In-situ concrete building – Innovations in Formwork

Ingemar Löfgren (M.Sc. in Civil Engineering) and Kent Gylltoft (Professor. Dr.)
Department of Structural Engineering, Chalmers University of Technology, Sweden.
Tomas Kutti (Dr.) – Head of Research of Thomas Concrete Group.

1. Introduction

In the ongoing research programme, which is a collaboration between Thomas Concrete Group[1] and Chalmers University, principles and methods for industrialised building with in-situ cast concrete are investigated. The goal is to increase the understanding of industrial building/construction with in-situ cast concrete and the primary aim is to develop new/improved methods and formwork systems. The study is focused on permanent formwork systems with the main application for slabs. The aim of the new formwork system is to reduce arduous and costly labour activities and to achieve a more industrialised construction. Apart from development of formwork systems, there are several areas for improvement in the concrete industry. They include buildability, operational methods, logistics and supply chain management, resource allocation, information technology/management, etc.; these are studied more briefly in this project.

There is a general consensus in the building and construction industry that innovations are the key to success and that innovative approaches are needed in design and construction. Developments in material and production techniques are also needed. Even though the construction industry has continuously developed during the years, there is need for a fundamental cultural and technical change. The constructions of concrete buildings need to be more efficient and industrialised; this is necessary for the competitiveness of in-situ concrete and essential if the construction industry is to move forward. At present, the expenditure on labour (preparation and dismantling of formwork, reinforcing, and casting and finishing of concrete) almost equals the cost of material (roughly 40 percent is labour). Consequently, the need to reduce the manpower involved is obvious. Development towards ‘on-site’ industrialisation of in-situ concrete construction presents challenges for all parties involved (i.e. clients, consultants, designers, contractors, and material suppliers). From the viewpoint of structural engineering there is an urgent need to address these problems, to look for innovative design solutions and to develop new building/formwork systems.

2. Industrialised construction

The term ‘industrial building’ is often misinterpreted and at occasions it is used with a negative meaning - for many people the term is inextricably linked to the 1950s and 1960s. To compose a straightforward and clear-cut definition of industrialised building is perhaps not as easy as one might imagine, since different forms and techniques exist. Nonetheless, CIB W24 (International Council for Research and Innovation in Building and Construction, work group 24 [1]) has made an effort and offers the following, quite general, definition: “*Industrialised Building is the term given to building technology where modern systematised methods of design, production planning and control as well as mechanised and automated manufacture are applied.*”

2.1 General views

A typical building today consists of several standardised and industrially manufactured components (e.g. doors, windows) – components no one would consider manufacturing on

---

[1] Thomas Concrete Group is a multinational ready-mixed concrete company with enterprises in Sweden, USA, and Germany.

site. Building materials, as well, are industrially manufactured in factories (such as reinforcement, prefabricated elements, and ready-mixed concrete, etc). Unfortunately, the industrial production often ends in the factories and the construction, on the building site, is still craft-based production (or manufacturing on site). Industrialised construction of in-situ concrete buildings should be seen as an attempt to move from largely craft-based production to a systematic production process where resources are utilised efficiently. Furthermore, it involves the application of modern systematised design, production planning and control as well as mechanised and automated manufacturing processes; see Sarja [2]. It is important to make clear that industrialised building does not automatically imply increased productivity, reduction of man-hours, or a better economy. However, it offers these possibilities if a holistic concept is applied. Likewise, production indoors, in a factory, can also be craft-based (or manual) which implies that it is not the location that is decisive, but the conditions are important – the benefit in this case is that the workers have a roof over their heads. There is a broad spectrum of techniques available for industrialised building. It is impossible to mention all because, firstly, the techniques are steadily under development and new ones being invented and, secondly, opinions differ on whether a technique is or is not 'industrial'. In any case, techniques mentioned in connection with industrial building include the following:

- standardisation (e.g. components, methods, processes or dimensional standardisation and modularisation);
- prefabrication (manufacturing of components beforehand, similar to off-site fabrication);
- on-site fabrication (manufacturing of components on site or in a field factory);
- pre-assembly (materials, prefabricated components and/or equipment are joined together for subsequent installation);
- the building system (a product system with an organised entity consisting of components with defined relationships, including design rules);
- mechanisation (the use of mechanical equipment instead of manual labour); and
- automation (utilisation of programmable machines – e.g. robots – performing tasks, or of computerised tools for planning, design and operation).

