The Second Generation Eurocodes

Key changes and benefits through design examples

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Design Example 1
Design of simply supported column under compression

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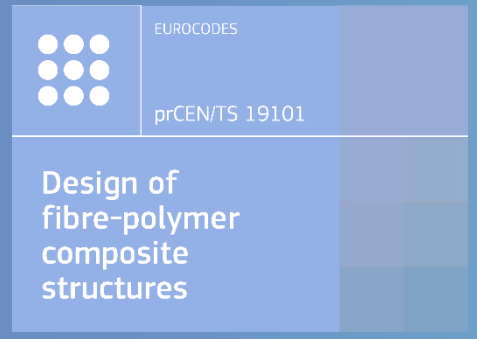
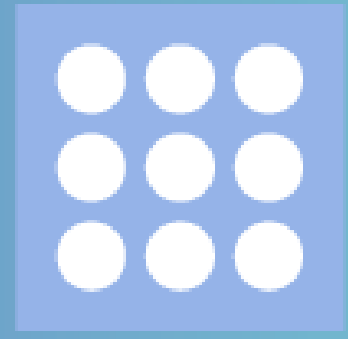




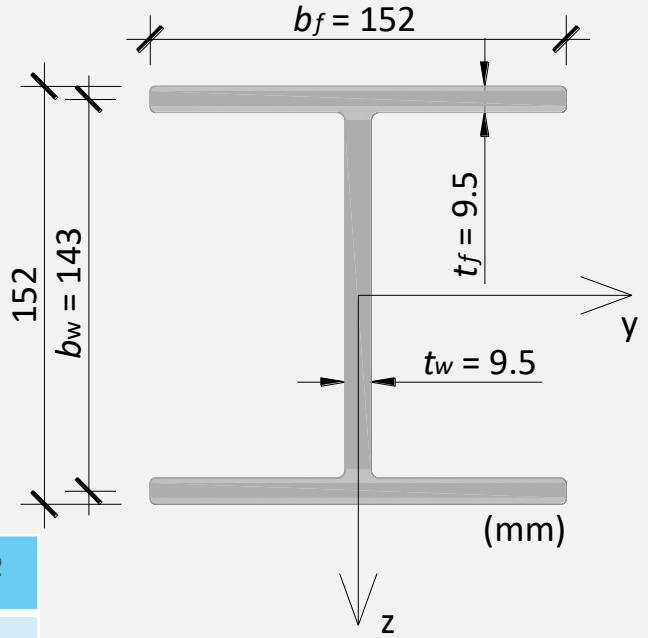
OUTLINE

I. DATA OF THE PROBLEM

I.1. GEOMETRICAL AND MATERIAL DATA

The column under analysis is a simply supported interior FRP column of a two-storey residential building:

1) Cross-section – H-profile 152×152×9.5 mm
2) Storey height (corresponding to the column length between storeys) – L = 2800 mm
3) Area of influence – A_{load} = 4000 × 2400 = 9.6×10^6 mm^2
4) Manufacturing – pultrusion
5) Materials – polyester resin and E-glass fibres
6) Service temperature (T_s) – 20°C
7) Fibre volume fraction (V_f) – 50%
8) Density (γ_{GFRP}) – 18 kN/m^3



Cross-section Area (A)	4152 mm^2
Major-axis radius of gyration (i_y)	63 mm
Minor-axis radius of gyration (i_z)	37 mm

I.2. MATERIAL PROPERTIES

- Material properties obtained from **standardized material characterization tests**
- **10 samples** were tested per test type

Property	Average	$V_{x,exp}$ [1]
Modulus in x-direction ($E_{x,cm}$)	29,9 GPa	6,3%
Modulus in y-direction ($E_{y,cm}$)	10,8 GPa	16,6%
Shear modulus in xy-plane ($G_{xy,m}$)	2,89 GPa	12,1%
Major Poisson's ratio ($v_{xy,m}$)	0,28	10,0%
Minor Poisson's ratio ($v_{yx,m}$)	0,10	10,0%
Compressive strength in x-direction ($f_{x,cm}$)	441,5 MPa	6,5%
Compressive strength in y-direction ($f_{y,cm}$)	121,6 MPa	13,7%
Shear strength in xy-plane ($f_{xy,m}$)	67,1 MPa	3,1%

