Dlubal

Structural Analysis & Design Software

www.dlubal.com

网络课堂

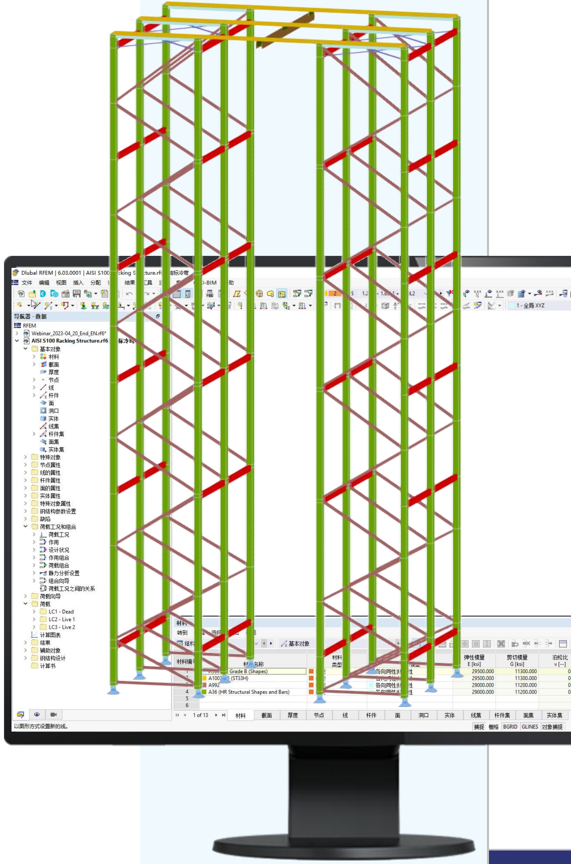
RFEM 6
美标AISI S100
冷弯薄壁型钢设计

郑伟伟

技术支持
德儒巴软件（上海）有限公司

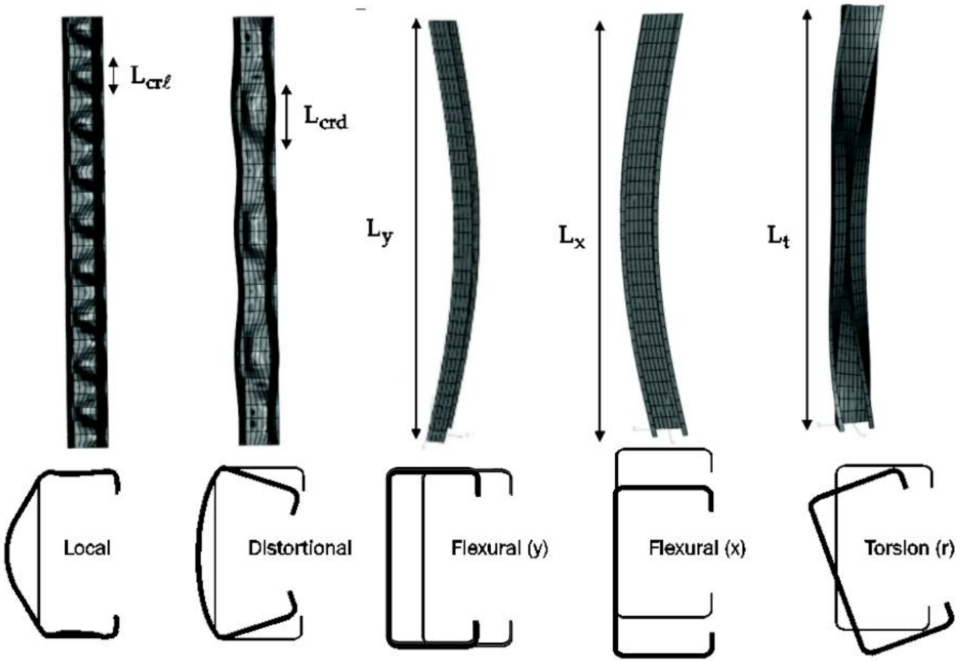
张涛

技术支持
德儒巴软件（上海）有限公司



主要内容

基于直接分析法进行结构系统稳定设计



冷弯薄壁构件最少有三种失稳模态：局部/畸变/整体

(附录2条文说明)

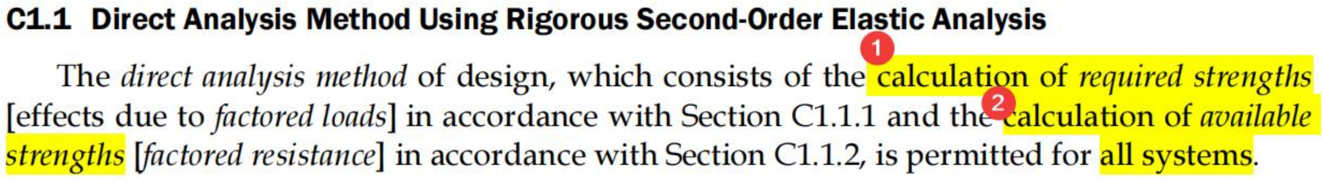
基于直接分析法进行结构系统稳定设计

无论采用什么稳定设计方法，都需要考虑以下因素：

- 要考虑结构的弯曲/剪切/轴向变形，其他组件和节点的变形
- 二阶效应（P-Δ和P-δ）
- 几何缺陷
- 刚度折减（截面局部塑性/残余应力）
- 刚度折减（截面变形/局部或畸变屈曲）
- 强度和刚度的不确定性

与AISC 360-16的要求基本相同。

基于直接分析法进行结构系统稳定设计



C1.1 Direct Analysis Method Using Rigorous Second-Order Elastic Analysis

The *direct analysis method* of design, which consists of the ① calculation of *required strengths* [effects due to *factored loads*] in accordance with Section C1.1.1 and the ② calculation of *available strengths* [*factored resistance*] in accordance with Section C1.1.2, is permitted for all systems.

