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Novel design equations for shear strength of local web-post buckling in cellular beams

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A B S T R A C T

To complement available design methods, this study develops a practical and economical approach to estimate shear strength of non-composite symmetric and asymmetric cellular beams, based on failure by local web-post buckling. Influence of geometric web-post parameters on the buckling strength and mechanism, such as section size, opening depth ratio, spacing ratio and tee depth, are investigated with a validated finite element (FE) web-post model. The validation is against 13 cases reported in the literature, and 390 parametric web-post models are analyzed. Tee depth is found to be the key parameter distinguishing failure modes between buckling and Vierendeel bending. The buckling design equation is adopted based on a simple strut model. The observed stress distributions from simulations suggest half the web-post width for the effective strut width and half the length of a line segment tangent to neighboring openings as the strut length. Based on the simulation study, an effective length is proposed to incorporate the effects of restraint due to the tee section and the stress variation around the opening. The strut models of the upper and lower parts of the web-post are separately computed for their buckling shear strength according to BS EN 1993-1-1 and ANSI/AISC 360-10. The shear strength of each part is related to the web-post shear strength through the vertical shear area of the tee section. Accuracy of the proposed model is validated against existing experiments or their FE models. The new design equations facilitate safe and cost-effective design of cellular beams.

1. Introduction

Cellular beams are rolled steel H or I sections with regular circular openings along their length as shown in Fig. 1. The beams are produced by cutting and re-welding rolled beam sections. The openings allow service integration within the beams depth, which advantageously reduces, indirectly, the height of floors. An increase in beam depth provides greater flexural rigidity and strength to weight ratio.

Load capacity as well as failure behavior of cellular beams varies depending on geometry, assuming fixed material properties. To design cellular beams for load carrying, overall strength and local strength of the beams need to be estimated in addition to serviceability limit state [1]. The overall beam strengths are the flexural capacity, the beam shear strength and the overall beam buckling strength. The web openings may also allow local failure, such as buckling and flexural failure of the web-post, and secondary bending effects of the upper and lower tees (Vierendeel bending). In various series of cellular beam experiments [2–7], local web-post buckling has typically limited the strength. The buckling is most critical in cellular beams with a narrow web-post, and this type of failure is illustrated in Fig. 2(a) where the coloring indicates deformation out of plane.

An early design method for the shear strength limit from web-post buckling was officially presented in SCI publication 100 [1]. The buckling strength is governed by two modes, namely flexural failure by development of plastic hinge in the web-post, and buckling of the web-post. The buckling strength depends on geometric details of the web-post such as its opening space, opening diameter and web thickness. Based on simulation studies with nonlinear finite elements, design curves for the buckling strength have been developed. This method is widely used to design cellular beams [8,9].

Other empirical buckling models were proposed in Bitar et al. [10], and Tsavdaridis and D'Mello [2]. Bitar's method first determines the critical buckling section in the web-post by using some factors based on his numerical studies. The compressive force applied in the critical section is used to compare with the design strength of the web-post. The strength is a function of imperfections, web thickness and web-post width, and a factor dependent on the opening spacing. Tsavdaridis and D'Mello's method also provides empirical design curves derived from finite element

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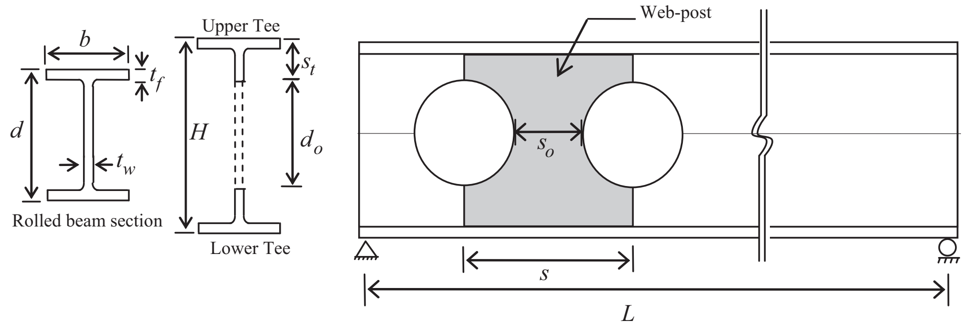

Fig. 1. Geometry of cellular beams.

