Towards the Reduction of the Construction Time and Cost of Reinforced Concrete Earthquake-Resistant Multistory Buildings

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Abstract
The purpose of the present research is the reduction of the construction time in the structural system of a tall concrete building with the higher goal of reducing the time required for the construction of the whole project. This reduction can be achieved mainly through removing the beams of a multi-storey building (flat slab) and through using modern science achievements in the field of materials (concretes with high manifestation of their strength). The time required for the construction of one floor is about 4 days. In this way it is easy to improve the economy, the functionality and the aesthetics of the final project without losing any earthquake protection. Thus, reinforcement concrete can be used in buildings' projects where the speed of the construction process is of a high priority. Steel is no more the only alternative solution in such cases. The owner and the contractor of the project can both be benefited by using these techniques for many reasons. The reduction of the construction time can affect the cost of the project by reducing it, while the earlier completion of the whole project offers important advantages.

Keywords
reduction of the construction time, tall concrete buildings, flat slab, time management

1. Introduction

Building structures constitute the first strand of the investment activity and, as a consequence, the study of the financial data of these projects is of high interest. The profitability of a financial investment in a project is directly related to the time required for the completion of its construction, so, the effort to save time during the manufacturing process is critical to the overall success of a project. Through the capabilities of science, it is possible to significantly reduce the construction time of a building project, while considerable savings can be achieved. It is well known that reinforced concrete structures are commonly used in countries with high seismicity, instead of steel buildings. The advantages of such structures originate from parameters such as seismic capacity, serviceability, cost and aesthetics. In addition, a reinforced concrete building provides more safety against fire, and also the maintenance cost of a steel building is high. On the other hand, the advantages of steel buildings are the low self-weight, which allows the construction of long spans, as well as the rapid construction. In concrete structures where the spans' length has to be increased, the solution is the use of prestressed concrete. While the last advantage of the steel structures is the rapid construction of the structural system, the aim of the current study is the reduction of the construction time in the structural system of a tall concrete building with the higher goal of reducing the time required for the construction of the whole project. That aim can be achieved mainly by the construction of flat slab buildings.

The main advantage of the steel structures is the reason why some of the buildings in countries with high seismicity have been erected in this way. A characteristic case of that situation is a building at the region of Kalamaria in the city of Thessaloniki. The profits resulting from the rapid construction of the building were significant for the contractor, and the criterion for the choice of the structural system was the time required for its completion. The solution was a steel building, as well as reinforced concrete was used for the basement. Many structural engineers avoid the design of flat slab buildings due to the response of such structural systems under seismic loading. In particular, structural engineers are influenced from the major earthquakes in Central America in the 60's. (Erberik & Elnashai, 2003) However, modern codes (CEN, Eurocode 2 & 8, 2004) have special provisions concerning such buildings, under seismic loading. One of the pioneering efforts to reduce the construction time of the structural system of reinforced concrete buildings has been held in Germany-Stuttgart at the end of 80’s. Especially, the Office building for EVT in Stuttgart, having a total area of 20000 m^2, is a flat-slab 6-storey building. Some of the main characteristics of that structure are the long spans (8.64 m), the long cantilevers (3.6 m) and the absence of expansion joints for a longitudinal dimension of 80.6 m (Figure 1). Prestressed concrete was used for the slabs and the main advantages resulting from that solution are the low total building height, through the absence of the beams, as well as the elimination of time-dependent deflections of the cantilevers. The most important advantage arising from the use of post-tensioning is that 1 to 2 days after the setting of the concrete, the formwork was removed, and used for the next section of construction. The reduction of the time required for the completion of one slab led to the reduction of the total construction cost. (H. Dinkelacker et al., 1990). Another effort in order to achieve that aim has been held for the construction of the hotel “Stuttgart International”. It is a 25-storey building and the first flat-slab building constructed in Europe having drops and unbonded prestressing. The span lengths of the structure are between 6 and 13 m, as well as the cantilevers’ length is 2.9 m. The building was erected in record time, as the time required for the completion of one floor was 4 days. It has to be mentioned that while at the 17th floor the setting of the concrete was taking place, the carpets were placed at the lower floors. (H. Dinkelacker et al., 1997). The current study examines the means that can be used for the construction of an 8-storey building, so that the rapid construction of the structural system can be achieved, in comparison with a conventional solution.

