Finite Element Modelling of Hollow Core Concrete Slabs

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ABSTRACT

Cobiax AG is a company who specialises in the design and manufacture of large span concrete flat-slab systems with internal spherical void formers. The internal spherical void formers aim to displace the dead load in the neutral zone of the concrete, hence reducing its dead load. This technology has been used in Europe for over a decade, however the use of Cobiax in Australia remains scarce. This may be due to the fact that Cobiax AG has not provided any scientific data to back up their claims; a serious issue which is addressed in this thesis.

This thesis examines the benefits of Cobiax optimised slabs using a finite element (FE) method. Strand7 (2010) FE analysis software and Rhinoceros4 (2010) was used to carry out this study. Solid and Cobiax slabs were modelled in Strand7 and cross-analysed to explore their relative merits. Parameters that were of interest included: the slab's short-term elastic deflections; steel tension stresses; and concrete compressive stresses. The sustainability benefits of using Cobiax were also explored. It was found that Cobiax displayed up to 10% reductions across all parameters explored compared to solid slabs. Further, Cobiax optimised slabs significantly reduced carbon emissions when compared to solid slabs.

ACKNOWLEDGEMENTS

I would like to thank my supervisor and mentor, Dr Hui Jiao for his support, guidance and patience throughout the course of this thesis. I am grateful to Dr Damien Holloway for his expertise and advice with methodological modelling issues, Dr Jon Shanks and Mr Daniel Hugo for their willingness to provided assistance. I would also like to thank my parents for providing me with an opportunity to study at the University of Tasmania because without this opportunity, I would not be here today. Lastly, without the continuous support of my partner Annabel Cocker, this thesis would not have been possible.

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1 INTRODUCTION

1.1 Cobiax Technologies AG

Cobiax Technologies Group is a company based in Switzerland with branch offices throughout Europe. It is internationally active in the construction industry through its various license partners throughout the world. Cobiax Technologies specializes in the design and construction of lightweight hollow core concrete slabs optimised with void formers. These void formers are light spheres made from recycled plastic.

Figure 1-1: Cobiax pre-cast concrete base

The desired effect of the spherical void formers is to displace concrete in the neutral zone of the slab. This section of a solid slab has no structural effect and simply increases the dead load of the slab. The idea behind the spherical formers is that the imposed load capacity of the slab can be increased without increased dead load. The formwork involved with Cobiax slabs is minimal; this can either be achieved via off-site precast concrete setups (Figure 1-1) or on-site in-situ methods.

This is achieved by displacing the concrete in the neutral zone of the slab as shown in Figure 1-2 using spherical void formers.

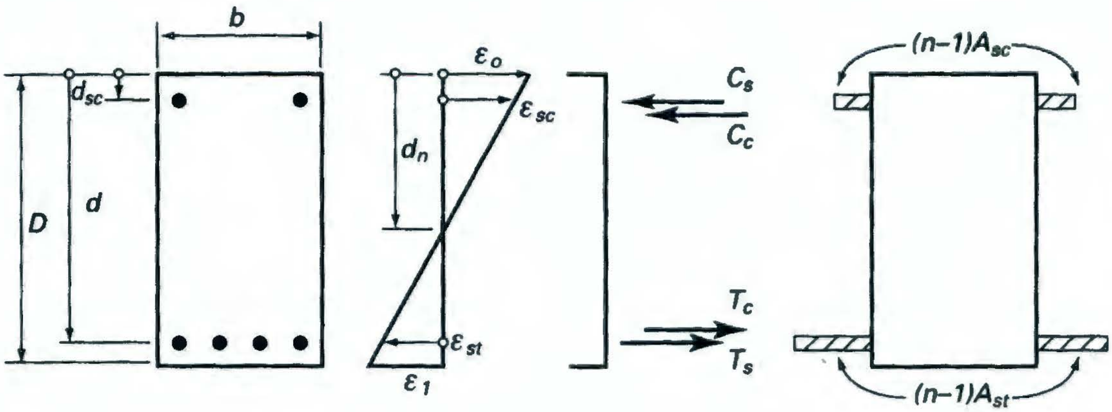

Figure 1-2: Stress & Strain Diagram

(Obtained from Warner et al. 1998)

Figure 1-2 extracted from Warner et al. (1998) shows the stress on the neutral depth to be zero.

1.1.1 Claimed Benefits

Cobiax Technologies has made significant major claims regarding Cobiax optimized slabs. This has been done without any supporting evidence. A snapshot (Figure 1-3) was taken from the Cobiax website, which details the claims graphically.

Benefits

The numerous advantages of the Cobiax technology lead to an increased value for all stakeholders involved in the design and execution process of concrete structures for buildings.

Resource efficiency leads to increased static performance, economic costing and sustainable **climate friendly building structures**.

Weight reduction

- Up to 35% lighter than solid flat slabs
- Up to 15% less load acting on foundations
- Increased freedom for structural conception

Large spans

- Up to 20 m spans
- Flat soffits with no obstructing beams
- Up to 40% less columns

Earthquake safety

- Reduction of the accelerated mass
- Eased earthquake design verification
- Reduced damage risks

Cost effectiveness

- Concrete and reinforcement steel savings
- Reduced floor-to-floor height
- Eased retrofitting of building

Sustainability

- Resource efficiency trough building materials savings
- CO2 emission reductions trough concrete volume optimization
- Use of recycled material for Cobiax products

Figure 1-3: Snapshot of Cobiax's claimed benefits

(Obtained from Cobiax Technologies 2009)

Should these claims be verified by a finite element (FE) method, Cobiax optimized slabs are a more sustainable alternative to solid slabs due to its reductions in CO_2 emission through concrete volume optimization and usage of recycled materials.

2 LITERATURE REVIEW

Most of the literature reviewed shed little light on the claims Cobiax has made regarding the benefits of the product. There is very little information available on UTAS's subscription databases such as Scopus, Compendex or Engineering Village regarding Cobiax. Most of the literature available on Cobiax only discusses the basic concepts and recognises the product for innovative design.

Elliot, Morris and Pickering (2010) noted in *'The Structural Engineer'* that Pinnacle, a leading consulting engineers company, has developed an innovative solution for the construction of TESCO, a supermarket giant based in the UK. Cobiaxdeck was the solution for the project; this was ground-breaking technology which enabled the construction of a seven-storey building for mixed use worth £42M. According to the article, if constructed without Cobiaxdeck, this building would not have achieved a significantly reduced construction program of only 48 weeks compared to 80 weeks.

Similarly, Hansford (2008) also reported in the *'New Civil Engineer'* that the construction of TESCO not only achieved a significantly reduced construction time, but also increased column to column spacing. This meant that there is an increased effective area for stores within TESCO achieving an "enriched customer experience, giving the car park areas and store an open and less claustrophobic feel" (Hansford 2008).

Stephenson (2007) and Concrete Society (2006) both highlighted the innovation and pioneering approach shown by Stephenson Holdings Ltd. They were awarded the *'Construct Award for Innovation and Best Practice 2006'* by Concrete Society (London) for successfully constructing Sheffield University's Learning Resource Centre. This article clearly demonstrates the trust professional institutions have towards Cobiax Technologies and their claims, despite the lack of unbiased, scientific investigation of the claims.

Thus, while Cobiax may be beneficial, the need for evidence to back up these claims is clear.

Upon request, a preliminary design guide entitled *'Cobiax Cage Module Specifications'* by Cobiax Technologies (2009) was obtained from Danley Constructions, who are the official licensee of Cobiax in Australia. This design guide provides information on typical design specifications of Cobiax void former elements. While the guide does not provide much scientific data to back their claims, it does provide valuable information regarding the dimensions of various configurations of Cobiax slabs.

Below is a direct extract from the guide, listing some useful information for both the Slim-Line and Eco-Line product ranges.

Cage module type		CBCM-S-100	CBCM-S-140	CBCM-S-160	CBCM-S-180	CBCM-E-225	CBCM-E-270	CBCM-E-315	CBCM-E-360	CBCM-E-405	CBCM-E-450
Void former height	[cm]	10.0	14.0	16.0	18.0	22.5	27.0	31.5	36.0	40.5	45.0
Void former horizontal diameter	[cm]	22.5	31.5	31.5	31.5	22.5	27.0	31.5	36.0	40.5	45.0
Spacing between void formers	[cm]	2.5	3.5	3.5	3.5	2.5	3.0	3.5	4.0	4.5	5.0
Void former centre line spacing	[cm]	25.0	35.0	35.0	35.0	25.0	30.0	35.0	40.0	45.0	50.0
Positioning cage support height	[cm]	11.0	15.0	17.0	19.0	23.0	27.5	32.0	36.6	41.1	45.7
Equivalent area covered per void	[m²]	0.063	0.123	0.123	0.123	0.063	0.090	0.123	0.160	0.203	0.250
Number of void formers per m²	[-]	16.00	8.16	8.16	8.16	16.00	11.11	8.16	6.25	4.94	4.00
Concrete displacement per m²	[m³/m²]	0.053	0.074	0.086	0.099	0.096	0.114	0.134	0.153	0.172	0.191
Weight reduction* per m²	[kN/m²]	1.32	1.85	2.16	2.48	2.39	2.86	3.34	3.82	4.29	4.77
Void formers per positioning cage	[-]	10	7	7	7	10	8	7	6	5	5

*) assuming a concrete density of 25 kN per m^3

Figure 2-1: Cobiax Cage Module Specifications

(Obtained from Cobiax Technologies 2009)

In an unpublished thesis, Johnson (2009) carried out an FE study to investigate some of the claims made by Cobiax. His findings were only based on one configuration. A configuration here means varying Cobiax void former diameters against the slab depth. This modelling of both cracked and un-cracked sections determined that there was a 30% reduction in concrete used to cast the slab and approximately 10% reductions in concrete compression stresses, steel tension stresses and deflections. Based on

Johnson's findings, he concluded that hollow core concrete slabs have some significant structural benefits due to the diminished dead load.

From the literature obtained and reviewed, it can be concluded that apart from Johnson's unpublished thesis (2009), Cobiax has carried out internal research into its claims without publishing findings and there has been no third party companies investigating these claims. Peer reviewed research is a vital part of scientific research and development (Dominiczak 2003) , and the lack of it is a serious issue which this thesis aims to address.

3 PROJECT SCOPE

The aim of this thesis is to investigate and analyse using a FE method, the claims made by Cobiax Technologies.

The project scope includes:

- Carry out a literature review on Cobiax Technologies and hollow core concrete structures;
- Build FE models using Strand7 (2010) for both solid and hollow-core slabs
  - Determine adequate mesh sizes for models;
- Compare computed values of solid slab in FE program in accordance with AS 3600 to determine validity of modelling methods:
  - Upon verification, continue modelling of hollow core slabs using same methods to preserve model accuracy
  - Vary Cobiax configurations in relation to void diameter
    - Void former diameter ranges from 180 mm to 450 mm diameter as specified in the *'Cobiax Cage Module Specifications'*.;
- Cross analysis between Cobiax slab and solid slab to determine:
  - Maximum section stresses – tensile and compressive
  - Slab deflections;
- Sustainability benefits of using Cobiax;
- Suggest practical design factors for Cobiax slabs based on FE method findings.

4 MODEL CREATION

Rhinoceros4 (Rhino4) 3D (2010) was chosen as the preferred CAD package because of its user friendly interface for creating complex 3D models. This made modelling both the solid and Cobiax slabs simple and yet efficient due to the different views of the model within Rhino4 (2010).

Autodesk's AutoCAD package was also explored; however due to the limited file export formats available Rhino4 (2010) was used as it is able to export the 3D model geometry files as a Standard ACIS Text (SAT) file. The SAT file is part of the Alan, Charles, Ian's System (ACIS) and essentially stores the 3D geometry information in a text format.

Strand7 (2010) was chosen as the FE analysis software because of its nodal interface and the ability to import SAT files created from Rhino4 (2010); the model can then be meshed and further analysed in Strand7 (2010).

