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Determination of geometrical imperfection models in finite element analysis of structural steel hollow sections under cyclic axial loading

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Global and local imperfections are required to capture accurate buckling loads and overall structural behaviour of axially loaded structural steel hollow sections in finite element (FE) models. In this paper, three methods of geometrical imperfections are considered for square and rectangular structural steel hollow sections: (i) creating the profile of the brace using a half sine wave, (ii) applying an equivalent notional lateral load at mid-length, and (iii) combining sinusoidal local imperfections with an equivalent notional lateral load for global imperfections. When modelling the initial shape of brace members with global imperfection at mid-length of the magnitude used to establish the European buckling curves (L/1000, where L is the length of the brace member), it was found that the equivalent notional lateral load methodology could best predict the buckling capacity of brace members when compared to physical test data and European buckling curves. However, both methodologies neglect the effect of local imperfection on the initial buckling loads. When it was included by generating a continuous sinusoidal wave along the member length, it did not affect the initial buckling loads, but gave a more overall representative behaviour of the brace members.

The FE model is then validated using sixteen cyclic tests for brace members. The FE results are found to match the physical tests values relatively well. In other words, when comparing the ratio of yield force, buckling resistance, and total energy dissipated estimated from the FE model to the measured values in physical tests, the mean values are found to be 1.04, 0.99 and 1.24, respectively, with a coefficient of variation of 0.07, 0.07 and 0.17, respectively.

1. Introduction

Geometrical imperfections are one of the largest sources of uncertainty when building numerical models of structural elements. These imperfections can be any irregularity that deviates from the idealized geometry. From the mechanical aspect, they are the geometrical residuals that fail to obtain integration into a perfect shape due to the fabrication process. The residuals that persist along the length of the member after fabrication are considered as global imperfections and those along the section as local imperfections, in addition to the stresses that are usually locked within geometry of a member. These imperfections should not be confused with framing imperfections, which are caused by construction activity. The effects of imperfections have been successfully incorporated by design standards within the formula given for design buckling curves, particularly, European buckling curves by Eurocode 3 (EC3) [1]. However, EC3 [1] does not give guidance on how to model the imperfections when modelling structural elements in Finite Element (FE) models. In this context, the authors carried out a preliminary imperfection sensitivity study [2] to investigate the effects of global and local imperfection models on the structural behaviour of steel hollow sections under static monotonic compressive axial loading. The study was limited to one brace section size, but did identify potential suitable ranges of imperfection amplitudes for the numerical modelling of hot-rolled tubular brace member. The current paper builds on this work through a parametric study to choose the most suitable method to be used to represent global and local imperfections of square and rectangular thin-walled tubular sections under quasi static cyclic tests. The approach has been informed by past research on how imperfections have been incorporated into steel section models for thin-walled members, which is summarised in Table 1. The studies are categorised into (i) the study type (either experimental or numerical: 1D, 2D, and 3D), (ii) structural component/classification (which is sub-categorised into structure: open section (OS) and closed section (CLS), geometry: symmetry (SY), one-line symmetry (LS), and asymmetry (AS), forming route: hot-rolled (HR) and cold formed (CF), material: carbon steel (CS) and stainless steel (SS)), (iii) section profile, (iv) cross-section configuration, and (v) initial imperfection (which is categorised into shape and amplitude of imperfection). As shown in

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Table 1
A summary of the studies conducted previously in the context of initial geometric imperfections in relation to thin-walled sections.

