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# Shear buckling strengths of web-posts in a castellated steel beam with hexagonal web openings

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ABSTRACT

Shear buckling behaviors of web-post in a Castellated Steel Beam (CSB) with hexagonal web openings under vertical shear were investigated using finite element method. Through treating the upper part of the web-post as a free body under horizontal shear force, whose shear buckling strength can be calculated by the thin-plate shear buckling theory, design equations for the vertical shear buckling strength of the web-post were proposed. Parameters that affected the vertical shear buckling strength of the web-post were studied, which were the opening height to web thickness ratio $h_0/t_w$, the web-post width to web thickness ratio $e/t_w$, the web height of Tee-section above the opening to the web thickness $h_f/t_w$, the web thickness $t_w$ and the incline angle of the opening edge $\alpha$. After obtaining the vertical shear buckling strength of a CSB through finite element model, the shear buckling coefficient $k$ can be obtained through inverse analysis. Research results showed that $k$ decreased nonlinearly with the increase in $e/t_w$ and $h_f/t_w$ and it increased linearly with the increase in $\alpha$ and $h_0/t_w$. Practical calculating method for $k$ was proposed based on parameter analysis results. The vertical shear buckling strength of the web-post calculated using the proposed shear buckling coefficient $k$ agreed well with that obtained from the finite element simulation. For the proposed method was based on the elastic buckling of the web-post, it overestimated the shear buckling strength when the web-post buckled in the elastic–plastic state.



## 1. Introduction

The Castellated Steel Beam (CSB) can be made through cutting an H-section steel beam in a zig-zag pattern along the web and then re-welding the two parts together at the convex area. The strength to weight ratio of the beam is increased without additional usage of steel. At the same time, the story height of the building can be reduced by installing the service pipelines in web openings.

Existences of web openings break the continuity of beam web. Compared with the solid web steel beam, the CSB may fail in new modes, such as the formation of plastic hinges at ends of the Tee-sections above and below the web opening [1–4], and the buckling of the web-post under vertical shear force [5–7].

The plastic failure at the perforated section of a CSB was usually named as the Vierendeel Mechanism failure. Based on analytical and numerical studies, Chung, et al. [1] and Liu and Chung [2] proposed empirical M-V interaction curves at the perforated sections for practical design of steel beams with circular web openings against the Vierendeel mechanism failure. Wang, et al. [3] investigated effects of opening dimensions and opening shapes on the Vierendeel failure of CSBs with filet corner web openings. The M-V interaction equation for predicting the load bearing capacity of the CSB with filet corner web openings was proposed. Panedpojaman, et al. [4] proposed an interaction curve to check the Vierendeel failure of non-composite symmetric cellular beams, or steel beams with circular or elongated circular openings, which was based on a quadratic nonlinear failure criterion.

The buckling of web-post was also very common, especially for the CSB with great web height to thickness ratio. Ellobody [5] investigated the behavior of CSBs under combined lateral torsional and distortional buckling modes. Finite element simulation results showed that the presence of web distortional buckling caused a considerable decrease in the failure load of the slender CSB.

Except for the traditional circular and hexagonal openings, many new opening shapes were developed recently. Abidin and Izzuddin [7] employed Element Free Galerkin method to study local buckling of the CSB with different opening shapes and sizes. Durif and Bouchaïr [8,9] carried out experimental studies on the CSB with sinusoidal openings. Tsavdaridis and D'Mello [10,11] investigated web-post buckling behavior of the CSB with novel elliptically-based web openings.

Inclined compression strut would be formed in the web-post under vertical shear force, as shown in Fig. 1(a). The stability of the compression strut can be checked by the buckling curve "c" of a steel column [12]. Wang, et al. [13] proposed a modification to the strut model for predicating the shear buckling capacity of the web-post in the CSB with filet corner openings. Tsavdaridis and D'Mello [10] carried out experimental and analytical study on two beams with circular web openings and five perforated beams with novel web opening shapes to

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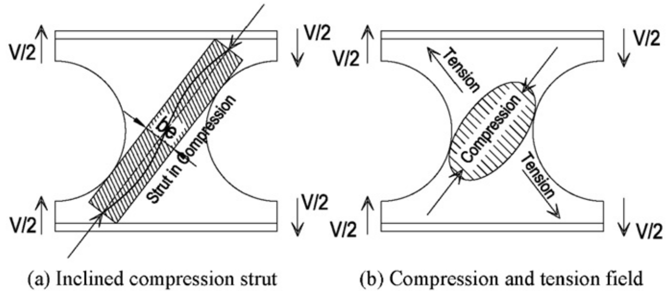


**Fig. 1. Strut in the web-post**. (a) Inclined compression strut. (b) Compression and tension field.

investigate the failure mode and shear buckling strength of the web-post. An empirical formula which predicted the ultimate vertical shear buckling strength of web-posts was formulated for the particular web opening shapes. Lawson, et al. [14] presented simplified equations for web-post buckling based on strut model, which was calibrated against results of finite element analyses. Under vertical shear force, the web-post buckled in an "*S*" shape. Hence, it was discordant to check its stability using the column buckling curves. And the beneficial effect of the inclined tension zone was not included in the design.

