WHICH TYPE OF SLAB IS THE MOST EFFECTIVE SOLUTION TO CONCRETE STRUCTURES?

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Declaration by student

I, the undersigned, hereby confirm that the attached treatise is my own work and that any sources are adequately acknowledged in the text and listed in the bibliography

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Signature of acceptance and confirmation by student

Abstract

Title of treatise	:	Which type of slab is the most effective solution to concrete structures?
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Reinforced concrete has established itself as a favourable material for structural frame construction of the majority of sizeable buildings. As years have progressed, various alternative methods of concrete frame construction have evolved.

The objective of this study is to compare different concrete construction methods in order to reach a conclusion as to which is the most effective. Three well established and commonly used methods are compared with each other as well as with a newly introduced method to the market. The study focuses mainly on the characteristics of each method's slab and compares them by evaluating each slab against various sets of criteria.

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Introduction

1.1 Topic Overview

Most sizeable buildings are constructed with the majority of their structural frame consisting of reinforced concrete. This frame is designed to carry all loads that will be imposed on any part of the structure and to transfer these loads to the foundations in such a way that the earth on which it rests will be able to support the entire structure.

What makes concrete a favoured material in structural components is the fact that it has great compressive strength. It does however have two major weaknesses as well: It is very weak under stress and the severe weight thereof. Concrete's weakness under tension is overcome by reinforcing it with steel which is very strong under stress as well as under compression. Steel thus plays a major role in achieving spans with concrete members and can also play a great role in reducing the size of concrete members which constitutes savings in weight.

Concrete slabs act as flat surfaces, carrying vertical loads imposed on them, as well as the weight of the slab itself, by transferring these loads horizontally either directly, or via beams, to columns. This creates tensile forces within the slab/beam which has to span from column to column. Beams help to reduce the overall thickness of slabs by providing additional strength only in areas where it is specifically necessary.

Columns receive horizontal loads from the slab and/or beams and then transfer it vertically downward to the foundations. The weight of the slab creates compressive forces within the columns which must then be large and strong enough to carry the slabs weight as well as the weight of the column itself. The foundations on which the columns rest must then ensure that the total load of the structure can safely be transferred to the earth on which it rests.

Having explained how loads are distributed throughout a concrete structure, it is thus obvious that the heavier a structure is, the harder it will be to safely anchor it in the earth. Starting from the top downward: The heavier a slab and its beams are, the stronger the columns on which it rests must be. To increase column strength, larger columns with more concrete and steel must be used. This adds additional weight to the structure which necessitates even larger and stronger foundations to safely carry the structure which means even more concrete is used.

As explained above, the larger a structure gets, the stronger its members have to be to safely carry it. To do this, these structural members' size are increased, but together with the gain in strength, there is also a gain in weight. Increasing the size means more concrete, more steel, and more money. Do you see where this is leading?

Keeping the structural frame of a building as light as possible is thus a top priority when trying to limit the amount of material going into the structure to as little as possible. But how does lessening the amount of material affect the various characteristics of the slab?

A discussion and comparison of four different concrete construction methods will follow in an attempt to reach an answer as to which method is the most effective alternative.

1.2 Statement of the Main Problem

Concrete has evolved from being a construction material only suitable for low rise buildings due to concrete's low tensile strength to a material suitable for almost all types of construction mostly thanks to the effective use of steel's high superior tensile strength together with the high compressive strength of concrete.

One of concrete’s major drawbacks is its weight. Although it is very strong in compression, in traditional methods, large quantities of concrete were used in combination with steel reinforcement to try and overcome its weak tensile strength. Over the years various methods have been developed as alternatives to the conventional solid slab construction in an effort to reduce the weight of concrete construction.

Weight reduction in concrete structures is accomplished by removing concrete that does not contribute to the structural integrity of the building. There have been many different approaches on how to achieve this. A few of these approaches have established themselves in the construction industry as acknowledged methods: The introduction of beams as well as coffers. A relatively new method introduced to the market is the biaxial hollow slab. These three methods, together with conventional solid flat slabs, are compared regarding their performance in a range of criteria. This is done in an attempt to answer the main problem:

Which type of slab is the most effective solution to concrete structures?

1.3 Statement of Sub-problems

In order to answer the main problem, four different concrete construction methods will be discussed each of which will obviously have their own strengths and weaknesses.

Each method is based on the same design principles: Concrete’s large compressive strength and steel’s strength under tension. Even though the principle is identical, each method has its own approach on how to utilize these design principles. This ranges from a “more is better” approach to a more conservative approach by trying to reduce the amount of concrete to a minimum.

The four types of slabs will each be evaluated and compared with regards to their:

- Structural strength
- Aesthetic qualities
- Buildability
- Cost

1.3.1 Do structural requirements influence the choice of slab type?

The different structural characteristics of the various slab types will be investigated and compared to determine which situations they would be suitable for. The factors which will be addressed are:

- Load carrying capabilities
- Spanning capabilities
- Ability to accommodate services - vertically

1.3.2 What influence does the type of slab have on the visual aspects of the structure?

Although the concrete frame might not always be a large contributor to how a building looks, it does however have an influence, whether it being directly or indirectly. Slab influences on visual aspects of the structure will be discussed and compared regarding:

- Flexibility
- Building height
- Ability to accommodate services - horizontally

1.3.3 How does buildability influence the choice of slab type?

Different types of slabs will obviously be constructed in different ways. The influence of these various construction methods on the buildability will be evaluated and compared with relation to:

- Time of erection
- Labour intensiveness
- Ease of repetitive work
- Installation of services horizontally suspended below the slab

1.3.4 Which type of slab is the most cost effective alternative?

After having discussed all of the abovementioned aspects, at the end of the day, the bottom line is price: how much is the structure going to cost. The four types of slabs will be compared by means of doing a cost estimate of each alternative.

1.4 Hypotheses

The following findings are expected to be made regarding aspects discussed:

1.4.1 Do structural requirements influence the choice of slab type?

Each type of slab has its own unique structural qualities implying that varying requirements will have a definite influence on the choice of slab type.

1.4.2 What influence does the type of slab have on visual aspects of the structure?

The visual aspects of the various types of slabs will make each of them suitable for different situations.

1.4.3 How does buildability influence the choice of slab type?

Buildability plays a large role in the selection process of choosing the type of slab.

1.4.4 Which type of slab is the most cost effective alternative?

The biaxial hollow slab (Cobiax system) will be the most cost effective solution.

1.5 Delimitations

- This study is limited to the comparison of three commonly used slab types as well as a relatively new alternative.
- The majority of the study's focus is based on the various characteristics of the types of slabs, largely disregarding other building elements.
- The cost estimates are comparisons of the slab cost only of a single storey office building with above ground basement parking on ground floor.

1.6 Assumptions

- Cost estimate rates are based on competitive construction market conditions relative in the greater Pretoria area during August of 2009

1.7 Importance of the study

The choice of which concrete construction method to use is more often than not based on personal preference exercised either by the architect or engineer. This is done without taking into account the various advantages and disadvantages of the different methods. The architect/engineer often has a prefabricated idea of other construction methods that he is not use to applying himself. This study will help such architects/engineers to at least look at alternative methods and take them into consideration before pronouncing his preferred method as superior.

1.8 Research Methodology

- How each concrete construction method works will have to be investigated and explained thoroughly in order to gain a proper understanding of all the elements which will contribute to the overall structure.
- Literature will be researched to gain information on the better established concrete slab types.
- For relatively new methods, articles and website will be investigated to gather relative information which has not been published in hard copies as of late.
- Interviews with various persons in the industry will be conducted to gain a more thorough insight and understanding.
- After having evaluated and compared each method, a cost estimate based on a similar structure will be drawn up to determine each method’s cost.

Chapter 2:
Do structural requirements influence the choice of slab type?

2.1 Introduction

When making a decision on which type of slab will be suitable for a specific design, various factors must be taken into account in order to select the most favourable alternative. According to Park and Gamble (1980) imposed design loads, spans, serviceability and strength requirements are all very important aspects to be taken into consideration.

During this chapter the basic design principles of each type of slab will be explained. Thereafter, the abilities and capabilities of the various slab types with regards to their structural capacity will be discussed in order to determine each slabs strengths and weaknesses. This in turn will act as a basis for decision making as to which is the most favourable alternative for which situation.

Each slab’s capacity will be assessed through discussing its:

- Load carrying capabilities
- Spanning capabilities
- Ability to accommodate services - vertically

2.2 Solid Flat Slabs

A flat slab is in essence, as described by Park (1980): “an extremely simple structure in concept and construction, consisting of a slab of uniform thickness supported directly on columns.”

Flat slabs are thus commonly characterised as flush soffitted, easily and quickly constructed slabs making them most economical (Goodchild 1997). This is however not always the case as many “flat” slabs often require a certain (“panel”) size thickening of the slab where it rests on columns which are often referred to as “drop panels.” These thickenings are often necessary to overcome the slabs relatively weak resistance to punching shear and deflection – this will be further discussed under the load carrying capabilities. An alternative method of overcoming punching shear and deflection, albeit to a lesser degree, could be to create a capital (a widened, tapering column head) which would then still leave a flush soffit.

2.2.1 Load carrying capabilities

Although flat slabs are often seen as the simplest and easiest way of construction, its load carrying capabilities are often limited due to its weakness to punching shear at sections around columns. What this basically means is that the columns supporting the slab tend to want to “puncture” through the slab. This happens as a result of the difficulty to transfer loads, imposed on the slab and/or the dead weight of the slab itself, successfully to the columns

The slab is punctured either because the area of exposure of the column head is too small to successfully transfer the loads, or because the slab thickness itself does not provide sufficient strength to resist the punching shear.

