Vierendeel failure mechanisms of composite cellular beams: Non-linear finite element analysis

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Abstract

The objective of this work is to investigate, through a numerical analysis, the non-linear behavior of composite cellular beams. In this investigation, the Vierendeel′ failure mechanisms of composite cellular beams are examined through a Finite Element modeling.

This analysis is designed to predict the Vierendeel effect by estimating the ultimate load at the openings of composite cellular beams with the same geometric and mechanical characteristics.

The finite element investigation into the behaviour, including Vierendeel effect, of composite cellular beams subjected to transverse loading has also been conducted, considering material and geometrical non-linearities.

This analyze was used to show the reduction of the resistance to composite cellular beams in the non-linear domain.

Keywords: composite cellular beams; non-linear behavior; Vierendeel′failure mechanisms; ultimate load; numerical simulation

1. Introduction

Composite cellular floor beams are currently widely used in multi-storey building construction, especially to achieve long spans at the same time as providing passage for service ducts, hence reducing overall building height. The down stand composite beams make use of their full structural depth, maximizing the lever arm between the compressed concrete flange and the steel section which acts essentially in tension. The optimization of this structural form, however, raises questions about potential failure modes.

The presence of the openings causes the appearance of specific failure modes of cellular beam, the most significant (notable) of which is the formation of plastic hinges by Vierendeel bending at the opening (Figure1).

Figure 1. Vierendeel Mechanisms [1]

The design of composite cellular beams is not fully covered by existing guidance but is an area of important practical application. Few work has been done on this type of beams, we quote:

Design for simply supported steel and composite cellular beams as used in structures was presented by Ward J.K. [2]. Design procedures were associated with British Standard 5950: Part I and Part 3.1 provisions [3]. The behavior of these beams was described and flexural, local, web-post strengths and bending modes of non-composite and composite cellular beams were also derived from parametric study involving detailed finite element analysis.

R.M. Lawson et al **[4]** have showed that the asymmetry in the shape of the cross-section of cellular beams causes development of additional bending moments in the web-posts between closely placed openings. Furthermore, the development of local composite action influences the distribution of forces in the web-flange Tees. The Web-post moments also influence buckling of the web-post between openings, which is accentuated by adjacent long openings.

D. Bitar et al **[**1**]** have presented a new analytical model for the buckling verification of the composite cellular beam posts.

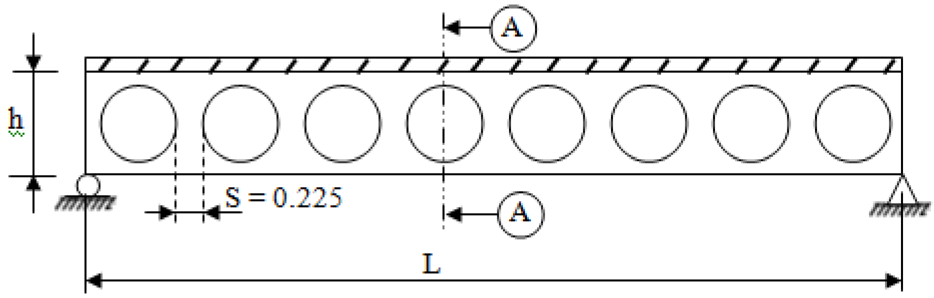
It can be noted that in the revised version of the European Standard (Eurocode 4, 1994) provisions [5], no specific approach for calculating of composite cellular beam is specified.

The paper presents an investigation of the Vierendeel mechanism by estimating ultimate load at the openings in composite cellular beams based on nonlinear finite element analysis in using the Cast3m calculation code [6]. For this purpose, the numerical tests are performed on a composite cellular beam, with an even number of opening (8 holes) under transverse loading effect.

