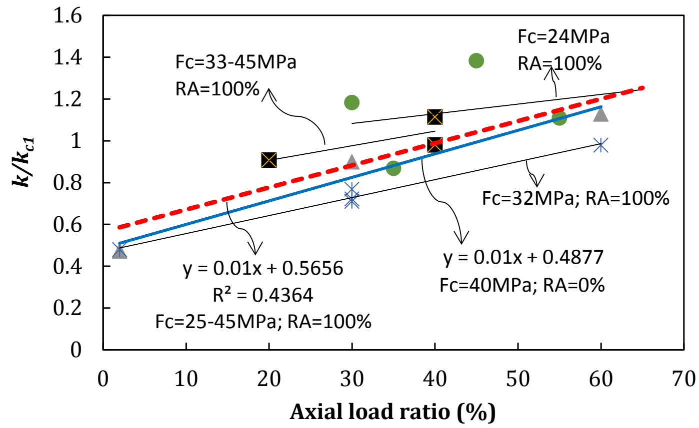

Fig. 8 – Relationship between axial load ratio and evaluation results of Eq. (4)

Therefore, the initial stiffness ratio of RAC columns subjected to seismic loads is modified as ,

$$k_c = (0.2\,a/D - 0.3)(0.01n + 0.60) \tag{5}$$

The comparative results plotted in Fig.9 show the proposed model can evaluate the experimental results very well and much better than the previous existing models. The result also shows that the model evaluates the RAC columns using recycled brick aggregates too large. This could be explained by that the brick aggregate has a weaker self-strength than recycled concrete aggregate which affects the basic properties of concrete even at early stage. On the other hand, the model cannot be used to evaluate the concrete columns just using RAC in the core zone of the cross section of concrete columns. Because the initial elastic flexural deformation of columns finishes when the first flexural crack is confirmed at the tensile margin of concrete section, which means the tensile resistance of core concrete is not activated. In other word, the negative effect of the mechanical degradation behavior of the core concrete does not appear at this stage. As described previously, the shear behavior of short-span columns at initial stage also affects significantly the prediction of initial stiffness of column, as shown in Fig.9. For the columns using fine and coarse RAs, on the other hand, this model also presents certain degree of conservatism. This indicates more experimental investigations need to be performed to explain these.

4.2 Maximum drift ratio R_{max}

On the other hand, ductility property is a useful assessment and has been widely used in dynamic analysis of concrete structures, however, it has a precise and quantitative meaning only for the structures or the components that exhibit the idealized linear elastic-plastic performance under seismic loading. For normal concrete columns, the displacement ductility (μ) is not a direct and clear indicator to evaluate the actual lateral deformation degree of columns, in design stage. This is because the definition of yield displacement (Δ_y) is not consensus in research community such as reported one in previous studies [24, 31, 32]. In addition, the calculation of the yield displacement is also a tedious process for concrete columns, since there is not a reliable and simple design equation to calculate the ideal flexure strength of RC columns. It usually is obtained by conducting sectional moment–curvature analysis of column. The addition of RA increases further the calculative difficulty and randomness of the displacement ductility. These disadvantages make many previous seismic assessment models present a low design-oriented operation, which is similar to the completed shear model reported by the first author [24]. It is very important to keep a good consistency in this index for the evaluation and comparison of seismic behavior of RAC columns studied by researchers from different countries. Therefore, this study uses drift ratio *R* to evaluate the lateral deformation of RAC columns under seismic loads, which has been widely accepted as a direct and clear indicator of deformation degree for concrete members.

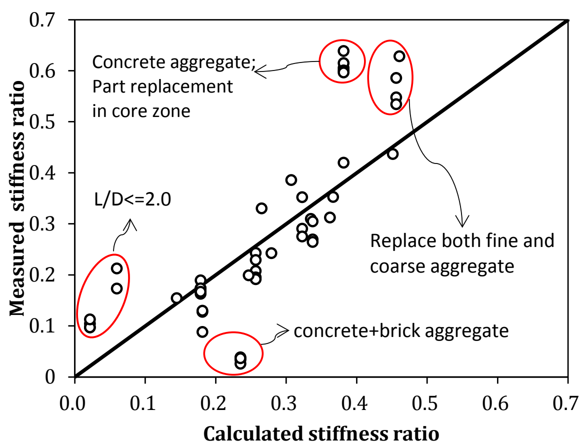

Fig. 9 – Comparison between the experimental and calculated initial stiffness ratios

The maximum drift ratio corresponds to the drift ratio at the experimental measured peak lateral force, which was considered as a start point of shear degradation [24], has an important significance. Many factors might affect the value of maximum drift ratio, in particularly the lateral confinement of columns. Since the shear strength of hoop or spiral can be considered as a constant contribution to shear resistance of element up to its yielding [34], the shear strength degradation of columns is attributed mainly to shear deterioration from concrete. Therefore, among the main structural factors, the volumetric ratio of transverse reinforcement to the core concrete and lateral confinement index I_c ($=f_{yv}\rho_{sv}/f_c$) can be presumed to be the main factors because both of them strongly affect the material properties of confined concrete [e.g. 32, 34, 35].

