NUMERICAL ANALYSIS OF THE INFLUENCE OF STEEL ON THE FAILURE MODES OF STEEL-CONCRETE COMPOSITE CELLULAR BEAMS

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Abstract. The use of steel-concrete composite cellular beams expands the options in civil construction projects, as it results in greater strength capacity compared to components acting separately, as well as greater steel savings compared to full-span beams. In this respect, it is interesting to study the influence of high-strength steel on the failure modes and strength capacity of composite cellular beams. Therefore, this study aims to contribute to the field of composite cellular beams under positive moments, with the replacement of ordinary steel with high-strength steel, identifying the influence of this parameter on its failure modes and the strength capacity of the composite cellular beam. Thus, using ABAQUS software, a numerical model was developed and validated using experimental results from the literature, to obtain the original behavior, and then parametric analysis focused on replacing ordinary steel with high-strength steel. The study resulted in four numerically validated cellular composite beam models and three variations of each with the application of high-strength steel. It was noted that applying high-strength steel can lead to a change in the beam's failure mode. As for the resistance capacity, in all the beams there was a considerable increase, also increasing the deflection presented in the beam before reaching the resistance limit.

Keywords: composite cellular beam, high-strength steel, failure modes, strength capacity, finite element modeling, positive moment.

1 Introduction

Composite steel and concrete cellular beams are structural elements formed by joining steel cellular beams and concrete slabs using shear connectors. The main characteristic of this type of beam is the joint behavior of concrete and steel, with steel resisting traction and concrete resisting compression. Combining these two materials promotes the mobilization of an effective width of the concrete slab, contributing to the beam's resistance capacity. Using composite cellular beams in multi-store buildings has a few benefits, such as increasing the speed of execution, reducing the structure's weight, making it possible to pass pipes and conduits through the beam, and reducing the necessary floor height.

Various failure modes can be observed in composite cellular beams, two of which stand out for this study: Web-post buckling (WPB) and plasticization caused by the Vierendeel moment. Web-post buckling depends on the geometry of the cellular steel profile, especially the diameter of the opening and the thickness of the web. In cellular beams, WPB can occur due to compression, in which the beam's web is subjected to a concentrated force without adequate reinforcement. On the other hand, plasticization caused by the Vierendeel moment is caused by distortion and the formation of plastic hinges in regions close to the openings in a steel cellular beam. This plasticization occurs when the steel reaches its yield strength at the ends of the T-sections, because of the combination of normal and shear stresses, according to Ferreira et al. [1].

Among the studies on composite cellular beams, Ferreira et al. [2] numerically analyzed symmetrical and asymmetrical beams. In their study, they applied variations in the openings of the steel cellular beam, as well as the spacing between the openings. The authors found that the dominant failure modes in the composite cellular beam models were plasticization due to the Vierendeel moment and web-post buckling. They also pointed out that the failure mode of the composite cellular beam is governed by the concrete slab.

Nadjai et al. [3] analyzed two composite cellular beams, one of which was symmetrical and the other asymmetrical. The main failure mode found in the study was web-post buckling, resulting in a sudden loss of the beams' resistance capacity. Similarly, the study carried out by Müller et al. [4] when evaluating composite cellular beams with symmetrical and asymmetrical sections, observed that the predominant failure modes were web-post buckling and plasticization due to the Vierendeel moment.

In this way, we have a lack of studies about composite cellular beams with high-strength steel. Therefore, this study aims to investigate the behavior of composite cellular beams made of high-strength steel and simply supported concrete using finite element numerical simulation, to understand the influence of the steel yield strength on these elements. Regarding this, the influence of the variation in steel yield strength on the failure mode and resistance capacity of high-strength steel composite beams under positive moment was analyzed.

