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Structural behaviour of arched steel beams with cellular openings

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ABSTRACT

Arched beams with cellular openings (referred to here as arched cellular beams) are used as roof beams with several practical advantages and architectural-appearance requirements. This paper presents a discussion regarding the performance of arched cellular beams. An experimental program comprising four full-scale specimens was performed. The perforated cellular arched I-sections with hinged-hinged supports under a mid-span vertical concentrated load were tested. Manufacturing, material properties, boundary conditions, and the test setup are discussed in detail in this paper. The experimental investigation was carried out to study the effects of cellular web openings, subtended angles, and radii of curvature. The failure modes and key parameters were investigated. The web buckling resistance of the experimental specimens was calculated using two models from the literature. The analytical model for straight cellular beams proposed by Lawson et al. [1] yielded feasible conservative values for the critical buckling resistance of web posts for arched cellular beams. Finally, a finite element (FE) model is proposed to analyse the behaviour of arched cellular beams. It was validated by experimental results. The FE model accurately predicted the ultimate loads, the critical buckling loads and the failure modes of the tested specimens. It can be used for similar future studies.

1. Introduction

A cellular beam is a modern type of a ‘castellated beam’ [2], and both are known as expanded beams. The solid sections of roof or floor beams could be replaced by expanded beams (castellated or cellular), where the web openings are used as passages for mechanical, electrical, and plumbing systems without increasing the height of ceilings, as well as reducing the cost of engineering services. Structurally, the vertical bending stiffness of the castellated beam is greater than the parent solid beam because of increasing the beam depth. In addition, cellular beams have sections with greater efficiency than castellated beams, where the cellular openings provide a more regular stress distribution as well as increased usable areas than any other opening shapes [3].

Castellated beams were first developed in the United States by the Chicago Bridge and Iron Works in 1910 [4], and since then, a wide range of web opening shapes have been studied [5–10]. Choosing the shape of the web opening depends upon the design purpose of the opening, and regular-shaped openings, for instance circular, are typically chosen. Using ANSYS software, a comparative analytical study for castellated and cellular beams was presented by Pachpor et al. [2]. The results showed that the von Mises stress is smaller in circular openings compared to hexagonal openings of the same area. The performance of cellular beams was investigated by Kuchta and Maslak [11]. Their study of cellular beam stability showed that the design procedures of cellular beams should differ significantly from the solid parent beam. Therefore, the design equations of cellular steel beam were presented [1, 12–14]. Erdal and Saka [15] conducted experimental and finite element studies to establish the load-carrying capacity of non-composite cellular steel beams. Sheehan et al. [16] studied experimentally a long span composite cellular beam under flexural and shear stresses, and investigated the ability of composite beams to develop their plastic bending resistance with low degrees of shear connection.

A new type of web opening was proposed by forming a cellular beam with sinusoidal openings [17–20]. An analytical model, based on experimental tests and numerical simulations, was developed and discussed. The analytical model presented by Durif et al. [19] considered both the behaviour of each quarter around the openings and Vierendeel mechanisms. The analytical methods presented by Martin et al. [20] presented the criteria of the resistance of beams to Vierendeel bending and the resistance to the horizontal shear force in web-posts.

Currently, engineers incorporate arch-shaped beams into a variety of modern buildings and bridges. Because of their elegant shape, arches offer architects opportunities to express their ideas. Numerous studies have reported on the structural stability behaviour of solid steel arches, and design rules have been proposed for both in-plane buckling [21–23] and out-of-plane buckling [24–28].

Spoorenberg et al. [29, 30] studied the mechanical properties of roller-bent wide flange sections. The employment of a single bi-linear stress-strain relationship across the entire section led to a significant simplification of the analysis. The roll bending process has an impact on the material parameters. Based on the experimental and analytical

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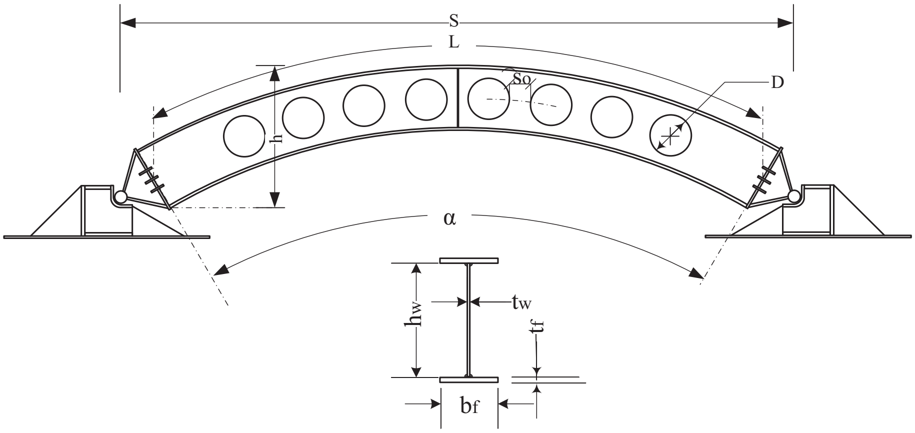

Fig. 1. Dimensions of test specimens.

results presented by Spoorenberg et al., a series of equations were proposed to obtain the stress-strain relationships for roller-bent wide flange steel arches.

