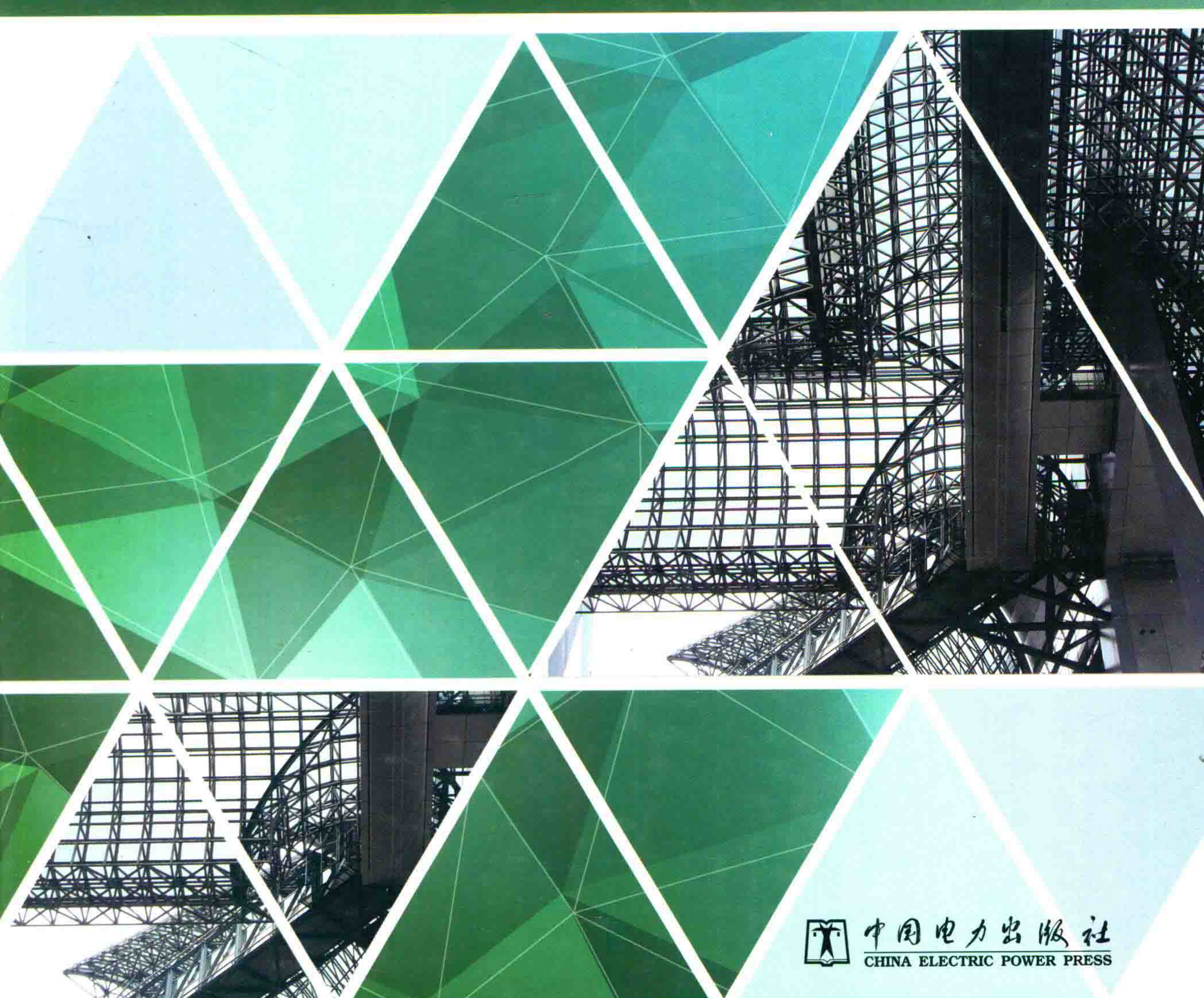
STABILITY OF STEEL STRUCTURES THEORY AND APPLICATION

钢结构稳定—理论与应用

Ji Chen （陈 骥）



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内 容 提 要

全书共十五章，主要内容包括以下几个方面：

（1）失稳分类：分岔失稳的类型，极值点失稳和跃越失稳。

（2）轴心受压柱、梁柱、刚接和半刚接刚架的平面弯曲屈曲性能和实用设计方法。

（3）柱、梁和梁柱的平面外弯扭屈曲性能和实用设计方法。

（4）薄板的凸曲和屈曲后性能，冷弯薄壁板件的局部屈曲、畸变屈曲、整体屈曲和它们之间的相关屈曲，有效宽度和直接强度两种设计方法。

（5）弹性和弹塑性钢结构的能量法和数值法及其试验验证。

（6）圆柱壳屈曲性能和设计方法。

（7）均匀与非均匀温度构件的屈曲承载力。

全书内容注重钢结构材料和整体结构的几何非线性特点，使之符合实际的结构设计。同时，书中还附有依照国内外钢结构设计规范设计的许多钢结构构件、刚架和壳体的有关理论分析、试验研究和设计方法的实例。

本书可作为普通高等院校工程结构、工程力学专业研究生的教材，也可作为结构工程师和研究人员的参考用书。

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Preface

The theory of structural stability is, strictly speaking, a branch of structural mechanics. But, from the process of the development, it can be observed that this learning is closely linked with the progress of structural engineering. S. Timoshenko, in his classic monograph *Theory of Elastic Stability* published in 1936, wrote: "The modern use of steel and high-strength alloys in engineering structures, especially in bridges, ships and aircraft, has made elastic instability a problem of great importance". This statement made more than 60 years ago is still holding true nowadays, whereas buildings and offshore platforms are added to the rank of above structures and plasticity is more involved in stability issues. Constructional steel by itself is an elasto-plastic material welding, the contemporary art of connection, gives rise to residual stresses which accentuate the inelastic behavior of steel members.

This book *Stability of Steel Structures* • *Theory and Application* by Professor CHEN Ji not only reflects the up-to-date achievement of this discipline, but also proves to be a good integration of stability theory with structure design. The topics have been expanded from traditional analysis of elastic members and plate elements to that of inelastic ones, from perfect structural components to imperfect ones and from buckling load to post-buckling capacity as well. In the first chapter, the concept of stable and unstable bifurcation is introduced and post-buckling behavior of both perfect and imperfect members are revealed through analysis of a series of