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Danish Cancer Center – An engineering challenge

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Abstract
The Danish Cancer Center by architects Gehry Partners has presented the engineering team with a number of challenges. This paper describes primarily the challenges posed by the used of 450x450mm solid wooden members for a Mikado-like beam and column system, and the preservation of the existing historic building from 1908. These included developing a robust structural concept that allows the wooden members freedom to twist and crack over time. The paper also provides an insight into the extensive fire and building services engineering carried out. The use of BIM, in particular Revit Structure, for the fabrication drawings of more than 500 steel/wood connections, is also described.

Keywords: Conceptual design, parametric design, BIM, wooden structure, masonry structure, integrated design, steel detailing.

1. Introduction
Inspired by the Maggie's Centres in the U.K., the Danish Cancer Society in 2005 started collaborating with Gehry Partners on the society's first new counseling centre, the Danish Cancer Centre (DCC). Maggie's Centres are unique in that they are places to turn to for help with any of the problems associated with cancer. Under one roof one can access help with information, benefits advice, psychological support, courses and more without an appointment and free of charge. Part of the vision for the Maggie's Centres are their architectural intent and quality, which Maggie Jencks formulated while she was battling cancer herself. She believed the centers should be located at the edge of hospitals while also standing out by being enticing and intriguing, as architecture affects the feelings of those who enter. More specifically they should be open plan and centered on a kitchen, whereby creating a welcoming environment and encouraging conversation. For the DCC, Gehry Partners have brought along much of this vision and added a distinctive Danish element to the vision – hygge – as the Danes call homely coziness.

2. Design team
The team for the project has been led by Gehry Partners as design architects and with Aarhus-based CUBO architects as executive architects and landscape architect Kristine

Jensen. Transsolar of Stuttgart has provided conceptual design for the climate engineering and ag Light of Bonn the lighting design. Consulting engineers Søren Jensen have provided geotechnical, structural, fire and building services engineering for the project.

3. Architectural design

The site for the Danish Cancer Centre was chosen in late 2004. The new counseling centre is a renovation of an existing 1918 building, designed by the Danish architect Rudolf Clausen, which was originally the porters lodge for the Municipality Hospital campus in Aarhus. The building originally had a pitched roof with a 55-degree incline. However, an extension by famous Danish architect Kay Fisker in 1939 had given the building a partly flat roof as well as increased the floor plan by 30%. The extended part of the building was also given a basement unlike the existing part.

Figure 1: Existing porters lodge from (a) Northwest, and (b) Southwest

During 2005 Gehry Partners investigated a number of concepts for the project. Many of these explored the qualities of keeping parts of the original building and the choice of materials. During the first part of 2006 a conceptual design was developed by Gehry Partners, and approved by the client and is currently under construction. The design preserves the existing facades only, and within their shell a highly unusual wooden Mikado-like structure is erected. This is then covered with a completely glazed roof recreating the building's original pitched roof shape.

The entrance to the building has been moved from the westward facade to a new south facing extension to the building, housing the main stairs and elevator. The elevator shaft is clad in masonry while the stair house is fully glazed creating an open and welcoming entrance to the building.

Inside the building a new Garden level has been created by extending the basement to cover the full plan of the building. To the north an amphitheatre is being created in the garden. The amphitheatre meets the garden level through a new, glazed north entrance thus creating a visual connection between the internal spaces and the outdoor garden space. This allows sufficient daylight to penetrate into the garden level to allow workspaces to be created in the former basement. The garden level gives space, in addition to workspaces, to a small atelier, an area for physical activity, various toilet/storage cores and a plant room.

For the Ground level a new floor plate is constructed, which floats in the middle of the building allowing light to pass between the floor and existing east and west facades, creating tall canyons of openness on either side of the building. The ground level has a single open floor plan with a living-room-like setting with soft furniture, fireplace and common kitchen area in centre of the house.

The Upper level has a similar shaped floor plan to that of the Ground level but instead of an open floor plan it has several small meeting rooms for private conversation and a toilet. The Upper level and Ground level are connected through an internal stair.

