SYMPHONY – INDUSTRIAL PRODUCTION OF MULTI-STOREY BUILDINGS
REPORT FROM THE RESEARCH TOWER PROJECT

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ABSTRACT

During the last years a building concept has been developed at the Division of Building Technology at the Royal Institute of Technology in Stockholm. The concept called Symphony is a holistic concept for industrial production of multistory buildings. In 2005 theory was put to practice, when – with the help of corporate sponsors – an experimental building called the Research Tower was raised according to this concept. The building consists of a load bearing steel structure with hollow core concrete elements and a climatic shell of lightweight prefabricated roof and outer wall elements. The outer wall elements, the roof element and the joint elements were produced in a factory and were later transported out to the yard where they were mounted up on the steel frame structure that was erected there. The full height vertical outer wall elements (11.2m) were plastered on the exterior façade in the factory, they also included windows, doors and all the vertical installations.

The assembly of the prefabricated elements was accomplished with satisfying results. Much of it thanks to the detailed design of the building. The majority of the components were modeled in 3-D; this gave the possibility of "assembling the building in the computer beforehand".

KEY WORDS

Industrial construction, prefabrication, multistory buildings, integrated design, optimized building process

INTRODUCTION

During the last years a building concept has been developed by this research group at the Division of building technology at the Royal Institute of Technology in Stockholm. The building concept called Symphony is a holistic concept for industrial production of multistory buildings and extends from the design phase to production methods and materials used. In 2005 theory was put to practice, when – with the help of corporate sponsors – an experimental building called the Research Tower was raised according to this concept. The

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building consists of a load bearing steel structure with hollow core concrete elements and a climatic shell of lightweight prefabricated roof and outer wall elements. With a building area of 13 m^2 and a total height of 11.4 meters it has the proportions of a tower. The research tower is a co-operation project between the "Symphony" project and the "Termodeck revisited" project (Karlström 2005).

INDUSTRIAL CONSTRUCTION

The term industrial construction is being used more often in the past years and has a in a way become a goal that especially larger enterprisers endeavor to achieve. There is a tendency of connecting industrial production with automated machines as a substitute for workers which is incorrect. The keyword is in fact optimization. Automation is only a result of production optimization. The task is thus to optimize the construction of a building. This is a process that has been going on during a long period; items like the nail-punch and ready to install windows have optimized the construction. Today the sector is in a type of paradigm shift that is moving towards a radical change in the way we construct our general type of buildings through more industrialized construction methods. The key words for success in industrial construction are (according to the author) optimization, control and precision.

Manual labor costs are rising and contribute to the high construction costs. Apart from the cost it is the construction time at site that needs to be reduced. In an enclosed space the work area is more controlled both in terms of climatic changes and access to equipment. When the item being produced is in movement while the production equipment is unmoving it gives the possibility of using larger and more powerful equipment. Controlling this movement is the reason for the success of the manufacturing industry, not the mass production as we often incorrectly believe. The mass production is only a result of the optimization of the use of this equipment. According to the vice president of one of the major construction companies in Sweden the efficient working time of a construction worker at site is approximately 40%. Rest of the time is spent on covering and uncovering, waiting time for other craftsmen, looking for tools and so on. It requires an ergonomic study of the human body together with a psychological analysis of the workers mind to find the optimized conditions for production. A great part of those conditions are found in a controlled environment such as a factory. Walking around consumes too much energy that does not produce and also increases the chance of unexpected scenarios such as accidents. Furthermore the tasks of each worker need to be optimized. Take for example a simple thing as measuring. Measuring is a very time-consuming task that has serious effect on the product. Freeing the worker from this task will save him a great deal of time while it at the same time will increase the precision. With a more detailed design it is possible to receive building components that are pre-cut and thus will not require the same amount of measuring. When Volvo is producing cars you don't see people running around with rulers?

In a controlled space you don't have any climatic changes, no snow blizzards or hot summer days that can affect workers, equipment or structures. It gives an overall more regular working speed which results in a more precise calculation of the required working time and thus the cost. The product will most certainly be produced in the exact same amount of time every time it is produced.

Of course it is not possible to produce an entire multistory building inside a factory and deliver it to the site, at least not yet but the goal is to finish as much building elements as possible in advance. The fewer the elements to be mounted together at site the faster will the mounting proceed giving that the prefabricated elements must be large. The larger the elements are the fewer elements are required. This will automatically lead us to the next subject which is the tolerances.

TOLERANCES

The biggest problem today with prefabricated building elements is the fitting on site. Prefabricated elements are often delivered by a different contractor with little adaptation to the actual building being built. This is a classic example of local optimization; one component is optimized without taking into consideration the rest of the building. There is often no guarantee that the prefabricated component will fit as it was intended to.

