In this case study, we analyze the PAT Center of Richard Rogers and Ove Arups & Partners structural engineering.

The PAT Center in Princeton, NJ, USA is a single-storey building with a floor area of 3,700 m2. Specializing in design and telecommunications, PA Technology LTD wanted the most flexible and expandable space possible as a technological center that could be adapted to unpredictable space requirements. That is why the building consists of a single large room, which can be subdivided as desired. Along the central axis, there are serially distributed pylons from which the roof is suspended.

Task 1 Calculation of the loads

The primary longitudinal beams together with the secondary cross beams carry a ceiling of prefabricated concrete elements with a thickness of 12 cm. Concrete has a volume load γ_k of 20 kN/m³. On top there is the finished roof (composed by: insulation, gravel, covers) with a surface load of $\bar{g}_k$ = 1.3 kN/m². Also it is likely to snow in Princeton in winter, so a snow load of $\bar{q}_k$ = 2 kN/m² has to be considered.

a) Calculate the total area load for the concrete elements as well as the roof structure including snow at design level and round up the value to whole kN/m².

b) Calculate the point loads F1-3 acting on the primary beam with the rounded value from 1a). In the axonometric drawing, the respective dimensions of the load-influencing zones can be recognized. Important: Two bars are neglected because their weight is not transferred directly by a rope.

1a) $\bar{s}_{k\,concrete} = \gamma_k \cdot d = 20\ \text{kN/m}^3 \cdot 0.12\ \text{m} = 2.4\ \text{kN/m}^2$

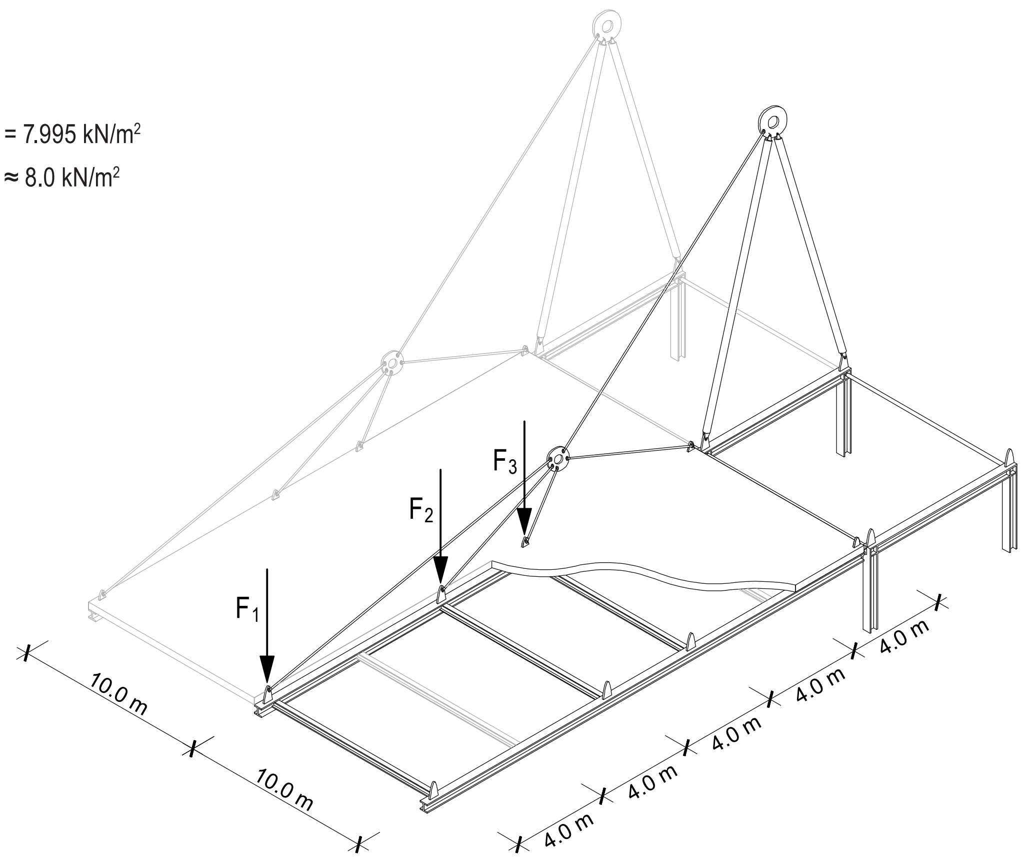
$\bar{s}_d = (\bar{s}_{k\,concrete} + \bar{g}_k) \cdot 1.35 + \bar{q}_k \cdot 1.5$

