High technology production methods in the construction sector

Introduction

Ever since concrete was first invented by the Romans it has become the most used construction material. Concrete has obvious benefits in terms of its structural behaviour but its ability to take upon any shape provides architects with a unique degree of architectural freedom compared to other building materials. However, the architects vision can only be realised to the extent the technical knowhow and economy allows it.

Fig. 1: Tenerife Opera House – an example of complex concrete architecture.

In many ways concrete structures consist of building blocks which are assembled to form the final shape. The blocks may be cast at the building site or at the precast element plant and they may be more or less complicated/unique.

From a concrete technology point of view, the last 10 years have shown the potential of new types of concrete. Especially Self-Compacting concrete (SCC), fibre reinforced concrete and textile reinforced concrete have opened up for new and more interesting concrete architecture. With SCC it is possible to cast very complex form work geometries which would have been very difficult or even impossible to cast using traditional vibrated concrete and fibre reinforced concrete opens up for much thinner cross sections introducing a lighter appearance to the concrete structure. However, fibre reinforced and textile reinforced concrete is mainly for use in non barring structures and cannot replace conventional steel bar reinforcement.

Fig. 2: The extension of the Ordrupgaard Museum in Copenhagen. Complex shape cast in self-compacting concrete.

From a construction point of view, advances in new construction techniques can push the limits of possible concrete architecture e.g. the Tietgenkollegiet in Copenhagen. Another example which may appear in the future is large thin shell structures. Today the use of shells is gaining more importance in architectural designs for facades, interior design and roof structures.

Fig. 3: Tietgen Collegium, Copenhagen. The circular main building has 45 hanging concrete boxes in two stories, which contain kitchens and other common facilities. The largest boxes have a free span of 8 m and weigh 250 tons. Cowi, the consultant company, solved this structural challenge by using innovative solutions and "free forward construction". It is a construction method that normally is applied for building bridges. The method has no need for scaffoldings and the result is a significant saving in time and money.

For the creation of large surface structures a viable connection technique is necessary. The connection of the elements will be established by post-tensioning. This allows for a blunt connection, that is able to transfer normal forces and moments across the connection e.g. test setup Post-Tensioned arch. In the following, the focus will be on the individual concrete building blocks and new developments especially in relation to automation, digital fabrication and handling.

Formwork manufacturing processes

Today, a lot of effort and costs go into formwork production including the load carrying formwork, recesses, and reinforcement. The formworks consist for the main part of standard modules which offer only little to the architectural quality of the structure. Complex formworks are very expensive and are mainly done in relation to prestige projects as the level of craftsmanship is very high. Especially singular or unique elements are extremely costly. That is also the reason why most of the concrete structures we see e.g. for housing are low cost constructions of low architectural quality.

Fig. 4: Complex formwork for the Ordrupgaard extension manufactured with a high level of craftsmanship.

However, digital architecture and fabrication is the future with a large potential in terms of automation and free form fabrication. The digital format has given architects a powerful tool to design concrete structures. It was only within the late 90ies that the advances in computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies started to have an impact on building design and construction practices. They opened up new opportunities by allowing production and construction of very complex forms that were until recently very difficult and expensive to design, produce and assemble using traditional construction technologies. The consequences will be profound, as the historic relationship between architecture and its means of production is increasingly being challenged by new digitally driven processes of design, fabrication and construction. Manufacturing processes include precise placement of individual parts, cutting, lifting, milling, spraying, polishing etc.

The ability to mass-produce irregular building components with the same facility as standardized parts introduced the notion of mass-customization into building design and production. Mass-customization, sometimes referred to as systematic customization, can be defined as mass production of individually customized goods and services, thus offering a tremendous increase in variety and customization without a corresponding increase in costs.

Digital fabrication refers to the computationally based processes of form production and fabrication based on a digital architectural model. Several digital fabrication processes are identified based on the underlying computational concepts such as:

- 2D Fabrication. Examples are shown in: Multi-Function-Shuttering-Robot 1/2, Multi-Function-Shuttering-Robot 2/2, Water jets, plasma-arc CNC cutting.
- Subtractive Fabrication involves removal of specified volume of material from solids using multi-axis milling.
- Additive Fabrication involves incremental forming by adding material in a layer-by-layer fashion, in a process converse of milling e.g. sprayed concrete. It is often referred to as layered manufacturing, solid freeform fabrication, rapid prototyping, or desktop manufacturing. All additive fabrication technologies share the same principle in that the digital (solid) model is sliced into two-dimensional layers. The information of each layer is then transferred to the processing head of the manufacturing machine and the physical product is incrementally generated in a layer-by-layer fashion. Shotcreting may also be thought of as additive fabrication and fully automized robotic systems are under development.
- Assembly. After the components are digitally fabricated, their assembly on site can be augmented with digital technology. Digital three-dimensional models can be used to determine the location of each component, to move each component to its location, and finally, to fix each component in its proper place.
- Surface treatment: Different processes like polishing, sand blasting and spraying are operations which can be applied to both the formwork and the final concrete element.

Fig. 5: Digital fabrication using robot technology, laboratory of the Concrete Center at the Danish Technological Institute

Formwork materials and coatings

Precast forms are normally made of either steel or plywood. In the production of precast concrete elements, the forms are typically reused, i.e. a large number of castings are performed in the same forms which results in saving of raw materials. The number of times a Plywood form can be reused is limited to about 20 to 50 castings depending upon the complexity, maintenance and shape of the form. Standardized elements cast in steel forms are one step towards sustainable production as an almost unlimited number of castings can be made using steel forms. Standardization of precast products will save cost. Attempts by the precast industry to standardize precast cross sections are designed to save costs and increase market share by getting the maximum number of casts out of every form. The most often used alternative to the smooth appearance obtained from steel and plywood forms is by lining the formwork with timber.

A number of materials that can be used as an alternative to the traditional concrete shuttering and that are also well suited for processing using robots are listed below:

- Textiles: One of the new technologies in formwork technology is textile formwork – an alternative to traditional concrete shuttering that allows for more efficient and expressive structures.
- Polystyrene foam: Single use moulds can be created quickly using polystyrene foam and can be used for casting words, numbers or artistic elements to add interest to otherwise monotonous and stark concrete surfaces or to create unique standalone features. The main challenge is to find a good coating which can provide not only the right slip properties but also the right surface quality of the final concrete element.
- Silicone rubber: Multiple use moulds or form liners are created from a polystyrene pattern using silicone rubber. Large and complex patterns can be reproduced multiple times for use on precast architectural panels, and sound barriers.

Fig. 6: Textile formwork used for the casting of a concrete column.

Summary
Formwork manufacturing is still to a large extent based on craftsmanship and in order to keep costs low the flexibility in formwork design is very limited. New advances in automation and digital fabrication are beginning to appear in the concrete industry. One of the methods providing the greatest degree of free form manufacturing is subtractive processing i.e. where milling of the formwork material is performed. So far, only examples of milling in polystyrene have been found, which is a cheap and quick material to process. Further research will focus on coating of polystyrene to obtain good slip properties and the intended surface appearance. Combined with new advances in automated spraying technology it may be possible to find a coating material which offers a good balance between price and performance. The coming research will also focus on producing complicated elements which require closed formwork and good planning of the inlet position and the properties of Self-Compacting Concrete. Finally, research will focus more on the potential of industrial molding sand. This is a completely new material to the concrete

industry and the first laboratory results have been promising and especially recycling and easy de-molding makes it a very interesting formwork material.