STUDY AND ANALYSE THE EXCESSIVE CAMBER DEVELOPMENT IN PRECAST PRESTRESSED SLAB PANELS

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Degree of Master of Science in Structural Engineering

Department of Civil Engineering

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Thesis submitted in partial fulfilment of the requirements for the degree of
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Dr K. Baskaran Date: ….……………........

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I owe my deepest gratitude to all my batchmates who helped me in this research project. If not for their help and courage gave to me this research won't be a success.

M. D. D. Gamage
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Abstract

In Prestressed concrete, the initial compression is applied to the concrete before applying any external load so that stress from external loads is counteracted in a favourable way. Camber in precast prestressed slab panels can be defined as the upward deflection that is caused due to the moment caused by the eccentric prestressing force. Excessive camber development in precast prestressed slab panels can lead to several problems such as needing extra amount of topping concrete meaning extra cost and extra dead load. In addition, cracking of top surface of slab leads to durability problems. Therefore, accurate prediction of camber is essential to minimize these problems. The objective of this research is to identify the causes for the difference between design and actual camber and to propose suggestions to minimize excessive camber in precast prestressed slab panels.

To achieve the research objective, a literature review was carried out to identify camber calculation methods in precast prestressed slabs and to identify the reasons for difference between calculated and actual camber. Then did manual calculations for designing of sample precast prestressed slab panel. Electronic strain gauges were installed to high strength strands to measure the strain developed in the strands during stressing and destressing processes and obtained the data logger readings. Then comparative analysis of literature review findings, theoretical calculations and practical observations were done, and the conclusion was derived based on above analysis results. From the recalculation process by using the material properties and parameters obtained by experimental data, it is shown that it is adequate to use 5 number of strands instead of 6 number of strands.

From the experimental values obtained from concrete cylinder tests, the actual Modulus of Elasticity in concrete used is lower than the values considered in design. When the Modulus of Elasticity of concrete decreases, the upward deflection also increases. Because of excessive camber development we had to put extra amount of topping concrete thickness to maintain the minimum topping concrete layer thickness of 75 mm and to maintain levelled floor surface. This increases extra 5.27% of topping concrete material cost.

Stress releasing process of strands was done one by one and is not symmetrical. Therefore, the stress at strands varies during the releasing process. Due to this reason, there can be a twist in the precast prestressed slab panel and the camber value also varies along a cross section considered. Therefore, it is suggested to release all strands simultaneously.

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A = Cross section area of precast prestressed slab

A_{ps} = Area of prestressing strands

b = Width of the precast prestressed slab

E_{ci} = Elastic modulus of concrete

E_s = Elastic modulus of prestressing strands

e = Eccentricity of prestressing strands

f_{cu} = Characteristic compressive strength of concrete

f_{pu} = Characteristic strength of prestressing strands

f_{max} = Maximum permissible stress in concrete at service condition

f_{min} = Minimum permissible stress in concrete at service condition

f_{maxt} = Maximum permissible stress in concrete at transfer condition

f_{mint} = Minimum permissible stress in concrete at transfer condition

I = Second moment of area of precast prestressed slab

M_0 = Moment due to self-weight of slab

M_s = Moment at serviceability limit state

P_j = Jacking force

P_i = Initial prestress force

P_e = Effective prestress force

P_{sr} = Loss due to steel relaxation

P_{sc} = Loss due to creep of concrete

P_{ss} = Loss due to shrinkage of concrete

V_{co} = Design ultimate shear strength of uncracked section

V_{cr} = Design ultimate shear strength of cracked section

V_c = Critical shear strength of concrete section

Z_1 = Section modulus at bottom of precast prestressed slab

Z_2 = Section modulus at top of precast prestressed slab

α = Loss ratio

δ_{ps} = Deflection due to prestress force

δ_{sw} = Deflection due to self-weight of slab

γ_m = Partial factor of safety for material strength

1.0 INTRODUCTION

1.1 Background

Prestressed concrete is a combination of concrete and high strength steel which is subjected to a high-tension force. In Prestressed concrete the initial compression is applied to the concrete before applying any external load so that stresses from external loads are counteracted in a favourable way during the loading condition. This initial compression is introduced to the precast slabs by high strength steel wires eccentrically located in the concrete section. Camber in precast prestressed slab panels can be defined as the upward deflection that is caused due to the moment induced by the eccentric prestressing force.

