lateral buckling restraint - attaches - steel check - creep - charges climatiques - dynamic analysis - lateral buckling - brandweerstandsanalyse - timber - 1st order - verstijvers - buisverbinding - diseño de planos de armaduras - pandeo lateral - verbindingen - shear connection - verificación - armatures longitudinales - pórtico - unión base columna - voorontwerp - unión tubular - haunch - connexion moment - cimbras - vérification acier - unity check - Eurocode 2 - mesh - retaining wall - raidisseur - Eurocode 3 - longitudes de pandeo - connections - ACI 138 - acero - 2nd ordre - portal frame - Eurocode 8 - andamios - kip - dwarskrachtverbinding - BS 8110 - dalle de fondation - seismische analyse - armaduras longitudinales - BIM - gelaste verbinding - 2de orde - buckling - funderingszool - poutre sur plusieurs appuis - maillage - malla - uniones - 2D raamwerken - fire resistance analysis - voiles - cracked deformation - gescheurde doorbuiging - longueurs de flambement - pandeo - reinforcement - unity check - cantonera - dynamische analyse - hout - ossatures 3D - koudgevormde profielen - placa de extreme - 1er orden - continuous beam - connexion soudée - momentverbinding - praktische wapening - renforts au déversement - fluencia - estribos - déformation fissurée - EHE - beugels - Eurocódigo 3 - platine de bout - análisis dinámico - column base plate - kruip - rigid link - welded connection - charpente métallique - moment connections - estructuras 2D - kniestuk - assemblage métallique - 3D raamwerken - second ordre - beam grid - cargas climáticas - Eurocode 2 - Eurocode 5 - wall - deformación fisurada - lien rigide - enlace rígido - 2D frames - estructuras 3D - éléments finis - vloerplaat - steel connection - scheurvorming - integrated connection design - armatures pratiques - analyse sismique - nieve y viento - practical reinforcement - charges mobiles - dalle - wapening - perfiles conformados en frío - Eurocode 3 - connexion tubulaire - unión a momento - 3D frames - treillis de poutres - roof truss - practical reinforcement design - portique - kipsteunen - análisis sísmico - Eurocode 8 - seismic analysis - B.A.E.L 91 - uniones atornilladas - bolts - ossatures 2D - eindige elementen - losa de cimentación - restricciones para el pandeo lateral - optimisation - wand - kniklengtes - end plate - dakspanten - kolomvoetverbinding - stirrups - acier - staalcontrole - cálculo de uniones integrado - paroi - dessin du plan de ferraillage - stiffeners - mobiele lasten - Eurocódigo 8 - Eurocódigo 5 - longitudinal reinorcement - doorlopende liggers - rigidizador - beton armé - fluage - CTE - connexion pied de poteau - langswapening - connexions - hormigón - neige et vent - elementos finitos - armaduras - cold

Design of steel structures

BS EN1993-1-1

formed steel - jarret - uittekenen wapening - puente grúa - analyse dynamique - flambement - keerwanden - optimisation - steel - cercha - 2º orden - slab on grade foundation - entramado de vigas - Eurocode 5 - prédimensionnement - multi span beam - bouten - armatures - floor slab - poutre continue - pared - staal - 1er ordre - NEN 6770-6771 - connexion cisaillement - losa - déversement - viga continua - predimensionering - 1ste orde - unión metálica - CM 66 - madera - análisis resistencia al fuego - verbindingen - 2nd order - bois - Eurocode 2 - profilés formés à froid - verificación acero - predesign - unión soldada - fisuración - beton - muro de contención - optimalisatie - foundation pads - fissuration - concrete - AISC-LRFD - HCSS - assemblage métallique - Eurocode 3 - viga con varios apoyos - armaduras prácticas - balkenroosters - unión a cortante - buckling length - boulons - cracking - Eurocode 8 - knik - Eurocode 2 - radier - eindplaat - Eurocódigo 2 - FEM - tornillos - NEN 6720 - moving loads - balk op meerdere steunpunten - cargas móviles - funderingsplaat - étriers - analye resistance au feu - cercha - moment connections - estructuras 2D - kniestuk - assemblage métallique - dalle

Table of contents

1. Introduction

About this document

This document provides guidance for the global analysis and design of steel structures according to Eurocode 3 BS EN 1993-1-1. This document is by no means intended to replace the text of Eurocode 3 and therefore only contains the basic principles. For the all details and complete background information we refer to Eurocode 3.

This document presumes that the reader is familiar with basic Eurocode principles such as: load types, load combinations ULS and SLS, partial safety factors, …

About the authors

Geert Goossens (MSc.) – CEO and founder of BuildSoft since 1989. As the lead software developer for several years, Geert knows the finest details of Eurocodes. The last years he has moved more towards building public and customer relations and he seated in several national commissions to discuss Eurocodes.

Dorien Elleboog (MSc.) – Support Engineer at BuildSoft since 2011. Taking several advanced courses per year, Dorien is always up to date with the latest progressions in Eurocodes.

Together they have together more than 35 years of experience in structural analysis and Eurocodes.

About the company

BuildSoft
structurally loved by engineers

BuildSoft is Belgium's leading company in advanced **software for structural analysis** and design of **reinforced concrete, steel and timber constructions**, according to Eurocodes and American standards.
http://www.buildsoft.eu/en

Athena Horizons

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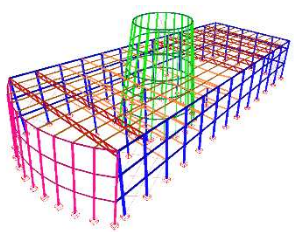
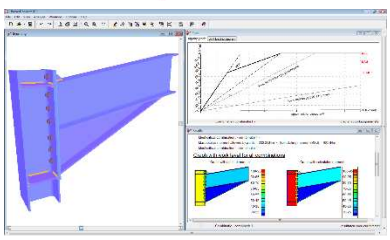
https://athena-horizons.co.uk

About the software



Diamonds
Easy to use software for structural analysis of steel, concrete and timber constructions according to Eurocode (NA BS, DE, FR, ..)
Free 30-day trial at:
http://www.buildsoft.eu/en/freetrial



PowerConnect
Steel connection design software
Free 30-day trial at:
http://www.buildsoft.eu/en/freetrial

2. Structural engineering

Structural Engineering is the art and science of designing and creating a skeleton or frame that can resist the loads that are applied to it. The skeleton or structure should be efficient and although draped in a skin or façade, the structure should be considered as architecture in its purest form.

