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# Strength, interactive failure and design of web-stiffened lipped channel columns exhibiting distortional buckling

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ABSTRACT

The paper reports experimental and numerical results concerning the post-buckling behaviour, strength and failure of fixed-ended cold-formed steel web-stiffened lipped channel columns that buckle in distortional modes. The experimental results, obtained from the tests carried out at The University of Hong Kong, (i) include initial imperfection measurements, equilibrium paths and failure loads and modes, and (ii) provide evidence of the occurrence of flange-triggered local-distortional interaction. After presenting and discussing a comparison between some test results and the values yielded by the corresponding Abaqus shell finite element numerical simulations, the experimental failure loads obtained in this work, together with additional data reported in the literature, are used to assess whether the available Direct Strength Method (DSM) design approaches are capable of predicting them efficiently (safely and accurately). It is found that this is not the case, mainly because of the fact that the mechanics of the flange-triggered and web-triggered local-distortional interactions are quite different. Although fairly good failure load predictions are provided by a new DSM design approach proposed in this work, further research is required on the mechanics of local–distortional interaction in web-stiffened lipped channel columns.



## 1. Introduction

Most thin-walled cold-formed steel columns are known to be highly susceptible to local, distortional or global (flexural or flexural–torsional) buckling (see Fig. 1(b)–(e)) – depending on the geometry (cross-section dimensions and length) and support conditions, any of these instability phenomena may be the critical one. Moreover, commonly used column geometries often lead to similar local, distortional and/or global buckling stresses, which means that their post-buckling behaviour, ultimate strength and failure mechanism are affected by interaction effects involving two or more of the above three buckling mode types.

It is well known for a long time that thin-walled members exhibit stable local and global post-buckling behaviours with high and low/marginal post-critical strength reserves, respectively. On the other hand, relatively recent studies (e.g., [1,2]) showed that the distortional post-buckling behaviour fits in between the previous two (intermediate post-critical strength reserve) and, moreover, exhibits a non-negligible asymmetry with respect to the sense of the flange-lip motions (outwards or inwards). Concerning mode interaction phenomena affecting the column post-buckling behaviour, those involving local and global buckling are, by far, the better understood, as attested by their inclusion in virtually all text books and current design specifications for hot-rolled and cold-formed steel structures – these mode coupling effects are taken into account either through the classical "plate effective width" concept or by means of the much more recent Direct Strength Method (DSM – e.g., [3]). Nevertheless, a considerable amount of research work has been devoted to investigate local–distortional (L–D) interaction in cold-formed steel thin-walled columns – this work involves mostly lipped channel columns and comprises experimental investigations, numerical simulations and design proposals (e.g., [4–13]).

It was found that the local–distortional interaction effects are relevant when the ratio between the column distortional and local buckling loads is either (i) in the close vicinity of 1.0 (at least comprised between 0.9 and 1.1), which corresponds to the occurrence of a "true L–D interaction" (the coupling effects gradually evolve as loading progresses and take place regardless of the yield stress value), or (ii) above 1.0 (possibly by a large margin), provided that the squash load exceeds the distortional buckling load by a "large enough" amount to allow for the development of significant L–D interaction effects prior to failure, which corresponds to "L–D interaction due to a secondary (distortional) bifurcation". While the first finding stemmed from research work involving plain (no intermediate stiffeners)

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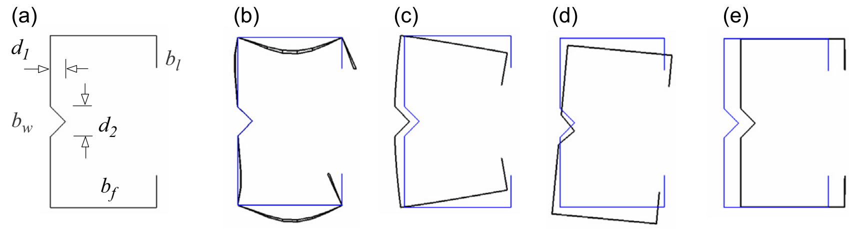


**Fig. 1.** Web-stiffened lipped channel (a) geometry and cross-section deformed shapes associated with column, (b) local (flange-triggered), (c) distortional, (d) flexural–torsional and (e) flexural buckling.

