



BSI Standards Publication

Design examples of concrete-filled steel tubular (CFST) hybrid structures in accordance with ISO 16521

National foreword

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Technical Report

ISO/TR 25439

Design examples of concrete-filled steel tubular (CFST) hybrid structures in accordance with ISO 16521

Exemples de conception de structures hybrides en tubes d'acier remplis de béton (CFST) conformément à l'ISO 16521

**First edition
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Foreword

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A list of all parts in the ISO/TR 25439 series can be found on the ISO website.

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

This document provides informative design examples of concrete-filled steel tubular (CFST) hybrid structures in accordance with ISO 16521, *Design of concrete-filled steel tubular (CFST) hybrid structures*. ISO 16521 stipulates the conceptional design, refined analysis method, simplified design formulae based on refined analysis and experimental verifications, and detailing design of CFST hybrid structures. Detailed calculations are provided in the design examples and the corresponding reference subclauses in ISO 16521 are indicated.

For trussed CFST hybrid structures, four design examples are provided, which include a three-chord structure and two four-chord structures without concrete slab, and a four-chord structure with a concrete slab. General requirements are verified and indices for cross-sections are calculated. The resistances of the hybrid structures as well as the CFST chords in compression, bending, combined compression and bending, and shear, are calculated in accordance with ISO 16521:2024, Clause 11. The protective design of corrosion resistance and impact resistance is presented in accordance with ISO 16521:2024, Clause 14. The detailing requirements and the resistances of the joints are verified in accordance with ISO 16521:2024, Clause 15. Finally, the verification of the limiting value of the core concrete void in the steel tube is carried out in accordance with ISO 16521:2024, Clause 16.

For concrete-encased CFST hybrid structures, four design examples are presented, i.e., a single-chord structure, a six-chord structure, and a four-chord structure with circular CFST members and a four-chord structure with rectangular CFST members. General requirements are verified and indices for cross-sections are calculated. Resistances in compression, combined compression and bending, resistance considering long-term load effects, shear resistance, are verified in accordance with ISO 16521:2024, Clause 12. Fire resistance is calculated in accordance with ISO 16521:2024, Clause 14.

[Clause 6](#) of this document presents a global structural analysis example. A concrete-encased CFST hybrid arch structure is analysed in accordance with ISO 16521:2024, Clause 10, which employs a fibre-based model. It includes the determination of load, model establishment, load-displacement relationship analysis, deformation analysis, and stress and strain analysis.

[Annex A](#) is provided in this document to present some experimental data on CFST hybrid structures. These published experimental data serve as an important basis for the development of ISO 16521. Furthermore, they provide verifications of the design methods of CFST hybrid structures and examples for design of the structures based on experimental data, as stipulated in the standard.

It is worth pointing out that the design examples are only provided to help readers in using ISO 16521 and they are not based on any specific engineering projects.

Design examples of concrete-filled steel tubular (CFST) hybrid structures in accordance with ISO 16521

1 Scope

This document provides design examples of concrete-filled steel tubular (CFST) hybrid structures in accordance with ISO 16521.

This document includes the design calculation of major structural types in ISO 16521, i.e., trussed CFST hybrid structures, concrete-encased CFST hybrid structures. The design examples cover the major loading cases for the structures and follow the design procedure presented in ISO 16521:2024, Clause 6.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes 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 16521, *Design of concrete-filled steel tubular (CFST) hybrid structures*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 16521 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/>

4 Design examples of trussed CFST hybrid structures

In this clause, the design of four examples of trussed concrete-filled steel tubular (CFST) hybrid structures with and without a concrete slab are conducted in accordance with the corresponding clauses of ISO 16521. The general design and construction procedure in ISO 16521:2024, 6.1, is followed, and the correspondence between this clause and the detailed clauses of ISO 16521:2024 are shown in [Table 1](#).

Table 1 — Design and construction procedure of trussed CFST hybrid structures

Procedure	Clause in ISO 16521:2024	Subclause in this document
Preliminary structural design	Clauses 5 to 8	4.1
Definition of actions (loads)	Clause 9	/
Structural analysis	Clause 10	4.2
Ultimate limit states design	Clause 11	4.3
Serviceability limit states design	Clause 13	/
Protective design	Clause 14	4.4
Detailing design	Clause 15	4.1 and 4.5
Construction and acceptance	Clause 16	4.6

Four examples are designed as shown in Table 2. Circular (Examples T1, T2, T4) and square (Example T3) steel tubes are used for the CFST chords and circular steel tubes are used as the webs, and the interval lengths of the chords l_1 (Figure 13 in ISO 16521) are 3 000 mm, 7 750 mm, 7 750 mm, and 3 000 mm for the four examples respectively.

