Journal of Constructional Steel Research 122 (2016) 455–468

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Time-dependent behaviour of steel tubular columns filled with recycled coarse aggregate concrete

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ARTICLE INFO

Article history:
Received 23 December 2014
Received in revised form 9 April 2016
Accepted 9 April 2016

Keywords:
Steel-concrete composite structure
Concrete filled steel tube
Recycled aggregate concrete
Creep
Time effects

ABSTRACT

Encasing recycled aggregate concrete (RAC) inside steel tubes provides a solution to use RAC in vertical-load bearing members. Such composite members are referred to as recycled aggregate concrete filled steel tubular (RACFST) columns. Previous researches have focused on RACFST elements with concrete strength of 30 MPa. This paper intends to provide new experimental data for the benchmarking of numerical models using RAC with compressive strength of 50 MPa. Twenty-one RACFST specimens with different aggregate replacement ratios were prepared for the tests. The adequacy of using available RAC concrete models to predict the long-term responses of the RACFST specimens was evaluated based on the experimental results. Parametric study was then carried out to evaluate the long-term responses of RACFST members during their whole service life. The accuracy of different algebraic methods that suitable for design calculations was investigated based on the results obtained using the step-by-step procedure. Finally, a finite element model was developed with ABAQUS, which has been validated against measurements of long-term tests on slender RACFST columns. Investigation shows that the incorporation of recycled aggregates can increase the long-term deformation of composite columns by up to 40%. By considering a nil exposed perimeter, the available amplification factors proposed for RAC members can be directly introduced to the Eurocode 2 to well predict the long-term responses of RACFST specimens. The Mean Stress method was recommended for simple design calculations.

1. Introduction

Recycling demolished concrete for use as coarse aggregate in new concrete reduces the consumption of natural resources and saves the landfills for the disposal of concrete waste. Despite being an environmentally-friendly product, the recycled aggregate concrete (RAC) has not been widely used in structural applications due to its inferior mechanical performance (e.g. 10%–30% decrease in strength and elastic modulus [1–3]) in comparison with normal concrete. Among the disadvantages of using RAC in structures, the significant increase in the creep and shrinkage, which is induced by the attached old mortar around stone particles of the recycled aggregates, is one of the key issues that need to be addressed in the design. Actually, the old mortar and cement paste from original concrete make the recycled coarse aggregates (RCA) exhibit higher water absorption, which will lead to 20%–60% increase in the long-term deformation of the RAC [4–6].

Although the use of RAC in structures has been strictly limited in current standards due to its inferior behaviour, significant efforts are being made to extend their application by improving their behaviour (e.g. [7–9]). One possible solution to promote the use of RAC in vertical load bearing members is to encase the RAC inside steel tubes. By doing this the compressive capacity of the RAC can be considerably increased due to the confinement effects at the ultimate condition (e.g. [10–12]), and the shrinkage and creep deformation can be reduced by 1/2–2/3 as the concrete core is under sealed condition (e.g. [13]). Traditional concrete filled steel tubes (CFSTs) have been well investigated for decades and have been widely used in building and bridge applications [14]. Extensive studies have been devoted to achieve a better understanding of the mechanical behaviour of the RACFST members under ultimate condition (e.g. [15–23]). It is commonly accepted that due to the contribution of steel tubes, the capacities of RACFST members to resist compressive, flexural, and cyclic loading are similar to (the order of 10% decrease in maximum) that of the companion normal CFST members, which have provided a promising future for the extensive application of the recycled aggregate concrete filled steel tubular (RACFST) columns in multi-level buildings.

Unlike the observation in ultimate tests, the incorporation of recycled aggregates has been recognised to have notable influence on the creep and shrinkage of RACFST members, which can lead to 30% increase in the time-dependent deformation [24–26]. Despite this, relatively few researches have been focused on the time-dependent

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http://dx.doi.org/10.1016/j.jcsr.2016.04.009

behaviour of these members. Yang et al. [24] reported the first shrinkage and creep tests on RACFST columns. Based on the experimental results, Yang [25] conducted parametric analysis using algebraic method to evaluate time effects on the static responses of RACFST columns at both service and ultimate conditions. Geng et al. [26] carried out more long-term tests on RACFST stub columns with different aggregate replacement ratios. All the available researches have highlighted that the time-dependent deformation of RACFSTs takes >40% of the total one and should be carefully considered in the design, and that the concrete models for traditional CFST members cannot be directly used for RACFST members due to the considerable influence of the recycled aggregates.

Despite the need for reliable concrete model, current available experimental data from 16 specimens at similar concrete strength level (of the order of 30 MPa) [24,26] seem not enough to well understand how the inclusion of recycled aggregates influences the time-dependent behaviour of RACFST members. Although low strength RAC (e.g. with $f_{cm28} = 30$ MPa) is easier to produce and to be accepted by engineers, the use of higher strength RAC (e.g. with $f_{cm28} = 50$ MPa) is more practical for composite columns to achieve the best economic benefits. This is especially the case considering the fact that the discreteness of the responses for RACFST members which is induced by the uncertainty of the mechanical properties of recycled aggregates can be considerably reduced by the steel tubes.

