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Behaviors of steel-reinforced ECC columns under eccentric compression

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HIGHLIGHTS

- Eccentric compression behaviors of R/ECC columns were tested and evaluated.
- A numerical model was proposed to predict the mechanical response of R/ECC column.
- Good agreements are observed between the predicted and the measured strengths.
- Parametric study was conducted on moment-load interaction curves of R/ECC columns.

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ABSTRACT

Engineered cementitious composite (ECC) is a type of high-performance composite with pseudo strain hardening behavior and multiple cracking properties. The cracking and durability problems induced by concrete brittleness can be effectively avoided by substituting concrete with ECC. In this study, a total of eight steel-reinforced columns with various longitudinal reinforcement ratios and load eccentricities were tested under eccentric compression. It was determined from the test results that steel-reinforced ECC (R/ECC) columns exhibit superior performance to reinforced concrete (RC) columns in terms of load-carrying capacity, ductility, crack control ability, and damage tolerance. All columns finally failed in matrix crushing; however, the failure patterns of R/ECC columns are extremely different from those of RC columns. Significant concrete spalling occurred in the RC columns, while no sign of ECC spalling was observed in the R/ECC columns, owing to the fiber bridging effect of ECC. In addition to experimental work, a theoretical model was proposed to predict the moment-curvature response of the R/ECC column. The prediction results are in strong agreement with test data. Furthermore, parametric studies were conducted to illustrate the effects of matrix types, longitudinal reinforcement ratio, ECC compressive strength, and ECC tensile ductility on the moment-load interaction curves of columns.

1. Introduction

Cracking owing to the brittleness of concrete in tension is a major durability problem in widely used reinforced concrete (RC) structures, resulting in serious steel reinforcement corrosion in RC structures in offshore or chemical treatment environments. A potential solution to the corrosion problem is replacing steel reinforcement with non-corroding fiber-reinforced polymer (FRP) reinforcement. However, the extensive use of FRP reinforcement is limited owing to the inherent drawbacks of FRP materials with respect to the low elasticity modulus and lack of ductility [1]. In RC structures, other major problems caused by concrete brittleness include concrete spalling, bond splitting, and loss of composite action between the steel reinforcement and concrete, which weaken the ductility and damage the tolerance of these structure types [2,3].

Over the past several decades, a type of high-performance fiber-reinforced cementitious composite known as called engineered cementitious composite (ECC), with tensile strain hardening behavior and multiple cracking properties, has been developed and applied in infrastructure engineering [4–9]. ECC and concrete exhibit similar ranges of tensile strength (4–6 MPa) and compressive strength (30–80 MPa), but deform totally differently under tension. Conventional concrete fails in a brittle manner once the first crack occurs. However, in an ECC member, after the first cracking, the stress still increases with increasing deformation until final crack localization occurs, accompanied by multiple cracks along the tested member. Typically, mechanical softening only begins at a tensile strain of 3–5%, with a crack spacing of 3–6 mm and a crack width of approximately 60 μm [10]. Existing research results indicate that the mechanical properties of ECC material in shear are

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Nomenclature

A_{st}	tension reinforcement area	$\varepsilon_{0.4}$	compressive strain of ECC at 40% of ultimate strength
b	cross section breadth	ε_c	strain at extreme compressive fiber
c	compression zone depth	ε_{c0}	compressive strain of ECC at peak stress
d	cross-section depth	ε'_{c0}	compressive strain of concrete at peak stress
e_0	load eccentricity	ε_{cu}	ultimate compressive strain of ECC
E_0	elastic modulus of ECC	ε_y	yield strain of steel reinforcement
E_s	elastic modulus of steel reinforcement	ε_{cu}'	ultimate compressive strain of concrete
f	deflection at mid-height section	ε_{su}	ultimate strain of steel reinforcement
f_c	compressive cylinder strength of concrete	ε'_{t0}	cracking strain of concrete
f_{cu}	compressive cube strength	ε_{tc}	first cracking strain of ECC
f_{su}	ultimate strength of steel reinforcement	ε_{tu}	ultimate tensile strain of ECC
f_t	tensile strength of concrete	σ_c	compressive stress of ECC
f_y	yield strength of steel reinforcement	σ_{c0}	compressive strength of ECC
L	column length	σ_{cu}	ultimate compressive stress of ECC
M_m	moment at mid-height section	σ_c'	compressive stress of concrete
M_u	ultimate bending moment of column	σ_s	tensile stress of steel reinforcement
N	eccentric load	σ_t	tensile stress of ECC
N_u	ultimate eccentric load of column	σ_{tc}	first cracking stress of ECC
N_{uc}	predicted ultimate strength of column	σ_{tu}	ultimate tensile stress of ECC
N_{ue}	experimental ultimate strength of column	ϕ	curvature
x	vertical coordinate of centerline	ϕ_m	curvature at mid-height section
y	horizontal coordinate of centerline	ρ_s	longitudinal reinforcement ratio
ε	strain		

