Continental Steel Public Seminar on "Impact of Structural Eurocodes on Steel and Concrete Structures"

A Beginner’s Guide to Simple Plate Girder Design to EC3 Part 1-5

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Topics of presentation

Introduction
- Overview
- Behaviors of plated structural elements

Design of plate girder
- Design principles
- Comparing BS5950 with EC3 Part 1-5 in plate girder design
- Bending resistance
- Shear resistance
- Stiffener and end post design

Summary and Conclusions
Introduction

- Overview
- Basic behaviors of plated structural elements
Introduction

## Overview

- Plate girder is essentially a DIY deep I-section
- Formed by welded steel plates (at least 3) together to form a deep section
- Large distance between the two flanges gives more optimal structural solution than rolled or compound sections (weight and cost) to resist bending
- Span is defined by practical requirement, the maximum depth usually fixed by headroom requirement
Introduction

Overview

- Bending is mainly taken up by the flanges \(\Rightarrow\) tensile/compressive stress
  \(\Rightarrow\) Class 1 section
- Breadth of flange plate from 1/5 to 1/3 of depth, web depth from 1/8 to one 1/12 of span
- Web \(\Rightarrow\) as thin as possible for weight control \(\Rightarrow\) Class 4 section
- Web subjected to direct bending stress and shear stress
- Stiffeners and end posts: To prevent buckling due to bending and shear as well as local failure under patch loads
Introduction

- Basic behaviors of plated structural elements

- Plated structural element subjected to direct stress: Plate-like and column-like buckling
  - A thin plate subjected to direct stress (e.g. web of plate girder under bending) tends to buckle before $f_y$ is reached for the whole plate
  - A thin plate with aspect ratio $\alpha = a/b \geq 1$ will have sufficient post-buckling strength $\Rightarrow$ “Plate-like buckling”
  - Pre and post critical behaviors are obvious for a perfect plate but more gradual for imperfect plate

(Beg: 2.4.1, Fig. 2.12)

Note: $b$ is always the dimension of the edge where the direct stress is applied, in plate girder $b$ is the depth of the girder or web height
Introduction

- Basic behaviors of plated structural elements

- Non uniform stress distribution developed when ultimate resistance reached
- The Effective Width Method is used to account for the effect of plate-like buckling by reducing the gross width to an appropriate effective width $b_{eff}$ adjacent to the edges and assume that $f_y$ is reached there
- For a Class 4 thin plate, the reduced width $b_{eff}$ should be used in section properties calculations (More details in “Surviving Class 4 Slender Section in Eurocode 3” presented at the Regency Steel Asia Symposium, 5 August 2013)
Introduction

- **Basic behaviors of plated structural elements**
- **Plated structural element subjected to shear stress**
  - The thin and deep web is also subjected to large shear force and thus vulnerable to shear buckling
  - Web buckling could occur before the “full” shear capacity $A_v f_y / \sqrt{3}$
  - Shear buckling strength depends on aspect ratio, plate thickness, imperfections, material properties and **boundary conditions**
  - Shear buckling could be delayed if appropriate **rigid** transverse stiffeners are constructed to limit the extent and separate the buckling regions

![Unstiffened web](image1.png)  ![Stiffened web](image2.png)
References


Design of plate girder

- Design principles
- Comparing BS5950 with EC3 Part 1-5 in plate girder design
- Bending resistance
- Shear resistance
- Stiffener and end post design
Design of Plate girder

Design principles

- **Design inputs**
  - Span (L), Loadings, Depth and width

- **Section portioning**
  - Flange (b_f, t_f), Web (h_w, t_w)

- **End post type and stiffener spacing**
  - End post type, stiffener spacing (a)

- **Intermediate stiffeners**
  - Shape, size and thickness

- **End post and load bearing stiffeners**
  - Shape, size and thickness

**Internal forces**
- BMD and SFD

**Bending resistance**
- Effective width method
  - Effective section area, A_eff
  - Effect second moment of area, I_eff
  - Elastic modulus W_eff → M_y,Rd
- Modified/Flanges-only method
  - Flange plastic modulus, W_p,f → M_y,Rd

