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Design of concrete-filled steel tubular (CFST) hybrid structures

Conception de structures hybrides en tubes d'acier remplis de béton (CFST)

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Foreword

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This document was prepared by Technical Committee ISO/TC 71, *Concrete, reinforced concrete and prestressed concrete*.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Concrete-filled steel tubular (CFST) hybrid structures employ CFST members as their main members, and construct with steel or reinforced concrete members or components to act compositely. They consist of trussed CFST hybrid structures, concrete-encased CFST hybrid structures, etc. The economic and environmental benefits of CFST hybrid structures have made them one of the desirable structural types for constructions in relatively tough and harsh conditions, such as mountainous areas, earthquake-prone regions, corrosive environments, and less-developed regions. They can also be used in conventional structures, such as multi-storey residential buildings and relatively short-span bridges.

Design of concrete-filled steel tubular (CFST) hybrid structures

1 Scope

This document provides guidelines for the design, construction, and inspection of concrete-filled steel tubular (CFST) hybrid structures. These structures can be used as main structural components like columns, girders, piers, or arches in buildings, bridges, especially in high-rise structures, long-span spatial structures, and large-scale bridges.

CFST hybrid structures can employ CFST members with a circular cross-section as their chords, and they can also use square or rectangular CFST chords.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes the requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 19338, *Performance and assessment requirements for design standards on structural concrete*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
concrete-filled steel tubular hybrid structure
CFST hybrid structure
structure in which concrete-filled steel tubular (CFST) members serve as its main members, and are in contact with and act compositely with steel or reinforced concrete members or components, including trussed CFST hybrid structure, concrete-encased CFST hybrid structure, etc.

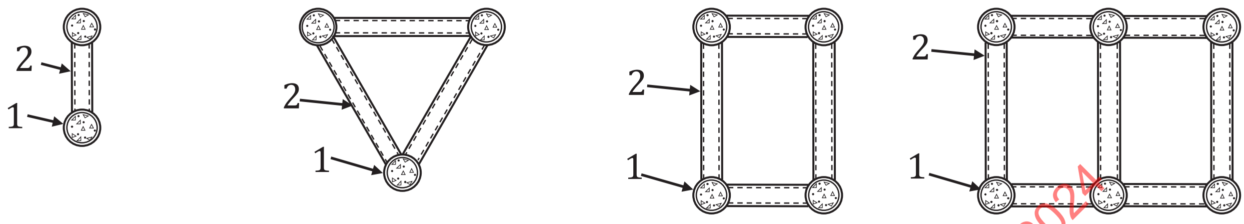
Note 1 to entry: CFST hybrid structures more frequently employ circular CFST members due to the higher confinement effect provided by circular hollow steel tubes to the core concrete; square or rectangular CFST members can also be used when design or construction conditions require. CFST members require full composite effects between steel tubes and the core concrete. Steel tubular members using infilled concrete to only enhance their stiffness are beyond the scope of this document.

3.2
trussed concrete-filled steel tubular (CFST) hybrid structure
trussed CFST hybrid structure
truss structure consisting of CFST chords and webs of steel tubes, CFST members or other steel profiles

Note 1 to entry: There are two-chord, three-chord, four-chord and six-chord trussed CFST hybrid structures (see Figures 1 and 2), and the chords are normally placed symmetrically. Trussed CFST hybrid structures generally serve as main structural members, such as truss girders, bridge piers or columns.

Note 2 to entry: During a typical construction process of cast-in-place trussed CFST hybrid structures, the steel components, such as the hollow steel tubes, are first erected; the core concrete in the chords is then placed (see Figure 3). Prefabricated CFST members can also be used in trussed CFST hybrid structures when construction conditions allow.

Note 3 to entry: For trussed CFST hybrid structure with rectangular CFST members, the CFST chords are generally placed to have the strong axes of their rectangular cross-sections all in parallel with the strong axis of the whole cross-section of the trussed CFST hybrid structure.



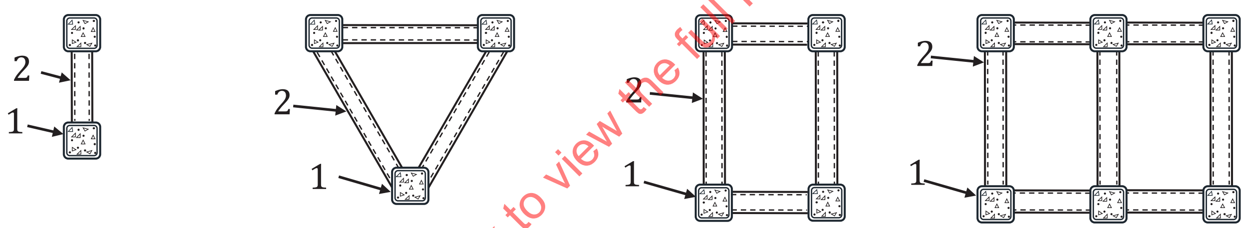
a) Two-chord **b) Three-chord** **c) Four-chord** **d) Six-chord**

Key

1 CFST chords

2 webs

Figure 1 — Cross-sections of trussed CFST hybrid structures with circular CFST members



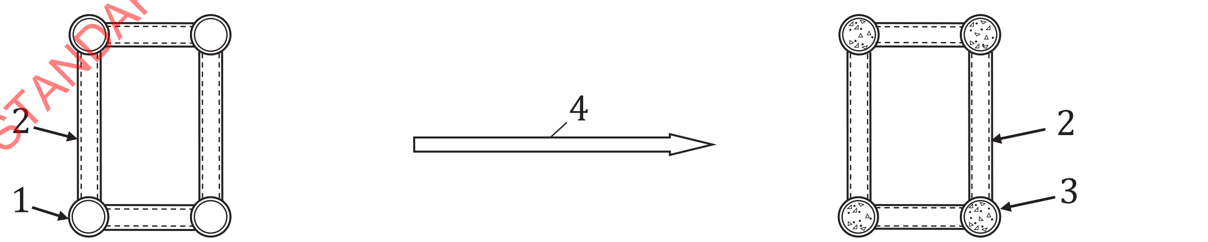
a) Two-chord **b) Three-chord** **c) Four-chord** **d) Six-chord**

Key

1 CFST chords

2 webs

Figure 2 — Cross-sections of trussed CFST hybrid structures with square or rectangular CFST members



a) As hollow steel tubular structure **b) As trussed CFST hybrid structure**

Key

1 hollow steel tubular chords

2 webs

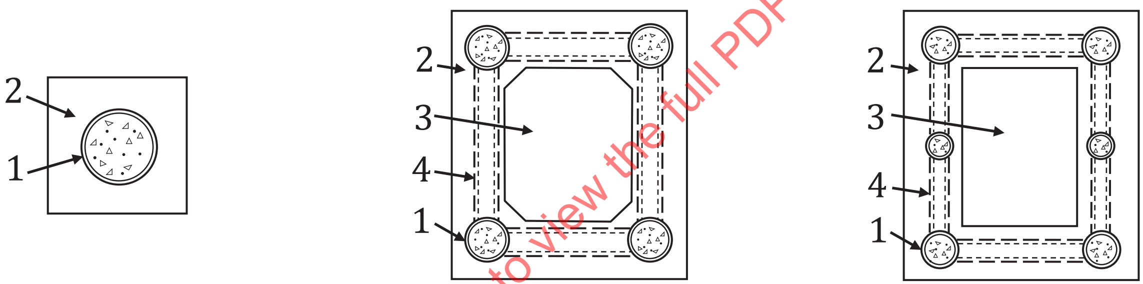
3 CFST chords

4 placement of core concrete in chords

Figure 3 — Typical construction process of a trussed CFST hybrid structure

3.3
concrete-encased concrete-filled steel tubular hybrid structure
concrete-encased concrete-filled steel tubular (CFST) hybrid structure
structure consisting of reinforced concrete encasement and one or more embedded CFST members

Note 1 to entry: The encased CFST member(s) in the concrete-encased CFST hybrid structure can be single or multiple, as shown in Figures 4 and 5, and are normally symmetrically placed. For the single-chord type, the CFST member is placed at the centre of the cross-section with a square or rectangular concrete encasement, forming a solid cross-section. For the multi-chord type, CFST chords are placed at the corners (four-chord type) and also mid-height of the cross-section (six-chord type) of the rectangular concrete encasement; steel tubes, or CFST or other steel profiles are used as webs to connect the CFST chords; to reduce self-weight, an internal hollow section, which is octagonal or rectangular, is generally formed. The multi-chord concrete-encased CFST hybrid structures are a derivation of the trussed CFST hybrid structures, and are generally used as columns, bridge piers, arches, etc.



a) Single-chord, solid cross-section **b) Four-chord, with an internal hollow section** **c) Six-chord, with an internal hollow section**

Key

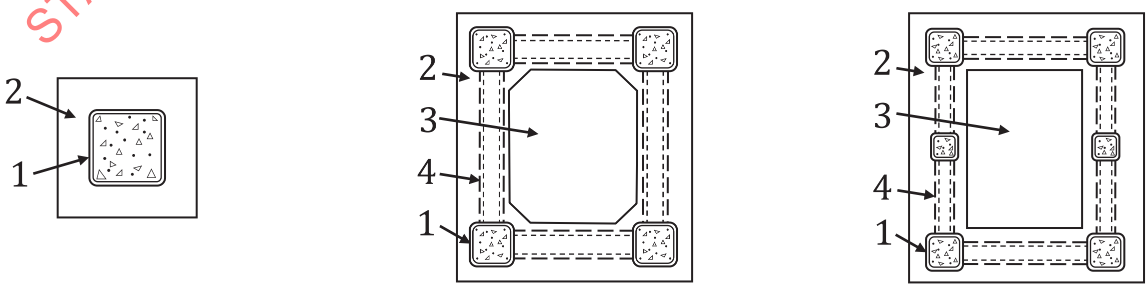
1 CFST members

2 concrete encasement

3 internal hollow section

4 webs

Figure 4 — Cross-sections of concrete-encased CFST hybrid structures with circular CFST members



a) Single-chord, solid cross-section **b) Four-chord, with an internal hollow section** **c) Six-chord, with an internal hollow section**

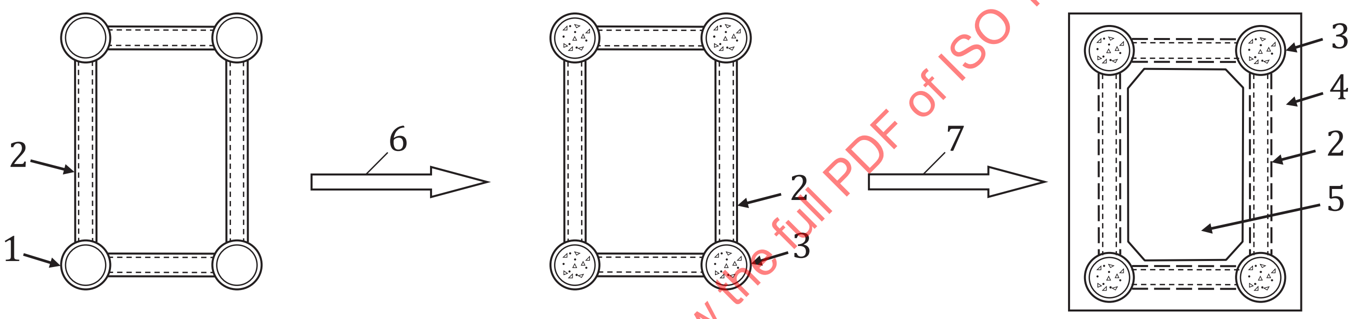
Key

1 CFST members
2 concrete encasement
3 internal hollow section
4 webs

Figure 5 — Cross-sections of concrete-encased CFST hybrid structures with square or rectangular CFST members

Note 2 to entry: A typical construction process for cast-in-place concrete-encased CFST hybrid structure consists of erection of hollow steel tubular chords and webs, placement of core concrete in chords, installation of reinforcement, and placement of concrete encasement, as shown in Figure 6. Prefabricated CFST members can also be used in concrete-encased CFST hybrid structures when construction conditions allow.

Note 3 to entry: For concrete-encased CFST hybrid structure with rectangular CFST members, the CFST chords are generally placed to have the strong axes of their rectangular cross-sections all in parallel with the strong axis of the whole cross-section of the concrete-encased CFST hybrid structure.



a) As hollow steel tubular structure

b) As trussed CFST hybrid structure

c) As concrete-encased CFST hybrid structure

Key

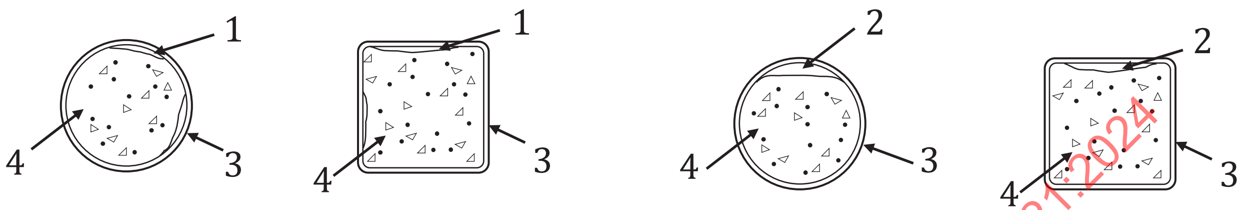
1 hollow steel tubular chords
2 webs
3 CFST chords
4 concrete encasement
5 internal hollow section
6 placement of core concrete in chords
7 placement of concrete encasement

Figure 6 — Typical construction process of a concrete-encased CFST hybrid structure

3.4
limiting value of initial stress in the steel tube
limiting value of the stress level in the steel tube before the steel tube and the core concrete in the CFST member can act together

3.5
limiting value of core concrete void in the steel tube
limiting value of the void ratio of the circumferential void, or the maximum height of the spherical-cap void between the steel tube and its core concrete in the CFST member

Note 1 to entry: The compactness of the core concrete in a CFST member is crucial to ensure that the steel tube and its core concrete act together. However, due to concrete shrinkage and construction issues, circumferential void [see Figure 7 a)] and spherical-cap void [see Figure 7 b)] will possibly develop in the cross-sections of vertical members and horizontal members, respectively. When the void is within a limiting value, its influence on the structural resistance is negligible. Therefore, the concept of limiting value of core concrete void in the steel tube is proposed.



a) Circumferential void **b) Spherical-cap void**

Key
1 circumferential void
2 spherical-cap void
3 steel tube
4 core concrete

Figure 7 — Schematic diagram of core concrete voids in CFST members

3.6
confinement factor
ratio of the nominal compressive strength of cross-section of the steel tube to that of the core concrete in a CFST member

Note 1 to entry: Confinement factor is a representative parameter that reflects the interaction between steel tube and core concrete of the CFST member. Within the parametric ranges in this document, with the increase of the confinement factor, the steel tube provides stronger confinement to its core concrete during loading, and the strength and ductility of the CFST member increases, and vice versa. In other words, the confinement factor represents the degree of composite effects between the steel tube and its core concrete.

3.7
equivalent slenderness ratio
slenderness ratio converted from a trussed CFST hybrid structure to a CFST member when calculating its global stability in axial compression

4 Symbols

The following symbols are used generally throughout the document.

Factored actions, action effects and resistances		
Symbol	**Explanation**	**Unit**
M	factored bending moment	N·mm
M_u	bending resistance	N·mm
N	factored axial force	N
N_0	resistance of cross-section of the CFST hybrid structure to compression	N
N_c	resistance of cross-section of the CFST chord to compression	N

N_{cfst}	resistance of cross-section of the encased CFST member to compression	N
N_{rc}	resistance of cross-section of the concrete encasement to compression	N
N_{t}	resistance of cross-section of the CFST chord to tension	N
N_{u}	resistance of the CFST hybrid structure in axial compression	N
V	factored shear force	N
V_{cfst}	shear resistance of the encased CFST member	N
V_{rc}	shear resistance of the concrete encasement	N
V_{u}	shear resistance of the CFST hybrid structure	N
	Material properties	
Symbol	**Explanation**	**Unit**
E_{c}	modulus of elasticity of concrete	MPa
$E_{c,c}$	modulus of elasticity of the core concrete in the CFST member	MPa
$E_{c,oc}$	modulus of elasticity of the concrete slab or concrete encasement	MPa
E_{s}	modulus of elasticity of steel	MPa
f	design tensile, compressive and flexural strength of steel	MPa
f_{c}	design compressive cylinder strength of concrete	MPa
f_{ck}	characteristic compressive cylinder strength of concrete	MPa
$f_{c,oc}$	design compressive strength of the concrete encasement	MPa
f_{l}	design tensile strength of the longitudinal reinforcement	MPa
f_{sc}	design compressive strength of the CFST cross-section	MPa
f_{scy}	characteristic compressive strength of the CFST cross-section	MPa
f_{sv}	design shear strength of the CFST cross-section	MPa
f_{y}	characteristic yield strength of steel	MPa
f_{yl}	characteristic yield strength of steel reinforcement	MPa
$G_{c,c}$	shear modulus of the core concrete in the CFST member	MPa
$G_{c,oc}$	shear modulus of the concrete slab or concrete encasement	MPa
G_{s}	shear modulus of steel	MPa
	Geometric parameters	
Symbol	**Explanation**	**Unit**
A_{c}	cross-sectional area of the core concrete in the CFST member	mm^2
A_{l}	cross-sectional area of the longitudinal reinforcement	mm^2
A_{oc}	cross-sectional area of the concrete slab or concrete encasement	mm^2
A_{s}	cross-sectional area of the steel tube	mm^2
A_{sc}	cross-sectional area of the CFST member	mm^2
A_{sv}	total cross-sectional area of stirrups	mm^2
A_{v}	cross-sectional area of stirrup-confined concrete	mm^2
b	width of the CFST hybrid cross-section	mm
B	width of the square or rectangular CFST member	mm
d_{r}	mean width of the circumferential void	mm
d_{s}	maximum height of the spherical-cap void	mm
D	outside diameter of the circular CFST member	mm
D_{i}	diameter of the core concrete in the CFST member	mm
h	height of the CFST hybrid cross-section	mm
h_{i}	distance along the cross-sectional height between the centroids of compression and the tension chords	mm

H	height of the rectangular CFST member	mm
I_c	second moment of area of the core concrete in the CFST member	mm^4
I_s	second moment of area of the steel tube	mm^4
l_0	effective length of the structure	mm
l_1	length of a single chord in an interval of the trussed CFST hybrid structure	mm
l_v	length of stirrups	mm
s	spacing of stirrups	mm
t	wall thickness of the steel tube or thickness of the steel plate	mm
u_0	initial deflection	mm
W_{sc}	section modulus of cross-section of the trussed CFST hybrid structure	mm^3
ρ	longitudinal reinforcement ratio	
ρ_v	volumetric stirrup ratio	
Coefficients and others		
Symbol	**Explanation**	**Unit**
c	distance between the neutral axis and the compressive edge of the cross-section	mm
k_{cr}	long-term load coefficient	
n_{cfst}	resistance coefficient of the encased CFST member	
n_L	long-term load ratio	
R	load ratio during fire	
α_1	strength coefficient of the equivalent uniform stress block for concrete encasement	
α_c	strength adjustment coefficient	
α_s	cross-sectional steel ratio of the CFST member	
ε	strain	
ε_{cu}	ultimate compressive strain of concrete at the compressive edge	
γ_m	plastic development factor of the bending resistance	
γ_{msc}	partial factor for the compressive strength of the CFST member	
φ	stability factor for the axial compression structure	
λ	equivalent slenderness ratio	
λ_o	critical slenderness ratio for the elasto-plastic buckling of the structure	
λ_p	critical slenderness ratio for the elastic buckling of the structure	
ξ	confinement factor	
σ	stress	MPa
χ_r	circumferential void ratio	
χ_s	spherical-cap void ratio	

5 Materials

5.1 General

Materials employed in the construction of concrete-filled steel tubular (CFST) hybrid structures should conform to the requirements of relevant ISO standards, such as the ISO 1920 series, or other applicable standards.

5.2 Concrete

5.2.1 Cement

Cement should conform to the requirements of relevant ISO standards, such as ISO 679, ISO 863, and ISO 9597, or other applicable standards.

5.2.2 Aggregates

Aggregates should conform to the requirements of relevant ISO standards, such as ISO 19595 and the ISO 20290 series, or other applicable standards.

5.2.3 Water

Water used in mixing concrete shall be potable, clean and free from injurious amounts of oils, acids, alkalis, salts, organic materials, or other substances deleterious to concrete or reinforcement, and should conform to the requirements of relevant ISO standards, such as ISO 12439, or other applicable standards.

5.2.4 Admixtures

Admixtures used in mixing concrete should conform to the requirements of relevant ISO standards, such as ISO 19596, or other applicable standards.

5.2.5 Additions

Additions used in mixing concrete should conform to the requirements of relevant ISO standards, such as ISO 22904, or other applicable standards.

5.2.6 Concrete mixture specification

The procedure for concrete mixture proportioning should conform to the requirements of relevant ISO standards, such as ISO 22965-1 and ISO 22965-2, or other applicable standards. The characteristic compressive strength (f_{ck}) of the core concrete in CFST members shall not be lower than 24 MPa. For concrete-encased concrete-filled steel tubular (CFST) hybrid structures, the characteristic compressive strength (f_{ck}) of the core concrete in CFST members shall not be lower than that of the concrete encasement, and the characteristic compressive strength (f_{ck}) of the concrete encasement shall not be lower than 24 MPa.

To ensure that the steel tube and its core concrete are complementary to each other and have strong composite effects, the strength class of core concrete should reasonably match the steel grade, as shown in Table 1.

Table 1 — Strength class for core concrete in the steel tube

f_y (MPa)	< 390	390 to 460
f_{ck} (MPa)	24 to 70	41 to 70

5.3 Steel tubes

Carbon structural steel or high strength low alloy structural steel shall be used for the steel tubes in CFST hybrid structures. The characteristic yield strength (f_y) of steel tubes should not be lower than 355 MPa and should not be higher than 460 MPa. The steel material should conform to the requirements of ISO 630-2, or other applicable standards. Cold-formed, welded, hot-finished steel tubes, etc., can be used in CFST hybrid structures. Mechanical properties of steel tubes should conform to the requirements of relevant ISO standards, such as the ISO 10799 series and the ISO 12633 series, or other applicable standards.

5.4 Steel reinforcement

In CFST hybrid structures, longitudinal steel reinforcement shall be deformed reinforcement, and stirrups should be deformed or plain reinforcement. Steel reinforcement should conform to the requirements of relevant ISO standards, such as ISO 10144, or other applicable standards.

5.4.1 Deformed reinforcement

Deformed reinforcement can be used as longitudinal reinforcement or stirrups. The characteristic yield strength (f_{yl}) for deformed reinforcement used in CFST hybrid structures should not be greater than 500 MPa. Deformed reinforcement should conform to the requirements of relevant ISO standards, such as ISO 6935-2, or other applicable standards.

5.4.2 Plain reinforcement

Plain reinforcement should only be used as stirrups. The characteristic yield strength (f_{yl}) for plain reinforcement used in CFST hybrid structures should not be greater than 300 MPa. Plain reinforcement should conform to the requirements of relevant ISO standards, such as ISO 6935-1, or other applicable standards.

5.5 Other materials

5.5.1 Welding consumables

Welding consumables used in the construction of CFST hybrid structures should conform to the requirements of relevant ISO standards, such as ISO 2560, ISO 3580, ISO 14174, ISO 14341, ISO 17632, ISO 17634, ISO 20378, ISO 21952 and ISO 24598, or other applicable standards.

5.5.2 Fasteners

Fasteners used in the connections of CFST hybrid structures should conform to the requirements of relevant ISO standards, such as the ISO 898 series, or other applicable standards.

5.5.3 Protective paint systems

Protective paint systems for CFST hybrid structures should conform to the requirements of relevant ISO standards, such as the ISO 12944 series, or other applicable standards.

5.6 Storage of materials

Cement and aggregates shall be stored in such a manner as to prevent deterioration and intrusion of foreign matter. Any material that has deteriorated or has been contaminated shall not be used for concrete. Steel reinforcement and steel tubes shall be stored in such a manner as to prevent further corrosion of the steel material. Storage of other materials shall conform to the requirements of the corresponding materials and prevent their deterioration.

6 Design and construction procedure

The general design and construction procedure of concrete-filled steel tubular (CFST) hybrid structures is listed in Figure 8 and should include the following contents:

a) preliminary structural design: design of the structural plans, including the structural forms, arrangement of structures, and selection of materials and cross-sections;

b) definition of actions (loads);

c) structural analysis: analysis of actions and their effects;

d) ultimate limit states design: verification of the ultimate limit states of the structures;

e) serviceability limit states design: verification of the serviceability limit states of the structures;

f) protective design: verification of the limit states under corrosion, fire, impact, etc.;

g) detailing design: detailing design of the structures, members, and connections;

h) construction and acceptance: transportation and erection of steel tubes, placement of core concrete and concrete encasement, etc.