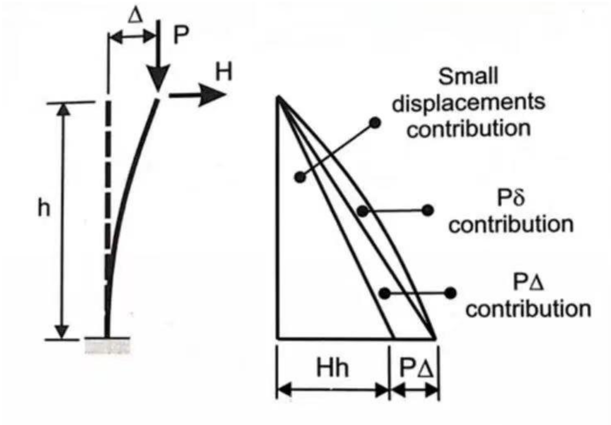
利用直接分析法进行结构系统稳定设计包含两个方面：

1.计算需要的强度（内力设计值）
2.计算可用的强度（承载力设计值）

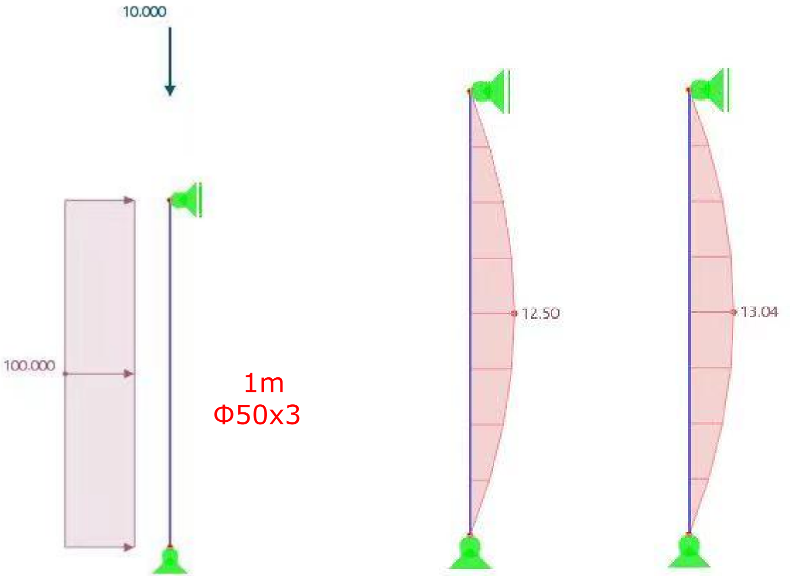
基于直接分析法进行结构系统稳定设计

二阶效应：

手算时，单工况分开
实际中，多工况同时作用



(a) Column (b) Bending Moments



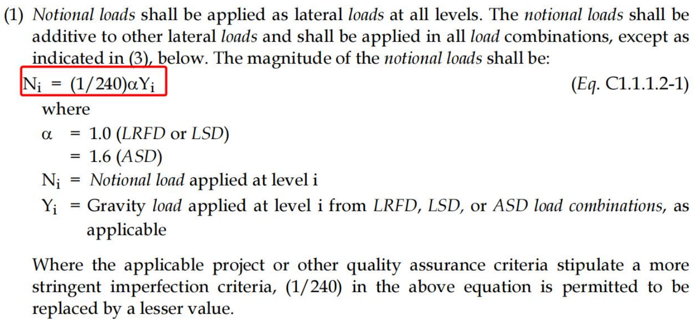
p-δ效应：放大系数1.0432

（杆件中间没有网格节点也能考虑，更不需要打断杆件）

基于直接分析法进行结构系统稳定设计

几何缺陷：AISI VS AISC 不同之处：

AISI



(1) *Notional loads* shall be applied as lateral *loads* at all levels. The *notional loads* shall be additive to other lateral *loads* and shall be applied in all *load* combinations, except as indicated in (3), below. The magnitude of the *notional loads* shall be:

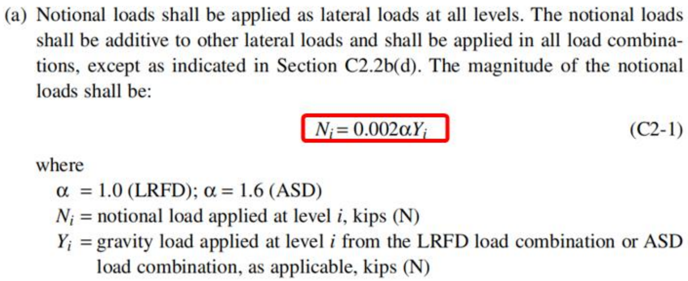
$$\boxed{N_i = (1/240)\alpha Y_i} \qquad (Eq.\ C1.1.1.2\text{-}1)$$

where

α = 1.0 (*LRFD* or *LSD*)
= 1.6 (*ASD*)
N_i = *Notional load* applied at level i
Y_i = Gravity *load* applied at level i from *LRFD*, *LSD*, or *ASD load combinations*, as applicable

Where the applicable project or other quality assurance criteria stipulate a more stringent imperfection criteria, (1/240) in the above equation is permitted to be replaced by a lesser value.

AISC



(a) Notional loads shall be applied as lateral loads at all levels. The notional loads shall be additive to other lateral loads and shall be applied in all load combinations, except as indicated in Section C2.2b(d). The magnitude of the notional loads shall be:

$$\boxed{N_i = 0.002\alpha Y_i} \qquad (C2\text{-}1)$$

where

α = 1.0 (LRFD); α = 1.6 (ASD)
N_i = notional load applied at level i, kips (N)
Y_i = gravity load applied at level i from the LRFD load combination or ASD load combination, as applicable, kips (N)

相同之处：

1.仅竖向荷载的组合:假想荷载考虑两个方向，每个方向考虑正负两种情况。

2.有水平荷载的组合：仅考虑与水平荷载相同方向的假想荷载。

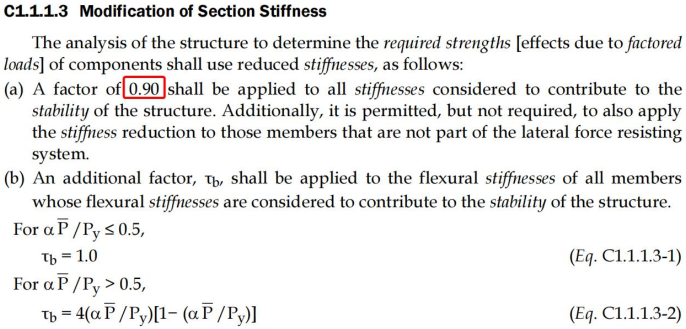
3.二阶计算得到的层间位移/一阶计算得到的层间位移≤1.7，假想荷载可以仅与竖向荷载组合而不与水平荷载组合。

4.正常使用极限状态验算时可以不考虑。

基于直接分析法进行结构系统稳定设计

刚度折减：AISI VS AISC 不同之处：

AISI



C1.1.1.3 Modification of Section Stiffness

The analysis of the structure to determine the *required strengths* [effects due to *factored loads*] of components shall use reduced *stiffnesses*, as follows:

(a) A factor of 0.90 shall be applied to all *stiffnesses* considered to contribute to the *stability* of the structure. Additionally, it is permitted, but not required, to also apply the *stiffness* reduction to those members that are not part of the lateral force resisting system.

(b) An additional factor, τ_b, shall be applied to the flexural *stiffnesses* of all members whose flexural *stiffnesses* are considered to contribute to the *stability* of the structure.

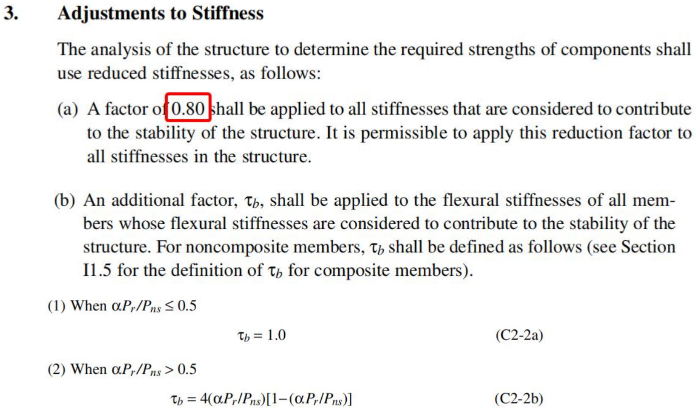
For $\alpha \overline{P} / P_y \le 0.5$,

$$\tau_b = 1.0 \quad (Eq.\ C1.1.1.3\text{-}1)$$

For $\alpha \overline{P} / P_y > 0.5$,

$$\tau_b = 4(\alpha \overline{P} / P_y)[1 - (\alpha \overline{P} / P_y)] \quad (Eq.\ C1.1.1.3\text{-}2)$$

AISC



3. Adjustments to Stiffness

The analysis of the structure to determine the required strengths of components shall use reduced stiffnesses, as follows:

(a) A factor of 0.80 shall be applied to all stiffnesses that are considered to contribute to the stability of the structure. It is permissible to apply this reduction factor to all stiffnesses in the structure.

