European Commission

Eurocodes
Background and Applications

Design of **Steel Buildings**
with worked examples

16-17 October 2014
Brussels, Belgium

Organised and supported by

European Commission
DG Enterprise and Industry
Joint Research Centre
European Convention for Constructional Steelwork
European Committee for Standardization
CEN/TC250/SC3

Design of Structural Steel Joints

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Design of Structural Steel Joints

- Introduction
- Integration of joints into structural design process
- Moment resistant joints
- Simple joints
- Design tools

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- Design tools

Joint Research Centre

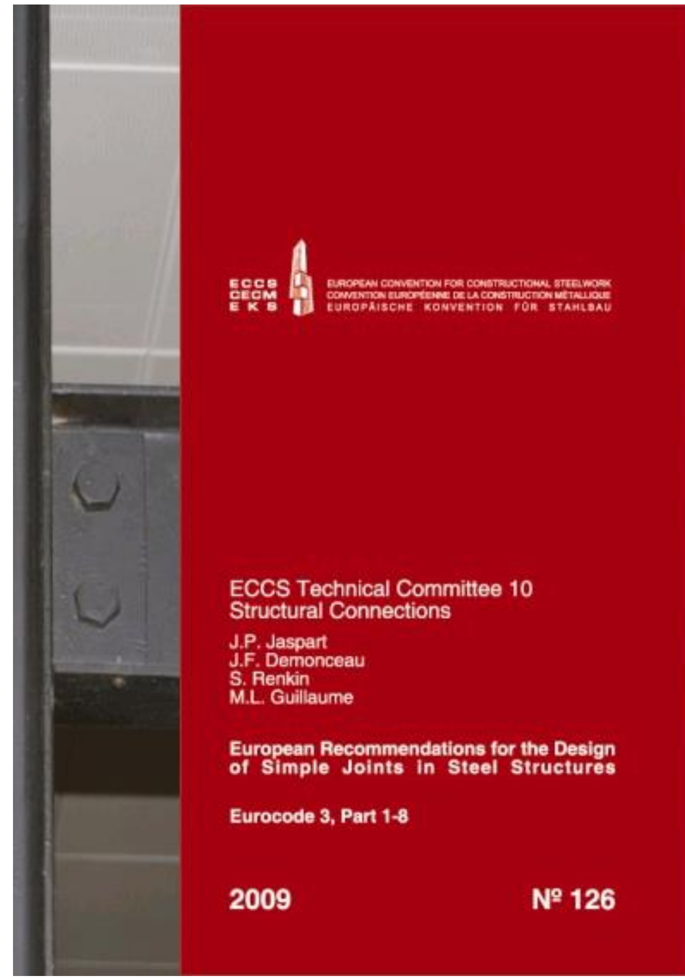
EN 1993 Part 1.8

Chapter 1 – Introduction
Chapter 2 – Basis of design
Chapter 3 – Connections made with bolts, rivets or pins
Chapter 4 – Welded connections
Chapter 5 – Analysis, classification and modelling
Chapter 6 – Structural joints connecting H or I sections
Chapter 7 – Hollow section joints

Design of simple joints

ECCS Publication Nº 126 (EN)

- Background information
- Design guidelines



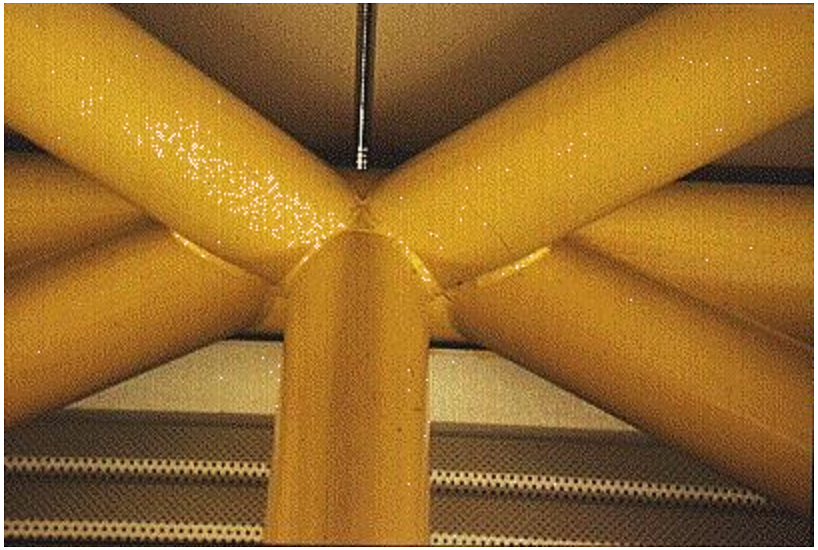
2 – Basis of design → Partial safety coefficients

Resistance of members and cross-sections	γ_{M0} , γ_{M1} and γ_{M2} see EN 1993-1-1
Resistance of bolts	γ_{M2}
Resistance of rivets	
Resistance of pins	
Resistance of welds	
Resistance of plates in bearing	
Slip resistance - at ultimate limit state (Category C) - at serviceability limit state (Category B)	 γ_{M3} $\gamma_{M3,ser}$
Bearing resistance of an injection bolt	γ_{M4}
Resistance of joints in hollow section lattice girder	γ_{M5}
Resistance of pins at serviceability limit state	$\gamma_{M6,ser}$
Preload of high strength bolts	γ_{M7}
Resistance of concrete	γ_c see EN 1992

NOTE: Numerical values for γ_M may be defined in the National Annex. Recommended values are as follows: $\gamma_{M2} = 1{,}25$; $\gamma_{M3} = 1{,}25$ and $\gamma_{M3,ser} = 1{,}1$; $\gamma_{M4} = 1{,}0$; $\gamma_{M5} = 1{,}0$; $\gamma_{M6,ser} = 1{,}0$; $\gamma_{M7} = 1{,}1$.

3 – Connections made mechanical fasteners

4 – Welded connections



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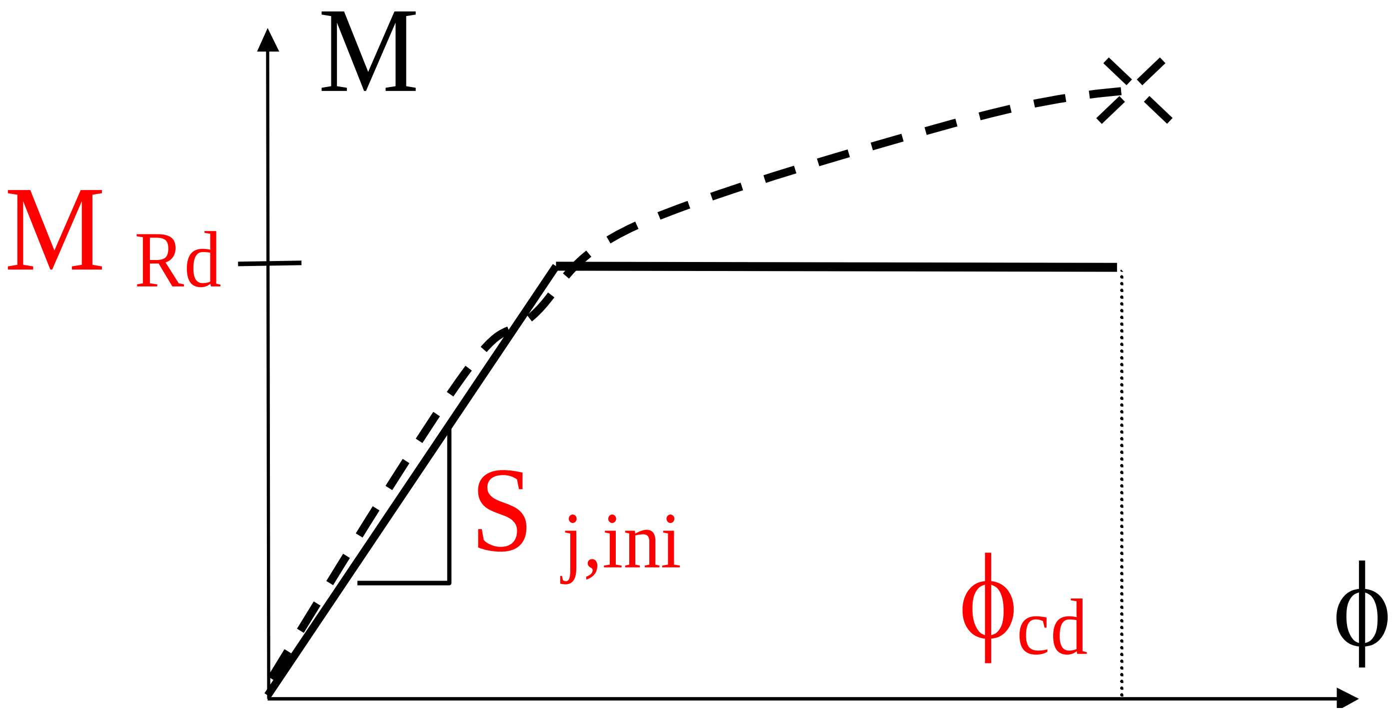
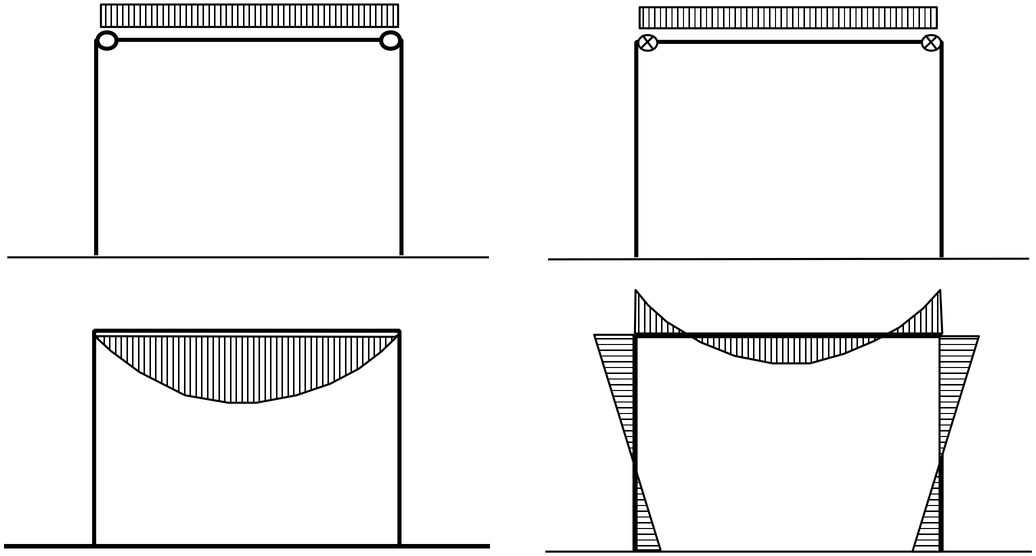
Actual joint response

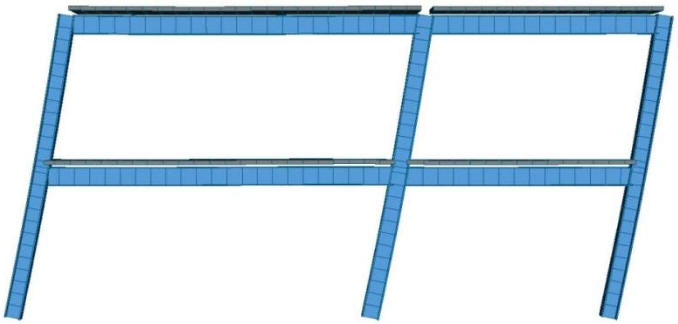
Actual joint response



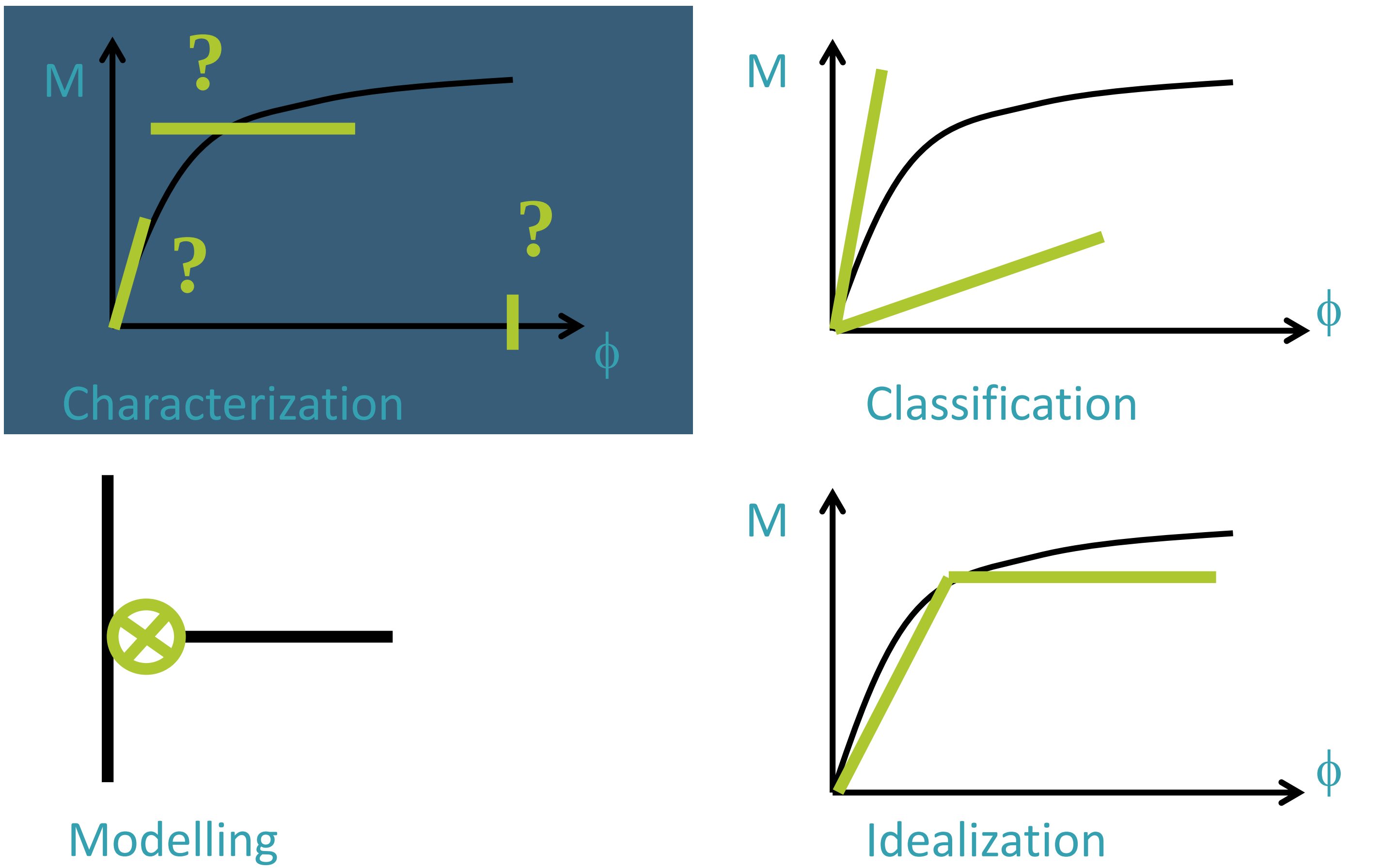
Influence on the structural response

- Displacements
- Internal forces
- Failure mode and failure load



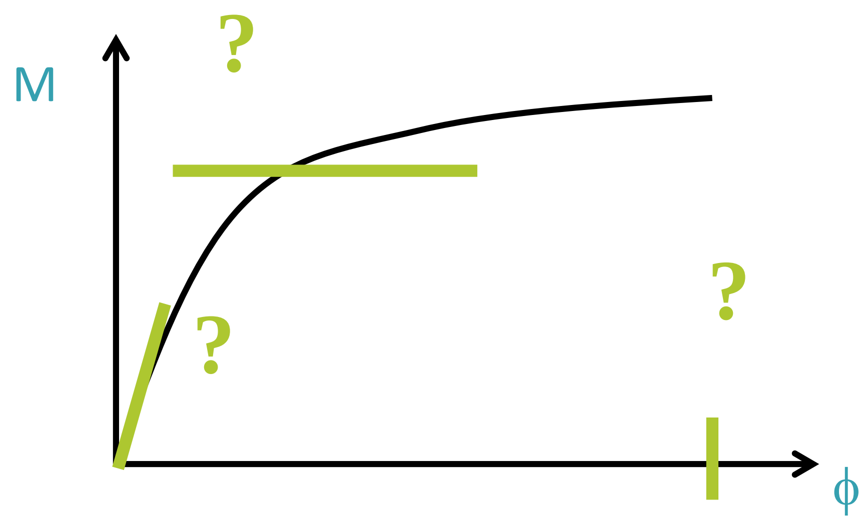


Four successive steps for structural integration



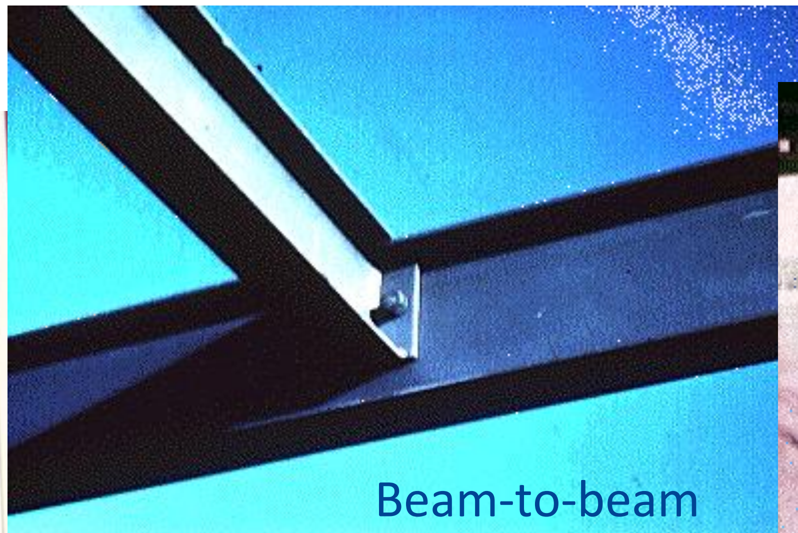
Characterization

Search for a unified approach whatever the material

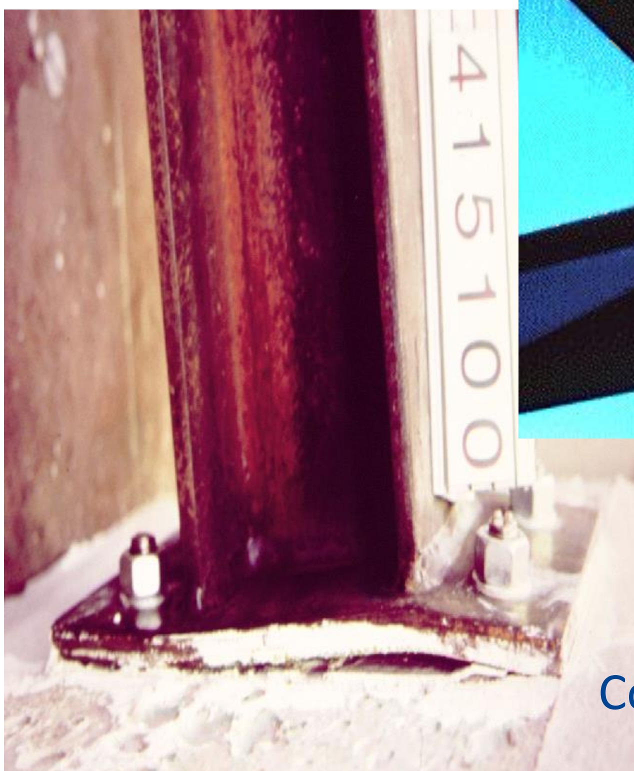


Various configurations (1)