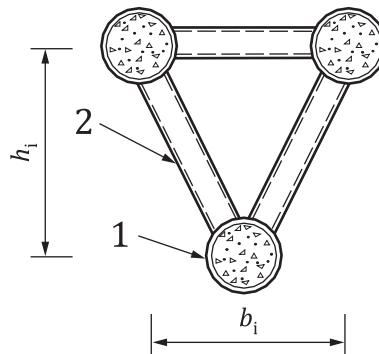
Table 2 — Geometric and material properties of design examples

Example	Chords in compression $D \times t$ or $B \times t$ (mm)	Chords in tension $D \times t$ or $B \times t$ (mm)	Web $d_w \times t_w$ (mm)	h_i (mm)	b_i (mm)	f_y (MPa)	f_{ck} (MPa)
T1	$D \times t$, 720×20	$D \times t$, 720×20	392×18	2 000	2 000	355	41
T2	$D \times t$, 1 400×30	$D \times t$, 1 400×30	850×18	8 500	8 500	420	60
T3	$B \times t$, 1 400×40	$B \times t$, 1 400×40	850×18	8 500	8 500	420	60
T4	$D \times t$, 400×10	$D \times t$, 700×25	280×14	1 875	1 875	355	41

NOTE D is the outside diameter of the circular CFST member, B is the width of the square CFST member, t is the wall thickness of the steel tube of the CFST member, d_w is the outside diameter of the web, t_w is the wall thickness of the steel tube of the web, h_i is the distance along the cross-sectional height between the centroids of compression and the tension chords, b_i is the distance between the centre points of chords out of the plane of bending moment, f_y is the characteristic yield strength of steel, f_{ck} is the characteristic compressive cylinder strength of concrete.

Among them, Example T1 is a three-chord trussed CFST hybrid structures without a concrete slab and with circular CFST members (Figure 1); Example T2 and Example T3 are four-chord trussed CFST hybrid structures without a concrete slab and with circular and square CFST members, respectively (Figure 2 and Figure 3); Example T4 is a four-chord trussed CFST hybrid structure with a concrete slab and with circular CFST members (Figure 4).

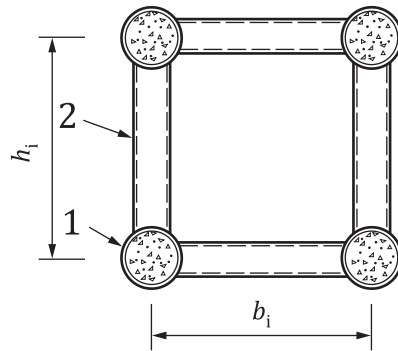
For example T4, the characteristic compressive strength of concrete slab is 33 MPa, and the thickness h_b is 150 mm. Other dimensions (shown in Figure 4) are: $b_f = 1\,300$ mm, $b_t = 900$ mm, $b_m = 950$ mm. Twenty-five longitudinal reinforcement bars with a diameter of 25 mm are uniformly distributed in the concrete slab. The thickness of the concrete cover is 35 mm.



Key

- 1 CFST chords
- 2 webs

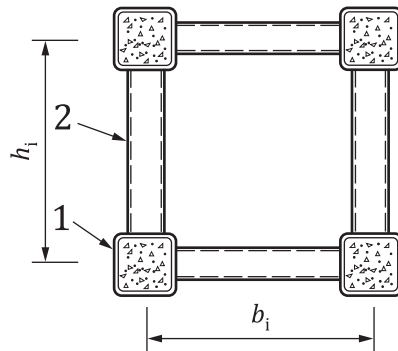
Figure 1 — Cross-section of three-chord trussed CFST hybrid structure with circular CFST members (Example T1)



Key

- 1 CFST chords
- 2 webs

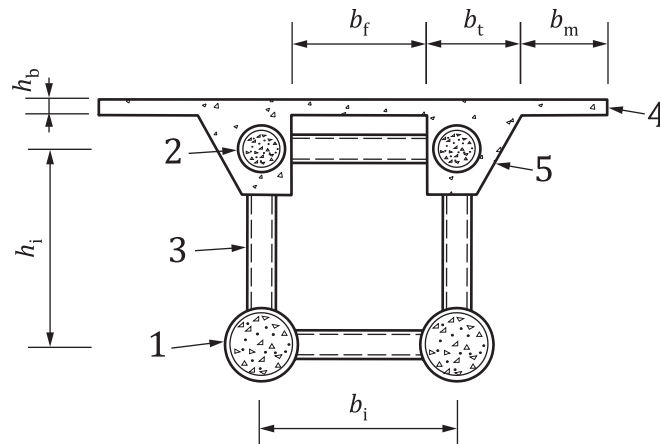
Figure 2 — Cross-section of four-chord trussed CFST hybrid structure with circular CFST members (Example T2)



Key

- 1 CFST chords
- 2 webs

Figure 3 — Cross-section of four-chord trussed CFST hybrid structure with circular CFST members (Example T3)

**Key**

- 1 CFST chords in tension
- 2 CFST chords in compression
- 3 webs
- 4 concrete slab
- 5 concrete encasement

Figure 4 — Cross-section of four-chord trussed CFST hybrid structure with a concrete slab and circular CFST members (Example T4)

4.1 General requirements

4.1.1 Match of materials (ISO 16521:2024, 5.2.6)

As shown in [Table 3](#), the four examples meet the requirements of ISO 16521:2024, 5.2.6, for the match relationships between the steel tubes and their core concrete. Other requirements of material strength in ISO 16521:2024, Clause 5, are also checked and confirmed for the four examples.

Table 3 — Match of materials

Example	Characteristic yield strength of steel tube f_y (MPa)	Characteristic strength of core concrete f_{ck} (MPa)
T1	355	41
T2	420	60
T3	420	60
T4	355	41

4.1.2 Requirements of CFST chords (ISO 16521:2024, 7.1)

The outside diameters of the steel tubes in the four examples are greater than 200 mm and their wall thicknesses are greater than 4 mm, which meet the requirements of ISO 16521:2024, 7.1.1.1 and 7.1.1.2. The outside diameter-to-thickness ratios (D/t) or width-to-thickness ratios (B/t), cross-sectional steel ratios (α_s), and confinement factors (ξ) of the CFST chords are also checked in [Table 4](#), which satisfy the requirements of ISO 16521:2024, 7.1.1.3, 7.1.1.4 and 7.1.1.5.

