Structural Steel Virtual Excursion

Design, manufacturing, erecting and full physical test of a simple portal frame of structure

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PROMSTAL engineering

Structural Steel Virtual Excursion

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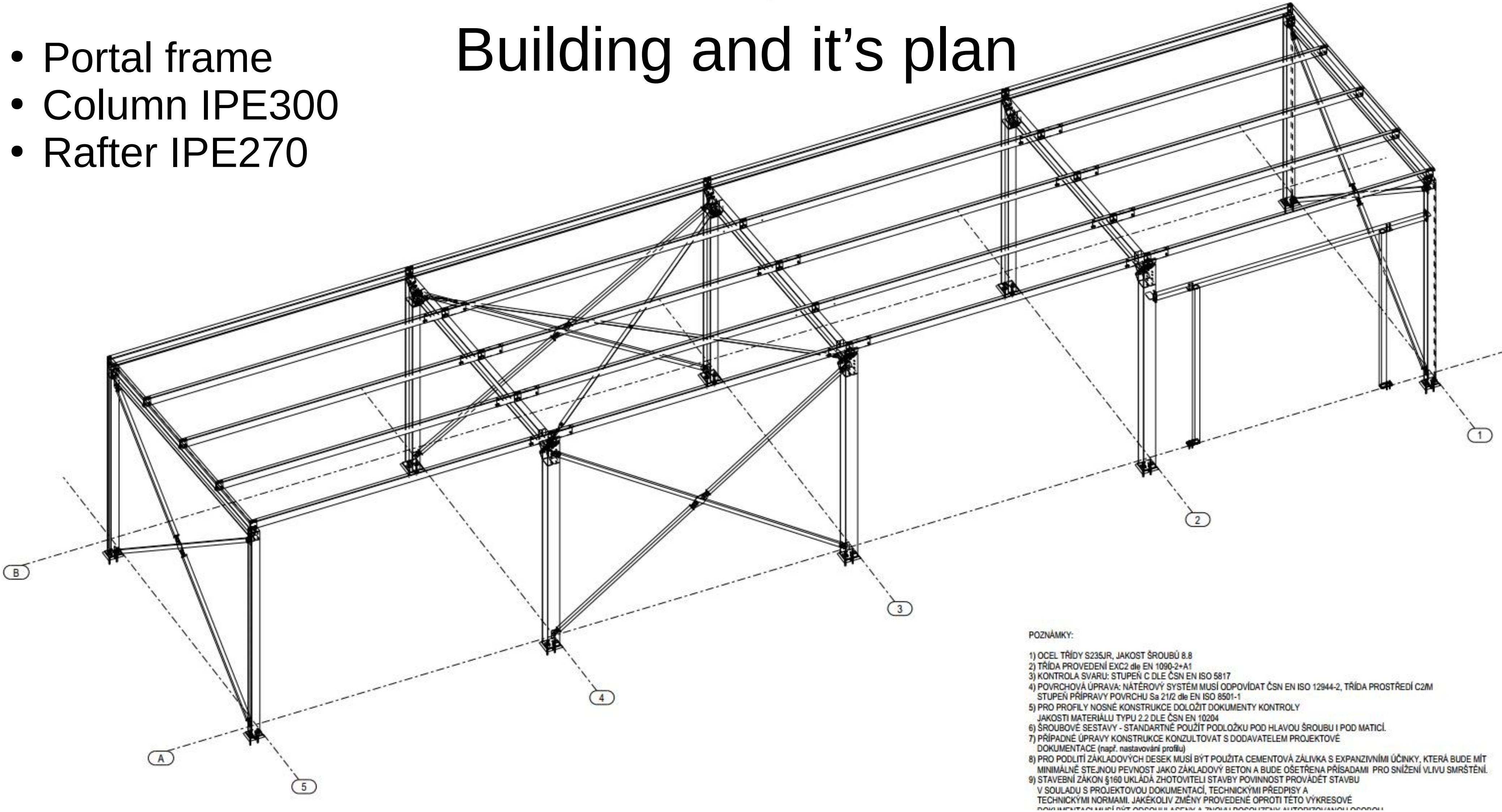
Structural Steel Virtual Excursion

- **Objectives**:
- Build portal frame type of building (5.6 m structural span, 4.3 m structural height and 23.5 m building length),
- Perform full scale physical test on building with and without roof cladding (to test the effect of cladding on overall stiffness of the building),
- Do not damage building during the test! We will be checking just response to the side horizontal load at serviceability limit state,
- Some damage may occur to cladding connections. Check this damage.
- Investigate the contribution of roof cladding to the stiffmess of the building,
- Shot video from manufacturing and building assembly,
- Record full scale test.

Building and it’s plan

- Portal frame
- Column IPE300
- Rafter IPE270



Building and it’s plan

- Portal frame
- Column IPE300
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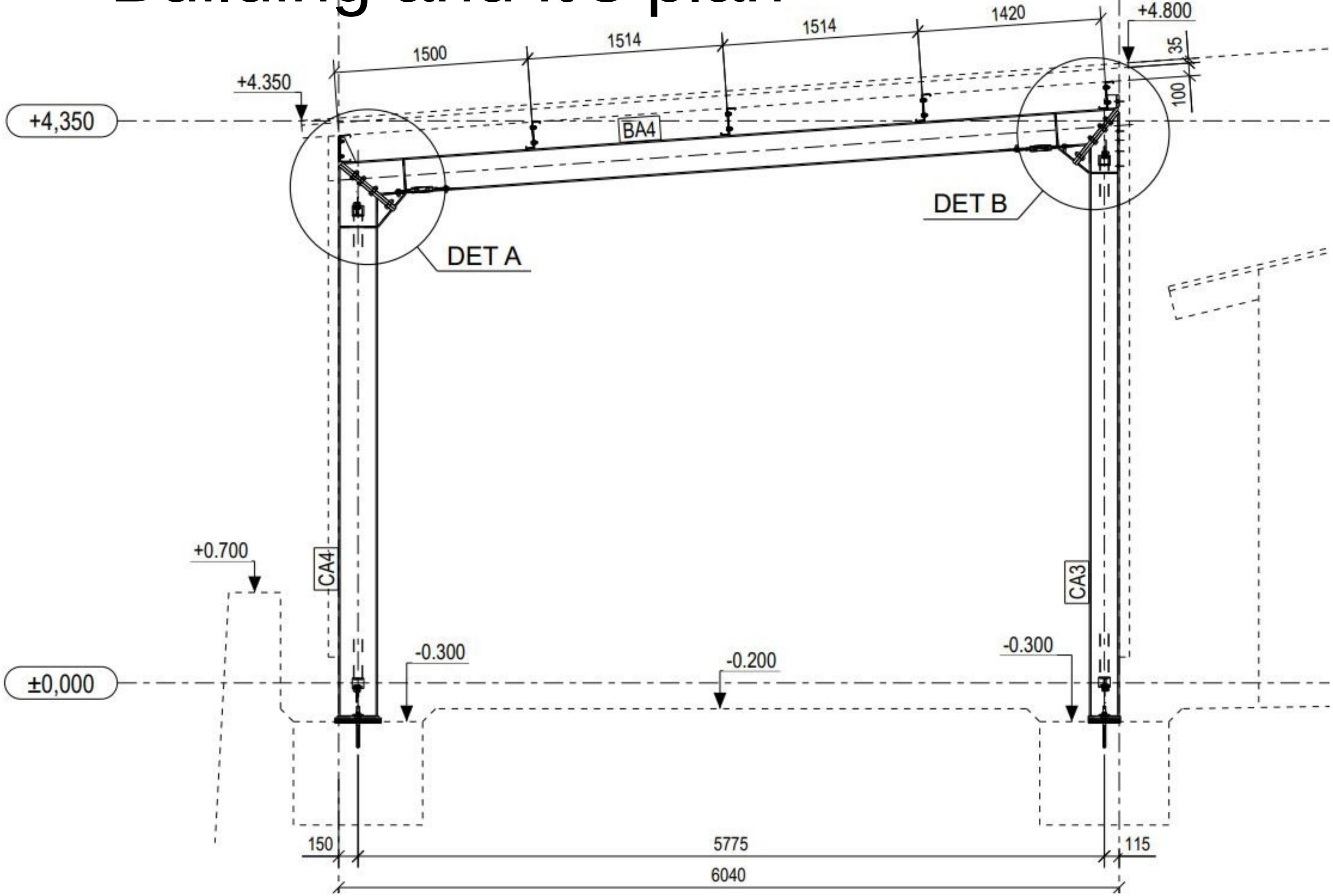


Manufacturing and assembly

- CNC cutting
- Manual welding
- Surface treatment
- Primer and final paint
- Assembly took 2 days
- Details in video

Experiment

- Video
  - https://odysee.com/@jxm:7/2021_experiment_hala_v01:4

Experiment

- Simple frame
- Hot rolled I-profiles (IPE 300 for column, IPE270 for rafter)
- Roof clad with composite panels (PUR)
- Test performed on UNCLAD building
- Another test on CLAD building (bare frame)
- Unit used by lab team when collecting experimental data, force and displacements shown on the photograph

Experiment

- Forklift
  - Max. force about 50 kN (5 tons)
  - 30 kN was required and achieved during the test

