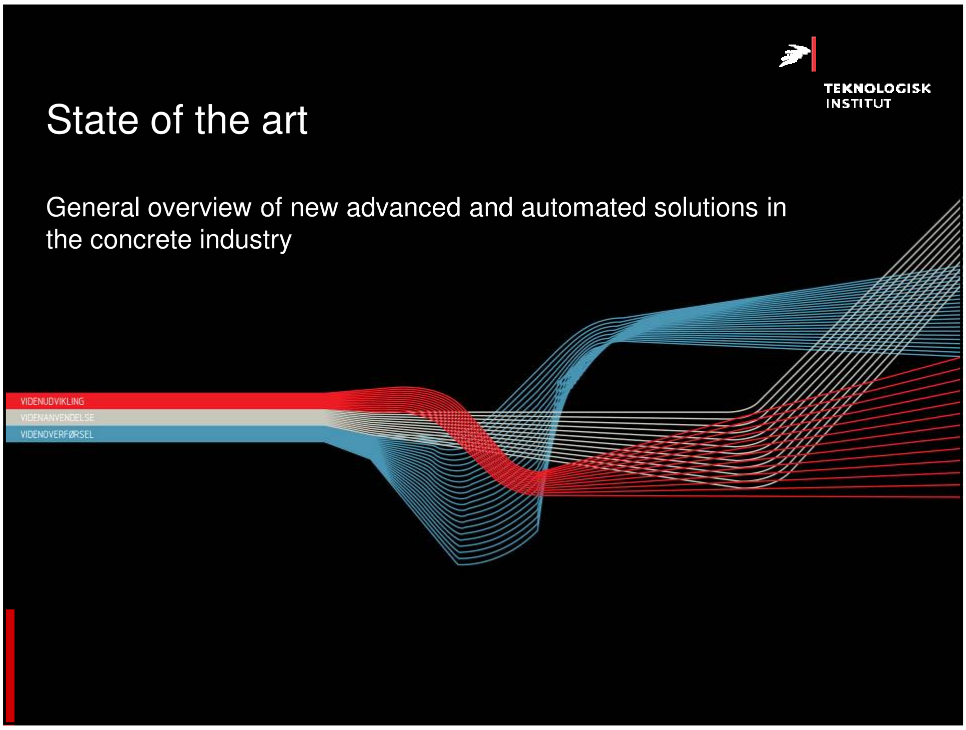

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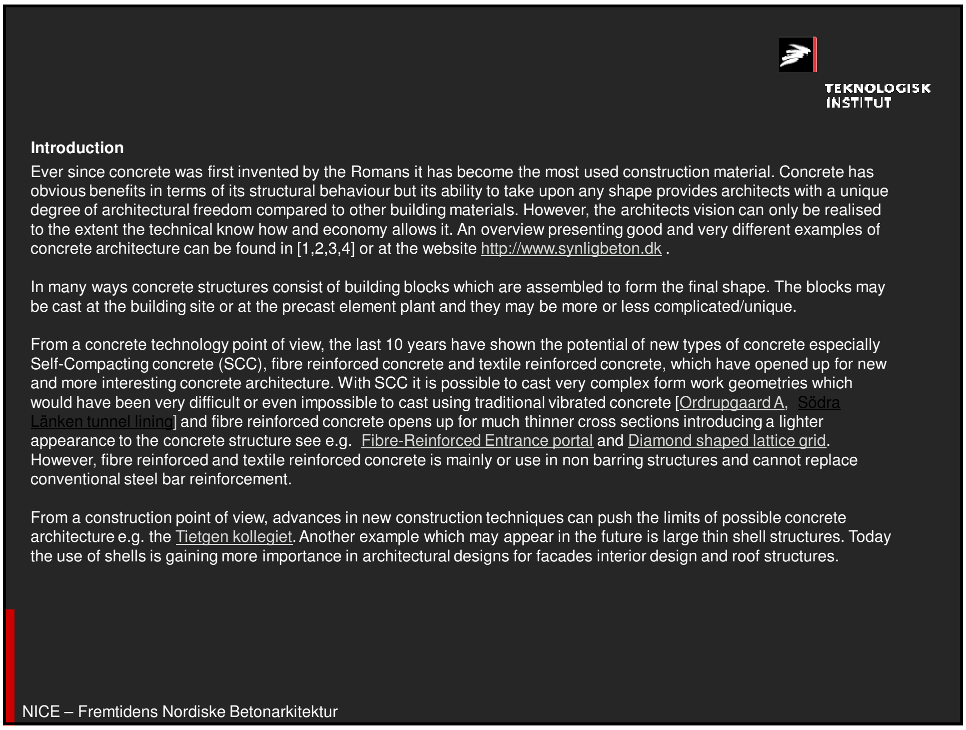
State of the art

General overview of new advanced and automated solutions in the concrete industry



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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 know how and economy allows it. An overview presenting good and very different examples of concrete architecture can be found in [1,2,3,4] or at the website http://www.synligbeton.dk .