Continuity



Beam-to-beam



Column bases

Various configurations (2)

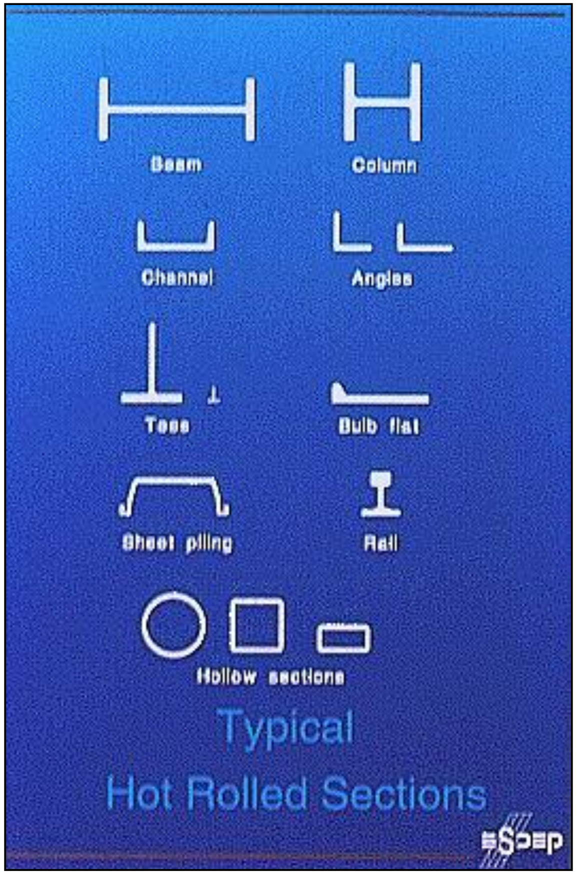
Joints in portal frames

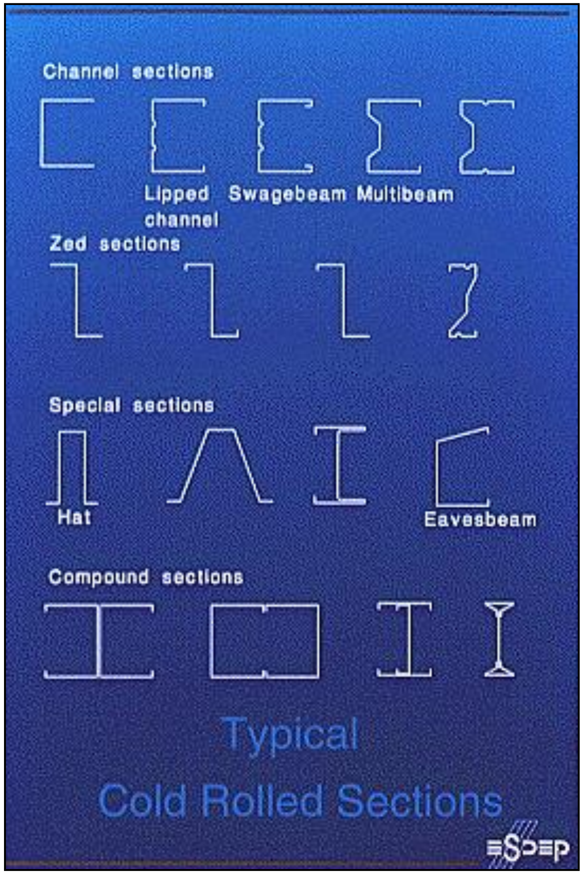
Various configurations (3)

Connections and joints in composite construction

Various cross-section shapes (1)

Hot-rolled and
cold-formed

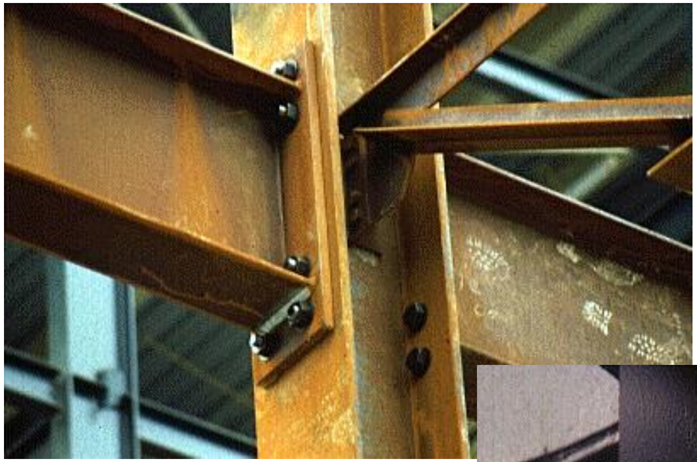




Various cross-section shapes (2)

Built-up profiles

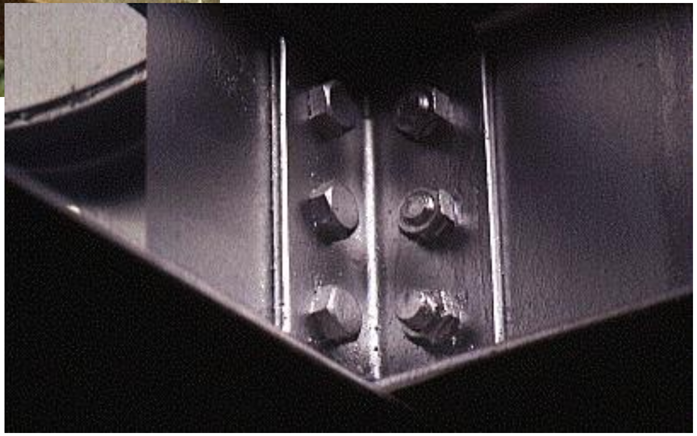
Various connection elements



End plates

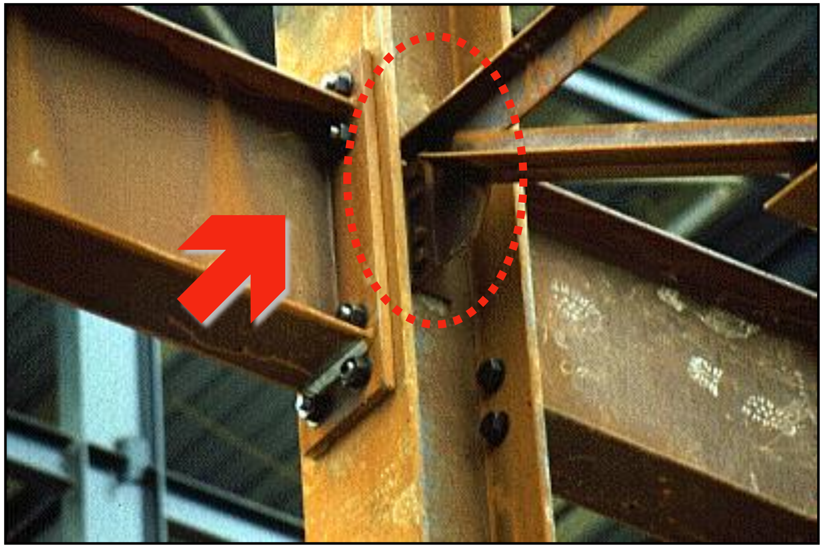
Splices

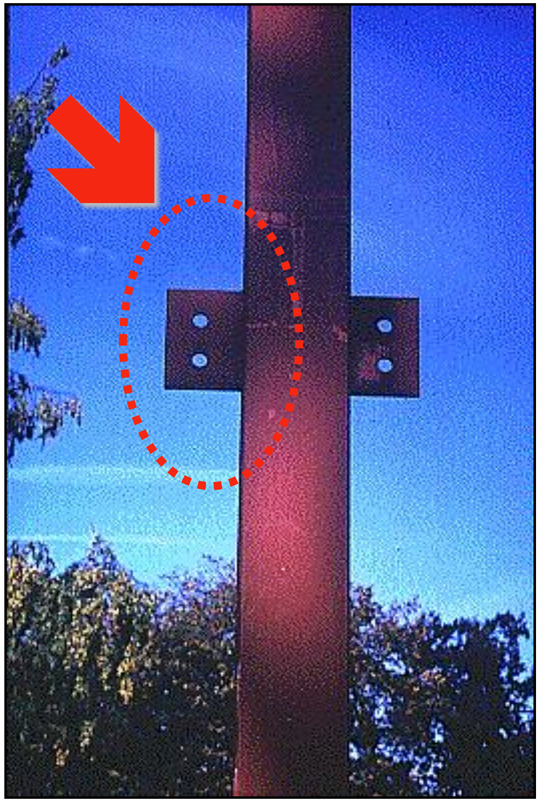
Cleats



Economy

Reduced fabrication, transportation and erection costs





Specific design criteria

Robustness

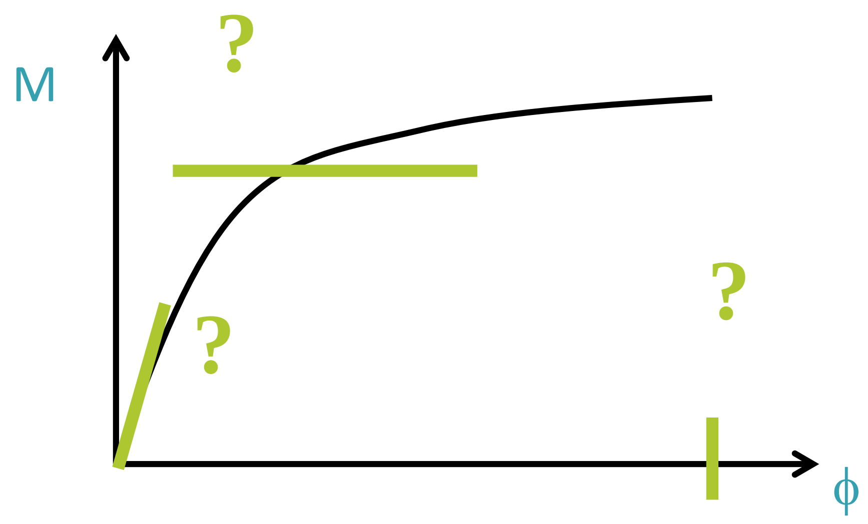
→ Joints as key elements

Spencer Platt / Getty Images

Shannon Stapleton / Reuters

Characterization (1)

Search for a unified approach



Characterization (2)

Eurocode 3 – Part 1-8

- Beam-to-beam joints, splices, beam-to-column joints and column bases:
  - welded connections
  - bolted connections (anchors for column bases)

Background: COMPONENT METHOD

Characterization (3) - component method

Three steps

First step

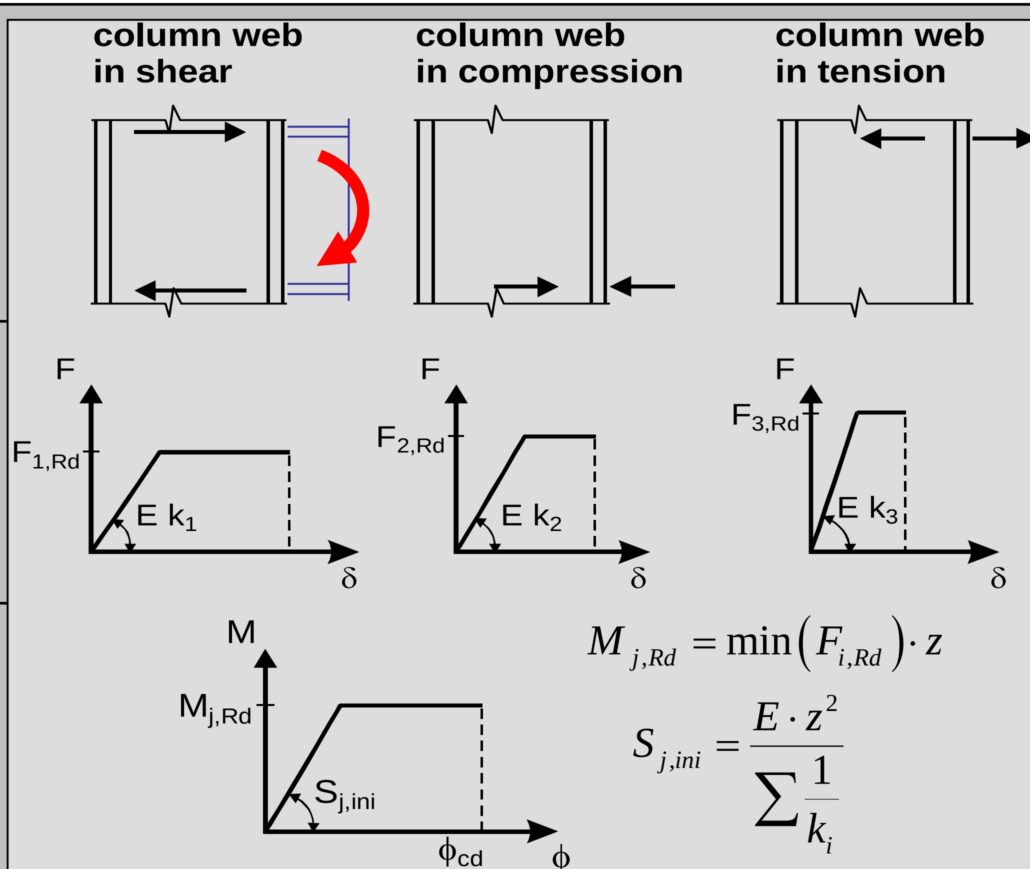
Identification of the active components

Second step:

Response of the components

Third step:

"Assembly" of the components



$$M_{j,Rd} = \min\left(F_{i,Rd}\right)\cdot z$$

$$S_{j,ini} = \frac{E\cdot z^2}{\sum \frac{1}{k_i}}$$

Characterization (4) - component method

EC3 Part 1-8 provides therefore:

- a library of components
- rules for the evaluation of the properties of the components (stiffness, resistance, deformation capacity)
- rules for the evaluation of the possible component interactions
- « assembly » rules for components

Applicable for simple joint and moment resistant joint

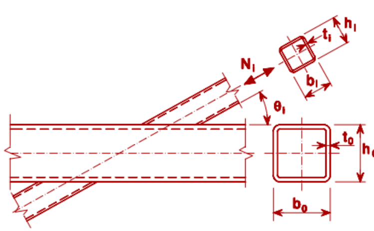
Characterization (4) – Hollow section joints

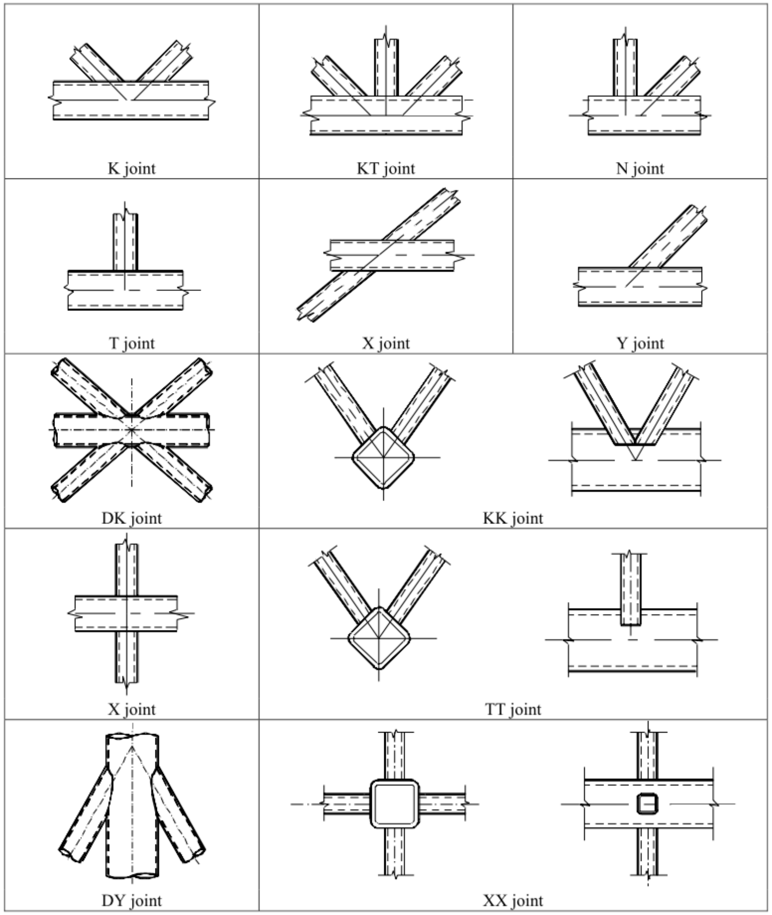
Different approach for lattice girder joints

For many types of joint configurations:

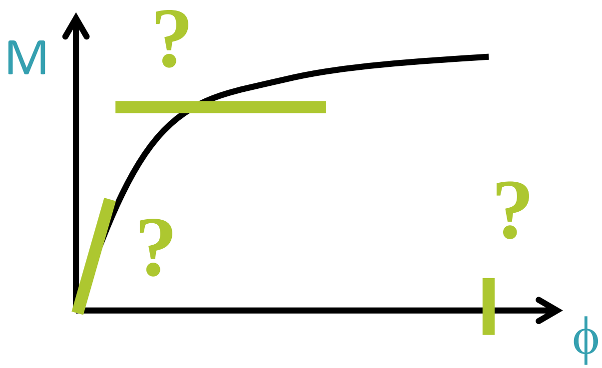
- Joints considered as a whole
- Check of relevant failure modes
- Scope of application to be checked

Table 7.11: Design axial resistances of welded T, X and Y joints between RHS or CHS braces and RHS chords

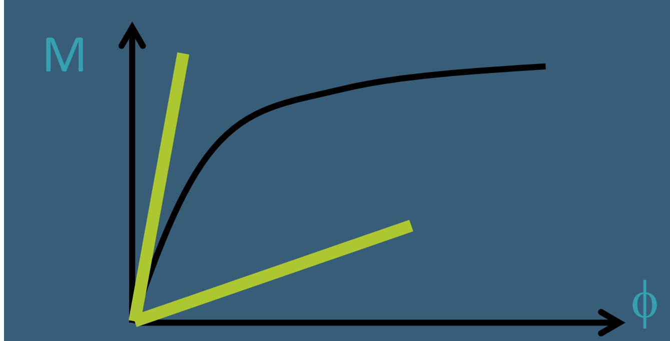
Type of joint	Design resistance [$i = 1$]
	Chord face failure $\beta \leq 0{,}85$
	$N_{i,Rd} = \frac{k_n f_{y0} t_0^2}{(1-\beta)\sin\theta_1}\left(\frac{2\eta}{\sin\theta_1} + 4\sqrt{1-\beta}\right)/\gamma_{M5}$
	Chord side wall buckling [1] $\beta = 1{,}0$ [2]
	$N_{i,Rd} = \frac{f_b t_0}{\sin\theta_i}\left(\frac{2h_i}{\sin\theta_1} + 10t_0\right)/\gamma_{M5}$
	Brace failure $\beta \geq 0{,}85$
	$N_{i,Rd} = f_{yi} t_i (2h_i - 4t_i + 2b_{eff})/\gamma_{M5}$
	Punching shear $0{,}85 \leq \beta \leq (1 - 1/\gamma)$
	$N_{i,Rd} = \frac{f_{y0} t_0}{\sqrt{3}\sin\theta_1}\left(\frac{2h_i}{\sin\theta_1} + 2b_{e,p}\right)/\gamma_{M5}$



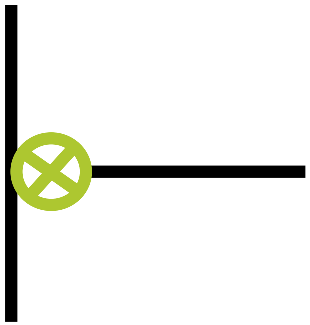
Four successive steps for structural integration



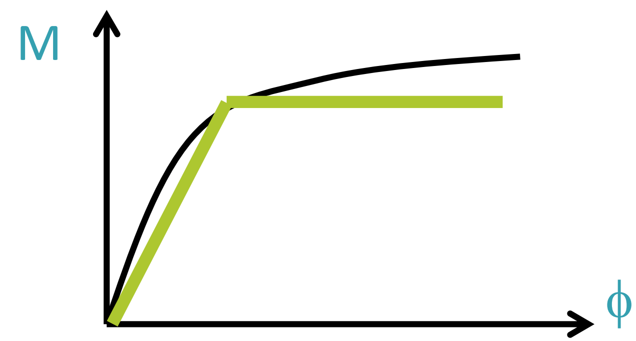
Characterization



Classification



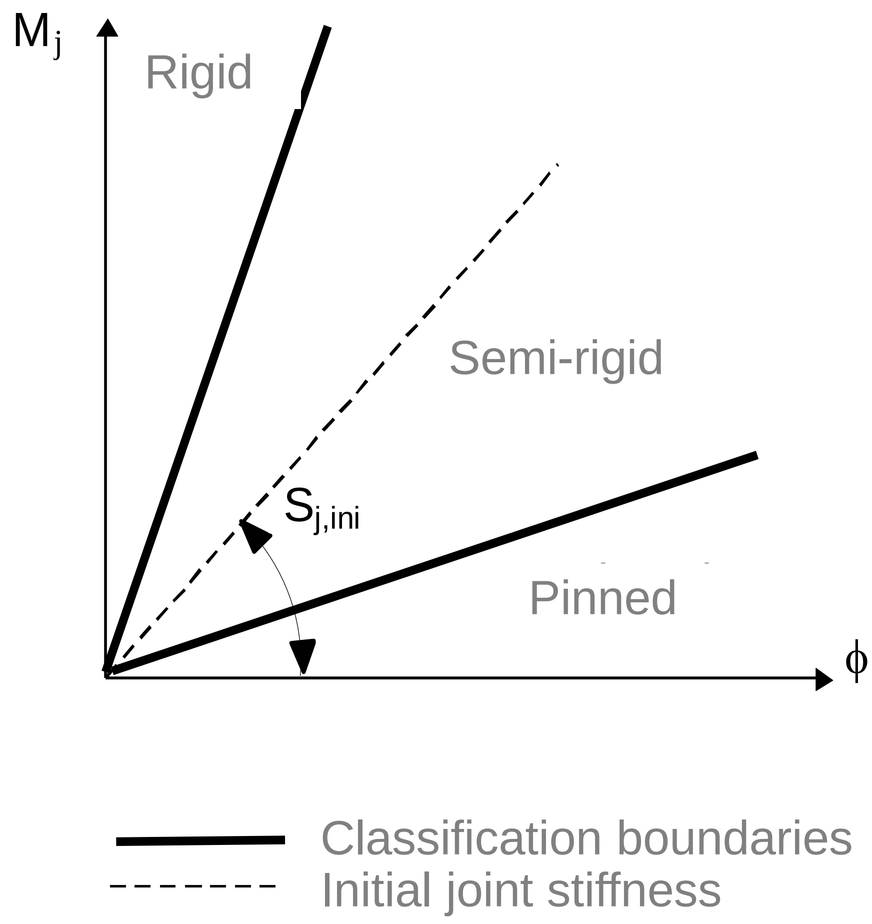
Modelling



Idealization

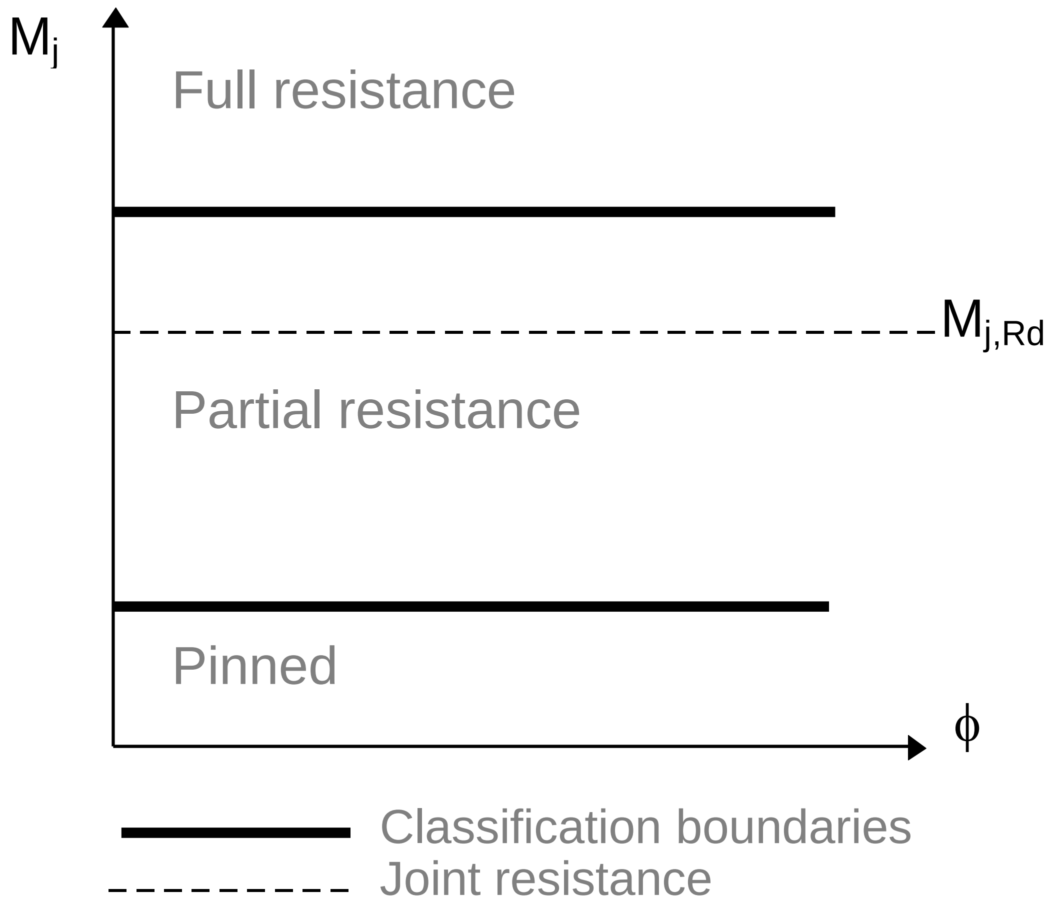
Classification (1)

Stiffness



Classification (2)

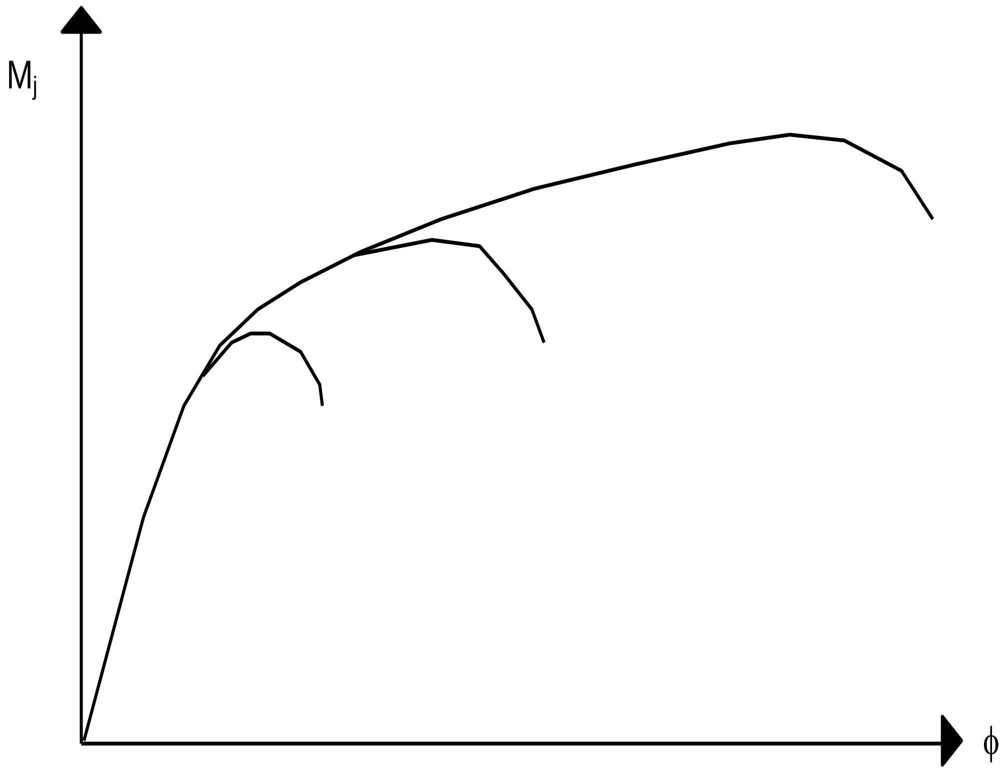
Resistance



Classification (3)

Ductility

- Brittle
- "Semi-ductile"
- Ductile



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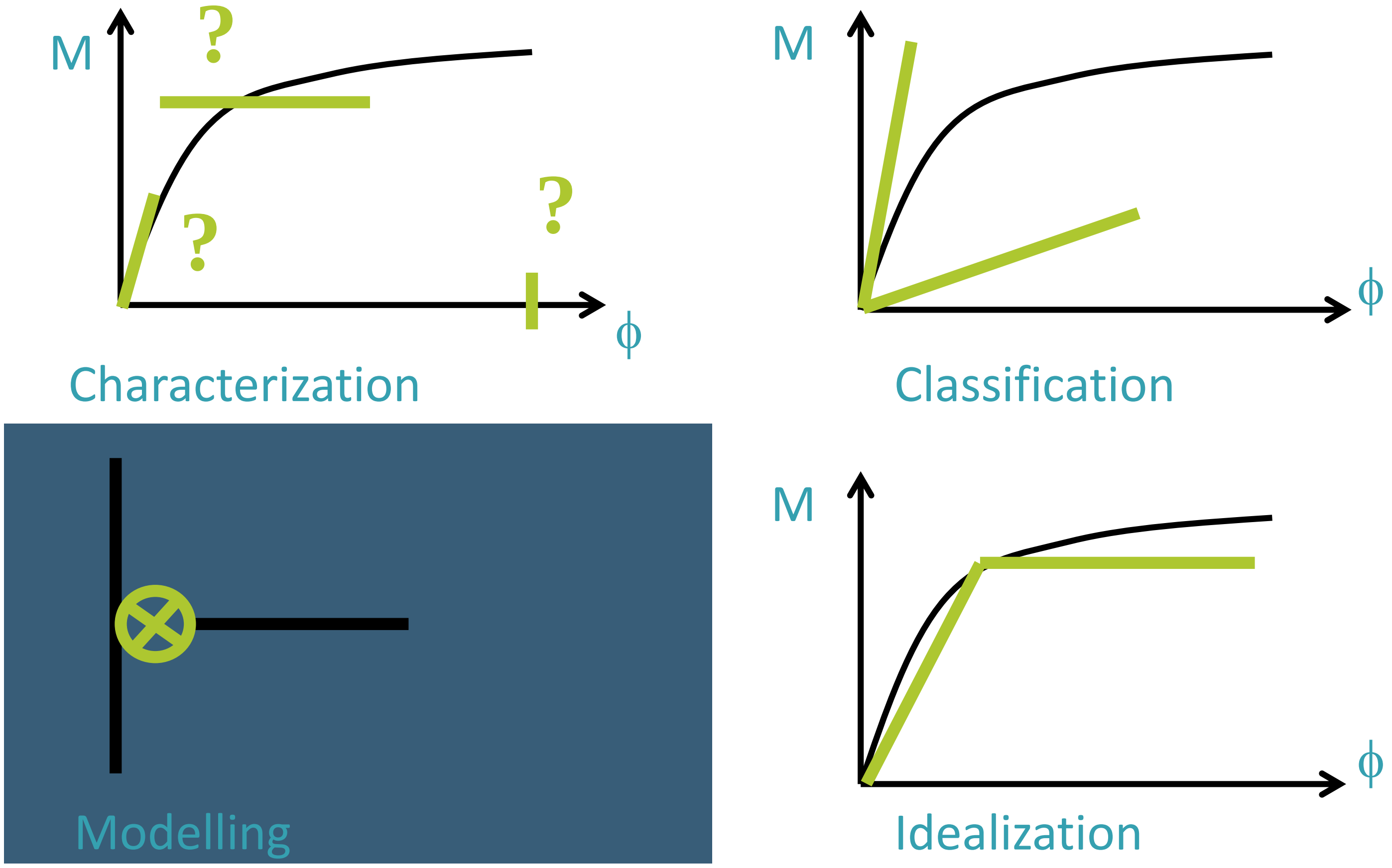
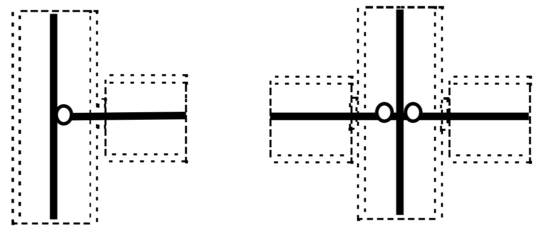
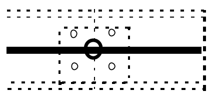
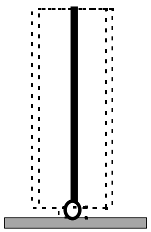
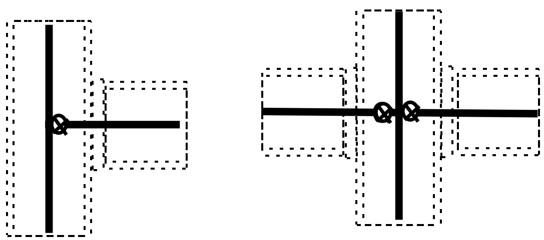
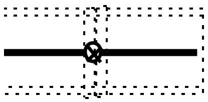
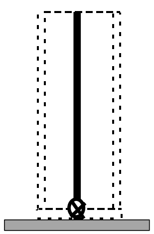
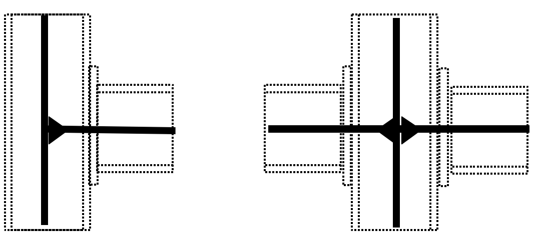
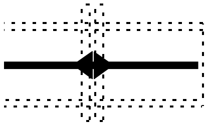
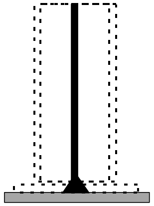


Modelling

JOINT MODELLING	BEAM-TO-COLUMN JOINTS MAJOR AXIS BENDING	BEAM SPLICES	COLUMN BASES
SIMPLE			
SEMI- CONTINUOUS			
CONTINUOUS			