Fig.10 presents the relationship between the experimental maximum drift ratio of RAC columns under seismic loads and several main structural factors. Similar to the reported results in the research [32] and as presumed above, the volumetric ratio of hoops/spirals and lateral confinement index both present a higher correlation with the experimental maximum drift ratio of RAC columns. Therefore, by conducting a linear regression analysis on the results shown in Fig. 10, Eq.(6) can be applied to calculate the maximum drift ratio R_{max} for RAC columns under seismic loads. Besides, regarding the effect of RA on the maximum drift ratio of the columns, a detailed examination of RA replacement ratio to R_{max} was conducted, as shown in Fig.11. The results show RA replacement ratio has no significant influence on the maximum drift ratio of the RAC columns. Therefore, the study suggests to use Eq.(6) to simply model the maximum lateral deformation of RAC columns under seismic loads. The comparison results presented in Fig.12 show the model evaluates the experimental results with a good agreement, except for the specimens using fine and coarse RAs or containing some recycled brick aggregates.

$$R_{\max} = \frac{6\rho_{sv} f_{yv}}{f_c^{'}} + 1.25 \text{ (in \%)} \tag{6}$$

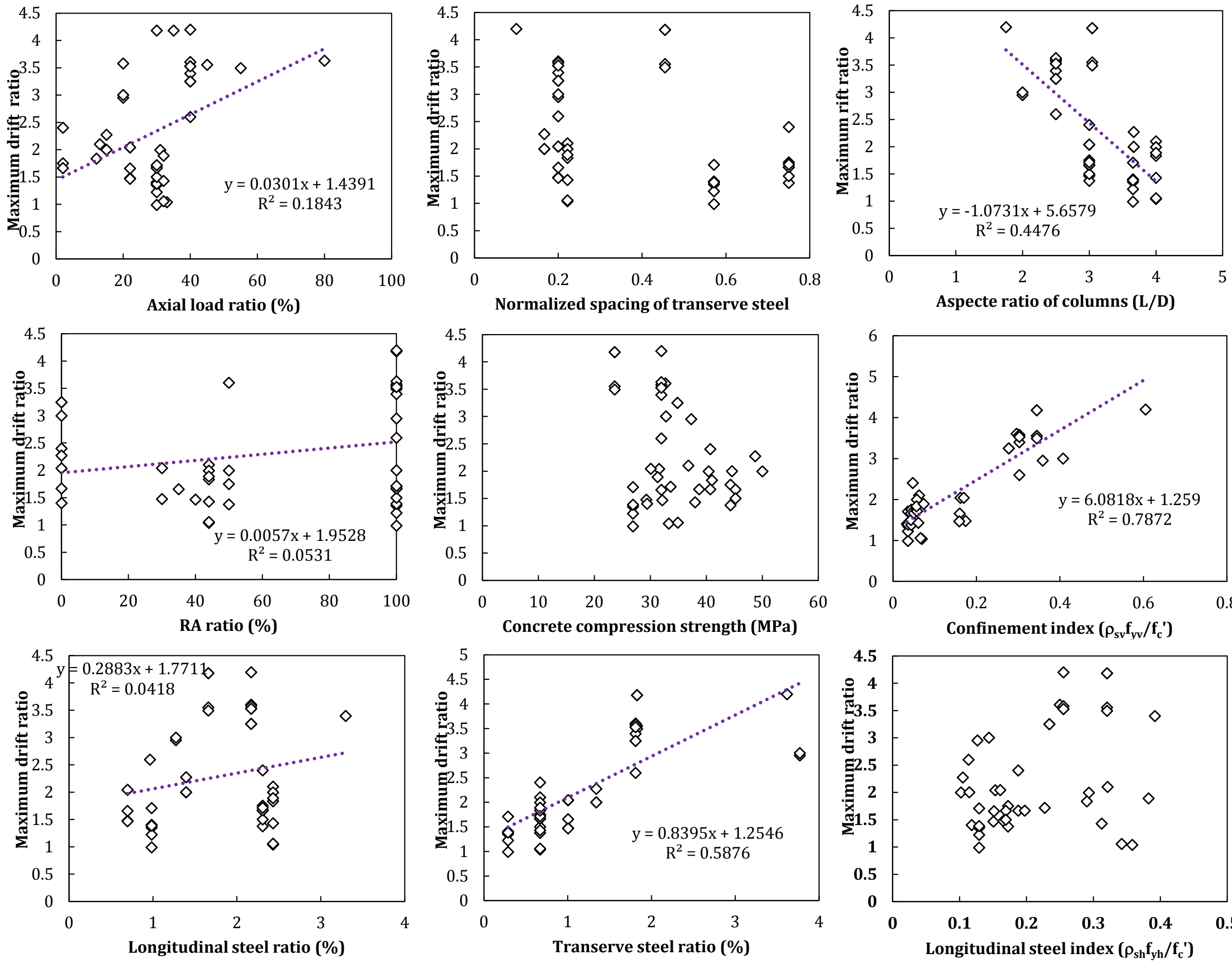

Fig. 10 – Relationships between the experimental maximum drift ratios and several structural factors

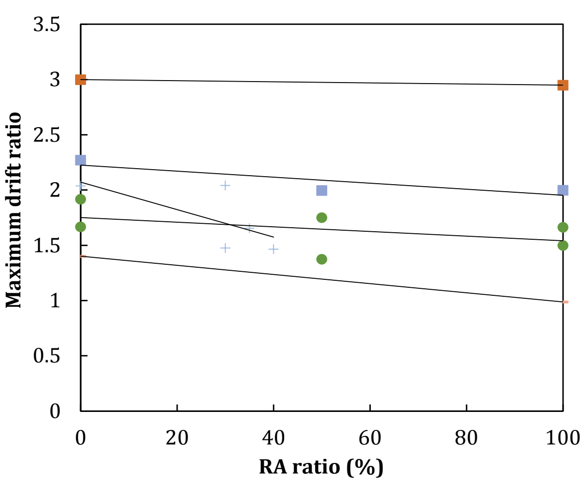

Fig. 11 – RA replacement ratio vs. initial stiffness ratio

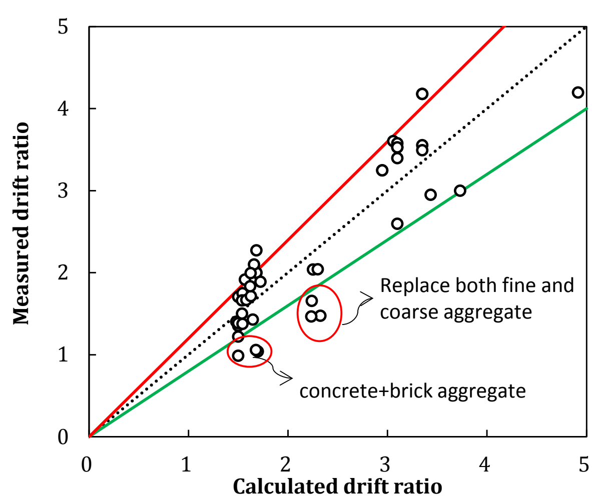

Fig. 12 – RA replacement ratio and axial ratio vs. initial stiffness ratio

5. Conclusions

