Nonlinear finite element analysis of steel-concrete composite beams with cellular I-section under hogging moment

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Abstract. The use of composite structures is increasing in the construction industry due to their higher load-bearing capacity, better structural fire performance, and more significant potential to provide optimized structural solutions, effectively creating synergies between structural materials. Steel-concrete composite cellular beams are a good option for the dematerialization of this structural element. However, local failure modes can occur due to web openings, such as Web-Post Buckling (WPB) and Vierendeel Mechanism (VM). Regarding composite cellular beams under hogging moment, which are the case of continuous and cantilever elements, the WPB phenomenon needs more investigation. This way, nonlinear finite element analyses are developed via Abaqus software. A parametric study is carried out to analyze the influence of geometric parameters and the I-section steel grade on the WPB resistance cantilever composite cellular beams. It was observed that the models failed by WPB or its interaction with VM, in which those with higher strength steels prevented or delayed the formation of plastic mechanisms on the web-post and VM phenomenon. In addition, the greater the opening diameter and web-post width are, the smaller and greater the ultimate global shear that causes WPB, respectively.

Keywords: Web-post buckling, Vierendeel mechanism, composite cellular beams, hogging moment, nonlinear finite element analysis.

1 Introduction

Steel-concrete composite cellular beams are susceptible to failure modes such as Web-Post Buckling (WPB) and Vierendeel Mechanism (VM) due to the web openings, which are collapse modes that do not occur in full web beams. These web openings originate from the manufacturing process of the cellular I-section, which is cut and welded, expanding the I-section depth. This way, WPB and VM occur in composite cellular beams under intense shear loads. WPB is characterized by the web-post torsion about its vertical axis, while VM presents the formation of plastic hinges on the corners of the web openings.

Composite cellular beams under hogging moment are observed in continuous and cantilever structural members, which can fail by Lateral-Distortional Buckling (LDB), WPB and VM. When these beams have higher global slenderness, they become more susceptible to global instabilities (LDB). In contrast, the local failure modes (WPB and VM) are more critical when the composite cellular beams have lower global slenderness or higher local slenderness.

Some investigations focused on the LDB behavior of composite cellular beams in hogging moment regions. However, there is a gap in the investigation that addressed the WPB phenomenon in these beams. Therefore, this paper aims to analyze the influence of geometric parameters and the I-section steel grade on the WPB resistance of cantilever composite cellular beams. Nonlinear finite element models are used in the analyses developed via ABAQUS software.

2 Nonlinear finite element analysis

The nonlinear finite element modeling used in this study is the same as previous studies by De Oliveira et al. [1,2]. The authors validated the numerical model against four tests performed by Salah [3], in which the divergences of the ultimate loads and their respective deflections were below 4%. In addition, an elevated agreement on the deformed shapes was obtained. Section 2.1 provides information about numerical modeling, while the results are discussed in section 2.2.

2.1 The numerical model

Salah [3] performed three-point bending tests in cantilever composite cellular beams, as illustrated in Fig. 1. The present parametric study adopted the same layout of these tests, as the numerical modeling was validated against them.

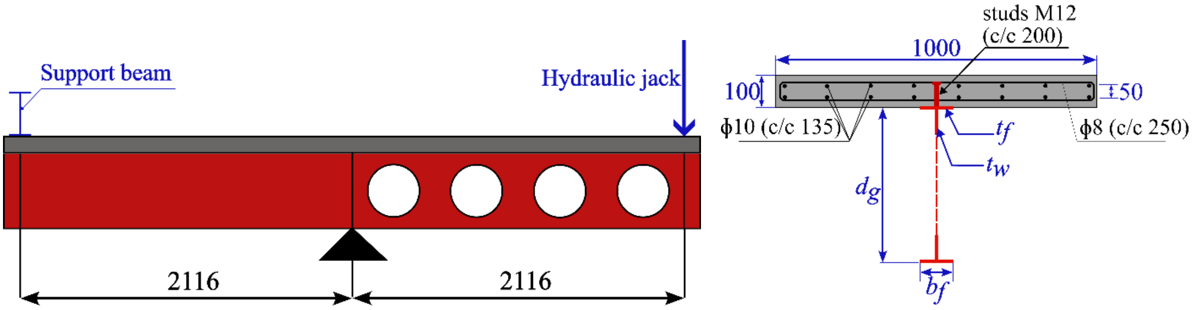


Figure 1. Three point-bending tests of cantilever composite cellular beams (adapted from Salah [3])

