Engineering Structures 86 (2015) 192–212

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

# Testing and analysis of axially loaded normal-strength recycled aggregate concrete filled steel tubular stub columns

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ARTICLE INFO

*Article history:*
Received 17 May 2014
Revised 17 December 2014
Accepted 3 January 2015
Available online 21 January 2015

*Keywords:*
Concrete filled steel tubes
Recycled aggregate concrete
Substitution level
Scatter
Confinement effects
Stress–strain relationship

ABSTRACT

Thirty-nine stub columns were tested to failure to investigate the compressive behaviour of normal-strength recycled aggregate concrete filled steel tubular (RACFST) stub columns under axial loading. Study parameters included recycled coarse aggregate (RCA) substitution level, source of RCA, compressive strength of recycled aggregate concrete (RAC) core and ratio of steel area over concrete area. Experimental results showed that the scatter in the mechanical properties of RACFST stub columns is smaller than that in RACs due to the contribution of steel tubes. The source of RCA had little effect on the compressive behaviour of axially loaded RACFST stub columns within the parameter range adopted in the tested specimens. A reduction of less than 10% was measured in the compressive strength of RACFSTs due to the incorporation of RCA, which is smaller than that for RAC samples in material tests. As part of the work, confinement effects of the steel tubes to the RAC cores during the whole loading process were investigated based on the strain gauge measurements. Model equations were then proposed to predict the longitudinal stress–strain relationships for both steel tubes and RAC cores. Current CFST design provisions are compared with the RACFST stub columns test results, and the design recommendations are presented.



## 1. Introduction

The use of crushed waste concrete as recycled coarse aggregate (RCA) for producing new concrete reduces the consumption of natural sources and saves the landfills for the disposal of waste concrete [1–3]. Many countries have provided design codes to regulate the use of recycled aggregate concrete (RAC), such as RILEM TC 121-DRG [4], BS6543 in Britain [5], DAfStb in Germany [6], ACI 555-01 in US [7], and JCJ/T 240-2011 in China [8]. Despite this, the structural application of RAC is limited due to its low strength and high short- and long-term deformations, which are mainly induced by the residual mortar adhered to the recycled aggregate [9–11]. It is also worth noting that the incorporation of RCA increases the scatter of the compressive strength of RAC [12], especially when RCA is derived from different sources [13]. For example, the scatter of the compressive strength for 31 RAC specimens tested by Eexberria et al. is 16.7% [12], which is 89.8% higher than that observed for the control conventional concrete (with a corresponding increase of 8.8%). The scatter of the compressive strength for RAC specimens with RCA from different sources can reach up to 20.0% [13].

Concrete filled steel tubular (CFST) columns are gaining increasing usage in practice owing to their inherent advantages, including high load capacity, excellent anti-seismic performance and ease of construction [14–18]. Encasing RAC into steel tube can increase its compressive strength due to the confinement effects and meanwhile, reduce its shrinkage and creep because of the sealed environment provided by the outer steel tube [19,20]. Besides, it is highly possible that the scatter of the strength of this composite member is smaller than that of the RAC owing to the contribution of the steel tube. Thus, as an innovative structural member, the recycled aggregate concrete filled steel tubes (RACFSTs) are supposed to overcome the challenges associated with structural application for RAC [21].

Experimental data from 36 circular RACFST stub columns were currently available to investigate their static response to axial loads (12 columns by Yang and Han [22], 20 by Chen et al. [23] and 4 by Hou et al. [24]). Yang and Han [22] reported one of the earliest studies on axially loaded circular and square RACFSTs. The considered RCA replacement ratios ($r$) were 0%, 25% and 50%. The concrete mean cylinder compressive strength at the test days ($f_{cm,test}$) was 32 MPa and the ratio of steel area over concrete area

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http://dx.doi.org/10.1016/j.engstruct.2015.01.007
0141-0296/