The models created within Rhino4 (2010) need to be created with appropriate dimensions considering the minimum concrete cover needed as well as the position of the void former within. Based on Abramski's (2010) article, a typical Cobiax cross section has been provided detailing the concrete cover needed for the void former as well as for the steel reinforcement as shown in Figure 4-1

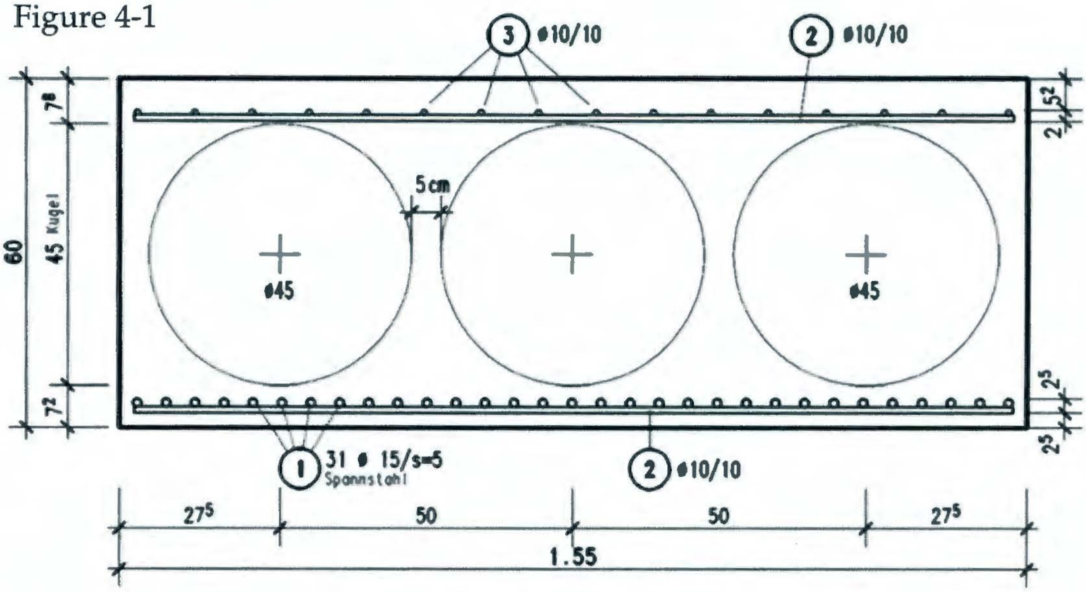

Figure 4-1: Typical Cobiax Slab Cross Section (Dimensions in cm)

(Obtained from Abramski et al. 2010)

In Rhino4 (2010), complex shapes can be created simply by adding or subtracting polygons from each other. Simple steps will be outlined in this section for a typical model construction in both Rhino4 (2010) and Strand7 (2010). The table below outlines all model dimensions used in the model creation and analysis.

Void former diameter [mm]	Width [mm]	Effective depth [mm]	Total depth [mm]	Section Length [mm]
180	200	240	270	7200
225	250	285	315	9000
270	300	330	360	10800
315	350	375	405	12600
360	400	420	450	14400
405	450	465	495	16200
450	510	500	530	18360

Table 4-1: Model Dimensions and Length

Note : Section length in Table 4-1 refers to the length of one-way slabs used for analysis in Section 7.1. The length of two-way slabs used was half of the length of the one-way slabs due to limited processing resources as discussed in Section 7.2.

4.1 Un-cracked Model Creation

This section outlines the procedures used in both Rhino4 (2010) and Strand7 (2010) to create the FE models.

Step 1 : Creation of Cobiax element.

- Create a rectangular section with appropriate dimensions for intended model size

  Toolbar → Solid → Box → Corner to Corner, Height

- Create a sphere centred within the rectangular section with appropriate dimensions.(See Figure 4-2)

  Toolbar → Solid → Sphere → Centre, Radius

- The sphere must now be subtracted from the rectangular section to produce a symmetrical half Cobiax section. (See Figure 4-3)

  Toolbar → Solid → Difference

(Note that the rectangular section is required to be selected first for the correct subtraction to be applied)

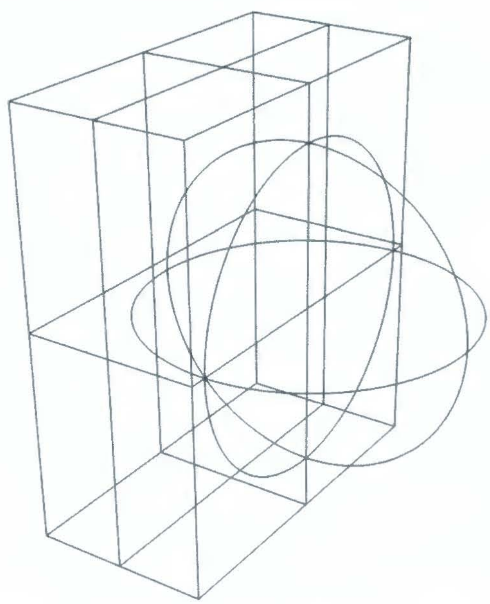

Figure 4-2: Sphere within Rectangular Section

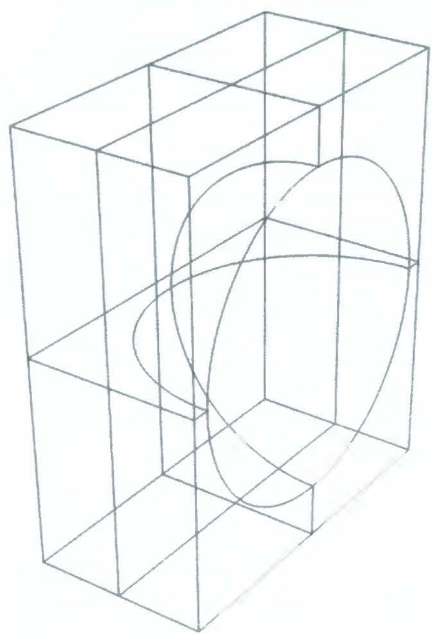

Figure 4-3: Subtracted Sphere (Cobiax element)

Step 2 : Importing into Strand7.

- Rhino4 (2010) has the ability to export 3D geometries into an SAT file, which is recognised by Strand7 (2010).

  Toolbar → File → Save As → ACIS* (.sat)

- Once the geometry is imported, it can then be auto-meshed within Strand7 (2010). This is done so that nodes and plates are created on each face of the geometry.

  Toolbar → Tools → Automeshing → Surface Mesh

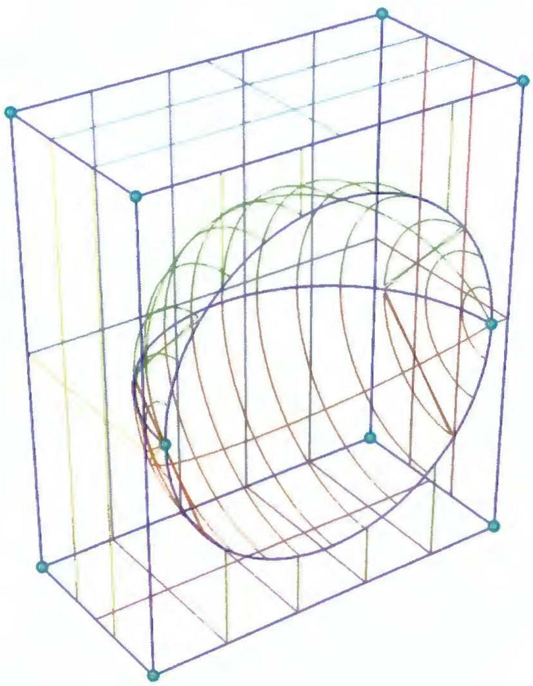

Figure 4-4: Strand7 Imported Wireframe Geometry

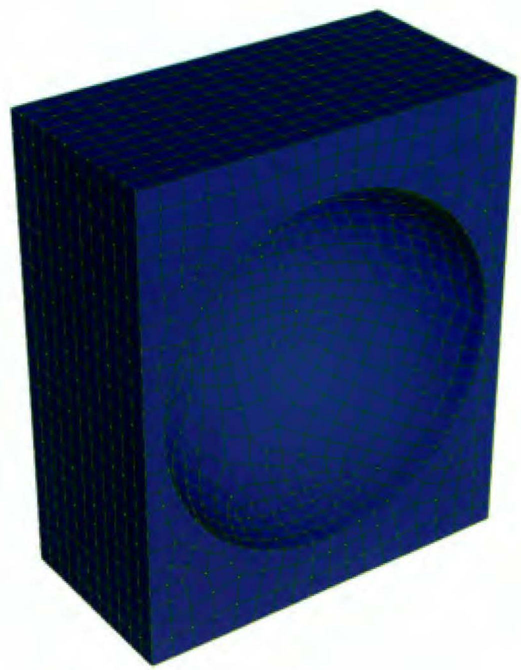

Figure 4-5: Strand7 Geometry with 7.5mm mesh

Step 3 : Application of steel reinforcing and concrete cover.

- Steel reinforcing can be added in the form of a Beam2 element within Strand7 (2010). Adequate spacing must be calculated and the number of bars pre-determined prior to application. The steel beams must be connected in a straight line and at each node that it passes through.

  Toolbar → Create → Element → Beam2

- Adequate concrete cover must also be applied to the surface at the level of reinforcement. This can be done by the following steps and selecting entire bottom face.

  Toolbar → Select by Region → Toggle Plate Select → Tools → Extrude → by Increments

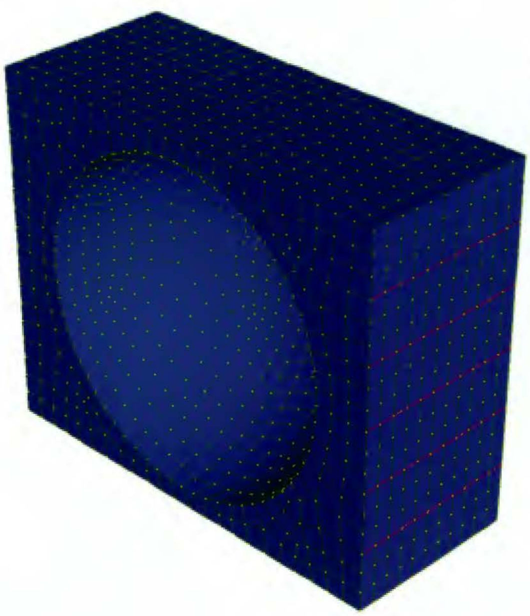

Figure 4-6: Surface Mesh with Steel Reinforcement

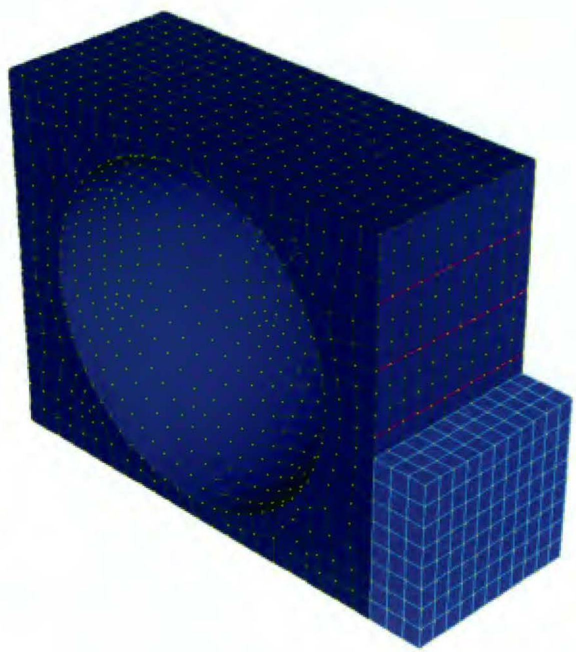

Figure 4-7: Surface Mesh with Applied Concrete Cover

Note : As a general rule of thumb, approximately 2% steel reinforcement has been assumed. The reinforcement type and number of bars was determined according to OneSteel (2011), who provide industry standard for reinforcements in Australia.

Step 4 : Solid meshing and assembly of element

- Following the surface mesh performed, the model needs to be solid meshed. This must be done so that the model can be solved.

  Toolbar → Tools → Automeshing → Solid Mesh

(Note that since the concrete cover elements are already solids, the remaining plates need to be selected and only the plate selection solid meshed)

- Now that the semi Cobiax element is created, the model can then be mirrored about its frontal axis to form a unit cube, and be copied longitudinally and then transversely to form either a beam or slab element.