Precast prestressed concrete slab panels are a type of prestressed concrete slabs that facilitates rapid construction of buildings. These slabs are fabricated off-site and then transported and erected into place at the job site.

Figure 1.1 – Precast prestressed slab panels rest on beams without having falsework for slab.

Once the topping concrete is poured, the structural section becomes composite, minimizing deflections. Because precast prestressed concrete slab panels require no falsework, they are a preferred solution for jobs where speed of construction and minimum environmental impact is required. The figure 1.1 shows the precast prestressed slab panels rest on beams without having falsework. Precast prestressed concrete slab tends to be more economical and competitive when significant repeatability exists in a project.

Precast prestressed slabs offer many advantages over conventional insitu slabs such as

- Downward deflection less due to initial upward deflection
- Facilitate rapid construction of structures.
- Usability in large spans
- Reduction in cost of formwork
- Good quality construction.

Precast concrete elements such as girders and deck panels are being used rapidly with expansion of construction industry in Sri Lanka. This report focuses exclusively on precast prestressed concrete slab panels used in precast building construction industry.

1.2 Research Problem

Even though there are some research papers related to the properties of precast prestressed slabs, less consideration is given to conduct an analysis regarding excessive camber development in precast prestressed slab panels. To overcome this problem this research was carried out to conduct an analysis regarding excessive camber development in precast prestressed slab panels.

Excessive camber development in precast prestressed slab panels can lead to several problems. Using extra amount of topping concrete to minimize the effect of excessive camber will lead to extra cost and extra dead load. Also, cracking of top surface of slab panels due to excessive camber leads to durability problems. Therefore, accurate prediction of camber is essential to minimize the cost of construction problems.

1.3 Objectives

This research is focused to analyse the excessive camber development in precast prestressed slab panels. The objective of this research is to identify the causes for the difference between design camber and actual camber and to propose suggestions to minimize excessive camber development in precast prestressed slab panels.

1.4 Summary of Research Methodology.

A literature survey was carried out to identify camber calculation methods in precast prestressed slabs and to identify the reasons for difference between calculated and actual camber. Then identified a project which consists of precast prestressed slab panel construction.

Then selected a sample slab panel and did manual calculations for designing of precast prestressed slab panel.

The precast prestressed slab panels were cast in ICC precast concrete yard complex at Madapatha, Piliyandala. Electronic strain gauges were installed to high strength strands to measure the strain developed in the strands during stressing and destressing processes.

The steel tests and concrete cylinder tests were carried out at Civil Engineering Department, University of Moratuwa.

Then comparative analysis of literature review findings, theoretical calculations and practical observations were done, and the conclusion was derived based on above analysis results.

1.5 Significance of Research

As mentioned earlier, main problem of excessive camber development in precast prestressed slab panels is using extra amount of topping concrete to minimize the effect of excessive camber. This will lead to extra cost and extra dead load. Therefore, accurate prediction of camber is essential to minimize the cost of construction problems.

1.6 Outline of the Thesis

This thesis consists of literature review, theoretical design calculations and experimental data collection and analysis of precast prestressed slabs.

The literature review was conducted to study the past research papers which were conducted to predict the causes for excessive camber development of precast prestressed slabs. The summary of literature review findings is given in Chapter 2.

The research methodology was finalized to conduct this research. The research methodology is given in Chapter 3.

The theoretical design calculation was carried out to predict the required prestress force, prestress losses and deflection of the selected precast prestressed slab panel for this research. The theoretical design calculations are given in the Annexure A.

Then the experimental data collection and laboratory tests were conducted at ICC precast concrete yard complex at Madapatha, Piliyandala and Civil Engineering Department, University of Moratuwa. The precast prestressed slab panel tests for this research were conducted at ICC precast concrete yard complex at Madapatha, Piliyandala. The observations at site are given in Chapter 5.

The other testing including concrete cylinder tests and steel tests for this research was conducted at Civil Engineering Department, University of Moratuwa. The laboratory test results are given in Chapter 4. Then the comparative analysis of results was done, and the details are given in Chapter 6.