Experiment

- Detail of Z purlins, cladding by composite panels and column-rafter connection

Experiment

- Detail of displacement sensors used during the experiment

Experiment

- Column base, bracing plate and bracing connection

Experiment

- Crossing of bracing diagonals

Experiment

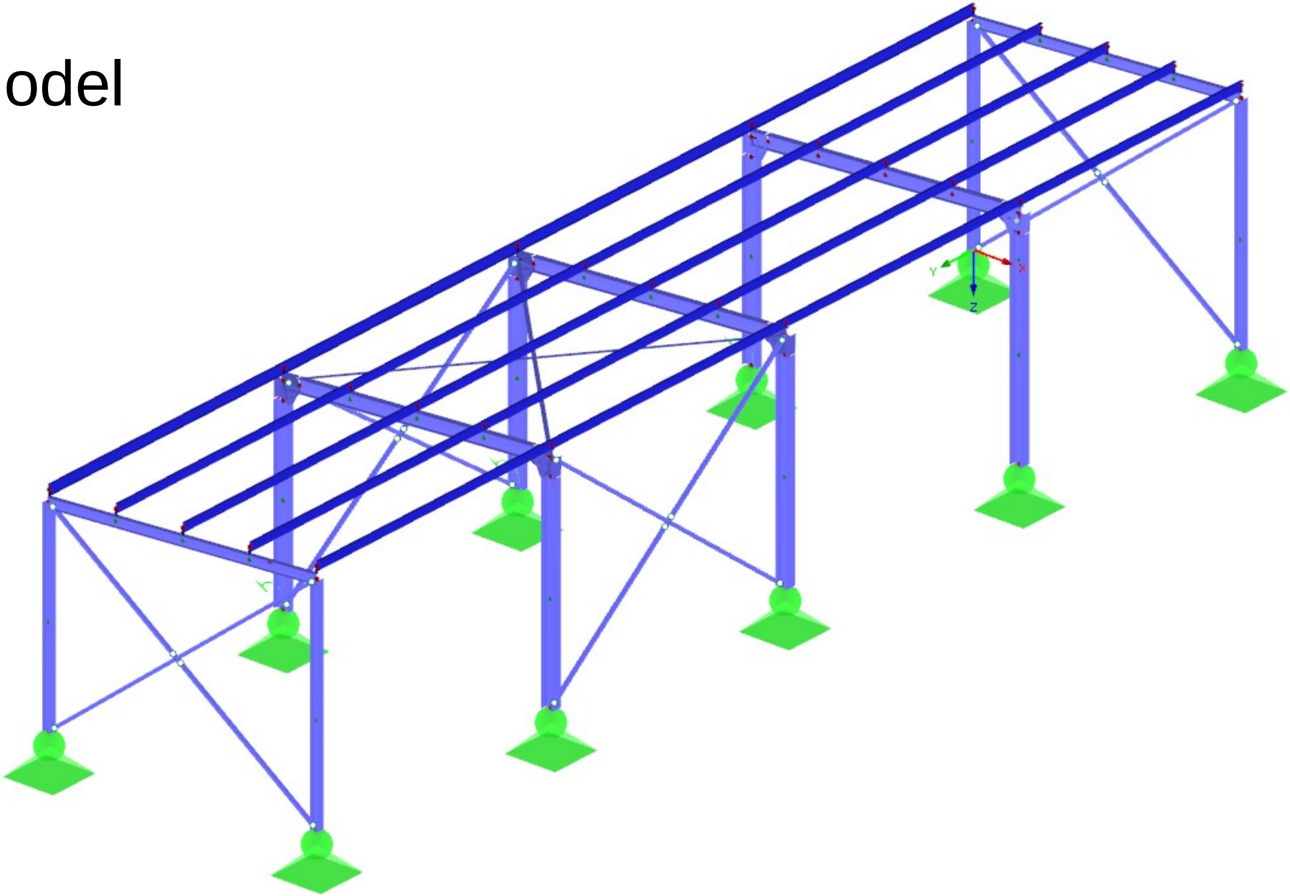
- Roof cross bracing

Experiment

- Detail of cladding as well as fin plate used to connect dynamic rope to exert force by forklift