Figure 2: (a) Exterior from Southeast, and (b) Mikado-like internal structure

To realize the building, the Danish Cancer Society set up a new foundation to fund and build the counseling centre. The Danish Cancer Society will rent the building from the foundation after completion. The foundation has raised money specifically for the project and taken loans to bridge the gap between the funds raised and the €5.5 mil. budget for the 583 m^2. The budget was fixed early in the project and the design team has continuously had to adjust the project to keep within it. As the project nears completion the project is still on target to meet the budget.

4. Structural engineering

The unique building proposed by Gehry Partners has required an engineering response of high creativity and ingenuity. A structural concept was developed, which separated the building's structural components into two distinct structures, with only limited interaction: an external and an internal structure.

The external structure includes the entire building envelope and provides stability to the building whereas the internal structure consists of the Mikado-like structure with its inclined columns and floor beams. By being able to separate the two structural systems the design team has had more freedom to develop and explore the two individually.

4.1 External structure

The architectural concept required that all internal walls and floors be removed from the existing building as well as the existing roof. Also the expansion of the basement required significant underpinning of the remaining facades. Thus it was important to find a structural scheme for the external structure that would re-establish sufficient support for the facades. Also of vital importance was the stiffness of the supporting structure for the glazed roof.

The architectural proposal would not allow for a traditional cross-tie between the rafters in the roof and hence an alternative structural scheme had to be developed. Instead a scheme was developed that relies on the 16 side-rafters being rigidly fixed to a stiff tubular ridge beam. By rigidly fixing the rafters to the ridge beam the loads are concentrated at the ridge and hence the existing facades are not exposed to heavy vertical loads. Furthermore by introducing a pinned connection at the cornice, where the rafters connect to the facades, the facades gain a lateral support at their top. The base of the facades are relieved of the earth pressure by introducing pre-cast L-shaped concrete elements on the outside of the basement. This also allowed the basement to be insulated and waterproofed. Thus the transverse stability for the facades and roof is provided by steel connections to the L-shaped earth retaining walls and the lateral stiffness of the ridge beam.

From the ridge beam both the lateral and vertical loads are transferred down to the masonry structure through the four corner rafters that form two inclined triangles at either gable making them capable of carrying lateral loads. To contain the outwards thrust of the corner rafters a steel tie in the form of a c-section has been placed along the cornice on all four facades. By placing the c-section laying down on its web and bolting it to the masonry the facades lateral stiffness has been enhanced.

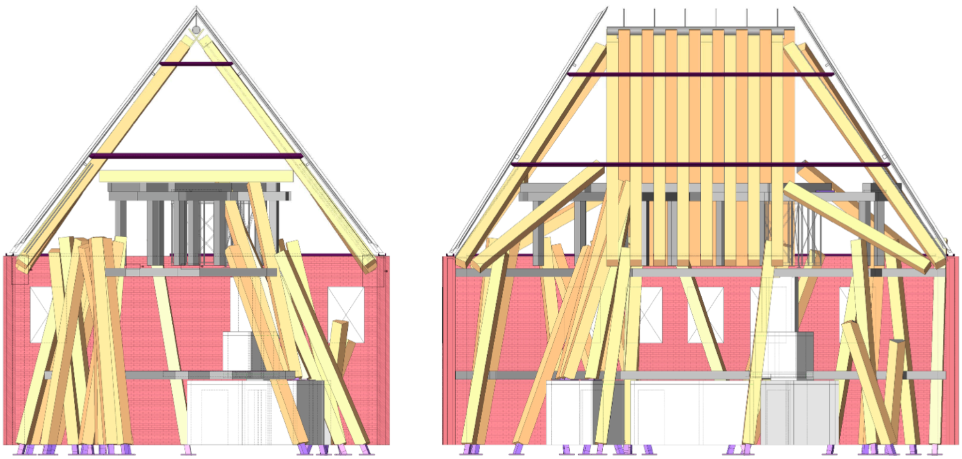


Figure 3: (a) Transverse, and (b) longitudinal cross sections

The longitudinal stability of the roof is similarly derived by allowing the forces to be collected by the ridge beam and from there transferred to the structure below using the two triangles created on both sides of the roof by the corner rafters and their neighboring side rafters.