Table 4 — General requirements check of CFST chords

Example	Outside diameter-to-thickness ratio D/t or width-to-thickness ratio B/t		Cross-sectional steel ratio α_s		Confinement factor ξ	
	Value	Limiting value	Value	Limit value	Value	Limiting value
T1	36,0	16,6 to 99,3	0,12	0,06 to 0,23	1,33	0,6 to 4,0
T2	46,7	14,0 to 83,9	0,09		0,87	
T3	35,0	7,5 to 48,6	0,12	0,10 to 0,23	1,18	1,0 to 4,0
T4 (chords in compression)	40,0	16,6 to 99,3	0,11	0,06 to 0,23	1,18	0,6 to 4,0
T4 (chords in tension)	28,0	16,6 to 99,3	0,16		1,70	

NOTE Steel ratio (α_s) as defined in ISO 16521:2024, 7.1.1.5, is the ratio of the cross-sectional area of the hollow steel tube to the cross-sectional area of the core concrete. Confinement factor (ξ) as defined in ISO 16521:2024, 3.6, is the ratio of the nominal compressive strength of cross-section of the steel tube to that of the core concrete in a CFST member.

4.1.3 Requirements of webs (ISO 16521:2024, 15.2.4)

The requirements of ISO 16521:2024, 15.2.4, regarding the geometric parameters of the webs are checked, as shown in [Table 5](#).

Table 5 — Ratios of steel tubular webs

Example	l_1/h_i		A_w/A_s	
	Value	Limiting value	Value	Limiting value
T1	1,5	$\leq 4,0$	0,48	$\geq 0,2$
T2	0,9		0,36	
T3	0,9		0,28	
T4	1,6		0,22	

NOTE l_1 and h_i are the distance between the centroids of horizontal webs and the distance between the centroids of chords, respectively. A_w and A_s are the cross-sectional area of the hollow steel tubular web and the cross-sectional area of the single chord, respectively.

4.2 Calculation of indices for cross-sections

Both the strength and stiffness indices for cross-sections of the four examples are calculated in [4.2](#) in accordance with ISO 16521:2024, 10.3.

4.2.1 Strength (ISO 16521:2024, 10.3.1)

The CFST chord of Example T1 is taken as an example:

The characteristic compressive strength of CFST cross-section f_{scy} [Formula (64) of ISO 16521:2024], the design compressive strength f_{sc} [Formula (63) of ISO 16521:2024], and the design shear strength f_{sv} [Formula (65) of ISO 16521:2024] are calculated as follows:

$$\begin{aligned}
 f_{scy} &= (1,14 + 1,02\xi) \alpha_c f_{ck} \\
 &= (1,14 + 1,02 \times 1,33) \times 0,79 \times 41 \\
 &= 80,86 \text{ MPa}
 \end{aligned} \tag{1}$$

$$f_{sc} = \frac{f_{scy}}{\gamma_{msc}} = \frac{80,86}{1,40} = 57,76 \text{ MPa} \quad (2)$$

$$f_{sv} = (0,422 + 0,313\alpha_s^{2,33})\xi^{0,134} f_{sc} = (0,422 + 0,313 \times 0,12^{2,33}) \times 1,33^{0,134} \times 57,76 = 25,46 \text{ MPa} \quad (3)$$

where, α_c is the strength adjustment coefficient as defined in ISO 16521:2024, 7.1.1.6. γ_{msc} is taken as 1,40 in accordance with ISO 16521:2024, 10.3.1.1.

The design strength indices of CFST cross-sections for each example are summarized in [Table 6](#).

Table 6 — Design values of strength indices of CFST chords

Example	CFST chord	
	f_{sc} (MPa)	f_{sv} (MPa)
T1	57,76	25,46
T2	64,17	26,64
T3	69,23	32,99
T4 (upper chords)	54,32	23,55
T4 (lower chords)	66,54	30,46

4.2.2 Stiffness (ISO 16521:2024, 10.3.2)

Example T1 is taken as an example.

Elastic compression stiffness $(EA)_{c,h}$ [Formula (70) of ISO 16521:2024], elastic tension stiffness $(EA)_{t,h}$ [Formula (71)], elastic flexural stiffness $(EI)_h$ [Formula (72) of ISO 16521:2024], and elastic shear stiffness $(GA)_h$ [Formula (73) of ISO 16521:2024] of the cross-section of the trussed CFST hybrid structure are calculated as follows:

$$(EA)_{c,h} = \sum (E_s A_s + E_{s,l} A_l + E_{c,c} A_c) + E_{c,oc} A_{oc} = 3 \times (206\,000 \times 43\,982 + 28\,814 \times 363\,168) = 5,86 \times 10^7 \text{ kN} \quad (4)$$

$$(EA)_{t,h} = \sum (E_s A_s + E_{s,l} A_l) = 3 \times (206\,000 \times 43\,982) = 2,72 \times 10^7 \text{ kN} \quad (5)$$