**Shear resistance and interactions**
- Shear resistance
  - Stocky/Non-stocky check
  - Web contribution V_{bw,Rd}
  - Flange contribution V_{pf,Rd}
- Shear and bending intersection

**Intermediate stiffener**
- General requirements
- Effective cross section
- Direct and shear stress verifications

**End post and load bearing stiffener**
- Minimum requirements
- Design as a load bearing column
Design of plate girder

Comparing BS5950 with EC3 Part 1-5 in plate girder design

**BS5950**
- Most design rules found in Sections 4.4 and 4.5
- Annex H for web buckling resistance and end anchorage
- Mainly "descriptive" design rules with explicit formulae given for strength calculation and limiting values (e.g. maximum $h_w/t_w$ value)
- Bending resistance: "Flanges only" method for fast calculation
- Simplified method and more exact method for shear buckling resistance
- Table provided for quick calculation using simplified method
- Explicit rules given in Section 4.5 for web bearing and stiffener strength calculation

**EC3 Part 1-5**
- Part 1-5 devoted to "Plated Structural Elements" rather than plated girders only
- Five Annexes for analysis/calculation aids → Annex C for FE analysis guidelines
- More "performance based" design approach: fewer explicit formulae but more descriptions on performance requirements
- Bending resistance: No more "Flanges only" method → Effect Width Method for bending resistance calculation
- Only one method suggested for shear buckling resistance
- No table provided → All calculations based on formulae or analysis
- No explicit rule for stiffener strength design and calculation
Design of plate girder

Bending resistance

- **Flange:** Class 1 or Class 2, **Web:** Almost inevitably Class 4
- EC3 Part 1-5 requires special treatment for Class 4 plate using the Effective Width Method
- Part of compressive web become ineffective → relocation of centroid → compressive flange yielded but tension flange remains elastics at ULS
- Bending resistance: $M_{y,Rd} = W_{eff}f_y$

![Diagram of Bending Resistance](image)
Design of plate girder

Bending resistance

- Effective width method needs at least one iteration to calculate $W_{\text{eff}}$ → inconvenience when portioning the flange size
- The “flanges-only” method is much more convenient in flange portioning since

$$M_{f,Rd} = 2b_f t_f (h_w/2 + t_f/2) f_y = b_f t_f (h_w + t_f) f_y = A_f (h_w + t_f) f_y$$

- Note that in the “flanges only” method the flanges is full plastic at the ULS
- EC3 Part 1-5 does not explicitly allow or disallow the use of “flanges-only” method
- Hence, it is safe to use if we could show that for a given section

$$M_{f,Rd} \leq W_{\text{eff}} f_y \quad \text{or} \quad A_f (h_w + t_f) \leq W_{\text{eff}}$$
Design of plate girder

- **Bending resistance**

  - Research done by Lee and Chiew (NTU, CEE) shown that
    
    \[ A_f(h_w + t_f) \leq W_{eff} \]
    
    whenever
    
    \[ 0 \leq A_w/A_f \leq 5 \quad 0 \leq t_f/h_w \leq 0.2 \quad h_w/(t_w\varepsilon) \leq 680 \]
    
    \[ \varepsilon = \sqrt{235/f_y} \]

  - This implies that the flanges only method is conservative within most design range
  
  - In fact, the flanges only method is “too conservative” in the sense that in many cases
    
    \[ R = A_f(h_w + t_f)/W_{eff} \leq 0.75 \]

  - The modified flanges only method is suggested to improve the efficiency in design
Design of plate girder

**Bending resistance: Modified “Flanges-only” method**

- It is found that the efficiency for bending resistance could be improved by modified the flanges only method so that

\[
M_{y,Rd} = W_{eff} f_y
\]

\[
\approx \bar{M}_{f,Rd} = \bar{R} A_f (h_w + t_f) f_y \quad \bar{R} = 1 + \frac{A_w}{A_f} \left( 0.028 + \left( \frac{400 - \frac{h_w}{t_w \varepsilon}}{950} \right)^2 \right)
\]