However, previous studies on the structural behaviour of steel arch-shaped beams have focussed primarily on the arched beam with solid webs. Concerning the advantages of cellular beams, this paper presents an experimental investigation of an arch pin-ended steel I-section having cellular web openings under concentrated loads. The full-scale tests aim to: 1) Investigate the structural stability of steel arch-shaped beams with cellular web openings, 2) Focus on the buckling behaviour of the web, 3) Calibrate a finite element (FE) model with the load-deformation and load-strain relationships, 4) Discuss the experimental results and compare them with the analytical model presented in the literature, and 5) Propose and validate a detailed FE model with the experimental results. The FE model in this study is considered to be a preliminary analysis which was proposed and verified for similar future work.

2. Experimental program

In this section, the details of the experimental program are presented and discussed. This study is seen as an initial analysis to encourage similar future studies, using FE analysis.

2.1. Geometry of tested arches

To investigate the structural elastic-plastic stability of arched steel beams with cellular web openings, four manufactured arched steel specimens were tested: one with a solid web (B1), and three with cellular web openings (B2, B3, and B4). Two different spans and two subtended angles were chosen, such that the failure could be generated within the dimensions and the capacity of the test rig. The geometrical details of the test specimens are presented in Fig. 1 and Table 1, where h_w, t_w, b_f, and t_f are the web height, web thickness, flange width, and flange thickness respectively, L is the arc length, S is the span, α is the subtended angle in degrees, and h is the rise of the arch. For the cellular web openings, D is the hole diameter and s_o is the arched distance between the outer edges of the holes, which is taken as being equal to 0.5D, which gives $D/s_o = 2$ and $h_w = 1.5D$. The dimensions were chosen according to the BS EN 1993-1-1 [31] class 1 cross sections. These sections cover a significant range of beams primarily used as roof beams, and they can form a plastic analysis without any reduction of resistance due to local buckling. The depth of the circular web opening is small enough to prevent Vierendeel effects before web post buckling failure. Therefore, the hole diameter $D = 0.67\ h_w$ is chosen, such that web post buckling failure is expected. In order to focus on local failures of the cellular arched beams around the openings, lateral buckling of the beams was prevented by lateral supports.

It is noteworthy that in order to investigate the effect of web openings on obtaining a competitive advantage, the heights of solid specimen B1 and perforated test specimen B2 were 170 mm and 240 mm, respectively, such that they had the same weight. Therefore, test specimens B1 and B2 had the same weight, same developed arc length, and same angle of curvature.

2.2. Manufacturing

All webs and flanges of the arched specimens were cut from 4-mm- and 8-mm-thick flat plates, respectively. The webs, both solid or cellular, were cut in an arched shape, and then the flanges were welded to the arched web. Cellular specimens were perforated, with the holes cut in the solid beam achieved by cutting the required profiled holes out of a full-sized parent web. All parts of the beams (webs, flanges, holes, and stiffeners) were cut by a laser-cutting machine. The cutting procedure was managed by computer numerical control to ensure highly accurate dimensions. As opposed to cold bending, this type of assembly reduced the residual stresses in the cross sections.

In order to have full strain compatibility between the different components in the steel section, manual fillet welds were used to assemble different parts of the built-up cellular arched-beam specimens. The welding process was applied as follows:

1. Flange plates were spot welded to the web. The distance between two adjacent welding spots was 300 mm,
2. Tension plates were welded first, followed by the compression plates,

Table 1
Dimensions of test specimens.

Specimen	Web height h_w [mm]	Web thickness t_w [mm]	Flange width b_f [mm]	Flange thickness t_f [mm]	Develop arc Length L [mm]	Span S [mm]	Arch rise h [mm]	Subtended angle α [degree]	Holes diameter D [mm]
B1	170	4	120	8	2451	2590	472	60	–
B2	240	4	120	8	2451	2590	538	60	160
B3	240	4	120	8	2651	2590	699	90	160
B4	240	4	120	8	2032	2190	484	60	160