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

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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).

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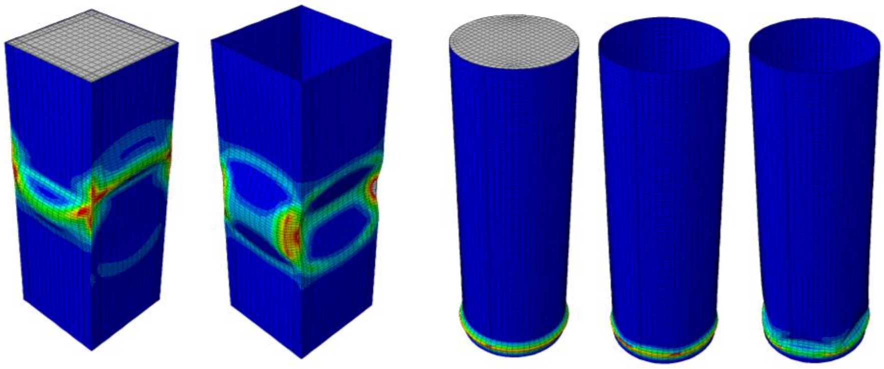

Fig. 1 Different local buckling modes for filled and hollow, box and circular sections.

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:

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

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

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.

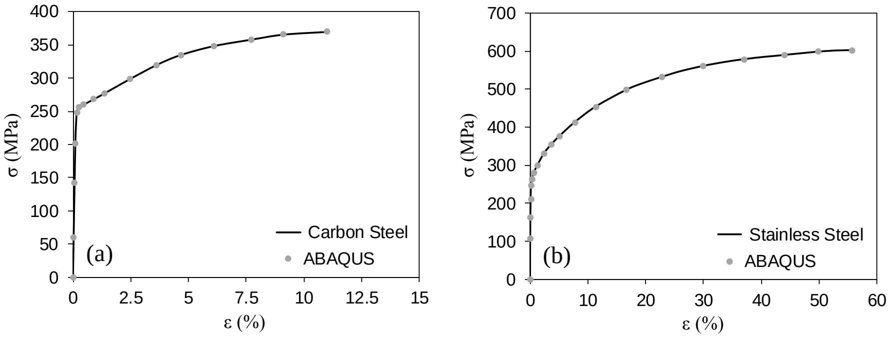

Fig. 2 Stress-strain curves based on the data reported by (a) O'Shea (1997) and (b) Kazemzadeh Azad et al. (2019).

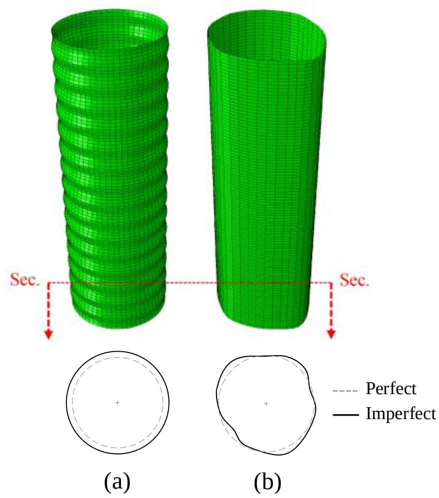

Fig. 3 Introducing imperfections using the (a) eigenvalue and (b) direct methods.

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.