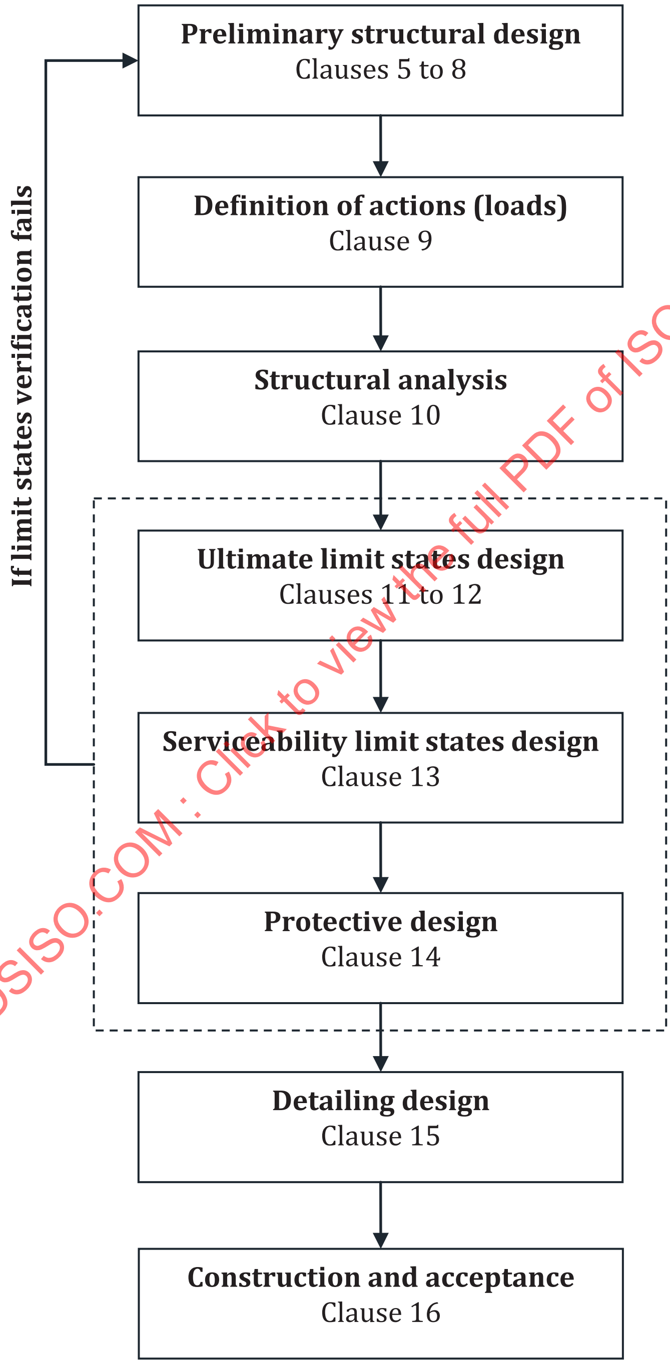


Figure 8 — General design and construction procedure

7 General guides

7.1 Limitations

7.1.1 CFST members

The detailing of concrete-filled steel tubular (CFST) members in concrete-filled steel tubular (CFST) hybrid structures should conform to the following requirements to realize full composite effects between the steel tube and the core concrete. When reliable tests or analyses are available, they can also be used instead.

7.1.1.1 Outside diameter (width/height)

The outside diameter or width/height of the hollow steel tubular cross-section shall not be less than 200 mm. When the outside diameter or width/height is equal to or greater than 2 000 mm, effective measures should be taken to reduce the shrinkage of the core concrete.

7.1.1.2 Wall thickness

The wall thickness of the hollow steel tubular cross-section shall not be less than 4 mm.

7.1.1.3 Outside diameter (width/height)-to-thickness ratio

The outside diameter-to-thickness ratio of the circular hollow steel tubular cross-section shall not be greater than $150\left(\frac{235}{f_\mathrm{y}}\right)$ and should not be less than $25\left(\frac{235}{f_\mathrm{y}}\right)$. The width/height-to-thickness ratio of the square or rectangular hollow steel tubular cross-section shall not be greater than $65\sqrt{\frac{235}{f_\mathrm{y}}}$ and should not be less than $10\sqrt{\frac{235}{f_\mathrm{y}}}$, where f_y is the characteristic yield strength of the steel tube (MPa).

7.1.1.4 Aspect ratio

The aspect ratio of the rectangular hollow steel tubular cross-section (H/B) shall not be greater than 1,5, where H and B are the height and width of the cross-section, respectively.

7.1.1.5 Cross-sectional steel ratio

The cross-sectional steel ratios of CFST members, which shall be calculated in accordance with Formula (1), should not be less than 0,06 and shall not be greater than 0,23 for circular cross-section, and should not be less than 0,10 and shall not be greater than 0,23 for square or rectangular cross-section:

$$\alpha_\mathrm{s} = \frac{A_\mathrm{s}}{A_\mathrm{c}} \tag{1}$$

where

α_s cross-sectional steel ratio;

A_s cross-sectional area of the steel tube (mm^2);

A_c cross-sectional area of the core concrete (mm^2).

7.1.1.6 Confinement factor

The confinement factor of the CFST cross-section, which shall be calculated in accordance with Formula (2), should not be less than 0,6 and shall not be greater than 4,0 for circular cross-section, and should not be less than 1,0 and shall not be greater than 4,0 for square or rectangular cross-section:

$$\xi = \frac{f_y A_s}{\alpha_c f_{ck} A_c} \tag{2}$$

where

f_y characteristic yield strength of steel (MPa);

α_c strength adjustment coefficient, should be determined according to Table 2;

f_{ck} characteristic compressive strength of core concrete (MPa).

Table 2 — Strength adjustment coefficient α_c

f_{ck} (MPa)	24	33	41	51	60	70
α_c	0,84	0,81	0,79	0,75	0,74	0,72

7.1.2 Trussed concrete-filled steel tubular (CFST) hybrid structures

7.1.2.1 Slenderness ratio

The limiting values of slenderness ratios for the chords and webs of trussed concrete-filled steel tubular (CFST) hybrid structures should conform to the requirements of relevant ISO standards, such as ISO 10721-1, or other applicable standards.

7.1.2.2 Limiting value of initial stress in the steel tube

The limiting value of initial stress in the steel tube of a single chord due to the construction loads shall be 35 % of the critical stress value corresponding to the resistance of the hollow steel tube. When the initial stress of the steel tube in CFST member is lower than the limiting value, the influence of construction load on the resistance of the completed structures may be ignored; otherwise, the influence shall be considered.

7.1.3 Concrete-encased concrete-filled steel tubular (CFST) hybrid structures

7.1.3.1 Slenderness ratio

The global slenderness ratios of concrete-encased concrete-filled steel tubular (CFST) hybrid structures should conform to the requirements of relevant ISO standards, such as ISO 15673 and ISO 28842, or other applicable standards and shall not be greater than 60.

7.1.3.2 Outside diameter-to-sectional width ratio

For single-chord concrete-encased circular CFST hybrid structures, the ratio of the outside diameter of the circular CFST member (D) to the width of the cross-section (b), defined as outside diameter-to-sectional width ratio (D/b), should not be less than 0,5 and not be greater than 0,75; and for multiple-chord concrete-encased circular CFST hybrid structures, the outside diameter-to-sectional width ratio (D/b) should not be less than 0,15 and not be greater than 0,25.

7.1.3.3 Limiting value of initial stress in the steel tube

During the construction stage of core concrete placement in the steel tube, the limiting value of initial stress in the steel tube caused by the construction load shall conform to the requirements of 7.1.2.2.

7.1.3.4 Thickness of concrete cover

The thickness of the cover of the concrete encasement should conform to the requirements of relevant structural forms and relevant ISO standards, such as ISO 15673 and ISO 28842, or other applicable standards.

7.1.3.5 Longitudinal reinforcement ratio

The longitudinal reinforcement ratio of the concrete encasement shall be calculated in accordance with Formula (3). It should conform to the requirements of relevant ISO standards, such as ISO 15673 and ISO 28842, or other applicable standards based on the types of structures.

$$\rho = \frac{A_l}{A_{oc}} \tag{3}$$

where

ρ longitudinal reinforcement ratio;

A_l total cross-sectional area of the longitudinal reinforcement (mm^2);

A_{oc} cross-sectional area of the concrete encasement (mm^2).

NOTE Types of structures include but are not limited to buildings, bridges, electric transmission towers, offshore structures, etc.

7.1.3.6 Stirrups

The diameter of the stirrups, the spacing of the stirrups and the volumetric stirrup ratio in the concrete encasement shall conform to the requirements of national concrete structure standards or other applicable standards based on the types of structures. When calculating the stirrup ratios, the cross-sectional area of stirrup-confined concrete should be taken as the cross-sectional area of the concrete encasement within the stirrups.

7.1.3.7 Steel webs

The outside dimensions and layout of steel webs in the concrete-encased CFST hybrid structures shall conform to the requirements of the cover thickness of the concrete encasement.

7.2 Limit states

The following limit states are considered in the design of CFST hybrid structures:

a) ultimate limit state is stipulated in Clauses 11 and 12 for trussed CFST hybrid structures and concrete-encased CFST hybrid structures, respectively;

b) serviceability limit state is stipulated in Clause 13 for CFST hybrid structures;

c) durability limit state for trussed CFST hybrid structures subjected to corrosion is stipulated in 14.2;

d) fire resistance limit state for CFST hybrid structures is stipulated in 14.3;

e) fatigue limit state for trussed CFST hybrid structures is stipulated in 15.5;

f) restorability limit state for CFST hybrid structures shall be verified in accordance with the requirements of ISO 19338.

7.3 Ultimate limit state design format

7.3.1 General

The basic requirement for the ultimate limit state of CFST hybrid structures is presented in Formula (4):

$$E_d \leq R_d \tag{4}$$

where

E_d is the factored load effects;

R_d is the corresponding design resistance.

7.3.2 Factored load effects

The factored load effects should be computed by multiplying the service loads, or forces on CFST hybrid structures using load partial factors and combinations described in Clause 9.

7.3.3 Design resistances

The design resistances of CFST hybrid structures should be determined according to Clauses 11, 12 and 14. The design resistances shall be calculated using the design strength of the materials. The design strength of concrete and steel is obtained by applying a material partial factor, as shown in Formulae (5) to (7).

$$f_c = \frac{f_{ck}}{\gamma_{mc}} \tag{5}$$

$$f = \frac{f_y}{\gamma_{ms}} \tag{6}$$

$$f_l = \frac{f_{yl}}{\gamma_{ml}} \tag{7}$$

where

f_c, f_{ck} is the design and characteristic compressive strength of concrete, respectively;

f, f_y is the design and characteristic yield strength of structural steel, respectively;

f_l, f_{yl} is the design and characteristic yield strength of steel reinforcement, respectively;

γ_{mc}, γ_{ms}, γ_{ml} are the material partial factors for concrete, structural steel and steel reinforcement, respectively.

The material partial factors should be determined based on the types of structures and design situations, and should conform to the requirements of relevant ISO standards, such as ISO 15673, ISO 28842 and ISO 10721-1, or other applicable standards. The values in Table 3 can also be used.

When adopting material partial factors from specified ISO standards, such as ISO 15673, ISO 28842 and ISO 10721-1, or other applicable standards, corresponding load partial factors from the same standards shall be used in the limit state verifications to satisfy the required target reliability.

Table 3 — Partial factors for materials

Concrete	γ_{mc}	1,5
Structural Steel	γ_{ms}	1,15
Steel reinforcement	γ_{ml}	1,15

7.4 Serviceability limit state design format

Serviceability limit states correspond to conditions beyond which specified performance requirements for the structure, or the structural elements, are no longer met. Compliance with the serviceability limit state under these guidelines can be obtained indirectly through the observance of the limiting dimensions, cover, detailing and construction requirements. These serviceability conditions include but are not limited to effects such as the following:

a) dimensional changes due to variations in temperature, relative humidity, and other effects;

b) excessive cracking of the concrete;

c) excessive horizontal deflections;

d) excessive vertical deflections;

e) excessive vibration.

8 Specific guides

8.1 Design working life

The safety classes and design working life of concrete-filled steel tubular (CFST) hybrid structures should conform to the requirements of relevant ISO standards, such as ISO 2394, ISO 13823 and ISO 22111, or other applicable standards. The safety classes of CFST hybrid structures shall not be lower than those of the whole structures.

8.2 Selections of materials, structural plans and detailing

When designing CFST hybrid structures, materials, structural plans and detailing shall be properly chosen so that the resistance, stiffness and stability of structures can satisfy the respective requirements. The requirements for corrosion, fire and impact resistances shall also be satisfied.

8.3 Seismic design requirements

The design requirements of CFST hybrid structures in seismic zones should conform to the requirements of relevant ISO standards, such as ISO 15673, ISO 28842 and ISO 14346, or other applicable standards based on the types of structures.

8.4 Selections of constructional methods and techniques

In the design of CFST hybrid structures, the levels of constructional techniques and constructional conditions shall be taken into account, based on which reasonable construction methods shall be chosen and relevant technical requirements shall be drafted.

9 Actions (loads)

9.1 General

Actions (loads) applied on concrete-filled steel tubular (CFST) hybrid structures shall be defined based on the types of structures. This clause provides the minimum load requirements for the design of CFST hybrid structures. Loads and the appropriate load combinations should be used together.

9.2 Dead loads

Dead loads on CFST hybrid structures consist of the total weight of the structures, calculated as the sum of the weights of all the structural and non-structural elements. For buildings, elements include but are not limited to, walls and partitions, floors, roofs, ceilings, stairways, ramps, finishes, cladding, and other incorporated architectural and structural systems, and fixed service equipment, etc. For bridges, elements include but are not limited to, substructure elements, superstructure elements, deck surface, median permanent or removable structures, sidewalks, railings, and all other elements supported by the bridge like public utility services and ducts.

Calculation of the dead loads should conform to the requirements of relevant ISO standards, such as ISO 9194, or other applicable standards.

9.3 Live loads

Live loads on CFST hybrid structures are loads produced by the use and occupancy of buildings, bridges or other structural types that do not include the construction or environmental loads such as snow loads, wind forces, and earthquake forces. For buildings, live loads include but are not limited to roof live load, floor live load, etc. For bridges, live loads include but are not limited to the traffic loads and the dynamic effect of the live loads shall be considered. Calculation of the live loads should conform to the requirements of relevant ISO standards, such as ISO 15673 and ISO 28842, or other applicable standards.

9.4 Snow loads

When snow loads should be considered in the structural design, the calculation of snow loads should conform to the requirements of relevant ISO standards, such as ISO 4355, or other applicable standards.

9.5 Wind forces

When wind forces should be considered in the structural design, the calculation of wind forces should conform to the requirements of relevant ISO standards, such as ISO 4354, or other applicable standards.

9.6 Earthquake forces

Inertial forces due to earthquakes depend on the mass of the CFST hybrid structures and on the structural response to ground acceleration which, in turn is a function of the seismic hazard and the soil characteristics at the site of the structures.

The requirements of relevant ISO standards, such as ISO 9194, or other applicable standards shall be met when calculating the mass of the materials.

For CFST hybrid structure bridges designed under these guidelines, an equivalent lateral force applied directly to the substructure and superstructure elements can be employed to represent the dynamic response of the structure to the ground acceleration.

Calculation of design seismic forces on CFST hybrid structures should conform to the requirements of relevant ISO standards, such as ISO 3010, or other applicable standards.

9.7 Thermal forces

When CFST hybrid structures are used in bridges, thermal forces due to temperature variation shall be considered. Calculation of the thermal forces should conform to the requirements of relevant ISO standards, such as ISO 28842, or other applicable standards.

9.8 Load partial factors and load combinations

Load partial factors and load combinations for CFST hybrid structures shall be determined based on the types of structures and design situations.

a) The selection of load factors and load combinations should conform to the requirements of relevant ISO standards, such as ISO 2394, ISO 15673, ISO 28842 and ISO 10721-1, or other applicable standards.

   NOTE Generally, the fundamental combination, the accidental action combination or the seismic combination is selected for the ultimate limit state design; the normal combination, the frequent combination, or the quasi-permanent combination is selected for the serviceability limit state design.

b) When adopting load partial factors from specified ISO standards, such as ISO 15673, ISO 28842 and ISO 10721-1, or other applicable standards, corresponding material partial factors from the same standards should be used in the limit state verifications to satisfy the required target reliability.

10 Analysis

10.1 General

10.1.1 Structural analysis purpose

Action effects on concrete-filled steel tubular (CFST) hybrid structures, such as the distribution of internal forces and moments, deformation and vibration, etc., shall be obtained through a global structural analysis. Where necessary, detailed analysis shall be carried out for local areas with particular loading conditions.

10.1.2 Structural analysis methods

Elastic analysis, elasto-plastic analysis or experimental analysis can be chosen for the structural analysis of CFST hybrid structures based on the structural types, material properties and load characteristics.

When using modelling software like commercial finite element software to carry out structural analysis, the results shall be verified to make sure the results are reasonable and valid before applying them to engineering designs.

10.1.3 Structural analysis requirements

Structural analysis shall conform to the following requirements:

a) force equilibrium is achieved;

b) deformation compatibility, including constraints at joints and boundaries, is satisfied;

c) constitutive models for materials presented in 10.2 can be employed for the analysis;

d) where necessary, second-order effects should be considered in the analysis in accordance with the requirements of relevant ISO standards, such as ISO 10721-1 and ISO 22111, or other applicable standards;

e) imperfections, such as residual stresses and geometrical imperfections, should be considered in the analysis according to the requirements of relevant ISO standards, such as ISO 10721-1 and ISO 22111, or other applicable standards;

f) indices for the strength and stiffness in 10.3 can be employed for structural analysis of CFST hybrid structures;

g) analyses shall be conducted for both construction and service stages.

10.1.4 Loading cases

When structures are subjected to various loading conditions during the construction and service stages, structural analysis shall be conducted for each of the loading conditions to determine the most unfavourable load combination. Furthermore, the following requirements shall be satisfied:

a) When the structures are subjected to earthquakes, fire, impact, etc., corresponding analysis shall be conducted.

b) For earthquake analysis, damping ratios for trussed concrete-filled steel tubular (CFST) hybrid structures can be taken as 0,03-0,04; for concrete-encased concrete-filled steel tubular (CFST) hybrid structures, damping ratios can be taken as 0,045-0,05. They can also be determined through structural experiments.

c) Structural analysis for CFST hybrid structures shall consider the static and dynamic effects of wind forces. For special structures, their shape factors should be determined through wind tunnel tests.

d) When the effects of shrinkage and creep of concrete, support settlement, temperature variation, corrosion, etc., are significant enough to endanger the safety or serviceability of the structures, corresponding analysis of the action effects shall be conducted, and corresponding technical arrangements shall be employed to tackle the issue.

e) Structural analysis for the service stage shall consider the influence of internal force and deformation during the construction stage on the structural performance.

10.1.5 Construction stage analysis

For CFST hybrid structures, the following verifications during the main construction stages shall be conducted:

a) the strength, deformation and stability of steel tubes during their fabrication, transportation and erection;

b) the strength, deformation and stability of steel structures during the placement of the core concrete;

c) the strength, deformation and stability of steel and concrete structures during the placement of the concrete encasement of concrete-encased CFST hybrid structures.

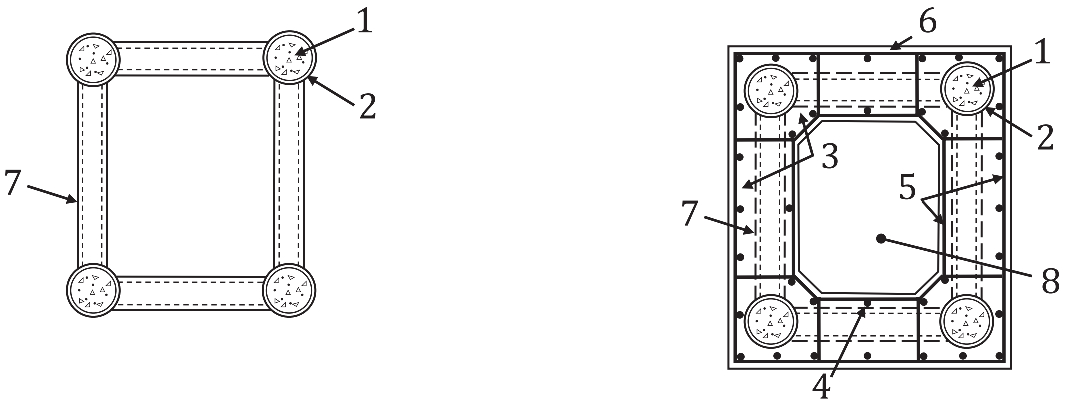
For the structural analysis of the construction stages, all the actual loads and effects during the whole construction, including the installation of machines and materials, steel structures during erection, concrete during placement, installation and dismantling of temporary supporting structures, temperature variation, wind forces, other temporary construction load, etc., shall be considered.

10.2 Stress-strain relationships for materials

10.2.1 General

When analysing CFST hybrid structures, the confinement effect of the steel tubes on its core concrete shall be considered for CFST members. In concrete-encased CFST hybrid structures, concrete encasement consists of unconfined concrete and stirrup-confined concrete, as shown in Figure 9, respectively.

In 10.2, stress-strain relationships for materials in CFST hybrid structures are recommended based on experimental tests. When available, reliable experimental test models, corresponding models from ISO standards, or other available standards can also be used.



a) Trussed CFST hybrid structure **b) Concrete-encased CFST hybrid structure**

Key

1 core concrete
2 steel tubes
3 stirrup-confined concrete encasement
4 longitudinal reinforcement
5 stirrups
6 unconfined concrete encasement
7 webs
8 internal hollow section

Figure 9 — Schematic diagram of components and partition of materials in cross-sections of CFST hybrid structures

10.2.2 Concrete

10.2.2.1 Uniaxial monotonic compressive stress-strain relationship of core concrete

The uniaxial monotonic compressive stress (σ) – strain (ε) relationship of core concrete in CFST members should be determined according to Formulae (8) to (25):

a) For circular CFST members:

$$y = 2x - x^2 \qquad (x \le 1) \tag{8}$$

$$y = \begin{cases} 1 + q\left(x^{0,1\xi} - 1\right) & (\xi \ge 1,12) \\ \dfrac{x}{\beta(x-1)^2 + x} & (\xi < 1,12) \end{cases} \qquad (x > 1) \tag{9}$$

$$x = \frac{\varepsilon}{\varepsilon_0} \tag{10}$$

$$y = \frac{\sigma}{\sigma_0} \tag{11}$$

$$\sigma_0 = \left[1 + \left(-0,054\xi^2 + 0,4\xi\right)\left(\frac{24}{f_{ck}}\right)^{0,45}\right] f_{ck} \tag{12}$$

$$\varepsilon_o = \varepsilon_{cc} + \left[1\,400 + 800\left(\frac{f_{ck}}{24} - 1\right)\right]\xi^{0,2} \quad (13)$$

$$\varepsilon_{cc} = 1\,300 + 12,5 f_{ck} \quad (14)$$

$$q = \frac{\xi^{0,745}}{2+\xi} \quad (15)$$

$$\beta = \left(2,36\times10^{-5}\right)^{\left[0,25+(\xi-0,5)^7\right]} f_{ck}^2 \times 3,51\times10^{-4} \quad (16)$$

where

σ	is the stress (MPa);
ε	is the strain (με);
ξ	is the confinement factor, and shall be calculated by Formula (2);
f_{ck}	is the characteristic compressive strength of concrete (MPa).

b) For square or rectangular CFST members:

$$y = 2x - x^2 \qquad (x \le 1) \quad (17)$$

$$y = \frac{x}{\beta(x-1)^{\eta} + x} \qquad (x > 1) \quad (18)$$

$$x = \frac{\varepsilon}{\varepsilon_o} \quad (19)$$

$$y = \frac{\sigma}{\sigma_o} \quad (20)$$

$$\sigma_o = \left[1 + \left(-0,013\,5\xi^2 + 0,1\xi\right)\left(\frac{24}{f_{ck}}\right)^{0,45}\right] f_{ck} \quad (21)$$

$$\varepsilon_o = \varepsilon_{cc} + \left[1\,330 + 760\left(\frac{f_{ck}}{24} - 1\right)\right]\xi^{0,2} \quad (22)$$

$$\varepsilon_{cc} = 1\,300 + 12,5 f_{ck} \quad (23)$$

$$\eta = 1,6 + \frac{1,5}{x} \quad (24)$$

$$\beta = \begin{cases} \dfrac{(f_{ck})^{0,1}}{1,35\sqrt{1+\xi}} & (\xi \le 3,0) \\ \dfrac{(f_{ck})^{0,1}}{1,35\sqrt{1+\xi}\,(\xi-2)^2} & (\xi > 3,0) \end{cases} \quad (25)$$

where

σ is the stress (MPa);

ε is the strain (με);

ξ is the confinement factor, and shall be calculated by Formula (2);

f_{ck} is the characteristic compressive strength of concrete (MPa).