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, which 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 [Ordrupgaard A, Södra Länken tunnel lining] and fibre reinforced concrete opens up for much thinner cross sections introducing a lighter appearance to the concrete structure see e.g. Fibre-Reinforced Entrance portal and Diamond shaped lattice grid. However, fibre reinforced and textile reinforced concrete is mainly or use in non barring structures and cannot replace conventional steel bar reinforcement.

From a construction point of view, advances in new construction techniques can push the limits of possible concrete architecture e.g. the Tietgen kollegiet. 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.

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.

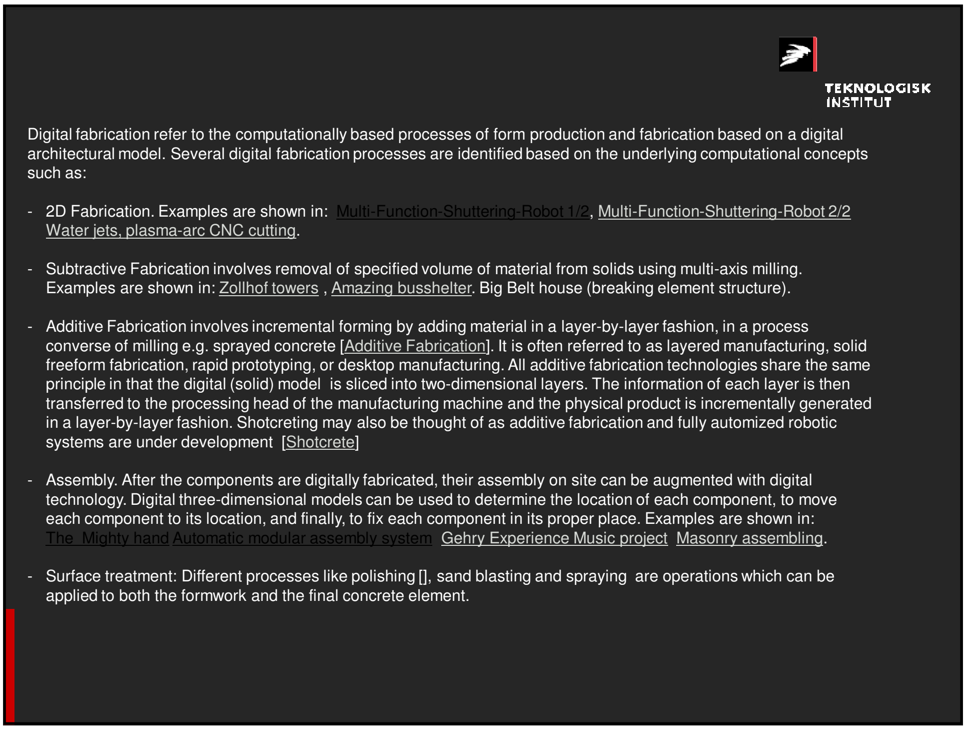
In the following the focus will be on the individual concrete building block and new developments especially in relation to automation, digital fabrication and handling.

Formwork manufacturing processes

Today, a lot of effort and costs goes into form work production including the load carrying formwork, recesses, and reinforcement. The formworks consist for the main part of standard modules which offer only little architectural flexibility [High Way bridge , Conventional in-situ wall , Horizontal formwork]. Complex form works are very expensive and are mainly done in relation to prestige projects as the level of craftsmanship is very high [Ordrupgaard B and Metropolitan]. 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 [Conventional concrete housing architecture].

However, digital architecture and fabrication is the future with a large potential in terms of automation and free form fabrication [13]. 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.