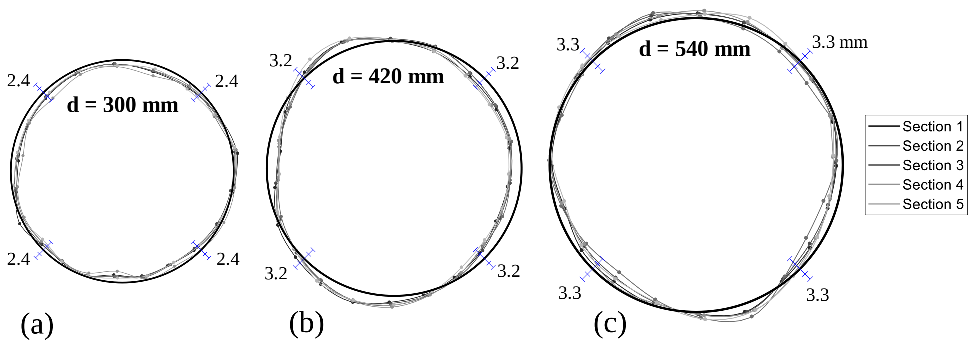

Fig. 4 Imperfection measurement results reported by Kazemzadeh Azad et al. (2019) for austenitic circular sections. Imperfections are magnified by a factor of 5.0.

Measurements of imperfections for circular sections are rather limited in the literature. In a recent study by Kazemzadeh Azad et al. (2019), a method was developed and used for measuring the actual shape of nominally circular sections using radial measurements. Details of the measurement method are not repeated here for brevity. In order to use the direct method in the second set of analyses, some of the measurement results reported by Kazemzadeh Azad et al. (2019) were used. As it is seen in Fig. 4, the actual shape of three austenitic stainless steel circular specimens fabricated from 3mm-thick plates was measured by these researchers at five sections along the length. Consequently, in the present paper, three base columns with nominal outer diameters of 300, 420, and 540 mm were first modelled in the FE software using the average of the measured shapes shown in the figure. Next, in order to extend the study to sections with other slenderness values, the plate thickness (t) was changed in each model. Geometrical details of the models are given in Section 3.

2.4 Residual stresses

Since the present study is of a comparative nature (investigating the local stability of hollow vs filled circular sections) the effect of residual stresses on the results was considered to be minimal and was neglected in the analyses. The verification results presented in the following section further substantiated that neglecting residual stresses did not adversely affect the outcome.

3. VERIFICATION AND DETAILS OF PARAMETRIC STUDY

Accuracy and applicability of the described finite element modelling approach was verified by comparing the numerical results with those reported in a number of experimental studies. In line with this, a total of 4 hollow and filled, carbon steel and stainless steel specimens were considered which were tested previously by O'Shea and Bridge (1997), Kazemzadeh Azad et al. (2019), and Uy et al. (2011). Details of the specimens are summarised in Table 2. Each specimen was modelled following the details outlined in Section 2.

The comparison between the obtained numerical and reported experimental results is presented in Fig. 5. In the figure, P is the axial resistance and u is the axial shortening of the specimen. As it is seen, the followed FE modelling procedure produced reasonable results when compared to the test results. Main characteristics of each test such as the initial stiffness, ultimate strength, and trend of axial response are resembled closely in the FE models.

Table 2 Specimens considered in the verification process.

Specimen ID*	Reference	Filled /Hollow	d (mm)	t (mm)	L (mm)	d/t
S20BS	O’Shea and Bridge (1997)	H	190	1.94	665	98
S20BSC	O’Shea and Bridge (1997)	F	190	1.94	657	98
H2-152	Uy et al. (2011)	H	152	1.60	450	95
A-C360	Kazemzadeh Azad et al. (2019)	F	360	3.00	1080	120

* For material details refer to Table 1 and Fig. 2.

