ARISTOTLE UNIVERSITY OF THESSALONIKI
SCHOOL OF CIVIL ENGINEERING
DIVISION OF STRUCTURAL ENGINEERING
LABORATORY OF METAL STRUCTURES

DIPLOMA THESIS

STUDY ON OPTIMAL FINITE ELEMENT ANALYSIS MODELLING OF STEEL-CONCRETE COMPOSITE BUILDING WITH INNOVATIVE ARCHITECTURAL DESIGN

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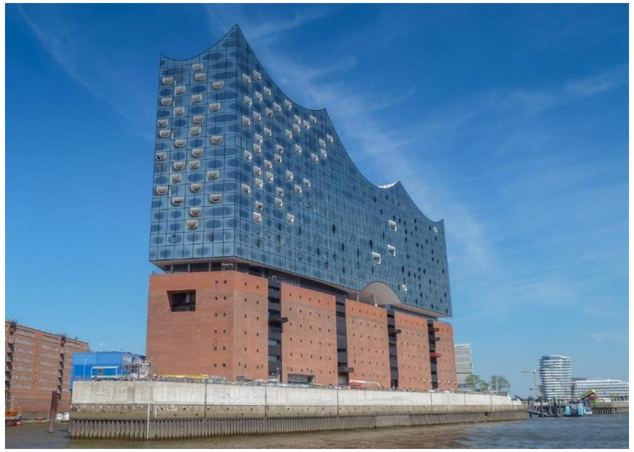
Steel-Concrete composite structures

- Diverse architectural design
- Lighter structures
- Steel members are prevented from buckling
- Steel members are protected from fire
- Sustainability of buildings

Composite structures

Milstein Hall at Cornell University, New York, USA

German Museum of Technology, Berlin, Germany



Elbphilharmonie, Hamburg, Germany

FIBA's headquarters, Switzerland

Purpose of this Project

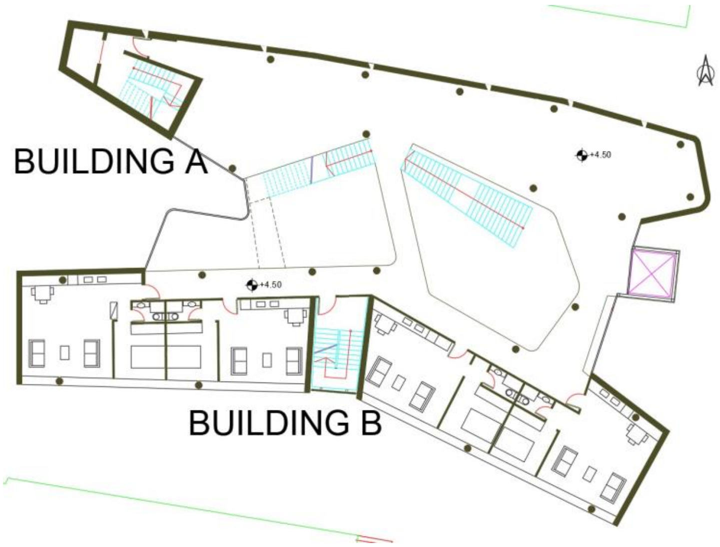
- Understanding the Eurocodes
- Definition of the imposed loads
- Study on composite structural systems
- Designing the structural members
- Optimizing the structure’s response with respect to the architectural demands

The building

- Nominated in the architectural contest «*Housing for Biennale garden district Venice, Italy*» in 2019
- Purpose: Museum
- Location: Venice, Italy
- Innovative architectural design

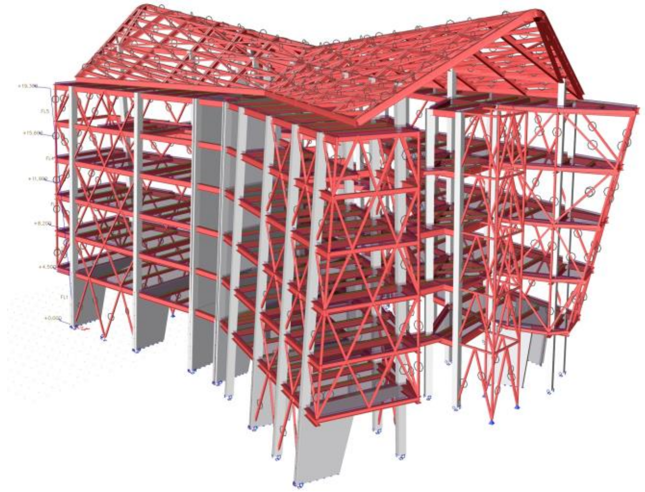
General information

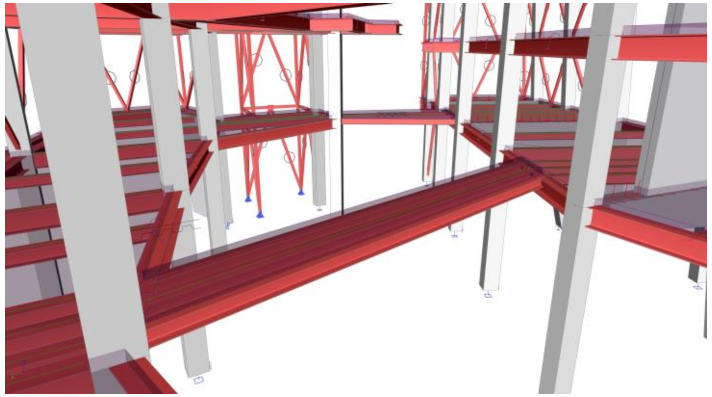
- Four storey structure with total height of 25.6 m
- Consists of two individual buildings A and B
- Common height for the ground floor at 4.5 m
- Structure’s A storey height 3,70 m
- Structure’s B storey height 3,00 m



Architectural particularities

- Leaning South side with zenith angle 5.70^o
- Building A, East side cantilever span increasing with level

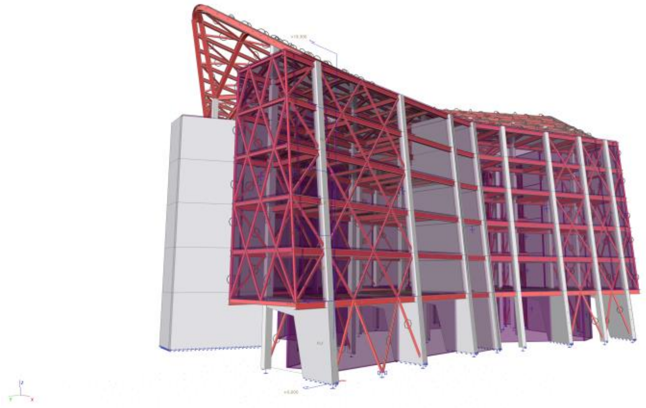


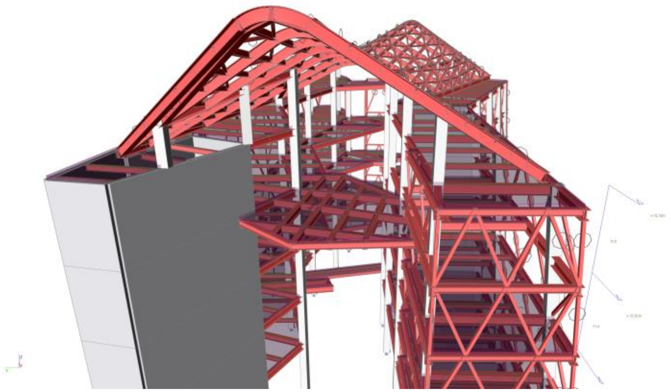


- Different heights between the slabs of the two buildings
- Two internal bridges connecting the two buildings at 1st floor level