The conclusion of this thesis was derived based on the findings from literature review, theoretical calculations and experimental data collection and analysis of precast prestressed slabs. The conclusion of this research and recommendation for future works are given in Chapter 7.

2.0 LITERATURE REVIEW

Camber is referred for the upward deflection of eccentrically prestressed concrete elements. The amount of camber depends on the combined effect of the prestress force which causes the camber and the self-weight of the concrete element to work against the camber. Camber or deflection are also a function of time dependent variables such as concrete creep and prestress loss. Proper estimation of camber or deflection is important for an efficient use of precast prestressed slabs.

Excessive camber development in precast prestressed slab panels can lead to several problems. Using extra amount of topping concrete to minimize the effect of excessive camber will lead to extra cost and extra dead load. And also cracking of top surface of slab panels due to excessive camber leads to durability problems. Therefore, accurate prediction of camber is essential to minimize the cost of construction problems. Therefore, this literature review is conducted to find the literature, which describes accurate prediction of camber in precast prestressed slab panels.

2.1 Literature Review Findings

Precast Prestressed elements tends to gain higher camber with higher specified concrete compressive strength. Therefore, the concrete strength at transfer stage should be closer to the design strength, but should not exceed design strength for accurate camber prediction. According to Sritharan and Rouse, (2015), aim for reaching and not exceeding the design strength value of concrete at transfer stage can minimize the excessive camber development in precast pretensioned concrete beams after accounting for the effect of the prestress losses. The concrete strength at transfer stage should be closer to the design strength, but should not exceed design strength for accurate camber prediction. The material properties used in design and construction should be consistent, not to result in differential camber values for a same design.

According to Tadros, et al. (2011), some fabricators leave prestressed panels scheduled for release on weekend in the bed until the start of next week, couple of days later than due date. Actual initial concrete strength can change dramatically in a short period depending on the mixture, and the designer may not know the actual time for camber prediction. Due to extra concrete compressive strength of concrete, excessive camber gain can happen.

According to Ibrahim, (2013), the design camber value is linearly varied with the jacking force. Therefore, accurate application of jacking force is important for a specified design camber value. The variation in actual prestress force with respect to the specified design prestress force will affect the accurate prediction of camber in precast slabs. According to Jones and Furr, (1977), variations of 10% in prestress force could cause from 24% to 33% variation in camber and variation of elastic modulus of 20%, could cause camber varying from about 2/3 to 2 times design value.

Concrete properties can potentially vary from element to element within the same casting bed due to the use of multiple batches of concrete along the bed as well as delays in concrete batching that occasionally occurs during a casting. According to Storm, et al. (2010), camber at prestress release is highly influenced by the modulus of elasticity of concrete. Therefore, using accurate values of modulus of elasticity of concrete leads to accurate prediction of camber value in precast prestressed slabs. The elastic modulus of the concrete was found to be on average 15% less than the value predicted at the design. Due to production variables, the measured camber can vary significantly among elements that are identical in their design even if the elements are cast at the same time on the same casting bed, in part because multiple batches of concrete are typically used for a single casting

The curing method for concrete cubes used to check the strength should be matched with site curing method. When there is a change in material or the curing method, time-dependent properties including shrinkage and creep behaviour of concrete should be revised. According to Storm, et al. (2013), Precast, prestressed concrete girders are typically cured either by moist curing or by heat curing using steam pipes. The particular curing method used was found to significantly affect the net camber at the time of prestress transfer. For cored slabs and box beams, the mean relative error of the camber predictions is approximately 70% for the heat-cured girders, while it is only approximately 20% or less for moist-cured girders of the same types.

Prestress losses cause to reduce the prestressing force applied to the slab over time, resulting reduction of the slab camber value over time. Several types of prestress losses occurring at different times cause to the long-term prestress loss in a slab. The initial prestress loss is due to elastic shortening at stress release. Thermal losses can occur prior to release when the temperature of strands is lower at the time of stressing than at the time of casting. During this period, heating of the strand results in a loss of stress because the strands tends to lengthen with the increases in temperature. Variation in prestress losses effect the effective prestress force directly. Therefore accurate prediction of prestress losses leads to accurate prediction of effective prestress force and design camber value. According to Tadros, et al. (2011), accurate estimate of elastic shortening losses at prestress release would allow for more accurate prediction of camber at release.