![Graph showing bending resistance ratio vs. \(h_w\) from 1010 mm to 3000 mm.](image)

- **Flanges only resistance/ Effective modulus resistance**
- **Modified flanges only resistance/Effective modulus resistance**

\(f_y = 355\,\text{MPa}\)  
\(\varepsilon = 0.814\)
Design of plate girder

Bending resistance: Verification

• If no axial force is present, verification should be performed as a normal section check using $\eta_1$

$$\eta_1 = \frac{M_{Ed}}{M_{y,Rd}} \leq 1.0$$

where $M_{Ed}$ is the maximum design moment

• To prevent flange induced buckling, we also need

$$\frac{h_w}{t_w} \leq k \frac{E}{f_{yf}} \sqrt{\frac{A_w}{A_{fc}}}$$

$A_{fc}$ is the effective area of the compression flange. The factor $k$ is taken as 0.3, 0.4 and 0.55 for Class 1, 2, 3 and 4 flanges, respectively
Design of plate girder

- **Shear resistance**
  - Unless the web is Class 1, we need to check whether the web is *stocky* or not for shear buckling.
  - For unstiffened web
    
    \[
    \frac{h_w}{t_w} \leq 72 \frac{\varepsilon}{\eta}
    \]
  - For stiffened web (either transverse or longitudinal or both)
    
    \[
    \frac{h_w}{t_w} \leq 31 \frac{\varepsilon}{\eta} \sqrt{k_{\tau}}
    \]

  where \( \eta = 1.0 \), and for plate girder without longitudinal stiffener:

  \[
  k_{\tau} = 5.34 + 4.00 \left( \frac{h_w}{a} \right)^2 \quad \text{for } a/h_w \geq 1
  \]

  \[
  k_{\tau} = 4.00 + 5.34 \left( \frac{h_w}{a} \right)^2 \quad \text{for } a/h_w < 1
  \]
Design of plate girder

- **Shear resistance**
  - If the web is stocky, no shear buckling of web shall occur and the shear strength of the web is given by EC3 Part 1-1
    \[ V_{pl,Rd} = \frac{A_v (f_y / \sqrt{3})}{\gamma_{M0}} \]
  - If the web is NOT stocky, shear buckling governs the failure
    \[ V_{b,Rd} = V_{bw,Rd} + V_{bf,Rd} \leq \frac{\eta f_{yw} h_w t_w}{\sqrt{3} \gamma_{M1}} \]

Web contribution (TFA)   Flange contribution (PH formation)
Design of plate girder

- **Shear resistance**
  - For the contribution from the web $V_{bw,Rd}$

  $$V_{bw,Rd} = \frac{\chi_w f_{yw} h_w t_w}{\sqrt{3} \gamma_{M1}}$$

  $\chi_w$ is the shear reduction factor which depends on the end post conditions and the modified web slenderness $\lambda_w$, $\eta=1$ for all steel.

  **Table 5.1: Contribution from the web $\chi_w$ to shear buckling resistance**

<table>
<thead>
<tr>
<th>$\lambda_w$ condition</th>
<th>Rigid end post</th>
<th>Non-rigid end post</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_w &lt; 0.83/\eta$</td>
<td>$\eta$</td>
<td>$\eta$</td>
</tr>
<tr>
<td>$0.83/\eta \leq \lambda_w &lt; 1.08$</td>
<td>$0.83/\lambda_w$</td>
<td>$0.83/\lambda_w$</td>
</tr>
<tr>
<td>$\lambda_w \geq 1.08$</td>
<td>$1.37/(0.7 + \lambda_w)$</td>
<td>$0.83/\lambda_w$</td>
</tr>
</tbody>
</table>

For transverse stiffeners at supports only (e.g. end post only)

$$\lambda_w = \frac{h_w}{86.4 t_w \varepsilon}$$

For the presence transverse and intermediate transverse stiffener

$$\lambda_w = \frac{h_w}{37.4 t_w \varepsilon \sqrt{k_\tau}}$$
Design of plate girder