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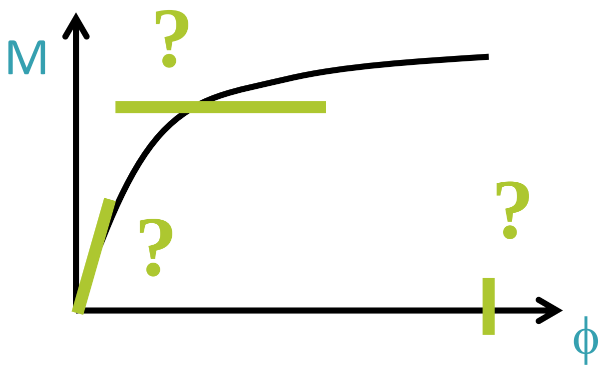
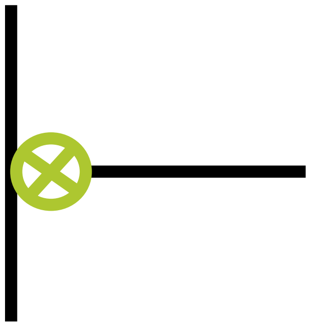
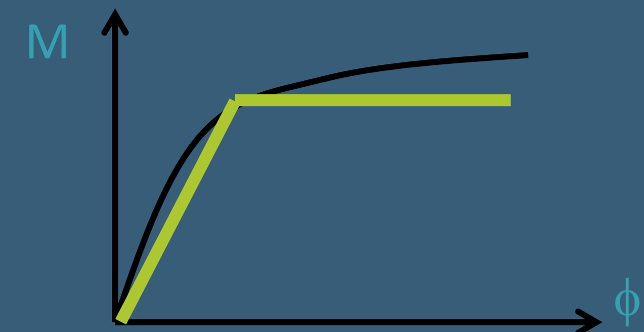


Characterization

Classification



Modelling



Idealization

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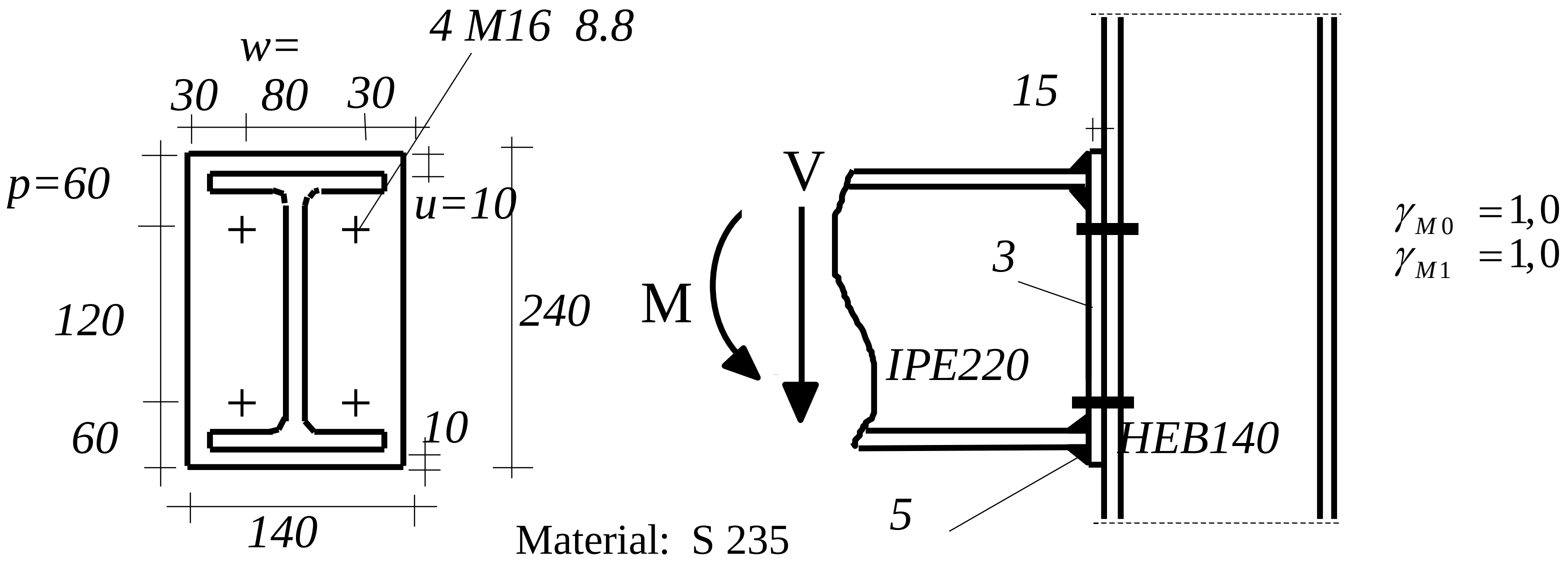
Example

Single sided beam-to-column joint configuration, bolted end-plate connection



To be evaluated:

Design moment resistance , initial stiffness

General data

Column

$$h_{wc} = h_c - 2t_{fc} - 2r_c = 140 - 2\times12 - 2\times12 = 92mm$$

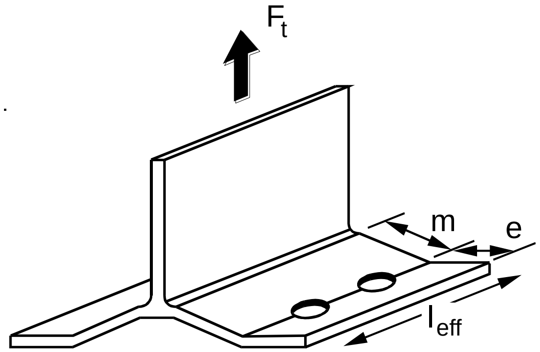
$$A_{vc} = A_c - 2b_c t_{fc} + (t_{wc} + 2r_c)$$
$$= 4295,6 - 2\times140\times12 + (7 + 2\times12)\times12 = 1307,6mm^2$$

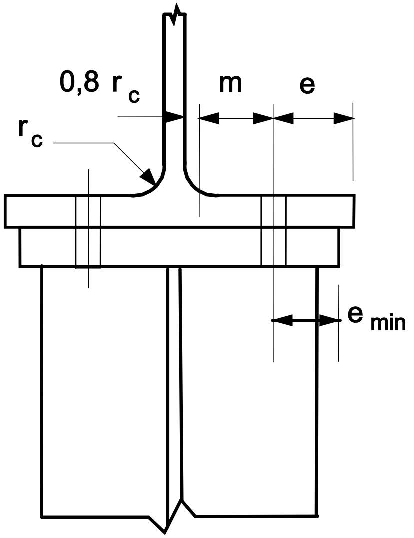
$$m = \frac{w - t_{fc}}{2} - 0,8r_c = \frac{80-7}{2} - 0,8\times12 = 26,9mm$$

$$e = \frac{b_c - w}{2} = \frac{140-80}{2} = 30mm$$

$$m_{pl,fc} = 0,25\frac{t_{fc}^2 f_{yc}}{\gamma_{M0}} = 0,25\frac{12^2\times235}{1,0} = 8460Nmm/mm$$

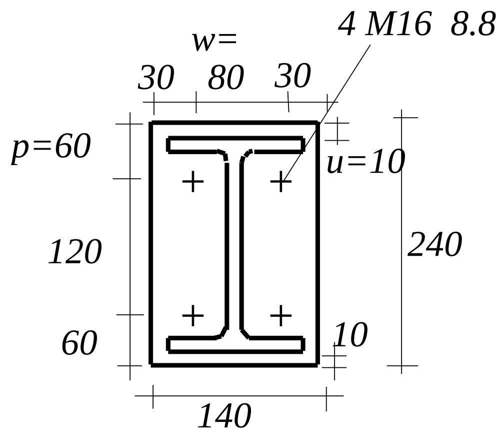
Equivalent T-stub in tension

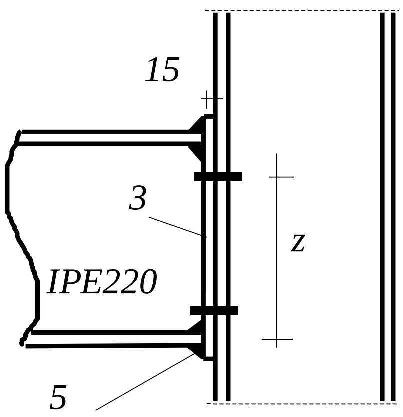




General data

Beam





Lever arm

$$z = h_b + u - \frac{t_{fb}}{2} - p = 220 + 10 - \frac{9,2}{2} - 60 = 165,4\, mm$$

$$M_{c,Rd} \text{ (classe 1 section) } = \frac{W_{pl,yb}\, f_{yb}}{\gamma_{M0}} = \frac{285.406 \times 235 \times 10^{-6}}{1,0} = 67,07\, kNm$$

General data

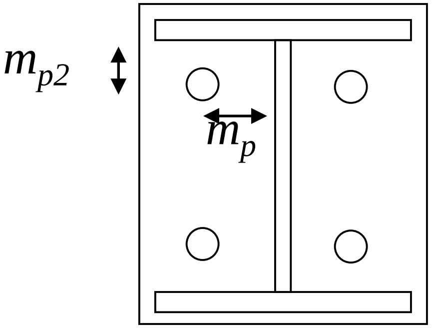
End plate

$$m_p = \frac{w - t_{wb}}{2} - 0,8\sqrt{2}a_w = \frac{80-5,9}{2} - 0,8\times\sqrt{2}\times 3 = 33,66mm$$

$$m_{p2} = p - u - t_{fb} - 0,8\sqrt{2}a_f = 60 - 10 - 9,2 - 0,8\sqrt{2}\times 5 = 35,14mm$$

$$e_p = \frac{b_p - w}{2} = \frac{140-80}{2} = 30mm$$

$$m_{pl,p} = 0,25\frac{t_p^2 f_{yp}}{\gamma_{M0}} = 0,25\frac{15^2\times 235}{1,0} = 13.218 Nmm/mm$$



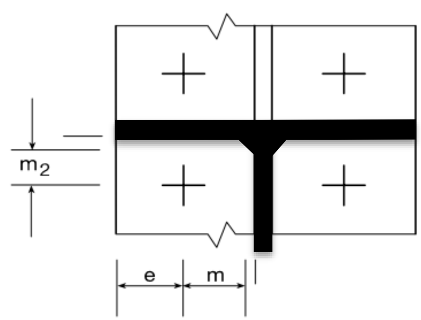
General data

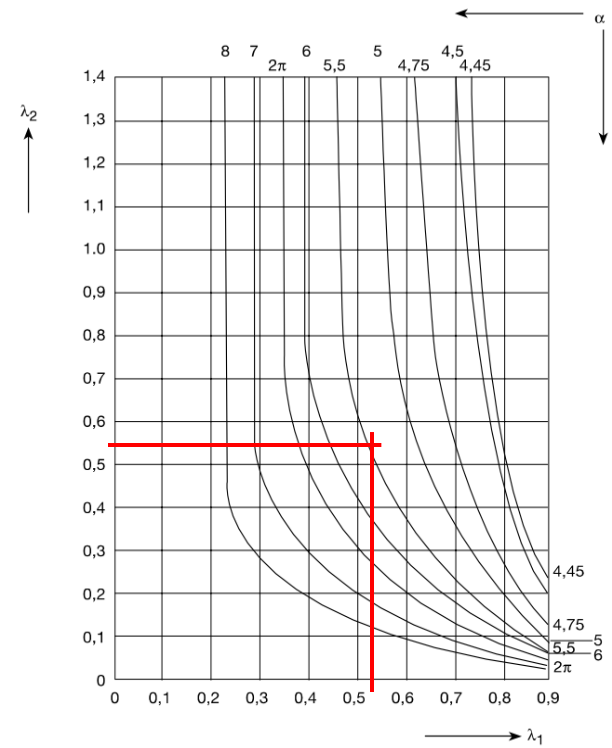
End plate

Alpha factor for effective lengths

$$\lambda_1 = \frac{m_p}{m_p + e_p} = \frac{33,66}{33,66+30} = 0,53$$

$$\lambda_2 = \frac{m_{p2}}{m_p + e_p} = \frac{35,14}{33,66+30} = 0,55$$





$$\alpha = 5,5$$

General data

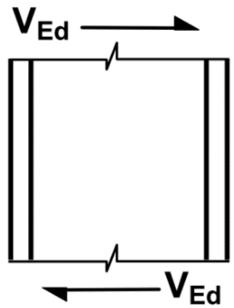
Bolts

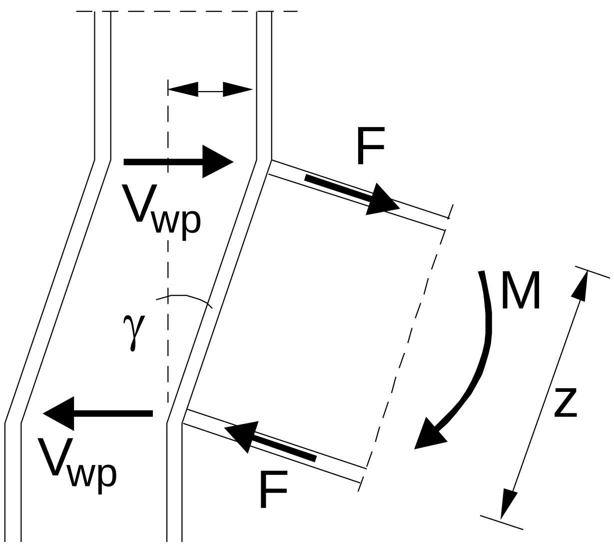
$$F_{t,Rd} = \frac{0,9\, f_{ub} A_s}{\gamma_{Mb}} = \frac{0,9 \times 800 \times 157 \times 10^{-3}}{1,25} = 90,43kN$$

$$F_{v,Rd} \text{ (shear plane in thread) } = \frac{0,6\, f_{ub} A_s}{\gamma_{Mb}} = \frac{0,6 \times 800 \times 157 \times 10^{-3}}{1.25} = 60,3kN$$

$$L_b = t_{fc} + t_p + 0,5\left(h_{bolt} + h_{nut}\right) = 12 + 15 + \frac{1}{2}\left(10 + 14,8\right) + 2 \times 4 = 47,4mm$$

Component Nº 1 – Column web in shear





Resistance

$$V_{wc,Rd} = \frac{0,9\,A_{vc}\,f_{y,cw}}{\sqrt{3}\,\gamma_{M0}} = \frac{0,9 \times 1307,6 \times 235 \times 10^{-3}}{\sqrt{3} \times 1,0} = 159,7\,kN$$

Transformation parameter

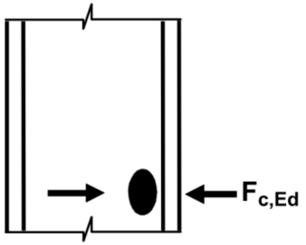
$$\text{Assumption}: \quad \beta = 1$$

$$F_{Rd,1} = \frac{V_{wc,Rd}}{\beta} = \frac{159,7}{1} = 159,7\,kN$$

Stiffness coefficient

$$k_1 = \frac{0,38\,A_{vc}}{\beta\,h} = \frac{0,38 \times 1307,6}{1 \times 165,4} = 3,004\,mm$$

Component Nº 2 – Column web in compression



Resistance

$$b_{eff,c,wc} = \min\left[t_{fb} + 2a_f\sqrt{2} + 2t_p + 5\left(t_{fc} + s\right);\, t_{fb} + a_f\sqrt{2} + t_p + u + 5\left(t_{fc} + s\right)\right]$$
$$= \min\left[9,2 + 2\times 5\times\sqrt{2} + 2\times 15 + 5\times(12+12);\; 9,2 + 5\times\sqrt{2} + 15 + 10 + 5(12+12)\right] = 161,27\,mm$$

Reduction factors to account for compression stresses and instability

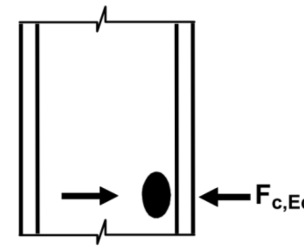
$$\text{Assumption:}\quad k_{wc} = \min\left[1,0;\; 1,7 - \sigma_{com,Ed} / f_{y,wc}\right] = 1,0$$

$$\bar{\lambda}_p = 0,932\sqrt{\frac{b_{eff,c,wc}\, d_c\, f_{y,wc}}{E\, t^2_{wc}}} = 0,932\sqrt{\frac{161,27\times 92\times 235}{210000\times 7\times 7}} = 0,543 \le 0,673 \quad\rightarrow\quad \rho = 1,0$$

$$\omega = \omega_1 = \sqrt{\frac{1}{1 + 1,3\left(b_{eff,c,wc}\, t_{wc} / A_{vc}\right)^2}} = \sqrt{\frac{1}{1 + 1,3(161,27\times 7/1307,6)^2}} = 0,713$$

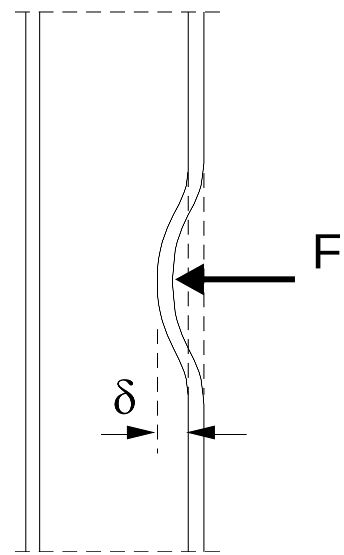
$$F_{Rd,2} = k_{wc}\,\omega\,\rho\, b_{eff,c,wc}\, t_{wc}\, f_{y,wc} / \gamma_{M1} = 1\times 0,713\times 1\times 161,27\times 7\times 235\times 10^{-3}/1,0 = 189,1\,kN$$

Component Nº 2 – Column web in compression



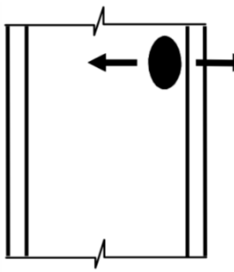
Stiffness coefficient

$$k_2 = \frac{0,7\, b_{eff,c,wc}\, t_{wc}}{h_{wc}} = \frac{0,7 \times 161,27 \times 7}{92} = 8,589 mm$$



$$F_i = k_i\, E\, \delta_i$$

Component Nº 3 – Column web in tension



Resistance

$$b_{eff,t,wc} = \min\left[2\pi m; 4m + 1,25e\right] = \min\left(2\pi \times 26,9; 4 \times 26,9 + 1,25 \times 30\right) = 145,10mm$$

