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Design and construction of the complex steel structure for the Amager Bakke waste-to-energy plant

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Amager Bakke (English: Amager slope) is the name of Copenhagen's new waste-to-energy-plant located on the Amager peninsula. Once finished, it will be one of the largest incinerators in northern Europe and will be used for the combined production of district heat and electricity. On top of the waste-to-energy plant there will be a landscaped park featuring artificial ski slopes and a viewing platform. The support structure is mainly formed by a steelwork. The model-based design and construction of the complex, three-dimensional steel structure proved to be a challenging task for all the engineers and companies involved.

1 Building and structure

The inner space of the energy plant is ruled by the technical requirements. The external shape of the building is representing the strong idea to create a slope with its continuous way down from top. By integrating complex industrial technology into a compact building structure such as a mountain segment, Copenhagen-based architects BIG and structural engineers MOE A/S have created a structure with very high construction requirements. The building parts are arranged in line with the technological sequences of the power plant, from east to west, into the fuel delivery and storage areas and into a process building for the incineration, exhaust treatment and power generation. The western end, at the highest part of the building, is formed by the chimney rising more than 60 m. A storey for administrative functions has been "pushed in" underneath the chimney (Figs. 1 and 2). As the support structure for this compact building, MOE A/S chose a steel frame structure, which sits up from a height of 17 to 30 m on a reinforced concrete structure. For technological reasons, the waste bunker is surrounded by reinforced concrete walls up to 40 m high. The foundations to the delivery building located in the east form the supports for the steel columns at a height of 8 m. The steel structure is divided into different types of construction: a single-storey-shed construction in the delivery and waste bunker area, a tree-like structure in the process building and a multi-storey structure with prestressed concrete floors in the administrative area. It is worth highlighting the process area, where the structure largely spans over the industrial components with few possibilities for support and stabilization in the inner space. The roof of the process building follows the three-dimensional and irregular shape of the skiing park. In the area of the waste bunker, the 11 m high, triangular roof trusses carry the heavy concrete roof 40 m above the waste bunker pit. The multi-storey administrative building is shielded from the process area by concrete elements to comply with fire protection requirements. The supporting shell of the roof is made of prestressed concrete elements on which the ski slope surfaces are modelled.

2 Contract of Züblin Stahlbau

In March 2014 Züblin Stahlbau GmbH successfully passed the prequalification procedure for construction of the building's structural steelwork and the precast concrete element construction and was awarded the contract for

Fig. 1. AmagerBakke, aerial view © ARC-BIG

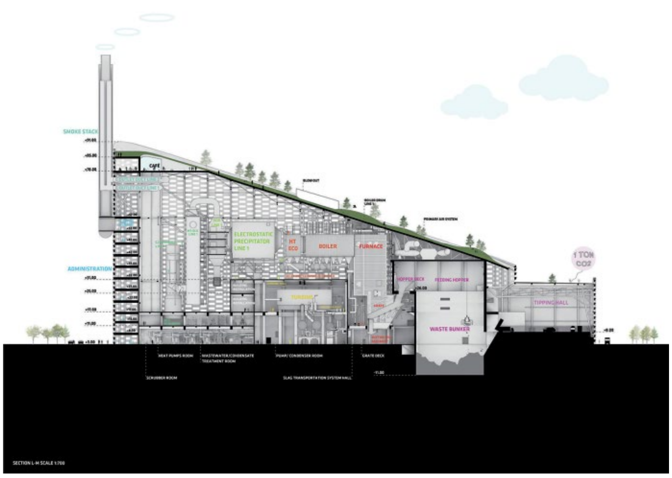

Fig. 2. AmagerBakke, section © ARC-BIG

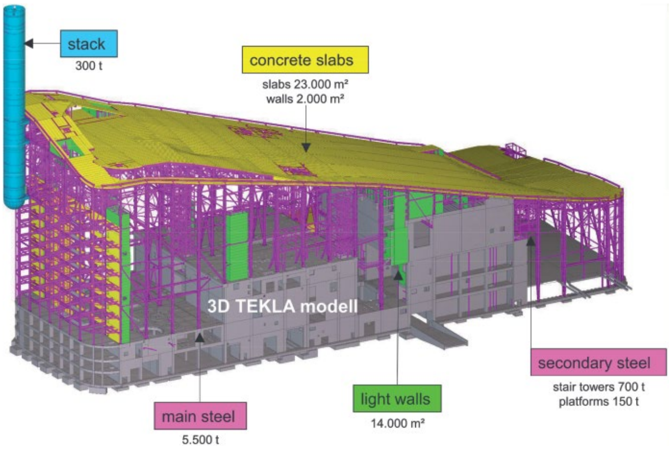

Fig. 3. 3D-TEKLA model – contract scopes of Züblin Stahlbau (by Züblin Stahlbau)