In an effort to enlarge the area of exposure, the heads of column are often enlarged where they make contact with the slab, gradually tapering back to the actual size of the column. This would greatly increase the shear carrying capacity of the slab.

To resist puncturing of the slab due to insufficient slab strength, ones first thoughts might be to thicken the entire slab in order to give it more strength whilst at the same time retaining the advantages of a flush soffit. The main problem with a thickened slab is the major gain in dead weight which must now also be transferred to the columns adding additional strain.

Drop panels are commonly used as the solution to the slab's "thickness versus strength" problem. The panels allow for thickenings in the slab at areas around columns where the additional strength is specifically necessary. According to Goodchild (1997) these panels increase the shear capacity as well as the stiffness of the slab allowing for thinner slabs to be used as more concrete is only being used in these panels, in other words, where necessary.

Where making use of these drop panels or enlarged column heads is not possible due to other factors such as architect's requirements, aesthetic properties, etc, Park (1980) states that other forms of shear reinforcement, such as metal shear heads, could be alternative solutions, but they are usually costly.

2.2.2 Spanning capabilities

The distance that a slab is required to span between columns will have a great influence on its shear carrying capacity. This principle can also be applied vice versa: the spanning capabilities of a slab can also be largely influenced by the slab's shear carrying capacity.

As stated above, flat slabs have a relatively low resistance to punching shear. This can however greatly be influenced by the span between columns. Take for instance a slab with columns spaced at smaller intervals, thus requiring more columns, in comparison to one which requires large spans, entailing fewer columns. Where columns are spaced closer together, the imposed loads as well as the dead weight of the slab can now be transferred to a greater number of columns at smaller intervals, lightening the load that each column has to carry, thus lowering the shear stress that the slab must resist. In Afrikaans one would say "vele hande maak vir ligte werk" emphasizing the basic principle that if a load is spread out, it is carried easily.

The two major problems that many columns bring forth are that columns take up valuable floor space and that more columns add more weight to the structure. It would thus be advantageous for the designer to find the balance between the correct carrying capacity for the intended imposed loads on the structure and the optimum spacing of, or span between, columns.

Because spanning and load carrying capabilities are so closely related to one another, each situation must be individually assessed in order to determine and adhere to specific requirements.

Goodchild (1997) recommended that:

- solid flat slabs (with flush soffits) be utilised as in situations such as offices, hospitals, hotels, flats, etc. where imposed loads are relatively light and columns are spaced at 5 to 9 meter spans in square panels,
- flat slabs with enlarged column heads be used for offices, retail buildings, hospitals, hotels, etc. where slabs will be more heavily loaded, with columns spaced at 6 to 10 meter spans in square panels,
- flat slabs with drop panels should, similarly to with enlarged column heads, be used for offices, hospitals, hotels, etc. where slabs will be more heavily loaded, with columns spaced at 5 to 10 meter spans in square panels.

Park (1980) found that:

- flush soffit flat slabs have limited strength in punching shear and are thus most suitable for residential as well as some office construction, both with relatively short spans,
- flat slabs with drop panels as well as with capitals at column heads are more suitable for larger loads and spans as often the case in heavily loaded industrial structures.

2.2.3 Ability to accommodate services - vertically

Many services within a building, for example plumbing, air-conditioning, electrical, etc. are linked from floor to floor and must thus be able to run concurrently from one floor to the next. This is usually done by having sleeves run through the floor slab, creating a void in the slab for the services to pass through.

As punching shear to most flat slabs is usually a worrying factor, creating large holes/voids, especially near to columns, could prove to be a problem. Proper planning of how and where services are to run through slabs is thus a necessity in order not to influence the structural integrity of the slab.

2.3 Slabs with beams

When referring to “slabs with beams”, there are two possible ways of interpreting the term. It could refer to one-way slabs which, for design as well as practical purposes, only span in one direction. For the purposes of this study, slabs with beams will however refer to two-way slabs.

Two-way slabs are described by Park (1980) as “slabs supported on beams on all sides of each panel.” The panel refers to the square or rectangular slab spanning between the surrounding beams. The beams are in essence thickenings in the floor slabs in areas where it is most necessary. These thickenings project vertically downwards from the slab and are referred to as down stand beams, spanning between the columns that carry them.

2.3.1 Load carrying capabilities

The load carrying capabilities of slabs with beams is one of the major advantages it has over its rival systems. Because each panel of slab is in essence resting on its surrounding beams, the main carriers of the loads are thus the beams and not the slab itself. This makes it possible to minimize slab thickness, in comparison to that of flat slabs, to merely the thickness necessary for enough strength to suspend loads between the beams. The span will obviously have a large influence on this thickness as will be described in the section here after.

Down stand beams greatly strengthen a slab's ability to deal with shear stresses as well as deflection (Park 1980). This is done through the fact that the effective depth of the beam can be so much greater than that of a slab as it is only enlarged in the required areas. The transfer of loads from the slab to columns produces high local and twisting moments as well as shear forces. Beams can be easily reinforced to resist these forces and moments without influencing the design and thickness of the entire slab.

2.3.2 Spanning capabilities

As stated above, the slab with beams has a very large carrying capability. This is largely due to the fact that the slab does not need to support itself from the columns only, meaning that all loads imposed on the slab do not need to be transferred to the columns directly form the slab. The slab is now divided into panels which only need to span between their surrounding beams. The beams span between the columns, acting as a sort of stronger "middle man" for transferring the loads.

Larger spanning distances between columns can now be easily accommodated: larger spans mean larger panels. The panels within the slab only require enough strength to transfer loads to their individual perimeters as they span between their supporting beams. The beams are thus the ones who ensure the safe transfer of loads to the columns and, as explained above, beams can easily be reinforced to deal with larger moments and forces.

Goodchild (1997) explains that the functionality of slabs with beams makes it a viable option for:

- retail developments, warehouses, stores, etc. with spans of between 9 to 12 meters able to carry heavier loads.

Park (1980) found slabs with beams contribute greatly to the overall stiffness of a building and are thus suitable for:

- structures that must resist large horizontal loads by means of the concrete frame.

2.3.3 Ability to accommodate services - vertically

Panels within slabs are supported on all four sides by the perimeter beams. Creating voids in the slab thus cause few structural problems as most of the stress is carried by the beams. Where structural integrity is however affected by these voids, it can often be accommodated by increasing the steel content of the slab with regards to the affected area.

2.4 Coffer slabs

Also commonly known as waffle slabs, the term “coffer slabs” could also be interpreted in more than one way. Coffer slabs could for instance be designed as flat slabs, where use is made of drop panels around columns. Another alternative is where these slabs are designed as two-way slabs with down stand beams running between columns. For the purposes of this study, coffer slabs refer to slabs designed as two-way slabs but with integral beams enabling a “level” soffit – not noting the recesses.

Coffer slabs are described by Park (1980) as “a set of crossing joists, set at small spacings relative to the span, which support a thin top slab.” The joists are formulated by creating a series of recesses in the soffit of the concrete slab by means of placing removable, void forming, forms on top of the usual flat slab formwork over which the concrete is then poured. The concrete poured into the gaps between these forms now form the joists.

To form the integral beams, no recess forms are placed for the width of the beam between columns enabling concrete to fill this entire area. The soffits of the beams are thus flush with the soffits of the joists running in between the recesses.

2.4.1 Load carrying capabilities

Recesses in the soffit of the slab mean that much less concrete is used which leads to a large reduction in the dead weight of the slab itself. This is made possible by joists formed between the recesses. These joists produce a large effective depth within the slab without the accompanying dead weight associated with thicker slabs.

The slender thickness of the top slab is made possible by the joists acting as beams, able to carry the loads imposed on the slab and transfer them to the often heavily reinforced integral beams. The top slab itself thus only needs to transfer its loads to the joists.

The beams spanning between columns, although they do not project below the soffit, fulfil the role of down stand beams. They are the main carriers of the loads and load transfer to the columns takes place through them. Because their effective depth is equal to the entire thickness of the slab, it can easily deal with the moments and forces encountered at beam-column connections.

The relatively low weight of the slab itself together with the large effective depth of joists and the carrying and load transferring capabilities of the integral beams enable a coffer slab to accommodate large imposed loads with relative ease.

2.4.2 Spanning capabilities

The thin top slab of the coffer slab system merely spans between its supporting joists and as these are in close proximity of each other, the span of the top slab is usually not an issue.

The joists running in between the recesses must carry the weight of the slab, their own weight, as well as the loads imposed on the slab and transfer these loads to the integral beams. The relative light weight of the slab however, in conjunction with the large effective depth of the joists enables them to span between beams with relative ease.

Since the integral beams are the main load carriers and the transferors of the loads, they are the ones who largely influence the spanning capabilities of the slab. These beams are however wide, with large effective depths, enabling them to be thoroughly reinforced for larger spans.

Park (1980) found that the large effective depth of these slabs lead them to be relatively stiff structures making them suitable for:

- demanding spans larger than 10 meters.

Goodchild's (1997) findings were that these are popular for:

- medium spans of up to 10m

2.4.3 Ability to accommodate services - vertically

Creating voids through the thin top slab will not have major structural implications. It would not be advisable to attempt transfer of services through the integral beams, or even the joists for that matter, as they are the carriers of the loads and this could have large structural implications.