$$(EI)_h = E_s I_{s,h} + E_{s,l} I_{l,h} + E_{c,c} I_{c,h} + E_{c,oc} I_{oc,h} = (2 \times 206\,000 \times 2,22 \times 10^{10} + 206\,000 \times 8,09 \times 10^{10}) + (2 \times 28\,814 \times 1,72 \times 10^{11} + 28\,814 \times 6,56 \times 10^{11}) = 5,46 \times 10^7 \text{ kN} \cdot \text{m}^2 \quad (6)$$

$$\begin{aligned}
 (GA)_h &= \sum (G_s A_s + G_{c,c} A_c) + G_{c,oc} A_{oc} \\
 &= 3 \times (79\,231 \times 43\,982 + 12\,006 \times 363\,168) \\
 &= 2,35 \times 10^7 \text{ kN}
 \end{aligned}
 \tag{7}$$

where the modulus of elasticity, Poisson's ratio, and shear modulus of the steel are taken as $2,06 \times 10^5$ MPa, 0,3, and 79 231 MPa, respectively; the modulus of elasticity, Poisson's ratio and shear modulus of the core concrete are taken as 28 814 MPa, 0,2 and 12 006 MPa, respectively.

The calculation results of each example are summarized in [Table 7](#).

Table 7 — Stiffness values of trussed CFST hybrid cross-sections

Example	$(EA)_{c,h}$ (kN)	$(EA)_{t,h}$ (kN)	$(EI)_h$ (kN·m ²)	$(GA)_h$ (kN)
T1	$5,86 \times 10^7$	$2,72 \times 10^7$	$5,46 \times 10^7$	$2,35 \times 10^7$
T2	$3,03 \times 10^8$	$1,06 \times 10^8$	$5,52 \times 10^9$	$1,23 \times 10^8$
T3	$4,22 \times 10^8$	$1,79 \times 10^8$	$7,72 \times 10^9$	$1,70 \times 10^8$
T4	$1,00 \times 10^8$	$2,69 \times 10^7$	$4,69 \times 10^6$	$4,09 \times 10^7$

4.3 Calculation of structural resistances

The design processes for the ultimate limit states of trussed CFST hybrid structures are presented. The resistances of the global structures ([4.3.1](#)) as well as their chords and webs ([4.3.2](#) and [4.3.3](#)) are both calculated.

4.3.1 Resistance in axial compression (ISO 16521:2024, 11.2.1)

In accordance with ISO 16521:2024, 11.2.1, the resistances in axial compression of the trussed CFST hybrid structures without a concrete slab, i.e., Example T1, Example T2 and Example T3, are calculated.

Geometric parameters: The longitudinal lengths L of the trussed CFST hybrid structures in Example T1, Example T2 and Example T3 are 40 000 mm, 223 784 mm and 223 784 mm, respectively.

Example T1 is taken as an example for calculation:

Step 1: Calculation of the equivalent slenderness ratio

Through a global structural analysis, the equivalent slenderness ratio of the trussed CFST hybrid structure is determined as 76,53.

Step 2: Calculation of the stability factor φ

In accordance with ISO 16521:2024, 11.2.1, the stability factor φ for the trussed CFST hybrid structure in axial compression is determined.

Critical slenderness ratio for the elasto-plastic buckling [Formula (84) of ISO 16521:2024]:

$$\begin{aligned}
 \lambda_o &= \pi \sqrt{\frac{420\xi + 550}{(1,02\xi + 1,14)\alpha_c f_{ck}}} \\
 &= \pi \times \sqrt{\frac{420 \times 1,33 + 550}{(1,02 \times 1,33 + 1,14) \times 0,79 \times 41}} \\
 &= 11,63
 \end{aligned}
 \tag{8}$$

Critical slenderness ratio for the elastic buckling [Formula (83) of ISO 16521:2024]:

$$\begin{aligned}\lambda_p &= \frac{1743}{\sqrt{f_y}} \\ &= \frac{1743}{\sqrt{355}} \\ &= 92,51\end{aligned}\quad (9)$$

$$\begin{aligned}d &= \left[13\,000 + 4\,657 \ln\left(\frac{235}{f_y}\right) \right] \left(\frac{25}{\alpha_c f_{ck} + 5} \right)^{0,3} \left(\frac{\alpha_s}{0,1} \right)^{0,05} \\ &= \left[13\,000 + 4\,657 \times \ln\left(\frac{235}{355}\right) \right] \times \left(\frac{25}{0,79 \times 41 + 5} \right)^{0,3} \times \left(\frac{0,12}{0,1} \right)^{0,05} \\ &= 9\,908,52\end{aligned}\quad (10)$$

$$\begin{aligned}e &= \frac{-d}{(\lambda_p + 35)^3} \\ &= -\frac{9\,913,07}{(92,51 + 35)^3} \\ &= -4,78 \times 10^{-3}\end{aligned}\quad (11)$$

$$\begin{aligned}a &= \frac{1 + (35 + 2\lambda_p - \lambda_0)e}{(\lambda_p - \lambda_0)^2} \\ &= \frac{1 + (35 + 2 \times 92,51 - 11,63) \times (-4,78 \times 10^{-3})}{(92,51 - 11,63)^2} \\ &= 5,96 \times 10^{-7}\end{aligned}\quad (12)$$

$$\begin{aligned}b &= e - 2a\lambda_p \\ &= -4,78 \times 10^{-3} - 2 \times 5,96 \times 10^{-7} \times 92,51 \\ &= -4,89 \times 10^{-3}\end{aligned}\quad (13)$$

$$\begin{aligned}c &= 1 - a\lambda_0^2 - b\lambda_0 \\ &= 1 - 5,96 \times 10^{-7} \times 11,63^2 - (-4,89 \times 10^{-3}) \times 11,63 \\ &= 1,06\end{aligned}\quad (14)$$

The equivalent slenderness ratio of the trussed CFST hybrid structure λ is greater than λ_0 and less than λ_p , so the stability factor φ [Formula (77) of ISO 16521:2024]:

$$\begin{aligned}\varphi &= a\lambda^2 + b\lambda + c \\ &= 5,96 \times 10^{-7} \times 76,53^2 + (-4,89 \times 10^{-3}) \times 76,53 + 1,06 \\ &= 0,69\end{aligned}\quad (15)$$

Step 3: Calculation of the resistance

In accordance with ISO 16521:2024, 11.2.1, the resistance of the trussed CFST hybrid structure can be calculated.