Most people probably associate industrialised concrete building with precast concrete. It was during the mass production era, in the 1950s, 1960s and 1970s, that the first steps towards more industrialised construction started. However, industrialised building does not necessarily equate with mass production – industrialisation can be achieved in one-off projects by adopting system-based solutions. A system-based solution should include a concept of structural elements - which may be project specific - having standard interfaces so that they can be assembled in a simple and standard manner. Furthermore, it should also include predefined manufacturing and construction process with for instance Just In Time delivery.

2.2 Industrial in-situ cast concrete building

One may ask whether industrial in-situ cast concrete building is a paradox. It could be argued that, at times, it is used incorrectly and a more 'correct' term would be mechanisation – the reason for using it might be for marketing purposes. That it is a paradox (or a contradiction) is not true – there are no reasons why in-situ cast construction cannot be industrialised. As discussed earlier, the location is not decisive, but the systematised methods are. By improving site conditions, introducing new building systems, and adopting a system approach to its employment, industrialisation is a feasible goal. However, it requires that all parties involved (clients, designers, contractors, and suppliers) strive towards the same goal – the goal of industrial in-situ cast construction. In retrospect to the mistakes made with other forms of industrialised construction (which failed by not including and considering all steps of the process), a totality concept has to be applied. Actually, this necessitates new methods of work as well as a new philosophy for planning, design, and management. There is a tendency among engineers, whether natural or not, to make each beam and column as slender as possible – the smallest size that meets requirements on strength and serviceability – or to minimise the amount of reinforcement. This procedure will result in maximum economy of material but will certainly not result in minimum cost of the finished product. The keys to success and the foundation of industrial production are usually simplicity and repetition. Hence, the designer needs to understand the site activities, have a distinct picture of how the work will be conducted, and know which equipment is available. The designer also needs to comprehend which possibilities are offered and the limitations that are introduced when deciding on a solution. Camellerie [3] declares: *"designers need to orient the design to the men and machines who build the structure and the materials, times, and environment in which it will be built."*

3. Construction costs and distribution of labour activities

Building costs are a subject that has been studied thoroughly over the years and it is useful to study these to get a better understanding of the influence of various designs options. Several factors influence the total expenditure: material choices, labour costs and the working hours of those involved in executing the work, and cost for machinery used in executing the work. Furthermore, the cost of capital (financing) for the investor as well as the contractor has to be considered. A comparative breakdown of the construction costs of a concrete building (office or residential) reveals that the superstructure represents approximately 10 to 15 percent of the total cost. The costs for the concrete superstructure can generally be divided into formwork, reinforcement, concrete, repair of surfaces, and remaining (e.g. prefabricated elements). Before the process of improvement can commence, it is necessary to understand the current practice, its process, and the operations (or tasks) involved. Construction data for 11 office- and 16 house-buildings (built between 1989 and 1993) have been compiled by the Swedish Ready-Mix Association [4]. These data have been analysed in order to get an overview of the distribution of man-hours between the different operations and to get a picture of where major improvements are to be made. The analysed data refer to the relative distribution of construction costs for the concrete superstructure. Table 1 shows the relative expenditure for the concrete superstructure (material and labour costs). As expected, reinforcement and, above all, formwork are the most labour-intensive activities, while concrete accounts for the main part of the material costs.

Table 1. Approximate proportional cost breakdown (material and labour costs) of a concrete structure [4].

