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Numerical modelling of fibre reinforced concrete-filled stainless steel tubular columns

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ABSTRACT

The nonlinear behaviour of fibre reinforced (FR) concrete-filled stainless steel tubular columns is discussed in this paper. A nonlinear 3-D finite element model was developed for the analysis of the composite columns. The pin-ended axially loaded composite columns had different lengths, which varied from stub to long columns. The nonlinear material properties of the composite column's components comprising stainless steel tube and FR concrete were incorporated in the model. The effect of FR concrete confinement and interface between the stainless steel tube and FR concrete infill was also considered allowing the bond behaviour to be modelled. In addition, the measured initial overall (out-of-straightness) geometric imperfection was carefully incorporated in the model. The finite element model has been validated against tests recently conducted by the author on FR concrete-filled stainless steel tubular columns. The composite column strengths, load–axial strain relationships and failure modes were predicted from the finite element analysis and compared well against that measured experimentally. Furthermore, the variables that influence the composite column behaviour and strength comprising different lengths, external diameter-to-plate thickness (D/t) ratios and FR concrete strengths were investigated in a parametric study. The parametric study has shown that the increase in column strengths owing to the increase in concrete strength is more significant for the columns having L/D ratios less than 6 as well as for the columns having D/t ratios less than 50. The composite column strengths obtained from the finite element analysis were compared with the design strengths calculated using Eurocode 4 for composite columns. It is shown that the EC4, in most cases, accurately predicted the design strength for axially loaded FR concrete filled stainless steel tubular columns.

1. Introduction

Numerous experimental and numerical investigations were presented in the literature highlighting the advantages, behaviour and design of concrete-filled carbon steel tubular columns, as detailed for example in Refs. [1–15]. With growing use of stainless steel as an efficient structural material compared to traditional carbon steel, the aforementioned investigations were extended to study the performance and design of concrete-filled stainless steel tubular columns as presented in Refs. [16–19]. However, the presented studies [16–19] were limited to axially loaded concrete-filled stainless steel tubular short (stub) columns. Uy et al. [20] carried out a comprehensive experimental investigation on short and long concrete-filled stainless steel tubular columns. The stainless steel tubes had circular, square and rectangular cross-sections. The composite column strengths, failure modes, load–axial strain relationships, load–axial shortening relationships and load–mid-height relationships were measured in the tests. The test results were compared with that predicted using existing design methods for conventional concrete-filled carbon steel tubular columns. The authors have concluded that current codes of practice underestimate the load-carrying capacities of concrete-filled stainless steel tubular columns under both axial compression and combined actions. However, test data highlighting the structural performance of axially loaded concrete-filled stainless steel tubular long columns are rarely found in the literature, leading to the current investigation.

Fibre reinforced (FR) concrete has many advantages including elimination of micro-cracks at early age of concrete, limitation of large capillaries caused by bleed water migration, lower permeability, enhanced mix cohesion, improved freeze-thaw resistance, improved resistance to explosive spalling in case of a severe fire, improved impact resistance, minimization of erosion damage, reduction of plastic cracking of concrete and particularly greater flexural and tensile strengths compared to plain concrete. The

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Nomenclature

A_a	area of stainless steel tube
A_c	area of concrete
A_s	area of reinforcement bars
CC	concrete crushing failure mode
COV	coefficient of variation
D	outer diameter of tube
E_o	initial modulus of elasticity of stainless steel
E_{cm}	secant modulus of elasticity of concrete
$E_{c,eff}$	effective modulus of elasticity of concrete
f	equivalent uniaxial stress
f_c	unconfined compressive cylinder strength of concrete
f_{cc}	confined compressive strength of concrete
f_{ct}	tensile strength of concrete
f_{cu}	unconfined compressive cube strength of concrete
f_l	lateral confining pressure
f_s	yield stress strength of reinforcement bar
f_y	yield stress of stainless steel tube
$f_{0.2}$	static 0.2% proof stress
f_u	static ultimate strength
F	flexural failure mode
FR	fibre reinforced
G_f	fracture energy of concrete
h	crack band width
I_a	inertia of stainless steel tube cross-section
I_c	inertia of concrete infill
I_s	inertia of cross-section of reinforcement bars
k	factor for the calculation of design moment resistance
k_1	coefficient for confined concrete
k_2	coefficient for confined concrete
k_3	coefficient for confined concrete
L	length of column specimen
L_e	effective length
LB	local buckling failure mode
n	exponent in Ramberg–Osgood expression
$N_{pl,Rd}$	plastic resistance to compression
P_{EC4}	unfactored design ultimate load
P_{FE}	column strength obtained from finite element analysis
P_{Test}	test ultimate load
R	coefficient for confined concrete
R_E	coefficient for confined concrete
R_ε	coefficient for confined concrete
R_σ	coefficient for confined concrete
SY	steel yielding failure mode
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_t	tensile strain
υ_{cc}	Poisson's ratio of confined concrete
ε_f	elongation (tensile strain) after fracture
a	factor for the calculation of plastic resistance
c_o	factor for the calculation of plastic resistance
λ^{-}	no dimensional slenderness
χ	factor for the calculation of design ultimate load
ϕ	factor for the calculation of design ultimate load
$\lambda_{\circ}$	factor for the calculation of design ultimate load
α	factor for the calculation of design ultimate load