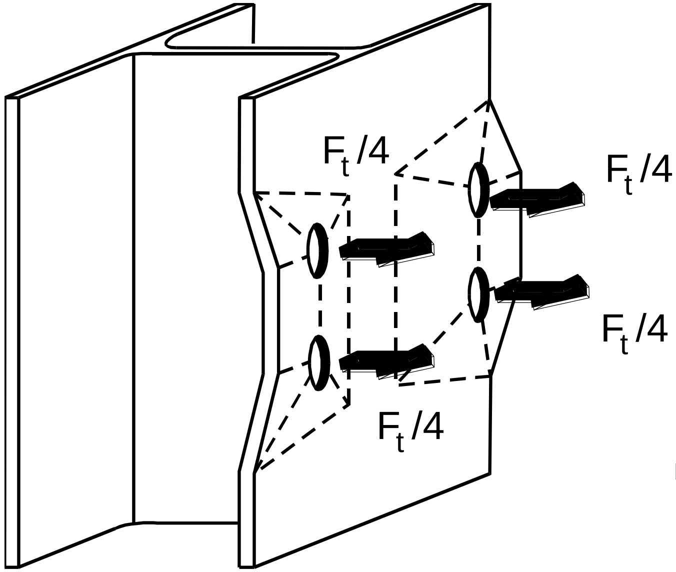
$$\omega_1 = \sqrt{\frac{1}{1 + 1,3\left(b_{eff,t,wc}\, t_{wc} / A_{vc}\right)^2}} = \sqrt{\frac{1}{1 + 1,3\left(145,1 \times 7/1307,6\right)^2}} = 0,749$$

$$F_{Rd,3} = \omega\, b_{eff,t,wc}\, t_{wc}\, f_{y,wc} / \gamma_{M0} = 0,749 \times 145,1 \times 7 \times 235 \times 10^{-3} / 1,0 = 178,7kN$$

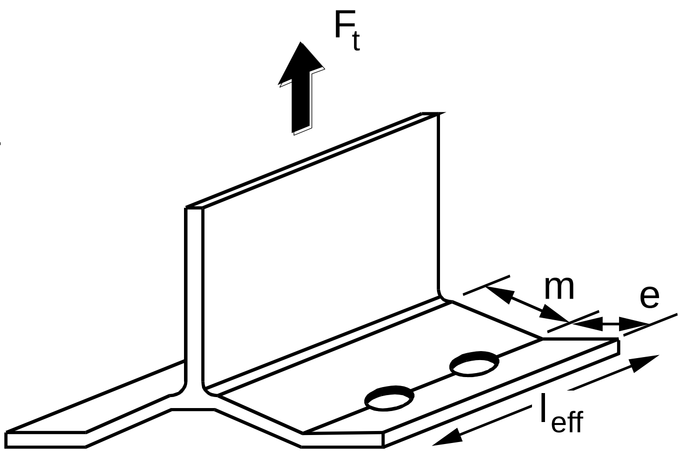
Stiffness coefficient

$$k_3 = \frac{0,7\, b_{eff,t,wc}\, t_{wc}}{h_{wc}} = \frac{0,7 \times 145,1 \times 7}{92} = 7,728mm$$

Component Nº 4 – Column flange in bending
Component Nº 5 – End plate in bending

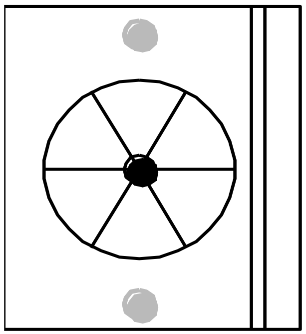


Equivalent T-stub in tension

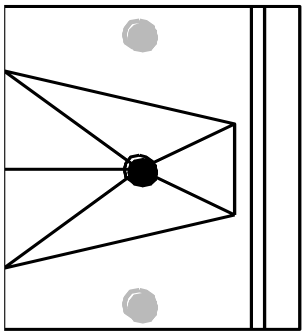


T-stub – Effective length

Distinction between circular and non-circular yield line patterns



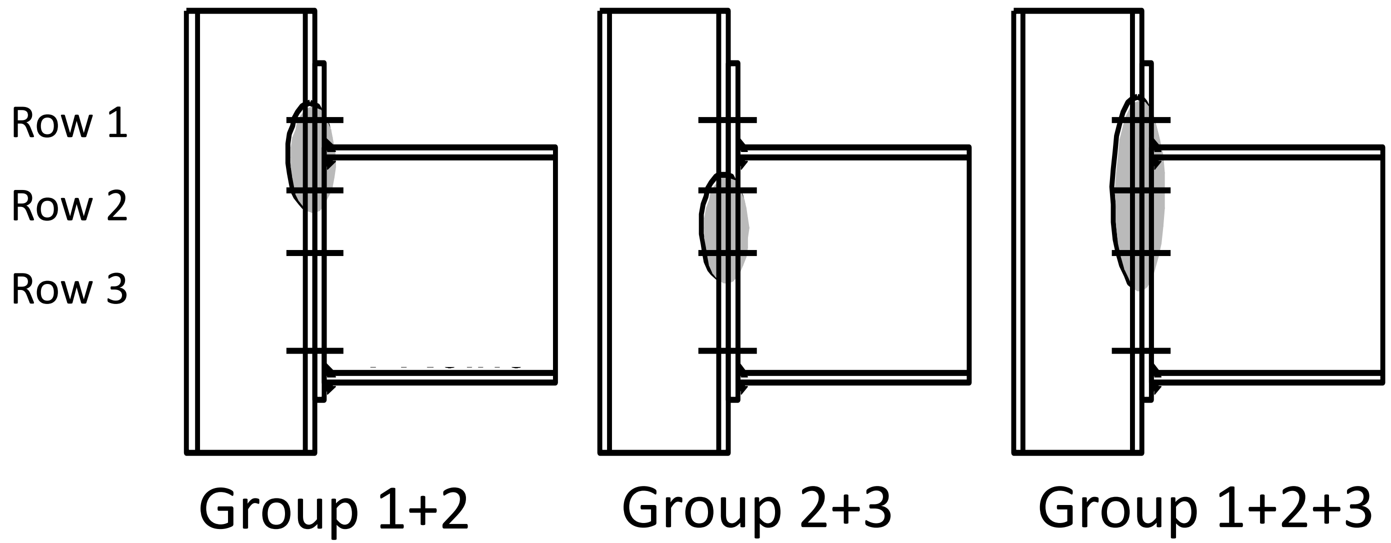
Circular patterns



Non-circular patterns

T-stub – Effective length

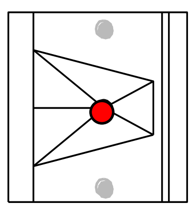
Groups effects to consider in addition to the individual response of each bolt-row

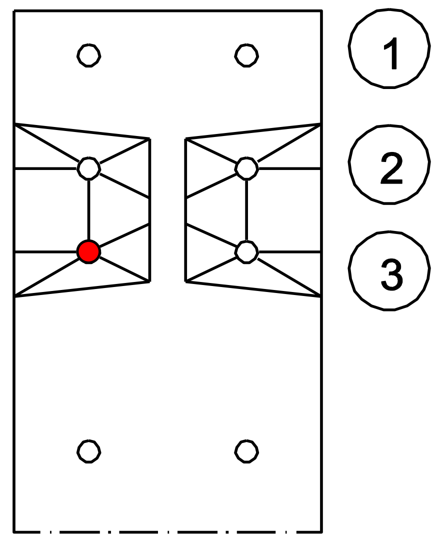


T-stub – Effective length

Groups effects to consider in addition to the individual response of each bolt-row

Row 3

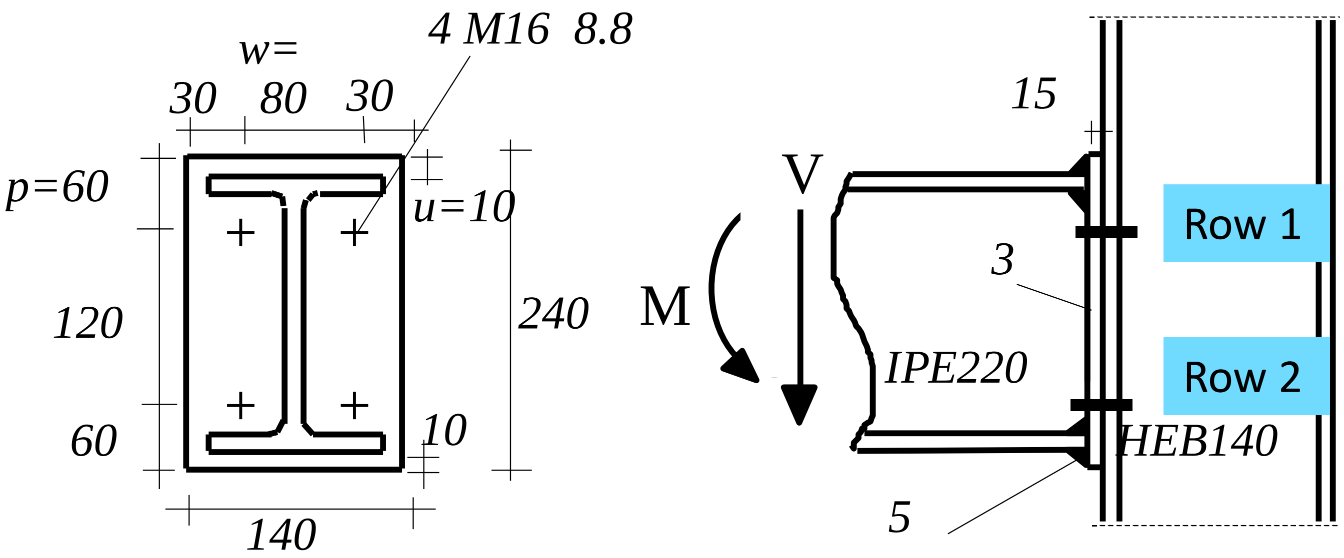




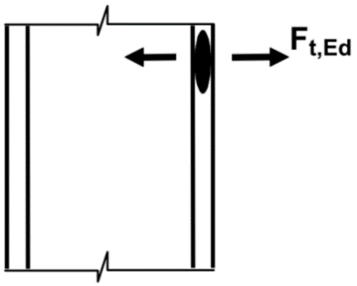
$$F_{Rd,3} = \min\left(F_{Rd,3,indiv}; F_{Rd,3,group}\right)$$

Bolt rows considered

In this example: only bolt row 1 is considered for tension forces



Component Nº 4 – Column flange in bending

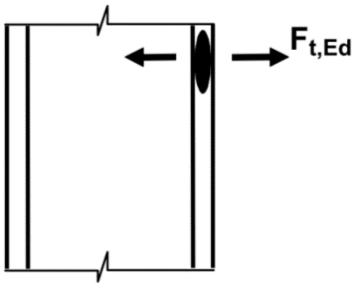


Resistance

$$l_{eff,t,fc} = b_{eff,t,wc} = 145{,}1mm \quad \text{(see column web in tension)}$$

$$n = \min\left[\, e; 1{,}25m; \left(b_p - w\right)/2 \right] = \min\left(30; 1{,}25 \times 26{,}9; 30\right) = 30mm$$

Component Nº 4 – Column flange in bending



Mode 1 - Complete yielding of the flange

$$F_{fc,Rd,t1} = \frac{4 l_{eff,t,fc}\, m_{pl,fc}}{m} = \frac{4 \times 145{,}1 \times 8460}{26{,}9} \times 10^{-3} = 182{,}5 kN$$

Mode 2 - Bolt failure with yielding of the flange

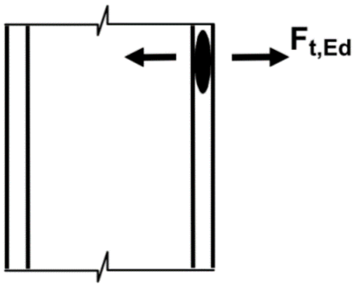
$$F_{fc,Rd,t2} = \frac{2 l_{eff,t,fc}\, m_{pl,fc} + 2 B_{t,Rd}\, n}{m+n} = \frac{2 \times 145{,}1 \times 8460 + 2 \times 90{,}4 \times 10^{3} \times 30}{26{,}9+30} \times 10^{-3} = 138{,}5 kN$$

Mode 3 - Bolt failure

$$F_{fc,Rd,t3} = 2 B_{t,Rd} = 2 \times 90{,}43 = 180{,}9 kN$$

Component Nº 4 – Column flange in bending

Resistance

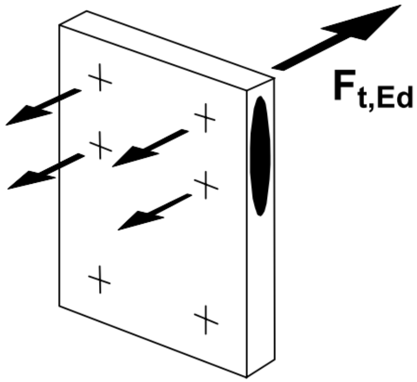


$$F_{Rd,4} = \min\left[F_{fc,Rd,t1}; F_{fc,Rd,t2}; F_{fc,Rd,t3} \right] = 138,5kN$$

Stiffness coefficient

$$k_4 = \frac{0,9 l_{eff,fc,t} t_{fc}^3}{m^3} = \frac{0,9 \times 145,1 \times 12^3}{26,9^3} = 11,59mm$$

Component Nº 5 – End plate in bending



Resistance

$$l_{eff,t,p} = \min\left[2\pi m_p ; \alpha m_p\right] = \min\left(2\pi\times 33,66;\ 5,5\times 33,66\right) = 185\ mm$$

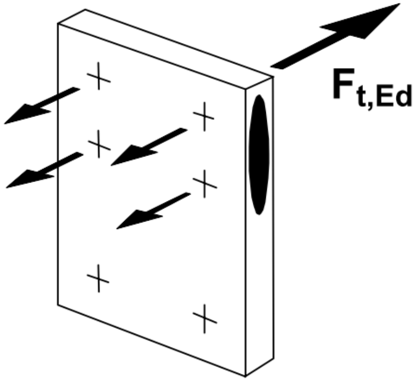
$$n_p = \min\left[e_p ; 1,25 m_p ; e\right] = \min\left(30;1,25\times 33,66;30\right) = 30 mm$$

Mode 1: $$F_{ep,Rd,1} = \frac{4 l_{eff,t,p}\, m_{pl,p}}{m_p} = \frac{4\times 185\times 13.218}{33,66}\times 10^{-3} = 291 kN$$

Mode 2: $$F_{ep,Rd,2} = \frac{2 l_{eff,p,t}\, m_{pl,p} + 2 B_{t,Rd}\, n_p}{m_p + n_p} = \frac{2\times 185\times 13.218 + 2\times 90,43\times 10^3\times 30}{33,66+30}\times 10^{-3} = 162,1 kN$$

$$F_{Rd,5} = \min\left[F_{ep,Rd,1} ; F_{ep,Rd,2} ; F_{ep,Rd,3}\right] = 162,1 kN$$

Component Nº 5 – End plate in bending

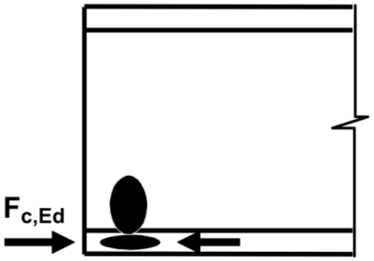


Stiffness coefficient

$$k_5 = \frac{0{,}9\, l_{eff,t,p}\, t_p^3}{m_p^3} = \frac{0{,}9 \times 185{,}0 \times 15^3}{33{,}66^3} = 14{,}73mm$$

Component Nº 7 – Beam flange and web in compression

Resistance

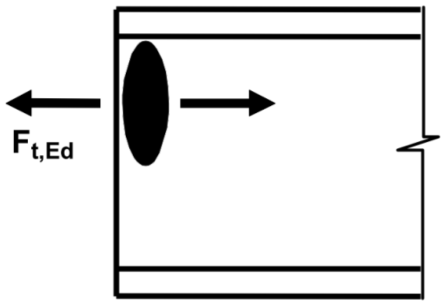


$$F_{Rd,7} = M_{c,Rd} / \left(h_b - t_{fb}\right) = \frac{67,07}{210,8 \times 10^{-3}} = 318,2 kN$$

Stiffness coefficient

$$k_7 = \infty$$

Component Nº 8 – Beam web in tension



Resistance

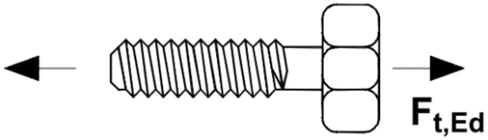
$$b_{eff,t,wb} = l_{eff,t,p} = 185mm$$

$$F_{Rd,8} = b_{eff,t,wb}\, t_{wb}\, f_{yb} / \gamma_{M0} = 185 \times 5,9 \times 235 \times 10^{-3} / 1,0 = 256,5kN$$

Stiffness coefficient

$$k_8 = \infty$$

Component Nº 10 – Bolts in tension



Resistance

$$F_{Rd,10} = 2\,B_{t,Rd} = 2 \times 90,43 = 180,9\,kN$$

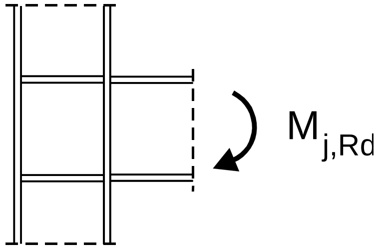
→ Mode 3 in T-stubs for components:

- "column flange in bending"
- "end plate in bending"

Stiffness coefficient

$$k_{10} = 1,6\,\frac{A_s}{L_b} = 1,6 \times \frac{157}{47,4} = 5,30\,mm$$

Design moment resistance



Relevant component

$$F_{Rd} = \min\left[F_{Rd,i}\right] = 138,5 kN \quad \text{(Column flange in bending)}$$