2. Parametric Study

The parametric study is performed for simply supported composite cellular beams, subjected to the transverse loading effect, and for different I-profile. The static scheme and the section of composite cellular beam are shown in Figure2.

a)



b)

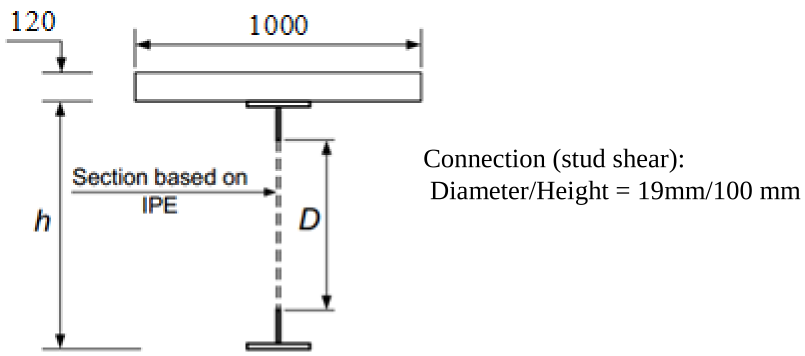


Figure 2. Composite Cellular Beam: a) Static Scheme, b) Cross-Section (A-A)

2.1 Numerical Modeling

2.1.1 Finite Element (FE) Modeling

In order to simulate the structural behavior of the composite cellular beams and investigate the Vierendeel mechanism, a finite element model was established that included both material and geometric nonlinearity.

The model used in the numerical simulation (Figure3) is integrated into a three dimensional model developed using the Cast3m calculation code [6]. The four-noded shell elements are used to model the steel beam, the reinforced concrete slab is modeled using four-node multilayer shell elements, and the connectors (studs shear) are modeled using two-node beam elements .

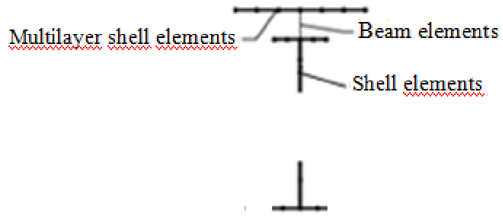


Figure 3. Finite Element Modeling

2.1.2 Materials Properties

The real properties of materials of the composite cellular beams are presented in Table1.

Table 1. Basic Material Properties of Composite Cellular Beams

Property (MPa)	I-Section	Concrete	Studs Shear
f_y	413	/	450
f_c	/	46	/
E	210000	34000	210000

2.1.3 Constitutive relations

It was considered that the steel section and steel connectors have a bi-linear elastic plastic constitutive relationship with an isotropic hardening consideration (figure4.a). In the case of composite structures, the concrete section has a bi-linear elastic plastic constitutive relationship with an isotropic hardening consideration, and with different yield stresses for tension and compression (figure4.b). Given the functioning of the beam (slab in compression), the adopted model for the concrete section is considered with yield stresses for compression.

The stress-strain curves followed the constitutive models presented in and they were used in and, as shown in Figure4.

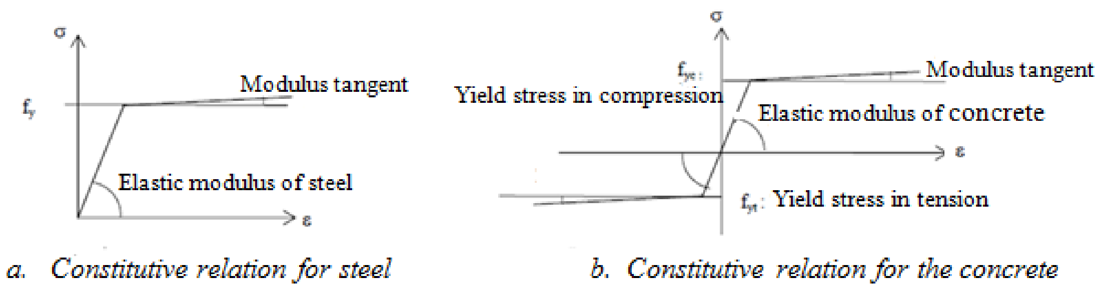


Figure 4. Stress-Strain Curves

It is assumed that deformations distributions in the concrete and in the metal section are parallel, that is to say, there is no separation in the concrete-steel interface and that the curvatures are equal in concrete and in the profile. This assumption is translated in the model by imposing that rotations of the ends of the studs are equal.