2 Numerical Modeling

Four experimental results from the literature were used to validate the numerical modeling. The specimens CCB1 and CCB2, CCB3 and CCB4 were tested by Nadjai et al. [3] and Muller et al. [4]. CCB1 is a symmetrical beam, with the profile produced based on the UB406 x 140 x 39 model, the opening diameter is 187.5 mm, while the spacing between the centers is 500 mm. CCB2 has an asymmetrical section, with its profile featuring the upper T being produced on the UB406 x 140 x 39 base and the lower T in UB457 x 152 x 52, with the diameters of the openings being 225 mm, while the spacing between their centers is 630 mm. The two beams have a total length of 5000 mm, plus an arrangement of shear connectors 19Øx120//150 mm, connected to a concrete slab in the Holorib HR51/150 standard, 150 mm high and 1200 mm wide, the concrete is class 28.6 N/mm². The steel yield strength used to model the two beams was 312 MPa. The CCB3 is a symmetrical beam with a total length of 7030 mm, the steel profile is based on the IPE 400 model with an opening diameter of 190 mm, while the spacing between its centers is 570 mm. The yield steel strength is 451 MPa in the flange and 489 MPa in the web. The concrete slab is 130 mm high and 1800 mm long in Holorib HR 51/150, the concrete is 33.6 N/mm², and the shear connectors are 19Øx100/150 mm. CCB4 is asymmetrical with a total length of 7030 mm, with a profile featuring the upper T based on the IPE 300 model and the lower T based on the IPE 340; the opening diameter is 190 mm, while the spread between its centers is 570 mm. The yield strengths of the steel are 453 MPa for the flange and 488 MPa for the web. The concrete slab of this beam is also in the Holorib HR 51/150 pattern, 130 mm high and 1800 mm wide, with a concrete of class 24 N/mm². The shear connectors are arranged in the 19Ø120/150 mm pattern. Table 1 summarizes the characteristics of the composite cellular beams studied.

Table 1: Details of specimens (in mm, MPa and GPa)

CELLULAR STEEL BEAM								
Model	*dg*	*Do*	*p*	Upper tee				
				bf	*tf*	*tw*	*fy* (Flange/Web)	*fu* (Flange/Web)
CCB1	575	375	500	152.4	8.6	6.4	312	438.5
CCB2	630	450	630	141.8	10.9	6.4	312	438.5
CCB3	555.2	380	570	180	13.5	8.6	451/489	541/587
CCB4	484.6	380	570	150	10.7	7.1	407/467	524/588

Model	*dg*	*Do*	*p*	Lower tee				
				bf	*tf*	*tw*	*fy* (Flange/Web)	*fu* (Flange/Web)
CCB1	575	375	500	152.4	8.6	6.4	312	438.5
CCB2	630	450	630	152.4	10.9	7.6	312	438.5
CCB3	555.2	380	570	180	13.5	8.6	451/489	541/587
CCB4	484.6	380	570	300	21.5	12	453/488	519/582

CONCRETE SLAB

Model	*E*	*fc*	*b*	*Lb*
CCB1	200	28.6	1200	4500
CCB2	200	28.6	1200	4500
CCB3	200	33.6	1800	6840
CCB4	200	24	1800	6840

ABAQUS® software was used to represent the experimental specimens of beams. The software allows each part of the numerical model to be built individually and allows materials, interactions, and boundary conditions to be applied to the model. For the numerical models to agree with those chosen from the literature, properties were defined for each material. For steel, we used the discontinuous yielding model from the study by Wang et al. [5]. This model, as shown in Figure 1, considers common steels and high-strength steels. The discontinuous yielding model presents four stages of behavior, the first being the elastic phase. In contrast, the second represents yielding, the third is the positive hardening of the steel, and the fourth is the hardening of the steel. It was chosen because it best represents the beams tested, presenting an ultimate load closer to that presented in the literature. To analyze the beams, it was assumed that the steel should enter the tensioning phase (stage 4 in Figure 1), reaching maximum tension before beginning to lose it.