these works in June 2014. The contractual work and services of Züblin Stahlbau GmbH included the fabrication planning with pro rata design of the structural joints and the fabrication and erection of 6500 t of building steelwork, 23 000 m^2 of prestressed concrete hollow-core elements with in situ concrete work, 2000 m^2 of reinforced concrete wall elements, 12 000 m^2 of sandwich walls with fire protection classification, the drainage for the roof structure and the supply and erection of the chimney (Fig. 3). Apart from preparing the fabrication planning, Züblin Stahlbau had also taken on responsibility for the structural design of some parts of the work ("design and build"). That work included the prestressed concrete floors, the approx. 10 to 80 m high stair and lift towers, made of steel and sandwich construction, and all secondary steel structures and the roof drainage system. The complex engineering tasks were coordinated and executed by Züblin Stahlbau, but assistance was also provided by external engineering consultants. The sophisticated welds were produced in the company's own workshops in Hosena. The reinforced concrete elements and the chimney, including the production planning, were implemented by the Group's internal departments of Ed. Züblin AG Direktion Ingenieurbau Nord und Züblin Chimney & Refractory GmbH. The steel structure was erected on the construction site in Copenhagen by our partner firm IMO Leipzig GmbH.

3 Design and interface clarification in 3D model

The 3D program TEKLA structures was used for the geometric clarification and coordination of the interfaces and the fabrication planning of the main structure (Fig. 3). Züblin Stahlbau has been using this program, in addition to other 3D software, for the fabrication planning of steel structures for about eight years. It is becoming increasingly clear that the exchange of model data with all participating engineers allows effective clarification of interfaces between construction stages and construction trades. In the project described here, a basic model from the client was available from the beginning of the fabrication planning. The model had been created by consulting engineers MOE A/S, who had been appointed by the client to produce the design and structural calculations for the structure. As MOE also uses the TEKLA program to edit building models, Züblin Stahlbau was able to import the data directly into the TEKLA program and working with interfaces for 3D data was unnecessary. Although the capabilities of interfaces for complex 3D building structures are being continuously developed, attributes of the objects are often lost during transfer of the data or time-consuming reworking is required. The direct transfer of model data into the TEKLA program provided decisive advantages and ensured the very fast and high-quality transfer of the geometric properties of all structural members and elements. In the basic model, the designers at Züblin Stahlbau were able to use the geometric data of the in situ and precast concrete elements, the steel structure of the main building and the chimney and the design data of interior work trades, e.g. drainage pipes. The positions of the members were defined in the axis system of the structure in the preliminary design phase and formed the basis for the structural calculations. The stage-by-stage detailing of the structural steelwork and precast concrete elements as the basis for the shop drawings was carried out in line with the overall timetable determined by the client. The production planning for the fire-resistant façades, drainage works and the interior work trades in the office building followed with the necessary time lag. The technical coordination work was particularly effective thanks to the continuous feedback of 3D model data to the client's consultant engineers. At the same time, Züblin Stahlbau provided the model data for the subcontractors involved. The status of the production planning based on this data was continuously fed into the 3D model in Züblin Stahlbau's engineering office. Owing to the diversity of the 3D software used, the standardized Industry Foundation Classes (IFC) interface was one method used to import and export data. The approval of the production planning by the client's design engineers was based on a model-based check of the design details and conflict checking in the 3D model incorporating all technical interior work trades, e.g. the plant and pipe construction.