It should be noted that the loading of the numerical model is carried by an imposed displacement at mid-span of the beams.

2.2 Results and Discussion

2.2.1 Local Yielding by "Vierendeel effect"

The "Vierendeel" mechanism is always critical in the most solicited section at the opening where the development of a plastic hinge is driven by these solicitations. This critical section is located at the Tes inclined at an angle φ (15 ° < φ < 25 °) [7] relative to the vertical axis of the opening (Figure5).

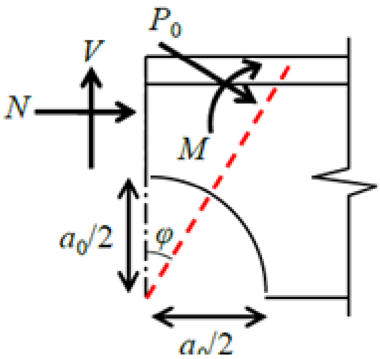


Figure 5. Vierendeel Bending in Critical Section

In order to confirm the location of the critical section (φ ranging between 15 ° and 25 °) at where the Vierendeel effect is striking, a comparison was made for different inclination angle (φ) namely 16 °, 20 ° and 24 ° at the central opening of the composite cellular beam fabricated from IPE400 profile, under progressive loading effect (Table2).

Table 2. The Displacement Value for Different Critical Sections

Inclination angle (φ)	Displacements (mm)	Ultimate Load (kN)
16 °	1.9	
20 °	2.0	84.15
24 °	1.9	

It should be noted that the displacements for different critical sections (φ ranging between 15 ° and 25 °) directly obtained from finite element modeling, have the same value 2mm with 84.15 kN applied load value, as given in table2.

In this context, a study on local yielding by Vierendeel effect (Figure6) of a composite cellular beam with two studs in the grip of the opening was presented. This study was carried out by interpreting the curves of the evolution force (load)-displacement.

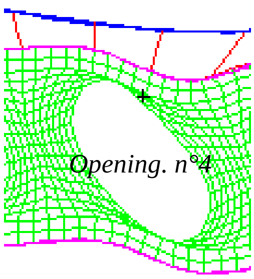
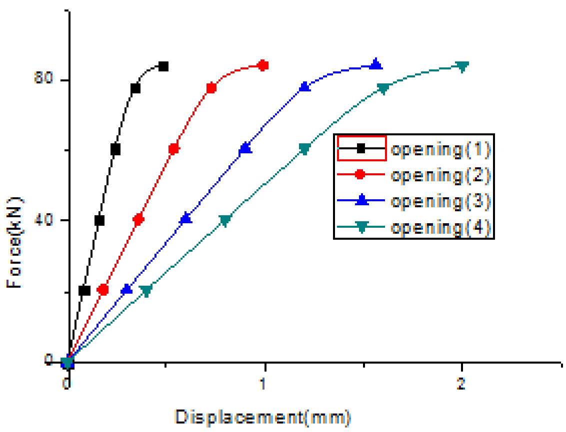
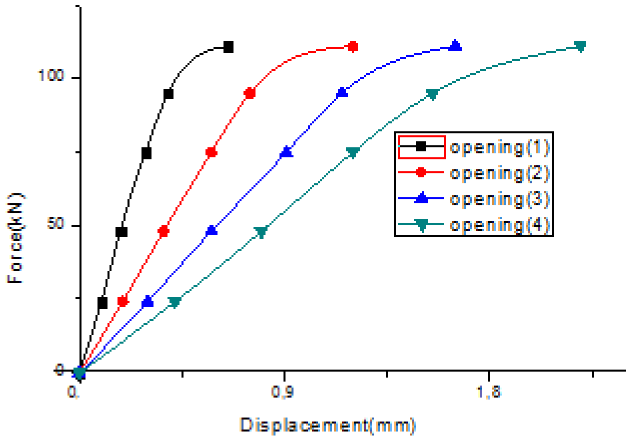