Furthermore it should be pointed out that the standard tolerances used today in construction need to be prescribed in a different way. The components and materials with the largest tolerances are often the ones that are used earliest during the production of the building such as the concrete foundation and the steel structure (Holm 1987). The earlier a component is built the more components it will affect. Thus will large tolerances in the early phase of the construction grow even larger towards the completion of the building. The earlier a component is built the more important is the precision. This will help keeping the total tolerances at a low level and assembly of the prefabricated elements successful.

THE SYMPHONY CONCEPT

Symphony (Hoseini et al. 2004) is a building concept developed by at the Division of Building Technology at the Royal Institute of Technology in Stockholm. It implies a different way of viewing the construction of buildings. It involves a holistic view of the whole production of the building and includes everything from design to construction and installations and extents to the long time performance of the building in operation. The building in full is seen as one product with everything that is included in it. It is not a structure filled with installations and finished with surface materials. Everything can be integrated and all the included components must be regarded and planned for during the design phase. To achieve this, a more detailed and competent design process is needed. The design team includes representatives from all the different contracting fields. The members need to work more intimate and share all the information in real time with the rest of the team. Symphony is about industrial prefabricated buildings that are assembled on site and also includes a range of technical solutions. The main innovations in the concept are the symphony elements:

- The full height vertical outer wall elements.
- The prefabricated installation elements with all the vertical installations integrated.
- The light weight prefabricated roof elements.
- The full height vertical joint elements.

PRODUCTION OF THE RESEARCH TOWER

The research tower was raised in the factory yard of an old concrete element factory near Stockholm. One of the factory halls was also reserved for the production of the building elements. The four outer wall elements, the roof element and the four joint elements were constructed here and were later transported out to the yard where they were mounted up on the steel frame structure with hollow core concrete slabs that was delivered by Strängbetong.

THE OUTER WALL ELEMENTS

Because of the small area of the building four outer wall elements were enough to cover the walls. One of the elements was a so called installation element containing all the vertical installations of the building. One wall was totally blind while the other two contained windows and doors. The Symphony elements are light weight elements. The core of the construction is based on the so called CasaBona system (Jóhannesson et al. 1995). CasaBona is a patented construction system which integrates sheet metal Z-profiles with stiff insulation blocks such as Expanded Polystyrene or stiff mineral wool. The system creates a case where the insulation contributes to the strengthening of the studs. Both the sheet metal and the stiff insulation are delivered to the factory pre-cut in exact measures. The insulation blocks have incisions for the flange of the Z-profile with which they will be built together (see Figure1). The width of the blocks gives automatically the distance between the studs and no measuring is required. The Expanded Polystyrene blocks are exchanged to blocks of stiff mineral wool alongside the connection to the intermediate floor slabs for fire security and acoustic reasons. In this phase preparations will be made for the connection of eventual windows or doors. Notice that the elements are produced in horizontal position beginning with the inside. After finishing the remaining layers of gypsum boards, horizontal studs and additional insulation the element is turned over to finish the outside layers. Before the turn over it is possible to integrate eventual electrical wiring behind the outermost gypsum layer. On the outside the element is covered with another layer of 50mm insulation before it is plastered. Notice that the walls are plastered in horizontal position facilitating the procedure and lowering the amount of working hours.

Figure 1. The CasaBona construction is seen in close up to the left and to the rigth can be seen an outer wall element during production.

Installation element

In the installation element all the vertical installations are integrated. Ventilation ducts are built in, together with the pipes for water and sewage. The electrical wiring is also built in. All the ducts have horizontal connections at the right level on each floor. This gives that after the assembly of the installation element remains only the local connection of the installations on each floor into the installation element. Integrating installations into the outer wall requires control of the heat transfer to the outside air and control of the distribution of the vibrations aroused in the installations from the acoustics point of view.

THE ROOF ELEMENT

The roof element is also a light weight element prefabricated in the factory. It consists of the same CasaBona construction. The element was finished with roof covering and roof dwell. It is a flat roof with an inclination of 1 degree and thus requires a type of roof covering that is suitable for lower inclinations. Here a roof covering of PVC material was used. Siphon full flow system is used for the roof water drainage. This means that drainage pipes with a smaller dimension can be used for the drainage system and that they can easily be hidden inside the construction. The PVC roof covering was mounted and welded on at the factory. It was mounted in bigger pieces than the roof, enough to make it possible to cover the joints between the roof and the internal side of the outer wall elements after assembly. In this way the roof covering can be finished easy and fast after the assembly of all elements since it only needs to be complemented. The roof gully witch will suck the water off the roof was also mounted on the roof at the factory and connected to a drainage pipe that would in turn be connected to the rest of the drainage system.

The roof element was thus completed with insulation, roof covering, roof gully and drainage system.