The steel structure of the shed-type building is divided into columns, cantilevered and suspended beams, irregular heavy trusses and a tree-like support structure for stabilizing the roof trusses in the process building. The columns are welded box sections, which are stiffened by longitudinal ribs and bulkheads. The box sections are up to 1600 mm deep and 800 mm wide. The chords and diagonal members of the trusses are mostly welded tubular or box sections with depths, widths and diameters of 500 mm. The coupling members in the walls and the tree-like structures of the process building are formed by tubular or box sections with a diameter of 200 to 800 mm (Fig. 4). Each of these structural members must be checked and at times also corrected at the beginning of the detailing with regard to their precise geometric position and dimensioning, according to the specifications from the main structural analysis system and the project drawings. At the same time, the general construction details from the main structural calculations of MOE, e.g. the anchoring of the columns or the truss joints, had to be adjusted or changed to suit the specific situations and according to the criteria of technically, economically and qualitatively optimum execution. The main changes to be agreed with the client's design engineer included, for example, the execution of the fully welded

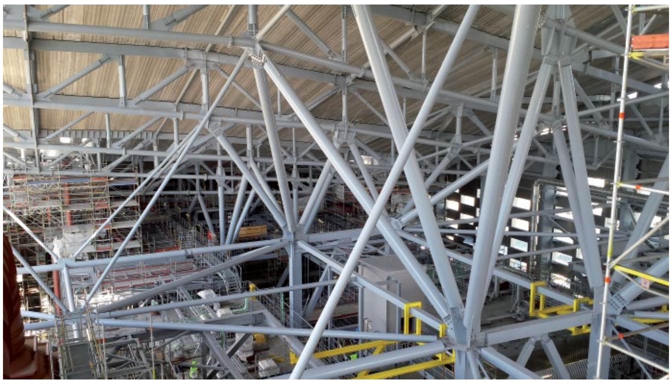

Fig. 4. Tree-like roof structure for process building (by Züblin Stahlbau)

Fig. 5. Preassembled truss for waste bunker (by Züblin Stahlbau)

node joints of the verticals and diagonals with the chord sections of the trusses. To exploit the advantages of the modern fabrication facilities in Hosena optimally and to organize the erection sequences on schedule, the Züblin Stahlbau engineers proposed that all on-site joints should be bolted.

The research carried out in advance of the project had determined that transport by road was the optimum solution. In this case the dimensions for economical logistics prescribe maximum widths and lengths of 3.50 and 22.0 m respectively. The existing dimensions of the assemblies then had to be optimized accordingly regarding the layout of bolted joints. This primarily concerned the trusses in the process area with widths of 5 to 7 m, due to the shape of the roof, lengths of 30 m to the middle support and the roof trusses of the waste bunker, which are 11 m deep at the western support and 40 m long in total. The trusses designated in the project as welded assemblies could generally be converted into bolted individual units. However, very massive node joints resulted. The roof area of the building is accessible to the public. As a result, additional failure scenarios are taken into account for the support structures below it, e.g. failure of a complete truss. These lead to very high design loads, above all, to compressive loads on the members. To prevent stability failure of the gusset plates, additional stiffening was designed and verified geometrically. The transfer of the model data to MOE for checking of the geometric data, e.g. checking gusset plates for conflicts with pipes, facilitated the approval procedures. During the preparation of the structural joint calculations, Züblin Stahlbau also carried out geometric iteration by exchanging 3D information between structural engineers and designers, both in-house and with the external consulting engineers. Using the example of the waste bunker trusses (Fig. 5), however, the engineers reached the limits of feasible bolted joint design during the structural analyses of the chords. In the exceptional case of the failure load case of a truss, additional forces acted on the chords, which were already highly stressed within the normal load range. The tension loads on the bottom chords are up to 17 000 kN. The truss sections are therefore made of the higher material grade S460.

Directly above the chords there is an access level made of prestressed concrete elements with a concrete topping, and below them there is an overhead crane. In addition to the economic aspects regarding the production of a bolted joint that can absorb these high tensile forces, the space available also limited the possible execution options. The chord joints of the bunker trusses were therefore welded on site. To this end, a weld backing and an auxiliary construction were added in the workshop to fix the joints. The diagonals and verticals were designed with bolted joints and were bolted before the welding to the chords. Execution class EXC 4 was specified for the waste bunker structure due to the load, type of construction and use.