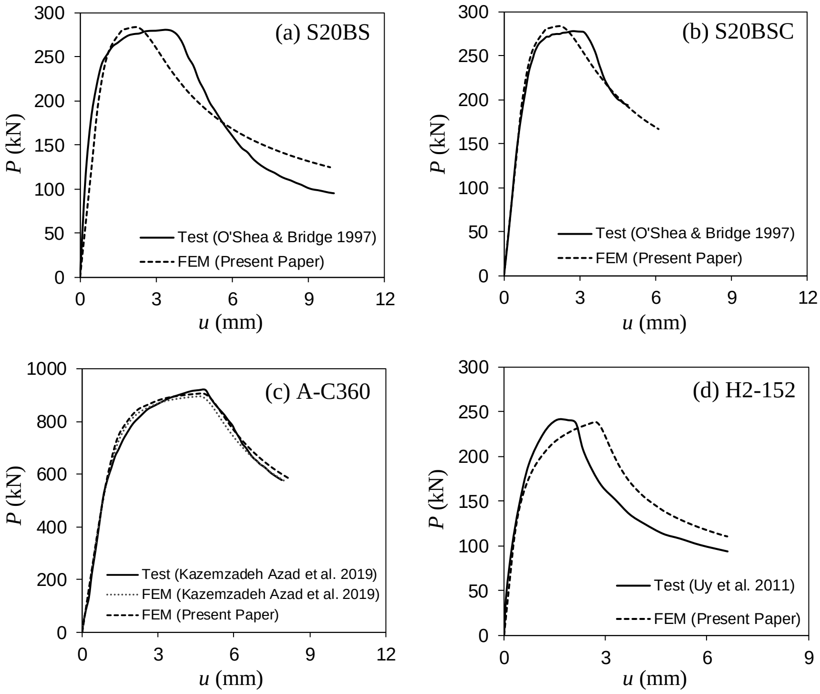

Fig. 5 Results of the verification of the FE modelling approach.

The effect of neglecting residual stresses is also depicted in Fig. 5e. In this figure, the FE results obtained in the present study (without residual stresses) are compared with the FE results reported in Kazemzadeh Azad et al. (2019) where residual stresses were explicitly included. The difference appears to be rather small.

Following the verification process, a parametric study was conducted to investigate in detail the role of concrete infill in the local buckling behaviour of circular sections. Details of the specimens investigated in the parametric study are presented in Table 3. As elaborated in Section 2.3, two methods for imposing initial imperfections were considered in the present paper. In line with this, the parametric study was conducted in two series, namely S1 and S2, as categorised in Table 3. In the first series (S1) the eigenvalue method (Fig. 3a) was used for the introduction of initial imperfections whereas in the second series (S2) the direct method (Fig. 3b) was utilised. For the S1 series, therefore, both carbon steel and stainless steel materials were considered using the stress-stress data presented in Fig. 2a and b, respectively. On the other hand, stainless steel material (Fig. 2b) was considered for the S2 series since, as explained in Section 2.3, the geometry of these specimens was based on the measurements of Kazemzadeh Azad et al. (2019) on austenitic circular columns. A wide range of dimeter-to-thickness (d/t) ratios (50 to 360) was covered in the parametric study as summarised in Table 3. In the S1 series, 2 mm and 10 mm thicknesses were considered in order to check whether tubes with similar d/t but different thicknesses would behave differently in terms of the effect of the concrete infill. The length of each specimen was set to 3d in order to focus on the local buckling behaviour (Uy et al. 2011).

Table 3 Specimens considered in the parametric study.

Series	*t* (mm)	Material*	Filled /Hollow	Imperfection Appl. Method	*d* (mm)	*L* (mm)	*d/t*
S1	2	CS & SS	F & H	Eigenvalue	100	300	50
		CS & SS	F & H	Eigenvalue	300	900	150
		CS & SS	F & H	Eigenvalue	600	1800	300
	10	CS & SS	F & H	Eigenvalue	500	1500	50
		CS & SS	F & H	Eigenvalue	1500	4500	150
		CS & SS	F & H	Eigenvalue	3000	9000	300
S2	1.5	SS	F & H	Direct	300	900	200
		SS	F & H	Direct	420	1260	280
		SS	F & H	Direct	540	1620	360
	3	SS	F & H	Direct	300	900	100
		SS	F & H	Direct	420	1260	140
		SS	F & H	Direct	540	1620	180

* CS: Carbon Steel (Fig. 2a); SS: Stainless Steel (Fig. 2b)

Each specimen was analysed twice, i.e. with and without the concrete infill. The naming convention used for the parametric study models includes details on the tube material (**C**arbon **S**teel/**S**tainless **S**teel), concrete infill (**H**ollow/**F**illed), tube geometry (Diameter and Thickness in mm), and utilised imperfection introduction approach (**E**igenvalue/**D**irect method). For instance, 'CS-H300-2-E' indicates a carbon steel hollow tube with a diameter of 300 mm and a thickness of 2 mm for which the initial imperfections are introduced using the eigenvalue method (Section 2.3). A total of 36 models were analysed and the obtained results are thoroughly discussed in the section that follows.