The existing masonry facades were determined not to have sufficient capacity to carry the vertical loads transferred to them from the four corner rafters. Therefore the masonry has been reinforced using very high strength fiber-reinforced concrete columns. These four columns have been placed in the 250 mm cavity in the masonry wall.

Having included these concrete columns in the structural scheme it was decided to use them for the lateral stability as well. This has been accomplished by cantilevering the columns from the concrete walls of the basement. To protect the existing masonry the deflections have been reduced to a minimum by introducing post-tensioning of the columns.

The south and north entrances are used to provide stability for the South and North facades respectively. This was done by letting the steel structures of the entrances grab the steel tie at the cornice, and using the concrete retaining walls in the amphitheatre and the basement of the south entrance to brace the steel structures and the basement walls.

4.2 Internal structure

The internal structure posed a very different structural challenge to that of the external structure. The initial studies for the internal structure concentrated on establishing whether the Mikodo-like structure was stable in itself or whether new elements had to be introduced. These studies showed that the structure had a significant lean towards one side of the building because the Upper level floor was offset sideways compared to that of the Ground level floor. To resist this lean, the structural system was planned such that the ground level floor is held in place by the basement walls and the concrete storage core. Thus it is possible to consider the columns as being fixed laterally at their base and at their connection to the ground floor. They are therefore cantilevering upwards and are used to hold the Upper level floor in place.

On the Upper level the toilet core is used to provide lateral stability to the vertical columns and the lattice structure above the meeting rooms. This has been done using a cross-braced steel frame for the toilet core.

Having determined a structural system that provides sufficient lateral stability, focus was moved to the beams in the floors.

The design team decided that it would be best aesthetically if there were few or no visible steel connections between the wooden beams. This was to prove a challenge, as the depth of the beams was not sufficient to allow traditional wood-only connections. Hence a new type of connections had to be developed.

The 450 mm wide by 320 mm deep wooden beams allowed for 130 mm from beam top to finished floor. To avoid visible connections these had to be kept within 100 mm from the top of beams in order to allow the flooring to be laid on top of them. To further complicate matters a number of building services such as sprinkler pipes had to be routed through the same void.

Another important aspect is the twisting and cracking of the wooden members. Due to the large section sizes the forces required to prevent the members from twisting would be very high. Hence it was decided to allow them to twist freely by only fixing them in torsion at one connection. This was to be a guiding principle for all the connections in the building.

For the connections in the floors it was determined that the best way of connecting the end of beam A to the side of beam B was to mount a cantilevering steel clip using tension bolts to the top of beam A and supporting it at the centerline of beam B allowing B to twist. The steel clip was given the shape of inverted double T's and constructed from a flat steel plate with welded ribs as this would allow beam A to twist without causing failure in the torsionally soft T-sections. Glued and nailed 22 mm cross veneer is used to create in-plane stiffness in the floor plates. Both steel clips and cross veneer is visible in Figure 4.

Figure 4: Structure under erection (a) Roof structure, and (b) Ground level

Having resolved the beam-to-beam connections the column-to-beam connections had to be resolved. Traditionally columns are placed under the floor and its beams. The design for the DCC has the columns placed on the outside of the floor plates. This coupled with the limited headroom in the Garden level meant that the column-to-beam connections had to be made on top of the beams. Using the spare capacity of the 450x450 mm columns, and to preserve the beams' ability to twist, the detail was developed as a laterally braced, vertical steel plate cantilevering off the side of the column and connected to the beam at the centerline of its top surface through a single bolt, see Figure 6(b).

4.3 Parametric design tool

As the design progressed the number of columns and particularly their positions were adjusted numerous times. These changes were primarily caused by a wish to improve the aesthetics but also structural considerations caused column positions to be adjusted.

The many changes were time consuming and thus it was decided to develop a parametric tool that would ease the analysis of the internal structure.

Gehry Partners were working with both Digital Project and Rhino, while Søren Jensen were working with Rhino, Revit and using STRAP for the structural analysis. The Digital Project model was used as the master model (and as a parametric model for the glazing) and hence many of the adjustments in the column positions were not implemented in this model as they were design developments only. Thus a tool was needed, which should work off the Rhino-models that were being exchanged between team members.

