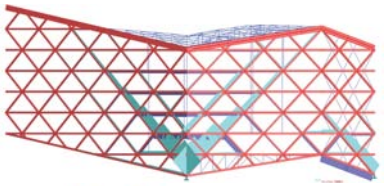
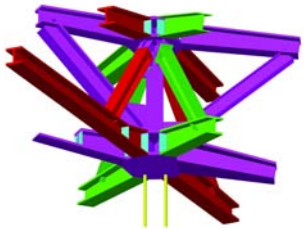
# Krystallen – IABSE Konstruktionspris





14. maj 2013 v/ Martin Venning Kjær

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# Dagsorden: Krystallen

- **Bygningens geometri (bærende konstruktioner)**
- **Bygningens statiske virkemåde**
  - Hovedstabilitet og understøtningsforhold
  - Lastnedføring
  - Tagkonstruktion
- **En ingeniørs udfordringer…**
- **Interimsunderstøtninger**
- **3D Projektering**
- **Afrunding**

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# KON - holdet fra Grontmij | Carl Bro

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# Generel præsentation af byggeriet

- 7000m$^2$ Kontorbyggeri
- 1900m$^2$ Parkeringskælder
- Ca. 350 personer dagligt i bygningen
- Glas hus, Lavenergi hus, Bæredygtigt byggeri
- Integrerede solceller i taget
- Særligt havvandskøleanlæg
- 30% mindre energiforbrug end krav i BR08

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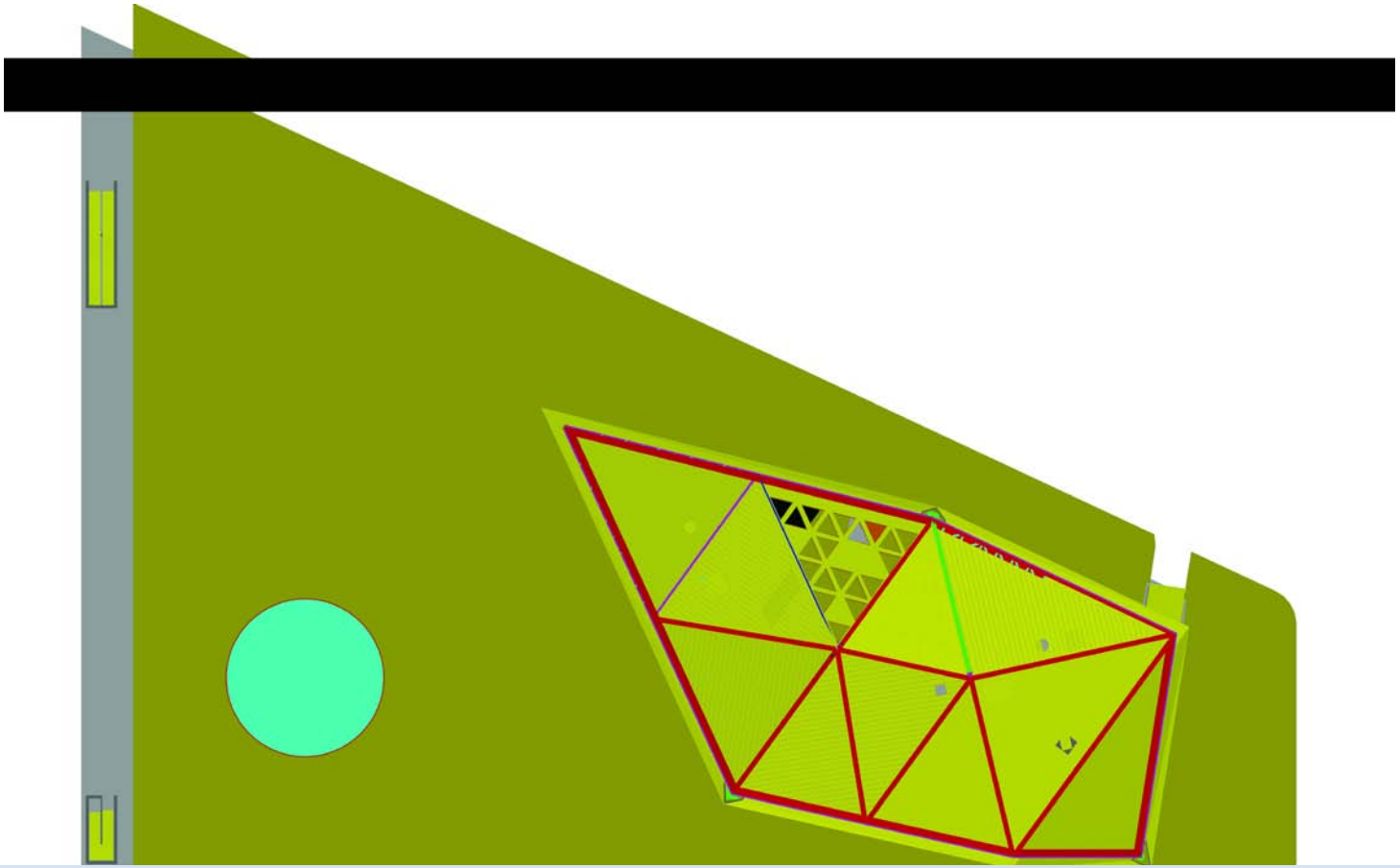
# Bygningens geometri - plan



Tegnet i 3D (Autodesk® Revit®) der muliggør udveksling af modeller mellem arkitekt og ingeniør. Vigtigt hjælpeværktøj ved samlingsdesign.

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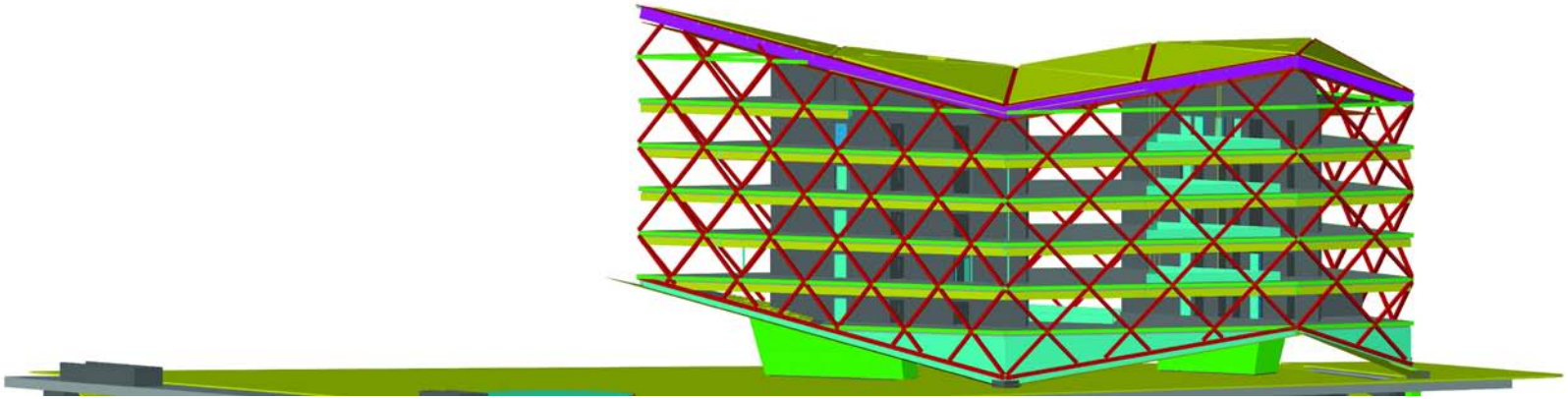
# Bygningens geometri – set fra syd

[redacted]



Længde ca. 70 m fra spids til spids. Udkragning ca. 34 m.

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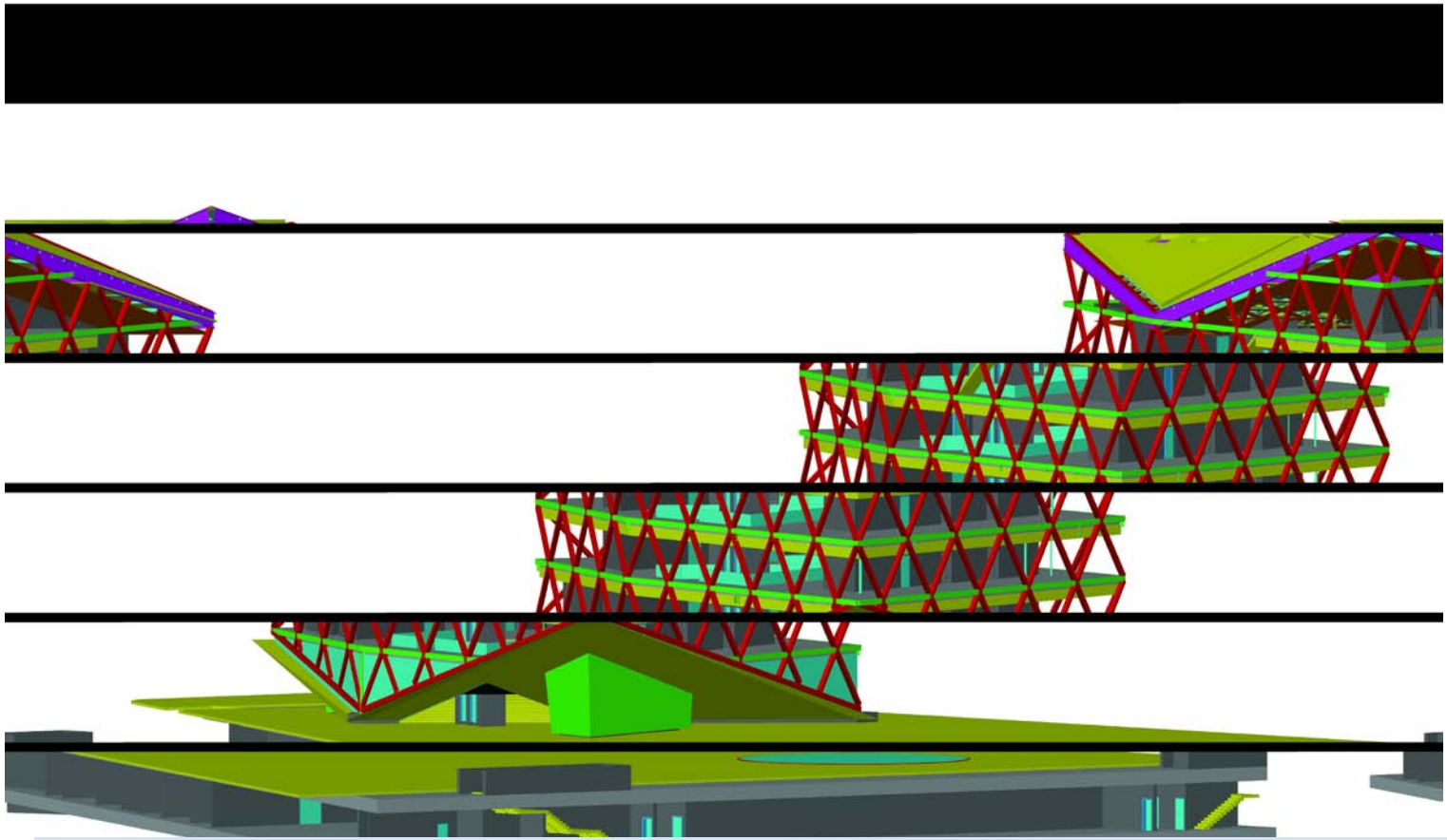
# Bygningens geometri – set fra vest



Bygningsbredde ca. 33 m ved punktunderstøtninger.

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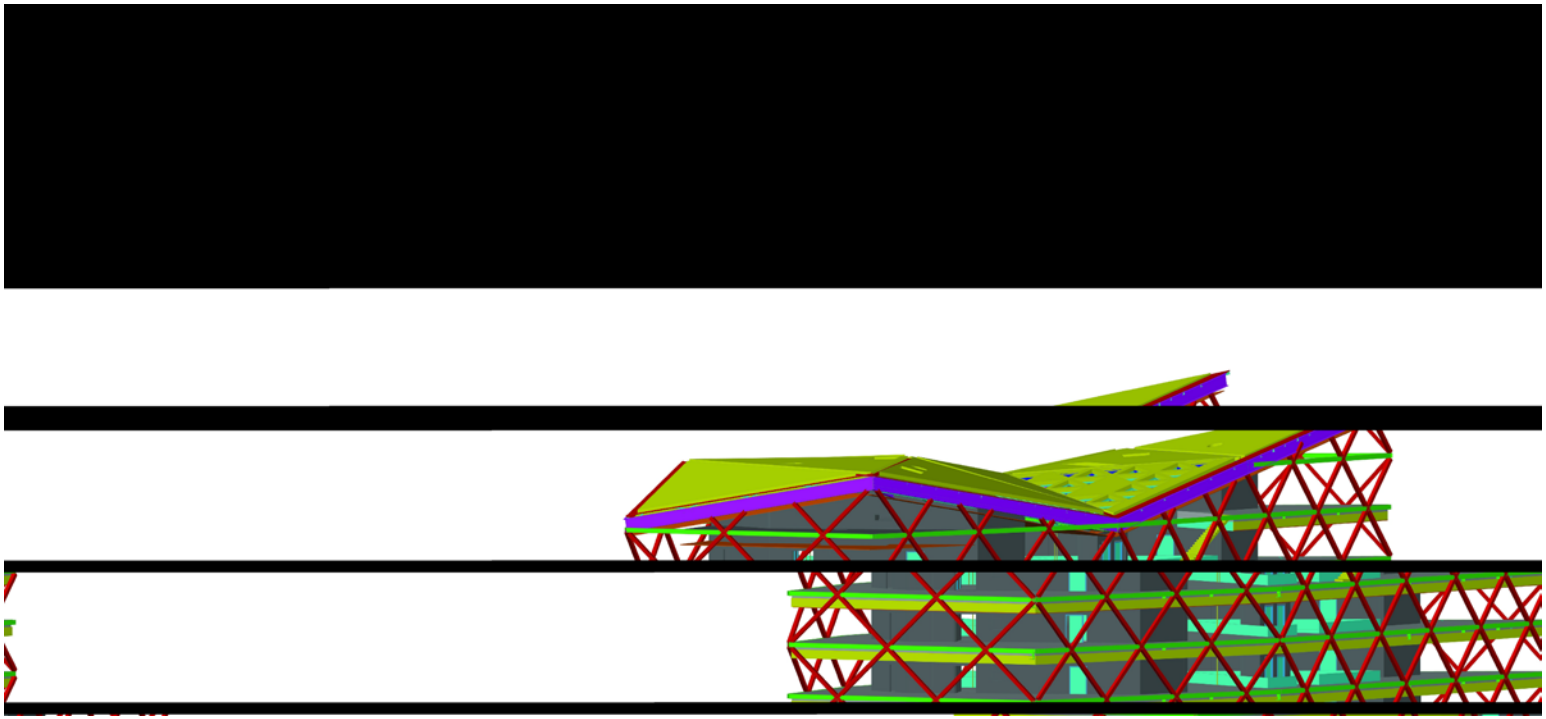
# Bygningens geometri – set fra nord



Udkraget spids næsten 9 m over terræn. Åbent område under bygningen.

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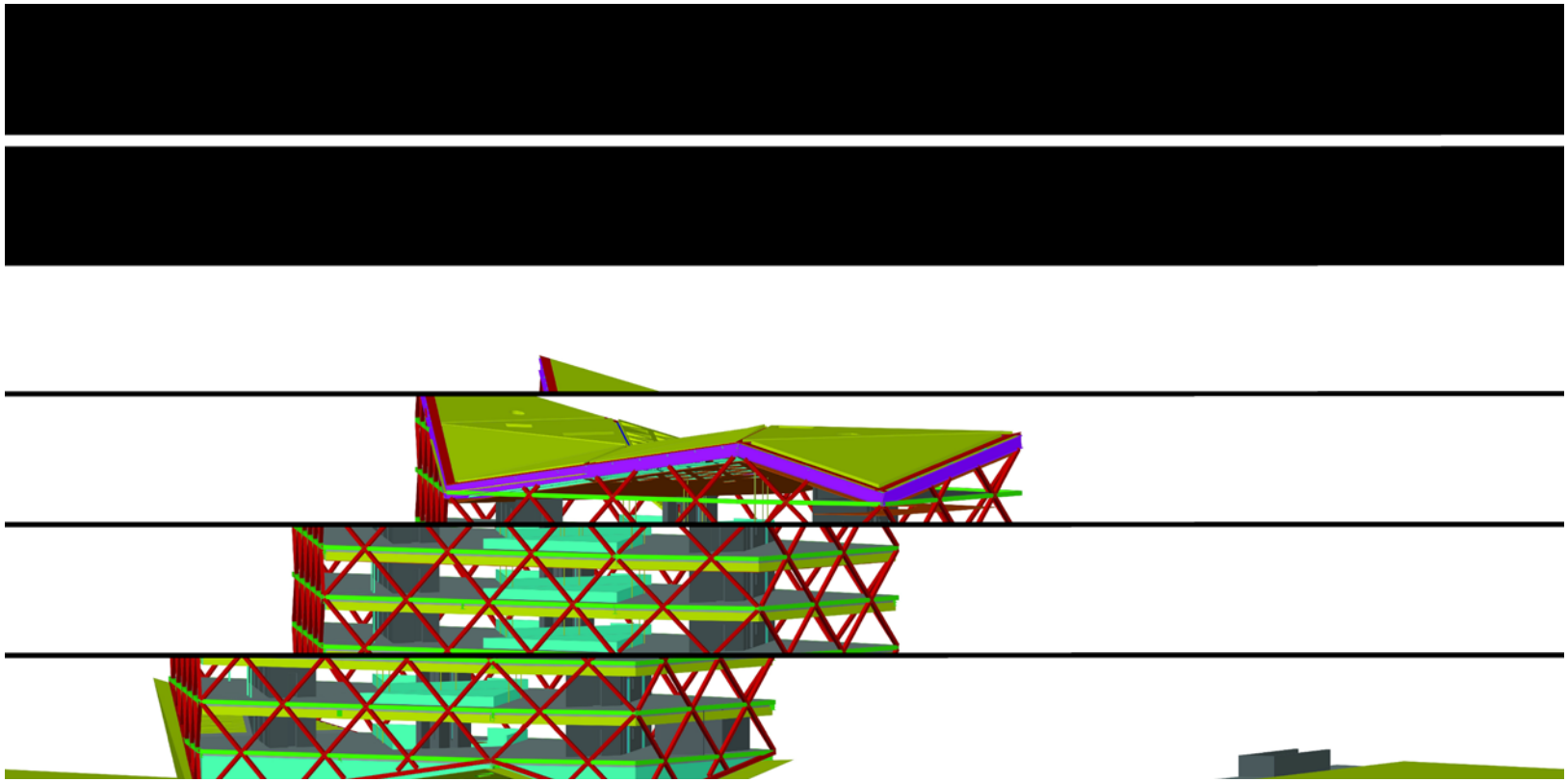
# Bygningens geometri – set fra øst



Bygningshøjde varierer fra 26 til 34 m over terræn. Mange knækflader i tagkonstruktion. Forskellige knækflader ud- og indvendigt.

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# Bygningens statiske virkemåde

- Beregningsforudsætninger
- Hovedstabilitet & understøtningsforhold
- Stålkonstruktion & hængestag
- Dækskiver
- Betonkerner

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# Beregningsforudsætninger

## Statisk projekteringsrapport - 29. juni 2007

- Høj sikkerhedsklasse
- Robusthed eftervist
- Fundering direkte - HGVS: +1.60
- Brandklassificering af konstruktioner - R60/R120
- Normer - DS 409→DS415
- Kontrolklasse - Normal
- Miljøklasse - M/A - C2/C3

- Egenlast - Nyttelast - Snelast
- Vindlast - Masselast
- Temperaturlast
- Ulykkeslast
- Dynamisk last

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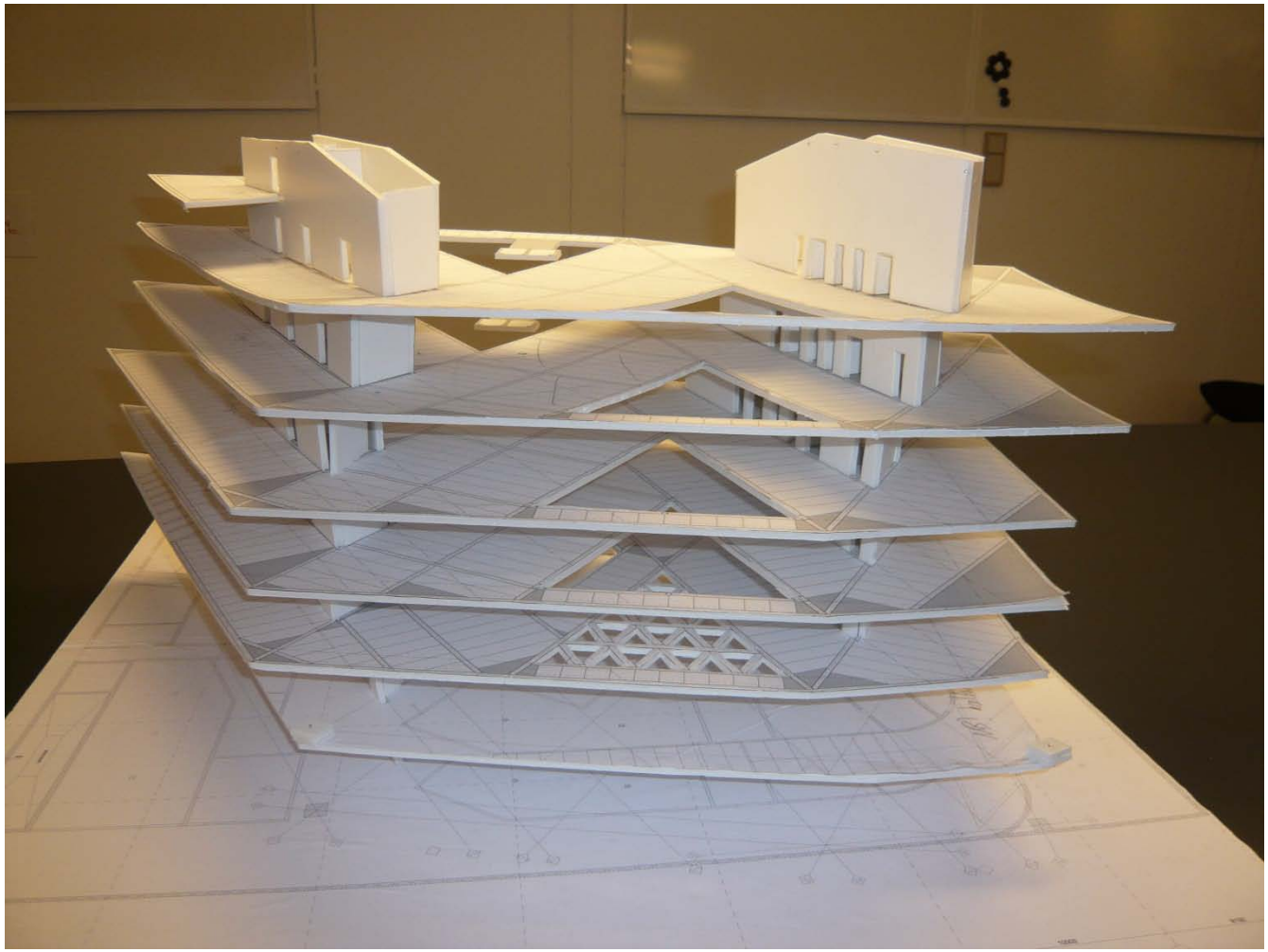
# Hovedstabilitet og understøtningsforhold



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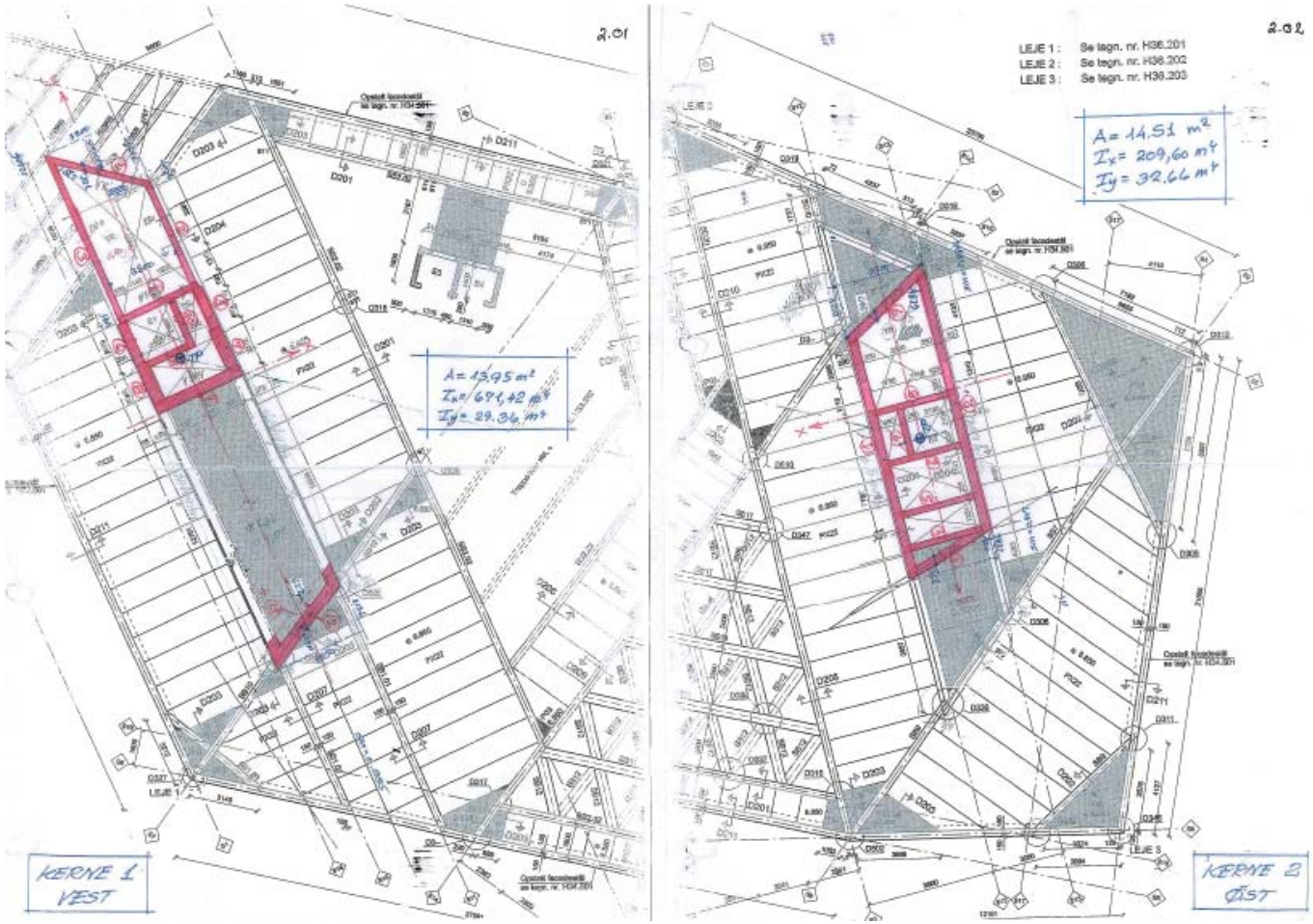
# Stabiliserende kerner 1 og 2

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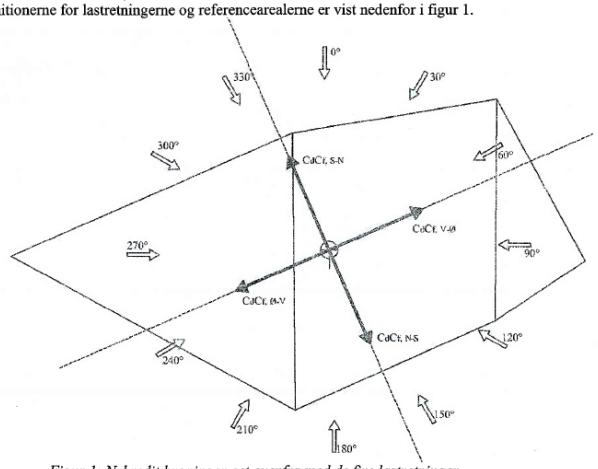
# Vindlast - Vindtunnelforsøg

3.31

2

De skønnede dimensionsgivende formfaktorer er markeret med gult i tabellen.
Definitionerne for lastretningerne og referencearealerne er vist nedenfor i figur 1.