Figure 1: Office building for EVT in Stuttgart

2. Increment of the Construction Speed of the Structural System

The total construction time of the structural system of a tall concrete building depends on the time required for the construction of the typical floor. As the horizontal elements of the building (especially the slabs) are the major part of the construction of the structural system, their completion is a crucial factor in determining the time requirements of the whole project. Therefore, certain changes can be made in the construction of the slabs of a building through appropriate choices so that a high speed of construction and significant time savings can be achieved. The correct estimation of the time required for manufacturing a selected floor system also provides a good basis for predicting the total construction time for the whole building.

The reduction of the construction time of the structural system can be achieved through (Naveed, 2013):

- The use of prefabrication (preconstruction)
- The use of automated methods
- The reduction of the structural components of the system
- The use of innovative structural systems
- The use of innovative manufacturing process
- The use of the techniques of project management

3. Conventional Construction Methods

The main steps for the construction of a typical floor in a conventional building are:

- The construction of the formwork of the vertical elements
- The installation of the reinforcement of the vertical elements
- The setting of the concrete of the vertical elements
- The construction of the formwork of the beams and the slab
- The setting of the reinforcement of the beams and the slab
- The setting of the concrete of the beams and the slab

Based on data collected as part of this work, from four construction companies in Thessaloniki for an average building, (about 400 m^2 floor area) 7-15 days for making a typical floor are required. Those data are based on actual duration values. After statistical analysis of the data collected, it possibly takes about 10 days (Figure 2) for a typical floor to be completed.

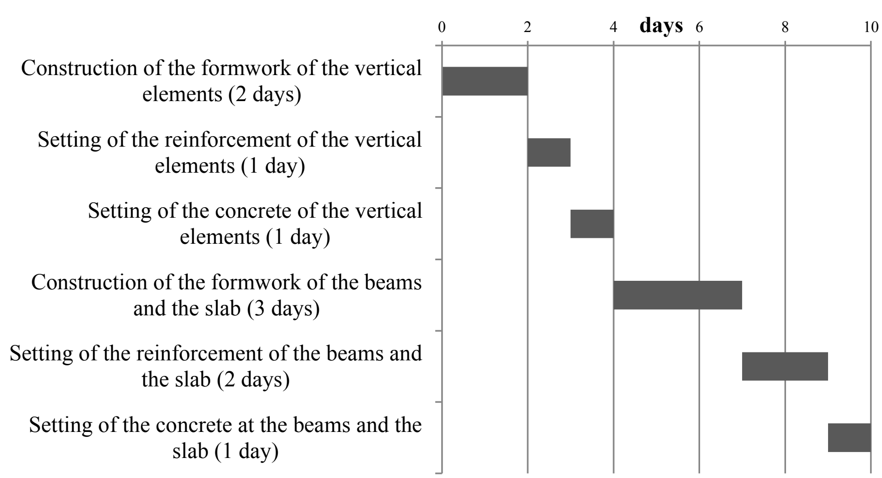

Figure 2: Gantt diagram for the construction of a typical floor of a conventional building

4. Reduction of the Construction Time

The reduction of the construction time of a typical floor of a tall concrete building can be achieved by the use of:

- Slabs without beams (flat slabs)
- Modern concretes having increased reliability and performativity
- Prestressed concrete, especially in cases of slabs with large openings
- Fabrication of the reinforcement
- Circular columns

4.1 Flat Slabs

The use of structural systems with slabs without beams (flat slab) contributes significantly to reducing the construction time of the building. The benefits in terms of design speed of such systems are even greater in the case of flat slabs without drops. The reduced construction time is directly related to the ease of installation of the panel formwork, which is very simple and cheaper than the formwork used in the conventional buildings with beams. The flat slab design facilitates the use of the flat formwork in large parts, increasing finally the productivity in the whole procedure. In addition, the use of the reinforcement mesh by placing additional bars, where it is necessary, contributes to the reduction of construction time. Flat slabs facilitate the manufacturing process because of the use of pre-constructed components (formwork, reinforcement), increasing the speed of construction, as it requires less time for their placement, improving control during the manufacturing process and increasing productivity. Moreover, the ease of setting the concrete plays an important role in achieving the objective goal, which is the reduction of the construction time of a typical floor. Obviously, it is common in such structures to use fewer staff to perform a task. Therefore there will be a significant reduction in labor costs and overall cost savings of the site if a reduction of the construction time of the building can be achieved.

