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Standard**

ISO 16521

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

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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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

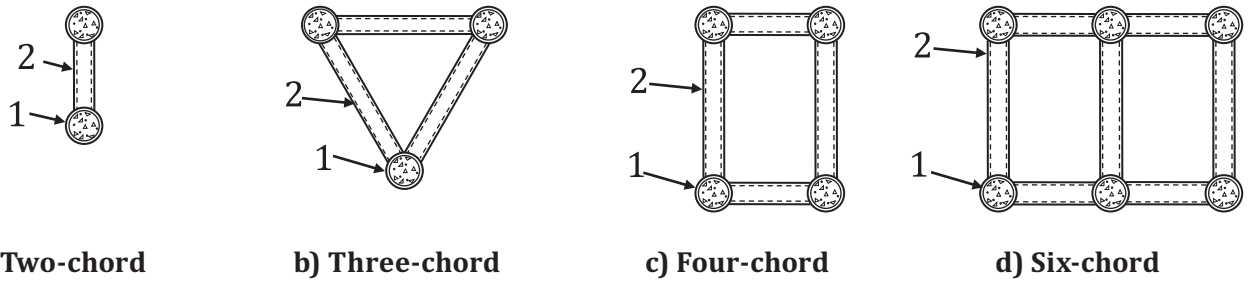
trussed concrete-filled steel tubular (CFST) hybrid structure **trussed CFST hybrid structure**

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.

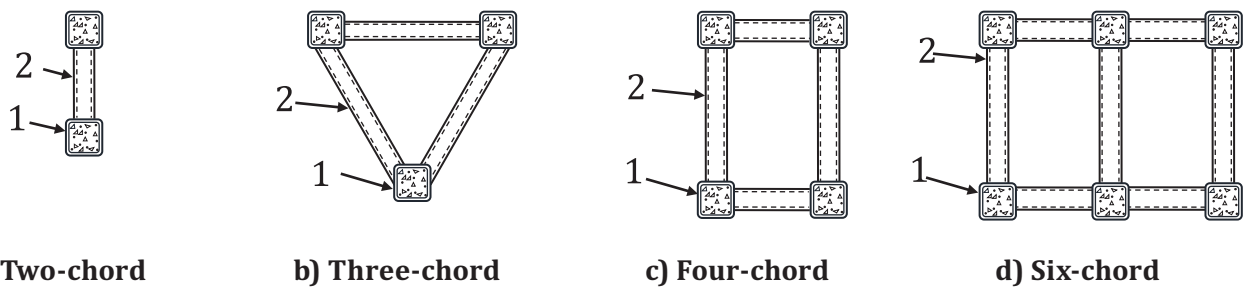
Note 3 to entry: For trussed CFST hybrid structure with rectangular CFST members, the CFST chords are generally placed to have the strong axes of their rectangular cross-sections all in parallel with the strong axis of the whole cross-section of the trussed CFST hybrid structure.



Key

- 1 CFST chords
- 2 webs

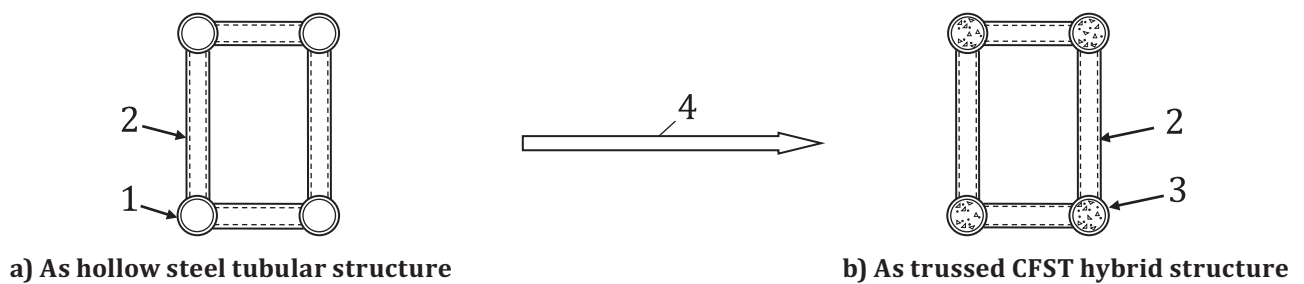
Figure 1 — Cross-sections of trussed CFST hybrid structures with circular CFST members