Figure 6. Plastic Hinge in the Upper Member of the Beam

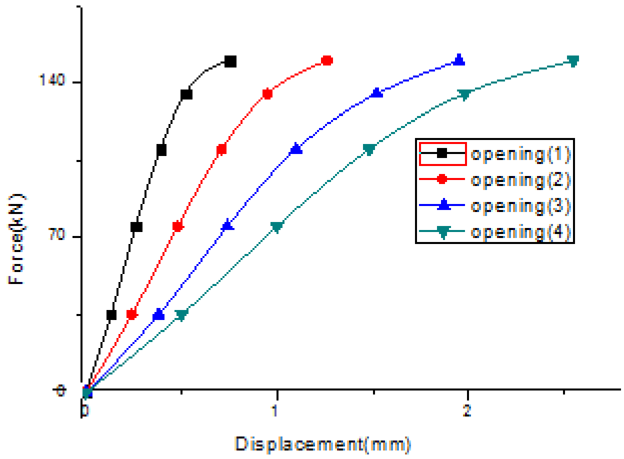
The curves of the Figure7 represent the variation of the force (load) versus displacement at a Te inclined an angle Ø = 20 °



a. Composite Cellular Beam Fabricated From IPE400



b. Composite Cellular Beam Fabricated From IPE500



c. Composite Cellular Beam Fabricated From IPE600

Figure 7. Behavior Force-Displacement at the Openings

It is noticed that the deflection at the critical section of central opening (opening n°4) of the composite cellular beams, is most significant than those of other openings.

For a better analysis on the “Vierendeel" mechanism, the loads values causing same displacements at the critical section (φ = 20 °) of the central openings for different I-profile, are presented in the table3.

Table 3. The Total Applied Load Value for Different I-Profile

Displacement	Total Applied Load		
	IPE400	IPE500	IPE600
0.50	25	28	32
1.00	50	56	64
1.50	75	84	95
2.00	83	108	127
2.50	96	116	149

It should be noted that an increase in the I-profile, always reduces the total applied load which causes the same displacement at the critical section (φ = 20 °) of the the central opening.

2.2.2 Effect of Connectors (Studs) Number at the Opening on the Vierendeel Mechanism

In this section, a study on local yielding by vierendeel effect due to the presence of a different connectors (studs) number in the openings grips (Figure8) of the previous composite cellular beams was presented.

A comparison was made on Vierendeel mechanism between the beams (p1), (p2) and (p3) having a single stud, two studs and three studs respectively in the grip of the opening.

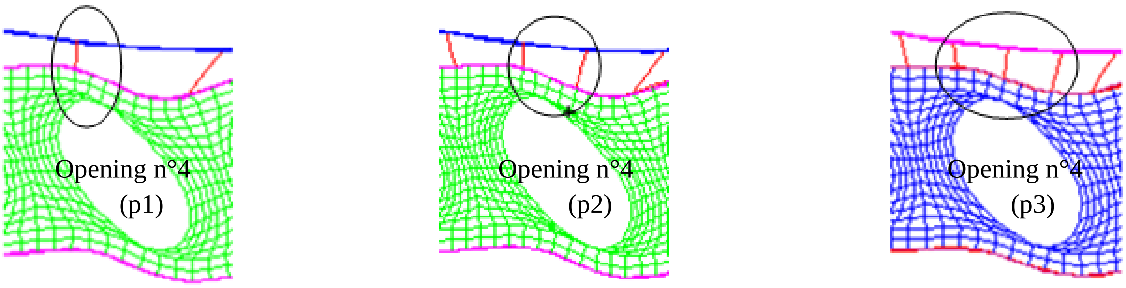


Figure 8. Plastic Hinge in the Upper Member of the Beams (p1, p2, p3)

This study was carried out by interpreting the curves of load (force-displacement) evolutions (Figure9) of the beams (p1), (p2) and (p3).

