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Cyclic loading tests and shear strength of steel reinforced recycled concrete short columns

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ABSTRACT

This paper presents the results of cyclic loading tests on steel reinforced recycled concrete (SRRC) columns, including nine short columns and one long column. The main objective of this research is to evaluate the seismic behaviour of short columns based on the seismic tests of 10 SRRC columns under low cyclic loads with vertical axial force. The main design parameters of the columns in the tests are the recycled coarse aggregate (RCA) replacement percentage, axial compression ratio, stirrups ratio and shear span ratio. The crack status, failure modes, hysteresis loops, skeleton curves, energy dissipation capacity and ductility of SRRC columns are presented and analysed. The influence of the design parameters on the seismic behaviour of the columns is also investigated in detail. The test results show that the SRRC short column has poor ductility, as demonstrated by its brittle shear failure, and that the long column has excellent ductility, as demonstrated by its ductile flexural failure. The ductility and energy dissipation capacity of the short columns decreases as the increasing magnitude of RCA replacement percentage whilst the seismic behaviour of SRRC short columns is effectively improved by the appropriate design of the axial compression and stirrups ratio. Although the bearing capacity and stiffness of SRRC columns decreases dramatically as the shear span ratio increases, the ductility increases considerably. Based on the test and analysis results, a modified ACI design method is proposed to calculate the nominal shear strength of SRRC short columns.

1. Introduction

The rapid development of the concrete industry in the past decades has been largely attributed to environmental impoverishment. Non-renewable natural resources are overly exploited because of the increasing demand for concrete structures. At the same time, large amounts of construction waste are produced with the rapid urbanisation. These wastes negatively affect the environment and strongly contribute to landfill saturation. Thus, lessening the negative effect of concrete industry on the ecological environment requires the use of only a small amount of natural resources in concrete production. To minimise the exploitation of natural resources, construction waste, particularly the concrete waste, must be reused. Some countries have exerted great effort to recycle the concrete waste, a new product of which is the recycled aggregate concrete (RAC), which is used to completely or partially replace the natural coarse aggregate (NCA) in concrete mixtures. RAC is a kind of green construction material that positively contributes to the sustainable development of concrete industry.

A considerable number of experimental studies on the material properties of RAC have been performed worldwide. Most studies focus on mix designs and mechanical properties, also including the durability, fatigue and fire resistance of RAC. The achievements on RAC material were extensively reviewed and summarised by Nixon [1], ACI Committee 555 [2], Xiao et al. [3], Li [4], Casuccio et al. [5], Tabsh and Abdelfatah [6], Thomas et al. [7] and Kim and Yun [8]. Although some test results are contradictory, some general conclusions can be drawn about the effects of recycled coarse aggregate (RCA). The available test data on RCA-based concrete are highly variable because the quality of RCA mostly depends on the quality of original waste concrete. RCA is an excellent choice for recycling the high-strength concrete waste in RAC. Given the adhered mortar, RCA has relatively higher water absorption and lower density compared with NCA. Therefore, RCA contributes to the reduction of mechanical properties of RAC. Although some mechanical properties of RAC may be inferior to

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Nomenclature

λ	shear span ratio
H	height of the columns
h	height of the sheared web of the rectangular columns
f_y	yield strength of steel or rebars
f_u	ultimate strength of steel or rebars
E_s	modulus of elasticity of steel or rebars
r	RCA replacement percentage
f_{racu}	cube compressive strength of RAC
E_{rac}	modulus of elasticity of RAC
n	axial compression ratio;
ρ_{sv}	stirrup ratio
N	axial loads
P	lateral loads
V	shear force
M	bending moment
P_{cr},Δ_{cr}	crack load and corresponding displacement, respectively
P_y, Δ_y	yield load and corresponding displacement, respectively
A_s	gross area of steel
P_m, Δ_m	maximum load and corresponding displacement, respectively
P_u, Δ_u	ultimate load and corresponding displacement, respectively
μ	ductility factor
R_u	maximum interstory drift ratio
V_n	nominal shear strength
V_{rac}	shear strength of RAC
$V_{a,w}$	shear strength of the web of steel section
V_s	shear strength of transverse stirrups
α	modification factor
A_g	gross area of the cross section of columns
f_{rac}	design strength of RAC
b	width of the non-sheared flange of the rectangular column
h_0	distance from extreme compression fiber to centroid of longitudinal reinforcement
$f_{a,w}$	yield strength of the steel web
$A_{a,w}$	area of the steel web
f_{sv}	yield strength of transverse stirrups
A_{sv}	total cross-section area of transverse stirrups
s	stirrup spacing
A_c	gross area of recycled concrete column