*Figur 1: Nykredit bygningen set ovenfra med de fire lastretninger*

2 laster vinkelret på hinanden påføres samtidig. De gives hver en vandret excentricitet på op til 10% af den projicerede bredde vinkelret på lastretningen.

Vindlasten på Nykredits tag og bund regnes svarende til en fri last med en formfaktor på henholdsvis -0.5 og -0.2. At vindlasten regnes fri vil sige, at den kun påsættes de dele af bygningen, hvor den virker til ugunst.

København den 21. februar 2007
Svend Ole Hansen ApS

Svend Ole Hansen  Simon Rex

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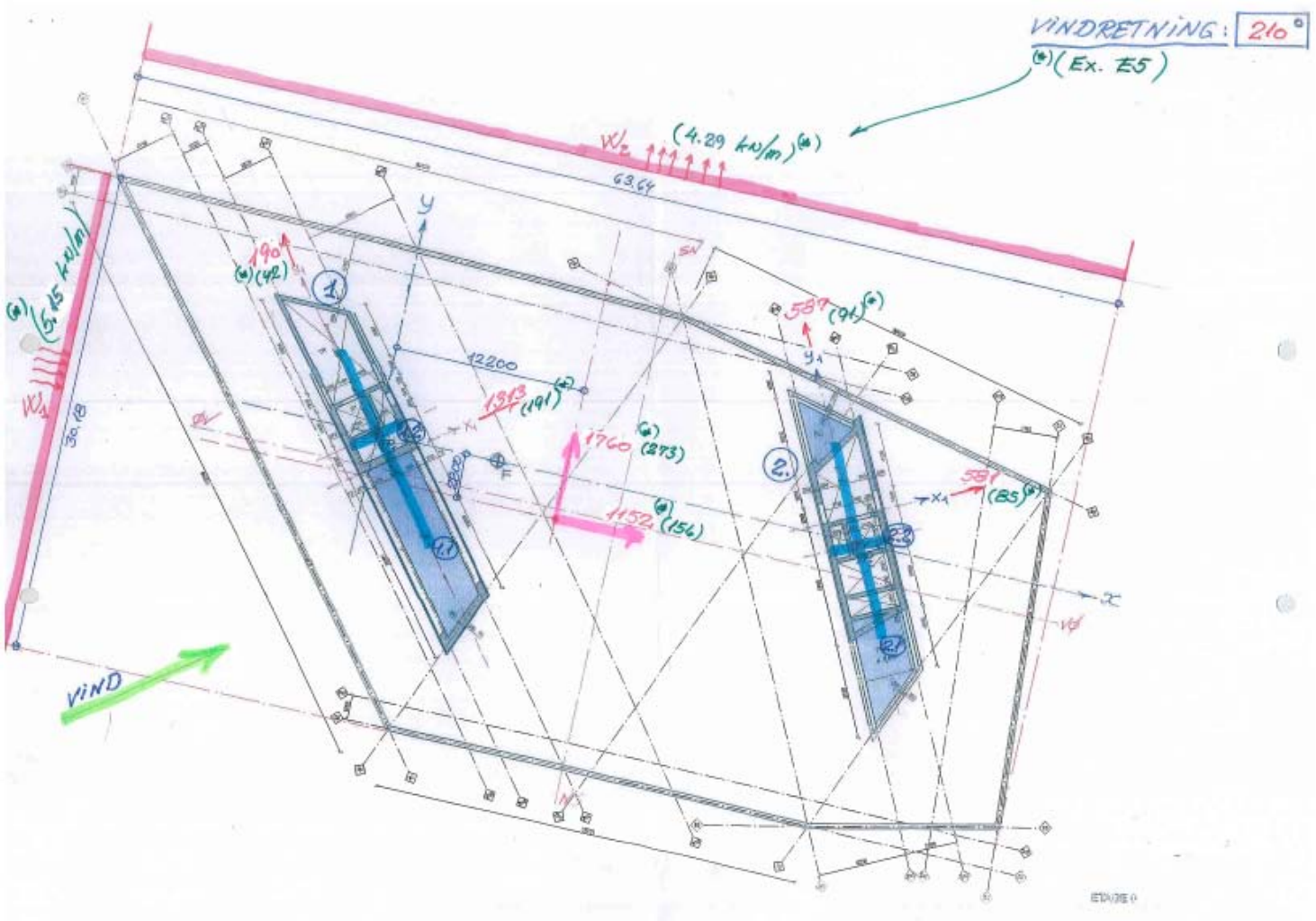
# Vindlast – Fordeling på tårne

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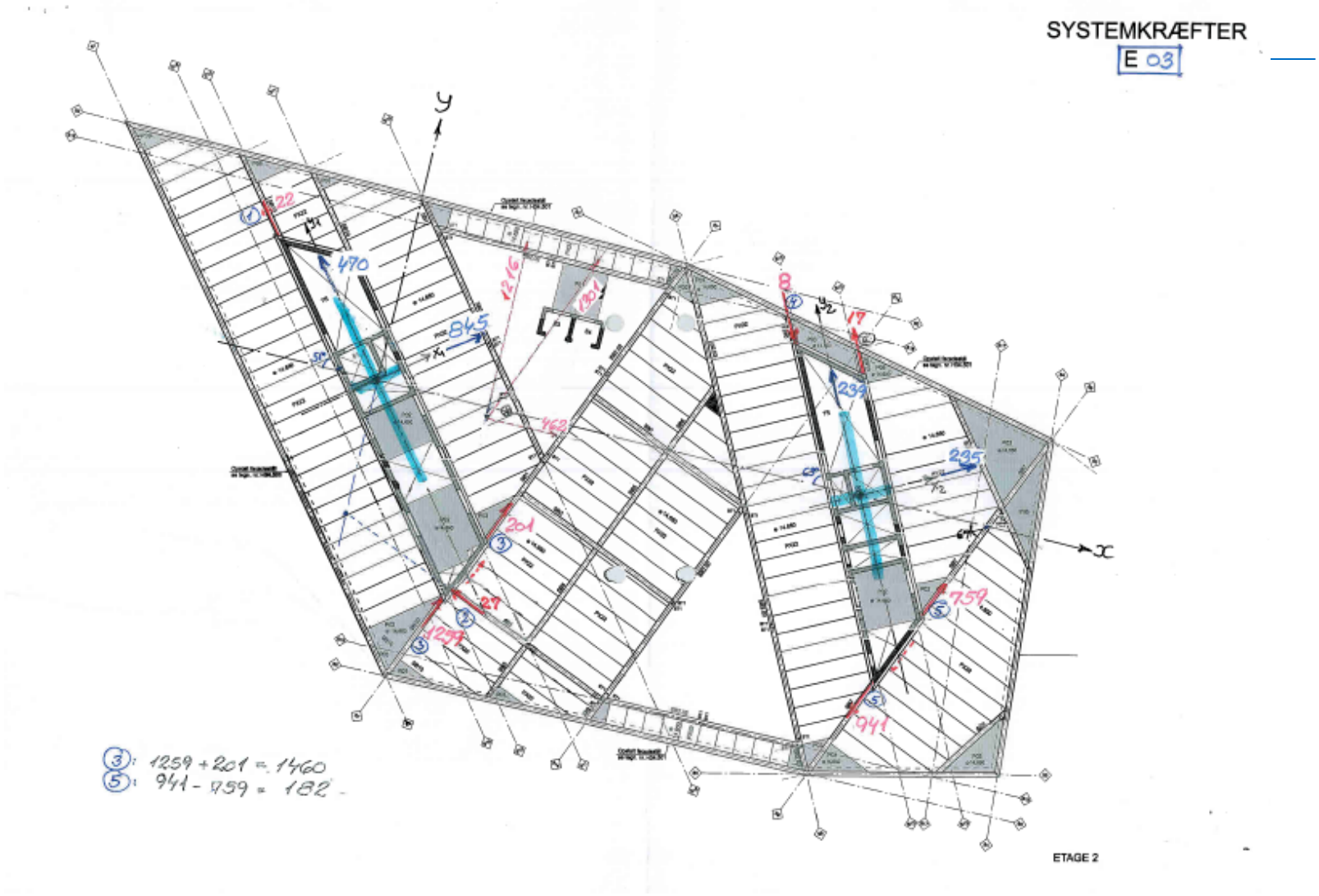
# Systemkræfter

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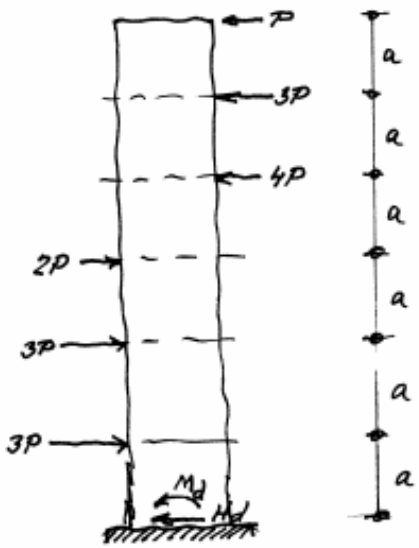
# Systemkræfter - Sum

SYSTEMKRÆFTER.

systemkræfter er vandrette kræfter i stålkonstruktionerne i dækskiverne, genereret af lodret last på facadekonstruktioner.




$$H_d = \Sigma H_i = \underline{\underline{0}}$$

$$M_d = Pa\,(1\cdot 6 + 3\cdot 5 + 4\cdot 4 - 2\cdot 3 - 3\cdot 2 - 3\cdot 1)$$

$$M_d = Pa\,(6 + 15 + 16 - 6 - 6 - 3)$$

$$M_d = \underline{\underline{22\,Pa}}$$

Nykredit - Krystal & Sky
6. maj 2008
Lastfordeling på kerner 1 og 2 Systemkræfter: **SUM**

**Samlet sum af systemkræfter - 7. maj 2008**

| | Kerne 1 | | | Kerne 2 | | |
|---|---|---|---|---|---|---|
| Nr. | Rx | Ry | R | Rx | Ry | R |
| TAG | -1565 | 1622 | 2254 | -131 | 1118 | 1126 |
| E6 | 40 | 74 | 84 | -8 | -7 | 11 |
| E5 | 534 | 364 | 646 | -76 | -263 | 274 |
| E4 | 476 | 169 | 505 | 233 | 295 | 376 |
| E3 | 840 | 464 | 960 | 208 | 187 | 280 |
| E2 | 439 | 162 | 468 | 152 | 152 | 215 |
| E1 | 1087 | -121 | 1094 | 1310 | 2006 | 2396 |
| Res. | 1851 | 2734 | 3302 | 1688 | 3488 | 3875 |
| E0 | -1970 | -2955 | 3551 | -1539 | -3224 | 3572 |
| | -119 | -221 | 251 | 149 | 264 | 303 |

Resultant: 394

**Samlet sum af systemkræfter - 9. maj 2008**

| | Kerne 1 | | | Kerne 2 | | |
|---|---|---|---|---|---|---|
| Nr. | Rx | Ry | R | Rx | Ry | R |
| TAG | -1723 | 1809 | 2498 | -127 | 1273 | 1279 |
| E6 | 64 | 90 | 110 | 0 | 0 | 0 |
| E5 | 543 | 408 | 679 | -123 | -344 | 365 |
| E4 | 498 | 148 | 520 | 296 | 399 | 497 |
| E3 | 845 | 470 | 967 | 235 | 239 | 335 |
| E2 | 431 | 246 | 496 | 130 | 144 | 194 |
| E1 | 2654 | -1767 | 3188 | 915 | -155 | 928 |
| E0 | -3362 | -1376 | 3633 | -1378 | -1631 | 2135 |
| | -50 | 28 | 57 | -52 | -75 | 91 |

Resultant: 108

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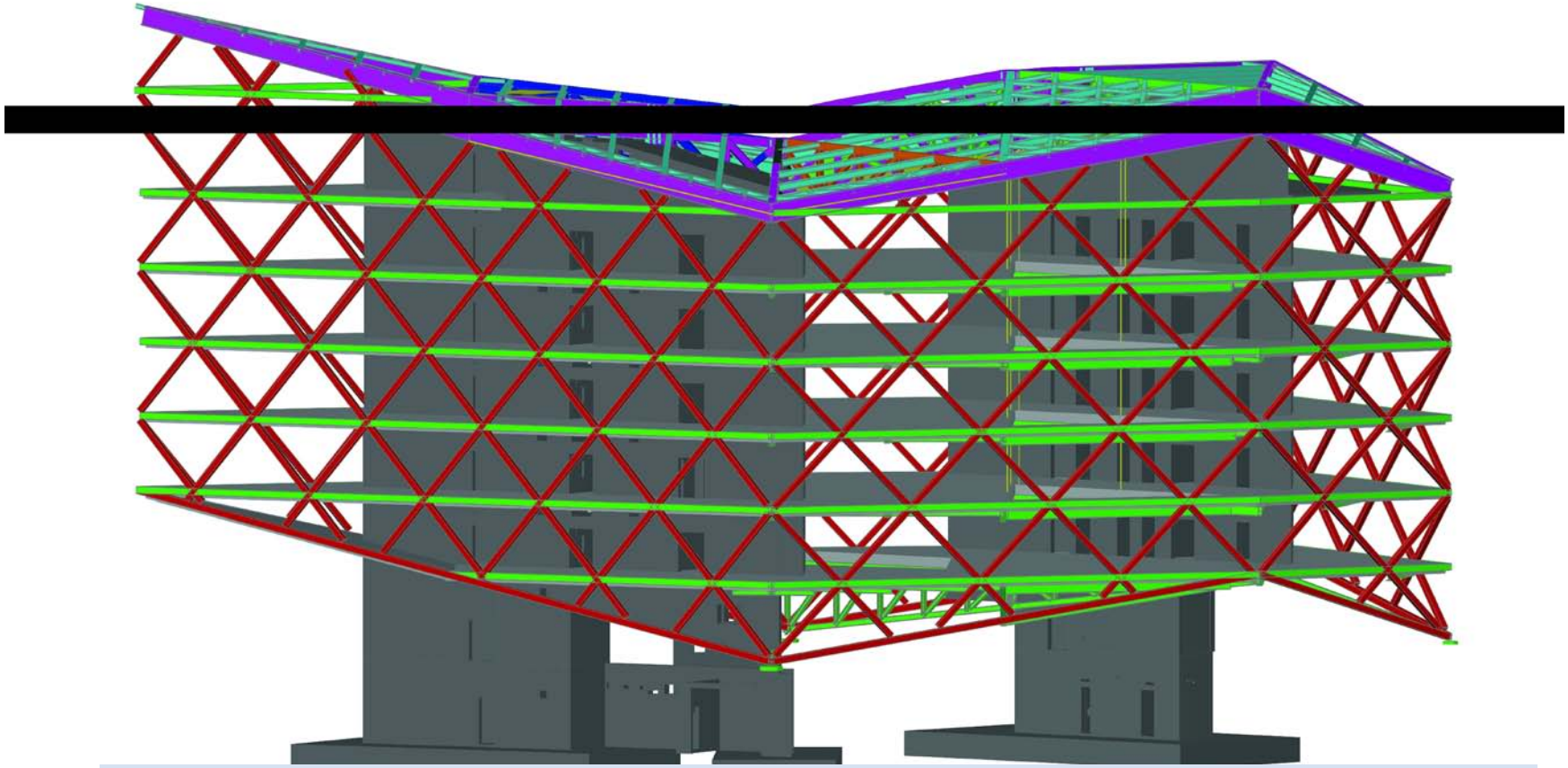
# Bygningens statiske virkemåde



Vandret stabilitet via to betonkerner. Facadekonstruktion lodret understøttet i tre punkter. Tagkonstruktion lodret understøttet til dels på kerner og til dels på facadekonstruktion via tagrandbjælke.

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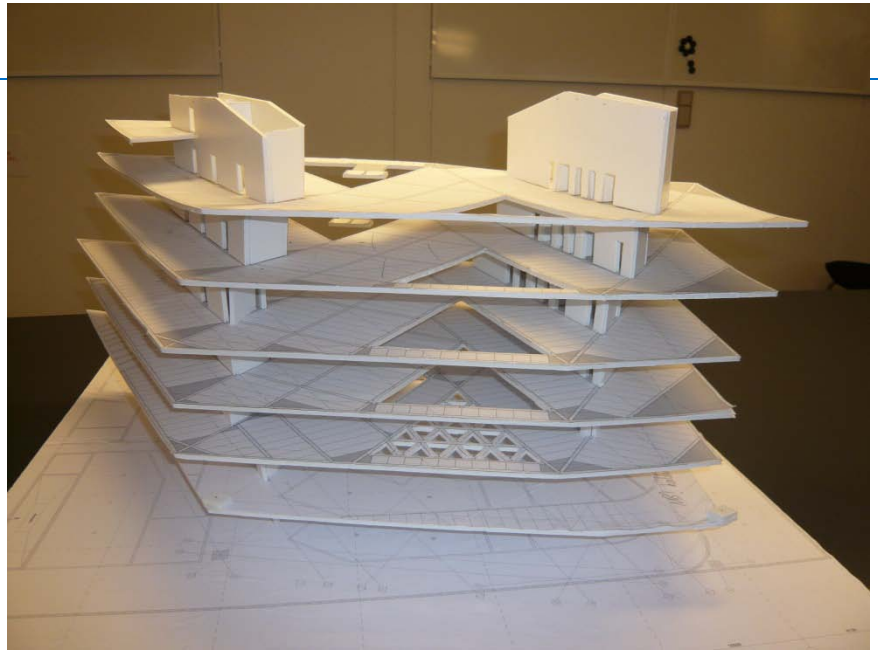
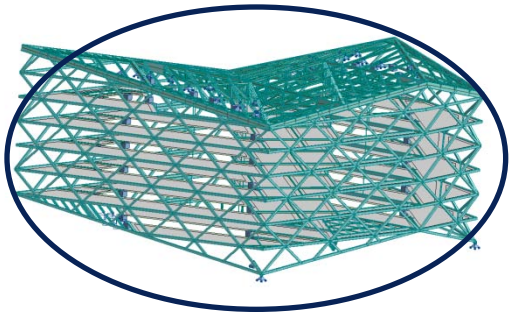
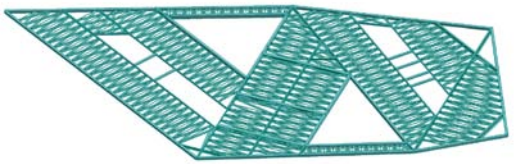
# Håndberegning

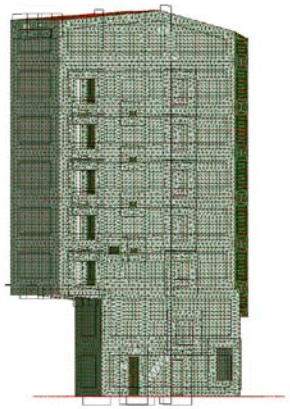




3D model - stålkonstruktion



2D model - dæk



3D model - kerner

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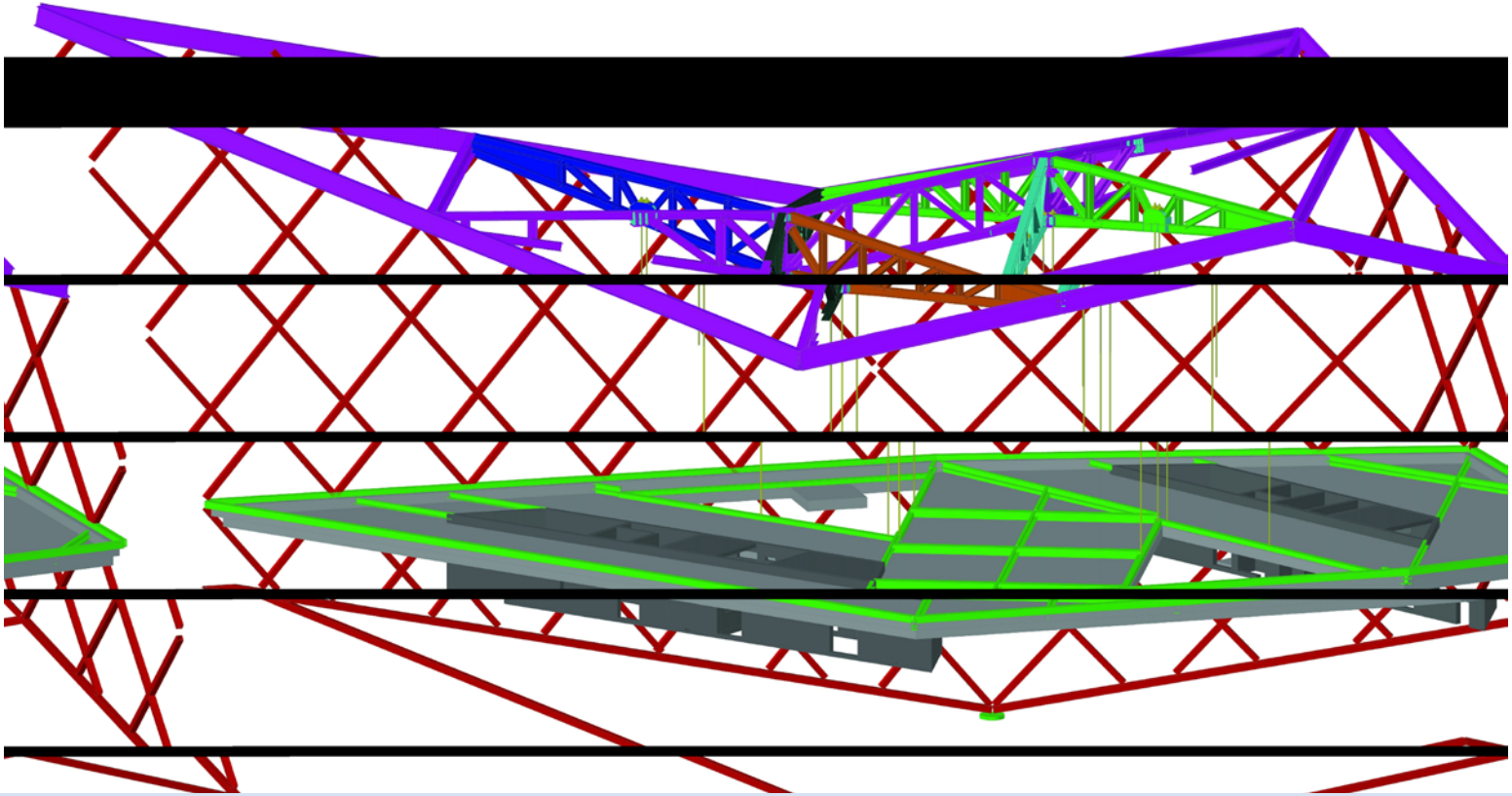
# Etagedæk - Lastfordeling



Lodret etagelast udveksles til kerner og facaderandbjælker, samt bæres på etagebjælker, der er ophængt via stag til tagkonstruktion. Vandrette systemkræfter i facadeknækpunkter forankres til betonkerner.