Architectural particularities

- Both East and West sides of building B are cantilevers with a span of 2.00 m and 2.60 m accordingly
- Bi-lateral slab on the 4th floor which is simply supported in both buildings

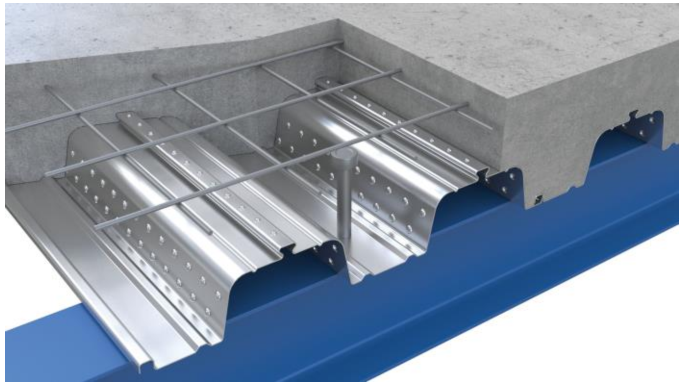


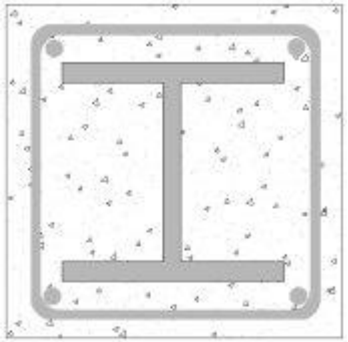


- Building B is four floors high plus an attic
- Asymmetrical structure with an increase in mass on upper floors: Irregularities in plan and elevation

Structural systems
Vertical loads

- Trapezoidal steel sheeting-concrete composite slabs with sheeting ribs spanning transverse to the secondary beams
- Primary and secondary steel beams
- Composite action via welded shear connectors (studs)

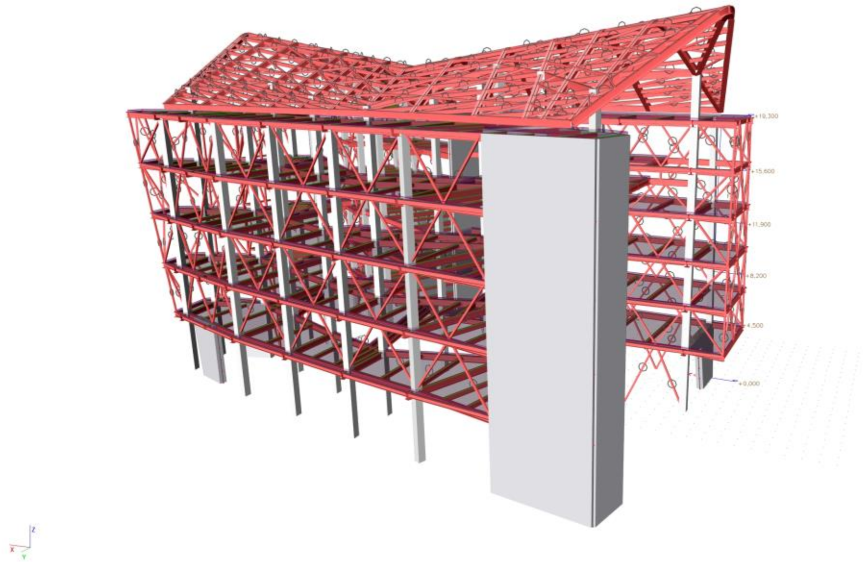




- Steel columns fully encased in concrete
- Concrete shear walls

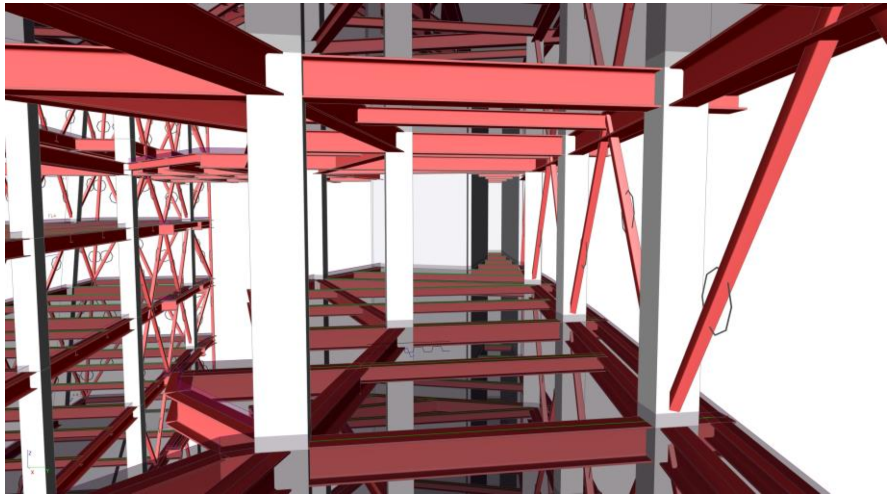
Structural systems
Horizontal loads

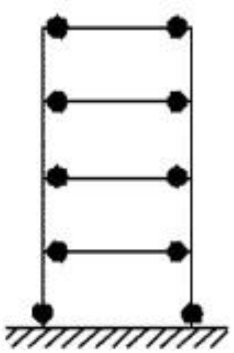
- Longitudinal direction
  - Type V and Λ concentric bracing system
  - Only in Building A: Concrete shear walls in the West side