rigid-elastic models, thus building a wide field of vision to the readers. On the other hand, inelastic properties of steel, including in the strain-hardening range, and the distribution of residual stresses (of both rolled and welded sections) are discussed thoroughly in this chapter, laying a solid foundation for seeking the actual behavior of members in practical engineering structures.

In the succeeding chapters, inelastic problems are solved by considering the effect of the specific residual stresses. This approach is certainly more realistic and rational than simply using tangent modulus in lieu of Young's modulus. Frames subject solely to loading on top of columns have been typical model for buckling analysis, although real structures always have gravity load on the girder. Due consideration of primary moment caused by girder loading in frame buckling analysis is discussed in this book, which is another example of close link between theory and practice. Besides comprehensive treatment of the basic knowledge of the structural stability theory, the authors pay adequate attention to the application of the theory. As design work always needs recourse to design specification, provisions of design code of several countries are introduces to suit the tendency of world-wide economic unification.

Stability assurance to structural members and systems is a predominant task of steel designers. But, at the present time, the learning of stability theory is not yet widespread among designers. This gap should be filled the soon the better. The publication of this book provides a useful tool toward this end.

CHEN Shaofan

Foreword

The publication of this text-book "*Stability of Steel Structures Theory and Application*" edition reflects the recently research advancement on the steel stability theory and design, which is selected in this second edition. These contents are as follows:

(1) Using some new practical examples to predicate the elastic and inelastic, linear and nonlinear behaviors of steel structures.

(2) Stability design of build-up beam-columns.

(3) Theoretical analysis and stability design of steel columns, beams and beam-columns under combined actions of compression, bending and torsion.