- Glass transition temperature – $T_g > 100$ °C

[1] Coefficient of variation

I.3. LOADS

- Characteristic loads
  - Floors self-weight and other permanent loads ($g_{opl,k}$) – 1,0 kN/m^2
  - Variable loads (q_k) – 2,0 kN/m^2
  - Self-weight of the column ($g_{sw,k}$) – $A \times \gamma_{GFRP} = 0{,}07$ kN/m
- Loads acting on the column
  - From floors self-weight and other permanent loads ($G_{opl,k}$) – $2 \times A_{load} \times g_{opl,k} = 19{,}2$ kN
  - From variable loads (Q_k) – $2 \times A_{load} \times q_k = 38{,}4$ kN
  - From the self-weight of the column ($G_{sw,k}$) – $2 \times L \times q_{sw,k} = 0{,}42$ kN
- Combined loads
  - For ULS[2] verification – $N_{c,Ed} = \gamma_G \times (G_{opl,k} + G_{sw,k}) + \gamma_Q \times Q_k = 84{,}1$ kN
  - For creep rupture verification – $N_{c,qperm} = (G_{opl,k} + G_{sw,k}) + \psi_{2,1} \times Q_k = 31{,}1$ kN

2 storeys

9,6 m^2

1,35

Column length – 2,8 m

1,50

0,30

[2]Ultimate limit states

II. CHARACTERISTIC MATERIAL PROPERTIES, PARTIAL FACTORS & NOMINAL CONVERSION FACTOR

II.1. CHARACTERISTIC VALUES OF MATERIAL PROPERTIES

- Determine the **characteristic values of material properties**

$$f_{x,c,k} = f_{x,c,m} \cdot \exp\left\{-k_n \cdot \sqrt{\ln\left(1+V_{x,exp}^2\right)} - \frac{\ln}{2}\left(1+V_{x,exp}^2\right)\right\}$$

  - k_n = 1,92 – **10 samples** (Table D1 of EN 1990)

Property	Average	$V_{x,exp}$	Characteristic
Modulus in x-direction ($E_{x,c}$)	29,9 GPa	6,3%	26,4 GPa
Modulus in y-direction ($E_{y,c}$)	10,8 GPa	16,6%	7,76 GPa
Shear modulus in xy-plane (G_{xy})	2,89 GPa	12,1%	2,28 GPa
Major Poisson's ratio (v_{xy})	0,28	10,0%	0,23
Minor Poisson's ratio (v_{yx})	0,10	10,0%	0,08
Compressive strength in x-direction ($f_{x,c}$)	441,5 MPa	6,5%	388,9 MPa
Compressive strength in y-direction ($f_{y,c}$)	121,6 MPa	13,7%	92,7 MPa
Shear strength in xy-plane (f_{xy})	67,1 MPa	3,1%	63,2 MPa

II.2. Material Partial Safety Factors

- Determine the **material partial safety factors**
  - It is assumed that V_x is not know from previous knowledge
  - $V_x = f_{V_x} \times V_{x,exp}$ – and $f_{V_x} = 1{,}19$ – **10 samples** (Table 4.2)

Property	Average	$V_{x,exp}$	Characteristic	V_x
Modulus in x-direction ($E_{x,c}$)	29,9 GPa	6,3%	26,4 GPa	7,5%
Modulus in y-direction ($E_{y,c}$)	10,8 GPa	16,6%	7,76 GPa	19,8%
Shear modulus in xy-plane (G_{xy})	2,89 GPa	12,1%	2,28 GPa	14,4%
Major Poisson's ratio (v_{xy})	0,28	10,0%	0,23	11,9%
Minor Poisson's ratio (v_{yx})	0,10	10,0%	0,08	11,9%
Compressive strength in x-direction ($f_{x,c}$)	441,5 MPa	6,5%	388,9 MPa	7,7%
Compressive strength in y-direction ($f_{y,c}$)	121,6 MPa	13,7%	92,7 MPa	16,3%
Shear strength in xy-plane (f_{xy})	67,1 MPa	3,1%	63,2 MPa	3,7%

II.2. MATERIAL PARTIAL SAFETY FACTORS

- Determine the **material partial safety factors**
  - Interpolate γ_m from Table 4.1

Table 4.1 — Material partial factor γ_m as a function of V_x when V_x is known *

V_x	0,05	0,10	0,15	0,20	0,25	0,30	0,35	0,40	0,45
γ_m	1,07	1,15	1,23	1,32	1,41	1,51	1,61	1,71	1,82

NOTE These values are based on the design value method (see EN 1990:—, Annex C), a lognormal distribution of the material or product property, a sensitivity factor of 0,8, and a 50-year reliability index of 3,8.