Key

- 1 CFST chords
- 2 webs

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



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

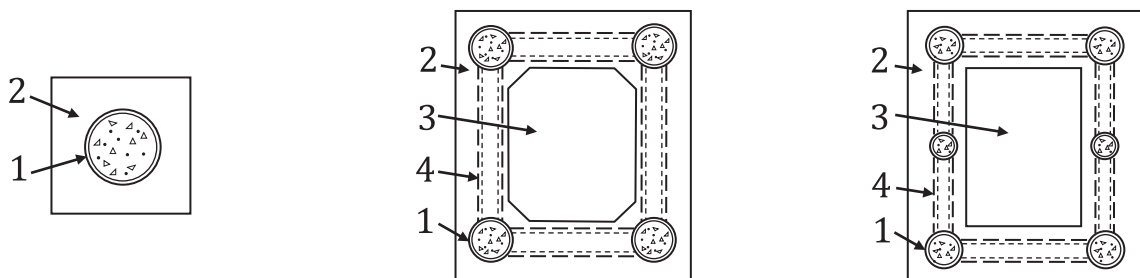
3.3

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

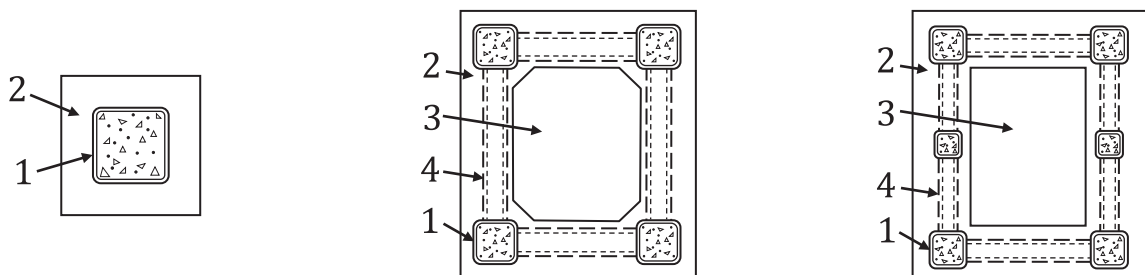
b) Four-chord, with an internal hollow section

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

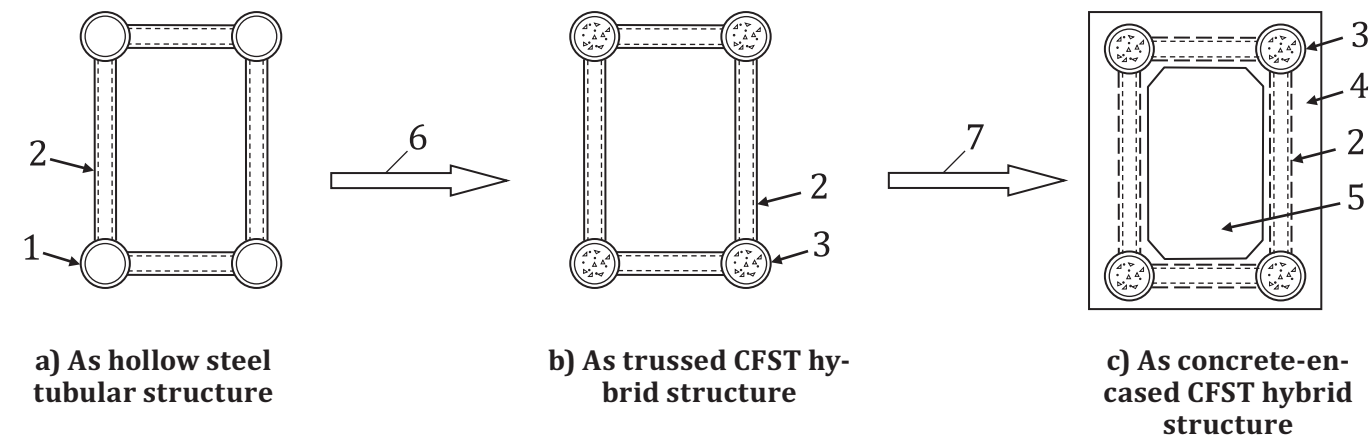
Key

- 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.



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

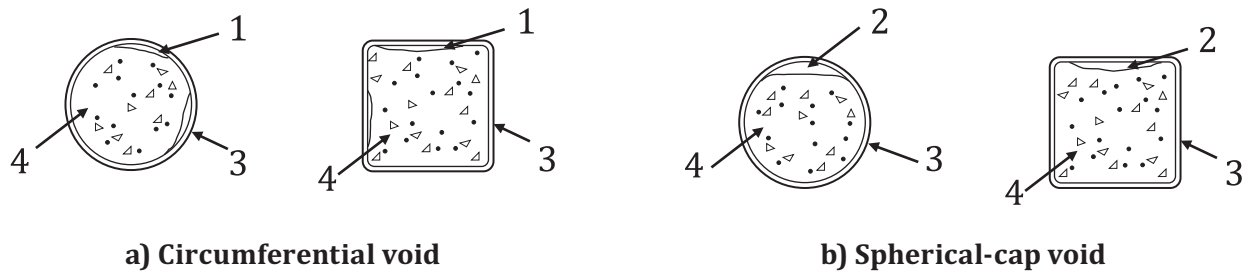
3.4
limiting value of initial stress in the steel tube
limiting value of the stress level in the steel tube before the steel tube and the core concrete in the CFST member can act together

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.



