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Shear strengthening of RC short columns with ECC jacket: Cyclic behavior tests

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ABSTRACT

This study aims at developing an easy-to-apply strengthening method for reinforced concrete (RC) short columns by using Engineered cementitious composite (ECC), which is a high-performance composite material with tensile strain-hardening behavior and multiple cracking mechanism in tension. Seven identical RC short columns were prepared, and five of them were strengthened with ECC jackets or ferrocement jacket. The main experimental parameters involve the jacketing schemes and the axial load. The failure modes, hysteresis response, deformation capacity, stiffness degradation and energy dissipation capacity of the specimens were studied by the lateral cyclic loading tests. The tests results show that the ECC jacketed columns failed in ductile modes, and exhibited significant improvement in plastic deformation ability and energy dissipation capacity compared with the control specimens. At the ultimate displacement point, the increase of the drift ratio and cumulative energy dissipation of the ECC jacketed columns were 19–111% and 102–549%, respectively, compared with the corresponding control specimens. Under higher axial loads, the ECC jacketing was still certified to be effectively in enhancing the seismic behavior of the original columns. The shear deformation and the shear strength of the original RC columns were effectively improved by the external ECC jacket, and a prediction method for the shear strength of the ECC jacketed columns was given based on the current Chinese codes.

1. Introduction

For RC frame structures, the main vulnerable elements in strong earthquake actions are beam-column joints [1–3] and short columns. However, it is difficult to carry out pre-earthquake strengthening for the beam-column joints in existing structures. RC short columns were prone to shear failure and non-ductile bend-shear failure [4,5]. Columns exhibited a drastic decrease of load-carrying capacity after such brittle failure, resulting in poor plastic deformation and insufficient energy dissipation. The fundamental cause of these brittle failures in short RC columns is the brittleness of concrete. When the columns are under high axial load, the brittle behavior of concrete also results in serve spalling and crushing of covers, which aggravates the degradation of the lateral shear strength and the axial load-carrying capacity. This condition increases the risk of collapse of the whole frame structures. Therefore, it is necessary to use practical and effective methods to enhance the shear resistance and plastic deformation capacity of these vulnerable columns before an earthquake.

Various strengthening materials such as fiber reinforced polymers (FRP) [6–10], steel jacket [11,12], RC jacket [13] and ferrocement jacket [14–17] have been used to wrap or confine RC columns for seismic enhancing. All these strengthening methods could improve the strength and deformation capacity of the RC columns. However, FRP jacketing and steel jacketing are relatively expensive, and the durability and high temperature resistance of these two strengthening schemes are relatively poor. The jacket matrix of ferrocement jacket and RC jacket are brittle materials, thus the ductility improvement of ferrocement or RC jacketed members is small.

ECC [18–20] is another group of strengthening materials, which exhibits multiple cracking mechanism and strain-hardening behavior in tension due to the bridging effect of fiber in the matrix of ECC. Based on the excellent tensile properties, ECC has been widely used as enhancement materials in beams [21,22], columns [23–25] and beam-column connections [26,27] to replace concrete and part of the transverse reinforcement, finding that the strength and ductility performance of the structural members were significantly enhanced. In addition, the compressive strain capacity of ECC is approximately two times that of the concrete [28,29] and the shear properties of ECC also exhibit strain-hardening behavior [30], these properties of ECC materials contributed to the fiber-bridging effect may effectively resolve the deficiencies of the concrete members associated with the brittleness of concrete. However, there are few reports on the application of ECC in

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Nomenclature

H	height of the column
b	column width (before, after strengthened)
h_0	effective depth of RC column
λ	shear span ratio
s	spacing of stirrup
f_t	tensile strength of concrete
f_y	yield strength of longitudinal bars
f_{yv}, f_{yvj}	yield strength of stirrups, mesh bars
f_{cu}	cube compressive strength of concrete
f_c, f_{cj}	axial compressive strength of concrete, jacket materials
f_{cd}, f_{cdj}	design axial compressive strength of concrete, jacket materials
N	axial load of column
n_t	test axial load ratio
n_d	design axial load ratio
A, A_j	cross section area of RC column, jacket
P_y, Δ_y	yield load, yield displacement
P_m, Δ_m	peak load, peak displacement
P_u, Δ_u	ultimate load, ultimate displacement
μ	displacement ductility factor
θ_u	ultimate drift ratio
K_i	secant stiffness of column
γ	shear strain of plastic hinge region
V_{mc}	shear strength of jacketed column
V_c, V_j	shear strength of RC column, jacket
f_{tj}	tensile strength of jacket materials
A_{sv}, A_{svj}	total cross section area of stirrups, horizontal mesh bars
s_j	spacing of horizontal mesh bar
h_{0j}	effective depth of jacketed column

strengthening or retrofitting of structural members. Deng et al. [31] conducted a study on the seismic performance of masonry walls strengthened with ECC layers, including two control specimens and two strengthened specimens. The test results indicated a remarkable improvement in the seismic response of the strengthened specimens, including higher load-carrying capacity, larger displacement ductility and slower stiffness degradation. Hung and Chen [32] investigated the performance of U-shaped ECC jacketing for retrofitting shear-deficient cantilever RC beams. The results of the study indicated that using ECC to replace the mortar in the ferrocement jacket can reduce the crack width and improve the energy dissipation capacity of the specimens significantly.