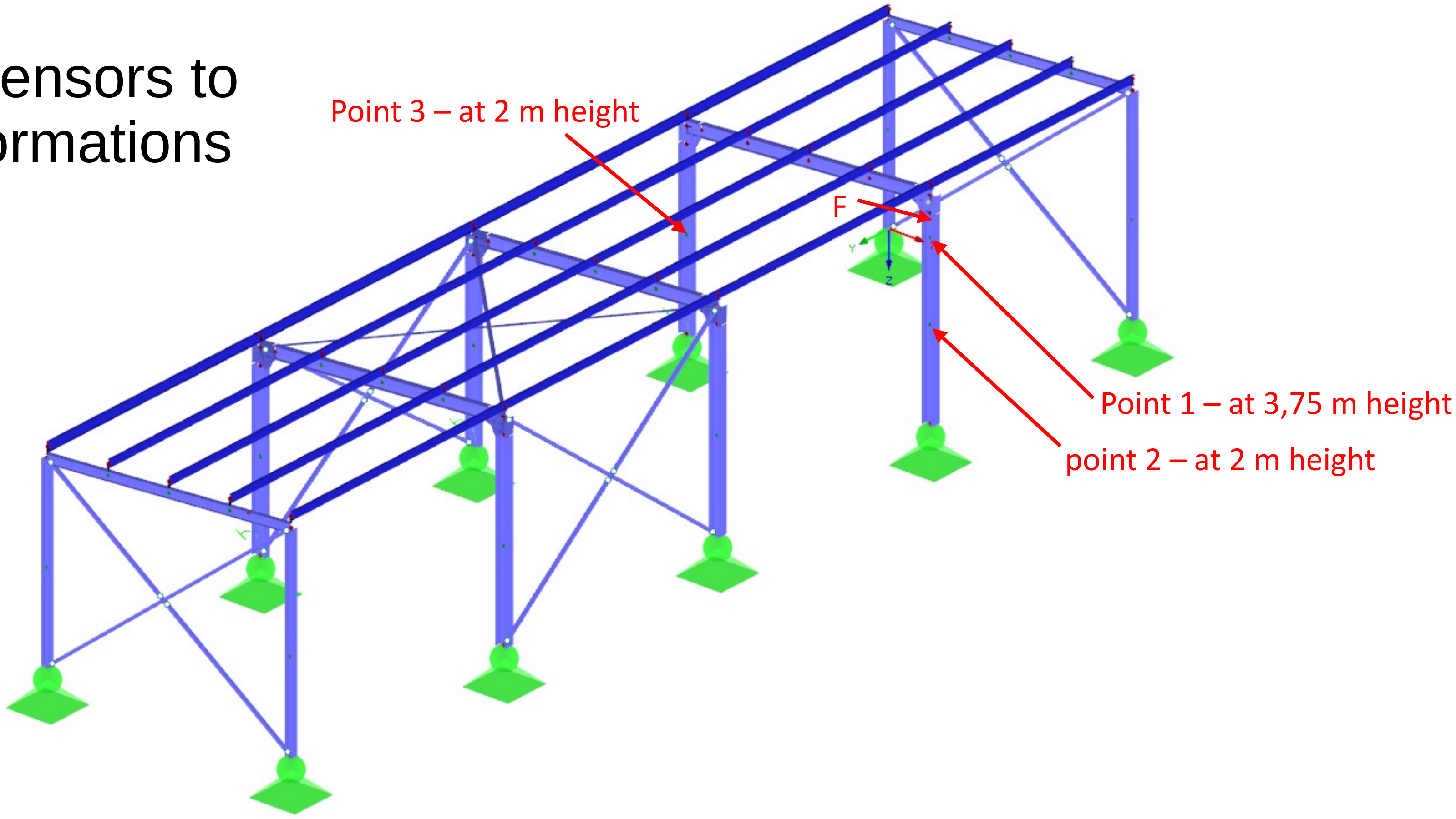
Behaviour

- Analysis model



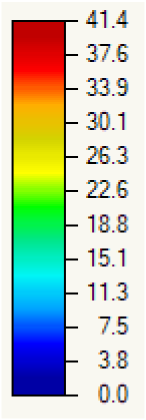
Behaviour

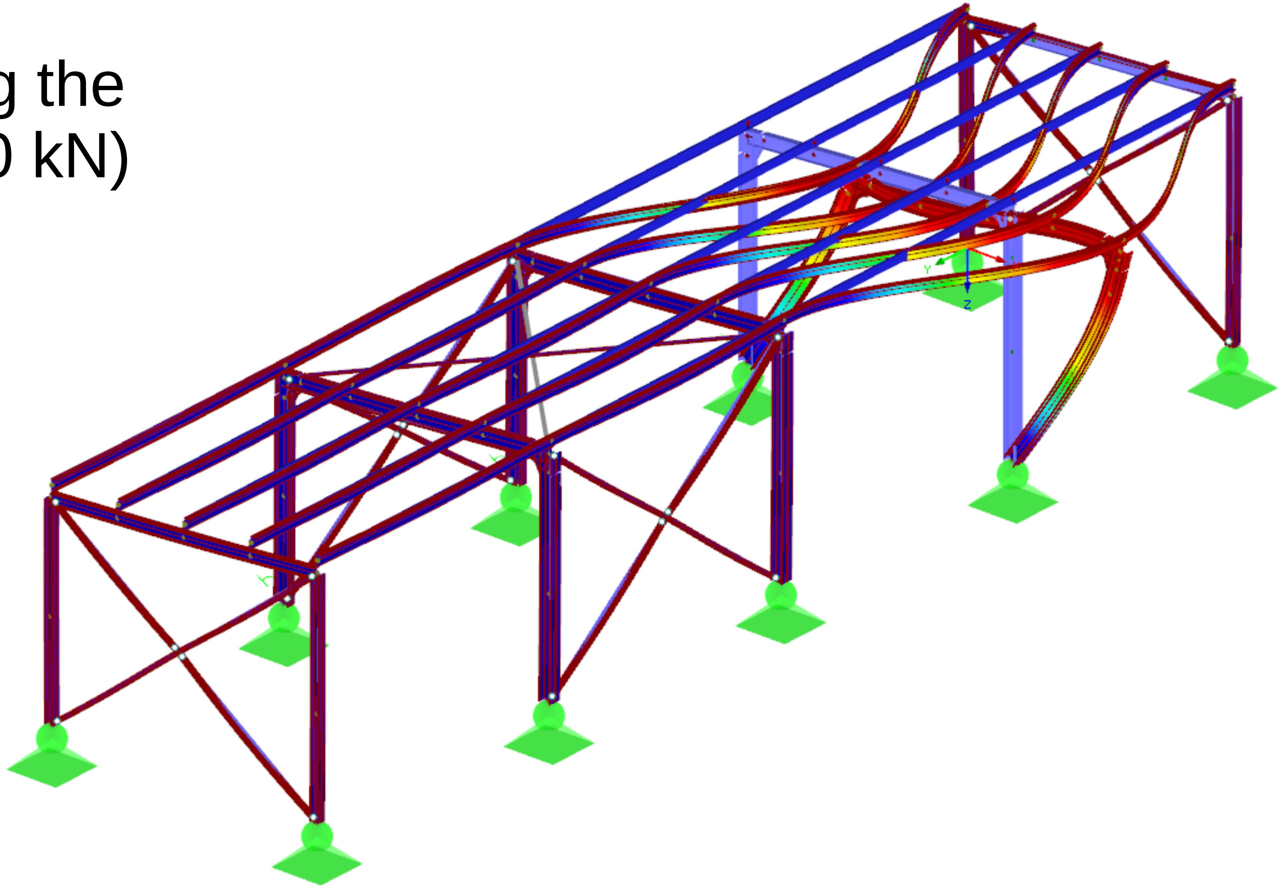
- Positions of sensors to measure deformations



Behaviour

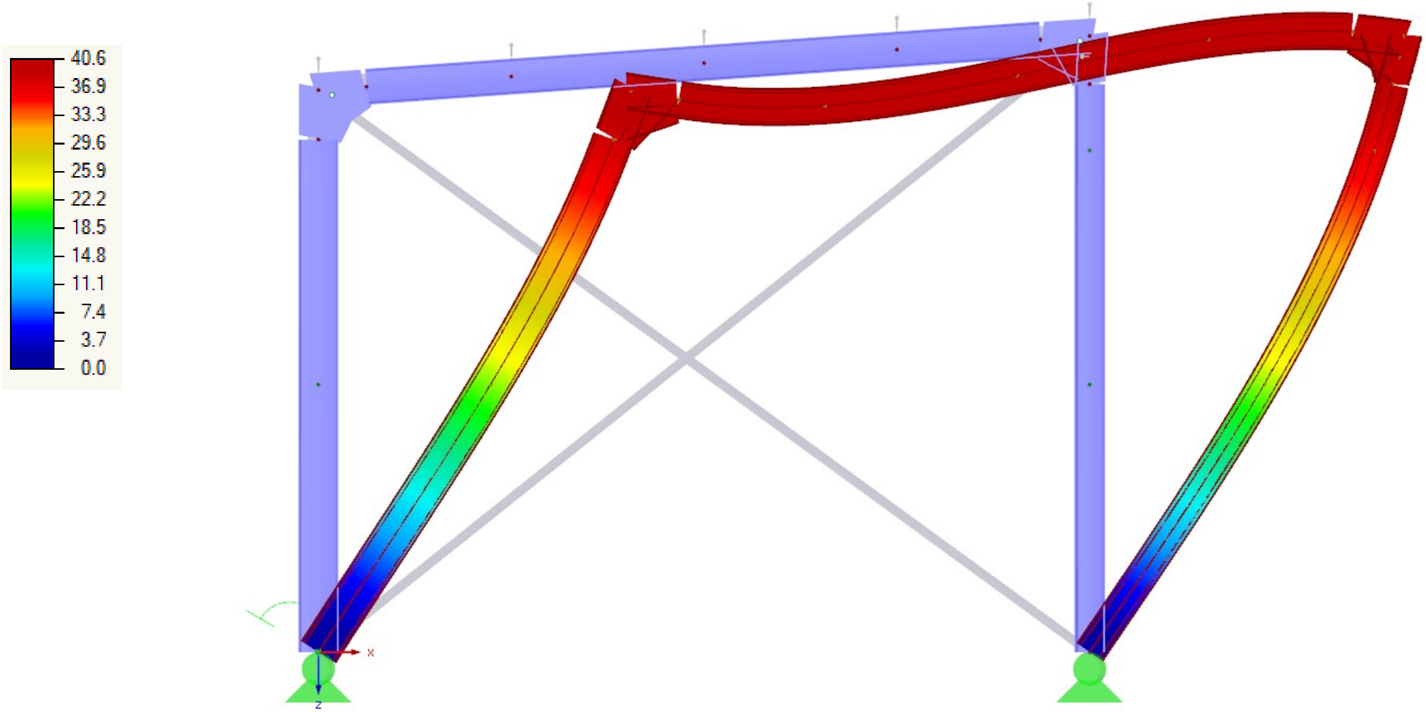
- Deformation during the experiment (F = 30 kN)