Structural systems
Horizontal loads

- Transverse direction
  - Composite moment resisting frames



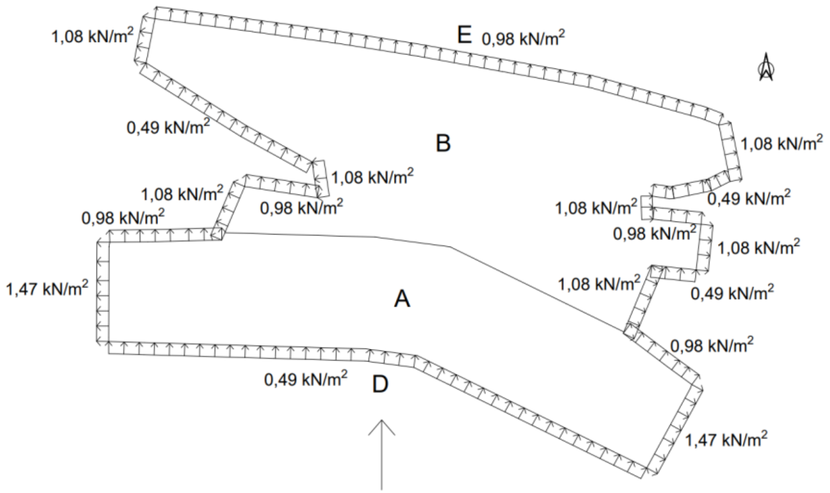


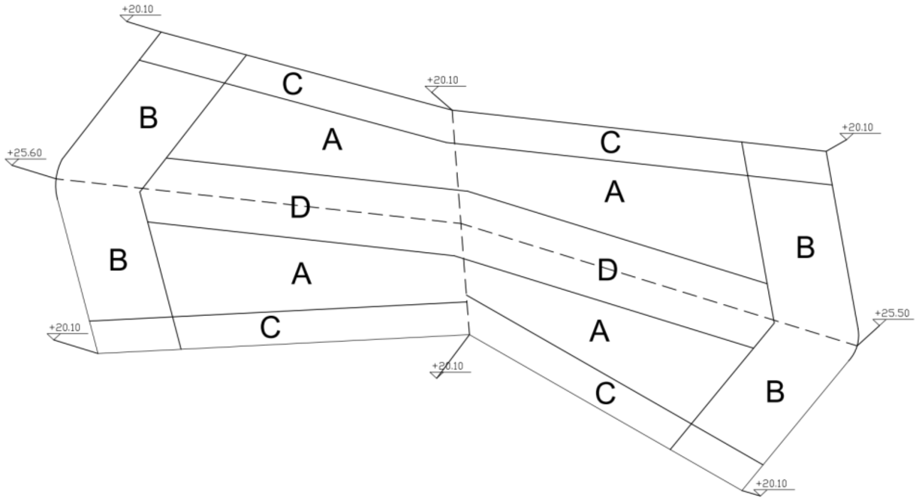
Imposed actions

- Permanent actions
  - Self weight: Steel members, composite slabs and reinforcement bars
  - Additional surface load 2,00 kN/m^2
  - Ceiling and services 0,50 kN/m^2
- Variable actions EN1991-1-1
  - Imposed floor load category C3 Q=5,00 kN/m^2
  - Partition walls q_k=0,80 kN/m^2
- Snow actions EN1991-1-3
  - Roof snow load s=0,64 kN/m^2

Imposed actions

- Wind loads EN1991-1-4
  - Aggregate of external and internal wind pressures for wind loading in all geographical orientations
  - Canopy wind loading with 3 positive and 3 negative wind pressures including roof's snatch away





Imposed actions

- Seismic action EN1998-1
  - Spectral analysis using spatial analysis model
  - Horizontal response spectrum data
    - Reference peak ground acceleration a_{gR}=0,16g
    - Importance class III γ_I=1,20
    - Soil type C according to EC8
  - Irregularity in elevation
    - Decreased value for the behavior factor q by 20%
    - Earthquake in X direction q=2,00·0,80=1,60
    - Earthquake in Y direction q=4,00·0,80=3,20
  - Accidental eccentricity of mass center $e_{ai}=\pm 0,05L_i$

Load combinations EN1990

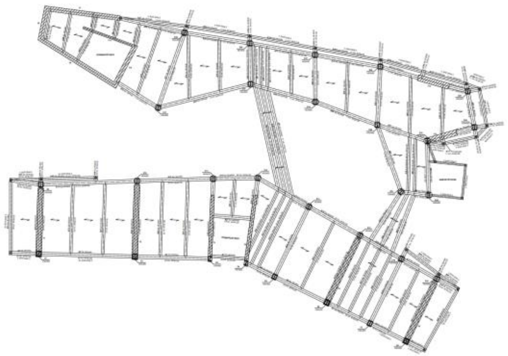
- 16 Ultimate limit state combinations (Eq. 6.10)
  - Permanent, variable and construction loads
  - Snow and wind actions

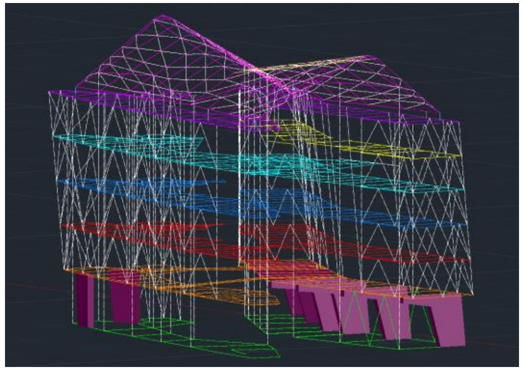
- 4 Seismic combinations (Eq. 6.12*b*)
  - Permanent and variable loads
  - Spatial superposition and additional accidental eccentricity loads

- 2 Serviceability limit state combinations (Eq. 6.14*b*)
  - Permanent, variable and construction loads
  - Snow actions

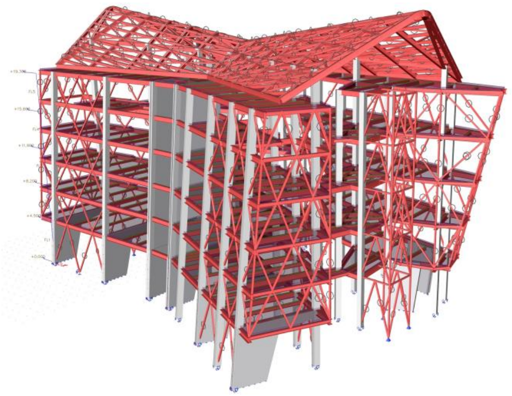
Analysis modelling

- Designing the beam grid in AutoCAD
- Designing the 3D model with member axles in AutoCAD





- Import the 3D DWG file to SCIA Engineer v20
- Modelling the structure



Materials and sections for the structural members

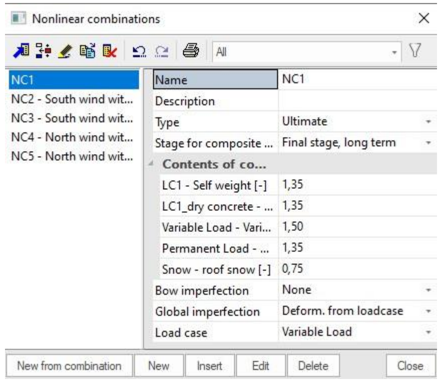
- Composite columns: Fully encased HEA400 Type a / S355-C30/37
- Primary beams: HEA340,HEA400 / S275
- Secondary beams: HEA240 / S275
- Trapezoidal steel sheeting: *ComFlor* 80 *t*=1,0mm / S235
- Shear connectors: *Φ*22/130mm / S355
- Slab's reinforcement bars: *Φ*12/200mm / B500C
- Concentric bracing: SHS120/6.3 / S275
- Concrete shear walls Γ shape: *t*=30cm / C30/37
- Concrete shear walls: *t*=40cm / C30/37

Supporting conditions

- Columns
  - Fixed in major axis
  - Hinged in weak axis
- Primary beams
  - Fixed beams in moment resisting frames
  - Hinged beams in beam to weak axis column connection
- Secondary beams
  - Hinged in both ends
- Diagonal elements
  - Development of axial force only
- Shear walls
  - Fixed in both directions

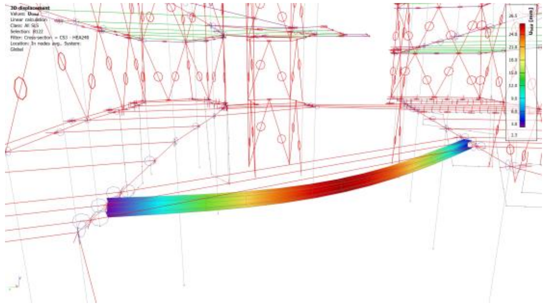
Model's imposed loads

- Defining all load cases
- Defining all load combinations
  - 22 linear elastic 1st order combinations
  - 16 global elastic instability combinations with a_{cr} factor
  - 5 geometrically non-linear elastic analysis combinations according to 2nd order theory
    - Elastic materials
    - Timoshenko beam theory
    - Global imperfections with deformation from the most unfavorable load case

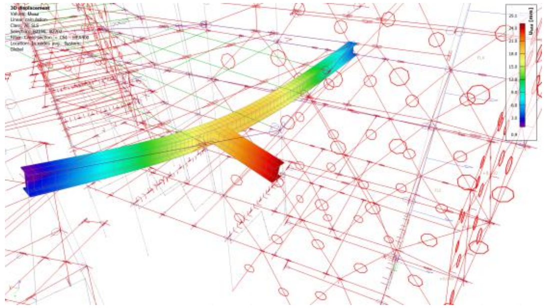


Analysis results
Serviceability limit state

- The maximum deflection of the secondary beams HEA240 is *w*=24,2 mm with limit *L*/250. Unity check *n*=0,65