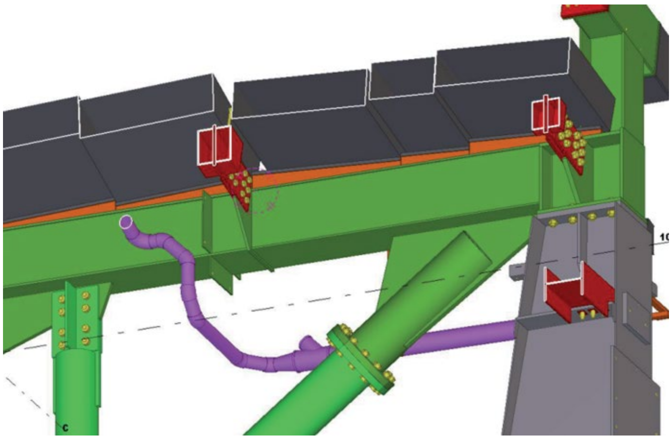

Fig. 6. 3D section through roof structure for process building (by Züblin Stahlbau)

The coordination of the steel structure for the roof trusses with the geometry of the roof support shell made of prestressed concrete elements is particularly worth highlighting due to the especially time-saving and precise clarification of the interfaces. The roof support shell follows the irregular 3D shape of the skiing park and is supported on the top chords of the roof trusses. The gap between the precast elements will be closed with reinforced in situ concrete after the elements have been laid. As the prestressed concrete elements have a constant depth per element due to the production technique and the adjacent roof girders follow different pitches, gaps of up to 100 mm result along the edge of the chords. The elastic support strips bridge a tolerance of up to 10 mm (Fig. 6).

After modelling the steel trusses, the TEKLA model was exported in subsections and the concrete elements laid out by the precast concrete element planner according to the profile of the roof surface. The positions of the ele-

Fig. 7. *Upper chords of roof trusses for process building (by Züblin Stahlbau)*

Fig. 8. *Column head in tree-like structure (by Züblin Stahlbau)*

ments had to be optimized so that an additional support element is required on one side only. After feeding this data back into the master model, the additional steel components were modelled to close the joints in order to carry the load. As a result, the top chords acquired an irregular toothed strip that could be dimensioned individually for each location along the roof truss. This procedure substantially shortened the time-consuming iteration between structural steelwork and concrete designers – a requirement for completion of the structural steelwork modelling and the shop drawings (Fig. 7).

With regard to the extensive interface clarifications in the 3D model, the coordination of the main structure with the interior work trades in the administrative area of the power plant will also be briefly discussed here. The administration building is a multi-storey building with a structural steel frame stiffened by the floors. The floors are made of composite steel girders on which precast prestressed concrete elements are laid. The voids between the precast elements, the edges and the composite girders, so-called delta beams, are filled with reinforced concrete on site. An in situ concrete floor is laid on the precast elements, which forms a support for the subsequent fixing of the structures for the lift shafts, the stairs and the glass balustrade. The innumerable geometric interfaces between the main steel structure, the composite girders, the precast pretensioned concrete elements and the interior work trades were coordinated in the 3D model by synchronizing the submodels exchanged with the engineering consultants of the respective suppliers.

4 Shop fabrication on the basis of the 3D model

Depending on the degree of detailing, all steel member data for materials ordering, job scheduling and fabrication can be generated from the 3D TEKLA model. Owing to the long lead times for ordering the sheet metal segments, especially in grade S460, rough materials lists were generated from the model at a very early stage and orders placed with the suppliers. Project-based rolling of the required dimensions and quantities was therefore feasible. However, this approach requires very early design reliability with regard to the main structural dimensions and preliminary item designations of the individual members. The preliminary item numbers were included as attributes of the component parts in the model through to the detailed modelling in order to enable continuous assignment to the final item numbers in the parts lists. Preparation of the shop drawings and generation of the NC data was semi-automated by means of software modules following completion of all modelling and positioning. Regardless of the complexity of the data, transfer of the NC data – in order to control the cutting to size of the component parts on the sawing/drilling and flame-cutting machines – can be fully automated. However, assembly of the steelwork members in the workshop is based on the two-dimensional shop drawings. These must be manually reworked for individual structures. For this project, clear representation of the welds, very exacting in terms of workmanship, involved very considerable work. The lead times – from provision of the shop drawings to the start of cutting the steel plates in the workshop – were a maximum of two weeks. As the preparation of the shop drawings could not always be completed on time, due to the high degree of complexity involved, accelerated handover of 3D model data and materials lists to the fabrication department was established to enable the job scheduling in the workshop to start exactly on time.