To keep the tool simple it was developed in MS Excel. As the changes were mainly limited to the columns, and only a few adjusted in each iteration, it was decided to focus on making it easy to adjust the end coordinates of the columns. Hence by changing the end point coordinates in Excel all connection points would be recalculated and an updated input-file for STRAP was written allowing for very rapid analysis and design guidance. As it became easier to carry out adjustments to the structural model, more options could be explored and used to improve the aesthetics and the structural performance

The many changes to the column positions were initially a problem for the foundation design as it required a continuous monitoring of the foundation positions and capacities. To get around this it was decided to make a 18cm raft foundation under the entire structure. The raft not only provided great flexibility during the continuing design but also provided a benefit during the erection as temporary supports could be placed anywhere.

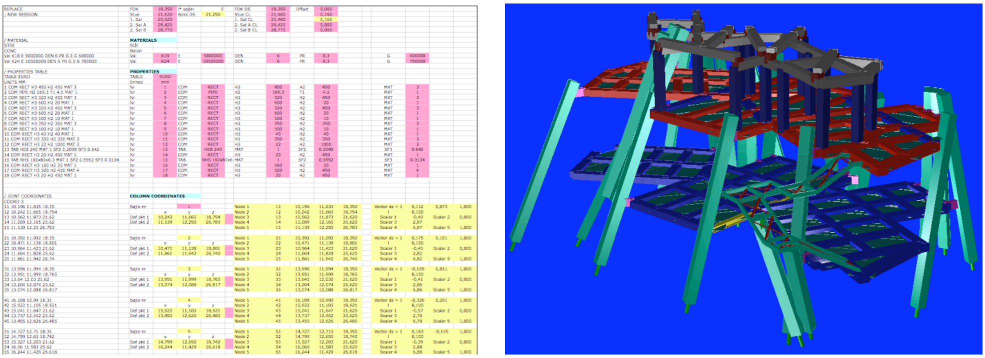


Figure 5: (a) Excel-spreadsheet for parametric modelling, and (b) FEA-model

4.4 Structural detailing

For the steel-wood connections both bolts and screws were considered. However, because of a desire to minimize the visibility of the connections it was decided to use glued anchors throughout. In accordance with Danish building codes these can be used in the end grain as well as the side of a member, giving the possibility of fixing steel endplates directly to the beam-ends. This was used for the rafter connection to the ridge beam and the column feet. The glued anchors also allow for compression forces to be transferred to the wood rather than just tension. This proved necessary in several places to prevent crunching failure.

Unfortunately, as fabrication of the wooden members began, tests carried out in order to verify the strength of these glued anchors showed that it would be very difficult to prevent the glue from running into the larger cracks of the wood. It was immediately decided to explore alternative connectors such as screws. A small number of tests were carried out and it was decided to change to screws where possible. Glued anchors were still used at the rafter and column ends.

As the already fabricated steel connectors required nuts to be used, special screws had to be fabricated so that they would have a wood screw thread at one end and a standard M20 thread at the other end. Together with Geka shear connectors these screws form the load transfer between the wood and the steel clips.

To ensure sufficient robustness and easier detailing, the screws in the connections were labeled as tension-only or shear-only. The tension-only screws were given significantly oversized holes in the steel plates. This ensured that the more critical tension-only screws would only be subject to tension forces, even when cracks develop in the middle of the connections. The design capacity of the screws was also set very conservatively, allowing for cracks to split the wooden members without the capacity being critically lowered.