THE JOINT ELEMENTS

The vertical joints between the full length outer wall elements were covered with full length joint elements. The joint element is also built up by sheet metal profiles integrated with expanded polystyrene. Inside the element a drainage pipe was built in with connections at the bottom and at the top – in height with the roof gully – for the connection to the day water drainage system and the roof gully respectively. The elements were designed to be connected from the inside at each floor level. The exterior finishing of the joint element has no restrictions but in this case it was chosen to enforce the joint by revealing it extra at the façade with stainless steel as finishing material. This led to full length, insulated joint elements with prepared connections and built in drainage system.

THE LOAD BEARING STRUCTURE

The load bearing structure is a conventional system that is used a lot in Sweden today. A steel frame carries hollow core concrete slabs that are prefabricated in right lengths. Some minor changes were however made to the standard formulation. The beams carrying the concrete slabs were changed from Z-beams to L-beams since the outer walls are different. the horizontal positioning of the columns was also adjusted to fit the Symphony elements.

THE ASSEMBLY

The assembly was started with the roof element. The purpose of this is to create a climatic protection as early as possible. In this project the roof element was very light and rather small and thus easy to assemble. After the roof was assembled the assembly of the outer walls started. However much the size of the building area facilitated the mounting of the roof element it complicated the assembly of the wall elements. The proportion of the building makes it very slender regardless of type of construction. Normally a building such as this would contain some kind of stabilizing elements such as a stair-case shaft, an elevator shaft or similar. The small building area did however not permit such elements in this building and made it necessary to integrate cross tensors in the outer wall elements. This rendered the assembly slightly complicated.

For the assembly the challenge had always been the lifting of the outer wall elements from horizontal to vertical position. If the element is lifted at the top point while the bottom point of it is resting on the ground the element can be seen as a beam with a span corresponding to its length. In this case it is important to control the radius of deflection. If the radius of deflection is too high it could damage the construction materials such as the gypsum boards and the plastering. Calculations showed that the elements could handle it but still there was the problem of the pressure on the element bottom. Consequently the elements were lifted in two points. The element was then raised from the ground to the level were it could be turned to almost vertical position. Then it was put to the ground in an angle of about 82 degrees where the bottom lifting yoke was removed (see Figure 2). Now the element could easily be lifted up and transported to any point. During the lifting of the outer wall elements it is of great concern to be aware of the wind velocity since the ratio weight /area is much smaller compared to for example concrete elements. Calculations were made to know the exact limits of the wind velocity in which the assembly could be performed without risk. The elements were assembled in a two step process. In the first step a preliminary connection was made to the structure with adjusting possibilities. Here the deflection of the elements from the plumb-line is controlled. After this step the crane could be disconnected and start with the lifting of the next element. The second step involved permanent connection to the structure that could be made from the inside of the building at each floor level.

After the mounting of all four outer wall elements the mounting of the joint elements would proceed. Just before the joint element is mounted bands of expanding polyurethane is put on the flanges to achieve automatic tightening after assembly. The element is easily lifted by one crane at the top and guided by one man at the bottom. During the assembly of the element no problems due to the tolerances were encountered. All four joint elements could be fitted in place without any problems. One of the joint elements had the roof drainage pipe built in as told earlier. When this element was mounted precision was that satisfying that only a slight twitch was enough to fit the pipe projecting out from the joint element into the pipe connected to the roof gully.

Now the façade of the building was finished and tight. The next move was to get on top of the roof and screw off all the lifting eye bolts which is done easily. The only thing remaining on the roof is to insulate the joint around the roof and to fasten the roof covering (which is bigger than the roof area) on to the walls and weld the edges. After this prefabricated top covers for the top of the outer wall elements were mounted and the exterior work of the roof was finished. The building was finished from a steel frame structure to a building with totally finished exterior in less than three working days without the use of any scaffoldings.

Figure2. assembly of the outer wall elements, the revealed joint elements can be seen in the picture to the rigth.

INTERIOR FINISHING

The climatic shell of the building is finished very fast. This will create a climatically controlled space inside the building. By planning the order for the rest of the work in an efficient way and to prevent different contractors from working at the same time, a controlled production space can be created to optimize the production. For the interior finishing of the research tower traditional methods are used with conventional techniques. Worth mentioning is that the outer wall elements were finished till gypsum board on the inside. These gypsum boards were moist after a couple of days because of the change in relative humidity of the air, they also needed to be complimented and there were even some damaging involved. Therefore some of the gypsum boards had to be replaced.

The floor is a raised floor which creates an air gap between the floor and the concrete slabs. This gap can be adjusted between 20 and 230 mm, in the research tower it is 200 mm high. The gap is used to put insulations such as water pipes and electrical cables.