Resistance of the cross-section of a single CFST chord to compression [Formula (75) of ISO 16521:2024]:

$$\begin{aligned} N_c &= f_{sc} A_{sc} \\ &= 57,76 \times 407\,150 \\ &= 2,35 \times 10^4 \text{ kN} \end{aligned} \quad (16)$$

where A_{sc} is the cross-sectional area of a single CFST chord.

Resistance of the trussed CFST hybrid structure in axial compression [Formula (74) of ISO 16521:2024]:

$$\begin{aligned} N_u &= \varphi \sum N_c \\ &= 0,69 \times 3 \times 2,35 \times 10^7 \\ &= 4,86 \times 10^4 \text{ kN} \end{aligned} \quad (17)$$

Similarly, the resistances of the trussed CFST hybrid structure in Example T2 and Example T3 in axial compression are determined as $1,61 \times 10^5$ kN and $2,15 \times 10^5$ kN, respectively.

4.3.2 Bending resistance (ISO 16521:2024, 11.2.2)

In accordance with ISO 16521:2024, 11.2.2, the bending resistances of the trussed CFST hybrid structures with and without a concrete slab, i.e., Examples T1-T4, are calculated.

Example T1 is taken as an example for calculation:

1) Trussed CFST hybrid structure without a concrete slab

Resistance of the cross-section of a single CFST chord to tension [Formula (95) of ISO 16521:2024]:

$$\begin{aligned} N_t &= (1,1 - 0,4\alpha_s) f A_s \\ &= (1,1 - 0,4 \times 0,12) \times 308,70 \times 43\,982 \\ &= 1,43 \times 10^4 \text{ kN} \end{aligned} \quad (18)$$

where the design strength of steel f is taken as $355/1,15 = 308,70$ MPa.

Bending resistance of the trussed CFST hybrid structure without a concrete slab [Formula (94) of ISO 16521:2024]:

$$\begin{aligned} M_u &= \min \left\{ \varphi \sum N_c, \sum N_t \right\} h_i \\ &= \min \left\{ 4,86 \times 10^4, 4,29 \times 10^4 \right\} \times 2 \\ &= 8,58 \times 10^4 \text{ kN} \cdot \text{m} \end{aligned} \quad (19)$$

Similarly, the bending resistances of the trussed CFST hybrid structure in Example T2 and Example T3 are determined as $1,37 \times 10^6$ kN·m and $1,83 \times 10^6$ kN·m, respectively.

2) Trussed CFST hybrid structure with a concrete slab

For the trussed CFST hybrid structure with a concrete slab, the position of the neutral axis is determined first.

As stipulated in ISO 16521:2024, 11.2.2.3, the resistance of the concrete slab in axial compression N_{slab} is calculated in accordance with relevant national standards. In this example, the resistance is calculated as the summation of the resistances of the concrete and the compression longitudinal reinforcement, with the stability factor (φ_c) considered, i.e., $N_{slab} = \varphi_c \left(\sum b_e h_b f_c + A_l' f_l' \right)$, where A_l' and f_l' are the cross-sectional area and design strength of the compression longitudinal reinforcement. The value of φ_c is determined as

0,75. The effective width of the concrete slab corresponding to the single chord (b_e) is determined as 2 500 mm.

The stability factor of the chord in compression $\varphi_{sc} = 0,94$ is calculated by the same method as in ISO 16521:2024, 11.2.1.

$$\begin{aligned} & \varphi_c \left[\sum b_e h_b f_c + A_l' f_l' \right] + \varphi_{sc} f_{sc} \sum A_{sc} \\ &= 0,75 \times (2 \times 2500 \times 150 \times 22 + 25 \times 490,63 \times 347,83) \\ &= 1,56 \times 10^4 \text{ kN} < (1,1 - 0,4\alpha_s) f \sum A_s \\ &= 3,39 \times 10^4 \text{ kN} \end{aligned} \quad (20)$$

Therefore, the neutral axis of the cross-section is determined to be within the height of the webs. Consequently, the bending resistance is calculated in accordance with the schematic diagram given by Figure 13 in ISO 16521:2024, 11.2.2.3.

$$\begin{aligned} M_u &= \varphi_c \left[\sum b_e h_b f_c + A_l' f_l' \right] (h - D_t / 2 - h_b / 2) + \varphi_{sc} f_{sc} \sum A_{sc} h_i \\ &= 0,75 \times [2 \times 2500 \times 150 \times 22 + 25 \times 490,63 \times 347,83] \times 2250 + 0,94 \times 54,32 \times 2 \times 125600 \times 1875 \\ &= 5,91 \times 10^4 \text{ kN} \cdot \text{m} \end{aligned} \quad (21)$$

where h is the height of the cross-section of the trussed CFST hybrid structure with a concrete slab, which is taken as 2 675 mm.