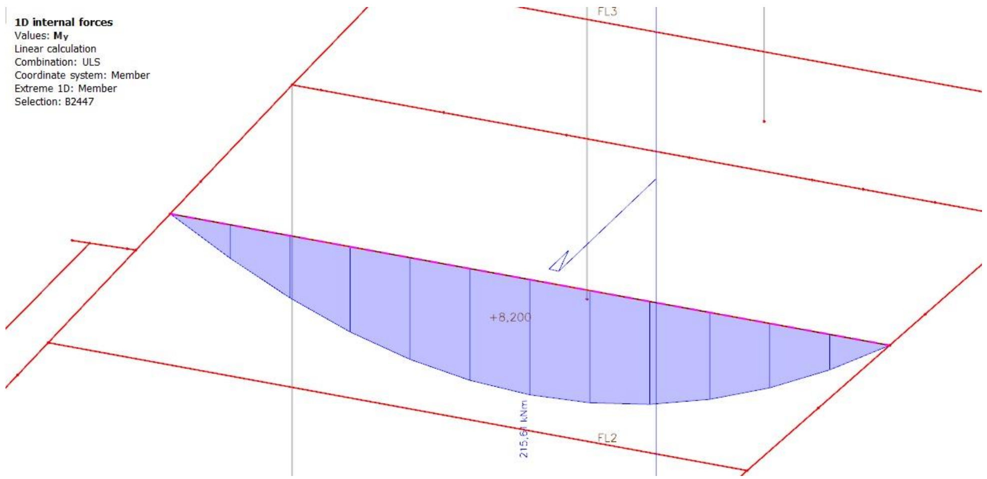


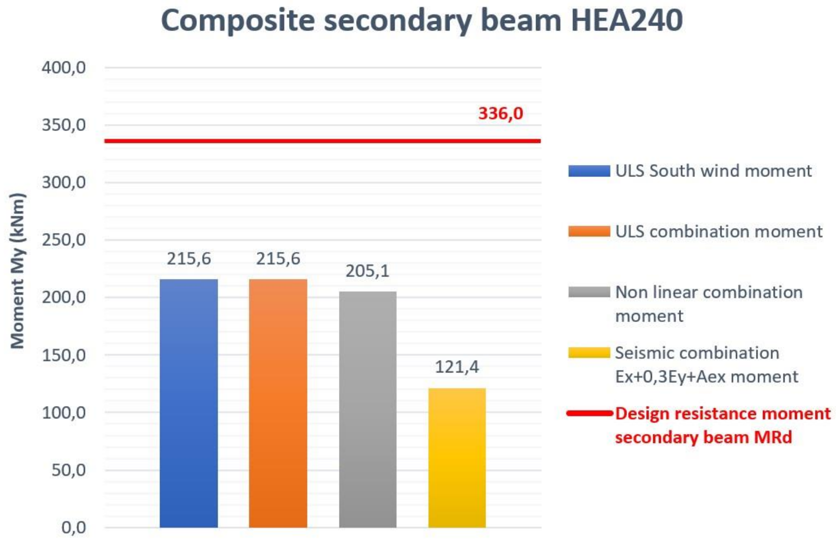
- The maximum deflection of the primary beams HEA400 is *w*=7,2 mm with limit L/250. Unity check *n*=0,97



Analysis results
Ultimate limit state: Secondary beams

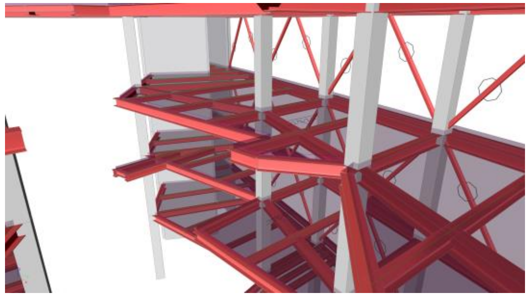
- Secondary beams HEA240
- Load case: Composite final stage ULS
- Unity check n=0,64

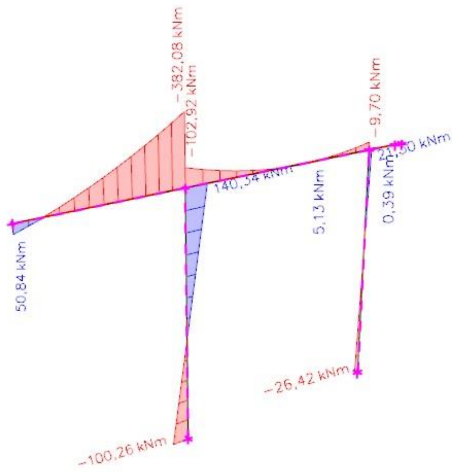


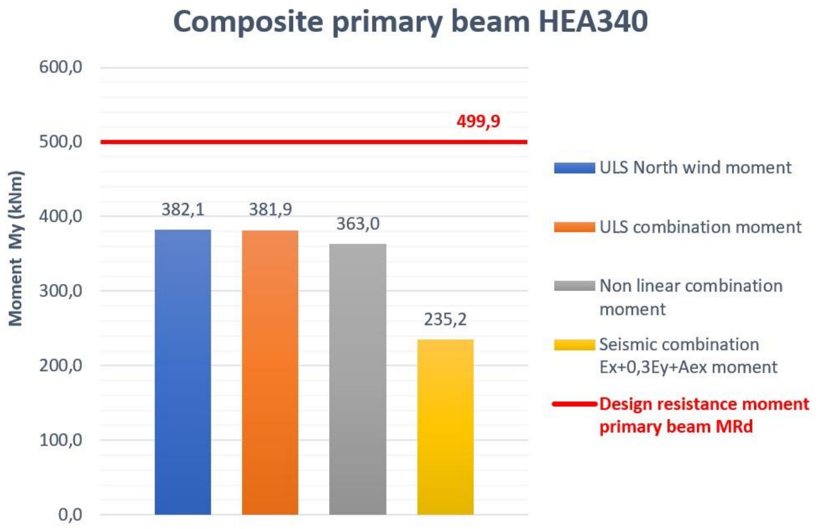


Analysis results
Ultimate limit state: MRF primary beams

- Primary beams HEA340
- Load case: Composite final stage ULS – North Wind
- Unity check n=0,76