Property	Average	$V_{x,exp}$	Characteristic	V_x	γ_m
Modulus in x-direction ($E_{x,c}$)	29,9 GPa	6,3%	26,4 GPa	7,5%	1,11
Modulus in y-direction ($E_{y,c}$)	10,8 GPa	16,6%	7,76 GPa	19,8%	1,32
Shear modulus in xy-plane (G_{xy})	2,89 GPa	12,1%	2,28 GPa	14,4%	1,22
Major Poisson's ratio (v_{xy})	0,28	10,0%	0,23	11,9%	1,18
Minor Poisson's ratio (v_{yx})	0,10	10,0%	0,08	11,9%	1,18
Compressive strength in x-direction ($f_{x,c}$)	441,5 MPa	6,5%	388,9 MPa	7,7%	1,11
Compressive strength in y-direction ($f_{y,c}$)	121,6 MPa	13,7%	92,7 MPa	16,3%	1,25
Shear strength in xy-plane (f_{xy})	67,1 MPa	3,1%	63,2 MPa	3,7%	1,07

II.3. NOMINAL CONVERSION FACTOR

- Influenced by environmental exposure
  - Conversion factor for **temperature effects**

20°C

$$\eta_{ct} = \min\left\{1{,}0 - 0{,}20 \cdot \frac{T_s - 20}{T_g - 20}; 1{,}0\right\} = 1{,}0 \quad \text{Eq. (4.5)}$$

Fibre-dominated properties

$$\eta_{ct} = \min\left\{1{,}0 - 0{,}80 \cdot \frac{T_s - 20}{T_g - 20}; 1{,}0\right\} = 1{,}0 \quad \text{Eq. (4.6)}$$

Matrix-dominated properties

  - Conversion factor for **moisture effects**

    Indoor exposure – Exposure class I – $\eta_{cm} = 1{,}0$ (Table 4.6)

  - **Nominal conversion factor**

$$\eta_c = \eta_{ct} \times \eta_{cm} = 1{,}0$$

III. COMPRESSIVE RESISTANCE TO CRUSHING

III. Compressive Resistance to Crushing

- Compressive resistance to crushing (**material failure**)

$$N_{c,Rd1} = \frac{\eta_c}{\gamma_m \cdot \gamma_{Rd}} \cdot A \cdot f_{x,ck} = \frac{1,0}{1,11 \cdot 1,40} \cdot 4152 \times 10^{-6} \cdot 388,9 \times 10^{3} = 1035,5\ \text{kN}$$

Eq. (8.25)

1,40 (Table 4.3)

Property	Characteristic	γ_m
Modulus in x-direction ($E_{x,c,k}$)	26,4 GPa	1,11
Modulus in y-direction ($E_{y,c,k}$)	7,76 GPa	1,32
Shear modulus in xy-plane ($G_{xy,k}$)	2,28 GPa	1,22
Major Poisson's ratio ($v_{xy,k}$)	0,23	1,18
Minor Poisson's ratio ($v_{yx,k}$)	0,08	1,18
Comp. strength in x-direction ($f_{x,c,k}$)	388,9 MPa	1,11
Comp. strength in y-direction ($f_{y,c,k}$)	92,7 MPa	1,25
Shear strength in xy-plane ($f_{xy,k}$)	63,2 MPa	1,07