NOTE Due to the confinement of the steel tube, the peak stress σ_o and peak strain ε_o of the core concrete in a CFST member increases, and the ductility of the core concrete improves. A confinement factor ξ is employed to represent the influence of the confinement effect on the stress-strain relationship of the core concrete. Different degrees of confinement can be provided by circular and square/rectangular hollow steel tubular cross-sections, corresponding forms for σ_o, ε_o and the descending branch are derived for them respectively based on the analysis of a large amount of experimental data of CFST stub columns subject to axial compression. The model is suitable for numerical analysis of CFST hybrid structures, such as fibre-based calculations. More information regarding the model can be found in GB/T 51446-2021[48].

10.2.2.2 Uniaxial monotonic compressive stress-strain relationship of stirrup-confined concrete encasement

The uniaxial monotonic compressive stress (σ) – strain (ε) relationship of stirrup-confined concrete encasement in concrete-encased CFST hybrid structures should be determined according to the Formulae (26) to (32):

$$y=\begin{cases}2x-x^2 & (\varepsilon \le \varepsilon_o) \\ 1-\dfrac{E_{des}}{\sigma_o}(\varepsilon-\varepsilon_o) & (\varepsilon > \varepsilon_o)\end{cases} \tag{26}$$

$$x=\frac{\varepsilon}{\varepsilon_o} \tag{27}$$

$$y=\frac{\sigma}{\sigma_o} \tag{28}$$

$$\sigma_o = f_{ck}\left(1+0{,}73\frac{\rho_v f_{yh}}{f_{ck}}\right) \tag{29}$$

$$\varepsilon_o = 0{,}002\,45+0{,}012\,2\frac{\rho_v f_{yh}}{f_{ck}} \tag{30}$$

$$\rho_v = \frac{A_{sv} l_v}{A_v s} \tag{31}$$

$$E_{des} = \frac{11{,}2 f_{ck}^2}{\rho_v f_{yh}} \tag{32}$$

where

f_{yh} is the characteristic yield strength of stirrups (MPa);

ρ_v is the volumetric stirrup ratio;

f_{ck} is the characteristic compressive strength of concrete encasement (MPa);

A_{sv} is the total cross-sectional area of stirrups (mm^2);

l_v is the length of stirrups (mm);

A_v is the cross-sectional area of stirrup-confined concrete encasement (mm^2), and shall be determined in accordance with 7.1.3.6;

s is the spacing of stirrups (mm).

NOTE The ascending branch of the stress-strain relationship of stirrup-confined concrete encasement is formulated by a second-order parabola, while the descending branch is simplified to be linear. Peak stress σ_o, peak strain ε_o, and the descending rate E_{des} are related to the volumetric stirrup ratio ρ_v of the concrete encasement. Based on experimental and numerical investigations, it has been shown that the calculation methods for σ_o, ε_o, and E_{des}[49] for stirrup-confined concrete can be adopted for the stress-strain curve of stirrup-confined concrete encasement in the concrete-encased CFST hybrid structures.

10.2.2.3 Uniaxial monotonic compressive stress-strain relationship of unconfined concrete encasement

The uniaxial monotonic compressive stress (σ) – strain (ε) relationship of unconfined concrete encasement in concrete-encased CFST hybrid structures should be determined according to Formulae (33) to (43):

$$y=\frac{Ax+Bx^2}{1+Cx+Dx^2} \tag{33}$$

$$x=\frac{\varepsilon}{\varepsilon_o} \tag{34}$$

$$y=\frac{\sigma}{\sigma_o} \tag{35}$$

$$\sigma_o=f_{ck} \tag{36}$$

$$\varepsilon_o=\frac{4{,}26 f_{ck}}{E_c\sqrt[4]{f_{ck}}} \tag{37}$$

$$A=\begin{cases}\dfrac{E_c\varepsilon_o}{f_{ck}} & (\varepsilon\le\varepsilon_o)\\[2ex] \dfrac{f_i(\varepsilon_i-\varepsilon_o)^2}{\varepsilon_i\varepsilon_o(f_{ck}-f_i)} & (\varepsilon>\varepsilon_o)\end{cases} \tag{38}$$

$$B=\begin{cases}\dfrac{(A-1)^2}{0{,}55}-1 & (\varepsilon\le\varepsilon_o)\\[2ex] 0 & (\varepsilon>\varepsilon_o)\end{cases} \tag{39}$$

$$C=A-2 \tag{40}$$

$$D=\begin{cases}B+1 & (\varepsilon \le \varepsilon_o)\\ 1 & (\varepsilon > \varepsilon_o)\end{cases} \tag{41}$$

$$f_i = f_{ck}\left[1{,}41-0{,}17\ln(f_{ck})\right] \tag{42}$$

$$\varepsilon_i = \varepsilon_o\left[2{,}5-0{,}3\ln(f_{ck})\right] \tag{43}$$

where

f_{ck} is the characteristic compressive strength of concrete encasement (MPa);

E_c is the modulus of elasticity of concrete, and shall be determined in accordance with relevant ISO standards, such as ISO 15673, or other applicable standards.

NOTE The compressive stress-strain relationship for unconfined concrete[50] is adopted to describe the unconfined concrete encasement in concrete-encased CFST hybrid structures.

10.2.2.4 Uniaxial monotonic tensile stress-strain relationship of concrete

The uniaxial monotonic tensile stress (σ) – strain (ε) relationship of concrete in CFST hybrid structures should be determined according to Formulae (44) to (48):

$$y=\begin{cases}1{,}2x-0{,}2x^6 & (x\le 1)\\ \dfrac{x}{0{,}31\sigma_p^2(x-1)^{1{,}7}+x} & (x>1)\end{cases} \tag{44}$$

$$x=\frac{\varepsilon}{\varepsilon_p} \tag{45}$$

$$y=\frac{\sigma}{\sigma_p} \tag{46}$$

$$\sigma_p = 0{,}26(1{,}25 f_{ck})^{2/3} \tag{47}$$

$$\varepsilon_p = 43{,}1\sigma_p \tag{48}$$

where

f_{ck} is the characteristic compressive strength of concrete (MPa);

ε_p is the peak uniaxial tensile strain (με);

σ_p is the peak tensile stress (MPa).

10.2.2.5 Uniaxial cyclic compressive stress-strain relationship of concrete

The unloading and reloading paths of uniaxial cyclic compressive stress (σ) – strain (ε) relationship of concrete in CFST hybrid structures, as shown in Figure 10, should be determined according to Formulae (49) to (55):

$$\varepsilon_B = \frac{\sigma_o\varepsilon_A - \sigma_A\varepsilon_1}{\sigma_o+\sigma_A} \tag{49}$$

$$\varepsilon_1 = 0{,}5\varepsilon_o \tag{50}$$

$$\sigma_C = \frac{0{,}75\sigma_o}{0{,}75\varepsilon_1 + \varepsilon_B}(\varepsilon_A - \varepsilon_B) \quad (51)$$

$$\varepsilon_D = \frac{D_1\varepsilon_A - D_2\varepsilon_B - \sigma_c}{D_1 - D_2} \quad (52)$$

$$\sigma_D = D_2(\varepsilon_D - \varepsilon_B) \quad (53)$$

$$D_1 = \frac{3\sigma_o + \sigma_C}{3\varepsilon_1 + \varepsilon_A} \quad (54)$$

$$D_2 = \frac{0{,}2\sigma_o}{0{,}2\varepsilon_1 + \varepsilon_B} \quad (55)$$

where

ε_B is the residual strain when stress is unloaded to zero (με);

σ_C is the stress at point C during reloading (MPa);

ε_D is the strain at point D during unloading (με);

σ_D is the stress at point D during unloading (MPa).

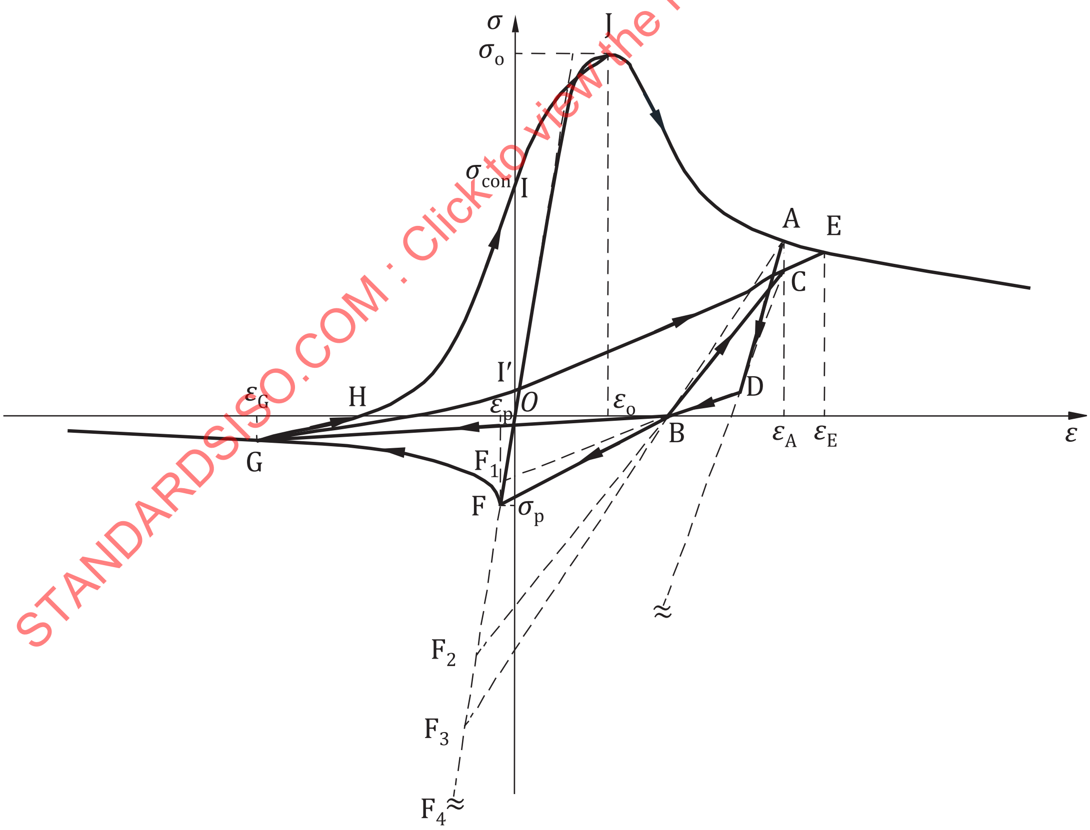


Figure 10 — Schematic diagram of stress-strain hysteretic relationship of concrete

NOTE 1 In the compressive unloading and reloading curves, when compressive strain $\varepsilon \leq 0{,}55\varepsilon_o$, the loading and unloading modulus is the elastic modulus; when $\varepsilon > 0{,}55\varepsilon_o$, the unloading and reloading paths are determined using the "focus point method", where ε_o is the peak strain of the skeleton curve of concrete, and σ_o is the corresponding stress. The stress values of the focus points F_1, F_2, F_3, and F_4 are $0{,}2\sigma_o$, $0{,}75\sigma_o$, σ_o, and $3\sigma_o$, respectively.

NOTE 2 For instance, if the unloading starts from point A on the skeleton curve, and continues through path A-D-B, where B is the intersecting point between line AF_3 and ε axis, C is the point on the extension line of BF_2 where the strain equals to ε_A, D is the intersecting point of CF_4 and the extension line of BF_1, and the residual strain when unloading to $\sigma = 0$ is ε_B. If the unloading exceeds point B and reloading begins, the reloading curve will go through B-C-E, where E is the point on the skeleton curve where the strain is $1{,}15\varepsilon_A$. For the unloading exceeds point B and reloading reversely, when the maximum tensile strain during the loading history $\varepsilon \leq \varepsilon_p$, i.e., the tensile concrete is not cracked, the stress and strain develop through BF, where $F(\varepsilon_p, \sigma_p)$ is the point on the skeleton curve corresponding to the tensile stress; when the maximum tensile strain during the loading history $\varepsilon > \varepsilon_p$, the stress and strain develop through BG, where $G(\varepsilon_G, \sigma_G)$ is the point on the skeleton curve corresponding to the maximum tensile strain.

10.2.2.6 Uniaxial cyclic tensile stress-strain relationship of concrete

The unloading and reloading paths of uniaxial cyclic tensile stress (σ) – strain (ε) relationship of concrete in CFST hybrid structures, as shown in Figure 10, should be determined according to Formulae (56) to (60):

$$\varepsilon_H = \varepsilon_G \left(0{,}1 + \frac{0{,}9\varepsilon_o}{\varepsilon_o + |\varepsilon_G|}\right) \tag{56}$$

$$\sigma_{con} = 0{,}3\sigma_W \left(2 + \frac{|\varepsilon_H|/\varepsilon_o - 4}{|\varepsilon_H|/\varepsilon_o + 2}\right) \tag{57}$$

$$\sigma_w = \begin{cases} \sigma_o & (\varepsilon_h \leq \varepsilon_o\text{, when loading and unloading through G-I-J}) \\ \sigma_A & (\varepsilon_h > \varepsilon_o\text{, when loading and unloading through G-I′-C-E}) \end{cases} \tag{58}$$

$$\sigma = \sigma_{con}\left(1 - \frac{2\varepsilon}{\varepsilon_H + \varepsilon}\right) \quad (\varepsilon_H \leq \varepsilon < 0) \tag{59}$$

$$\sigma = \begin{cases} \sigma_{con}\left(1 - \frac{\varepsilon}{\varepsilon_o}\right) + \frac{2\varepsilon}{\varepsilon_o + \varepsilon}\sigma_o & (0 \leq \varepsilon < \varepsilon_o\text{, when loading and unloading through G-I-J}) \\ \sigma_{con}\left(1 - \frac{\varepsilon}{\varepsilon_A}\right) + \frac{2\varepsilon}{\varepsilon_A + \varepsilon}\sigma_C & (0 \leq \varepsilon < \varepsilon_A\text{, when loading and unloading through G-I′-C-E}) \end{cases} \tag{60}$$

where

ε_H is the strain at point H when effect of cracked surface begins (με);

σ_{con} is the stress at point I or I′ when strain is zero during reloading (MPa);

ε_h is the maximum compressive strain during the loading history (με).

NOTE In the tensile unloading and reloading paths, when the strain at the unloading point $\varepsilon \leq \varepsilon_p$, the unloading modulus is taken as the elastic modulus and then the path goes to reverse reloading; when $\varepsilon > \varepsilon_p$, a curve function is used to describe the unloading and reloading paths. For instance, when the unloading begins at point G in the softening stage, considering the effect of cracked surface, the unloading first follows a straight line to point H, where H is the starting point of the effect of cracked surface. When the maximum compressive strain during the loading history $\varepsilon_h \leq \varepsilon_o$, the unloading and reloading go through G-I-J; when the maximum compressive strain during the loading history $\varepsilon_h > \varepsilon_o$, the unloading and reloading go through G-I′-C-E. If the unloading starts at any point on GI, the unloading path then is the straight line between the unloading point and point G.

10.2.3 Steel

10.2.3.1 Uniaxial monotonic stress-strain relationship of steel

The uniaxial monotonic stress (σ) – strain (ε) relationship of structural steel and steel reinforcement in CFST hybrid structures should be determined according to Formula (61):

$$\sigma = \begin{cases} E_s \varepsilon & (\varepsilon \le \varepsilon_y) \\ f_y + 0{,}01 E_s (\varepsilon - \varepsilon_y) & (\varepsilon > \varepsilon_y) \end{cases} \tag{61}$$

where

E_s is the modulus of elasticity of steel (MPa);

f_y is the characteristic yield strength of steel (MPa);

ε_y is the yield strain of steel.

10.2.3.2 Uniaxial cyclic stress-strain relationship of structural steel

The skeleton curve of the uniaxial cyclic stress (σ) – strain (ε) relationship of structural steel in CFST hybrid structures (see Figure 11) should be determined according to 10.2.3.1, and the modulus of the softening stage should be determined with Formula (62):

$$E_b = \begin{cases} \dfrac{f_y + \sigma_d}{\varepsilon_y + \varepsilon_d} & (1{,}65\varepsilon_y < \varepsilon_d \le 6{,}11\varepsilon_y) \\ 0{,}1 E_s & (\varepsilon_d > 6{,}11\varepsilon_y) \end{cases} \tag{62}$$

where

E_b is the modulus of elasticity of the softening stage de and the corresponding antisymmetric stage d′e′ (MPa);

E_s is the modulus of elasticity of steel (MPa);

σ_d is the stress at point d when the softening stage begins (MPa), point d is on the straight line parallel to ab;

ε_d is the strain at point d when softening stage begins;

ε_y is the yield strain of steel.

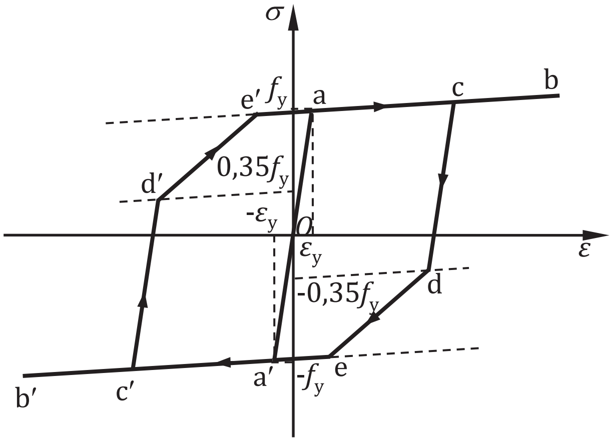


Figure 11 — Schematic diagram of stress-strain hysteretic relationship of structural steel

NOTE When $\varepsilon \leq \varepsilon_y$, the loading or unloading modulus is the elastic modulus E_s; and if steel begins to unload before the hardening stage ab, the Bauschinger effect is not considered. On the contrary, if steel begins to unload in the hardening stage ab, the Bauschinger effect is considered.

10.2.3.3 Uniaxial cyclic stress-strain relationship of steel reinforcement

The skeleton curve of the uniaxial cyclic stress (σ) – strain (ε) relationship of steel reinforcement in CFST hybrid structures (see Figure 12) should be determined according to 10.2.3.1; after the stress is unloaded to zero with the elastic modulus, if the reinforcement does not yield during reloading, then the reloading path should point to the original yield point of the reinforcement; if the reinforcement yields during reloading, then the reloading path should point to the maximum strain point during the loading history.

NOTE If steel reinforcement begins to unload before the hardening stage ab, the Bauschinger effect is not considered and the loading and unloading moduli are taken as the modulus of elasticity E_s; if steel reinforcement begins to unload in the hardening stage ab, the Bauschinger effect is considered and the stress unloads to zero with the modulus of elasticity E_s. In the reloading stage, the curve is a straight line directed at the original yield point (da') or the maximum strain point during the loading history (d'c), and then it keeps loading following the skeleton curve.

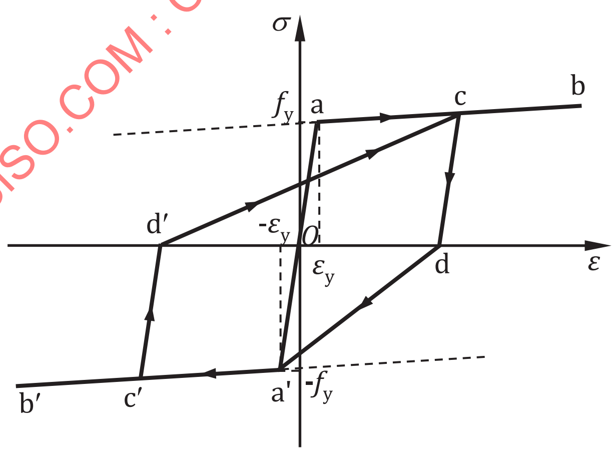


Figure 12 — Schematic diagram of stress-strain hysteretic relationship of steel reinforcement

10.3 Indices for the strength and stiffness of CFST hybrid structures

10.3.1 CFST cross-section

10.3.1.1 Compressive strength

The design compressive strength of CFST cross-section shall be calculated in accordance with Formula (63):

$$f_{sc} = \frac{f_{scy}}{\gamma_{msc}} \tag{63}$$

where

f_{sc} is the design compressive strength of the CFST cross-section (MPa);

f_{scy} is the characteristic compressive strength of the CFST cross-section (MPa);

γ_{msc} is the partial factor for the compressive strength of the CFST member.

The characteristic compressive strength of CFST cross-section should be calculated in accordance with Formula (64):

$$f_{scy} = \begin{cases} (1{,}14+1{,}02\xi)\alpha_c f_{ck} & \text{(For circular cross-section)} \\ (1{,}18+0{,}85\xi)\alpha_c f_{ck} & \text{(For square or rectangular cross-section)} \end{cases} \tag{64}$$

where

ξ is the confinement factor, and shall be calculated by Formula (2);

α_c is the strength adjustment coefficient, and should be determined by Table 2;

f_{ck} is the characteristic compressive strength of concrete (MPa).

NOTE 1 Formula (63) is a nominal strength for the composite CFST cross-section, which is proposed for the convenience of the design. Partial factor γ_{msc} for the compressive strength of CFST cross-section is calculated based on the target reliability index in accordance with the approach stipulated in ISO 2394. The required data include the uncertainty models and parameters of the materials, loads, geometries, and Formula (64), as well as the partial factors for the materials and loads.

NOTE 2 As for the uncertainty model for Formula (64), it shows that the ratio of the measured compressive strength to the predicted strength using Formula (64) can be modelled by Lognormal distribution, based on the statistics of experimental data of more than 1 000 circular CFST stub columns to compression; the mean value and coefficient of variation for the ratio are 1,121 and 0,135, respectively.

NOTE 3 As an example, when the target reliability index, uncertainty models in ISO 2394:2015, Annex E, and the partial factors in ISO 15673 and ISO 28842 are adopted, γ_{msc} is determined to be 1,6 and 1,4 for circular CFST members in buildings and bridges, respectively. When national statistical data regarding the materials, loads, and geometries, as well as the national target reliability index are available, they can be employed to calculate γ_{msc} according to ISO 2394.

10.3.1.2 Shear strength

The design shear strength of CFST cross-section f_{sv} should be calculated according to Formula (65):

$$f_{sv} = \begin{cases} \left(0{,}422+0{,}313\alpha_s^{2{,}33}\right)\xi^{0{,}134} f_{sc} & \text{(For circular cross-section)} \\ \left(0{,}455+0{,}313\alpha_s^{2{,}33}\right)\xi^{0{,}25} f_{sc} & \text{(For square or rectangular cross-section)} \end{cases} \tag{65}$$

where α_s cross-sectional steel ratio, shall be calculated by Formula (1).

10.3.1.3 Elastic compression stiffness and elastic tension stiffness

Elastic compression stiffness and elastic tension stiffness of CFST cross-section should be calculated according to Formulae (66) and (67), respectively:

$$(EA)_c = E_s A_s + E_{c,c} A_c \tag{66}$$

$$(EA)_t = E_s A_s \tag{67}$$

where

$(EA)_c$ is the elastic compression stiffness of the CFST cross-section (N);

$(EA)_t$ is the elastic tension stiffness of the CFST cross-section (N);

E_s is the modulus of elasticity of the steel tube (MPa);

$E_{c,c}$ is the modulus of elasticity of the core concrete (MPa), and shall be determined in accordance with relevant ISO standards, such as ISO 15673, or other applicable standards;

A_s is the cross-sectional area of the steel tube (mm^2);

A_c is the cross-sectional area of the core concrete (mm^2).

10.3.1.4 Elastic flexural stiffness

Elastic flexural stiffness of CFST cross-section should be calculated according to Formula (68):

$$EI = E_s I_s + E_{c,c} I_c \tag{68}$$

where

EI is the elastic flexural stiffness of the CFST cross-section ($N \cdot mm^2$);

I_s is the second moment of area of the steel tube (mm^4);

I_c is the second moment of area of the core concrete (mm^4).

10.3.1.5 Elastic shear stiffness

Elastic shear stiffness of CFST cross-section should be calculated according to Formula (69):

$$GA = G_s A_s + G_{c,c} A_c \tag{69}$$

where

GA is the elastic shear stiffness of the CFST cross-section (N);

G_s is the shear modulus of steel (MPa);

$G_{c,c}$ is the shear modulus of the core concrete (MPa).