	Cost of material	**Cost of labour**	**Total**
Formwork	14%	18%	32%
Reinforcement	10%	8%	18%
Concrete	30%	4%	34%
Repair	1%	5%	6%
Remaining	9%	1%	10%
Total	**64%**	**36%**	

The distribution of material and labour costs naturally differs between the projects, and additionally, the market situation affects the price of material and the cost of labour. However, the distribution of labour costs mainly depends on the methods and equipment used in construction, and is not so dependent on fluctuations of the market. Hence, the importance of the tasks is better understood by studying the distribution of man-hours. As can be seen in Figure 1, almost 50% of the total work on a concrete structure can be referred to the formwork; reinforcement operations require roughly 22 percent of the work; while concrete operations represent only 11 percent. On the other hand, if rework to fix surfaces (rework 15 percent) is added, it gives concrete a share of 26 percent.

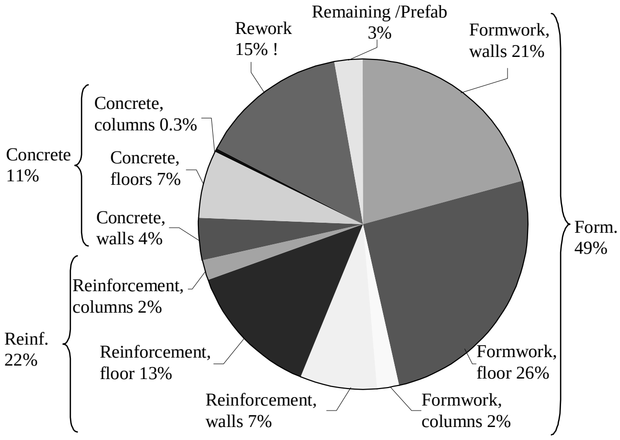

Figure 1. Approximate relative breakdown of man-hours for a concrete structure, average values [4].

4. Concrete Construction - improvement opportunities

In the construction industry, it is generally agreed that there are opportunities for improvement and development of concrete construction – the opinions on how to improve, and the means to use, probably differ depending on whom you talk to. Development can generally be divided into two categories: process development and product development. Examples of process development are management, planning, logistics, etc., while product development includes materials, components and systems. For example, research in material science has led to the development of new types of concrete (e.g. self-compacting and high strength) and new types of composite and fibre reinforcement. The challenge for the designers, suppliers, and contractors are to utilise these developments for innovations in construction methods and building materials/systems – holistic concepts for cost effective and production efficient building.

The Swedish part of Thomas Concrete Group participates in all stages of a project – from the early phase working with planning and design to delivery and construction. The aim is to assist the client to an optimal solution with regard to performance, functional requirements, quality, and cost. In addition, the company also manufacture permanent formwork systems (the semi-precast element or lattice girder element). The company has recently been involved in several projects where innovative construction methods and materials have been used. For example, a new tunnel for the E6 highway in Sweden (north of Uddevalla), it consists of two pipes with a length of 160 meters (see fig 2). The tunnel lining was cast using self-compacting concrete. As a result, the contractor managed to reduce the total cost and the manpower, the quality of the surfaces was excellent resulting in no repair. With the experience gained within these projects, it has been realised that there is need for development of in-situ cast concrete construction. For instance, the formwork and the shoring process is seen as a hindrance and a problem. Furthermore, it has also been realised that there are techniques available today that would significantly increase the productivity and rationalise the construction. However, there are some barriers that impede the use of these new techniques, some of the barriers can be summarised as follows:

- obstructive procurement practices;
- unpredictable market cycles;
- complex regulatory environment;
- shortage of approval mechanisms; and
- fragmentation and adversarial relationships.

Figure 2. View of the tunnel lining cast with self compacting concrete.

In view of this, a short presentation of recent developments and improvement opportunities will be made in the following section.