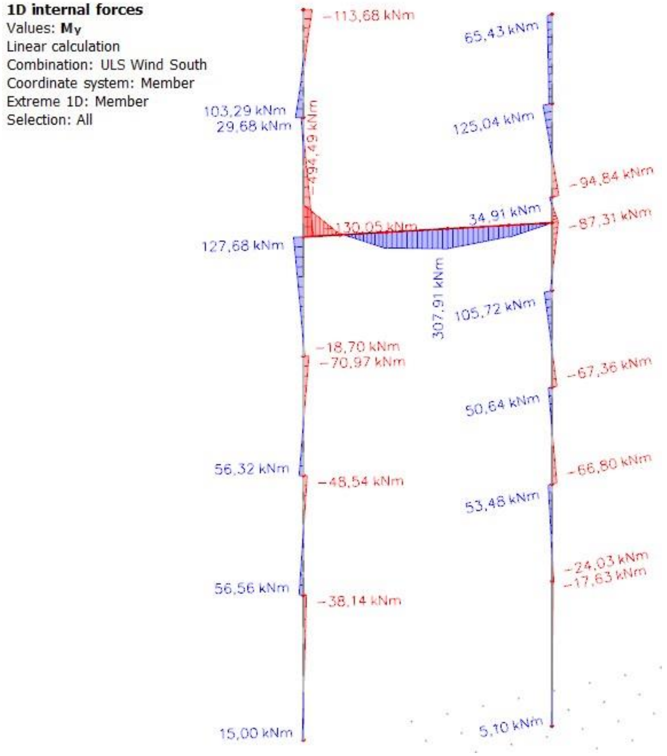


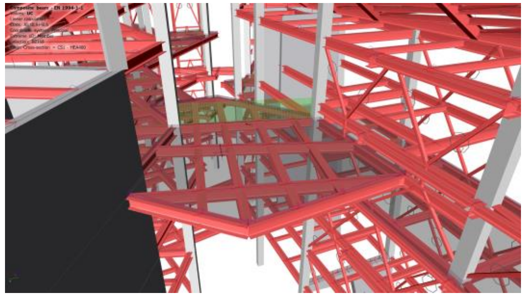


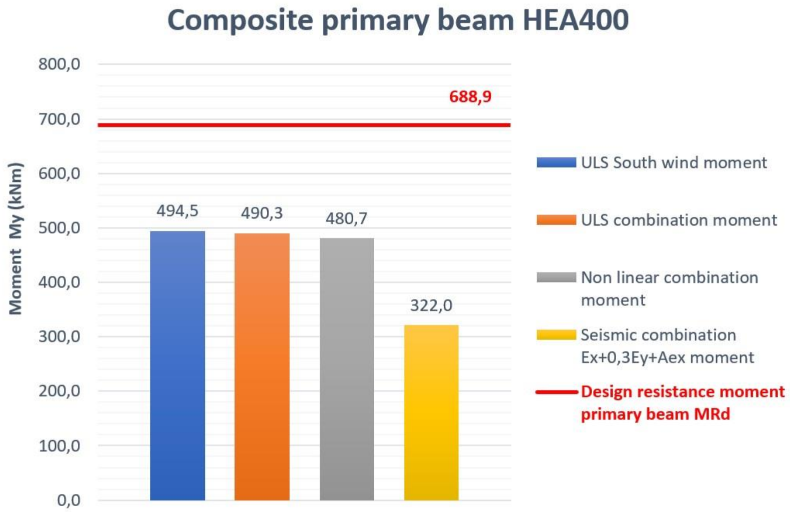


Analysis results
Ultimate limit state: Bi-lateral slab-primary beams

- Primary beams HEA400 – Frame Σ17-Σ10
- Load case: Composite final stage ULS
- Unity check n=0,72

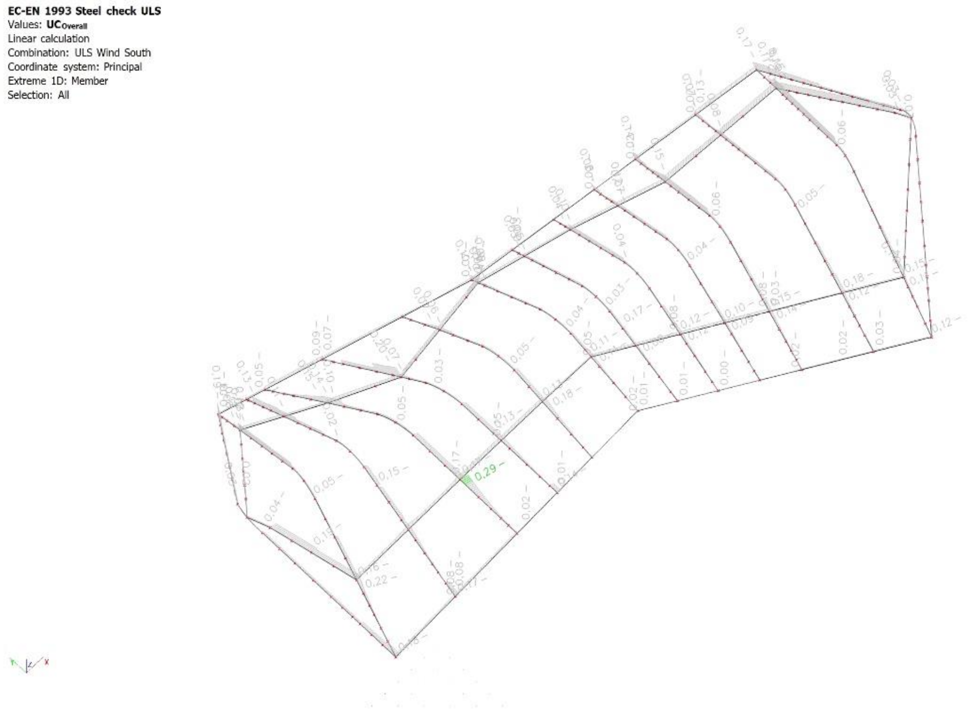






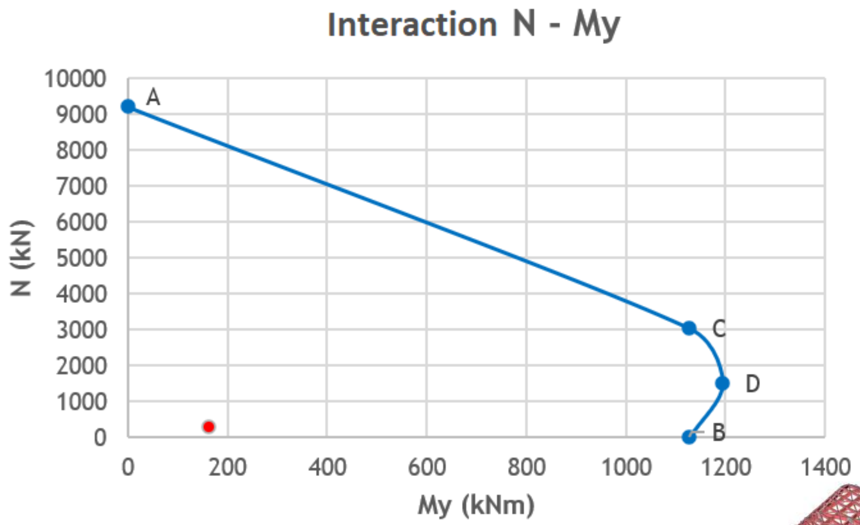
Analysis results
Ultimate limit state: Roof beams

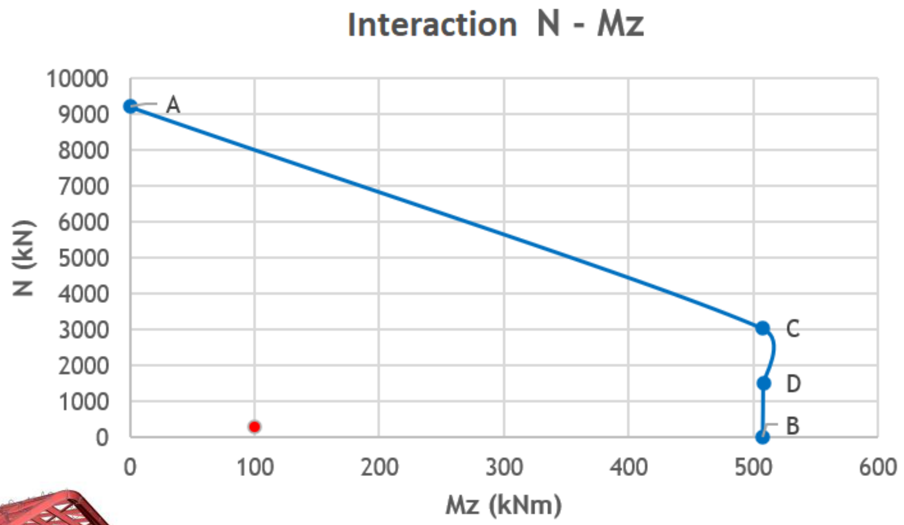
- Roof beams HEA400
- Load case: Positive air pressure
- Low Unity check n=0,29