Linear buckling analyses (LBA) and geometrically and materially nonlinear analyses with imperfections (GMNIA) are carried out using the ABAQUS software. The geometric imperfection amplitude of $d_g/100$ and the residual stress model proposed by Sonck, Impe and Belis [4] were adopted. The finite element types and the boundary conditions of the models are illustrated in Fig. 2. Tab. 1 shows the mechanical properties of the beams, in which E is the Young's modulus, v is the Poisson ratio, $f_{ck\text{-}cubic}$ is the characteristic compressive cubic strength of concrete, and f_y is the steel yield strength. De Oliveira et al. [1,2] provide more information on the constitutive models.

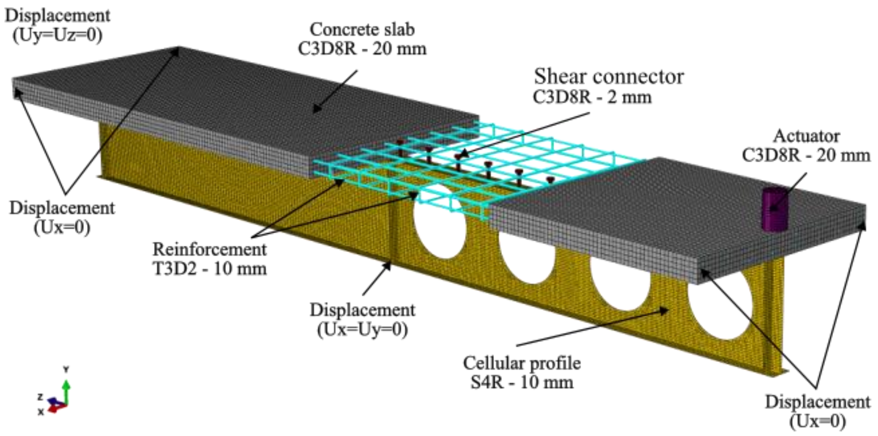


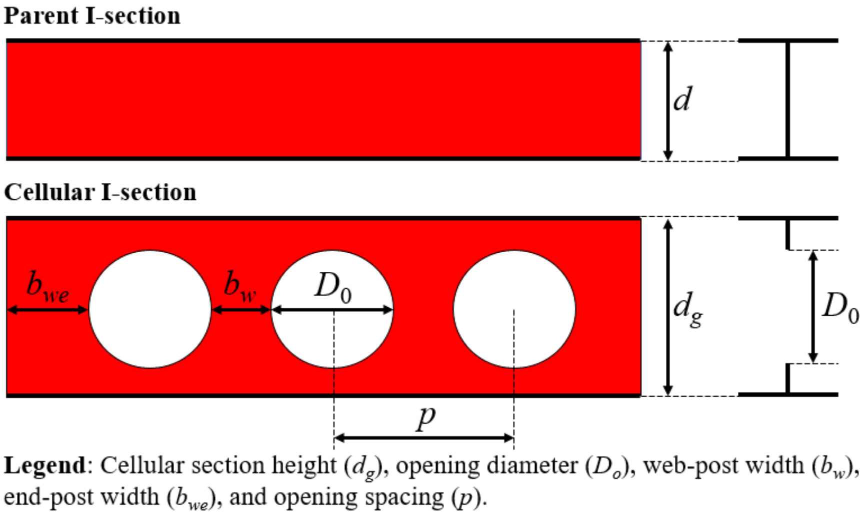
Figure 2. Finite elements and boundary conditions

Table 1. Mechanical properties of materials

Element	E (MPa)	v	$f_{ck\text{-}cubic}$ (MPa)	f_y (MPa)
Concrete slab	32,837	0.2	30	-
Headed studs	200,000	0.3	-	611.35
Rebars	210,000	0.3	-	459.6
S235 steel	200,000	0.3	-	235
S355 steel	200,000	0.3	-	355
S460 steel	200,000	0.3	-	460