- **Shear resistance**
  - For the contribution from the flange $V_{bf,Rd}$

$$V_{bf,Rd} = \frac{b_f t_f^2 f_{yf}}{c \gamma M_1} \left( 1 - \left( \frac{M_{Ed}}{M_{f,Rd}} \right)^2 \right)$$

where $M_{f,Rd}$ is the moment of resistance of effective area of the flanges only (as in the “flanges only” method) and

$$c = a \left( 0.25 + \frac{1.6 b_f t_f^2 f_{yf}}{t_w h_w^2 f_{yw}} \right)$$

- **Verification of shear resistance** is checked by calculating $\eta_3$

$$\eta_3 = \frac{V_{Ed}}{V_{b,Rd}} \leq 1.0$$
Design of plate girder

- **Interaction of bending and shear**
  - If \( \eta_3 = \frac{V_{Ed}}{V_{bw,Rd}} \leq 0.5 \) and \( M_{Ed} < M_{f,Rd} \), the design resistance to bending moment need not be reduced to allow for the shear force.
  - Otherwise, additional verification are needed, it is necessary that

\[
\eta_1 + \left( 1 - \frac{M_{f,Rd}}{M_{pl,Rd}} \right) \left( 2\eta_3 - 1 \right)^2 \leq 1.0
\]

\[
\eta_1 = \frac{M_{Ed}}{M_{pl,Rd}}
\]

where \( M_{pl,Rd} \) is the design plastic resistance of the cross section consisting of the effective area of the flanges and the fully effective effective web irrespective of its class.

- The above interaction check should be done at all sections other than those located at a distance less than \( h_w/2 \) from a support with vertical stiffener, as normally the shear force is overestimated there.
Design of Plate girder

- **Stiffeners and end post design**
  - **Intermediate transverse stiffener**
    - Takes no direct external loading but subjected to internal direct and shear force
    - Creates compartments to increase web buckling resistance
    - Provides **rigid support** for TFA and flange resistance (PH) for web buckling
  - **Load bearing stiffener**
    - Prevent yielding, crushing, local and global failures at where heavy patch loads are applied
  - **End Post**
    - A special form of load bearing stiffener
    - As “anchor” supports for TFA, flange resistance (PH) and reaction forces
    - Rigid and non-rigid end posts are possible
Design of plate girder

- **Stiffeners and end post design**
  - General requirements of all stiffeners
    - Independent design check needed
    - Cross section of the stiffener consists of
      1. gross area of the stiffener itself, and
      2. contribution width of $15\varepsilon t_w$ on each side (but no overlapping)
    - Normally, thin-walled open section (at least Class 2) are used

![Diagram of plate girder with stiffeners](image)

**Figure 9.1: Effective cross-section of stiffener**

**Fig. 2.64: Typical cross sections of stiffeners**
Design of plate girder

- **Stiffeners and end post design**
  - **General requirements of all stiffeners**
    - Two *general performance requirements* for *ALL* transverse stiffeners (intermediate, load bearing and end post) at section where $M_{Ed} \neq 0$
    - **Requirement (A) Stress and deflection limits:** To verify using a *second order elastic analysis* that at the ultimate limit state
      \[
      \sigma_{max} \leq \frac{f_{y}}{\gamma_{M1}} \quad \text{and} \quad w \leq \frac{b}{300}
      \]
      $\sigma_{max}$ is the ultimate stress (elastic) and $w$ is the ultimate lateral deflection while $b$ is the panel height (or web height)
Design of plate girder

- **Stiffeners and end post design**
  - **General requirements of all stiffeners**
    - **Requirement (B) Torsional buckling:** The stiffener will not fail by torsional buckling which requires *either*
      \[
      \frac{I_T}{I_p} \geq 5.3 \frac{f_y}{E}
      \]
      where
      \(I_T\) is the St. Venant torsional constant of the stiffener alone
      \(I_p\) is the polar second moment of area of the stiffener alone around the edge fixed to the plate

    - **Or** when warping stiffness is considered
      \[
      \sigma_{cr} \geq 2f_y
      \]
      where \(\sigma_{cr}\) is elastic critical stress for torsional buckling
Design of plate girder

- **Stiffeners and end post design**

  • General requirements of all stiffeners
    - For a stiffener consist of flat plates, the requirement for torsional buckling could be simplified to limit the width ($B$) to thickness ($t$) ratio of the plates to those values shown below.