greater flexural and tensile strengths are attributed to the fact that the presence of fibres in plain concrete results in post-elastic property enhancement that ranges from subtle to substantial, depending upon a number of factors, including matrix strength, fibre type, fibre Young's modulus, fibre volume, fibre strength, fibre surface bonding characteristics, fibre content, fibre orientation, and aggregate size effects. Fig. 1 shows a comparison between a stress–strain curve of plain concrete and that of FR concrete with low and high fibre volumes. It can be seen that the presence of fibres has resulted in a considerable improvement on the stress–strain curve of concrete. Although, the concrete first-crack strength is not increased, a significant enhancement from the fibres is clear in the post-cracking response, which improves long-term serviceability of the structure. Gopal and Manoharan [21] carried out tests on 12 slender carbon steel tubular circular columns filled with both plain and steel FR concrete. The test specimens were

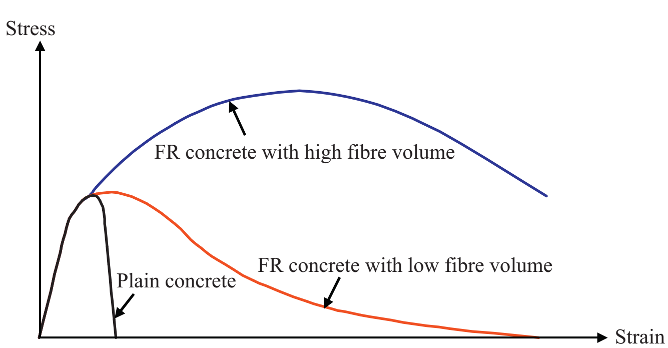

Fig. 1. Comparison of stress–strain curves of plain and FR concrete.

tested under eccentric compression to investigate the effects of FR concrete on the strength and behaviour of the composite columns. The load–mid-height lateral deflection and load–strain curves were reported in the paper. The study [21] has shown that the use of FR concrete as infill material has a considerable effect on the strength and behaviour of slender composite columns. Tokgoz and Dundar [22] have investigated experimentally the structural behaviour of plain and fibre reinforced concrete-filled steel tubular columns. The authors have conducted a total of 16 composite tests subjected to biaxial bending and short-term axial load. The main variables considered in the study were the cross section, slenderness, concrete compressive strength and the load eccentricity. The authors have also presented a theoretical method for the prediction of ultimate strength capacity and load–deflection curves of concrete-filled steel tube columns. The authors have concluded that the addition of steel fibres in core concrete has a considerable effect on the behaviour of concrete-filled steel tube columns. However, experimental investigations highlighting the performance of FR concrete-filled stainless steel tubular columns are rarely found in the literature, leading to the current study.

Recently, Ellobody and Ghazy [23,24] have carried out an experimental investigation on pin-ended FR concrete-filled stainless steel circular tubular columns. The investigation augmented available tests published in the literature on concrete-filled stainless steel composite columns [16,17]. The columns tested in [23,24] had different lengths equal to 3D of short columns, 6D of relatively long columns and 12D of long columns, where D is the external diameter of the stainless steel circular tubes. The circular tubes were cold-rolled from flat strips of austenitic stainless steel. The tubes had diameter-to-plate thickness (D/t) ratio of 50. The tests [23,24] have provided useful information