4. DISCUSSION

Typical failure modes observed during the analyses are depicted in Fig. 6. For filled circular sections, regardless of the material type, degree of slenderness, and the imperfection introduction method, the failure initiated in form of a ring-type uniform outwards bulging in one end of the specimen as shown in Fig. 6a. This was accompanied by a sudden drop in the axial resistance of the specimen as shown in Fig. 7a with a red dot for a representative case. With further loading, the outwards bulging was significantly magnified (Fig. 6b) while the column axial resistance decreased continuously. In a similar manner, for hollow circular sections with low or medium slenderness ratios, outwards bulging again initiated the failure of the specimen (Fig. 6c) which was exacerbated with further shortening of the column (Fig. 6d). A typical axial response for such specimens is plotted in Fig. 7b.

An important issue was however noted when investigating the response of hollow sections with high slenderness values (e.g. d/t > 150). As shown in Fig. 7c, for such

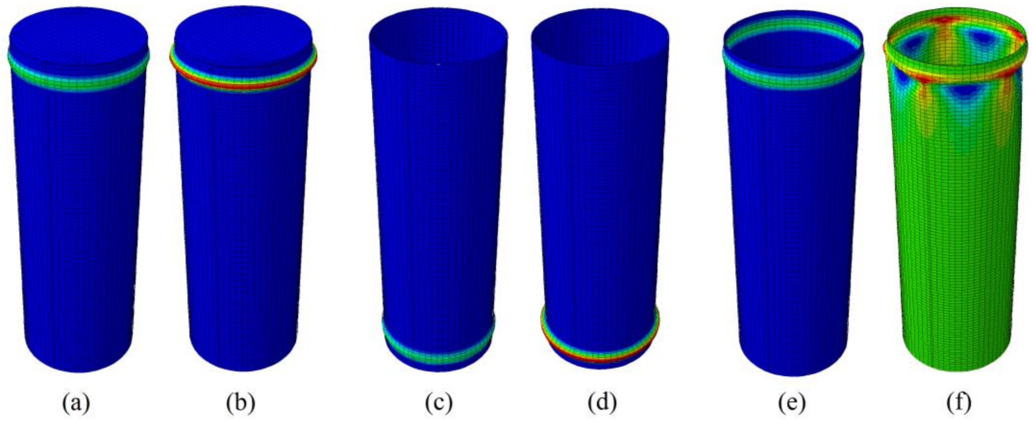

Fig. 6 Typical progress of failure for (a-b) filled sections, (c-d) hollow sections with low slenderness, and (e-f) hollow sections with high slenderness. Contours of radial displacement are shown.

hollow specimens, the ultimate axial capacity was again reached when a ring-type local buckling mode was initiated (Fig. 6e). However, with further shortening, in some cases, a mode change occurred in the deformed shape where parts of the section located underneath the buckling ring started to fold towards to inside of the column as shown in Fig. 6f yielding a diamond-shaped form. The effect of this mode change was noticed on the axial response of some specimens in the form of an increase in the stiffness of the descending branch (Fig. 7c).

Very similar results were found from carbon steel and stainless steel models. Furthermore, the impact of introducing initial imperfections using two different methods (i.e. eigenvalue and direct as discussed in Section 2.3) was found to be minimal. Results suggested that the post-local buckling reserve strength of filled and hollow circular sections is negligible since both section types lost their axial resistance immediately after local buckling.