  Toolbar → Tools → Mirror

  Toolbar → Tools → Copy → by Increments

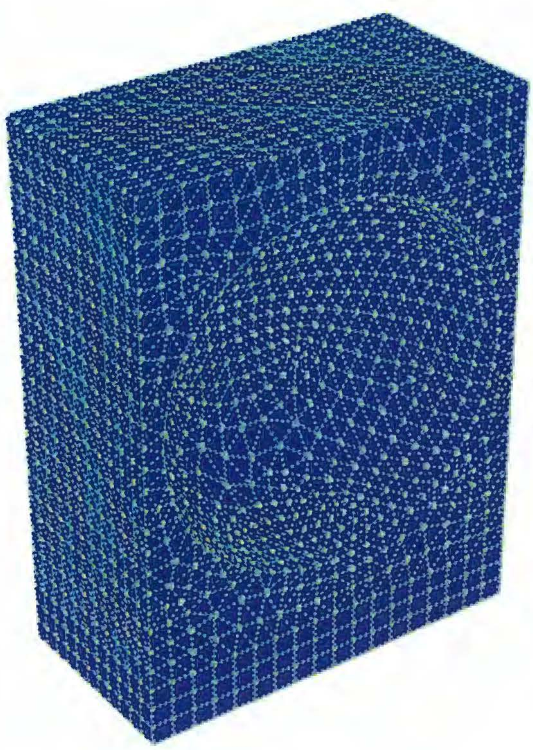

Figure 4-8: Solid Mesh Mirror Selection

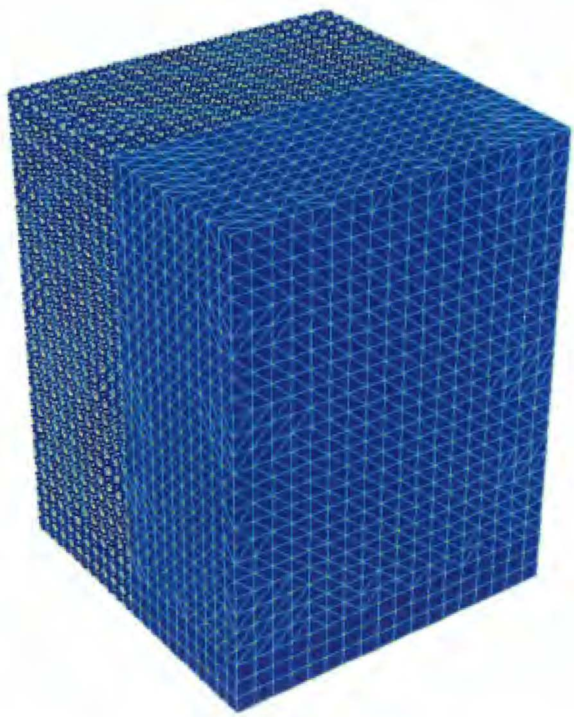

Figure 4-9: Cobiax Unit FEA Cube

4.2 One-Way Slab Creation

From the creation of the Cobiax unit cube, a one-way slab can be created simply by copying the cube transversely in the x-direction.

Step 1 : Creation of Cobiax one-way slab.

- Copy the cube transversely using the Strand7's copy by increment function.

Toolbar → Tools → Copy → by Increment

Step 2 : Implementing boundary conditions.

- To significantly reduce the model size and solve time, the slab's symmetry can be exploited by appropriate boundary conditions. Since the slab is symmetrical, only half of the model needs to be modelled.
- The nodes at the mid-span of the slab can be restrained in the x-direction to simulate half of the slab whereas the restraints on the front face can be restrained in both the y and z direction only.

Toolbar → Select by Region → Toggle Node Select

Attributes → Node → Restraint

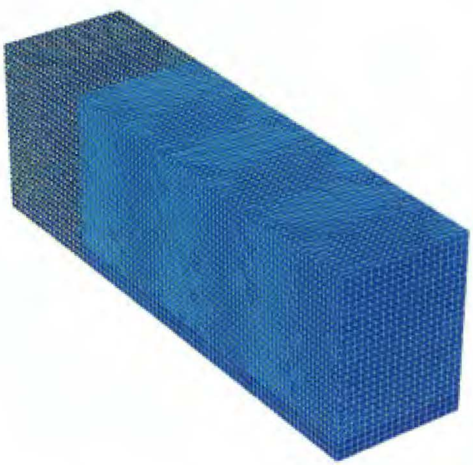

Figure 4-10: Copied One-Way Slab

Figure 4-11: One-Way Slab Half Section

4.3 Two-Way Slab Creation

A two-way slab system can be created by continuing from Step 3 of Section 4.1; as a two-way slab spans in both directions, adequate reinforcing will be required as well.

Step 1 : Application of longitudinal reinforcement.

- The steel reinforcement can be applied as described in Step 3 of Section 4.1 and the concrete cover elements copied to form a semi-cube. The semi-cube will need to be mirrored to form a unit cube.

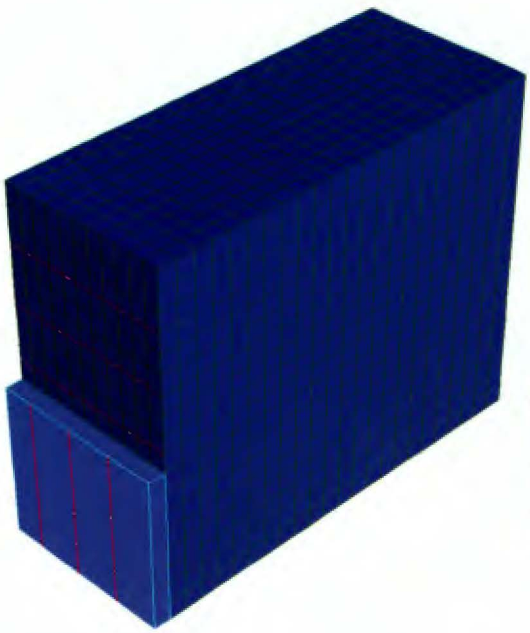

Figure 4-12: Second Layer of Reinforcement

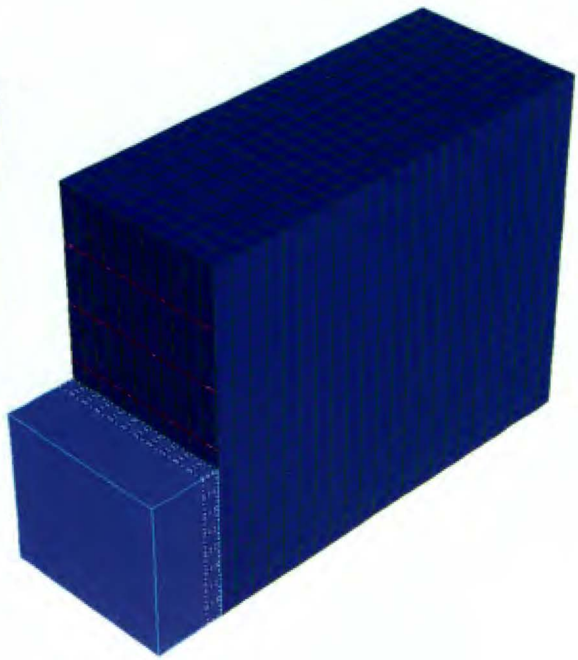

Figure 4-13: Concrete Cover on Two-way Slab

Step 2 : Creation of Cobiax two-way slab.

- Similar to a one-way slab creation method, a two-way slab has to be copied in both the transverse and longitudinal direction.

  Toolbar → Tools → Copy → by Increment

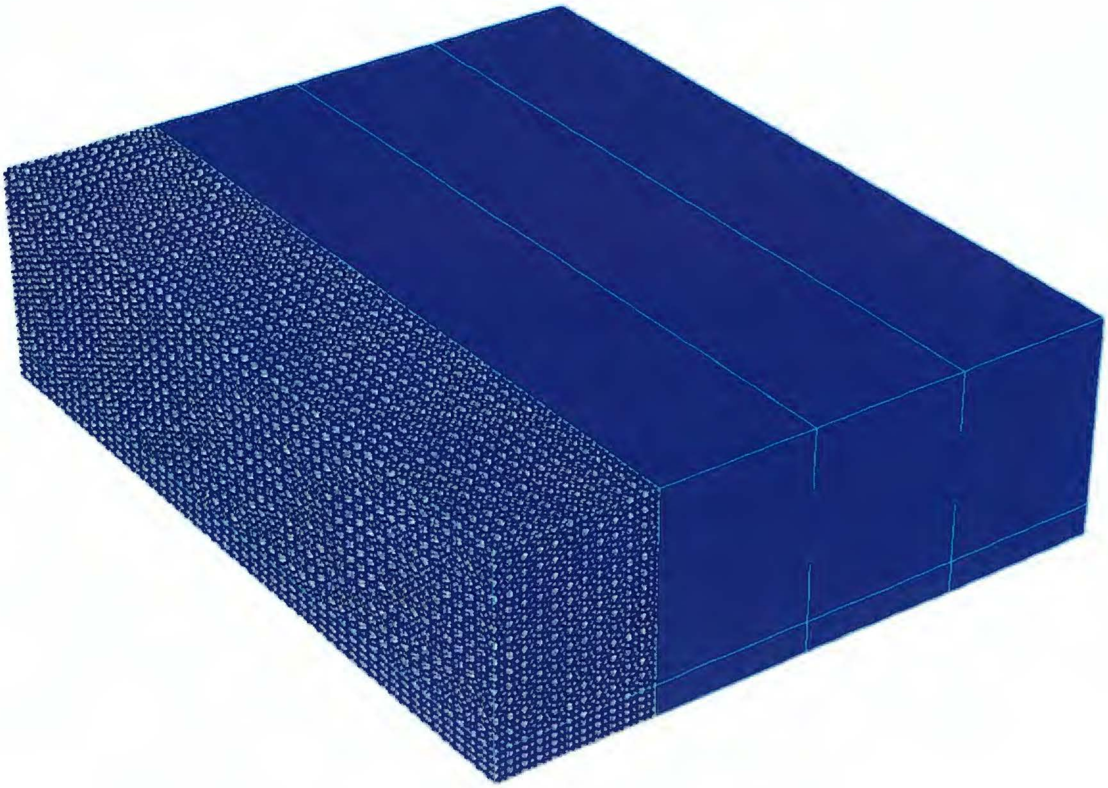

Figure 4-14: Two-way Slab Model

Note : The overall depth of the slab will increase by 10 - 20 mm depending on the reinforcement bar diameter due to the additional layer of reinforcement.

4.4 Boundary Conditions

There were some difficulties experienced whilst trying to implement the appropriate boundary conditions for both one-way and two-way slab models. The correct boundary conditions were obtained after much experimentation with different models. The models included an equivalent full scale one-way slab model against a half section model. Similar methods were used with two-way slabs with only a quarter of the slab modelled in Strand7 (2010). It was then found that the results of the full scale model and the half and quarter models were the same, thus validating the boundary conditions used.

The major advantage of exploiting symmetry is the reduced model size; this means that the solve time for a one-way slab and two-way slab can be halved and quartered respectively. As shown in Figure 4-15 below, one-way slab models can be restrained in the x axis at the mid-span and in the y and z axis on the edge. This essentially simulates a mirrored one-way slab with a pinned support on one end and a roller on the other. The model was verified against a full-scale model with identical deflections and stresses when solved.

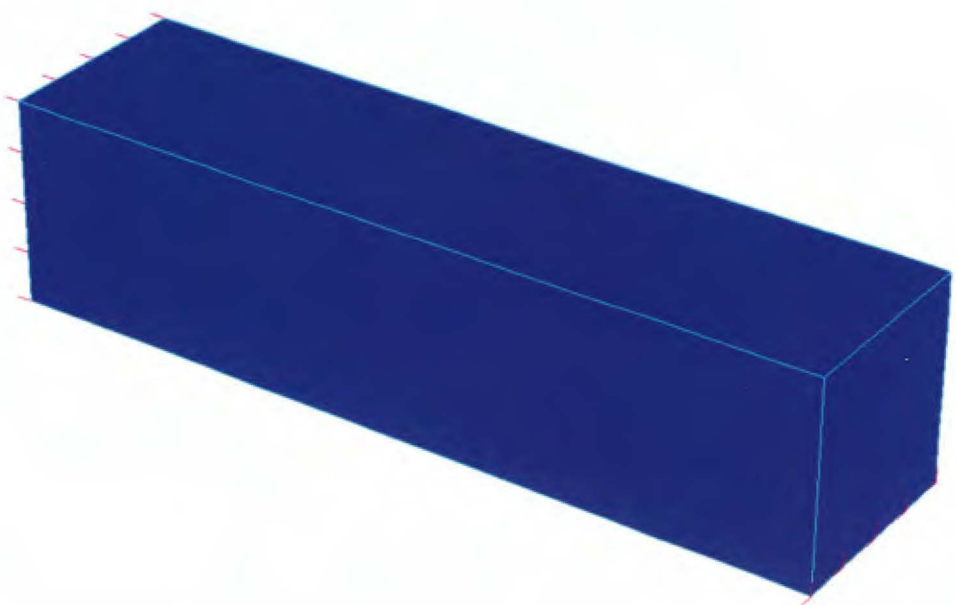

Figure 4-15: One-way Slab with Boundary Conditions

Similar to one-way slabs, the symmetry of two-way slabs can be exploited as well by modelling a quarter of the slab. This can be done by the use of appropriate boundary conditions on the cross section faces. The edge of the two-way slab must be restrained in the z direction to restrain any vertical movements caused by the load on the top face. In effect, this simulates a column support on the edge of the slab.