- John Roycroft, BDP

So, as a structural engineer or designer, one should:

1. Simplify and schematize the structure
2. Perform a global analysis to determine the internal forces caused by the loads (see §3)
3. Design the structure by verifying the internal forces vs structure’s strength and stiffness (see §4)

3. Structural analysis

The determination of the internal forces and moments is based on:

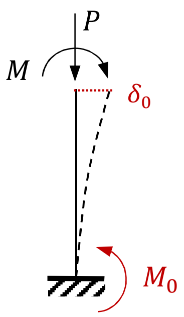
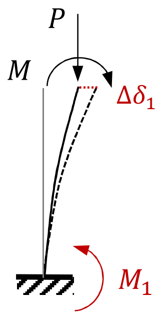
- Geometric response of the structure (§3.1)
- Material behaviour (§3.2)

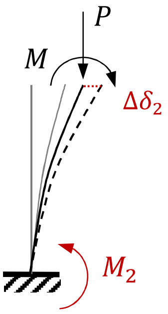
Both have different approaches and presumptions. In §5 we summarize which can be best used on your project.

3.1. The geometric response

The loads on a structure cause internal forces, stresses and deformations, together also known as the **geometric response**. The final, actual geometrical response of a structure cannot be determined in one single step. The process to the final state is iterative.

As an example, we determine the geometrical response of a fixed column ($IPE300$, $l = 4m$, $M = 75kNm$ and $P = 100kN$):

Iteration 1		The moment at the top of the column is: $M_0 = M = 75kNm$ Due to the moment, the top of the column will undergo a horizontal displacement: $\delta_0 = \frac{M \cdot L^2}{2 \cdot E \cdot I} = 34{,}19mm$
Iteration 2		The compressive force P is now acting upon the deformed position of the column and hereby receives an eccentricity δ_0. This causes an additional moment ΔM_1. $\Delta M_1 = P \cdot \delta_0 = 3{,}15kNm$ The moment at the top of the column is then: $M_1 = M_0 + \Delta M_1 = 78{,}42kNm$ The additional moment ΔM_1 results in extra deformation $\Delta\delta_1$ at the top: $\Delta\delta_1 = \frac{\Delta M_1 \cdot L^2}{2 \cdot E \cdot I} = 1{,}56mm$

<table>
<tr>
<td>Iteration 3</td>
<td>
</td>
<td>The compressive force P is now acting upon the deformed position of the column and hereby receives an eccentricity $\Delta\delta_1$. Causing an additional moment ΔM_2.
$\Delta M_2 = P \cdot \Delta\delta_1 = 0{,}16 kNm$
The moment at the top of the column is then:
$M_2 = M_0 + \Delta M_1 + \Delta M_2 = 78{,}58 kNm$
The additional moment ΔM_2 results in extra deformation $\Delta\delta_2$ at the top
$\Delta\delta_2 = \frac{\Delta M_2 \cdot L^2}{2 \cdot E \cdot I} = 0{,}071 mm$
The total horizontal displacement after 3 iterations is:
$\delta_2 = \delta_0 + \Delta\delta_1 + \Delta\delta_2 = 35{,}82 mm$</td>
</tr>
<tr>
<td>Iteration n</td>
<td>…</td>
<td>And so on until the additional deformation (or additional internal forces) is negligible.</td>
</tr>
</table>

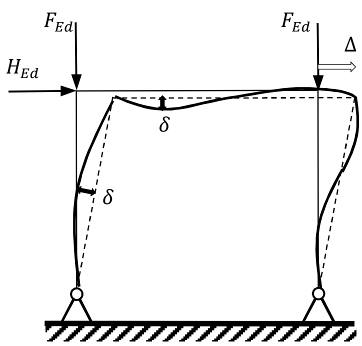
3.1.1. First order calculation

The calculation in the first step (= iteration 1) corresponds with a **first order calculation**. This type of calculation uses the initial geometry of the structure to determine the internal forces and deformations. If the boundary conditions are defined adequately, a solution can always be found. Because a first order calculation is relatively easy, this is the most frequently used method in hand calculations.

3.1.2. Second order calculation

The calculation of iteration 1 to n is called a **second order calculation**. This type of calculation takes into account the influence of the deformation of the structure This results in increased internal forces and additional deformations. In the example above, the horizontal deformation converges to $35{,}823mm$. Multiple steps or iterations are required to get to the final state of the structure. However, **convergence** is *not* a certainty. For some structures the deformation and forces will continue to increase until the structure collapses. Due to the complexity of the iteration process, second-order calculations are carry out by computers, with the help of structural engineering software.

These additional deformations that arise in a second order calculation are called '**second order effects'.** There are two types of second order effects: a P-Δ effect and a P-δ effect.

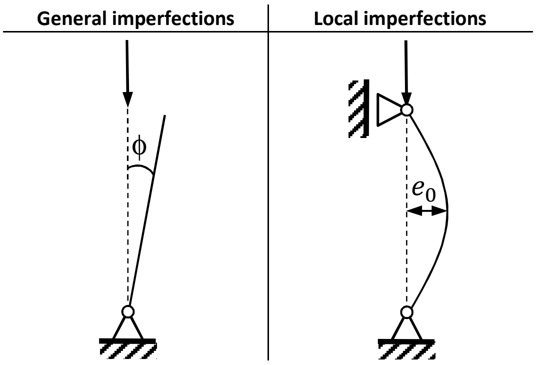


- **P-Δ effect** is a global effect caused by the movement of the line of action of a longitudinal force by an angular displacement of the rod. This effect causes an additional moment in the rods. The stiffness of the frame as a whole is affected.
- **P-δ effect** is a local effect, which is caused by the movement of the element relative to the chord between its end points. The stiffness of the elements is affected individually.

3.1.2.1. Imperfections

Furthermore, a structure in practice - even without load – will have imperfections, such as not fully straight profiles, fitting inaccuracies, small eccentricities in the joints etc. Imperfections will *amplify* the second-order effects, and must be taken into account. Eurocode 3 distinguishes two imperfections for 2D frames, which combine the potential impact of all types of imperfections:

- **General imperfections** for the framework as a whole (= global initial sway imperfections) (EN 1993-1-1 §5.3.2)
- **Local imperfections** for individual elements in frameworks (= local bow imperfections) (EN 1993-1-1 §5.3.4)



Details about the values of the imperfections can be found in the relevant parts of Eurocode. A basic value for $\phi_0 = 1/200$ (EN 1993-1-1 §5.3.2)

Local imperfections can be included in the global analysis (EN 1993-1-1 §5.3.4):

- By adding a local bow e_0 to the element.
- By performing the relevant stability verifications for elements in compression (buckling risk) and/or bending (lateral torsional buckling risk). These checks have local imperfection effects already incorporated in the formulas. (see also EN 1993-1-1 §6.3 or §4.2.2)

3.1.2.2. Sway and non-sway structures

Up to this point, the conclusion is that can conclude that the actual geometric response of a structure is obtained from a **second order calculation plus imperfections**. It will give the most realistic results, but it's quite complex and requires a lot of calculation.