10.3.2 CFST hybrid structures

10.3.2.1 Elastic compression stiffness and elastic tension stiffness

Elastic compression stiffness and elastic tension stiffness of CFST hybrid structures should be calculated according to Formulae (70) and (71), respectively:

$$(EA)_{\mathrm{c,h}} = \sum \left(E_{\mathrm{s}} A_{\mathrm{s}} + E_{\mathrm{s},l} A_{l} + E_{\mathrm{c,c}} A_{\mathrm{c}} \right) + E_{\mathrm{c,oc}} A_{\mathrm{oc}} \tag{70}$$

$$(EA)_{\mathrm{t,h}} = \sum \left(E_{\mathrm{s}} A_{\mathrm{s}} + E_{\mathrm{s},l} A_{l} \right) \tag{71}$$

where

$(EA)_{\mathrm{c,h}}$ is the elastic compression stiffness of the CFST cross-section (N);

$(EA)_{\mathrm{t,h}}$ is the elastic tension stiffness of the CFST hybrid structure (N);

E_{s} is the modulus of elasticity of the steel tube (MPa);

$E_{\mathrm{s},l}$ is the modulus of elasticity of the longitudinal steel reinforcement (MPa);

$E_{\mathrm{c,c}}$ is the modulus of elasticity of the core concrete (MPa);

$E_{\mathrm{c,oc}}$ is the modulus of elasticity of the concrete slab or concrete encasement (MPa);

A_{s} is the cross-sectional area of the steel tube (mm^2);

A_{l} is the cross-sectional area of the longitudinal reinforcement (mm^2);

A_{c} is the cross-sectional area of the core concrete (mm^2);

A_{oc} is the cross-sectional area of the concrete slab or concrete encasement (mm^2).

10.3.2.2 Elastic flexural stiffness

Elastic flexural stiffness of CFST hybrid structures should be calculated according to Formula (72):

$$(EI)_{\mathrm{h}} = E_{\mathrm{s}} I_{\mathrm{s,h}} + E_{\mathrm{s},l} I_{l,\mathrm{h}} + E_{\mathrm{c,c}} I_{\mathrm{c,h}} + E_{\mathrm{c,oc}} I_{\mathrm{oc,h}} \tag{72}$$

where

$(EI)_{\mathrm{h}}$ is the elastic flexural stiffness of the CFST hybrid structure (N·mm^2);

$I_{\mathrm{s,h}}$ is the second moment of area of the steel tube to centroidal axis of cross-section of the CFST hybrid structure (mm^4);

$I_{l,\mathrm{h}}$ is the second moment of area of the longitudinal reinforcement to centroidal axis of cross-section of the CFST hybrid structure (mm^4);

$I_{\mathrm{c,h}}$ is the second moment of area of the core concrete to centroidal axis of cross-section of the CFST hybrid structure (mm^4);

$I_{\mathrm{oc,h}}$ is the second moment of area of the concrete slab or concrete encasement to centroidal axis of cross-section of the CFST hybrid structure (mm^4).

10.3.2.3 Elastic shear stiffness

Elastic shear stiffness of CFST hybrid structures should be calculated according to Formula (73):

$$(GA)_h = \sum (G_s A_s + G_{c,c} A_c) + G_{c,oc} A_{oc} \quad (73)$$

where

$(GA)_h$ is the elastic shear stiffness of CFST hybrid structures (N);

$G_{c,c}$ is the shear modulus of the core concrete (MPa);

$G_{c,oc}$ is the shear modulus of the concrete slab or concrete encasement (MPa).

11 Ultimate limit states of trussed concrete-filled steel tubular (CFST) hybrid structures

11.1 General

When verifying the ultimate limit states of trussed concrete-filled steel tubular (CFST) hybrid structures, the resistances of the whole structures as well as the chords and webs shall be calculated. In addition to the simplified methods given in this clause, the resistances of trussed CFST hybrid structures can be determined through a global structural analysis in accordance with Clause 10.

11.2 Resistances to compression and bending

11.2.1 Axial compression

The resistance of trussed CFST hybrid structures with identical chords in axial compression should be calculated based on the summation of the resistances of cross-sections of CFST chords and with the stability factor taking into account. Long-term load effects should be considered when necessary.

a) When the long-term load effects are not considered, the resistance of trussed CFST hybrid structures in axial compression N_u should be calculated in accordance with Formulae (74) to (84):

$$N_u = \varphi \sum N_c \quad (74)$$

$$N_c = f_{sc} A_{sc} \quad (75)$$

$$A_{sc} = A_s + A_c \quad (76)$$

$$\varphi = \begin{cases} 1 & (\lambda \le \lambda_o) \\ a\lambda^2 + b\lambda + c & (\lambda_o < \lambda \le \lambda_p) \\ \dfrac{d}{(\lambda + 35)^2} & (\lambda > \lambda_p) \end{cases} \quad (77)$$

$$a = \frac{1 + (35 + 2\lambda_p - \lambda_o)e}{(\lambda_p - \lambda_o)^2} \quad (78)$$

$$b = e - 2a\lambda_p \quad (79)$$

$$c = 1 - a\lambda_o^2 - b\lambda_o \tag{80}$$

$$d = \begin{cases} \left[13\,000 + 4\,657\ln\left(\frac{235}{f_y}\right)\right]\left(\frac{25}{\alpha_c f_{ck} + 5}\right)^{0,3}\left(\frac{\alpha_s}{0,1}\right)^{0,05} & \text{(For circular cross-section)} \\ \left[13\,500 + 4\,810\ln\left(\frac{235}{f_y}\right)\right]\left(\frac{25}{\alpha_c f_{ck} + 5}\right)^{0,3}\left(\frac{\alpha_s}{0,1}\right)^{0,05} & \text{(For square or rectangular cross-section)} \end{cases} \tag{81}$$

$$e = \frac{-d}{(\lambda_p + 35)^3} \tag{82}$$

$$\lambda_p = \begin{cases} \frac{1\,743}{\sqrt{f_y}} & \text{(For circular cross-section)} \\ \frac{1\,811}{\sqrt{f_y}} & \text{(For square or rectangular cross-section)} \end{cases} \tag{83}$$

$$\lambda_o = \begin{cases} \pi\sqrt{\frac{420\xi + 550}{(1,02\xi + 1,14)\alpha_c f_{ck}}} & \text{(For circular cross-section)} \\ \pi\sqrt{\frac{220\xi + 450}{(0,85\xi + 1,18)\alpha_c f_{ck}}} & \text{(For square or rectangular cross-section)} \end{cases} \tag{84}$$

where

N_c is the resistance of cross-section of a single CFST chord to compression (N);

ΣN_c is the summation of resistances of cross-sections of chords to compression (N);

φ is the stability factor for the axial compression structure (taken as the lesser of the two values for the two principal axes), and shall be calculated by Formula (77) in accordance with the equivalent slenderness ratio of the structure;

f_{sc} is the design compressive strength for CFST cross-section (MPa), and shall be calculated by Formula (63);

f_y is the characteristic yield strength of the steel tube (MPa);

A_{sc} is the cross-sectional area of a single chord (mm^2);

ξ is the confinement factor, and shall be calculated by Formula (2);

λ is the equivalent slenderness ratio of the structure, and should be calculated based on a global structural analysis;

λ_p is the critical slenderness ratio for the elastic buckling of the structure;

λ_o is the critical slenderness ratio for the elasto-plastic buckling of the structure;

f_{ck} is the characteristic compressive strength of concrete (MPa).

b) When the axial compression of a single CFST chord caused by permanent load accounts for 50 % or higher of its total axial compression force, the influence of long-term load on the structural stability shall be considered. When the long-term load effects are taken into account, the resistance of trussed CFST hybrid structures in axial compression $N_{u,cr}$ should be calculated in accordance with Formula (85):

$$N_{u,cr} = k_{cr} N_u \tag{85}$$

where

k_{cr} is the long-term load coefficient, set as 1,0 when k_{cr} is greater than 1,0;

N_u is the resistance of trussed CFST hybrid structure in axial compression (N), and should be calculated by Formula (74);

1) For structures with circular CFST chords, k_{cr} should be calculated in accordance with Formulae (86) to (90):

$$k_{cr} = \begin{cases} \left(0{,}2a^2 - 0{,}4a + 1\right) b^{2{,}5a} k_{nL} & (a \leq 0{,}4) \\ \left(0{,}2a^2 - 0{,}4a + 1\right) b k_{nL} & (0{,}4 < a \leq 1{,}2) \\ 0{,}808 b k_{nL} & (a > 1{,}2) \end{cases} \quad (86)$$

$$a = \frac{\lambda}{100} \quad (87)$$

$$b = \xi^{0{,}05} \quad (88)$$

$$k_{nL} = \begin{cases} 1 - 0{,}07 n_L & (a \leq 0{,}4) \\ 0{,}98 - 0{,}07 n_L + 0{,}05a & (a > 0{,}4) \end{cases} \quad (89)$$

$$n_L = \frac{N_L}{N_u} \quad (90)$$

where

k_{nL} is the adjustment coefficient for long-term load ratio, taken as 1,0 when it is greater than 1,0;

λ is the equivalent slenderness ratio of the structure, and should be calculated based on a global structural analysis;

ξ is the confinement factor, and shall be calculated by Formula (2);

n_L is the long-term load ratio;

N_L is the long-term axial compression (N) in the trussed CFST hybrid structure.

2) For structures with square or rectangular CFST chords, k_{cr} should be calculated in accordance with Formulae (91) to (93):

$$k_{cr} = \begin{cases} (1 - 0{,}25a) b^a k_{nL} & (a \leq 0{,}4) \\ \left(0{,}13a^2 - 0{,}3a + 1\right) b^a k_{nL} & (0{,}4 < a \leq 1{,}2) \\ 0{,}83 b^{1{,}2} k_{nL} & (0{,}4 < a \leq 1{,}2) \end{cases} \quad (91)$$

$$a = \frac{\lambda}{100} \quad (92)$$

$$b = \xi^{0{,}08} \quad (93)$$

where k_{nL} is the adjustment coefficient for long-term load ratio, taken as 1,0 when it is greater than 1,0; calculated by Formula (89).

11.2.2 Bending

11.2.2.1 Basic assumptions

The following assumptions should be made in the calculation of bending resistance of trussed CFST hybrid structures:

a) there is full interaction between chords and webs;

b) when concrete slab is used with the trussed structure, there is full interaction between them;

c) plane section remains plane;

d) direct contribution of the tensile strength of concrete is neglected;

e) direct contribution of webs to the global bending resistance is neglected.

11.2.2.2 Bending resistance

The bending resistance M_u of trussed CFST hybrid structures with identical compression chords should be calculated by assuming both the CFST chords in compression and in tension have reached their ultimate resistances, and in accordance with Formulae (94):

$$M_u = \min\left\{\varphi \sum N_c, \sum N_t\right\} h_i \tag{94}$$

$$N_t = (1{,}1 - 0{,}4\alpha_s) f A_s \tag{95}$$

where

$\varphi \Sigma N_c$ is the summation of resistances of chords in axial compression (N);

ΣN_t is the summation of resistances of cross-sections of chords to tension (N);

N_t is the resistance of cross-section of a single chord to tension (N);

h_i is the distance between the centroids of the compression and the tension chords along the cross-sectional height (mm);

α_s is the cross-sectional steel ratio, and shall be calculated by Formula (1);

f is the design tensile, compressive and flexural strength of the steel tube (MPa);

A_s is the cross-sectional area of the steel tube of a single tension chord (mm^2).

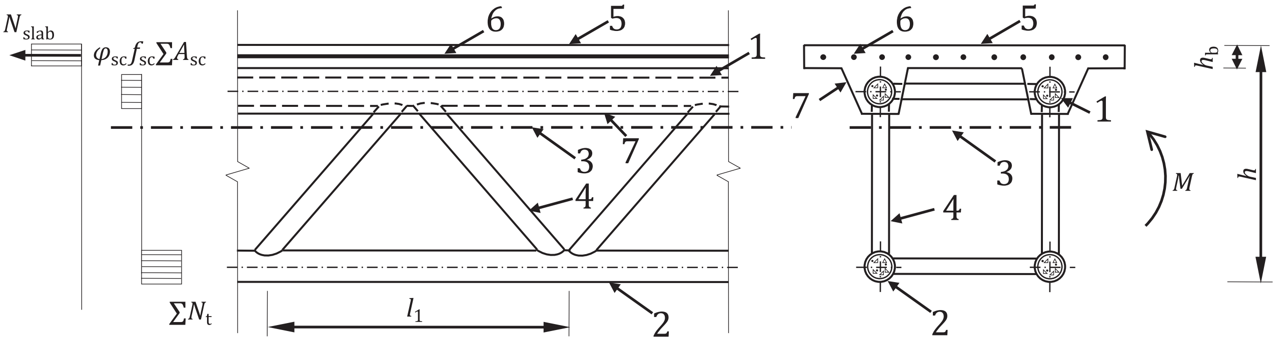
11.2.2.3 Bending resistance when concrete slab is used

The calculation of bending resistance of trussed CFST hybrid structures with a concrete slab and with identical compression chords shall conform to the following requirements:

a) The calculation of the bending resistance of structures in the positive moment zone shall conform to the following requirements:

When the neutral axis of the cross-section is within the height of the webs, the bending resistance of the structures should be calculated in accordance with the stress block and force equilibrium in Figure 13. In the figure, it is assumed both the CFST chords in axial compression and in tension, and the concrete slab in axial compression, have reached their ultimate resistances.

When the neutral axis of the cross-section is within the compression chords, the bending resistance of the structures should be calculated through a global structural analysis.



Key

1	compression chords
2	tension chords
3	neutral axis
4	webs
5	concrete slab
6	steel reinforcement
7	concrete encasement of chords
h_b	thickness of the concrete slab
h	height of the cross-section
l_1	interval length
N_{slab}	resistance of the reinforced concrete slab in axial compression which should be calculated in accordance with the requirements of relevant ISO standards, such as ISO 15673 and ISO 28842, or other applicable standards with the stability of the slab considered
ΣN_t	resistance of CFST chords in axial tension
$\varphi_{sc} f_{sc} \Sigma A_{sc}$	resistance of CFST chords in axial compression, where φ_{sc} is the stability factor for the compression chord and may be calculated in accordance with Formula (77); the effective length should be set as 90 % of the interval length l_1

Figure 13 — Schematic diagram of cross-sections of trussed CFST hybrid structures with a concrete slab

b) The bending resistance of the structures in the negative moment zone should be calculated with the contribution of the steel reinforcement in the slab considered, and may also be calculated in accordance with Formula (94).

11.2.3 Combined compression and bending

When trussed CFST hybrid structures with identical chords are subjected to the combined action of compression and bending, the resistance in combined compression and in-plane bending should conform to Formulae (96) to (102).

a) Obtain the fundamental factors:

$$N_B = \varphi \sum N_c - \sum N_t \tag{96}$$

$$M_B = \varphi \sum N_c r_c + \sum N_t r_t \tag{97}$$

$$r_c = \frac{N_{uc2}}{N_{uc1} + N_{uc2}} h_i \tag{98}$$

$$r_t = \frac{N_{uc1}}{N_{uc1} + N_{uc2}} h_i \tag{99}$$

b) Verify the resistance:

1) When $\frac{M}{N} \le \frac{M_B}{N_B}$

$$\frac{N}{\varphi f_{sc} \sum A_{sc}} + \frac{M}{W_{sc}(1-\varphi N/N_E) f_{sc}} \le 1 \quad (100)$$

$$N_E = \frac{\pi^2 \sum (EA)_c}{\lambda^2} \quad (101)$$

2) When $\frac{M}{N} > \frac{M_B}{N_B}$

$$-N + \frac{M}{r_c(1-N/N_E)} \le (1{,}1-0{,}4\alpha_s) \sum A_s f \quad (102)$$

where

N	is the factored axial force (N);
M	is the factored bending moment (N·mm);
r_c	is the distance between the cross-sectional centre of gravity and the centroidal axis for the chord in compression zone (mm);
r_t	is the distance between the cross-sectional centre of gravity and the centroidal axis for the chord in tension zone (mm);
N_{uc1}, N_{uc2}	is the summation of resistances to compression of chords in compression zone and chords in tension zone of the trussed CFST hybrid structure, respectively (N);
φ	is the stability factor for the axial compression structure, and shall be calculated with the equivalent slenderness ratio of the trussed CFST hybrid structure by Formula (77);
ΣA_{sc}	is the summation of cross-sectional areas of all chords (mm^2);
ΣA_s	is the summation of cross-sectional areas of steel tubes of all chords (mm^2);
N_c	is the resistance of cross-section of a single chord to compression (N);
ΣN_c	is the summation of resistances of cross-section to compression of all compression chords (N);
N_t	is the resistance of cross-section of a single chord to tension (N);
ΣN_t	is the summation of resistances of cross-section to tension of all tension chords (N);
W_{sc}	is the section modulus of cross-section of the structure (mm^3);
f_{sc}	is the design compressive strength of a single CFST chord (MPa), and shall be calculated by Formula (63);
N_E	is the Euler critical force calculated using equivalent slenderness ratio of the structure (N);
$(EA)_c$	is the elastic compression stiffness of cross-section of a single chord (N);
λ	is the equivalent slenderness ratio of the structure, and should be calculated based on a global structural analysis.

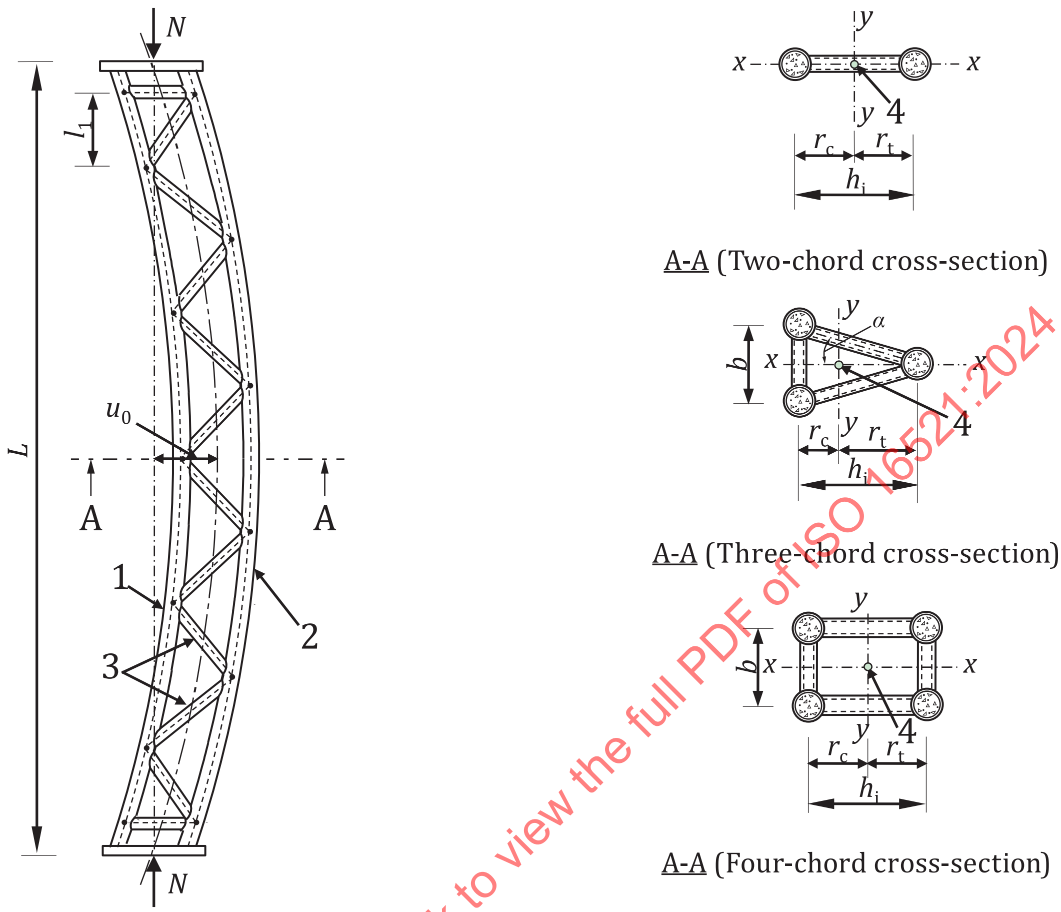
When the equivalent slenderness ratio is greater than 120, the resistance of trussed CFST hybrid structures in combined compression and in-plane bending should also satisfy the inequality in Formula (103):

$$\frac{N}{\varphi f_{sc}\sum A_{sc}}+\frac{M}{r_c\,(1{,}1\text{-}0{,}4\alpha_s)\,f\sum A_s\,(1-N/N_E)}\leq 1 \qquad (103)$$

c) For curved trussed CFST hybrid structures (see Figure 14) in axial compression, the factored bending moment M caused by the initial deflection of structures should be calculated in accordance with Formula (104):

$$M=Nu_0 \qquad (104)$$

where u_0 initial deflection of the curved trussed CFST hybrid structure (mm), defined as the vertical distance between the centroid of the middle section and the connecting line for the centroids of end sections.



Key

1	chords in compression zone
2	chords in tension zone
3	webs
4	cross-sectional centre of gravity
L	distance between the centre points of end cross-sections
u_0	initial deflection
h_i	distance along the cross-sectional height between the centroids of compression and the tension chords
b	distance between the centre points of chords out of the plane of bending moment
l_1	interval length
r_c, r_t	distance between the cross-sectional centre of gravity and centroidal axes for chords in compression zone and tension zone, respectively
α	half of the projection angle of web on the plane of chord cross-section

Figure 14 — Curved trussed CFST hybrid structures

11.2.4 Resistances of CFST chords

11.2.4.1 Internal forces

The internal forces, including the factored axial force and bending moment of CFST chords of curved trussed CFST hybrid structures, should be obtained from a global analysis of the structures in accordance with Clause 10.

11.2.4.2 Axial compression

The resistance of a single CFST chord in axial compression shall satisfy the inequality in Formula (105), and the effective length of chord should conform to the requirements of relevant ISO standards, such as ISO 10721-1, or other applicable standards:

$$N_{cd} \leq \varphi N_c \tag{105}$$

where

N_{cd} is the factored axial compression force (N);

N_c is the resistance of cross-section of a single CFST chord to compression (N), and should be calculated by Formula (75);

φ is the stability factor for the axial compression chord, and shall be calculated by Formula (77).

11.2.4.3 Axial tension

The resistance of a single CFST chord in axial tension shall satisfy the following inequality shown in Formula (106):

$$N_{td} \leq N_t \tag{106}$$

where

N_{td} is the factored axial tension force (N);

N_t is the resistance of cross-section of a single CFST chord in axial tension (N), and should be calculated by Formula (95).

11.2.4.4 Bending

The bending resistance of a single CFST chord shall satisfy the inequality in Formula (107), and should be calculated in accordance with Formulae (108) to (110):

$$M_{cd} \leq M_{cu} \tag{107}$$

$$M_{cu} = \gamma_m W_{sc1} f_{sc} \tag{108}$$

$$\gamma_m = \begin{cases} 1{,}1 + 0{,}48\ln(\xi + 0{,}1) & \text{(For circular cross-section)} \\ 1{,}04 + 0{,}48\ln(\xi + 0{,}1) & \text{(For square or rectangular cross-section)} \end{cases} \tag{109}$$

$$W_{sc1} = \begin{cases} \dfrac{\pi D^3}{32} & \text{(For circular cross-section)} \\ \dfrac{B^3}{6} & \text{(For square cross-section)} \\ \dfrac{BH^2}{6} & \text{(For rectangular cross-section about strong axis)} \end{cases} \tag{110}$$

where

M_{cd} is the factored bending moment of a single chord (N·mm);

M_{cu} is the bending resistance of cross-section of a single chord (N·mm);

γ_m is the plastic development factor of the bending resistance;

ξ is the confinement factor, and shall be calculated by Formula (2);

W_{sc1} is the section modulus of a single chord (mm^3);

f_{sc} is the design compressive strength of a single CFST chord (MPa), and shall be calculated by Formula (63);

D is the outside diameter of the circular CFST chord (mm);

B is the width of the square or rectangular CFST chord (mm);

H is the height of the rectangular CFST chord (mm).

