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Shear strength of tubular flange plate girders with square web openings

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ABSTRACT

In this paper, the influence of square opening sizes on the shear behavior of hollow tubular flange plate girders (HTFPGs) is investigated. A three-dimensional finite element (FE) modelling using the ABAQUS computer package has been employed to analyze HTFPGs containing central web openings at end panels. The results of the HTFPGs with web openings are analyzed and then compared with equivalent plate girders (IPGs) with such openings. The collapse behavior of such girders is examined considering the following parameters: the flange type; the flange size; the type of the web (solid web or web with opening); the web plate slenderness (h_w/t_w) and the relative opening depth to the web depth (d_o/h_w). The results indicate that employing the HTFPGs with unreinforced central web opening without curved corners instead of the corresponding IPGs with the similar weight and the web opening size is a high performance solution to avoid the reduction in shear resistance due to the presence of web openings. An optimum web opening depth ($d_{o,op}$) for a HTFPG with a slender web is additionally recommended at which its shear strength becomes higher than the corresponding value of the similar weight IPG with solid web. It is furthermore found that the design strength of such girders should consider the sum of the contributions of both the web and the tubular flanges. However, new conclusions on the shear strength and behaviour of HTFPGs with web openings are presented.

1. Introduction

Recently, a number of different types of girders with hollow tubular flanges have been developed for bridges and buildings [1–3]. The advantages of tubular flange plate girders include large local buckling resistance, reduced web slenderness and higher torsional stiffeness over that provided by the I-section girders with flat flanges of similar weight [4]; see Fig. 1. However, these girders are mainly proposed to support high loads that universal rolled sections and built-up I-section girders could not support or when they become uneconomical. In 2010, it was found by Hassanein and Kharoob [5] that the design equations given by EN 1993-1-5 [6] are extremely conservative compared to the finite element (FE) results of hollow tubular flange plate girders (HTFPGs). Hence, a modified Eurocode 3 design method was adopted to calculate the nominal shear strength of HTFPGs. This encouraged them to extend their work to compare the shear strength of the HTFPGs with the I-section plate girders with flat flanges (IPGs) [7]. The results of Hassanein and Kharoob [7] indicate two important remarks (beside others); namely that (1) using the HTFPGs instead of IPGs is a powerful tool not only to increase the shear strength of the girders provided by the additional vertical flange elements that share in resisting the applied shear force, but also save considerable weight; and (2) the development of the shear plastic hinge (SPH) shows that a considerable increase in the shear strength is reached through the increase of the relative distance between its place and the support, remembering that the final collapse occurs when plastic hinges are formed in the flanges.

On the other hand, large ducts and service spaces were traditionally provided beneath the girders of steel frames, in consequence resulting in high construction depths [8]. But in modern construction practices, openings are provided in the girder webs so that the services such as water pipes and air ducts could pass through them. For example, plate girders with large web openings are commonly used in offshore platforms for gas and oil exploration and production. Hence, due to space limitations that process pipes, electrical and instrumentation cables and ventilation ducts have to be routed through the girder webs [9]. In highway bridges, web openings in girders are in addition used to provide space for services, inspection and maintenance. The depths of the openings are some times as large as 60% of the beam depth [10].

It is, however, well known that the girders with web openings located in the high shear zone fail at significantly lower loads than those with openings in the zone of high bending and low shear [11]. This was then attributed to the fact that the width of membrane tensile stresses developed along the diagonal band of the web, which resist the applied load in the post-critical stage, is reduced by the largest dimension of the opening [12]. To decrease this reduction in the shear capacity, many solutions were

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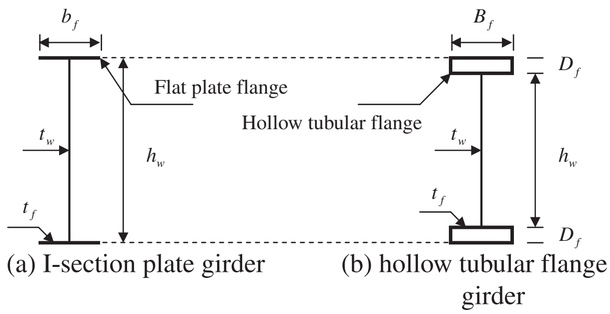

Fig. 1. Different types of plate girders.

recommended in the literature, such as: (1) the corners of rectangular/square openings are usually curved in order to minimize stress concentrations [10]; (2) reinforcements placed around openings may be used to enhance the strength reduced by the opening [9,10]. However, this could raise fabrication costs, induce welding residual stresses in the shear panel and lead to weld distortion; and (3) the openings are advantageous to be located in the corner of web panels in the compression diagonal, as far away as possible from the tension field [12]. It should be mentioned that many researchers investigated the behavior of IPGs with web openings using the FE modelling such as [9,10], as it can provide an efficient alternative to full-scale experiments.