There are structures for which the results first order and second order are practically the same, these structures are not sensitive to second order effects. A second order calculation will have no added value. The choice between a first or second order calculation dependents on how sensitive the structure is for horizontal deformations. This sensitivity is expressed through the **global buckling factor α_{cr}.** This is the factor by which the design loads should have to be increased to cause global elastic instability (EN 1993-1-1 eq. 5.1).

- A structure with a **global buckling factor $\boldsymbol{\alpha_{cr}} \geq \mathbf{10}$** is not sensitive for lateral deformations and the consequent second order effects. This is called a **non-sway** structure.

  The structure may be calculated using a first-order calculation. Alternatively, a second-order calculation also be used.

- A structure with a **global buckling factor $\boldsymbol{\alpha_{cr}} < \mathbf{10}$** is sensitive for lateral deformations and the consequent second-order effects. This is called a **sway** structure.

  The structure must be calculated using a second-order calculation. Alternatively, a first order calculation can be used, on the condition the sensitivity for second order effects is taken into account using an appropriate method.

Since imperfections (global initial sway and local bow) will increase the second order effects, they only have meaning when second order effects are relevant:

- For a non-sway structure ($\alpha_{cr} \geq 10$), imperfections do not need to be taken into account.
- For a say structure ($\alpha_{cr} < 10$), imperfections *must* be included in an appropriate way (through the global analysis and/or the stability verification).

We can conclude a **second order calculation plus imperfections** is always possible, but alternative paths are allowed, as shown in the summary flow chart on p.21.

3.2. The material behaviour

The special mechanical properties of steel are:

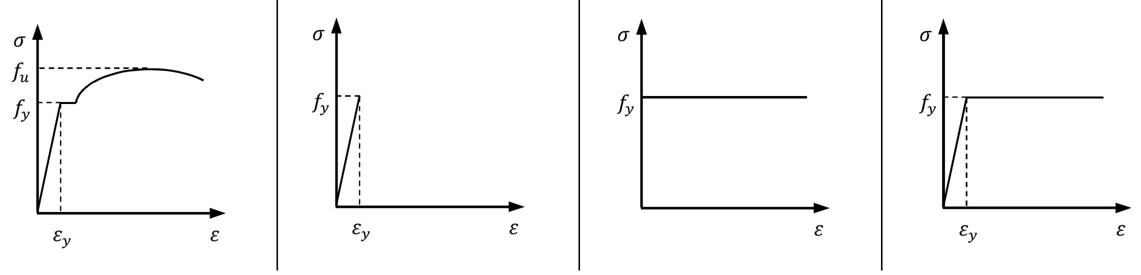
- The yield strength f_y
- The yield strain ε_y
- The ultimate strength f_u

These properties can be determined from a destructive tensile test. Where a cylindrical rod is subject to a load until failure occurs. The typical stress-strain diagram measured during a tensile test is given in the table below (first figure). However, this diagram is practically not usable in calculations. EN 1993-1-1 §5.4 suggests three simplifications for the diagrams:

- linear elastic
- rigid-plastic
- linear-elastic rigid-plastic

Stress-strain diagram for steel

real	linear elastic	rigid-plastic	linear-elastic rigid-plastic (bilinear)



Eurocode 3 indicates two ways to determine the characteristic value of the yield strength f_y (EN 1993-1-1 §3.2.1 (1)):

- Use the values from the product standard.
- Use a simplified table (EN 1993-1-1 Table 3.1).

The NA to BS ES 1993-1-1 states that the values for from the product standard should be used.

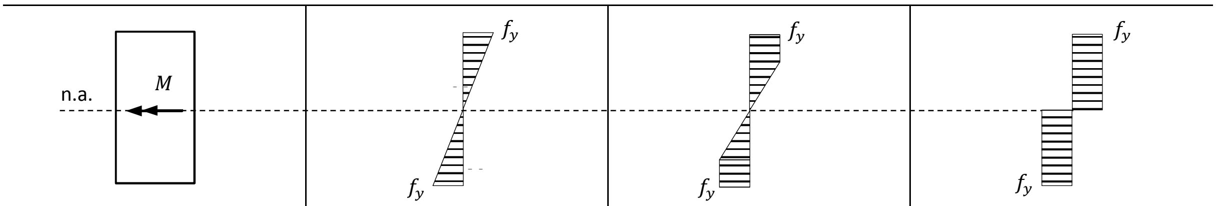
The yield strength f_y (N/mm^2) of different steel grades according to EN 10025-2:2004

Steel grade	≤ 16	$16-40$	$40-63$	$63-80$	$80-100$	$100-150$
S 235	235	225	215	215	215	195
S 275	275	265	255	245	235	225
S 355	355	345	335	325	315	295
S 450	450	430	410	390	380	380

There are two ways to approach the material behaviour in a global analysis:

- An **elastic calculation** assumes that the stress-strain diagram of steel is linear elastic. It follows that only the extreme fibre of the cross-section may be loaded with the yield stress f_y.
- A **plastic calculation** assumes that the stress-strain diagram of steel is plastic. It follows that several fibres of the cross-section may be subjected to the yield stress f_y. If a full cross-section is subject to the yield stress f_y, a **plastic hinge** is created. This plastic hinge allows **a redistribution of the loads**, so that the structure can bear more load relative to an elastic calculation.

Stress in a section



A cross section is loaded with a bending moment M. The bending moment gives compression in the upper fibre and tension the lower fibre.	$M = M_{el}$ The tension in the furthest fibre has reached the yield stress. The bending moment in which this occurs, is in proportion to the elastic resistance of the cross-sections and is called the elastic moment of resistance $M = M_{el}$.	$M_{el} < M < M_{pl}$ When the bending moment M further increases, so does the plastic zone.	$M = M_{pl}$ The stress over the whole of the cross-section has reached the yield strength. The bending moment in which this occurs, is in proportion to the plastic resistance of the cross-sections and is called the plastic moment of resistance $M = M_{pl}$. At this stress distribution a plastic hinge is created.

EN 1993-1-1 §5.2 gives the following guidelines regarding the material behaviour:

- An elastic calculation is always allowed (EN 1993-1-1 §5.4.1 (2)).
- A plastic calculation may only be used when the construction has **sufficient rotational capacity** at the location of the plastic hinges - whether in the member or in the joints. (EN 1993-1-1 §5.4.1 (3)). The assessment of whether a cross section has sufficient rotational capacity, is done based on **section classes** (see §4.1).