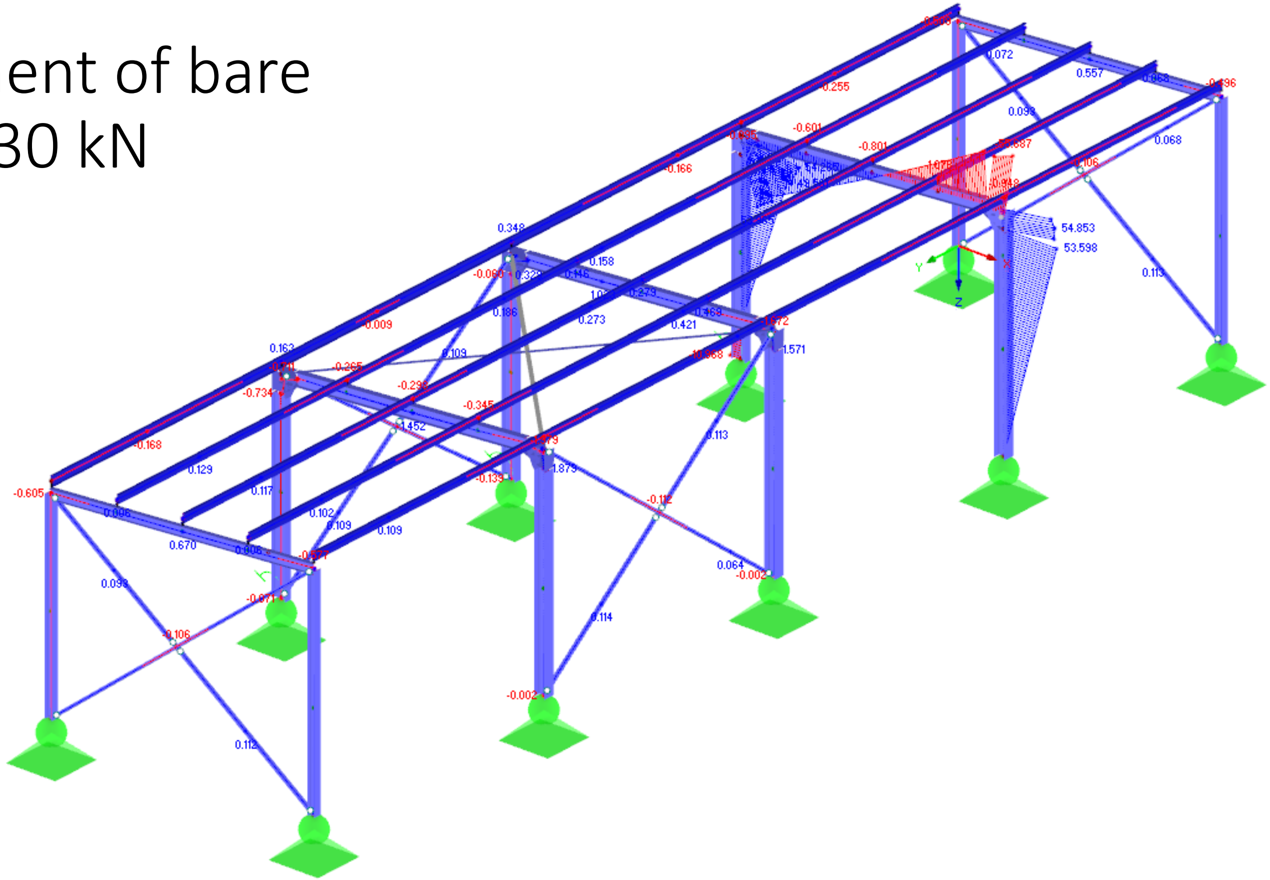
Behaviour

Horizontal deformation of bare frame for F = 30 kN



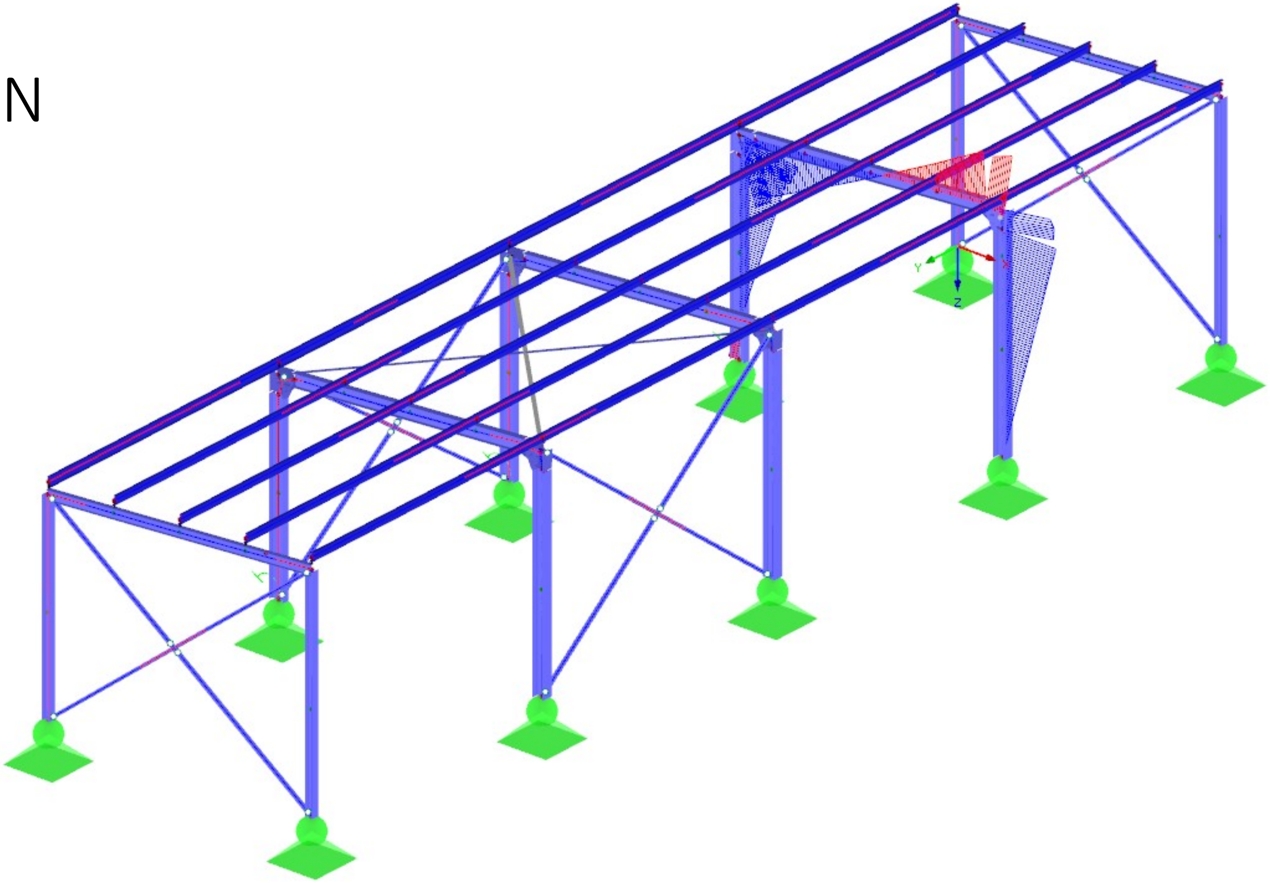
Behaviour

Bending moment of bare frame for F = 30 kN



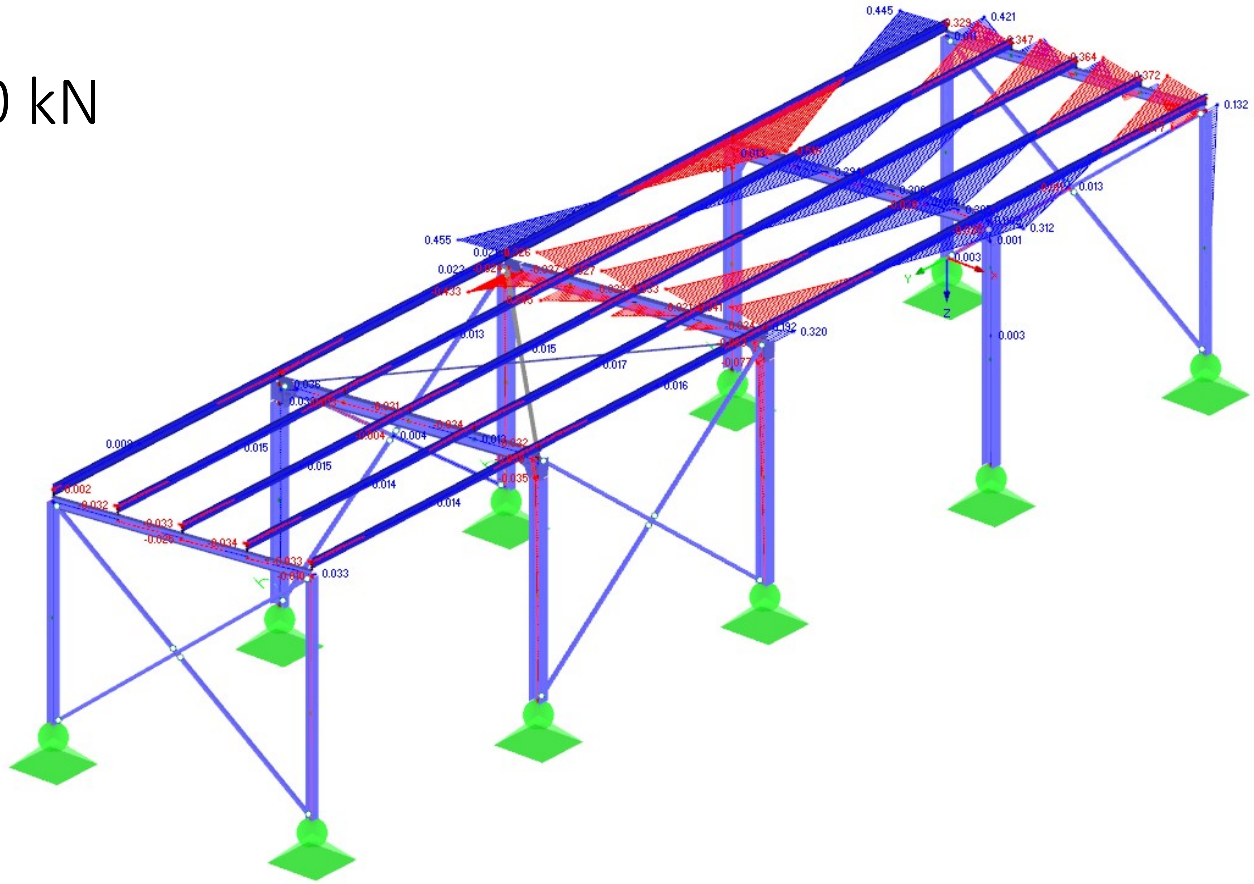
Behaviour

M_y for F = 30 kN



Behaviour

M_z for F = 30 kN



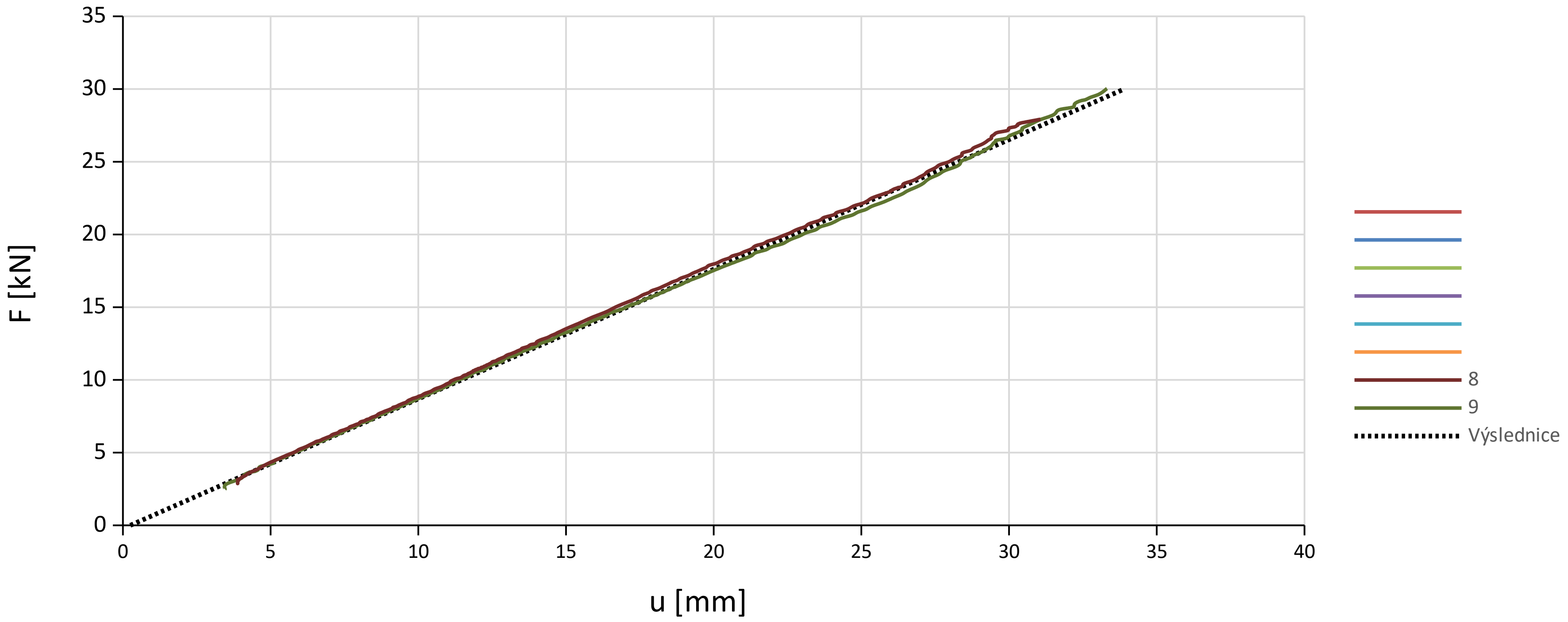
Behaviour - observations

Distortion of Zed roof purlin during the test

Damage and ovalization of holes in composite roof panel

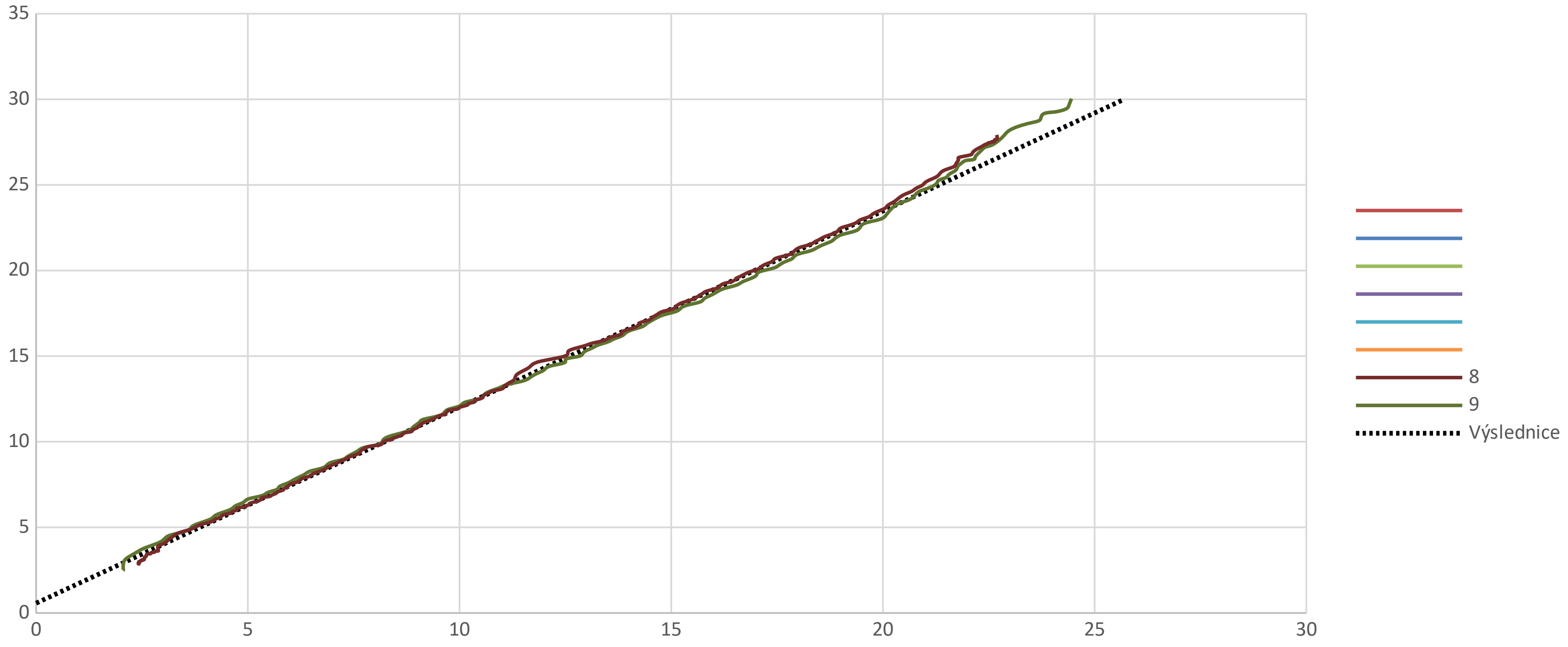
Behaviour

Point #1, F-u diagram, bare steel frame



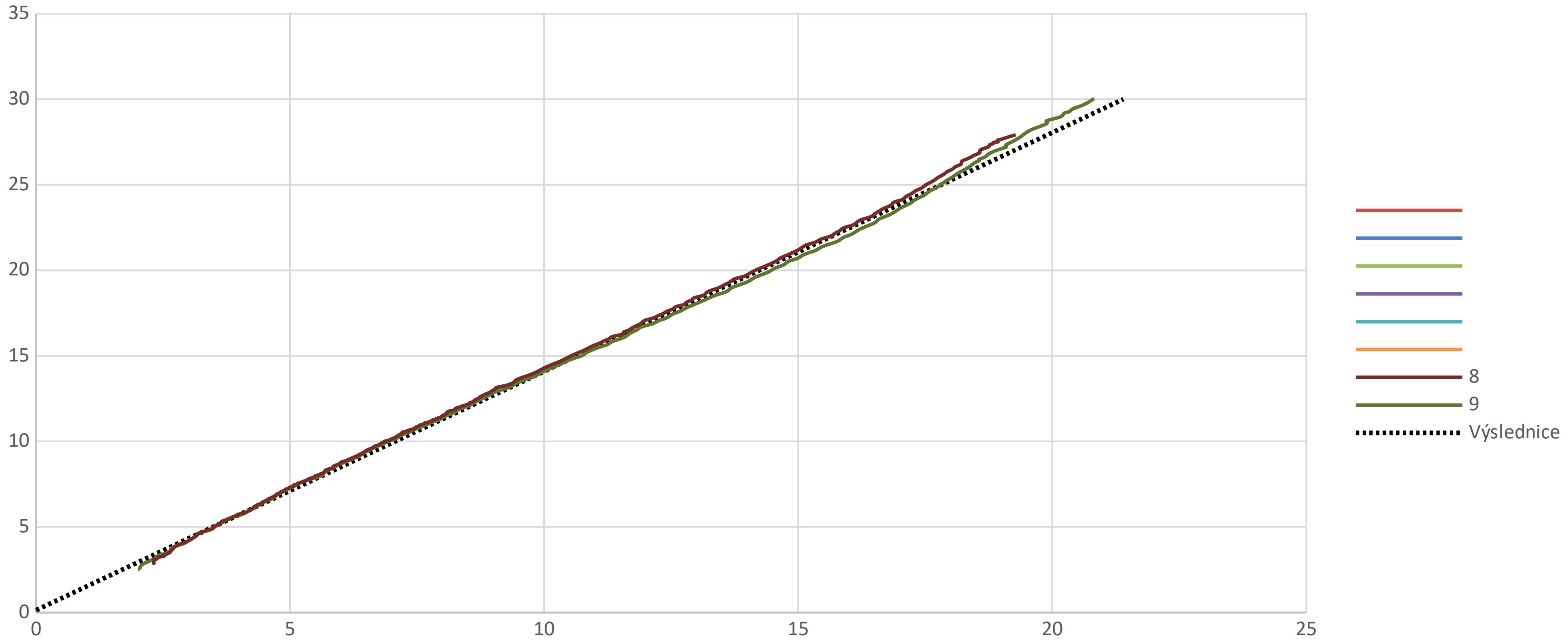
Behaviour

Point #2, F-u diagram, bare steel frame



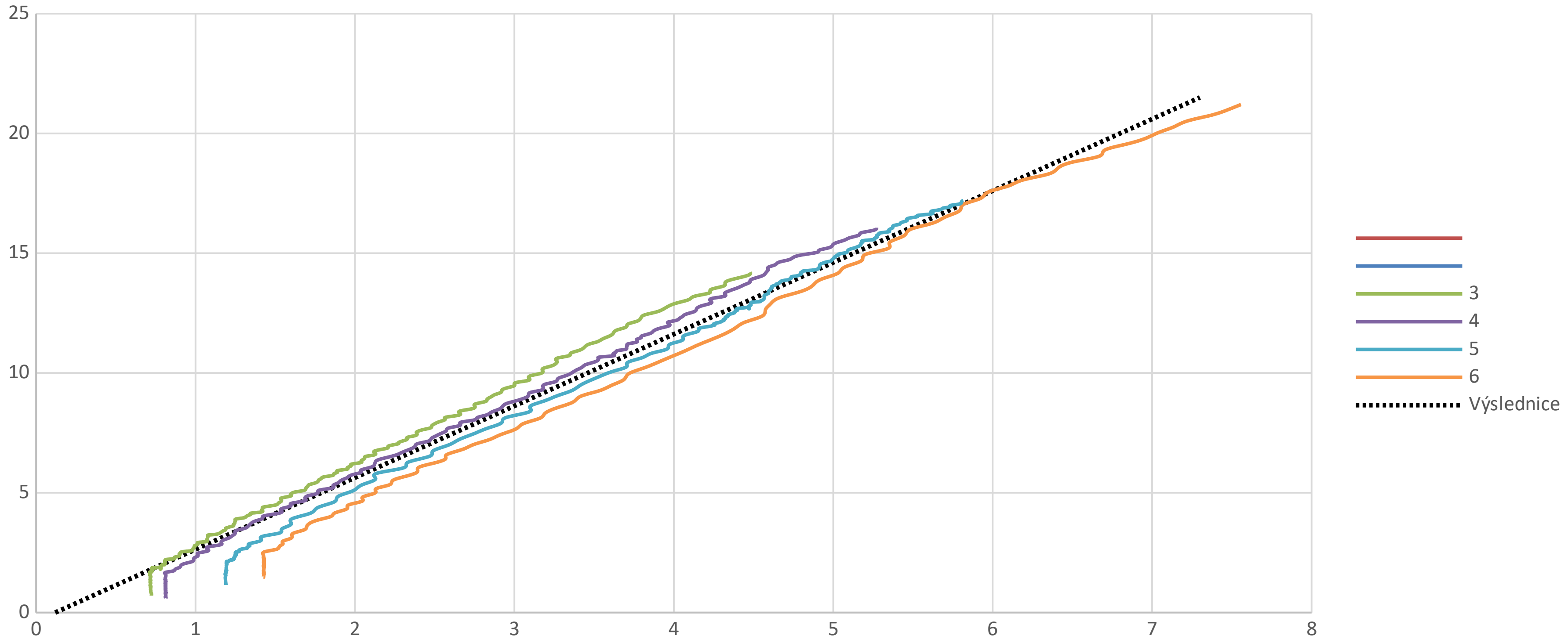
Behaviour