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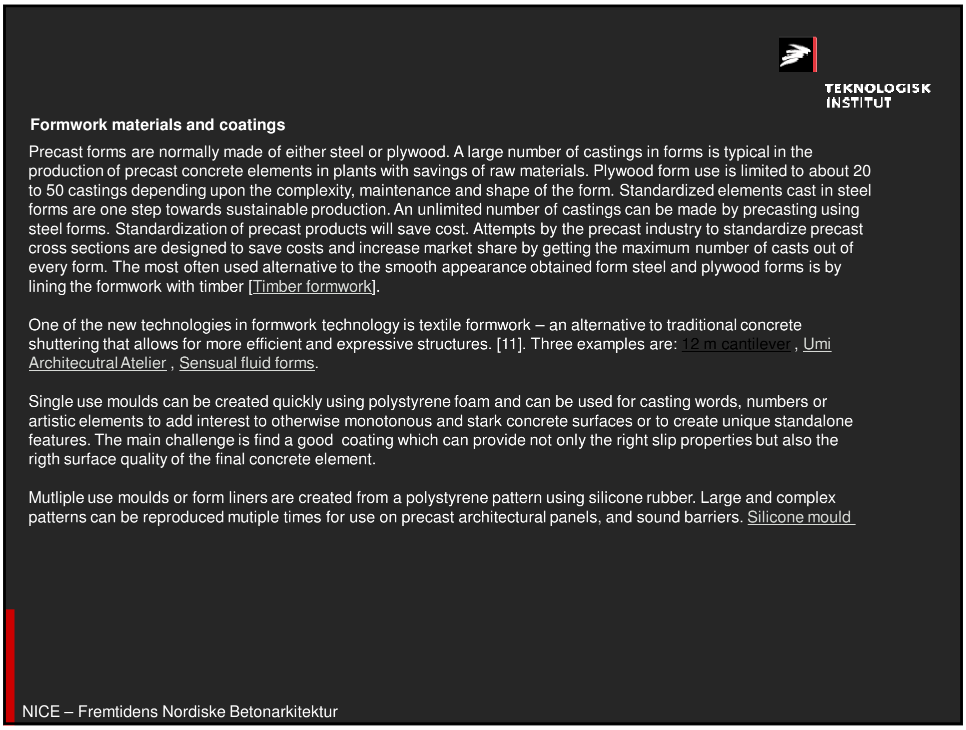
Digital fabrication refer to the computationally based processes of form production and fabrication based on a digital architectural model. Several digital fabrication processes are identified based on the underlying computational concepts such as:

- 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. Examples are shown in: Zollhof towers , Amazing busshelter. Big Belt house (breaking element structure).
- Additive Fabrication involves incremental forming by adding material in a layer-by-layer fashion, in a process converse of milling e.g. sprayed concrete [Additive Fabrication]. 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 [Shotcrete]
- 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. Examples are shown in: The Mighty hand Automatic modular assembly system Gehry Experience Music project Masonry assembling.
- 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.



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Formwork materials and coatings

Precast forms are normally made of either steel or plywood. A large number of castings in forms is typical in the production of precast concrete elements in plants with savings of raw materials. Plywood form use 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. An unlimited number of castings can be made by precasting 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 form steel and plywood forms is by lining the formwork with timber [Timber formwork].

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. [11]. Three examples are: 12 m cantilever , Umi Architecutral Atelier , Sensual fluid forms.

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 find a good coating which can provide not only the right slip properties but also the rigth surface quality of the final concrete element.

Mutliple use moulds or form liners are created from a polystyrene pattern using silicone rubber. Large and complex patterns can be reproduced mutiple times for use on precast architectural panels, and sound barriers. Silicone mould

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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 demolding makes it a very interesting formwork material.

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Ordrupgaard Museum, Copenhagen

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Ordrupgaard Museum, Copenhagen

In-situ concrete casting. Formwork plywood in felt sizes of 1600*2400 mm.