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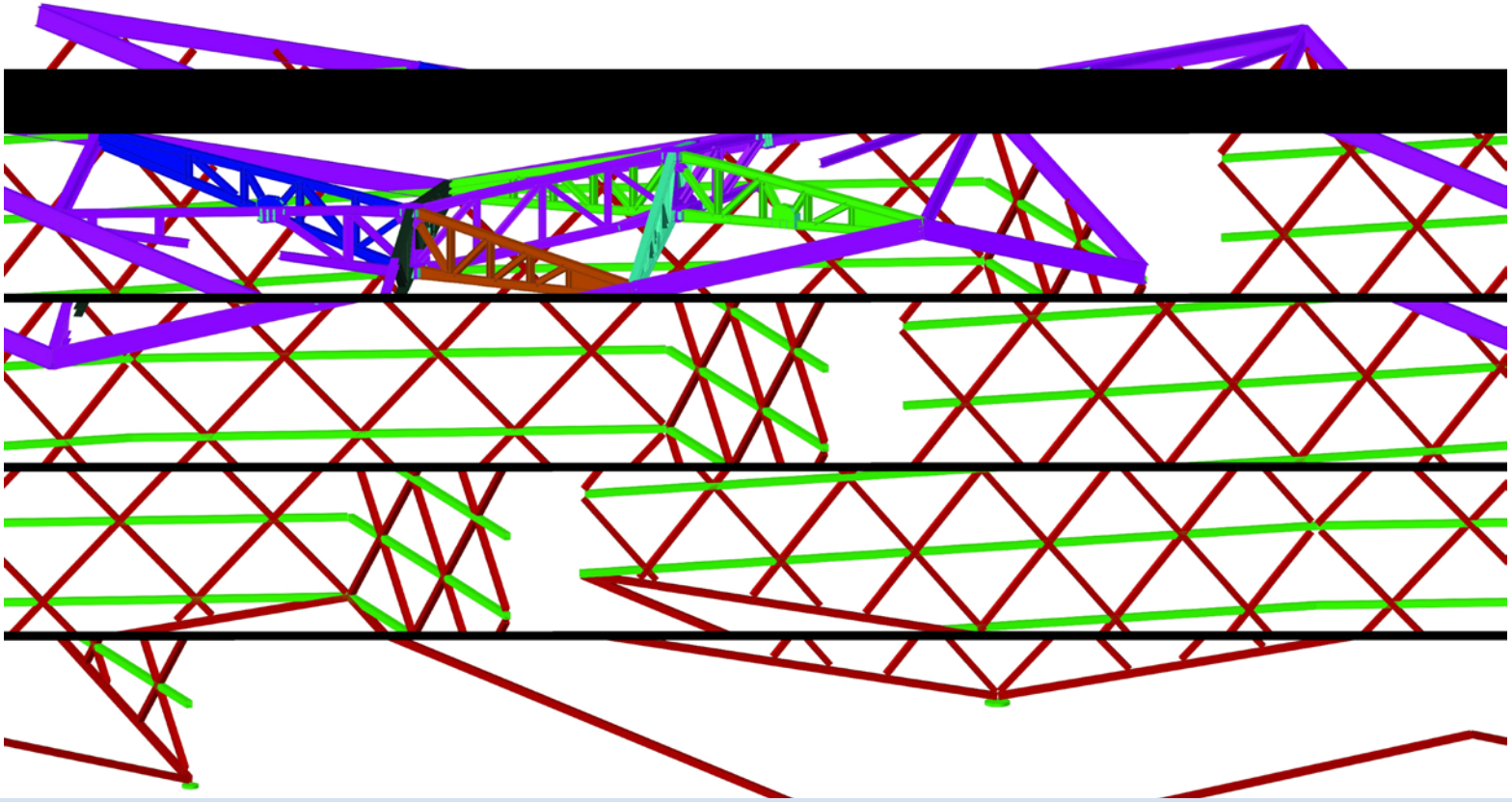
# Facadediagonaler



Randbjælker, langs etagedæk, lodret understøttet af facadediagonaler. Diagonaler lavet af opsvejste kasseprofiler. Dimensioner varierer fra 300x300x10 i stål S355 til 300x300x60 i S460 højstyrkestål.

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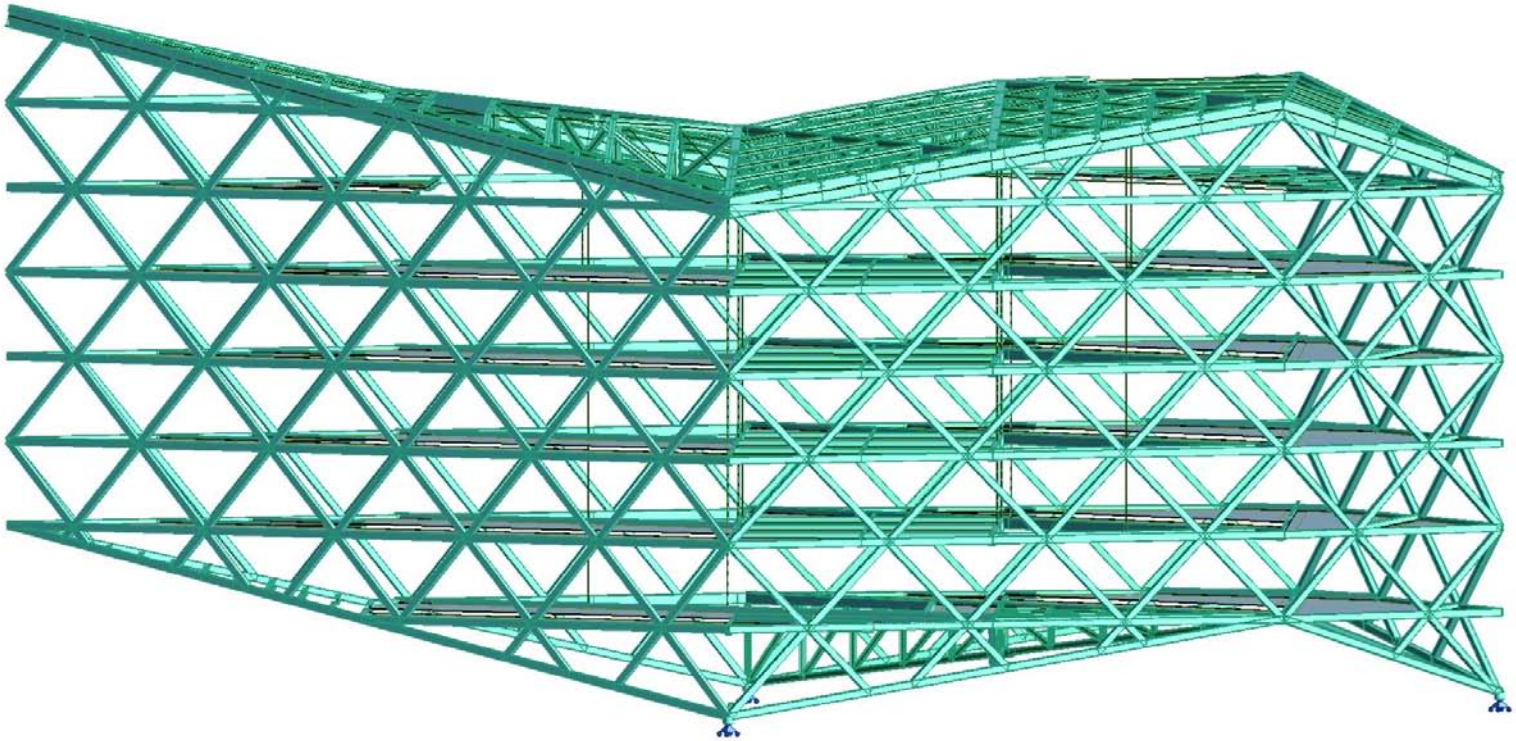
# 3D Beregningsmodel



Beregningsmodel (Autodesk® Robot™ Structural Analysis Professional 2010), der er dannet ud fra 3D Revit®-modellen.

Samlet stålmængde ca. 1.400 tons.

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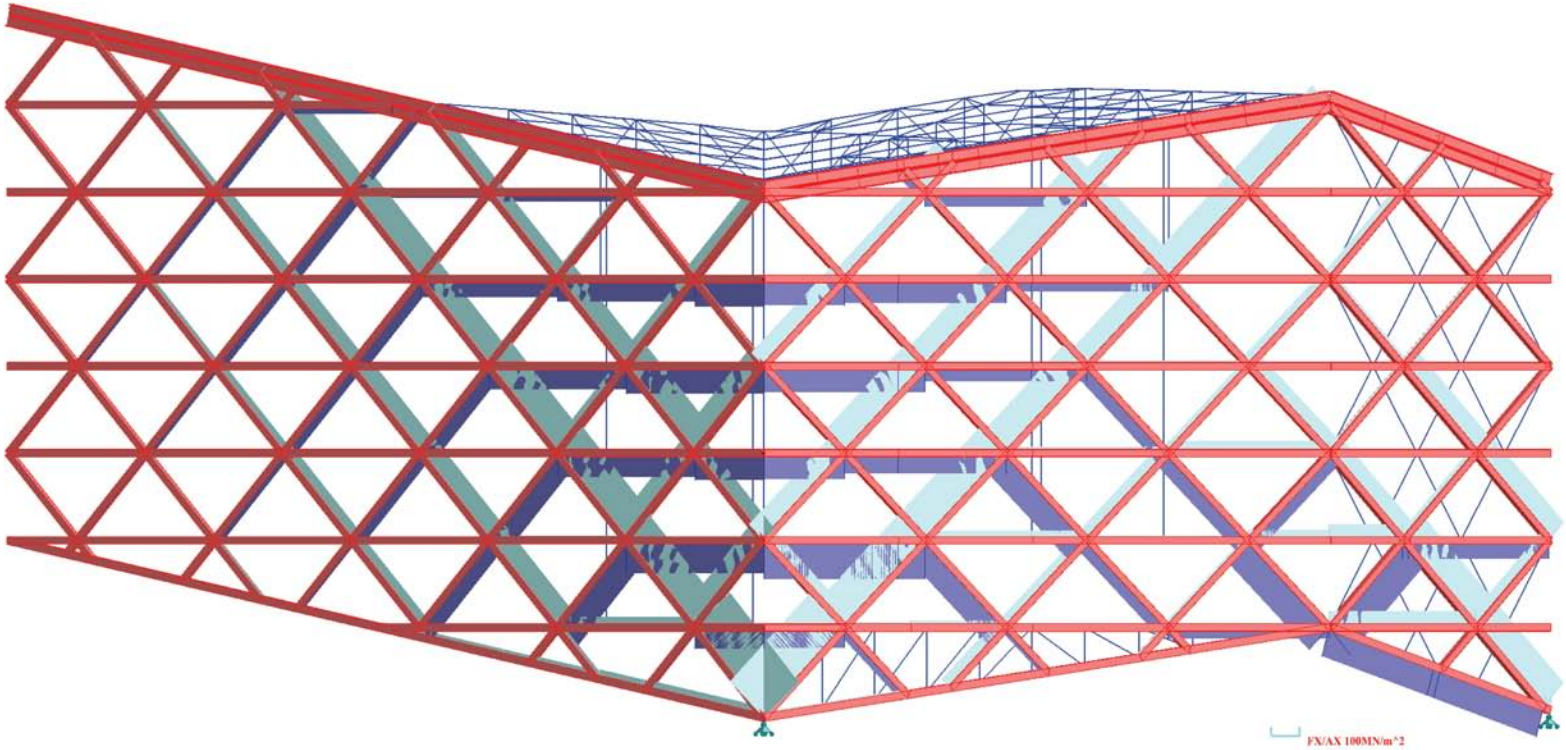
# Lastnedføring i facadekonstruktion




To hovedtryklinier ned til lejepunkt. Sekundære tryklinier kører forskudt og hives gradvist op til hovedlinier. Danner trækbuer mellem hovedlinier. Facaderandbjælker er opsvejste kasseprofiler, 350x300 i stål S355, med plade-tykkelser fra 10 til 45 mm. Randbjælker forstærket i samlingsknuder med op til 80 mm tykke plader. Facadekonstruktion samlet sektionsvis via montagesvejsninger.

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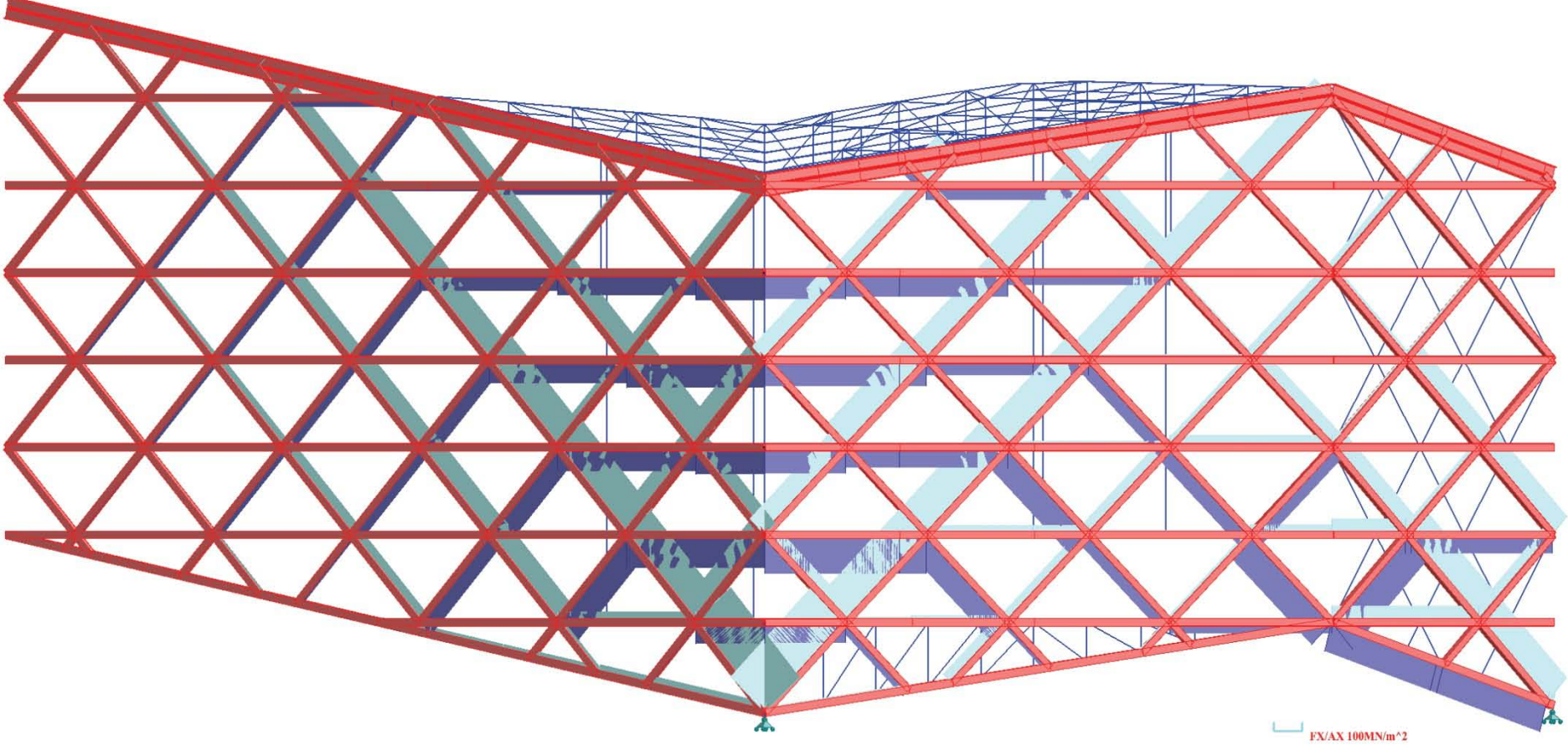


- Aksialspændinger i facadestål
- Jævnt fordelt pga. varierende tværsnit
- Klare tryklinier ned til understøtninger
- Trækbuer i diagonaler og kantbjælke over understøtninger

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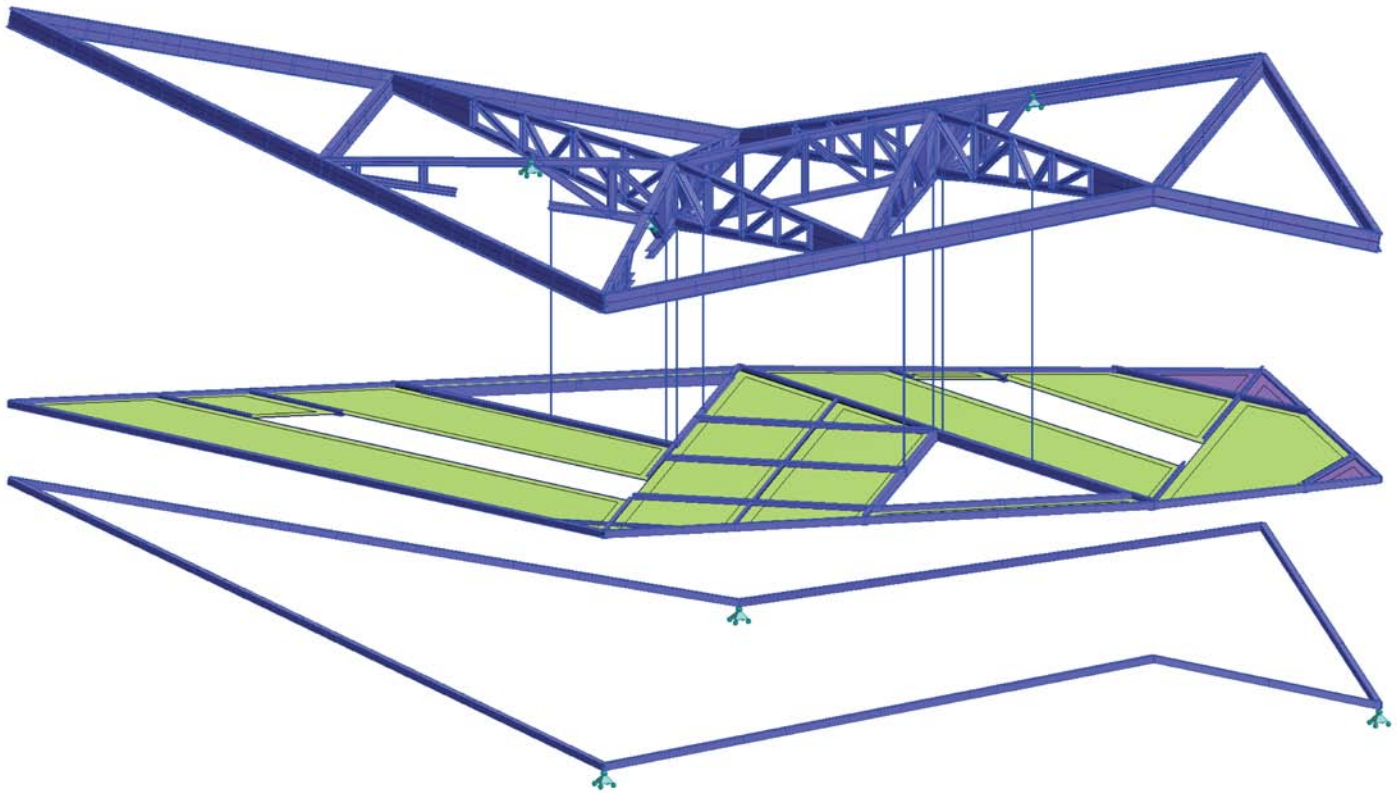
# Lodret reaktionsfordeling



Kerner samlet:
31.000 kN

Tag samlet:
14.000 kN
Hoveddrager:
9.000 kN

Ophængsstag
11.000 kN

Etager
17.000 kN

Lejer samlet:
38.500 kN
Centerlejer:
16 & 17.000 kN
Bagerste leje:
5.500 kN

Maksimal samlet regningsmæssig lodret last ca. 70.000 kN. Her af bæres 55% på de tre hovedlejer i bunden og 45% på de to kerner. Lidt under halvdelen af kernelasten stammer fra tagkonstruktionen (og dennes ophængslast fra fem etagedæk).

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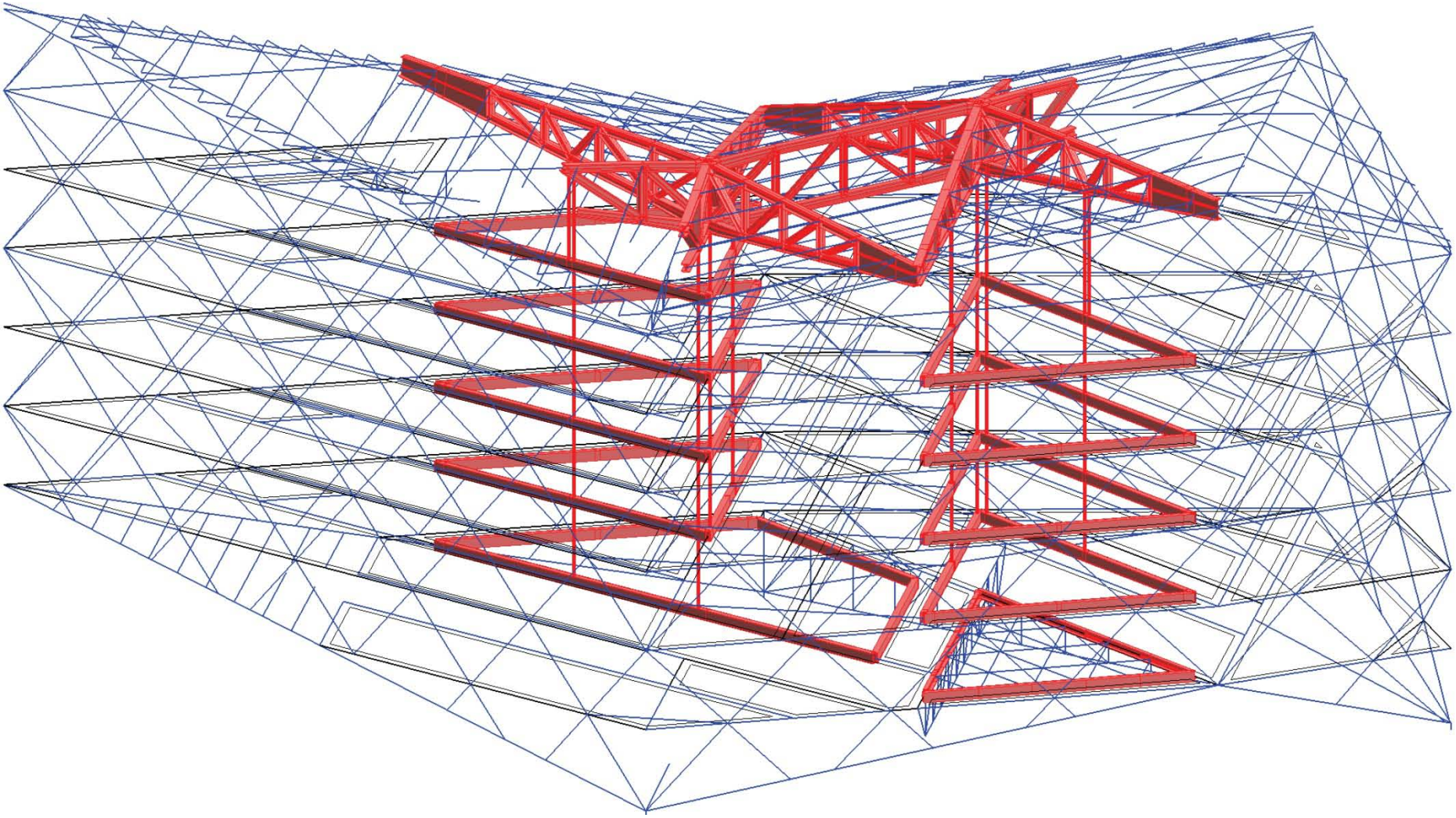

- Stag spænder fra etage til etage
- Samles med muffer under etagebjælker
- Stag opsamler laster fra etager der føres op til tagkonstruktion

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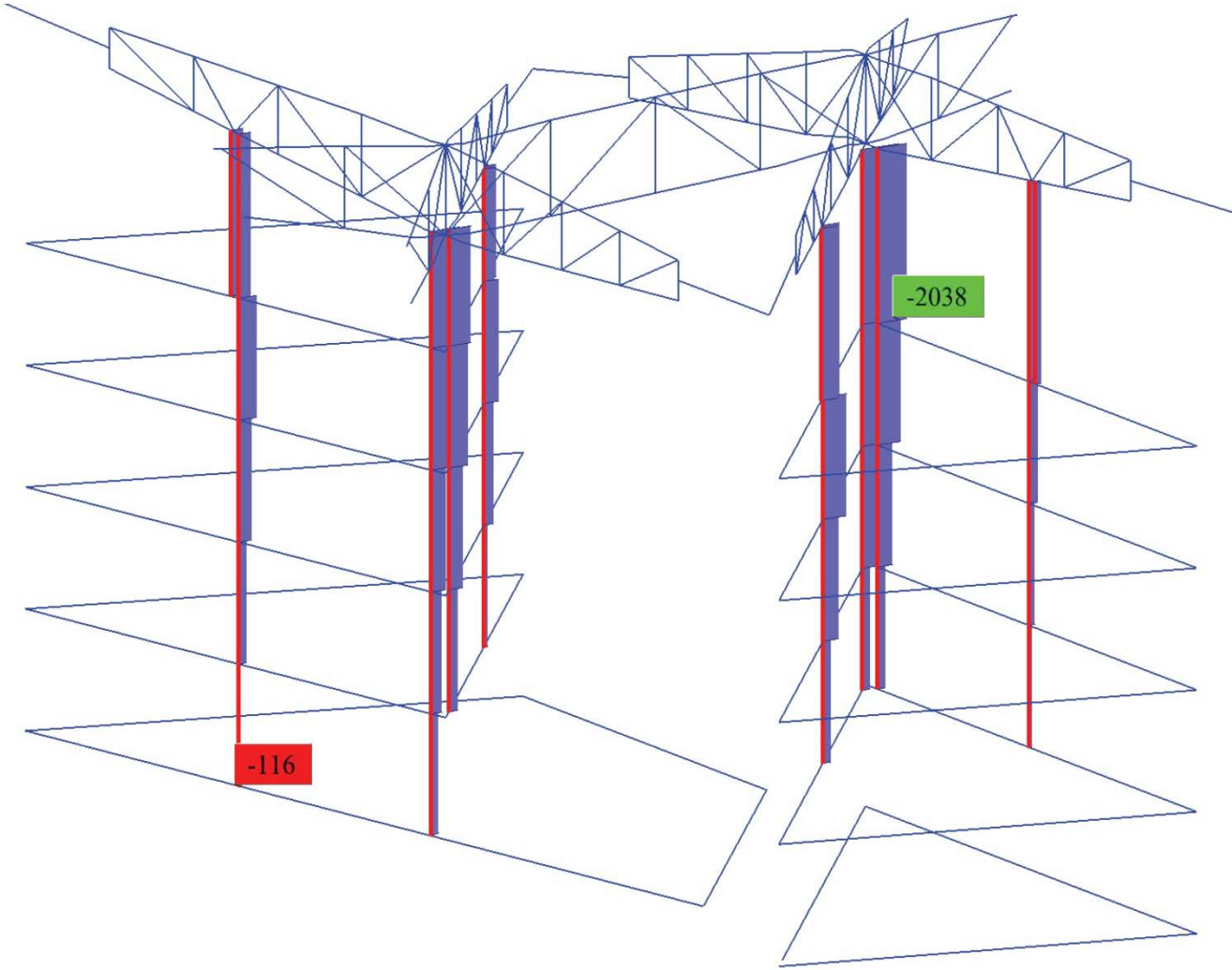


- Trækkræfter i stag varierer fra 12 tons – 204 tons
- Antal bestemt udfra bæreevne og arkitektur (symmetri om atrier)
- Brandmales med 4,8mm brandmaling (stag special testet i England under brandforhold)