(b) An additional factor, τ_b, shall be applied to the flexural stiffnesses of all members whose flexural stiffnesses are considered to contribute to the stability of the structure. For noncomposite members, τ_b shall be defined as follows (see Section I1.5 for the definition of τ_b for composite members).

(1) When $\alpha P_r/P_{ns} \le 0.5$

$$\tau_b = 1.0 \quad (C2\text{-}2a)$$

(2) When $\alpha P_r/P_{ns} > 0.5$

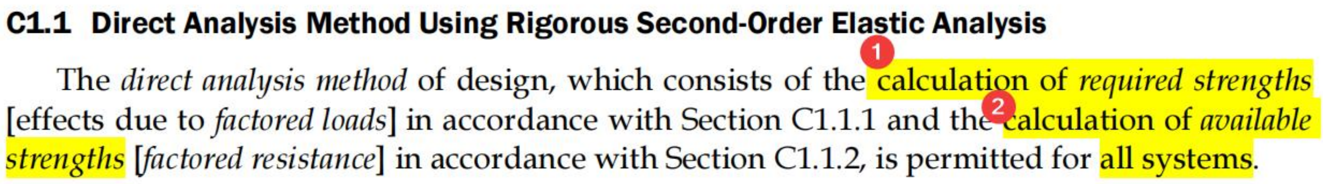
$$\tau_b = 4(\alpha P_r/P_{ns})[1-(\alpha P_r/P_{ns})] \quad (C2\text{-}2b)$$

相同之处：

1.正常使用极限状态验算时可以不考虑。

2.假想增加$0.001\alpha Y_i$后，τ_b可取1.0

基于直接分析法进行结构系统稳定设计



C1.1 Direct Analysis Method Using Rigorous Second-Order Elastic Analysis

The *direct analysis method* of design, which consists of the ① calculation of *required strengths* [effects due to *factored loads*] in accordance with Section C1.1.1 and the ② calculation of *available strengths* [*factored resistance*] in accordance with Section C1.1.2, is permitted for all systems.

利用直接分析法进行结构系统稳定设计包含两个方面：

1.计算需要的强度（内力设计值）
2.计算可用的强度（承载力设计值）

基于直接分析法进行结构系统稳定设计

计算可用强度（承载力设计值）：

1.构件弯曲屈曲计算长度系数可取1.0，经过合理分析的话也可以小于1.0

2.计算长度系数取1.0的只是弯曲屈曲验算，而扭转屈曲/弯曲扭转屈曲的计算长度系数仍需按照边界条件取（例如悬臂轴压柱：Ky=Kz=1.0,Kt=2.0)。

2.如果构件考虑了局部缺陷，弯曲屈曲承载力可取截面承载力而不用进行稳定计算（局部屈曲验算和畸变屈曲验算还是要考虑的）。(C1.1条文说明)

相比于计算长度系数法，直接分析法只是简化了弯曲屈曲验算的K的取值问题。其他类型的屈曲验算（扭转屈曲/弯曲扭转屈曲/横向扭转屈曲）时的有效长度还是跟构件支承情况有关的，此外还需要进行局部屈曲验算和畸变屈曲验算，并不是采用了直接分析法后仅验算截面强度!

构件局部/畸变稳定设计

- **有效宽度法（RFEM6 欧标采用的方法）：**
  - □ 对截面的每个板件计算有效宽度
  - □ 没有考虑板件之间的相互作用
  - □ 需要迭代

- **直接强度法（RFEM6 美标采用的方法）：**
  - □ 使用毛截面特性，不需计算有效宽度
  - □ 不需要迭代
  - □ 考虑板件之间的相互作用
  - □ 适用截面类型更广
  - □ 比有效宽度法更精准/更经济

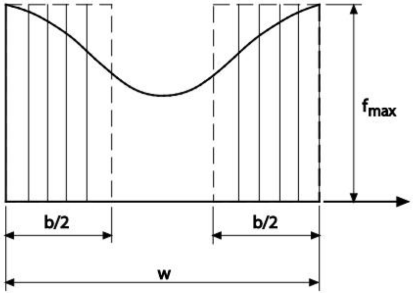


Figure C-1-4 Stress Distribution in Stiffened Compression Elements

等效原则：合理相等/最大应力相等

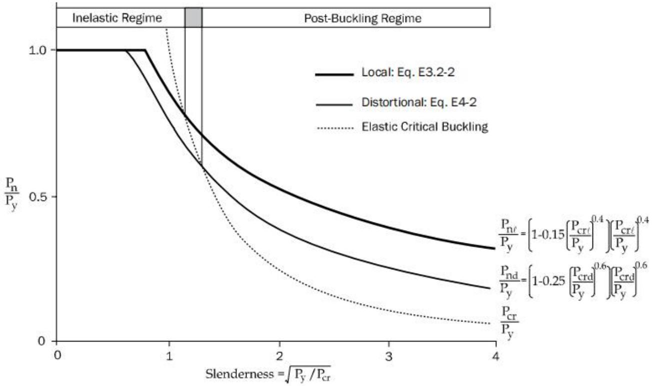
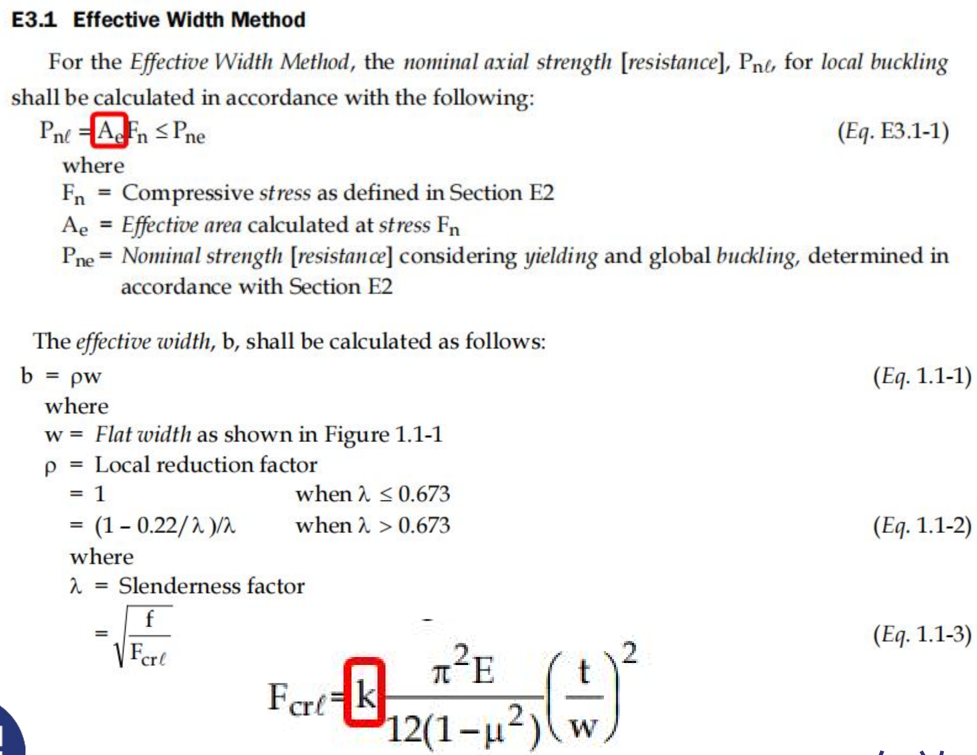