$\bar{s}_d = (2.4\ \text{kN/m}^2 + 1.3\ \text{kN/m}^2) \cdot 1.35 + 2\ \text{kN/m}^2 \cdot 1.5 = 7.995\ \text{kN/m}^2$

$\bar{s}_d \approx 8.0\ \text{kN/m}^2$

1b) $F_{1,6} = \bar{s}_d \cdot b \cdot t_1 = 8.0\ \text{kN/m}^2 \cdot 10\ \text{m} \cdot 4\ \text{m} = 320\ \text{kN}$

$F_{2,3,4,5} = \bar{s}_d \cdot b \cdot t_2 = 8.0\ \text{kN/m}^2 \cdot 10\ \text{m} \cdot 6\ \text{m} = 480\ \text{kN}$

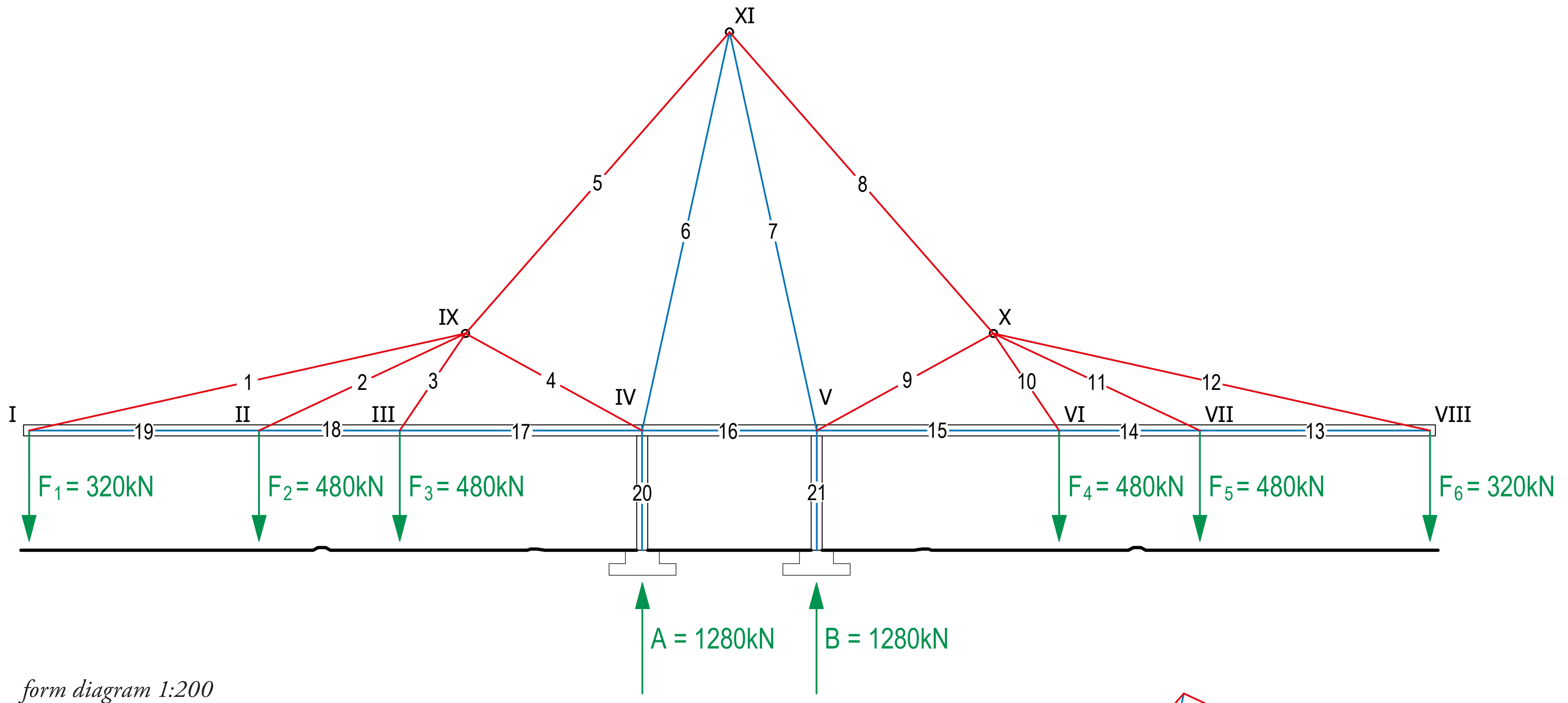