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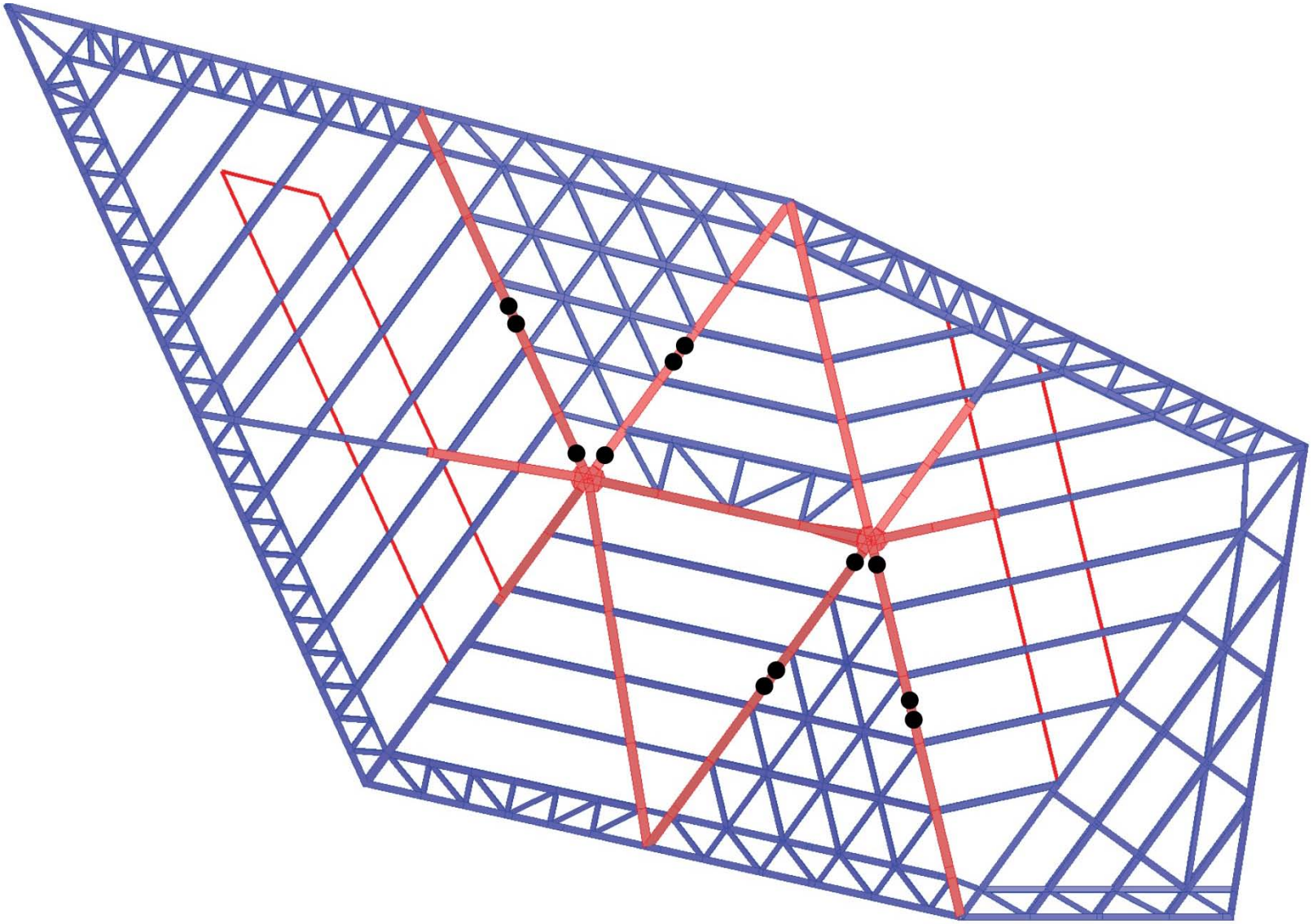

- Planbillede af tagkonstruktion med hoveddragere og kernekontur markeret
- Stag markeret

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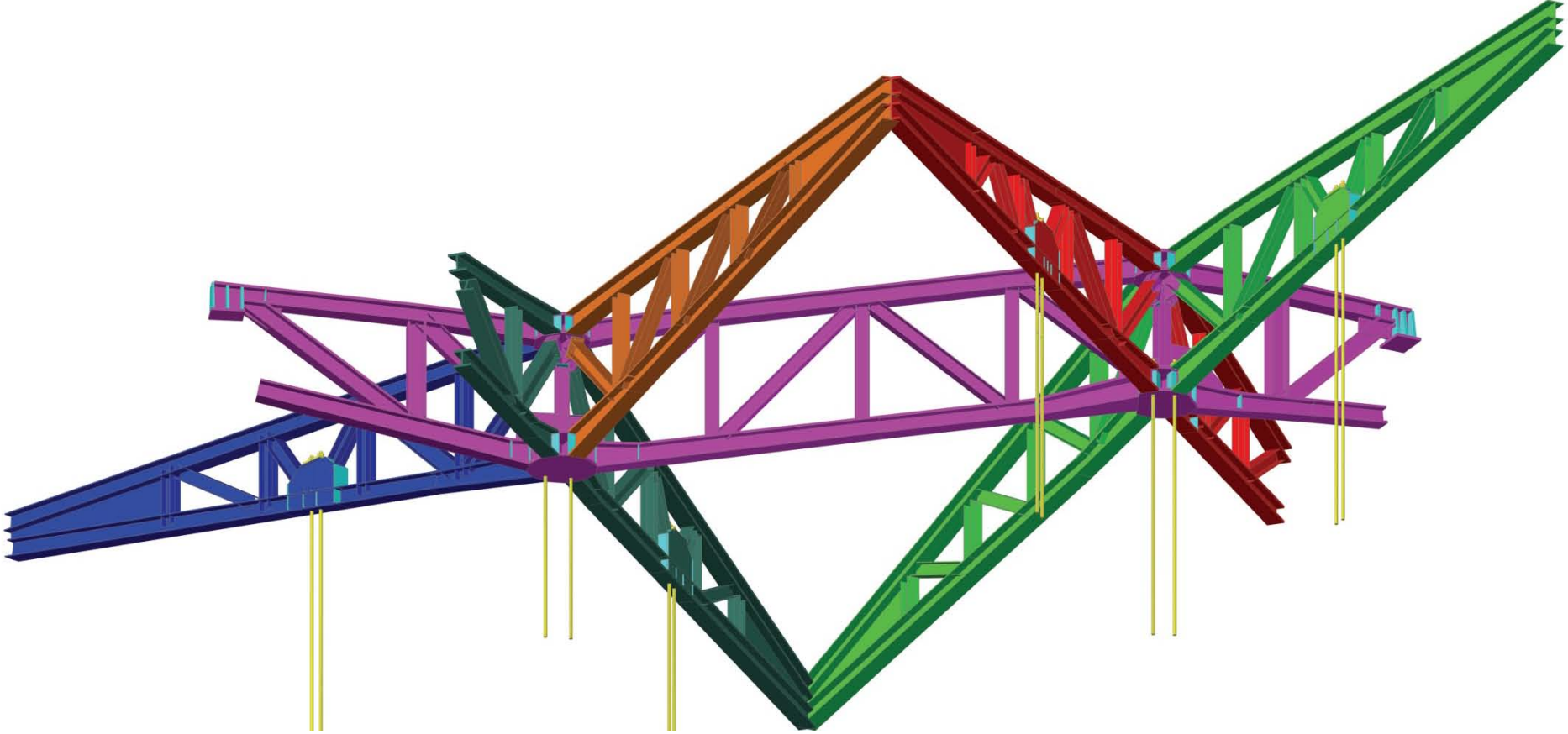

- Opsvejste gitterdragere i tag – varierende højde op til ca. 3m
- Hoveddrager spænder ca. 26m, vejer 43 tons, og løftes i et stykke på plads
- Øvrige dragere spænder op til 18m fra facade til hoveddrager
- Last fra stag ca. 1140 tons, hvoraf ca. 640 tons afleveres direkte ved hovedknuder
- Lodret reaktion på kerner hhv. 540 tons og 340 tons

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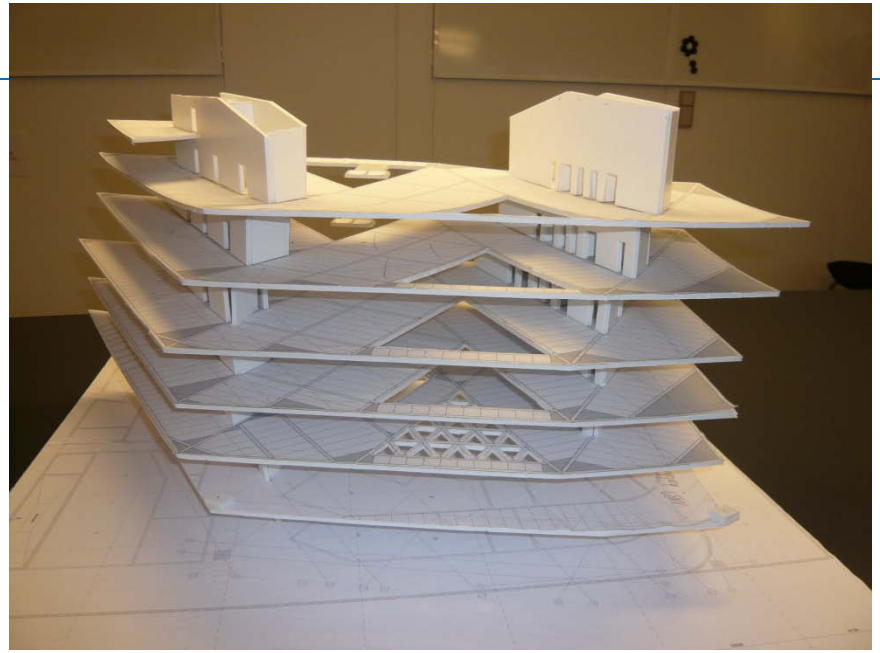
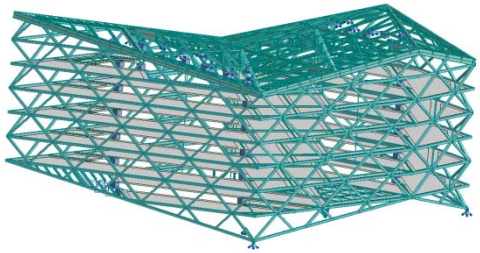
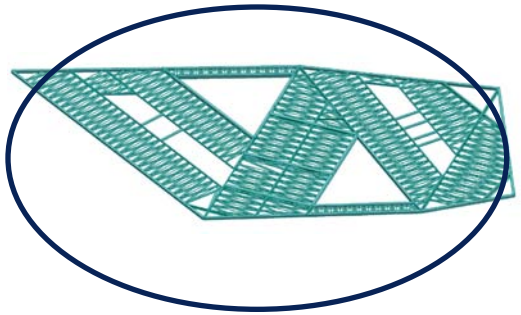
# Håndberegning

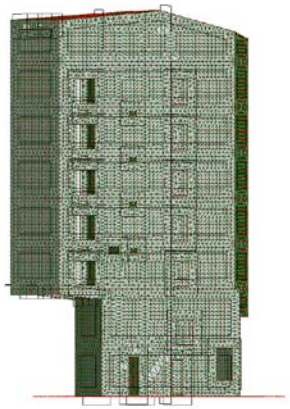




3D model - stålkonstruktion



2D model - dæk



3D model - kerner

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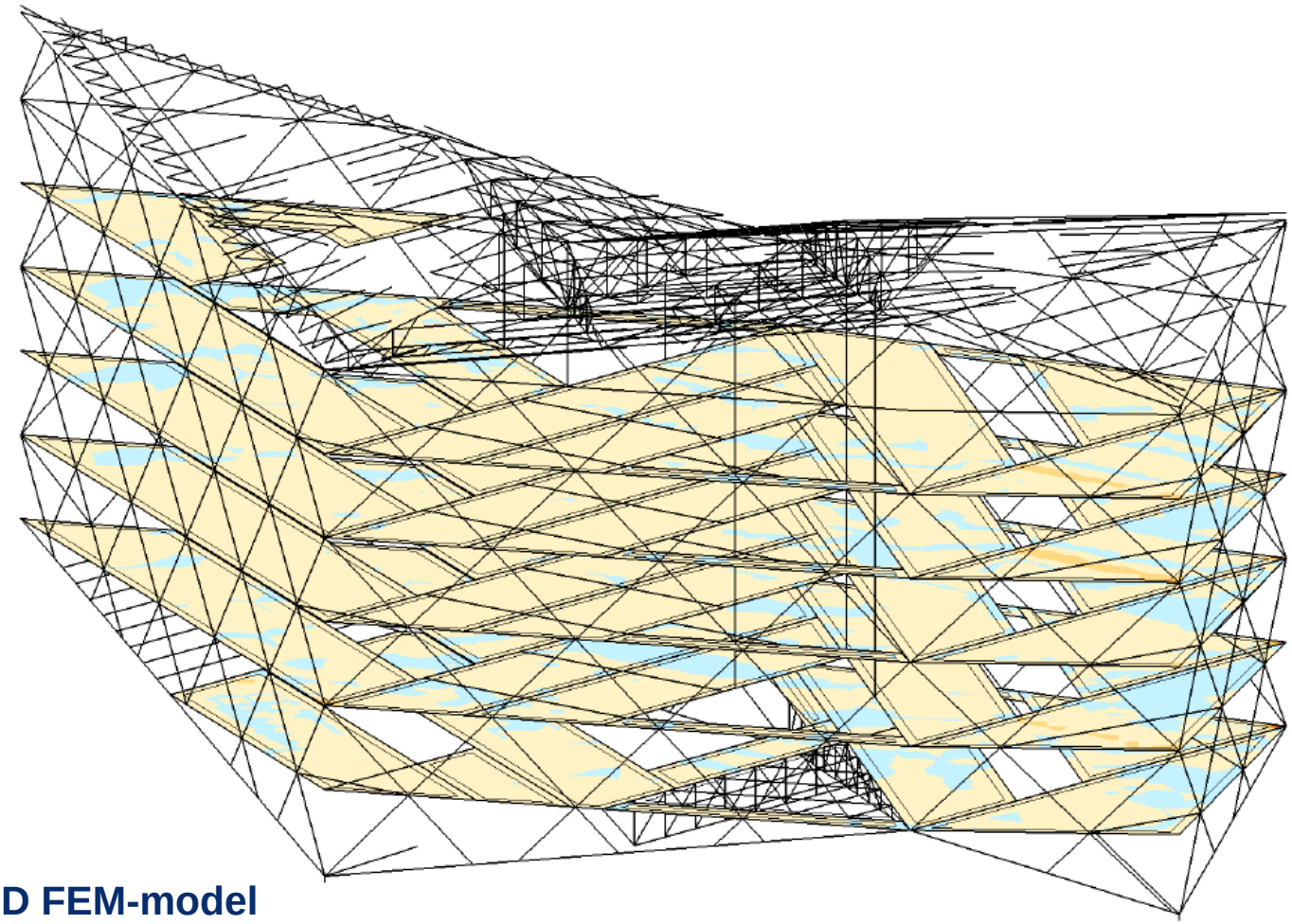
# Dækskiver



3D FEM-model

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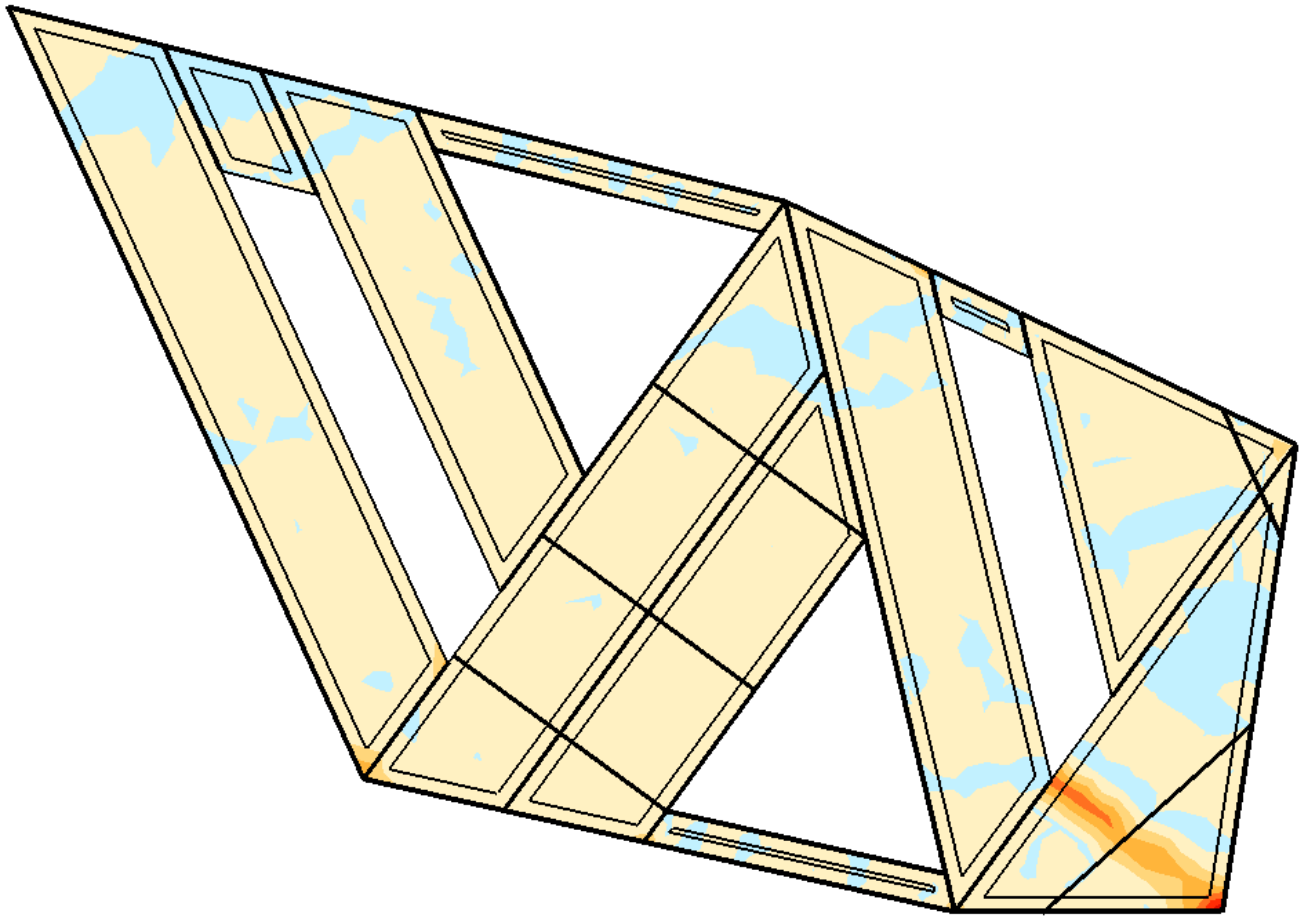

## 3D/2D FEM Model

## PX22 Huldæk

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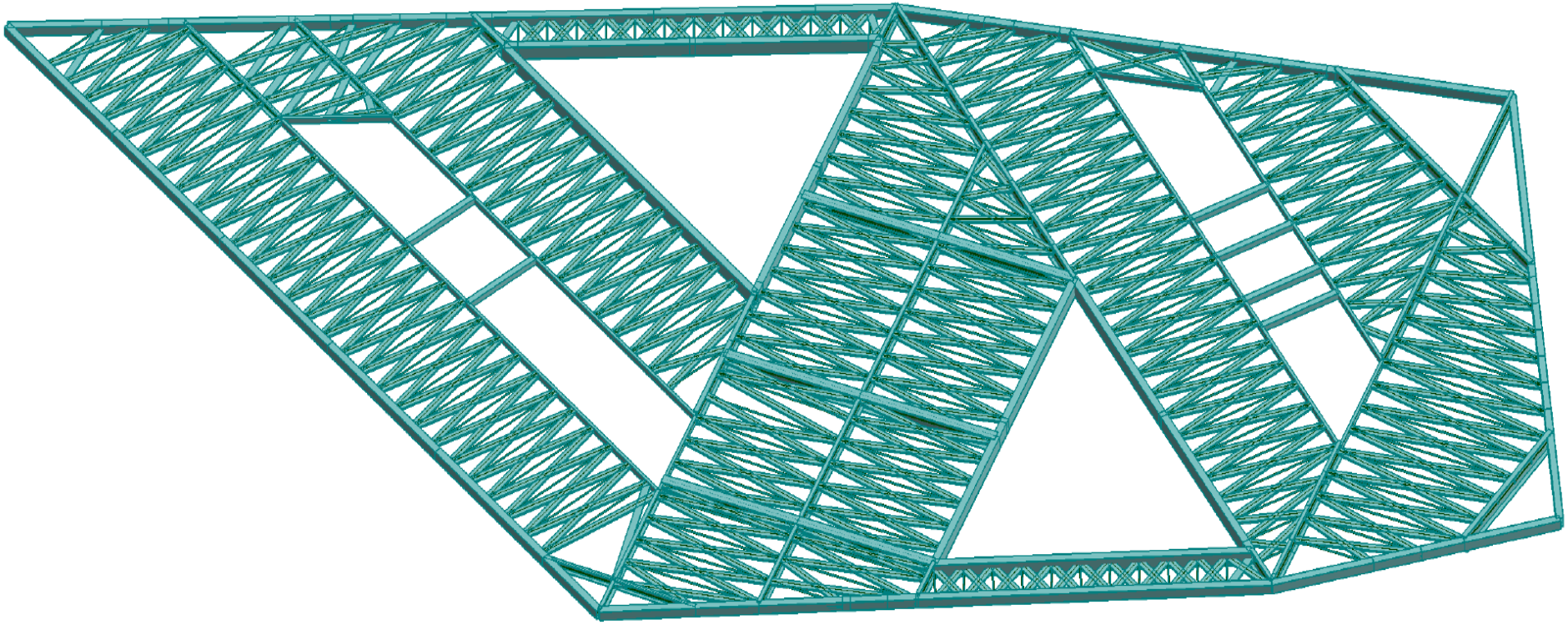

## 2D model, træk/tryk elementer

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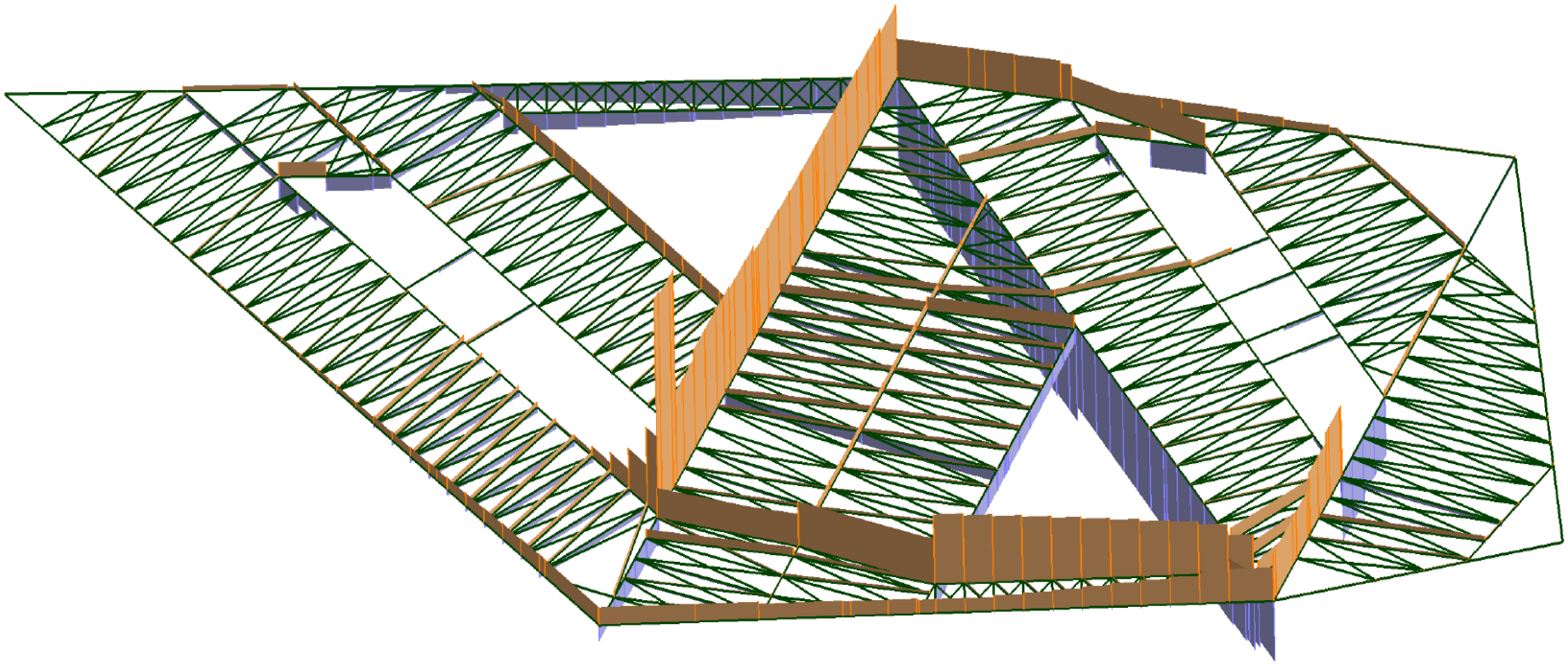

