Engineering Structures 56 (2013) 958–969

Contents lists available at SciVerse ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Shear strength model for reinforced concrete rectangular hollow columns

Myoungsu Shin [a], Yoon Young Choi [a], Chang-Ho Sun [b], Ick-Hyun Kim [b,*]

[a] School of Urban and Environmental Engineering, Ulsan National Institute of Science and Technology (UNIST), Ulsan, Republic of Korea
[b] Department of Civil and Environmental Engineering, University of Ulsan, Ulsan, Republic of Korea

ARTICLE INFO

Article history:
Received 12 January 2013
Revised 10 June 2013
Accepted 12 June 2013

Keywords:
Hollow column
Shear strength
Lateral loading
Column aspect ratio
Ductility

ABSTRACT

The primary purpose of this paper is to propose an assessment model for concrete contribution to the shear strength of reinforced concrete (RC) rectangular hollow columns subjected to lateral loading. The model was developed based on the test results of this study, as well as other hollow column tests available in literature. A total of thirteen ¼-scale RC rectangular hollow columns, with no transverse reinforcement, were tested under lateral loading in this study. The test variables included column length-to-depth aspect ratio, longitudinal steel ratio, hollow section ratio, web-to-gross section area ratio, and loading pattern. Also, a database of almost all RC hollow column tests available worldwide was assembled and used in quantifying the effect of increasing ductility on the column shear strength. Several popular shear models proposed earlier, all of which were mainly based on tests for columns with solid sections, were reviewed and compared with the developed model.

1. Introduction

Bridge columns are expected to have ductile flexural hinges at their bottoms under design-level earthquakes so as to function as primary sources for energy dissipation [1]. Special attention should be placed on such plastic hinges to prevent brittle shear failure of the columns, because the shear strength of RC columns degrades significantly when the lateral displacement ductility increases [2], as illustrated in Fig. 1.

The use of hollow columns has become increasingly popular in reinforced concrete (RC) bridge construction [3,4], 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 complicates the detailing of confining reinforcement. Also, the inner shear reinforcement tends to apply pressure to the inner concrete cover, so that it may spall off at high levels of axial strain, leading to a reduced ductility [4].

Differences may exist between the shear-resisting mechanisms of rectangular solid and hollow columns subjected to lateral loading. The distribution of shear flow in hollow sections is different from that in solid sections [5], and could be very similar to that in thin-walled tube sections (see Fig. 2); shear stresses are generally parallel to the boundaries of the section [6].

Numerous studies [7–13,26–30] proposed assessment models for evaluating the shear strength of RC columns under seismic forces. However, almost all of them were primarily based on experimental tests for columns with solid sections. Only a couple of research groups [13–16] have recently paid their attentions on RC hollow columns to date. Moreover, little investigation was made on the shear strength of such columns; most of the studies focused on evaluating the acceptability of different confining reinforcement details on the standpoint of sufficient ductility. Due to the lack of research data, current design codes [17–19] do not address specific shear strength formula for RC hollow columns.

Given this concern, the current study investigated concrete contribution to the shear strength of RC rectangular hollow columns subjected to lateral loading. Large-scale RC hollow column specimens with no transverse reinforcement were tested as part of this study. The test results were used to determine the two strength factors (α and β in Eq. (17)) accounting for the effects of column aspect ratio and longitudinal steel ratio on the column shear strength, as well as to support the use of effective area for shear resistance (A_e in Eq. (17)). The strength factor (γ in Eq. (17)) for the effect of displacement ductility was determined based on a database of almost all RC hollow column tests found in the literature.

* Corresponding author. Address: Department of Civil and Environmental Engineering, University of Ulsan, 93 Daehak-ro, Nam-gu, Ulsan 680-749, Republic of Korea. Tel.: +82 10 3872 3427.

E-mail address: ickhyun@ulsan.ac.kr (I.-H. Kim).