IV. LOCAL BUCKLING RESISTANCE

IV.1. FLEXURAL STIFFNESSES OF THE ORTHOTROPIC LAMINATES

$$D_{11} = \frac{\eta_c \cdot E_{x,c,k} \cdot t^3}{12\,(1 - v_{xy,k} \cdot v_{yx,k})} = \frac{1{,}0 \cdot 26{,}4 \cdot 9.5^3}{12\,(1 - 0.23 \cdot 0.08)} = 1926 \text{ Nm}$$ **Eq. (C.1)**

$$D_{22} = \frac{\eta_c \cdot E_{y,c,k} \cdot t^3}{12\,(1 - v_{xy,k} \cdot v_{yx,k})} = \frac{1{,}0 \cdot 7{,}8 \cdot 9.5^3}{12\,(1 - 0.23 \cdot 0.08)} = 565 \text{ Nm}$$ **Eq. (C.3)**

$$D_{66} = \frac{\eta_c \cdot G_{xy,k} \cdot t^3}{12} = \frac{1{,}0 \cdot 2{,}28 \cdot 9.5^3}{12} = 163 \text{ Nm}$$ **Eq. (C.2)**

$$D_{12} = v_{yx,k} \cdot D_{11} = 0.08 \cdot 1926 = 160 \text{ Nm}$$ **Eq. (C.4)**

Property	Characteristic
Modulus in x-direction ($E_{x,c,k}$)	26,4 GPa
Modulus in y-direction ($E_{y,c,k}$)	7,76 GPa
Shear modulus in xy-plane ($G_{xy,k}$)	2,28 GPa
Major Poisson's ratio ($v_{xy,k}$)	0,23
Minor Poisson's ratio ($v_{yx,k}$)	0,08
Comp. strength in x-direction ($f_{x,c,k}$)	388,9 MPa
Comp. strength in y-direction ($f_{y,c,k}$)	92,7 MPa
Shear strength in xy-plane ($f_{xy,k}$)	63,2 MPa

IV.2. ELASTIC LOCAL BUCKLING RESISTANCE

$$N_{cr,Rd} = \frac{1}{\gamma_m \cdot \gamma_{Rd}} \cdot A \cdot f_{x,cr,k}$$ Eq. (C.20)

- **1st approach** – without web-flange interaction (conservative)

$$f_{x,cr,k} = \min\{(f_{x,cr,k})_f; (f_{x,cr,k})_w\} = \mathbf{35,6\ MPa}$$ Eq. (C.21)

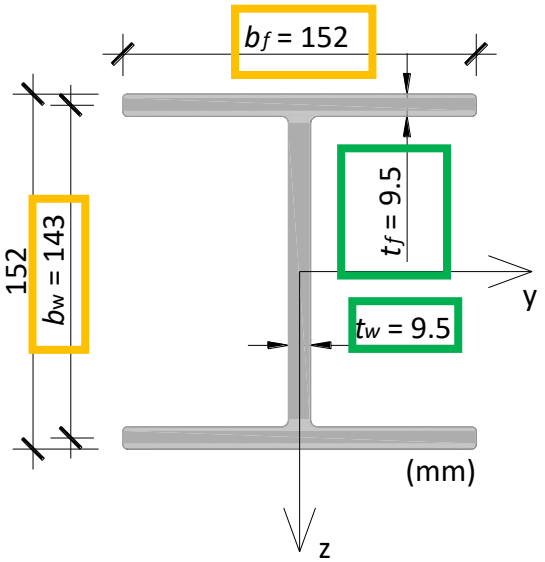
Flange ↑ Web ↑

- Flange

$$(f_{x,cr,k})_f = (f_{x,cr,k})_f^{SS} = \frac{12 \cdot (D_{66})_f}{t_f \cdot \left(\frac{b_f}{2}\right)^2} = \mathbf{35,6\ MPa}$$ Eq. (C.22)

- Web

$$(f_{x,cr,k})_w = (f_{x,cr,k})_w^{SS} = \frac{\pi^2}{t_w \cdot b_w^2}\left\{2\sqrt{(D_{11})_w \cdot (D_{22})_w} + 2[(D_{12})_w + 2(D_{66})_w]\right\} = \mathbf{156,5\ MPa}$$ Eq. (C.23)