## Kraftforløb

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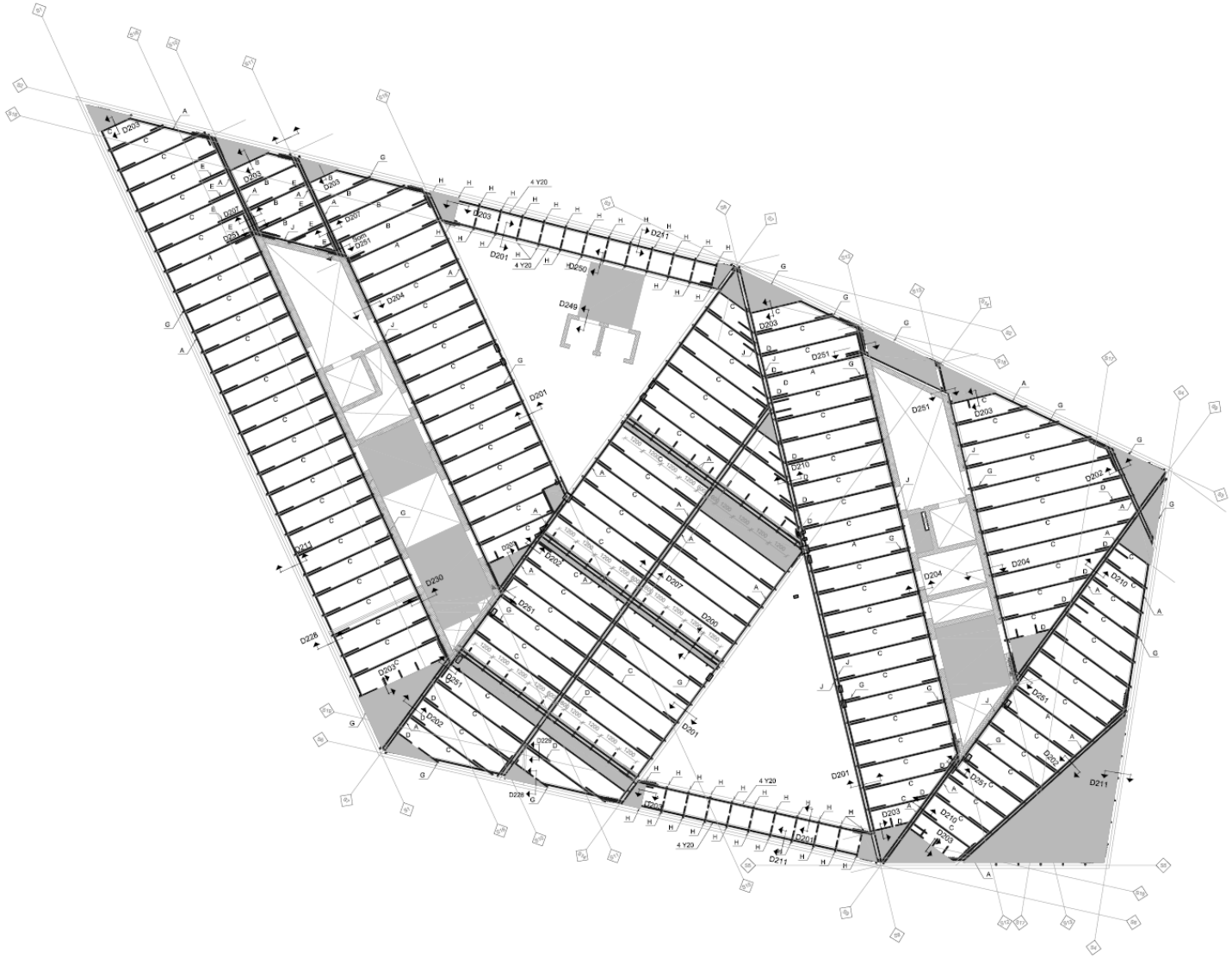

# Fugearmeringsplan

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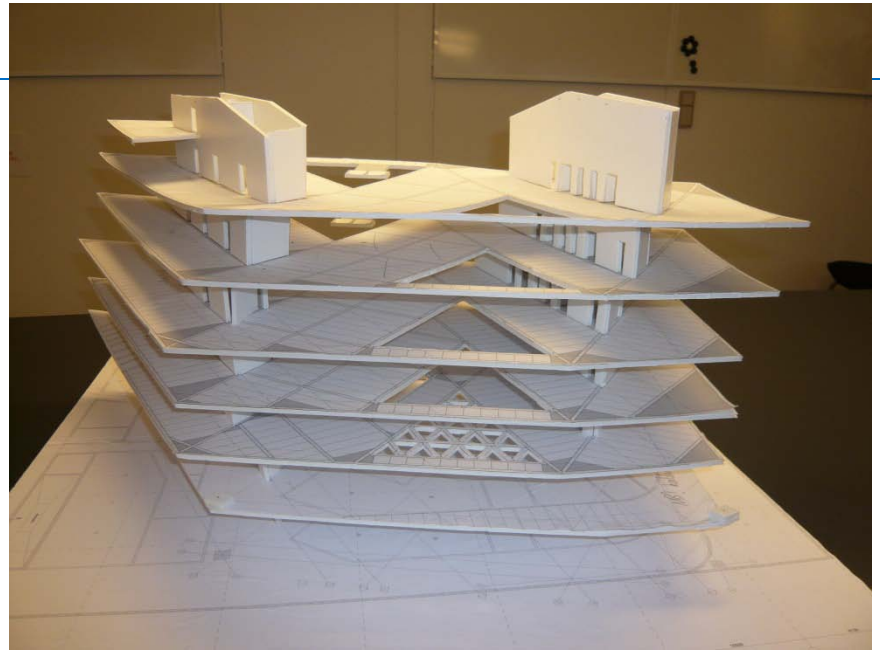
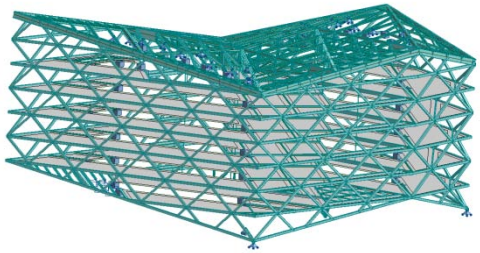
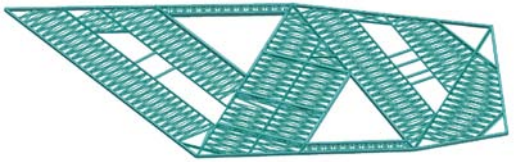
# Håndberegning

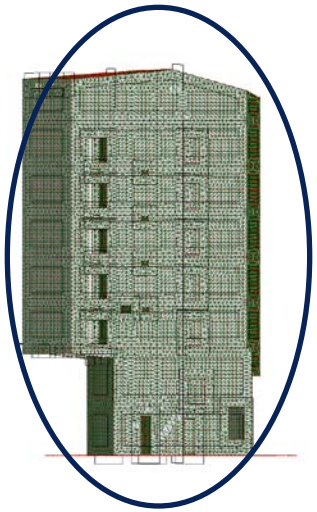




3D model - stålkonstruktion



2D model - dæk



3D model - kerner

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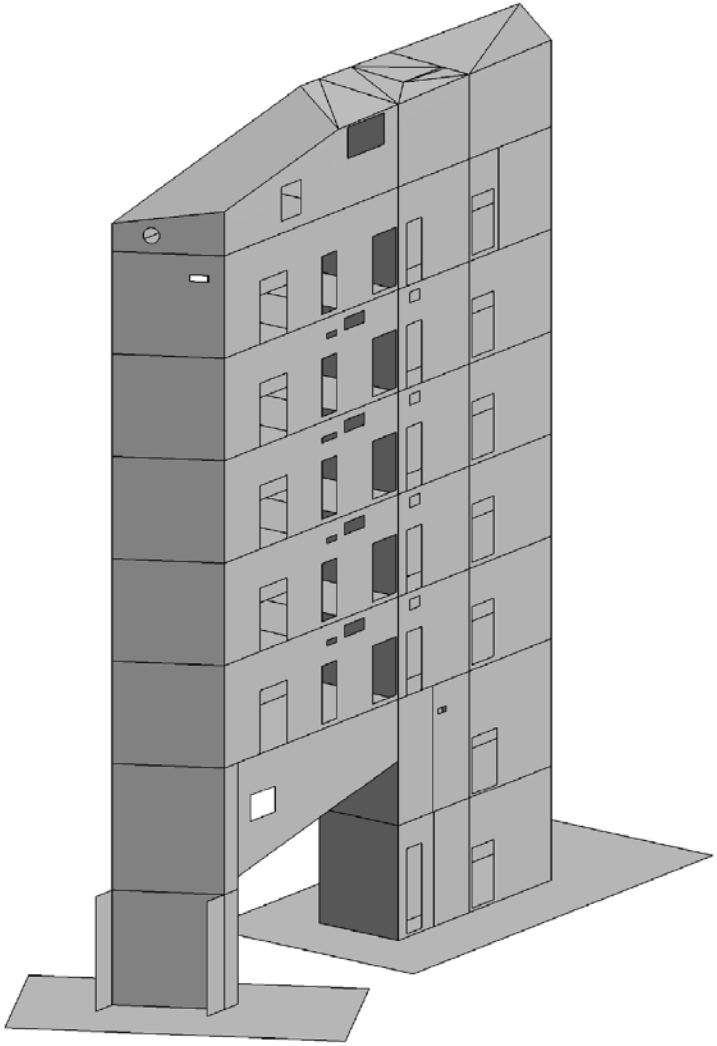
# Betonkerner



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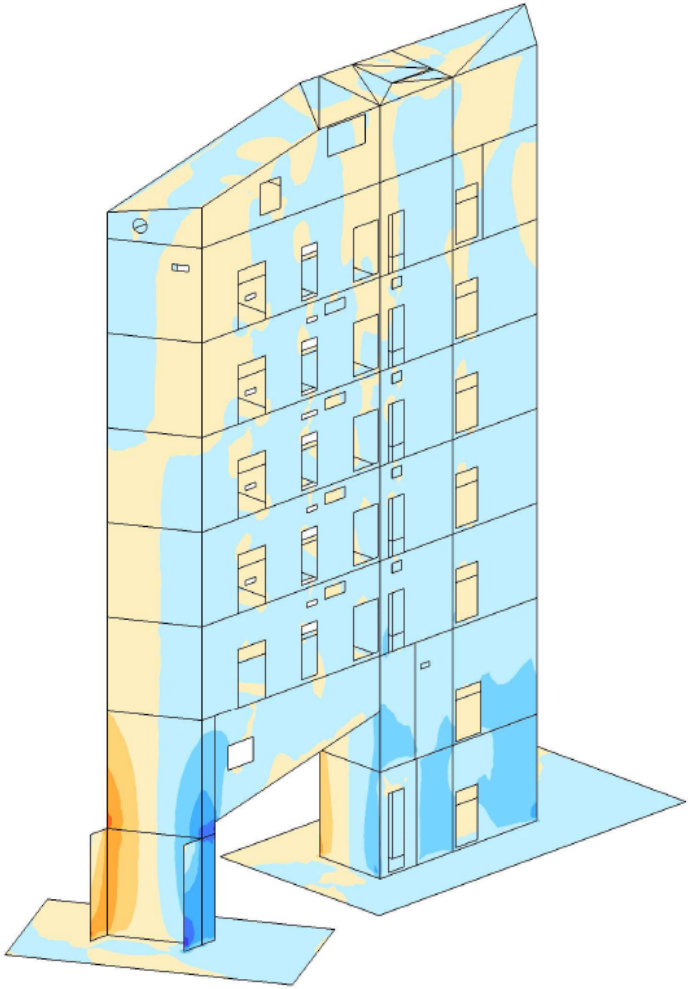

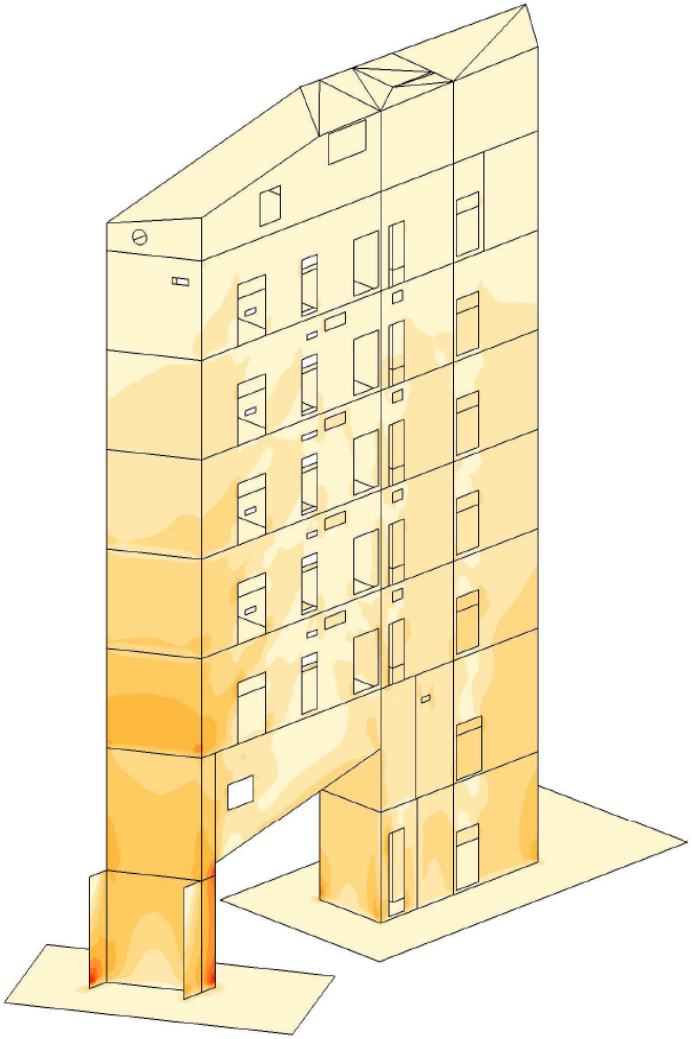

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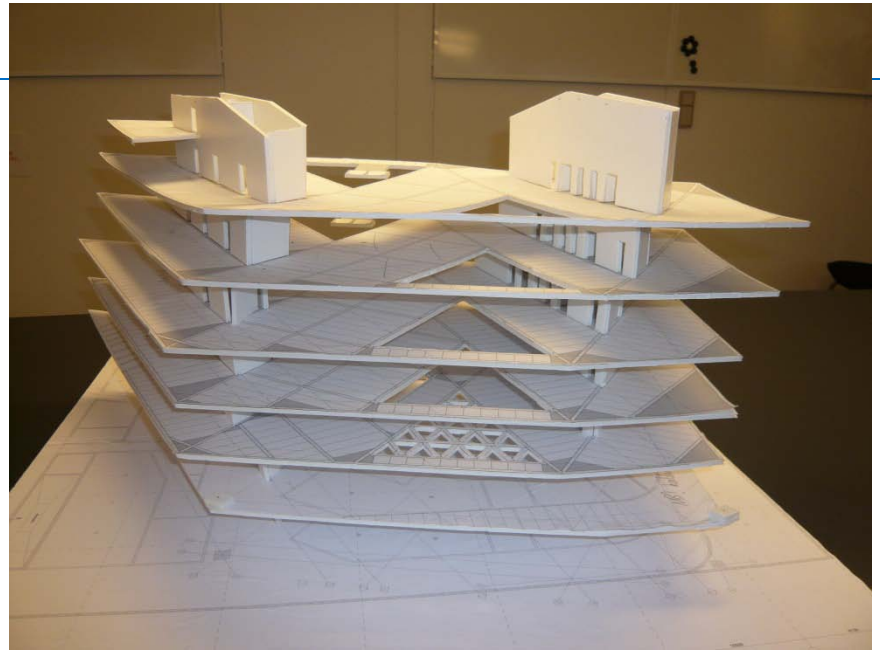
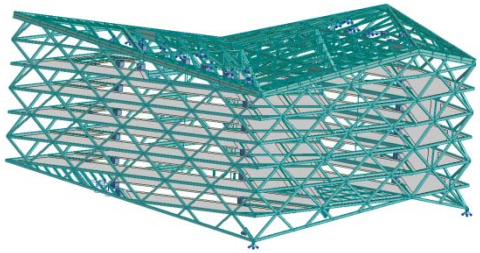
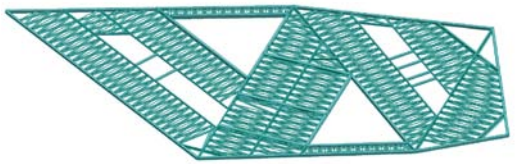
# Håndberegning

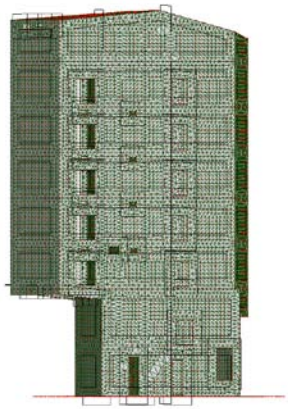




3D model - stålkonstruktion



2D model - dæk



3D model - kerner

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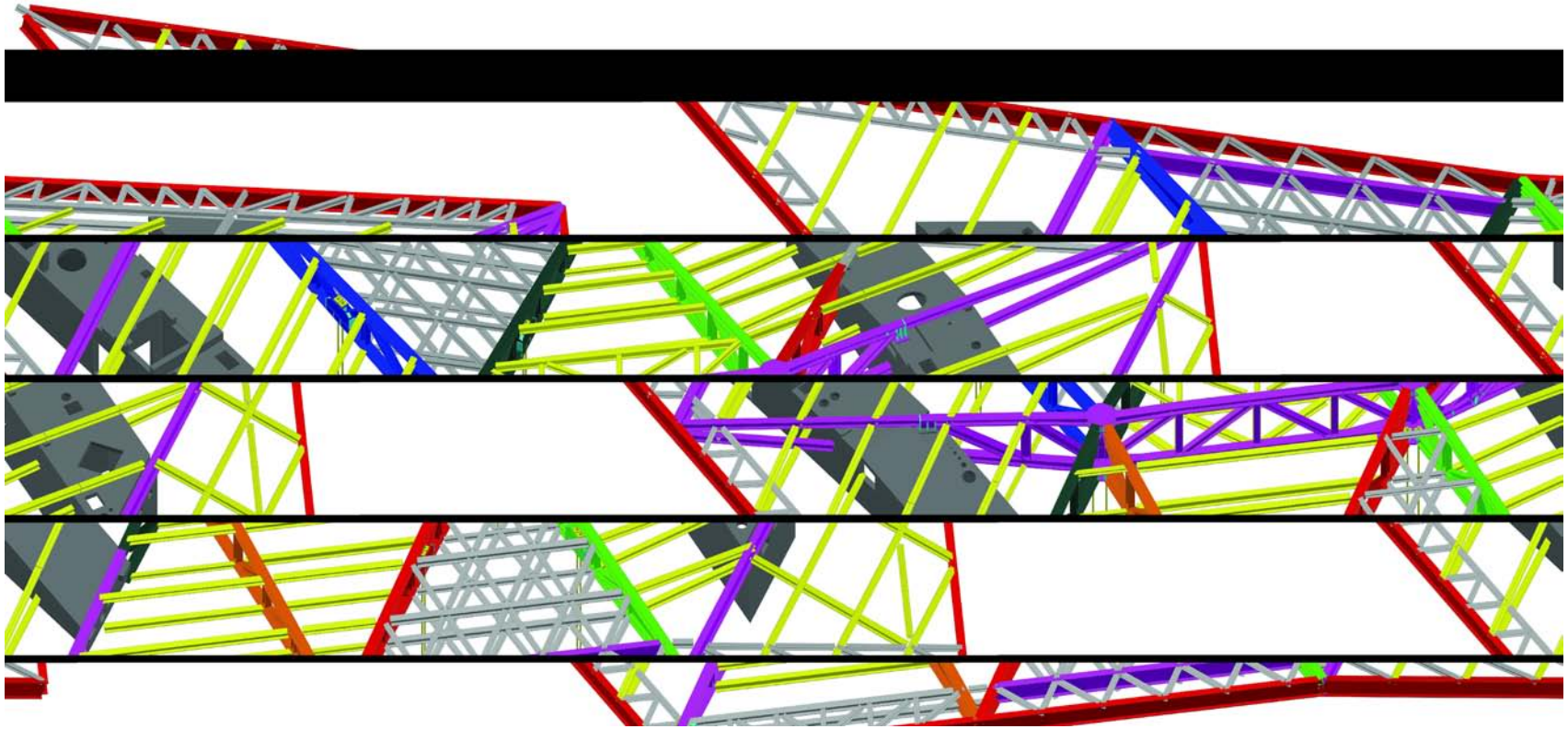
# Tagkonstruktion – Geometri



Tagkonstruktion i to bjælkelag, nederste bjælkelag hovedsageligt til bæring af installationer og nedhængte lofter, samt som stabiliserende elementer.

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# En ingeniørs udfordringer…

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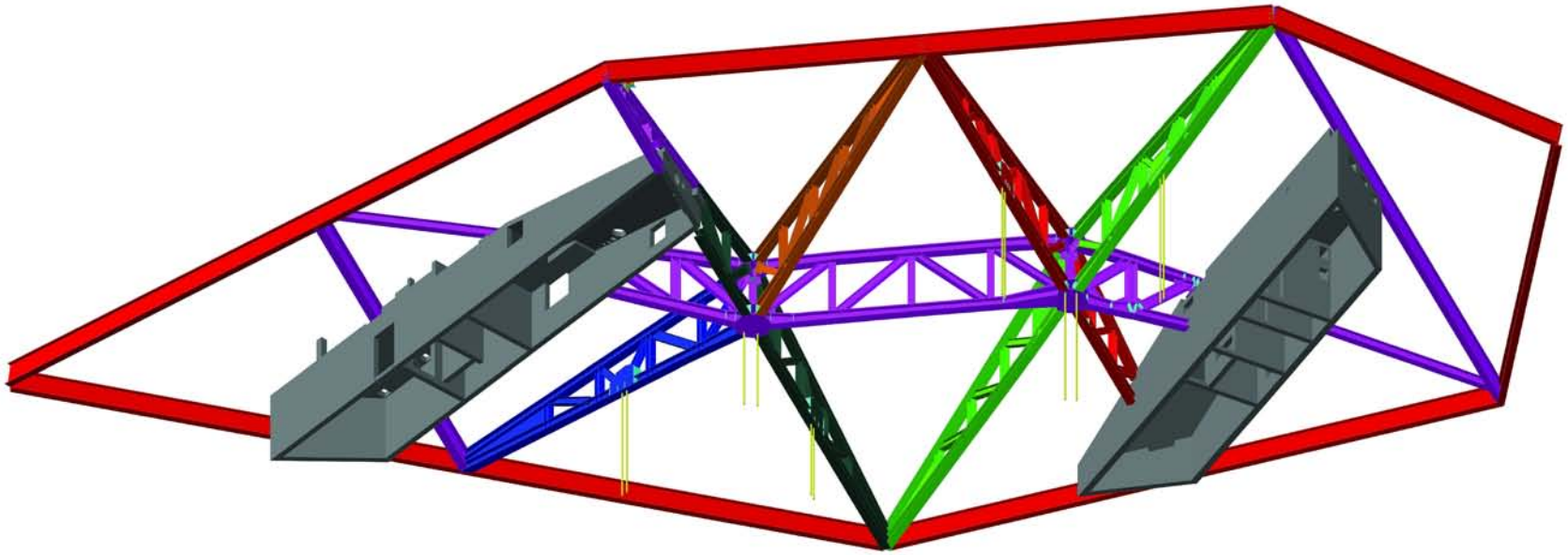
# Tagkonstruktion – Bærende system



Hovedgitterdrager spænder 26m mellem kerner, understøttet på kalottelejer.
Øvrige gitterdragere spænder mellem facader, eller understøttes på kerner.
Ophængsstag samles til to hovedknuder, samt til sidegitterdragere.

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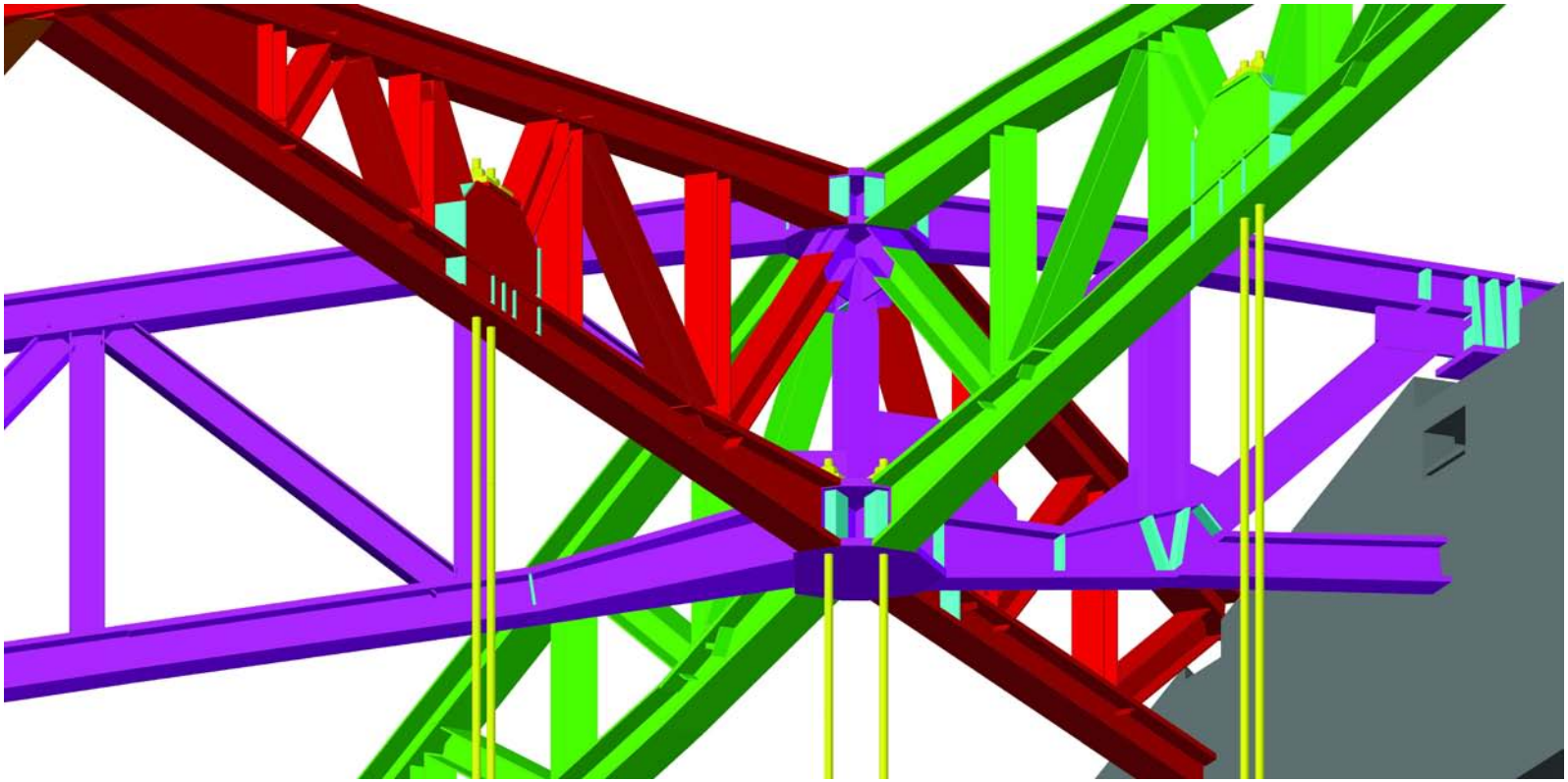
# Tagkonstruktion – Hovedknude



Samlingspunkt i hovedgitterdrager med Ø75 Macalloy ophængsstag, brud-styrke 1030 N/mm$^2$. Maks. trækkraft i stag ca. 2000 kN. Stag brandsikres med 4,8mm brandmaling (stag specielt testet i England under brandforhold).