11.2.4.5 Combined compression and in-plane bending

a) The resistance of cross-section of a single CFST chord to combined compression and in-plane bending should be verified in accordance with Formulae (111) to (117):

when $\dfrac{N_{cd}}{N_c} \geq 2\eta_o$:

$$\frac{N_{cd}}{N_c} + \frac{aM_{cd}}{M_{cu}} \leq 1 \tag{111}$$

when $\dfrac{N_{cd}}{N_c} < 2\eta_o$:

$$\frac{-bN_{cd}^2}{N_c^{\,2}} - \frac{cN_{cd}}{N_c} + \frac{M_{cd}}{M_{cu}} \leq 1 \tag{112}$$

$$a = 1 - 2\eta_o \tag{113}$$

$$b = \frac{1 - \varsigma_o}{\eta_o^{\,2}} \tag{114}$$

$$c = \frac{2(\varsigma_o - 1)}{\eta_o} \tag{115}$$

$$\eta_o = \begin{cases} 0{,}1 + 0{,}14\xi^{-0{,}84} & \text{(For circular cross-section)} \\ 0{,}1 + 0{,}13\xi^{-0{,}81} & \text{(For square or rectangular cross-section)} \end{cases} \tag{116}$$

$$\varsigma_o = \begin{cases} 1 + 0{,}18\xi^{-1{,}15} & \text{(For circular cross-section)} \\ 1 + 0{,}14\xi^{-1{,}3} & \text{(For square or rectangular cross-section)} \end{cases} \tag{117}$$

where

N_{cd}	is the factored axial force (N);
M_{cd}	is the factored bending moment (N·mm);
N_c	is the resistance of cross-section of a single CFST chord to compression (N), and should be calculated by Formula (75);
M_{cu}	is the bending resistance of cross-section (N·mm), and should be calculated by Formula (108);
a, b, c, η_o, ς_o	are the coefficients.

b) The resistance of a single CFST chord in combined compression and in-plane bending should be verified in accordance with Formulae (118) to (124):

when $\frac{N_{cd}}{N_c} \geq 2\varphi^3\eta_o$:

$$\frac{N_{cd}}{\varphi N_c} + \frac{a}{d}\frac{M_{cd}}{M_{cu}} \leq 1 \tag{118}$$

when $\frac{N_{cd}}{N_c} < 2\varphi^3\eta_o$:

$$\frac{-bN_{cd}^2}{N_c{}^2} - \frac{cN_{cd}}{N_c} + \frac{1}{d}\frac{M_{cd}}{M_{cu}} \leq 1 \tag{119}$$

$$a = 1 - 2\varphi^2\eta_o \tag{120}$$

$$b = \frac{1 - \varsigma_o}{\varphi^3\eta_o{}^2} \tag{121}$$

$$c = \frac{2(\varsigma_o - 1)}{\eta_o} \tag{122}$$

$$d = \begin{cases} 1 - 0{,}4\left(\dfrac{N_{cd}}{N_{cE}}\right) & \text{(For circular cross-section)} \\ 1 - 0{,}25\left(\dfrac{N_{cd}}{N_{cE}}\right) & \text{(For square or rectangular cross-section)} \end{cases} \tag{123}$$

$$N_{cE} = \frac{\pi^2 (EA)_c}{\lambda_c^2} \tag{124}$$

where

N_{cE} is the Euler critical force of a single chord (N);

$(EA)_c$ is the elastic compression stiffness of the chord cross-section (N), and should be calculated by Formula (66);

λ_c is the equivalent slenderness ratio of the chord, the effective length should be set as 90 % of the interval length;

φ is the in-plane stability factor for the axial compression chord, and should be calculated by Formula (77).

11.2.4.6 Combined tension and in-plane bending

The resistance of a single CFST chord in combined tension and bending should satisfy the following inequality shown in Formula (125):

$$\frac{N_{td}}{(1{,}1-0{,}4\alpha_s)fA_s}+\frac{M_{cd}}{M_{cu}}\leq 1 \quad (125)$$

where

N_{td} is the factored axial tensile force (N);

M_{cd} is the factored bending moment (N·mm);

α_s is the cross-sectional steel ratio, and shall be calculated by Formula (1);

f is the design tensile, compressive and flexural strength of the steel tube (MPa);

A_s is the cross-sectional area of the steel tube (mm^2);

M_{cu} is the bending resistance of cross-section (N·mm).

11.2.4.7 Shear

The shear resistance of a single CFST chord shall satisfy the inequality in Formula (126), and should be calculated in accordance with Formulae (127) and (128):

$$V_{cd}\leq V_{cu} \quad (126)$$

$$V_{cu}=\gamma_v A_{sc} f_{sv} \quad (127)$$

$$\gamma_v=\begin{cases}0{,}97+0{,}2\ln\xi & \text{(For circular cross-section)}\\ 0{,}954+0{,}162\ln\xi & \text{(For square or rectangular cross-section)}\end{cases} \quad (128)$$

where

V_{cd} is the factored shear force of a single chord (N);

V_{cu} is the shear resistance of a single chord (N);

γ_v is the coefficient of shear resistance;

A_{sc} is the cross-sectional area of CFST member (mm^2);

f_{sv} is the design shear strength (MPa), and should be calculated by Formula (65);

ξ is the confinement factor, and shall be calculated by Formula (2).

11.2.4.8 Torsion

The torsional resistance of a single CFST chord shall satisfy the inequality in Formula (129), and should be calculated in accordance with Formulae (130) to (132):

$$T_{cd} \leq T_{cu} \tag{129}$$

$$T_{cu} = \gamma_t W_{sc,t} f_{sv} \tag{130}$$

$$\gamma_t = \begin{cases} 1{,}294 + 0{,}267 \ln\xi & \text{(For circular cross-section)} \\ 1{,}431 + 0{,}242 \ln\xi & \text{(For square cross-section)} \end{cases} \tag{131}$$

$$W_{sc,t} = \begin{cases} \dfrac{\pi D^3}{16} & \text{(For circular cross-section)} \\ 0{,}208 B^3 & \text{(For square cross-section)} \end{cases} \tag{132}$$

where

T_{cd} is the factored torsional moment of a single chord (N·mm);

T_{cu} is the torsional resistance of a single chord (N·mm);

γ_t is the coefficient of torsional resistance;

$W_{sc,t}$ is the torsional modulus of cross-section (mm^3);

D is the outside diameter of the circular CFST chord (mm);

B is the width of the square CFST chord (mm).

11.2.4.9 Combined compression and torsion

The resistance of cross-section of a single CFST chord to combined compression and torsion should satisfy the inequality in Formula (133), and the resistance of the single CFST chord in combined compression and torsion should satisfy the inequality in Formula (134):

$$\left(\frac{N_{cd}}{N_c}\right)^{2,4} + \left(\frac{T_{cd}}{T_{cu}}\right)^2 \leq 1 \tag{133}$$

$$\left(\frac{N_{cd}}{\varphi N_c}\right)^{2,4} + \left(\frac{T_{cd}}{T_{cu}}\right)^2 \leq 1 \tag{134}$$

where

N_c is the resistance of cross-section to compression (N), and should be calculated by Formula (75);

N_{cd} is the factored axial force (N);

φ is the stability factor for the axial compression chord, and shall be calculated by Formula (77).

11.2.4.10 Combined compression, bending and torsion

The resistance of a single CFST chord in combined compression, bending and torsion should be verified in accordance with Formulae (135) to (143):

when $N_{cd} / N_c \geq 2\varphi^3 \eta_o \left[1 - \left(\frac{T_{cd}}{T_{cu}} \right)^2 \right]^{0,417}$:

$$\left(\frac{1}{\varphi} \frac{N_{cd}}{N_c} + \frac{a}{d} \frac{M_{cd}}{M_{cu}} \right)^{2,4} + \left(\frac{T_{cd}}{T_{cu}} \right)^2 \leq 1 \quad (135)$$

when $N_{cd} / N_c < 2\varphi^3 \eta_o \left[1 - \left(\frac{T_{cd}}{T_{cu}} \right)^2 \right]^{0,417}$:

$$\left[-b \left(\frac{N_{cd}}{N_c} \right)^2 - c \left(\frac{N_{cd}}{N_c} \right) + \frac{1}{d} \frac{M_{cd}}{M_{cu}} \right]^{2,4} + \left(\frac{T_{cd}}{T_{cu}} \right)^2 \leq 1 \quad (136)$$

$$a = 1 - 2\varphi^2 \eta_o \quad (137)$$

$$b = \frac{1 - \varsigma_e}{\varphi^3 {\eta_e}^2} \quad (138)$$

$$c = \frac{2(\varsigma_e - 1)}{\eta_e} \quad (139)$$

$$d = \begin{cases} 1 - 0,4 \left(\frac{N_{cd}}{N_{cE}} \right) & \text{(For circular cross-section)} \\ 1 - 0,25 \left(\frac{N_{cd}}{N_{cE}} \right) & \text{(For square or rectangular cross-section)} \end{cases} \quad (140)$$

$$\eta_e = \left(1 - \beta^2 \right)^{0,417} \eta_o \quad (141)$$

$$\varsigma_e = \left(1 - \beta^2 \right)^{0,417} \varsigma_o \quad (142)$$

$$\beta = \frac{T_{cd}}{T_{cu}} \quad (143)$$

where

M_{cd}	is the factored bending moment of a single chord (N·mm);
M_{cu}	is the bending resistance of cross-section of a single chord (N·mm);
η_o	is the coefficient, and shall be calculated by Formula (116);
a, b, c, d, η_e, ς_e, β	are the coefficients;
ς_o	is the coefficient, and shall be calculated by Formula (117);
N_{cE}	is the Euler critical force of a single chord (N), and should be calculated by Formula (124).

11.2.4.11 Combined compression, bending and shear

The resistance of a single CFST chord in combined compression, bending and shear should satisfy the inequalities in Formulae (144) and (145):

when $N_{cd} / N_c \geq 2\varphi^3\eta_o \left[1-\left(\frac{V_{cd}}{V_{cu}}\right)^2\right]^{0,417}$:

$$\left(\frac{1}{\varphi}\frac{N_{cd}}{N_c}+\frac{a}{d}\frac{M_{cd}}{M_{cu}}\right)^{2,4}+\left(\frac{V_{cd}}{V_{cu}}\right)^2 \leq 1 \quad (144)$$

when $N_{cd} / N_c < 2\varphi^3\eta_o \left[1-\left(\frac{V_{cd}}{V_{cu}}\right)^2\right]^{0,417}$:

$$\left[-b\left(\frac{N_{cd}}{N_c}\right)^2-c\left(\frac{N_{cd}}{N_c}\right)+\frac{1}{d}\frac{M_{cd}}{M_{cu}}\right]^{2,4}+\left(\frac{V_{cd}}{V_{cu}}\right)^2 \leq 1 \quad (145)$$

where

V_{cd}	is the factored shear force of a single chord (N);
V_{cu}	is the shear resistance of a single chord (N);
a, b, c, d	are the coefficients, and shall be calculated by Formulae (137) to (140), respectively.

11.2.4.12 Combined compression, bending, torsion and shear

The resistance of a single CFST chord in combined compression, bending, torsion and shear should satisfy the inequalities in Formulae (146) and (147):

when $N_{cd} / N_c \geq 2\varphi^3\eta_o \left[1-\left(\frac{T_{cd}}{T_{cu}}\right)^2-\left(\frac{V_{cd}}{V_{cu}}\right)^2\right]^{0,417}$:

$$\left(\frac{1}{\varphi}\frac{N_{cd}}{N_c}+\frac{a}{d}\frac{M_{cd}}{M_{cu}}\right)^{2,4}+\left(\frac{V_{cd}}{V_{cu}}\right)^2+\left(\frac{T_{cd}}{T_{cu}}\right)^2 \leq 1 \quad (146)$$

when $N_{cd} / N_c < 2\varphi^3\eta_o \left[1-\left(\frac{T_{cd}}{T_{cu}}\right)^2-\left(\frac{V_{cd}}{V_{cu}}\right)^2\right]^{0,417}$:

$$\left[-b\left(\frac{N_{cd}}{N_c}\right)^2-c\left(\frac{N_{cd}}{N_c}\right)+\frac{1}{d}\frac{M_{cd}}{M_{cu}}\right]^{2,4}+\left(\frac{V_{cd}}{V_{cu}}\right)^2+\left(\frac{T_{cd}}{T_{cu}}\right)^2 \leq 1 \quad (147)$$

where

T_{cd}	is the factored torsional moment of a single chord (N·mm);
T_{cu}	is the torsional resistance of a single chord (N·mm);
a, b, c, d	are the coefficients, and shall be calculated by Formulae (137) to (140), respectively.

11.2.5 Resistances of webs

Internal forces of webs of trussed CFST hybrid structures shall be determined through a global structural analysis and the resistances of the steel webs should conform to the requirements of relevant ISO standards, such as ISO 10721-1, or other applicable standards.

11.3 Resistance to shear

11.3.1 With horizontal webs

The shear resistance of trussed CFST hybrid structures with horizontal webs shall be taken as the lesser of the resistances of webs subjected to flexural-shear failure and chords subjected to shear failure. In the case of flexural-shear failure of webs, the calculation of resistance of the webs should conform to the requirements of relevant ISO standards, such as ISO 10721-1, or other applicable standards; in the case of shear failure of chords, the shear resistance of structures may be calculated in accordance with Formula (148):

$$V_u = 0{,}9 \sum V_{cu} \tag{148}$$

where V_{cu} shear resistance of a single CFST chord (N), should be calculated by Formula (127).

11.3.2 With diagonal webs

The shear resistance of trussed CFST hybrid structures with diagonal webs should be controlled by the resistance of the webs in compression. The calculation of the resistance of the webs should conform to the requirements of relevant ISO standards ISO 10721-1, or other applicable standards.

12 Ultimate limit states of concrete-encased concrete-filled steel tubular (CFST) hybrid structures

12.1 General

In this clause, simplified methods for the calculation of resistances of single-chord, four-chord, and six-chord concrete-encased concrete-filled steel tubular (CFST) hybrid structures are given respectively. In addition to the simplified methods, the resistances can be determined through a global structural analysis in accordance with Clause 10.

12.2 Resistances of single-chord structures

12.2.1 Axial compression

The resistance of cross-section of single-chord concrete-encased CFST hybrid structures to compression should be calculated in accordance with Formulae (149) to (151):

$$N_0 = 0{,}9(N_{rc} + N_{cfst}) \tag{149}$$

$$N_{rc} = \alpha_c f_{c,oc} A_{oc} + f_l' A_l \tag{150}$$

$$N_{cfst} = f_{sc} A_{sc} \tag{151}$$

where

N_0 is the resistance of cross-section of the concrete-encased CFST hybrid structure to compression (N);

N_{cfst} is the resistance of cross-section of the encased CFST member to compression (N);

N_{rc} is the resistance of cross-section of the concrete encasement to compression (N);

$f_{c,oc}$ is the design compressive strength of the concrete encasement (MPa);

A_{oc} is the cross-sectional area of the concrete encasement (mm^2);

f_l' is the design compressive strength of the longitudinal reinforcement (MPa);

A_l is the cross-sectional area of the longitudinal reinforcement (mm^2);

f_{sc} is the design compressive strength of the encased CFST cross-section (MPa), and shall be calculated by Formula (63);

A_{sc} is the cross-sectional area of the encased CFST member (mm^2).

12.2.2 Combined compression and bending

12.2.2.1 Basic assumptions

The following assumptions should be made in the calculation of resistance of cross-section of single-chord concrete-encased CFST hybrid structures to combined compression and bending:

a) there is full interaction between encased CFST member and concrete encasement;

b) plane section remains plane;

c) direct contribution of the tensile strength of core concrete in the encased CFST member and concrete encasement is neglected.

12.2.2.2 Verification of resistance — When neutral axis is within the height of the cross-section

When the neutral axis is located within the height of the cross-section, the resistance of cross-section of single-chord concrete-encased CFST hybrid structures to combined compression and bending shall satisfy the inequalities in Formulae (152) and (153):

$$N \leq N'_{rc} + N'_{cfst} \quad (152)$$

$$M \leq M_{rc} + M_{cfst} \quad (153)$$

where

N is the factored axial compression in the cross-section of the concrete-encased CFST hybrid structure (N);

M is the factored bending moment in the cross-section of the concrete-encased CFST hybrid structure (N·mm);

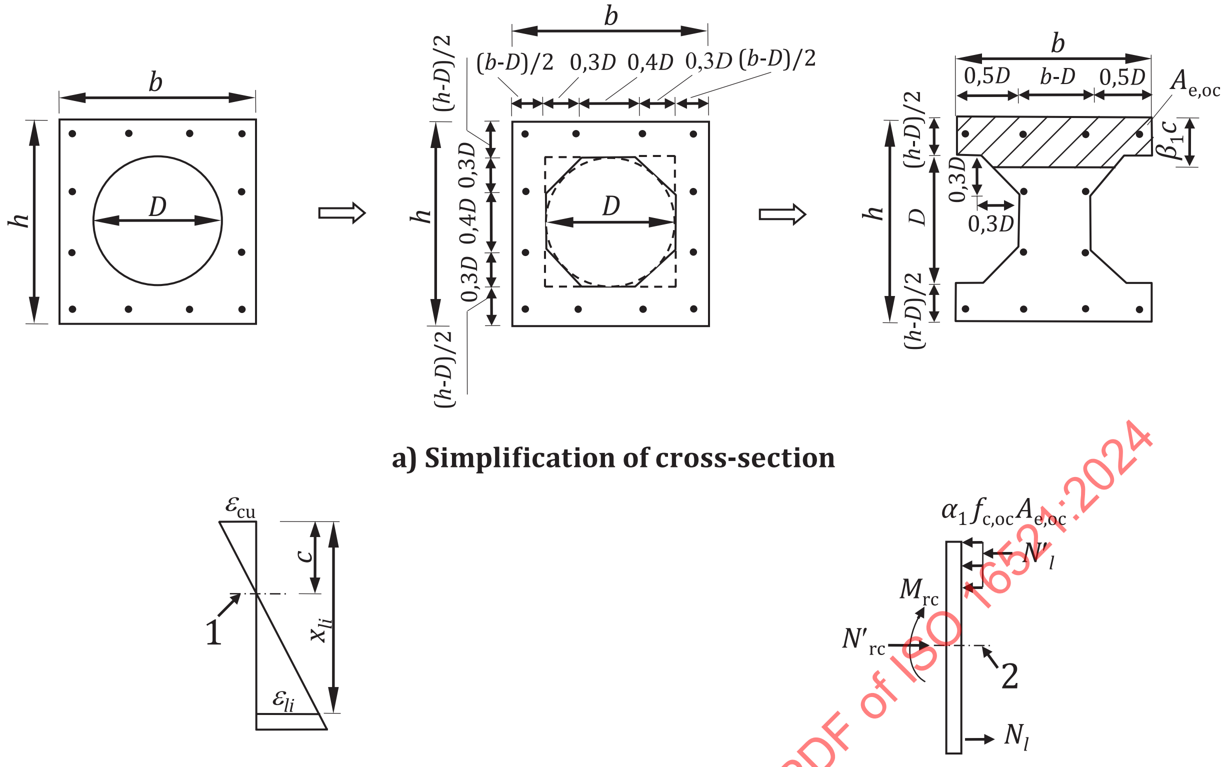
N'_{rc} is the compression resistance of cross-section of the concrete encasement to combined compression and bending (N);

M_{rc} is the bending resistance of cross-section of the concrete encasement to combined compression and bending (N·mm);

N'_{cfst} is the compression resistance of cross-section of the encased CFST member to combined compression and bending (N);

M_{cfst} is the bending resistance of cross-section of the encased CFST member to combined compression and bending (N·mm).

a) The resistance of cross-section of the concrete encasement of single-chord concrete-encased CFST hybrid structures to compression and the corresponding bending resistance should be calculated in accordance with the strain distribution and force equilibrium shown in Figure 15. For structures with circular CFST members, the cross-section can be simplified in accordance with Figure 15 a):



a) Simplification of cross-section

b) Strain distribution

c) Force equilibrium

Key

1	neutral axis
2	centroidal axis
b	cross-sectional width
h	cross-sectional height
D	diameter of the encased circular CFST member
c	distance between the neutral axis and the compressive edge of the cross-section
$A_{e,oc}$	area of equivalent uniform stress block of concrete encasement (mm^2), the height of which is $\beta_1 c$, β_1 is the height coefficient, set as 0,80 for concrete with f_{ck} not higher than 41 MPa, 0,74 for f_{ck} as 70 MPa, calculated by linear interpolation for concrete in-between; or can be taken from relevant ISO standards, such as ISO 15673 and ISO 28842, or other applicable standards
ε_{li}	strain of the ith longitudinal reinforcement
ε_{cu}	ultimate compressive strain of concrete
α_1	strength coefficient of the equivalent uniform stress block for concrete encasement, set as 1,0 for concrete with f_{ck} not higher than 41 MPa, 0,94 for f_{ck} as 70 MPa, calculated by linear interpolation for concrete in-between; or can be taken from relevant ISO standards, such as ISO 15673 and ISO 28842, or other applicable standards
$f_{c,oc}$	design compressive strength of concrete encasement
N_l	axial force of longitudinal reinforcement in tension zone, should be calculated in accordance with ε_{li} and the stress-strain relationship in 10.2.3.1
N'_l	axial force of longitudinal reinforcement in compression zone, should be calculated in accordance with ε_{li} and the stress-strain relationship in 10.2.3.1
x_{li}	distance between the ith longitudinal reinforcement and the compressive edge of the cross-section (mm)

Figure 15 — Resistance calculation of cross-section of the concrete encasement

b) The resistance of cross-section of the encased CFST member in single-chord concrete-encased CFST hybrid structures to compression N'_{CFST} and the corresponding bending resistance M_{CFST} should be calculated in accordance with Formulae (154) and (155), respectively:

$$N'_{\text{cfst}} = N'_{\text{c}} + N'_{\text{s}} \tag{154}$$

$$M_{\text{cfst}} = M_{\text{c}} + M_{\text{s}} \tag{155}$$

where

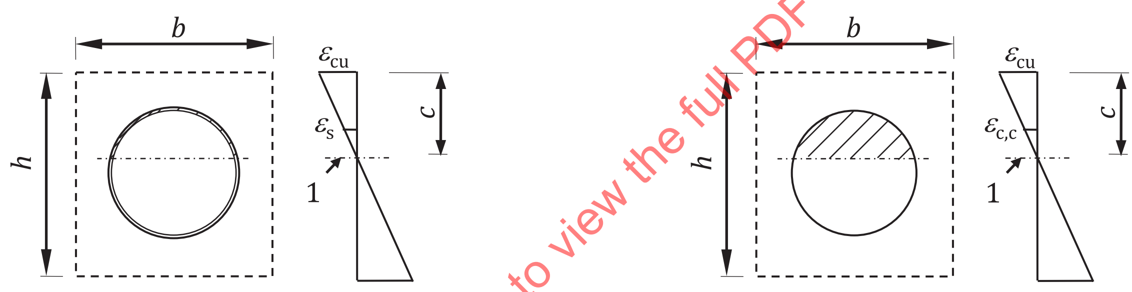
N'_c is the compression resistance of cross-section of the core concrete in the CFST member to combined compression and bending (N);

M_c is the bending resistance of cross-section of the core concrete in the CFST member to combined compression and bending (N·mm);

N'_s is the compression resistance of cross-section of the steel tube in the CFST member to combined compression and bending (N);

M_s is the bending resistance of cross-section of the steel tube in the CFST member to combined compression and bending (N·mm).

The compression and bending resistances of the steel tube and concrete should be calculated in accordance with the strain distribution shown in Figure 16 and the stress-strain relationships of the steel tube and core concrete in 10.2.3.1 and 10.2.2.1, respectively.



a) Steel tube　　　b) Core concrete

Key

1 neutral axis

ε_s strain of the steel tube, which can be circular, square, or rectangular

$\varepsilon_{c,c}$ strain of the core concrete

ε_{cu} ultimate compressive strain of concrete

Figure 16 — Resistance calculation of cross-section of the encased CFST member

12.2.2.3 Verification of resistance — When neutral axis is beyond the height of the cross-section

When the neutral axis is located beyond the cross-sectional height, the bending resistance of cross-section of single-chord concrete-encased CFST hybrid structures to combined compression and bending $M_{u,N}$ should be calculated in accordance with Formula (156):

$$M_{\text{u,N}} = \frac{N_0 - N}{N_0 - N_{\text{u,h}}} M_{\text{u,h}} \tag{156}$$

where

$N_{u,h}$ is the compression resistance of cross-section (N) when the distance c between the neutral axis and the compressive edge is equal to the cross-sectional height h, and should be calculated in accordance with 12.2.2.2;

$M_{u,h}$ is the bending resistance of cross-section (N·mm) when the distance c between the neutral axis and the compressive edge is equal to the cross-sectional height h, and should be calculated in accordance with 12.2.2.2;

N_0 is the resistance of cross-section to compression (N), and should be calculated by Formula (149).

NOTE The *N*-*M* relationship of single-chord concrete-encased CFST hybrid structures is shown in Figure 17. When $c = h$, the neutral axis is at the edge of the cross-section. When $c < h$, the compression and bending resistances can be calculated in accordance with 12.2.2.2. When $c > h$, to simplify the calculation, the segment in the *N*-*M* relationship is assumed as a straight line.