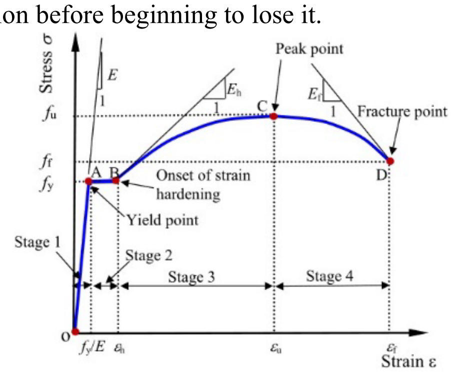
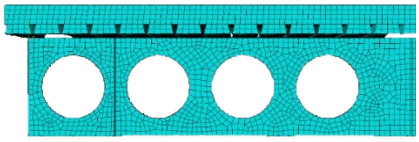
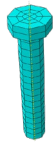


Figure 1: Discontinuous yielding model, Wang et al. [5]

The CDP (Concrete Damage Plasticity) was used for the concrete, based on the behavior and damage to traction and compression presented by Fédération Internationale du béton. et al. [6]. For this calculation, an angle of expansion of 40° was considered, the eccentricity of 0.1, the ratio of biaxial and uniaxial resistance (fb0/fc0) of 1.16, the K parameter of 0.667 and the viscosity parameter is 0.001. The shear connectors come from the bi-linear steel model used by Araújo et al. [7], with a yield strength of 460 MPa, a tensile strength of 559 MPa, and an elongation of 18.8%. The finite element used for the cellular beam is a shell element (S4R), a quadrilateral element with four nodes. A solid element (C3D8R) was used for the concrete slab and shear connector, which has eight nodes; Figure 2 shows the discretization of the elements.



(a) Composite Cellular Beam

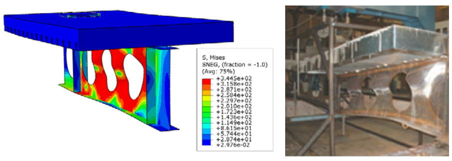


(b) Shear Connector

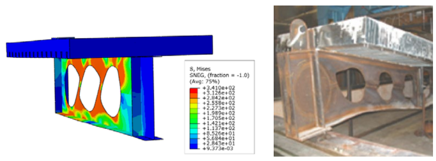
Figure 2: Discretization of elements

For the interaction between the shear connectors and the steel cellular beams, the "tie constraint" was applied, which allows perfect adhesion between the elements to be modeled. For the profile-slab and connector-slab contact surfaces, the "surface to surface" option was used, with the normal and tangential behavior defined respectively by "Hard contact" and "Penalty", the value for the friction coefficient was 0.4 according to Wijesiri Pathirana et al. [8] and used by Oliveira et al. [9] in their study. The beams were built considering symmetry (Uz = URx = Ury = 0) in half the length of the composite cellular beams, a horizontal restriction (Ux = 0) was applied to the side of the slab, and a vertical restriction (Uy = 0) was applied to the support of the beam. The CCB1 and CCB2 beams used displacement to validate and analyze the influence of the steel yield stress. This method was chosen because it presents fewer problems in the convergence of the numerical model. On the other hand, beams CCB3 and CCB4 were studied using load application for their validation and parametric analysis since displacement would generate complications in convergence for their distribution of loading points.

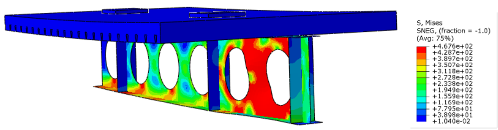
Once the modeling of the beams was complete, it was checked whether the behavior of the beams was similar to that presented in the studies on which they were based. For this purpose, the post-buckling analysis compared the deformation configuration of the beams, as shown in Figure 3, and checked the force-slip graph, as shown in Figure 4. In turn, Table 1 shows the relative error between the value of the maximum force extracted from the study by Nadjai et al. [3] and Müller et al. [4] compared to that found through numerical modeling in finite elements.