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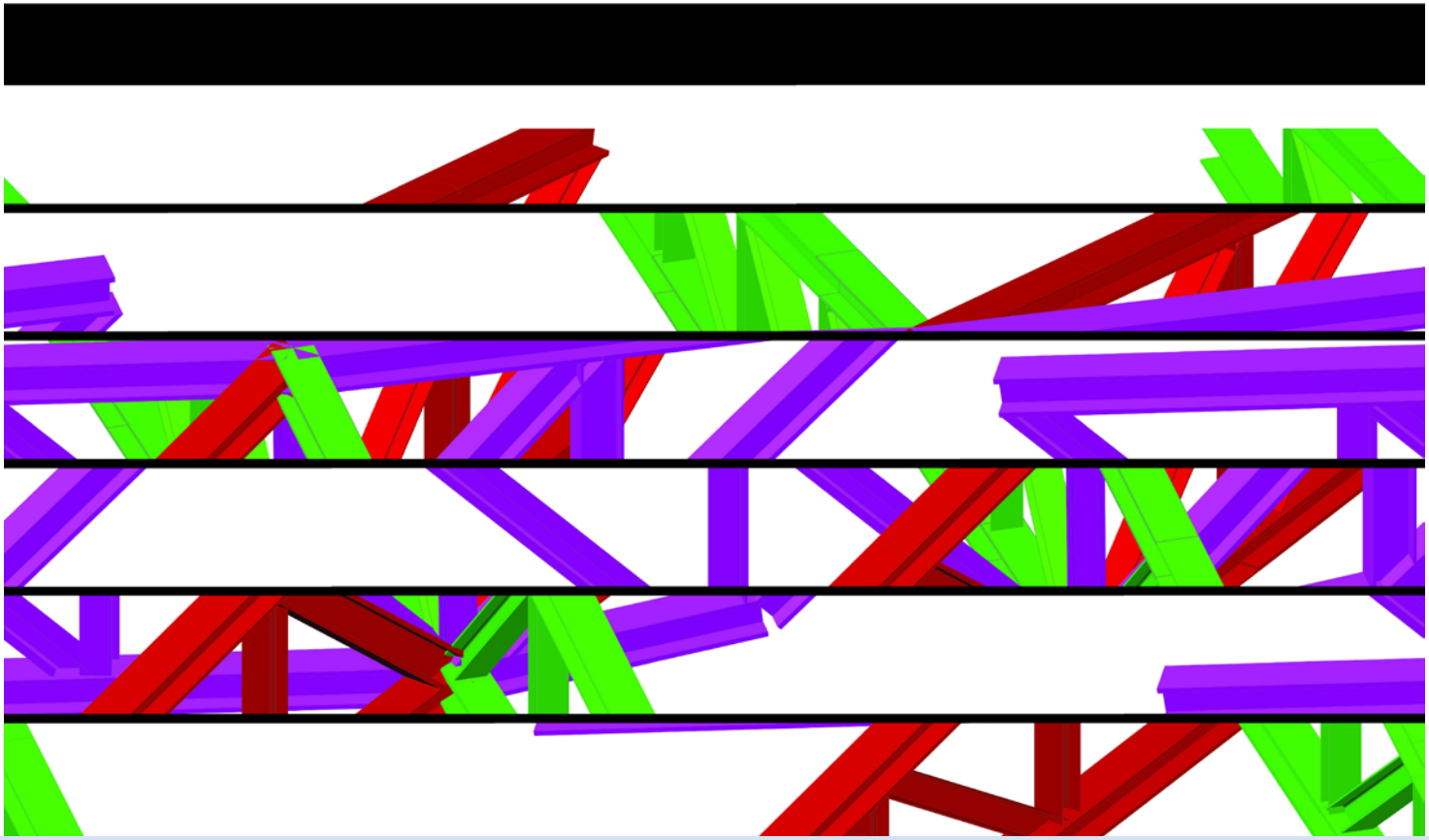
# Hovedknude – Samlingsdesign



Udfordring: Hvordan samles tre gitterdragere, med i alt nitten elementer, der mødes under forskellige vinkler og hældninger…

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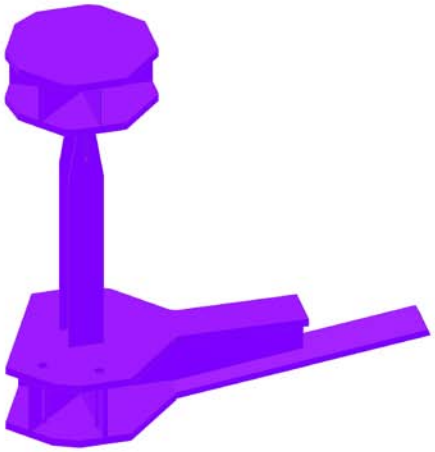
# Hovedknude – Samlingsdesign



Løsningen: Der dannes et fælles vandret samlingsplan i top og bund…

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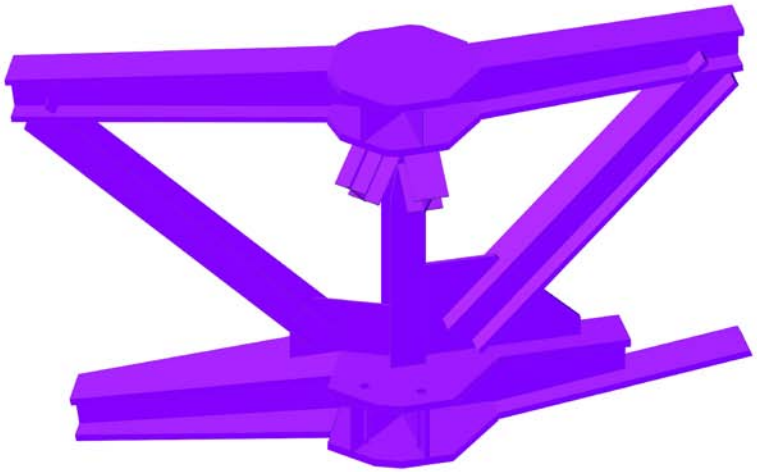
# Hovedknude – Samlingsdesign



…hvorefter hoveddragerens geometri tilpasses…

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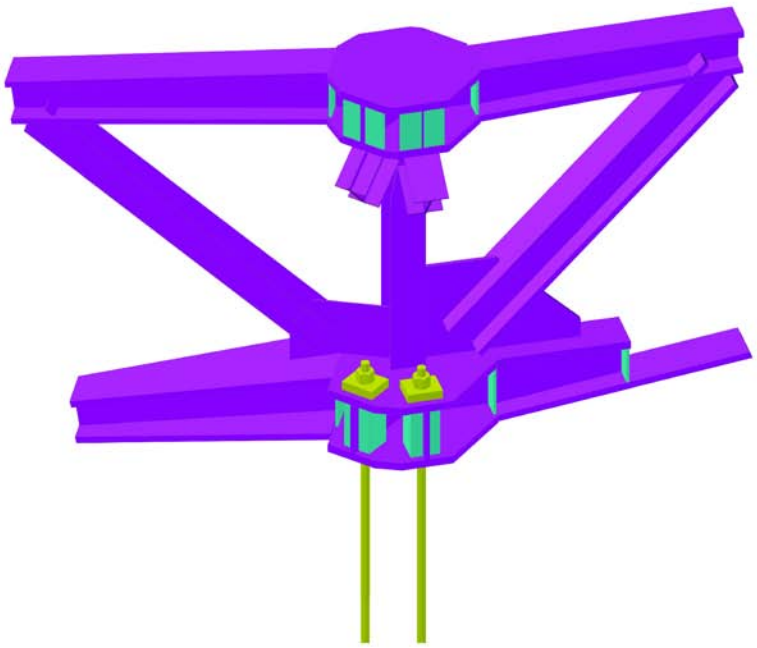
# Hovedknude – Samlingsdesign



…afstivninger og ophængsdetaljer kan nu udformes…

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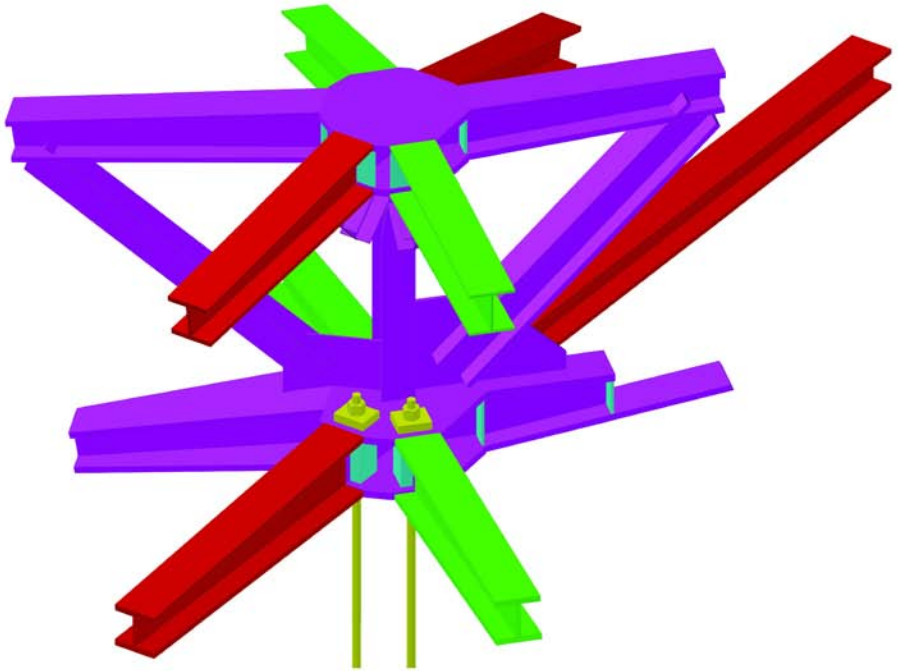
# Hovedknude – Samlingsdesign



…sidegitterdragere kan samles til knuden…

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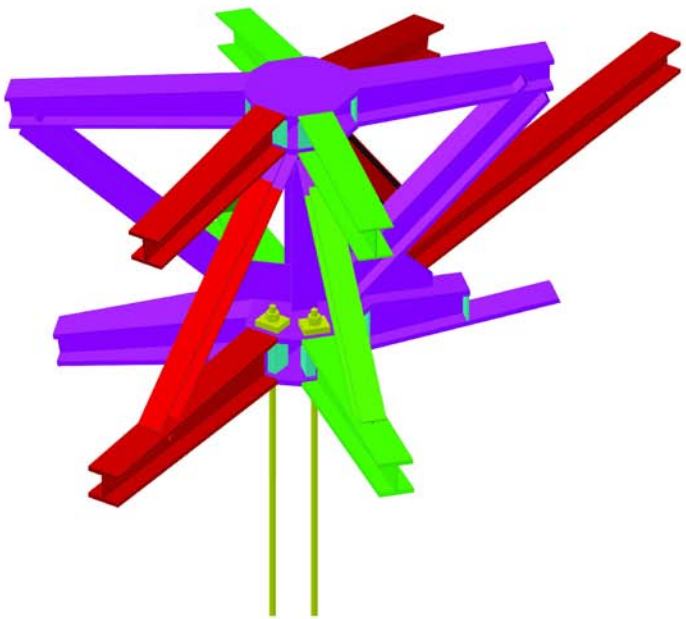
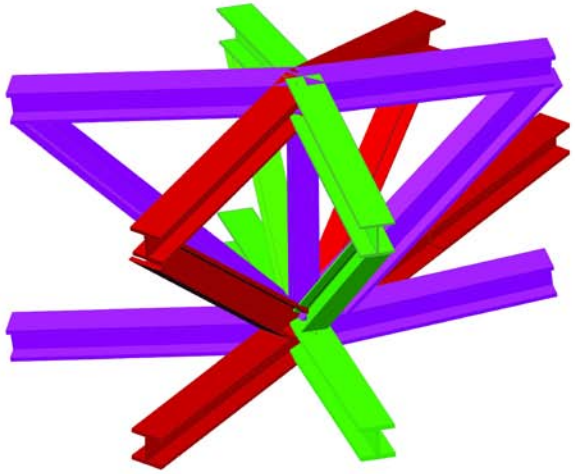
# Hovedknude – Samlingsdesign





…enkelte diagonaler vendes om, i forhold til oprindeligt layout, for at give bedre plads til ophængspunkter…

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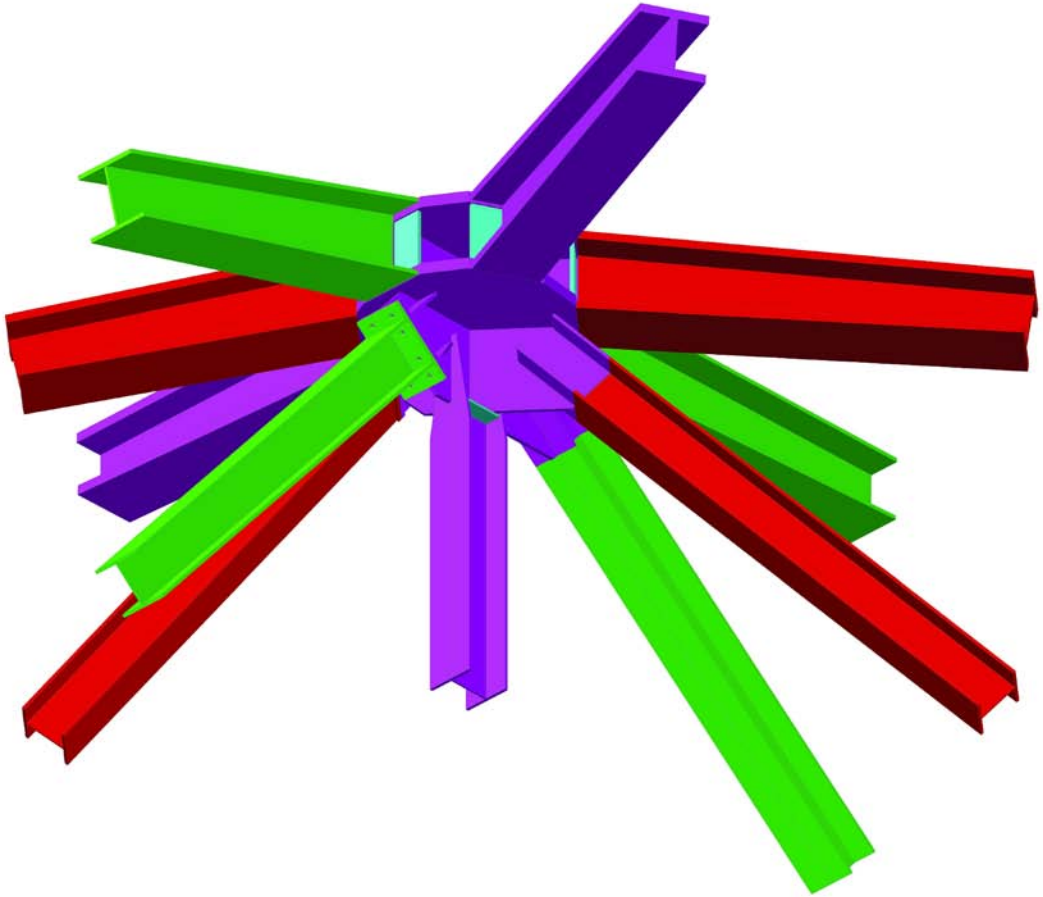
# Hovedknude – Samlingsdesign



… dermed kan samlingen udføres både i top…

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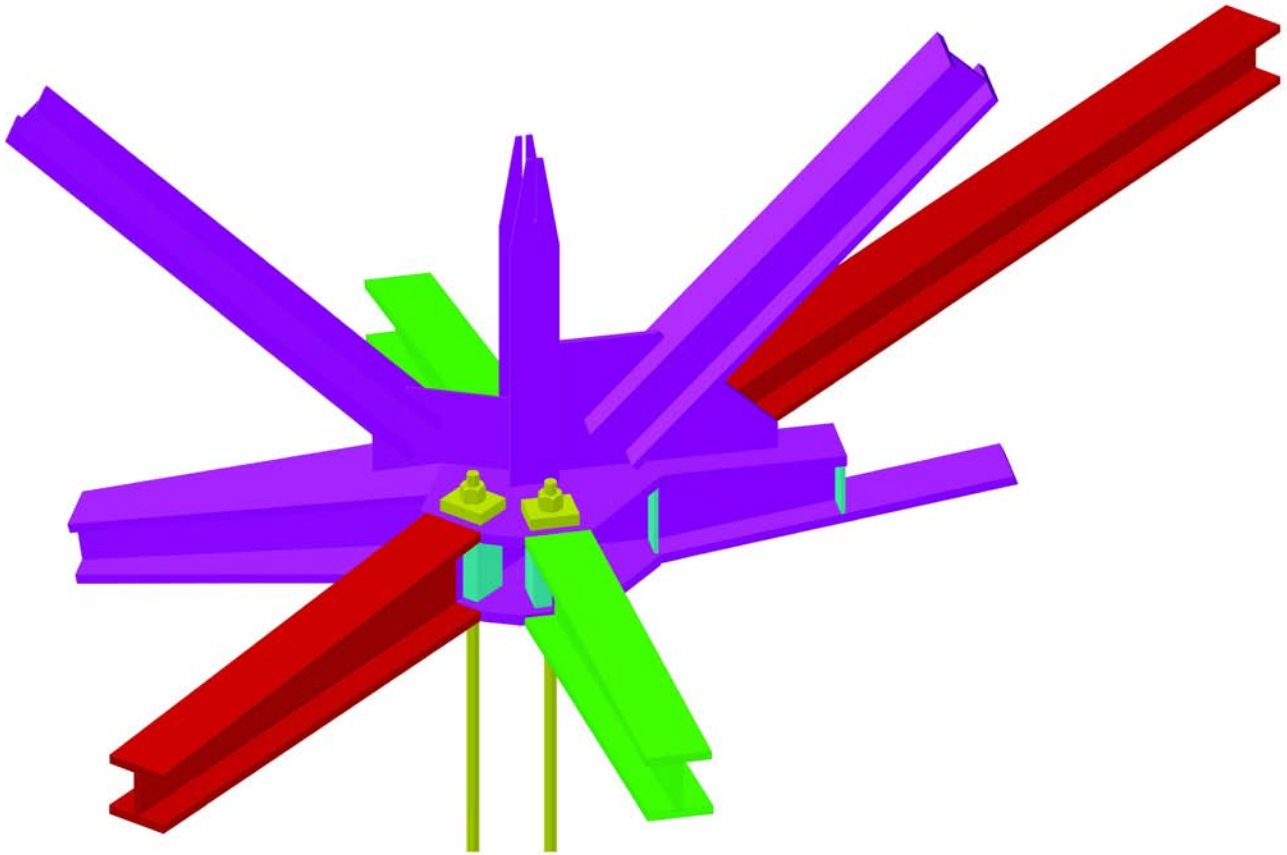
# Hovedknude – Samlingsdesign



…og bund…

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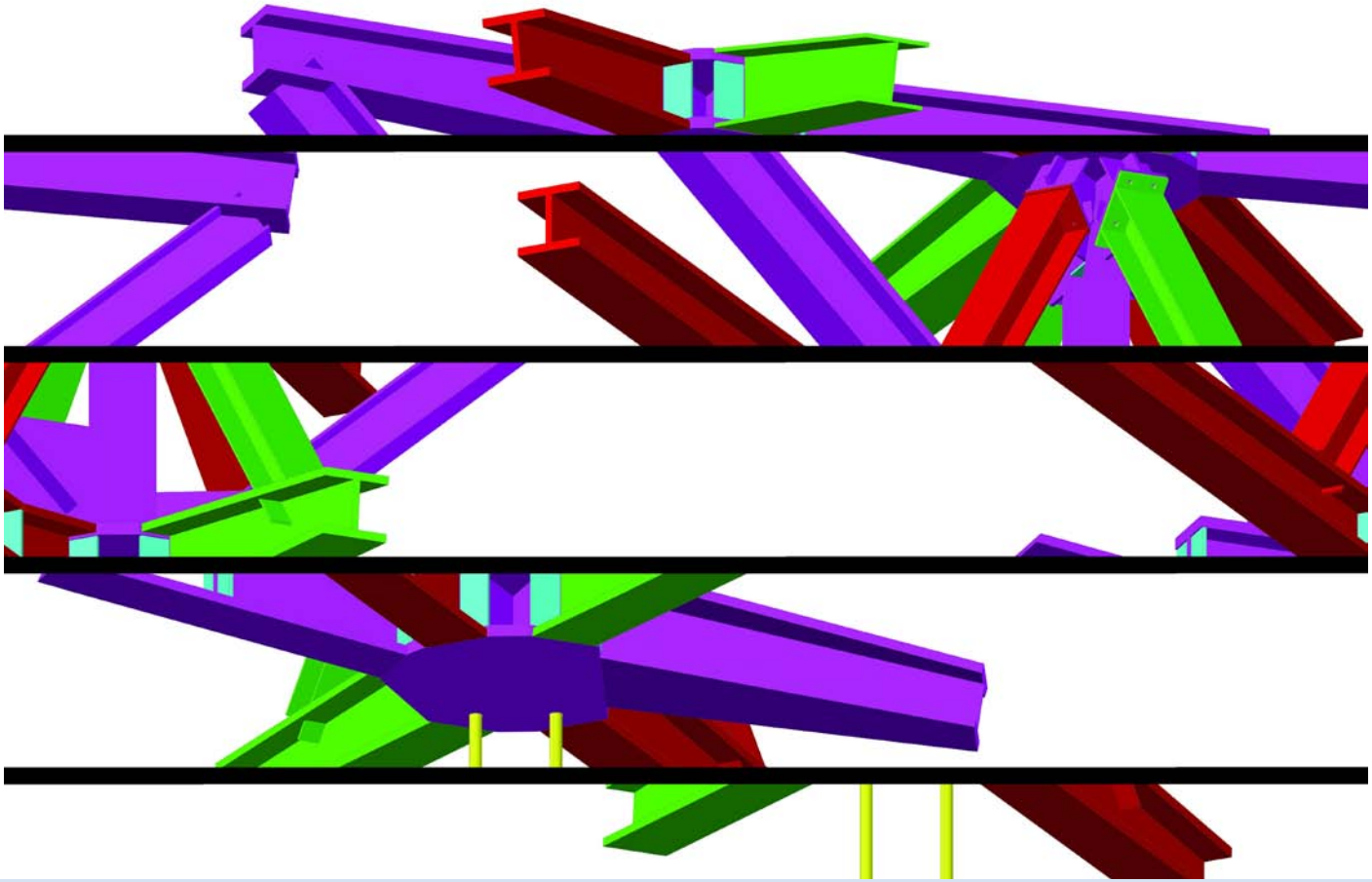
# Hovedknude – Samlingsdesign



…hvorved en udførlig, om end kompliceret, løsning er fundet.

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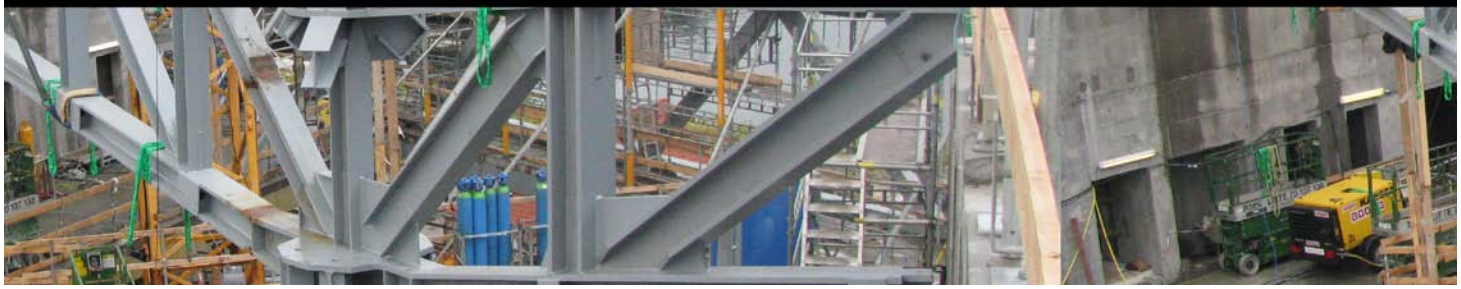
# Tagkonstruktion – Hovedgitterdrager



Hver af de to hovedknuder vejer op til seks tons og opbygges af 40-70 mm tykke plader. Sidegitterdragere montagesvejst til hoveddrager. Hoveddrager vejer omkring 43 tons og blev hejst i ét styk på plads.

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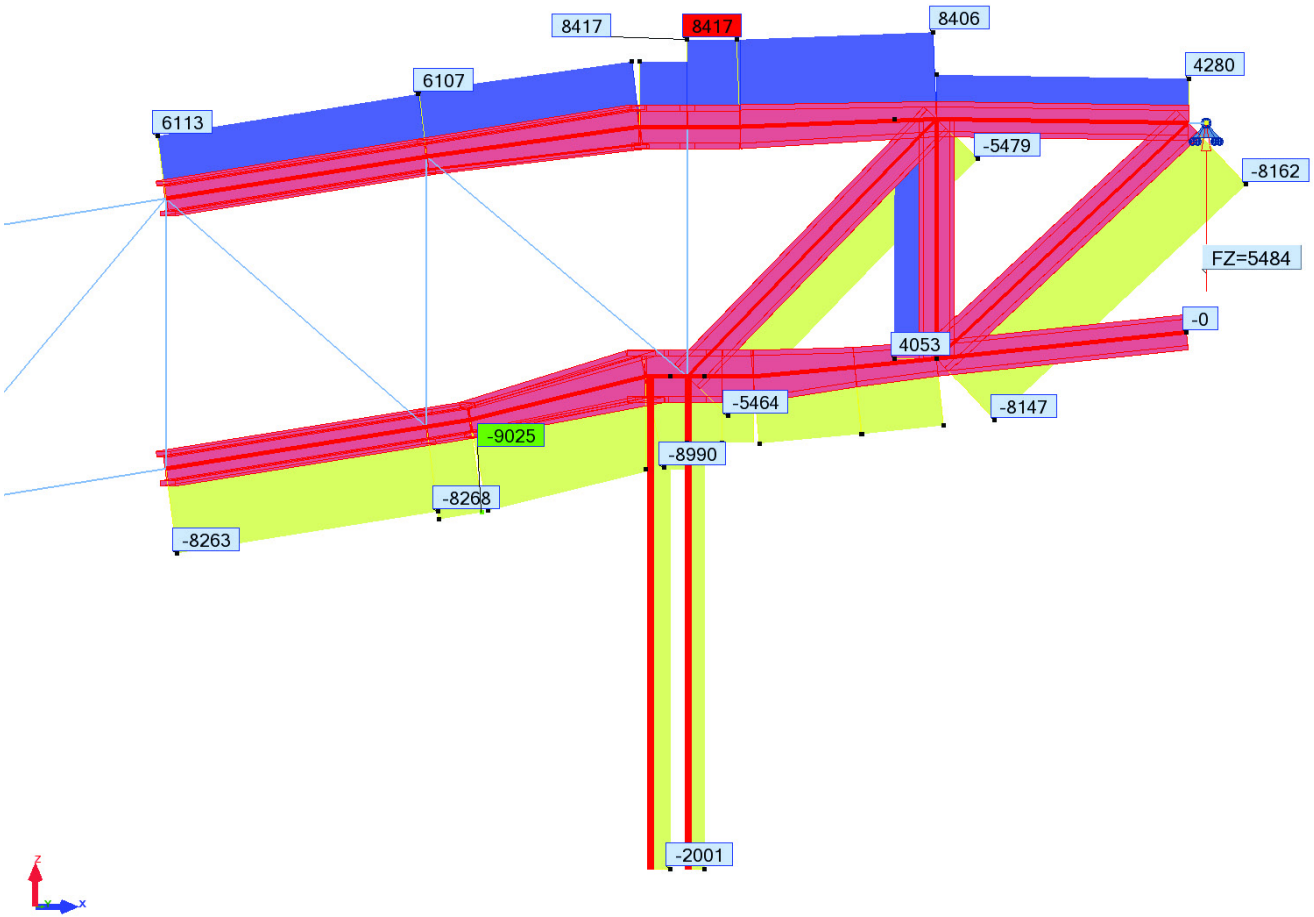
# Hovedgitterdrager - Normalkræfter




Hovedgitterdrager understøttet på kernetop (Reaktion ca. 5.500 kN). Maks træk/tryk ca. 9.000 kN. Maks trækkraft i stag på 2.000 kN.