The main drawback of these structural systems is the sensitivity of punching shear and against the risk of collapse chain which may be caused by a local failure. Therefore there are several concerns about the implementation of such structural systems in areas with intense seismic activity such as Greece. To solve this problem, it is necessary to increase the thickness of the slab. This is accomplished either by increasing the thickness of the whole slab or by increasing the thickness of the slab locally over the additional dead loads in the system, requiring larger vertical elements which obviously increases the requirements of the foundation making it consequently an uneconomical solution. As the slabs of the floors are the dominant part of the mass of the building, it is imperative to achieve the best economic solution. Therefore the avoidance of increasing the total thickness of the slab helps reducing the cost and the self-weight of the slab. So, it is necessary to use drops at the top of the vertical elements in order to increase the thickness of the slab locally at critical points against punching shear.

However, the construction of drops in the head of the columns creates particular problems, increasing the difficulty of the construction process and the time required for the construction of the formwork as well as the construction of a beam, which contradicts the purpose of the present study. Moreover, it increases the cost and decreases the aesthetic result. Therefore, where the local increase of the thickness of the slab is necessary, the use of reverse drops is the best solution. Reverse drops are made on top of the slab increasing locally, in the critical areas around the vertical elements, the thickness of a critical section. By the use of this type of drop it is possible to achieve significant reduction in the time of the construction of the horizontal portion of the structural system. The formwork of the slab is positioned as in the case of flat slabs providing positive results in increasing the speed of the whole project. However, formwork is required to be constructed on the top of the slab in order to manufacture the reinforced area which introduces time delays in the process but always less important compared with the conventional structure of drop. Although this solution requires more time compared to the solution of slab without drop, it contributes to the economy because of the thickness of the slab. Moreover, it is an appropriate solution when prestress has to be applied at the slabs of the superstructure, due to the prestressing tendon's geometry in such cases. While the reverse drop creates a "barrier" to the upper side of the slab, it certainly constitutes a functional disadvantage. However, the installation of the mechanical equipment of the floor at the rest of the area of the slab could incorporate the reverse drop into the wood flooring that covers those elements.

In areas with high seismicity such as Greece, the increment of the thickness of the horizontal components or the use of punching shear reinforcement often are not proper ways to ensure the construction of punching shear failure and consequently it is required to take indirect measures to address the problem. Therefore it is necessary to place more shear walls in the structural system to minimize the seismic intensity at connections of the slabs with the columns. The major part of the horizontal load is taken up by the walls of the structural system. In critical cases of high horizontal loads or very large displacements of the building, the maintenance of the perimeter beams of the floor plan and the abolition of the internal ones could reduce such displacements significantly. This option introduces time delays in the manufacturing process, less important compared with the conventional construction where the slab is overally supported by beams. The flat slab structural system having drops, without the presence of shear walls or even the existence of a minimum number of beams, is impossible even for a small number of stories. It is not allowed in countries with high seismicity and it is prohibited by the codes.

4.2 Developments in the Concrete Technology

Nowadays, new concrete technologies give special impetus to concrete structures (Mehta & Monteiro, 2014). Basic conditions for early strength development in concrete are:

- The use of concrete fine grinding (CEMI42,5R)
- The low ratio of water to cement
- The use of admixture (curing accelerator)
- The artificial warming at work after casting (only in special cases)

Therefore a high performance concrete derived from a cement of an increased grinding fineness could be used. The increased grinding fineness of the cement usually leads to faster onset of the concrete strength. This type of cement is aimed at achieving its strength earlier than the common types of cement to a wide variety of concrete, easier demolding, easier handling and better implementation of all types of concrete products. The main type of cement used in the construction industry of Thessaloniki is the CEMII42,5. Its cost is around 100 €/ton. The fine grinding cement costs about 102 €/ton. The cost difference between the two types of cement is negligible.

In the concrete mixture a hardening accelerator additive (1%) could be added. New technology hardening accelerators for concrete and mortar cause considerable increase in the early strength, especially before 24 hours. This additive, in accordance with ELOT EN 934-2 P.7, speeds up the development of strength significantly, without negatively affecting the final strength, and increases the early strength (<24 hours). It also facilitates the rapid reuse of the formwork. For example, the use of such an admixture to a concrete type C30/37, with characteristic compressive strength f_{ck} = 30MPa at 28 days since the day of casting is examined. The development of compressive strength equal to 23MPa is obtained in only 18 hours, at ambient temperature 20^{o}C. Therefore, it is estimated that after 24 hours since the casting there will be a compressive strength equal to 27MPa, which is the 90% of its final strength. At the same time it has developed a tensile strength 1,80MPa (with characteristic f_{ctk} = 2,0MPa at 28 days).