Task 2 Forces in the section

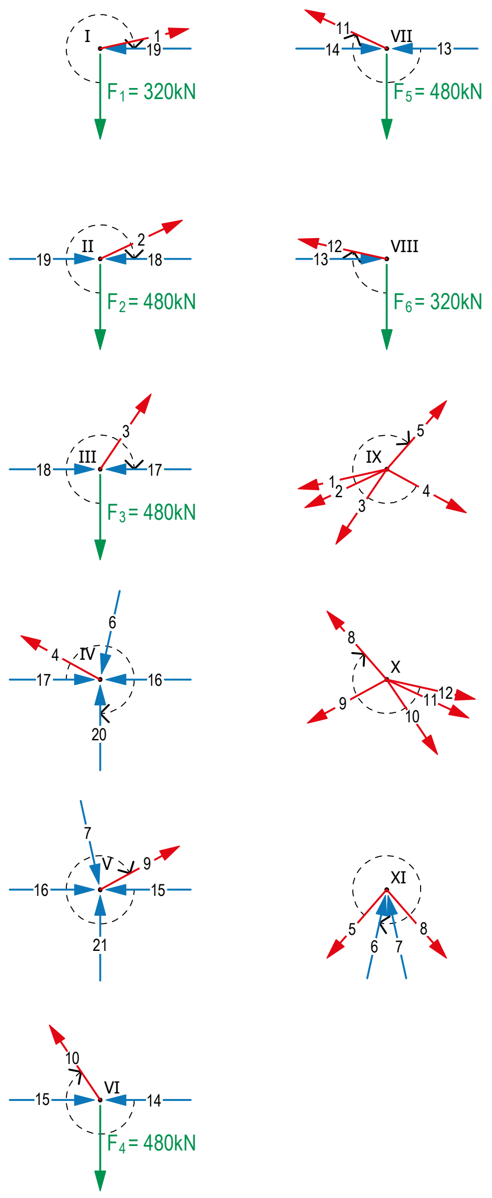
The primary structure consists of steel cables, steel tubes for the pylons and I-beams for the remaining pressure elements.

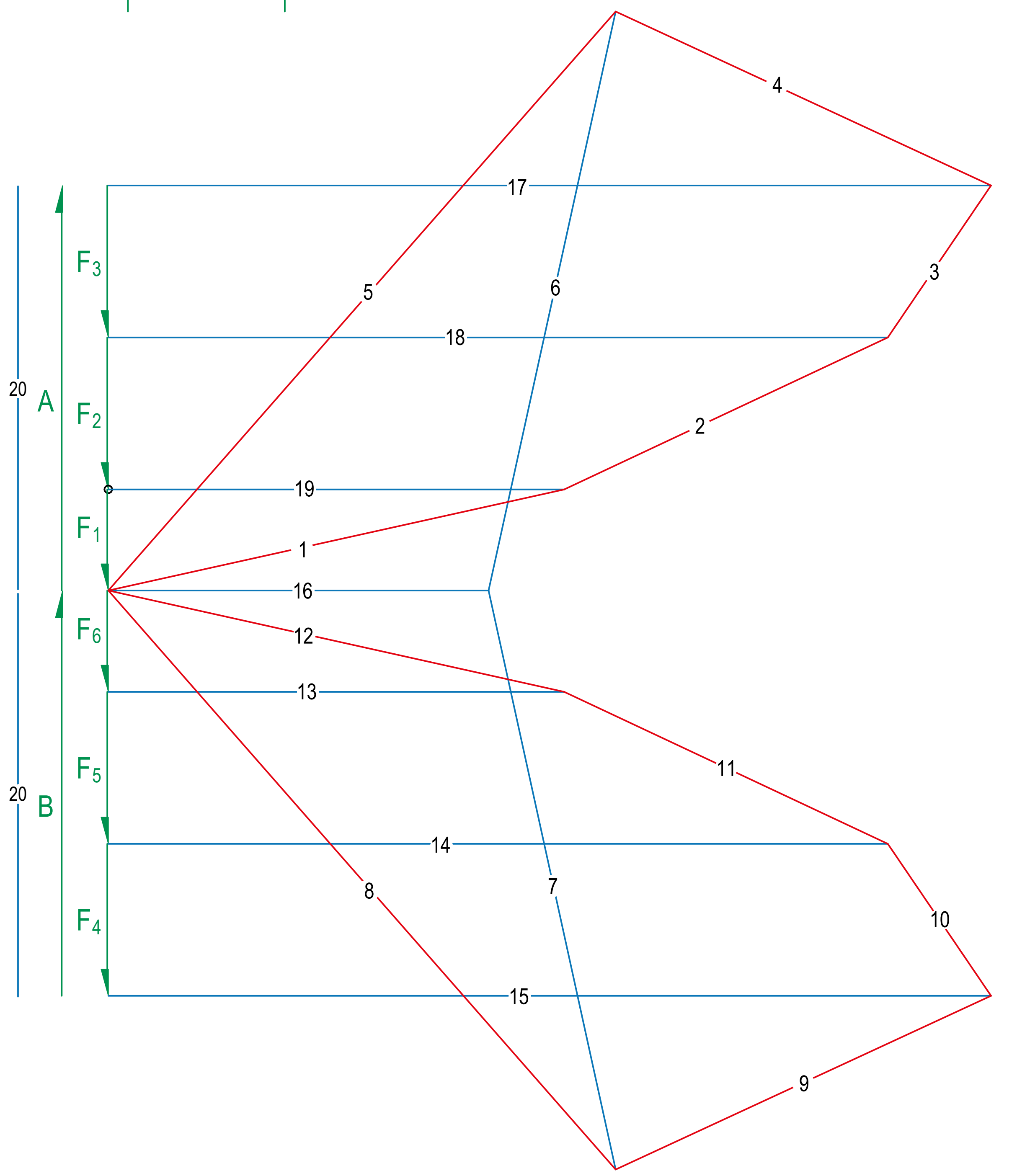
a) The cross-section of the building is shown below in the form diagram. Draw the corresponding force diagram. Use the point loads $F_{1\text{-}3}$ from 1b). Mark tension elements red and compression elements blue.