4.3.3 Resistance in combined compression and bending (ISO 16521:2024, 11.2.3)

In accordance with ISO 16521:2024, 11.2.3, the resistance of the trussed CFST hybrid structure without a concrete slab in combined compression and bending is calculated.

Load definitions and geometric parameters: The factored axial compression $N = 20\,000$ kN, the initial deflection of the structure $u_0 = 100$ mm, the distances between the centre points of end cross-sections (L in Figure 14 of ISO 16521:2024) of Example T1, Example T2 and Example T3 are 40 000 mm, 223 784 mm and 223 784 mm, respectively.

Example T1 is taken as an example for calculation:

Distance from the cross-sectional centre of gravity to the centroidal axis of the chord in the compression zone (r_c in Figure 14 of ISO 16521:2024) [Formula (98) of ISO 16521:2024]:

$$\begin{aligned} r_c &= \frac{N_{uc2}}{N_{uc1} + N_{uc2}} h_i \\ &= \frac{1}{3} \times 2000 \\ &= 666,67 \text{ mm} \end{aligned} \quad (22)$$

Distance from the cross-sectional centre of gravity to the centroidal axis of the chord in the tension zone (r_t in Figure 14 of ISO 16521:2024) [Formula (99) of ISO 16521:2024]:

$$\begin{aligned} r_t &= \frac{N_{uc1}}{N_{uc1} + N_{uc2}} h_i \\ &= \frac{2}{3} \times 2000 \\ &= 1333,33 \text{ mm} \end{aligned} \quad (23)$$

Axial force corresponding to the equilibrium point of the N - M correlation curve [Formula (96) of ISO 16521:2024]:

$$\begin{aligned} N_B &= \varphi \sum N_c - \sum N_t \\ &= 0,69 \times 2 \times (2,35 \times 10^4) - 1,43 \times 10^4 \\ &= 1,81 \times 10^4 \text{ kN} \end{aligned} \quad (24)$$

Bending moment corresponding to the equilibrium point of tension and compression boundary in resistance N - M correlation curve [Formula (97) of ISO 16521:2024]:

$$\begin{aligned} M_B &= \varphi \sum N_c r_c + \sum N_t r_t \\ &= (0,69 \times 2 \times 2,35 \times 10^4 \times 666,67 + 1,43 \times 10^4 \times 1333,33) / 1000 \\ &= 4,07 \times 10^4 \text{ kN} \cdot \text{m} \end{aligned} \quad (25)$$

Euler's critical force calculated from the equivalent slenderness ratio [Formula (101) of ISO 16521:2024]:

$$\begin{aligned} N_E &= \pi^2 \sum (EA)_c / \lambda^2 \\ &= \pi^2 \times 2 \times (8,80 \times 10^9 + 1,05 \times 10^{10}) / 76,53^2 \\ &= 6,50 \times 10^4 \text{ kN} \end{aligned} \quad (26)$$

Factored bending moment caused by the initial bending of the structure [Formula (104) of ISO 16521:2024]:

$$\begin{aligned} M &= Nu_0 \\ &= 20\,000 \times 0,1 \\ &= 2\,000 \text{ kN} \cdot \text{m} \end{aligned} \quad (27)$$

Since $u = \frac{M}{N} = 0,1 \text{ m} < \frac{M_B}{N_B} = 2,18 \text{ m}$, verify the resistance in combined compression and bending in accordance with Formula (100) of ISO 16521:2024:

$$\begin{aligned} &\frac{N}{\varphi f_{sc} \sum A_{sc}} + \frac{M}{W_{sc} (1 - \varphi N / N_E) f_{sc}} \\ &= \frac{20\,000 \times 10^3}{0,69 \times 57,76 \times (3 \times 407\,150)} + \frac{20\,000 \times 10^3 \times 100}{8,44 \times 10^8 \times [1 - 0,69 \times (2 \times 10^7) / (6,50 \times 10^7)] \times 57,70} \\ &= 0,46 \leq 1 \end{aligned} \quad (28)$$

Thus, Example T1 satisfies the requirements of the resistance of the trussed CFST hybrid structure in combined compression and bending.

Similarly, Example T2 and Example T3 also satisfy the requirements of the resistance of the trussed CFST hybrid structure in combined compression and bending.

4.3.4 Resistances of CFST chords (ISO 16521:2024, 11.2.4)

The resistances of each chord in trussed CFST hybrid structures are also calculated. In accordance with ISO 16521:2024, 11.2.4, the resistances of chords are calculated in various individual loads and combined loads, which are axial tension, axial compression, bending, combined compression and bending, combined tension and bending, shear, torsion, combined compression and torsion, combined compression bending and torsion, combined compression, bending and shear, and combined compression, bending, torsion and shear.

Factored loads for the verifications are set as follows:

Combined compression and bending: Factored axial compression $N = 5\,000$ kN, factored bending moment $M = 500$ kN·m.

Combined tension and bending: Factored axial tension $N = 4\,000$ kN, factored bending moment $M = 500$ kN·m.

Combined compression and torsion: Factored axial compression $N = 9\,000$ kN, factored torsional moment $T = 1\,000$ kN·m.

Combined compression, bending, and torsion: Factored axial compression $N = 4\,000$ kN, factored bending moment $M = 500$ kN·m, factored torsional moment $T = 1\,000$ kN·m.