A total of 81 cantilever composite cellular beams were assessed in the parametric study. These beams were designed to fail by WPB. This way, an unrestrained length (L) equal to 2m was adopted. Fig. 3 details cellular I-sections' parameters, which were varied in the parametrization. The steel parent I-section adopted for all composite cellular beams was IPE 400, which has the following dimensions: d= 400m. b_f= 180mm, t_w= 8.6mm, and t_f= 13.5mm. Four parameters with three values to each one were analyzed:

- d_g/d ratio: 1.4, 1.5 and 1.6;
- D_o/d ratio: 0.8, 1.0 and 1.2;
- p/D_o ratio: 1.2, 1.35 and 1.5;
- Steel grade: S235, S355 and S460.



Legend: Cellular section height (d_g), opening diameter (D_o), web-post width (b_w), end-post width (b_{we}), and opening spacing (p).

Figure 3. Cellular I-section parameters

2.2 Results and discussion

All composite cellular beams addressed in the parametric study characterized WPB in the failure mode, and some models presented the WPB+VM interaction. Additionally, all numerical models also presented the formation of plastic mechanisms. Tab. 2 shows the failure modes of the models with d_g/d= 1.4 and S235 steel varying D_o/d and p/D_o ratios, in which those with the combinations of D_o/d= 0.8 with p/D_o= 1.2-1.5 and D_o/d= 1.0 with p/D_o= 1.2-1.35 characterized only WPB. In contrast, the composite beams that have D_o/d= 1.0 with p/D_o= 1.5 and D_o/d= 1.2 with p/D_o= 1.2-1.5 reached the coupling between WPB and VM. As know, the tee height on the central region of the opening is one of the parameters with greater influence on the VM phenomenon. This way, the cellular I-beams with lower tee height (D_o/d= 1.2) were more susceptible to VM occurrence, as expected. The beams presented in Tab. 2 with D_o/d= 1.0 had an intermediate case for the occurrence of only WPB or its interaction with VM, as the models with p/D_o= 1.2-1.35 characterized only WPB and the one with p/D_o= 1.5 had WPB+VM. This is observed because these models have tee height sufficient to be susceptible to VM, but the WPB was more critical for the cellular beams with p/D_o= 1.2-1.35 due to their shorter web-post width. Finally, the models with the shortest web-post width (p/D_o= 1.2) regarding their respective D_o/d were the most critical case for the web-post yielding occurrence, which is the formation of plastic mechanism on the web-posts (Tab. 2).