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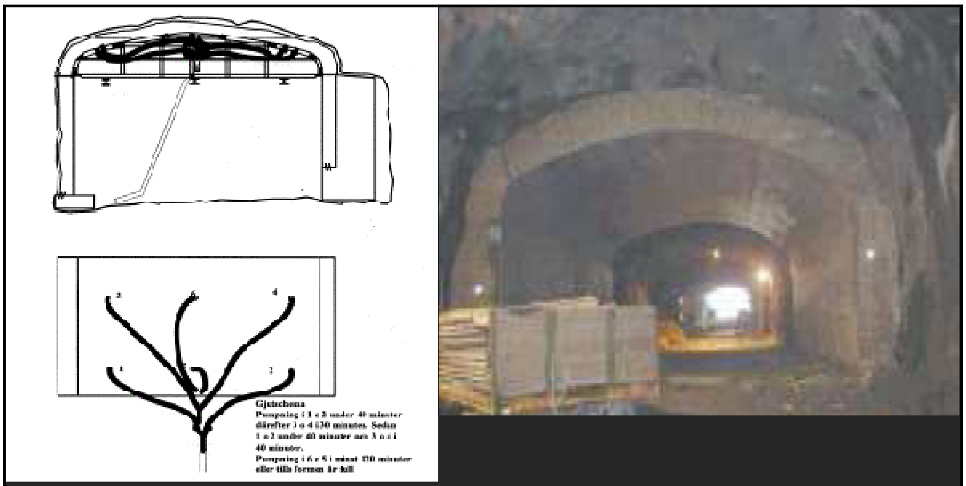

Concrete arch for tunnel lining at the Sodra Lanken project. The concrete arches were cast with SCC due to the complexity of the structure. To the left the placing of the pump hoses and to the right the final appearance of the south arch [5].

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To the left: Entrance portal of DUCON, height 4,50 m, span 4,50 m, thickness 80mm to 100 mm [7].
To the right: Stairway for new office building in Copenhagen made from CRC [www.crc-tech.dk]

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Prototype of a diamond-shaped lattice grid. Textile Reinforced Concrete (TRC) is a composite material made of open-meshed textile structures and a fine-grained concrete. Comparable to steel reinforcement the textile fabric bears the tensile forces released by the cracking of the concrete. Only a minimal concrete cover is required for the bond of the textile fabrics. Thus, the application ofTRC leads to the design of filigree and lightweight concrete structures with high durability and high quality surfaces. In recent years, TRC has been successfully employed for the production of ventilated façade systems. Current investigations enlarge the application range of TRC to façade systems with large spans and load-bearing structures. In this paper, the investigations on self-supporting and structural sandwich panels regarding production methods, results of bending and shear tests, tests on sound insulation and fire resistance as well as first prototypes of slender frames and shell elements are presented [8].

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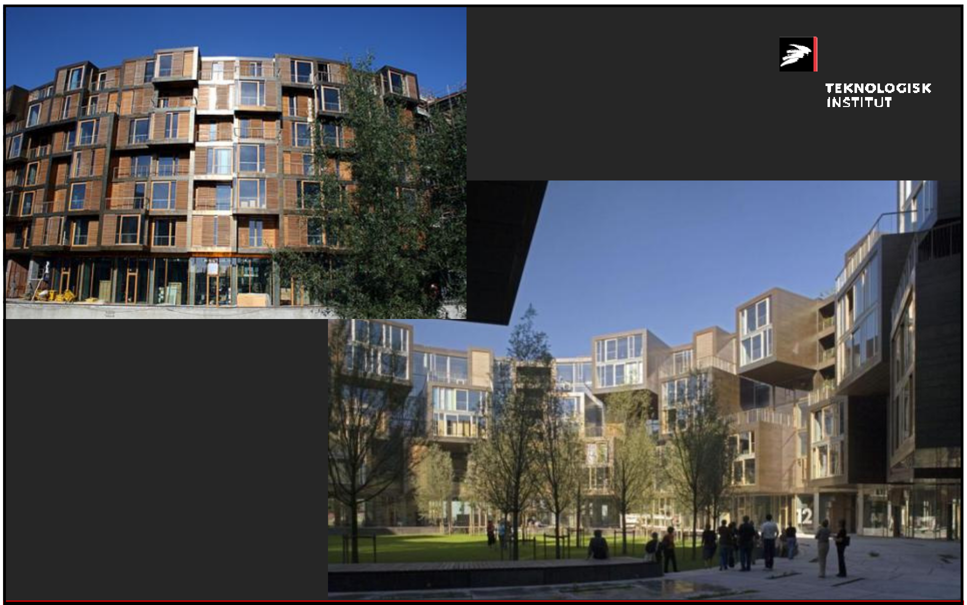

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Tietgen Collegium, Copenhagen. Winner of the Danish Precast Concrete price, 2007. The circular main building has 45 haning concrete boxes in two stories, which contain kitchens and other common facilities. De largest boxes have a free span of 8 m and weighs 250 tons. Cowi, the consultant company, solved this structural challenge by using innovative solutions and ”free forward construction”. Its a construction methods that normally is applied to build bridges. The methods has no need fore stilladser og the result is a significant saving in time and money.

