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Full slenderness range DSM approach for stainless steel hollow cross-section columns and beam-columns

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ABSTRACT

The behaviour of austenitic, ferritic and duplex stainless steel Rectangular and Square Hollow Section members subjected to compression and combined loading is investigated in this paper. A full slenderness range Direct Strength Method (DSM) approach is proposed based on experimental results and numerical strengths obtained from FE parametric studies. The method accounts for local buckling effects and enhanced material properties are also incorporated for those members stable enough to allow partial yielding of the cross-sections. The proposed method is based on strength curves previously provided for cross-sections although additional limitations have been adopted. The DSM approach for columns is based on existing buckling curves and provides accurate resistance predictions for slender and stocky cross-sections. The proposed DSM approach for beam-columns also improves capacity predictions for stocky and slender cross-sections obtained from the traditional methods for different bending moment distributions. This is attributed to the fact that the beam-column behaviour is directly calculated with a unique strength curve, considering the member and section slendernesses based on the elastic instabilities of the section subjected to the actual stress distribution instead of calculating the compressive and flexural strengths independently and combining these through an interaction equation, as is the traditional uncoupled approach. Finally, a reliability study of the full slenderness range DSM approach is presented to determine resistance factors for the different stainless steel grades columns and beam-columns.

1. Introduction

The development of accurate and simple design guidance for stainless steel structures is essential for the increased use of this corrosion resistant material, which is also characterized by excellent mechanical properties, excellent strength retention at elevated temperature and pleasing aesthetic appearance. Since most stainless steel grades are characterized by a nonlinear stress-strain relationship with a pronounced gradual yielding, efficient strength and stability design provisions need to include strain hardening effects instead of directly extending the expressions codified for carbon steel structures which are premised on steels with an extended yield plateau.

Commonly used in construction as cold-formed elements, stainless steel structures exhibit slender cross-sections subjected to local and distortional buckling modes. Stainless steel standards (e.g. EN1993-1-4 [1], AS/NZS4673 [2], SEI/ASCE 8-02 [3]) have traditionally accounted for these buckling effects by using the effective width method, resulting in tedious and iterative calculations. Instability effects can be easily considered through the strength curves in the Direct Strength Method (DSM), developed by Schafer and Pekoz [4], with the use of software to determine elastic buckling loads. Although the method has been implemented in the North American AISI-S100-12 Specification [5] for carbon steel structures and new strength curves have been proposed to adapt the DSM to stainless steel cross-sections (Becque et al. [6], Niu et al. [7], Huang and Young [8]), the DSM has not yet been included in stainless steel standards. Rossi and Rasmussen [9] proposed a full slenderness range approach which considers strain-hardening effects in the DSM formulation for stainless steel sections in compression, improving the capacity predictions for stocky cross-sections. Arrayago et al. [11] demonstrated the applicability of this approach for different loading conditions such as bending and combined loading. Based on the DSM approach proposed by Rasmussen [10] for beam-columns, the full slenderness range approach was also extended to the combined loading behaviour of stainless steel Square and Rectangular Hollow Sections (SHS and RHS) cross-sections by [11].

The study presented in this paper is an extension of the research work presented in [11] for SHS and RHS cross-sections to austenitic, ferritic and duplex stainless steel members subjected to compression and combined loading. The extension from section capacity to member capacity relies on an extensive experimental database and additional finite element parametric studies. The full slenderness range DSM