The vertical line of nodes in the middle of the slab must be restrained in both the x and y direction as the deflection of the slab can only be in the z direction. Similarly on each of the cross section faces, appropriate boundary conditions must be set. Figure 4-16 below shows a two-way slab model with its boundary conditions.

Figure 4-16: Two-way Slab with Boundary Conditions

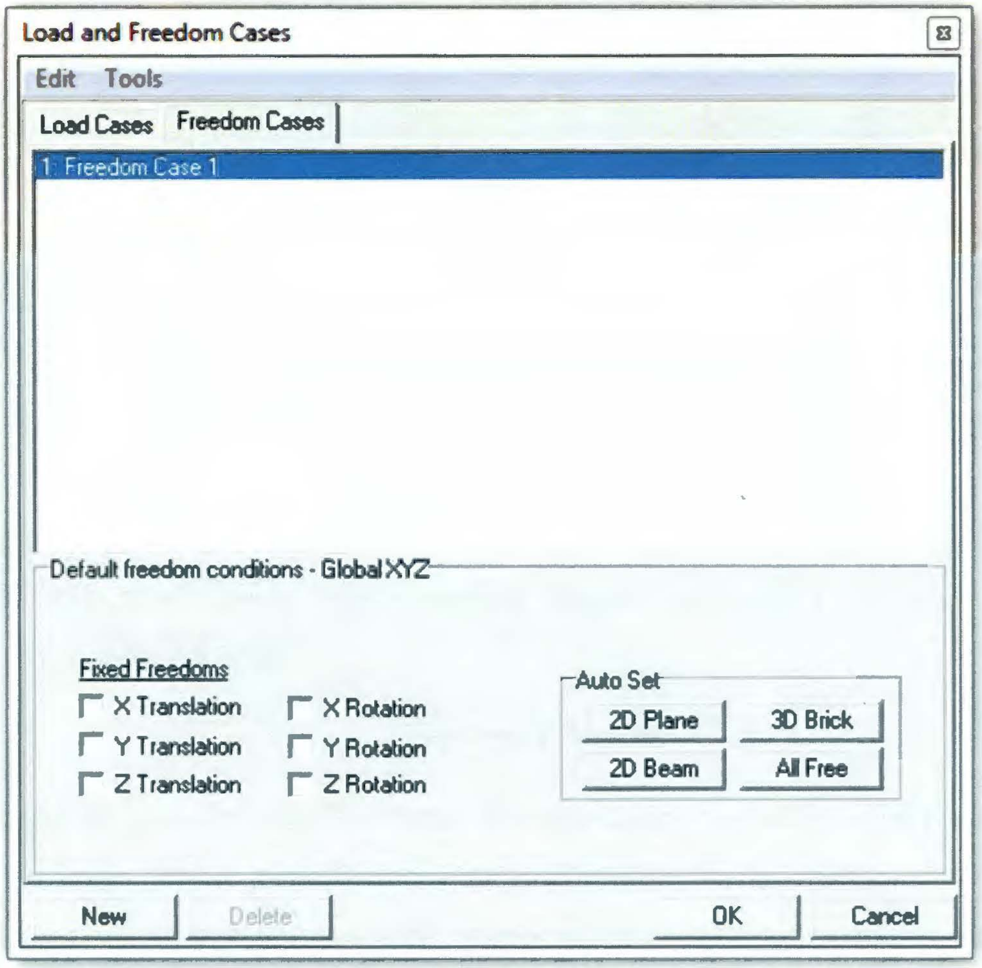

Figure 4-17: Strand7 Freedom Conditions

Note : Global freedom conditions must be set in each slab model. The one-way slab model will require no restraints for any rotation; however two-way slabs will require a '3D Brick' preset which will restrain rotations about the x, y and z axis.

5 MODEL VERIFICATION

Cobiax AG has not provided scientific data to back up their claims and there are no existing simplified design methods to verify the validity of the FEA results. As such, verification of the modelling methods described in Section 4.1 were carried out on a solid slab element prior to cross analysing with Cobiax slabs.

The geometry was modelled in Rhino4 (2010) and then imported into Strand7 (2010). As it is a solid element, no voids have been implemented in the geometry. The findings based on FEA will be compared with theoretical results calculated using the standard simplified design formulas in accordance with AS 3600.

5.1 General Notes

As noted in Johnson's (2009) thesis, the standard formulas involving the modular ratio (n) are usually implemented within in the form of $(n-1)$. This is because in practise, the steel reinforcement contained within the slab displaces the concrete volume in its place.

However, in Strand7 (2010), there are no known methods to model the reinforcement whilst taking into account the displaced concrete volume. In this instance, the modular ratio (n) will be utilised instead of $(n-1)$ in all equations as it does not displace concrete. The revised modular ratio will be used in Section 5.4.1.

As noted in Section 4.1, an assumption of 1% steel reinforcement will be implemented within all models for consistency.

5.2 Automeshing in Strand7

Initially, the model was drawn in Rhino (2010) as a full solid, which intuitively should mean that the cube can be copied transversely to form a one-way slab. However this was not the case; some difficulties were encountered during the copying phase.

The nodes created by Strand7 's (2010) automesh function were not a straight line of nodes on either the x-axis or the y-axis. This meant that adequate steel reinforcement bonding cannot be created between each cube because of the minute vertical gaps between the nodes once copied. This is especially visible when the model is statically solved and numerical discontinuity can be seen in the stress contours.

A simple solution was found to fix this problem; the model can be mirrored on its frontal facing plane to create a full cube (as shown in Figure 4-10) and on its side facing plane from the semi-cube configuration as shown in Figure 4-14. Using this method, the staggered line of nodes will be mirrored, hence eliminating the vertically misaligned nodes and enabling the unit cube to be copied transversely and longitudinally to form either beam or slab elements as required.

5.3 Gravity and Imposed Loads

An analysis was carried out to investigate the effects of using either gravity or an imposed dead load for the model's self-weight. It is anticipated that there should not be any significant differences between the two methods. The analysis was carried out using a 15 mm mesh size on a solid 270 mm deep slab.

The table below shows the correlation between using gravity and an imposed dead load to simulate the models self-weight. The slab was modelled at three spans, using 1.2 m, 2.4 m and 3.6 m sections. This was carried out to explore the effect of the model at larger spans.

Length	Method	Concrete		Steel Reinforcement	Deflection [mm]
		Compression [kPa]	Tension [kPa]	Tension [kPa]	
1.2 m	Gravity	102.585	93.524	442.751	0.0049
	Imposed	103.805	94.635	449.060	0.0050
	% Difference	1.189%	1.188%	1.425%	2.189%
2.4 m	Gravity	408.090	355.636	1786.330	0.0625
	Imposed	412.863	359.826	1808.420	0.0632
	% Difference	1.169%	1.178%	1.237%	1.042%
3.6 m	Gravity	911.293	799.123	4026.473	0.3068
	Imposed	917.977	804.977	4057.028	0.3088
	% Difference	0.734%	0.733%	0.759%	0.652%

Table 5-1: Gravity vs. Imposed Load Comparison

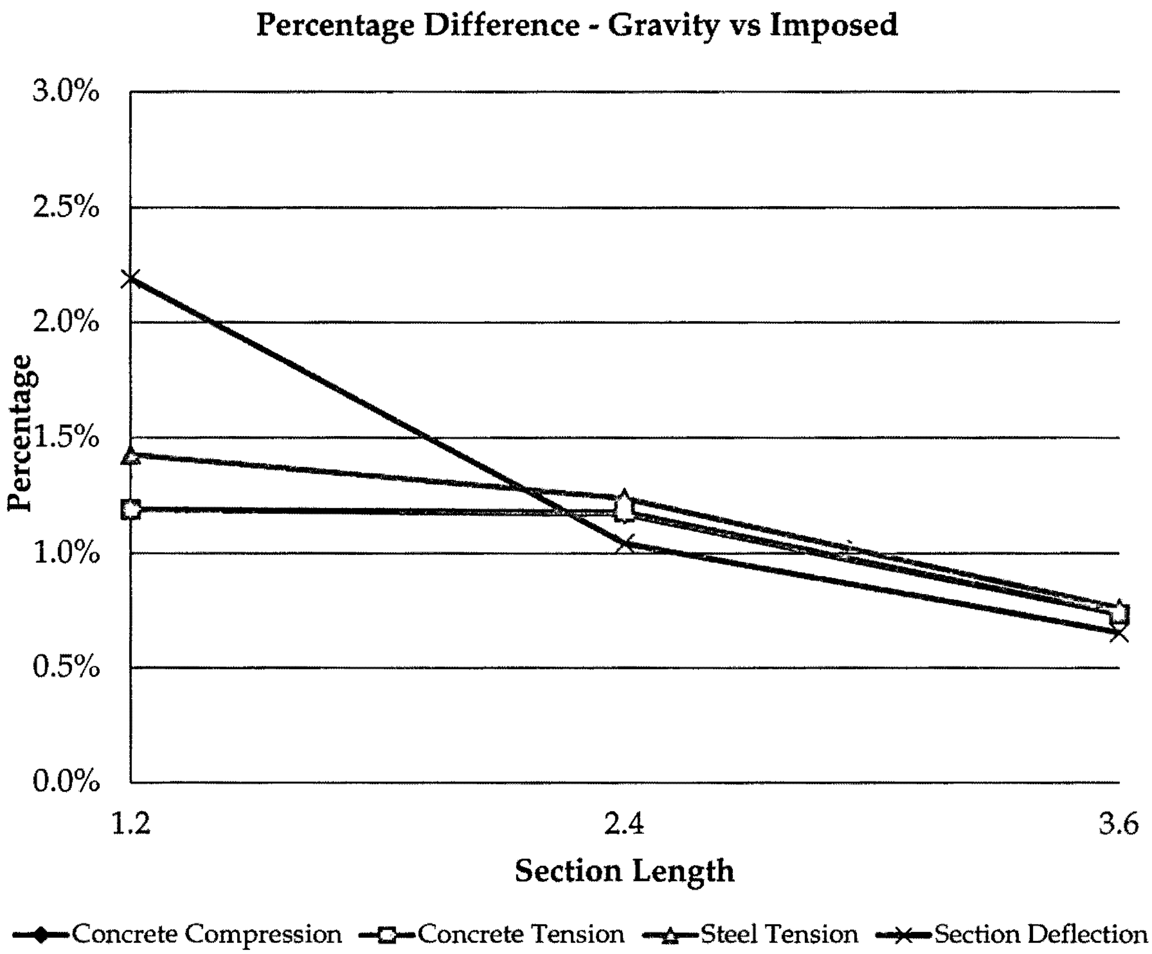

Figure 5-1: Percentage Difference – Gravity vs. Imposed

The imposed load case was consistently higher than the gravity load as shown in Figure 5-1. The effect of using an equivalent imposed load instead of gravity yields minor discrepancies as shown in Figure 5-1. As expected, it appears that shorter spanning models suffer from a higher percentage of error compared to larger spans.

It can be seen that from the three spans analysed, the discrepancies are approaching zero linearly. Since all further modelling to be carried out will be at least 7 m long, this method of applying the model's self-weight is adequate.

5.4 Stress Calculations for Solid Slab

Section stresses were calculated using the simplified design equations based on a transformed section analysis in accordance with AS 3600. It should be noted that an elastic analysis was carried out.

The analysis was carried out using a 15 mm mesh size of a solid 250 mm deep slab with 2 N 16 reinforcement bars spanning 1.2 metres.

5.4.1 Section Parameters

Table 5-2 below shows the section parameters used for the solid slab stress calculations.