Combined compression, bending, and shear: Factored axial compression $N = 4\,000$ kN, factored bending moment $M = 500$ kN·m, shear force $V = 2\,000$ kN.

Combined compression, bending, torsion, and shear: Factored axial compression $N = 4\,000$ kN, factored bending moment $M = 500$ kN·m, factored torsional moment $T = 1\,000$ kN·m, factored shear force $V = 2\,000$ kN.

1) Resistances in axial compression and axial tension

The CFST chord of Example T1 is taken as an example. The resistances in axial compression and tension of the chord [Formulae (105) and (106) of ISO 16521:2024] are calculated respectively as follows:

$$\begin{aligned}\varphi N_c &= 0,98 \times 2,35 \times 10^4 \\ &= 2,30 \times 10^4 \text{ kN}\end{aligned}\tag{29}$$

$$N_t = 1,43 \times 10^4 \text{ kN}\tag{30}$$

where the parameters for the calculation of the stability factor φ are listed in [Table 8](#).

Table 8 — Parameters for calculation of resistance in axial compression

Parameter	λ_0	λ_p	λ	a	b	c	d	e
Value	11,63	92,51	15	$-5,96 \times 10^{-7}$	$-4,89 \times 10^{-3}$	1,06	9 913,07	$-4,78 \times 10^{-3}$

Similarly, it can be calculated that the resistances in axial compression and tension of a single chord in Example T2 are $9,88 \times 10^4$ kN and $5,01 \times 10^4$ kN, respectively, and the resistances in axial compression and tension of a single chord in Example T3 are $1,36 \times 10^5$ kN and $8,34 \times 10^4$ kN, respectively.

2) Bending resistance

The CFST chord of Example T1 is taken as an example. The section modulus of the chord [Formula (110) of ISO 16521:2024] and the plastic development factor of the bending resistance [Formula (109) of ISO 16521:2024]:

$$\begin{aligned}W_{sc1} &= \frac{\pi D^3}{32} \\ &= \pi \times 720^3 / 32 \\ &= 3,66 \times 10^7 \text{ mm}^3\end{aligned}\tag{31}$$

$$\begin{aligned}
 \gamma_m &= 1,1 + 0,48 \ln(\xi + 0,1) \\
 &= 1,1 + 0,48 \times \ln(1,33 + 0,1) \\
 &= 1,27
 \end{aligned} \tag{32}$$

Bending resistance of the CFST chord [Formula (108) of ISO 16521:2024]:

$$\begin{aligned}
 M_{cu} &= \gamma_m W_{sc1} f_{sc} \\
 &= 1,27 \times (3,66 \times 10^7) \times 57,76 \\
 &= 2,68 \times 10^3 \text{ kN} \cdot \text{m}
 \end{aligned} \tag{33}$$

Similarly, the bending resistances of a single chord in Example T2 and Example T3 are $1,87 \times 10^4 \text{ kN} \cdot \text{m}$ and $3,67 \times 10^4 \text{ kN} \cdot \text{m}$, respectively.

3) Resistance in combined compression and in-plane bending

The CFST chord of Example T1 is taken as an example.

Step 1: Calculation of the resistance of the cross-section

$$\begin{aligned}
 \eta_0 &= 0,1 + 0,14 \xi^{-0,84} \\
 &= 0,1 + 0,14 \times 1,33^{-0,84} \\
 &= 0,21
 \end{aligned} \tag{34}$$

$$\begin{aligned}
 \varsigma_0 &= 1 + 0,18 \xi^{-1,15} \\
 &= 1 + 0,18 \times 1,33^{-1,15} \\
 &= 1,13
 \end{aligned} \tag{35}$$

$$\begin{aligned}
 c &= \frac{2(\varsigma_0 - 1)}{\eta_0} \\
 &= \frac{2 \times (1,13 - 1)}{0,21} \\
 &= 1,24
 \end{aligned} \tag{36}$$

$$\begin{aligned}
 b &= \frac{1 - \varsigma_0}{\eta_0^2} \\
 &= \frac{1 - 1,13}{0,21^2} \\
 &= -2,95
 \end{aligned} \tag{37}$$

$$\begin{aligned}
 a &= 1 - 2\eta_0 \\
 &= 1 - 2 \times 0,21 \\
 &= 0,58
 \end{aligned} \tag{38}$$

$N_{cd} / N_c = 0,21 < 2\eta_0$, so the resistance of the cross-section is verified in accordance with Formula (112) of ISO 16521:2024.

$$\frac{-bN_{cd}^2}{N_c^2} - \frac{cN_{cd}}{N_c} + \frac{M_{cd}}{M_{cu}} = \frac{2,95 \times (5 \times 10^6)^2}{(2,35 \times 10^7)^2} - \frac{1,24 \times (5 \times 10^6)}{2,35 \times 10^7} + \frac{5 \times 10^8}{2,68 \times 10^9} = 0,06 \leq 1 \tag{39}$$

Resistance of the cross-section satisfies the requirements.