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>235</th>
<th>275</th>
<th>355</th>
<th>420</th>
<th>460</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B/t \leq$</td>
<td>13.0</td>
<td>12.0</td>
<td>10.6</td>
<td>9.7</td>
<td>9.3</td>
</tr>
</tbody>
</table>

Limiting $B/t$ values to prevent torsional buckling

- Note: if $B/t >$ the above suggested values, normally is it very hard to satisfy the requirement unless more advance analysis (e.g. FEA) is used.
Design of Plate girder

- **Stiffeners and end post design**
  - **Design of intermediate transverse stiffener**
    - The main function of intermediate transverse stiffener is to provide rigid boundary supports for the panel and prevent web buckling due to direct stress (plate-like buckling) and to shear stress (axial force from TFA and PH formations).
    - Both **Requirements A and B** should be verified for both direct stress and shear stress.

![Diagram of Direct stress](image1)
![Diagram of Shear stress](image2)

- **Direct stress**
- **Shear stress**
### Design of plate girder

- **Stiffeners and end post design**
  - Design of intermediate transverse stiffener
  - Verification for direct stress

  - For intermediate stiffeners that is not subjected to external axial load, **Requirement (B)** can be ensured by simply limiting the B/t ratio

  - In general, verification for direct stress for **Requirement (A)** needs a second order elastic analysis but it is not convenient in practice.

  - Hence, EC3 allows two simplified methods for direct stress verification for intermediate transverse stiffener in the absent of external axial force
Design of plate girder

- Stiffeners and end post design

- Design of intermediate transverse stiffener

  ➢ Verification of direct stress: Method I: Refined $I_{st}$ requirement

  Requirements (A) is considered to be satisfied if $I_{st}$ is greater than

  \[
  I_{st,req} = \frac{\sigma_m}{E} \left( \frac{b}{\pi} \right)^4 \left( 1 + w_0 \frac{300}{b} u \right)
  \]

  where

  \[
  \sigma_m = \frac{\sigma_{cr,c}}{\sigma_{cr,p}} \left( \frac{N_{Ed}}{b} \right) \left( \frac{1}{a_1} + \frac{1}{a_2} \right)
  \]

  \[
  u = \frac{\pi^2 E e_{max}}{300 f_y b} \geq 1.0
  \]
Design of plate girder

- **Stiffeners and end post design**
  - Design of intermediate transverse stiffener
    - **Verification of direct stress:** Method I: Refined 1st requirement
      \[
      w_0 = \min \left[ \frac{b}{300}, \frac{a_1}{300}, \frac{a_2}{300} \right]
      \]
      The elastic critical stresses for column and plate like buckling
      \[
      \sigma_{cr,c} = \frac{\pi^2 E t_w^2}{12(1 - v^2)a^2}
      \]
      \[
      \sigma_{cr,p} = k_\sigma \frac{\pi^2 E t_w^2}{12(1 - v^2)b^2}
      \]
      and limiting values of their ratio: \(0.5 \leq \frac{\sigma_{cr,c}}{\sigma_{cr,p}} \leq 1.0\)

      \(k_\sigma\) is the plate buckling coefficient and dependent on the stress ratio \(\psi\) and can be calculation from Table 4.1 of EC3 Part 1-5, Section 4.4
Design of plate girder

- **Stiffeners and end post design**
  - Design of intermediate transverse stiffener
  - **Verification of direct stress:** Method I: Refined $I_{st}$ requirement
    - $e_{max}$ is the maximum distance from the edge of the stiffener to the centroid of the stiffener

\[ e_{max} = \max \text{distance} \]

- $N_{Ed}$ is the maximum force of both adjacent panels and should be at least equal to the maximum compressive stress at the edge of the panel times half of the effective compressive area of the panel.