4.1 Innovative technology for in-situ concrete building – recent developments.

Innovations can be put to use at every stage of the construction process - from design to demolition - and in any system, whether it is hardware, software, materials, systems, or management processes. For the uninitiated, who is unfamiliar with the industry, the work conducted on a construction site may seem as low-tech. Hence, it is easy to come to the conclusion that very little development has taken place. However, if one take a closer look one will notice many changes. For instance, the development of building materials, where high-quality and high-strength steels and concrete, plastics, glass, aluminium are used in construction today. Nowadays there is no problem to build the tower of Babel, structures reach hundreds of meters into the sky and they are bold and slender. This development would have been impossible if it were not for the development of materials, the modern construction equipment (e.g. hoisting gear and cranes), and the advanced design tools (e.g. CAD and Finite Element software). The incentives for the development of structural building systems and new materials are:

- economy (i.e. equivalent performance as existing system but to a lower cost per square meter);
- time (i.e. equivalent performance as existing system but shorter construction time); and
- improved performance (e.g. longer span, greater flexibility, better acoustic environment, better working conditions).

The concrete industry (suppliers and contractors) is constantly under pressure to improve productivity and reduce costs without lowering the standard of quality of its products. This driving force for technical development has had effects on both concrete and reinforcement technology. The result is new types of concrete and reinforcement as well as new building systems and methods. In a similar manner, the development of information technology (construction IT) has presented new possibilities and methods of work for the planning, design, manufacturing, transport, construction, and operation and maintenance of buildings.

In this section a limited number of techniques and research projects will be discussed - innovations well suited for an industrialised construction process - in order to illustrate the existing potential and to introduce ideas/materials that will be utilised in the continued work. Some examples of recent product developments are:

- Concrete technology - Self-Compacting Concrete (SCC), Lightweight Aggregate Concrete (LWAC), and High Performance Concrete Joints;
- Reinforcement technology - Fibre reinforcement and prefabricated systems (e.g. Batmtec®);
- Permanent formwork system - TRUSSDEK™ a patented permanent formwork system (OneSteel, see www.onesteel.com.au);

4.1.1 Concrete Technology

The concrete industry has developed into a high-tech industry in recent years; progress has been enormous, notably is the improvement of concrete strength. However, it is not only strength that has been increased. Lately other material properties have been recognised as equally important – for example, permeability, ductility, and workability. It is now possible to obtain certain predefined properties by adapting a certain mixture composition; to quote Walraven [5], the era of “tailor-made concrete” has arrived. For example, Self-Compacting Concrete is a customised concrete well suited for a mechanised and automated manufacturing process and will result in new possibilities of mechanising the work tasks and reducing the site labour. In a research project investigating rational production systems by utilising self-compacting concrete (SCC) it was found that SCC rationalised production and that the advantages were numerous (Grauers [6]):

- rationalised concrete production, faster construction and less casting time;
- reduction in labour at the building site;
- better working conditions and reduced health problems for the workers;
- good homogeneity, improved quality and durability, and smoother surfaces; and
- easier casting in difficult situations, e.g. complex forms or congested reinforcement.

Lightweight Aggregate Concrete has the advantage of reduced dead weight and better thermal insulation ability. By reducing the dead load longer spans can be achieved (resulting in fewer columns or un-propped permanent formwork) and savings can be made on the foundation. However, there is need for further development and research to be able to present an economical solution. As stated in the fib Bulletin 8 [7], *“The challenges for the aggregate industry are thus to produce an aggregate with*

- *high strength;*
- *low weight;*
- *good production properties (low water absorption); and*
- *reasonable price.”*

4.1.2 Reinforcement Technology

Today there are several different products, techniques, and materials available for reinforcement of concrete; they are a mix of ‘high-tech’ and ‘low-tech’. Sandberg and Hjort [8] remark: *“at the same time as there are advanced technical possibilities for prefabrication of reinforcement much of the work is conducted traditionally and manually (mostly on site) often leading to bad working conditions, poor quality, and a high total cost.”* Nevertheless, the use of prefabricated reinforcement increases and it is a technique for the future – the possibilities to reduce site activities are considerable. For example, it has already become common practice to use prefabricated wire-mesh mats. However, there remains much more to be done in these areas. An example of an innovative reinforcement system, developed lately, is BAMTEC® (see figure 3), which is a reinforcement carpet for slabs (a production level of 4.5 tons/man-hour has been achieved; see www.bamtec.com).