Figure C-E1-1 Local and Distortional Direct Strength Curves for a Braced Column (P_{ne} = P_y)

构件局部/畸变稳定设计



E3.1 Effective Width Method

For the *Effective Width Method*, the *nominal axial strength* [*resistance*], $P_{n\ell}$, for *local buckling* shall be calculated in accordance with the following:

$$P_{n\ell} = \boxed{A_e} F_n \le P_{ne} \quad \text{(Eq. E3.1-1)}$$

where

F_n = Compressive *stress* as defined in Section E2

A_e = *Effective area* calculated at *stress* F_n

P_{ne} = *Nominal strength* [*resistance*] considering *yielding* and global *buckling*, determined in accordance with Section E2

The *effective width*, b, shall be calculated as follows:

$$b = \rho w \quad \text{(Eq. 1.1-1)}$$

where

w = *Flat width* as shown in Figure 1.1-1

ρ = Local reduction factor

$= 1$ when $\lambda \le 0.673$

$= (1 - 0.22/\lambda)/\lambda$ when $\lambda > 0.673$ (Eq. 1.1-2)

where

λ = Slenderness factor

$$= \sqrt{\frac{f}{F_{cr\ell}}} \quad \text{(Eq. 1.1-3)}$$

$$F_{cr\ell} = \boxed{k} \frac{\pi^2 E}{12(1-\mu^2)} \left(\frac{t}{w}\right)^2$$

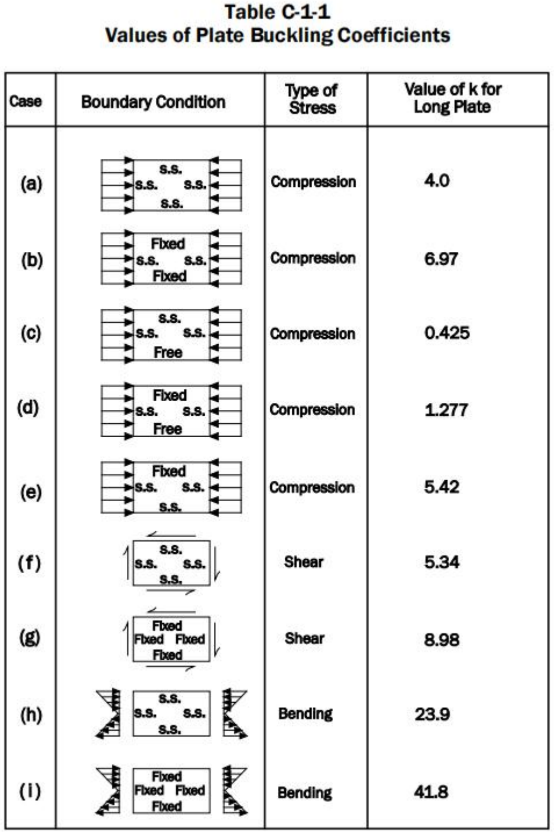
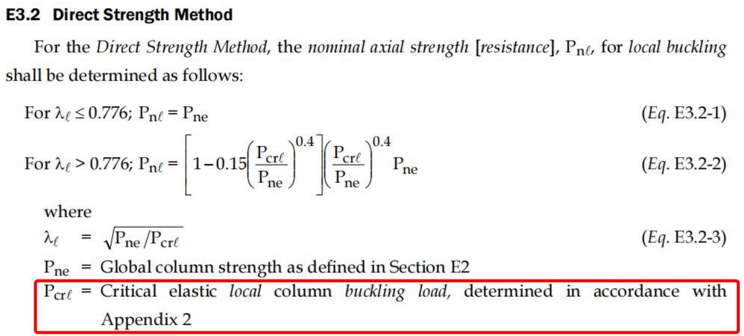


Table C-1-1
Values of Plate Buckling Coefficients

Case	Boundary Condition	Type of Stress	Value of k for Long Plate
(a)	s.s. s.s. s.s. s.s.	Compression	4.0
(b)	Fixed s.s. s.s. Fixed	Compression	6.97
(c)	s.s. s.s. s.s. Free	Compression	0.425
(d)	Fixed s.s. s.s. Free	Compression	1.277
(e)	Fixed s.s. s.s. s.s.	Compression	5.42
(f)	s.s. s.s. s.s. s.s.	Shear	5.34
(g)	Fixed Fixed Fixed Fixed	Shear	8.98
(h)	s.s. s.s. s.s. s.s.	Bending	23.9
(i)	Fixed Fixed Fixed Fixed	Bending	41.8

有效宽度法计算原理

构件局部/畸变稳定设计



E3.2 Direct Strength Method

For the *Direct Strength Method*, the *nominal axial strength* [*resistance*], $P_{n\ell}$, for *local buckling* shall be determined as follows:

For $\lambda_\ell \le 0.776$; $P_{n\ell} = P_{ne}$ (*Eq.* E3.2-1)

For $\lambda_\ell > 0.776$; $P_{n\ell} = \left[1-0.15\left(\frac{P_{cr\ell}}{P_{ne}}\right)^{0.4}\right]\left(\frac{P_{cr\ell}}{P_{ne}}\right)^{0.4} P_{ne}$ (*Eq.* E3.2-2)

where

$\lambda_\ell = \sqrt{P_{ne}/P_{cr\ell}}$ (*Eq.* E3.2-3)

P_{ne} = Global column strength as defined in Section E2

$P_{cr\ell}$ = Critical elastic *local* column *buckling load*, determined in accordance with Appendix 2

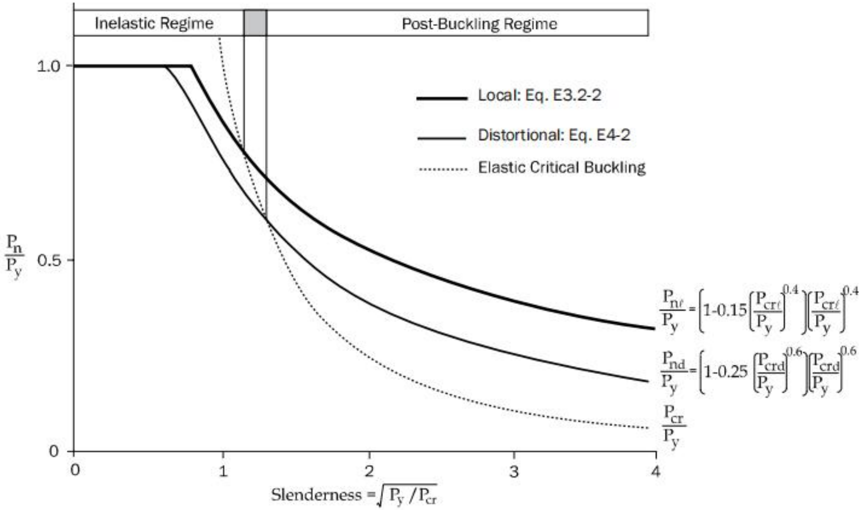


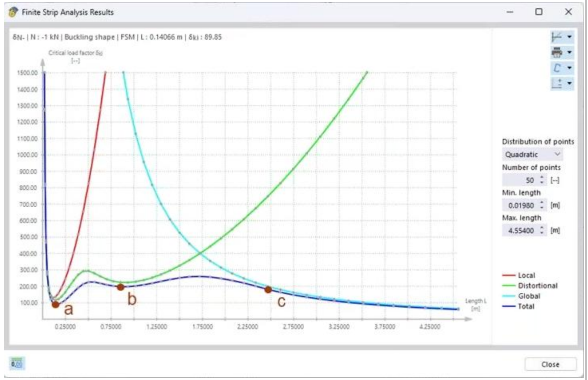
Figure C-E1-1 Local and Distortional Direct Strength Curves for a Braced Column ($P_{ne} = P_y$)

