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A critical assessment of the compressive behavior of reinforced recycled aggregate concrete columns

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ABSTRACT

This paper presents a critical assessment of the compressive behavior of reinforced recycled aggregate concrete (RRAC) columns. Previous research has demonstrated that recycled aggregate concrete (RAC), manufactured using crushed concrete aggregates obtained from construction and demolition waste, 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 RC elements manufactured with recycled concrete aggregates. With the aim of extending the available experimental data, a fiber section based nonlinear finite element (FE) model was developed so as to provide in-depth insights into the compressive behavior of RRAC columns. First, a comparison between simulation results of the compressive behavior of RRAC columns and available experimental results were made to validate the FE model. Then, using the validated FE model, a parametric study was performed to investigate the effects of different recycled concrete aggregate (RCA) contents, volumetric ratio and yield strength of longitudinal steel reinforcement, and spacing and yield strength of transverse steel reinforcement on the compressive behavior and load capacity of RRAC columns. Finally, based on the limited available experimental database, a grey correlation analysis was used to evaluate the parametric sensitivity of the compressive behavior of RRAC columns. The experimental and numerical investigations demonstrate that the method used for considering the additional water absorption of RCAs in manufacturing RAC has a significant influence on the compressive load capacity of RRAC columns and that the influence of the RCA content on the compressive load capacity of RRAC columns is lower when compared with other important parameters but this effect should not be ignored in modeling the behavior of RRAC columns.

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 conserve natural resources and to reduce the environmental impact of the construction industry [1–4]. 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 the use in structural applications. The resulting material can be lead to the construction of "Green Concrete" structures. However, RAC is characterized by generally slightly lower mechanical and durable properties compared to equivalent NAC [5–18].

Reinforced concrete (RC) structures manufactured using RAC, namely reinforced recycled aggregate concrete (RRAC), can promote the reuse of waste concrete and can be used in construction in widescale similarly to conventional RC structures made of NAC. Beams and columns are the main resistance components in frame structures, and their mechanical behaviors that relate to the shear, flexure and compression need to be accurately determined during the structural analysis and design process.

Han et al. [19], Sogo et al. [20], González-Fonteboa and Martínez-Abella [21], Choi et al. [22], Fathifazl et al. [23–25], Arezoumandi et al. [26], Knaack and Kurama [27], Sadati et al. [28] and Katkhuda and Shatarat [29] experimentally studied the effect of recycled concrete

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Nomenclature

A	sectional area of column
A_c	sectional area of concrete
A_{sb}	sectional area of longitudinal steel reinforcement in total
B	square sectional width of column
D	diameter of concrete cylinder specimens
D_e	external diameter of column cross section
d	diameter of longitudinal steel reinforcement
d_{hoop}	diameter of transverse steel reinforcement
E_c	elastic modulus of concrete
$E_{s,b}$	elastic modulus of longitudinal steel reinforcement
f_c	cylinder compressive strength of concrete
$f_{c,0}$	cylinder compressive strength of concrete when $r = 0\%$
$f_{c,r}$	cylinder compressive strength of concrete when $r \neq 0\%$
$f_{y,b}$	yield strength of longitudinal steel reinforcement
H	height of concrete cylinder specimens
h	square sectional height or circular sectional diameter of column
k_a	coefficient to allow for concrete specimen aspect ratio
k_d	coefficient to allow for concrete density
k_s	coefficients to allow for concrete specimen size
L_e	length of column
r	recycled concrete aggregate (RCA) content [%]
S	spacing of transverse steel reinforcement
P_u	ultimate axial load
$P_{u,0}$	ultimate axial load when $r = 0\%$
$P_{u,r}$	ultimate axial load when $r \neq 0\%$
$P_{u,t}$	experimental ultimate axial load
$P_{u,s}$	numerical ultimate axial load
w_{eff}/c	effective ratio of water to cement
ε	axial strain of RC column
ε_{co^r}	axial strain of RAC at peak stress
$\varepsilon_{co}{}^n$	axial strain of NAC at peak stress
ε_{co}	axial strain of concrete at peak stress
$\rho_{c,f}$	concrete density
ρ_s	volumetric ratio of longitudinal steel reinforcement
ρ_{sv}	volumetric ratio of transverse steel reinforcement
ξ_i	grey correlation coefficient
γ_i	grey correlation entropy density

aggregate (RCA) content on the shear failure and behavior of RRAC beams showing that the failure patterns 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. On the other hand, Katkhuda and Shatarat [29] using a particular treatment of the RCAs, i.e. acid treated RCAs, showed that the shear capacity of RRAC beams can be larger than that of RNAC beams due to the elimination of the weak and porous layer between RCA and new concrete. Sogo et al. [30], Sato et al. [31], Fathifazl et al. [32], Choi et al. [33], Ignjatović et al. [34], Disfani et al. [35], Kang et al. [36], Arezoumandi et al. [37] and Mohammed et al. [38] carried out a large number of simply-supported beam experiments on the flexural behavior of RRAC beams. Regardless of RCA content, the experimental observations demonstrate that the flexural failure patterns of the RRAC beams are similar to those of RNAC beams. Based on the available experimental results, Silva et al. [39] and Tošić et al. [40] using a database of tests developed a flexural capacity model of RRAC beams compatible with Eurocode 2 prescriptions. Wang et al. [41] and Choi and Yun [42] performed a number of experimental investigations to research the concentric compressive behavior of RRAC columns. They concluded that the cracking patterns of RRAC columns, from initiation to failure, are similar to those of RNAC columns, and increasing of the RCA content leads to decrease the concentric load capacity and initial stiffness of RRAC columns. In addition, the structural reliability of eccentrically-loaded RRAC columns was investigated by Breccolotti and Materazzi [43] demonstrating the consequences of the higher scattering of RAC compressive strength produce on the structural safety suggesting the adoption of an appropriate adjustment to the design procedure when dealing with RAC for structural use, such as a proper modification of the partial safety factor of concrete.

The literature review reported herein reveals that the investigation of the compressive behavior of RRAC columns has generally received limited attention. Moreover, very limited information is available about the methods to be used for designing RC elements manufactured with recycled concrete aggregates. Therefore, studying the compressive 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.

This paper presents a critical assessment of the compressive behavior of RRAC column. The primary objective of this study is to develop and validate a nonlinear finite element (FE) model of RRAC columns under concentric compression and to quantify the effect of RCA content on the behavior of RAC (Section 2). The secondary objective is to carry out a comprehensive parametric study to investigate the effects of different RCA contents, volumetric ratio and yield strength of longitudinal steel reinforcement, and spacing and yield strength of transverse steel reinforcement on the behavior of concentrically-loaded RRAC columns (Section 3). In the final part, a grey correlation analysis (GCA) is used to evaluate the parametric sensitivity of the compressive behavior of RRAC columns based on the available experimental test database (Section 4).

2. FE modeling and experimental 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 compressive behavior of RRAC columns under concentric axial load. The modeling and nonlinear analyses of RRAC columns were done by employing SeismoStruct [44]. 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. The axial load was applied at the end of the column top. Fig. 1 illustrates the boundary conditions and loading patterns for RRAC columns. In the following, the adopted stress-strain relationship of RAC and steel reinforcement are presented and discussed.

2.1.1. Stress-strain relationship of RAC

The so-called "*con_ma*" concrete model was used in SeismoStruct and its stress-strain relationship is based on the confinement effect initially developed by Madas [45] and improved by Mander et al. [46] and Martinez-Rueda and Elnashai [47], respectively. 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 (see Fig. 2a), 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 highlighted that the tensile strength was neglected in this concrete model.

Based on the available database of the compressive behavior of