Figure 6: (a) Test of glued anchors, and (b) beam-column connections

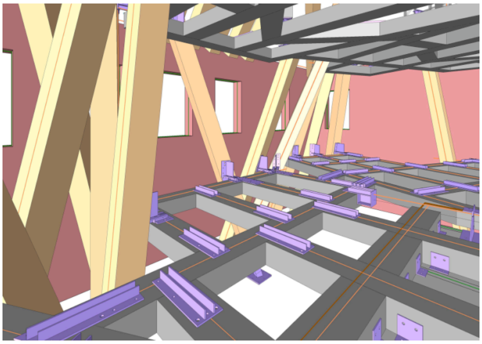
For the South and North entrances an unusual steel detailing had to be developed for the steel structures. It was architecturally required that the main steel H-sections would not connect to each other with their webs aligning. With one of the two sections rotated 90-degrees about its own axis, stiffener plates were introduced to allow full capacity, stiff connections. Such stiff connections were required to keep the deflections minimal and thus reducing the differential moment between the main glass roof and the secondary glass roofs over the two entrances.

To further stiffen the two steel structures the secondary rectangular members also had to have stiff connections to the primary steel, while still preserving constructability. This was resolved by using double stiffener plates that could be welded to the primary members on site, while also allowing connections to be made to all sides of the main members.

Contractually the steel contractor would be drawing up production drawings from the material supplied to him. This method of working was attempted with the contractor being supplied 2D-drawings of the more than 100 different types of steel connections and a 3D-model containing all steel and wood members. However, it was quickly established that the contractor was not able to produce the necessary material sufficiently quickly due to many exceptions to the typical details provided.

Instead of continuing it was decided, in consultation with the relevant contractors, that Søren Jensen would model all the connections in 3D BIM and provide both steel and wood contractors with fabrication drawings and cutting files for their machinery.

To carry out this task it was decided to increase the level of detail of the Revit Structure model that Søren Jensen was already using for the project. More than 500 steel details resulted in more than 4000 individual fabrication drawings. It was found that Revit Structure had significant performance problems with such a complex and detailed model.



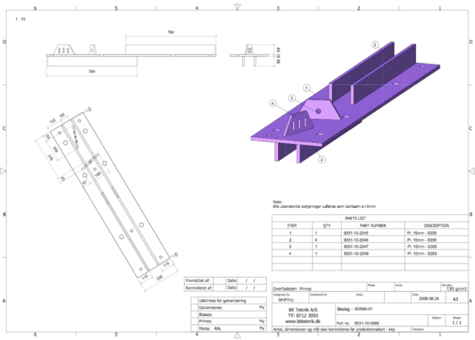


Figure 7: (a) Building Information Model, and (b) fabrication drawing

4.5 Glassing supporting structure

The mullion system uses standard aluminum profiles. However, the complicated geometry and load bearing structure required the facade system to be modeled as part of the external structure. This allowed the forces in all the connections between the mullions and the sub-structure to be determined. This was of particular importance at the corner rafters where glazing fly-bys were found to introduce significant bending in the horizontal mullions. It was determined that additional reinforcement was required at these locations and thus secondary steel was introduced in the roof structure.

Since the secondary steel was added at a rather late stage of the construction process, it was used not only to provide a more stable substructure for the roof glazing but also for carrying solar shading, convectors, sprinklers and electrical wiring in the roof.

The secondary steel is further used to help control the twisting of the wooden members in the roof and to further stiffen the roof. By having an intermediate layer between the mullion system and the potentially twisting wooden members the movement in the glazing is significantly reduced. This effect was further enhanced by fixing the wooden members to the secondary steel at mid-height of the roof and hence limiting any relative twisting. The rafter ends were then detailed to allow twisting. The secondary steel is also used to act as relief for the corner rafters by limiting their effective column lengths.

5. Fire engineering

The unusual design and the use of wood throughout the building has been a fire engineering challenge. Because the internal stair connecting the Upper level and the Ground level is not separated from the main room of the building it has been necessary to carry out evacuation simulations to show that occupants can escape the building during a fire. The simulations involved determining the number of openable windows required in the roof for smoke ventilation.

Because of the costs and aesthetics of installing a sprinkler system in the building the team aimed at designing a building that would not require sprinklers. However, due to a clause in the Danish building codes that classifies wooden floors as not being fire proof, the team had to incorporate a water mist sprinkler system. It was decided to use a mist system, as it is better suited for a space with complex geometry and would not cause severe water damage if activated.