similar to those in tension [11]. FRP reinforced ECC beams without transverse steel reinforcement demonstrate superior mechanical performance to concrete beams with closely spaced stirrups, indicating that the elimination of shear reinforcement is feasible when concrete is replaced with ECC [12]. A previous study also indicated that ECC deforms compatibly with steel reinforcement, resulting in decreased interfacial bond stresses and the elimination of bond splitting cracks and cover splitting [2]. Maalej and Li [13] pointed out that steel-reinforced ECC-concrete composite beams with an ECC layer on the tension side exhibited higher flexural strength and finer cracks prior to final failure compared to corresponding RC beams. Recently, Chen et al. [14] proposed the use of high-strength ECC for the flexural repair of RC structures with significant steel corrosion. With this novel technique, the flexural strength of the corrosive beam was retrieved, and splicing of additional reinforcements or removal of a large amount of concrete could be avoided. Experimental observations of the cyclic response of steel reinforced ECC (R/ECC) flexural members also demonstrated that the energy dissipation capacity can be improved significantly and member integrity can be better maintained when concrete is replaced with ECC [3,15,16]. Obviously, ECC can operate in conjunction with steel reinforcement to improve ductility and durability for R/ECC flexural members, owing to its unique properties.

Previous studies have focused on the flexural behavior of R/ECC members, but few experimental studies have investigated the eccentric compression behavior of R/ECC members. This gives rise to a need for further studies on this problem.

In this study, several R/ECC columns are tested under eccentric compression. The influence of different parameters, including longitudinal steel reinforcement ratios and load eccentricities, on the column ultimate strength, ductility, and damage tolerance, among other factors, are evaluated. For comparison purposes, additional tests were conducted on two RC columns. Subsequently, a simplified calculation method is proposed to predict the load versus deformation response of the R/ECC column. Finally, an extensive parametric study was conducted in order to further evaluate the main parameters influencing the ultimate strength of R/ECC members.

2. Experimental program

2.1. Specimen preparation

A total of eight steel-reinforced columns were tested under compression in the present work. All columns have the same cross-sections of breadth $(b)\times$depth (d) = 200 mm $\times$ 250 mm, and lengths (L) of 1200 mm. The column specimens in this experiment can be divided into two series. Series I consists of four columns tested under a load eccentricity of 40 mm, designed to fail in matrix crushing without reinforcement yield in tension. Series II includes four columns tested under a load eccentricity of 120 mm, designed to fail in matrix crushing beyond reinforcement yield in tension. The corresponding load eccentricity ratios (e_0/r) in Series I and II are 0.32 and 0.96, respectively, where r is given by $d/2$. Each series includes one RC column and three R/ECC columns. For each specimen, four steel bars with the same diameters of 12, 16, or 20 mm were used as longitudinal reinforcement. For all specimens, ribbed steel stirrups with a diameter of 8 mm and spacing of 100 mm were used as transverse reinforcement. Table 1 provides the details of each specimen, where, different specimen designations are employed to distinguish these columns. Specimen designations starting with the letter 'E' denote ECC specimens, while those starting with the letter 'C' represent concrete specimens. The Arabic numerals following the first hyphen indicate the longitudinal reinforcement diameter. The listed Arabic numerals following the second hyphen are used to distinguish specimens with different load eccentricities. For example, the specimen 'E–16–120' represents an R/ECC column with a longitudinal reinforcement diameter of 16 mm and load eccentricity of 120 mm.

2.2. Material properties

A high volume replacement (80%) of cement with fly ash was employed in the ECC composition in order to improve the environmental sustainability. The matrix compositions of the ECC and concrete are displayed in Table 2. The cement is Portland Type I cement (42.5R), in which the alkali content (calculated as Na_2O +