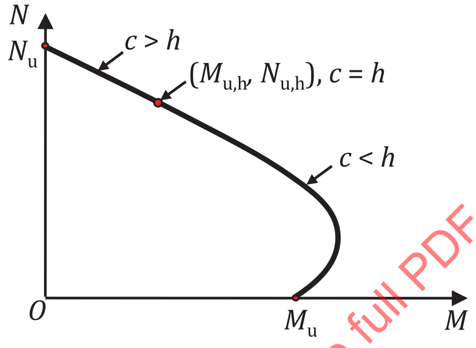


Figure 17 — *N*-*M* relationship

12.2.3 Tension

The resistance of cross-section of single-chord concrete-encased CFST hybrid structures to tension shall satisfy the inequality in Formula (157) and should be calculated in accordance with Formulae (158) and (159):

$$N \leq N_{rc,t} + N_{cfst,t} \quad (157)$$

$$N_{rc,t} = f_l A_l \quad (158)$$

$$N_{cfst,t} = (1,1\text{-}0,4\alpha_s) A_s f \quad (159)$$

where

N is the factored axial tension in the cross-section of the concrete-encased CFST hybrid structure (N);

$N_{rc,t}$ is the resistance of cross-section of the concrete encasement to tension (N);

$N_{cfst,t}$ is the resistance of cross-section of the encased CFST member to tension (N);

A_l is the cross-sectional area of the longitudinal reinforcement (mm^2);

A_s is the cross-sectional area of the steel tube (mm^2);

α_s is the cross-sectional steel ratio of the CFST member, and shall be calculated by Formula (1);

f_l is the design tensile strength of the longitudinal reinforcement (MPa);

f is the design tensile strength of the steel tube (MPa).

12.3 Resistances of four-chord structures

12.3.1 Axial compression

The resistance of cross-section of four-chord concrete-encased CFST hybrid structures to compression should be calculated in accordance with Formulae (160) to (162):

$$N_0 = 0{,}9(N_{rc} + N_{cfst}) \tag{160}$$

$$N_{rc} = \alpha_c f_{c,oc} A_{oc} + f_l{}' A_l \tag{161}$$

$$N_{cfst} = \sum f_{sc,i} A_{sc,i} \tag{162}$$

where

N_0 is the resistance of cross-section to compression (N);

N_{rc} is the resistance of concrete encasement to compression (N);

N_{cfst} is the resistance of cross-sections of encased CFST members to compression (N);

$f_{c,oc}$ is the design compressive strength of the concrete encasement (MPa);

A_{oc} is the cross-sectional area of the concrete encasement (mm^2);

$f_l{}'$ is the design compressive strength of the longitudinal reinforcement (MPa);

A_l is the cross-sectional area of the longitudinal reinforcement (mm^2);

$f_{sc,i}$ is the design compressive strength of cross-section of the ith CFST member (MPa), and shall be calculated by Formula (63);

$A_{sc,i}$ is the cross-sectional area of the ith CFST member (mm^2).

12.3.2 Combined compression and bending

12.3.2.1 Basic assumptions

The assumptions in 12.2.2.1 should be made in the calculation of resistance of cross-section of four-chord concrete-encased CFST hybrid structures to combined compression and bending.

12.3.2.2 Verification of resistance — When neutral axis is within the height of the cross-section

When the neutral axis is located within the height of the cross-section, the resistance of cross-section of four-chord concrete-encased CFST hybrid structures to combined compression and bending shall satisfy the following inequalities shown in Formulae (163) and (164):

$$N \le N'_{rc} + N'_{cfst} \tag{163}$$

$$M \le M_{rc} + M_{cfst} \tag{164}$$

where

N is the factored axial compression in the cross-section of the concrete-encased CFST hybrid structure (N);

M is the factored bending moment in the cross-section of the concrete-encased CFST hybrid structure (N·mm);

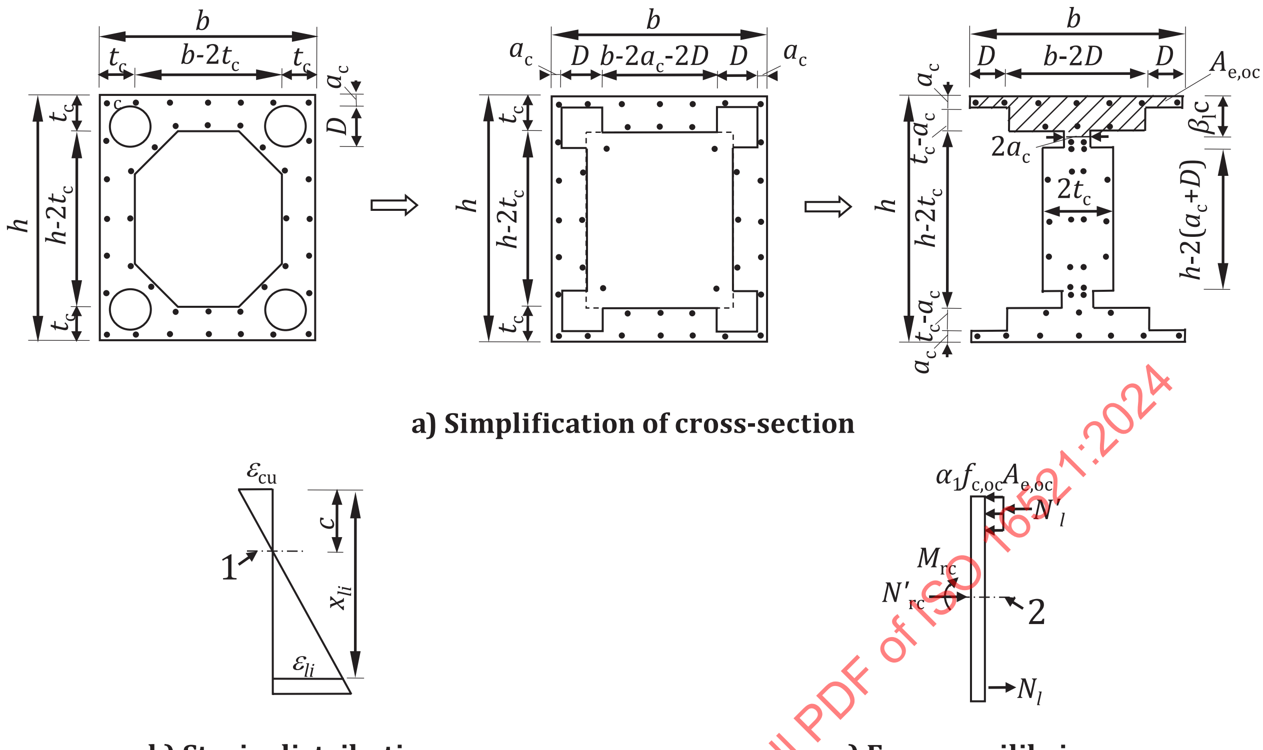
N'_{rc} is the compression resistance of cross-section of the concrete encasement to combined compression and bending (N);

N'_{cfst} is the compression resistance of cross-sections of encased CFST members to combined compression and bending (N);

M_{rc} is the bending resistance of cross-section of the concrete encasement to combined compression and bending (N·mm);

M_{cfst} is the bending resistance of cross-sections of encased CFST members to combined compression and bending (N·mm).

a) The resistance of cross-section of the concrete encasement in four-chord concrete-encased CFST hybrid structures to compression and the corresponding bending resistance should be calculated in accordance with the strain distribution and force equilibrium shown in Figure 18. For structures with circular CFST members, the cross-section can be simplified in accordance with Figure 18 a):



a) Simplification of cross-section

b) Strain distribution

c) Force equilibrium

Key

1	neutral axis
2	centroidal axis
b	cross-sectional width
h	cross-sectional height
D	diameter of the encased CFST members
t_c	distance between the edge of the internal hollow section and the outside edge of the concrete encasement
a_c	distance between the outside edge of the steel tube and the outside edge of the concrete encasement
c	distance between the neutral axis and the compressive edge of the cross-section
$A_{e,oc}$	area of equivalent uniform stress block of concrete encasement (mm^2), the height of which is $\beta_1 c$, β_1 is the height coefficient, set as 0,80 for concrete with f_{ck} not higher than 41 MPa, 0,74 for f_{ck} as 70 MPa, calculated by linear interpolation for concrete in-between; or can be taken from relevant ISO standards, such as ISO 15673 and ISO 28842, or other applicable standards
ε_{li}	strain of the ith longitudinal reinforcement
ε_{cu}	ultimate compressive strain of concrete
α_1	strength coefficient of the equivalent uniform stress block for concrete encasement, set as 1,0 for concrete with f_{ck} not higher than 41 MPa, 0,94 for f_{ck} as 70 MPa, calculated by linear interpolation for concrete in-between; or can be taken from relevant ISO standards, such as ISO 15673 and ISO 28842, or other applicable standards
$f_{c,oc}$	design compressive strength of concrete encasement
N_l	axial force of longitudinal reinforcement in tension zone, should be calculated in accordance with ε_{li} and the stress-strain relationship in 10.2.3.1
N'_l	axial force of longitudinal reinforcement in compression zone, should be calculated in accordance with ε_{li} and the stress-strain relationship in 10.2.3.1
x_{li}	distance between the ith longitudinal reinforcement and the compressive edge of the cross-section (mm)

Figure 18 — Resistance calculation of cross-section of the concrete encasement

b) The resistance of cross-sections of the encased CFST members in four-chord concrete-encased CFST hybrid structures to compression and the corresponding bending resistance should be calculated in accordance with Formulae (165) and (166), respectively:

$$N'_{\mathrm{cfst}} = N'_{\mathrm{c}} + N'_{\mathrm{s}} \tag{165}$$

$$M_{\mathrm{cfst}} = M_{\mathrm{c}} + M_{\mathrm{s}} \tag{166}$$

where

N'_{cfst} is the compression resistance of cross-sections of encased CFST members to combined compression and bending (N);

M_{cfst} is the bending resistance of cross-sections of encased CFST members to combined compression and bending (N·mm);

N'_{c} is the compression resistance of cross-sections of the core concrete to combined compression and bending (N);

N'_{s} is the compression resistance of cross-sections of steel tubes to combined compression and bending (N);

M_{c} is the bending resistance of the core concrete to combined compression and bending (N·mm);

M_{s} is the bending resistance of steel tubes to combined compression and bending (N·mm).

The compression and bending resistances of the steel tube and concrete should be calculated in accordance with the strain distribution shown in Figure 19 and the stress-strain relationships of the steel tube and core concrete in 10.2.3.1 and 10.2.2.1, respectively.

a) Steel tube   b) Core concrete

Key

1 neutral axis

c distance between the neutral axis and the compressive edge of the cross-section

$\varepsilon_{\mathrm{s1}}$, $\varepsilon_{\mathrm{s2}}$ strain of the steel tubes, which can be circular, square or rectangular

$\varepsilon_{\mathrm{c,c}}$ strain of the core concrete

$\varepsilon_{\mathrm{cu}}$ ultimate compressive strain of concrete

Figure 19 — Resistance calculation of cross-sections of the encased CFST members

12.3.2.3 Verification of resistance – when neutral axis is beyond the height of the cross-section

When the neutral axis is located beyond the height of the cross-section, the bending resistance of cross-section of four-chord concrete-encased CFST hybrid structures to combined compression and bending $M_{u,N}$ should be calculated in accordance with Formula (167):

$$M_{u,N} = \frac{N_0 - N}{N_0 - N_{u,h}} M_{u,h} \tag{167}$$

where

- $N_{u,h}$ is the compression resistance of cross-section to combined compression and bending (N) calculated in accordance with 12.3.2.2 when the distance c between the neutral axis and the compressive edge is equal to the sectional height h;
- $M_{u,h}$ is the bending resistance (N·mm) calculated in accordance with 12.3.2.2 when the distance c between the neutral axis and the compressive edge is equal to the sectional height h;
- $M_{u,N}$ is the bending resistance of cross-section (N·mm) taking into account axial compression N;
- N_0 is the resistance of cross-section to compression (N) calculated in accordance with 12.3.1.

12.3.2.4 Calculation of neutral axis location

For the verification of the resistance of cross-section to combined compression and bending, distance between the neutral axis and the compressive edge of cross-section (c) can be calculated by assuming that the factored axial compression is equal to the resistance of cross-section to compression. If $c \leq h$, the bending resistance (M_u) of cross-section should be calculated in accordance with 12.3.2.2. If $c > h$, the bending resistance (M_u) of cross-section should be calculated in accordance with 12.3.2.3.

12.4 Resistances of six-chord structures

12.4.1 Axial compression

The resistance of cross-section of six-chord concrete-encased CFST hybrid structures to compression should conform to the requirements of 12.3.1.

12.4.2 Combined compression and bending

12.4.2.1 Basic assumptions

The assumptions in 12.2.2.1 should be made in the calculation of resistance of cross-section of six-chord concrete-encased CFST hybrid structures to combined compression and bending.

12.4.2.2 Verification of resistance — When neutral axis is within the height of the cross-section

When the neutral axis is located within the height of the cross-section, the resistance of cross-section of six-chord concrete-encased CFST hybrid structures to combined compression and bending shall satisfy the inequalities in Formulae (168) and (169):

$$N \leq N'_{rc} + N'_{cfst} \tag{168}$$

$$M \leq M_{rc} + M_{cfst} \tag{169}$$

where

N is the factored axial compression in the cross-section of the concrete-encased CFST hybrid structure (N);

M is the factored bending moment in the cross-section of the concrete-encased CFST hybrid structure (N·mm);

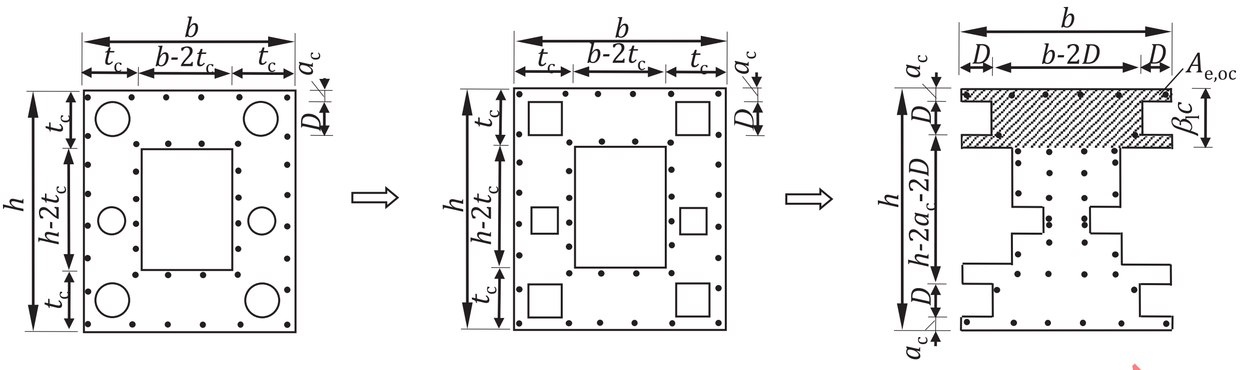
N'_{rc} is the compression resistance of cross-section of the concrete encasement to combined compression and bending (N);

N'_{cfst} is the compression resistance of cross-sections of encased CFST members to combined compression and bending (N);

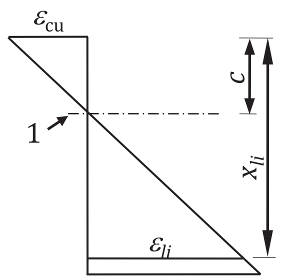
M_{rc} is the bending resistance of cross-section of the concrete encasement to combined compression and bending (N·mm);

M_{cfst} is the bending resistance of cross-sections of encased CFST members to combined compression and bending (N·mm).

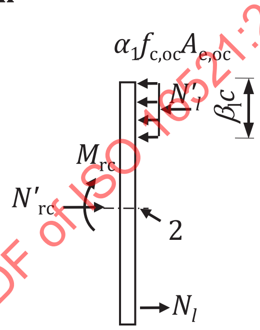
a) The resistance of cross-section of the concrete encasement of six-chord concrete-encased CFST hybrid structures to compression and the corresponding bending resistance should be calculated in accordance with the strain distribution and force equilibrium shown in Figure 20. For structures with circular CFST members, the cross-section can be simplified in accordance with Figure 20 a):



a) Simplification of cross-section



b) Strain distribution



c) Force equilibrium

Key

1	neutral axis
2	centroidal axis
b	cross-sectional width
h	cross-sectional height
D	diameter of the encased circular CFST members
t_c	distance between the edge of the internal hollow section and the outside edge of the concrete encasement
a_c	distance between the outside edge of the steel tube and the outside edge of the concrete encasement
c	distance between the neutral axis and the compressive edge of the cross-section
$A_{e,oc}$	area of equivalent uniform stress block of concrete encasement (mm^2), the height of which is $\beta_1 c$, β_1 is the height coefficient, set as 0,80 for concrete with f_{ck} not higher than 41 MPa, 0,74 for f_{ck} as 70 MPa, calculated by linear interpolation for concrete in-between; or can be taken from relevant ISO standards, such as ISO 15673 and ISO 28842, or other applicable standards
ε_{li}	strain of the ith longitudinal reinforcement
ε_{cu}	ultimate compressive strain of concrete
α_1	strength coefficient of the equivalent uniform stress block for concrete encasement, set as 1,0 for concrete with f_{ck} not higher than 41 MPa, 0,94 for f_{ck} as 70 MPa, calculated by linear interpolation for concrete in-between; or can be taken from relevant ISO standards, such as ISO 15673 and ISO 28842, or other applicable standards
$f_{c,oc}$	design compressive strength of concrete encasement
N_l	axial force of longitudinal reinforcement in tension zone, should be calculated in accordance with ε_{li} and the stress-strain relationship in 10.2.3.1
N'_l	axial force of longitudinal reinforcement in compression zone, should be calculated in accordance with ε_{li} and the stress-strain relationship in 10.2.3.1
x_{li}	distance between the ith longitudinal reinforcement and the compressive edge of the cross-section (mm)

Figure 20 — Resistance calculation of cross-section of the concrete encasement

b) The resistance of cross-sections of symmetrically encased CFST members in six-chord concrete-encased CFST hybrid structures to compression and the corresponding bending resistance should be calculated in accordance with Formulae (170) and (171), respectively:

$$N'_{\text{cfst}} = N'_{\text{c}} + N'_{\text{s}} \tag{170}$$

$$M_{\text{cfst}} = M_{\text{c}} + M_{\text{s}} \tag{171}$$

where

N'_{cfst} is the compression resistance of cross-sections of encased CFST members to combined compression and bending (N);

M_{cfst} is the bending resistance of cross-sections of encased CFST members to combined compression and bending (N·mm);

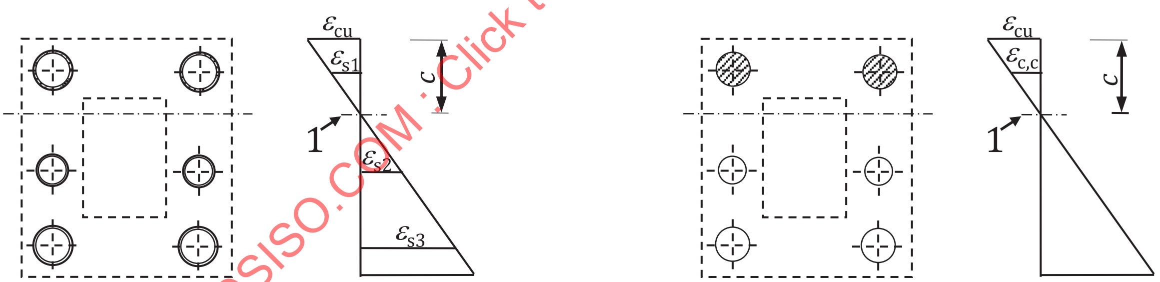
N'_{c} is the compression resistance of cross-sections of the core concrete to combined compression and bending (N);

N'_{s} is the compression resistance of cross-sections of steel tubes to combined compression and bending (N);

M_{c} is the bending resistance of cross-sections of the core concrete to combined compression and bending (N·mm);

M_{s} is the bending resistance of cross-sections of steel tubes to combined compression and bending (N·mm).

The compression and bending resistances of the steel tube and concrete should be calculated in accordance with the strain distribution shown in Figure 21 and the stress-strain relationships of the steel tube and core concrete in 10.2.3.1 and 10.2.2.1, respectively.



a) Steel tube **b) Core concrete**

Key

1 neutral axis

c distance between the neutral axis and the compressive edge of the cross-section

ε_{s1}, ε_{s2}, ε_{s3} strain of the steel tubes, which can be circular, square or rectangular

$\varepsilon_{\text{c,c}}$ strain of the core concrete

ε_{cu} ultimate compressive strain of concrete

Figure 21 — Resistance calculation of cross-sections of steel tubes

12.4.2.3 Verification of resistance — When neutral axis is beyond the height of the cross-section

When the neutral axis is located beyond the height of the cross-section, the bending resistance of cross-section of six-chord concrete-encased CFST hybrid structures to combined compression and bending should be calculated in accordance with Formula (172):

$$M_{u,N} = \frac{N_0 - N}{N_0 - N_{u,h}} M_{u,h} \tag{172}$$

where

$N_{u,h}$ is the resistance of cross-section to combined compression and bending (N), calculated by 12.4.2.2 when the distance c between the neutral axis and the compressive edge is equal to the sectional height h;

$M_{u,h}$ is the bending resistance of cross-section (N·mm), calculated by 12.4.2.2 when the distance c between the neutral axis and the compressive edge is equal to the sectional height h;

$M_{u,N}$ is the bending resistance of cross-section taking into account axial compression N (N·mm);

N_0 is the resistance of cross-section to compression (N), calculated by 12.4.1.

12.4.2.4 Calculation of neutral axis location

For the verification of the resistance of cross-section to combined compression and bending, distance (c) between the neutral axis and the compressive edge of cross-section can be calculated by assuming that the factored axial compression is equal to the resistance of cross-section to compression. If $c \leq h$, the bending resistance (M_u) of cross-section should be calculated in accordance with 12.4.2.2; if $c > h$, the bending resistance (M_u) of cross-section should be calculated in accordance with 12.4.2.3.

12.5 Resistances of slender structures

12.5.1 Axial compression

The resistance of slender concrete-encased CFST hybrid structures in axial compression N_u should be calculated in accordance with Formula (173):

$$N_u = 0{,}9\varphi(N_{rc} + N_{cfst}) \tag{173}$$

where

N_{rc} is the resistance of cross-section of the concrete encasement to compression (N);

N_{cfst} is the resistance of cross-sections of encased CFST members to compression (N);

φ is the stability factor for the concrete-encased CFST hybrid structure, and shall be calculated using the slenderness ratio λ or through a global structural analysis.

12.5.2 Combined compression and bending

12.5.2.1 Calculation of structural slenderness ratio

Structural slenderness ratio (λ) of concrete-encased CFST hybrid structures in combined compression and bending should be calculated in accordance with Formula (174). When the structural slenderness ratio (λ) satisfies the inequality in Formula (175), the effects of the secondary moment may be neglected. Otherwise, the effects of the secondary moment should be considered in accordance with 12.5.2.2.

$$\lambda = \frac{l_0}{i} \tag{174}$$

$$\lambda \le 34 - 12\frac{M_1}{M_2} \tag{175}$$

where

M_1, M_2 is the factored bending moment of two end sections about the same axis based on structural elastic analysis taking into account the influence of lateral deflection (N·mm). The absolute value of M_1 is lower than that of M_2. When the structure is under single-curvature bending, M_1/M_2 is positive. Otherwise M_1/M_2 is negative;

l_0 is the effective length of the structure (mm), can be determined in accordance with the boundary conditions or by a global structural analysis;

i is the radius of gyration in the eccentric loading direction (mm).

12.5.2.2 Calculation of resistance

The factored bending moment for the critical cross-sections of structures in combined compression and bending taking into account the second-order effects should be obtained based on a global structural analysis.

12.6 Resistance subjected to long-term loading

The resistance of concrete-encased CFST hybrid structures in axial compression considering the long-term load effects should be calculated in accordance with Formula (176):

$$N_{uL} = k_{cr} N_u \tag{176}$$

where

N_{uL} is the resistance of the concrete-encased CFST hybrid structure in axial compression considering long-term load effects (N);

N_u is the resistance of the concrete-encased CFST hybrid structure in axial compression (N), and should be calculated by Formula (173);

k_{cr} is the long-term load coefficient, and should be calculated through a global structural analysis or conform to Tables A.1 to A.3 of Annex A for concrete-encased circular CFST hybrid structures with identical CFST members.