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This connection technology was tested in experimental investigations. Finally, a feasibility studyvwas carried out by erecting a very slender arch using this connection technology.Post-tensioned arch made of 39 curved surface structure elements. The production of thin post-tensioned concrete shells using prefabricated elements which can be connected on site, will turn out to be a cost-effective, easy and time-saving method. For this construction procedure the joining technology is of great importance. On the one hand an easy handling is required and on the other hand forces and moments have to be transported over interfaces. This innovative joining technology for thin shells with post-tensioning presented in this paper shows that the construction of plane and curved surface structure elements is possible and moments as well as tensile forces can be carried across the interfaces [6].

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The first high way bridge made of Self-Compacting Concrete in Denmark, 2006.

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Conventional in-situ form work.

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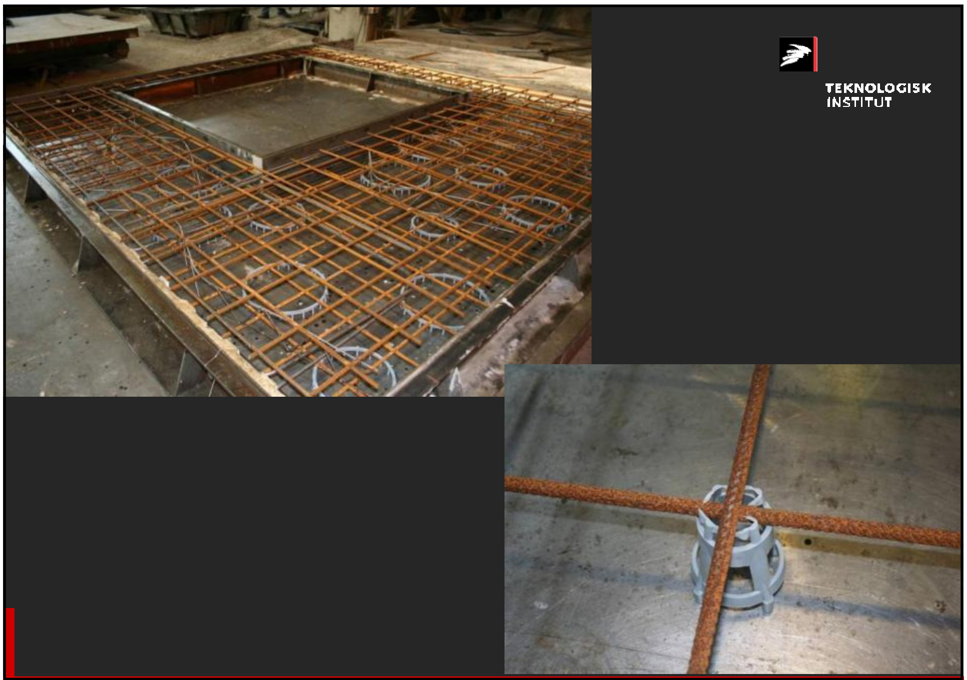

Conventional horizontal formwork at a precast plant.

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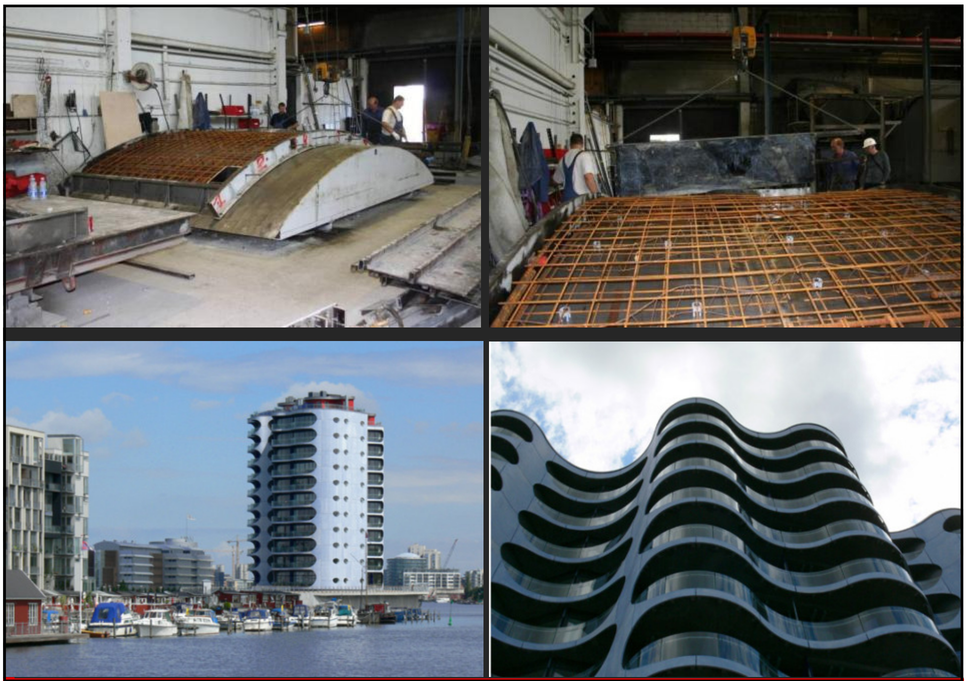