直接强度法计算原理

构件局部/畸变稳定设计

有限条带法（FSM）

- 使用直接强度法进行局部/畸变屈曲设计时，需要弹性临界力/弯矩
- 有限条带法是规范主推的弹性临界应力计算数值计算方法（附录2）
- 基于弯曲板带对简支构件进行屈曲分析（类似有限元）
- 每种截面都能生成四条特征曲线（signature graph):局部/畸变/整体/全部
- 更多内容见官网知识库 KB 1809, KB1841, KB1801


Finite Strip Analysis Results

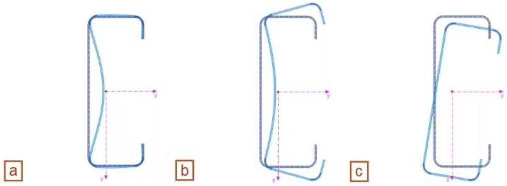
δN- | N : -1 kN | Buckling shape | FSM | L : 0.14066 m | δki : 89.85

Distribution of points: Quadratic

Number of points: 50 [--]

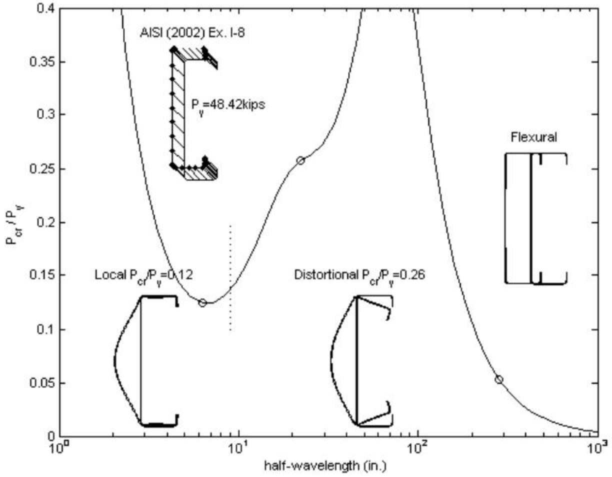
Min. length: 0.01980 [m]

Max. length: 4.55400 [m]



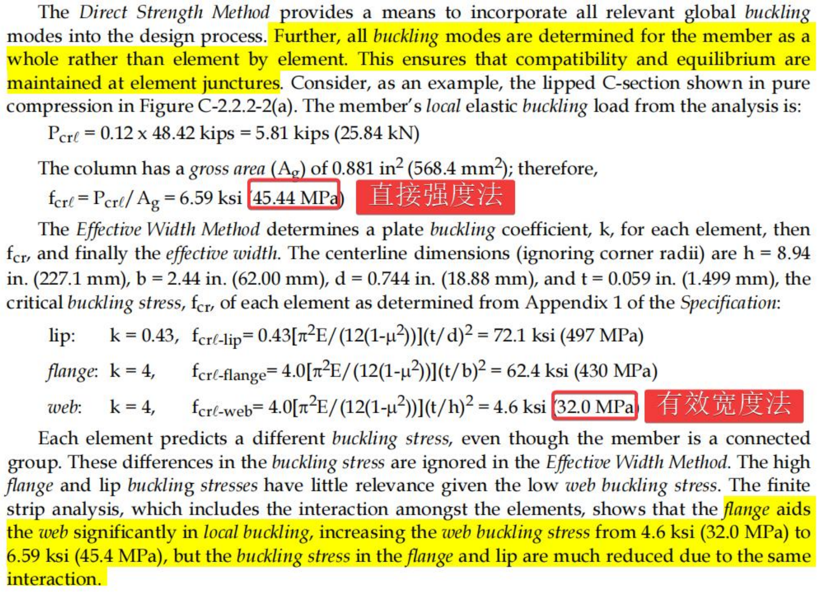
构件局部/畸变稳定设计

- **有效宽度法VS直接强度法 对设计结果的影响**



(a) 9CS2.5x059 of AISI *Cold-Formed Steel Design Manual* (2002), Example I-8

Figure C-2.2.2-2 Examples of Bending and Compression Elastic Buckling Analysis With Finite Strip Method



The *Direct Strength Method* provides a means to incorporate all relevant global *buckling* modes into the design process. Further, all *buckling* modes are determined for the member as a whole rather than element by element. This ensures that compatibility and equilibrium are maintained at element junctures. Consider, as an example, the lipped C-section shown in pure compression in Figure C-2.2.2-2(a). The member's *local* elastic *buckling* load from the analysis is:

$P_{cr\ell} = 0.12 \times 48.42$ kips = 5.81 kips (25.84 kN)

The column has a *gross area* (A_g) of 0.881 in^2 (568.4 mm^2); therefore,

$f_{cr\ell} = P_{cr\ell}/A_g = 6.59$ ksi (45.44 MPa) 直接强度法

The *Effective Width Method* determines a plate *buckling* coefficient, k, for each element, then f_{cr}, and finally the *effective width*. The centerline dimensions (ignoring corner radii) are h = 8.94 in. (227.1 mm), b = 2.44 in. (62.00 mm), d = 0.744 in. (18.88 mm), and t = 0.059 in. (1.499 mm), the critical *buckling stress*, f_{cr}, of each element as determined from Appendix 1 of the *Specification*:

lip: k = 0.43, $f_{cr\ell\text{-lip}} = 0.43[\pi^2E/(12(1-\mu^2))](t/d)^2 = 72.1$ ksi (497 MPa)