12.7 Resistance to shear

a) The shear resistance of concrete-encased CFST hybrid structures in bending shall satisfy the inequality in Formula (177):

$$V \leq V_{rc} + V_{cfst} \tag{177}$$

where

V is the factored shear force (N);

V_{rc} is the shear resistance of the concrete encasement (N);

V_{cfst} is the shear resistance of encased CFST members (N).

b) The shear resistance of the concrete encasement should be calculated in accordance with Formulae (178) and (179):

$$V_{rc} = 0{,}45 A_{oc} \sqrt{(2+60\rho)\sqrt{1{,}1 f_{ck,oc}}\, \rho_{sv} f_v} \tag{178}$$

$$\rho_{sv} = \frac{A_{sv}}{sb} \tag{179}$$

where

V_{rc} is the shear resistance of the concrete encasement (N);

A_{oc} is the cross-sectional area of the concrete encasement (mm^2);

ρ is the tensile longitudinal reinforcement ratio, set as 2,5 % when it is greater than 2,5 %;

$f_{ck,oc}$ is the characteristic compressive strength of the concrete encasement (MPa);

ρ_{sv} is the stirrup ratio;

A_{sv} is the total cross-sectional area of stirrups (mm^2);

s is the spacing of stirrups (mm);

b is the cross-sectional width (mm);

f_v is the design tensile strength of stirrups (MPa).

c) The shear resistance of the encased CFST members should be calculated in accordance with Formula (180):

$$V_{cfst} = \begin{cases} \sum 0{,}9(0{,}97+0{,}2\ln\xi_i)A_{sc,i} f_{sv,i} & \text{(For circular cross-section)} \\ \sum 0{,}9(0{,}954+0{,}162\ln\xi_i)A_{sc,i} f_{sv,i} & \text{(For square or rectangular cross-section)} \end{cases} \tag{180}$$

where

V_{cfst} is the is the shear resistance of the encased CFST members (N);

ξ_i confinement factor of the ith encased CFST member, and shall be calculated by Formula (2);

$A_{sc,i}$ is the cross-sectional area of the ith encased CFST member (mm^2);

$f_{sv,i}$ is the design shear strength of the ith encased CFST cross-section (MPa), and should be calculated by Formula (65).

12.8 Resistance to combined axial force, bending and shear

For single-chord concrete-encased CFST hybrid structures subjected to combined axial force, bending and shear, when the shear span-to-depth ratio of the calculated section $\lambda_v \left(= \frac{M}{Vh_0}\right)$ is not less than 1,5, and the outside diameter/width/height-to-sectional width ratio is not less than 0,5, and the reinforcement placement of concrete encasement conforms to the requirements of relevant ISO standards, such as ISO 15673 and ISO 28842, or other applicable standards, the verification of the resistance in combined compression and bending can be conducted based on 12.2, 12.5 and 12.6, and the influence of shear force on the resistance in combined compression and bending may be neglected.

13 Serviceability limit states of concrete-filled steel tubular (CFST) hybrid structures

13.1 Calculation of structural response

Calculation of structural response of concrete-filled steel tubular (CFST) hybrid structures, such as stress, deformation, crack of concrete, vibration, etc., should be conducted through a global structural analysis in accordance with Clause 10.

13.2 Serviceability limitations

Limitations for stress, deformation, crack of concrete, vibration, etc., should conform to the requirements of ISO 10137 and ISO/TR 4553, or other applicable standards.

14 Protective design

14.1 General

14.1.1 Corrosion resistance

The corrosion resistance design of concrete-filled steel tubular (CFST) hybrid structures shall be reliable and economical, and shall conform to the following requirements.

a) The design life for corrosion resistance shall be determined in accordance with the importance of the structures, the environmental corrosive conditions, construction and maintenance conditions.

b) Relevant requirements of environmental protection and energy conservation shall be taken into consideration in the corrosion resistance design.

c) In addition to the mandatory anti-corrosion requirements, unfavourable designs that bring accelerated corrosion shall be avoided.

d) The corrosion resistance shall be designed to be easy for the inspection, maintenance and repairment during the whole life-cycle.

e) Unfavourable detailing, such as blind spots that are easy to accumulate water and dirt, unclosed weld, and regions that are difficult to implement painting, shall be avoided in accordance with the requirements for anti-corrosion focus and process requirements.

f) The corrosion resistance of connecting materials consisting of welding rods, bolts, washers, gusset plates, etc., shall not be lower than those of the materials of the connected members. The diameter of the bolts shall not be less than 12 mm, and spring washers shall not be used. Bolts, nuts and washers shall be protected with methods such as galvanized coating and follow the same anti-corrosion design requirements for the connected structures after mounting.

g) For buildings, bridges, power towers, etc. whose design working life is equal to or greater than 25 years, additional protection shall be used for structures that are not easy to be repaired.

14.1.2 Fire resistance

For trussed concrete-filled steel tubular (CFST) hybrid structures without fire protection, when the fire resistance rating does not satisfy the design fire resistance rating, the outer surfaces of the chords and webs shall be protected by fireproof coating or other effective fire protection measures.

When high strength concrete is used as concrete encasement in concrete-encased concrete-filled steel tubular (CFST) hybrid structures, measures, such as steel mesh or glass fibre mesh, should be adopted to reduce the risk of concrete explosively spalling at elevated temperatures.

14.1.3 Impact resistance

For CFST hybrid structures impacted by vehicles, ships, etc., the design impact loads should conform to the requirements of relevant ISO standards, such as ISO 10252, or other applicable standards.

14.2 Design of corrosion resistance

14.2.1 Anti-corrosion measures

The outer surface of steel tubes in trussed CFST hybrid structures shall adopt anti-corrosion measures such as painting after rust removal or metal coating. Anti-rust and anti-corrosion coatings, rust removal degree of steel surfaces and the structural requirements of corrosion protection on steel structures should conform to the requirements of relevant ISO standards, such as the ISO 12944 series, or other applicable standards.

14.2.2 Corrosion resistance calculation

When uniform corrosion occurs in the walls of steel tubes of trussed CFST hybrid structures in corrosive environments, the resistance shall be determined based on the effective cross-sections after corrosion.

The parameters related to CFST chords after corrosion may be determined in accordance with Formulae (181) to (187):

$$\xi_e = \frac{f_y A_{se}}{\alpha_c f_{ck} A_c} = \alpha_e \frac{f_y}{\alpha_c f_{ck}} \tag{181}$$

$$\alpha_e = \frac{A_{se}}{A_c} \tag{182}$$

$$A_{se} = \begin{cases} \frac{\pi}{4}\left[D_e^2 - (D_e - 2t_e)^2\right] & \text{(For circular cross-section)} \\ B_e^2 - (B_e - 2t_e)^2 & \text{(For square cross-section)} \\ B_e H_e - (B_e - 2t_e)(H_e - 2t_e) & \text{(For rectangular cross-section)} \end{cases} \tag{183}$$

$$D_e = D - 2\Delta t \tag{184}$$

$$B_e = B - 2\Delta t \tag{185}$$

$$H_e = H - 2\Delta t \tag{186}$$

$$t_e = t - \Delta t \tag{187}$$

where

ξ_e is the nominal confinement factor after corrosion;

f_y is the characteristic yield strength of the steel tube (MPa);

f_{ck} is the characteristic compressive strength of concrete (MPa);

α_e is the cross-sectional steel ratio after corrosion;

A_{se} is the cross-sectional area of the steel tube after corrosion (mm^2);

A_c is the cross-sectional area of the core concrete (mm^2);

D_e is the outside diameter of the circular steel tube after corrosion (mm);

B_e is the width of the square or rectangular steel tube after corrosion (mm);

H_e is the height of the rectangular steel tube after corrosion (mm);

t_e is the wall thickness of the steel tube after corrosion (mm);

D is the outside diameter of the circular CFST member (mm);

B is the width of the square or rectangular CFST member (mm);

H is the height of the rectangular CFST member (mm);

Δt is the mean wall thickness loss of the steel tube after corrosion (mm);

t is the wall thickness of the steel tube (mm).

14.3 Design of fire resistance

14.3.1 Load ratio during fire

The load ratio of CFST hybrid structures during fire R shall be determined by Formula (188):

$$R = \frac{N}{N_u} \tag{188}$$

where

N is the factored axial compression force on the CFST hybrid structure during fire (N);

N_u is the resistance of the CFST hybrid structure in axial compression at ambient temperature (N); for trussed CFST hybrid structures, should be determined in accordance with Formula (74); for concrete-encased CFST hybrid structures, should be determined in accordance with Formula (173).

NOTE The load ratio of CFST hybrid structures during fire R characterizes the load level of the axial compression acting on the structures during fire. The denominator is the resistance of the structure at ambient temperature, which is normally assumed to be 20 °C. It is a crucial factor that affects the fire resistance ratings of CFST hybrid structures.

14.3.2 Fireproof coating

a) Where the fireproof coating for steel structures is used for the protection of trussed CFST hybrid structures, intumescent fireproof coating may be used when the design fire resistance rating does not exceed 3,0 h, while non-reactive fireproof coating should be used when the design fire resistance rating exceeds 3,0 h.

b) Where non-reactive fireproof coating for steel structures is used for the fire protection of trussed CFST hybrid structures, the thickness of the fireproof coating for a single chord may be taken as 1,2 times that for CFST member under the same conditions. For the webs and the connecting zones between the chords and the webs, the thickness of fireproof coatings should be identical to that for the chords.

c) Where intumescent fireproof coating for steel structures is used for trussed CFST hybrid structures, the thickness of the fireproof coating shall be determined by fire tests. When there are reliable references, it can also be determined based on calculation. The intumescent fireproof coating shall be used in conjunction with the anti-corrosion coating and should conform to the requirements of relevant ISO standards, such as the ISO 12944 series, or other applicable standards.

14.3.3 Fire resistance ratings

a) When verifying the fire resistance ratings of concrete-encased CFST hybrid structures in compression, the effective height of the column at the middle floor in supported frames may be taken as 50 % of the height of the column, and the effective height of the column at the top floor may be taken as 50 % to 70 % of the height of the column.

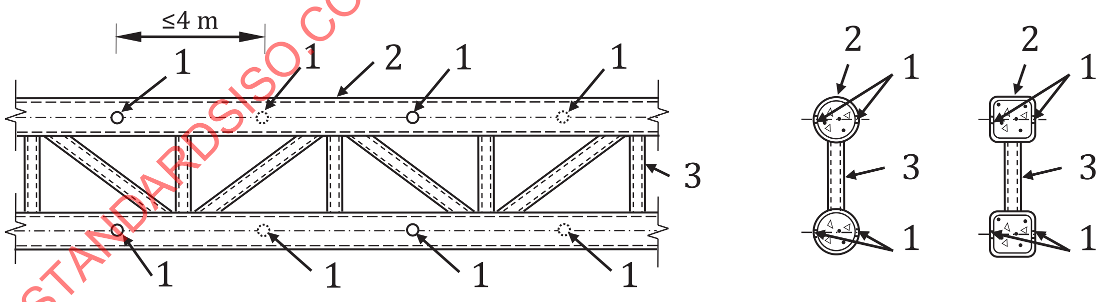
b) The fire resistance ratings of CFST hybrid structures should be determined using experimental methods or a global structural analysis. For single-chord concrete-encased circular CFST hybrid structures in axial compression, the fire resistance ratings can be determined based on the resistance coefficient of the encased CFST member (n_{cfst}) according to Table B.1 of Annex B.

NOTE The resistance coefficient of the encased CFST member (n_{cfst}) is calculated as the ratio between the resistance of cross-section of the encased CFST member to compression (N_{cfst}) and the resistance of cross-section of the concrete-encased CFST hybrid structure to compression (N_0).

14.3.4 Detailing requirements

The detailing of fire protection measures in the construction of the CFST hybrid structures shall ensure that the water vapor inside the steel tubes can be smoothly discharged during fire. The following arrangements of the vent holes that connect the core concrete to the outside air may be adopted. Other arrangements of vent holes can also be used provided that they are verified through fire tests.

a) The chords of the trussed CFST hybrid structures shall set vent holes with a diameter of not less than 20 mm. The vent holes shall be arranged anti-symmetrically along the chord and shall avoid the joint zone. The longitudinal spacing of the vent holes should not exceed 4 m (see Figure 22).



Key

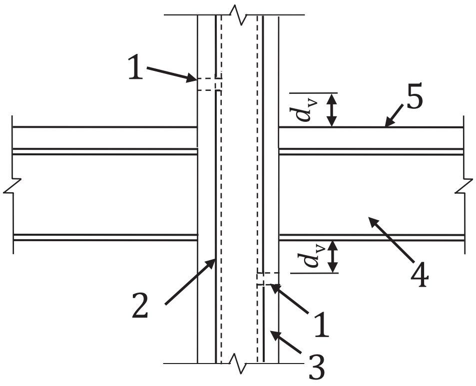
1 vent holes

2 CFST chords

3 webs

Figure 22 — Schematic diagram of positions of vent holes in trussed CFST hybrid structures

b) Vent holes with a diameter of not less than 20 mm shall be set on the steel tubes encased in the concrete-encased CFST hybrid structures. Vent holes should be arranged at the top and bottom of the intersection of each floor column and floor slab. The distance between the vent holes and the floor slab or the steel beam (d_v) shall be 100 mm to 200 mm, and the vent holes should be arranged anti-symmetrically along the column (see Figure 23).



Key

1 vent holes
2 encased CFST member
3 concrete encasement
4 steel beam
5 floor slab

Figure 23 — Schematic diagram of positions of vent holes in concrete-encased CFST hybrid structures

14.4 Design of impact resistance

14.4.1 Bending resistance under impact

The bending resistance of CFST hybrid structures subjected to impact shall satisfy the inequality in Formula (189):

$$M_d \le R_d M_u \tag{189}$$

where

M_d is the factored impact bending moment (N·mm);

R_d is the dynamic increase factor under impact, take as 1,0 when it is less than 1,0;

M_u is the static bending resistance (N·mm), and should be calculated in accordance with the requirements in Clause 11 for trussed CFST hybrid structures, and in accordance with the requirements in Clause 12 for concrete-encased CFST hybrid structures.

NOTE Within the general parametric ranges of this document, the failure of CFST members in CFST hybrid structures is dominated by a bending failure mode due to their high shear resistance. Consequently, the bending resistance design of CFST hybrid structures is specially provided.

14.4.2 Dynamic increase factor for circular CFST chords under impact

The dynamic increase factors for CFST chords under impact R_d may be calculated in accordance with Formulae (190) to (194):

$$R_d = 1{,}49 f_1 f_2 f_3 f_4 \tag{190}$$

$$f_1 = -4{,}00 \times 10^{-7} f_y^2 + 8{,}00 \times 10^{-5} f_y + 1{,}02 \quad (191)$$

$$f_2 = -3{,}66 \alpha_s^2 - 0{,}896 \alpha_s + 1{,}13 \quad (192)$$

$$f_3 = 7{,}00 \times 10^{-7} D^2 - 1{,}3 \times 10^{-3} D + 1{,}40 \quad (193)$$

$$f_4 = -1{,}00 \times 10^{-3} V_0^2 + 5{,}08 \times 10^{-2} V_0 + 0{,}385 \quad (194)$$

where V_0 is the impactor velocity (m/s).

14.4.3 Deformation of circular CFST chords under impact

The maximum deformation of circular CFST chords subjected to lateral impact load applied at mid-span may be calculated in accordance with Formula (195) and should satisfy the relevant structural requirements.

$$u_m = \kappa_b \left[\frac{E_i l_1 \times 10^3}{4 R_d M_u} + \frac{R_d M_u}{2(\pi / l_1)^2 EI} \right] \quad (195)$$

where

u_m	is the maximum deformation of circular CFST chord under impact (mm);
κ_b	is the coefficient of boundary conditions, taken as 1,0 for both ends pinned condition, 0,61 for pinned-fixed condition and 0,46 for both ends fixed condition;
E_i	is the impact energy (J);
l_1	is the length of a single chord in an interval of the trussed CFST hybrid structure (mm);
R_d	is the dynamic increase factor under impact, calculated by Formula (190);
EI	is the elastic flexural stiffness of the CFST cross-section (N·mm^2).

15 Connections

15.1 General

The design of joints and connections in concrete-filled steel tubular (CFST) hybrid structures shall conform to the requirements of strength, stiffness, stability, fatigue and seismic performance. It shall ensure that the force can be transferred effectively and that the steel tube and its core concrete can act together. It shall also take into account the ease of manufacturing, erection and placement of the core concrete.

In Clause 15, typical connections for CFST hybrid structures are recommended. When available, connection detailing based on reliably verified experimental tests, inter-relevant ISO standards, such as ISO 14346 and ISO 14347, or other available standards can also be applied.

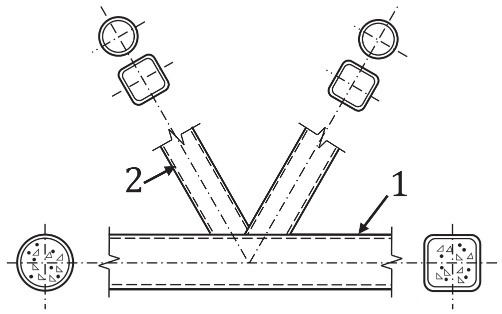
15.2 Joints of trussed concrete-filled steel tubular (CFST) hybrid structures

15.2.1 General requirements

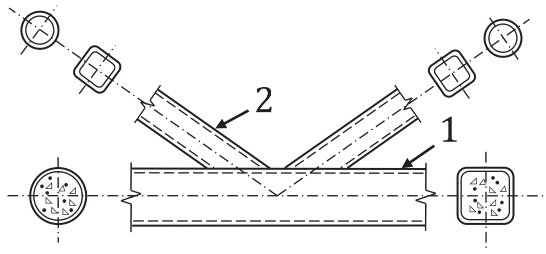
The detailing of the joints and connections in trussed concrete-filled steel tubular (CFST) hybrid structures should be simple enough and the loading conditions of the structures shall be clearly defined. The centrelines of loaded members should intersect at one point.

15.2.2 Typical forms of joints

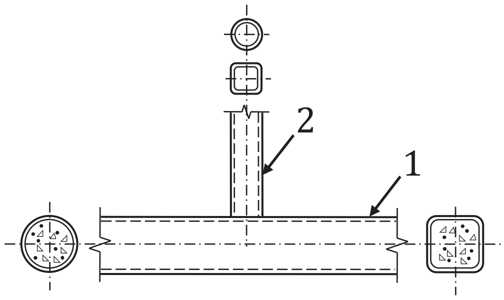
Overlap K-joint, gap K-joint, T-joint, Y-joint, X-joint, KT-joint, multiplanar TT-joint and multiplanar KK-joint may be used in trussed CFST hybrid structures, as shown in Figure 24.



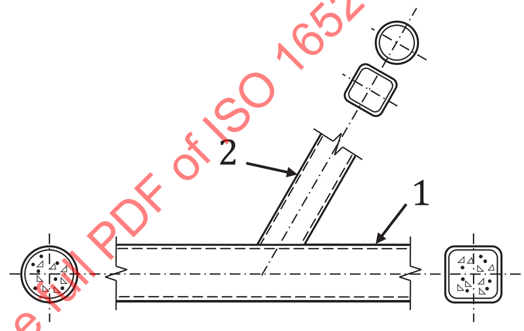
a) Overlap K-joint



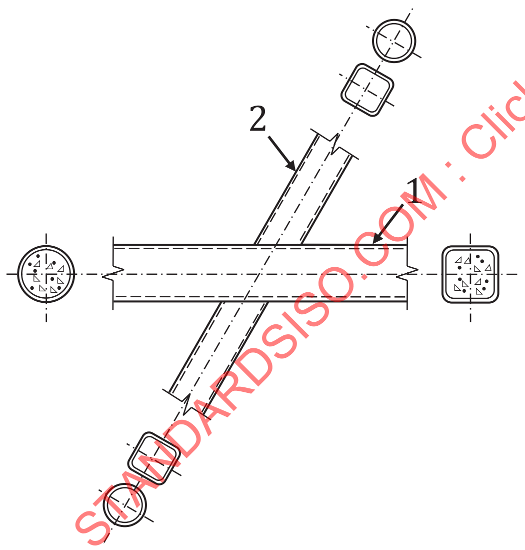
b) Gap K-joint



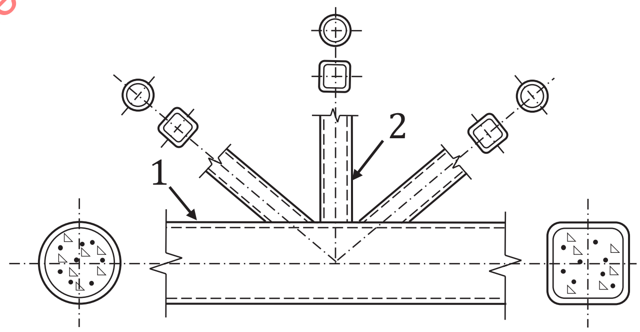
c) T-joint



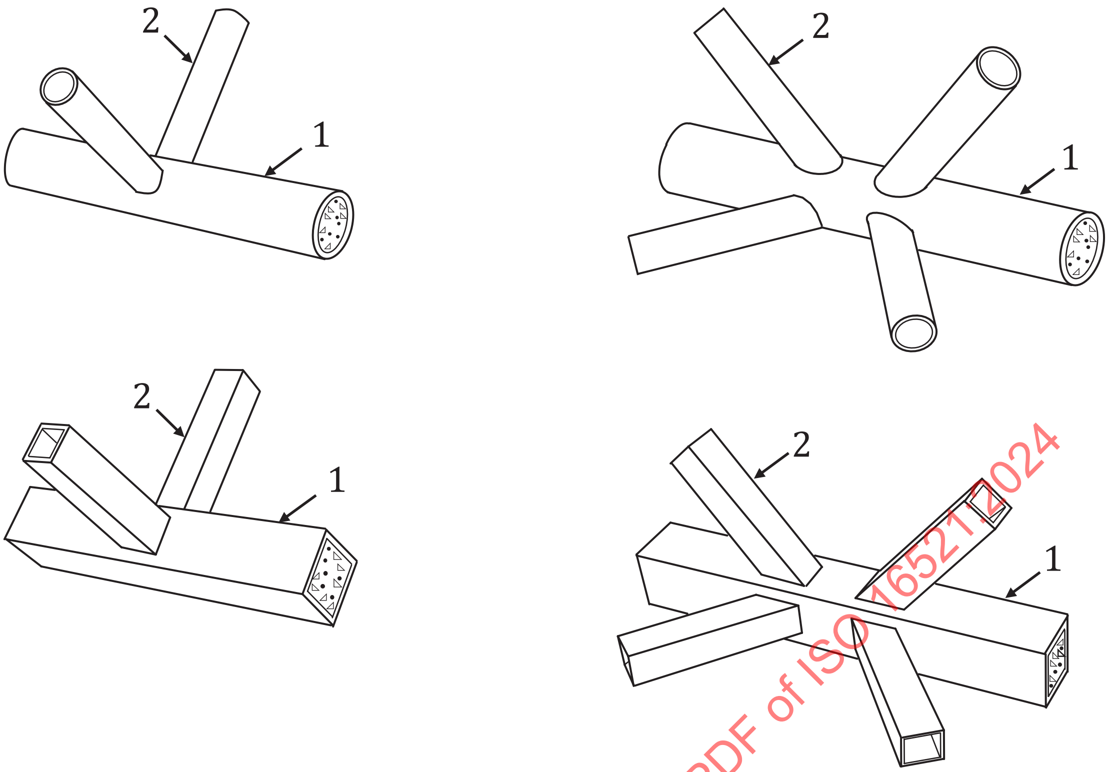
d) Y-joint



e) X-joint



f) KT-joint



g) Multiplanar TT-joint

h) Multiplanar KK-joint

Key

1 CFST chords

2 hollow steel tubular webs

Figure 24 — Typical forms of joints in trussed CFST hybrid structures

15.2.3 Welding requirements

For welded intersecting joints of trussed CFST hybrid structures, the hollow steel tubular webs shall be connected along the intersecting lines by butt welds with groove or fillet welds, and the welding consumables shall match the grade of the steel tubes. The design of the welds may be carried out in accordance with relevant standards, such as ISO 14346 and ISO 14347, or other applicable standards.

15.2.4 Detailing requirements of webs

15.2.4.1 Overlapping

For the plane K-joints and N-joints where webs overlap, when the two webs have different diameters (widths), the web with a greater diameter (width) shall be directly welded to the chord while the web with a smaller diameter (width) shall be overlapped to the web with the greater diameter (width). When the two webs have the same diameter (width), the web carrying a greater force shall be welded directly to the chord while the web carrying a lower force shall be overlapped to the web carrying the greater force.

15.2.4.2 Clear distance between the web ends

When using gap K-joints, the clear distance between the web ends should not be less than the summation of the thicknesses of the two webs.