Therefore, it is very important to reduce the prestress losses for accurate camber prediction and for economical design. Jaaseelan and Russel, (2007), suggested to add top prestressing strands in prestressed concrete beams to lower the long term losses and camber by approximately 69% and add mild steel which increases stiffness to the concrete beam as well as reduces the long term camber by approximately 17.4%. Also, it was found that reducing the creep coefficient by 20% led to total long-term camber reduction of 6.8% and 20% increase in the elastic modulus of concrete resulted in long term camber reduction of 12%.

2.2 Summary of the Literature Review

The findings of literature review can be summarised as following.

- Precast Prestressed elements tends to gain higher camber with higher specified concrete compressive strength. Therefore, the concrete strength at transfer stage should be closer to the design strength, but should not exceed design strength for accurate camber prediction

- The design camber value is linearly varied with the jacking force. Therefore, accurate application of jacking force is important for a specified design camber value. The variation in actual prestress force with respect to the specified design prestress force will affect the accurate prediction of camber in precast slabs. The upward deflection (Camber) of prestressed slab due to prestress force is given by the equation,
  Upward deflection due to pre-stress force $= -P_e \, e \, L^2 / 8E_{ci} \, I$
  Therefore, when the effective prestress force increase, the upward deflection also increased.

- Camber at prestress release is highly influenced by the modulus of elasticity of concrete. Therefore, using accurate values of modulus of elasticity of concrete leads to accurate prediction of camber value in precast prestressed slabs. The upward deflection (Camber) of prestressed slab due to prestress force is given by the equation,
  Upward deflection due to pre-stress force $= -P_e \, e \, L^2 / 8E_{ci} \, I$
  Therefore, when the modulus of elasticity of concrete decrease, the upward deflection increased.

- Also, accurate estimate of elastic shortening losses at prestress release would allow for more accurate prediction of camber at release. Reduction in losses increases the effective prestress force. Therefore, it will cause in higher camber value than design value.

3.0 RESEARCH METHODOLOGY

During this research, manual calculations were carried out to design the precast prestressed slab panels. Then variation of actual material properties of concrete and prestress strands with the values considered in the design was studied. For this purpose, laboratory tests were carried out to determine the actual material properties of concrete and prestress strands used in construction. The prestress losses were evaluated using experimental tests. To obtain the prestress losses, electronic strain gauges were installed to prestressing strands and the strain values were observed by connecting electronic strain gauges to data logger. The methodology of this research can be described in step form as following.

- Studied prestressed slab design methods to identify a suitable design calculation method for this research.
- Selected a sample slab panel and did manual calculations for designing of precast prestressed slab panel (Refer Annexure A). There were 3 types of precast prestressed slab panels in selected project according to the length and width of slab panels. To carry out this research, it was decided to study 7650mm length precast prestressed slab panels.

  The sample slab panel details are as follows

  Slab panel length = 7650 mm

  Width of slab panel = 1200 mm

  Thickness of slab panel = 125 mm

  Number of high strength strands provided = 6 strands

  Cross section area of high strength strand = 100 mm^2

- Then carried out laboratory tests to get material properties of high strength strands

  Three number of high strength strand samples were taken for testing before the stressing of high strength strands at precast yard. The samples were taken from the strands which were ready to stressing to get the actual material properties of the strands. The steel tests were carried out at Civil Engineering Department, University of Moratuwa.

  The material properties to be checked are as following.

  Modulus of Elasticity, E

  Yield strength, P_y

- Laying of high strength strands on prestress bed.

  Then six number of high strength strands were laid on prestress bed. Long line cast method was used in this precast yard as the construction method of precast prestressed slabs.

- Installation of electronic strain gauges to high strength strands to measure the strain developed in the strands during stressing and destressing processes.

  Then six number of strain gauges were installed in laid strands. (One strain gauge in each strand)

- Observations and readings before stressing the strands.

  Electronic data logger was set and connected to strands before stressing of strands. Then the data logger reading was recorded for each strand to get the initial strain.

- Observations and readings after stressing the strands.

  The stressing of strands was commenced one by one, and the stressing force was 133kN per strand. The Jacking dial gauge reading was recorded for each stressed strand and at the same time the elongation of strands was measured manually.