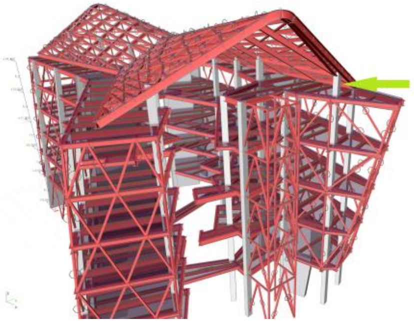


Analysis results
Ultimate limit state: Composite columns

- Maximum moments M_y and M_z of composite columns HEA400 on the top of column Σ24
- Static load combination; Positive wind pressure at the half east side of the canopy (ULS3)
- Unity check for combined compression and biaxial bending n=0,349

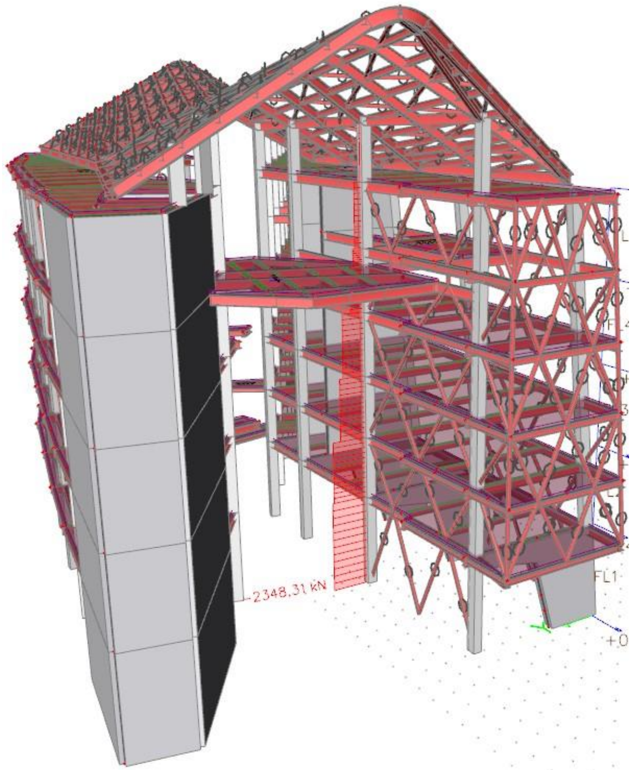






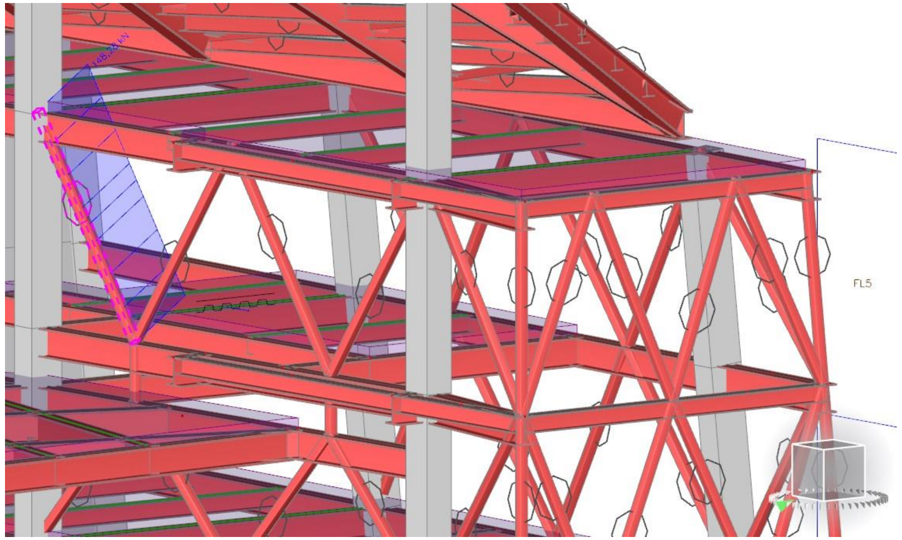
Analysis results
Ultimate limit state: Composite columns

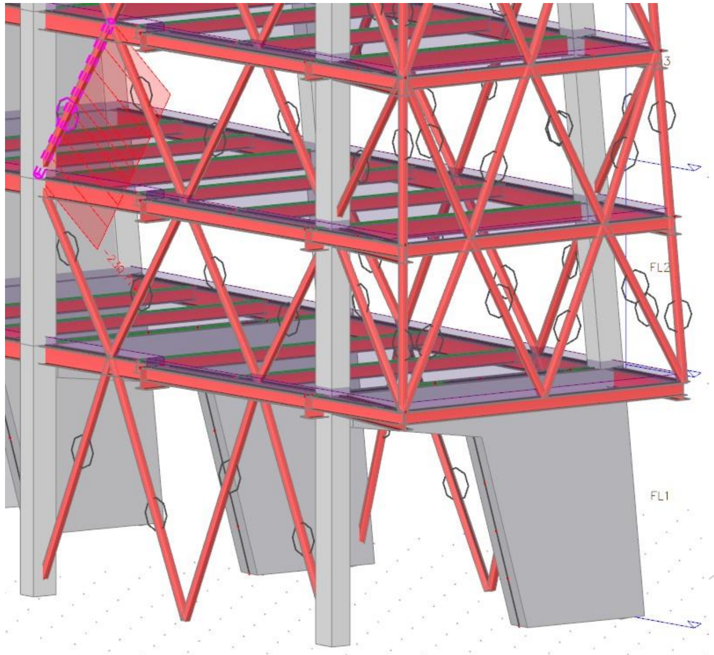
- Maximum axial load
- Static load combination; Composite final stage ULS – South Wind
- Unity check for flexural buckling n_y=0,275 and n_z=0,495



