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Effectiveness of low-cost fiber-reinforced cement composites in hollow columns under cyclic loading

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HIGHLIGHTS

- The effectiveness of low-cost FRCCs was investigated on the seismic performance of hollow columns.
- The stress–strain relationship was more ductile in both compression and tension when 2% fiber ratio (vs. 1%) was used.
- The load-drift responses of the FRCC specimens, even with no transverse reinforcement, were stable up to 3% or 4% drift.
- The higher fiber ratio improved energy dissipation, but 1% fiber ratio did not ensure satisfactory energy dissipation.
- The exclusion of coarse aggregates did not distinguish the seismic performance of the specimens with 1% fiber ratio.

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ABSTRACT

This study is to investigate the effectiveness of low-cost fiber-reinforced cement composites (FRCCs) on improving the seismic performance of hollow bridge columns. FRCCs with an economical type of hooked steel fibers were used. Five 1/4-scale rectangular hollow columns were tested under quasi-static lateral cyclic loading. The main test variables included steel fiber volumetric ratio (0%, 1%, or 2%), the presence of coarse aggregates, and column length-to-depth ratio (2 or 3). In all specimens, no transverse reinforcement was provided to identify the sole contribution of concrete or FRCCs on the confinement as well as the shear strength. The specimens having FRCCs exhibited stable inelastic load–displacement responses up to 3% or 4% drift, even though they suffered severe shear cracks. In contrast, one specimen with normal concrete only showed very limited ductility. The specimen with the higher fiber ratio generally achieved the larger displacement ductility and the greater energy dissipation, and also better sustained intensive cracking damage.

1. Introduction and background

Reinforced concrete (RC) bridge columns designed based on current codes (e.g., AASHTO LRFD specifications [1], Eurocode 2 [11]) are expected to endure significant inelastic demands in the plastic zones at their bottoms, when subjected to design-level earthquakes. The plastic zones may also serve as primary sources for energy dissipation [32]. Special attention should be placed on the plastic zones to prevent brittle shear failure of the columns, in that the shear strength of RC columns degrades when the flexural ductility demand increases [2]. Moreover, the recent development of performance-based seismic design methodology has recognized that post-earthquake damage control for such plastic zones must become an explicit design criterion in relation to the repair cost [12].

The use of hollow columns has become increasingly popular in RC bridge construction [8,27], owing to their substantial benefits in comparison to columns with solid sections. A hollow section with a larger depth and concentrated flanges carries a greatly larger moment-of-inertia than solid sections with similar areas. However, the relatively small thickness between the inner and outer faces of a hollow section necessitates complicated confinement reinforcement for the longitudinal bars (Fig. 1). Also, the inner transverse reinforcement tends to apply pressure to the inner concrete cover, so that it may spall off at high levels of axial strain, possibly resulting in a reduced ductility [27].

Until now, only a couple of research groups [27,36] have paid their attentions on RC hollow columns. Moreover, most of the studies focused on examining various confinement reinforcement details to develop proper methods of ensuring satisfactory ductility and relieving reinforcement congestion [8,21,22,36]. In this study,

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Nomenclature

A_g	gross section area
f'_c	compressive strength of concrete
f_y	yield strength of longitudinal steel
h	column section dimension parallel to the loading direction
l	column length from the base to the loading point
l/h	column aspect ratio
μ	displacement ductility
$P_{\max}$	measured maximum lateral load
P_n	nominal strength; calculated lateral load corresponding to the event of the extreme concrete compression fiber reaching the maximum allowable strain (taken as 0.003)
P_y	yield strength; calculated lateral load corresponding to the onset of outmost bar yielding
δ_y	yield displacement; measured displacement at the first yielding
δ_u	measured displacement at the point of a 20% strength drop from the peak load
γ	shear distortion
θ_h	rotation from the column-footing interface to the section h away from it
$\theta_{h/2}$	rotation from the column-footing interface to the section $h/2$ away from it
$\Delta_{f,h/2}$	displacement component caused by the rotation $\theta_{h/2}$ only
Δ_s	displacement component caused by the shear distortion γ only

an alternative method is investigated applying fiber-reinforced cement composites (FRCCs), to improve the aforesaid issues in hollow columns.