- In checking, calculate $u$ first, if $u < 1.0$ displacement check is decisive and set $u = 1.0$. Otherwise, a strength check governs.
Design of plate girder

- **Stiffeners and end post design**
  - Design of intermediate transverse stiffener
  - **Verification of direct stress:** Method II: Equivalent uniformly lateral load
    In this method, a first order elastic analysis is carried out on the stiffener which is loaded laterally with an equivalent u.d.l force $q_{\text{dev,Ed}}$ such that
    
    $$ q_{\text{dev,Ed}} = \frac{\pi}{4} \sigma_m (w_0 + w_{el}) $$
    
    $w_{el}$ is the elastic deflection of the stiffener (which could only be determined iteratively). In practice, it could be taken as the maximum deflection $= b/300$
    
    All other terms are defined in Method I
Design of plate girder

- **Stiffeners and end post design**
  - Design of intermediate transverse stiffener
  - Verification of shear stress
    - When shear force is present in a section, in addition to direct stress, intermediate transverse stiffener also act as rigid support for the interior panel.
    - EC3 1-5 also requires that verification for shear stress for Requirement (A) should be carried out using second order elastic analysis.
    - If both direct stress and shear stress are present at the same section (i.e. both $M_{Ed}$ and $V_{Ed}$ are not zero), then the effects of direct stress, which tends to produce additional deviation forces and lateral deflection, must be taken into account in the analysis.
Design of plate girder

- **Stiffeners and end post design**
  - Design of intermediate transverse stiffener
  - **Verification of shear stress:** Minimum stiffness requirement
    For intermediate transverse stiffener acts as rigid support for panel, on top of the general **Requirements (A) and (B)**, the following minimum stiffness is also required for its second moment of area for the axis parallel to the web plate, $I_{st}$
    \[
    I_{st} \geq \frac{1.5 h_w^3 t_w^3}{a^2} \quad \text{if } a/h_w < \sqrt{2}
    \]
    \[
    I_{st} \geq 0.75 h_w t_w^3 \quad \text{if } a/h_w \geq \sqrt{2}
    \]
    However, the above conditions does not demand very strong stiffener and **does not** ensure that **Requirements (A) or (B)** could be met.
Design of plate girder

- **Stiffeners and end post design**
  - Design of intermediate transverse stiffener
    - **Verification of shear stress:** Axial force generated by TFA
      It can be shown that when shear force is present, under the action of TFA, an axial force $N_{st,ten}$ will be imposed on the intermediate transverse stiffener such that

      $$N_{st,ten} = V_{Ed} - \frac{1}{(\lambda_w)^2} \frac{h_w f_{yw} t_w}{\sqrt{3} \gamma_{M1}} \geq 0$$

      $V_{Ed}$ is design shear force in the adjacent panels.

    - For the case of variable shear force, the value at the distance of $0.5h_w$ from the edge of the panel with the **larger** force should be taken.
Design of plate girder

- **Stiffeners and end post design**
  - Design of intermediate transverse stiffener
  - **Verification of shear stress:** Interaction with direct stress
    If direct stress is present (i.e. $M_{Ed} \neq 0$), a small lateral deflection will be induced and the deviation forces can be transformed into additional axial force in the stiffener:

  $$
  \Delta N_{st, ten} = \frac{\sigma_m h_w^2}{\pi^2}
  $$

  - After both $N_{st, ten}$ and $\Delta N_{st, ten}$ are calculated, an appreciate second order elastic model should be employed to check for the performance of the stiffener for Requirement (A)
  - However, EC3 1-5 does not suggest any simplified model for the verification of Requirement (A)
Design of plate girder

- **Stiffeners and end post design**
  - Design of intermediate transverse stiffener
  - **Model for double-sided stiffener**
    An appropriate mechanical model for double-sided stiffener is available from [Beg: 2.9.2.3, Fig. 2.69](#)

\[
\Delta N_{st, Ed} \quad \text{(effect of deviation force)}
\]

\[
N_{st, Ed} = N_{st, ten} + N_{st, ex} \quad \text{(tension field action and external forces)}
\]