Consequently, the removal of the formwork can be achieved in 2 days, with a good maintenance of the concrete. The fast development of the strength of the concrete shows the development in concrete production technology and allows the application of post-tensioning early in the construction, as the concrete at that time will have developed a remarkable percentage of its total strength.

4.3 Prestressed Concrete

Post-tensioning can be defined as the stress state generated in a structural element by the application of suitable and deliberate deformations. The advantages resulting from the use of prestressed concrete in building projects are:

- Less concrete volume required for the construction
- Less conventional reinforcement required
- The quick removal of the formwork, as well as its simple configuration

Moreover, apart from the reduction of construction time and the saving of materials, post-tensioning is the appropriate solution for large openings in structural systems requiring fewer columns and consequently allowing greater flexibility in the use of space and architectural freedom.

4.4 Fabrication of the Reinforcement

The most crucial factor for the strength of the Reinforced Concrete building, especially in areas with strong seismic activity, is the reinforcement which is positioned in its structural system. The more complex, difficult and time consuming part of the specific work is the setting of transversal reinforcement to the vertical elements. Nowadays, the cages or the prefabricated stirrups are both a considerable effort in the fabrication of the construction process. With the use of cages greater economy is achieved in manufacturing costs compared to traditional reinforcement "by hand", greater reliability as regards the correct distance between the bars, and more flexibility in positioning at the construction site.

The use of ready-mesh reinforcement has been established in Greek market and offers speed and convenience of configuration and installation, reduction in labor costs, precision in placement and construction because of the quality control in the industrial production.

It is necessary to respect certain standardization of specific sections of the columns in the structural system of the building projects. Standardization has many advantages such as:

- Reduction of the cost of the construction, because the use of standard molds and standard fasteners is more economical,
- Increment of the quality of the construction,
- Increment of the convenience of the construction and supervision of the structural system

4.5 Circular Columns

In columns of circular cross-section formwork from paper can only be used during the manufacturing process. This type of formwork allows high speed of the manufacturing process and also significant savings in labor costs permitting quick and easy molding, casting and removal of the formwork resulting in significant cost reduction of the entire process, reducing the need for materials and labor.

5. Construction Time Required for the Proposed Method of Construction

Taking advantage of the above options it is possible to achieve a significant reduction in the time required for the construction of a typical floor. The reduction of the time is mainly related to the reduction of the time required for the positioning of the formwork as well as the reinforcement of the slab (easier manufacture). It is also related to the reduction of the required time for the curing and the acquisition of the strength of the concrete. Given that the crews work nine hours a day, it is possible to construct a floor every 4 days. In conclusion, with favorable weather conditions, proper coordination of human resources and correct timing is possible to improve the manufacturing rate of typical floor from 10 to 4 days. The main steps for the construction of a typical floor of a flat slab building are described in Figure 3.

6. Case Study

The current study examines the cost of a regular multi-storey building having beams at the superstructure, as well as the same structure without the internal beams. The examined structure consists of one basement story, ground floor and eight stories. The first, conventional case has beams at the superstructure, dimensioning 0.25 x 0.70 m. The thickness of the slab has been calculated considering Eurocode 2, (CEN, 2004), and its value is 0.20 m. The characteristic of the second case is the absence of the internal beams at the superstructure. The thickness of the slab has been calculated in accordance to Eurocode 2, (CEN, 2004) and its value is 0.24 m. In the conventional building, for the typical floor, 89 m^3 of concrete is required and 12930 kg of reinforcement, with average demand 106 kg/m^3. For the typical floor of the flat slab building 87 m^3 of concrete is required and 16270 kg of reinforcement, with average demand 136 kg/m^3 (Figure 4).

Therefore, the required amount of concrete remains the same in both cases and an increment of 25% in the amount of steel in the second structural system is observed. The cost resulting from increasing the amount of reinforcement used in the case of the flat slab building is outweighed by the cost of the formwork because in such constructions the wear of the material is much smaller and it can be reused many times compared with the conventional construction of the formwork before the completion of its useful life. Furthermore, as the labor cost is considered equal to 25% of the cost per m^3 of concrete according to the collected data, the labor cost is about 45 €/m^3. For the construction of the typical floor of the conventional building, the required labor cost is approximately 90m^3 x 45 €/m^3 = 4050 €. Given that this cost is incurred during 10 days, it is possible to estimate the corresponding labor cost in a proportionate manner in the case where the construction will last four days, which is equal to 1620 € (Figure 4).