$D_{11} = 1926$ Nm

$D_{12} = 160$ Nm

$D_{22} = 565$ Nm

$D_{66} = 163$ Nm

IV.2. ELASTIC LOCAL BUCKLING RESISTANCE

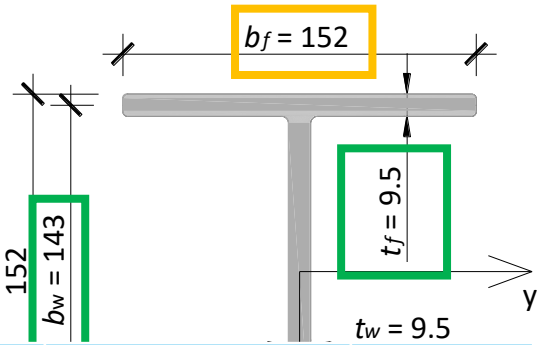
$$N_{cr,Rd} = \frac{1}{\gamma_m \cdot \gamma_{Rd}} \cdot A \cdot f_{x,cr,k} = \frac{1,0}{1,22 \cdot 1,30} \cdot 4152 \times 10^{-6} \cdot 75,7 \times 10^{3} = \mathbf{198,0\ kN}$$

γ_{Rd}: 1,30 (Table 4.3)

- **2nd approach** – considering the rotational restrain at the web-flange junction

$$R = \frac{(f_{x,cr,k})_f^{SS} \cdot (E_{x,c,k})_w}{(f_{x,cr,k})_w^{SS} \cdot (E_{x,c,k})_f} = 0,23 < 1$$

← Flange buckles first than the web — Eq. (C.50)



$$(f_{x,cr,k})_f = \frac{\sqrt{(D_{11})_f \cdot (D_{22})_f}}{t_f \cdot \left(\frac{b_f}{2}\right)^2} \left\{ K \cdot \left[15,1 \cdot \eta \sqrt{1-\rho} + 6(1-\rho) \right] + \frac{7(1-K)}{\sqrt{1+4,12\zeta}} \right\} = \mathbf{75.7\ MPa}$$

Paragr. C.5.2(1)

(for $K < 1$) ✓

$$\eta = \left(\sqrt{1 + (7,4 \cdot 3,1 - 3)^2} \right) = 2,43 \qquad = 0,25$$

Property	Characteristic	γ_m
Modulus in x-direction ($E_{x,c,k}$)	26,4 GPa	1,11
Modulus in y-direction ($E_{y,c,k}$)	7,76 GPa	1,32
Shear modulus in xy-plane ($G_{xy,k}$)	2,28 GPa	1,22
Major Poisson's ratio ($v_{xy,k}$)	0,23	1,18
Minor Poisson's ratio ($v_{yx,k}$)	0,08	1,18
Comp. strength in x-direction ($f_{x,c,k}$)	388,9 MPa	1,11
Comp. strength in y-direction ($f_{y,c,k}$)	92,7 MPa	1,25
Shear strength in xy-plane ($f_{xy,k}$)	63,2 MPa	1,07

V. GLOBAL (FLEXURAL) BUCKLING RESISTANCE

V.1. ELASTIC GLOBAL (FLEXURAL) BUCKLING

$$N_{E,Rd} = \frac{1}{\gamma_m \cdot \gamma_{Rd}} \cdot A \cdot f_{E,cr,k} \cdot \chi_{E,shear} = \frac{1{,}0}{1{,}11 \cdot 1{,}30} \cdot 4152 \times 10^{-6} \cdot 44{,}7 \times 10^{3} \cdot 0{,}97 = \mathbf{124{,}3\ kN}$$

1,30 (Table 4.3)

$$f_{E,cr,k} = \frac{\pi^2 \cdot \eta_c \cdot E_{x,c,k}}{(k \cdot L/i)^2} = 44{,}7\ \text{MPa}$$

Eq. (C.30)

Effective length

Radius of avration

$$\chi_{E,cr,k} = \left(1 + \frac{f_{E,cr,k}}{\eta_c \cdot G_{xy,k}} \cdot \frac{A}{A_v}\right) = 0{,}97$$

Eq. (C.31)

supports/storeys (2800 mm)

Shear area (2 × 152 × 9,5) / 1,2

Property	Characteristic	γ_m
Modulus in x-direction ($E_{x,c,k}$)	26,4 GPa	1,11
Modulus in y-direction ($E_{y,c,k}$)	7,76 GPa	1,32
Shear modulus in xy-plane ($G_{xy,k}$)	2,28 GPa	1,22
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Shear strength in xy-plane ($f_{xy,k}$)	63,2 MPa	1,07