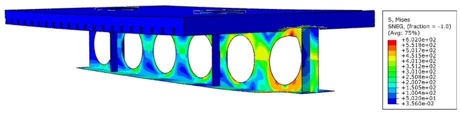
(a) CCB1, Nadjai *et al.* [3]



(b) CCB2, Nadjai *et al.* [3]

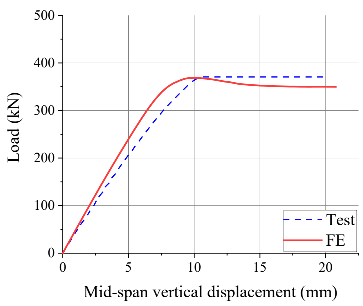


(e) CCB3

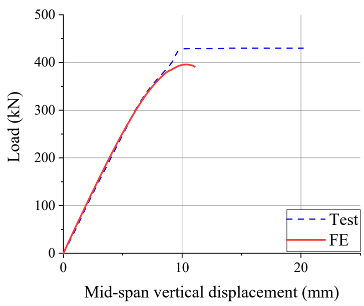


(f) CCB4

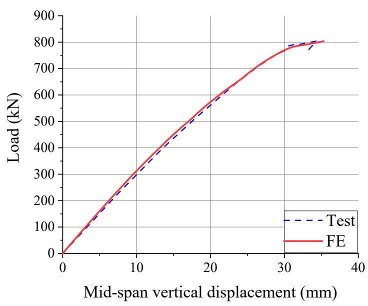
Figure 3: Deformed configuration of the validated beams



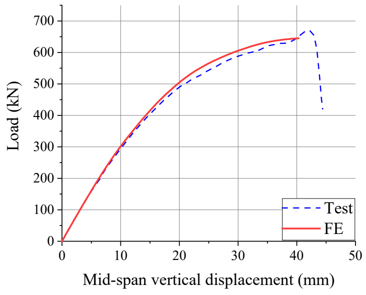
(a) CCB1



(b) CCB2



(c) CCB3



(d) CCB4

Table 2: Experimental, numerical loads, and relative error

Beam	Ultimate Load		
	Experimental (kN)	Numeric (kN)	Relative Error
CCB1	370.52	372.55	-0.54%
CCB2	429.91	403.4	6.57%
CCB3	804.11	803.44	0.08%
CCB4	669.5	645.11	3.78%

Figure 4: Validation results

After analyzing the representativeness of the numerical model, the next step was to modify the yield strength of the steel without changing the geometric characteristics of the composite cellular beams. For this, high-strength steels of 460 MPa, 690 MPa, and 960 MPa (represented by S460, S690, and S960, respectively) will be used to verify the modification of the failure mode, following the procedures shown in Figure 5. The failure criterion adopted, as was the case during the validation study, was that the steel should reach maximum stress before entering the stress-rupture phase, i.e., before entering stage 4 shown in Figure 1.

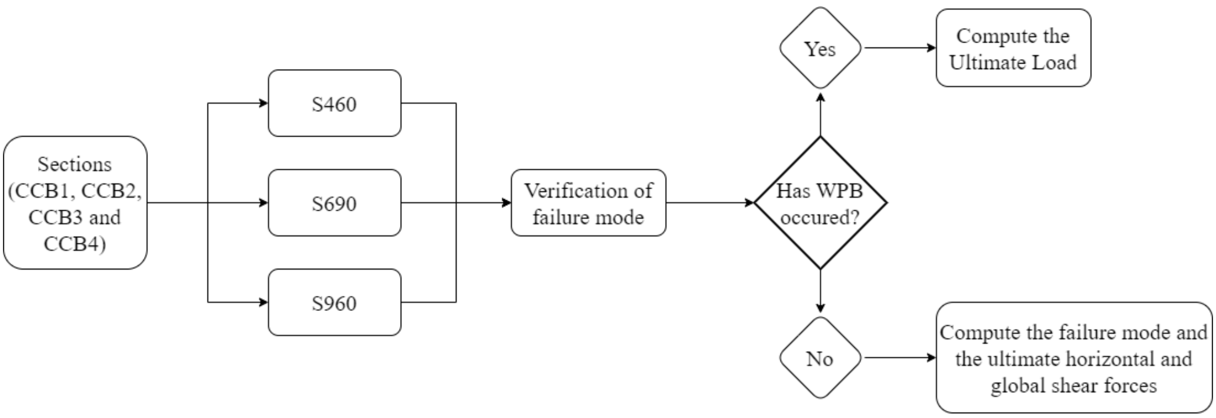
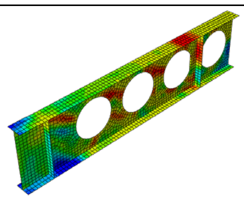
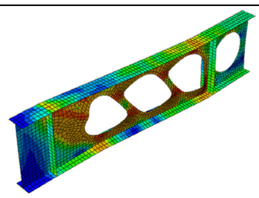
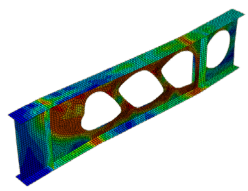