(4) Theoretical analysis and experimental investigation of sinusoidally and trapesoidally corrugated webs steel I-girders, about shear strength, moment bending and flexural-torsional moment capacities as well as their practical design methods.

(5) The new provisions of Recommendation for *Limit State Design of Steel Structures* AIJ—2010, instead of the corresponding AIJ—2002 content.

(6) The new provisions of *Specification for Structural Steel Buildings* ANSI/AISC 360—2010, instead of the corresponding ANSI/AISC 360—2005 content.

(7) Theoretical analysis, testing investigation and design method on axial compression strength capacity of single-angles connected with truss chords in same side of planar truss including the design visions of GB 50017—2014, JRA Part II —2002 and ANSI/AISC 360—2010.

(8) Buckling of cylindrical shells under axial compression, uniform hoop compression and torsion respectively and buckling of cylindrical shells under combined axial compression and uniform hoop compression.

(9) Buckling analysis and practical design formulas of perforated cold-formed steel columns and beams.

(10) Tests and design of cold-formed of web crippling.

(11) Behavior of stainless steel cold-formed oval hollow section (OHS) members.

(12) Direct Strength Method (DSM) for buckling capacity of steel cold-formed member design and its uses in uniform as well as non-uniform elevated temperatures.

(13) Analytical, experimental investigations and design methods for columns, beams and beam-columns under uniform and non-uniform, elevated and ambient temperature distributions leading to flexural or lateral-torsional buckling.

(14) Development of Direct Strength Method (DSM) for welded steel columns with buckling interactions.

Readers of this book are urged to communicate with authors regarding all aspects of this book, particularly on identification of errors and suggestions for improvement.

The editor gives a special credit to his wife Shen Xiuzhen and their family members on their patience and encouragement.

Ji, Chen-Editor
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Notation

The following notation is used in this book. Usually only one meaning is assigned to each symbol, but in those cases where more meanings than one are possible, then the correct one will be evident from the context in which is used.

A	Cross-sectional area
A_1	$P\text{–}\delta$ moment amplification factor of beam-columns
A_2	$P\text{–}\Delta$ moment amplification factor of unbraced frames
A_c	Area of corner
A_e	Elastic element area
	Effective cross-sectional area
A_f	Cross-sectional area of one flange
A_m	Moment amplification factor
A_n	Net cross-sectional area
A_w	Cross-sectional area of web
B	Flange width
B_1	$P\text{–}\delta$ moment amplification factor of beam-column as defined in ANSI/AISC 360—2010
B_2	$P\text{–}\Delta$ moment amplification factor of unbraced frame as defined in ANSI/AISC 360—2010
B_ω	Restrained warping bi-moment $= \int_A \sigma\omega \mathrm{d}A = -EI_\omega\varphi''$
C	Near end rotation stability function of beam-column
C_1	Modified near end rotation stability function of beam-column with elastically restrained ends
C_v	Web shear coefficient as defined in ANSI/AISC 360—2010
D	Elastic flexural stiffness of plate
	Cross-section depth of rafter
	Lip length
D_s	Elastic-plastic flexural stiffness of plate
	Rafter depth allowing for its slope
	Structural characteristic coefficient
E	Elastic modulus
E_r	Reduced modulus
E_s	Secant modulus
E_{st}	Strain-hardening modulus