Where services run vertically along columns, or even along walls that run between columns, there will be difficulty in creating voids for such services close to the columns/walls. This is the case due to the fact that the integral beams span between and come together at the columns. Careful design and planning must thus be exercised for the effective linking of services vertically.

2.5 Biaxial hollow slabs

When using the term “biaxial hollow slabs”, for the purposes of this study, reference is made to the in-situ cast product sold by the sole distributor of this system in South Africa, namely Cobiax.

The concept of the system is to have a flat slab with permanent void formers cast into the concrete, eliminating unnecessary concrete that is of no structural benefit to the structure. The spherical void formers are set in steel cages, holding them in place while contributing to the stiffness of the slab at the same time. Mesh reinforcement is placed below and above these cages, strengthening the concrete’s weak resistance to tensile forces. Integral beams can also be formed by not placing these void formers in specific bands, making way for the beam which will then once again be the main load carrier and transferor of loads to the columns. The concrete is then poured, incorporating all of the abovementioned into a much lighter flat slab.

2.5.1 Load carrying capabilities

Cobiax slabs are, for design as well as practical purposes, classified as flat slabs. Cobiax however claim that by using their system, slab weight can be reduced by up to 35% in comparison to equivalent solid flat slabs. Cobiax would tend to imply that their slab can thus carry 35% higher imposed load simply through the reduction in dead weight.

By conducting various tests, Schnellenbach-Held and Aldejohann (2005) found that Cobiax slabs in fact have an inferior load carrying capacity to comparable solid slabs. In determining the shear strength, it was found that these slabs have at least a 55% carrying capacity of a comparable solid slab. This can however be increased to equal the punching shear of the solid slab by removing all void formers from the punching region. This area is defined by Schnellenbach-Held (2005) as a "line connecting the corner at the columns section to the upper slab surface at an angle of 30.°" By omitting these void formers, one is in essence creating a sort of drop panel within the slab to improve resistance to punching shear, similar to solid flat slabs.

Having noted the abovementioned, the biaxial nature of the Cobiax slabs make it possible for them to transfer loads in any direction. This enables them to maintain a high load carrying capacity and flexibility (Schnellenbach-Held 2005).

2.5.2 Spanning capabilities

The enormous weight savings brought forth by the voids, together with the slab's biaxial spanning, enable this system to span over large distance with ease. The fact that integrated beams can also be incorporated into the system, make it possible to reach even larger spans through proper design.

Cobiax graphically illustrates their superior spanning capabilities by comparing their slabs with A: solid slabs of the same slab thickness in figure 1; and B: solid slabs with the same imposed loads and concrete volume in figure 2. Solid slabs being represented by the black line and Cobiax by the red area up to and including the white line.

Figure 1: Spans with the same slab thickness (Cobiax information brochure, 27 February 2009)

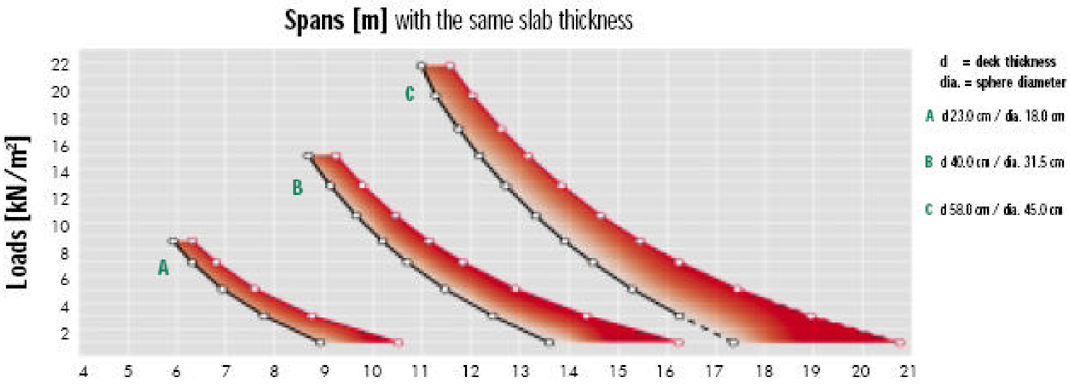
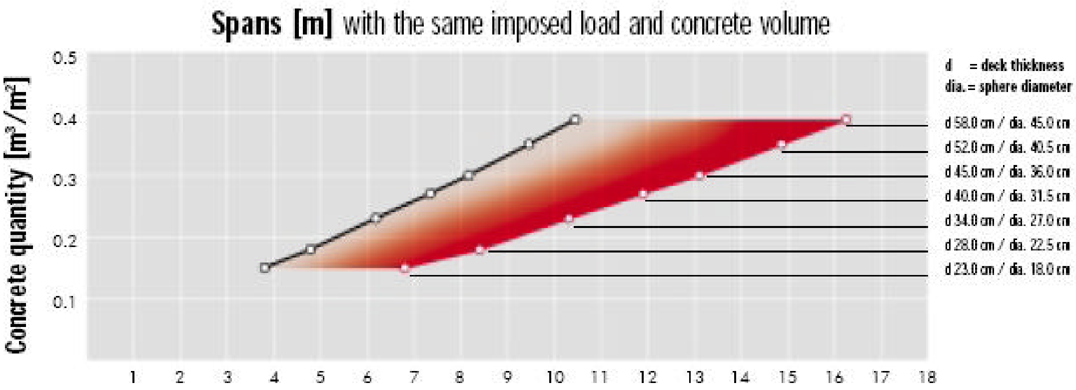


Figure 2: Spans with the same slab thickness (Cobiax information brochure, 27 February 2009)



As can be interpreted from these figures, Cobiax slabs are capable of reaching large spans with relative ease whilst having the amount of concrete used reduced to as little as possible. These graphs are however limited to comparisons between solid flat slabs and the Cobiax system.

Cobiax claim that because of the light weight of the slab and its biaxial bearing behaviour, spans of more than 20 meters are made possible by the reduced dead weight. This claim is supported, albeit not to its full extent, by the construction of a multi storey Tesco Superstore (Northam 2009), situated in Kent in the United

Kingdom, which has a 7500m² floor area per slab with columns spaced on a 16m grid.

The abovementioned Tesco Superstore was in fact constructed of a semi-precast variation of the Cobiax system, but the characteristics of this system are much the same as the in-situ application referred to in this study.

This same Tesco Superstore was a multi-use building and acts an example of the wide range of applications the Cobiax system is effective for, namely:

- Supermarkets, parking decks, residential units, etc. with spans 16 meters.

2.5.3 Ability to accommodate services - vertically

Cobiax claim that services like ducts, plumbing, electrical fittings, etc. can easily be integrated into the slabs design, even combining them with the void formers. This claim is backed by Johan du Plessis (Cobiax website 7 May 2009), Contract Manager for HSH Construction, whilst referring to their Diamond Pavilion contract in the Northern Cape where Cobiax slabs were used, he stated that: “It is very flexible and allows for designs with fewer columns and larger spans and it is also possible to run services piping through the concrete.”

2.6 Conclusion

Each of the discussed systems are effective solutions within their own rights and specific project requirements must be carefully looked at when deciding on which system to use.

From the above analysis of each system one can conclude the following findings as to which system is most suitable for which application:

- Load carrying capabilities:

Slabs with beams ensure effective depth and structural stability in areas where it is most needed.

- Spanning capabilities:

Cobiax structures have such a low dead weight that large spans are accommodated with ease.

- Ability to accommodate service – vertically:

The solid flat slab is the only system that doesn't accommodate service voids with relative ease, making all of the other options viable.

2.7 Test of hypothesis

The hypothesis was that each type of slab has its own unique structural qualities implying that varying requirement will have a definite influence on the choice of slab type.

The hypothesis was found to be correct in that although some of the structural qualities are shared by more than one system, the structural requirements do have an influence on one's decision making.

Chapter 3:
What influence does the type of slab have on the visual aspects of the structure?

3.1 Introduction

Each type of slab has its own unique qualities which influence their visual aspects in various ways. The person responsible for the aesthetic design (the architect for example) is interested in the visual aspects of the structure. While on the other hand, one has the person responsible for the structural design (the structural engineer for example), who is interested in how the structure works, rather than how it looks. This often leads to clashing priorities when it comes to bringing their designs together.

The visual aspects might in different cases have a varying influence on choice of slab, depending on how important the building's finishing is: A prestigious shopping centre requires a much higher aesthetic finish than an industrial warehouse for example. Another influencing factor is whether the concrete will be visible at all: Where there is a suspended ceiling below a soffit, the finish of the soffit itself is not important at all. Goodchild (1997) emphasizes the need for aesthetic requirements to be discussed by saying that "if the structure is to be exposed, a realistic strategy to obtain the desired standard of finish should be formulated and agreed by the whole team."

During this chapter the visual aspects of the various types of slabs will be discussed and will then be further evaluated with regards to:

- Flexibility
- Building height
- Ability to accommodate services – horizontally

3.2 Solid Flat Slabs

The flush soffit of the flat slab is easily accepted as an adequate ceiling finish, depending on the level of finish of the formwork. Where smooth formwork is used, the surface can be left as is, or be painted which often produces a finish of a high quality. Where rough formwork is used, the soffit is often plastered and then painted.

Similarly to the influence that the type of formwork used will have on how the soffit looks after being cast, the quality of workmanship applied by the contractor casting the concrete can have just as great an influence. This is especially applicable in the cases of flat slabs with drop panels and where use is made of widened column heads.