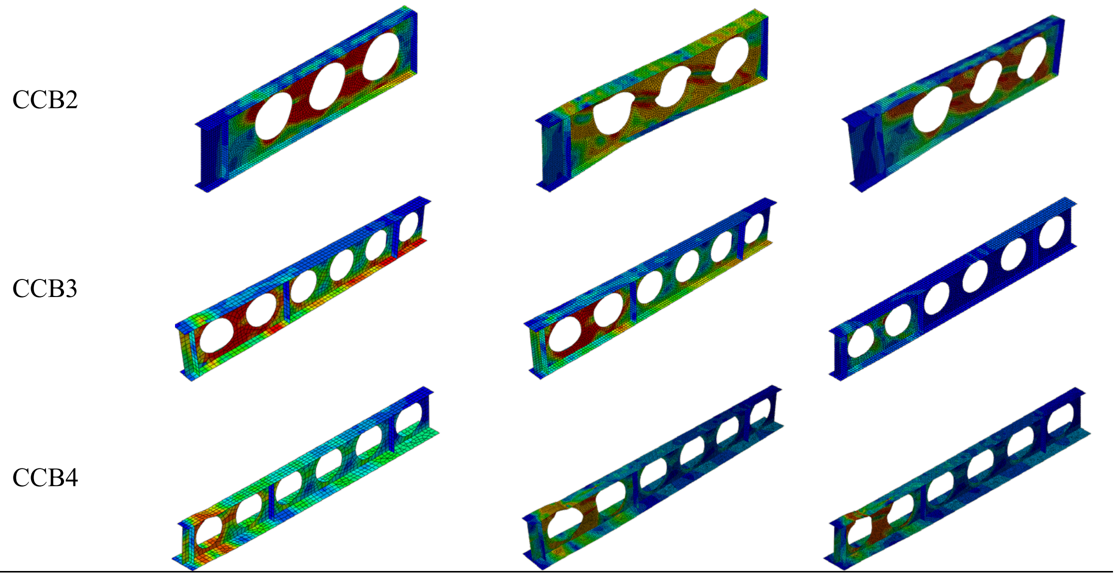
Figure 5: Procedure for parametric analysis

3 Results

A total of 12 beams modeled in finite elements were analyzed according to the proposed methodology. During pre-processing, the yield strength of the steel present in the cellular beams was changed to high-strength steels (S460, S690, and S960). Table 2 shows the deformed configurations of the beams. Among the failure modes observed, there is a predominance of plasticization due to the Vierendeel moment, as well as the appearance of web-post buckling.

Table 3: Deformed configurations

Beam	S 460	S 690	S 960
CCB1			



For the CCB1-S460 and CCB1-S690 combinations, web-post buckling was observed, while for CCB1-960, plasticization due to the Vierendeel moment was characterized as the failure mode. In turn, CCB2-S460 and CCB2 - S960 showed plasticization due to the Vierendeel moment and CCB2-S690 showed web-post buckling. In the study led by Nadjai et al [3], the verified beams equivalent to CCB1 and CCB2 showed web-post buckling as their predominant failure mode. Plasticization due to the Vierendeel moment was characterized for CCB3 and CCB4 regardless of the steel yield strength value. According to Müller et al. [4], web-post buckling was the primary failure mode observed in the beams analyzed experimentally. Figure 6 shows the influence of high-strength steel on the Load-Displacement relationship. The higher the steel yield strength, the higher the resistance capacity of the beams. Specimen CCB2-S690, it was noticed that the beam did not have significant changes after 40 mm, while for CCB2-S960, the displacement found was 55 mm. CCB3 - 460 was limited to 43 mm, while for CCB3 - S690, 48 mm was adopted. CCB4-S460 ended up at 53 mm. The application of S460 showed less growth and tended to have less deflection than the other steels, as can be seen in CCB1 and CCB2. CCB1, made with S690 steel, resulted in higher displacement compared to S960, while in beams CCB2 and CCB4 presented similar behavior. Table 3 shows the values of strength yield and load resistance for each specimen.

