



# Short-to-intermediate slender pin-ended cold-formed steel equal-leg angle columns: Experimental investigation, numerical simulations and DSM design

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## ABSTRACT

Angles exhibit a complex structural behaviour, responsible for the fact that, in the current North American Specification for Cold-Formed Steel Structures, short-to-intermediate equal-leg angle columns are (i) not yet pre-qualified for the Direct Strength Method (DSM) design and (ii) excluded from the application of the LFRD resistance factor  $\phi = 0.85$ , valid for all other cold-formed steel compression members. Recently, the specific behavioural features exhibited by the above angle columns were incorporated into the proposal of a novel DSM-based design approach, for both fixed-ended and pin-ended columns, and it was shown that this added rationality goes along with quite accurate and reliable failure load predictions. However, the investigation leading to this design proposal also unveiled that there are no available experimental failure loads of slender pin-ended columns with intermediate-to-high slenderness values, which implied that the design procedure was validated for such columns exclusively on the basis of numerical failure loads. The research work reported in this paper provides a contribution towards filling this gap, since it mainly consists of an experimental study, carried out at the Federal University of Rio de Janeiro, on the behaviour and collapse of short-to-intermediate slender pin-ended cold-formed steel equal-leg angle columns. After addressing the selection of the columns to be tested, the experimental set-up and test procedure are described in detail and the results obtained are presented and discussed. Such results involve (i) initial imperfection measurements, (ii) equilibrium paths relating the applied load to key column displacements, (iii) deformed configurations (including the collapse mode) and (iv) failure loads. Next, those same experimental results are used to validate a shell finite model previously developed by the authors, which is subsequently employed to obtain additional numerical failure load data concerning the pin-ended angle columns under scrutiny. Then, attention is turned to assessing the merits of the novel design approach. The comparison between the experimental and numerical values obtained in this work and their estimates provided by the design equations shows a very good correlation, perfectly in line with that observed in the recent studies available in the literature – this means that the validation and calibration of the above design approach may be deemed (successfully) completed. Finally, the paper closes with the presentation and assessment of small alterations to the existing design expressions, aimed at improving their accuracy and rationality, thus paving the way towards codification in the near future.

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## 1. Introduction

In spite of their geometrical simplicity, angle members, namely columns, are characterised by an extremely complex structural response, which has defied researchers and engineers for quite a long time. Although the non-linear behaviour, strength and design

of angle columns has attracted a lot of attention for decades (e.g., [1–14]), it was not until the last few years that the mechanics underlying the column non-linear behaviour were unveiled and properly understood [15,16] and it became clear why the current North American Specification (NAS) for Cold-Formed Steel Structures [17] still excludes short-to-intermediate equal-leg angle columns from (i) the pre-qualification for the Direct Strength Method (DSM) design and (ii) the application of the LFRD resistance factor  $\phi = 0.85$ , valid for all other cold-formed steel

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## Nomenclature

### List of symbols

|            |                                                      |                 |                                                     |
|------------|------------------------------------------------------|-----------------|-----------------------------------------------------|
| $A$        | cross-section area                                   | $G$             | shear modulus                                       |
| $b$        | leg width                                            | $L$             | nominal length                                      |
| $d_H$      | “horizontal” DT measurement                          | $L_0$           | measured length                                     |
| $d_M$      | translation due to major-axis flexure                | $P_{bt}$        | torsional buckling load                             |
| $d_m$      | translation due to minor-axis flexure                | $P_{cr}$        | critical buckling load                              |
| $d_V$      | “vertical” DT measurement                            | $P_{cr,ft}$     | flexural-torsional buckling loads                   |
| $E$        | young’s modulus                                      | $P_n$           | predicted failure load                              |
| $f_{bf}$   | major-axis flexural buckling stress                  | $P_{u,Exp}$     | experimental failure load                           |
| $f_{bt}$   | torsional buckling stresses                          | $P_{u,Num}$     | numerical failure load                              |
| $f_{cre}$  | minor-axis flexural buckling stress                  | $P_y$           | squash load                                         |
| $f_{crft}$ | major-axis flexural–torsional buckling stresses      | $r_i$           | internal bending radius                             |
| $f_{ne}$   | nominal strength against minor-axis flexural failure | $t$             | wall thickness                                      |
| $f_{nfte}$ | nominal strength against interactive failure         | $\phi$          | LRFD resistance factor                              |
| $f_u$      | ultimate stress                                      | $\lambda_c$     | minor-axis flexural (global) slenderness            |
| $f_y$      | yield stress                                         | $\lambda_{fte}$ | flexural-torsional slenderness (based on $f_{ne}$ ) |