4. Design

The design of the structures consists of checking the acting forces versus the structure's strength and stiffness:

- A **verification** in the Ultimate Limit State **ULS** (§4.2) – strength and stability
  (also known as 'steel verification')
  - **A resistance verification** - on cross-section level
    Can each cross-section resist to the acting forces upon it?
  - **A stability verification** - on element level
    Can each element resist buckling and lateral torsional buckling?
- A **verification** in the Serviceability Limit State **SLS** (§4.3) – stiffness
  - The deformation cannot not be too high.
  - The vibrations should remain within limits.

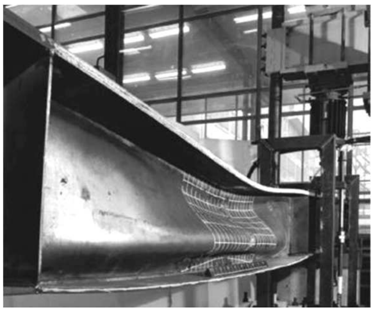
For the steel verification, the section class is required (§4.1).

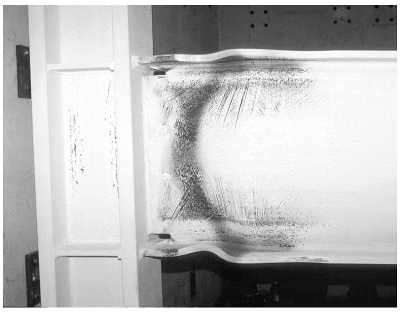
4.1. Cross-section classes and cross-section properties

In §3.2 it was shown that a global analysis can be performed elastic or plastic. A plastic global analysis is allowed when cross sections have sufficient rotational capacity. In other words, not all cross sections are able to develop a plastic stress distribution. Even more, not all cross sections are capable of developing an elastic stress distribution. To carry out a steel verification, it is important to know which profiles can or cannot a support plastic / elastic stress distribution (because the used area and section modulus are a function of this).

The ratio in which a cross-section can develop a plastic / elastic stress distribution, dependents on the ratio between the width and the thickness of the compressed plate parts (flange or web) from which the cross-section is constructed. The thicker the compressed plate member with respect to its width, the less chance of **local buckling** and the greater the resulting capacity.

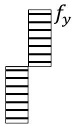
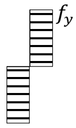
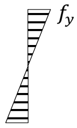
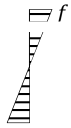
Examples of local buckling





Based on the width / thickness ratio, the cross-sections are subdivided in four cross-section classes:

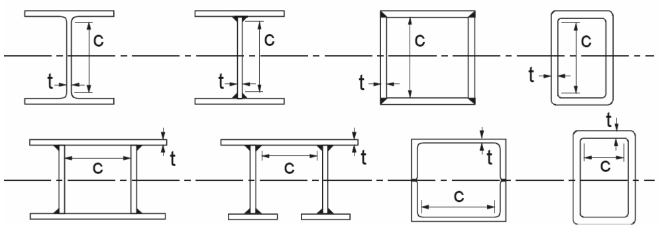
Cross section classes

	Class 1	**Class 2**	**Class 3**	**Class 4**
Stress distribution over the cross-section				
Global Analysis	Plastic	Elastic	Elastic	Elastic
Steel Control	Yielding can occur over the whole cross-section. The cross-section properties are **plastic.**	Yielding can occur over the whole cross-section. The cross-section properties are **plastic.**	Local buckling prevents the yielding from being reached over the whole cross-section. The cross-section properties **shall be elastic.**	Local buckling occurs before the yield strength is reached in the cross section. The cross-section properties **shall be reduced.**

Remark: Only the profiles from class 1 have enough rotational capacity to form plastic hinges. Thus only class 1 sections may be used in a plastic global analysis

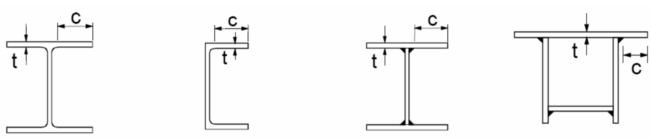
Determining the section class is based on the c/t ratio of the compressed parts and the steel quality (see table below). The cross-section is classified in accordance with the least favourable class of the pressure loaded plate parts of which the cross section is constructed. If a section does not belong to class 3, then it is Class 4.

Internal compression parts

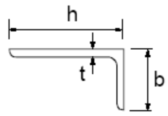
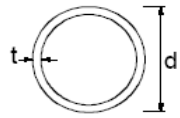


Class	Part subjected to bending	Part subjected to compression
1	$c/t \leq 72\varepsilon$	$c/t \leq 33\varepsilon$
2	$c/t \leq 83\varepsilon$	$c/t \leq 38\varepsilon$
3	$c/t \leq 124\varepsilon$	$c/t \leq 42\varepsilon$

Outstanding flanges



Class	Part subjected to compression
1	$c/t \leq 9\varepsilon$
2	$c/t \leq 10\varepsilon$
3	$c/t \leq 14\varepsilon$

Other profiles		
		
Class	Section in compression	Section in compression and/or bending
1	-	$d/t \leq 50\varepsilon^2$
2	-	$d/t \leq 70\varepsilon^2$
3	$\frac{h}{t} \leq 15\varepsilon : \frac{b+h}{2t} < 11.5\varepsilon$	$d/t \leq 90\varepsilon^2$

Value for ε

$$\varepsilon = \sqrt{\frac{235}{f_y}}$$

4.2. Verifications in Ultimate Limit State (ULS)

With to the following formulas, it can be checked whether the structure has sufficiently strength and stability to withstand the internal forces.

Remarks:

- The area and section modulus are a function of the section class!
- In order to not overload the formulas, it is assumed that the material safety factors are equal to 1: $\gamma_{M0} = \gamma_{M1} = 1$. This is compliance with BS EN 1993-1-1 §6.1
- The index 'i' is
  - The axis according to which the shear force is considered
  - The axis around which the moment is considered
  - The axis around which buckling is considered.
- For double symmetrical profiles the local y' and z' axis will be used. For non-double symmetrical profiles the main inertia axes u and v will be used.