The NC data-controlled cutting machines enable precise and mostly error-free transfer of even complex geometries to the component parts, which are assembled in the workshop. The assembly of individual members with low repetition character, however, is subject to the classic laws of skilled manual work. Accordingly, the complex and extensively stiffened cross-sections and node joints required highly skilled manual input during assembly and welding. This resulted in a great deal of work in the preparation and execution of the checks and tests regarding geometry and welding quality. When drawing up the extensive inspection and test plans, in addition to classic geometric checks, an additional control step using a 3D scanner was introduced in order to realize precise fitting of complex 3D substructures (Fig. 8).

The 3D scanner was set up with the coordinates of the 3D TEKLA model and referenced at pinchpoints along the main axes on the physical component. Following the assembly of a selected node joint, the measured data was recorded by scanning the edges of the steel plates of the planes and the drilled holes of all attached parts (Figs. 9 and 10). The set of points acquired in this way was compared separately by the software of the scanner for the geometric planes and the drilled holes with the design coordinates from the 3D TEKLA model.

Fig. 9. *3D survey of column heads in fabrication shop (by Züblin Stahlbau)*

Fig. 11. *Preassembly of the 40 m long truss chord for waste bunker in fabrication shop (by Züblin Stahlbau)*

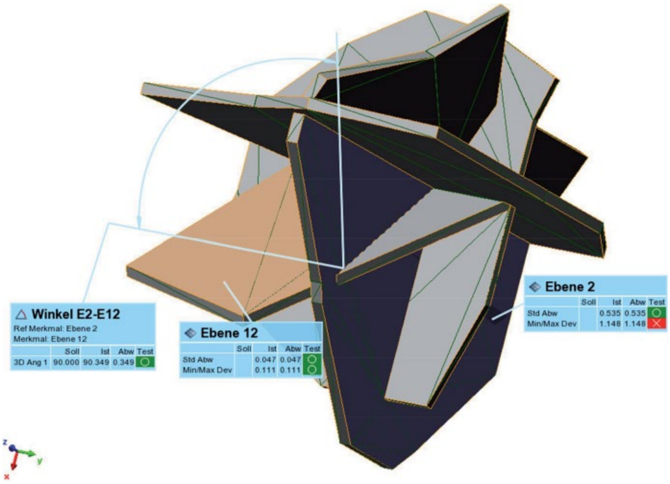

Fig. 10. *Report of 3D survey of column head planes © Hemminger*

If deviations occurred outside the tolerance of > 1 mm, the measured coordinates were imported into the model to enable simulation of the assembled item. The version of the assembly thus created was used to check the effect of the deviations on the adjacent components in the model. Where it was still possible with regard to the timing of the production sequence, corrections were incorporated in the model and the shop drawings. It was found that, on a case-by-case basis, deviations of 3 to 5 mm were tolerable, as the adjacent nodes of the spatially inclined, connected diagonal girders were mostly 15 m away and the deviations could be compensated for within the given area through the hole clearance or additional filler plates. The change in the assembled items on the basis of the measured data was discarded due to the experience acquired. There was no reduced risk of renewed deviations for a second assembly, as the measured data could not be used effectively for the correction due to the complex spatial positions of the component parts. The components were not finally welded together until after the measured data had been evaluated positively. In addition to checking the geometry of spatial nodes using a 3D scanner, the assembly of the trusses for the roof structure required conventional control through temporary preassembly during fabrication. To this end, all the bracing members of the trusses were produced completely; however, the chord beams of the truss were not finally welded until after preliminary assembly and successful measurement. In this way, geometric deviations due to weld shrinkage, unfavourable superimposition of tolerances or other errors could be analysed in good time and corrected immediately (Fig. 11).