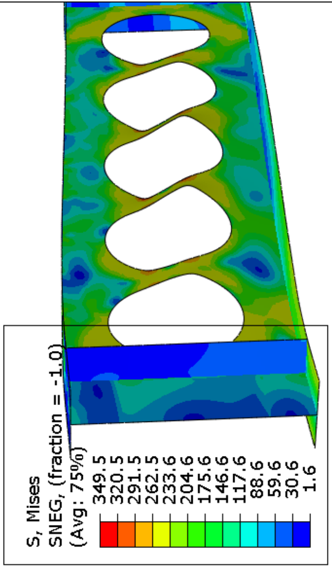
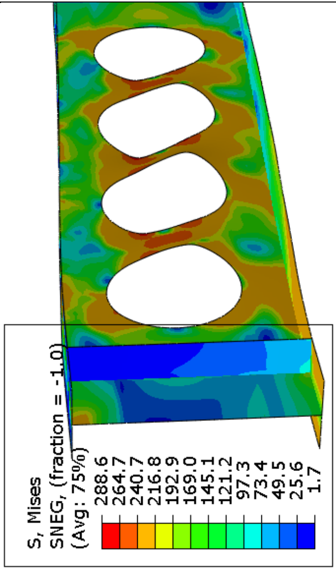
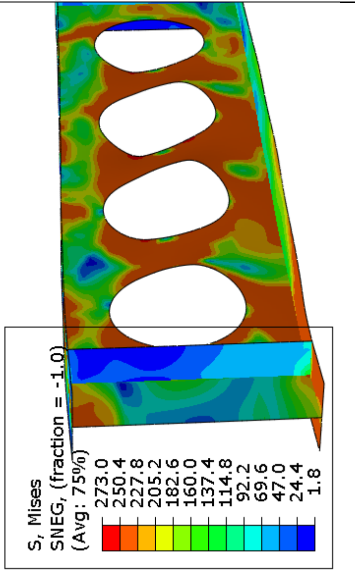
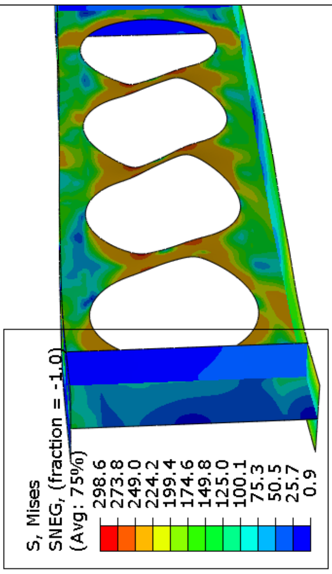
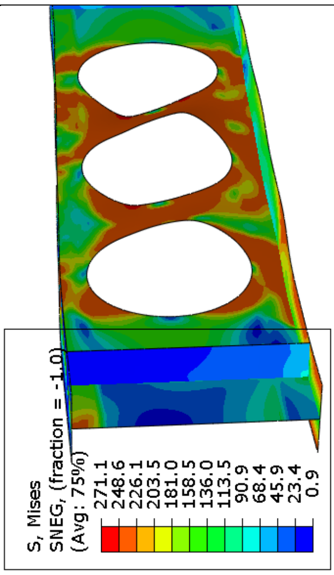
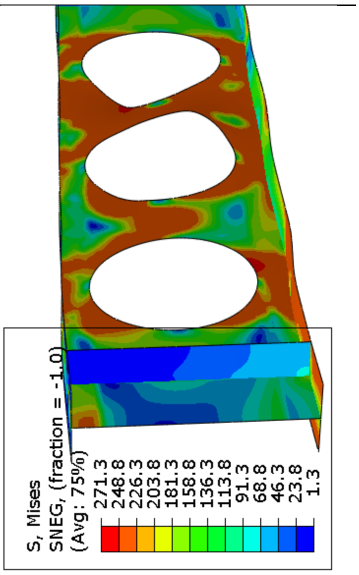
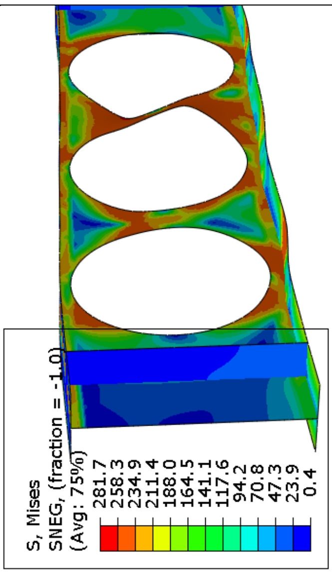
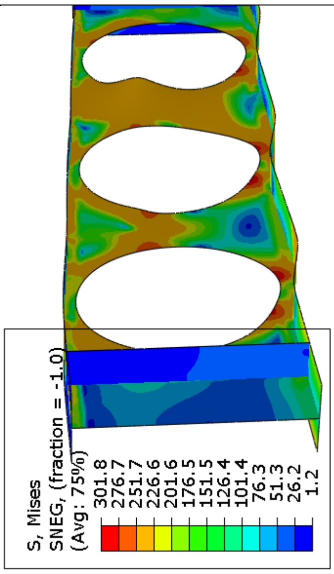
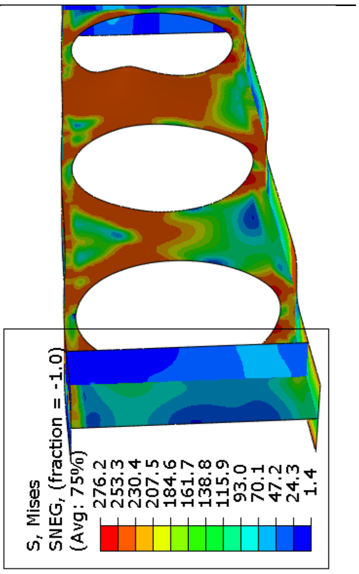
All models with d_g/d= 1.4 and S355 steel had the same failure modes described for those with d_g/d= 1.4 and S235 steel (Tab. 2). On the other hand, the composite beams with d_g/d= 1.4 and S460 steel reached the WPB+VM interaction only with D_o/d= 1.2 - p/D_o= 1.2-1.5, as the higher strength steel delays the appearance of the plastic hinges on the corners of the web openings, resulting in higher resistance to VM.