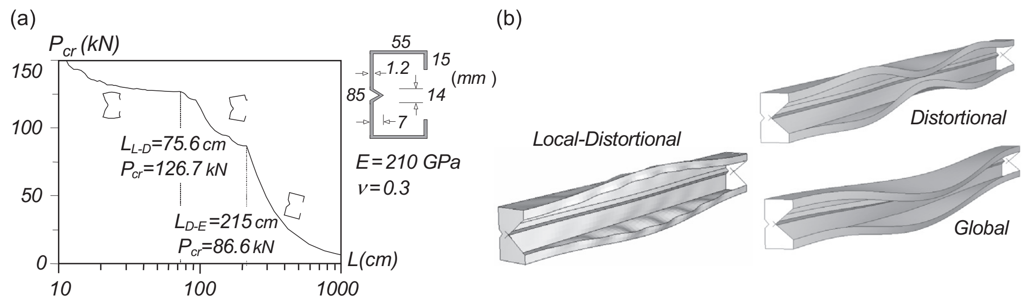


**Fig. 2.** (a) Column critical buckling curve $P_{cr}$ vs. $L$, ($b_1$) $L_{L-D}$ column local–distortional interactive buckling mode and ($b_2$) $L_{D-E}$ column distortional and global buckling modes.

lipped channel, hat-section, zed-section and rack-section columns [10,14], the second one was based on investigations concerning only plain lipped channel and rack-section columns [6,12,15]. Concerning columns for which the critical distortional buckling load precedes its local counterpart, the information is much more scarce – however, very recent numerical investigations involving exclusively plain lipped channel columns [16] seem to indicate that the influence of the L–D interaction effects is less relevant than in the two situations addressed before, particularly when the difference between the two buckling loads is sizeable (and regardless of the yield stress value). At this stage, it is worth noting that, in all the columns mentioned above, the L–D interaction effects are triggered by the web, which exhibits considerable deformation due to both the local and distortional critical buckling modes – this is not the case for the web-stiffened lipped channel columns dealt with in this work, as the L–D interaction effects are triggered by the flanges (the local critical buckling mode causes virtually no deformation in the web – see Fig. 1(b)).

Although the amount of research work devoted to web-stiffened lipped channel columns is not comparable to that concerning plain lipped channel columns, there exist available experimental, numerical and design results [6,7,17,18], namely concerning columns buckling in distortional modes and/or experiencing L–D interaction effects causing a perceptible ultimate strength erosion. The fact that several of the tests performed by Yap and Hancock [7,18] (i) involved columns that buckle in distortional critical modes (the distortional critical buckling load is visibly lower than its local counterpart) and (ii) provided clear experimental evidence of the occurrence of flange-triggered L–D interaction raised some suspicion on the ability of the current DSM distortional design curve to estimate adequately the corresponding failure loads – moreover, it provided the motivation for this research effort, which deals with the fixed-ended web-stiffened lipped channel columns buckling in distortional modes.

Therefore, the objective of this work is to report experimental, numerical and design results concerning the post-buckling and ultimate strength behaviour of cold-formed steel fixed-ended web-stiffened lipped channel columns selected to buckle in distortional modes, in the sense that the critical distortional buckling stress is below (but not excessively so) its local and global (flexural–torsional) counterparts. The experimental results, obtained from the tests carried out at The University of Hong Kong, (i) include initial imperfection measurements, equilibrium paths, failure loads and collapse modes, and (ii) provide experimental evidence of L–D interaction – before presenting and discussing the test results, the experimental set-up and procedure are briefly described. Next, the results concerning some of the tested specimens are compared with the values yielded by the corresponding numerical simulations, performed by means of the Abaqus [19] shell finite element analyses (SFEA) – an in-depth numerical investigation addressing the column imperfection-sensitivity is also presented and discussed. Then, the obtained experimental failure loads, together with additional ultimate strength data reported in the literature [6,7,17,18], are used to assess and discuss the ability of the current DSM distortional design curve, as well as other DSM design approaches available in the literature, to predict efficiently (safely and accurately) the ultimate strength of web-stiffened lipped channel columns that (i) buckle in distortional critical modes and (ii) are susceptible to exhibit L–D interactive failures. It is found that this is not the case and it is shown that the inability is due to the occurrence of ultimate strength erosion stemming from flange-triggered L–D interaction, which is mechanically quite different from its web-triggered counterpart. It is worth noting that the vast majority of the existing numerical/experimental investigations and design considerations/proposals concerning L–D interactive failures involve exclusively columns with either (i) plain webs and flanges or (ii) stiffened webs and flanges, all of which exhibit web-triggered L–D interaction (*e.g.*, [4,5,8–16]) – the exceptions are the investigation reported by Kwon et al. [6] and Yap and Hancock [7]. Although a new DSM design approach proposed in this work, which combines two existing interactive strength curves, provides fairly good predictions of the experimental failure load available (including those reported herein), it is also concluded that further research is required in order to acquire in-depth knowledge on the mechanics of flange-triggered local–distortional interaction in web-stiffened lipped channel columns.

## 2. Buckling behaviour – column geometry selection

The column geometries (cross-section dimensions and length) were selected to ensure critical distortional ($D$) buckling loads that