E_t	Tangent modulus
E	Reduced tangent modulus
F	Function of stress
G	Elastic shear modulus
G_A	Relative stiffness factor at joint A as defined in ANSI/ AISC360—2010
G_B	Relative stiffness factor at joint B as defined in ANSI/AISC 360—2010
G_{st}	Strain-hardening shear modulus
G_t	Elastic-plastic shear modulus
H	Horizontal load
	Equivalent notional lateral load
	Fictitious horizontal force
	Column height
	Height of section
I	Moment of inertia
I_1	Moment of inertia of compression flange about y axis
I_2	Moment of inertia of tension flange about y axis
I_b	Moment of inertia of a beam
I_c	Moment of inertia of a column
I_e	Moment of inertia of elastic core of cross-section
	Moment of inertia of effective cross-section
I_{et}	Moment of inertia of torsional resistance of elastic core
I_{ex}	Moment of inertia of elastic core about x axis
I_{ey}	Moment of inertia of elastic core about y axis
$I_{e\omega}$	Warping moment of inertia of elastic core
I_{min}	Minimum moment of inertia of intermediate stiffness
I_{pt}	Moment of inertia of torsional resistance of plastic core
I_s	Moment of inertia of lip section
I_t	Moment of inertia of torsional resistance of cross-section
	Saint-Venant torsion constant
I_x	Moment of inertia of cross-section about x axis
I_{xy}	Product of inertia = $\int_A xy \, \mathrm{d}A$
I_y	Moment of inertia of cross-section about y axis
	Moment of inertia of longitudinal stiffener
I_{yc}	Moment of inertia about y axis refereed to compression flange as defined in ANSI/AISC 360—2010
I_{yt}	Moment of inertia about y axis referred to tension flange
I_z	Moment of inertia of transverse stiffener
I_ω	Warping moment of inertia

	Moment of inertia of sector section
K	Complete elliptic integral of first kind
	Linear stiffness
	Torsion parameter $=\sqrt{\pi^2 EI_\omega/(GI_t l^2)}$
K_1	Ratio of sum of beam linear stiffness to sum of column linear stiffness at joint A as defined in GB 50017—2014
K_2	Ratio of sum of beam linear stiffness to sum of column linear stiffness at joint B as defined in GB 50017—2014
$\overline{K}$	Wagner effect $=\int_A \sigma\rho^2 \,\mathrm{d}A=\int_A \sigma[(x-x_0)^2+(y-y_0)^2]\,\mathrm{d}A$
L	Span in pitched-roof frame
L_b	Effective span in pitched-roof frame
L_h	Haunch length in pitched-roof frame
L_r	Total developed length of rafters
M	Bending moment
M_1	Larger end moment of beam-column as defined in GB 50017—2014 and also in AIJ—2010
M_2	Smaller end moment of beam-column as defined in GB 50017—2014 and also in AIJ—2010
M_A	Absolute value of moment at quarter point of unbraced segment
M_B	Absolute value of moment at centerline of unbraced segment
M_b	Buckling resistance moment as defined in BS 5950-1—2000
$M_{\mathrm{b,fi,Rd}}$	Lateral-torsional buckling resistance moment of beam in case of fire
M_C	Absolute value of moment at three-quarter point of unbraced segment
M_cr	Critical moment
M_crd	Elastic distortional buckling moment
M_crl	Elastic local interactive buckling moment
M_d	Distortional interactive ultimate moment
M_e	Elastic critical moment
	End moment of connection
	External applied moment
M_eq	Equivalent critical moment
M_f	Warping bending moment of flange
$M_{\mathrm{F}A}$, $M_{\mathrm{F}B}$	Fixed-ended bending moment of member AB
M_i	Internal resisting moment
M_l	Local interactive ultimate moment
M_lt	First-order elastic moment of framed column of lateral translation
M_max	Absolute value of maximum moment of unbraced segment
	Maximum bending moment