4.2.1. Resistance verification

- BS EN 1993-1-1 §6.2.3 Tension

$$\frac{N_{Ed}}{N_{t,Rd}} \leq 1,0$$

$$N_{t,Rd} = N_{pl,Rd} = A \cdot f_y$$

- BS EN 1993-1-1 §6.2.4 Compression

$$\frac{N_{Ed}}{N_{c,Rd}} \leq 1,0$$

Cross section class 1,2 and 3	Cross section class 4
$N_{c,Rd} = A \cdot f_y$	$N_{c,Rd} = A_{eff} \cdot f_y$

- BS EN 1993-1-1 §6.2.5 Bending

$$\frac{M_{Ed}}{M_{i,Rd}} \leq 1{,}0$$

Cross section class 1 and 2	Cross section class 3	Cross section class 4
$M_{i,Rd} = W_{i,pl} \cdot f_y$	$M_{i,Rd} = W_{i,el} \cdot f_y$	$M_{i,Rd} = W_{i,eff} \cdot f_y$

- BS EN 1993-1-1 §6.2.6 Shear

$$\frac{V_{Ed}}{V_{i,pl,Rd}} \leq 1{,}0$$

$$V_{i,pl,Rd} = A_{i,v} \cdot \left(f_y/\sqrt{3}\right)$$

Cross section (BS EN 1993-1-1 §6.2.6 (3))	**Shear area $A_{i,v}$**
Rolled I and H sections, load parallel to web	$A - 2bt_f + (t_w + 2r)t_f \geq h_w t_w$
Rolled C-sections, load parallel to web	$A - 2bt_f + (t_w + r)t_f$
Rolled T-sections, load parallel to web	$0.9\left(A - bt_f\right)$
Welded I, H and box sections, load parallel to web	$\eta \sum (h_w t_w)$
Welded I, H, C and box sections, load parallel to flanges	$A - \sum (h_w t_w)$
Rolled rectangular hollow sections of uniform thickness • Load parallel to depth • Load parallel to width	 $\frac{A \cdot h}{b + h}$ $\frac{A \cdot b}{b + h}$
Circular hollow sections and tubes of uniform thickness	$\frac{2A}{\pi}$

- BS EN 1993-1-1 §6.2.7 Torsion

$$\frac{T_{Ed}}{T_{Rd}} \leq 1{,}0$$

Cross section class 1 and 2	Cross section class 3	Cross section class 4
$T_{Rd} = T_{wm,pl} \cdot f_{yd}/\sqrt{3}$	$T_{Rd} = T_{wm,el} \cdot f_{yd}/\sqrt{3}$	$T_{Rd} = T_{wm,eff} \cdot f_{yd}/\sqrt{3}$

Cross section	$T_{wm,el}$	**Remarks**
■	$0.208a^2 \; if \; a = b$	$a = min(B, H)$
	$\frac{a^2 b^2}{3b + 1.8a} \; if \; b < 10a$	
	$\frac{a^2 b}{3} \; if \; b > 10a$	
T	$\frac{h_p^3 b_p + B^3\left(H - h_p\right)}{3a_m}$	$a_m = max\left(h_p, B\right)$
Ι	$1.3\frac{2t_f^3 B + t_w^3\left(H - 2t_f\right)}{3a_m}$	$a_m = max\left(t_w, t_f\right)$
L	$\frac{t^3 B + t^3(H - t)}{3t}$	-
[	$\frac{2t_f^3 B + t_w^3\left(H - 2t_f\right)}{3a_m}$	$a_m = max\left(t_w, t_f\right)$
	$2H\left(H - t_f\right)(B - t_w)t$	$t = min\left(t_w, t_f\right)$
●	$\frac{\pi H^3}{16}$	-
○	$\frac{\pi(r^4 - (r - t_w)^4)}{2r}$	$r = 0.5H$

- BS EN 1993-1-1 §6.2.8 Bending and shear

$$\frac{M_{i,Ed}}{M_{i,V,Rd}} \leq 1{,}0$$

$$M_{i,V,Rd} = (1-\rho_{i'})M_{i,Rd}$$

If $\frac{V_{i',Ed}}{V_{i',pl,Rd}} \leq 0.5$ then $\rho_{i'} = 0$, otherwise $\rho_{i'} = \left(\frac{2 \cdot V_{i',Ed}}{V_{i',pl,Rd}} - 1\right)^2$

In the case of I profile with identical flanges $M_{y,V,Rd} = min\left(\left[W_{y,pl} - \frac{\rho_z \cdot (h_w \cdot t_w)^2}{4 \cdot t_w}\right] \cdot f_{yd}, M_{y,Rd}\right)$.

Cross section class 1 and 2	Cross section class 3	Cross section class 4
$M_{i,Rd} = W_{i,pl} \cdot f_y$	$M_{i,Rd} = W_{i,el} \cdot f_y$	$M_{i,Rd} = W_{i,eff} \cdot f_y$

- BS EN 1993-1-1 §6.2.9 Bending and normal force

<table>
<tr><th>Cross section class 1 and 2</th><th>Cross section class 3 and 4</th></tr>
<tr><td>

$$\left(\frac{M_{y,Ed}}{M_{N,y,Rd}}\right)^{\alpha} + \left(\frac{M_{z,Ed}}{M_{N,z,Rd}}\right)^{\beta} \leq 1{,}0$$

With:

- For H-profiles
  - $M_{N,y,Rd} = M_{y,Rd}$ If $N_{Ed} \leq 0{,}25 \cdot N_{pl}$ and $N_{Ed} \leq 0{,}5 \cdot h_w \cdot t_w \cdot f_{yd}$
  - $M_{N,z,Rd} = M_{z,Rd}$ if $N_{Ed} \leq h_w \cdot t_w \cdot f_{yd}$
  - $\alpha = 2$ and $\beta = max\{1; 5n\}$
- For -profiles
  - $M_{N,y,Rd} = min\left\{M_{pl,y,Rd}; \frac{M_{pl,y,Rd}(1-n)}{(1-0.5a)}\right\}$
  - $M_{N,z,Rd} = M_{pl,z,Rd}\left(1 - \left(\frac{n-a}{1-a}\right)^2\right)$ if $n > a$, otherwise $M_{N,z,Rd} = M_{pl,z,Rd}$
  - $n = \frac{N_{Ed}}{N_{pl,Rd}}, a = min\left\{0{,}5 ; \frac{A-2bt_f}{A}\right\}$
  - $\alpha = \beta = min\left\{\frac{1{,}66}{1-1{,}13n^2}; 6\right\}$

</td><td>

$$\frac{N_{Ed}}{N_{Rd}} + \frac{M_{y,Ed} + \Delta M_{y,Ed}}{M_{y,Rd}} + \frac{M_{z,Ed} + \Delta M_{z,Ed}}{M_{z,Rd}} \leq 1.0$$

With:

- N_{Rd} determined by pure tension or compression
- $M_{y,Rd}$ en $M_{z,Rd}$ determined at the check 'bending and shear force'
- $\Delta M_{y,Ed} = \Delta M_{z,Ed} = 0$ if cross section class is 3, otherwise $\Delta M_{y,Ed} = e_{N,y} N_{Ed}$ and $\Delta M_{z,Ed} = e_{N,z} N_{Ed}$