High performance fiber-reinforced cement composites (HPFRCCs), one classification belonging to FRCCs, are characterized by strain-hardening response under direct tension by developing multiple micro-cracks with assistance of engineered fibers [16,20,23,25,35]. HPFRCCs generally show high ductility under both tension and compression in comparison to normal concrete [4,14,20,30]. Thus, confinement requirements may be relaxed in members of high reinforcement congestion by using HPFRCCs [30]. Also, HPFRCCs may significantly increase the shear strength of structural members [9,19,24]. When subjected to seismic forces, in particular, HPFRCCs are deemed to improve energy dissipation through fiber bridging over micro-cracks and by providing excellent bond between reinforcing steel and cement composites [7,20].

During the last decade, several leading research groups played major roles in large-scale experimental investigations for the effectiveness of HPFRCCs in earthquake-resistant structures. Most of them tested shear-dominated building components such as coupling beams, beam-column joints, slab-column connections, and infill panels [6,10,13,19,26,28,29,31]. From the previous studies, it has been revealed that materials falling into the HPFRCC classification were effective in improving their seismic performance such as ductility, energy dissipation, and damage control.

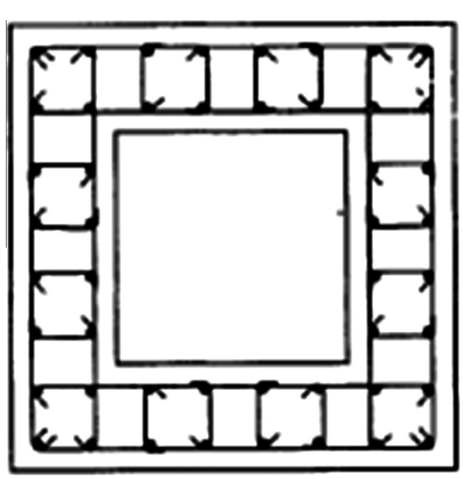

Fig. 1. Typical configuration of confinement reinforcement in R/C hollow columns (adopted from Mo et al. [21]).

However, the increased material cost, compared with normal concrete, is one of the critical issues that impede the use of HPFRCCs in real construction projects. Nevertheless, little research was conducted to alleviate the material cost issue [5,18,33,37]. Also, no tests have been done for hollow columns built with any types of FRCCs to date. Given the concerns, this study aims at evaluating the effectiveness of low-cost FRCCs on improving the seismic performance of hollow bridge columns. FRCCs with an inexpensive type of steel fibers are used to construct the plastic zones of hollow column specimens in this study. One of the FRCC types considered includes coarse aggregates; in this case, the mixed material can be simply called "fiber-reinforced concrete".

2. Descriptions for hollow column tests

In this study, five approximately 1/4-scale rectangular hollow column specimens were tested under reversed lateral displacements (see Fig. 3). Each specimen represented a cantilever bridge column subjected to lateral earthquake loading. Four of them were constructed with steel fiber-reinforced cement composites (FRCCs), and one specimen with normal concrete only. The significance of this study exists in the point that the seismic application of relatively low-cost FRCCs was investigated to improve ductility, energy dissipation, and damage control.

2.1. Specimen details and test variables

Fig. 2 illustrates section and elevation views of the test specimens. In all specimens, exterior dimensions of the column section were 900 mm by 600 mm, and interior dimensions were 640 mm by 340 mm. A single layer of twenty D19 longitudinal bars was used in the specimens for simple construction, with the steel ratio of 1.8%. No transverse reinforcement was provided in all specimens, so that the confinement and the shear strength of the column were solely attributed to concrete and/or steel FRCCs.

Table 1 summarizes the design details and test variables of the five specimens. The main test variables were (a) the volumetric ratio of steel fibers (0%, 1% or 2%), (b) the presence of coarse aggregates in FRCCs, and (c) the column length-to-depth (l/h) aspect ratio (2 or 3). Here, l stands for the column length from the base to the loading point, and h is the column section dimension parallel to the loading direction (i.e., 600 mm in all specimens). In the four FRCC specimens, the steel FRCCs were used only for the lower part of the column as one way of maximizing cost effectiveness, 600 mm long (i.e., depth of the section) from the base (see Fig. 2), in which intensive flexural and/or shear (diagonal tension)