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Finite element analysis on the capacity of circular concrete-filled double-skin steel tubular (CFDST) stub columns

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ABSTRACT

This paper presents the behaviour of circular concrete-filled double-skin steel tubular (CFDST) stub columns compressed under concentric axial loads. To predict the performance of such columns, a finite element analysis is conducted. Herein, for the accurate modelling of the double-skin specimens, the identification of suitable material properties for both the concrete infill and steel tubes is crucial. The applied methodology is validated through comparisons of the results obtained from the finite element analysis with those from past experiments. Aiming to examine the effect of various diameter-to-thickness (D/t) ratios, concrete cube strengths and steel yield strengths on the overall behaviour and ultimate resistance of the double-skin columns, a total of twenty-five models are created to conduct the parametric study. In addition, four circular concrete-filled steel tubes (CFST) are included to check the dissimilarities, in terms of their behaviour and weight, when compared with identical double-skin tubes. A new formula based on Eurocode 4 is proposed to evaluate the strength of the double-skin specimens. Based on the comparison between the results derived from the analysis, the proposed formulae for the concrete filled double-skin would appear to be satisfactory.

1. Introduction

Concrete-filled double-skin steel tubes consist of two concentric steel tubes, an outer and an inner, with concrete sandwiched between them and a void at their centre. The outer and inner tubes can either have the same or different cross-sections, e.g. circular-circular, circular-square etc. Having recently been introduced for construction purposes, double-skin columns belong to the family of composite columns and therefore combine the best qualities of both steel and concrete. These columns are said to have similar behaviour to the single-skin columns, but with a lesser weight and greater stiffness.

Researchers in recent years have carried out experiments and finite element analyses to investigate the behaviour of concrete-filled double-skin stub members tested against compressive forces. Huang et al. [1] created fourteen specimens identical to those initially introduced by Tao et al. [2] and Lin and Tsai [3], aiming to investigate the accuracy of modelling in ABAQUS. From the analysis of the stress–strain curves it was concluded that sections with a greater confinement factor (ξ) demonstrated strain-hardening behaviour, whilst strain-softening behaviour was shown for smaller ξ values. Yu et al. [4] focused on the parameters that affect the performance of concrete within a new kind of hybrid double-skin column. A new and simple stress–strain model was suggested for concrete in this type of cross-section. Elchalakani et al. [5] tested eight specimens with circular outer and square inner skins and Zhao et al. [6] tested six specimens with circular outer and inner skins. From the results, it was found that the buckling of both the outer and inner tubes were due to the failure of concrete. In addition, sections with large slenderness values appeared to be more ductile than those with small slenderness values. Similar tests were conducted by Tao et al. [2] who examined fourteen stub columns having both outer and inner circular hollow sections. The primary aspects under consideration in this study were the diameter-to-thickness ratio (D/t) and the hollow section ratio (a parameter relating the diameter of the inner hollow tube to the diameter of the outer tube). The analysis proved that the failure mode of the inner tube highly depends upon its D/t ratio, as opposed to that of the outer tube which was the same for various D/t ratios. Furthermore, the double-skin specimens did not appear to be influenced by the hollow section ratio. Polymer concrete sandwiched between the concentric tubes was studied by Wei et al. [7,8]. The stability, strength and ductility of twenty-six columns were inspected. It was noticed that polymer concrete has an equivalent behaviour to the commonly used concrete, since it was the fracture of this