Curved formwork for production of elements for the new prestigious apartment building Metropolis in Copenhagen.

Home

Mark West has designed a 12m-long double cantilever beam (pictured right) that uses 30 per cent less concrete than a rectangular concrete equivalent, and was made using a flat sheet of geotextile fabric. Once the bearing points and dimensional requirements of a beam are determined, the fabric naturally deflects under the wet load of concrete to create catenary geometries. Using this method, the formwork for a 10m-tall structural column can be carried within a small rucksack. It was invented by Mark West, a fabric formwork researcher based at Canada's University of Manitoba, specialising in exploring how fabric provides simple ways of shaping efficiently curved structural members [11].

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For Tokyo-based firm Umi Architectural Atelier's Stone Renaissance House, concrete formwork was created using the 'frame restraint' method, developed by the practice's Kenzo Unno. Netting is stretched along the inside of steel pipes, restrained by standard form ties running through holes drilled in the pipes. Concrete is poured in and, when the walls set, the restraining pipes are removed, leaving a vertical impression. For this project Unno experimented with a diagonal pattern [11].

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Remo Pedreschi has researched how a new architectural 'language' of sensual fluid forms could emerge from flexible formwork

The wide variety of column-section shapes produced in Remo Pedreschi's workshop at Edinburgh University, where he is an professor, is the result of manipulating the hydrostatic pressure of wet concrete. The formwork, which consists of stretched and twisted fabric tubes, produces figure-of-eight-shaped forms, hollow columns and columns with voids. To connect the various elements, Pedreschi developed interlocking male and female components. A vacuum-formed mould was incorporated into the ends of the formwork to ensure geometric accuracy. Independent of the columns, the prototype connection can be used in other components [11].

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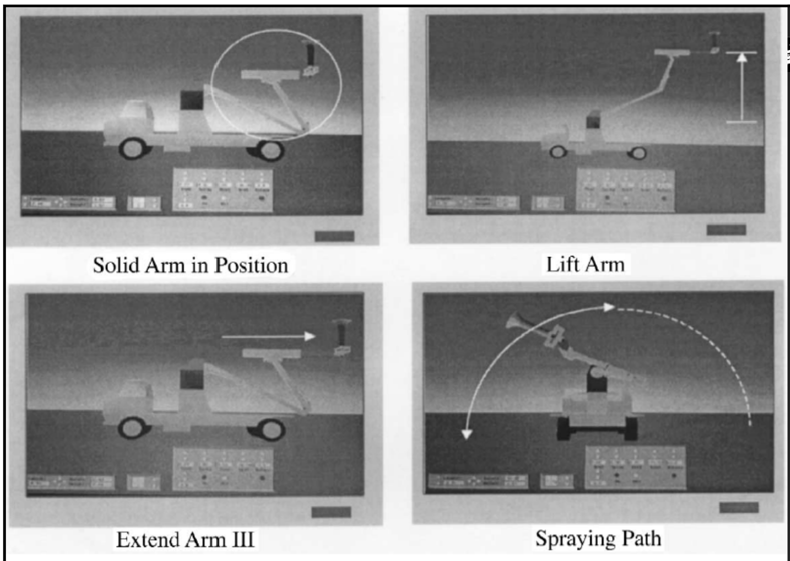

Solid Arm in Position

Lift Arm

Extend Arm III

Spraying Path

Fig. 5. Graphic animation model.