Figure 3. Bamtec, from www.bamtec.com.

Fibre-reinforced concrete (FRC) has recently enjoyed a breakthrough in the construction industry, numerous scientific reports have been published and new products are developed. Fibres are mainly added to control cracking in the service state and to increase the ductility, other enhanced properties of the concrete include: tensile strength, compressive strength, elastic modulus, reduced plastic shrinkage, durability, etc. One disadvantage of fibres is that it is difficult to control their distribution, resulting in a fairly high and uneconomical fibre-ratio. Textile Concrete is a recent development that offers a solution to these problems. By producing planar fabrics the fibres can be oriented in the main direction and placed where they are needed, see Curbach et al [9].

Densit® (see www.densit.com) is an ultra high strength fibre reinforced concrete - a concrete with remarkable performance. However, due to the high cost - three to four times the price of ordinary concrete – it has limited economical applications (at least at the moment). For example, it is suited for connection details and joints since it allows short anchorage lengths and thus simple solutions.

4.2 New technology – always a solution?

Bearing in mind the innovations, a word of caution may be in order: "E*very improvement is the result of change, but … not every change is an improvement*" [10]. There is a widespread notion that by adopting state-of-the-art technology, problems will be rectified and an improvement achieved. However, history shows otherwise; Girmscheid and Hofmann [11] remark that industrialised construction often failed by prioritising the production while ignoring product and management processes. Koskela [12] and Warszawski [13] draw similar conclusions. To avoid such mistakes it is important (if not necessary) to study the building process and methods in use today, in order to realise the importance of a totality (holistic) concept – a concept including all steps of the process (i.e. planning, design, manufacturing, transport, erection/construction, and operation and maintenance). In Lean Production, e.g. Koskela [14], it is suggested that major investments in new technology are to be considered only after improving the present process; implementation of new technology is easier in controlled production processes. Or to quote Badger [10]: *"It is relatively easy to create new technology, but the payback remains low until tools and processes are developed and people take ownership of the new knowledge."* It is often neglected, or not properly understood, that many problems are caused by basic structural deficits within organisations (i.e. the management, planning, and methods of work) and cannot be solved solely by means of new technology.

4.3 New building process – a prerequisite for innovations and new technology!

The current building process is beset by many problems; each of the parties to the process has helped to develop it, but only from his own needs and views, and competition is mainly focused on lowest cost instead of quality, sustainability and customer-perceived value. Thus, the building process is fragmented and the link between the client/end-user and the producer is weak, and the same can be said about the link between designers and contractors - this is a major impediment for innovations. The problems in the construction industry have led to governmental reports: e.g. in Sweden, the Swedish Delegation for Construction Cost, SOU 2000:44 [15]; in the United Kingdom, Rethink Construction, presented by Egan [16]; and the European Commission's 'The Competitiveness of the Construction Industry' [17]. Brian Atkin asserts that the building industry has a 'best' method of working within reach, [15]. These reports point out deficiencies in the building industry and give recommendations for a changed project process. Some problems that must be addressed are:

- the industry must replace competitive tendering with long-term relationships based on clear measurement of performance and sustained improvements in quality and efficiency;
- the need to focus on life-cycle design and encompass whole-life costs;
- clients need to formulate clearer project goals and specify priorities regarding quality, cost, and time; and
- clients need to understand the importance of the design stage and accept that it requires time.

5. Permanent Formwork Systems – Innovations needed

The cost of formwork is an essential element in the total cost of an in-situ casted concrete building. As shown in section 3.1, the cost of a concrete element (e.g. a slab or a beam) can be separated into the cost of labour (the cost of the employee and the time required to construct it) and cost of the material used. These are the two primary factors that affect the economics of a system. When analysing construction costs from actual projects it was established that formwork is the most labour-intensive activity. Permanent formwork is an attempt to rationalise the construction, and two different types can be distinguished (as well as two different materials - reinforced/prestressed concrete and steel decking):

- leave-in-place forms, which derive their economy from saving the cost of stripping and cleaning; and
- participating forms, which function as an integral part of the structure when in service; they achieve their economy by saving the cost of stripping and cleaning, by replacing some of the reinforcement, and by composite action adding to the load-carrying capacity.