The overheads of the construction site are directly related to the project construction time and include costs that are required for the installation as well as its operation. The reduction of the construction time for the structural system of the building implies reducing the time required for completion of the entire project. Therefore, as the maintenance of the construction site is necessary for a shorter period, it is obvious that it will bring about a reduction in all cost items according to the number of days reduced (Papathanasiou et al., 2004).

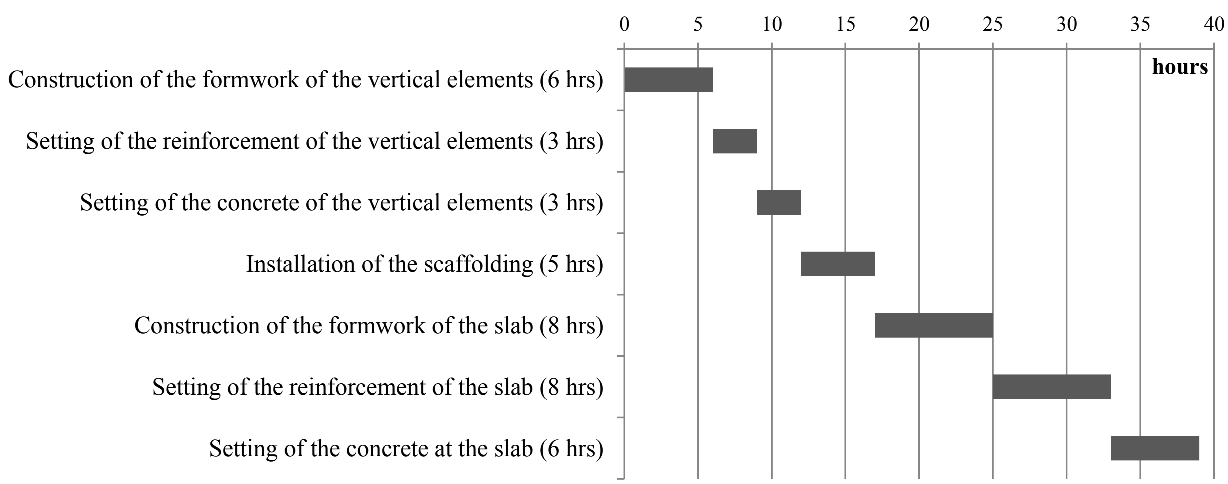

Figure 3: Gantt diagram for the construction of a typical floor of a flat slab building

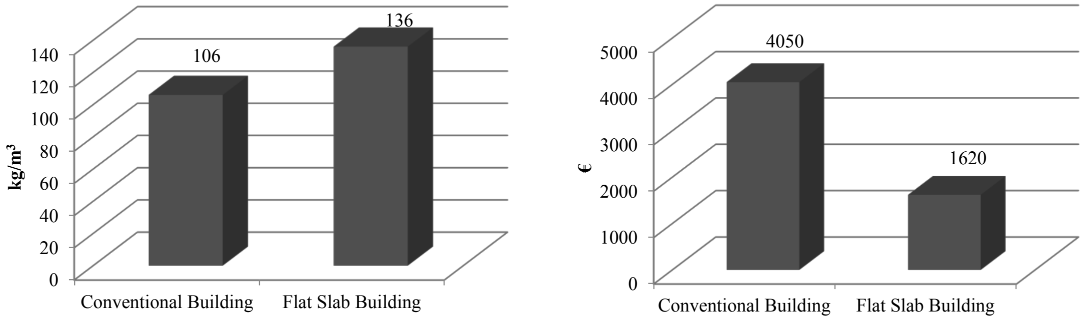

Figure 4: Average demand of reinforcement per m^3 of concrete (left). Labor cost for the construction of the typical floor (Right)

7. Conclusions

The completion of a new floor every 4 days is a record for concrete structures, while the last advantage of steel structures, the speed of construction, is supplanted. Steel structures are not the only alternative solution any more, in case that enhanced speed construction is required. Through the use of new technological means, the whole range of objectives when designing concrete structures, namely serviceability, economy, aesthetics, seismic safety and durability could be achieved. Concrete winning the battle with time seems to excel the number one competitor, steel structures, and continues to be the most reliable manufacturing solution extending its sovereignty to a greater range of construction cases.

It is obvious that the reduction of the construction time in combination with the reduction of the corresponding construction cost, maintaining stable build quality, contrasts with the general principle of project management, according to which a change in one of the essential parts of project management (cost, time, quality), implies inversely proportional change in another. (eg time is increased, cost is reduced).

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