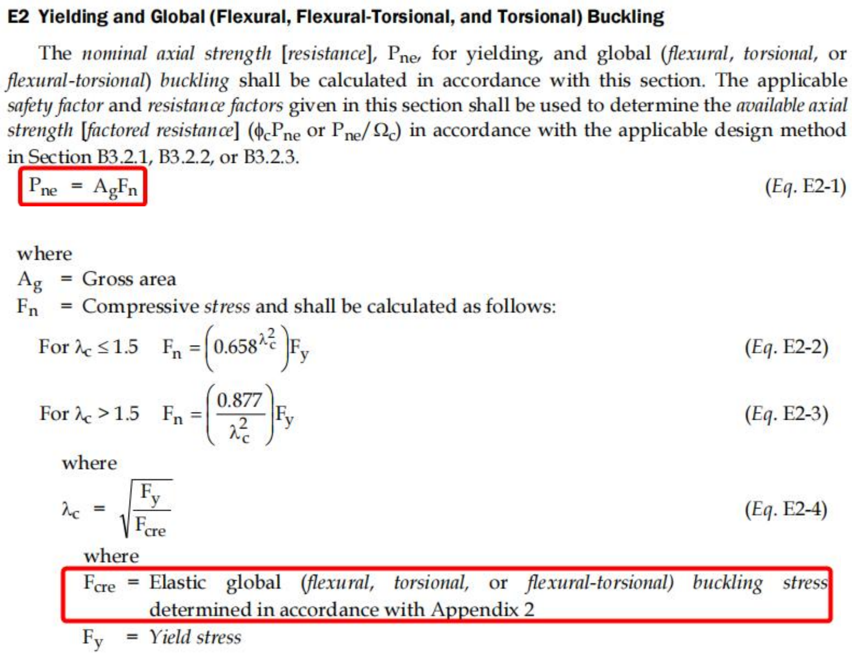
flange: k = 4, $f_{cr\ell\text{-flange}} = 4.0[\pi^2E/(12(1-\mu^2))](t/b)^2 = 62.4$ ksi (430 MPa)

web: k = 4, $f_{cr\ell\text{-web}} = 4.0[\pi^2E/(12(1-\mu^2))](t/h)^2 = 4.6$ ksi (32.0 MPa) 有效宽度法

Each element predicts a different *buckling stress*, even though the member is a connected group. These differences in the *buckling stress* are ignored in the *Effective Width Method*. The high *flange* and lip *buckling stresses* have little relevance given the low *web buckling stress*. The finite strip analysis, which includes the interaction amongst the elements, shows that the *flange* aids the *web* significantly in *local buckling*, increasing the *web buckling stress* from 4.6 ksi (32.0 MPa) to 6.59 ksi (45.4 MPa), but the *buckling stress* in the *flange* and lip are much reduced due to the same interaction.

有限条带法考虑了板件之间的相互作用，翼缘和卷边的加强作用使得腹板的局部屈曲临界应力从32Mpa提高到了45.4Mpa

构件整体稳定设计



E2 Yielding and Global (Flexural, Flexural-Torsional, and Torsional) Buckling

The *nominal axial strength* [*resistance*], P_{ne}, for yielding, and global (*flexural*, *torsional*, or *flexural-torsional*) *buckling* shall be calculated in accordance with this section. The applicable *safety factor* and *resistance factors* given in this section shall be used to determine the *available axial strength* [*factored resistance*] ($\phi_c P_{ne}$ or P_{ne}/Ω_c) in accordance with the applicable design method in Section B3.2.1, B3.2.2, or B3.2.3.

$$\boxed{P_{ne} = A_g F_n} \qquad (Eq.\ E2\text{-}1)$$

where
A_g = Gross area
F_n = Compressive *stress* and shall be calculated as follows:

For $\lambda_c \leq 1.5$ $\quad F_n = \left(0.658^{\lambda_c^2}\right) F_y$ $\qquad$ (*Eq.* E2-2)

For $\lambda_c > 1.5$ $\quad F_n = \left(\dfrac{0.877}{\lambda_c^2}\right) F_y$ $\qquad$ (*Eq.* E2-3)

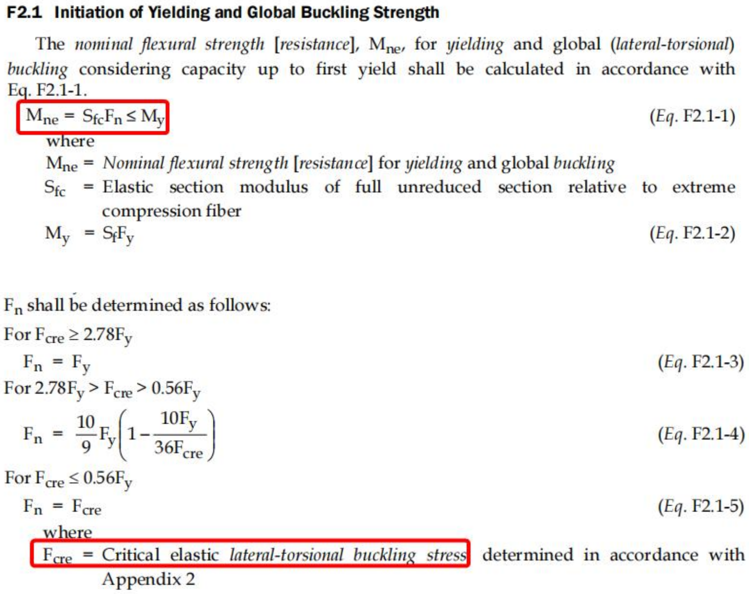
where

$$\lambda_c = \sqrt{\frac{F_y}{F_{cre}}} \qquad (Eq.\ E2\text{-}4)$$

where
F_{cre} = Elastic global (*flexural*, *torsional*, or *flexural-torsional*) *buckling stress* determined in accordance with Appendix 2
F_y = *Yield stress*

轴压稳定设计

（弯曲屈曲/扭转屈曲/弯曲扭转屈曲）



F2.1 Initiation of Yielding and Global Buckling Strength

The *nominal flexural strength* [*resistance*], M_{ne}, for *yielding* and global (*lateral-torsional*) *buckling* considering capacity up to first yield shall be calculated in accordance with Eq. F2.1-1.

$$\boxed{M_{ne} = S_{fc} F_n \leq M_y} \qquad (Eq.\ F2.1\text{-}1)$$

where
M_{ne} = *Nominal flexural strength* [*resistance*] for *yielding* and global *buckling*
S_{fc} = Elastic section modulus of full unreduced section relative to extreme compression fiber
M_y = $S_f F_y$ $\qquad$ (*Eq.* F2.1-2)

F_n shall be determined as follows:

For $F_{cre} \geq 2.78F_y$
$F_n = F_y$ $\qquad$ (*Eq.* F2.1-3)

For $2.78F_y > F_{cre} > 0.56F_y$

$$F_n = \frac{10}{9} F_y \left(1 - \frac{10F_y}{36F_{cre}}\right) \qquad (Eq.\ F2.1\text{-}4)$$

For $F_{cre} \leq 0.56F_y$
$F_n = F_{cre}$ $\qquad$ (*Eq.* F2.1-5)

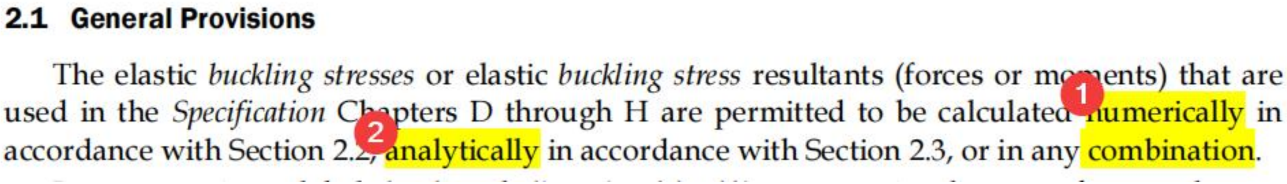
where
F_{cre} = Critical elastic *lateral-torsional buckling stress* determined in accordance with Appendix 2

受弯整体稳定设计

（横向扭转屈曲）

Dlubal

构件整体稳定设计

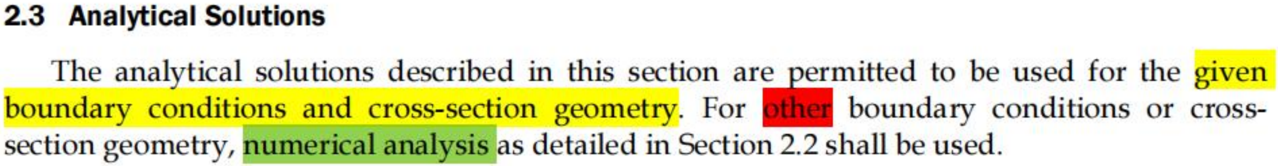


2.1 General Provisions

The elastic *buckling stresses* or elastic *buckling stress* resultants (forces or moments) that are used in the *Specification* Chapters D through H are permitted to be calculated numerically in accordance with Section 2.2, analytically in accordance with Section 2.3, or in any combination.