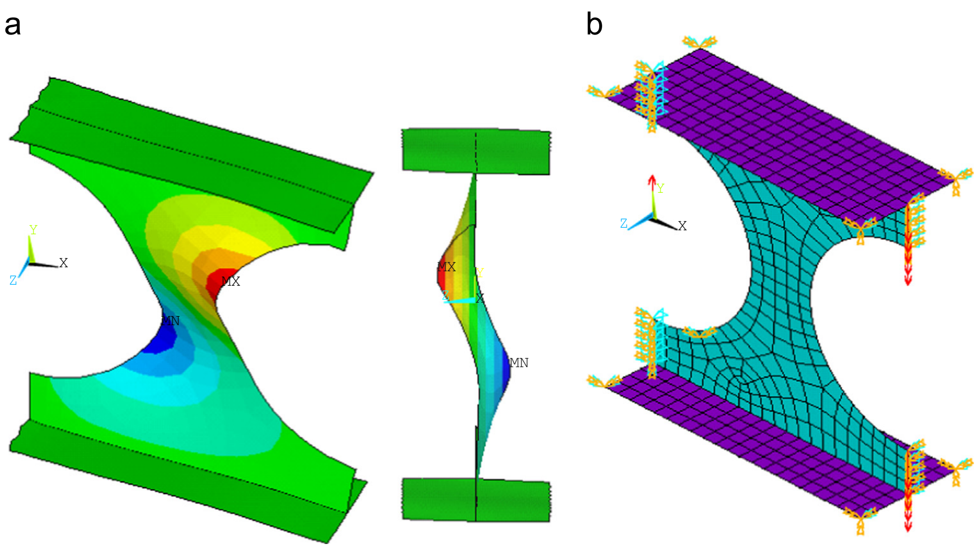

Fig. 2. Single web-post model: (a) web-post buckling and (b) boundary conditions.

analyses. The curves depend on the opening spacing, the opening diameter and the web thickness.

The empirical methods in [1,2,10] are not applicable to asymmetric cellular beams since the methods are developed based on analytical results for symmetric cellular beams. To model the buckling strength of asymmetric cellular beams, Lawson et al. [11,12] proposed a new simple approach based on the observed stress distribution in their finite element analysis. The web-post is modeled as a simple strut with a restraint point in the middle. The buckling strength depends on the effective slenderness of the strut and refers to the buckling strength design in BS5950 [13] or BS EN1993-1-1 [14]. Compared with the buckling shear strength obtained from finite element analysis, the designed strength is significantly conservative up to 79% for narrow and thin web-posts [2]. The level of conservatism tends to reduce for wider web-posts and greater web thicknesses [2,12]. The method is used in several research works [2,15]. Even though this method is simple to apply, the conservative strength estimates increase costs relative to an optimal design. Furthermore, the application to asymmetric cellular beams has not been clearly described for this method.

Note that finite element analysis of the single web-post model as shown in Fig. 2, which is not a beam model, is normally applied to develop design models [2,12]. The web-post model is used to investigate the buckling shear strength of non-composite cellular beams by neglecting the effect of their span length, stiffener and load location. The accuracy of the model was not clearly described in both publications. Geometric details of the web post such as its opening space, opening diameter and web thickness are arbitrarily specified, mostly not corresponding to practical regular cellular beams.

Due to the drawbacks of available buckling designs based on buckling strength, this study aims to develop a practical and economical design, as well as to study the buckling mechanism from experiments in literatures [2–6] and finite element analyses. The scope of the study is confined on non-composite cellular beams with a wide range of web post geometric details.

2. Validation of FE model

2.1. General

A single web-post model as shown in Fig. 2 is normally applied in buckling studies with finite element (FE) analysis. The aim of this section is to validate the web-post model before its use in a parametric study. In terms of evaluated buckling shear load, the web post model is validated against the full beam model and specimens tested by Tsavdaridis and D'Mello [2], Surtees and Liu [3], Warren [4], European (ECSC) research project contributed by RWTH and PROFILARBED-research [5] and Nadjai et al. [6]. The specimens include various symmetric, asymmetric, composite and non-composite cellular beams.

The models account for their measured geometry, geometric imperfections and nonlinear material properties. The graphic definition of symbols for the geometry of cellular beams investigated in this study is shown in Fig. 1. Details of the experiments are tabulated in Table 1, where f_{cb} is the compressive cube strength of concrete, f_y is the yield stress of steel, H is the height of cellular beam, d_o is the opening diameter, s is the web-post