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Effect of concrete infill on local buckling of circular columns: a detailed investigation

*Sina Kazemzadeh Azad[1)] and Brian Uy[2)]

[1), 2)] *School of Civil Engineering, The University of Sydney, NSW 2006, Australia*
[1)] *sina.kazemzadehazad@sydney.edu.au*

ABSTRACT

Manufactured or fabricated, carbon steel or stainless steel circular columns are all commonly used in structural applications as load-bearing members. The use of slenderness limits is a typical approach in international standards for the design of these members where a limiting diameter-to-thickness ratio is defined above which the member would not reach to its yield capacity under compression. Another common concept is that filling such circular members with concrete would increase their local buckling capacity (and the slenderness limit) since the concrete infill would restrain the tube from inwards local buckling. A number of recent studies have however raised questions on whether the concrete infill has any notable effect on the local buckling capacity of circular sections and consequently on the corresponding slenderness limit. It has been argued in these studies that circular sections under axial compression, filled or unfilled, buckle predominantly outwards and, thus, the infill is not much effective in terms of local buckling capacity. To investigate this issue thoroughly, a numerical study is conducted in the present paper considering a wide range of circular sections with and without infill. Special attention is paid regarding the modelling of geometrical imperfections where different initial patterns are imposed to the specimens to substantiate the conclusions. Results of the numerical simulations are summarised to clarify the role of concrete infill in the local buckling behaviour of circular sections.

1. INTRODUCTION

The main objective in composite construction is to increase the structural efficiency through the combined use of concrete and steel. In line with this, in a box concrete-filled tubular (CFT) column, the outer steel or stainless steel tube acts as formwork during concrete casting. After curing, the tube takes the role of a confining system for the concrete infill to enhance the load-bearing capacity of the column. On the other hand, in addition to contributing to the strength, stiffness, and fire resistance of the column, the concrete infill would enhance the local stability of the outer tube by preventing its inwards buckling. The behaviour of such columns has been extensively studied in the literature. Comprehensive review studies on steel and stainless steel CFTs were conducted by Shanmugam and Lakshmi (2001) and Han et al. (2019).

[1)] PhD Candidate
[2)] Professor, Head of School

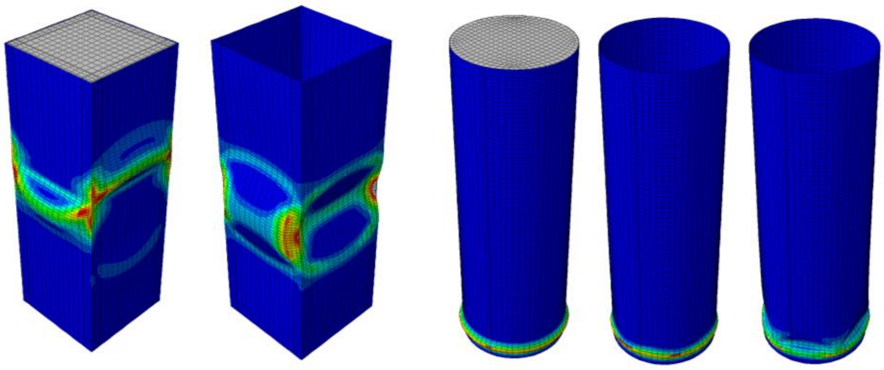

Fig. 1 Different local buckling modes for filled and hollow, box and circular sections.

Previous studies on box concrete-filled steel tubular (CFST) columns clearly demonstrated that filling a hollow section with concrete will change its local buckling mode (to a higher mode) which only contains outwards bulging (Wright 1995; Bridge and O'Shea 1998; Uy 2001). This is depicted in Fig. 1a,b for a sample box CFST column under axial compression. Such a mode change can result in enhancements in the tube strength in excess of 50% for box CFSTs (Bridge and O'Shea 1998). More recent studies reported similar observations for box concrete-filled stainless steel tubular (CFSST) columns (Kazemzadeh Azad et al. 2018; 2019). In line with these studies, in most international design specifications such as the American and Australian standards (AS 4100 1998; AISC 2016; AS/NZS 2327 2017), the positive effect of concrete infill on local buckling has been acknowledged through defining two different axial slenderness limits for hollow and filled box sections. The codified axial slenderness limit in these standards for filled box sections is approximately 60% higher than that for hollow box sections.