E_s	200	GPa	b	200	mm	Reinforcement	N16	
E_c	30.96	GPa	D	250	mm	No. bars	2	
Conc. cover	30	mm	d	220	mm	Span	1200	mm

Table 5-2: Section Parameters for Calculations

Area of steel in tension

$$A_{st} = \pi \cdot r^2 \cdot (\text{Bars})$$

$$= 402\ mm^2$$

Neutral depth

$$d_n = \frac{\left(\frac{b \cdot D^2}{2} + n \cdot A_{st} \cdot d\right)}{(b \cdot D + n \cdot A_{st})}$$

$$= 129.69\ mm$$

Modular ratio

$$n = \frac{E_s}{E_c}$$

$$= 6.460$$

Second moment of area of an uncracked section

$$I_u = \frac{b \cdot D^3}{12} + b \cdot D \cdot \left(\frac{D}{2} - d_n\right)^2 + n \cdot A_{st} \cdot (d - d_n)^2$$

$$= 282.697 \times 10^6\ mm^4$$

5.4.2 Section Loading

For verification purposes, a 5 kPa face pressure was applied on the upper face of the modelled beam to act as a uniformly distributed load.

$$Face\ Pressure = 5\ kPa$$

$$Equivalent\ Line\ Load\ (w) = 0.005\ \frac{N}{mm^2} \cdot 200\ mm = 1\ N/mm$$

$$Equivalent\ Resultant\ Moment\ (M) = \frac{w \cdot L^2}{8} = \frac{1 \cdot 1200^2}{8} = 180 \times 10^3\ Nmm$$

5.4.3 Section Stresses

Concrete compressive stress on the top surface,

$$\sigma_{C_{top}} = \frac{M \cdot d_n}{I_u} = 82.58\ kPa$$

Concrete tensile stress on the bottom surface,

$$\sigma_{C_{bottom}} = \frac{M \cdot (D - d_n)}{I_u} = 76.60\ kPa$$

Concrete tensile stress at level of reinforcement,

$$\sigma_{C_{at\,steel}} = \frac{M \cdot (d - d_n)}{I_u} = 57.50\ kPa$$

Steel reinforcement tensile stress,

$$\sigma_{st} = n \cdot \sigma_{C_{at\,steel}} = 371.46\ kPa$$

Note : A Microsoft Excel spreadsheet was used to calculate stresses in Section 5.4.3, please see *"Slab Calculations.xlsx"* provided in Appendix A – (DVD) for reference.

5.5 Meshing Convergence

Based on the calculations in accordance to AS 3600, the results from Strand7 (2010) were compared. Several mesh sizes were explored to demonstrate convergence of analysed results to theoretical results.

Mesh size [mm]	Concrete		Steel Reinforcement
	Compression [kPa]	Tension [kPa]	Steel Tension [kPa]
67	75.67	71.43	332.32
50	76.49	74.54	358.95
25	80.12	75.66	361.33
15	82.58	76.05	362.37
10	84.97	76.99	366.91
7.5	84.87	77.31	367.29
5	84.23	77.39	367.81
Theoretical	82.58	76.60	371.46
% Difference to 5 mm mesh on model	- 2.78%	- 0.93%	0.98%
% Difference to 15 mm mesh on model	0.07%	0.72%	2.45%

Table 5-3: Convergence by Mesh Size

Note : Mesh size in Table 5-3 refers to the maximum edge length of the model; elements in the model may have mesh sizes less than the value but not greater.

Due to the limitations of computer hardware and time taken to run models with a 5 mm mesh size, it was not a viable option. As can be seen from Table 5-3, a 15mm mesh size provides adequate accuracy, and thus a 15 mm mesh size will be used for all further modelling due to its accuracy to time ratio, verified in accordance to AS 3600, shown in Section 5.4.

5.6 Deflection Calculations for Solid Slab

Section deflections were calculated using the standard simplified design equations in accordance with AS 3600. It should be noted that an elastic analysis was carried out.

5.6.1 Section Parameters

Table 5-4 below shows the section parameters used for the solid slab deflections calculations.

E_s	200	GPa	b	300	mm	Reinforcement	N 24	
E_c	30.96	GPa	D	360	mm	No. bars	5	
Conc. cover	30	mm	d	330	mm	Span	10800	mm

Table 5-4: Section Parameters for Deflection Calculation

Area of steel in tension $\quad A_{st} = \pi \cdot r^2 \cdot (\text{Bars})$

$$= 2260\, mm^2$$

Neutral depth $\quad d_n = \frac{\left(\frac{b \cdot D^2}{2} + n \cdot A_{st} \cdot d\right)}{(b \cdot D + n \cdot A_{st})}$

$$= 197.86\, mm$$

Modular ratio $\quad n = \frac{E_s}{E_c}$

$$= 6.460$$

Second moment of area of an un-cracked section $\quad I_u = \frac{b \cdot D^3}{12} + b \cdot D \cdot \left(\frac{D}{2} - d_n\right)^2 + n \cdot A_{st} \cdot (d - d_n)^2$

$$= 1455.771 \times 10^6\, mm^4$$

Gross second moment of area of cross section $\quad I_g = \frac{b \cdot D^3}{12}$

$$= 1166.400 \times 10^6\, mm^4$$

Second moment of cracked transformed section	I_{cr}	$= \frac{b \cdot D^3}{3} + n \cdot A_{st} \cdot (d - d_n)$
		$= 1029.534 \times 10^6\ mm^4$
Concrete tensile strength from flexure test	$f_{ct.f}$	$= 0.6 \cdot \sqrt{(f'_c)}$
		$= 3.394$
Dead load of slab section	G	$= 2.60\ kN/m$ (Refer to "*Slab Calculations.xlsx*")
Live load of slab section	Q	$= 3.00\ kN/m$ (Refer to "*Slab Calculations.xlsx*")
Short term factor	ψ_s	$= 0.7$ (AS 1170.1 Table 4.1)
Short term load	W	$= G + \psi_s \cdot Q$
		$= 4.70\ kN/m$
Service bending moment	M_s	$= \frac{W \cdot L^2}{8}$
		$= 68.46\ kNm$
Cracking moment	M_{cr}	$= \frac{f_{ct.f} \cdot I_u}{D - d_n}$
		$= 30.47\ kNm$
Effective second moment of area	I_{ef}	$= I_{cr} + (I_g + I_{cr}) \cdot \left(\frac{M_{cr}}{M_s}\right)$
		$= 1041.604 \times 10^6\ mm^4$
Short term deflection	Δ_s	$= \frac{5}{384} \cdot \frac{(W \cdot L_{ef}{}^4)}{E_c \cdot I_{ef}}$
		$= 25.79\ mm$

Note : A Microsoft Excel spreadsheet was used to calculate deflections for all models, please see "*Slab Calculations.xlsx*" provided in Appendix A – (DVD) for reference.

6 MODEL LIMITATIONS

The Strand7 (2010) models created are based on an un-cracked analysis. This is mainly due to the fact that cracks within concrete are extremely hard to model. An option of creating unit cubes with cracks formed to the neutral axis has been trialled. These however produced inaccurate data because the cracks (created in Rhino (2010) and imported into Strand7 (2010)) can only be as wide as the minimum mesh size used.

7.5 mm and 15 mm cracks will not be accurate at all due to size of the large crack width modelled. In practice, cracks that form in concrete are generally between 0.5 mm to 1 mm in size. This is very impractical to model with Strand7 (2010) because a model with a 1 mm mesh size will take far too long to solve; this is a limitation accounted for by current computer hardware capabilities.

This study has considered cracks models, however due to the complexity of cracked model creation, cracked analysis of Cobiax slabs have not been carried out. Several models have been created and tested but were inaccurate. Figure 6-1 below shows a typical section of the cracked slab and the solved steel tension contours.

Although the modelling methods are correct in theory, they are of little practical use due to the large crack width proposed.

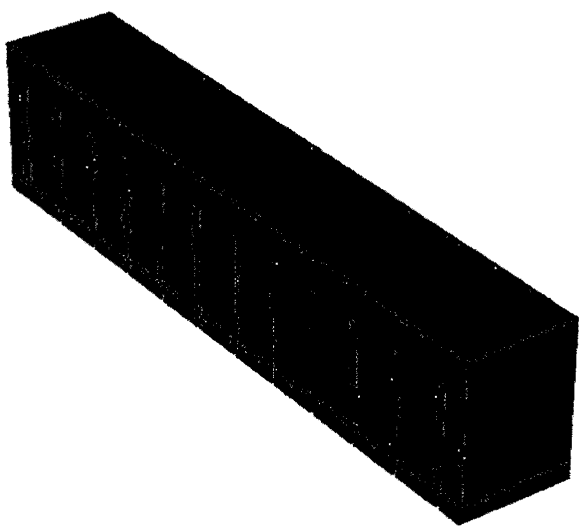

Figure 6-1: Typical Cracked Slab Section

7 ANALYTICAL COMPARISON

The solid and Cobiax models created as shown in Section 4 were loaded with various load cases and solved to verify the section stresses and deflection experienced.

The bending stresses of the solid models were checked and verified in accordance with AS 3600, and then compared with both the modelled solid and modelled Cobiax findings. Analysis was carried out for a one-way slab as well as a two-way slab.

7.1 One-Way Slab

Concrete slabs designed in accordance with AS 3600 Concrete structures and AS 1170.0 Structural design actions generally have the deflections as the limiting factor for longer spans. This has been calculated and solved for comparison in this section.

Load Case 1 and 2 explored the responses of both slabs under varying loads and a constant 10 kPa load respectively. The pressure was applied on the slab's top surface; gravity has been ignored in both cases to see the differences between the slabs structural effectiveness. It was anticipated that the Cobiax slab would have higher deflections as well as stresses, due to the fact that the self-weight had not been reduced, resulting in less concrete being able to take the load.

Load Case 3 explored the responses of both slabs under a constant 10 kPa load, however this time gravity had been considered. As such, Cobiax was anticipated to outperform solid slabs in terms of its deflection as well as stresses within to some extent due to the reduced weight by the void former.

It should be noted that different reinforcement bars were used for most of the slab configurations. Consistent reinforcement bars were used for both one-way and two-way slab configurations. Table 7-1 shows the reinforcement types used.

Void Former Diameter [mm]	Reinforcement Type
180	N 20
225	N 24
270	N 24
315	N 28
360	N 28
405	N 28
450	N 28

Table 7-1: Reinforcement Type

The deflection, steel tension and concrete compression values shown in this section were obtained using Strand7's (2010) graph tool and the 'Peek' function. The 'Peek' function was very useful as it is able to search globally within the model for maximum and minimum values.

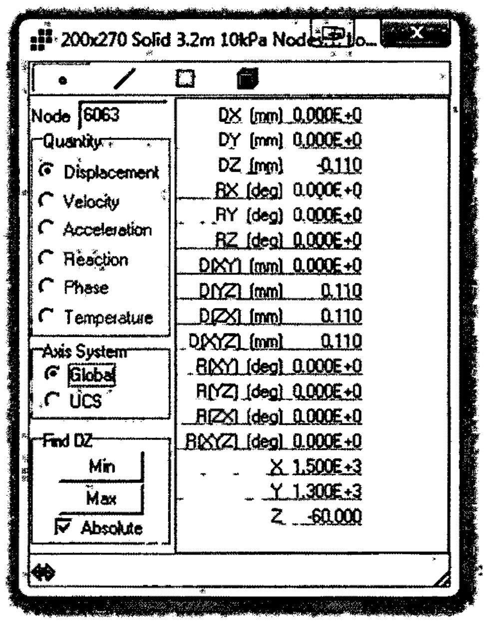

Figure 7-1: Strand7's 'Peek' Function

7.1.1 Load Case 1 – Varied Load + No Self-Weight

Table 7-2 below shows the results obtained from all configurations modelled with varied pressure loads on the top face of the slab and Table 7-3 shows the percentage comparison for this load case. Theoretical calculations were not carried out for this load case as this load case has varied pressure loads. Load cases 2 and 3 will have theoretical calculations included. Figure 7-2 shows a graphical representation of the data obtained from the FE model.