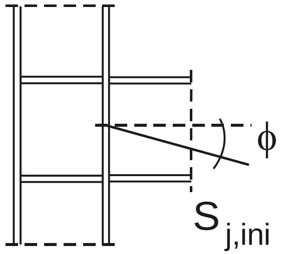
Design plastic moment resistance

$$M_{j,Rd} = F_{Rd}\, z = 138,5 \times 165,4 \times 10^{-3} = 22,91 kNm$$

Design elastic moment resistance

$$M_{j,el,Rd} = \frac{2}{3} M_{j,Rd} = 15,27 kNm$$

Stiffness



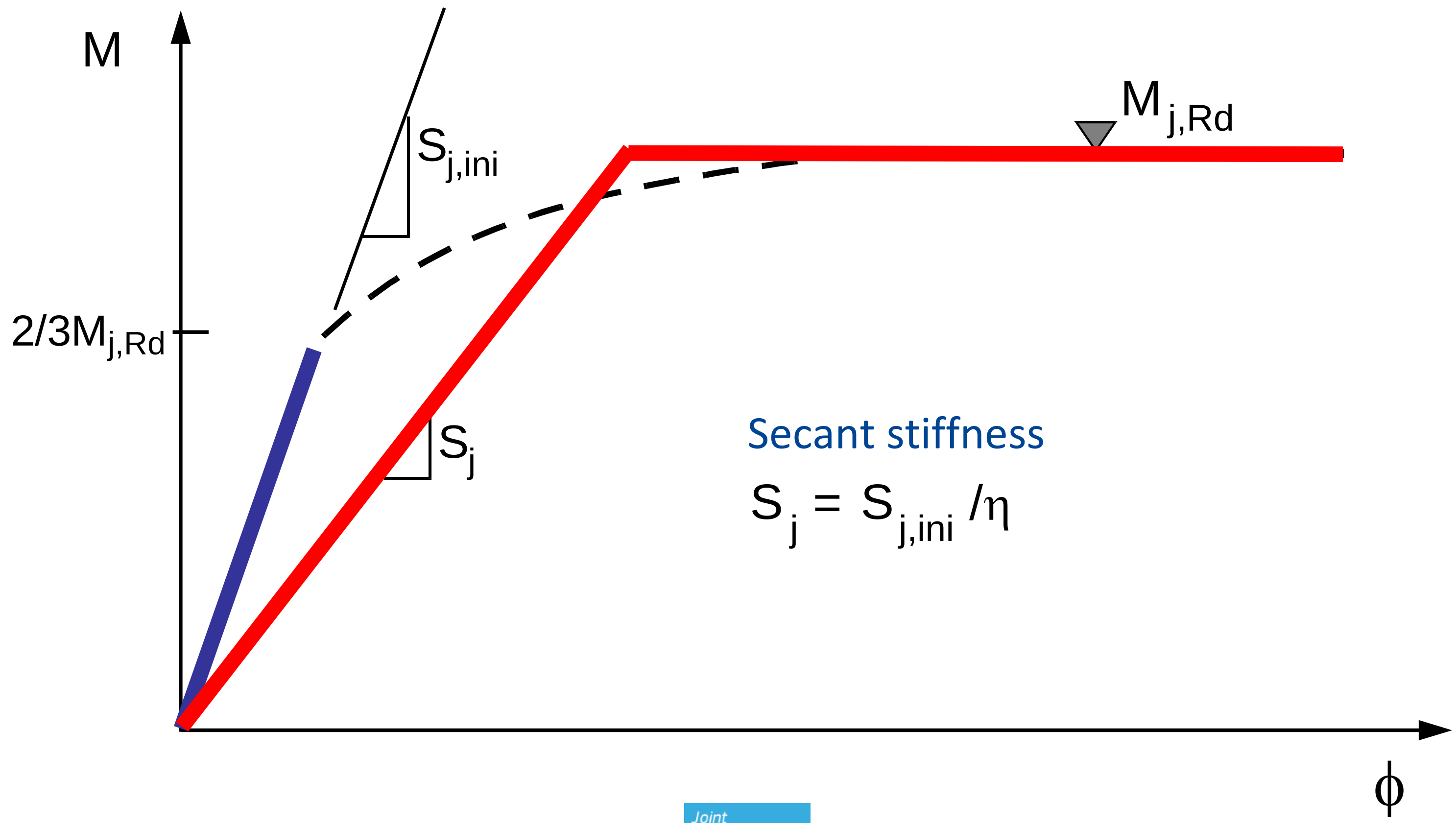
Initial stiffness

$$S_{j,ini} = E\,h^2 / \sum_i 1/k_i = \frac{210000 \times 165,4^2 \times 10^{-6}}{\frac{1}{3,004} + \frac{1}{8,589} + \frac{1}{7,728} + \frac{1}{11,59} + \frac{1}{14,73} + \frac{1}{5,30}} = 6234\ kNm/rad$$

Secant stiffness

$$S_j = S_{j,ini}/2 = 3117\ kNm/rad$$

Design moment-rotation characteristic



Secant stiffness

$$S_j = S_{j,ini} / \eta$$

European Commission

Eurocodes
Background and Applications

Design of **Steel Buildings**
with worked examples

16-17 October 2014
Brussels, Belgium

Organised and supported by

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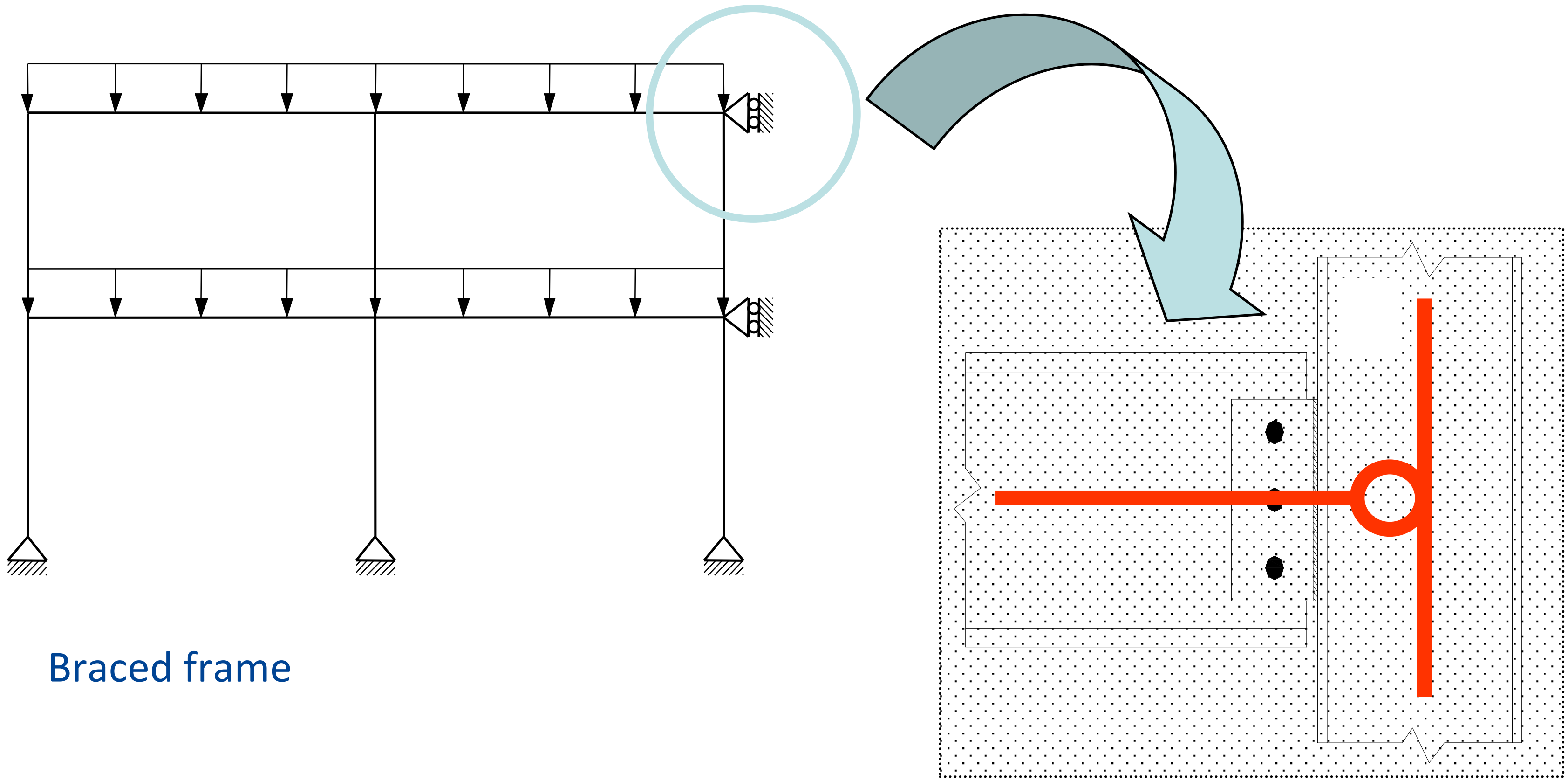
DG Enterprise and Industry
Joint Research Centre
European Convention for Constructional Steelwork
European Committee for Standardization
CEN/TC250/SC3

Design of Structural Steel Joints

- Introduction
- Integration of joints into structural design process
- Moment resistant joints
- **Simple joints**
- Design tools

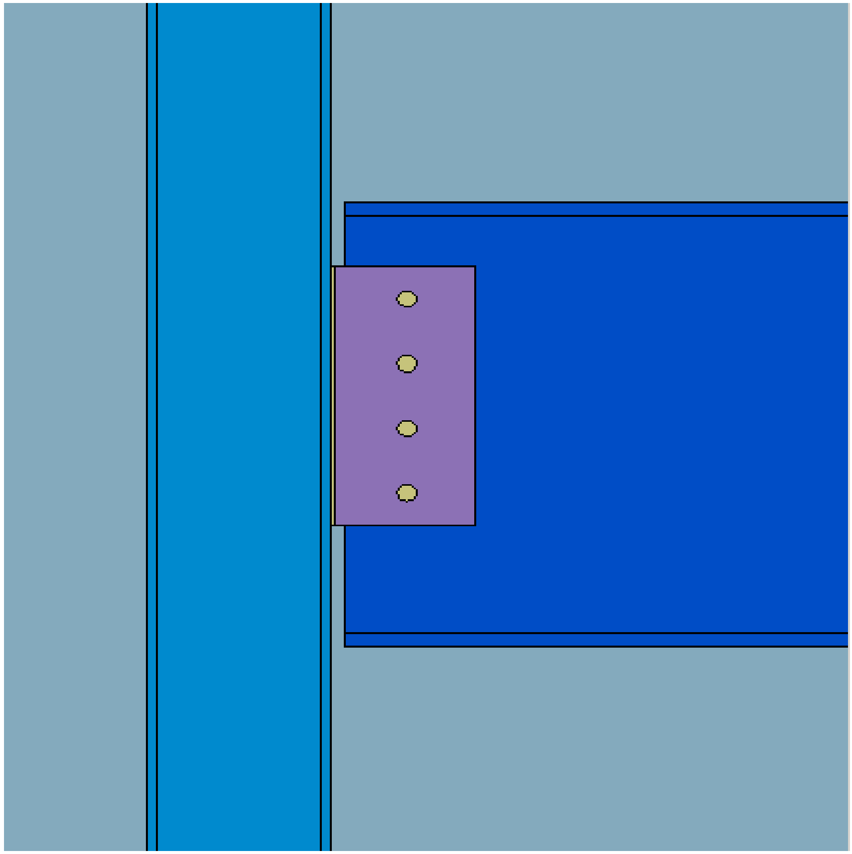
Joint Research Centre

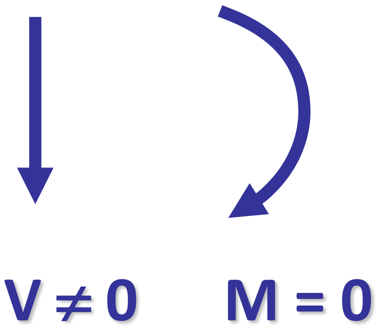
Nominally pinned joints



Braced frame

Nominally pinned joints

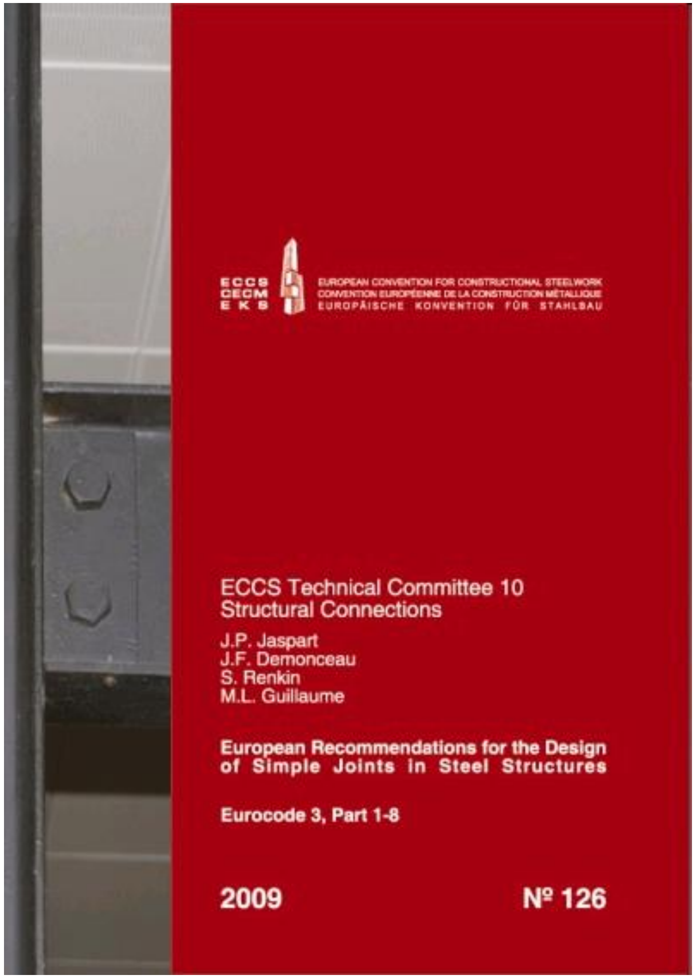




Design of simple joints

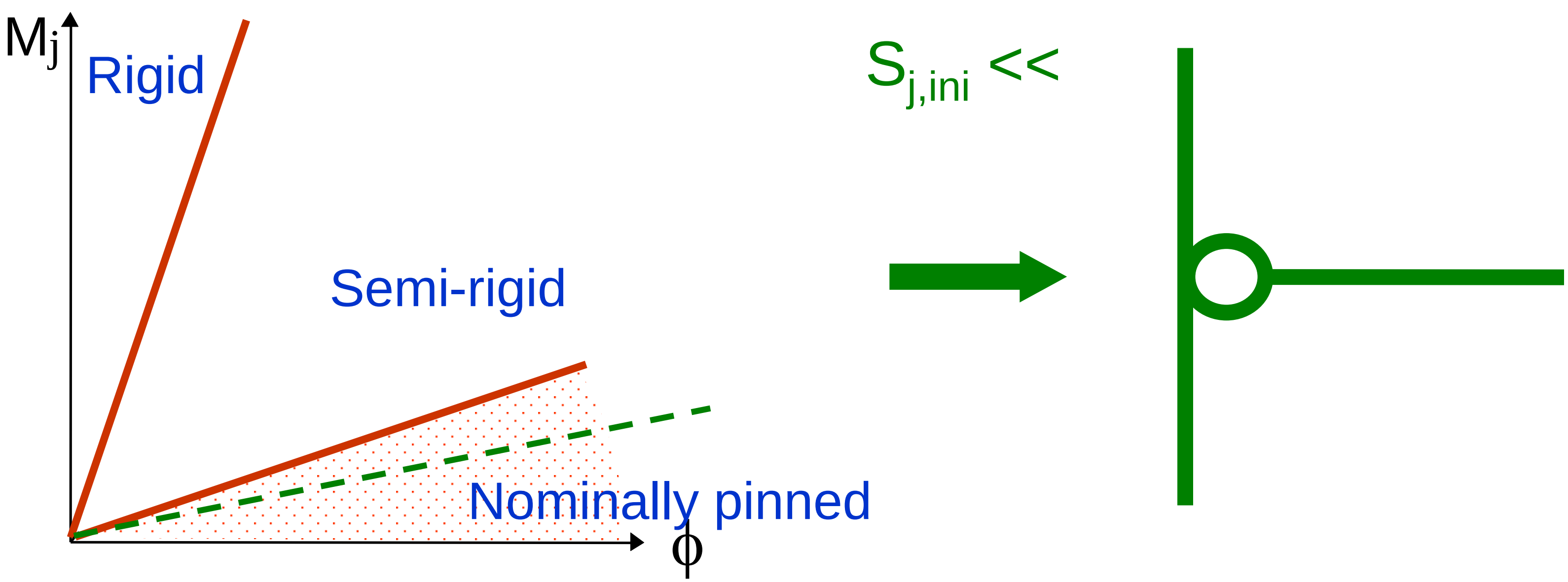
ECCS Publication Nº 126 (EN)

- Background information
- Design guidelines



Classification and modelling of joints

"Nominally pinned" joints :

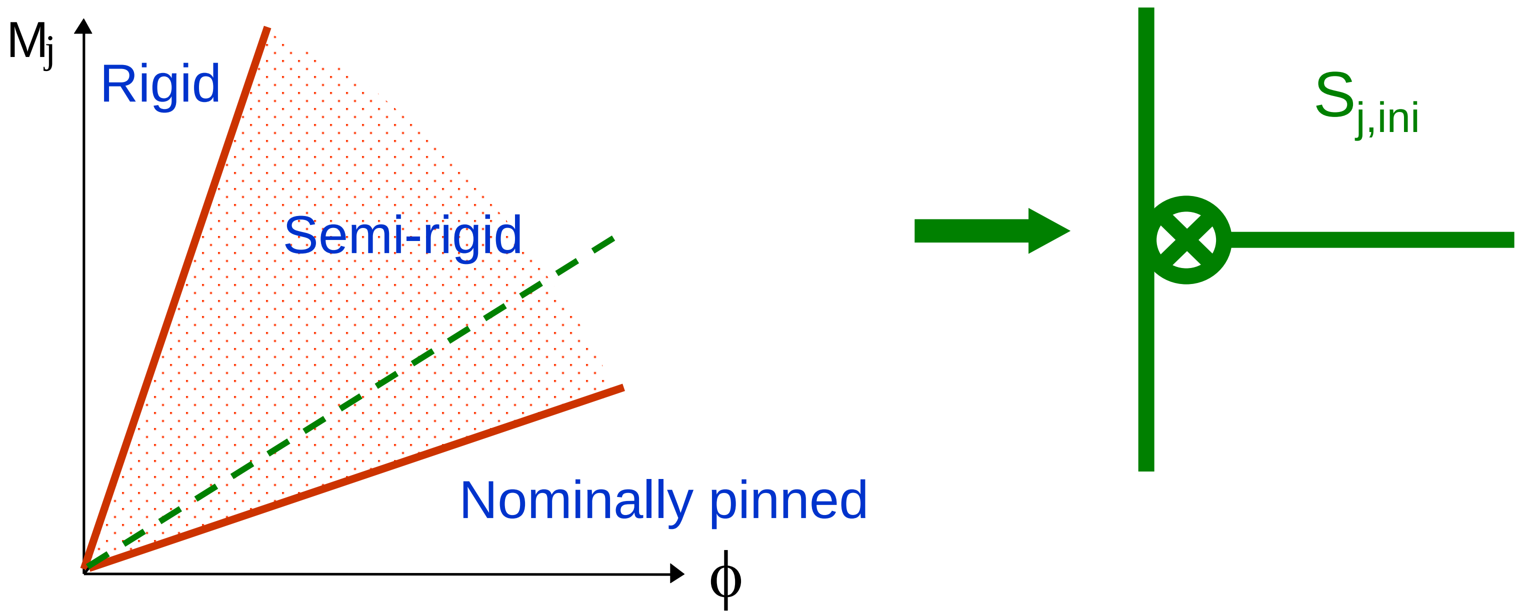


Limits for classification of joints by stiffness

Initial stiffness of the joint

Classification and modelling of joints

"Semi-rigid" joints :



Limits for classification of joints by stiffness

Initial stiffness of the joint

Classification and modelling of joints

As an alternative to a semi-continuous modelling (semi-rigid joints), is it safe to model the joints as nominally pinned whilst they are actually semi-rigid?