Drop panels require formwork to be boxed out around columns and thickenings at column heads special and/or purpose made formwork. Concrete in its liquid state will fill any irregularity in the boxed out and purpose made formwork leaving the soffit/column head with an often noticeably irregular finish. This is so because the surrounding slab and rest of the column were cast on/in matching forms which produces a uniform look.

The figures below illustrate how the three types of flat slab would ideally look when cast on smooth formwork to a good quality of workmanship.

Figure 3: Flat slab (Goodchild 1997)

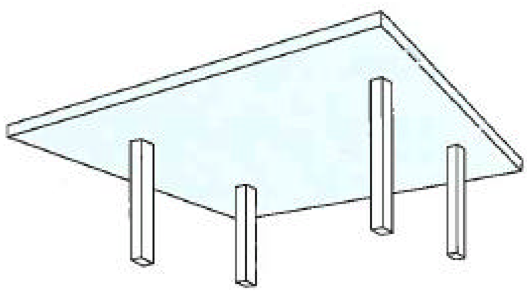


Figure 4: Flat slab with drop panels (Goodchild 1997)

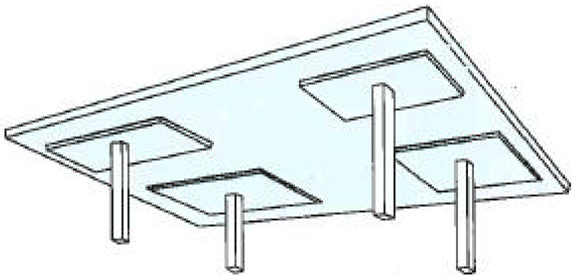
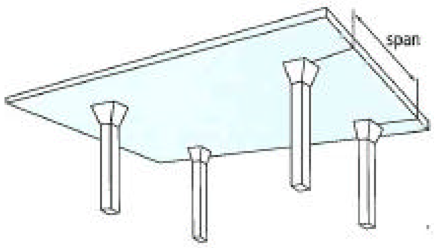


Figure 5: Flat slab with thickened columns heads (Goodchild 1997)



3.2.1 Flexibility

The layout of internal divisions within the building, partitions for example, can easily be accommodated and changed without the need for any in depth consideration on how the layout will fit into the grid of beams in order to eliminate unsightly junctions of beams with partitions. The partitions will always look like they fit as there are no unwanted obstructions in their way.

3.2.2 Building height

The floor-to-floor height of a multi-storey building is predominantly determined by its floor to ceiling height. The flush soffit, or relatively flat soffit in some cases, of flat slabs can be an advantageous characteristic when trying to regulate the building height. As there are no, or rather insignificant (drop panels), projections from the soffit, in cases where no suspended ceiling is required, the floor to ceiling height can be measured from the finished floor level to the soffit of the slab above.

Comparing the abovementioned to slabs with beams, it is thus obvious that as saving in the floor-to-floor height can be made as ceiling height is not measured to the underside of beams, but rather the slab itself. This leads Park (1980) to construe that one may be enabled “to have and additional floor for approximately each 10 floors, as compared with a two-way slab (slab with beams).”

3.2.3 Ability to accommodate services - horizontally

Services of a smaller nature, electrical wiring for example, can easily be accommodated by flat slabs by casting conduits into the slab and drawing the wiring through these conduits. This also makes it possible to mount light fittings directly onto the soffit at the points where the wiring emerges out of the slab, concealing the wiring entirely within the slab.

Because the slab has no, or relatively minor, projections from the soffit, services mounted to soffits can run uninterruptedly in any direction as there are no obstructions in the way.

In cases where floor-to-floor height has been kept to a minimum in order to reduce overall building height, this system does however have the disadvantageous characteristic of having limited head room. This can prove to be problematic when trying to accommodate large air-conditioning ducts, as they can not be so easily concealed in ceiling voids as there are no, or very small, ceiling voids. Careful design co-ordination between the mechanical engineer and the architect will be necessary to overcome this hurdle.

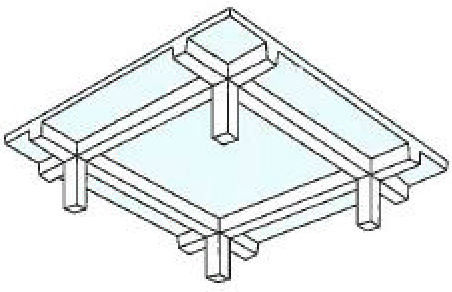
3.3 Slabs with beams

In order to obtain a good quality finish to the soffit of slabs with beams, one of two things is required: 1.) high quality workmanship to ensure a refined finish is left by smooth forms or; 2.) plastering, preferably the entire soffit, but otherwise, the areas with most the noticeable imperfections. Only such well rounded off soffits will usually grant the slab with beams to be an acceptable ceiling finish.

In most cases, where aesthetic quality is of importance, suspended ceilings are usually hung from the slabs, concealing the slab with its projections and imperfections while at the same time producing a void where other services can be hidden.

A well finished slab and beam system is illustrated below:

Figure 6: Slab with beams (Goodchild 1997)



3.3.1 Flexibility

Where the soffit of the slab is utilized as the ceiling finish, the grid of downstand beams must be taken carefully into consideration when designing the internal layout of the building. A lack thereof could lead to many unsightly junctions of beams and partitions at unusual angles, which can create a sort of "awkward," feel to a room.

In cases where use is made of a suspended ceiling, the internal layout is entirely flexible and independent of the beam layout.

3.3.2 Building height

Even though the presence of beams reduces the required floor thickness, the overall height of the beam itself, in comparison to the thickness of flat slabs, is still larger. As the floor to ceiling height is determined from the floor to the lowest point projecting from the soffit, the overall floor-to-floor distance necessary will thus be greater to satisfy the height requirements.

3.3.3 Ability to accommodate services - horizontally

Electrical conduits and wiring can, just like with flat slabs, be cast into the slab with relative ease. Because floor-to-ceiling height is measured to the underside of the beams, a large, unused void is now created between the beams and according to Hale (1972) "this space can often be used to accommodate services."

The downstand beams do however also cause a problem where these services must bypass these beams. This complicates the design of such services and could necessitate an even lower suspended ceiling to keep the services concealed where they cross paths with beams.

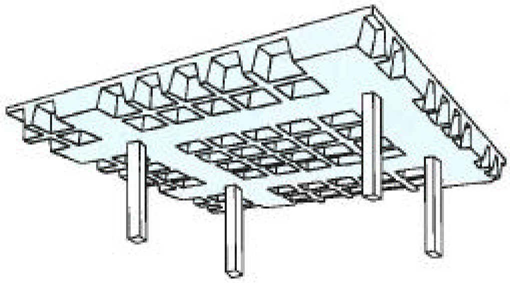
3.4 Coffer slabs

Special forms are used to create the necessary voids in the slab soffit to produce a coffer slab. Few contractors actually own these types of forms and will mostly hire them from a formwork supplier for the time it takes to get the job done. This would imply that in most cases, factory fabricated, standard forms are used. These forms are usually of good quality and thus produce a good quality finish to the concrete which is poured over them.

It is however just as important that the supporting formwork that the concrete will be exposed to be of just as good a quality as the void formers and that the contractor practices good workmanship when casting the slab. In such cases, coffer slabs can produce a ceiling that is pleasing to the eye and that doesn't require any further finishing to it.

Herewith follows an illustration of a well finished coffer slab:

Figure 7: Coffer slab with integral beams (Goodchild 1997)



3.4.1 Flexibility

Since this form of a coffer slab produces a flush soffit, it shares the advantage of flexibility with that of flat slabs. There is however one problem that can occur: if partitions run across the voids in the soffit, the void itself is still not closed off which reduces the amount of perceived privacy. The problem can be overcome by ensuring partitions are placed in line with the beams and joists running in between the voids. This does however limit the flexibility of the partition layout to some extent.

3.4.2 Building height

This form of coffer slab has similar characteristics to that of a flat slab in that since no downstand beams are present, a saving in building height is possible. This is however not always the case as according to formwork specialists KasetKalip's website (Access: 25 May 2009), standard form depth ranges between 200-425mm with a topping of approximately 100mm. When taking into account that in slabs with beams, beam depth seldom exceeds 600mm (Goodchild 1997), it does seem that a height saving is possible, but that it would not be a substantial one.

3.4.3 Ability to accommodate services - horizontally

Although the slab has a thin top layer, the beams and joists of the slab give it a large effective depth and according to All Slab's website (Access: 12 March 2009), suppliers and sub-contractors who specialize in supply and placing of concrete slabs, this depth enables one to cast "electrics and plumbing" into the slab.

The flush soffit also means that services fixed to the soffit can be distributed in any direction as there are no unwanted obstructions.

3.5 Biaxial hollow slabs

When looking at a biaxial hollow slab after it has been cast and cured, one would find it difficult to distinguish it as such. To the naked eye, the slab itself appears to be a flat slab, but with much larger spans between columns.

The large savings in weight due to the void formers within the slab help to obviate the need for drop panels or widened column heads. This produces a smooth, depending on the choice of formwork, flush soffitted slab with right angle intersections with columns.

The following figure illustrates how, to the naked eye, the biaxial hollow slab appears to be a flat slab with large spans:

Figure 8: Biaxial hollow slab, Parking building, Freistadt, Austria (Cobiax website 27 February 2009)

3.5.1 Flexibility

The flush soffit of these slabs deems them just as advantageous as flat slabs. The fact that there are even less columns present in the general floor area, make for an even more flexible layout due to even less obstructions.