Compared to box sections, circular sections are less explored in the literature. Research focusing on the local stability of circular sections in the filled and unfilled conditions is even more limited. An early experimental study on the behaviour of circular CFSTs was conducted by Gardner and Jacobson (1967) where the effect of concrete infill was reported to be minimal on the local buckling of the outer tube. A direct study on the effect of internal restraint on the local stability of circular steel sections was conducted later by O'Shea and Bridge (1997) where the axial response of hollow circular sections was compared with that of filled circular sections with unbonded concrete where only the outer steel tube was loaded. The results suggested that the infill had in fact no notable effect on enhancing the local buckling strength of the tested circular steel sections since the observed buckling mode was of the form of outwards ring-type buckling in both the hollow and filled cases (Fig. 1c,d). The only exception was a specimen which showed a modest increase in the local buckling strength when it was filled with concrete. This was attributed to local buckling occurring at the mid-height of that particular specimen whereas for the other specimens local buckling occurred near the column ends (O'Shea and Bridge 1997).

A theoretical study was conducted afterwards by Bradford et al. (2002) where an analytical formula was developed for determining the elastic local buckling stress of filled circular sections. Although compared to the classic elastic buckling stress formula for hollow circular sections an increase of about 70% was noted, it was emphasised that the classic formula produced drastically unreasonable results when compared to the available test data for hollow sections. Results of a few tests were also reported in the same year by Johansson and Gylltoft (2002) where it was concluded that while the local buckling modes for filled and unfilled circular sections might differ, the buckling strengths are very similar. More recently, Uy et al. (2011) conducted an experimental work on the behaviour of box and circular CFSST columns. It was again reported that the local buckling strengths of the tested filled and hollow circular sections were very similar, both showing 'elephant's foot'-type outwards buckling near the ends. The most recent set of tests to investigate this issue was conducted by Lume (2018) where highly slender circular sections were tested under axial compression with and without the internal restraining effect of the infill concrete. It was reported that the local buckling modes for the two cases were different (such as Fig. 1c,e) which resulted in lower local buckling strengths for the unfilled cases. On the other hand, results of a recent numerical study by Kazemzadeh Azad et al. (2018) on stainless steel circular sections suggested that filling such sections with concrete did not lead to a notable change in their local buckling strength.

Based on the above discussion, it can clearly be seen that there is no consensus among different studies and international design standards on the effect of concrete infill on the local stability of circular sections. Two main approaches are as follows:

i. The concrete infill has a notable effect on increasing the local buckling strength of a circular section under axial compression by changing the local buckling mode shape (Lai and Varma 2015; Lume 2018). This approach is in line with the design philosophy behind most international standards where a significantly higher (~40%) axial slenderness limit is used for filled circular sections compared to unfilled circular sections (AS 4100 1998; AISC 2016; AS/NZS 2327 2017).

ii. The concrete infill may (Johansson and Gylltoft 2002) or may not (O'Shea and Bridge 1997; Uy et al. 2011) change the final local buckling mode shape of a circular section. Nevertheless, the presence of concrete infill does not lead to any notable increase in the local buckling strength of a circular section under axial compression.

In order to understand the reasons behind such a drastic discrepancy between the two approaches, a numerical study considering hollow and filled, steel and stainless steel circular sections is conducted in the present paper. The main aim is to identify the effect of concrete infill on the local buckling strength of circular sections. The results shall also clarify if there should exist a notable difference between the axial slenderness limits of filled and hollow circular sections such as that currently stipulated by most international design standards. In line with this, the modelling details considered in the simulations are first discussed in the next section. The verification of the modelling approach and details of a parametric study are presented in Section 3 followed by the discussion of the results in Section 4. Finally, the conclusions are presented in Section 5.

2. FINITE ELEMENT MODELLING

2.1 General modelling details

The analyses considering both material and geometrical nonlinearities were conducted using the finite element (FE) software ABAQUS 6.14-1 (2014). Although static analysis was used for most cases, in some very slender models the dynamic implicit solver was utilised in order to overcome convergence issues. The outer tube was modelled using S4R shell elements with nine integration points through the thickness of the plate. The concrete infill was on the other hand modelled using 8-node 3D elements (C3D8R). The mesh size was selected as d/20 (in the section) and L/100 (along the length) following the recommendations of Kazemzadeh Azad et al. (2019), which were based on a sensitivity analysis, where d is the outer diameter of the tube and L is the specimen length.