Patrick [20] suggest that because a composite, permanent, formwork can serve dual roles – firstly acting as the formwork before the concrete hardens and than as a integral part of the structure – economic advantages should result compared using removable formwork systems. For example, permanent formwork usually reduces site manpower and the floor-cycle time but increases the material cost. In a case study of seven construction projects (Burwick [18]) the advantages and drawbacks of permanent formwork (precast concrete panels) were investigated. All projects demonstrated time savings of 10 to 35 percent and the system required fewer workers (by 10 to 30 percent). Other advantages were better surface finish (less rework) and improved working conditions.

The recent advances in material technology (e.g. high strength steel, concrete, and fibre reinforcement) and the development of analysis methods (e.g. advanced Finite Element Models) that has made new innovative concepts possible. For example, the demand for unpropped construction – less congestion and disturbance - and the desire to minimise the needs for temporary works has led to the development of a 'new generation' of permanent steel formwork (e.g. TRUSSDEK™ and Slimdek® SD 225). These systems are capable of spanning 6 m, unpropped, during construction (supporting construction loads and the wet concrete) and up to 12 m in the composite stage. The semi-precast element (solid plank system or lattice girder element) is widely used as a permanent formwork system. It offers many advantages over cast in-situ floors while maintaining the full structural integrity and monolithic requirements of the slab; the use of the product at Cardington [19] resulted in savings of up to 25% being made in both erection and stripping times. However, the semi-precast concrete element used in Sweden (lattice girder element) has a moderate performance during the construction stage and propping is required. The challenge is to utilise new material technology in order to improve these formwork systems. However, it is also important to adapt the systems to the construction process, the workers and the machines – concrete construction is a consecutive process and must be considered as a whole.

5.1 General Design Principles

For a permanent formwork system to achieve an economic advantage is it necessary that it is utilised efficiently during both the construction stage (as formwork) and the composite stage (in the completed structure). To achieve this advantage an optimisation of structural shape, geometry, material properties, combination of materials, thickness of elements, etc. is needed. For this optimisation there are different stages that have to be considered. Patrick [20] identified stages I and II as relevant to the design of the system. However, for a complete design stage III also need to be considered.

- (a) Stage I – prior to placement of concrete, which includes the time:
  - (i) during transportation, handling and erection – e.g. damage during lifting; and
  - (ii) once the formwork is erected but prior to placement of the concrete – e.g. damage from construction loads and temporary stabilisation.
- (b) Stage II – during placement of concrete up until concrete hardens – e.g. deflections during casting and safety.
- (c) Stage III – during usage of the structure, which includes:
  - (i) normal usage (serviceability limit stage) - e.g. deflections, cracks, vibrations, acoustics, thermal comfort;
  - (ii) at overloads (ultimate limit state) - e.g. strength, ductility.

The different stages of the construction process affect the stresses in the serviceability limit stage in a composite structure. As a consequence, the construction sequences and cycle must be considered; e.g. at which time are loads introduced (on the composite section or on the initial section), what is the strength of the concrete at the time of loading, are temporary support used, and will the structure (beam/slab) have continuity after in-situ casting. In addition, when designing composite structures, attention has to be paid to the effects of differential creep and shrinkage as well as the effects of loss of prestress after hardening of the in-situ concrete.

6. Summary

Current concrete construction and design are meeting new challenges from other construction materials and techniques (e.g. steel, precast concrete, and timber). The 'on-site' industrialisation of concrete construction is intended to address this challenge and the problems affecting the construction industry. New building/formwork systems for site-cast concrete structures are expected to have a strong impact on production efficiency and market shares. New building/formwork systems has the potential to reduce on-site labour, increase productivity, improve quality, result in efficient material usage, and shorten the time between project commencement and occupation of the building by paying tenants. It will, however, require improved materials as well as a design and construction management able to plan and control their use. Furthermore, the 'one-off mentality' is something that the industry must abandon if it is to move forward and improve. Projects must be designed for ease of construction, and the knowledge possessed by builders and material suppliers must be utilised in order to reap the full value, and to be able to realise the potential, of concrete as a construction material. It can be concluded that there exist considerable opportunities for improvement in the construction industry; thus, these opportunities should be exploited. However, there is need for a cultural change and that client decision-making, design and production management have to be changed. Many of the problems in the building and construction industry concern fundamental deficits within organisations and methods of work, and thus cannot be solved solely by means of new technology.