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The shotcreting robot has an arm with six degrees of freedoms, which is remotely controlled by an operator. Due to current utilization drawbacks, an improvement plan has been developed in two stages. First, the control system of the semi-automated robot was improved by reducing the number of joysticks from six to two, incorporating a real-time computer simulation model enhanced to identify model feasibility. Second, the robot was enhanced from semi-automated to fully automated. Thus, an automated profile measuring instrument is used to measure the excavated surface and a simulation model calculates the nozzle path for shotcreting. The automated shotcreting robot was completed by integrated the graphical model with the robot control system [23]

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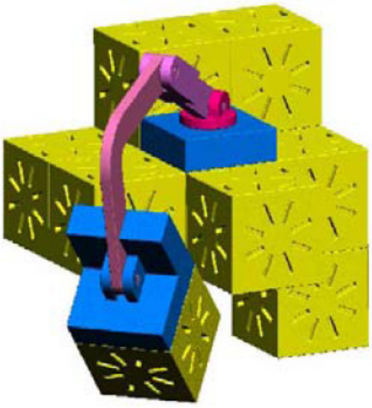


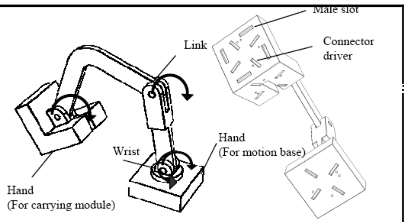
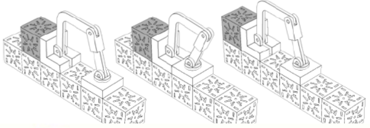
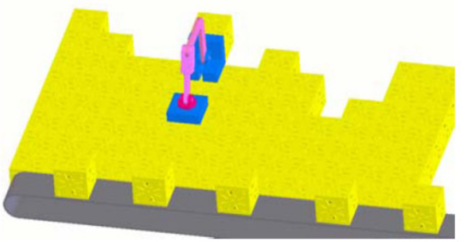


Fig. 4 Assembler robot





Construction work should be simplified by introducing modularity into both structural components and means of assembly. Based on this idea, we have proposed a novel concept of fully automated construction system called Automatic Modular Assembly System (AMAS), which drastically reduces the difficulty of automated construction task [21]. The system consists of cubic structure modules and assembler robots compatible with the modules. The assembler robots transport and assemble the modules to build a large-scale structure without any human intervention. In [21] the focus is on the coordination problem among multiple assembler robots, and a distributed algorithm based on the gradient field has been proposed.

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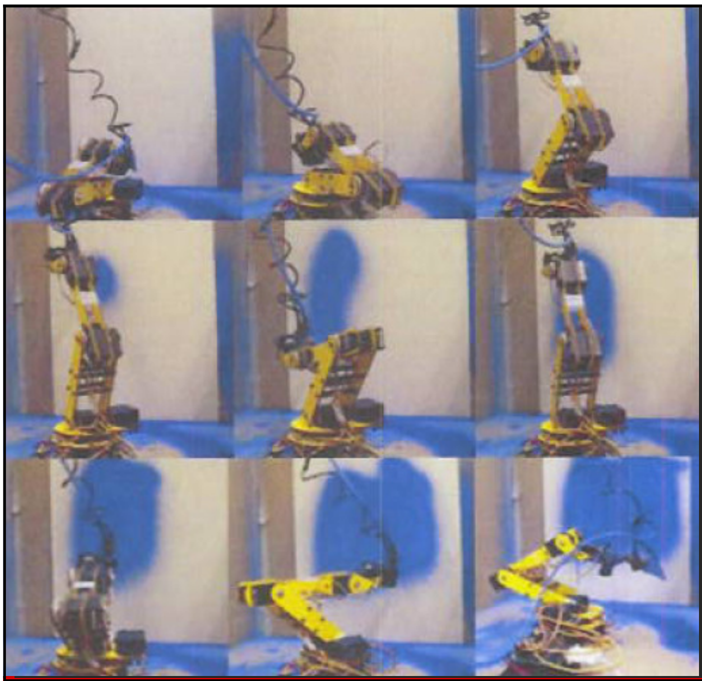

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Set up of a robotized system for interior wall painting [18].