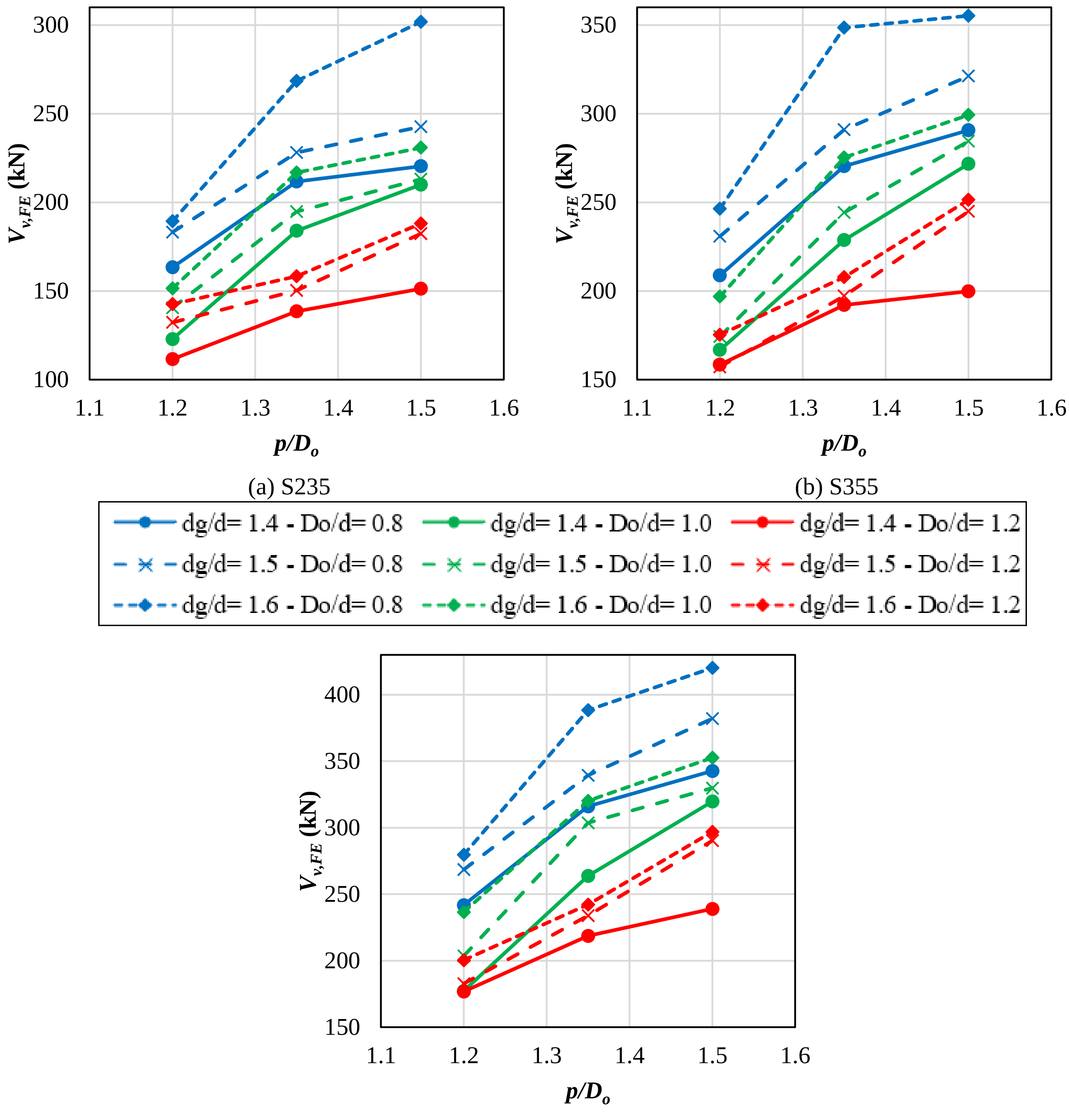
Regarding the models with d_g/d= 1.5 that have S235 and S355 steels, the coupling between WPB+VM occurred only in those with D_o/d= 1.2 - p/D_o= 1.35-1.5, while in the models with D_o/d= 1.2 - p/D_o= 1.2, the WPB was more critical because the narrow web-post width. In contrast, the composite beams with d_g/d= 1.5 and S460 steel presented the WPB+VM interaction only with D_o/d= 1.2 - p/D_o= 1.5. Because of the higher resistance to VM, most of these beams were more critical to WPB, presenting VM only in the most resistant model to WPB (D_o/d= 1.2 - p/D_o= 1.5). Finally, all composite beams with d_g/d= 1.6 characterized only WPB in the failure mode, as all these models have considerable tee height, sufficient to avoid VM.