7. References

[1] Asko Sarja CIB W24: Glossary of characteristic properties of open idustrialised building, 1996. (http://cic.vtt.fi/cib_w24/cib4.html).
[2] Sarja, Asko: Open and Industrialised Building. CIB Publication 222, Report of Working Commission W24. E & FN Spon. London, 1998, pp. 3-94 &159-184.
[3] Camellerie, J.F.: Construction Methods and Equipment. Handbook of concrete engineering. Edited by Fintel. Van Nostrand Reinhold, New York, 1985, pp. 793-819.
[4] Betongbanken. Construction data compiled by the Swedish Ready-Mix Association – received on 02-05-00 from Frank Johansson – personal contact.
[5] Walraven J.: The evolution of concrete. Structural Concrete – Journal of the fib. No. 1 March, pp. 3-11. Thomas Telford, 1999.
[6] Grauers, M.: Rational production and improved working environment through using self compacting concrete. Brite-EuRam project BRPR-CT96-0366, 1998. (http://scc.ce.luth.se/public/Summary).
[7] fib Bulletin 8: Lightweight Aggregate Concrete, Recommended extension to Model Code 90. Lausanne, 2000.
[8] Sandberg, J. & Hjort, B.: Rationell armering – ergonomi – ekonomi – miljö. Fundia Bygg AB, 1998. (In Swedish.)
[9] Curbach et al: New building material – Textile Concrete. Betonwerk + Fertigteil-Technik, BFT 6/1998, pp 45-56.
[10] Badger, W.: Wisdom in Managing the Construction Process – Construction Forum. Practice Periodical on Structural Design and Construction, February 2000, pp. 92-95. ASCE.
[11] Girmscheid, G. & Hofmann, E.: Industrielles Bauen – Fertigungstechnologie oder Managementkonzept? Bauingenieur, Band 75, September 2000, pp. 586-592. Springer Verlag.
[12] Koskela, Lauri: An exploration towards a production theory and its application to construction. VTT Publications 408. Technical Research Centre of Finland, Espoo, 2000.
[13] Warszawski, A.: Industrialized and automated building systems – A managerial approach. E & FN Spon, London, 1999.
[14] Koskela, Lauri: Lean production in construction. In Lean Construction, edited by Alcarón. A.A. Balkema, Rotterdam, 1997, pp. 1-9.
[15] SOU 2000:44: Från byggsekt till byggsektorn. Byggkostnadsdelegationen, 2000. (In Swedish.) (http://www.regeringen.se/propositioner/sou/index.htm)
[16] Egan, Sir J.: Rethink Construction. The Construction Task Force. Department of the Environment, Transport and the Regions. London, 1998. (http://www.construction.detr.gov.uk/cis/rethink/index.htm)
[17] European Commission. The Competitiveness of the Construction Industry. Version 3.3. (http://europa.eu.int/comm/enterprise/construction/old/construc/constpol.htm)
[18] Burwick, M.: Betongbyggande med kvarsittande gjutformar – en jämförande studie. Examensarbete 334, Avd. för byggandets organisation och ekonomi, KTH. Stockholm, 1998. (In Swedish.)
[19] European Concrete Building Project: Best Practice Guides: Improving concrete frame construction. Concreteing for improved speed and efficiency. Rationalisation of flat slab reinforcement. 2000, http://www.bca.org.uk.
[20] Patrick M.: The Application of Structural Steel Decking in Commercial and Residental Buildings. Malaysian Structural Steel Association, Convention 1998.