数值法: 有限条带法；基于板壳的有限元法；通用梁理论

（注意：大多数结构软件使用的传统梁元理论不能考虑弯曲和扭转的相互作用，在进行横向扭转屈曲/弯曲扭转屈曲弹性临界应力计算时需要特别注意。）



2.3 Analytical Solutions

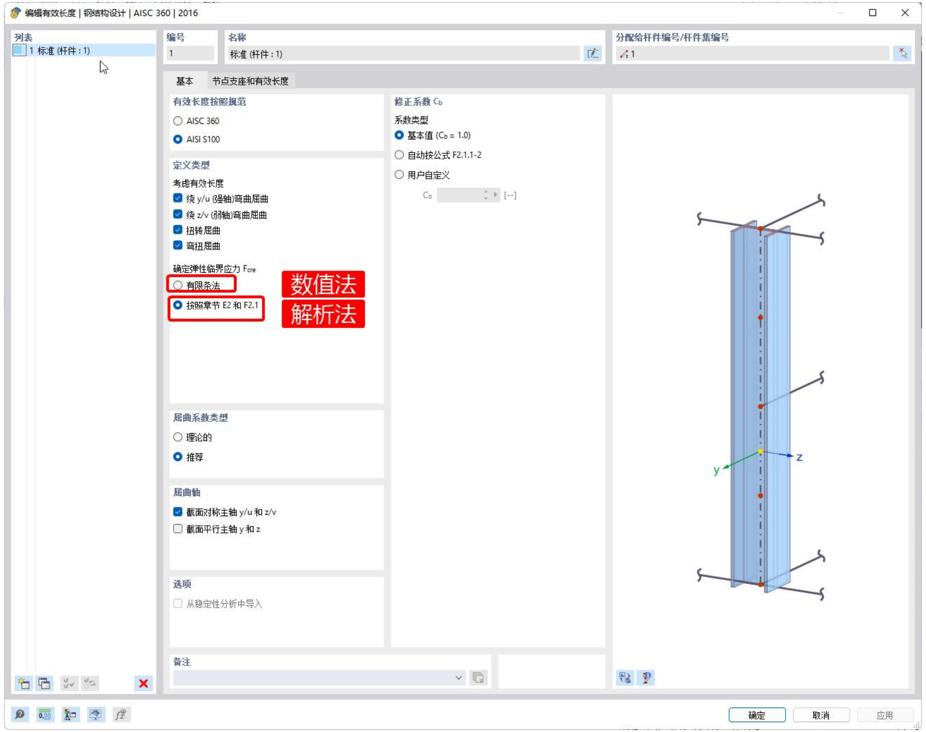
The analytical solutions described in this section are permitted to be used for the given boundary conditions and cross-section geometry. For other boundary conditions or cross-section geometry, numerical analysis as detailed in Section 2.2 shall be used.

解析法:仅适用于限定支座条件和截面形状，其他情况需要使用数值法计算。

构件整体稳定设计

有限条带法（数值法）：

- 根据截面特征曲线获得局部/畸变/整体弹性屈曲临界力/弯矩
- 强/弱轴弯曲屈曲和扭转屈曲不能单独验算，而是作为整体考虑验算一项（FSM法局限性）
- 如果K_y,K_z,K_T不相等，程序按照最大值从特征曲线上获得轴压失稳临界力
- 强/弱轴单个方向有支承时，建议用解析法，否则验算结果偏大



编辑有效长度 | 钢结构设计 | AISC 360 | 2016

列表
1 标准 (杆件 : 1)

编号: 1
名称: 标准 (杆件 : 1)
分配给杆件编号/杆件集编号: 1

基本 | 节点支座和有效长度

有效长度按照规范
○ AISC 360
● AISI S100

定义类型
考虑有效长度
☑ 绕 y/u (强轴)弯曲屈曲
☑ 绕 z/v (弱轴)弯曲屈曲
☑ 扭转屈曲
☑ 弯扭屈曲

确定弹性临界应力 F_{cre}
○ 有限条法　数值法
● 按照章节 E2 和 F2.1　解析法

屈曲系数类型
○ 理论的
● 推荐

屈曲轴
☑ 截面对称主轴 y/u 和 z/v
☐ 截面平行主轴 y 和 z

选项
☐ 从稳定性分析中导入

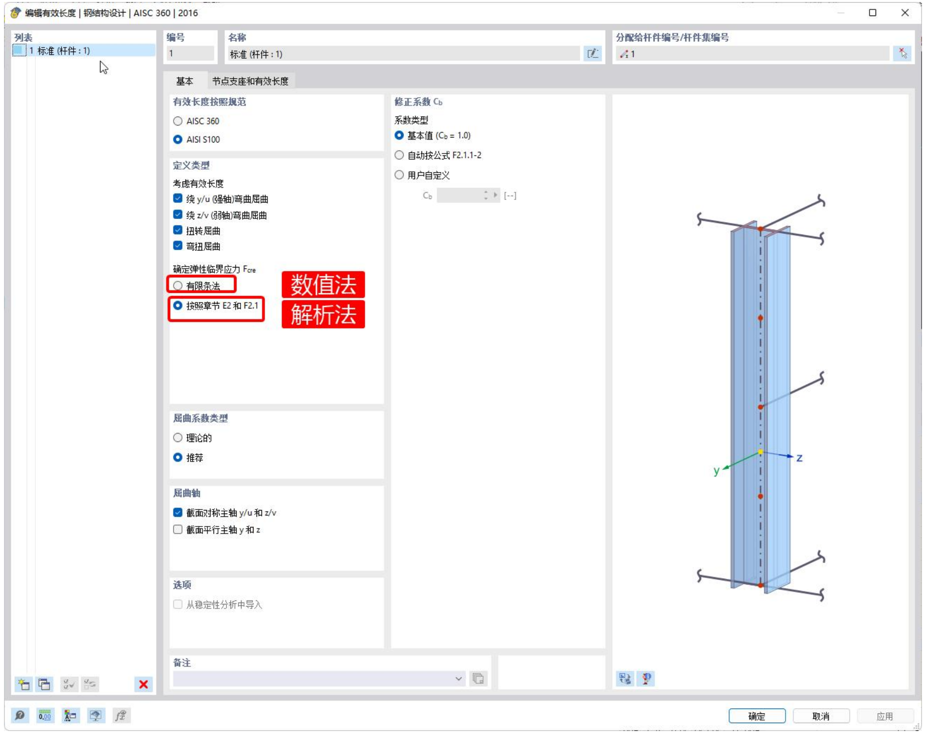
备注

修正系数 C_b
系数类型
● 基本值 (C_b = 1.0)
○ 自动按公式 F2.1.1-2
○ 用户自定义
C_b [--]