200 mm x 270 mm 30 kPa	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Modelled)	16.00	53700	13525
Cobiax (Modelled)	18.80	53140	18059

250 mm x 285 mm 30 kPa	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Modelled)	24.24	61803	15114
Cobiax (Modelled)	28.48	61792	19504

300 mm x 360 mm 30 kPa	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Modelled)	35.22	77329	17888
Cobiax (Modelled)	41.92	79903	22299

350mm x 405 mm 30 kPa	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Modelled)	45.09	82549	18920
Cobiax (Modelled)	54.36	88759	22650

400 mm x 450 mm 30 kPa	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Modelled)	55.36	87293	19955
Cobiax (Modelled)	68.61	95090	23510

450 mm x 495 mm 20 kPa	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Modelled)	65.72	93668	20600
Cobiax (Modelled)	81.85	101356	23882

510 mm x 530 mm 20 kPa	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Modelled)	58.40	68224	15149
Cobiax (Modelled)	72.82	78374	17090

Table 7-2: Results for Load Case 1 (Varied Load + No Self-Weight)

Cobiax Diameter [mm]	One-way Slab Comparison between Solid (Modelled) and Cobiax (Modelled) Varied Load + No Self-Weight		
	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
180	17.50%	-1.04%	33.52%
225	17.49%	-0.02%	29.05%
270	19.02%	3.33%	24.66%
315	20.56%	7.52%	19.71%
360	23.93%	8.93%	17.82%
405	24.54%	8.21%	15.93%
450	24.69%	14.88%	12.81%

Table 7-3: Comparison for Load Case 1 (Varied Load + No Self-Weight)

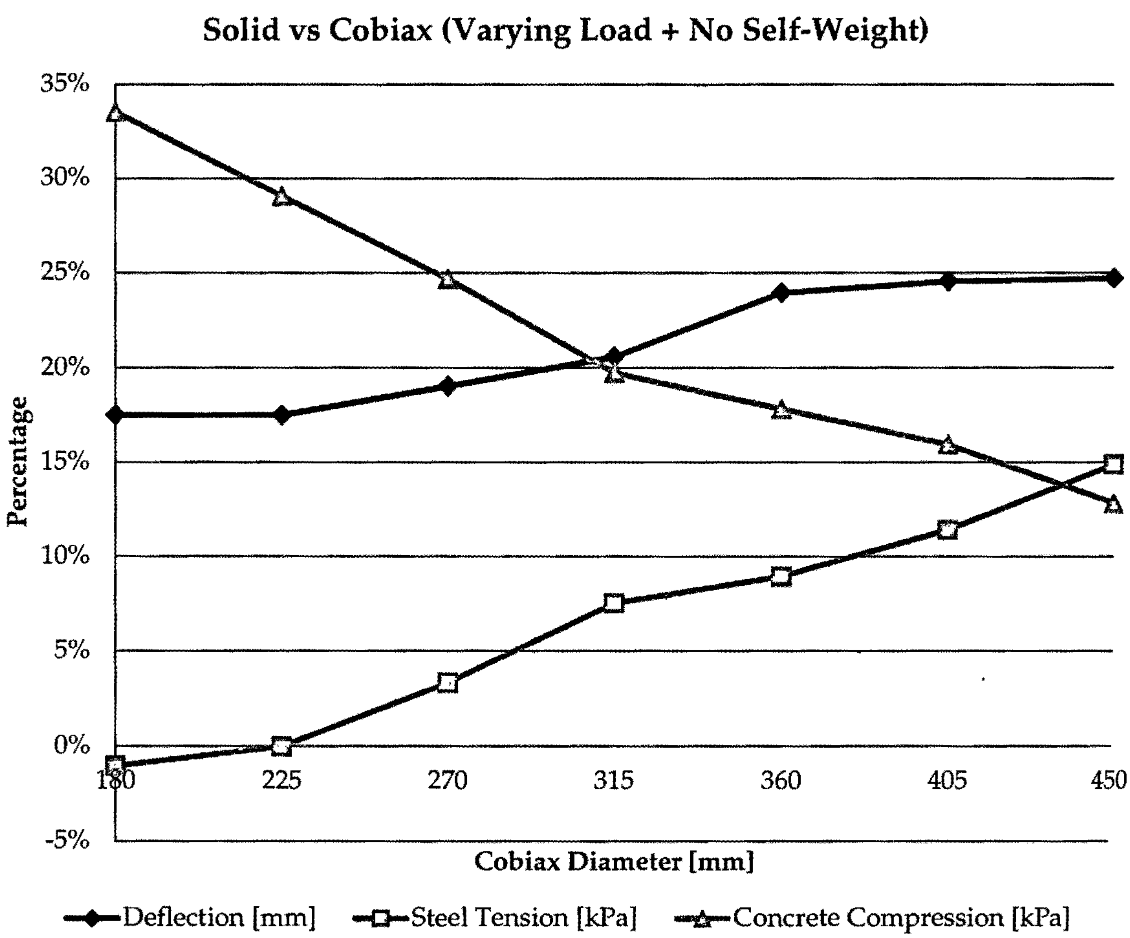

Figure 7-2: Graph – Load Case 1 (Varied Load + No Self-Weight)

7.1.2 Load Case 2 – 10 kPa + No Self-Weight

Table 7-4 below shows the results obtained from all configurations modelled with a constant 10 kPa pressure on the top face of the slab and Table 7-5 shows the percentage comparison for this load case. Figure 7-3 shows a graphical representation of the data obtained from the FE model.

200 mm x 270 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Theoretical)	6.96	17529	4654
Solid (Modelled)	5.33	17901	4592
Cobiax (Modelled)	6.27	17712	6029
250 mm x 285 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Theoretical)	10.71	20658	5276
Solid (Modelled)	8.08	20601	5259
Cobiax (Modelled)	9.49	20597	6732
300 mm x 360 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Theoretical)	15.96	25647	5945
Solid (Modelled)	11.74	25776	5925
Cobiax (Modelled)	13.97	26634	7354
350mm x 405 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Theoretical)	20.47	27627	6325
Solid (Modelled)	15.03	27516	6307
Cobiax (Modelled)	18.12	29586	7605
400 mm x 450 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Theoretical)	25.1	29263	6634
Solid (Modelled)	18.45	29098	6651
Cobiax (Modelled)	22.87	31097	7803
450 mm x 495 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Theoretical)	29.8	30594	6887
Solid (Modelled)	21.9	31223	6867
Cobiax (Modelled)	27.28	33785	7898
510 mm x 530 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Theoretical)	39.72	34241	7675
Solid (Modelled)	29.2	34112	7574
Cobiax (Modelled)	36.41	38187	5453

Table 7-4: Results for Load Case 2 (10 kPa + No Self-Weight)

Cobiax Diameter [mm]	One-way Slab Comparison between Solid (Modelled) and Cobiax (Modelled) 10 kPa + No Self-Weight		
	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
180	17.60%	-1.06%	31.29%
225	17.45%	-0.02%	28.01%
270	18.99%	3.33%	24.12%
315	20.56%	5.71%	20.58%
360	23.96%	6.87%	17.32%
405	24.57%	8.21%	15.01%
450	24.69%	11.95%	11.61%

Table 7-5: Comparison for Load Case 2 (10 kPa + No Self-Weight)

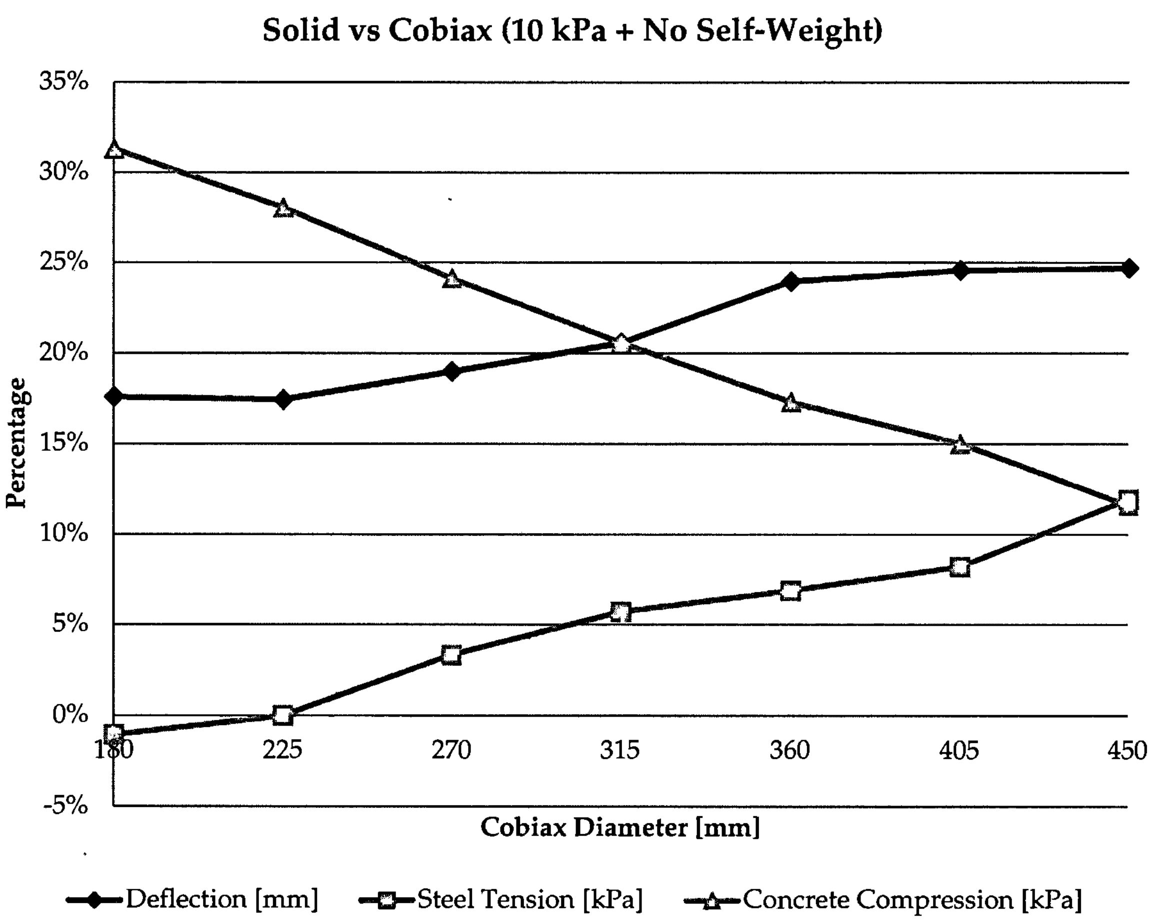

Figure 7-3: Graph – Load Case 2 (10 kPa + No Self-Weight)

7.1.3 Load Case 3 – 10 kPa + Self-Weight

Table 7-6 below shows the results obtained from all configurations modelled with a constant 10 kPa pressure on the top face of the slab and Table 7-7 shows the percentage comparison for this load case. Figure 7-4 shows a graphical representation of the data obtained from the FE model.

