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# Shear capacity of steel plate girders with large web openings, Part II: Design guidelines

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ABSTRACT

The present design procedure for the shear capacity of steel girders with large web openings is based on the shear buckling capacity of webs, as given by Eurocode 3, modified to account for the effect of the openings by means of reduction factors determined on the basis of numerical simulations. Guidelines are given for the use of the design procedure in practical design. Equations for determination of the secondary effects are presented, as well as some cut-off factors which limit the shear capacity for certain opening configurations. Requirements for design of welds are also given. Further, the paper presents equations for shear and primary moment interaction. Finally, two design examples illustrate the features of the guidelines in practical design of girders with openings.



## 1. Introduction

EN 1993-1-5 [1] gives the design shear capacity of a girder without openings in the form

$$V_{\mathrm{bw,Rd}} = \chi_w \frac{f_{yw}}{\sqrt{3}\gamma_{M1}} ht \qquad (1)$$

when only the contribution from the web is considered. $h$ and $t$ are the web height and thickness respectively and $f_{dw} = f_{yw}/\gamma_{M1}$ is the design stress for the web. The buckling reduction factor $\chi_w$ is a function of the reduced slenderness $\bar{\lambda}_w$ and $\gamma_{M1}$ is the material factor.

Hagen [2] also used the same design format for girders with openings. Based on a total of 260 numerical simulations by means of the FE code Abaqus, the primary, secondary and tertiary effects of the web openings on the shear capacity of the web were determined. A brief review of the fundamental assumptions, the FE models used for the numerical simulations and some results for girders with circular openings are given by Hagen et al. [3].

The simulations showed that the main reduction in shear capacity for girders with openings could be given by the factor $(1-D_h/h)$, where $D_h$ is the height of the opening. Reductions due to shear buckling can be covered by $\chi_w$, i.e. the same reduction factor as for webs without openings, provided that an adjustment factor $c_2$ is introduced. Thus, the design shear capacity of girders with openings may be given by

$$V_{\mathrm{bw,mod,Rd}} = \left(1 - \frac{D_h}{h}\right) \chi_w c_2 \frac{f_{yw}}{\sqrt{3}\gamma_{M1}} ht. \qquad (2)$$

In the present paper, guidelines are given for the use of Eq. (2) in practical design. Fig. 1 shows some typical web openings and the most common dimensional symbols. Equations for determination of $c_2$ are presented, as well as cut-off factors which limit the shear capacity for certain opening configurations. Requirements for design of welds are also given. Further, the paper suggests equations for shear and primary moment interaction. Finally, two design examples illustrate the features of Eq. (2) in the practical design of girders with openings.

It should be noted that these guidelines are intended to be a useful tool for the practicing engineer. The equations are based on the results from 219 simulations described in [3]. No direct comparison between the guidelines and experimental results are available today. However, the simulations were carried out by means of the general purpose non-linear FEM program Abacus, using state-of-the-art modelling techniques for representation of geometry, initial deformations and material behaviour. The quality in general of the simulations has been verified against experimental results and results obtained by the rotated stress field method. In the authors' opinion the guidelines are conservative. However, the use of the present guidelines in practical design is solely the responsibility of the user.

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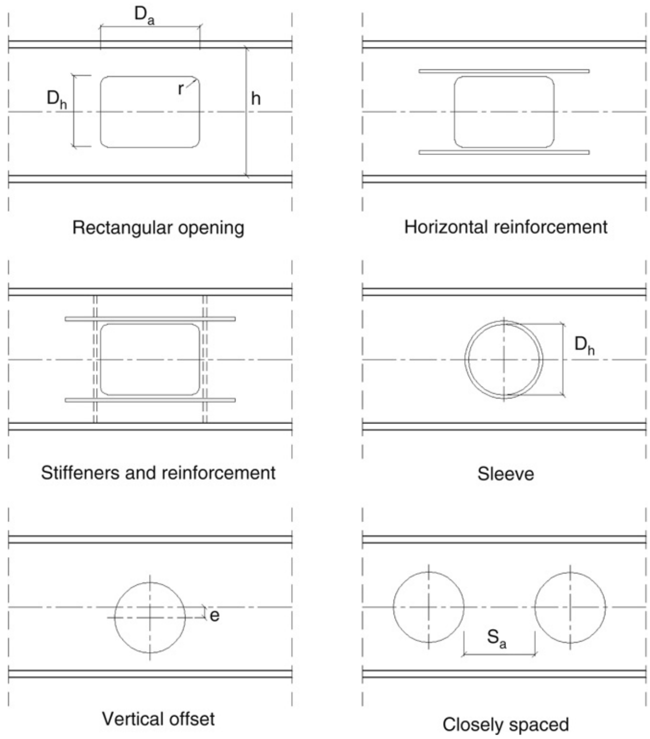


