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Experimental and numerical investigation on web-post specimen from cellular beams with sinusoidal openings

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ABSTRACT

The study is focused on the experimental and numerical analyses of isolated web-posts specimens with four opening quarters taken from whole cellular beams. The external loads are applied at the ends of two opening quarters to obtain well known internal forces in the cross sections along the analyzed quarters. The tests showed that the failure modes are characterized either by the formation of plastic hinges in the linear part or by local instability in the sinusoidal parts of the opening quarter similarly to those observed on the corresponding whole beams. A numerical model is built to analyze the behavior of the web-posts considering large displacements and plasticity of materials. The model validated by comparison with experimental results predicts well the failure mode and the ultimate load of the isolated web-posts. It can be used as a tool to develop more extensive studies to propose efficient and reliable design methods.

1. Introduction

Cellular beams are commonly used as long span systems in steel construction. They are generally built from hot rolled sections with oxy-cutting of the parent profile. Then the two parts of the parent profile are separated, positioned and finally welded so as to get the cellular beam. Thus, with the same weight, the cellular beam can reach 1.5 times the height of the parent profile [1]. However, the presence of the openings in the web weakens its torsional stiffness that leads to global buckling. Besides, cellular beams are generally considered laterally supported due to the presence of secondary beams or composite slab [2]. As a consequence, the common design approaches are focused on the failure modes arising around the openings either by the Vierendeel mechanism [3,4] or the web-post buckling [5–8]. The latter mode usually concerns cellular beams with closely spaced openings.

Redwood [9] was one of the first authors who proposed a design method for the cellular beams at the ultimate limit state. The published results of experimental studies on rectangular and hexagonal openings [3,5,7,9] pointed out that the failures arise by local bending creating plastic hinges at the four corners of the opening (Fig. 1). As this failure mode is similar to that observed in the Vierendeel girder, the analogy between the cellular beams and the Vierendeel beams is adopted in the commonly used analytical models [9–11]. In these models, the global shear force and the global bending moment are equilibrated by the internal forces representing the local bending moments and normal forces. These internal moments and forces are compared to the resistances of the constituting openings parts.

Many studies proposed design rules to predict the load carrying capacity of steel beams with multiple circular openings. The work of Ward [11] based on a curved beam theory and finite elements results provided substantial results used to define a reliable design method for cellular beams considering the Vierendeel mechanism. The study showed that the best way to predict the local resistance around a circular opening is to check the resistance of each inclined section around the opening. Thus, a first analytical model based on the approach of inclined sections, initially proposed in the SCI publication [11], has been used in the Annex N of ENV 1993-1-1 [12]. The same approach validated on experimental and numerical results was developed by the CTICM [13] and used as a reference in the software ACB^{+} [5,13,14]. The normal and shear internal forces, in the mid-length section, are used to evaluate those in each inclined section (normal force, shear force and local bending moment). Those forces are compared to the plastic or elastic resistance for each inclined Tee section.

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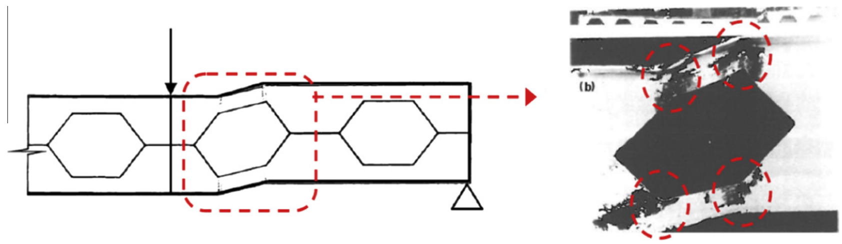

Fig. 1. Plastic hinges around the opening due to the Vierendeel bending [9].

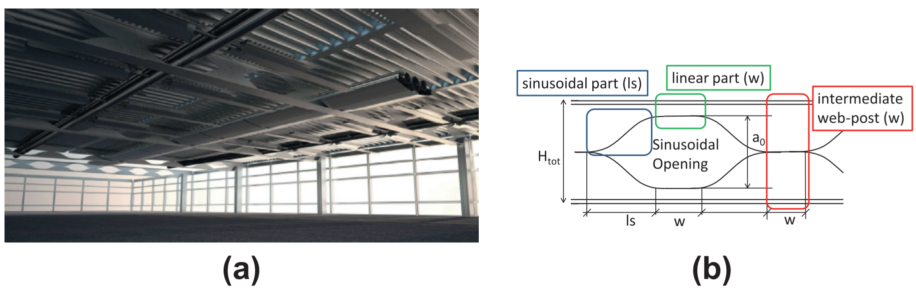

Fig. 2. Example of a floor with Angelina™ beams (a), sinusoidal opening description (b).