those of ordinary concrete, RAC is still suitable for the structural engineering.

To popularise the structural engineering application of RAC further, the structural performance of RAC needs to be studied. In recent years, numerous test investigations on the structural behaviour of reinforced recycled concrete (RRC) have been performed. Some studies reported on the mechanical properties of RRC beams [9,10], columns [11–13], beam–column joints [14], slabs [15], shear walls [16] and frames [17]. The major findings of most investigators are positive and meaningful. The cracking status and final failure modes of RRC structural members and structures are similar to those of ordinary reinforced concrete. However, as the RCA replacement percentage increases, the bearing capacity and deformation performance of RRC are somewhat reduced to an allowable extent compared with those of ordinary reinforced concrete.

Steel and concrete composite structures have the high strength and good ductility of steel structures as well as the stiffness and rigidity of concrete structures. Therefore, composite structures possess a high strength-to-weight ratio, good seismic performance, high fire resistance and high durability [18,19]. Composite structures have been widely used in tall buildings, bridge constructions and offshore structures, particularly in the earthquake-prone regions. Considering the advantages of composite structures in terms of their mechanical properties, some researchers examined the mechanical properties of steel and RAC composite structural members, such as RAC-filled steel tube columns [20,21] and steel reinforced recycled concrete (SRRC) columns [22,23]. The results show that RAC-filled steel tube columns subjected to axial compression have good mechanical properties and that SRRC columns exhibit better seismic behaviour than RRC columns. The previous test results obtained by the authors for the SRRC long columns are positive and encouraging [23]. However, no research has investigated the seismic behaviour and nominal shear strength of SRRC short columns.

In the present work, the seismic behaviour of 10 SRRC columns, including 9 short columns and 1 long column, are investigated. The influence of RCA replacement percentage, axial compression ratio, stirrup ratio and shear span ratio on the seismic behaviour of the columns is analysed and summarised. Based on the test and analysis results, a modified ACI design method is adopted to calculate the nominal shear strength of SRRC short columns.

2. Experimental programme

2.1. Materials and mixture proportions

In this test, No. 14 I-steel of Q235 was adopted, and HRB335 ribbed rebar with diameters of 8 and 14 mm were used for the transverse stirrups and longitudinal reinforcements, respectively. Table 1 lists the mechanical properties of the profile steel and rebars adopted in the SRRC columns.

Ordinary Portland cement (C) with a 28-day nominal compressive strength grade of 42.5 MPa was used in the investigation. River sand (S) and crushed aggregate were chosen as the fine aggregate and NCA, respectively. Commercially available RCA from demolished concrete structures was also utilised in the test. The grain sizes, gradation and physical properties of the RCA met the requirements of Chinese code GB/T25177-2010, namely, RCA for concrete [24].

The RCA was pre-soaked in water before concrete mixing because of its water absorption capacity. The designed 28-day cube compressive strength for all the RAC mixture was around 40 MPa. The main mix proportion parameters of these four groups were water–cement (W/C) ratio, water content, cement content, sand

Table 1
Mechanical properties of steel section and rebars.

I-steel and rebars		f_y (MPa)	f_u (MPa)	E_s (GPa)	Yield strain (με)
No. 14 I-steel	Steel flange	311.5	446.5	199	1565
	Steel web	325.6	474.9	198	1644
Longitudinal reinforcements	ϕ14	358.0	560.9	203	1764
Transverse stirrups	ϕ8	479.9	607.0	202	2376