Point #3, F-u diagram, bare steel frame



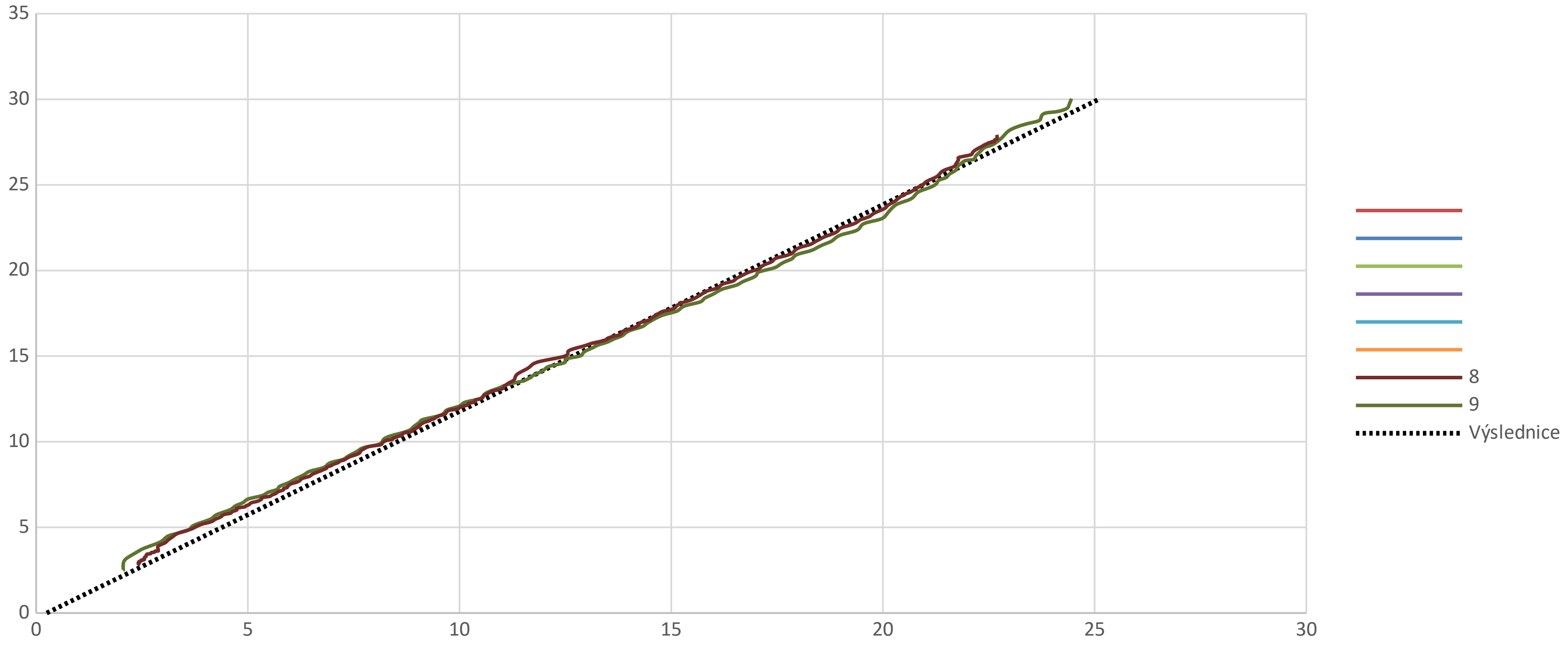
Behaviour

Point #1, F-u diagram, Frame with roof cladding



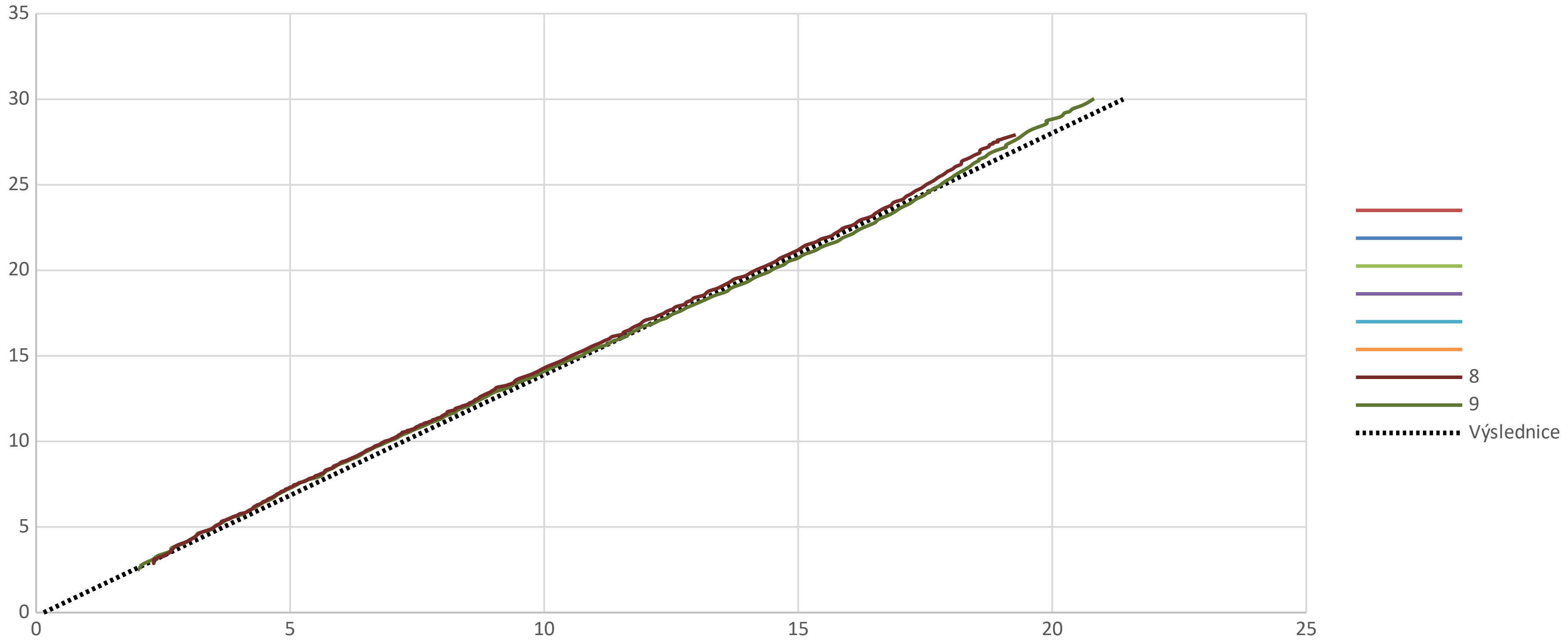
Behaviour

Point #2, F-u diagram, Frame with roof cladding



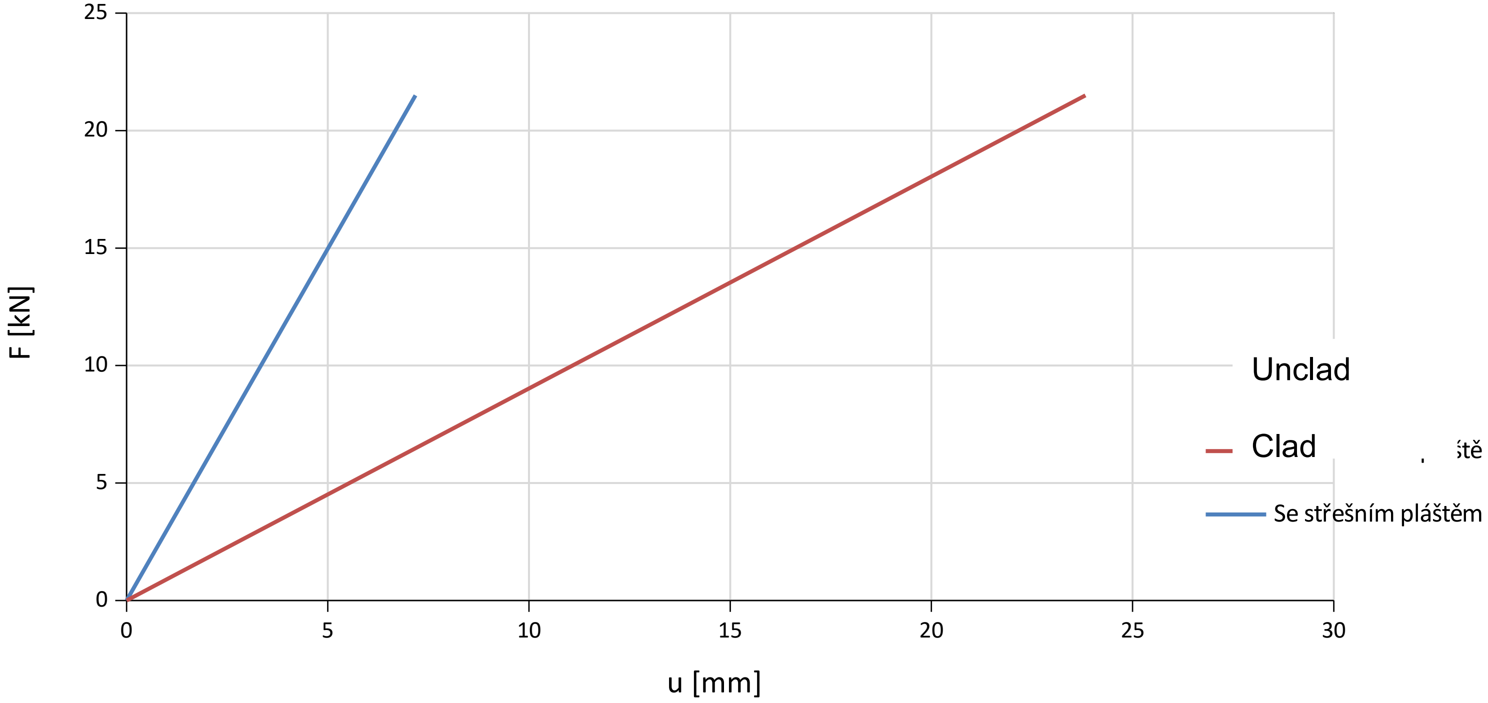
Behaviour

Point #3, F-u diagram, Frame with roof cladding



Behaviour

Comparison of horizontal deformations of clad and unclad building for Point 1

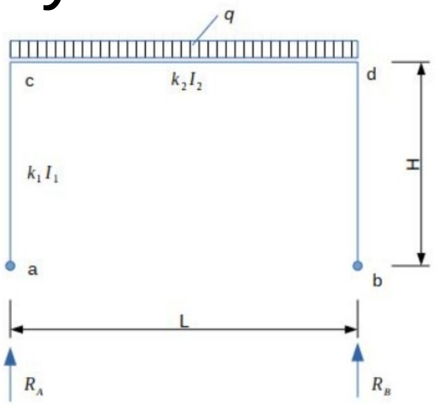


Example of a simplified analysis

- **Objectives**:
- Analysis of internal forces and displacements based on frame equations (no need for software)
- Investigate sensitivity of frame to sway imperfections
