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Experimental tests and numerical modeling of cellular beams with sinusoidal openings

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ABSTRACT

New type of cellular beams with sinusoidal shape of openings shows a specific behavior in comparison with the standard circular openings. Full scale tests were realized on three beams representing various dimensions of the openings. The aim was to observe the failure modes of these beams and to obtain the ultimate values of strength. The specimens were heavily gauged to clearly identify the local failure modes of the opening zone. Two specific failure modes were observed. For the opening with large height, the failure is reached by the formation of four plastic hinges at the corners of the critical section (Vierendeel bending). This mode is similar to that of the rectangular opening. Whereas with the small opening, failure arises by the local instability of the compressed out stand panel in the sinusoidal parts of the opening. A numerical model is developed and calibrated on the basis of the experimental results. The numerical model is used to analyze with more details the behavior of the critical opening including the stress distribution in its different parts. The experimental results provided useful qualitative and quantitative information to understand the behavior of the cellular beams with sinusoidal openings. The numerical model showed a good accuracy in the prediction of the experimental results. It can be used as a tool to generate complementary results to develop an analytical model.

1. Introduction

Long span beams commonly used in steel construction started to use large web openings during the last century in order to reduce the floors depth by passing all services through the web heights. The presence of the large openings changes the local transfer of the internal forces mainly the shear force. In 1978, Redwood [1] presented one of the first experimental studies on beams with large isolated rectangular web openings described in Fig. 1. These tests showed a new local failure mode due to Vierendeel bending [2–5]. In fact, the shear transfer around the opening is equilibrated by the local bending of both upper and lower members of the opening represented by tee section. This local bending creates local hinges at the four corners of the opening.

Later, castellated beams composed of regularly spaced hexagonal openings were proposed. As continuation, following the architectural and technical demands, constructors developed circular shapes of openings instead of the hexagonal shapes to obtain the well known cellular beams. These beams produced by cutting and re-welding of hot rolled sections are made of regularly spaced circular openings. Thus, for the same weight of steel, the cellular beam can reach 1.5 times the height of the parent profile [6]. Nowadays cellular beams are widely used in steel construction and have become the most popular long span system.

This new type of beam showed a mechanical behavior similar to that of isolated rectangular openings mainly regarding the Vierendeel bending [7]. However, unlike rectangular or hexagonal openings where the critical sections are in the corners, it is not easy to define the position of the critical section around circular openings [8]. Numerous investigations and especially the work of Ward [9] based on finite element study provided substantial results that were used to develop a reliable design method to check the resistance of cellular beams with circular openings. The method proposes to check incrementally all the inclined sections around the opening starting from the straight section at the mid span of the opening. Then, the internal load of each inclined tee section is compared to its resistance as shown in Fig. 2 where V_{Ed} and M_{Ed} are the global shear force and bending moment.

Moreover, several works on castellated and cellular beams showed a new local failure mode due to the buckling of the intermediate web-post. This failure mode is observed for closely spaced openings and slender profiles [10] (Fig. 3). The reference [11] describes

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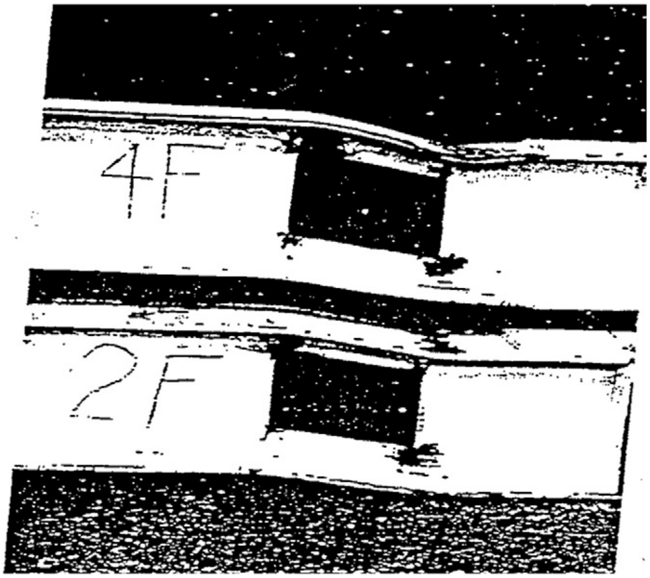

Fig. 1. Failure modes of beams with isolated large rectangular opening [1].

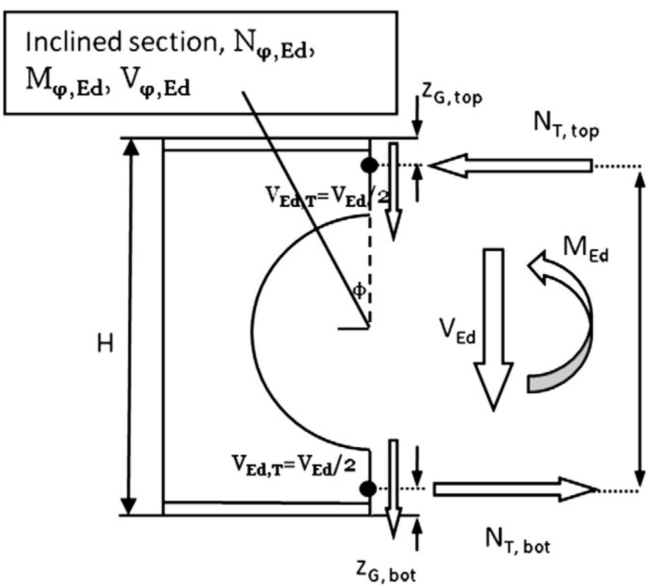

Fig. 2. Local distribution of global forces M_{Ed} and V_{Ed}.

Fig. 4. Specimen of cellular composite beam with wide openings (RFCS project) [6].

experimental and numerical studies led by the CTICM to understand the behavior of these beams and to propose analytical formulae predicting the resistance of the intermediate web-posts of cellular beams.

Many other researches have been conducted to develop design methods and to propose expressions for standard codes on the basis of experimental and numerical studies [11–14]. Extensive experimental studies were led as part of a European research project to investigate the evolution of composite action near the supports of a cellular beam, the influence of the local load due to secondary beams, the influence of the asymmetry of cross-section and the influence of the elongated openings in cellular beams (Fig. 4) [6,14]. The buckling of web-post in cellular beams exposed to fire was also analyzed (Fig. 5) [13] to propose an analytical model predicting the resistance. The analytical model was validated on the basis of numerical models and added to the software ACB+. An experimental study combined with numerical approach concerned the cellular beams with closely spaced openings and different opening shapes close to the circle [15]. This study analyzed the web-post buckling and an empirical formula predicting this failure mode is proposed for various opening shapes.

A new type of castellated beam made from hot rolled profiles called Angelina™ with sinusoidal openings has been developed [16]. The Angelina™ beam is constructed from a hot rolled profile with only one oxycutting line instead of two for the standard cellular beam with circular openings. This new opening shape has some similarities with the circular and the hexagonal openings. However, the main common point between the circular and the sinusoidal openings is the variation of the tee sections to be checked around the opening, which makes the critical section position difficult to predict. Furthermore, due to the fabrication process, having large openings implies

Fig. 3. Failure modes of composite cellular beams: Vierendeel bending (left), web-post buckling (right).