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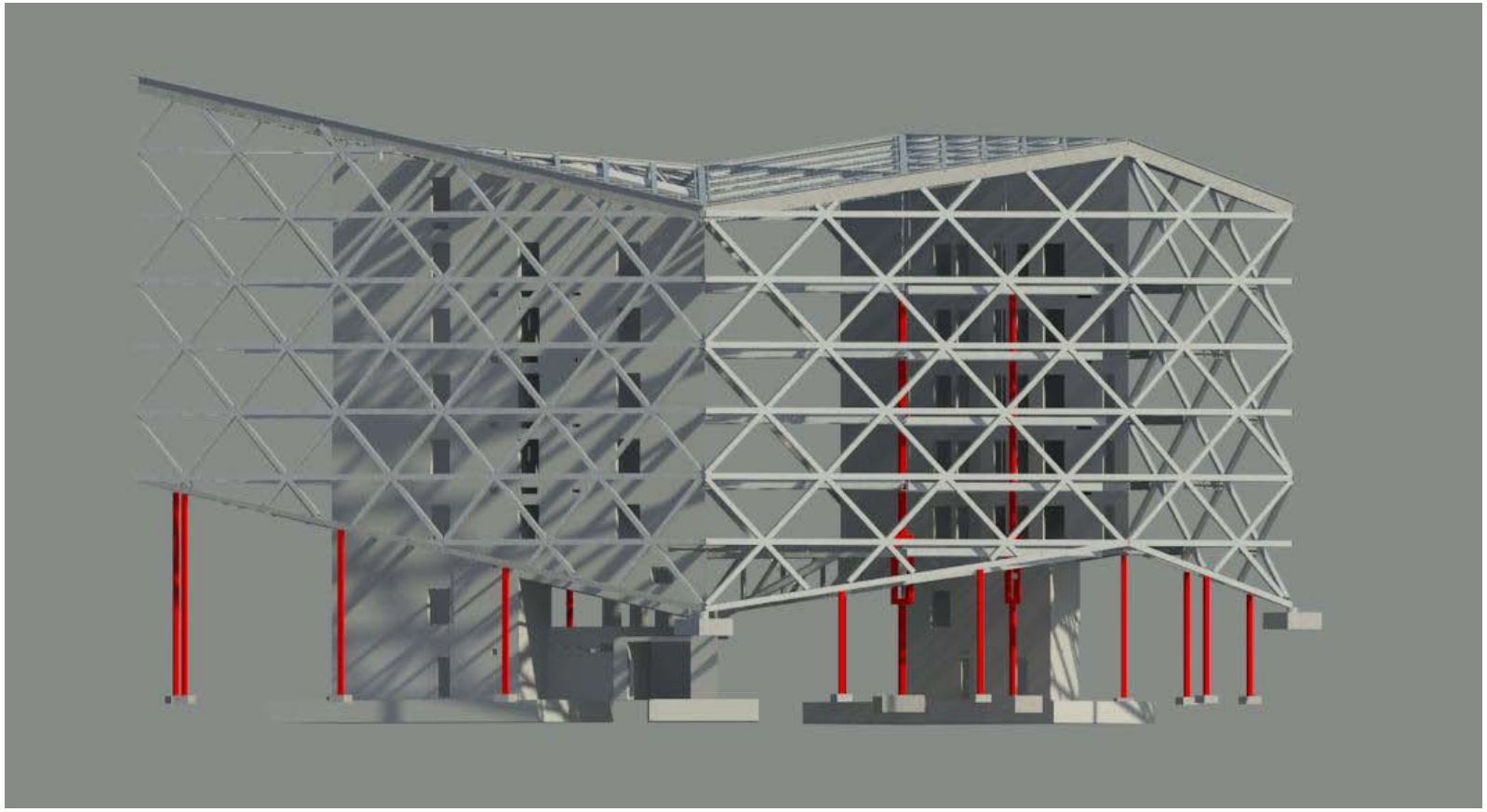
# Interimssøjler



Under montagen er facadekonstruktion og etagebjælker midlertidigt understøttet på interimssøjler.

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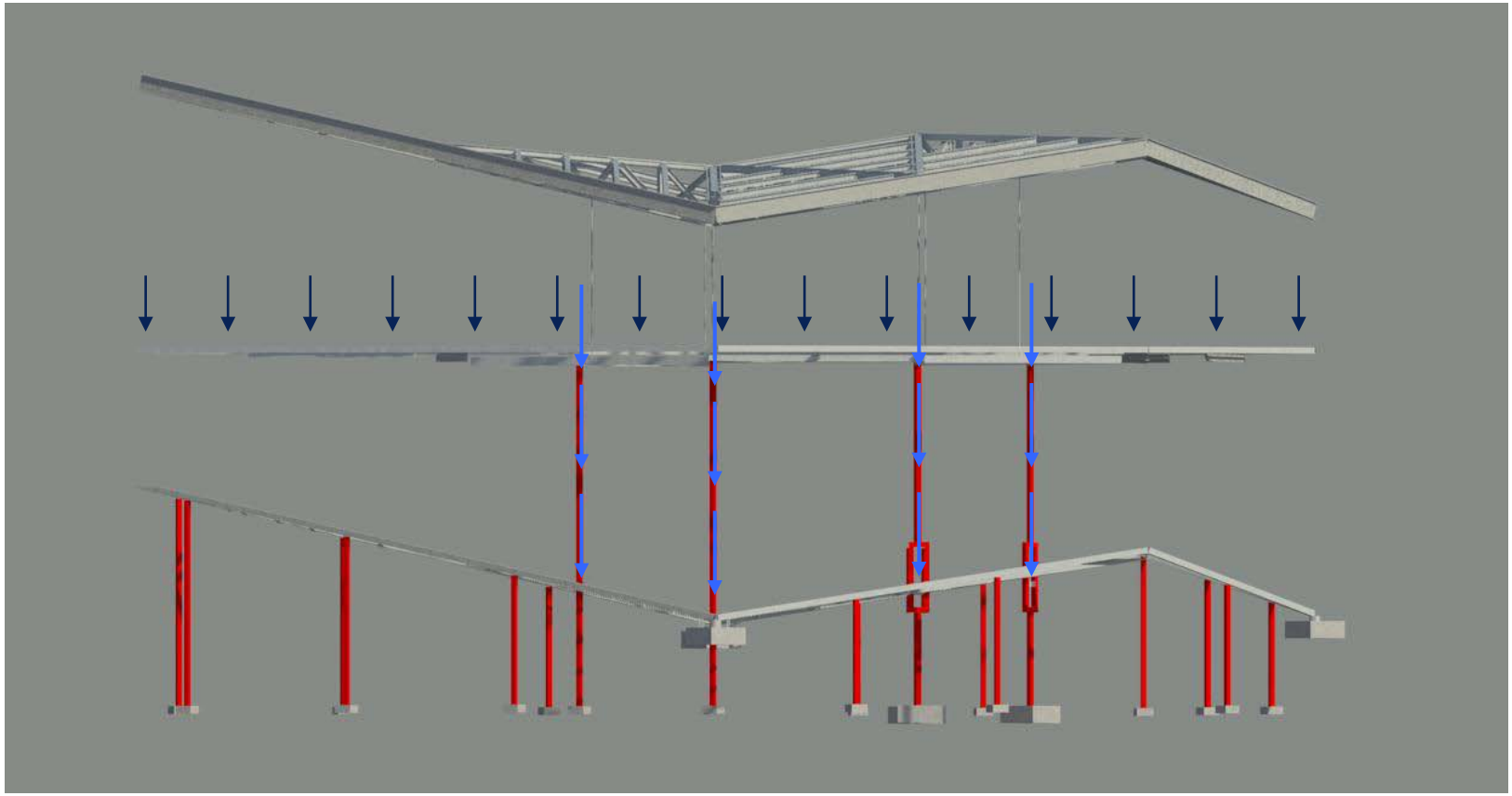
# Lastgang med interimssøjler - Etagedæk



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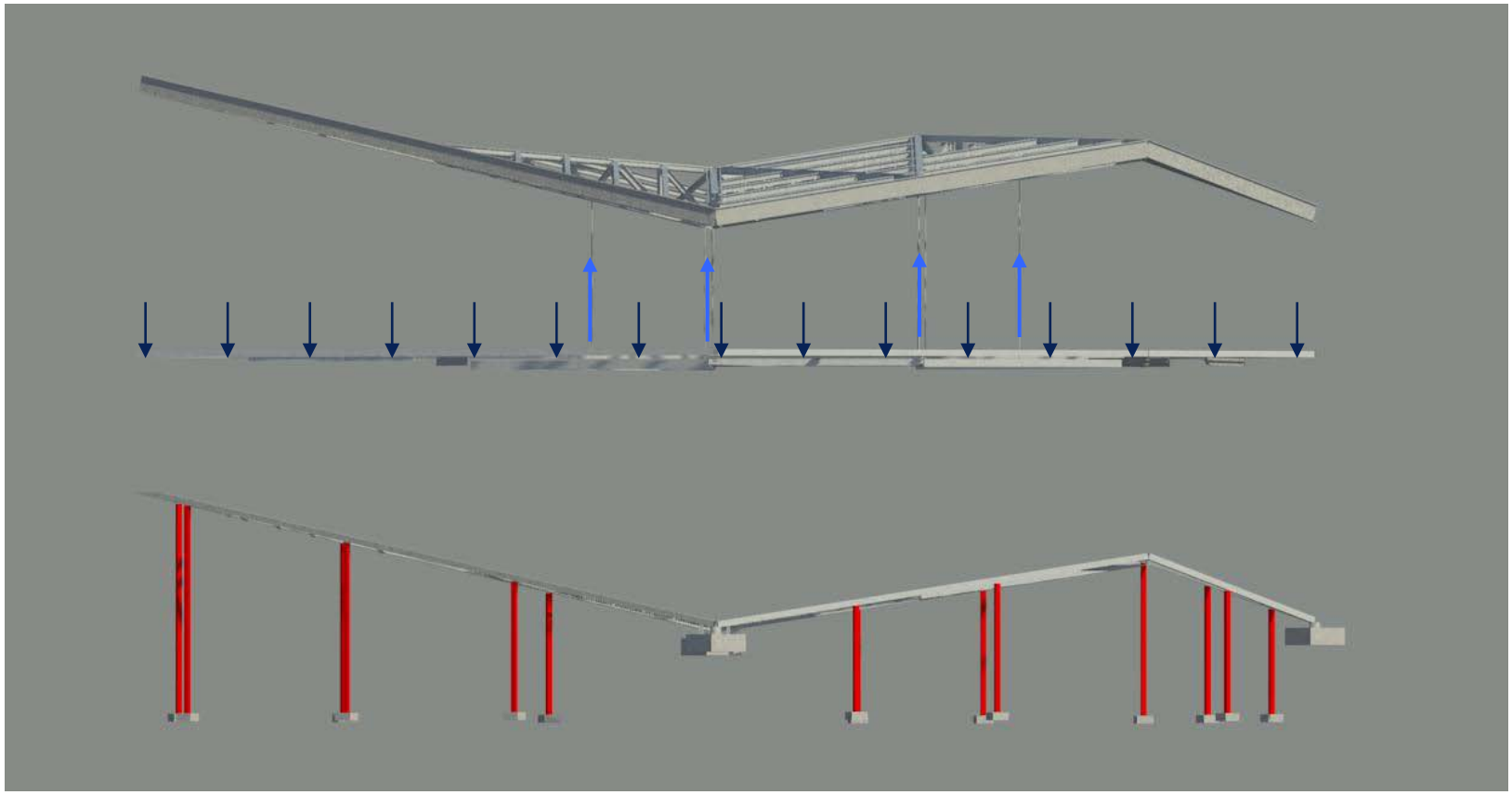
# Lastgang uden interimssøjler - Etagedæk



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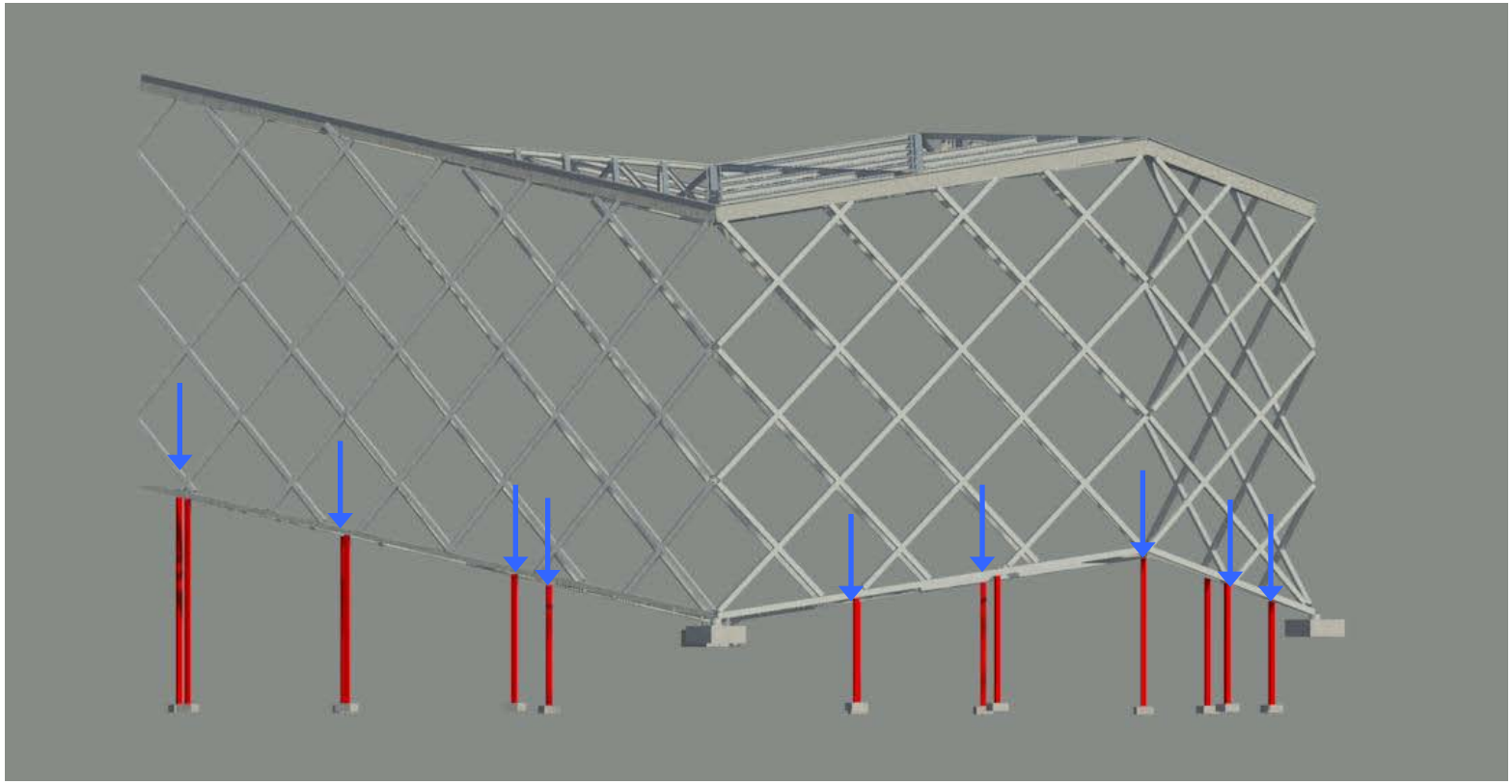
# Lastgang med interimssøjler - Facadegitter



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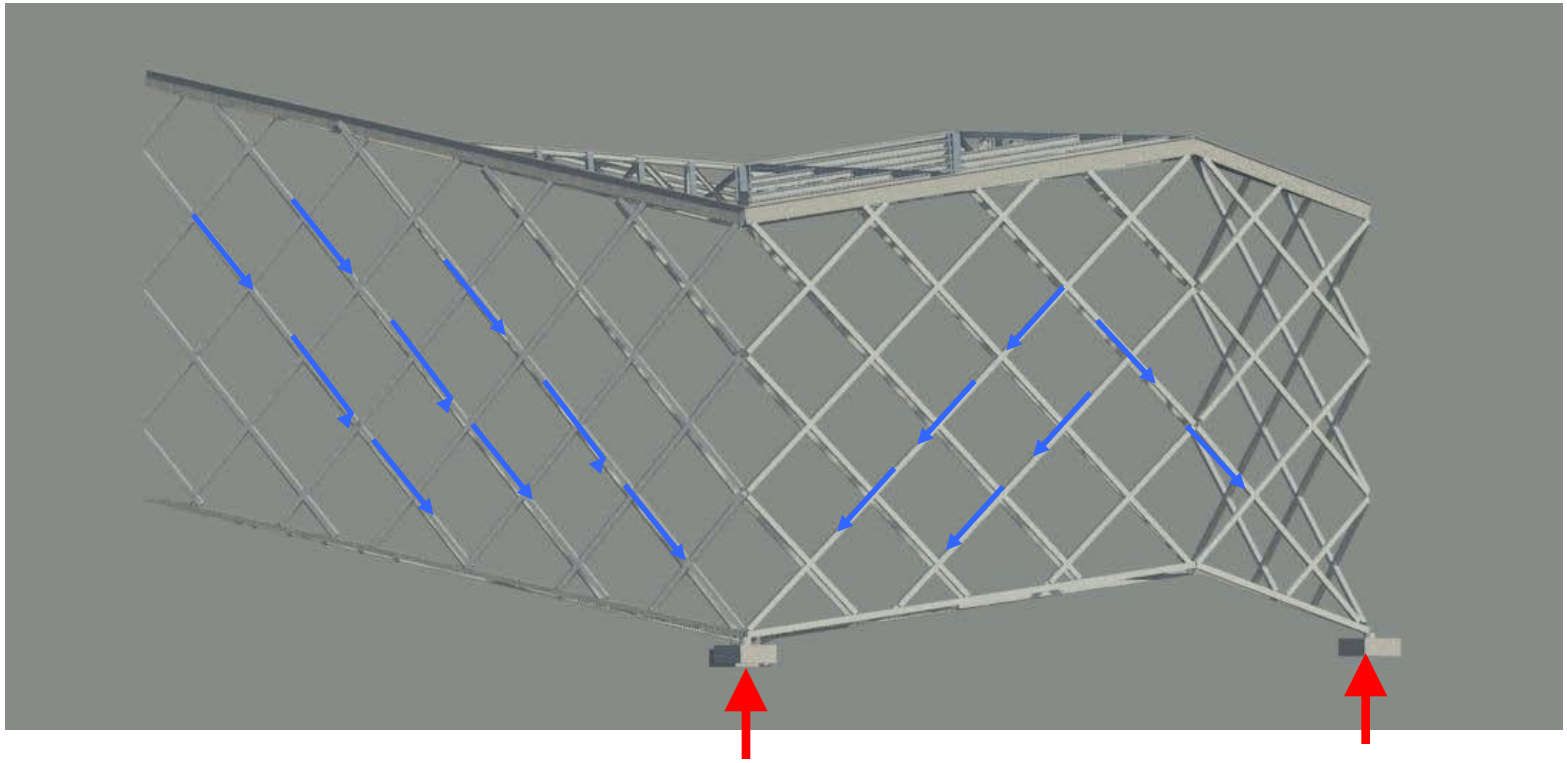
# Lastgang uden interimssøjler - Facadegitter



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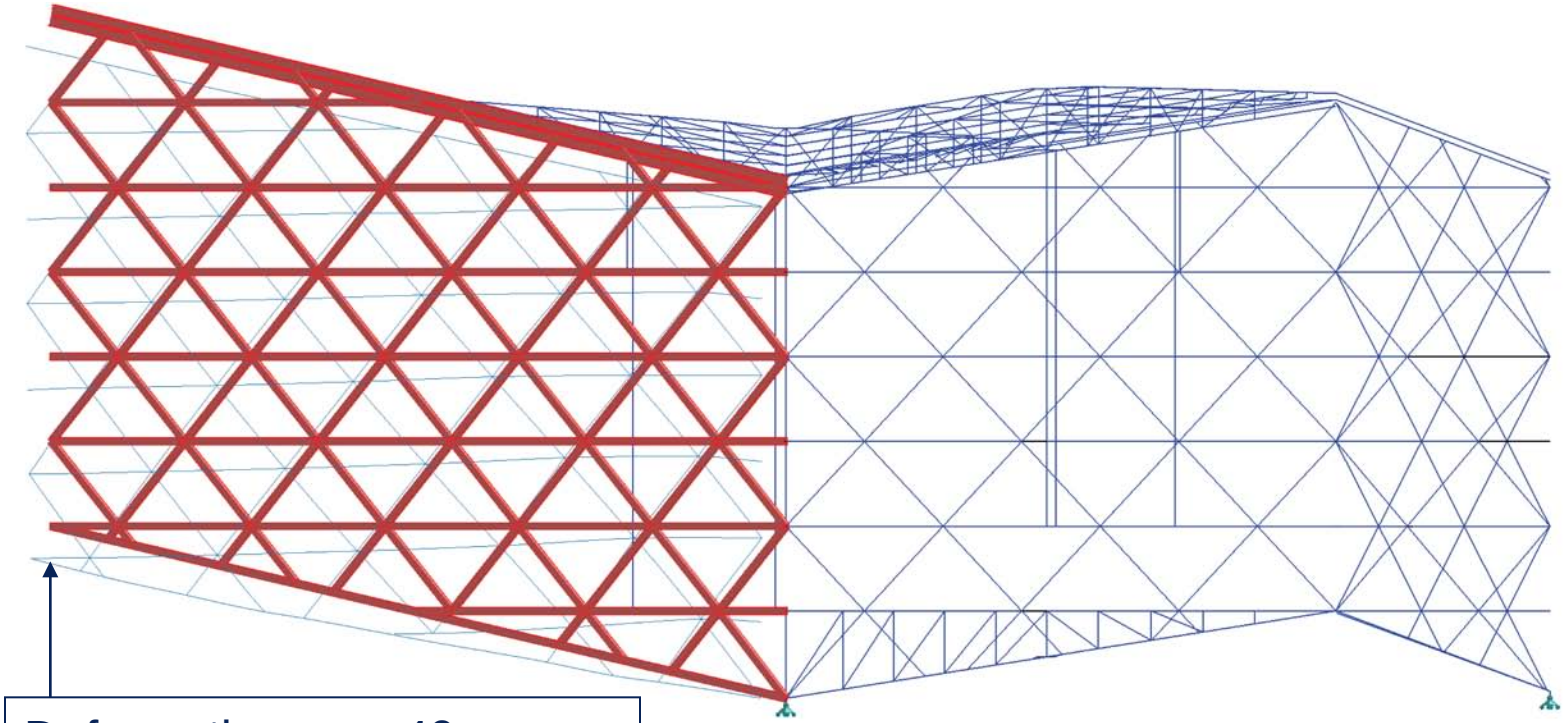
# Lodret flytning af udkraget spids



Deformation max 40 mm

Her af 15 mm sætning ved fjernelse af interimssøjler.