An important control step in the quality monitoring of the fabrication sequence is the testing of the welds. For the parts of the building classified as execution class EXC 4 in particular, substantial test and inspection work arose, the organization of which had to be fitted in during the fabrication sequence. The scope of non-destructive weld tests was based on European standard EN 1090-2 in accordance with the project specifications. Consequently, the areas with classification EXC 4 and the areas with mostly full utilization of the capacities of the cross-sections (capacity utilization U > 50 %) required complete testing (100 %) of all penetration welds (butt joints). The tests were organized and verified on the basis of weld lists extracted from the 3D model. Clear assignment of the weld to the welder and the test results could thus be shown clearly and tracked. With the help of this data, it was possible to verify the statistical size of tests of other weld types, or rather, lower test requirements in other areas. Additional marking of the welds according to the standardized sequences with hard stamping also enabled clear assignment to the welder.

5 Erection planning based on 3D simulation

To prepare for the erection work, the erection steps were mapped in the 3D TEKLA model. This offered the best conditions for interlinking the examination of the interim construction states with the hoist load planning and controlling the flow of materials to the construction site. For the processing of the work planning in the 3D TEKLA model, the building was divided into subsystems that were based on the system of the building structures and the time schedule of the client. Upon incorporating the time schedule, time-slots of approx. 2 to 4 weeks were collated as separate subsystem groups. Completion of the planned processing chain of a subsystem group in the engineering office, in the materials order and in the fabrication thus corresponded to the expected erection progress on the construction site. The detailed planning of deliveries was based on separate attributes that were assigned to the components with a lead time of approx. 4 weeks before delivery and the subsequent erection. These "call orders" were transferred to the transport units during the dispatch planning; the transport units were then taken on trucks by road to the construction site.

The final modelling of the aforementioned subsystem groups was followed by detailed planning of the individual erection steps depending on requirements. To do this, the subsystems were handed over to the erection planners of the erection contractor in TEKLA format for further processing. The display of individual steps by selective marking of the components enabled, in the further processing, the determination of weights and centres of gravity of assemblies, geometric checking of hoisting scenarios and the handover of information and model data, e.g. to external engineering consultants for the structural analysis of intermediate construction states.

In the case of intervention in the overall structural system, the information handed over was also used by the client's design engineers, MOE, to perform structural analyses. An erection step basically described the planned erection performance for a day, as the aim was to attain a structurally secure interim state at the end of each day. This procedure resulted due to the wind conditions on the construction site, which is located directly on the Baltic Sea coast. The coastal wind blows irregularly and with high speeds, so large components are exposed to very high loads. In addition, rapidly changing wind conditions and gusts leading often to a failure of the large, wind-sensitive cranes. The large cranes used with crawler tracks and a safe working load of 130 to 750 t can only work up to certain wind speeds for safety reasons. At the height of the crane booms used (approx. 130 m), the wind speeds must not exceed 9 m/s (or 13 m/s for smaller cranes). Thus, securing intermediate construction statuses by relieving the loads needing cranes is only possible for a short time. The assistance by crane was therefore not planned for use overnight. Hoisting work began according to the expected wind time-slot with adequately low speeds based on the weather report.

Using the example of the heavy truss construction for the waste bunker, the exacting erection preparations become particularly clear. The roof structure of the waste bunker consists of 40 m long triangular trusses positioned longitudinally with the roof slope, whose top chords are stiffened in the plane of the roof by transverse diagonals. Vertical transverse trusses, on which the roof structure is supported, are located on the support axis of the highest point. The stiffening of the bottom chords and the bottom support for the roof structure is provided by a concrete slab made of prestressed concrete elements and in situ concrete in the bottom chord plane of the trusses. This structure does not have sufficient stability until the final step after the in situ concrete slab has cured. The erection sequence was therefore divided into 14 operations, which required more or less the entire structure and the necessary auxiliary construction works to be incorporated in the structural analyses. The substructures were defined in the 3D TEKLA model and processed further using the structural design software for frames accordingly.

Fig. 12. Intermediate construction step of the roof trusses for the waste bunker (by Züblin Stahlbau)

The first erection step was defined as the lowering of a single truss onto the two supports. The structural elements of the roof truss, including the temporary anti-tilt bracket, had to remain stable with a self-weight of 900 kN and the horizontal wind load of 300 kN. Based on this, the hoist load studies were carried out, the erection aids dimensioned and the erection description drawn up for approval of the erection works and for instructing the erection personnel. The other structural systems to be checked ranged from the partially completed sections of several trusses through to analysis of the structure during placement of the in situ concrete (Fig. 12). Similarly, an erection study for the entire roof structure of the process building was carried out on the basis of the daily erection progress. Individual systems were derived from this for the structural analyses, which were coordinated and carried out by Züblin Stahlbau. The work on the 3D TEKLA model, which also took place online during the regular video conferences, meant that the client's design engineers could be quickly and effectively integrated and involved in the determination of the internal forces and moments for larger building sections.