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
$E_{\text{c,c}}$	modulus of elasticity of the core concrete in the CFST member	MPa
$E_{\text{c,oc}}$	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
$f_{\text{c,oc}}$	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
$G_{\text{c,c}}$	shear modulus of the core concrete in the CFST member	MPa
$G_{\text{c,oc}}$	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_{yk}) 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_{yk}) 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:

- preliminary structural design: design of the structural plans, including the structural forms, arrangement of structures, and selection of materials and cross-sections;
- definition of actions (loads);
- 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.

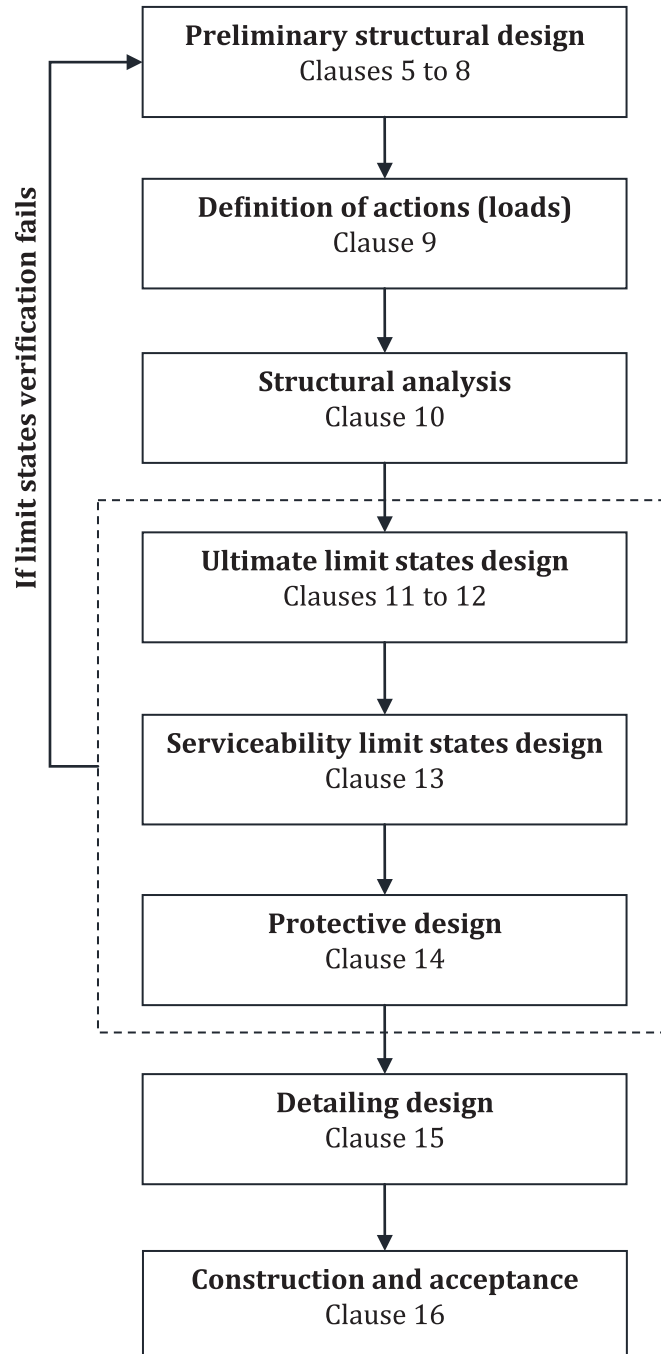


Figure 8 — General design and construction procedure

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 $150 \left(\frac{235}{f_y} \right)$ and should not be less than $25 \left(\frac{235}{f_y} \right)$. The width/height-to-thickness ratio of the square or rectangular hollow steel tubular cross-section shall not be greater than $65 \sqrt{\frac{235}{f_y}}$ and should not be less than $10 \sqrt{\frac{235}{f_y}}$, 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:

$$\alpha_s = \frac{A_s}{A_c} \quad (1)$$

where

- α_s cross-sectional steel ratio;
- A_s cross-sectional area of the steel tube (mm²);
- A_c cross-sectional area of the core concrete (mm²).