0141-0296/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engstruct.2013.06.015

Nomenclature

A_e	effective area for shear
A_g	gross section area
A_v	area of transverse steel
b	column width, perpendicular to the loading direction
$b_w d$	web area
f'_c	compressive strength of concrete
f_y	yield strength of longitudinal steel
f_{yv}	yield strength of transverse steel
h	column depth, parallel to the loading direction
l	column length
M_u	ultimate moment
P	axial load
s	spacing of transverse steel
V_c	concrete contribution to shear strength
$V_{c,exp}$	measured maximum load without shear reinforcement
V_{exp}	measured maximum load with shear reinforcement
V_{flex}	lateral load corresponding to the nominal moment strength
V_s	transverse steel contribution to shear strength
V_{str}	predicted shear strength
V_u	ultimate shear force
V_{yield}	lateral load corresponding to the onset of reinforcement yielding
μ	displacement ductility
ρ	longitudinal steel ratio equal to the total area of longitudinal steel divided by A_g
ρ_l	total area of longitudinal steel divided by the area enclosed by the exterior circumference of a circular column
ρ_s	transverse steel ratio
ρ_w	area of longitudinal tension steel divided by $b_w d$
ρ_{solid}	total area of longitudinal steel divided by the area enclosed by the exterior dimensions (b times h) of a rectangular hollow column section
σ_x	normal stress perpendicular to the column axis
σ_y	normal stress parallel to the column axis
τ	shear stress
τ_c	concrete shear strength in stress term
$\tau_{c,exp}$	measured concrete shear strength in stress term

2. Research significance

The use of hollow columns has greatly increased due to substantial cost savings in materials and equipment during construction of the columns and their foundations. Nevertheless, little research has been conducted to date for the seismic design or assessment of RC columns with hollow sections. In particular, no shear strength model was warranted to be used specifically for such columns. Given this concern, this study focused on developing an assessment model for concrete contribution to the shear strength of RC hollow columns subjected to lateral loading.

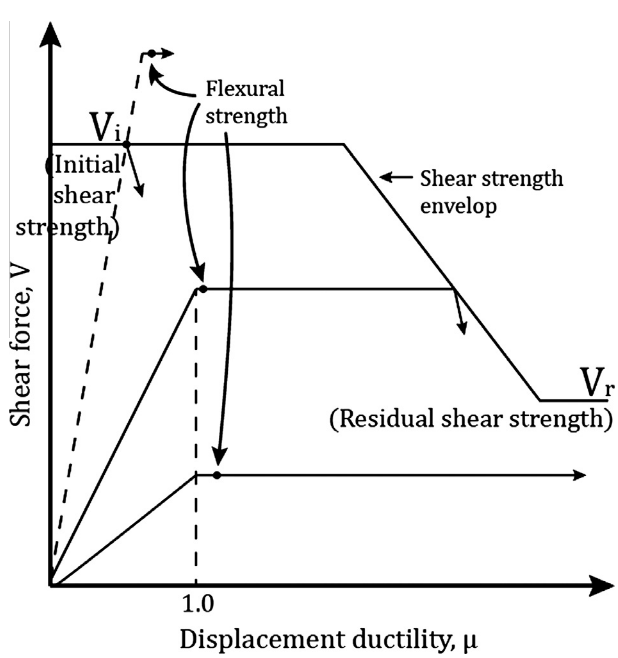

Fig. 1. Relationship between shear strength and ductility [2].

3. Descriptions for experimental program

3.1. Specimen details and test variables

Thirteen approximately ¼-scale rectangular hollow column specimens were tested in this study. The specimens represented cantilever bridge columns subjected to lateral loading (see Fig. 3). All specimens were designed to fail in shear before reaching their nominal moment strengths, in order to investigate the initial shear strength (see Fig. 1). The two important test variables were column length-to-depth aspect ratio (l/h) and longitudinal reinforcement layout, in which l stands for the column length from the base to the loading point and h is the column depth parallel to the loading direction. The other test variables included web-to-gross section area ratio ($b_w d/A_g$), hollow section ratio, and loading pattern. The hollow section ratio was defined as the area enclosed within interior edges of a hollow section divided by the area within exterior edges of the section. Fig. 3 illustrates plan and elevation views of the test specimens, and Table 1 summarizes the design details and test variables.

The testing program was divided into two groups of specimens: Series-A and Series-B. In all specimens, exterior dimensions of the

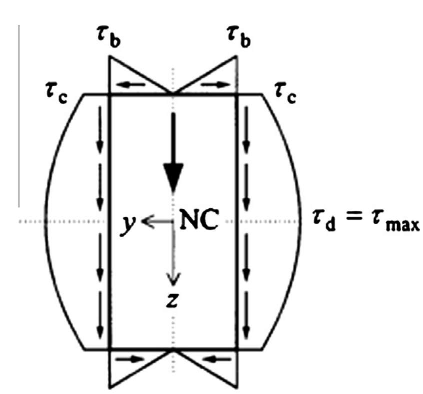

Fig. 2. Shear flow in thin-walled rectangular tube sections (adapted from [6]).