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An analytical method for the resistance of cellular beams with sinusoidal openings

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ABSTRACT

A new type of cellular beams fabricated from hot rolled profiles appeared recently, whose openings have a sinusoidal shape. These beams are used either for steel or composite structures and they allow rectangular ducts, even with large sizes, to pass through their openings. They can thus lead to a substantial reduction of the floor thickness and they contribute to increase the competitiveness of steel buildings. The aesthetic shape of the openings is also an advantage to improve the architectural attractiveness of steel frames.

To take benefit from these possibilities, accurate design methods are required and this research project has been undertaken to establish the static behaviour of these beams with sinusoidal openings. This paper presents the results of 4 tests (on 3 steel beams and on a composite beam) and of 287 numerical simulations carried out to determine ultimate loads and failure modes under the simultaneous effects of bending and shear. A new analytical design method is then proposed for the resistance of cellular beams with sinusoidal openings taking into account the Vierendeel effect. This new model can be used within the range of the geometrical and mechanical scope. Finally the comparison of the ultimate loads according to this new model and according to the reference database (experimental or numerical data) is provided to assess the safety and accuracy of the proposed expressions.

1. Introduction

A cellular beam is made by cutting a hot rolled steel profile following a specific path, and welding of the two chords, which forms a beam with regularly spaced openings having identical shapes. This type of beam has several advantages:

- cellular beams allow ducts and services to pass through their openings, and then lead to a substantial reduction of the floor thickness;
- the final beam has a greater height than the basic profile and thus a greater second moment of area: it is then possible, for the same steel weight, to achieve larger spans;
- the aesthetic aspect is generally of major interest and can be expressed in the structure.

Historically, the hexagon was the first shape used for openings since the 1960's [1]. More recently, cellular beams with circular openings (CBCO) have been developed, based on important experimental and numerical research programs [2,3,4]. The Vierendeel mechanism due to the local bending induced by the shear transfer around the opening is generally the failure mode for rectangular/hexagonal openings [5,6,8] or circular openings [7,8].

Lately, a new type of opening has been proposed, based on a sinusoidal shape of the cutting to form cellular beams with sinusoidal openings (CBSO). This type of beams is given the trade name of Angelina.

An important research study, including experimental tests and numerical simulations, has been carried out in order to develop a calculation model for the design of the beam. In the same time, additional research was also conducted on steel beams by Durif et al., based on the same experimental background [10–13]. Durif et al. [13] considered also the Vierendeel mechanisms and the behaviour of each quarter around openings based on the calculation of a critical stress coefficient.

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Nomenclature

a_0	height of an opening
b_f	width of the flanges of the basic profile
$b_{f,eff}$	effective width of the flange
c_w	height of the straight part of the CBSO web, given by: $c_w = H_t - 2\,(t_f + r_c)$
E_{slab}	total depth of the slab of a composite CBSO
f_y	yield strength of the basic profile
h_p	height of the basic profile
H_t	final height of the CBSO beam: $H_t = h_p + a_0/2$
ℓ_{op}	length of an opening, given by: $\ell_{op} = 2\,s + w$
P_{Rd}	shear resistance of a stud
r_c	radius of the fillet of the basic profile
s	length of the sinusoidal part of an opening
t_f	thickness of the flanges of the basic profile
t_w	thickness of the web of the basic profile
w	length of the straight part of an opening, which is also the width of the post at the welding between chords
w_{end}	width of the two end posts at their welding between chords
ε	parameter for the profile's steel defined by: $\varepsilon = \sqrt{235/f_y}$

This paper presents the results of a study on steel and composite beams, which especially focused on the ultimate limit state. After the presentation of the scope in Section 2, the experimental tests performed on three steel beams and one composite beam are summarized in Section 3. A numerical model based (Section 4) on the finite element code ANSYS have been developed to extent the scope of experimental tests. A total of 150 steel beams and 137composite beams have been studied during this extensive parametric analysis. From these numerical and experimental database an analytical model is proposed in Section 5 for steel beams and Section 6 for composite beams taking into account the Vierendeel effect and the longitudinal shear of posts. Finally the comparison of the ultimate loads according to this new model and according to the reference database (experimental or numerical data) is provided to assess the safety and accuracy of the proposed expressions.