A displacement controlled loading scheme was utilised in all the simulations. For the case of unfilled models, all degrees of freedom (DOFs) of the top and bottom end nodes of the tube were restrained except the vertical DOFs of the top end nodes which were used for imposing the axial shortening to the specimen. For the case of filled sections, the same boundary conditions (as the hollow case) were imposed which indicates that the loading was only applied to the outer tube. This approach is commonly used in the literature in order to focus the study on the local stability of the outer tube in filled sections (Gardner and Jacobson 1967; O'Shea and Bridge 1997; Johansson and Gylltoft 2002; Uy et al. 2011; Lume 2018; Kazemzadeh Azad et al. 2019). This loading technique allows easy tracking of the exact load applied to the tube while the concrete infill acts as an internal restraint against inwards local buckling. In line with this, a frictionless contact condition was defined between the concrete infill and the tube in each model. The effect of friction was conservatively neglected in order to ensure that no part of the applied load was transferred to the concrete infill. Furthermore, a nodal adjustment technique was used in the filled models to ensure that the concrete outer surface will have the same shape as the inner surface of the imperfect steel tube.

2.2 Material behaviour

Both carbon steel and stainless steel tubes were considered in the present paper. The stress-strain curves used in the analyses are summarised in Fig. 2 which were obtained from previous studies on circular specimens. The plots are based on the coupon test results of O'Shea (1997) on mild carbon steel and Kazemzadeh Azad et al. (2019) on austenitic 304 stainless steel (Fig. 2a,b, respectively). Regarding Fig. 2a, it should be mentioned that the full extent of the material response was not reported in the original coupon test results of O'Shea, however, the available data was smoothly extrapolated in the present paper to converge to the values reported by him for the ultimate strength of the material. The corresponding properties for the materials are summarised in Table 1. In the table, the measured elastic modulus (E); yield stress (f_y), defined as the 0.2% proof stress; and ultimate stress (f_u) are reported.

Table 1 Properties of the materials used in the numerical models.

Material (Grade)*	Reference	E (GPa)	f_y (MPa)	f_u (MPa)
Mild CS	O'Shea (1997)	204.7	256	369
Austenitic SS (304)	Kazemzadeh Azad et al. (2019)	201.9	263	606

* CS: Carbon Steel; SS: Stainless Steel

The (engineering) stress-strain curves should first be converted to true stress versus true plastic strain (σ_{tr} - ε_{tr}^{pl}) data and then used as an input for the von Mises plasticity constitutive model in ABAQUS. Consequently, the datapoints designated with grey dots in Fig. 2 were converted to true stress and true plastic strain as follows:

$$\sigma_{tr} = \sigma(1+\varepsilon) \quad (1)$$

$$\varepsilon_{tr}^{pl} = \left[\ln(1+\varepsilon)\right] - \frac{\sigma_{tr}}{E} \quad (2)$$

For the concrete in filled models, elastic material properties were defined since the infill only acted as a restraining mechanism with no direct load-bearing role in the simulations (Kazemzadeh Azad et al. 2018; Huang et al. 2019). In line with this, a typical elastic modulus of 25 GPa and Poisson's ratio of 0.2 were considered in all the filled models for the concrete infill.

2.3 Initial imperfections

An important issue to be considered when investigating the local stability of circular sections is the introduction of initial geometrical imperfections in the FE models. The most commonly used approach is to introduce the shape of imperfections in the form of an eigenmode obtained from an eigenvalue analysis and to select the amplitude of imperfections based on a sensitivity analysis or recommendations available in the literature or codes of practice (Gardner and Nethercot 2004; Lai and Varma 2015). Such an approach is schematically illustrated in Fig. 3a.