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Nomenclature

A_{ai}	the cross-sectional area of the inner steel tube
A_{ao}	the cross-sectional area of the outer steel tube
A_c	the cross-sectional area of the concrete
D	the diameter of a single-skin concrete-filled tube (CFST)
D/t	diameter to thickness ratio of a single-skin concrete-filled tube (CFST)
D_o/t_o	outer diameter to outer thickness ratio of a double-skin concrete-filled tube (CFDST)
D_i/t_i	inner diameter to inner thickness ratio of a double-skin concrete-filled tube (CFDST)
D_i	the inner diameter of a double-skin concrete-filled tube (CFDST)
D_o	the outer diameter of a double-skin concrete-filled tube (CFDST)
E_{cc}	modulus of elasticity of confined concrete
E_s	modulus of elasticity of steel
$E_s(T)$	modulus of elasticity of steel under a particular temperature
$E_1(T)$	modulus of elasticity of steel multiplied by 0.01
f	stress values
f_c, f_{cyl}	the unconfined concrete cylinder compressive strength (=0.8 × cube strength)
f_{cc}	the confined concrete compressive strength
f_{ck}	characteristic strength of concrete
$f_{sy}(T)$	the yielding strength of the steel after exposure to high temperature (T)
f_{yi}	the yield strength of the inner steel tube
f_{yo}	the yield strength of the outer steel tube
f_1	the lateral confining pressure imposed by the circular steel tube
k_1, k_2	enhancement factors of concrete taken as 4.1 and 20.5, respectively
k_3	the material degradation parameter
L	the length/height of the column
n_a	the reduction coefficient of the steel tube
n_{ai}	the reduction coefficient of the inner steel tube
n_{ao}	the reduction coefficient of the outer steel tube
n_c	the enhancement coefficient of concrete
n_{ci}	the enhancement coefficient of concrete from inner steel tube
n_{co}	the enhancement coefficient of concrete from outer steel tube
N_{FE}	the ultimate strength derived from the FE analysis
N_u	the ultimate strength calculated by Eurocode 4
$P_{analysis}$	the maximum load capacity of a specimen attained from the finite element analysis
P_{test}	the maximum load capacity of a specimen attained from the experimental tests
r	reduction factor that takes into account the effect of concrete strength
R	parameter dependent upon R_E and two equivalent constraints $R\sigma$ and $R\varepsilon$ and is equal to 4
R_E	parameter related to the modulus of elasticity of concrete and the ratio of the confined strain ε_{cc} to the corresponding compressive strength f_{cc}
R_ε	parameter in defining the stress-strain relationship of confined concrete
$R\sigma$	parameter in defining the stress-strain relationship of confined concrete
t	the thickness of a single-skin concrete-filled tube (CFST)
T	temperature to which concrete-filled tube is exposed
t_i	the thickness of the inner tube of a double-skin concrete-filled tube
t_o	the thickness of the outer tube of a double-skin concrete-filled tube
ε	strain values
ε_c	the unconfined strain corresponding to f_c
ε_{cc}	the confined strain corresponding to f_{cc}
ε_{sy}	the strain corresponding to the $fsy(T)$ value
ξ	confinement factor for concrete-filled tube
σ_i	stress in steel exposed to high temperatures

component that allowed buckling of the tubes to begin. A formula by which the strength of these members could be calculated was recommended and found to be accurate. Zhao et al. [9] performed tests on a series of short columns subjected to static and cyclic loads. It seemed that the latter loading condition can significantly influence the load–deformation curve, especially for specimens with large diameter to thickness ratios. Hu and Su [10] recommended three equations in order to best evaluate the lateral confining pressure f_1 and one design specification for the material degradation parameter k_3, which are needed for the modelling of the confined concrete in ABAQUS. Out of the three obtained values, the minimum value of f_1 was found to be the most suitable to be adopted for engineering purposes. Research by Uenaka et al. [11] based on twelve specimens observed that as D_i/D_o was increased, the performance of the double-skin columns reduced. It was noted that tensile stresses occurred in the outer tube, whereas compressive stresses occurred in the inner tube. The load bearing capacity of the specimens was found to be considerably influenced by the degree of confinement offered by the outer tube. The thermal as well as structural response of double-skin columns was investigated by Lu et al. [12], who simulated sixteen stub specimens in ABAQUS. The typical performance of a double-skin specimen included the outward and inward buckling of the outer and inner tube, respectively. After the analysis, it was concluded that the yield strength of the tubes, the length of the column and the perimeter of the outer tube were some of the most important constraints affecting the resistance of such members against fire. Experiments under long-term and short-term compressive loads were carried out by Han et al. [13]. In the long-term test, the strain of the columns increased rapidly during the early stages of the test and stabilized later. The ultimate strength, on the other hand, decreased under the maintained loads. Yang et al. [14] reported the behaviour of partially loaded double-skin specimens. Following the investigation, the results clarified that the bigger the hollow area at the centre of the column the less concrete required to fill the empty space between the two steel tubes, and the weaker the confinement of concrete.

This study aims to examine the overall behaviour of double-skin specimens tested under axial compressive forces. In order to achieve this, finite-element models were generated in ABAQUS paying particular attention to identifying appropriate stress–strain relationships for the materials. Past experimental tests on double-skin columns conducted by Tao et al. [2] and Zhao et al. [6] were utilized to verify the adopted methodology. An extensive parametric study was carried out, where the parameters investigated were the outer diameter-to-thickness (D_o/t_o) ratio, the inner diameter-to-thickness (D_i/t_i) ratio, the cube strength of the concrete infill (f_{cc}) and the yield strength of both steel tubes (f_{yo},f_{yi}). A comparison between identical double-skin and single-skin concrete-filled tubes was also made in terms of their behaviour and weight.