Having settled on a sprinkler system, the team then used fire simulations to show that the maximum temperature in the building during fire would remain very low and hence none of the structural steel parts needed to be designed for significant temperatures and are thus not fire proofed. The investment in the sprinkler system was thus partly recovered by avoiding fireproofing of the exposed steel members and connections.

6. Climate engineering

The fully glazed roof and its effects on the internal environment governed the ventilation strategy for the building. Transsolar developed a climate model, which allowed for the building to be partly naturally ventilated and without mechanical cooling.

The roof glazing has 50% frit to reduce glare in the building as well as limit direct sunlight. The glzsing was chosen to be a double layer instead of a triple layer, as it is more difficult to get rid of the heat during the summer conditions than keeping the heat inside the building in winter. The glazing has also been treated with a low emission coating to limit the heat radiation into the building.

Below the glazing, a solar screen has been placed so when deployed it not only further shades the sunlight but also creates a void between itself and the glazing, which is then naturally ventilated using openable windows at the cornice and ridge of the roof. The natural ventilation is driven by the stack effect in the space between the glazing and the solar screen. The solar screen itself has also been treated with a low emission coating lowering the heat radiation into the building still further.

As some radiation will enter the building there is still a need to supply the occupants with air cooler than the outside temperature if acceptable conditions are to be maintained in the summer. This has been achieved by placing the air intake for the mechanical ventilation away from the building and letting the air run in an underground duct before being blown into the building. By running the air below ground and the foundation raft, it is cooled by several degrees on hot summer days. Similarly in the winter the warmer ground preheats the air.

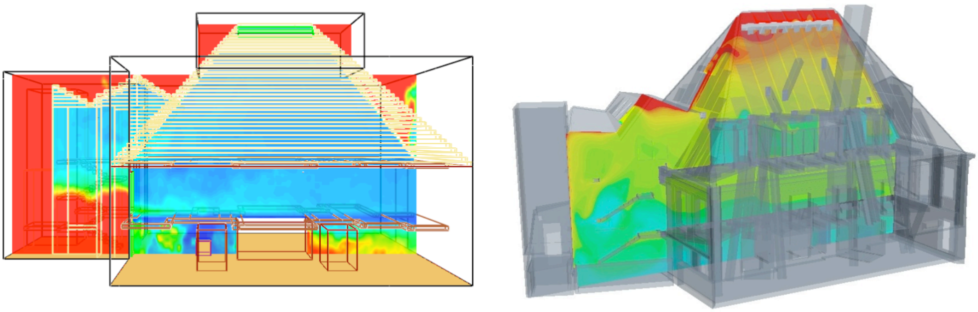


Figure 8: (a) Fire simulation, and (b) comfort simulation

7. Building services engineering

Finding appropriate routes for the building services has been a challenge due to the limited number of elements that run the full height of the building. Similarly, finding a suitable location for the plant room was difficult but finally located outside the main building below the terrace in the garden.

The use of the raft foundation allowed the building services to be distributed either below as with the ventilation or above the raft in the insulation layer between the raft and the screed layer.

Figure 9: (a) Routing through fireplace and chimney, and (b) routing on foundation raft

In general the Garden level has been supplied directly from below, while the Ground level has been supplied up through the storage core on the Ground level. The Upper level proved more difficult as most services had to be routed through the concrete blocks that make up the fireplace and chimney on the Ground floor. This required significant 3D modeling to ensure that all services could be built inside the fireplace while it also acts as a primary structural member carrying nearly a third of the weight of the Upper level. The electrical, sprinkler and heating required in the roof and the South and North entrances were routed either visibly at the entrances or inside the cavity of the masonry walls.

One particular challenge has been to bring fresh air up to the meeting rooms on the Upper level. Here it was chosen to fabricate two hollow columns, which allowed the air to be brought up unostentatiously.

8. Construction

The contractors have all been selected by the consultants based on their previous work. The primary contractors have been involved in an informal construction partnering since the early stages of design development. This method was chosen in order to establish a reliable construction budget early on and secure the buildability of the project.

The construction began in April 2007 and is due to be completed by August 2009.

Figure 10: The Upper level under construction (a) stair house, and (b) meeting rooms

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