This study built a research database focusing on the experimental investigation of RAC columns under simulated seismic loads based on a comprehensive literature review, which includes 7 shear failure columns and 45 flexural failure columns. All tested RAC columns uses small scale specimens and rectangular section. Through a linear analysis and simplified numerical fitting of this database, the effective initial stiffness and maximum drift ratio of the RAC columns subjected to seismic loads have been discussed modeled. Comparing with the existing models of these two factors, the proposed initial stiffness model can evaluate the experimental results with a good agreement than other models for the RAC used recycled concrete aggregates. Due to the brick aggregate has a too weaker self-strength which affects the basic properties of concrete even at early stage, the result showed that the model evaluate this kind of RAC columns too high. Because of a very limited research data can be available for RAC using recycled brick aggregate, in the future, more studies are expected. For the columns used fine and coarse RAs both, besides, this model also presents certain degree of conservatism. On the other hand, based on the data analyses reported in this study, the maximum drift ratio of RAC columns depends significantly on their lateral confinement levels, i.e. lateral confinement index, the drift ratio of these RAC columns increases linearly as the index. The propose model has a good accuracy to predict the maximum drift ratio of RAC columns. Though the propose models present a good evaluation accuracy and reasonability in the RAC columns subjected to seismic load, more experimental studies are expected in the future.

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