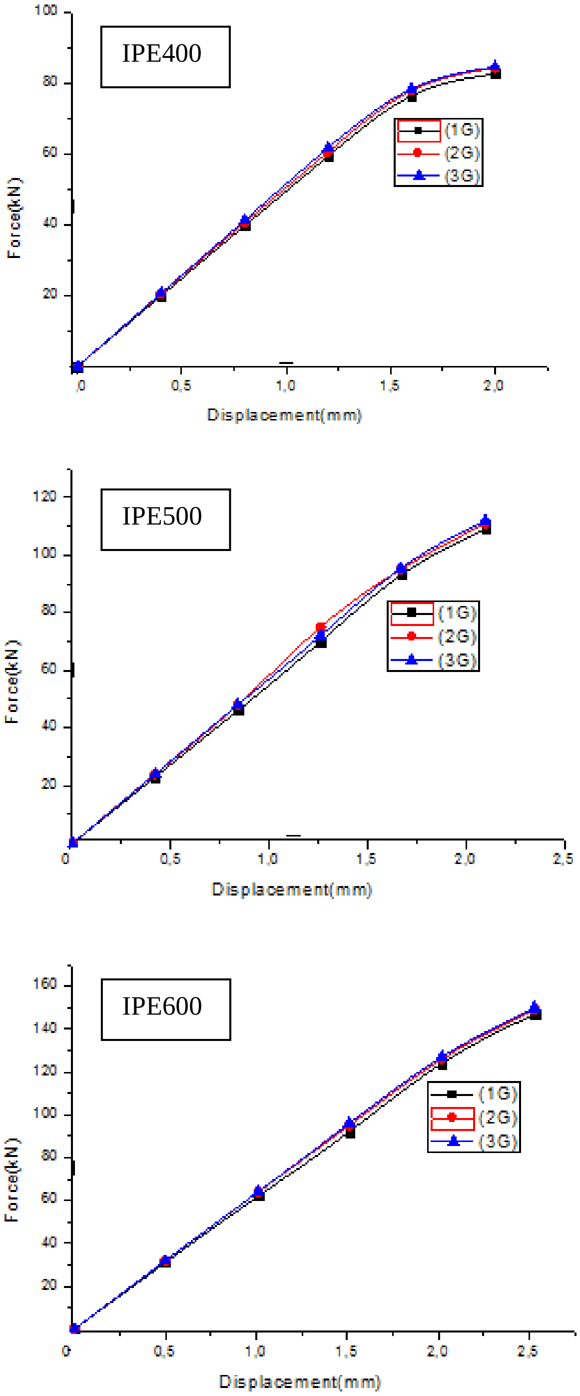


Figure 9. Behavior Force-Displacement at the Opening (n°4).

According to Figure9, it is noticed that the ultimate loads producing the vierendeel mechanism are almost of the same order of magnitude.

It should be noted that the Vierendeel effect occurred at the central openings of the beams (p1), (p2) and (p3), under ultimate loads of:

82.47kN, 84.15kN and 84.44kN respectively for the case of composite cellular beam fabricated from IPE400.

109kN, 111kN and 112kN respectively for the case of composite cellular beam fabricated from IPE500.

147kN, 149kN and 150kN respectively for the case of composite cellular beam fabricated from IPE600.

3. Conclusion

Ultimate load capacity was measured numerically to predict the Vierendeel mechanism in composite cellular beams with the same geometric and mechanical characteristics, under the effect of an imposed displacement at mid-span. It was found that the local yielding by "Vierendeel effect" is most striking in the critical section of the opening. Thus, whatever the number of connectors (studs) which affects the opening grip, the Vierendeel mechanism represents the same effect.

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