b) For the supporting elements rope, deck and pylon, indicate the position and load of the relevant segments.



form diagram 1:200





subsystem

force diagram 1cm ≙ 200kN

	segment	load
rope	5 / 8	2431.2 kN
deck	15 / 17	2790.4 kN
pylon	6 / 7	1872.2 kN

Task 3 Dimensioning the main elements

a) Check whether the rope D=100mm made of steel S355 can withstand the maximum tensile load from task 2.

b) The pylon shall be a round hollow section of S355 steel with an outer diameter D_1=160 mm and an inner diameter D_2=116 mm. Check on the basis of the diagram below whether this cross-section would buckle under the maximum compressive stress from task 2. (The respective lines in the diagram mark the critical limit of the buckling. If a point is below it, the segment will not buckle under the given load. l_{cr} means the length of the segment. How could a possible buckling be prevented?

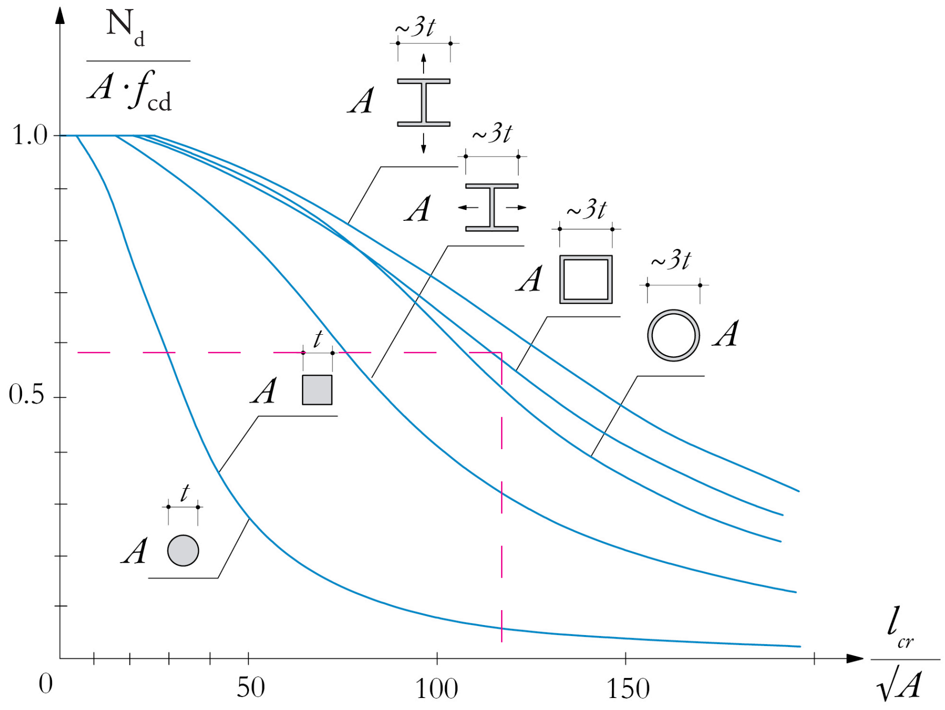
c) The main beam is constructed with the shown steel profile made of steel S500. The flange thickness corresponds to that of the web which is 35 mm. Verify that this cross-sectional area is sufficient to absorb the maximum compressive stress of the deck as determined in task 2.