Based upon the previous introduction, the author currently presents a *high performance solution* for the above discussed reduction in shear resistance owing to the presence of web openings. This solution is to employ the HTFPGs with *unreinforced central web opening without curved corners* instead of the corresponding IPGs with similar weight as well as web opening size as can be seen in Fig. 2. It should also be noted that no published information is currently available in the literature in respect of the influence of web openings on the strength and behavior of HTFPGs. Hence, it seems that new research needs to be carried out to recognize the possible behavioral differences between the HTFPGs and IPGs with web openings. Only by doing so can a rational design method be put forward to design HTFPGs with web openings. It should be mentioned that this paper is an extended version of the contribution presented by the author at the ESMC 2012 Conference in Graz, Austria.

2. Current finite element model

2.1. General

A three-dimensional (3D) FE model was developed to simulate the behavior of the HTFPGs and IPGs with web openings. Modelling was conducted using the general-purpose FE software package ABAQUS (version 6.8) [13].

In the current program, simply supported HTFPGs and IPGs with a fixed span of $l = 12m$ were considered. The web thickness was taken as 6 and 10 mm and the aspect ratio of web panel (a/h_w) was taken as unity. The web opening in each girder was centrally located in the first panel, i.e. the panel of the maximum shear. The web depth of the girders was taken as 1500 mm. Control HTFPGs [5] and IPGs with solid webs were also simulated (six for each type). It is worth noting that the IPGs with web openings, control HTFPGs [5] and IPGs with solid webs were analysed in this paper for comparison purposes. Three different flange cross-sections for the HTFPGs were used in the current study as listed in Table 1. The FE program consists from twenty-four pairs of HTFPGs and IPGs with the same cross-sectional area for each pair. Hence, for each plate girder with tubular flange, an equivalent flat flange was generated having the same width (B_f). The flange thickness of the IPGs was then calculated so that an equivalent flange area was maintained. The cross-section dimensions of the analyzed girders were however selected to cover, and extend beyond, the practical range of opening depth to web depth ratios (d_o/h_w) of such girders. Accordingly, openings up to $d_o/h_w = 0.7$ were considered. In proportion to the above discussion, five geometrical variables were included in the current investigation which could be summarized as:

1. flange type; flat flange and hollow tubular flange,
2. flange size; depth of tubular flange (D_f = 101.6, 203.2 and 304.8 mm) and thickness of flat flange (t_f = 29.71, 34.29 and 39.37 mm),
3. type of the web; solid web or web with opening,
4. web plate slenderness (h_w/t_w); 150 and 250, and
5. relative web opening size (d_o/h_w); 0.1, 0.3, 0.5 and 0.7.

The plate girders are labelled such that the cross-section of the flange (S1, S2, S3) for tubular flanges or (F1, F2, F3) for flat flanges could be identified from the label followed by two numbers separated by (–) between each other. The first number presents the thickness of the web (t_w) in millimetres followed by the second number which represents the relative web opening size (d_o/h_w). For example, the label "S3-6-0.5" defines the HTFPG with web thickness and relative opening size of 6 mm and 0.5, respectively, which is formed from the tubular flange cross-section (S3).

2.2. Finite element model

3D models were developed by idealizing the flanges, the web and the transverse web stiffeners in plate girders using the four-node thin shell element with reduced integration S4R in the ABAQUS element library [13]. In a nonlinear analysis, imperfections are usually introduced by perturbations in the geometry. Herein, an initial geometrical imperfection with a value of ($h_w/125$), following Ref. [5] to allow the comparison with the HTFPGs with solid webs, was derived from elastic buckling analysis and then introduced into the FE model in the nonlinear load–displacement analysis. On the other hand, a convergence test in order to assess the requirement of the mesh refinement of the FE discretization was carried out especially for cases involving buckling. However, this has made in literature several times for similar plate girders under shear; refer to Refs. [14,15]. In these papers, a rectangular plate subjected to pure shear was examined using different meshes. As a result, the former paper decided to use mesh refinement of 16 × 16 elements while the later used 30 × 30. However, both meshes sufficiently produced accurate results compared to the theoretical values of the elastic shear buckling stress. Based on these works, an intermediate mesh of 20 × 20 was used providing

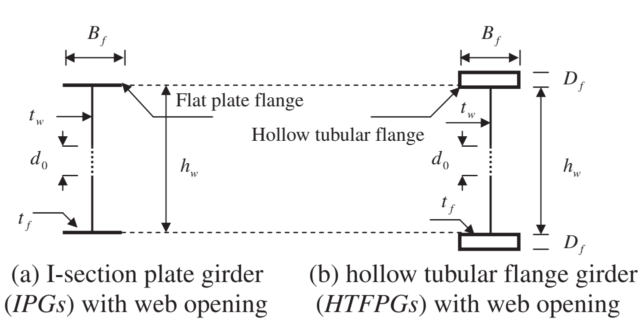

Fig. 2. Definition of symbols of typical plate girders with web openings.