</td></tr>
</table>

- BS EN 1993-1-1 §6.2.10 Bending, shear and axial force

<table>
<tr><th>Cross section class 1 and 2</th><th>Cross section class 3 and 4</th></tr>
<tr><td>

$$\left(\frac{M_{y,Ed}}{M_{NV,y,Rd}}\right)^{\alpha} + \left(\frac{M_{z,Ed}}{M_{NV,z,Rd}}\right)^{\beta} \leq 1{,}0$$

$$M_{NV,y,Rd} = (1-\rho_z)M_{N,y,Rd}$$

$$M_{NV,z,Rd} = (1-\rho_y)M_{N,z,Rd}$$

With:

- If $\frac{V_{z,Ed}}{V_{z,pl,Rd}} \leq 0.5$ then $\rho_z = 0$, otherwise $\rho_z = \left(\frac{2 \cdot V_{z,Ed}}{V_{z,pl,Rd}} - 1\right)^2$
- If $\frac{V_{y,Ed}}{V_{y,pl,Rd}} \leq 0.5$ then $\rho_y = 0$, otherwise $\rho_y = \left(\frac{2 \cdot V_{y,Ed}}{V_{y,pl,Rd}} - 1\right)^2$

</td><td>

$$\frac{N_{Ed}}{N_{Rd}} + \frac{M_{y,Ed} + \Delta M_{y,Ed}}{M_{y,V,Rd}} + \frac{M_{z,Ed} + \Delta M_{z,Ed}}{M_{z,V,Rd}} \leq 1.0$$

With:

- N_{Rd} determined by pure tension or compression
- $M_{y,Rd}$ en $M_{z,Rd}$ determined at the check 'bending and shear force'
- $\Delta M_{y,Ed} = \Delta M_{z,Ed} = 0$ if cross section class is 3, otherwise $\Delta M_{y,Ed} = e_{N,y} N_{Ed}$ and $\Delta M_{z,Ed} = e_{N,z} N_{Ed}$

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</table>

4.2.2. Stability verification

- BS EN 1993-1-1 §6.3.1 Members subjected to compression (buckling)

$$\frac{N_{Ed}}{N_{b,i,Rd}} \leq 1{,}0$$

Cross section class 1,2 and 3	Cross section class 4
$N_{b,i,Rd} = \chi_i \cdot A \cdot f_y$	$N_{b,i,Rd} = \chi_i \cdot A_{eff} \cdot f_y$

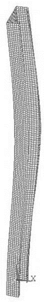
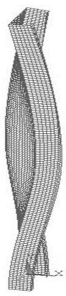
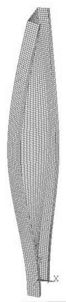
$$\chi_i = \frac{1}{\Phi_i + \sqrt{\Phi_i^2 - \bar{\lambda}_i^2}} \leq 1.0$$

$$\Phi_i = 0{,}5\left[1 + \alpha_i(\bar{\lambda}_i - 0{,}2) + \bar{\lambda}_i^2\right]$$

$$\bar{\lambda}_i = \sqrt{\frac{A_{eff} \cdot f_y}{N_{cr,i}}}$$

α_i, $N_{cr,i} = ft(L_{cr,i})$, $L_{cr,i}$ en $L_{cr,LT}$ are defined as follows:

- α_i imperfection factors for buckling in accordance with BS EN 1993-1-1 Table 6.1 and 6.2
- $L_{cr,i}$ is the relevant buckling length
- $L_{cr,LT}$ is the relevant lateral torsional buckling length
- $N_{cr,i}$ is the elastic critical force for the relevant buckling mode based on the gross cross sectional properties[1]:

Bending buckling	**Torsional buckling**	**Bending torsion buckling**
 $N_{cr,i} = \frac{\pi^2 E I_i}{L_{cr,i}^2}$	 $N_{cr,T} = \frac{A}{I_y + I_z}\left(G I_t + \frac{\pi^2 E I_w}{L_{cr,LT}^2}\right)$	 $N_{cr,TF} = \frac{1}{\frac{I_y + I_z}{A} + y_0^2 + z_0^2} \cdot \frac{1}{y_0\left(\frac{I_{yr^2}}{I_z} - 2y_0\right) + z_0\left(\frac{I_{yr^2}}{I_z} - 2z_0\right)} \cdot \left(G I_t + \frac{\pi^2 E I_w}{L_{cr,LT}^2}\right)$

[1] NBN EN 1993-1-1 Appendix E

- EN 1993-1-1 §6.3.2 Uniform members in bending (lateral torsional buckling)

$$\frac{M_{Ed}}{M_{b,Rd}} \leq 1.0$$
$$M_{b,Rd} = \chi_{LT} M_{y,Rd}$$

Method 1 to determine χ_{LT}[2]	**Method 1 to determine χ_{LT}**[3]
$\chi_{LT} = \frac{1}{\Phi_{LT} + \sqrt{\Phi_{LT}^2 - \bar{\lambda}_{LT}^2}} \leq 1.0$	$\chi_{LT} = \frac{1}{\Phi_{LT} + \sqrt{\Phi_{LT}^2 - \beta\bar{\lambda}_{LT}^2}} \leq \begin{cases} 1.0 \\ \frac{1}{\bar{\lambda}_{LT}^2} \end{cases}$
$\Phi_{LT} = 0{,}5\left[1 + \alpha_{LT}(\bar{\lambda}_{LT} - 0{,}2) + \bar{\lambda}_{LT}^2\right]$	$\Phi_{LT} = 0{,}5\left[1 + \alpha_{LT}(\bar{\lambda}_{LT} - \bar{\lambda}_{LT,0}) + \beta\bar{\lambda}_{LT}^2\right]$

$$\bar{\lambda}_{LT} = \sqrt{\frac{W_y f_y}{M_{cr}}} \geq 0{,}2$$

$$M_{cr} = C_1 \frac{\pi^2 E I_z}{(k_z L_{cr,LT})^2}\left[\sqrt{\left(\frac{k_z}{k_w}\right)^2 \frac{I_w}{I_z} + \frac{(k_z L_{cr,LT})^2 G I_t}{\pi^2 E I_z} + (C_2 z_g - C_3 z_j)^2} - (C_2 z_g - C_3 z_j)\right]$$

$\alpha_{LT}, \beta, \bar{\lambda}_{LT,0}, M_{cr} = ft(L, C_1, k_z, k_w), L, C_1, k_z, k_w$ are defined as follows:

- α_{LT} the imperfection factor for lateral torsional buckling according to EN 1993-1-1 Table 6.3, 6.4 and 6.5
- $\beta = 1$, $\bar{\lambda}_{LT,0} = 0{,}2$ for welded sections, $\beta = 0{,}75$ $\bar{\lambda}_{LT,0} = 0{,}4$ for rolled, hot finished and cold-formed hollow sections according to NA to BS EN 1993-1-1 NA.2.17
- M_{cr} is the elastic critical lateral torsional buckling moment according to NBN EN 1993-1-1 Appendix D §2
- C_1 is a factor which takes the moment distribution into account NBN EN 1993-1-1 Appendix D §2
- The effective length factor k_z relates to the final rotation in plane, k_w relates to the warping of the ends (NBN EN 1993-1-1 Appendix D §2).
- $L_{cr,LT}$ is the relevant lateral torsional buckling length