Analysis results
Ultimate limit state: Concentric bracing

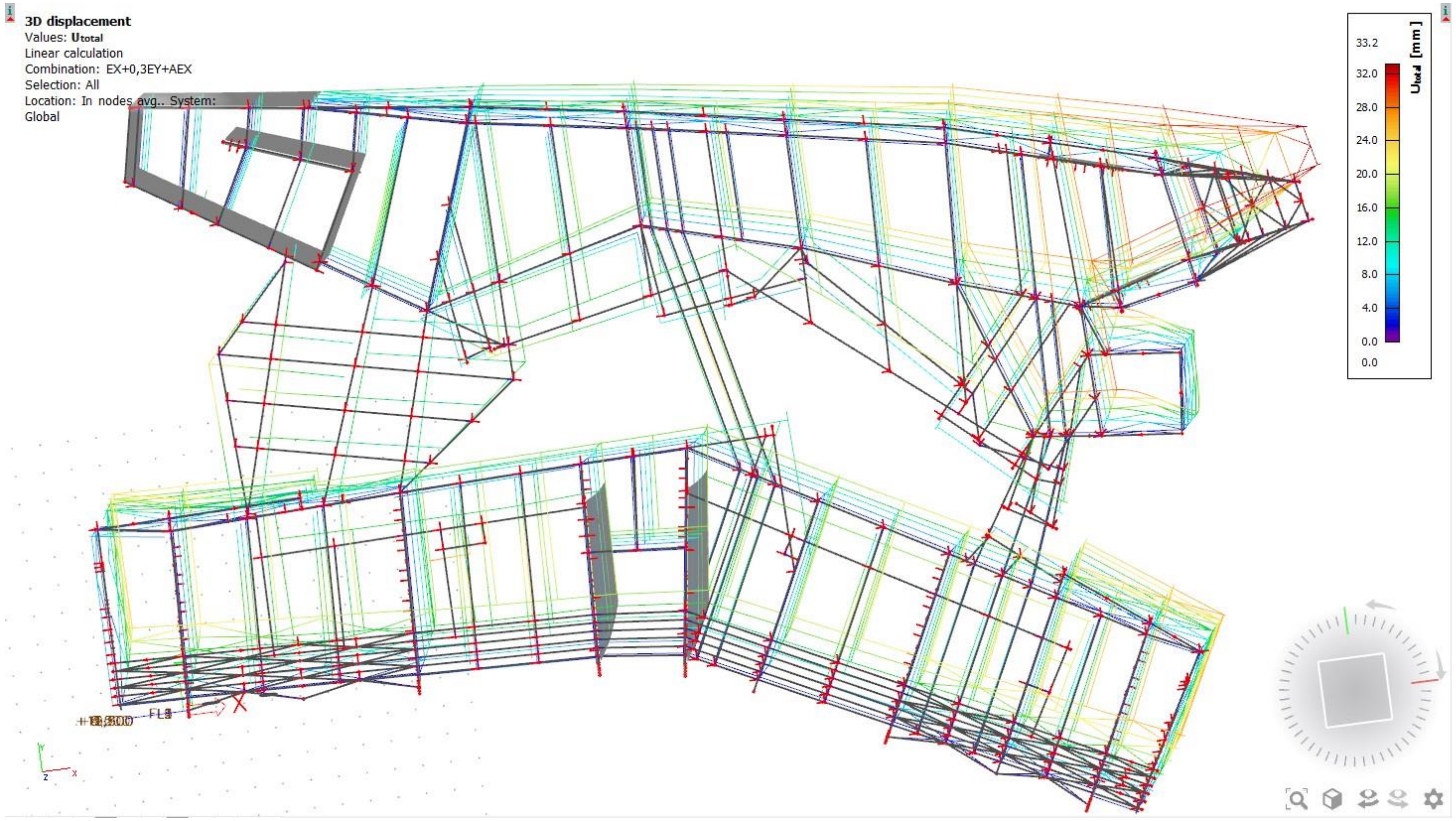
- Building B
- Static load combination; Composite final stage ULS – South Wind
- Unity check for diagonal in tension n=0,19 and diagonal in compression n=0,40





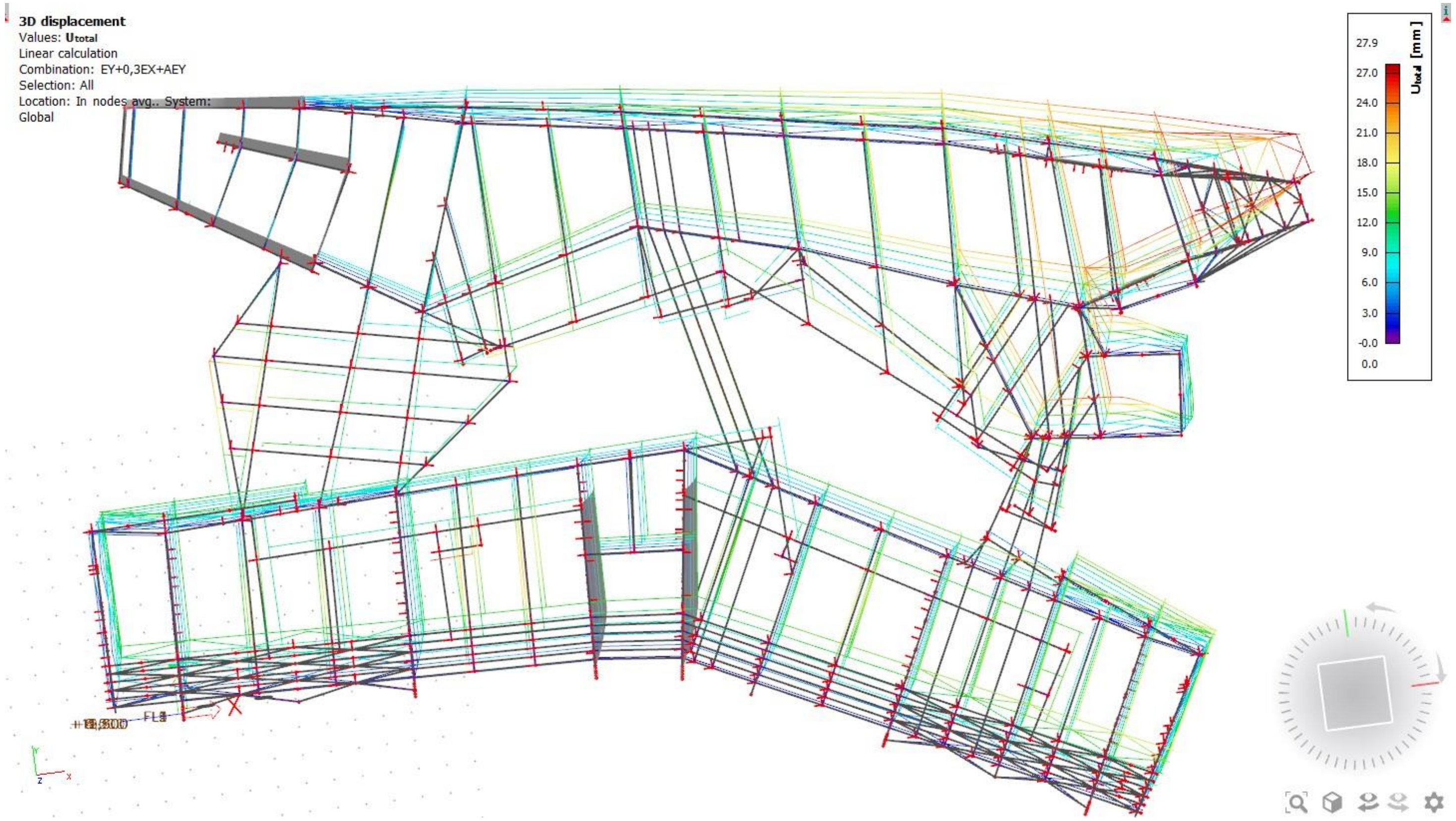
Analysis results
Seismic loads

- Maximum displacement for the Seismic combination E_x+$0,3E_y$+A_{ex} u_{total}=3,32 cm