15.2.4.3 Distance between the centroids of horizontal webs

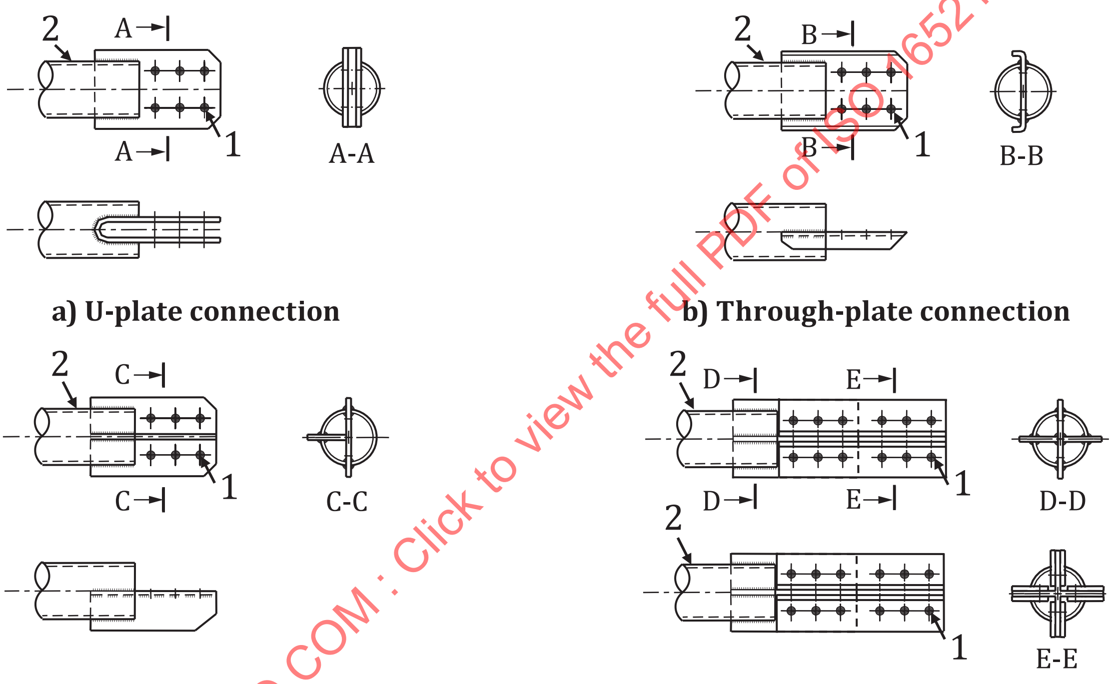
The distance between the centroids of horizontal webs should not be greater than four times the distance between the centroids of chords.

15.2.4.4 Cross-sectional area of the hollow steel tubular web

The cross-sectional area of the hollow steel tubular web should not be less than 1/5 of that of the single chord.

15.2.5 Inserted plate connections

When the webs and chords in the joints of trussed CFST hybrid structures are connected by gusset plates and bolts, the insert plates at the ends of the webs may adopt U-plates, through-plates, T-plates or cross-plates (see Figure 25 for circular cross-section). The opening gap of the U-plates may be 2 mm to 3 mm greater than the thickness of the gusset plates. The weld length of the plates inserted into the steel tubes shall be determined in accordance with the internal force calculation.



a) U-plate connection **b) Through-plate connection**

c) T-plate connection **d) Cross-plate connection**

Key

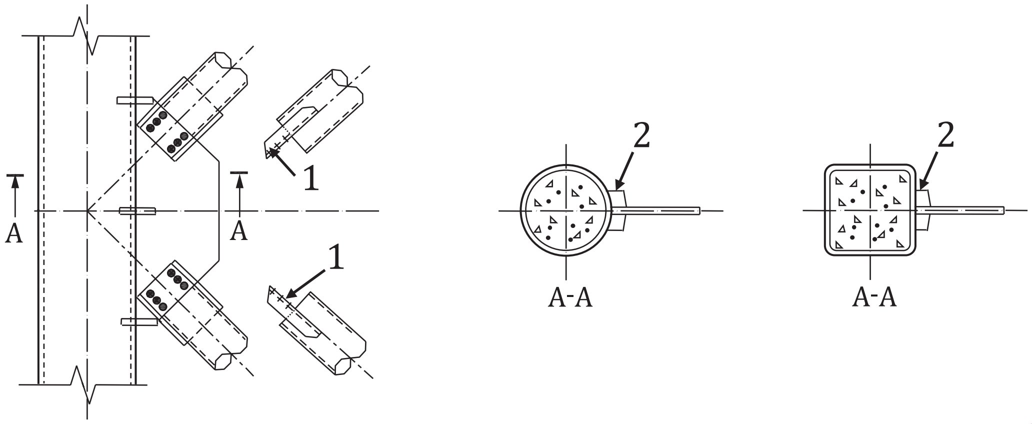
1 bolts

2 webs

Figure 25 — Detailing of inserted plate connections at the web ends

15.2.6 Gusset plate connections

When the joint of trussed CFST hybrid structures is connected by gusset plates, ring or sector-shaped stiffeners may be set on both sides of the gusset plates (see Figure 26), and the corresponding central angle should not be less than 30°. Adjacent stiffeners in the same plane shall be connected to form a single piece. When the ratio of the length of free edge of the gusset plate to its thickness is greater than $60\sqrt{235/f_y}$, flanged edge should be used, or longitudinal stiffeners should be set. The calculation for resistance of the gusset plates should conform to the requirements of relevant ISO standards, such as ISO 10721-1, or other applicable standards.



Key

1 through plates

2 stiffeners

Figure 26 — Detailing of the gusset plate connection

15.2.7 Intersecting welded plane K-joints and N-joints

The detailing of the intersecting welded plane K-joints and N-joints of trussed CFST hybrid structures shall conform to the following requirements:

a) Web shall not be inserted into the chord at the connection between web and chord.

b) Eccentricity should be avoided at the connection of web and chord; and when eccentricity is unavoidable, the eccentricity for joints (see Figure 27) shall satisfy the inequality in Formulae (196) to (198).

For chords and webs with circular cross-section:

$$-0{,}55 \leq \frac{e}{D} \leq 0{,}25 \quad (196)$$

For chords and webs with square cross-section:

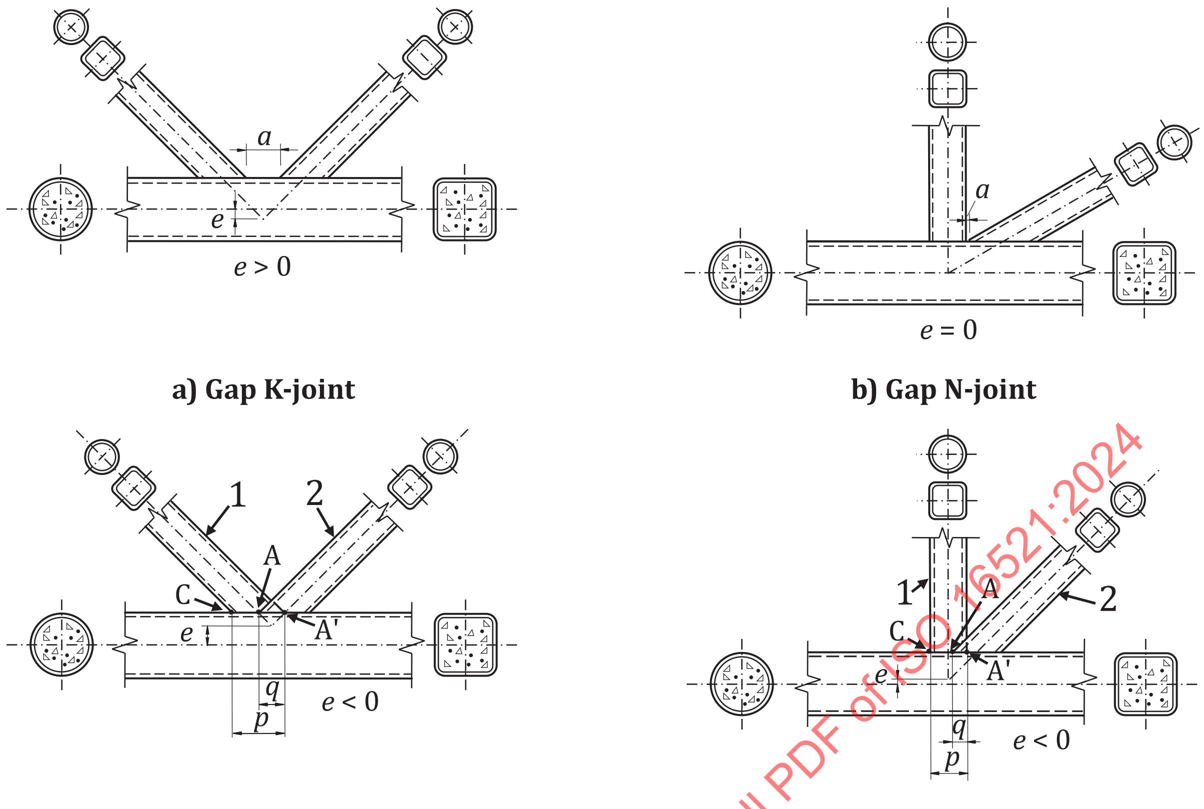
$$-0{,}55 \leq \frac{e}{B} \leq 0{,}25 \quad (197)$$

For chords and webs with rectangular cross-section:

$$-0{,}55 \leq \frac{e}{H} \leq 0{,}25 \quad (198)$$

where

e	is the load eccentricity (mm), as shown in Figure 27;
D	is the outside diameter of the circular CFST chord (mm);
B	is the width of the square CFST chord (mm);
H	is the height of the rectangular CFST chord (mm).



a) Gap K-joint **b) Gap N-joint**

c) Overlap K-joint **d) Overlap N-joint**

Key

1 overlapping webs

2 overlapped webs

a gaps

Figure 27 — Eccentricities and gaps of plane K-joints and N-joints

c) For the plane K-joints and N-joints overlapped by the web, the overlap ratio (η_{ov}) for joints with a circular cross-section may be calculated in accordance with Formula (199) and shall not be less than 25 %, or greater than 100 %.

$$\eta_{ov} = \frac{q}{p} \times 100\,\% \tag{199}$$

where

q is the distance AA' (mm) between the crown point (A'), where the overlapping web and the chord intersect theoretically, and the crown toe (A), where the overlapped web and the chord surface intersect (see Figure 27);

p is the distance A'C (mm) between the crown point (A'), where the overlapping web and the chord intersect theoretically, and the crown heel (C), where the overlapping web and the chord surface intersect (see Figure 27).

d) The weld in the connection between the chord and the web should conform to the requirements of relevant ISO standards, such as ISO 14346 and ISO 14347, or other applicable standards.

e) For the plane gap K-joints and N-joints, the gap between adjacent webs welded on the surface of the chord shall not be less than the sum of the wall thicknesses of the two webs.

f) For the hollow plane K-joints of trussed CFST hybrid structures before concrete placement, the resistance of the webs to compression and webs to tension shall be verified in accordance with ISO 14346.

g) The resistances of the hollow steel tubular webs to compression and to tension in the plane gap K-joints of trussed CFST hybrid structures should be calculated in accordance with relevant ISO standards, such as ISO 14346, or other applicable standards.

h) The resistance of the connection between a circular chord of a K-joint and a web with circular cross-section in trussed CFST hybrid structures to lateral local bearing shall satisfy the inequality in Formula (200) and should be calculated according to Formulae (201) to (204):

$$N_{\text{LF}} \leq N_{\text{uLF}} \tag{200}$$

$$N_{\text{uLF}} = \beta_{\text{c}} \beta_{l} \alpha_{\text{c}} f_{\text{c}} \frac{A_{l\text{c}}}{\sin\theta} \tag{201}$$

$$\beta_{l} = \sqrt{\frac{A_{\text{b}}}{A_{l\text{c}}}} \tag{202}$$

$$A_{l\text{c}} = \pi d_{\text{w}}^{2} / 4 \tag{203}$$

$$A_{\text{b}} = \frac{A_{l\text{c}}}{\sin\theta} + 2 d_{\text{w}} D \tag{204}$$

where

N_{LF} is the factored lateral local bearing force on the chord in joint zone (N);

N_{uLF} is the resistance of the chord to lateral local bearing (N);

θ is the angle between the chord and the web that transmits lateral local bearing;

β_{l} is the strength increase factor of concrete when under lateral local bearing;

$A_{l\text{c}}$ is the direct bearing area when under lateral local bearing;

d_{w} is the outside diameter of the web;

A_{b} is the dispersed bearing area when under lateral local bearing (mm^2);

β_{c} is the coefficient of concrete strength when under lateral local bearing, and shall be determined according to Table 4, where intermediate values in the table are obtained by linear interpolation.

Table 4 — Strength class for core concrete in the steel tube

$\sqrt{\frac{A_{l\text{c}}}{A_{\text{b}}} \frac{f_{\text{y}}}{\alpha_{\text{c}} f_{\text{ck}}}}$	0,4	0,8	1,2	1,6	2,0	≥3,0
β_{c}	1,07	1,22	1,47	1,67	1,87	2,00

i) At the joints of trussed CFST hybrid structures, webs shall be welded to chords along their perimeters; where webs overlap each other, overlapping webs shall be welded to the overlapped webs along the lap edges.

15.2.8 Plane T-joints, Y-joints and X-joints

The detailing and calculation of plane T-joints, Y-joints and X-joints of trussed CFST hybrid structures shall conform to the following requirements:

a) The detailing of plane T-joints, Y-joints and X-joints of trussed CFST hybrid structures shall conform to the requirements of 15.2.7.

b) For the hollow plane T-joints, Y-joints and X-joints of trussed CFST hybrid structures before concrete placement, the resistance of webs to compression and webs to tension shall be verified according to relevant ISO standards, such as ISO 14346, or other applicable standards.

c) The calculation for resistance of webs to compression and to tension in plane T-joints, Y-joints and X-joints of trussed CFST hybrid structures should conform to the requirements of relevant ISO standards, such as ISO 14346, or other applicable standards.

d) When plane T-joints, Y-joints and X-joints of trussed CFST hybrid structures are subjected to lateral local bearing, the resistance shall be verified in accordance with 15.2.7. The angle θ between webs and CFST chords of plane T-joints shall be taken as 90°.

15.2.9 Multiplanar joints

The detailing of steel structures in multiplanar joints of trussed CFST hybrid structures should conform to the requirements of relevant ISO standards, such as ISO 14346 and ISO 14347, or other applicable standards. The resistance of webs at the joints shall be calculated by multiplying the resistance of the corresponding plane joints by a multiplanar factor. The value of the multiplanar factor shall be determined in accordance with relevant ISO standards, such as ISO 14346, or other applicable standards.

15.3 Joints of concrete-encased concrete-filled steel tubular (CFST) hybrid structures

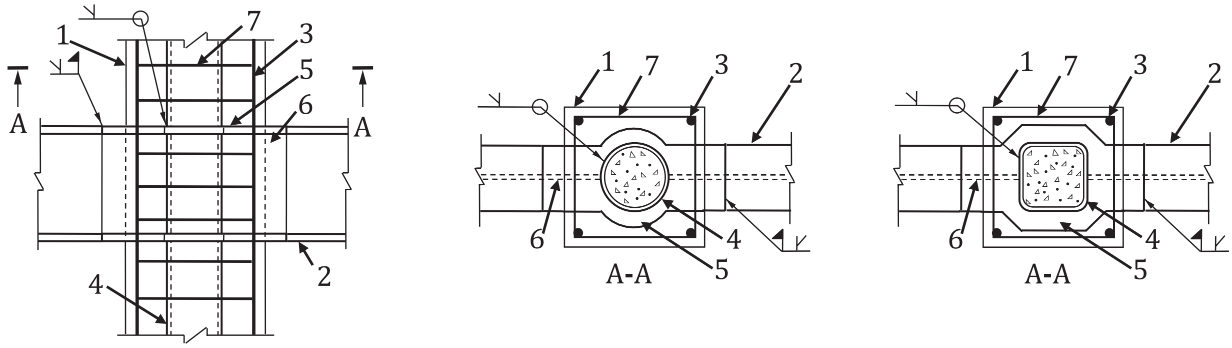
15.3.1 Steel beam-to-column ring plate joints

In frame structures, the rigid joints of concrete-encased concrete-filled steel tubular (CFST) hybrid structural columns and the I-section steel beams shall conform to the following requirements:

a) ring plate connections should be used;

b) the extension length of the ring plate flanges and vertical stiffening plates shall satisfy the construction requirements of the steel beams;

c) the flange and web of the steel beams shall be connected to the ring plates and the vertical stiffening plates, respectively, on site (see Figure 28).



Key

1 column
2 steel beam
3 longitudinal reinforcement
4 steel tube
5 ring plate
6 vertical stiffening plates
7 stirrups

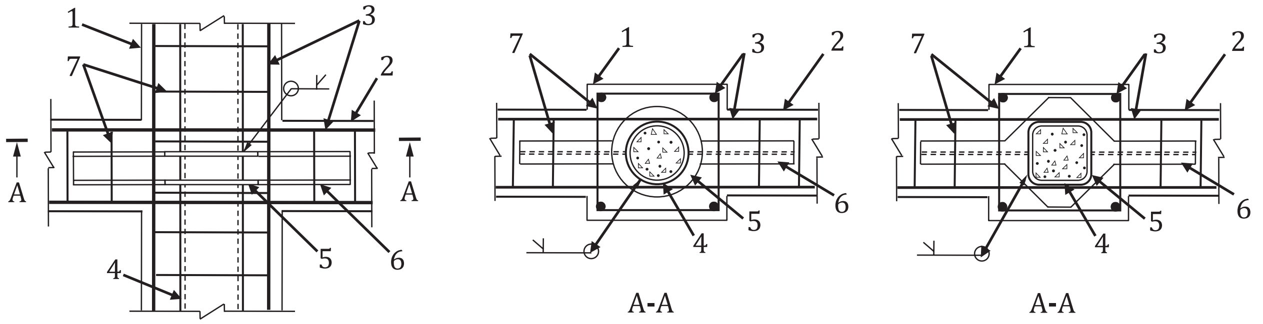
Figure 28 — Steel beam-to-concrete-encased CFST hybrid column ring plate joints

15.3.2 Reinforced concrete beam-to-column joints

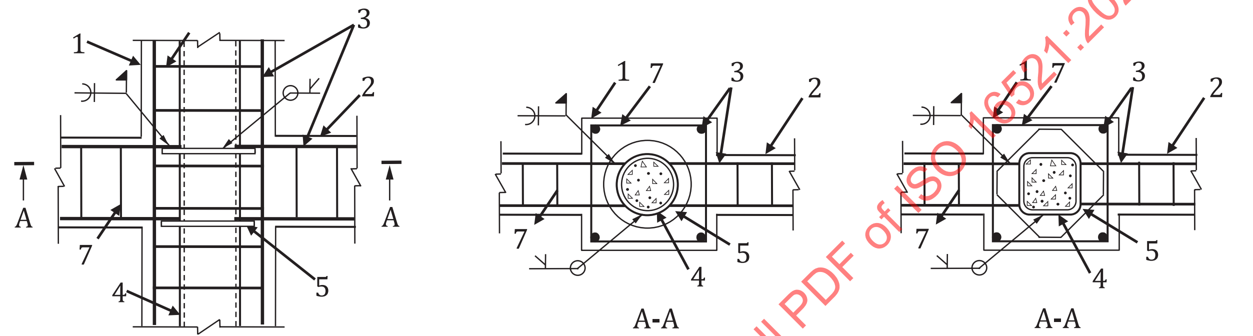
In frame structures, the rigid joints of concrete-encased CFST hybrid structural columns and reinforced concrete beams shall conform to the following requirements:

a) When the spacing between the longitudinal reinforcement on both sides of the beams is greater than the outside diameter (width/height) of the encased CFST member, stiffening ring plate and stiffening I-beam connections [see Figure 29 a)] should be adopted.

b) When the spacing between the longitudinal reinforcement on both sides of the beams is less than the outside diameter (width/height) of the encased CFST member, the longitudinal reinforcement should bypass the steel tube; when the joint stiffening ring plate connection [see Figure 29 b)] is adopted, the ring plate should be prefabricated on the steel tube. During construction, the longitudinal reinforcement of reinforced concrete beam shall be welded to the surface of the ring plate.



a) When the spacing between the longitudinal reinforcement of the beam is greater than the outside diameter (width/height) of the steel tube



b) When the spacing between the longitudinal reinforcement of the beam is less than the outside diameter (width/height) of the steel tube

Key

1 column
2 reinforced concrete beam
3 longitudinal reinforcement
4 steel tube
5 stiffening ring plate
6 stiffened I-section steel
7 stirrups

Figure 29 — Reinforced concrete beam-to-concrete-encased CFST hybrid column joints

15.3.3 Detailing requirements of beam-to-column joints

The seismic design of beam-to-column joints shall conform to the following requirements:

a) When steel beams are used, the design of the beam end cross-section should conform to the requirements of relevant ISO standards, such as ISO 10721-1, or other applicable standards.

b) When reinforced concrete beams are used, the seismic verification of the stiffening ring plate should conform to the requirements of relevant ISO structures such as ISO 10721-1, or other applicable standards.

c) The shape of the stiffening ring plate shall be smooth and free of cracks and nicks; the horizontal weld between the steel tubes of the joint and the steel tubes of the column shall be of the same strength grade as the base material; the butt weld of the stiffening ring plate and the flange of the steel beam shall adopt penetration groove weld.

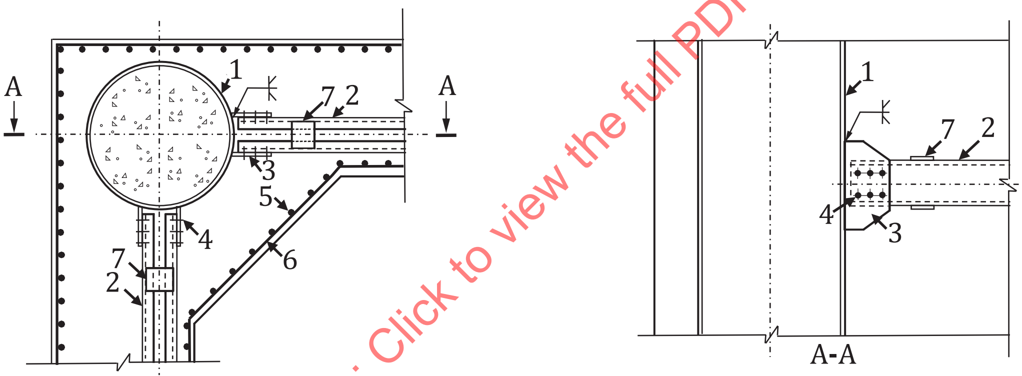
d) The diameter and spacing of the stirrups in the joints should conform to the requirements of relevant ISO standards, such as ISO 15673 and ISO 28842, or other applicable standards.

e) The thickness of the ring plate in a joint shall be greater than the lesser value between 10 mm and the wall thickness of the steel tube. The width of the ring plate shall be greater than 40 mm and conform to the requirements of steel welding length. The characteristic yield strength of the ring plate steel shall not be lower than that of the steel tube and should not be lower than 355 MPa. The weld process should conform to the requirements of relevant ISO standards, such as ISO 10721-1, or other applicable standards.

f) When the longitudinal reinforcement of the beams and the steel tube are connected by a reinforcement connector, the connection length of the longitudinal reinforcement in the reinforcement connector shall not be less than the diameter of the longitudinal reinforcement, and the mechanical connection process should conform to the requirements of relevant ISO standards, such as ISO 6935-2, or other applicable standards.

15.3.4 Connections between steel tubes

The transverse connections between the steel tubes in the multi-chord concrete-encased CFST hybrid structural columns shall conform to the stiffness requirements of the structures and the corresponding detailing requirements. The built-in gusset plates of CFST members should be welded, and the gusset plates and the cross webs should be connected by bolts (see Figure 30 for circular cross-section). No blind spots of concrete placement shall exist.



Key

1 steel tube
2 cross webs
3 gusset plates
4 splice bolts
5 longitudinal reinforcement
6 stirrups
7 batten plate

Figure 30 — Connections between steel tubes in a multi-chord column

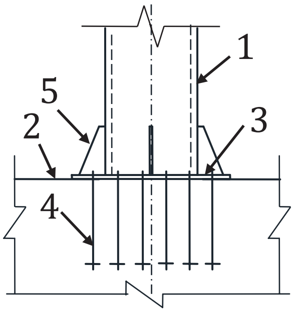
15.4 Column bases and supporting connections

15.4.1 Column bases and supporting connections of trussed CFST hybrid structures

15.4.1.1 Column base forms

The chords of trussed CFST hybrid structures and the foundations can adopt end-bearing connection, embedded connection or encased connection, and shall conform to the following requirements:

a) The diameter (or width) of the bearing plate of the end-bearing connection (see Figure 31) should be 1,5 to 2,0 times the outside diameter (width/height) of the CFST chord, and the thickness should not be less than 25 mm.



Key

1 CFST chord

2 foundation

3 bearing plate

4 anchor bolts

5 stiffeners

Figure 31 — End-bearing column base

b) The embedded depth of chords of the embedded connection (see Figure 32) should be greater than 1,5 times the outside diameter (width/height) of the CFST chord and not less than 1,0 m. Anchoring detailing such as distributed circumferential ribs, welded studs or perfobond connectors shall be arranged in the embedded section.