3.5.2 Building height

Similar to coffer slabs, biaxial hollow slabs would also appear to produce savings in overall building height because of its similarities with flat slabs. As the case is with coffer slab, the void formers in these slabs are relatively large, producing a slab which thickness can be compared to that of the depth of downstand beams.

These figures illustrate the two types of void formers available for installation in the slabs:

Figure 9: Eco-line (Cobiax website 27 February 2009)

Figure 10: Slim-line (Cobiax website 27 February 2009)

These void formers range in size from 100-450mm. The Slim-line is used in slabs ranging from 200-280mm thick while the Eco-line slabs range from 300-600(+)mm. This would imply that with the use of the Slim-line product, a considerable height saving is possible, but when opting for the Eco-line, the height saving potential diminishes.

3.5.3 Ability to accommodate services - horizontally

The relatively large thickness of the slab produces a large enough effective depth to enable services to be cast into the slab with ease.

The slab's flush soffit means that services fixed to the soffit are very easily distributed in any direction.

3.6 Conclusion

The different slab types each have various contributing factors to how they look and thus to where they will be most suited. Certain guidelines can however be followed and applied to all slab types in order to attain the desired visual finish:

1.) Determine whether the soffit will be exposed or not
2.) If exposed, determine type of formwork for finish
3.) Ensure good quality workmanship or repair defects after casting

With regards to the further aspects discussed, the following findings were made:

- Flexibility

The biaxial hollow slab has no soffit obstructions and fewer columns than any other system and is thus an obvious choice in this regard.

- Building height

By comparison, the solid flat slab system produces the most certain saving in height. The Slim-line Cobiax as well as smaller form variations of the coffer slab could also produce potential height savings.

- Ability to accommodate services – horizontally

Flush soffitted slab can produce a lack of overhead space for larger service requirements, while slabs with beams provide ample head room, but complications can arise from intersections with services with beams.

3.7 Test of hypothesis

The hypothesis was that the visual aspects of the various types of slabs will make each of them suitable for different situations.

The hypothesis was found to be partially correct. Personal preference may mean that what seems suitable for a certain situation by some, can be seen as unsuitable by other and vice versa.

Chapter 4:
How does buildability influence the choice of slab type?

4.1 Introduction

Buildability is a factor which is often overlooked in the construction industry, especially during design stages. This often leads to buildability problems which usually only surface themselves after construction commences. One of the major reasons why buildability problems occur is because designers and builders must be able to look at a project through each other's eyes in order to overcome such issues and this would require knowledge in two aspects by both parties (Tindiwensi, 2000).

Buildability is defined as "the extent to which a building design facilitates ease of construction whilst other clients' requirements are met" (Wong et al, 2006). Looking at the latter part of the definition, "clients' requirements" relate to the three major client objectives that must be met during a project: time, cost and quality.

Quality has been dealt with in previous chapters in terms of the quality of the various slabs' finishes as well as their structural qualities. Cost, on the other hand, will be dealt with in the following chapter.

The focus of this chapter will be directed on the "ease of construction" part of the abovementioned definition which is in close relation to the project time requirements of the client. Further factors influencing the ease of construction of the various slab types will be discussed accordingly, namely:

- Time of erection
- Labour intensiveness
- Ease of repetitive work

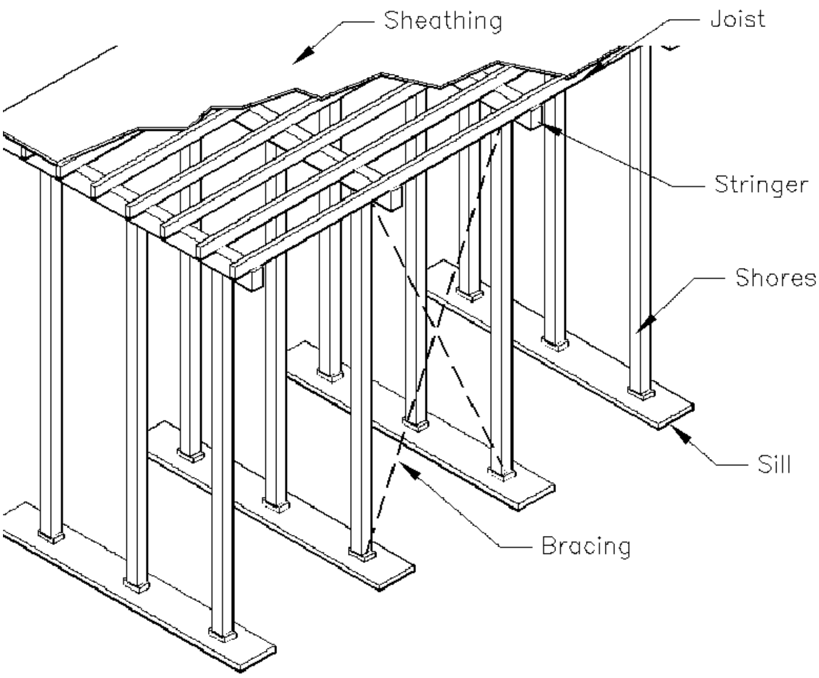
- Installation of services horizontally suspended below the slab

4.2 Solid Flat Slabs

The erection of a cast in situ concrete slab is a time consuming and laborious process. Props are to be placed at appropriate interval, carrying the bearers/stringers. Joists are laid at right angles on top of theses bearers, on which the formwork panels rest. These joists must be spaced at the correct width to support the panel size. Props are then adjusted to position the formwork at the correct height above bearing level. This must be done very carefully to ensure that the slab is poured at the correct level throughout. Once the formwork is laid correctly, the steel reinforcement must now be laid down on the formwork and fixed in the appropriate manner. Only after this process is completed successfully and to the engineer's approval can the concrete be poured.

Typical flat slab formwork is illustrated in the figure below.

Figure 11: Traditional flat slab formwork (www.widipedia.org/traditionalformwork/ 23 July 2009)



In the construction of solid flat slabs, this erection process is limited to its simplest form: since the soffit of the slab is flush, all formwork is placed at the same height and reinforcing can be laid on a flat, uniform surface.

In the case of flat slabs with dropped panels, this simplicity is somewhat reduced. The general slab area's formwork remains the same, but the dropped panels around columns necessitate formwork to be propped at a lower level than the rest of the slab and would thus need additional, vertical formwork to the edges of the panel to compensate for the change in height. Steel reinforcement must now also be stepped down from the general slab area into the drop panels and back out again.

Where column heads are used in conjunction with flat slabs, the ease of slab erection remains the same. It is now the ease with which columns are erected which is influenced. Where custom heads are required, they must specifically be made. Where use is made of standard heads which can be purchased off of the shelf, or hired, this nonetheless requires more effort in erecting the formwork into position than would uniformly shaped formwork from top to bottom.

4.2.1 Time of erection

As solid flat slabs are one of the simplest forms of slab construction, it is also one of the fastest to erect. Goodchild (1997) points out that one of the main advantages of constructing flat slabs is the speed with which formwork can be placed and construction can commence. He also points out that in flat slabs with drop panels, formwork may be disrupted, extending the construction period thereof.

The use of column heads often necessitate that columns be poured to below where the head thickening starts, and the head be poured thereafter. Goodchild (1997) states that: "unless the whole column can be poured at one time, column heads can disrupt cycle times."

4.2.2 Labour intensiveness

Any form of slab requires a large quantity of labour to construct. With solid flat slabs being the simplest, it requires the least labour. Dropped panels and widened column heads do however necessitate additional labour, increasing their labour intensiveness.

4.2.3 Ease of repetitive work

This form of slab is of uniform thickness and is flush soffitted throughout, signifying that the construction of any section of slab is repeated throughout the entire area of the slab. Only the reinforcing placed on the formwork can vary in different areas of the slab as this is to an engineer's specific, load bearing, design requirements.

The additional work required to be done at each drop panel or widened column head is repeated at all columns specified and the work will also become easier as the process is repeated throughout the slab.

4.2.4 Installation of services horizontally suspended below slab

Buildability is affected in that where services are suspended below the flush soffit of the slab, there are no obstructions in the way of these services. There thus would be no need to step such services around downstand beams, necessitating extra bends, fittings and labour, nor to cast sleeves into/core drill though beams for them to run through.

Since dropped panels do not project greatly from the general slab soffit, they would also have a minimal effect. Different hanger lengths would be necessary though.

Thickened column heads would have no effect.

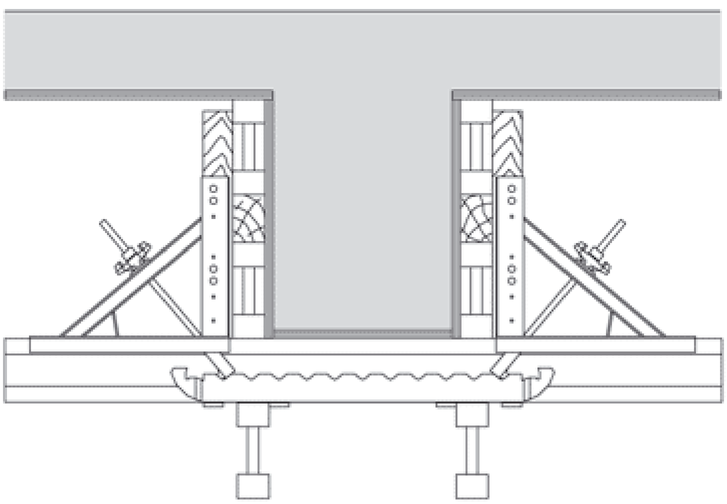
4.3 Slabs with beams

Slabs with beams are erected in much the same way as flat slabs. Formwork is propped up, reinforcing is placed and the concrete is poured. Beams are however usually cast monolithically with the slab, which necessitates their appropriate forms and reinforcement to be prepared and ready together with that of the slab. This is done by placing the slab formwork at the appropriate level, leaving voids in bands where the beams are to be situated. These voids are then closed up with formwork to the soffit of the beam at the desired level – lower than that of the slab. Vertical formwork is then placed to create the sides of the beam.