The electronic data logger reading was also recorded to measure strain developed in strands.

- Observations and readings during casting stage at precast yard.

  Seven number of concrete cylinder samples were casted during concreting stage of prestressed slabs. Four number of concrete cylinders were tested at the age of releasing the strands and the other three were tested at the age of 28 days. All the concrete cylinder tests were carried out at the Civil Engineering Department, University of Moratuwa.

- Observations and readings before releasing the strands.

  Electronic data logger was set and connected to strands before releasing of strands. Then the data logger reading was recorded for each strand to get the developed strain in each strand.

  Also spot levels were taken from six locations on the prestressed slab panel which were selected for testing by using levelling instrument. This spot levels were taken to get the developed camber values after releasing the strands.

- Observations and readings after releasing the strands.

  Electronic data logger was set and connected to strands after releasing the strands. Then the data logger reading was recorded for each strand to get the developed strain in each strand.

  Also spot levels were taken from the same locations on the prestressed slab panel which were selected for testing by using level instrument.

- From these spot levels taken before and after releasing strands the developed camber value was determined at the transfer stage. From these values, the difference between actual camber value and the design camber value was determined.

- Then let the prestressed slab to develop camber and spot levels were taken 5 hours after releasing of all strands.

- Observations made after placing the slab panels on the load bearing walls.

  The precast prestressed slab panels were placed on top of the precast load bearing walls and placed topping concrete on precast prestressed slab panels. The minimum topping concrete thickness was maintained as 75mm at the mid span of the slab. Then the spot levels were taken at six locations from the bottom side of the precast prestressed slab panel under observations. This spot levels were taken to determine the reduction of camber value due to the self-weight of topping concrete and also to determine the actual volume of topping concrete used in construction.

- Then again conducted manual calculations for designing of precast prestressed slab panel using actual material properties obtained from concrete and steel tests (Refer Annexure B).

4.0 DESIGN CALCULATIONS AND LABORATORY TESTS

4.1 Design Calculation for Precast Prestressed Slab

There were 3 types of precast prestressed slab panels according to the length and width of slab panels. To carry out this research it was selected to study 7650mm length precast prestressed slab panels. The design calculation for 7650mm length precast prestressed slab panel was done using Magnel diagram.

The sample slab panel details are as follows

Slab panel length = 7650 mm

Width of slab panel = 1200 mm

Thickness of slab panel = 125 mm

Number of high strength strands provided = 6 strands

Cross section area of high strength strand = 100 mm^2

The design calculation for 7650mm length precast prestressed slab panel is described in Annexure A.

4.2 Tensile Test of Prestressing Strands

The high strength strands were tested for tensile capacity by using universal testing machine. Two number of high strength strand samples were taken for testing. The high strength strand tests were carried out at Civil Engineering Department, University of Moratuwa.

The high strength strands were tested by using universal testing machine which is shown in figure 4.2.1 and the output data was recorded in the computer which is connected to the universal testing machine. The computer which is used to record output data is shown in the figure 4.2.2.

The material properties to be checked are as following.

Modulus of Elasticity, E

Yield strength, P_y

Figure 4.2.1 – Universal testing machine

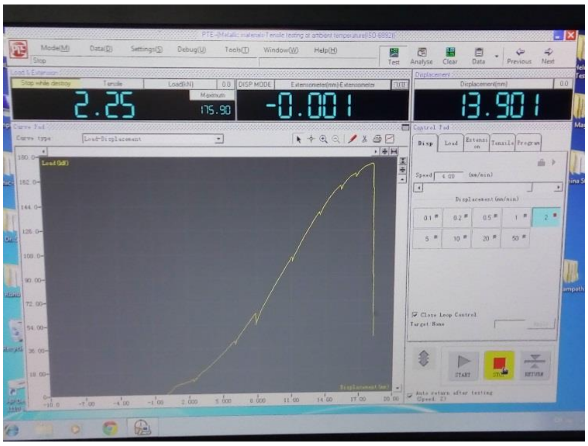


Figure 4.2.2 – Computer screen connected to universal testing machine

The prestressing strand sample details are given in the table 4.2.1.