Based on the above research works, ECC materials were used as the external strengthening jacket to enhance the shear resistance and ductility of the RC short columns. In the present work, the seismic performance of 7 short columns, including 2 control specimens and 5 strengthened specimens, are investigated by reversed cyclic loading tests. The influence of the design variables on the behavior of the test specimens, including the jacketing schemes (i.e., (a) ECC or mortar as the jacket matrix, (b) presence or absence of bar mesh spacing in ECC jacket) and axial load level, are presented and analysed.

2. Materials properties

2.1. ECC and mortar

The mixed proportions for the matrix of the ECC and the mortar used in this study are summarized in Table 1. The components of ECC include cement (42.5R Portland Cement), fly ash, river sand (maximum aggregate size < 1.18 mm), water and Polyvinyl alcohol (PVA) fibers. A 1.5% volume incorporation of PVA fibers is used in the ECC, and the mechanical and geometric properties of the fibers are shown in Table 2. The direct tensile stress-strain curve of ECC and the crack pattern of the test specimen are shown in Fig. 1. The tensile strength of ECC used in this study is approximately 5 MPa and the ultimate tensile strain is approximately 2.8%. The compressive strength of ECC and mortar were tested by three cubes (100 mm × 100 mm × 100 mm), respectively, and the average cube compressive strength of ECC and mortar was 59 MPa and 54.9 MPa, respectively. Thus, the strength grade of ECC and mortar are evaluated as C50 according to GB 50010-2010 Code for Design of Concrete Structures [33].

2.2. Concrete and steel bars

The concrete used in this study had a design strength grade of C30, and its compressive strength was tested by three cubes (150 mm × 150 mm × 150 mm). The average cube compressive strength f_{cu} of the concrete was 34.7 MPa. Table 3 lists the mechanical properties of three types of steel bars used in this test, namely, the longitudinal reinforcing bars, hoops and the mesh bars. f_y and f_u are the yield strength and the ultimate strength of the steel bars respectively. The mesh bars used in the jackets are regular plain round bars with a diameter of 6 mm.

3. Experimental program

3.1. Test specimens

Seven identical 1:2-scaled RC short columns with a cross section of 250 mm × 250 mm and a height of 600 mm were fabricated. The effective height H, defined as the distance from the top surface of the foundation beams to the lateral loading point of the columns, was 500 mm. Six 16 mm-diameter steel bars (HRB400) were used as the longitudinal reinforcements, and 8 mm-diameter steel bars (HPB335) were used as the hoops spacing at 100 mm. All longitudinal bars were anchored into the foundation beams. The foundation beams had a cross section of 450 mm × 450 mm with a length of 1400 mm. Table 4 lists the experimental parameters and the main information of the specimens.

Specimen C-1 and specimen C-5 were employed as control specimens, specimen C-2 was strengthened by the ferrocement jacket, specimen C-3 was strengthened by ECC jacket without bar mesh (0-ECC jacket), and specimens C-4, C-6 and C-7 were strengthened by bar mesh reinforced ECC jackets (B-ECC jacket). The construction steps of the prepared columns to be strengthened were gouging the concrete covers, cleaning the concrete debris, installing the steel mesh (specimens C-2, C-4, C-6 and C-7) and casting the external jackets. All strengthening jackets were four-sided layers with a thickness of 25 mm. The horizontal spacing and the vertical spacing (h × v) of the mesh bars in the jackets are listed in Table 4. For specimen C-2, the templates were erected after the installing of mesh bars, and the mortar was then cast in the templates. The ECC jackets were plastered manually using a trowel, and the jackets were plastered in two layers. The inner layer was plastered with a thickness of approximately 15 mm. After the initial setting of the inner ECC layer, the outer layer with a thickness of approximately 10 mm was plastered. In this tests, putting on a ferrocement jacket consumed approximately 15 h, while the time to install an

Table 1
Mixed proportion of ECC and mortar (kg/m^3).

Materials	Cement	Fly ash	Sand	Water	PVA fiber
ECC	652	534	427	344	26
Mortar	487	487	780	292	0