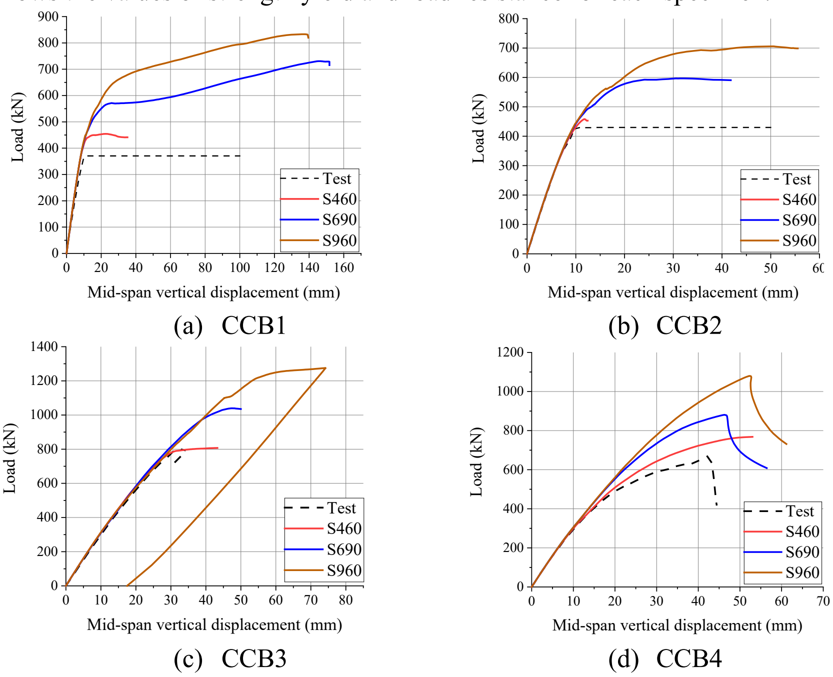


Figure 5: Load – Mid-span vertical displacement

Table 4: Influence of yield strength values on load capacity of beams

Beam	Load (kN)	Load variation	Beam	Load (kN)	Load variation
CCB1-460	454.37	-	CCB3-460	807.34	-
CCB1-690	730.74	61%	CCB3-690	1039.38	29%
CCB1-960	833.13	83%	CCB3-960	1275.05	58%
CCB2-460	458.31	-	CCB4-460	767.96	-
CCB2-690	596.75	30%	CCB4-690	880.92	15%
CCB2-960	705.82	54%	CCB4-960	1079.71	41%

4 Conclusion

This study investigated the influence of yield strength steel on the behavior and load capacity of composite beams under positive moments using numerical simulation. The main findings were:

- The numerical model developed for validation represented the beams chosen from the literature;
- The failure mode in beams CCB1 and CCB2 was modified with the application of high-strength steel. In the study by Nadjai et al. [3], web-post buckling was observed in both beams. In CCB1-S460, CCB1-S690, and CCB2-S690, web-post buckling was characterized. On the other hand, CCB1-S960, CCB2-S460, and CCB2-S960 showed plasticization due to the Vierendeel moment as the primary failure mode.
- All the combinations of beams CCB3 and CCB4 showed plasticization due to the Vierendeel moment as the primary failure mode, unlike the study by Müller et al. [4], in which the beams presented web-post buckling.
- Higher resistance capacity was recorded in composite beams with high-strength steel.

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Authorship statement. The authors confirm that they are solely responsible for the authorship of this work and that all material that has been included as part of this article is the property (and authorship) of the authors or has the permission of the owners to be included here.

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