Recently, new opening shapes were developed by the steel industry and the applicability of the methods developed for circular openings needs to be evaluated and adapted [15]. Cellular beams with sinusoidal openings called Angelina™ beam (Fig. 2a) are made from hot rolled profiles with regular openings as for circular openings. In addition to the aesthetical aspects, the sinusoidal shape offers a wider range of opening sizes in comparison with circular shapes. Indeed, the sinusoidal length (*ls* in Fig. 2b) can be changed independently of the linear part (*w* in Fig. 2b). As a consequence, the obtained opening shape is either close to rectangle, hexagon or circle. The sinusoidal openings are characterized by a wide web-post (Fig. 2b). Thus, the web-post buckling which is a typical failure mode of cellular beams with circular openings does not arise with sinusoidal openings [16]. However, the sinusoidal part generates a specific mechanical behavior with local instabilities in addition to the common failure mode due to the four plastic hinges around the openings. Thus, depending on the opening dimensions, the Vierendeel bending induced by the shear transfer around the opening implies either the formation of four plastic hinges in the linear part (Fig. 3) or the development of local instabilities in the slender sections of the sinusoidal part (Fig. 6) [16].

In fact, with small sinusoidal web parts and high opening depth, the failure mode is generally due to the formation of plastic hinges in the linear part. Whereas, the large and slender web in sinusoidal parts around the opening promote the development of local instabilities needing to be evaluated through experimental and numerical analyses before proposing advanced analytical approaches. Till now, the behavior of sinusoidal openings has been analyzed in a limited number of published studies despite its complexity [16–18]. The present paper investigates this local behavior through experimental and analytical analyses of isolated parts of cellular beams with sinusoidal openings.

This study is focused on the behavior of an isolated web-post representing basic units in cellular beams. The aim is to evaluate the pertinence of the use of a simple specimen to represent the local behavior of the cellular beam opening part. Thus, an experimental campaign is performed on isolated web-posts taken from real beams to observe the local behavior of the sinusoidal openings under known internal load. Each web-post is composed of two half-openings loaded in shear to generate local bending (Fig. 5). The experimental results provide the failure modes and the ultimate loads of the sinusoidal half-openings.

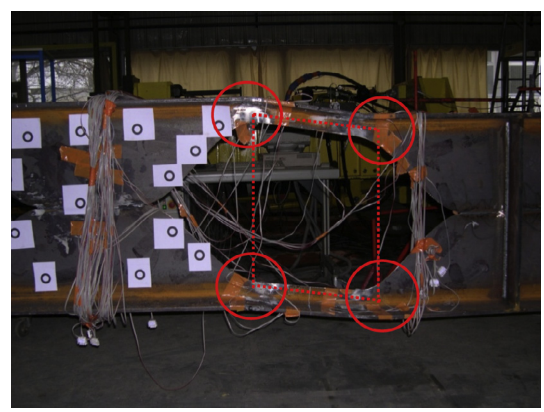

Fig. 3. Four plastic hinges around the opening at ultimate load [16].

In parallel, a numerical model is developed using Cast3M software [19] with large displacements and non-linear behavior of materials. The numerical model is validated by comparison of its failure load and mode with those of the experiments. It is developed as a numerical tool for further parametric studies to quantify, for example, the rotational partial restraint provided by the intermediate web-post to the adjacent opening quarters subjected to local buckling [18]. The relationship between the isolated web-post and the whole beam is discussed to evaluate the possibility of extending the existing analytical models of circular openings to sinusoidal openings.

2. Mechanical behavior of beams with sinusoidal openings

Experimental and numerical investigations have been performed on full scale Angelina™ beams (see Fig. 6) with three different geometrical configurations at Blaise Pascal University Clermont-Ferrand [16]. They showed the specific failure modes