3a) $N_d / A_{ef} \leq f_{cd}$
$N_{d\ rope}$ = 2431.2 kN
A_{ef} = (50 mm)^2 · π = 7853.98 mm^2
f_{cd} = 355 N/mm^2 / 1.05 = 338.1 N/mm^2
N_d / A_{ef} = 309.55 N/mm^2 ≤ f_{cd}
309.55 N/mm^2 ≤ 338.1 N/mm^2

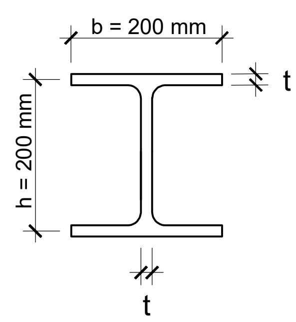
3b) A = r_1^2 · π - r_2^2 · π = 20106.19 mm^2 - 10568.32 mm^2 = 9537.87 mm^2
N_d / (A · f_{cd}) = 1872.2 kN / (9537.87 mm^2 · 338.1 N/mm^2) = 0.581
l_{cr} / √A = 11.6 m / 97.662 mm = 118.78

The determined point is above the critical limit for the proposed circular profile. This would buckle under the given load. However, it would be possible to select a I-beam that is stressed in the direction of the web.

3c) A_{web} = 35 mm · 165 mm = 5775 mm2
A_{flange} = 35 mm · 200 mm · 2 = 14000 mm2
A_{ef} = 19775 mm2
$N_d / A_{ef} \leq f_{cd}$
$N_{d\ deck}$ = 2790.4 kN
f_{cd} = 500 N/mm^2 / 1.05 = 476.2 N/mm^2
N_d / A_{ef} = 141.11 N/mm^2 ≤ f_{cd}
141.11 N/mm^2 ≤ 476.2 N/mm^2