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:

$$\xi = \frac{f_y A_s}{\alpha_c f_{ck} A_c} \quad (2)$$

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.

$$\rho = \frac{A_l}{A_{oc}} \quad (3)$$

where

- ρ longitudinal reinforcement ratio;
- A_l total cross-sectional area of the longitudinal reinforcement (mm²);
- A_{oc} cross-sectional area of the concrete encasement (mm²).

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 \(4\)](#):

$$E_d \leq R_d \quad (4)$$

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 \(7\)](#).

$$f_c = \frac{f_{ck}}{\gamma_{mc}} \quad (5)$$

$$f = \frac{f_y}{\gamma_{ms}} \quad (6)$$

$$f_l = \frac{f_{yl}}{\gamma_{ml}} \quad (7)$$

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;

$\gamma_{mc}, \gamma_{ms}, \gamma_{ml}$ 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.

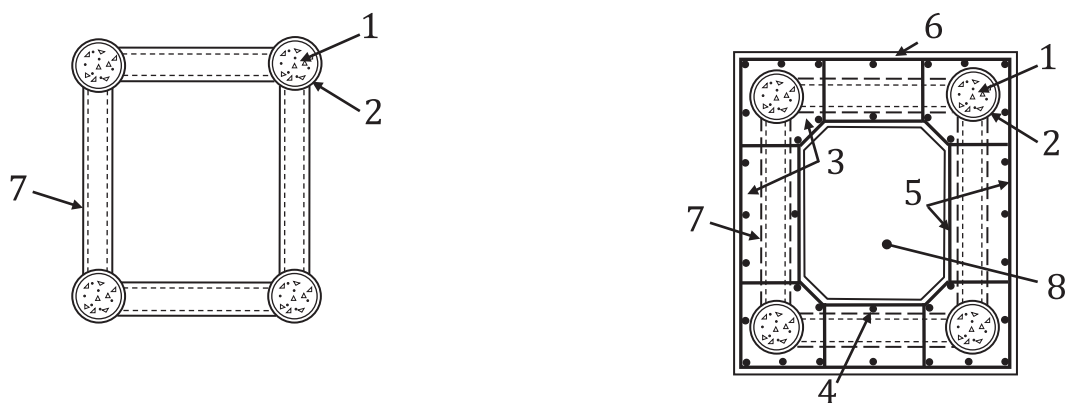
For the structural analysis of the construction stages, all the actual loads and effects during the whole construction, including the installation of machines and materials, steel structures during erection, concrete during placement, installation and dismantling of temporary supporting structures, temperature 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:

$$y = 2x - x^2 \quad (x \leq 1) \quad (8)$$

$$y = \begin{cases} 1 + q(x^{0,1\xi} - 1) & (\xi \geq 1, 12) \\ \frac{x}{\beta(x-1)^2 + x} & (\xi < 1, 12) \end{cases} \quad (x > 1) \quad (9)$$

$$x = \frac{\varepsilon}{\varepsilon_0} \quad (10)$$

$$y = \frac{\sigma}{\sigma_0} \quad (11)$$

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

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

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

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

$$\beta = \left(2,36 \times 10^{-5} \right)^{\left[0,25 + (\xi - 0,5)^7 \right]} f_{ck}^2 \times 3,51 \times 10^{-4} \quad (16)$$

where

σ is the stress (MPa);

ε is the strain ($\mu\varepsilon$);

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:

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

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

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

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

$$\sigma_o = \left[1 + \left(-0,0135\xi^2 + 0,1\xi \right) \left(\frac{24}{f_{ck}} \right)^{0,45} \right] f_{ck} \quad (21)$$

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

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

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

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

where

- σ is the stress (MPa);
- ε is the strain ($\mu\varepsilon$);
- 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 \(32\)](#):

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

$$x = \frac{\varepsilon}{\varepsilon_o} \quad (27)$$

$$y = \frac{\sigma}{\sigma_o} \quad (28)$$

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

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

$$\rho_v = \frac{A_{sv} l_v}{A_v s} \quad (31)$$

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

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 (mm²);
- l_v is the length of stirrups (mm);
- A_v is the cross-sectional area of stirrup-confined concrete encasement (mm²), 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 [\(43\)](#):