**Nomenclature**

| | |
|---|---|
| CFST | concrete filled steel tube |
| ITZ | interfacial transition zones in recycled aggregate concrete |
| NCA | natural coarse aggregate |
| RAC | recycled aggregate concrete |
| RACFST | recycled aggregate concrete filled steel tube |
| RCA | recycled coarse aggregate |
| RCA-L | recycled coarse aggregate from laboratory waste concrete |
| RCA-P | recycled coarse aggregate from real building demolition project |
| SSD | saturated-surface-dry condition for recycled coarse aggregates |
| $A$ | cross-sectional area of column |
| $A_c$ | cross-sectional area of concrete core |
| $A_s$ | cross-sectional area of steel tube |
| $D$ | external diameter of steel tube |
| $EA$ | elastic stiffness of columns |
| $E_c$, $E_{c,r}$ | Young's modulus of conventional control concrete and RAC, respectively |
| $E_s$ | Young's modulus of steel tube |
| $E_{sec}$ | secant modulus of concrete corresponding to peak strength |
| $f_c$, $f_{c,r}$ | prismatic strength of control conventional concrete and RAC, respectively, 0.76 times the concrete cubic strength |
| $f'_{cc}$ | cylinder strength of confined concrete |
| $f_{ck}$ | concrete characteristic compressive strength |
| $f_{cm}$ | nominal 28-day concrete cylinder strength |
| $f_{cm,28}$ | concrete cylinder strength at 28 days |
| $f_{cm,test}$ | concrete cylinder strength at test days |
| $f_{cu}$, $f_{cu,r}$ | cubic strength of control conventional concrete and RAC, respectively |
| $f_{cu,28}$ | concrete cubic strength at 28 days |
| $f_{cu,test}$ | concrete cubic strength at test days |
| $f_u$ | ultimate tensile strength of steel tube |
| $f_y$ | yield strength of steel |
| $k$, $k_r$ | ratio of the peak vertical stress over the yield stress in steel tube for CFST and RACFST members, respectively, $k = \sigma_{su}/f_y$ and $k_r = \sigma_{su,r}/f_y$ |
| $L$ | length of columns |
| $N_{ce}$ | axial load resisted by columns corresponding to the onset of confinement effects |
| $N_u$ | experimental maximum compressive load of columns |
| $N_{uc}$ | maximum compressive load of specimens predicted with designing equations |
| $r$ | replacement ratio of RCA |
| $t$ | wall thickness of steel tube |
| $w/c$ | water–cement ratio |
| $\alpha$ | ratio of steel area over concrete area, $\alpha = A_s/A_c$ |
| $\varepsilon_{c1}$ | strain at peak stress of concrete under uniaxial compression |
| $\varepsilon_{cc}$, $\varepsilon_{cc,r}$ | strain at peak stress of confined conventional concrete core and RAC core under triaxial compression, respectively |
| $\varepsilon_{c,v}$ | vertical strain of concrete core |
| $\varepsilon_{s,c}$ | circumferential strain of steel tube |
| $\varepsilon_{s,v}$ | vertical strain of steel tube |
| $\varepsilon_u$ | vertical strain of steel tube measured in the tests corresponding to $N_u$ of columns |
| $\varepsilon_v$ | vertical axial strain of columns |
| $\varepsilon_{sp}$ | strain of steel tube corresponding to proportional stress in steel tube |
| $\varepsilon_{su}$, $\varepsilon_{su,r}$ | strain of steel tube corresponding to peak vertical stress in steel tube for CFST and RACFST member, respectively |
| $\mu_s$ | Poisson's ratio of steel tube |
| $\mu_{steel}$ | ratio of horizontal deformation over vertical deformation for steel in coupon tests |
| $\theta$ | confinement factor, $\theta = \alpha f_y/f_c$ |
| $\sigma_{c,c}$ | circumferential stress in concrete core |
| $\sigma_{c,v}$ | vertical stress in concrete core |
| $\sigma_s$ | equivalent stress in steel, $\sigma_s = \sqrt{\sigma_{s,v}^2 + \sigma_{s,c}^2 - \sigma_{s,v}\sigma_{s,c}}$ |
| $\sigma_{sp}$ | proportional stress in steel tube |
| $\sigma_{su}$, $\sigma_{su,r}$ | peak vertical stress in steel tube for CFST and RACFST member, respectively |
| $\sigma_{s,c}$ | circumferential stress in steel tube |
| $\sigma_{s,v}$ | vertical stress in steel tube |

($\alpha = A_s/A_c$) was 7%. Following Yang's work, Chen et al. [23] conducted experiments on RACFSTs with $f_{cm,test}$ of 25 MPa and wider RCA replacement ratios ranging from 0% to 100%. Hou et al. [24] examined the compressive behaviour of RACFST stub columns with RCA substitution levels of 0%, 25%, 50%, 75% and 100%. The $f_{cm,test}$ in the experiment was 35 MPa and the $\alpha$ ratio was 8%.

The available studies have focused on the effect of the substitution level of RCA on the maximum compressive load and elastic stiffness of the RACFST stub columns with particular concrete strengths, $\alpha$ ratios, and sources of RCA. No experiment has been conducted to investigate whether such effects are different for RACFST members with different concrete strengths or $\alpha$ ratios, or with RCA from different sources. There is no reported research on this topic that is relevant to the confinement effects affected by the substitution level of RCA. The stress–strain relationship of the steel tube and that of the RAC core with the consideration of composite interaction have not been revealed for RACFST columns either.

This paper presents further experiments to reveal the mechanical behaviour of normal-strength RACFST stub columns under axially compressive loading. Thirty-nine stub columns were tested to failure. The study parameters include RCA replacement ratio ($r$), source of RCA, nominal 28-day concrete cylinder strength ($f_{cm}$), and $\alpha$ ratio. The static responses of steel tubes and RAC cores were carefully investigated on the basis of the strain gauge readings to reveal the confinement effects of the steel tubes to the RAC cores during the whole loading process. Models were then proposed to predict the stress–strain relationship of the steel tube and that of the RAC core taking the composite interaction into account. As part of the work, comparative analysis was carried out on the scatter of the experimental results for RACFST specimens, CFST specimens and RAC specimens. Finally, the accuracy of current CFST design provisions for predicting the sectional capacity of RACFST members was evaluated using these test results as well as data from prior studies. The existing design provisions from current European, North American, Japanese, and Chinese Standards were evaluated.

## 2. Experimental program

### 2.1. Preparation of specimens

#### 2.1.1. Specimen parameters

Thirteen groups of stub columns (3 identical specimens for each group) were prepared for the test. Among the 39 specimens, 30