VI. COMPRESSION ULTIMATE LIMIT STATE VERIFICATION

VI.1. INTERACTION BETWEEN LOCAL AND GLOBAL BUCKLING

$$N_{c,Rd2} = \chi_E \cdot N_{cr,Rd} = 0{,}48 \times 198{,}0 = \mathbf{94{,}3\ kN}$$ **Eq. (8.27)**

$$\chi_E = \frac{1}{c_E \cdot \lambda_E^2}\left(\Phi_E - \sqrt{\Phi_E^2 - c_E \cdot \lambda_E^2}\right) = \frac{1}{0{,}65 \cdot 1{,}26^2}\left(1{,}30 - \sqrt{1{,}30^2 - 0{,}65 \cdot 1{,}26^2}\right) = 0{,}48$$

0,65 (Paragr. C.5.2(7))

$$\lambda_E = \sqrt{\frac{N_{cr,Rd}}{N_{E,Rd}}} = \sqrt{\frac{198{,}0}{124{,}3}} = 1{,}26$$ **Eq. (C.28)**

$$\Phi_E = \frac{1 + \lambda_E^2}{2} = \frac{1 + 1{,}26^2}{2} = 1{,}30$$ **Eq. (C.27)**

VI.2. ULS OF COMPRESSION SAFETY VERIFICATION

$$N_{c,Rd} = \min\left\{N_{cr,Rd1}, N_{cr,Rd2}\right\} = \mathbf{94,3\ kN}$$ Eq. (8.24)

$$\boldsymbol{N_{c,Ed} \leq N_{c,Rd} <=> 84,1\ kN \leq 94,3\ kN}$$ Eq. (8.23) ✓

- The ULS safety verification for the column under compression is completed

VII. CREEP RUPTURE VERIFICATION

VII.1. CREEP RUPTURE

- Creep rupture is an **ULS** safety verification under **quasi-permanent loads**

$$\sigma_{c,creep,Ed} \leq \sigma_{c,creep,Rd} <=> \mathbf{7,5\ MPa \leq 77,8\ MPa}$$ ✓ Eq. (8.113)

$$\sigma_{c,creep,Ed} = \frac{N_{c,qper}}{A} = \frac{31{,}1 \times 10^3}{4152} = 7{,}5\ \text{MPa}$$

$$\sigma_{c,creep,Rd} = \frac{\eta_c}{\gamma_{M,creep}} \cdot k_{c,creep} \cdot f_{i,c,k}$$ Eq. (C.8.114)

1.5 - Paragr. 8.5(4)

$$= \frac{1{,}0}{1{,}5} \cdot 0{,}3 \cdot 388{,}9 = 77{,}8\ \text{MPa}$$

compression

$$k_{c,creep} = 0{,}75 \cdot k_{t,creep} = 0{,}75 \cdot 0{,}4 = 0{,}3$$

Paragr. 8.5(4), Table 8.3

Property	Characteristic	γ_m
Modulus in x-direction ($E_{x,c,k}$)	26,4 GPa	1,11
Modulus in y-direction ($E_{y,c,k}$)	7,76 GPa	1,32
Shear modulus in xy-plane ($G_{xy,k}$)	2,28 GPa	1,22
Major Poisson's ratio ($v_{xy,k}$)	0,23	1,18
Minor Poisson's ratio ($v_{yx,k}$)	0,08	1,18
Comp. strength in x-direction ($f_{x,c,k}$)	388,9 MPa	1,11
Comp. strength in y-direction ($f_{y,c,k}$)	92,7 MPa	1,25
Shear strength in xy-plane ($f_{xy,k}$)	63,2 MPa	1,07

VIII. SUMMARY

VIII. SUMMARY

- Summary of the (partial and complete) ULS verifications performed

Type of verification	E_d	R_d	Check
Compressive resistance ($N_{c,Rd}$)	**84,1 kN**	**94,3 kN**	✓
Crushing ($N_{c,Rd1}$) – partial	84,1 kN	1035,5 kN	✓
Local buckling ($N_{cr,Rd}$) – partial	84,1 kN	198,0 kN	✓
Global buckling ($N_{E,Rd}$) – partial	84,1 kN	124,3 kN	✓
Creep rupture ($\sigma_{c,creep,Rd}$)	**7,5 MPa**	**77,8 MPa**	✓

Thank you!

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