Semi-rigid $S_{j,ini} > 0,5EI_b/L_b$

Partial strength $M_{j,Rd} > 0,25\ M_{full\text{-}strength}$

Nominally pinned $S_{j,ini} = 0$

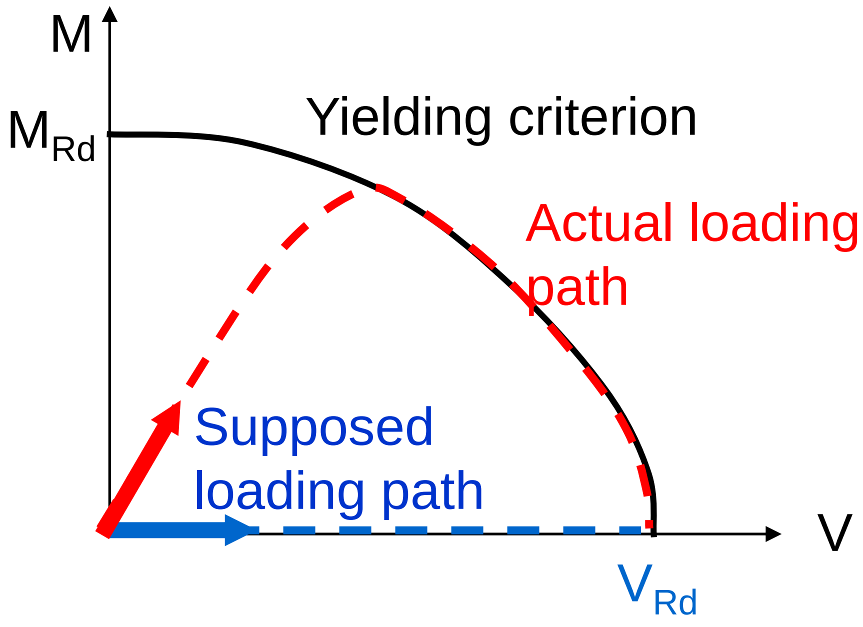
Nominally pinned $M_{j,Rd} = 0$

??

Classification and modelling of joints

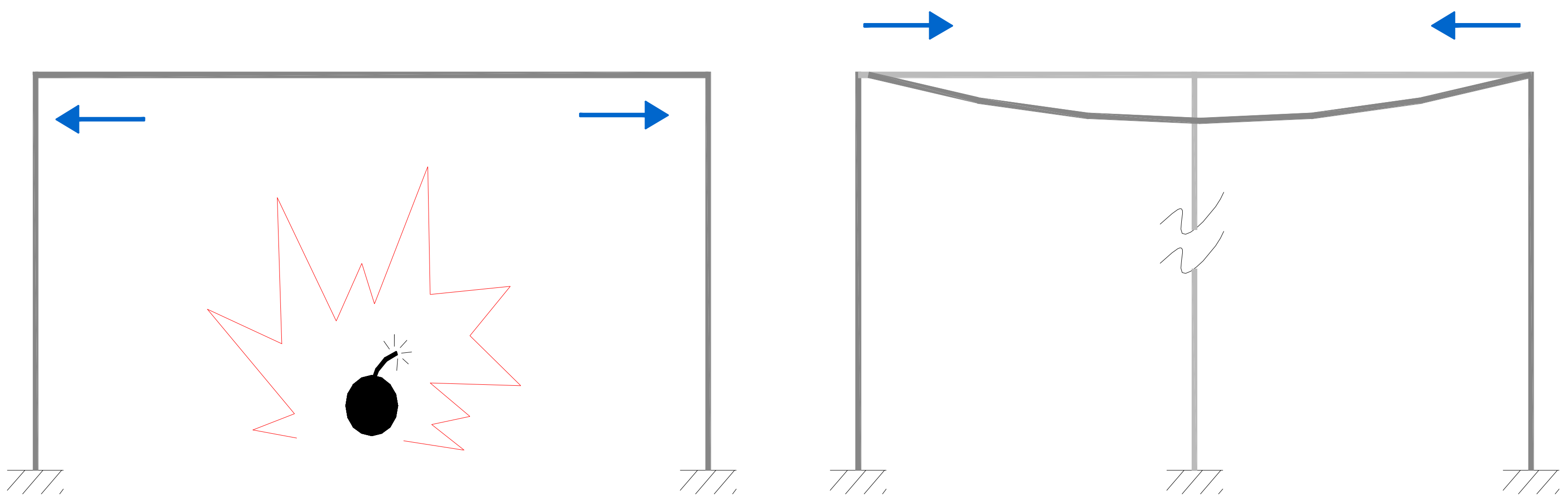
Yes, …under the reservation the joint has:

- a sufficient rotation capacity
  = capacity to "rotate"
- a sufficient ductility
  = capacity to follow the actual loading path in a ductile way



Supplementary design requirement

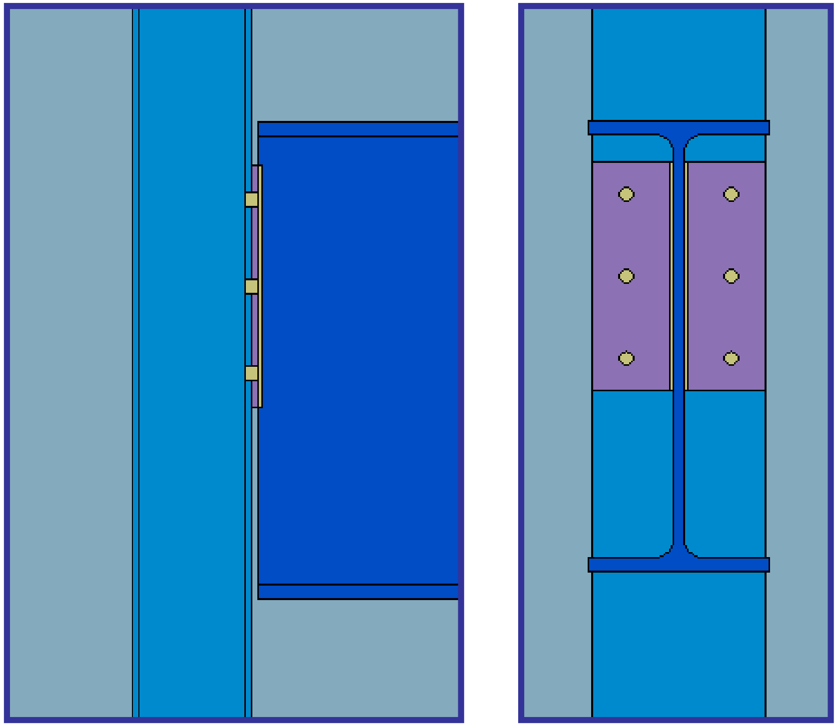
Sufficient resistance to «catenary effects» so as to provide required structural robustness



Example: Partial depth end-plate

Components

- Bolts in shear
- End-plate in bearing
- End-plate in shear (gross section)
- End-plate in shear (net section)
- End-plate in shear block
- End-plate in bending
- Beam web in shear
- Welds in shear
- Column flange in bearing



Partial depth end-plate

Strength requirement

- Use of “component method” for the assessment of V_{Rd}

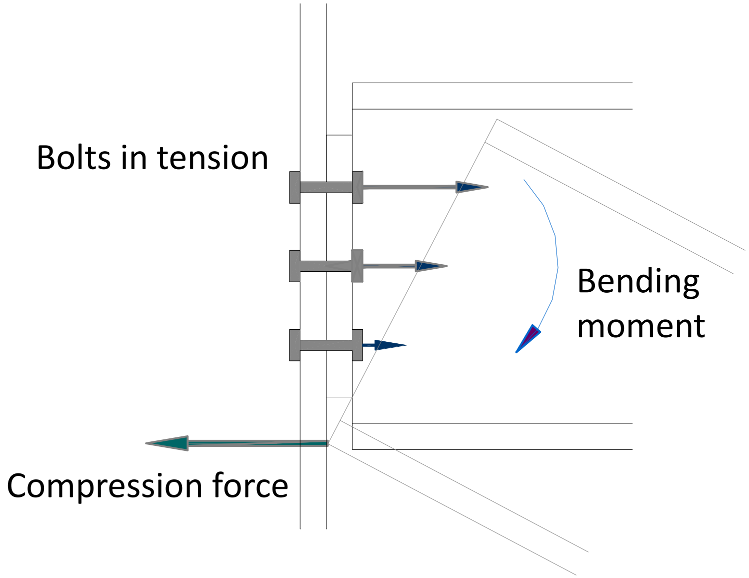
Assessment of the strength of all the constitutive components of the joint

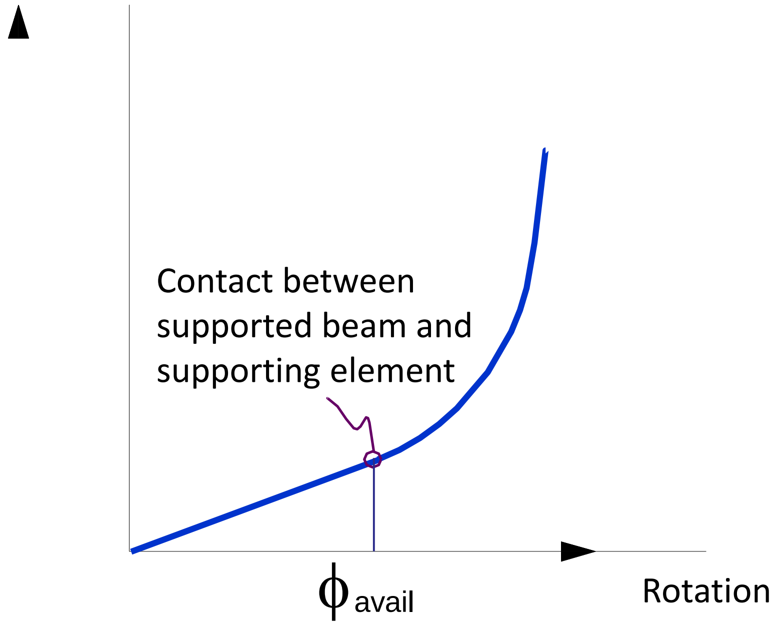
+

“Assembly” of these components

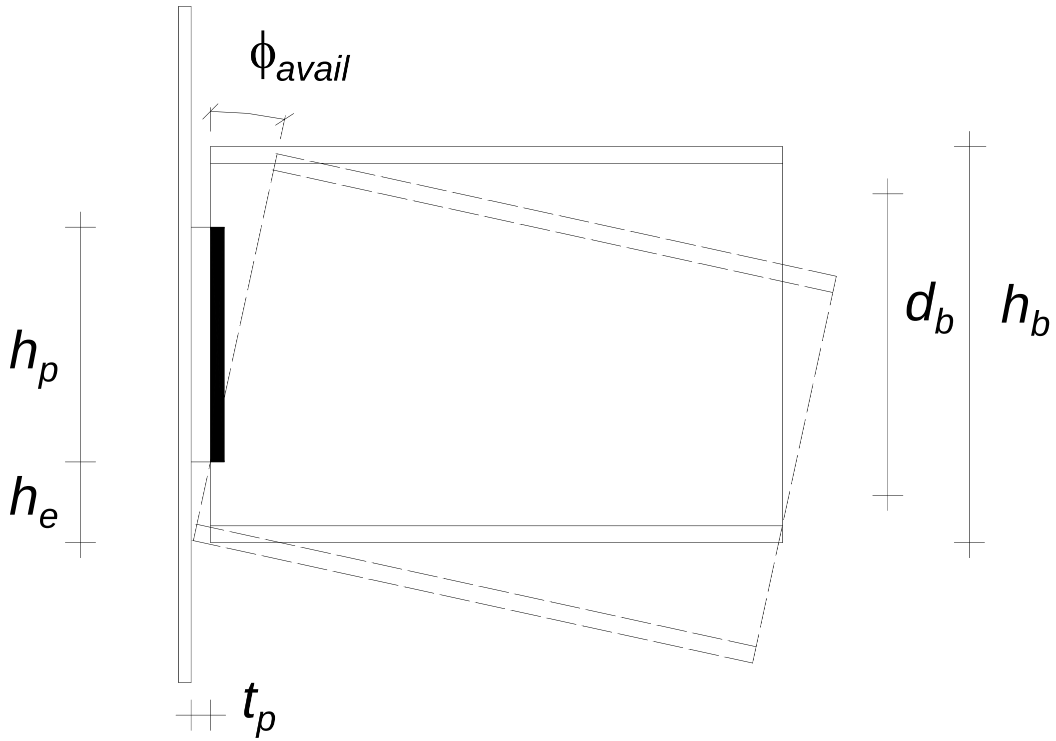
Partial depth end-plate

Rotation capacity requirement





Partial depth end-plate



$$h_p < d_b$$

$$\phi_{avail} = \frac{t_p}{h_e}$$

Partial depth end-plate

Ductility requirement

- Prevent premature fracture of the bolts
- Prevent premature fracture of the welds

under unavoidable bending moment in the joint

Partial depth end-plate

Ductility requirements

- Prevent premature collapse of the bolts

$$\frac{d}{t_p} \geq 2,8\sqrt{\frac{f_{yp}}{f_{ub}}}$$ for the end-plate

$$\frac{d}{t_p} \geq 2,8\sqrt{\frac{f_{ycf}}{f_{ub}}}$$ for the supporting column

d and f_{ub} : diameter and tensile strength of bolts

→ **Yielding of end-plate prior to tensile fracture of bolts**

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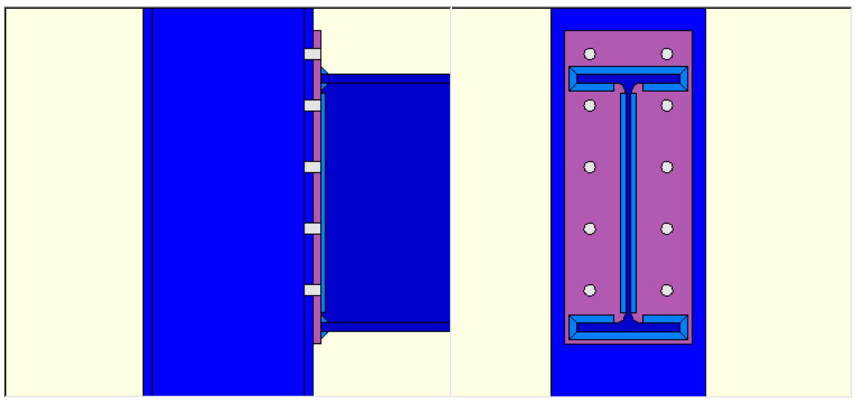
Joint Research Centre