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List of symbols

Latin upper case letters

A	Gross-section area
A_{eff}	Effective cross-section area
B	Width of the cross-section
C_m	Equivalent moment factor
C_y	Compression strain factor
D_1, D_2, D_3	Parameters for beam-column interaction
E	Young's modulus
E_t	Tangent modulus
L	Length of the member
M	Bending moment
M_{crl}	Critical elastic local buckling moment
M_n	Bending moment capacity of the cross-section accounting for inelastic stress distribution
M_{ne}	Bending moment strength of fully effective members
M_{nl}	Nominal bending moment resistance
M_{ocr}	Bending moment causing local buckling under combined loading conditions
M_{on}	Bending moment strength causing failure under combined loading conditions
M_{one}	Bending moment strength of fully effective members in combined loading
M_p	Full plastic moment capacity
M_y	First yielding bending moment
P	Compression axial load
P_{AS}	Predicted flexural buckling resistance using the AS/NZS4673 buckling curves
P_{cre}	Minimum of the elastic flexural, torsional and flexural-torsional buckling load
P_{crl}	Critical elastic local buckling load under compression
$P_{DSM,AS}$	Predicted flexural buckling resistance using the DSM approach with buckling curves in AS/NZS4673
$P_{DSM,EN}$	Predicted flexural buckling resistance using the DSM approach with buckling curves in EN1993-1-4
P_{EN}	Predicted flexural buckling resistance using EN1993-1-4 buckling curves
P_{enh_ne}	Flexural buckling resistance of columns accounting for enhanced material properties
P_{ne}	Flexural buckling resistance of the fully effective cross-section
P_{nl}	Cross-section or member resistance under compression
P_{ocr}	Compression load causing local buckling under combined loading conditions
P_{on}	Compression strength causing failure under combined loading conditions
P_{one}	Compression strength of fully effective members in combined loading
$P_{u,exp.}$, $P_{u,FE}$	Experimental or numerical column strength
P_y	Cross-section squash load
R_0	Gross-section capacity of the cross-section or member
R_{crl}	Critical elastic local buckling resistance
R_{enh_nl}	Nominal resistance of the cross-section or member accounting for enhanced material properties
R_{nl}	Nominal resistance of the cross-section or member

Latin lower case letters

$d_{u,exp.}$, $d_{u,FE}$	Experimental or numerical lateral deflections
e	Load eccentricity
e_{eq}	Equivalent load eccentricity
k	Interaction factor for beam-column checks
m	Second strain hardening exponent
n	First strain hardening exponent
$r_{AS/NZS}$	Predicted beam-column resistance parameter using the DSM approach interaction factor in AS/NZS4673
r_{crl}	Local buckling behaviour parameter for beam-columns
$r_{EN1\text{-}1}$	Predicted beam-column resistance parameter using the DSM approach interaction factor in EN1993-1-1
$r_{EN1\text{-}4}$	Predicted beam-column resistance parameter using the DSM approach interaction factor in EN1993-1-4
r_{enh_nl}	Nominal resistance parameter for beam-columns accounting for enhanced material properties
r_{ne}	Resistance parameter corresponding to fully effective member strength
r_u	Resistance parameter of experimental and numerical beam-columns
r_y	Resistance parameter corresponding to the yielding of cross-sections subjected to combined loading
r_{Zhao}	Predicted beam-column resistance parameter using the DSM approach interaction factor by Zhao et al. [35]

Greek lower case letters

α	Imperfection factor for flexural buckling
β	Factor for flexural buckling in AS/NZS4673; reliability index
β_0	Target reliability index
χ	Reduction factor for flexural buckling
ε_u	Ultimate strain
ε_y	Yield strain
ϕ	Value to determine the reduction factor χ
ϕ_c	Resistance factor for columns
γ_{M1}	Partial safety factor for resistance of members to instability
λ_0	Limiting slenderness for flexural buckling
λ_1	Factor for flexural buckling in AS/NZS4673
λ_c	Member slenderness
λ_l	Cross-section/local slenderness
λ_{lim}	Limiting slenderness for local buckling in DSM
λ_n	Generalized slenderness for beam-columns
ρ	Reduction factor for local buckling in EWM
$\sigma_{0.2}$	Proof stress corresponding to the 0.2% plastic strain
σ_{enh_nl}	Stress at which the column fails
σ_u	Tensile strength
Ψ	Ratio of moments in segment

approach is evaluated for members in compression and the applicability of the method proposed in [10] for beam-columns is also assessed. Results are compared with those obtained using the design provisions based on the effective width method and the most appropriate buckling curves and interaction expressions are identified.

2. Direct Strength Method

The Direct Strength Method (DSM) is a design procedure developed by Schafer and Pekoz [4] which allows the consideration of local, distortional and member buckling effects in an easy and consistent manner as an alternative to effective width calculations. The method is based on strength curves which depend on the buckling slenderness for the three modes measuring the susceptibility of the member to local, distortional and member buckling, and uses software to determine elastic buckling loads. For SHS and RHS, only the local and member buckling modes are relevant. Although the DSM approach is currently included in the AISI-S100-12 Specification [5]