Step 2: Calculation of the resistance of the single CFST chord

$$c = \frac{2(\zeta_0 - 1)}{\eta_0} = \frac{2 \times (1,13 - 1)}{0,21} \quad (40)$$

$$N_{cE} = \pi^2 (EA)_c / \lambda_c^2 = \frac{\pi^2 \times 1,956 \times 10^{10}}{15^2} \quad (41)$$

$$= 8,58 \times 10^5 \text{ kN}$$

$$d = 1 - 0,4 \left(\frac{N_{cd}}{N_{cE}} \right) = 1 - 0,4 \times \left(\frac{5 \times 10^6}{8,58 \times 10^5 \times 1000} \right) \quad (42)$$

$$= 1,00$$

$$b = \frac{1 - \zeta_0}{\varphi^3 \eta_0^2} = \frac{1 - 1,13}{0,98^3 \times 0,21^2} \quad (43)$$

$$= -3,13$$

$$a = 1 - 2\varphi^2 \eta_0 = 1 - 2 \times 0,98^2 \times 0,21 \quad (44)$$

$$= 0,60$$

Since $N_{cd} / N_c = 0,21 < 2\varphi^3 \eta_0$, the resistance is verified in accordance with Formula (119) of ISO 16521:2024:

$$\frac{-bN_{cd}^2}{N_c^2} - \frac{cN_{cd}}{N_c} + \frac{1}{d} \frac{M_{cd}}{M_{cu}} = \frac{3,13 \times (5 \times 10^6)^2}{(2,35 \times 10^7)^2} - \frac{1,24 \times (5 \times 10^6)}{2,35 \times 10^7} + \frac{1}{1,00} \cdot \frac{5 \times 10^8}{2,66 \times 10^9} \quad (45)$$

$$= 0,07 \leq 1$$

The resistance of the single CFST chord in combined compression and in-plane bending satisfies the requirements.

Similarly, for Example T2 and Example T3, the resistances of a single chord in combined compression and in-plane bending satisfy the requirements, respectively.

4) Resistance in combined tension and in-plane bending

The CFST chord of Example T1 is taken as an example [Formula (125) of ISO 16521:2024]:

$$\frac{N_{td}}{(1,1 - 0,4\alpha_s) fA_s} + \frac{M_{cd}}{M_{cu}} = \frac{4 \times 10^6}{(1,1 - 0,4 \times 0,12) \times 308,70 \times 43\,982} + \frac{5 \times 10^8}{2,66 \times 10^9} \quad (46)$$

$$= 0,47 \leq 1$$

The resistance in combined tension and in-plane bending of the single CFST chord satisfies the requirements.

Similarly, the resistances in combined tension and in-plane bending of a single chord in Example T2 and Example T3 satisfy the requirements, respectively.

5) Shear resistance

The CFST chord of Example T1 is taken as an example [Formulae (127)-(128) of ISO 16521:2024].

$$\begin{aligned}\gamma_v &= 0,97 + 0,2 \ln \xi \\ &= 0,97 + 0,2 \times \ln 1,33 \\ &= 1,03\end{aligned}\tag{47}$$

$$\begin{aligned}V_{cu} &= \gamma_v A_{sc} f_{sv} \\ &= 1,03 \times 407\,150 \times 25,46 \\ &= 1,07 \times 10^4 \text{ kN}\end{aligned}\tag{48}$$

Similarly, the shear resistances of a single chord in Example T2 and Example T3 are $3,86 \times 10^4$ kN and $5,78 \times 10^4$ kN, respectively.

6) Torsional resistance

The CFST chord of Example T1 is taken as an example [Formulae (130)-(132) of ISO 16521:2024].

$$\begin{aligned}W_{sc,t} &= \frac{\pi D^3}{16} \\ &= \frac{\pi \times 720^3}{16} \\ &= 7,33 \times 10^7 \text{ mm}^3\end{aligned}\tag{49}$$

$$\begin{aligned}\gamma_t &= 1,294 + 0,267 \ln \xi \\ &= 1,294 + 0,267 \times \ln 1,33 \\ &= 1,37\end{aligned}\tag{50}$$

$$\begin{aligned}T_{cu} &= \gamma_t W_{sc,t} f_{sv} \\ &= 1,37 \times (7,33 \times 10^7) \times 25,46 \\ &= 2,56 \times 10^3 \text{ kN} \cdot \text{m}\end{aligned}\tag{51}$$

Similarly, it can be calculated that the torsional resistances of a single chord in Example T2 and Example T3 are $1,80 \times 10^4$ kN·m and $2,52 \times 10^4$ kN·m, respectively.

7) Resistance in combined compression and torsion

The CFST chord of Example T1 is taken as an example.

Step 1: Calculation of the resistance of the cross-section [Formula (133) of ISO 16521:2024]

$$\begin{aligned}\left(\frac{N_{cd}}{N_c}\right)^{2,4} + \left(\frac{T_{cd}}{T_{cu}}\right)^2 &= \left(\frac{9 \times 10^6}{2,35 \times 10^7}\right)^{2,4} + \left(\frac{10^9}{2,55 \times 10^9}\right)^2 \\ &= 0,25 \leq 1\end{aligned}\tag{52}$$

Step 2: Calculation of the resistance of the chord [Formula (134) of ISO 16521:2024]

$$\begin{aligned}\left(\frac{N_{cd}}{\phi N_c}\right)^{2,4} + \left(\frac{T_{cd}}{T_{cu}}\right)^2 &= \left(\frac{9 \times 10^6}{0,98 \times 2,35 \times 10^7}\right)^{2,4} + \left(\frac{10^9}{2,55 \times 10^9}\right)^2 \\ &= 0,26 \leq 1\end{aligned}\tag{53}$$

Resistance of the single CFST chord in combined compression and torsion satisfies the requirements.