  - Calculate horizontal deformations and internal forces
  - Check α_{cr}
  - Check limiting vertical loading at which sway imperfections need to be considered
- Ultimate Limit State of column, check:
  - Lateral torsional buckling of column
  - Interaction of axial force and bending moment

Example of a simplified analysis

- Python based code developed in Jupyter notebook
- Procedure:
  - Internal forces and deformations based on equations (sketches)
  - Level of loading is hardcoded (can be adjusted as appropriate)
  - Check frame imperfections
  - Check α_{cr} and it's limits
  - Check if sway imperfections need to be considered
  - Check interaction of axial compression (flexural buckling, flexural torsional buckling) and lateral torsional buckling (Table NB.3.1 of CSN EN 1993-1-1)



$$k_1 = \frac{I_1}{H}$$

$$k_2 = \frac{I_2}{L}$$

$$M_s = \frac{qL^2}{8}$$

$$M_{ca} = -M_{cd} = \frac{qL^2}{4} * \frac{k_1}{3k_1 + 2k_2}$$

$$M_{max} = \frac{qL^2}{8} - M_{cd}$$

$$R_A = R_B = \frac{ql}{2}$$

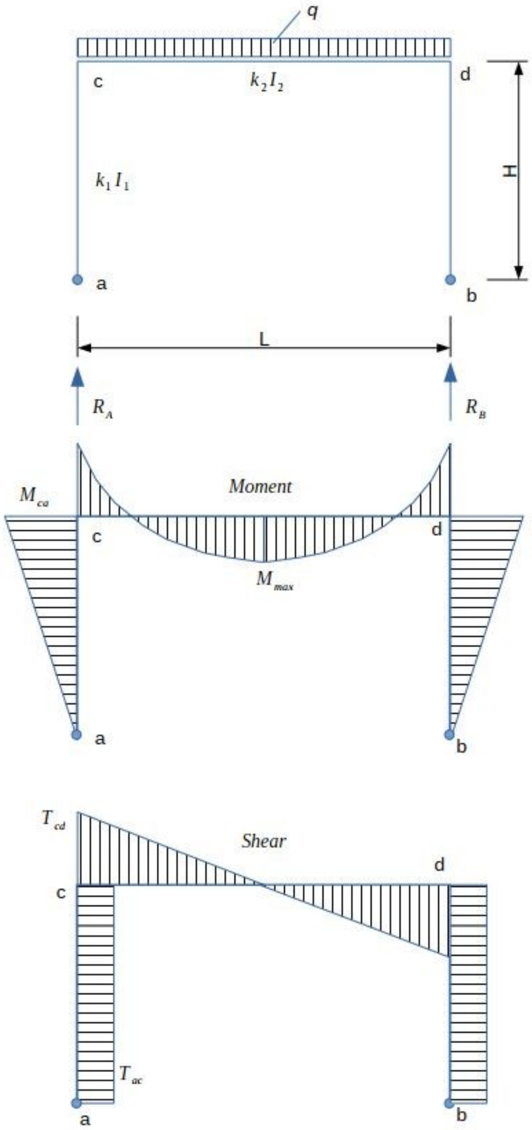
In [145]:

```
# Loading
# Total factored UDL on rafter
qd = 20 #[kN/m]
Fd = 20 #[kN]
```

Example of a simplified analysis

- Code could be found at:
  https://github.com/maresjiri/Simple-portal-frame

- Frame equations



$$k_1 = \frac{I_1}{H}$$

$$k_2 = \frac{I_2}{L}$$

$$\bar{M}_s = \frac{q L^2}{8}$$

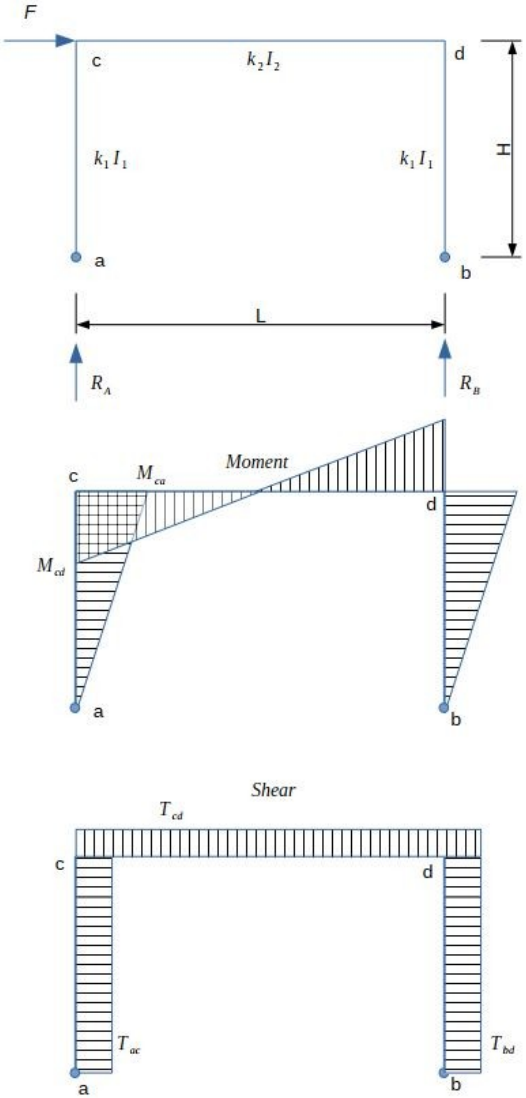
$$M_{ca} = -M_{cd} = \frac{q L^2}{4} * \frac{k_1}{3 k_1 + 2 k_2}$$