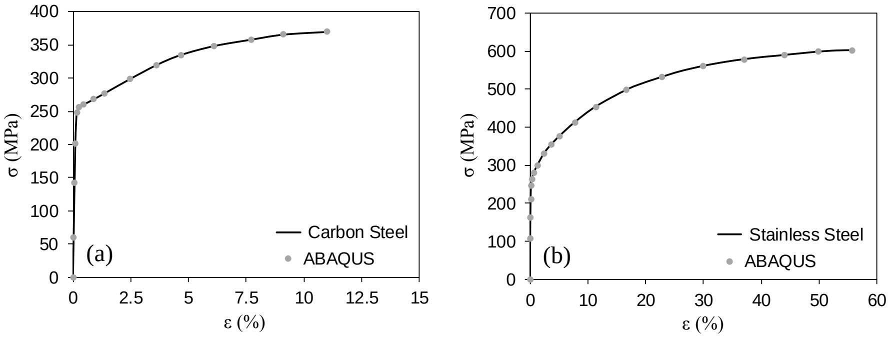

Fig. 2 Stress-strain curves based on the data reported by (a) O'Shea (1997) and (b) Kazemzadeh Azad et al. (2019).

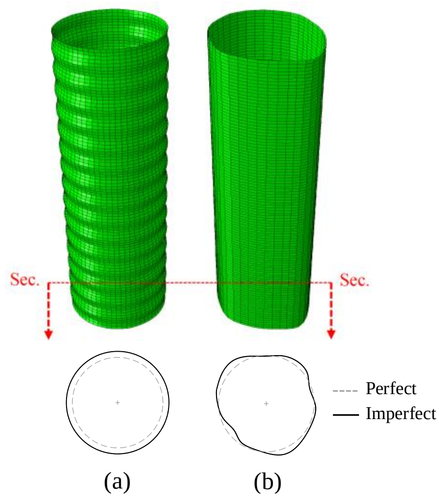

Fig. 3 Introducing imperfections using the (a) eigenvalue and (b) direct methods.

In the above-discussed method (referred to hereafter as the 'eigenvalue method'), when for instance the first eigenmode is selected as the shape of imperfection, as shown in Fig. 3a, axisymmetric outwards imperfections are typically introduced at critical sections. As a result, it might be argued that, in the case of unfilled sections, the selected eigenvalue method might trigger an outwards buckling mode which would not have happened if the actual imperfect shape of the section (with both inwards and outwards imperfections) had been introduced. In order to address this concern and to provide more conclusive findings, it was decided to analyse two set of models in the numerical investigation. In the first set, the eigenvalue method, which is the commonest approach in the literature, was used for the introduction of imperfections considering an amplitude of 0.01*t* as recommended in recent studies on circular sections (Zhao et al. 2016; Kazemzadeh Azad et al. 2019). In the second set, however, an alternative approach (referred to hereafter as the 'direct method') was followed where the imperfections were directly introduced in each model based on measurement results available in the literature as schematically depicted in Fig. 3b. The main aim of using the direct method was to see if the results would alter when a realistic imperfection pattern was used instead of an eigenvalue mode shape.

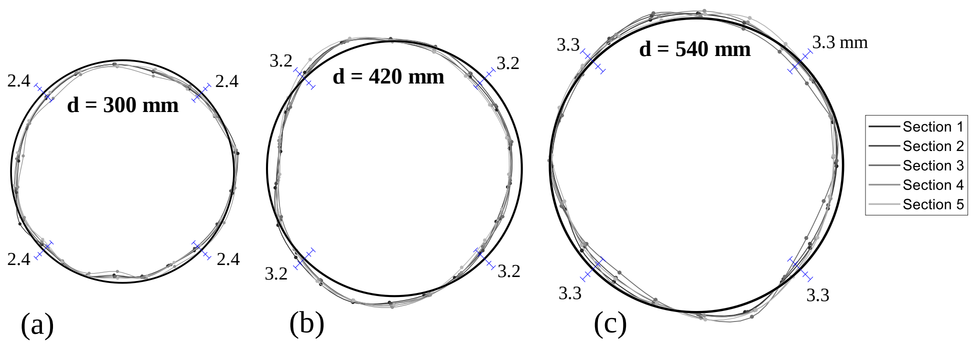

Fig. 4 Imperfection measurement results reported by Kazemzadeh Azad et al. (2019) for austenitic circular sections. Imperfections are magnified by a factor of 5.0.