200 mm x 270 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Theoretical)	9.62	28905	7674
Solid (Modelled)	9.05	30363	8195
Cobiax (Modelled)	9.52	26910	9151
250 mm x 285 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Theoretical)	15.77	36298	9271
Solid (Modelled)	14.65	37309	9746
Cobiax (Modelled)	15.25	33086	10825
300 mm x 360 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Theoretical)	25.79	43838	11089
Solid (Modelled)	22.38	49119	11720
Cobiax (Modelled)	22.99	43819	12756
350mm x 405 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Theoretical)	34.63	54520	12484
Solid (Modelled)	30.4	55617	13013
Cobiax (Modelled)	31.17	50879	13800
400 mm x 450 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Theoretical)	45.43	60912	14810
Solid (Modelled)	41.23	66652	14472
Cobiax (Modelled)	42.31	62186	14866
450 mm x 495 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Theoretical)	56.91	66993	16280
Solid (Modelled)	52.94	79130	16628
Cobiax (Modelled)	54.10	74716	16577
510 mm x 530 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Theoretical)	78.85	87858	17452
Solid (Modelled)	75.34	96619	18347
Cobiax (Modelled)	76.51	93933	17611

Table 7-6: Results for Load Case 3 (10 kPa + Self-Weight)

Cobiax Diameter [mm]	One-way Slab Comparison between Solid (Modelled) and Cobiax (Modelled) 10 kPa Load + Self-Weight		
	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
180	5.19%	-11.37%	11.65%
225	4.10%	-11.32%	11.06%
270	2.73%	-10.79%	8.83%
315	2.53%	-8.52%	6.06%
360	2.62%	-6.70%	2.72%
405	2.00%	-5.58%	-0.31%
450	1.55%	-2.78%	-4.01%

Table 7-7: Comparison for Load Case 3 (10 kPa + Self-Weight)

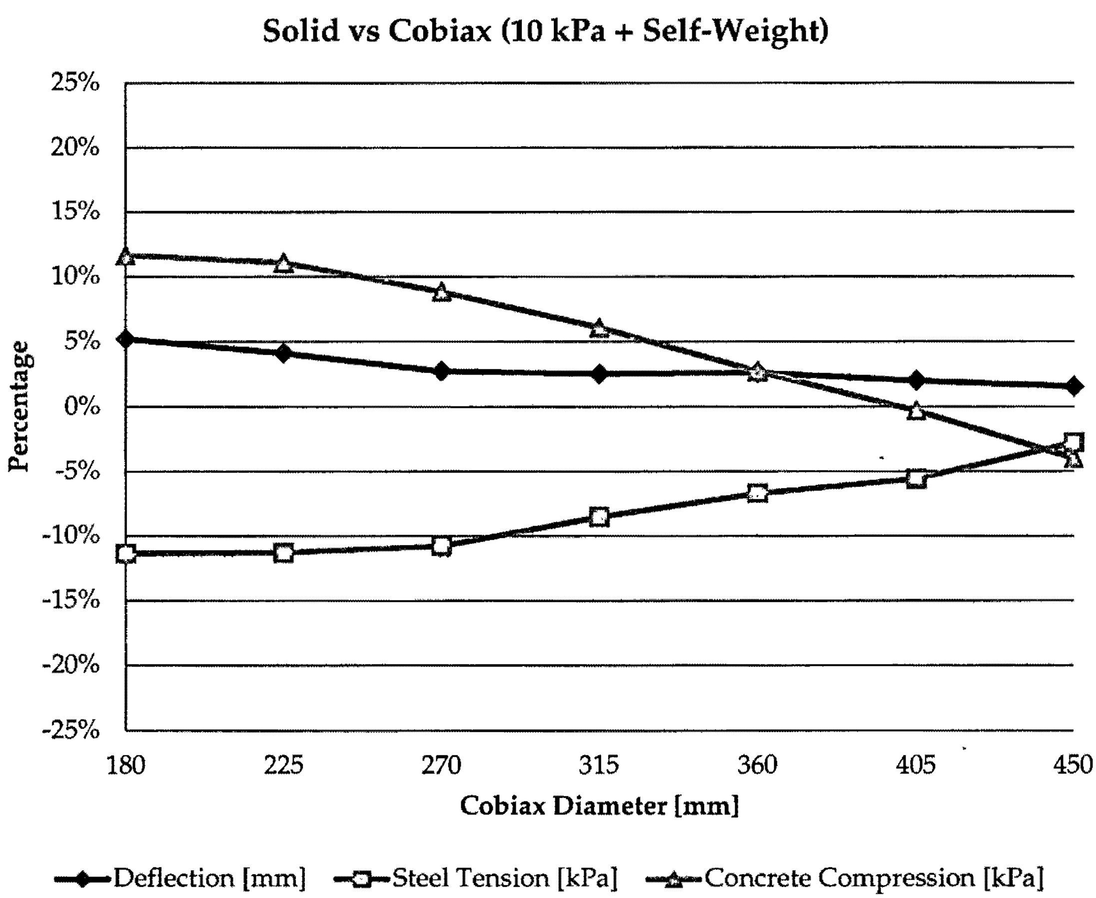

Figure 7-4: Graph – Load Case 3 (10 kPa + Self-Weight)

7.1.4 Discussion – One-way Slab

From the values obtained as shown in Figure 7-2, the solid slab appeared to be superior in terms of its deflection and stresses experienced compared to Cobiax slabs without its self-weight.

The deflection and steel tension of the slab in Load Case 1 can be seen to be increasing linearly with the void former diameter, whereas the concrete compression is decreasing with each void former increment. Similar results can be seen in Figure 7-3 representing Load Case 2; this is because both load cases had not considered dead loads and a constant pressure applied for both slabs. These results were expected because hollow core slab systems rely heavily upon their dead load reduction to offset any additional loads experienced. This is shown in Figure 1-2 where the neutral axis of the slab cross section experiences no stresses as the compressive forces transition into tensile forces.

On the other hand, Load Case 3 which considered both the constant 10 kPa load as well as its self-weight due to gravity showed contrasting results compared to the previous two load cases. Figure 7-4 shows a 3 to 10% decrease in steel tension within the Cobiax slab whereas the short term deflection of the slab shows between 2 to 5% decrease. The concrete compression of Cobiax slabs however tells a different story; it was found that there was an 11% increase with the 180 mm diameter void former and transitions in a linear fashion to a 1% reduction with the 450 mm diameter void former.

Some of these results are contrary to Johnson's (2009) findings. Johnson (2009) reported a 5% decrease in short term deflection, 12.2% reduction in steel tension and 22.7% increase in concrete compression based on an un-cracked analysis. The contrasting results are shown on the following page in Table 7-8.

It should be noted that the reductions of a similar configuration for one-way slabs was used for comparison between the findings.

	One-way Slab Reduction Comparison		
	Deflection	Steel Tension	Concrete Compression
Current Research	5.19%	-11.37%	11.65%
Johnson (2009)	-5.00%	-12.20%	22.70%
Difference	10.19%	0.83%	11.05%

Table 7-8: Comparison between One-way Findings

It is hypothesised that this is because Johnson only considered one configuration of the Cobiax's slab system (180 mm diameter void former) and drew conclusions based on that. Johnson's (2009) findings are consistent with the findings of the current research; however, there are small discrepancies concerning the increase in concrete compression and the reduction in short term deflection.

7.2 Two-Way Slabs

Two-way slabs were also modelled in this study. However, a full scale two-way slab with a 15 mm mesh could not be modelled due to limitations in processing resources available. Models in this case were meshed with a higher mesh size to enable the analysis. A mesh size of 25 mm was chosen, and as can be seen from Table 5-3, this means a slightly higher percentage of error will be introduced in the results. However, this error level is still within tolerance.

The models were similarly loaded to Load Case 3 of Section 7.1.3 with both the 10 kPa load and self-weight due to gravity considered. It was anticipated that results from the two-way slab analysis should be similar to one-way slabs.

Table 7-9 on the following page shows the results obtained from all configurations modelled with a constant 10 kPa pressure on the top face of the slab and Table 7-10 shows the percentage comparison for this load case. Figure 7-5 shows a graphical representation of the data obtained from the FE model.

200mm x 280 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Modelled)	0.1025	2003	171
Cobiax (Modelled)	0.1005	1873	169

250 mm x 295 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Modelled)	0.2137	2884	339
Cobiax (Modelled)	0.2085	2655	335

300 mm x 370 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Modelled)	0.3772	4183	537
Cobiax (Modelled)	0.3673	3844	526

350 mm x 415 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Modelled)	0.6839	6122	798
Cobiax (Modelled)	0.6635	5576	769

400 mm x 460 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Modelled)	0.7816	6528	758
Cobiax (Modelled)	0.7481	5786	710

450 mm x 495 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Modelled)	0.9240	7157	853
Cobiax (Modelled)	0.8847	6219	786

510 mm x 540 mm	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
Solid (Modelled)	1.1352	7212	656
Cobiax (Modelled)	1.0777	6176	573

Table 7-9: Results for Two-way Slab (10 kPa + Self-Weight)

Cobiax Diameter [mm]	One-way Slab Comparison between Solid (Modelled) and Cobiax (Modelled) 10 kPa Load + Self-Weight		
	Deflection [mm]	Steel Tension [kPa]	Concrete Compression [kPa]
180	-2.0%	-6.5%	0.7%
225	-2.4%	-7.9%	-1.1%
270	-2.6%	-8.1%	-2.0%
315	-3.0%	-8.9%	-3.7%
360	-4.3%	-11.4%	-6.3%
405	-4.3%	-13.1%	-17.9%
450	-5.1%	-14.4%	-12.6%

Table 7-10: Comparison for Two-way Slab (10 kPa + Self-Weight)

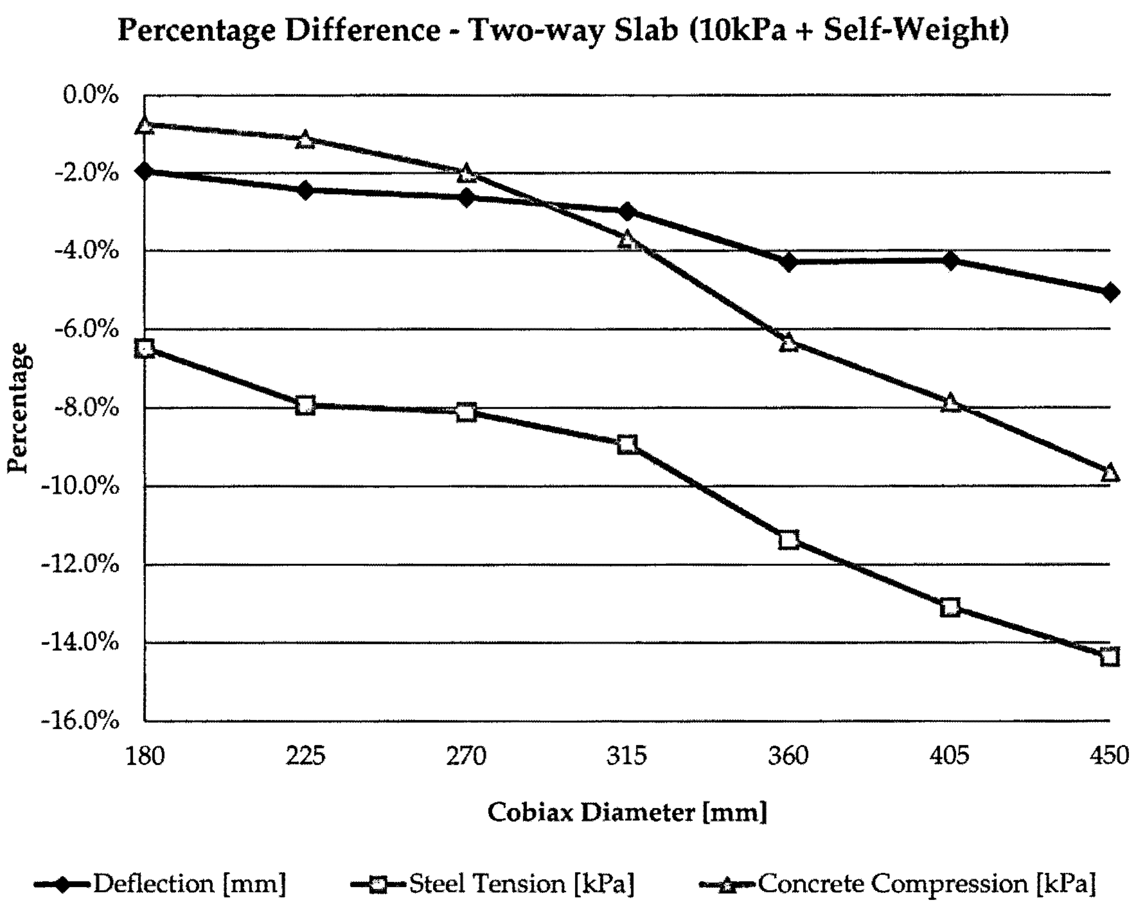

Figure 7-5: Graph – Two-way Slab (10 kPa + Self-Weight)

7.2.1 Discussion – Two-way Slab

The two-way slab analysis showed very different results compared to the previous three load cases of a one-way slab configuration. There were significant reductions in all three result categories. The short term deflection, steel tension and concrete compression peaked with reductions of 5%, 14% and 12% respectively. It appears that there is a trend of a linear reduction across all parameters with increasing void formers.

These models were meshed using the automesh function which created some distorted tetrahedral elements within the model; this would explain the slight differences within the observed parameters. Having distorted elements in an FE model can cause inaccuracies; this appears to be what happened to some of these configurations.

Overall, the results seem to favour Cobiax slabs as a more effective structural system compared to solid slabs. This is consistent with Johnson's (2009) findings; he reported that with a two-way slab configuration, there were reductions across all results. Johnson (2009) obtained a reduction of 15% in concrete compression, 15.9% in steel tension and 10.5% for short term deflection. The contrasting results are shown below in Table 7-11.