The graph from Fig.4 presents the influence of D_o/d and p/D_o ratios varying d_g/d. It is observed that increasing d_g/d, increases the ultimate global shear. Even with higher web slenderness (d_g/t_w), the greater d_g enhances the global flexural performance of the composite beam, favoring the higher ultimate capacity. In addition, the range of D_o (320, 400 and 480mm) is the same, even varying the d_g/d ratio. This way, the models with the highest d_g (640mm) have a higher D_o/d_g ratio, providing higher resistance to WPB and VM phenomenon. Fig. 4 shows that the greater the D_o/d and p/D_o are, the smaller and greater the ultimate global shear that causes WPB, respectively. The models with p/D_o= 1.2 had bearing capacities significantly lower than their respective D_o/d and d_g/d ratios, as the narrow web-post width favors the WPB occurrence. A considerable reduction in the ultimate load is also observed in the models with D_o/d= 1.2, which have the highest opening diameter in their respective p/D_o and d_g/d ratios, increasing their web-post slenderness. Due to their lower tee depth, those with d_g/d= 1.4-1.5 were also susceptible to VM phenomenon within these composite beams.

Fig. 5 brings the influence of D_o/d and p/D_o ratios varying the steel grade. In most cases, it is noted in Fig 5a that the models with D_o/d= 1.2 and S235 had bearing capacities considerably lower than the respective p/D_o and d_g/d ratios. As previously discussed, these cellular I-beams were the most susceptible to VM phenomenon due to the smallest tee height and lowest steel yield strength, favoring the formation of plastic hinges on the corners of the web openings. Within the models with d_g/d= 1.4 and S235 (Fig 5a), only the one with D_o/d= 1.0 and p/D_o= 1.2 had a close ultimate load to the respective D_o/d= 1.2. It is noteworthy that it did not occur VM phenomenon in the cellular I-beam in question (D_o/d= 1.0 and p/D_o= 1.2), but it was significantly critical to WPB occurrence, as the narrow web-post width and lowest steel yield strength contributed to the web-post yielding. In contrast, the differences between ultimate loads varying the steel grade were more uniform for the models with d_g/d= 1.5-1.6 (Fig. 5b-c), as these composite beams were less susceptible to VM and web-post yielding.

Table 2. Failure modes of the models with d_g/d= 1.4 and S235 steel varying D_o/d and p/D_o ratios