$$M_{max} = \frac{q L^2}{8} - M_{cd}$$

$$R_A = R_B = \frac{q l}{2}$$

$$T_{ac} = \frac{-M_{ca}}{H}$$

$$T_{cd} = R_A = \frac{q l}{2}$$

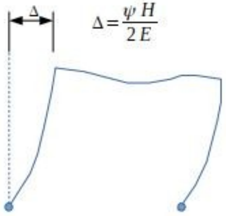


$$k_1 = \frac{I_1}{H}$$

$$k_2 = \frac{I_2}{L}$$

$$\phi_c = \frac{F H}{6 k_2}$$

$$\psi = \frac{F H}{6} * \frac{k_1 + 2 k_2}{k_1 k_2}$$



$$\Delta = \frac{\psi H}{2 E}$$

$$M_{ca} = -M_{cd} = \frac{-F H}{2}$$

$$T_{ac} = \frac{-M_{ca}}{H} = \frac{F}{2}$$

$$T_{cd} = \frac{-F H}{L} = \frac{2 M_{cd}}{L}$$

$$T_{bd} = T_{ac} = \frac{-M_{ca}}{H} = \frac{F}{2}$$

$$R_A = T_{cd}$$

$$R_B = -R_A$$

Example of a simplified analysis

- Profiles and material

```
# Profiles
# Column
# IPE 300
Ac = 5381 #[mm^2], cross-sectional area
Iyc = 83560000 #[mm^4]
Wyc = 557000 #[mm^3]
Izc = 6038000 #[mm^4]
Itc = 201200
Iwc = 125900000000
zg = 0  #[m]
zj = 0  #[m]


# Rafter
# IPE 270
Ar = 4594 #[mm], cross-sectional area
Iyr = 57900000  #[mm^4]
Wyr = 429000  #[mm^3]
Izr = 4199000  #[mm^4]


# Material
E = 210000000 #[kPa]
G = 80700000  #[kPa]
fy = 275000
gammaM1 = 1
```

Example of a simplified analysis

- Loading and frame imperfections

```
# Loading
# Total factored UDL on rafter
qd = 20 #[kN/m]
Fd = 20 #[kN]
```

```
# Frame imperfections
alpha_h = 2 / math.sqrt(H)
m = 2
alpha_m = math.sqrt(0.5 * (1 + 1/m))
phi0 = 1 / 200
phi = phi0 * alpha_h * alpha_m

# Equivalent horizontal force
EHF = qd * L * phi
k1 = Iyc * 10**(-12) / H
k2 = Iyr * 10**(-12)/ L
psi_EHF = (EHF * H / 6) * ((k1 + 2*k2) / k1 / k2)
DELTA_EHF = psi_EHF * H / 2 / E
```

Example of a simplified analysis

- α_{cr} and amplification factor
- Here, α_{cr} >> 10 therefore linear analysis ignoring sway imperfections is acceptable
- When loading on rafter is increased α_{cr} gets reduced and imperfections need to be accounted for in analysis
- Re-running the code with increased qd shows sensitivity of the frame to the imperfections

```
Hd = Fd + EHF
Vd = qd * L
alpha_cr = (Hd / Vd) * (H / DELTA)
```

```
alpha_cr                        =  26.21  [-]
```

```
# Amplification factor
amp = 1 / (1 - 1 / alpha_cr)
```

```
errmsg = "Method is adequate."
if alpha_cr < 3:
    errmsg = "ERROR: alpha_cr out of limits."
if alpha_cr > 10:
    errmsg = "Linear elastic analysis is adequate."
    amp = 1

print(errmsg)
```

```
Linear elastic analysis is adequate.
```

```
amp                             =  1.000  [-]
```

Example of a simplified analysis

- Buckling curves and critical buckling moment M_{cr}

```
PHI_y = 0.5*(1 + alpha_y *(lambda_dash_y - 0.2) + lambda_dash_y**2)
PHI_z = 0.5*(1 + alpha_z *(lambda_dash_z - 0.2) + lambda_dash_z**2)
chi_y = min(1 / (PHI_y + math.sqrt(PHI_y**2 - lambda_dash_y**2)),1)
chi_z = min(1 / (PHI_z + math.sqrt(PHI_z**2 - lambda_dash_z**2)),1)
```

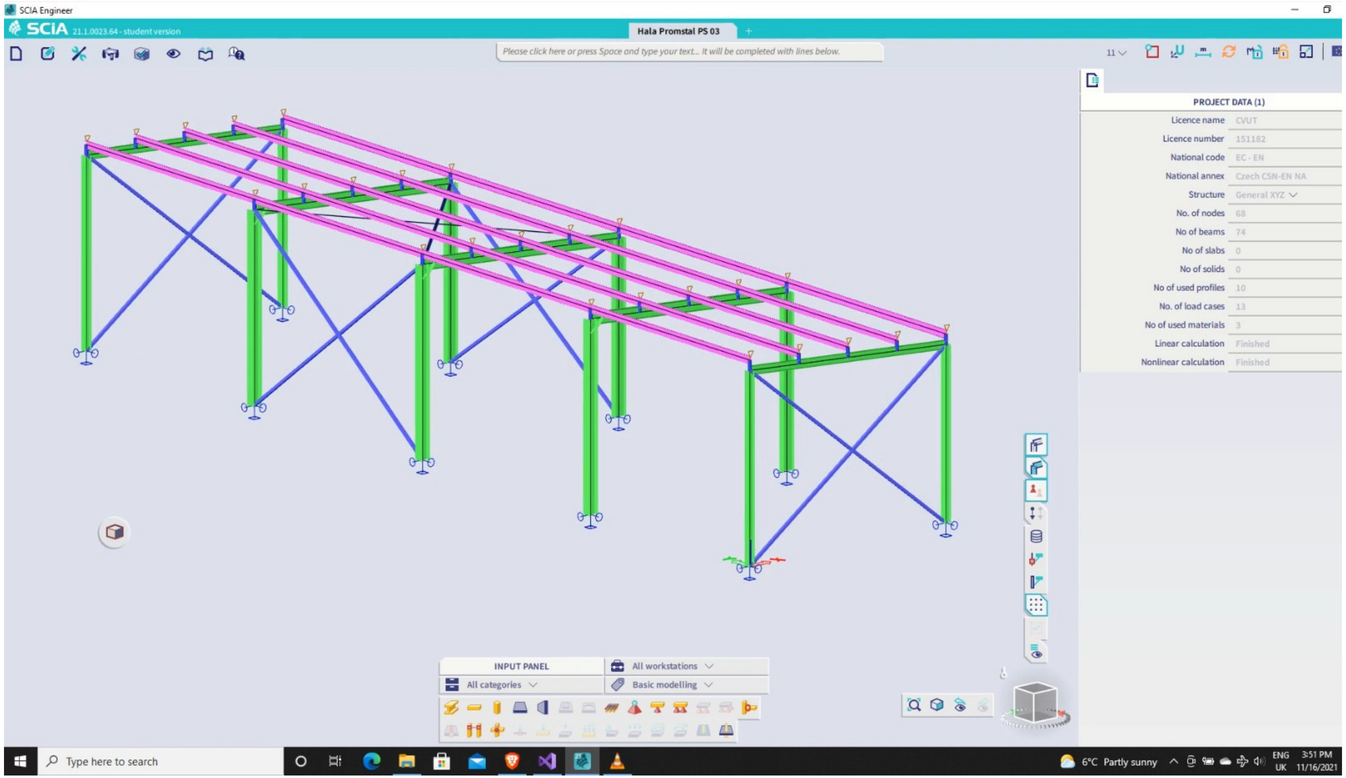
- Table NB.3.1 of CSN EN 1993-1-1 or use an alternative solution specific to your NAD
- Interaction of axial force and bending moment

```
UF1 = NEd * gammaM1 / chi_y / NRk + kyy * MEd * gammaM1 / chi_LT / MyRk
UF2 = NEd * gammaM1 / chi_z / NRk + kzy * MEd * gammaM1 / chi_LT / MyRk
```

```
UF1                    =  0.641  [-]
UF2                    =  0.712  [-]
```

Analysis using commercial software

- Modelled in SCIA Engineer
- Model can be downloaded from project site



Conclusions

- Cladding contributes to the stiffness of building but the analysis needs to assure that it does not get damaged,
- Contribution of cladding to the overall stiffness of building will depend on quality and frequency of it’s connection to the framework,
- Certain permanent damage occurs in composite panel at the serviceability limit state,
- Distortional stiffness/flexibility of roof purlins also contributes to this deformation,
- Simple analysis shows as the sensitivity of imperfect frame to vertical loading, the level of loading at experiment is fairly below these limits.