As shown in Fig. 1(b), it was much reasonable to check the stability of the web-post based on the plate shear buckling theory. Redwood and Demirdjian [15] investigated buckling behavior of the web-post in the CSB with hexagonal openings through studying the upper part of the web-post under horizontal shear force, as shown in Fig. 2. The horizontal shear buckling strength, $V_{h,cr}$, of the free body was calculated by

$$V_{h,cr} = k\frac{Eet_w}{(h_0/t_w)^2} \tag{1}$$

where *k* was the shear buckling coefficient of the upper part of the web-post under horizontal shear force. *E* was the Young's modulus of steel. *e* was the width of web-post. $t_w$ was the web-post thickness. $h_0$ was the height of web opening. From the force equilibrium of the free body shown in Fig. 2, the vertical shear buckling strength of the web-post was calculated by

$$V_{cr} = \frac{h-2y_i}{s}V_{h,cr} \tag{2}$$

where *h* was the section height of CSB. $y_i$ was the distance from the flange to the centroid of Tee-section. *s* was the distance between two adjacent web openings. The buckling strength of the web-post could be easily determined if *k* was provided. However, Redwood and Demirdjian [15] only presented curves to calculate the shear buckling coefficient *k* of the web-post with limited geometric parameters.

Substitute Eq. (1) into Eq. (2), the vertical shear buckling strength of the web-post can be obtained by

$$V_{cr} = k\cdot\frac{h-2y_i}{s}\cdot\frac{Eet_w}{(h_0/t_w)^2} \tag{3}$$

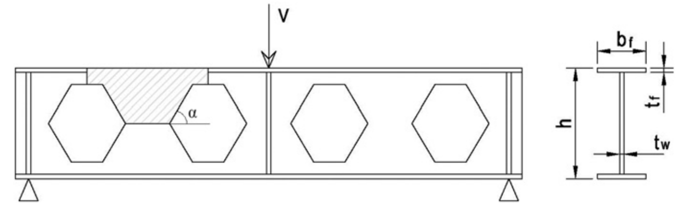


**Fig. 3.** Configuration of studied CSB.

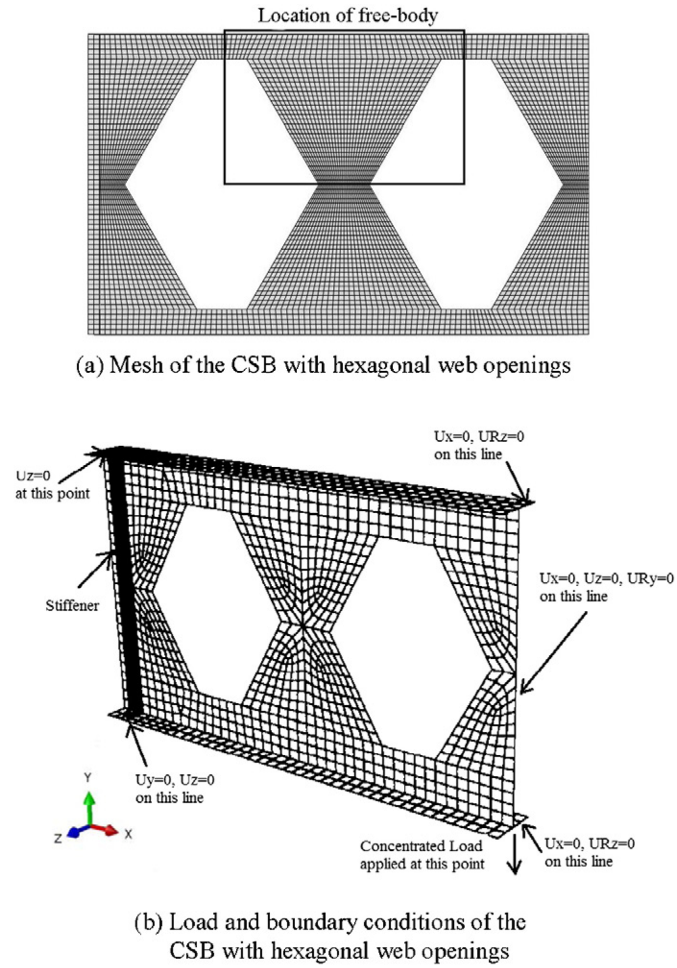


**Fig. 4. FEM of the CSB with hexagonal web openings**. (a) Mesh of the CSB with hexagonal web openings. (b) Load and boundary conditions of the CSB with hexagonal web openings.

In this paper, after obtaining the vertical shear buckling strength of the web-post through FEM simulation, the shear buckling coefficient *k* was calculated through reverse analysis. And then an equation was

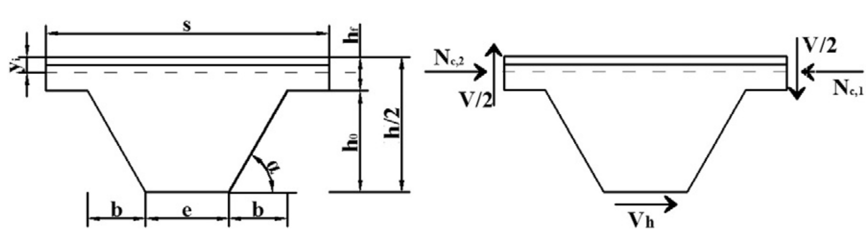


**Fig. 2.** Free body in the CSB with polygonal web openings.