buckling diagram



section main beam

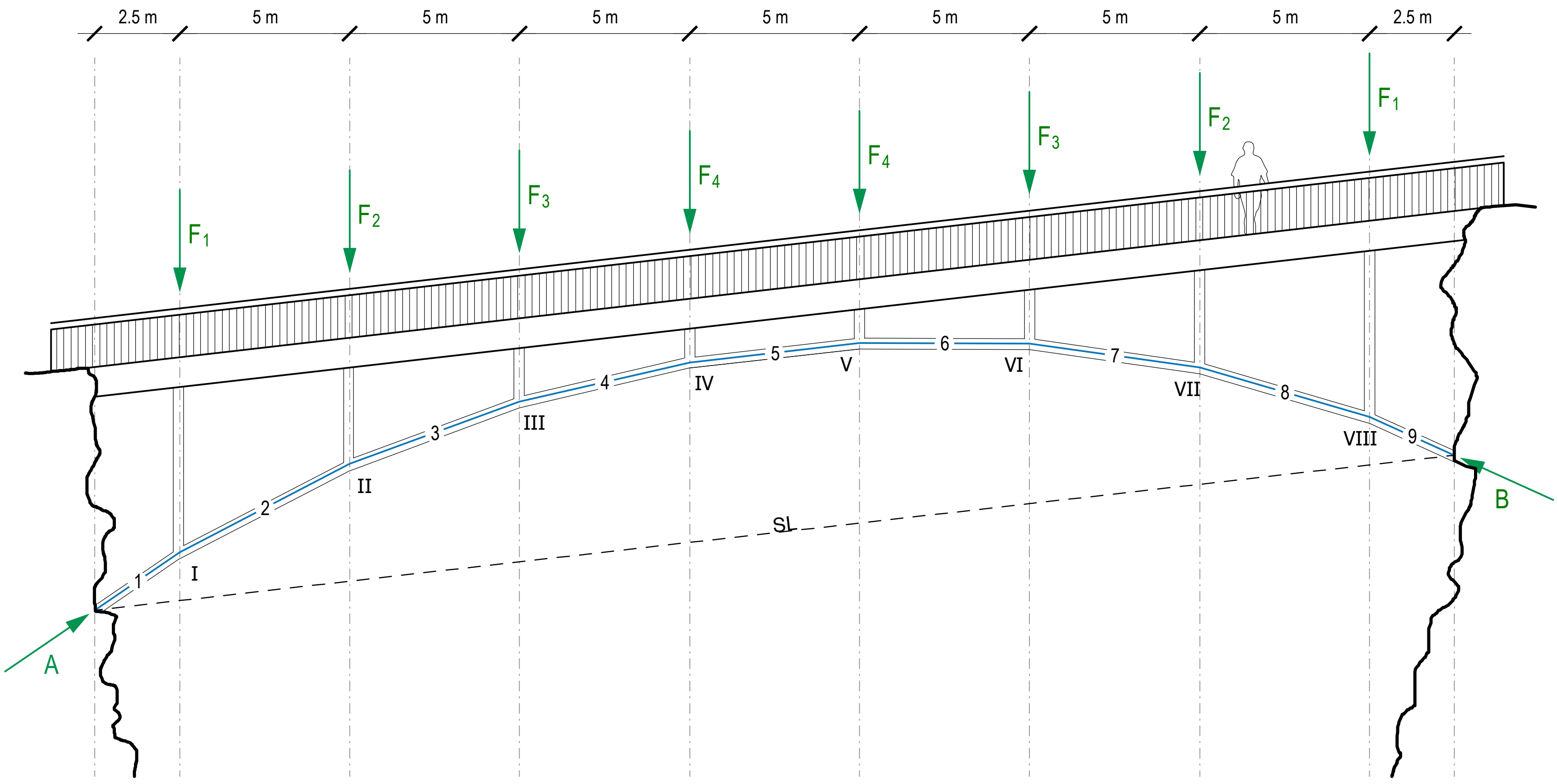
Additional Task 1

Concrete arch bridge

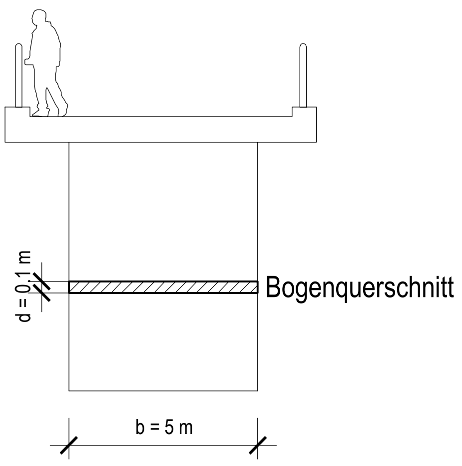
a) Calculate $N_{d,max}$ with a characteristic stress of f_{ck} =16 N/mm² in compression and the resistance coefficient γ_m = 1.5. The bridge is made out of concrete C 16/20. The dimensions of the arch's cross-section are: d=0.1m and b=5.0m.

b) Find the funicular form of the arch in pure compression and give the size, location and direction of the reaction forces. The middle segment of the arch should be parallel to the deck.

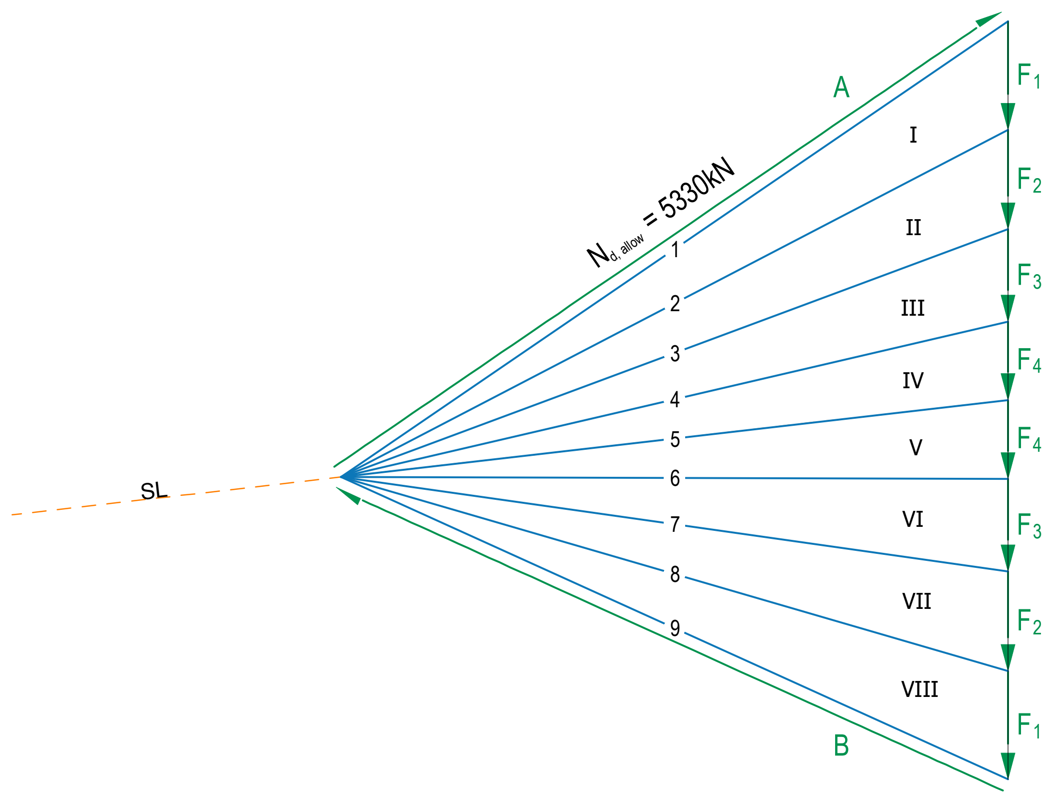
F_1 = 715 kN F_2 = 656 kN F_3 = 611 kN F_4 = 581 kN