	Two-way Slab Reduction Comparison		
	Deflection	Steel Tension	Concrete Compression
Current Research	-1.95%	-6.48%	-0.75%
Johnson (2009)	-10.50%	-15.90%	-15.00%
Difference	8.55%	9.42%	14.25%

Table 7-11: Comparison between Two-way Findings

Some of Johnson's findings align closely with this thesis, in particular the short term deflection. However, it should be noted that Johnson (2009) carried out modelling with cracked elements and as previously discussed, this has limited validity.

Similar to one-way slabs, these reductions in stresses and deflection are contributed by the reduced self-weight due to Cobiax. Cobiax appear to be far more effective compared to one-way slabs as seen by the findings of all load cases and configurations.

8 PRACTICAL DESIGN FACTORS

The results obtained from modelling in Strand7 (2010) showed an interesting array of results for both one-way slabs and two-way slabs. The reductions are greater in two-way slabs compared to one-way slabs. A statistical analysis program, SPSS Statistics (2011) was used to carry out analyses on the percentage reductions from Strand7 (2010) to obtain the appropriate sample mean and confidence intervals to obtain practical design factors.

The means, standard deviations and 95% confidence intervals (CIs) are displayed in Table 8-1.

					95% CI	
		N	Mean	Std. Deviation	Lower	Upper
One-Way Slab	Deflection	7	.0304	.01249	.0189	.0420
	Steel Tension	7	-.0843	.03671	-.1182	-.0503
	Concrete Compression	7	.0542	.06319	-.0042	.1126
Two-Way Slab	Deflection	7	-.0337	.01161	-.0444	-.0230
	Steel Tension	7	-.1004	.02943	-.1276	-.0732
	Concrete Compression	7	-.0448	.03499	-.0771	-.0124

Table 8-1: Means & Standard Deviations of Results

A 95% CI indicates the range of values between which it is 95% certain that the true mean lies. That is, deflection for a one-way slab, it is 95% certain that the true mean of deflection across configuration lies between 0.0189 and 0.0420. This information allows for more accurate design factors to be calculated. It should be noted that different design factors may be used depending on the application as there are the means as well as the lower and upper bounds of the 95% CI.

For example, the mean might be more applicable for a more balanced approach to design whereas the lower and upper bound of the 95% CI could be used for a more liberal or conservative approach. Table 8-2 below shows the suggested design factors for both one-way and two-way slab configurations.

		Suggested Design Factor		
		Conservative	**Balanced**	**Liberal**
One-Way Slab	Deflection	1.019	1.030	1.042
	Steel Tension	0.882	0.916	0.950
	Concrete Compression	0.996	1.054	1.113
Two-Way Slab	Deflection	0.956	0.966	0.977
	Steel Tension	0.872	0.900	0.927
	Concrete Compression	0.923	0.955	0.988

Table 8-2: Suggested Design Factors

9 SUSTAINABILITY

Concrete is the most used and most misused construction material in the world; it has been mismatched and mixed incorrectly throughout the years. Products such as accelerators, retarders and plasticisers have been added to bend concrete to our will. In spite of all this, concrete is still the most reliable and versatile building material in use today (Hageman, Beeston & Hageman 2006).

According to Collins et al. (2008), cement production is the 3rd largest man-made source of carbon dioxide (CO_2) in the world, coming close after fossil fuels and deforestation. This equates to more than two billion tonnes of CO_2 produced in a year alone from cement production.

Of the total carbon emissions produced from cement manufacture, 60% of the emissions come from the chemical reaction required to make it. Calcium carbonate ($CaCO_3$) is heated until it breaks down into calcium dioxide followed by the by-product of carbon oxide. McLeod (2005) also reported that cement production is responsible for 7 to 10% of total CO_2 emissions worldwide. It is therefore vital that initiatives are taken to reduce carbon emissions as every little bit counts in our battle with global warming for a sustainable future.

Cobiax Technologies have advertised their product to be significantly more sustainable compared to solid slab systems as shown in their claims in Figure 1-3. An analytical approach to determine the actual benefits such as carbon emissions due to reduced cement usage and material savings was carried out.

9.1 Carbon Emissions

As the construction industry is still showing strong growth, with the estimated total engineering construction work done rising 3.8% in the March 2011 quarter, as reported by the Australian Bureau of Statistics (2011). The Australian Bureau of Statistics predicts that carbon emissions due to the production of cement are projected to increase exponentially.

An example calculation will be carried out outlining the carbon emissions produced. A typical concrete mix of 15% cement, 65% aggregate and 20% water was obtained from Portland Cement Association (2011). Only the cement component of the mix will be analysed as it is the chemical reactions of cement manufacture that contributes the most to these emissions.

Hendriks et al. (2004) reported in their paper presented to the International Conference on Greenhouse Gas Technologies Conference, that the average world carbon intensity of carbon emissions in cement production is found to be 0.81 kg CO_2/kg cement.

This figure was used to calculate the approximate reductions of CO_2 emissions due to the reduced concrete volume as shown in the table below.

Cobiax Diameter [mm]	Volume concrete [m³]		Volume cement [m³]		CO_2 emitted [kg]		Percentage Reduction
	Solid	Cobiax	Solid	Cobiax	Solid	Cobiax	
180	13.997	10.039	2.100	1.506	1.701	1.220	28.3%
225	25.515	17.786	3.827	2.668	3.100	2.161	30.3%
270	41.990	28.634	6.299	4.295	5.102	3.479	31.8%
315	64.298	43.088	9.645	6.463	7.812	5.235	33.0%
360	93.312	61.652	13.997	9.248	11.337	7.491	33.9%
405	129.908	84.829	19.486	12.724	15.784	10.307	34.7%
450	178.657	116.822	26.799	17.523	21.707	14.194	34.6%

Table 9-1: Reduction in CO_2 Emissions

9.2 Material Savings

A volume-based analysis was carried out similar to Table 9-1, Cobiax void formers come in specific sizes and these sizes are in increments of 45 mm, as shown in Table 4-1. Note that the percentage comparison is identical to Table 9-1; this is because of the volume-based analysis carried out.

The total depths of these slabs have taken into account minimum covers needed on the top and bottom of the slabs. The volume of concrete calculated below is based on a one-way slab with typical dimensions and lengths as specified in Table 4-1. As shown in Figure 9-1, the reduction in concrete volume is consistent across all Cobiax configurations, obtaining a mean volume reduction of 32.4%.

Cobiax Diameter [mm]	Volume [m³]		Percentage Comparison
	Solid	Cobiax	
180	13.997	10.039	28.3%
225	25.515	17.786	30.3%
270	41.990	28.634	31.8%
315	64.298	43.088	33.0%
360	93.312	61.652	33.9%
405	129.908	84.829	34.7%
450	178.657	116.822	34.6%

Table 9-2: Concrete Volume Comparison

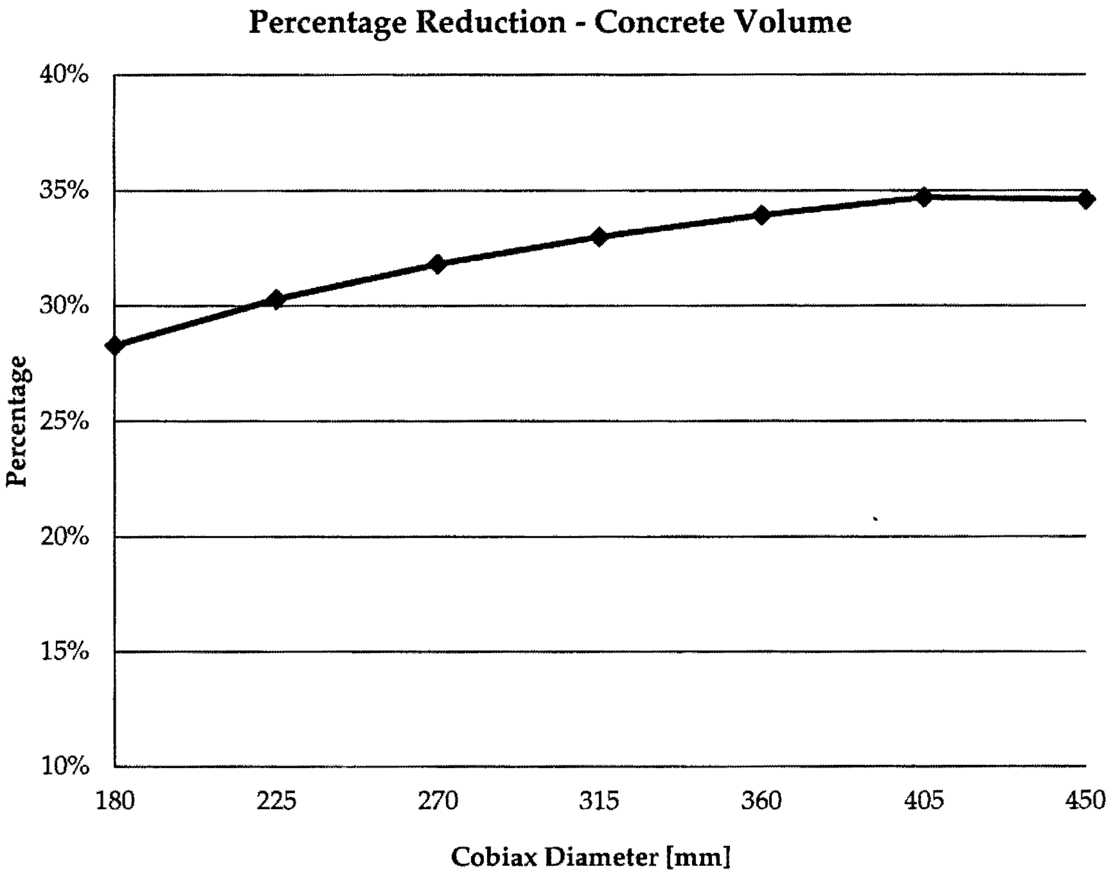

Figure 9-1: Percentage Reduction – Concrete Volume

This modelling shows that the use of Cobiax's Eco-Line product range will have a reduction in total concrete usage and CO_2 emissions of approximately 30%. Both the total concrete usage and CO_2 emissions have the same reduction values because they are volume-based analyses and cement has been assumed to make up 15% of the mix as previously stated.

The void formers that Cobiax's Eco-Line uses are essentially air-filled plastic balls which are produced from recycled plastic, which is another added bonus for their sustainable design. From a developer's perspective, Cobiax can also offer improved build-speed through reduced bracing and formwork simply because there is less concrete volume on site to work with.

From the analysis carried out, the use of Cobiax can significantly reduce the carbon footprint of a new building and add to the building's value for being environmentally friendly.

10 CONCLUSIONS

Based on current analysis, some of the claimed benefits of Cobiax have been verified; however, not all of the claims were tested in this research and some still require verification from a third party. This research was successful in achieving its aim and scope which was to verify the claims Cobiax have made using Strand7 (2010) FEA program. All models were verified in accordance with AS 3600 (2009) and design actions in accordance to AS 1170.0 (2002a) and AS 1170.1 (2002b).

Through the model testings and comparisons carried out, it can be concluded from a scientifically structured analysis, Cobiax is certainly beneficial due to reduced deflections, steel tensile stresses, concrete compressive stresses as well as the ability to span large distances effectively.

Although different diameter void formers displayed varying results, based on the statistical analysis carried in Section 8, design factors were suggested including conservative, balanced and liberal scenarios.

10.1 Directions for Future Research

To gain a better understanding of Cobiax systems, a more effective cracked analysis should be carried out to explore the cracked behaviour of these systems. Further analysis into the model accuracy could be carried out by considering an option to attempt to account for the steel displacing the concrete volume in its place. Current modelling methods have simply created the reinforcing bars to coexist in the same model space.

A practical full-scale test model may be created obtained from Danley Constructions, who are the official licensee of Cobiax based in Queensland, to further verify practical test results against FE results solved using Strand7 (2010).

In this thesis, only practical design factors have been determined based on the different configurations of Cobiax carried out. A sensitivity analysis may be carried out on these factors to explore the effects of concrete strength, steel reinforcement spacing and optimum concrete cover required for the Cobiax void formers.

Ultimately, it is hoped that practical design formulas may be developed through extensive model testing and a comprehensive FE study to aid in the design of Cobiax systems and to promote its use in Australia.

With sufficient support from University of Tasmania's School of Engineering, a paper for publication may be a viable option.

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12 APPENDIX A – (DVD)

The results of this thesis have been carried out using FE models and solve in Strand7. Theoretical calculations were also carried out using Microsoft Excel.

The DVD attached contains all FE models and calculations made and used in this research. The DVD also contains all literature obtained and reviewed.