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

$$x = \frac{\varepsilon}{\varepsilon_o} \quad (34)$$

$$y = \frac{\sigma}{\sigma_o} \quad (35)$$

$$\sigma_o = f_{ck} \quad (36)$$

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

$$A = \begin{cases} \frac{E_c \varepsilon_o}{f_{ck}} & (\varepsilon \leq \varepsilon_o) \\ \frac{f_i (\varepsilon_i - \varepsilon_o)^2}{\varepsilon_i \varepsilon_o (f_{ck} - f_i)} & (\varepsilon > \varepsilon_o) \end{cases} \quad (38)$$

$$B = \begin{cases} \frac{(A-1)^2}{0,55} - 1 & (\varepsilon \leq \varepsilon_o) \\ 0 & (\varepsilon > \varepsilon_o) \end{cases} \quad (39)$$

$$C = A - 2 \quad (40)$$

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

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

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

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 [\(48\)](#):

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

$$x = \frac{\varepsilon}{\varepsilon_p} \quad (45)$$

$$y = \frac{\sigma}{\sigma_p} \quad (46)$$

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

$$\varepsilon_p = 43,1\sigma_p \quad (48)$$

where

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

ε_p is the peak uniaxial tensile strain ($\mu\varepsilon$);

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 [\(55\)](#):

$$\varepsilon_B = \frac{\sigma_o \varepsilon_A - \sigma_A \varepsilon_1}{\sigma_o + \sigma_A} \quad (49)$$

$$\varepsilon_1 = 0,5\varepsilon_o \quad (50)$$

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

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

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

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

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

where

ε_B is the residual strain when stress is unloaded to zero ($\mu\varepsilon$);

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

ε_D is the strain at point D during unloading ($\mu\varepsilon$);

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

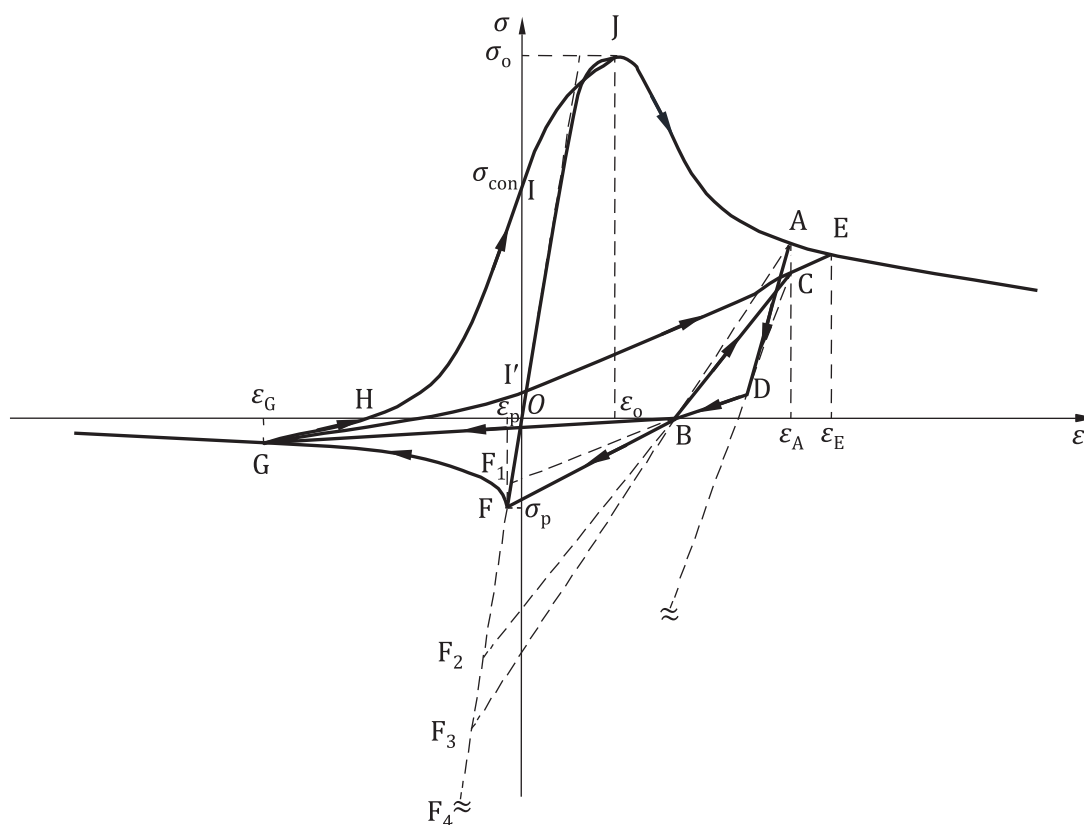


Figure 10 — Schematic diagram of stress-strain hysteretic relationship of concrete

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 \(60\)](#):

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

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

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

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

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

where

ε_H is the strain at point H when effect of cracked surface begins ($\mu\varepsilon$);

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 ($\mu\varepsilon$).

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.