![Mechanical model for a double-sided stiffener](#)
Design of plate girder

- Stiffeners and end post design
  - Design of intermediate transverse stiffener
  
  Model for double-sided stiffener
  By using this model, the lateral deflection and maximum stress can be calculated as

  \[ w = w_0 \left( \frac{1}{N_{cr,st}} \left( \frac{N_{st,Ed}}{N_{st,Ed} + \Delta N_{st,Ed}} - 1 \right) \right) \leq \frac{h_w}{300} \]

  \[ N_{cr,st} = \frac{\pi^2 EI_{st}}{h_w^2} \]

  elastic buckling (Euler) load of the stiffener

  \[ \sigma_{\text{max}} = \frac{N_{st,Ed}}{A_{st}} + \left( \frac{N_{st,Ed} + \Delta N_{st,Ed}}{I_{st}} e_{\text{max}} \right) w_0 \left( \frac{1}{1 - \left( \frac{N_{st,Ed} + \Delta N_{st,Ed}}{N_{cr,st}} \right)} \right) \leq \frac{f_y}{\gamma_{M1}} \]
Design of plate girder

- **Stiffeners and end post design**
  - **Design of end post**
    - Two types of end posts: Rigid and Non-Rigid
    - To provide support for TFA and support reaction
    - Rigid end post should comprises of two double-sided transverse stiffener which forms the flange of a short column of length $h_w$ and the following two requirements should be met

\[
e \geq 0.1h_w
\]

\[
\min(A_e, A_u) \geq \frac{4h_w t_w^2}{e}
\]

**Figure 9.6:** Rolled section forming an end-post
Design of plate girder

- **Stiffeners and end post design**
  - **Design of end post**
    - **Requirements (A) and (B)** should still be satisfied for the end post and the double-sided model mentioned could be used.
    - As end post often subjected to large reaction force, satisfaction of Requirement (A) which limits the maximum stress to $f_y$ may not able to prevent the buckling of the end post as a strut.
    - EC3 requires separate checking of the end post as a column with buckling length not less than $0.75h_w$.
    - **Curve c** from EC3 Part 1-1 should be used for buckling check.
    - The total force acting on the end post should equal to the sum of reaction, force due to TFA and interaction with direct stress.
    - If both ends of the end post are fixed laterally, the buckling length could be taken as $0.75h_w$. Otherwise, a larger value should be used.
Design of plate girder

- **Stiffeners and end post design**
  - Design of load bearing stiffeners
    - Patch loads and concentrated loads are common in plate girder
    - Sufficient bearing resistance is needed to resist transverse force acting on the flange plate
    - In case that the bearing strength provided by the web plate is insufficient, load bearing stiffener should be constructed.
    - In general, **Requirements (A) and (B)** are also needed to be satisfied for loading bearing stiffeners.
    - Again, the total force acting on a load bearing stiffener should equal to the sum of reaction, force due to TFA and interaction with direct stress
    - Similar to end post, their design is often government by the buckling resistance as a strut (with buckling length $\geq 0.75h_w$) but without the compulsory use of two double-side plates
Summary and conclusions

• EC3 Part 1-5 is devoted to “Plated structural elements”
• While the basic principles for design (limited state design) is the same, the design procedure of EC3 Part 1-5 is different from BS5950
• In general, EC3 may require higher level of analytical and numerical modellings for the design of plated structural elements
• Important topics that are not covered here:
  ➢ Deflection (serviceability limit state): [EC3 Part 1-5: E.2]
  ➢ Interactions between transverse forces, bending moment and axial force [EC3 Part 1-5: 7.2]
  ➢ Web to flange weld [EC3 Part 1-5: 9.3.5]
  ➢ Guideline for finite element analysis: [EC3 Part 1-5: C]
End of presentation
Thanks for your attentions!
All questions are welcome!