Steel reinforcing is placed on top of the slab formwork, as with flat slabs, but must now also be fixed to the beam reinforcing, laid in the downstand. The slab's concrete is then poured over these forms, filling the downstands and so doing, creating beams.

The figure below illustrates the additional formwork that is used to create downstand beams.

Figure 12: Beam formwork (PERI website 22 July 2009)



4.3.1 Time of erection

The additional formwork required to create the downstands in the slab formwork will increase the time it will take to prepare the formwork to receive the reinforcing and will "deter fast formwork cycles" (Goodchild 1997).

The steel reinforcement must now also be placed into the confined space of the downstand and must still be fixed to the adjacent slab reinforcing. This will also take more time than fixing the steel on a uniform surface.

4.3.2 Labour intensiveness

The already labour intensive process of preparing the formwork and reinforcing for the concrete to be poured now requires even more labour in erecting and propping up beam soffit formwork at an additional lower level than that of the slab. The sides of the beam now also require vertical formwork to be erected and appropriately supported to resist the forces of the concrete in its liquid state.

4.3.3 Ease of repetitive work

The addition of beam downstands to soffits of slabs interrupts the repetitive nature of erecting a flush soffitted slab. Beams are also often of varying sizes which leads one to conclude that this form of slab does not lend itself to repetitive work.

4.3.4 Installation of services horizontally suspended below slab

Services running below the slab can either run through beams, or bend around them. Sleeves can be cast into beams to allow for services to run through, but the layout of services have are hardly ever determined by the time the structural frame is being erected. Bending of services around beams require additional (usually costly) fittings as well as labour in installing such fittings. This again contributes to the labour intensiveness.

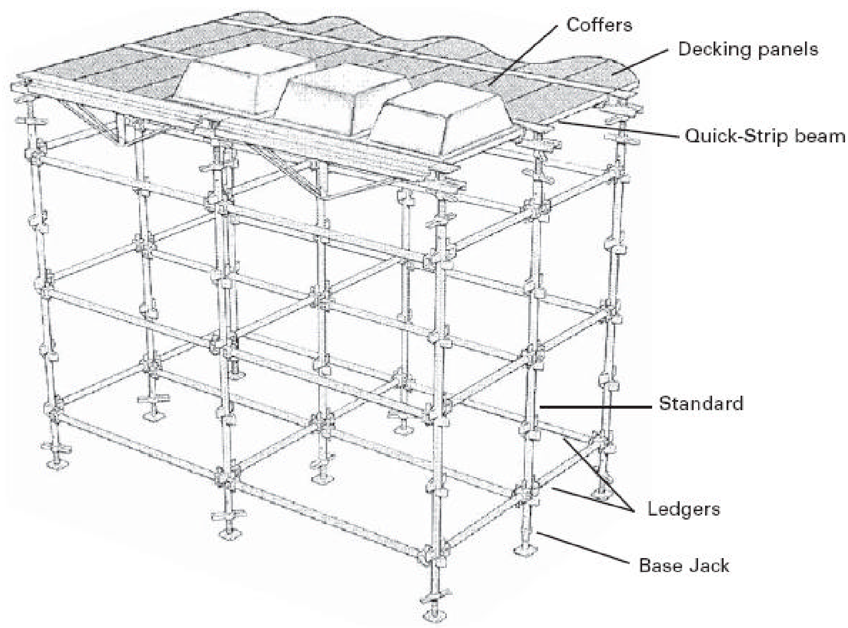
4.4 Coffer slabs

For the construction of coffer slabs, formwork is placed to a uniform height/level, in the same way as with flat slabs. Hollow block coffers are then placed on top of the flat surface. The necessary formwork is then placed over and in between such forms and the concrete can be poured.

The major difference with the construction of flat slabs is thus the placement and positioning of the coffers as required on top of the flat slab formwork. The amount of work and effort is thus increased dramatically.

The following figure illustrates how coffers are placed on top of and in conjunction with traditional flat slab formwork.

Figure 13: Coffer slab formwork (Wiehahn website 25 July 2009)



4.4.1 Time of erection

As coffers are placed on top of forms similar to flat slab formwork, erection time amounts to the time it takes to construct a flat slab, with the additional time of coffer placement. Fixing of reinforcement between forms can also prove to be a more time consuming task.

4.4.2 Labour intensiveness

Although formwork is propped up to a uniform height, limiting the amount of labour required, additional labour is needed for placement of the coffers. The fixing of steel reinforcement in between and on top of the coffers is also more strenuous than on a flat surface and proves to be more labour intensive.

4.4.3 Ease of repetitive work

Coffers are all placed in the same manner on top of the flat surface. This means that although placement of coffers does contribute additional labour, the work is of a repetitive nature, making it possible to do such work with relative ease.

4.4.4 Installation of services horizontally suspended below slab

Since coffer slabs have a "flush" soffit (disregarding the coffer voids), they share the advantages of being able to install horizontal services with relative ease with flat slabs.

4.5 Biaxial hollow slabs

Biaxial hollow slabs are, just as coffer slabs, constructed on formwork much the same as that of a flat slab, but with the addition of hollow ball shaped void formers in cages placed in between steel reinforcing on top of the uniform height formwork.

For the in situ application of this slab system, the steel cages in which the “balls” are housed must be fixed to the reinforcing placed below them. This is done to “compensate for the buoyancy created by the Cobiax void formers in the wet mix” (Cobiax website 25 July 2009). After the bottom reinforcement has been secured by the concrete, the remainder of slab’s concrete can be poured.

The following figure illustrates how cobiax modules are built in between steel reinforcing.

Figure 14: Cobiax slab ready for concrete to be poured (own information)

4.5.1 Time of erection

Much like coffer slab construction, cobiax slabs are placed on flat slab formwork with the additional time of placing the cobiax modules in place. The fixing of the cages in which the “balls” are located to the bottom reinforcing will contribute additional time to the erection process over and above the mere placement of the modules.

4.5.2 Labour intensiveness

The construction of cobiax slabs requires a large amount of labour input. Steel reinforcement must be placed on top of the flat formwork, the cobiax modules must all be placed and arranged in their required positions, the cages must then be fixed to the bottom reinforcing and top reinforcement is then placed over. Only after this entire process requiring an ample amount of labour can the concrete be poured.

4.5.3 Ease of repetitive work

There are many cobiax modules that must be placed and fixed, all in the same way on formwork of a uniform height. This large amount of labour is at least of a repetitive nature, simplifying as the process is repeated.

4.5.4 Installation of services horizontally suspended below slab

As the slab’s soffit is flush, horizontal services can be installed with relative ease without any obstructions.

4.6 Conclusion

In order to facilitate the buildability of concrete slabs, cognizance must from as early as design stage be taken thereof. How the building is built must thus be integrated into its design.

One must also not overlook the way of doing things that locals are accustomed to, but one should however also not be blinded thereby. This is highlighted by Park (1980) when he says that: “There is a natural human tendency to want to repeat what one has previously done successfully… However, old habits should not be allowed to dominate sound engineering decisions.”

Deducing out of the above discussions, the following conclusions were made:

- Time of erection

As the erection of a solid flat slab is portrayed as concrete slab construction in its simplest form, it would also take the least time to erect as there is no additional work.

- Labour intensiveness

The solid flat slab has the least amount of labour as all the other slabs are constructed in much the same way, but with additional work to be executed, complicating the erection process

- Ease of repetitive work

In solid flat slabs, the erection of any panel is repeated throughout the slab, making it the easiest to construct. In both coffer and biaxial hollow slabs however, the placement of additional coffers and cobiax modules is a very repetitive process, simplifying the additional work that is to be done.

- Installation of services horizontally suspended below slab

Solid flat slabs and biaxial hollow slabs are the obvious favourite as their flush soffits ensure unobstructed installation. Although coffer slabs also produce a “level” soffit, for hangers to all be of the same length, they must be fixed to the soffit of the ribs running between the coffer voids, complicating installation.

4.7 Test of hypothesis

The hypothesis was that buildability plays a large role in the selection process of choosing the type of slab.

The hypothesis was found to be incorrect as designers do not see the project through the eyes of the person who must erect the structure. Their focus is on the end product and how it will function, neglecting to look at how it has to be built.

Chapter 5:
Which type of slab is the most cost effective alternative?

5.1 Introduction

The decision as to which type of slab will be utilized for a certain project is made by looking at various factors and satisfying necessary criteria. For the employer, the defining factor would be cost.

Structural design is done by the structural engineer and it is his responsibility to ensure that the structure is able to carry and withstand the loads for which it is designed. The visual aspects of the building are mainly determined by the architect's design and he is responsible for producing a building which is in compliance with the aesthetic requirements. It is the responsibility of the contractor to construct the building and he must thus overcome any buildability constraints encountered.