Table 4.2.1 – Prestressing strand sample data

Prestressing strand sample number	Prestressing strand sample length	Diameter of prestressing strand	Cross section area of prestressing strand
01	695 mm	12.9 mm	100 mm^2
02	695mm	12.9 mm	100 mm^2

The cross section of a prestressing strand is shown in figure 4.2.3.

Figure 4.2.3 – Cross section of prestressing strand.

The prestressing strand samples were inserted to the universal testing machine as shown in the figure 4.2.4. Then observed displacement of prestressing strand sample against applied load recorded in the computer monitor as shown in the figure 4.2.5, until the failure load achieved.

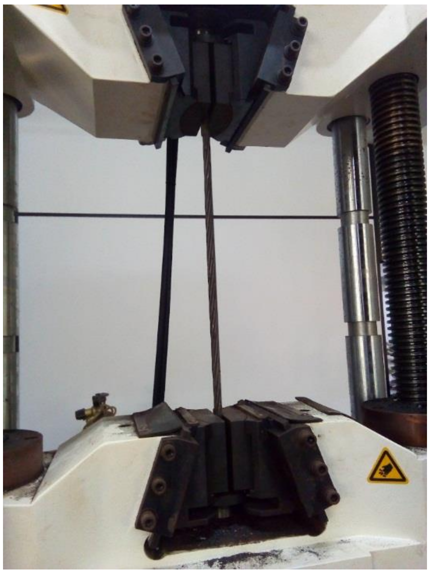
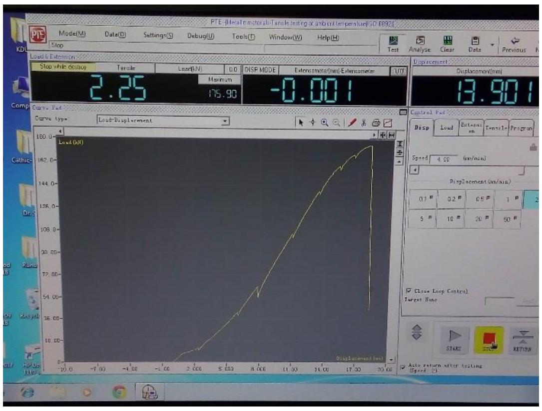


Figure 4.2.4 – Universal testing machine with prestressing strand sample inserted



Load(kN) 2.25

Maximum 175.90

Extensometer(mm)-Extensometer -0.001

Displacement(mm) 13.901

Curve type: Load-Displacement

Speed 4.00 (mm/min)

☑ Close Loop Control

Target None

☑ Auto return after testing (Speed 2)

Figure 4.2.5 – Output data recorded in the computer connected to universal testing machine

The figure 4.2.6 shows the failure of prestress strand during tensile testing using universal testing machine. The reason for the failure of prestressing strand can be identified as tensile failure of wires.

Figure 4.2.6 – Failure of prestress strand during tensile testin

The observed readings of two samples are shown in annexure A. The stress vs strain graph for two strand samples are shown in figure 4.2.7.