The most important aim of the present study was to investigate whether the presence of concrete infill can increase the local buckling capacity of circular sections. Results of the parametric study are summarised in Table 4. The table clearly suggests that filling a carbon steel or stainless steel circular section with concrete does not lead

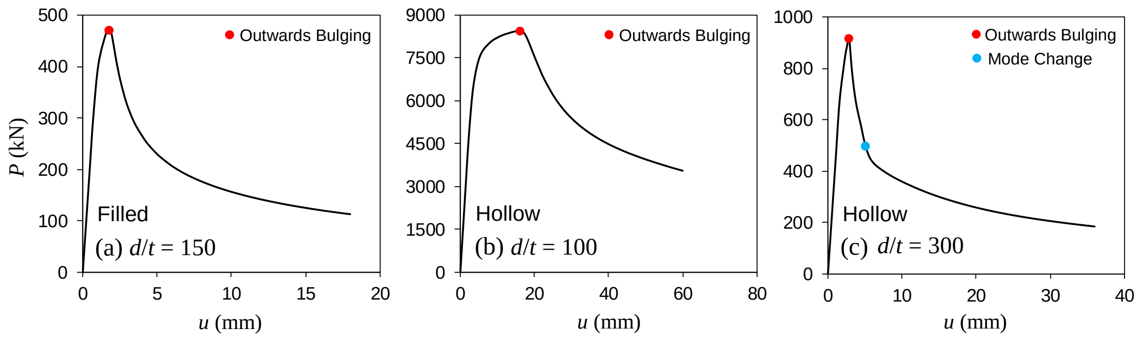

Fig. 7 Typical axial responses for (a) filled sections, (b) hollow sections with low slenderness, and (c) hollow sections with high slenderness.

Table 4 Results of the parametric study.

Series	Specimen ID	P_u (Hollow) (kN)	P_u (Filled) (kN)
S1	SS-H(F)100-2-E	193.73	193.72
	SS-H(F)300-2-E	487.92	487.89
	SS-H(F)600-2-E	914.84	914.91
	CS-H(F)100-2-E	173.62	173.82
	CS-H(F)300-2-E	470.14	470.09
	CS-H(F)600-2-E	916.23	916.23
	SS-H(F)500-10-E	4843.13	4843.00
	SS-H(F)1500-10-E	12184.90	12184.90
	SS-H(F)3000-10-E	22843.20	22843.62
	CS-H(F)500-10-E	4340.40	4340.38
	CS-H(F)1500-10-E	11752.91	11752.90
	CS-H(F)3000-10-E	22900.10	22901.05
S2	SS-H(F)300-1.5-D	355.43	355.44
	SS-H(F)420-1.5-D	478.99	477.85
	SS-H(F)540-1.5-D	604.45	610.05
	SS-H(F)300-3-D	791.08	791.50
	SS-H(F)420-3-D	1038.67	1038.64
	SS-H(F)540-3-D	1292.89	1295.25

to any increase in its local buckling strength. In all the studied specimens, the filled and hollow sections failed at almost the same axial load level by forming a ring-type local buckling shape. The same conclusion was reached considering the results of both parametric study series (S1 and S2) which incorporated different initial imperfection modelling techniques. The difference between the local buckling capacities of filled and hollow sections did not exceed 1% in all the studied circular columns.

As representatives, the obtained axial responses for three of the studied circular columns are plotted in Fig. 8 considering hollow and filled conditions. As it is seen in Fig. 8a, for the case of circular sections with low or medium d/t values, the axial response for the hollow and filled cases are almost identical. As discussed above, for such sections, the buckling mode in both the hollow and filled cases is the same with no further mode change in the hollow case even after significant deformations (Fig. 6c-d). The behaviour is however somewhat different for the case of circular sections with high slenderness values. As it can be seen in Fig. 8b-c, in such columns the behaviour is again very similar until the ultimate load when a ring-type local buckling was observed in both the hollow and filled cases. However, after this point, the axial responses for the two cases start to deviate from one another. The reason is of course the above-discussed mode change that occurs in the hollow case where the ring-type outwards bulging changes to a diamond-shaped buckling mode with inwards and outwards components (Fig. 6e-f). Based on Fig. 8b-c, during the initial stages of this mode change, the axial resistance of the hollow section would fall below that of the filled section, however, with further axial deformation of the column, the hollow section could exhibit a higher resistance compared to the filled case.