**Fig. 1.** Typical web openings.

**Table 1**
Reduction factor $\chi_w$ for shear buckling

| | Rigid end post | Non-rigid end post |
|---|---|---|
| $\overline{\lambda_w} < 0.83$ | 1.00 | 1.00 |
| $0.83 \le \overline{\lambda_w} < 1.08$ | $0.83/\overline{\lambda_w}$ | $0.83/\overline{\lambda_w}$ |
| $\overline{\lambda_w} \ge 1.08$ | $1.37/(0.7+\overline{\lambda_w})$ | $0.83/\overline{\lambda_w}$ |

## 2. Suggested design guidelines

### 2.1. Shear capacity

The design shear resistance for girders with regularly shaped openings, with and without stiffeners or reinforcement, may be given by

$$V_{\mathrm{bw,mod,Rd}} = \left(1 - \frac{D_h}{h}\right) \chi_w c_2 \frac{f_{yw}}{\gamma_{M1}\sqrt{3}} ht \tag{3}$$

but not larger than

$$V_{\mathrm{bw,modcutoff,Rd}} = \alpha_c \left(1 - \frac{D_h}{h}\right) \frac{f_{yw}}{\gamma_{M1}\sqrt{3}} ht. \tag{4}$$

$D_h$ is the height of the opening and $h$ and $t$ are the clear web height (depth) between flanges and the web thickness respectively. $c_2$ is an adjustment factor that accounts for the secondary effects of the opening, see Section 3. $\alpha_c$ is a cut-off factor defined in Section 4. $\chi_w$ is the buckling reduction factor for shear as given in EN 1993-1-5 [1] for girders without openings, and is given in Table 1 as a function of the relative slenderness $\overline{\lambda_w}$. In the following, Ref. [1] is referred to as EC3.

Vertical stiffeners close to the opening will modify the shear buckling coefficient $k_\tau$ and thereby increase the shear capacity. For determination of $k_\tau$ the aspect ratio refers to the panel between the vertical stiffeners. For design of the vertical stiffeners the aspect ratio should be based on a virtual case with a fictitious stiffener located in the centre of the opening. The EC3 stiffness criteria should apply to this stiffener, but no strength criteria are given. As vertical stiffeners are usually provided in pairs, i.e. one one-sided stiffener on each side of the opening, it is sufficient that each vertical stiffener has 50% of the stiffness required for the fictitious stiffener. When calculating the stiffness of the real vertical stiffener, the effective width is taken according to the EC3 rules. Usually the vertical stiffeners are located so near the opening that a part of the effective width may fall within the opening. This part must be subtracted. Only minimum welds are required between the web and vertical stiffeners.

### 2.2. Moment capacity

The moment capacity of girders is given by

$$M_{\mathrm{mod,Rd}} = M_{\mathrm{buckl,mod,Rd}} = \frac{f_y}{\gamma_{M0}} W_{\mathrm{eff,mod}}. \tag{5}$$

The effective section modulus $W_{\mathrm{eff}}$ is determined according to EN 1993-1-5, as the case with no opening or reinforcement. $W_{\mathrm{eff,mod}}$ is then computed by neglecting all parts of the effective web area that fall within the opening. Horizontal reinforcement, if any, is not included.

The moment capacity of beams is given by

$$M_{\mathrm{mod,Rd}} = M_{\mathrm{plastic,mod,Rd}} = \frac{f_y}{\gamma_{M0}} \left[ W_p - D_h t \left( \frac{D_h}{4} + e \right) \right]. \tag{6}$$

Here, the term beam refers to Class 1 and Class 2 sections that can develop full plastic moment capacity if they have no openings. $W_p$ is the plastic section modulus if there is no opening or reinforcement. $e$ is the absolute value of the vertical eccentricity of the opening relative to the plastic neutral axis.

For the sake of simplicity the yield stress $f_y$ is assumed to be the same for the web and the flanges. It is always conservative to calculate $M_{\mathrm{mod,Rd}}$ on the basis of the flanges only for both girders and beams.

### 2.3. Interaction between moment and shear

For all girders and beams with openings the verification may be based on the interaction equation

$$\left(\frac{M_{\mathrm{Ed}}}{M_{\mathrm{mod,Rd}}}\right)^3 + \left(\frac{V_{\mathrm{Ed}}}{V_{\mathrm{bw,mod,Rd}}}\right)^3 \le 1. \tag{7}$$

$M_{\mathrm{Ed}}$ and $V_{\mathrm{Ed}}$ are the primary moment and shear force, acting at a vertical section through the centre of the opening. Eq. (7) is a modified AISC interaction formula, which is explained in Section 6.

### 2.4. Welds

Requirements for welds may be found in Section 5.

## 3. The adjustment factor $c_2$

The adjustment factor accounts for the secondary effects of the opening, and depends on the opening shape and location, spacing of multiple openings, and amount of reinforcement, sleeves and doubler plates.

### 3.1. Single circular opening

Simulations have shown that the value $c_2 = 1$ may be used without any loss of accuracy for girders with a single, non-reinforced circular opening located on the horizontal centreline of the girder.