2. Parameters and scope of the research

Three main parameters describe the shape and dimensions of the opening of a CBSO beams (cf. Fig. 1): a_0 the height, w and s the lengths of the straight part and of the sinusoidal parts respectively.

During the study, it was necessary to distinguish the openings and posts located at the ends of the beam from the posts between openings. Thus the specific terminology indicated on Fig. 2 will be used in the paper.

All the results presented in this paper have been obtained for cellular beams fulfilling the following criteria:

- both chords of the beam come from the same basic profile, and thus are symmetrical and have the same material properties;
- the height is constant along the beam;
- the minimum height of the basic profile is 140 mm ($h_p \geq 140$ mm);
- the width of intermediate posts is at least 150 mm ($w \geq 150$ mm);
- the width of end posts is at least 100 mm ($w_{end} \geq 100$ mm);
- the slenderness of an opening is limited by $\ell_{op}/a_0 \leq 5$;
- the distance between the opening edge and the flange is at least 50 mm: $(H_t – a_0 – 2\ t_f)/2 \geq 50$ mm
- the slenderness of a web post is limited by $c_w/t_w \leq 124\ \varepsilon$;
- the beam has at least four openings;
- the beam is simply supported and stiffened at its both ends.

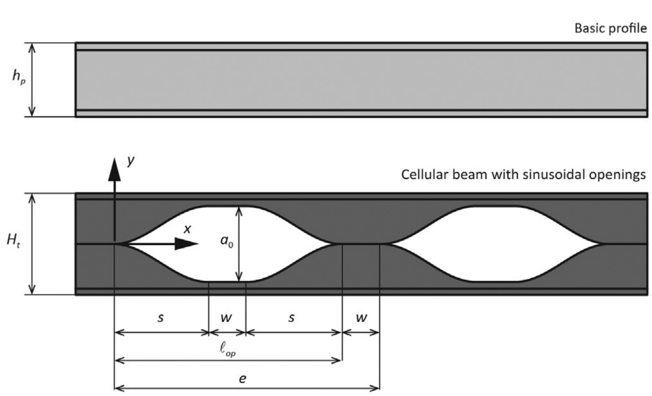

Fig. 1. Main parameters.

3. Experimental program

Three steel cellular beams have been tested during the program at the University of Clermont-Ferrand (France) and one composite beam at the University of Louvain (Belgium). The main objective of these tests was to study the ultimate behaviour under static loads. The sensitivity to the web buckling was also under consideration and the profiles selected were chosen with high values of slenderness. This paper summarizes the main outcomes of the tests. It is to be noted that tests carried out at University of Clermont-Ferrand were also part of the thesis work of Durif [11].

All four beams tested were simply supported at their both ends and have been loaded by a single jack, which transmitted its force through a crossbeam in two locations (cf. Fig. 3). Regularly spaced lateral restraints prevent any lateral buckling of the beams. For each test, the same procedure was applied, divided in the following steps:

- Measurement of the geometrical dimensions of the beam (sections, openings and length) – cf. Table 1;
- Characterisation of the yield strength for the steel of the beams (mean values are given in Table 2);
- Test in the elastic range, to determine the elastic initial rigidity, by 3 loading/unloading cycles;
- Reinforcement of the openings at one end of the beam, to impose the failure at the other end where the instrumentation is concentrated (cf. Fig. 4);
- Ultimate loading test, where the beam is loaded incrementally until a mode of failure is obtained (control of the jack by displacement).

For the composite beam, the average concrete cylinder strength was 34.9 N/mm^2, whereas the specified class of concrete was C30/37.

From all the four beams tested, the main failure mode appeared to be a Vierendeel mechanism, with the development of plastic