Practical design tools

- Tables of standardized joints

- Dedicated software

Worked Example



Configuration

- Beam IPE 500
- Column HEA 340
- End plate connection

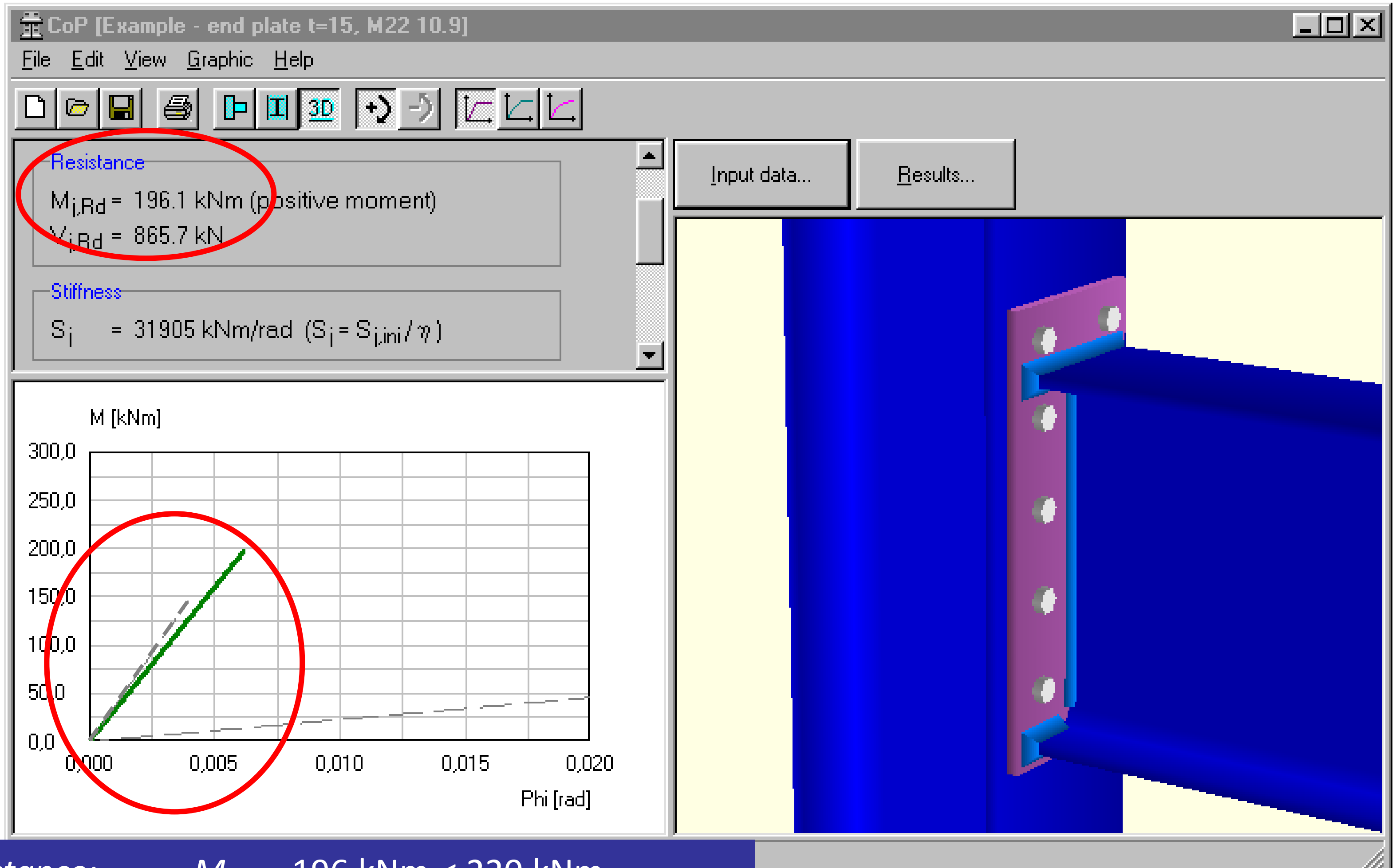
Design assumption

- Rigid joint

Frame analysis

- M_{Ed} = 220 kNm

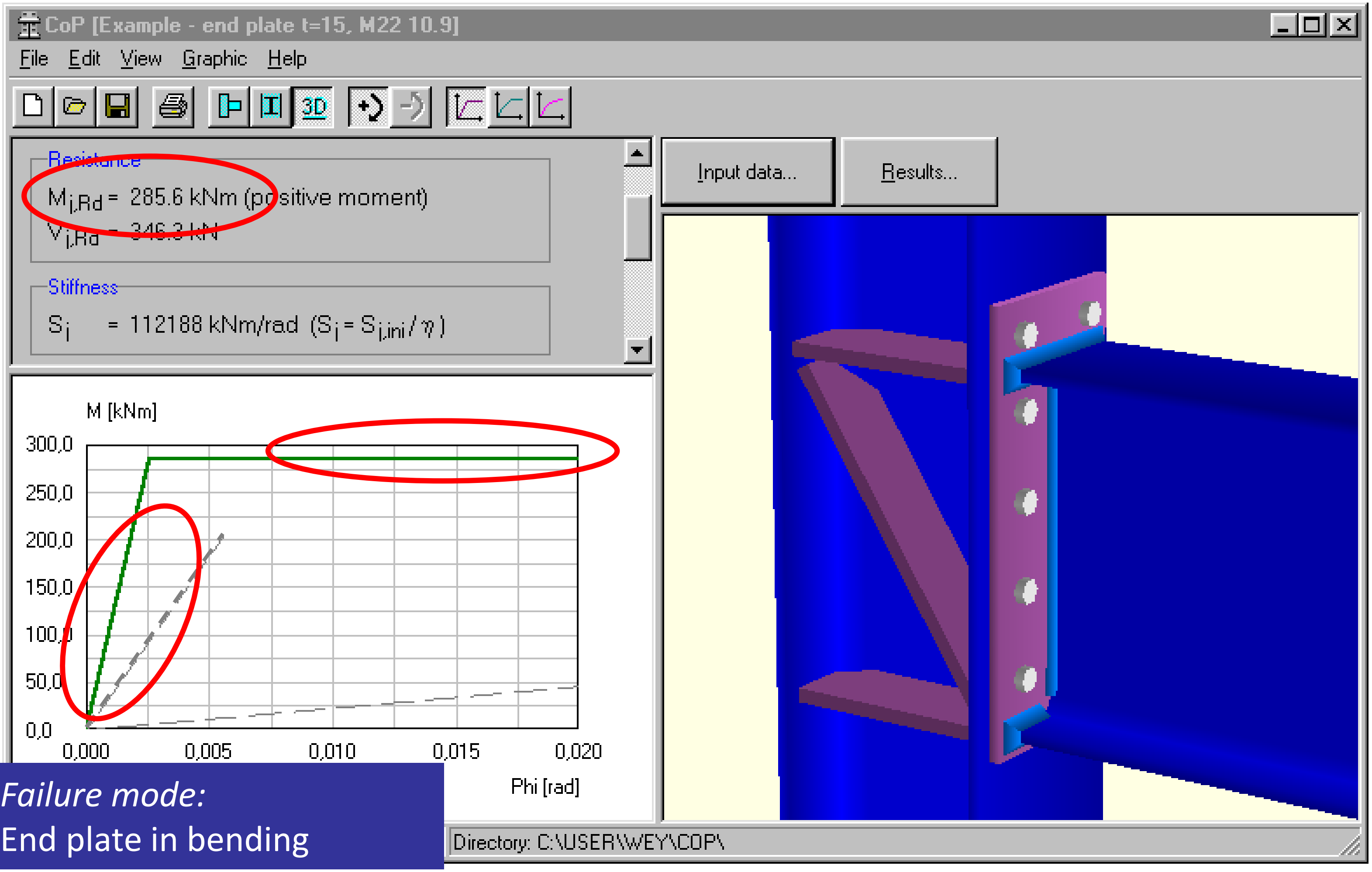
CoP software used for this example: http://cop.fw-ing.com



Design resistance: M_{Rd} = 196 kNm < 220 kNm

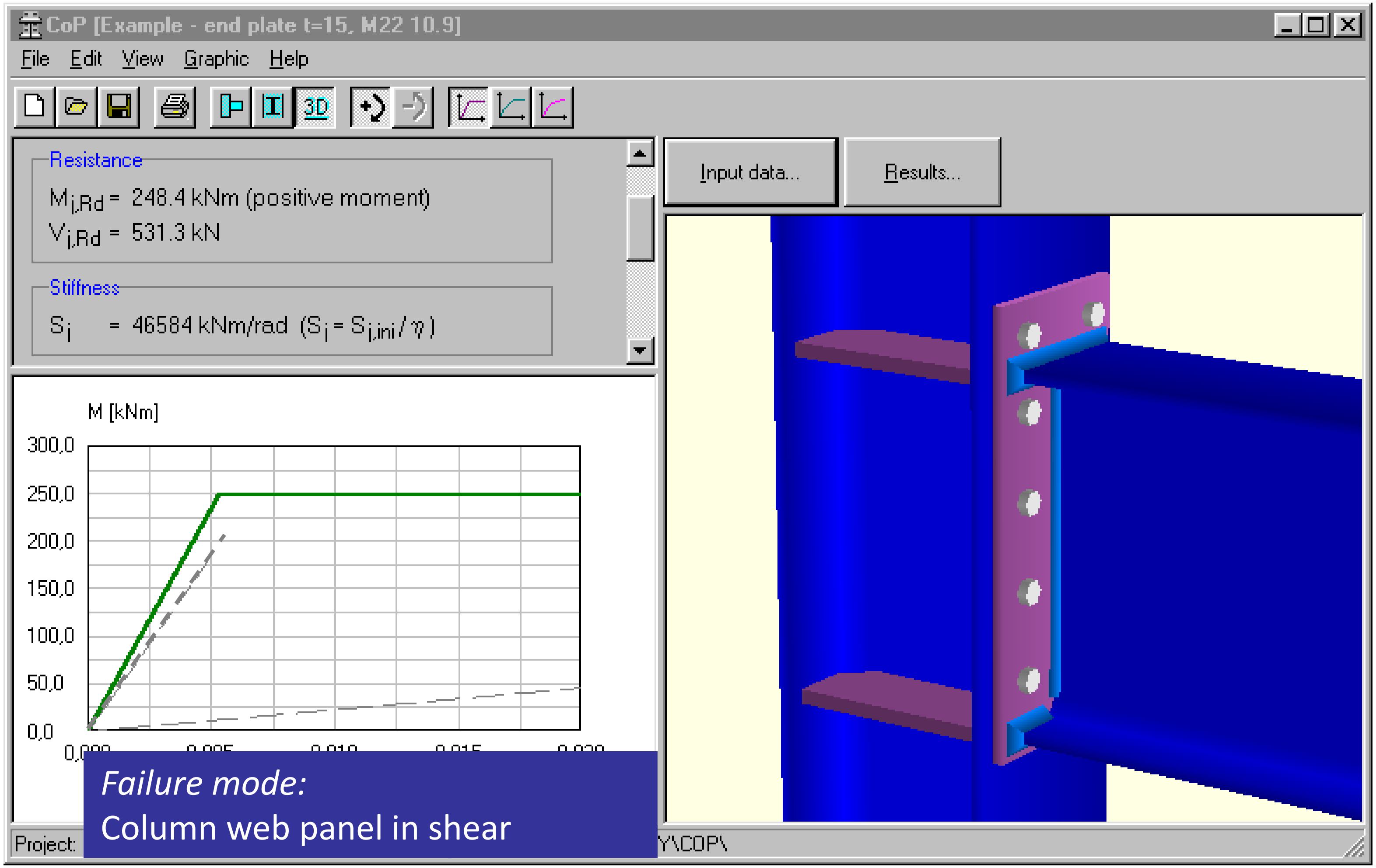
Classification: Semi-rigid

Failure mode: Column web in compression



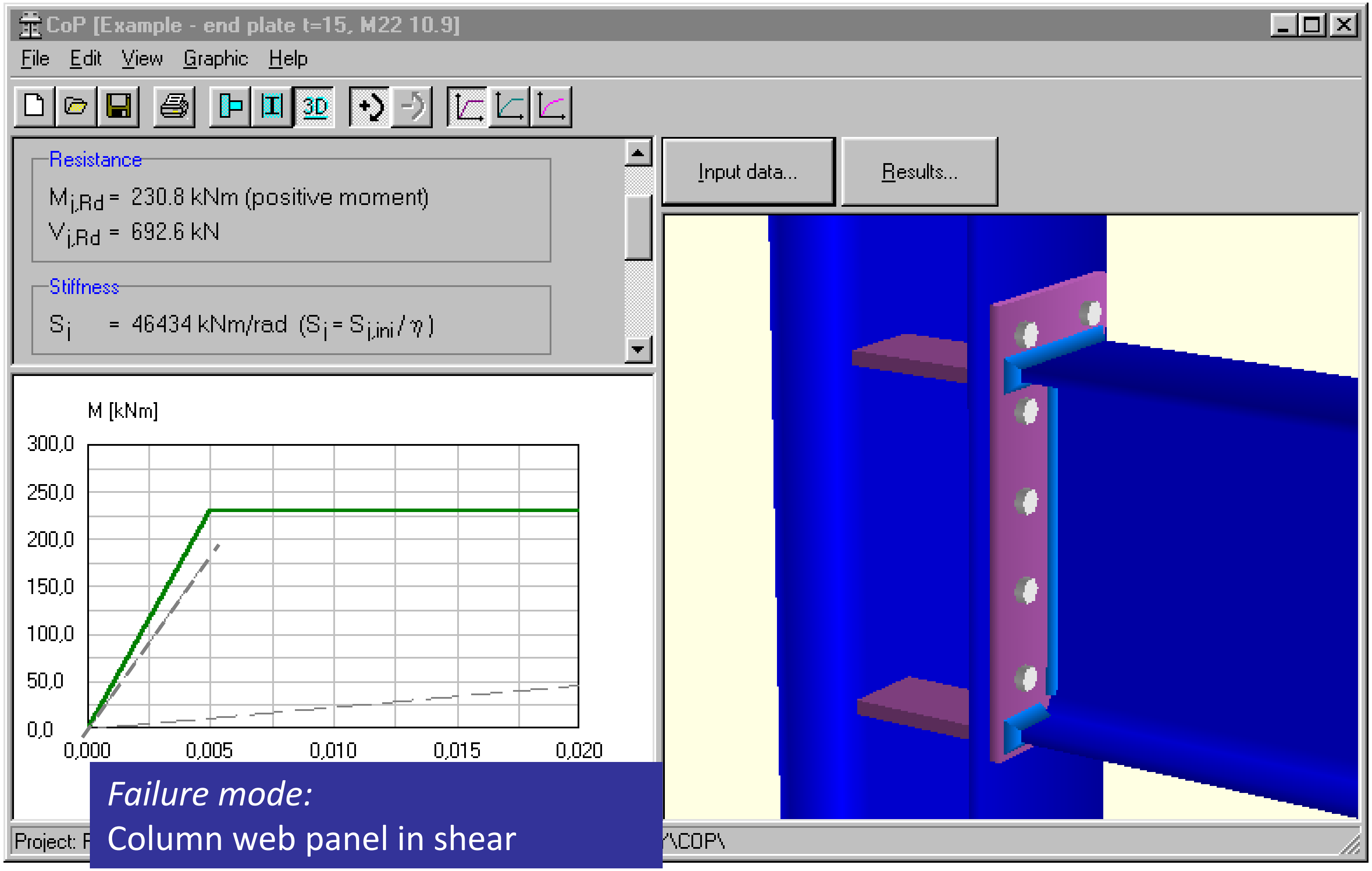
Failure mode:

End plate in bending



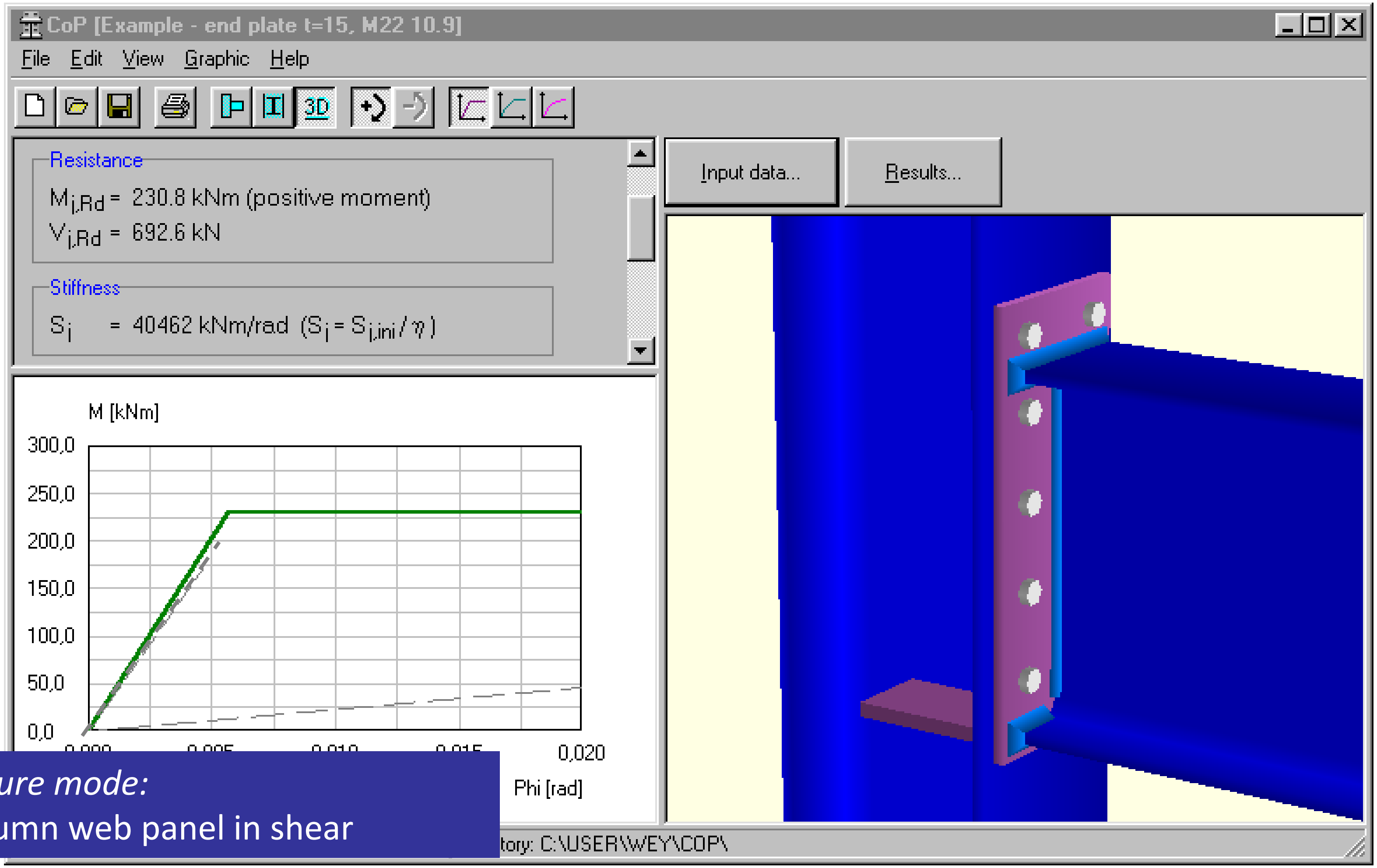
Failure mode:

Column web panel in shear



Failure mode:

Column web panel in shear



Failure mode:

Column web panel in shear

European Commission

Eurocodes
Background and Applications

Design of **Steel Buildings**
with worked examples

16-17 October 2014
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