构件整体稳定设计

章E2和F2.1（解析法）：

- 根据理论公式获得整体体弹性屈曲临界力/弯矩（局部/畸变屈曲仍按FSM法）
- 强轴弯曲屈曲、弱轴弯曲屈曲、弯曲扭转屈曲独立验算，可考虑$K_y/K_z/K_T$不同的情况
- 仅适用于限定支座条件和截面形状，其他情况需要使用数值法计算。



编辑有效长度 | 钢结构设计 | AISC 360 | 2016

列表: 1 标准 (杆件 : 1)

编号: 1

名称: 标准 (杆件 : 1)

分配给杆件编号/杆件集编号: 1

有效长度按照规范
○ AISC 360
● AISI S100

定义类型

考虑有效长度
☑ 绕 y/u (强轴)弯曲屈曲
☑ 绕 z/v (弱轴)弯曲屈曲
☑ 扭转屈曲
☑ 弯扭屈曲

确定弹性临界应力 F_{cre}
○ 有限条法
● 按照章节 E2 和 F2.1

数值法

解析法

屈曲系数类型
○ 理论的
● 推荐

屈曲轴
☑ 截面对称主轴 y/u 和 z/v
☐ 截面平行主轴 y 和 z

选项
☐ 从稳定性分析中导入

备注

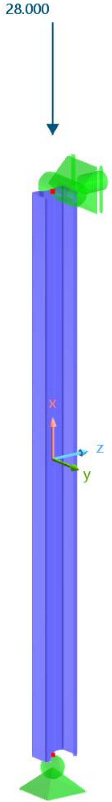
修正系数 C_b

系数类型
● 基本值 (C_b = 1.0)
○ 自动按公式 F2.1.1-2
○ 用户自定义

C_b [--]

思考：如果支座/截面超出解析法适用范围，而且$K_y/K_z/K_T$不同时怎么办？

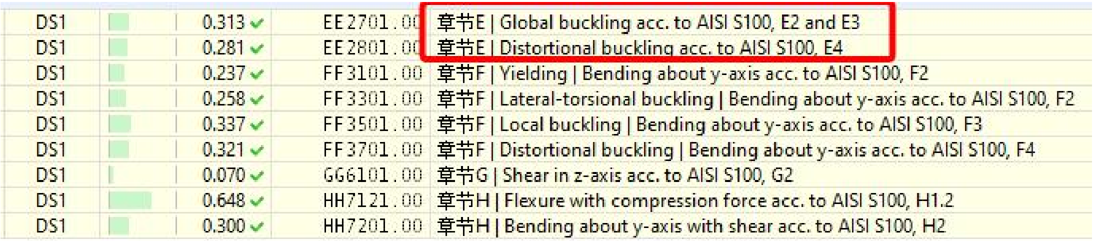
构件整体稳定设计



有效长度系数

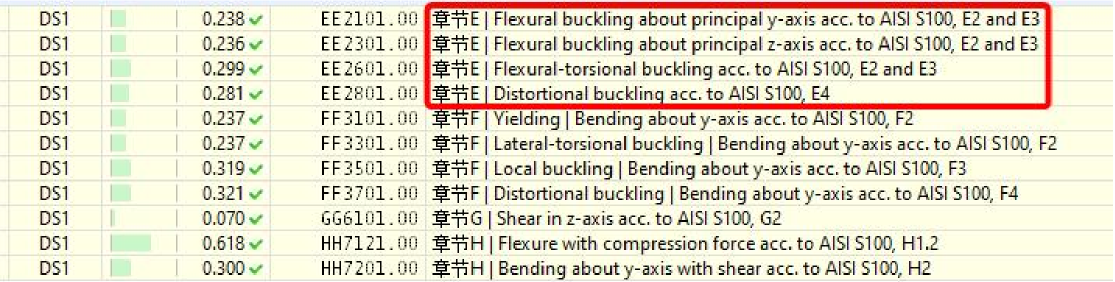
部分 顺序编号	主轴 Ky/u [--]	 Kz/v [--]	扭转 KT [--]	弯扭屈曲 KLT [--]
.1	1.00	0.50	1.00	1.00

有限条带法



DS1	🟩	0.313 ✓	EE2701.00	章节E | Global buckling acc. to AISI S100, E2 and E3
DS1	🟩	0.281 ✓	EE2801.00	章节E | Distortional buckling acc. to AISI S100, E4
DS1	🟩	0.237 ✓	FF3101.00	章节F | Yielding | Bending about y-axis acc. to AISI S100, F2
DS1	🟩	0.258 ✓	FF3301.00	章节F | Lateral-torsional buckling | Bending about y-axis acc. to AISI S100, F2
DS1	🟩	0.337 ✓	FF3501.00	章节F | Local buckling | Bending about y-axis acc. to AISI S100, F3
DS1	🟩	0.321 ✓	FF3701.00	章节F | Distortional buckling | Bending about y-axis acc. to AISI S100, F4
DS1	🟩	0.070 ✓	GG6101.00	章节G | Shear in z-axis acc. to AISI S100, G2
DS1	🟩	0.648 ✓	HH7121.00	章节H | Flexure with compression force acc. to AISI S100, H1.2
DS1	🟩	0.300 ✓	HH7201.00	章节H | Bending about y-axis with shear acc. to AISI S100, H2

解析公式法



DS1	🟩	0.238 ✓	EE2101.00	章节E | Flexural buckling about principal y-axis acc. to AISI S100, E2 and E3
DS1	🟩	0.236 ✓	EE2301.00	章节E | Flexural buckling about principal z-axis acc. to AISI S100, E2 and E3
DS1	🟩	0.299 ✓	EE2601.00	章节E | Flexural-torsional buckling acc. to AISI S100, E2 and E3
DS1	🟩	0.281 ✓	EE2801.00	章节E | Distortional buckling acc. to AISI S100, E4
DS1	🟩	0.237 ✓	FF3101.00	章节F | Yielding | Bending about y-axis acc. to AISI S100, F2
DS1	🟩	0.237 ✓	FF3301.00	章节F | Lateral-torsional buckling | Bending about y-axis acc. to AISI S100, F2
DS1	🟩	0.319 ✓	FF3501.00	章节F | Local buckling | Bending about y-axis acc. to AISI S100, F3
DS1	🟩	0.321 ✓	FF3701.00	章节F | Distortional buckling | Bending about y-axis acc. to AISI S100, F4
DS1	🟩	0.070 ✓	GG6101.00	章节G | Shear in z-axis acc. to AISI S100, G2
DS1	🟩	0.618 ✓	HH7121.00	章节H | Flexure with compression force acc. to AISI S100, H1.2
DS1	🟩	0.300 ✓	HH7201.00	章节H | Bending about y-axis with shear acc. to AISI S100, H2

软件操作-操作流程

自定义截面

(RSECTION导入Dxf)

↓

建模计算

(二阶效应/几何缺陷/刚度折减)

↓

构件设计

(k/ULS/SLS验算配置)

Dlubal

www.dlubal.com