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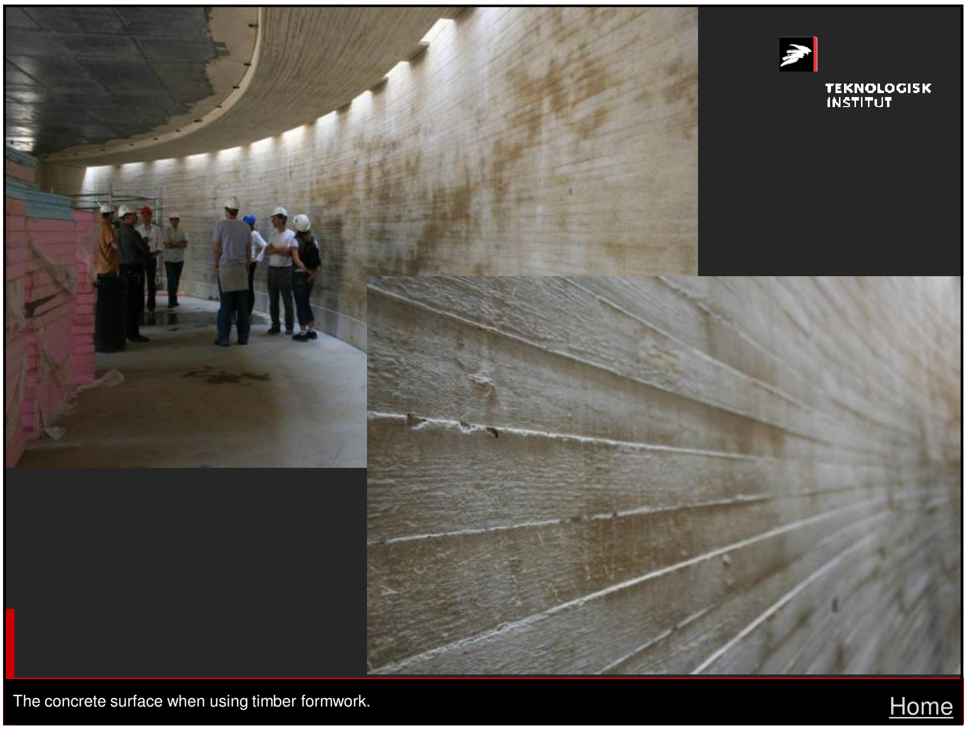

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The concrete surface when using timber formwork.

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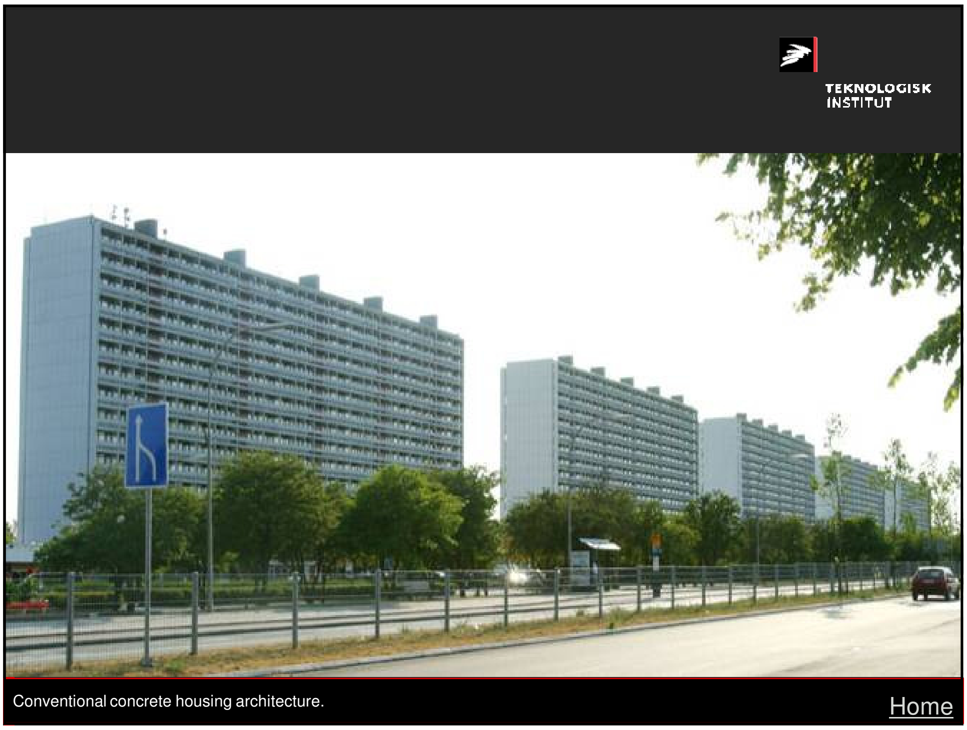

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Conventional concrete housing architecture.

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