Based on this concern, this paper presents long-term experiments on 21 RACFST circular short columns with the concrete strength of the order of 50 MPa. Twelve specimens are subjected to sustained axial loads and nine specimens are remained unloaded during the long-term tests. The considered parameter includes the aggregate replacement ratio (0%, 50%, and 100%) and the concrete ages at first loading (7 days, 14 days, 28 days and 55 days). EC2 model [27] is modified by introducing an amplification factor [4,28] to account for the influence of the recycled aggregates on the long-term behaviour of RACFST members. Comparative study is then carried out to evaluate the accuracy of the modified model using test data currently available. For this purpose cross-sectional analysis is carried out to simulate the long-term response of the RACFST members in which the time-dependent behaviour of the concrete is modelled by means of the step-by-step procedure. Using the same analysis method, extensive parametric study is conducted to evaluate the long-term response of RACFST members. The accuracy of the algebraic methods, i.e. the Effective Modulus (EM) method, the Mean Stress (MS) method, and the Age-Adjusted Elastic Modulus (AAEM) method, has been evaluated with the step-by-step method on RACFST specimens for a wide range of material and geometric properties. A finite element model which uses refined methods to predict time effects is finally proposed for complicated structural analysis. Based on these results, design recommendations have been provided.

2. Experimental programme

2.1. Preparation of specimens

Twenty-one RACFST short columns were prepared for testing, including 6 groups of specimens for long-term tests (2 identical specimens for each group), and 3 groups of companion specimens for ultimate capacity tests consisting 3 identical specimens for each group. The details of specimens are listed in Table 1. Some main test results are also included in Table 1, which will be illustrated later in the paper. Tabulated values include the aggregate replacement ratio r, the 28-day cylinder compression strength of core concrete f_{cm28}, the concrete age at first loading t_0, the cylinder compression strength of core concrete at the time of loading $f_{cm}(t_0)$, the outer diameter D, the thickness of the steel tube t_s, the ratio of steel area over concrete area $\alpha = A_s/A_c$, the sustained axial force N_L, the initial stress level in the concrete core $n_c(t_0) = \sigma_c(t_0)/f_{cm}(t_0)$ (where $\sigma_c(t_0)$ denotes the initial concrete stress at the time of first loading; $f_{cm}(t_0)$ defines the corresponding mean cylinder compressive strength), the tested initial deformation of the specimens at the instant when sustained loads first applied ε_o, the tested ultimate failure load N_{ul}, and the ratio K_f of the ultimate failure load observed for specimens tested under sustained load over the ultimate capacity of the specimen kept unloaded during the long-term tests. The ratio K_f provides an overview of the effect of creep on the ultimate capacity of the RACFST specimens.

When producing recycled coarse aggregates, the collected waste concrete was crushed with a jaw crusher and then sieved with square mesh to assure the size fraction of coarse aggregates in accordance with the European Code UNE-EN 933-1 [29]. The recycled coarse aggregate fractions were added to the mixture in a saturated surface dry (SSD) condition, which is recommended by extensive researchers (e.g.

Table 1
Details of the tested RACFST specimens.

Group	Specimen	r	f_{cm28} (MPa)	t_0 (days)	$f_{cm}(t_0)$ (MPa)	$D \times t_s$ (mm)	α	N_L (kN)	$n_c(t_0)$	$\varepsilon_o(\mu\varepsilon)$	N_{ul} (kN)	K_f
Specimens under long-term loading	R100-T7-a	100	47.8	7	42.3	137.96 × 2.58	0.079	278	0.30	503	1469	1.022
	R100-T7-b	100	47.8	7	42.3	137.92 × 2.65	0.082	278	0.30	502	1512	
	R100-T14-a	100	47.8	14	46.8	137.99 × 2.70	0.083	308	0.30	564	1477	1.008
	R100-T14-b	100	47.8	14	46.8	137.64 × 2.63	0.080	308	0.30	561	1464	
	R100-T27-a	100	47.8	27	47.8	137.63 × 2.66	0.082	308	0.30	509	1509	1.038
	R100-T27-b	100	47.8	27	47.8	138.05 × 2.63	0.081	308	0.30	564	1520	
	R50-T28-a	50	52.0	28	52.0	137.29 × 2.64	0.080	323	0.30	546	1486	1.030
	R50-T28-b	50	52.0	28	52.0	137.89 × 2.66	0.081	323	0.30	529	1502	
	R0-T29-a	0	50.1	29	50.1	137.39 × 2.55	0.079	300	0.30	543	1508	1.052
	R0-T29-b	0	50.1	29	50.1	137.56 × 2.55	0.079	300	0.30	522	1499	
	R100-T55-a	100	47.8	55	55.6	137.86 × 2.62	0.081	360	0.30	624	1478	1.028
	R100-T55-b	100	47.8	55	55.6	137.54 × 2.61	0.081	360	0.30	622	1522	
Companion specimens maintained unloaded during long-term tests	R100-a	100	47.8	–	58.7	137.27 × 2.62	0.081	–	–		1475	–
	R100-b	100	47.8	–	58.7	137.89 × 2.62	0.080	–	–		1459	–
	R100-c	100	47.8	–	58.7	138.11 × 2.67	0.082	–	–		1443	–
	R50-a	50	52.0	–	61.2	138.11 × 2.68	0.082	–	–		1435	–
	R50-b	50	52.0	–	61.2	137.86 × 2.69	0.083	–	–		1522	–
	R50-c	50	52.0	–	61.2	137.71 × 2.61	0.080	–	–		1395	–
	R0-a	0	50.1	–	60.7	137.54 × 2.68	0.083	–	–		1413	–
	R0-b	0	50.1	–	60.7	137.25 × 2.71	0.084	–	–		1455	–
	R0-c	0	50.1	–	60.7	137.68 × 2.69	0.083	–	–		1419	–

Note: Typical specimen label for specimens in long-term tests is R*xxx*-T*xx*-*x*, while that for companion specimens in ultimate tests is R*xxx*-*x*. For example, R100-T28-a means the specimen has coarse natural aggregates 100% replaced by weight with recycled ones, subjected to sustained axial loads applied at 28 days after the concrete casting, and the column number is a; R100-a denotes specimen with aggregate replacement ratio of 100%, maintained unloaded during long-term tests, and the column number is a.