M_{nt}	First-order elastic moment of framed column of no lateral translation
M_{ocr}	Elastic-plastic critical moment under uniform bending
M_p	Full plastic moment
M_{pc}	Plastic moment under compression and bending
M_r	Limit state of inelastic flexural-torsional buckling moment
M_s	Saint-Venant torque
	Uniform torque
	Effective plastic moment as defined in AS 4100—1998
M_t	Applied torque
M_u	Ultimate moment capacity
M_x	Bending moment about major x axis
	Unit moment of plate about y axis
M_y	Bending moment about minor y axis
	Yield moment
	Unit moment of plate about x axis
M_{xy}	Unit twisting moment of plate
M_z	Torque about longitudinal z axis
M_{ξ}, M_{η}	Bending moments about ξ and η axes in a deformed cross-section
M_{ζ}	Torsional moment about ζ axis in a deformed cross-section
M_{ω}	Warping torque
$[N]$	Integration operator
N_x, N_y	Middle surface forces of plate in x and y directions respectively
N_{xy}	Middle surface shear force of plate
N'_x, N'_y, N'_{xy}	Membrane forces
O	Centroid of cross-section
P	Load
	Axial compression force
P_{cr}	Buckling load
P_{crd}	Elastic distortional buckling load
P_{crl}	Elastic local interactive buckling load
P_{crx}, P_{cry}	Buckling loads about x and y axes respectively
P_d	Design load
	Distortional interactive ultimate load
P_E	Euler buckling load
P_e	Extreme fiber yield load of section
P_l	Local interactive ultimate load
P_p	First-order rigid-plastic collapse load
P_r	Reduced modulus buckling load

P_t	Tangent modulus buckling load
P_u	Ultimate load
P_x	Elastic buckling load about x axis
P_y	Elastic buckling load about y axis
	Yield load
$P_{x\omega}, P_{y\omega}, P_{xy\omega}$	Flexural-torsional buckling load
P_{ω}	Torsional buckling load
Q	Transverse force
Q_i	Shear force at framed column end of i th story
	Gravity load acting on i th story
Q_x, Q_y	Shear forces of thin-walled open section in x and y axes
	Unit shear forces of plate
R	Outer radius at corner of cold-formed section
$\overline{R}$	Wagner effect coefficient due to residual stress distribution $=\int_A \sigma_r \rho^2 dA = \int_A \sigma_r[(x-x_0)^2+(y-y_0)^2]\ dA = \int_A \sigma_r (x^2+y^2) dA$
S	Far end rotation stability function of beam-column
	Parameter of stiffened element with lip of thin-walled cross-section for limit of full section effective, $S=1.28\sqrt{E/\sigma_{max}}$ as defined in NAS AISI 2001 and AS/NZS 4600—2005
	Shear center
	Statical moment about neutral axis
S_1	Modified far end rotation stability function of beam-column with elastically restrained ends
S_{bi}	Translational stiffness induced by unit translation angle at i th story of frame as defined in GB 50017—2014
S_{ω}	Warping statical modulus
T_f	Temperature of fire
T_s	Temperature of steel
U	Strain energy
V	Potential energy of external load
W	Generalized force
	Section modulus
	Work done by external load
W_e	Effective section modulus
W_{px}, W_{py}	Plastic section modulus about x and y axes
W_{xc}	Section modulus corresponding to compression flange
W_{xt}	Section modulus corresponding to tension flange
W_x, W_y	Elastic section modulus about x and y axes

W_{ω}	Warping section modulus
Z	Shape factor
a	Clear distance between transverse stiffeners
	Element length
	Plate dimension
a_{w}	Ratio of two times web area in compression due to application of major axis bending moment alone to area of compression flange components as defined in ANSI/AISC 360—2010
b	Flange width
	Plate dimension
	Section width
b_1	Outstanding width of flange
b_{e}	Effective width of slender compression element
b_{fc}	Width of compression flange
b_{ft}	Width of tension flange
d	Depth of section
	Diameter
	Diameter of web hole
	Flat depth of lip
$\mathrm{d_e}$	Effective flat depth of lip
e	Eccentricity
e_0	Initial eccentricity
e_x, e_y	Eccentricities on major and minor axes
f	Design strength of steel
	Deflection of plate
f_{b}	Allowable stress for flexure
	Design bending stress of beam under uniform bending as defined in BS5950-1—2000
f_{c}	Allowable stress for compression
f_{e}	Effective stress as defined in ANSI/AISC 360—2010
f_0	Initial deflection of plate
f_{p}	Proportional limit stress
f_{u}	Allowable ultimate stress fore shear
f_{v}	Design shear stress of steel, allowable stress for shear
f_{vy}	Yield shear stress
f_{ya}	Average yield strength
f_{yc}	Yield point at corner of cold-formed section
f_{yf}, f_{yw}	Yield stresses of flange and web respectively
h	Depth of cross-section