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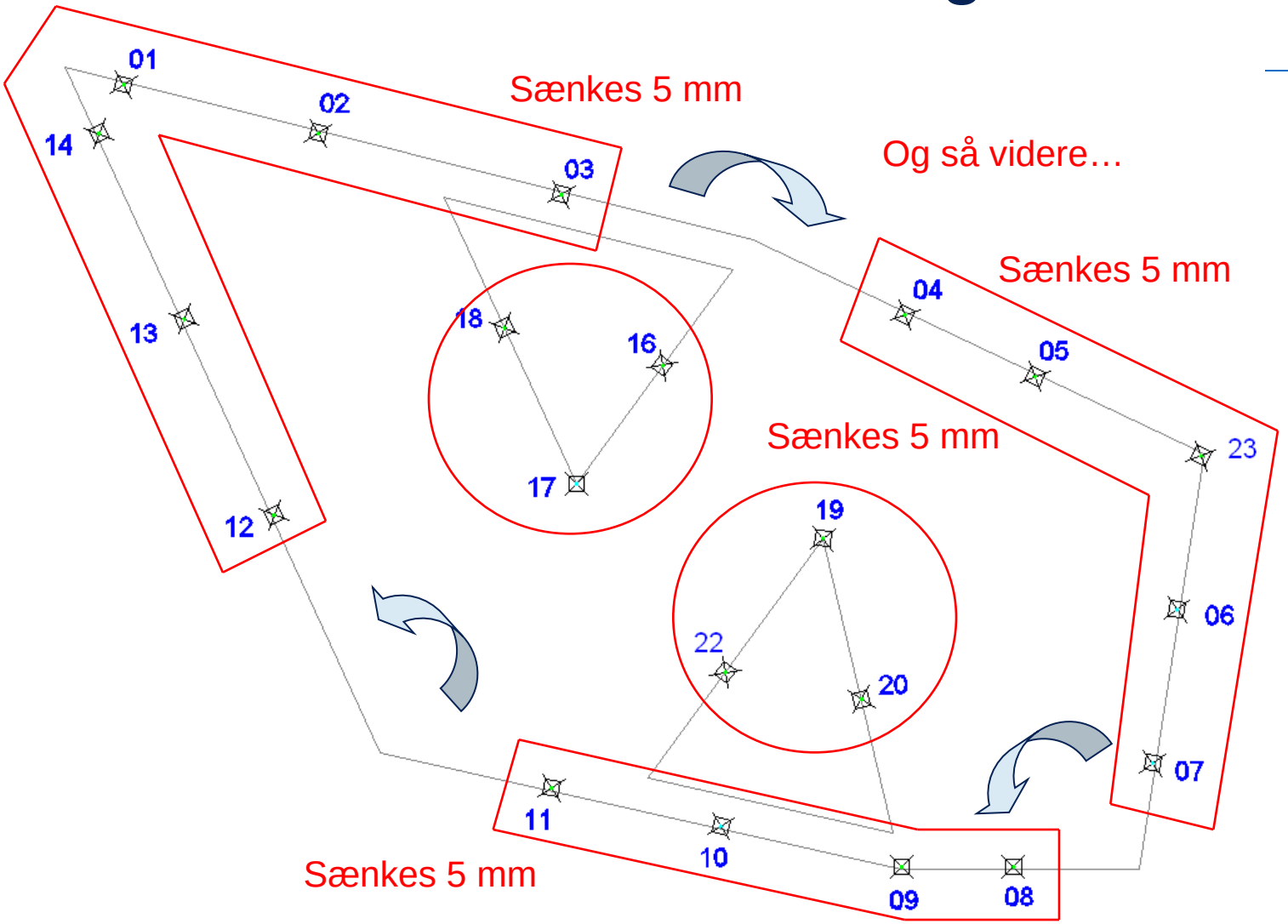
# Procedure for demontagen

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# Interimssøjler - Fuldskalatest

Fuldskalatest af nedtagningsmetode hos Promecon

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# Interimssøjler - Demontering

Demontering af interimssøjler via skærebrændermetoden

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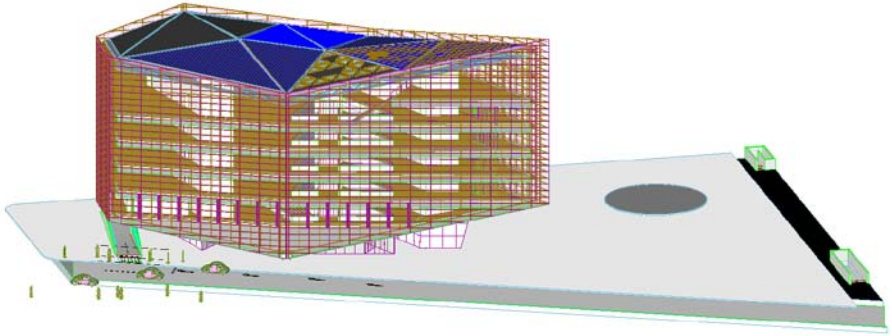
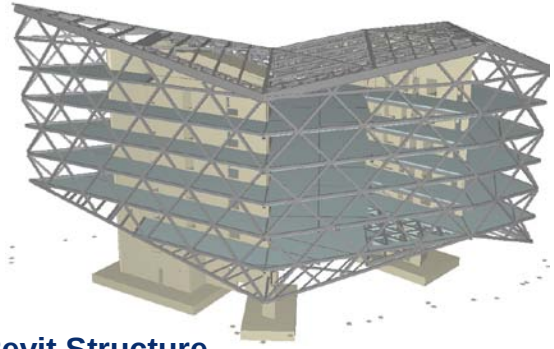
# 3D projektering

## Koordinering mellem arkitekt og ingeniør med Revit Architecture og Structure

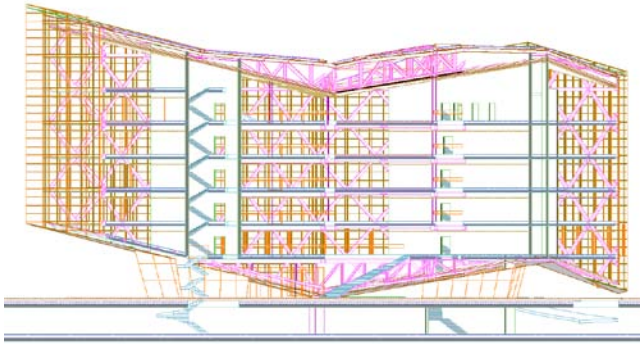


**Revit Architecture**

**Direkte link**



**Revit Structure**



**Koordinering af konstruktioner, geometri og grænseflader**

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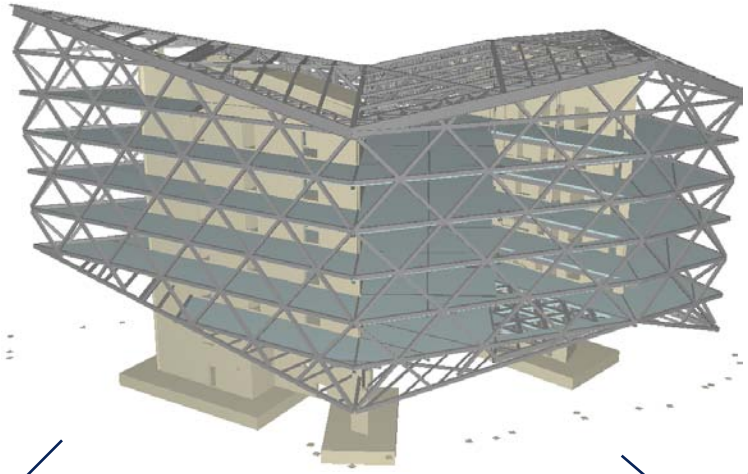
# 3D projektering

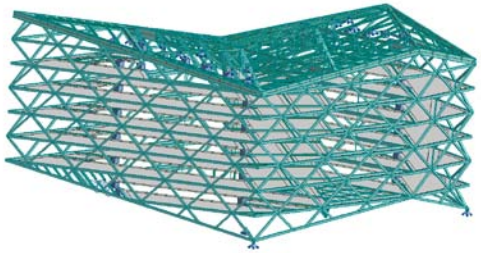
## Koordinering mellem konstruktionsmodel og FEM beregningsmodeller

**Revit Structure**

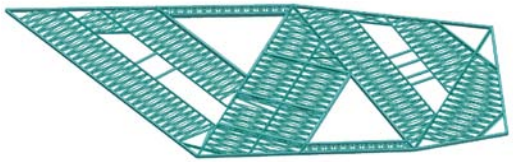


**Robot Millennium**

**Knudepunktsmodel**



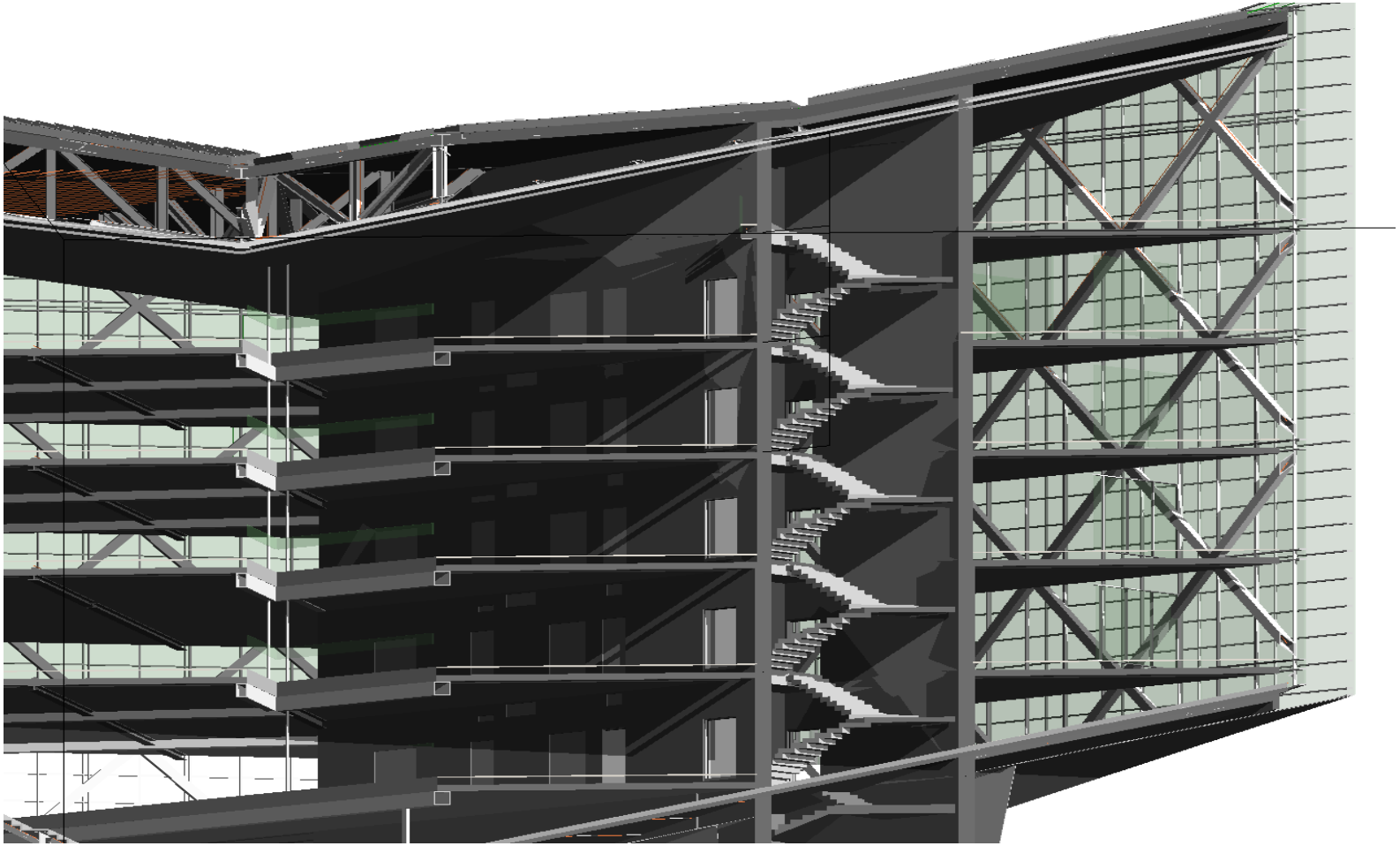
**Skivemodel - dæk**



**FEM analyse - kerner**

# 3D projektering

## Revit structure



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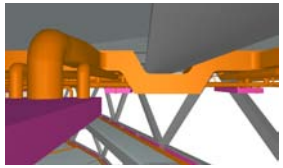
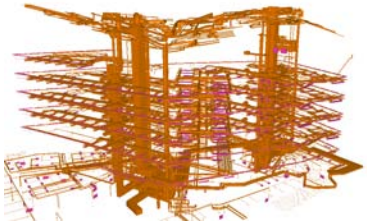
# 3D projektering

## Intern koordinering mellem ingeniørfagene

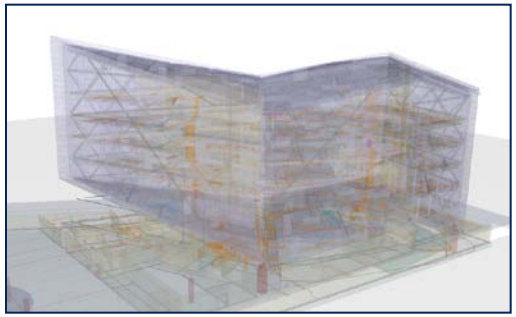
**Konsistenskontrol**
Solibri Model Checker



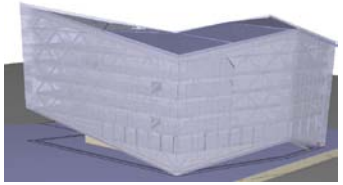
**Installationer**
MagiCAD



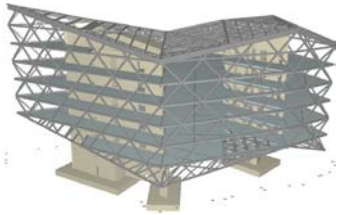
**GMCB fællesmodel**
IFC format



**SHL- Arkitektfagmodel**
Revit Architecture

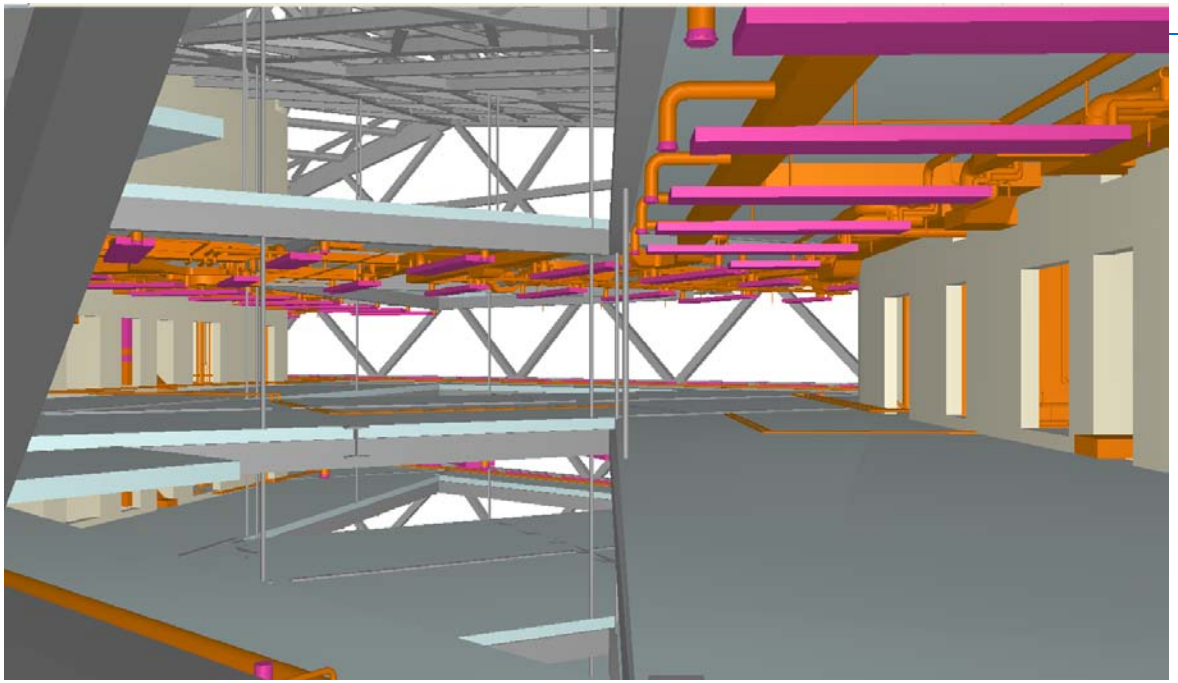


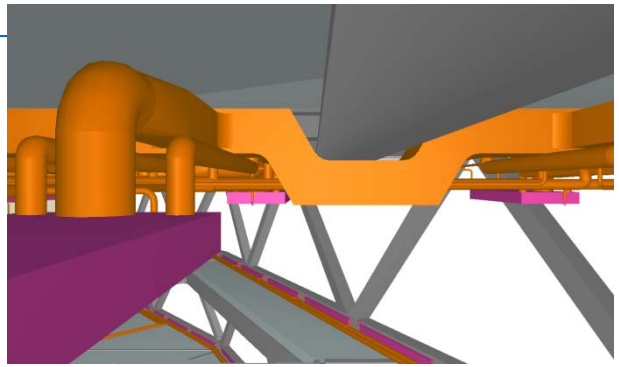
**Konstruktionsfagmodel**
Revit Structure

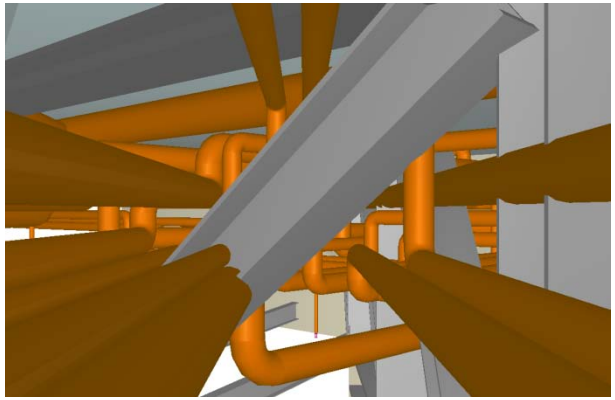


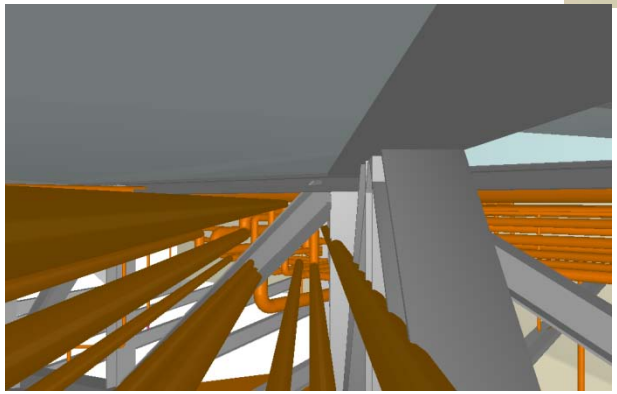
# 3D projektering

## Kollisionskontrol i Solibri Model Checker









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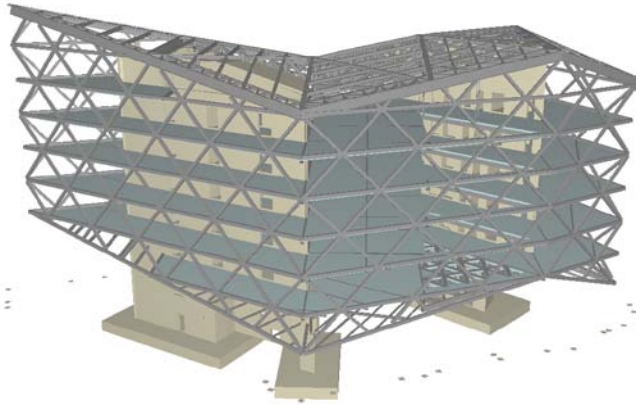
# 3D projektering

## Koordinering med entreprenør

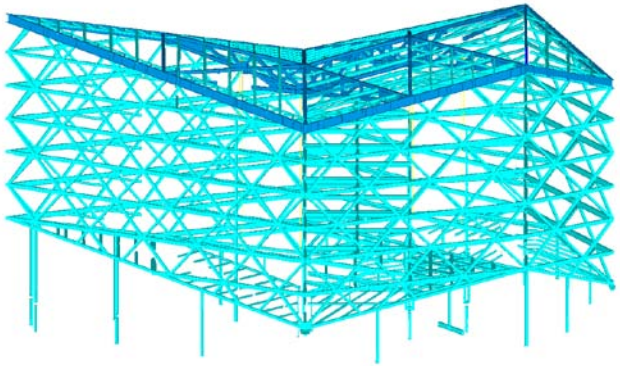
**Konstruktionsfagmodel**

**Revit Structure**



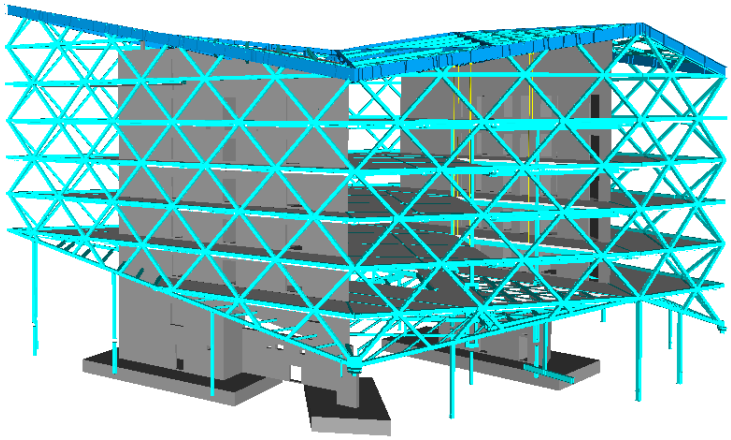
**Promecon - Fabrikation**

**StruCAD**



**Geometrisk konsistenskontrol**

**Navis Works Jetstream**



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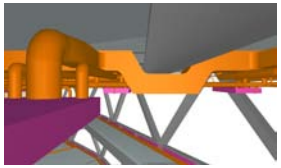
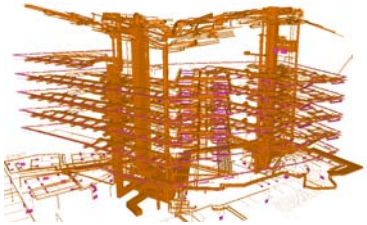
# Samlet overblik over 3D modeller

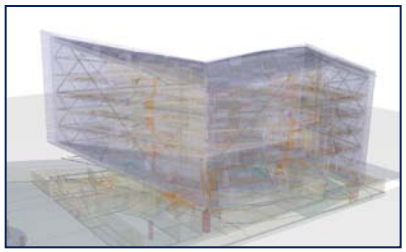
**Konsistenskontrol**
Solibri Model Checker



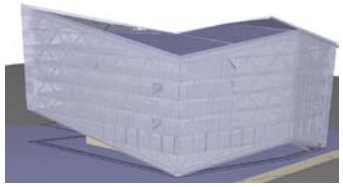
**Installationer**
MagiCAD



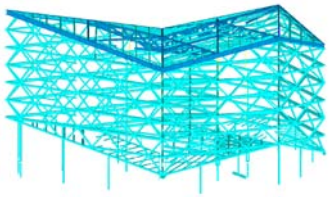
**GMCB fællesmodel**
IFC format



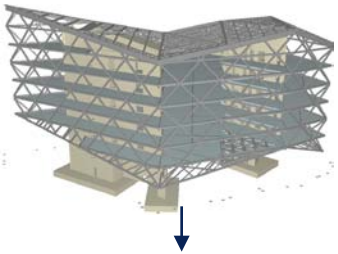
**SHL- Arkitektfagmodel**
Revit Architecture



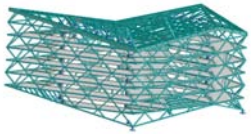
**Promecon - Fabrikation**
StruCAD



**Konstruktionsfagmodel**
Revit Structure



**Knudepunktsmodel**
Robot Structural



**Skivemodel - dæk**
Robot Structural

**FEM analyse - kerner**
Robot Structural

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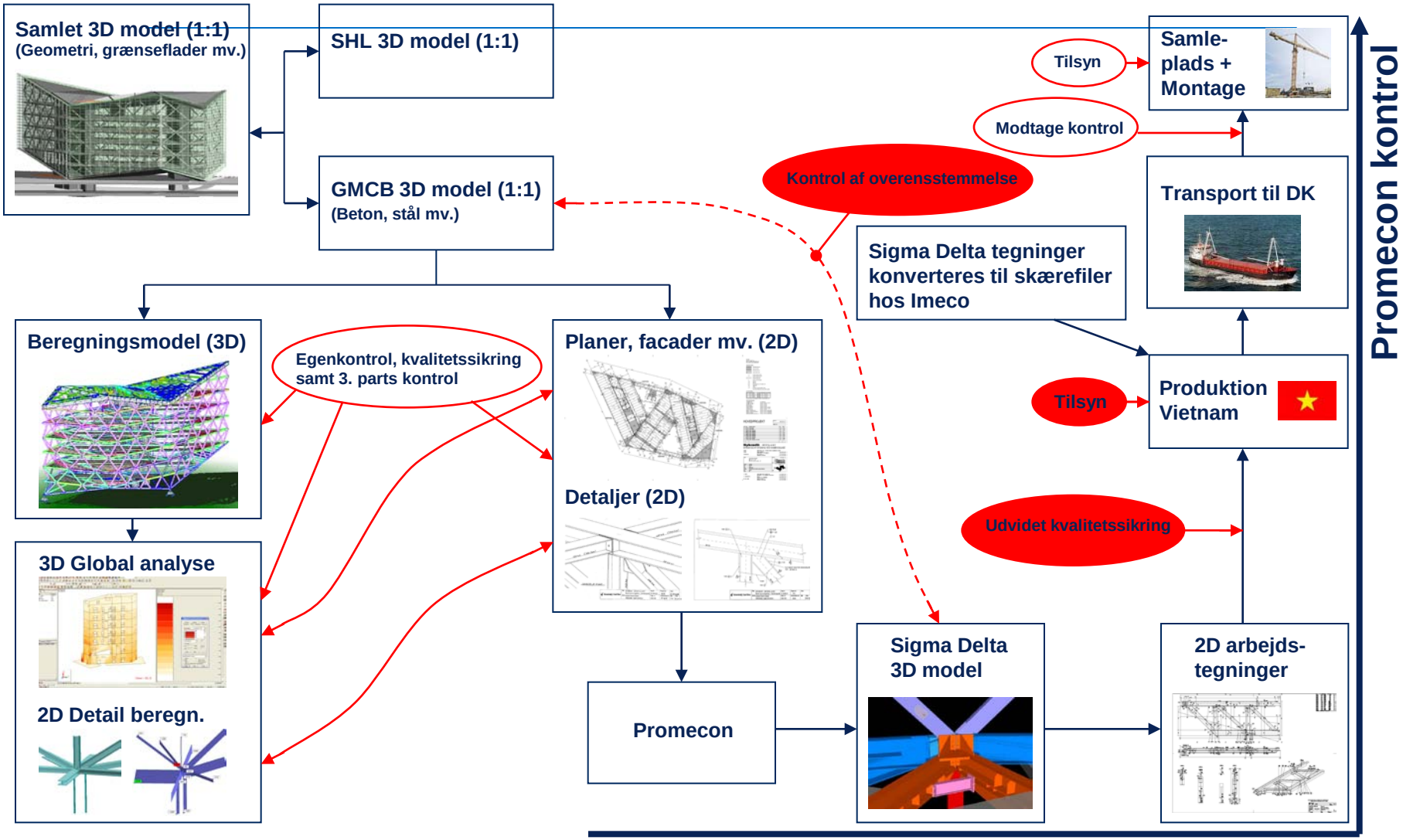
# Stålproduktion i Vietnam - proces

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# Beregningsdokumentation

Statiske beregninger til myndigheder og tredjepartskontrol

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# Spørgsmål?

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