For the electrical installations plug-in connections are used. This means that cables can be plugged in to the central in one end and in to the wall socket in the other end. This will save large amounts of time for the electrical work.

RESULTS

PRODUCTION OF THE ELEMENTS

The production of the elements in the factory showed good results. The precut components were really a time saver. As soon as measuring and cutting or sawing was involved production speed was reduced. Activities such as cutting of the gypsum boards were really time-consuming. Large efforts were required for adjusting the outer wall elements to get exact perpendicular edges. This could be speeded up remarkably with a simple table of the same size as the elements. The table should have two perpendicular sides in rigid steel against which you could adjust the element components. Since the building components are pre-cut it's enough with two guiding sides. The table should have a third steel beam that can compress the element in its plane perpendicular to the sheet metal studs. Further should the table be able to turn the element around, this technology already exists. It was not used in the project because of financial reasons. The turn over of the elements was made with overhead cranes which was time consuming and required too much preparation. In general the production of the elements could be made automated to a great extent and decrease the amount of workers required from four to less than two.

With more detailed planning the pipes and ducts used inside the installation element can be delivered pre-cut and easily be fitted into the element speeding up the production of the installation element which has been the most time consuming element to produce.

The joint element was successful to produce and to assemble. However optimization could be achieved even in this field. The production of the element required a great deal of screwing which should be reduced. Also the design of the element should be modified. In its present form it creates cavities around the load bearing columns of the structure after assembly. These cavities are difficult to tighten afterwards. The same joint element can also be produced to not be visible after assembly. This is very important for the esthetical flexibility of the building.

The roof element was easy to produce and to assemble in this project because of its size. Larger roof surfaces will require longer and heavier roof elements. Here it's important to predict and have total control of the deflections that will appear.

ASSEMBLY

The rigidity of the elements was as predicted high, and resulted in smaller radius of deflections than estimated at the time of lifting to vertical position. This led to the fact that the plaster was not damaged at all (which was one of the main challenges from the start). The rigidity of the element is a direct consequence of the strength of the Z-profiles in the CasaBona construction. Apparently the stiffening effect of the polystyrene on the sheet metal profiles has been underrated. A closer examination of the interaction of the sheet metal profiles and the stiff insulation blocks must be performed to render more precise predictions possible. The results preliminary show that elements up to 15 m long could be produced and assembled. For the actual lifting simple devices could eliminate the need of the second crane and speed up the assembly remarkably. In the future the elements will be lifted directly off the truck with only one crane needed.

INTERIOR FINISHING

The fire protection that needs to be done on the interior could be optimized as well. The beams and the columns of the steel structure could for example be delivered painted with fire protective paint and the joints tightened with sprayed sealing compound. The experience shows that fire safety engineers are needed in the initial design team. In this way optimal solutions for the fire safety could be integrated in the initial design of the building.

As told earlier the elements were produced with the final gypsum board mounted on the interior. The boards did not reach the roof and the bottom because of the tolerances needed for the assembly so this space needed to be covered afterwards. Further are the gypsum boards sensitive to humidity and physical damage which results in replacement of some of the boards after assembly. This has raised the question of the actual gains of having the dry sheets mounted at the factory. In some situations it would be better to not screw on the last layer of gypsum board until the elements are mounted.

The problem with the plug-in electrical cables is that the connections as they are produced today are too big resulting in unaesthetic big wall sockets and similar. Further is the system not fully developed today which means that there is a mix of traditional connections and plug-in connections.

CONCLUSIONS

The detailed design drawings of the research tower were a great part of the success during the assembly of the building. The majority of the components were modeled in 3-D. This gave the possibility of "assembling the building in the computer beforehand". The goal was to examine the benefits of detailed design. All the drawings were also discussed with all the participating engineers and even the workers such as the crew from the crane company. The purpose of this was to use their experience to discover details in the components that would in some way complicate the assembly or the long time performance of the component in question or the adjacent components. This shows the great strengths of an integrated design team that design the entire building in close collaboration with total transparency and sharing of information.

The 3-D modeling technology is wide spread today and there are also softwares that allow simultaneous modeling on the same object in different locations of the world using the internet (Tekla-structures). This is vital to keep costs down during the design phase. Costs are really the only thing that prevents the 3-D modeling of all buildings. Today 3-D modeling is too expensive and a luxury that can only be afforded in costly projects. The softwares usually require a great amount of time and the capability of such modeling is not widespread among all the consulting firms. This makes the competition limited and the price tag high.

The use of 3-D modeling is growing among the young generation and the universities are teaching it more seriously. This will increase the capability in the future while the software developers are launching more intelligent and rapid modeling tools. In the near future it is realistic to predict that the majority of the buildings designed are modeled in 3-D in advance.

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