On the basis of the analysis results, the authors believe that the local buckling strength of hollow and filled circular sections are in fact similar. In other words, although filling a circular section with concrete will significantly increase its composite strength and stiffness, from the local buckling point of view, it does not have any significant positive effects. Although the local buckling mode can subsequently change in highly slender hollow circular sections (Fig. 6e-f), this change happens later and only after the ultimate load has been achieved. In the studied models, regardless of the occurrence of the mode change, the initial ring-type outwards bulging always marked the ultimate load in both the hollow and filled specimens.

Acknowledging that the concrete infill is not effective in increasing the local buckling strength of circular sections will indeed affect the codified slenderness limits for these members. As noted earlier, in most international design standards, a significantly higher (~40%) axial slenderness limit is used for filled circular sections compared to unfilled circular sections on the basis of the concept that filling such sections with concrete will enhance their local buckling strength. Results of the numerical investigation of the present study as well as a number of tests in the literature (O'Shea and Bridge 1997; Johansson and Gylltoft 2002; Uy et al. 2011) do not support this concept. Therefore, it is advisable to revisit the codified axial slenderness limits for hollow and circular sections. The authors believe that defining a single axial slenderness limit for both hollow and filled circular sections would be more reasonable as their local buckling behaviour is indeed very similar. It might be beneficial to consider the previous test results on both hollow and (unbonded) filled circular sections simultaneously when defining such a unified axial slenderness limit. Answering the question of ‘whether to decrease the slenderness limit of filled circular sections or to increase that of the hollow circular sections’ requires further investigation and is out of the scope of the present paper.

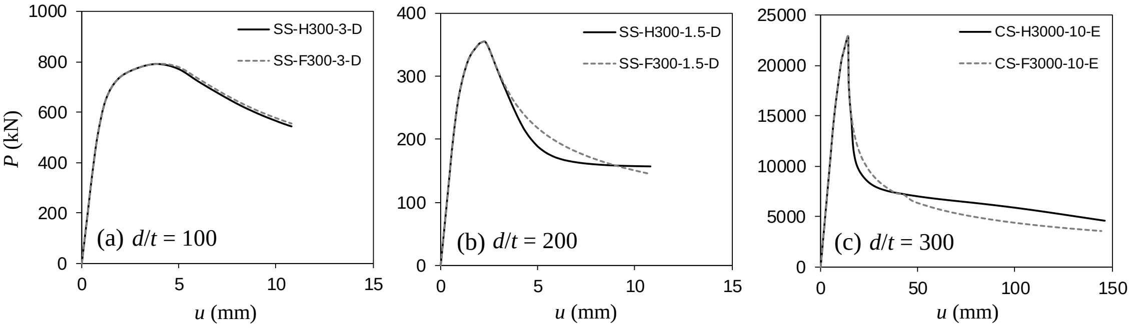

Fig. 8 Axial response obtained for some of the studied hollow and filled sections.

5. CONCLUSIONS

A detailed numerical investigation was conducted in the present paper to clarify the role of concrete infill in the local buckling strength and behaviour of circular sections. Results of a parametric study on hollow and filled, carbon steel and stainless steel circular sections with d/t values between 50 and 360 and considering two initial imperfection introduction techniques suggested that filling circular sections with concrete does not lead to any notable increase in their local buckling capacity. The difference between the local buckling capacities of filled and hollow cases did not exceed 1% in all the studied circular columns. In both cases, a ring-type outwards bulging caused a sudden reduction in the axial resistance of the section with no post-local buckling reserve strength. Although a subsequent change in the local buckling mode was observed in highly slender hollow circular sections, the mode change occurred only after the ultimate load was achieved.

Based on the outcome of the parametric study, it is advisable to revisit the axial slenderness limits stipulated by international design standards where typically a higher limit is defined for filled circular sections compared to hollow circular sections. Considering the close similarities between the local buckling responses of hollow and filled circular sections, defining a single, unified axial slenderness limit for both the hollow and filled cases appears to be more reasonable.

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