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ScienceDirect
Thin-Walled Structures 45 (2007) 259–273
THIN-WALLED STRUCTURES
www.elsevier.com/locate/tws

Nonlinear behavior of concrete-filled stainless steel stiffened slender tube columns

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Received 16 November 2006; accepted 27 February 2007
Available online 30 April 2007

Abstract

This paper investigates the nonlinear behavior of concrete-filled high strength stainless steel stiffened slender square and rectangular hollow section columns. The stiffened slender tubes had overall depth-to-plate thickness (D/t) ratios ranging 60–160. The concrete strengths covered normal and high-strength concrete. The investigation focused on short axially loaded columns. A nonlinear finite element (FE) model has been developed to study the behavior of the concrete-filled stiffened tube columns. A parametric study was conducted to investigate the effects of cross-section geometry and concrete strength on the behavior and strength of the columns. The results of the concrete-filled stiffened tube columns were compared with the results of the companion concrete-filled unstiffened tube columns. It is shown that the concrete-filled stiffened slender tube columns offer a considerable increase in the column strength and ductility than the concrete-filled unstiffened slender tube columns. The column strengths obtained from the FE analysis were compared with the design strengths calculated using the American specifications and Australian/New Zealand standards. A design equation was proposed for concrete-filled stainless steel stiffened slender tube columns. It is shown that the proposed modified equation provides more accurate design strengths compared to the American and Australian/New Zealand predictions.

Keywords: Composite columns; Design; Finite element; High strength; Stainless-steel tubes; Square and rectangular hollow sections; Stiffened and unstiffened columns

1. Introduction

There are many published investigations on the behavior of concrete-filled carbon steel tube columns as presented by Schneider [1], Uy [2–4], Huang et al. [5], Han and Yao [6], Mursi and Uy [7], Liu et al. [8], Uy [9], Hu et al. [10], Sakino et al. [11], Giakoumelis and Lam [12], Lam and Williams [13] and by other researchers. Limited data are available in the literature on concrete-filled stainless steel unstiffened tube columns as detailed in Roufegarinejad et al. [14], Lam and Wong [15], Young and Ellobody [16] and Ellobody and Young [17]. The behavior of high strength stainless steel stiffened and unstiffened slender hollow section columns has been recently investigated by Ellobody [18]. The investigation has shown that high strength stainless steel stiffened slender tube columns offer much higher increase in column strength than that of unstiffened slender tube columns. So far, no test data were found in the literature investigating the behavior of concrete-filled high strength stainless steel stiffened slender tube columns.

The main objective of this study is to investigate the behavior and design of concrete-filled high strength stainless steel stiffened slender tube columns. The finite element (FE) program ABAQUS [19] was used in the analysis. The material nonlinearities of concrete and high strength stainless steel tubes as well as concrete confinement were considered in the analysis. Parametric study was conducted to investigate the effects of cross-section geometry and concrete strength on the behavior and strength of the concrete-filled stiffened tube columns. The results of the concrete-filled stiffened tube columns were compared with that of the companion concrete-filled unstiffened tube columns. The column strengths obtained from the FE analysis were compared with the design strengths calculated using the general design guides

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0263-8231/$ - see front matter
doi:10.1016/j.tws.2007.02.011

Nomenclature

A_c	cross-sectional area of concrete
A_e	effective cross-section area of stainless steel tube
A_s	cross-sectional area of stainless steel tube
B	overall width of cross-section (smaller dimension)
b_s	internal width of intermediate stiffener
C	proposed factor for design equation
D	overall depth of cross-section (larger dimension)
d	depth of flat portion of cross-section
E_{cc}	Young's modulus of confined concrete
E_o	initial Young's modulus of stainless-steel tube
E_t	tangent modulus
e_{FE}	axial shortening at ultimate load obtained from finite-element analysis
$e_{Stiffened}$	axial shortening at ultimate load for stiffened columns obtained from finite-element analysis
$e_{Unstiffened}$	axial shortening at ultimate load for unstiffened columns obtained from finite-element analysis
F_n	design stress
F_y	yield stress of stainless-steel tube ($F_y = \sigma_{0.2}$)
f	equivalent uniaxial stress
f_c	unconfined compressive cylinder strength of concrete
f_{cc}	confined compressive strength of concrete
f_{cu}	unconfined compressive cube strength of concrete
f_l	lateral confining pressure
h_s	internal depth of intermediate stiffener
k_3	coefficient for confined concrete
L	length of column
n	exponent in Ramberg–Osgood expression
$P_{ACI/ASCE}$	nominal axial strength calculated using the American specifications (unfactored design strength)
$P_{ACI/ASCE-1}$	nominal axial strength calculated using the American specifications (unfactored design strength according to approach one)
$P_{ACI/ASCE-2}$	nominal axial strength calculated using the American specifications (unfactored design strength according to approach two)
$P_{ACI/ASCE-p}$	nominal axial strength calculated using the proposed equation specifications (unfactored proposed design strength)
P_{FE}	ultimate load obtained from finite-element analysis
$P_{Stiffened}$	ultimate load obtained from finite-element analysis for stiffened columns
P_{Test}	test ultimate load (test strength)
$P_{Unstiffened}$	ultimate load obtained from finite-element analysis for unstiffened columns
r	reduction factor for confined concrete
t	plate thickness of stainless-steel tube
ε	equivalent uniaxial strain
ε_c	unconfined concrete strain
ε_{cc}	confined concrete strain
ε_f	elongation (tensile strain) after fracture based on gauge length of 50 mm
υ_{cc}	Poisson's ratio of confined concrete
$\sigma_{0.2}$	static 0.2% proof stress
σ_u	static ultimate strength

specified in the American specifications [20,21] and Australian/New Zealand standards [22,23] for stainless-steel and concrete structures.

2. Background

2.1. Tests on concrete-filled stainless steel unstiffened tube columns

The tests on axially loaded concrete-filled high strength stainless steel unstiffened slender tube short columns were conducted by Young and Ellobody [16]. The unstiffened tube columns had square hollow sections (SHS) and rectangular hollow sections (RHS) cold rolled from flat strips of high strength stainless steel that is approximately equivalent to EN 1.4462 [24] and UNS S31803 [20]. Young and Ellobody [16] tested five series that included two series of concrete-filled unstiffened SHS columns (SHS1 and SHS2) and three series of concrete-filled unstiffened RHS columns (RHS1, RHS2 and RHS3). The nominal section sizes ($D \times B \times t$) of series SHS1, SHS2, RHS1, RHS2 and RHS3 are $150 \times 150 \times 6$, $150 \times 150 \times 3$, $200 \times 110 \times 4$, $160 \times 80 \times 3$ and $140 \times 80 \times 3$ mm, respectively, where D is the overall depth, B the overall width and t the plate thickness in mm. The measured specimen dimensions are detailed in Young and Ellobody [16]. The specimens were tested using different concrete cylinder strengths. The material properties of the stainless steel unstiffened hollow section specimens were determined by tensile coupon tests of flat and corner portions. The coupon dimensions conformed to the Australian Standard AS 1391 [25] for the tensile testing of metals using 12.5 mm wide coupons of gauge length 50 mm. The initial Young's modulus E_o, static 0.2% proof stress $\sigma_{0.2}$, static ultimate tensile strengths σ_u and elongation after fracture ε_f were measured. The Ramberg–Osgood [26] parameter n that describes the shape of the stress–strain curve was also determined for the five series. The tensile coupon tests are detailed in Young and Lui [27]. The concrete cylinder dimensions and test procedures conformed to the American Specification [21] for concrete testing. The concrete cylinder tests are detailed in Young and Ellobody [16]. The load