Author	Study type				Structural component/classification										Cross-section configuration	Initial imperfection used/proposed		
	Physical test	Numerical			Structure	Geometry				Forming		Material		Profile				
		1D	2D	3D	OS	CLS	SY	LS	AS	HR	CF	CS	SS			Shape	Amplitude	
Dawson & Walker [4]	✓				✓		✓				✓	✓			Perfectly square plate	–	ω_1 = not found $\omega_2/t = \alpha\ (\sigma_y/\sigma_{cr})^{0.5}$	*a
Kayvani & Barzegar [5]			✓			✓	✓					✓			D/t 33, (for brace) D/t 50, (for portal column)	Out-of-straightness	ω_1 = not found ω_2 = not found	*b
Schafer, Pekož [6]	✓				✓			✓			✓	✓			Lipped channel section	Eigen modes	ω_1 = not found ω_2 = 0.006w	
Gardner et al. [7]	✓					✓	✓			✓	✓	✓			RHS 100 × 100 × 4, 60 × 60 × 3, 60 × 40 × 4, 40 × 40 × 4, 40 × 40 × 3	–	ω_1 = not found $\omega_2/t = \beta\ (\sigma_y/\sigma_{cr})^{0.5}$	*c
Kaitila [8]				✓		✓		✓			✓	✓			C 100 × 40 × 15	Eigen modes	ω_1^{*a} = 0.2%L ω_2 = h/200	*d
Elchalakani et al. [9]	✓					✓	✓				✓	✓			CHS 19 < D/t < 56,	Out-of-straightness	ω_1 = 0.032%L, $\omega_2 = 0$	
Dubina & Ungureanu [10]				✓	✓			✓			✓	✓			C 815 × 37 × 1.5, 1315 × 37 × 1.5 CL 815 × 37 × 1.5, 1316 × 37 × 1.5	Eigen modes	ω_1 = 0.1%L ω_2 = from [6]	
Mamaghani et al. [11]		✓				✓	✓			✓		✓			S ≅ 15 × ≅ 15 CHS 15.42 ≤D/t ≤49.56 RHS 150 × 110 × 4.5	Half sine wave	ω_1 = 0.1%L $\omega_2 = 0$	
Uriz et al. [12]		✓			✓	✓	✓		✓		✓	✓			CHS D/t = 11.2 RHS 100 × 100 × 6, 100 × 100 × 3 W 200 × 500, 150 × 500 AA 150 × 87.5 × 9 150 × 500	V-shape	0.01%L < ω_1 < 3%L $\omega_2 = 0$	
Fell [13]	✓			✓	✓	✓	✓				✓	✓			W 300 × 400 × 5.5 CHS D/t = 16.2 & 21.6 RHS 100 × 100 × 6, 100 × 100 × 9	Eigen modes	ω_1 = 0.1%L, ω_2 = from [6].	
Salawdeh & Goggins [14]			✓			✓	✓			✓	✓	✓	✓		RHS 40 × 40 × 2.5, 20 × 20 × 2, 50 × 25 × 2.5, 60 × 60 × 3, 40 × 40 × 3, 40 × 40 × 4, 60 × 40 × 3	V-shape	0.1%L < ω_1 < 1.0%L $\omega_2 = 0$	
Dicleli & Mehta [15]			✓			✓	✓			✓		✓			RHS 102 × 102 × 12.7	V-shape	$\omega_1 = \frac{M_{pb}}{P_b}\left(1-\frac{P_b L^2}{12EI}\right)$ $\omega_2 = 0$	*e
Dicleli & Calik [16]			✓		✓	✓	✓	✓	✓	✓	✓	✓			W 200 × 500, 150 × 625, 150 × 500, 150 × 388,C 200 × 288,T 200 × 563 RHS 20 × 20 × 2, 40 × 40 × 2.5,CHS 100 × 6	Half sine wave	$\omega_1 = \frac{M_{pb}}{P_b\left(1+\frac{P_b L^2}{8EI\left(1-\frac{P_b L^2}{\pi^2 EI}\right)}\right)}$	

[a]ω_1 = amplitude for global imperfection, ω_2 = amplitude for local imperfection, σ_y = yield strength, σ_{cr} is critical buckling stress, α is coefficient to be determined experimentally. *bD stands for diameter of circular section and t for thickness of tube. *cβ = 0.028 and 0.034 for hot-rolled and cold formed sections, respectively, cross-section classification as (depth × width × thickness). *dL = length of member, h is the height of web. *e$M_{pb}$is plastic moment at buckling load, P_b, E is the modulus of elasticity, and I is the moment of inertia.