6 Structural steel erection

The erection works on the construction site started on schedule in January 2015. To this end, large crawler cranes and safe working loads of 600 t, 300 t and 130 t were mobilized in order to be able to achieve the hoist weights and to reach all the locations in the structure. Mobile cranes were used to enable permanent deployment on the construction site. Notwithstanding the extensive preparations and planning, the erection of the steel structure was a particular challenge. The implementation of the erection concept described for hoisting the trusses above the waste bunker from April to May 2015 was an outstanding event. The five 40 m long roof trusses weighing 90 t were preassembled upright and were lowered onto their supports by two crawler cranes with capacities of 300 and 600 t and an outreach of up to 40 m (Fig. 13). Erecting the trusses following horizontal preassembly would have required extensive auxiliary construction works in order to prevent lateral buckling of the truss members during putting up the truss.

In addition to these heavy lifts, particular hoisting work repeatedly had to be carried out during the erection

Fig. 13. Lifting the first truss for the waste bunker (by Züblin Stahlbau)

Fig. 14. Lifting a preassembled unit for the process building (by Züblin Stahlbau)

Fig. 15. AmagerBakke, view from south-east towards waste bunker © Christoffer

Fig. 16. Lifting unit 2 of the chimney (by Züblin Stahlbau)

Fig. 17. View of south side of Amager Bakke in April 2016 (by Züblin Stahlbau)

of the trusses for the process building, which span over the boilers and filter units. Not only were the dimensions of the preassembled units – up to 40 × 15 × 10 m – a challenge for the steelwork erectors (Fig. 14), but also the access for erection crews at heights of up to 90 m, above the already installed power plant technology, also had to be planned in precise detail for each hoist (Fig. 15). A highlight in the erection work on the main structure was reached with the lifting into place of the 300 t, 60 m high chimney. The chimney was lifted in six parts with maximum weights of 80 t to a level of 130 m and was anchored to the building at three support points (Fig. 16). Before detaching the chimney parts from the crane, it was necessary to align the 72 drilled holes of the connection plates above each other at each support point, to partly drill in the building-side plates and to connect them with high-strength bolts with diameters of M36 to M48.

The wind was not only a serious influencing factor with regard to applied loads during the interim construction states. The time lost due to excessive wind speeds was also an organizational challenge during the erection work. During the winter months, as well as in the summer of 2015, downtimes amounting to as much as 50 % of the working hours occurred because of strong winds. In order to counteract the delays that resulted, an additional crawler crane with a safe working load of 750 t was also deployed at times. Using this measure it was possible for work on the process building to take place on two sides at the same time. However, the time schedule delays could not be fully made up. Nevertheless, the waste incineration plant went into comissioning on time in June 2016 (Figs. 17 and 18). Completion of the whole building structure will be concluded with the erection of the ramp structure, which leads skiers from the roof level at 30 m to the starting point. This is scheduled for mid-2017. Following that, the power plant operator plans to carry out the construction work for the ski park above the roof covering.

The numbers at a glance

Steel structure:	approx. 6500 t
Number of steelwork components:	approx. 43 000
Structural bolts up to M48: bolting assemblies	approx. 71 000 high-tension
Sandwich elements:	approx. 14 000 m^2
Prestressed concrete hollow-core slabs:	approx. 20 000 m^2
Precast reinforced concrete elements:	approx. 2000 m^2
Start of steelwork erection:	beginning of 2015
Completion of main building:	September 2016

Construction team

Client:	ARC Amager Resource Center
Architects:	BIG Bjarke Ingels Group Copenhagen
Structural engineers:	MOE A/S Consulting & Engineers
Design, fabrication, supply, erection:	Züblin Stahlbau GmbH, Hosena, Germany

Fig. 18. Amager Bakke in September 2016 (by Züblin Stahlbau)

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