compression members. It was found that, although such columns buckle in flexural–torsional modes associated with a critical load plateau, the corresponding post-critical strength reserve changes considerably along that same plateau, thus affecting significantly the column failure load. Moreover, there was also clear numerical evidence that the failure of most angle columns stems from the interaction between two global instabilities, namely major-axis flexural torsional and minor-axis flexural buckling, a rather unique fully global coupling phenomenon. Based on these findings, Dinis and Camotim [18] very recently developed, validated and proposed a novel rational procedure for the DSM design of equal-leg angle columns with short-to-intermediate lengths, which is valid for both pin-ended and fixed-ended support conditions and was shown to yield quite accurate and reliable failure load predictions. At this stage, it is worth noting that, in the context of angle-columns, the designation “pin-ended” stands for (i) pinned supports concerning minor-axis flexure, (ii) fixed supports concerning major-axis flexure and (iii) fully prevented torsional rotations and (secondary) warping – physically speaking, the end cross-sections are attached to rigid plates resting on cylindrical hinges oriented along the minor-axis. However, the investigation leading to this design proposal also exposed the unavailability of experimental failure loads concerning slender pin-ended columns, thus meaning that the validation procedure for such columns involved exclusively numerical failure loads in the intermediate-to-high slenderness range.

The main objective of this work is to fill the gap identified in the previous paragraph, by reporting an experimental study carried out at the Federal University of Rio de Janeiro and concerning short-to-intermediate slender pin-ended cold-formed steel equal-leg angle columns. After presenting a brief overview of the DSM procedure proposed in [18], the paper addresses the careful selection of the columns to be tested (and also analysed numerically by means of shell finite element simulations), describes in some detail the experimental set-up and procedure employed, and presents and discusses the results obtained. Such experimental results consist of (i) initial imperfection measurements, (ii) equilibrium paths relating the applied load to key column displacements, (iii) deformed configurations (including the collapse modes) and (iv) failure loads. Next, those same experimental results are used to validate a shell finite model previously developed by the authors, which is subsequently employed to obtain additional numerical failure load data concerning the pin-ended angle columns under

scrutiny, but covering also the small and small-to-intermediate slenderness ranges. Then, attention is turned to assessing the merits of the aforementioned novel DSM design approach. The comparison between the failure load estimates provided by the appropriate strength equations and the experimental and numerical values obtained in this work shows a very good correlation, qualitatively similar to that observed earlier for all the other columns, which means that the validation and calibration of the above design approach may be deemed (successfully) completed. Finally, the paper closes with the presentation and assessment of a few small alterations to the existing design expressions, aimed at improving their accuracy and rationality, thus paving the way towards a proposal for codification that will be made in the near future.

## 2. Overview of the novel DSM design approach for angle columns

As mentioned above, Dinis and Camotim [18] have recently developed, validated and proposed a novel rational DSM-based procedure for the design of thin-walled cold-formed steel fixed-ended and pin-ended equal-leg angle columns with short-to-intermediate lengths, which was shown to yield quite accurate and reliable failure load predictions. The main features of this design approach are the following:

- (i) It is based on the fact that short-to-intermediate angle columns fail in interactive modes combining major-axis flexural-torsional and minor-axis flexural deformations.
- (ii) It involves the use of (ii<sub>1</sub>) the currently codified DSM global design curve and (ii<sub>2</sub>) a set of genuine flexural-torsional strength curves, developed for columns with minor-axis bending fully prevented.
- (iii) The above flexural-torsional curves make it possible to capture the progressive erosion of the column post-critical strength as its length increases within the  $P_{cr}(L)$  curve plateau.
- (iv) The effective centroid shift effects, strongly affecting the pin-ended column failure loads (not the fixed-ended ones), are included in the design approach through a parameter  $\beta$ , which must also reflect the change in column flexural-torsional behaviour along the length (within the  $P_{cr}(L)$  curve plateau).

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