form diagram 1:200



section 1:200

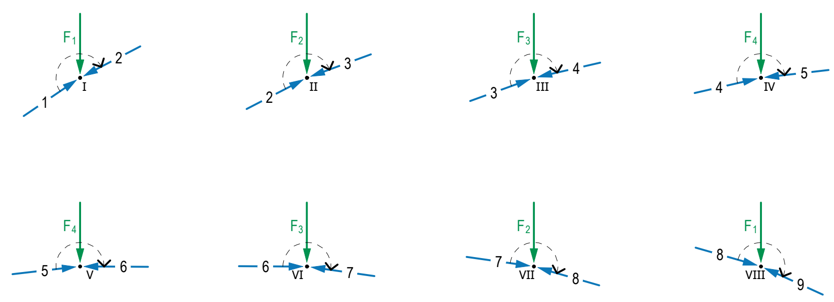


force diagram 1cm ≙ 500kN

a) A_{eff} = b · d = 5000 mm · 100 mm = 500'000 mm²

f_{cd} = f_{ck} / γ_M = 16 N/mm² / 1.5 = 10.66 N/mm²

$N_{d,allow}$ = f_{cd} · A_{eff} = 10.66 N/mm² · 500'000 mm² = 5330 kN



subsystem

Additional Task 2

Estádio Municipal de Braga by Eduardo Souto de Moura

a) Precast concrete panels are placed over both of the two 55m wide terraces. Every concrete panel with a width of b=3.7m and a thickness of d=240mm is fixed on two hanging cables. Calculate the uniform lineload g_d per cable at measuring level and enter the value in kN/m. Spatial load reinforced concrete γ_k=25kN/m³

b) After a heavy snowfall the snow only remained on the north side of the roof whilst it melted on the southern side. This leads to asymmetrical loads. Calculate the live load q_d. Area load snow $\bar{q}_k$ = 5.4 kN/m²

c) Find the static form of the hanging cable which spans between the supports A and B. The maximum cable strength is 2'454 kN. Draw the form and force diagram. How big are the reaction forces A and B?

d) Dimension the cross-section of the cable if steel S500 is used. Enter the diameter D rounded off to mm.

a)
$A = l \cdot b = 3.7\ \text{m} \cdot 0.24\ \text{m} = 0.89\ \text{m}^2$

$g_k = A \cdot \gamma_k = 0.89\ \text{m}^2 \cdot 25\ \text{kN/m}^3 = 22.2\ \text{kN/m}$

$g_d = g_k \cdot \gamma_G = 22.2\ \text{kN/m} \cdot 1.35 = 30.0\ \text{kN/m}$

g_d p. cable: 30.0 kN/m / 2 = **15 kN/m**

b)
$q_k = \bar{q}_k \cdot l = 5.4\ \text{kN/m}^2 \cdot 3.7\ \text{m} = 20\ \text{kN/m}$