Depth of web hole

Distance between flange centroids

h_0 Depth of web

h_1 Distance between centroid of cross-section and upper flange

h_2 Distance between centroid of cross-section and lower flange

h_c Twice distance from centroid to inside face of compression flange when welds are used as defined in ANSI/AISC 360—2010

h_e Effective height of slender bending web

h_p Twice distance from plastic neutral axis to inside face of compression flange when welds are used as defined in ANSI/AISC 360—2010

h_{1s}, h_{2s} Distances from shear center of cross-section to upper and lower flanges

k Parameter= $\sqrt{P/EI}$

Spring stiffness under compression

Buckling coefficient of plate

k_0 Buckling coefficient of single plate

k_1 Distribution factor at joint A as defined in BS 5950-1—2000

k_2 Distribution factor at joint B as defined in BS 5950-1—2000

k_c Coefficient for slender unstiffened elements as defined in ANSI/AISC 360—2010

Correction factor on strength reduction factor of beam under non-uniform bending as defined in EN 1993-1-1 EC 3—2005

k_e Elastic buckling coefficient of plate

$k_{E,\theta}$ Reduction factor for slope of linear elastic range at temperature θ_a

$k_{y,\theta}$ Reduction factor for yield strength of steel at steel temperature θ_a reached at time t

$k_{y,\theta,com}$ Reduction factor for yield strength of steel at maximum temperature in compression flange $\theta_{a,com}$ reached at time t

$k_{E,T}$ Elastic modulus reduction factor in fire

k_f Interactive buckling coefficient of flange

k_P Elastic-plastic buckling coefficient of plate

$k_{p,T}$ Proportional limit reduction factor in fire

k_s Buckling coefficient of plate under shear

k_x Translational spring constant, translational stiffness as defined in AS/NZS 4600—2005

k_w Interactive buckling coefficient of web

$k_{y,T}$ Yield stress reduction factor in fire

k_φ Rotational spring constant, rotational stiffness as defined in AS/NZS 4600—2005

l Length of member

l_1	Unsupported length of compression flange
l_b	Length of beam
l_c	Length of column
l_0	Effective length of member
l_p	Limiting laterally unbraced length for limit state of yielding as defined in ANSI/AISC 360—2010
l_r	Limiting laterally unbraced length for limit state of inelastic flexural-torsional buckling as defined in ANSI/AISC 360—2010
l_x, l_y	Effective lengths about x and y axes
l_ω	Effective torsion –buckling length
m	Number of half buckling waves in x direction
n	Number of half buckling waves in y direction
	Number of corners in cold-formed section
	Shape parameter in three-parameter power model connection
o	Origin of coordinates
p	Parameter $= \sin\theta_0 / 2$
p_{crx}, p_{cry}, p_{crxy}	Unit buckling loads of plate
p_x, p_y	Unit middle surface loads in x and y axes
p_{xy}	Unit middle surface shear load of plate
q	Unit distributed load
q_{cr}	Unit distributed critical load
r	Inter radius at corner of cold-formed section
	Rotational spring constant
	Radius of gyration
	Spring stiffness under bending
R_0	Polar radius of gyration $=\sqrt{(I_x+I_y)/A+x_0^2+y_0^2}=\sqrt{r_x^2+r_y^2+x_0^2+y_0^2}$
r_b	Connection secant stiffness determined by beam-line
r_{fe}	Flexural stiffness provided by compression flange in lipped channel
r_{fg}	Geometric stiffness provided by compression flange in lipped channel
r_i	Initial connection stiffness
r_{i0}	Initial connection secant stiffness
r_s	Connection secant stiffness due to service moment M_s of a partially restrained connection
r_t	Connection tangent stiffness
	Radius of gyration of flange components in flexural compression plus one-third of web area in compression due to application of major axis bending moment alone as defined in ANSI/AISC 360—2010