	p/D_o = 1.2	p/D_o = 1.35	p/D_o = 1.5
D_o/d = 0.8			
D_o/d = 1.0			
D_o/d = 1.2			

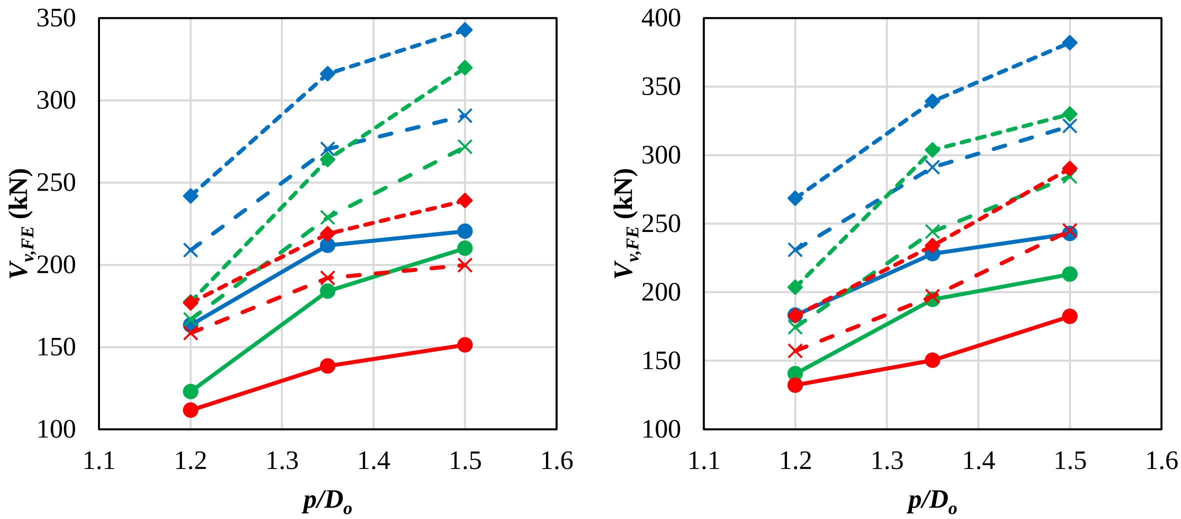


(a) S235

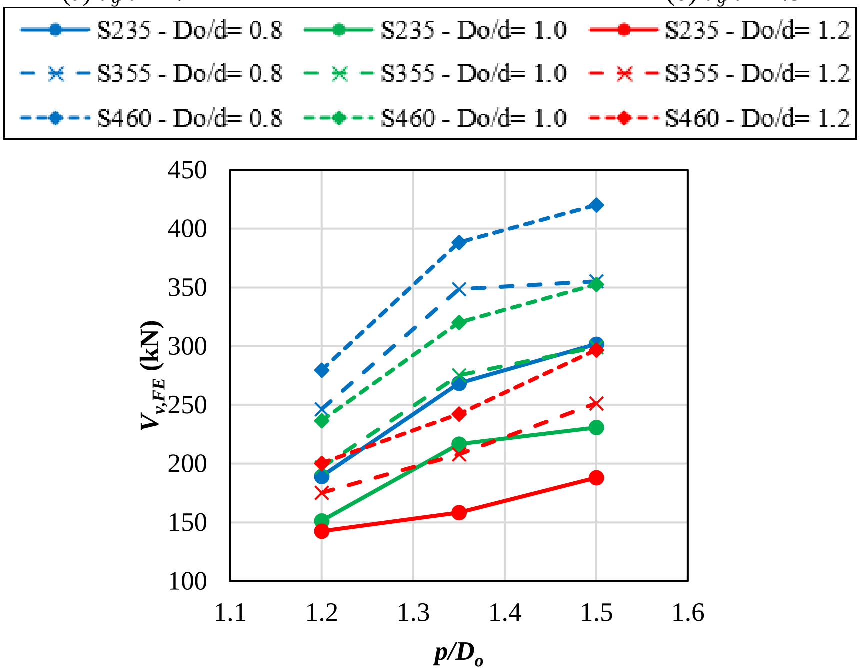
(b) S355

(c) S460

Figure 4. The influence of D_o/d and p/D_o ratios varying d_g/d



(a) d_g/d= 1.4 (b) d_g/d= 1.5



(c) d_g/d= 1.6

Figure 5. The influence of D_o/d and p/D_o ratios varying the steel grade

3 Conclusions

The present paper presents numerical analyses of the web-post buckling resistance of cantilever composite cellular beams. It was concluded that the I-section steel grade was influential in the bearing capacity of the beams, in which higher strength steels prevented or delayed the formation of plastic mechanisms and VM phenomenon. In contrast, the models with lower tee depth (D_o/d_g ratio) were critical for the VM occurrence. Finally, the greater the opening diameter and web-post width are, the smaller and greater the ultimate global shear that causes WPB, respectively.

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