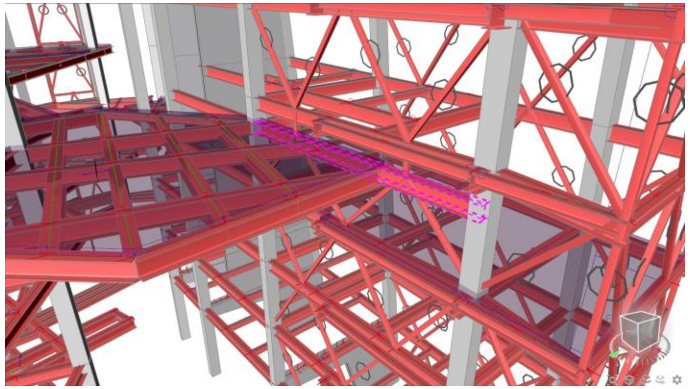
Analysis results
Seismic loads

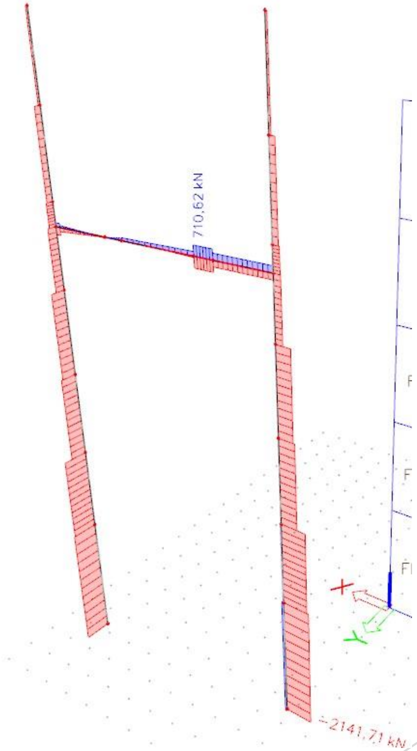
- Maximum displacement for the Seismic combination E_y+$0,3E_x$+A_{ey} u_{total}=2,79 cm



Analysis results
Seismic loads: Beams

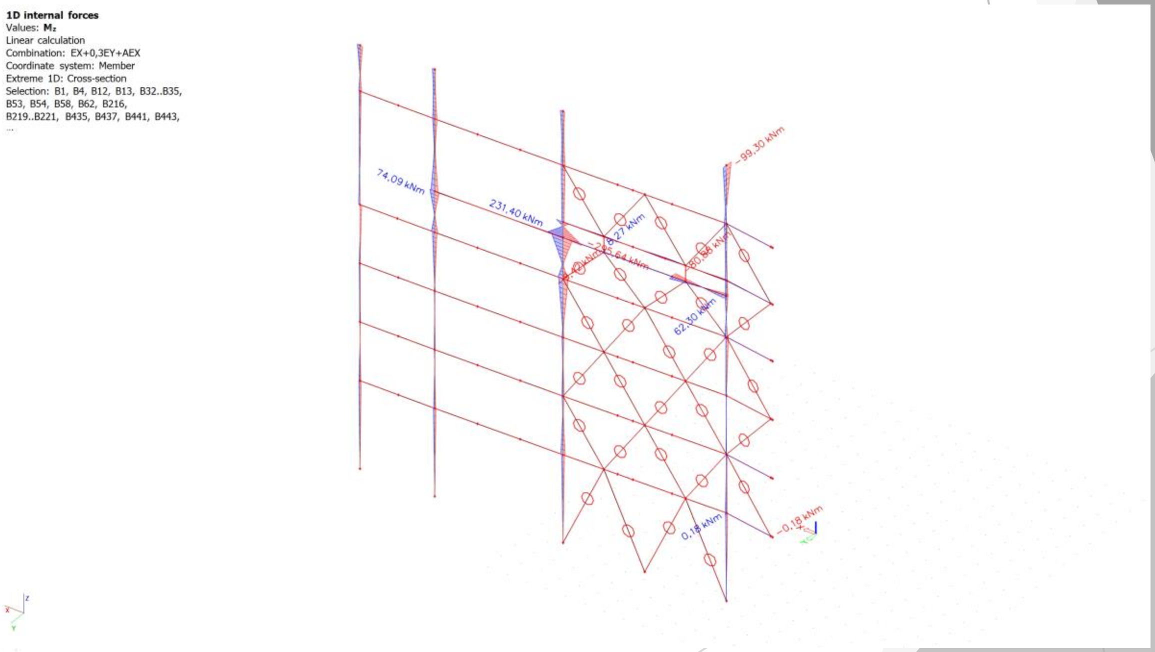
- Secondary beams do not develop larger inertial forces than in static loads
- The main steel beam HEA400 part of the frame Σ9-Σ10 has the most unfavorable unity check n=0,58. The bi-lateral slab is supported in this beam





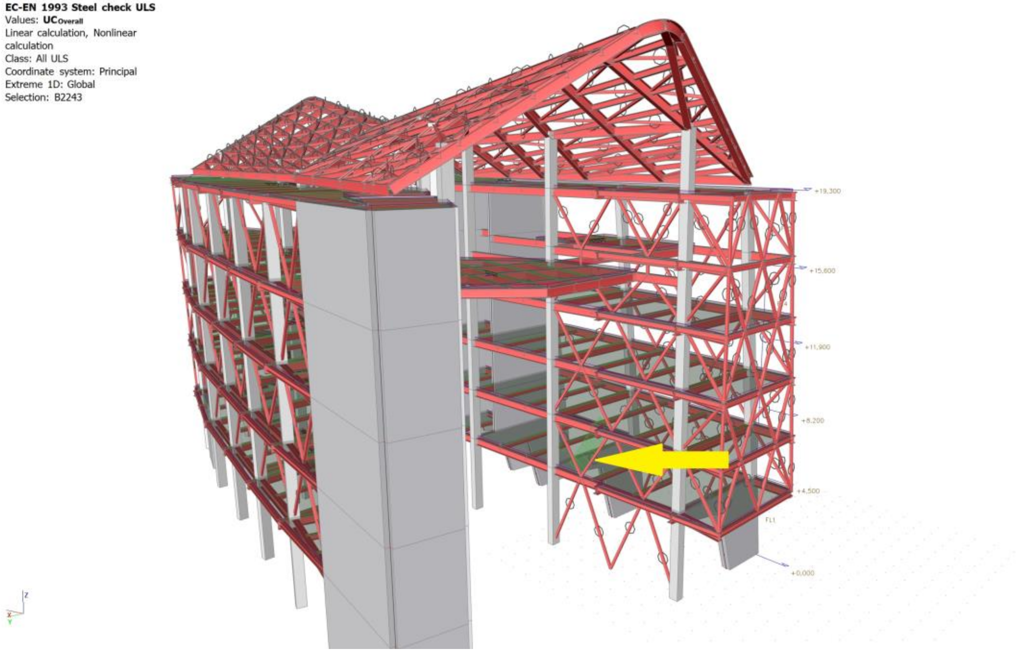
Analysis results
Seismic loads: Composite columns

- Seismic combination E_x+0,3E_y+A_{ex}
- Column Σ10 – HEM500 with longitudinal reinforcement 16Φ20
- Maximum unity check for combined compression and biaxial bending n=0,859



Analysis results
Seismic loads: Concentric bracing

- Seismic combination $E_x+0,3E_y+A_{ex}$
- Diagonal SHS120/6.3
- Maximum unity check for diagonal in compression n= 0,71 and in tension n=0,41



Conclusion

- The Seismic combinations are the most unfavorable load combos for the columns and the diagonal bracings. In the contrast, the ULS – South wind with positive canopy pressure is the most unfavorable for the primary and secondary beams
- The asymmetrical placement of the structural elements has as a result the domination of the rotational displacements during the earthquake
- The extended use of trusses in the cantilevers brings on minimal vertical displacements
- The spectral design acceleration which is used in the design process is actually 4 times larger than the expected in the area of Venice
- The bespoke canopy is designed with the standard EN1991-1-4 [25] and there has not been a further investigation in a wind tunnel in which the holes that the initial designer had suggested would have been taken into account

Conclusion

- It is proved that the fine corporation between an Architect and a Structural engineer can bring to the end successfully every complicated project with innovative architectural design despite all the challenges

- Steel-concrete composite structures are able to sustain flexible architectural design and they can support innovative ideas

References

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