$q_d = q_k \cdot \gamma_Q = 20\ \text{kN/m} \cdot 1.5 = 30\ \text{kN/m}$

q_d p. cable: 30.0 kN/m / 2 = **15 kN/m**

c)
$R_L = g_d \cdot l = 15\ \text{kN/m} \cdot 55\text{m} = 825\ \text{kN}$

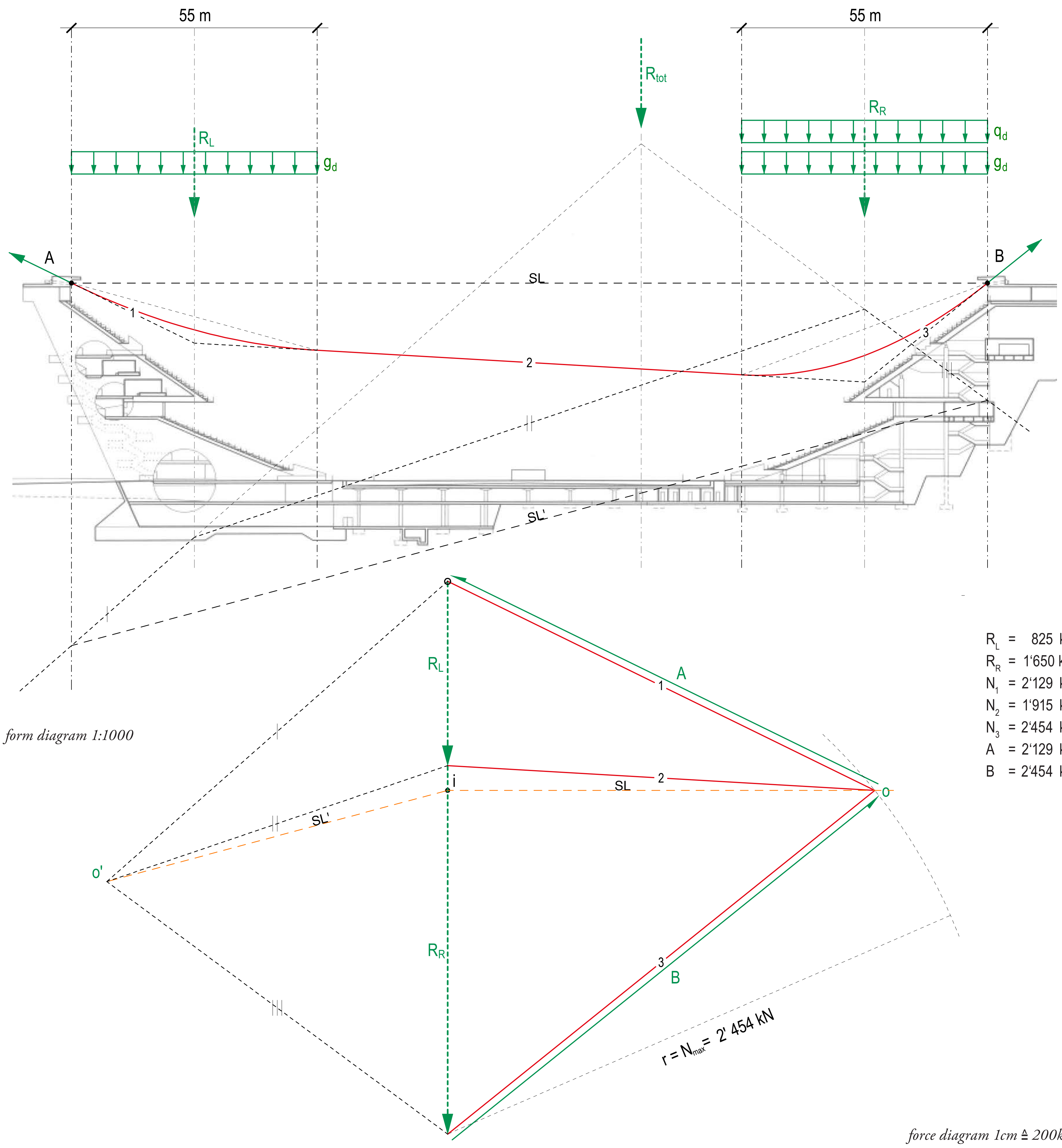
$R_R = g_d \cdot q_d \cdot l = 2 \cdot 15\ \text{kN/m} \cdot 55\text{m} = 1'650\ \text{kN}$

d)
$N_d = 2'454\ \text{kN}$

$f_{td} = f_{tk} / \gamma_M = 500\ \text{N/mm}^2 / 1.05 = 476.2\ \text{N/mm}^2$

$A_{req} = N_d / f_{td} = 2'454\ \text{kN} / 476.2\ \text{N/mm}^2 = 5'153\ \text{mm}^2$

$D = \sqrt{4 \cdot A / \pi} = \sqrt{4 \cdot 5'153\ \text{mm}^2 / \pi} = \mathbf{82\ mm}$



form diagram 1:1000

R_L = 825 kN
R_R = 1'650 kN
N_1 = 2'129 kN
N_2 = 1'915 kN
N_3 = 2'454 kN
A = 2'129 kN
B = 2'454 kN

force diagram 1cm ≙ 200kN