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# Strength curves for web crippling design of cold-formed stainless steel hat sections

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ABSTRACT

The web crippling design guides are based on empirical adjustments of available test data. These equations differ from the basic concept underpinning most of the other instabilities, the so-called strength curves. This investigation presents a new design approach for web crippling design of stainless steel hat sections based on strength curves controlled by slenderness-based functions $\chi(\bar{\lambda})$. The effects of web crippling on such cross-sections were studied numerically and the obtained results were used to derive the design expressions. Comparisons with tests and FE data, and with design guides show that the proposed design approach provides more accurate web crippling resistance.


## 1. Introduction

The use of stainless steel in construction has been permanently increasing during the last years due to its favourable characteristics in terms of strength, durability, formability and aesthetics. Cold-formed stainless steel hat sections are frequently used as secondary structural elements in roof or wall cladding subjected to local transverse loads or reactions which produce local high stresses. These cross-sections present high web-to-thickness ratio, and its web is therefore susceptible to local buckling (localized crushing or crippling of the web).

The first web crippling experimental investigation was conducted at Cornell University [1,2] on cold-formed carbon steel I-sections. Within this investigation, two types of load locations and two types of loading were examined, resulting in the four types of loading cases: interior one-flange (IOF), interior two-flanges (ITF), exterior one-flange (EOF) and exterior two-flanges (ETF). Exterior loading defines a situation when the load is applied at the end of the member whereas in the case of interior loading, the load is applied within the span. Distinction is made between one-flange loading or two-flanges loading if the load is applied through one flange or acting on both flanges, respectively. This classification was adopted in the early versions of the AISI specification [3] for cold-formed carbon steel and later on, in the first version [4] of the current SEI/ASCE 8-02 standard [5] for application to stainless steel. The European design guidance for stainless steel, EN 1993-1-4 [6], refers to the European design guidance for cold-formed carbon steel, EN 1993-1-3 [7], to predict web crippling strength where different empirical equations are given. In this latter, for the particular case of hat sections, two categories are codified: Category 1 which corresponds to EOF, ETF and ITF loading; and Category 2 which is equivalent to IOF loading.

The theoretical treatment of web crippling is rather complex because many parameters are involved [8]: cross-section geometry (I-sections, C-sections, Z-sections, hat sections and multi web sections); inclination of the web element; inside bending radius; relative slenderness of the web; the length over which the load is distributed (bearing length); loading case; steel properties; and support conditions. Consequently, current standards [5,7] provide various empiric design equations for a given load case and particular cross-section geometry which were derived from regression analysis of existing test on different cold-formed carbon steel sections. Despite accurate plastic mechanism models based on yield line theory were derived for cold-formed carbon steel hat sections [9,10], their application is rather tedious for hand calculation purposes. Relevant research regarding these adjustments is summarized in Table 1 for cold-formed carbon steel.

The applicability of the aforementioned empiric equations to stainless steel was found to be not always acceptable [11] and further research was conducted in order to adapt these equations to different stainless steel grades and cross-section types [12–16]. Other relevant studies on cold-formed stainless steels are summarized in Table 2. Indeed, these adjustments correlate well with the data they allow for but such empiric design approach

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**Table 1**
Relevant research on cold-formed carbon steel members subjected to web crippling.

| Source | Section | Load case | Relevant contribution |
|---|---|---|---|
| Winter and Pian [1] | I-sections (stiffened flanges unfastened) | 30 EOF; 10 IOF; 27 ETF; 36 ITF | First consideration of the four load cases: IOF, EOF, ITF and ETF. First study on webs restrained against rotation (I-sections) and on single unreinforced webs (Hat sections) |
| Winter [2] | Hat sections (stiffened/unstiffened flanges unfastened) | 60 EOF; 30 IOF | Derived expressions for computing the web crippling resistance for IOF and EOF which were included in AISI 1968 [3] |
| Baehre [37] | Multi-web sections (hat type) | IOF | First study on single unreinforced webs of multi-web sections Introduced the web inclination $\phi$ on the web crippling strength. Derived expressions for computing the web crippling resistance for IOF |
| Hetrakul and Yu [38] | I-sections (stiffened flanges unfastened) | 50 EOF; 19 IOF; 30 ETF; 30 ITF | Collection of existing tests. Recalibration of coefficients proposed in previous studies. New expressions for IOF, EOF, ITF and ETF suitable for vertical webs and small r/t and $s_s$/t ratios included in more recent versions of AISI 1968 [3] |
| | I-sections (unstiffened flanges unfastened) | 4 EOF; 2 IOF | |
| | C-sections (stiffened flanges fastened) | 8 EOF | |
| | C-sections (stiffened flanges unfastened) | 34 EOF; 24 IOF; 26 ETF; 26 ITF | |
| | C-sections (unstiffened flanges unfastened) | 18 EOF; 4 IOF 4 ETF; 4 ITF | |
| Yu [39] | Multi-web sections (hat type and unfastened) | 18 EOF | Study of combined web crippling and bending on multi-web sections |
| Wing [40] | Hat sections (fastened) | 25 IOF; 7 ETF; 23 ITF | Study of combined web crippling and bending effects Derived expressions to predict web crippling resistance for IOF, ITF and ETF |
| | Multi-web sections (hat type and unfastened) | 34 IOF; 63 ETF; 57 ITF | |
| Studnicka [41] | Multi-web sections (hat type and unfastened) | IOF; EOF | Assessment of the Canadian Standard [42] and AISI 1986 [43]. Obtained good agreement for IOF loading but discrepancies for EOF loading |
| Bhakta et al. [44] | I-sections (stiffened flanges fastened) | 6 IOF | Long span roof deck and floor deck tests. Flange restraint study (fastened flanges to the support). Provided strength comparisons between different cross-sections and highlighted the influence of flange restraint on the ultimate web crippling resistance for different load cases |
| | I-sections (stiffened flanges unfastened) | 6 EOF | |
| | C-sections (stiffened flanges fastened) | 6 EOF | |
| | C-sections (stiffened flanges unfastened) | 6 EOF | |
| | Z-sections (stiffened flanges fastened) | 4 EOF | |
| | Z-sections (stiffened flanges unfastened) | 4 EOF | |
| | Hat sections (unfastened) | 2 EOF | |
| | Hat sections (fastened) | 2 EOF | |
| | Multi-web sections (hat type and unfastened) | 2 EOF | |
| | Multi-web sections (hat type and fastened) | 2 EOF | |
| | Multi-web sections (hat type and unfastened) | 2 IOF | |
| | Multi-web sections (hat type and fastened) | 2 IOF | |
| Prabhakaran [45] | – | – | Collection of all existing tests. A unified expression for web crippling design is derived which was adopted in the Canadian Standard [46] and in the North American Specification (NAS) [47] |
| Langan et al. [48] | C-sections (stiffened flanges unfastened) | 23 EOF; 8 IOF | Assessment of available specifications and design recommendations |
| Cain et al. [49] | I-sections (stiffened flanges fastened) | 12 IOF | Assessment of available specifications and design recommendations |
| | Z-sections (stiffened flanges fastened) | 14 EOF | |
| | Z-sections (stiffened flanges unfastened) | 14 EOF | |