r_{ts}	Effective radius of gyration used in determination of l_r for flexural-torsional buckling limit state for major axis bending of doubly symmetric compact I-shaped members and channels as defined in ANSI/AISC 360—2010
r_{we}	Flexural stiffness provided by web in lipped channel
r_{wg}	Geometric stiffness provided by web in lipped channel
r_x, r_y	Radii of gyration about x and y axes
s	Coordinate along the middle line of thin-walled section
$[r_0]$	Rotational spring constant limitation
t	Thickness of element
	Thickness of thin-walled cross-section
t_1	Compression flange thickness
t_s	Stiffener thickness
t_{fc}	Compression flange thickness as defined in ANSI/AISC 360—2010
t_{ft}	Tension flange thickness
t_w	Web thickness
u	Displacement of shear center in x direction
	Displacement of any point at plate in x direction
u_B	Displacement of point B at cross-section in x direction
u_0	Displacement of any point at middle surface of plate in x direction
v	Displacement of shear center in y direction
v_B	Displacement of point B at cross-section in y direction
v_0	Displacement of any point at middle surface of plate in y direction
	Amplitude of initial deflection
v_s	Displacement of any point at cross-section in tangent direction
w	Displacement of any point at plate in z direction
x_0, y_0	Coordinates of shear center of cross-section
x_i, y_i	Coordinates of an element
y_{max}	Maximum deflection
z_{ei}	Distance between elastic element and y axis
z_i	Distance between element and y axis
Δ	Displacement of unbraced frame
Δ_0	First-order displacement of unbraced frame
Φ	Curvature
Π	Total potential energy
Ω	Arching ratio
Ω_b	Safety factor for compression as defined in ANSI/AISC 360—2010
Ω_c	Safety factor for flexure as defined in ANSI/AISC 360—2010
α	Amplification factor for compression as defined in ANSI/AISC 360—2010
	Aspect ratio of plate

	Imperfection factor
	Modification factor of linear stiffness of beam
	Modification coefficient of plate element in thin-walled cross-section
	Separation ratio for built-up compression members as defined in ANSI/AISC 360—2010
	Strain gradient
	Warping restraint coefficient of thin-walled compression member
α_b	Ratio of moments of inertia for compression flange to cross-section about y axis
α_0	Stress gradient
α_x, α_y	Ratios of normal stresses in x and y directions to equivalent stress respectively
α_{xy}	Ratio of shear stress to equivalent stress in elastic-plastic plate
α_y	Influence factor of steel in unbraced frame as defined in GB 50017—2014
β	Critical moment modification factor of beam considering effect of in-plane deformation on lateral buckling
	Critical moment factor of double-angle section and tee section beams
β_1	Modification factor of critical moment of beam due to type of load
β_2	Modification factor of critical moment of beam due to position of load
β_3	Modification factor of critical moment of mono-symmetric section beam due to position of load
β_b	Equivalent moment factor of lateral-torsional buckling beam
β_m	Equivalent moment factor in plane of beam-column
β_t	Equivalent moment factor out of plane of beam-column
β_x	Unsymmetric section flexural constant $=\dfrac{\int_A x(x^2+y^2)\mathrm{d}A}{2I_y}-x_0$
β_y	Unsymmetric section flexural constant $=\dfrac{\int_A y(x^2+y^2)\mathrm{d}A}{2I_x}-y_0$
β_ω	Unsymmetric section warping constant $=\dfrac{\int_A \omega(x^2+y^2)\mathrm{d}A}{2I_\omega}$
γ	Full reduction factor for slender compression elements
	Reduction factor of flexural stiffness of beam
	Reduction factor of elastic critical moment for non-uniform section beam
	Shear angle in built-up compression members
γ_e	Reduction factor for slender stiffened compression elements
γ_1	Reduction factor for slender unstiffened compression elements
γ_{m0}	Safety factor for design strength of section , equal to 1.0 as defined in EN 1993-1-1 EC3—2005
γ_{m1}	Safety factor for stability design of member, equal to 1.0 as defined in EN