As it can be seen, these various factors discussed in the aforementioned chapters are to be addressed by parties, appointed by the client to do so. The factor with which the client is thus mainly concerned is the cost of the project, as it is his responsibility to provide the financing.

There are countless factors which can have an influence on the cost of erecting a structure. This chapter will focus on estimating the cost of constructing the various types of slabs, focussing on the main cost contributing elements as highlighted by Goodchild (1997): "Concrete, formwork and reinforcement in floor plates (slabs) constitute up to 90% of superstructure costs."

5.2 Cost estimating

For cost estimating purposes, a comparison will be done on four slabs of a uniform size, incorporating all and only the elements which influence the cost of erecting the slab itself. A typical double storey office will be used for the example: A 30 x 30m (900m²) floor plan with above ground basement parking to ground floor and office space to the first floor.

Foundation types and sizes can only be determined once ground conditions are known and will thus be excluded from these calculations. Columns will be spaced at 7.5m centres, roughly creating a 7.5 x 7.5m grid to adequately accommodate the spacial requirements of the above ground parking. Because column spacing is fixed due to parking requirements and column sizes will not vary much between the different slab types, they have also been excluded from the calculations. Other elements like stairs or lift shafts for example have also been excluded as they will also be constructed in much the same way in all slab types. (Interview: Van Rensburg 2009)

The following estimates are thus comparisons of the relative costs of various slabs intended to be used as offices.

5.2.1 Solid flat slabs

Figure 15: Solid flat slab cost estimate

TOTAL COST : SOLID FLAT SLAB	**R**	**560 880**

SOLID FLAT SLAB

Concrete slab 255mm thick								m²	900	623.20	560 880.00
- Concrete	1.00	1.00	1.00	0.26	920.00	:	239.20				
- Reinforcement	100.0	1.00	1.00	0.26	9.00	:	234.00				
- Formwork	1.00	1.00	1.00	1.00	150.00	:	150.00				

For the conventional flat slab, use is made of a 255mm thick slab with a steel reinforcing allowance of 100kg/m³ of concrete which is in this case conceived as adequate for a flat slab office floor, not necessitating any drop panels or widened column heads (Interview: Van Rensburg 2009).

The flush soffit of the flat slab contributes to it being the easiest to prop up and formwork to the soffit is priced at a relatively low rate of R150/m² (Interview: Visser 2009).

5.2.2 Slabs with beams

Figure 16: Slab with beams cost estimate

TOTAL COST : SLAB WITH BEAMS										**R**	**683 530**
SLAB WITH BEAMS											
Concrete slab 170mm thick								m²	900	459.40	413 460.00
- Concrete	1.00	1.00	1.00	0.17	920.00	:	156.40				
- Reinforcement	100.0	1.00	1.00	0.17	9.00	:	153.00				
- Formwork	1.00	1.00	1.00	1.00	150.00	:	150.00				
Beams 230 x 690mm								m	300	900.23	270 069.60
- Concrete	1.00	1.00	0.23	0.52	920.00	:	110.03				
- Reinforcement	120.0	1.00	1.00	0.52	9.00	:	561.60				
- Formwork	1.00	1.00	1.00	1.27	180.00	:	228.60				

The introduction of 230 x 690mm deep beams between columns makes it possible to lower the thickness of the slab to 170mm. A rather conservative, but safe approach would be to leave the allowance for concrete in the slab at 100kg/m³ and to allow for 120kg/m³ in beams (Interview: Van Rensburg 2009).

It is considered acceptable to have the rate for formwork to soffits of slabs remains at R150/m². The application of formwork to sides and soffits of beams does however require more effort and labour producing a higher rate of R180/m² (Interview: Visser 2009).

5.2.3 Coffer slabs

Figure 17: Coffer slab cost estimate

TOTAL COST : COFFER SLAB										**R**	**677 088**
COFFER SLAB											
Concrete slab 425mm thick								m²	900	655.56	590 004.00
- Concrete	1.00	1.00	1.00	0.23	920.00	:	210.68				
- Reinforcement	80.0	1.00	1.00	0.23	9.00	:	164.88				
- Formwork	1.00	1.00	1.00	1.00	280.00	:	280.00				
Band beams								m	300	290.28	87 084.00
- Concrete	1.00	1.00	1.00	0.18	920.00	:	162.84				
- Reinforcement	80.0	1.00	1.00	0.18	9.00	:	127.44				

For the coffer slab a 425mm thick slab will be used together with an overall sized 900 x 900 x 325mm deep coffer, commonly used in practice. Internal band beams will be introduced by omitting one row of coffers for the areas spanning between columns. The reinforcement required for this slab is much lower at 80kg/m³ thanks to the ribs formed between the coffer voids creating "beams" in effect, and the much lighter weight of the slab due to the voids (Interview: Van Rensburg 2009).

The cost of providing formwork to the slab is very much increased as the system applied for this estimate requires conventional flat slab formwork to be placed and for the hired coffers to then be placed in the required patterns on top. The rate allowed is thus much higher at R280/m² (Interview: Visser 2009).

To incorporate the saving of concrete produced by the coffer voids, the amount of concrete displaced by each coffer is calculated (0.159m³) and the number of coffers per square meter of slab is determined (1.234). The product of these two amounts to the total saving per square meter of slab. This is subtracted from the m³ of concrete per m² (0.425m³) produced by the overall thickness of slab, finally giving one the correct amount of concrete for every m² of coffer slab (0.229m³).

The concrete within the band beams where the voids have been omitted do however still need to be included and this can be calculated by determining the amount of coffers omitted per meter of band beam (1.111) and multiplying it with the cubic meters of concrete displaced by each coffer (0.159m³), as this omission is now being filled producing the correct amount of concrete to be added for band beams (0.177m³).

5.2.4 Biaxial hollow slabs

Figure 18: Biaxial hollow slab cost estimate

TOTAL COST : COBIAX SLAB	**R**	**744 012**

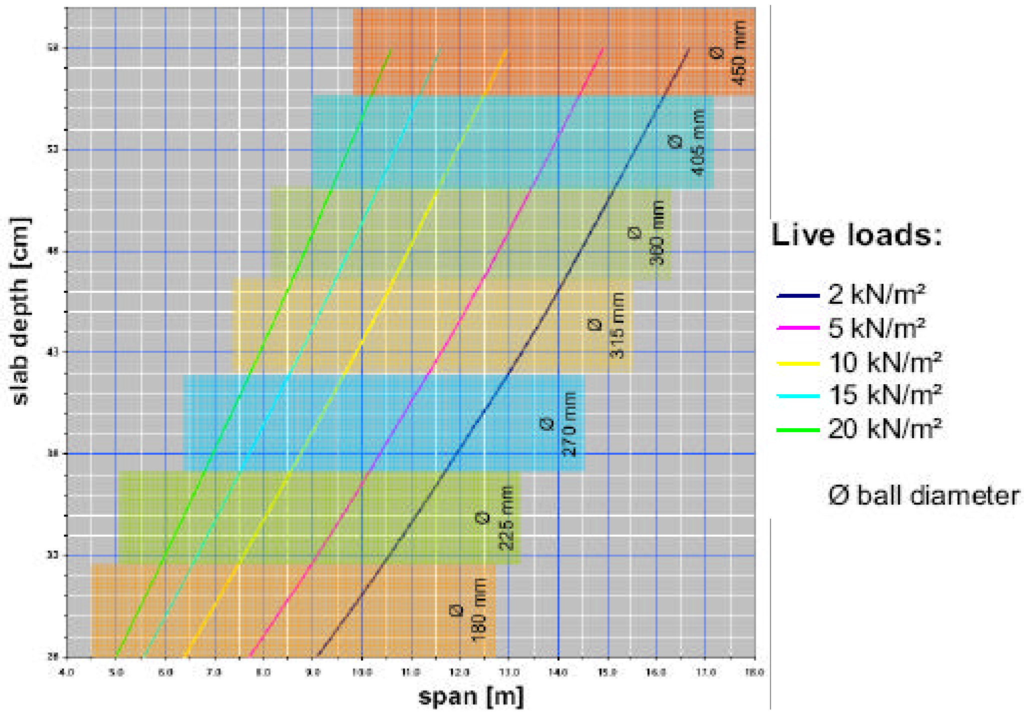
COBIAX SLAB

Concrete slab 425mm thick								m²	900	826.68	744 012.00
- Concrete	1.00	1.00	1.00	0.31	920.00	:	287.04				
- Reinforcement	80.0	1.00	1.00	0.31	9.00	:	224.64				
- Formwork	1.00	1.00	1.00	1.00	150.00	:	150.00				
- Cobiax balls	1.00	1.00	1.00	1.00	165.00	:	165.00				

For Cobiax slabs, similarly to coffer slabs, a 425mm thick slab is used which incorporates 270mm diameter hollow balls. A reinforcement allowance similar to coffer slabs can be made as these slabs have much the same characteristics and 80kg/m³ is allowed (Interview: Linnow 2009).

A nearly identical 425mm thick cobiax slab was constructed at the Oubaai Hotel in Heroldsbay where, at the end of the day, the reinforcing amounted to roughly 80kg/m³ as well. The slab's span between columns was also similar to the 7.5 x 7.5m grid used in these calculations which is very much on the conservative side and if one looks at and interprets figure 19, it can be seen that a much thinner slab or even much larger spans were possible when considering that characteristic imposed loads for offices range between 2.5 and 5 kN/m² (indicated by the blue and pink lines).