Cross section class 1 and 2	Cross section class 3	Cross section class 4
$M_{y,Rd} = W_{y,pl} \cdot f_y$	$M_{y,Rd} = W_{y,el} \cdot f_y$	$M_{y,Rd} = W_{y,eff} \cdot f_y$

- EN 1993-1-1 §6.3.3 Members under compression and bending (buckling + lateral torsional buckling)

$$\frac{N_{Ed}}{\chi_y N_{Rd}} + k_{yy}\frac{M_{y,Ed} + \Delta M_{y,Ed}}{\chi_{LT} M_{y,Rd}} + k_{yz}\frac{M_{z,Ed} + \Delta M_{z,Ed}}{M_{z,Rd}} \leq 1$$
$$\frac{N_{Ed}}{\chi_z N_{Rd}} + k_{zy}\frac{M_{y,Ed} + \Delta M_{y,Ed}}{\chi_{LT} M_{y,Rd}} + k_{zz}\frac{M_{z,Ed} + \Delta M_{z,Ed}}{M_{z,Rd}} \leq 1$$

[2] Lateral torsional buckling curves according to the General method, EN 1993-1-1 §6.3.2.2
[3] Lateral torsional buckling curves according to the equivalent method, EN 1993-1-1 §6.3.2.3

Method 1 for the determination of k_{ii}[4]	Method 2 for the determination of k_{ii}[5]
Interaction coefficients k_{ii} as a function of the cross-section class, C_{ii} and C_{mi}	Interaction coefficients k_{ii} as a function of the torsional stiffness of the cross section and C_{mi}
Plasticity coefficients C_{ii} as a function of the torsional stiffness of the cross section and C_{mi}	-
Equivalent moment factors C_{mi} as a function of the torsional stiffness of the cross section and $C_{mi,0}$	Equivalent moment factors C_{mi}
Moment factors $C_{mi,0}$	-

Cross section class 1 and 2	Cross section class 3	Cross section class 4
$M_{i,Rd} = W_{i,pl} \cdot f_y$ $\Delta M_{y,Ed} = \Delta M_{z,Ed} = 0$	$M_{i,Rd} = W_{i,el} \cdot f_y$ $\Delta M_{y,Ed} = \Delta M_{z,Ed} = 0$	$M_{i,Rd} = W_{i,eff} \cdot f_y$ $\Delta M_{y,Ed} = e_{N,y} N_{Ed}$ $\Delta M_{z,Ed} = e_{N,z} N_{Ed}$

Method 1 may only be used on doubly symmetric sections. Where the sections are not I, H or hollow sections Class 1 and Class 2, sections should be designed as Class 3 (NA to BS EN 1993-1-1 NA.3.1).

4.3. Verifications in Serviceability Limit State (SLS)

In addition to the resistance and stability verifications, also the stiffness of the structure must be checked. For a structure with static loads, this usually boils down to limiting the deflections. However, depending on the type of structure and type of loading, other limits and requirements may apply.

4.3.1. Vertical deflections

The following table gives suggested limits for calculated vertical deflections of members under the characteristic load combination due to variable loads and should *not* include dead loads. Circumstances may arise where greater or lesser values would be more appropriate. Other members may also need deflection limits.

Vertical deflection (NA to BS EN 1993-1-1 NA.2.23)

Cantilevers	Span/180
Beams carrying plaster or other brittle finish	Span/180
Other beams (except purlins and sheeting rails)	Span/180
Purlins and sheeting rails	To suit the characteristics of particular cladding

[4] EN 1993-1-1 Appendix A

[5] EN 1993-1-1 Appendix B

4.3.2. Horizontal deflections

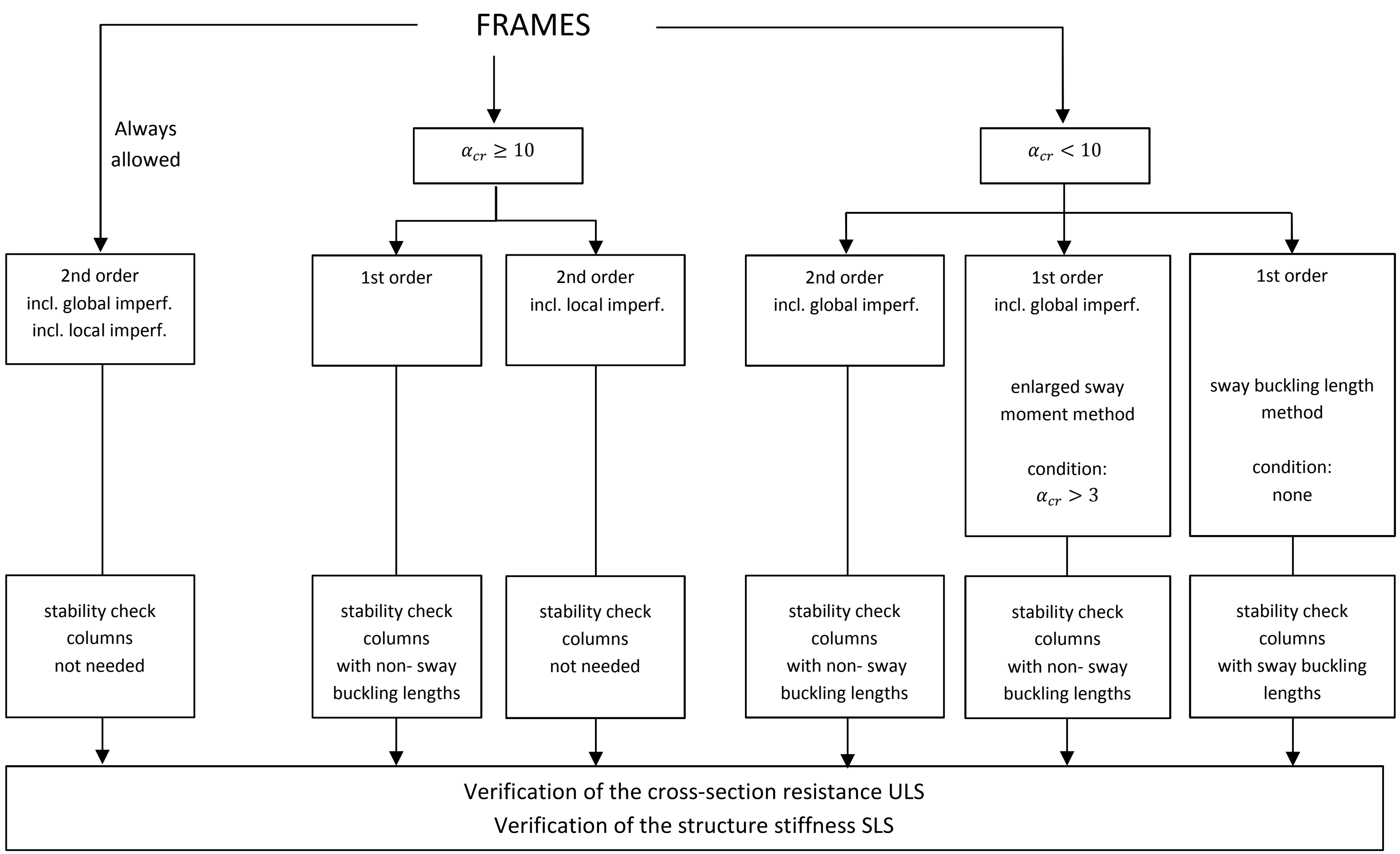
The following table gives suggested limits for calculated horizontal deflections of certain members under the characteristic load combination due to variable load. Circumstances may arise where greater or lesser values would be more appropriate. Other members may also need deflection limits.