Figure 19: Preliminary span / depth ratios for cobiax flat slabs (Interview: Linnow 2009)



One of the reasons for the short spans was however, as the case is here, that column spacing was relatively fixed due to underlying parking lot. Another major reason for the "over design" as highlighted by Park (1980) could be the designing engineers hesitance to make use of the extreme spans Cobiax claim is possible because of the building industry's "resistance to change".

In order to construct the Cobiax slab, traditional flat slab formwork is propped up (rate used as before: R150/m²) and the Cobiax balls within their cages are placed on top. For the purchase as well as the placement of these balls, a rate of R165/m² of slab is used (Interview: Visser 2009).

The amount of concrete saved due to the voids formed by the 270mm diameter balls can be read from table 1 as 0.11m³/m² of slab. This amounts to only 0.312m³ of concrete per square meter of 425mm thick slab.

Table 1: Cobiax Properties (Cobiax Design Guide, 25 August 2009)

BALL DIAMETER	[mm]	180	225	270	315	360	405	450
Minimum slab thickness*	[mm]	300	350	400	450	500	550	600
Ball spacing (center to center)	[mm]	200	250	300	350	400	450	500
CBCM-eco support height	[mm]	185	230	275	320	365	410	455
Number of balls per m²	[-/m²]	25,00	16,00	11,11	8,16	6,25	4,94	4,00
Concrete savings per m²	[m³/m²]	0.07	0.09	0,11	0,13	0,15	0,17	0,19
Dead load reduction	[kN/m²]	1,91	2,39	2,86	3,34	3,82	4,29	4,77
Stiffness correction factor	[-]	0,94	0,93	0,92	0,91	0,91	0,90	0,89
Shear reduction factor	[-]	0,55	0,55	0,55	0,55	0,55	0,55	0,55

5.3 Summary

The cost of constructing the four types of slabs compared is summarized as follows.

Table 2: Building Cost Summary

BUILDING COST SUMMARY

CONSTRUCTION AREA	900	m²

		% Variance from lowest	RATE/m² Construction area	AMOUNT R c
BUILDING COST				
1	SOLID FLAT SLAB	-	623.20	560 880.00
2	SLAB WITH BEAMS	21.9%	759.48	683 529.60
3	COFFER SLAB	17.0%	752.32	677 088.00
4	COBIAX SLAB	27.0%	826.68	744 012.00

5.4 Conclusion

The cost estimation and comparison of different types of slabs is a very comprehensive process with many variables that can contribute to what the outcome will be. Although these estimates were done on relatively simple examples of structures, the outcome is clear: The conventional solid flat slab is the most cost effective solution, albeit for this specific example only.

In slabs with beams, the extra cost of constructing beams offset the saving in slab thickness, making it quite costly.

The high formwork cost together with the additional concrete to band beams lower the coffer slab's saving potential, making it the second favoured option.

Although Cobiax claim many savings in various different areas on the entire building, determining the exact extent thereof proves to be a near impossibility without redesigning a building from scratch in order to incorporate all aspects. Because Cobiax is so new in the local market, their product is often only considered in later stages of the design process, at which stage the benefits are usually cancelled out by the additional costs.

5.5 Test of hypothesis

The hypothesis was that the Cobiax slab system would be the most cost effective solution.

The hypothesis was found to be untrue as the Cobiax slab was found to be the most costly. If one does however take all possible savings into consideration, the Cobiax system might still be able to contribute to a saving on the overall project cost.

Chapter 6:
Conclusion

6.1 Background

The building industry has evolved from producing small, simple structure that are created with the mere purpose of fulfilling basic necessities such as shelter and security, to an industry that creates intricate structures that need still satisfy their basic requirements, but must now also accomplish a whole variety of other objectives regarding functionality, practicality, buildability, aesthetics, etc. etc.

Concrete has established itself as a suitable material for the frame of many of these structures despite it being very heavy and extremely weak under tensile forces. This has lead to the evolution of many different ways of constructing suitable concrete structures. The main aim of the continuously evolving alternatives is to try and eliminate as much weight as possible from the structure without compromising structural integrity. This is done by removing concrete in places where it does not contribute structurally to the building.

In most cases, the floor slab forms the most significant part of the structure and all other frame elements are constructed to ensure that the floors, and the loads that they are carrying, can be supported safely. The main focus of this study was thus based on floor slabs as it is they which vary in construction methods with the supporting structure following suit and being altered as would best suit the slab's capabilities.

A study was done by comparing four different types of slabs: Three that are commonly made use of in the industry and one which is a relatively new innovation trying to prove itself in the market.

In an attempt to determine the most suitable slab, they were compared with regards to four aspects:

- Strength
- Aesthetics
- Buildability
- Cost

6.2 Summary

In order to reach a conclusion, the objective was to decide on a clear favourite within each aspect under review. This was done by breaking down each sub-problem into further criteria in order to effectively compare the slabs. This is summarized by giving a short description on how a favourite was decided upon while stipulating how the various slabs compared within the sub-criteria in a table format being scored as follows:

1 - Poor
2 - Average
3 - Best

6.2.1 Do structural requirements influence the choice of slab type?

Different slabs are intended to be used for different situations making use of the slab best able to carry the loads that it is intended for. From a pure strength aspect however, the slab with beams proves to be the favourite with its ability to be strengthened in the necessary zones by means of beams.

Table 3: Slab strength comparison

Slab type:	Load carrying capabilities	Spanning capabilities	Accommodation of services – vertically
Solid flat slabs	**1**	**1**	**1**
Slabs with beams	**3**	**2**	**3**
Coffer slabs	**3**	**2**	**2**
Biaxial hollow slabs	**1**	**3**	**2**

6.2.2 What influence does the type of slab have on visual aspects of the structure?

The main factor to determine is firstly whether the slab will be visual. If so, then the desired quality finish must be determined and so constructed. From an aesthetic point of view, the flush soffit and relatively reduced building height makes the solid flat slab a good choice. The spanning capabilities of the cobiax slab do however help to reduce the amount of columns, also making it a flexible and thus viable choice although building height might be sacrificed.

Table 4: Slab aesthetic comparison

Slab type:	Flexibility	Building height	Accommodation of services – horizontally
Solid flat slabs	**2**	**3**	**3**
Slabs with beams	**1**	**1**	**2**
Coffer slabs	**2**	**2**	**2**
Biaxial hollow slabs	**3**	**2**	**3**

6.2.3 How does buildability influence the choice of slab type?

Buildability often turns out to be “the builder’s problem” with not much though being given thereto by the designers. From a buildability perspective, the obvious choice would be slab construction in its simplest form: Solid flat slabs.

Table 5: Slab buildability comparison

Slab type:	Erection time	Labour intensity	Repetitive work	Horizontal service installation
Solid flat slabs	**3**	**3**	**3**	**3**
Slabs with beams	**1**	**1**	**1**	**1**
Coffer slabs	**1**	**1**	**2**	**2**
Biaxial hollow slabs	**1**	**1**	**2**	**3**

6.2.4 Which type of slab is the most cost effective alternative?

In limiting the cost comparison to slab cost only, many other factors might not have been taken into account. Such factors could well have contributed to potential cost saving on some of the slabs (especially cobiax). Albeit so, such savings would have to amount to a great deal before they bring the other slabs in contention with the most economical construction of the conventional solid flat slab.

Table 6: Slab cost comparison

Slab type:	Cost of slab	% from lowest
Solid flat slabs	**R 560 880**	**-**
Coffer slabs	**R 677 088**	**17%**
Slabs with beams	**R 683 530**	**22%**
Biaxial hollow slabs	**R 744 012**	**27%**

6.3 Conclusion

In making a decision as to "*which type of slab is the most effective solution to concrete structures,*" there are many factors which one must take into account. The first of which being: What will the intended use of the building be? This will determine its structural requirements and only after this criterion has been satisfied, can other factors be considered.

Each type of slab discussed has its own set of characteristics and although many of these characteristics were shared by more than one slab, it was found that different slabs were more suited for different situations. For example: beams would provide extra strength for carrying capacity, biaxial hollow slabs allow for larger spans, etc.

However, in order to address the main problem, one must look at the overall picture of how these slabs faired in all aspects compared. In doing so, a conclusion can be reached that in most cases; the conventional solid flat slab would be the most effective solution to concrete structures. This conclusion is reached by deducing from the studies that although the three other slab variations do each have their various advantageous characteristics over those of the solid flat slab, other positive attributes of the slab is lost in trying to gain such advantages.

In actual fact, when looking at how the solid flat slab faired in all comparisons, one finds that it was a favourable option for almost all criteria. The only major weak point identified being its severe weight, having an impact on its load carrying and spanning capabilities as well as not allowing gaps for services close to columns. The introduction of widened columns heads and/or dropped panels in the slab could however reduce such weaknesses to a lesser degree without having a major influence on other compared criteria.

After taking all factors into consideration, the main problem is solved by the solid flat slab which in most cases is *the most effective solution to concrete structures.*

6.4 Possible further research

- Pre- and post tensioning

Pre- and post tensioning an in-situ cast slab will have a large influence on its characteristic qualities and can be applied to almost any type of slab creating many possible outcomes.

- Precast slabs

The use of precast slabs has not been implemented locally to such a large degree as it has overseas: Europe, America, etc. In our country, the precast field with it pros and cons is relatively unexplored.

- Compare all building elements

This study was limited to mainly a comparison of the slab itself. One could broaden the study field to take other building elements into account as well when comparing different construction methods.

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