Horizontal deflection (NA to BS EN 1993-1-1 NA.2.24)

Tops of columns in single-storey buildings except portal frames	Height/300
Column in portal frame buildings, not supporting crane runways	To suit the characteristics of particular cladding
In each storey of a building with more than one storey	Height of that storey/300

5. Conclusion – what calculation path to follow and when?

In §3.1 we have seen that the geometric response can be calculated first or second order. This results in a wide range of options for the global analysis. The following flow chart summarizes the possibilities together:



6. References

- BS-EN 1993-1-1 - Eurocode 3: Design of steel structures - General rules and rules for buildings (+ AC:2009) UK Annex
- NBN-EN 1993-1-1 - Eurocode 3: Design of steel structures - General rules and rules for buildings (+ AC:2009) BE Annex
- Snijder H.H. & Steenbergen H.M.G.M. (2011), *Krachtswerking – grondslagen voor het berekenen en toetsen van staalconstructies voor gebouwen volgens Eurocode 0, 1 en 3*, Bouwen met Staal
- Staalinfocentrum (2006), *Eurocode 3 EN 1993 – Rekenvoorbeelden van staalconstructies*, Staalinfocentrum.
- Technical Committee 8, (2006) *Rules for Member Stability in EN 1993-1-1 – Background documentation and design guidelines*, ECCS
- Xiong Y. (2011), *Formulaire de résistance des matériaux*, Eyrolles

lateral buckling restraint – attaches – steel check – creep – charges climatiques – dynamic analysis – lateral buckling – brandweerstandsanalyse – timber – 1st order – verstijvers – buisverbinding – diseño de planos de armaduras – pandeo lateral – verbindingen – shear connection – verificación – armatures longitudinales – pórtico – unión base columna – voorontwerp – unión tubular – haunch – connexion moment – cimbras – vérification acier – unity check – Eurocode 2 – mesh – retaining wall – raidisseur – Eurocode 3 – longitudes de pandeo – connections – ACI 138 – acero – 2nd ordre – portal frame – Eurocode 8 – andamios – kip – dwarskrachtverbinding – BS 8110 – dalle de fondation – seismische analyse – armaduras longitudinales – BIM – gelaste verbinding – 2de orde – buckling – funderingszool – poutre sur plusieurs appuis – maillage – malla – uniones – 2D raamwerken – fire resistance analysis – voiles – cracked deformation – gescheurde doorbuiging – longueurs de flambement – pandeo – reinforcement – unity check – cantonera – dynamische analyse – hout – ossatures 3D – koudgevormde profielen – placa de extreme – 1er orden – continuous beam – connexion soudée – momentverbinding – praktische wapening – renforts au déversement – fluencia – estribos – déformation fissurée – EHE – beugels – Eurocódigo 3 – platine de bout – análisis dinámico – column base plate – kruip – rigid link – welded connection – charpente métallique – moment connections – estructuras 2D – kniestuk – assemblage métallique – 3D raamwerken – second ordre – beam grid – cargas climáticas – Eurocode 2 – Eurocode 5 – wall – deformación fisurada – lien rigide – enlace rígido – 2D frames – estructuras 3D – éléments finis – vloerplaat – steel connection – scheurvorming – integrated connection design – armatures pratiques – analyse sismique – nieve y viento – practical reinforcement – charges mobiles – dalle – wapening – perfiles conformados en frío – Eurocode 3 – connexion tubulaire – unión a momento – 3D frames – treillis de poutres – roof truss – practical reinforcement design – portique – kipsteunen – análisis sísmico – Eurocode 8 – seismic analysis – B.A.E.L 91 – uniones atornilladas – bolts – ossatures 2D – eindige elementen – losa de cimentación – restricciones para el pandeo lateral – optimisation – wand – kniklengtes – end plate – dakspanten – kolomvoetverbinding – stirrups – acier – staalcontrole – cálculo de uniones integrado – paroi – dessin du plan de ferraillage – stiffeners – mobiele lasten – Eurocódigo 8 – Eurocódigo 5 – longitudinal reinorcement – doorlopende liggers – rigidizador – beton armé – fluage – CTE – connexion pied de poteau – langswapening – connexions – hormigón – neige et vent – elementos finitos – armaduras – cold

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formed steel – jarret – uittekenen wapening – puente grúa – analyse dynamique – flambement – keerwanden – optimisation – steel – cercha – 2° orden – slab on grade foundation – entramado de vigas – Eurocode 5 – prédimensionnement – multi span beam – bouten – armatures – floor slab – poutre continue – pared – staal – 1er ordre – NEN 6770-6771 – connexion cisaillement – losa – déversement – viga continua – predimensionering – 1ste orde – unión metálica – CM 66 – madera – análisis resistencia al fuego – verbindingen – 2nd order – bois – Eurocode 2 – profilés formés à froid – verificación acero – predesign – unión soldada – fisuración – beton – muro de contención – optimalisatie – foundation pads – fissuration – concrete – AISC-LRFD – HCSS – assemblage métallique – Eurocode 3 – viga con varios apoyos – armaduras prácticas – balkenroosters – unión a cortante – buckling length – boulons – cracking – Eurocode 8 – knik – Eurocode 2 – radier – eindplaat – Eurocódigo 2 – FEM – tornillos – NEN 6720 – moving loads – balk op meerdere steunpunten – cargas móviles – funderingsplaat – étriers – analye resistance au feu – cercha – moment connections – estructuras 2D – kniestuk – assemblage métallique – dalle