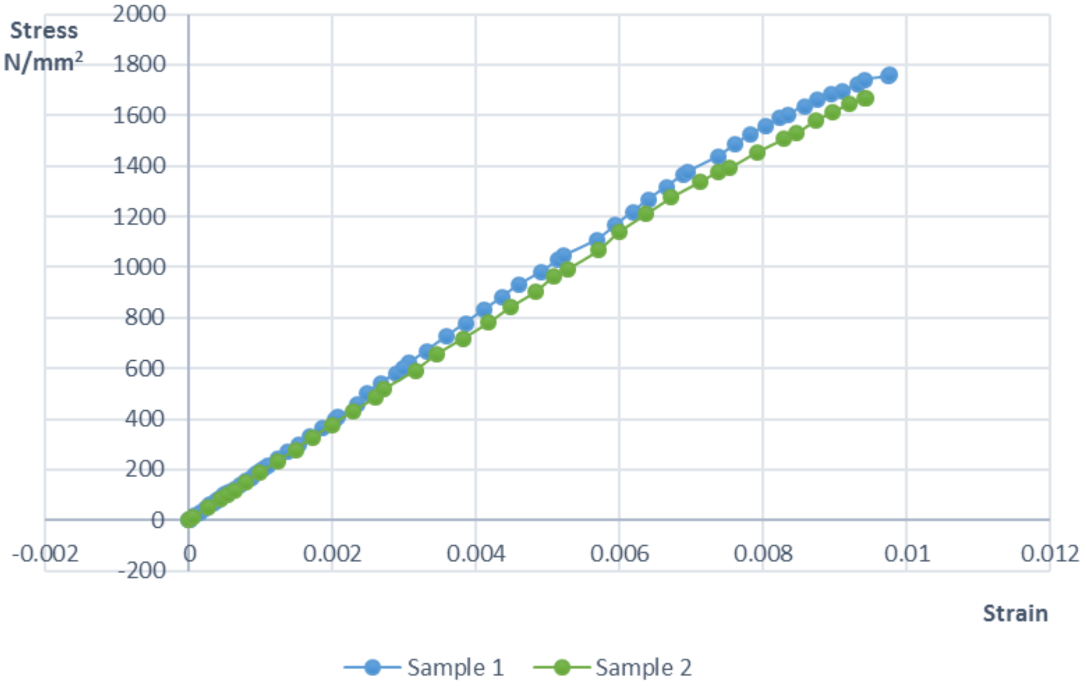


Figure 4.2.7– Stress Vs Strain diagram obtained for Sample 1 and Sample 2.

From above graphs, the modulus of elasticity for each sample can be calculated. The modulus of elasticity values obtained are given in table 4.2.2.

Table 4.2.2 – Modulus of Elasticity for each sample

Sample number	Modulus of Elasticity (N/mm^2)	Ultimate Tensile Stress (N/mm^2)
01	202.22 x 10^3	1760.00
02	190.00 x 10^3	1680.00

Therefore, the average Modulus of Elasticity obtained from test = 196.11 x $10^3 N/mm^2$

Therefore, the average Ultimate Tensile Strength obtained from test = 1720.00 N/mm^2

4.3 Concrete Cylinder Test

Seven number of concrete cylinder samples were casted during concreting stage of pre-stressed concrete slabs. Four number of concrete cylinders were tested at the age of releasing the strands and the other three were tested at the age of 28 days. All the concrete cylinder tests were carried out at the Civil Engineering Department, University of Moratuwa.

The concrete cylinders were tested by using compression testing machine which is shown in figure 4.3.1

The material properties to be checked are as following.

Modulus of Elasticity, E

Concrete cylinder strength, f_c

Figure 4.3.1 – Compression Testing Machine

The concrete cylinder specimen was prepared for the installation to compression testing machine as shown in the figure 4.3.2 and the compression testing machine with concrete cylinder specimen placed in is shown in the figure 4.3.3.

Figure 4.3.2 – Prepared concrete cylinder specimen for testing

Figure 4.3.3 – Compression testing machine with Specimen placed in

The concrete cylinder specimen was loaded with 20kN load increments and the dial gauge readings were observed until failure load achieved. The applied load on concrete cylinder was observed from the digital screen of compression testing machine as shown in the figure 4.3.4 and the displacement values were observed from dial gauge as shown in the figure 4.3.5.

Figure 4.3.4 – Digital screen of compression testing machine

Figure 4.3.5 – Dial gauge connected to concrete cylinder specimen

The crushed concrete cylinder specimen is shown in the figure 4.3.6.

Figure 4.3.6 – Compression Testing Machine with Crushed Specimen

The concrete cylinder test sample details are given in table 4.3.1.

Table 4.3.1 – Concrete cylinder sample data

Sample number	Sample height	Diameter of Sample	Age of test
01	300 mm	150 mm	2 days (At transfer stage)
02	300 mm	150 mm	2 days (At transfer stage)
03	300 mm	150 mm	2 days (At transfer stage)
04	300 mm	150 mm	2 days (At transfer stage)
05	300 mm	150 mm	28 days
06	300 mm	150 mm	28 days
07	300 mm	150 mm	28 days

The concrete cylinder test samples were placed in to the compression testing machine and observed displacement of concrete cylinder sample against applied load until the failure load achieved. The observed readings of seven samples are shown in annexure A.

The stress vs strain graph for concrete cylinder Sample 1,2,3 & 4 are shown in figure 4.3.7.

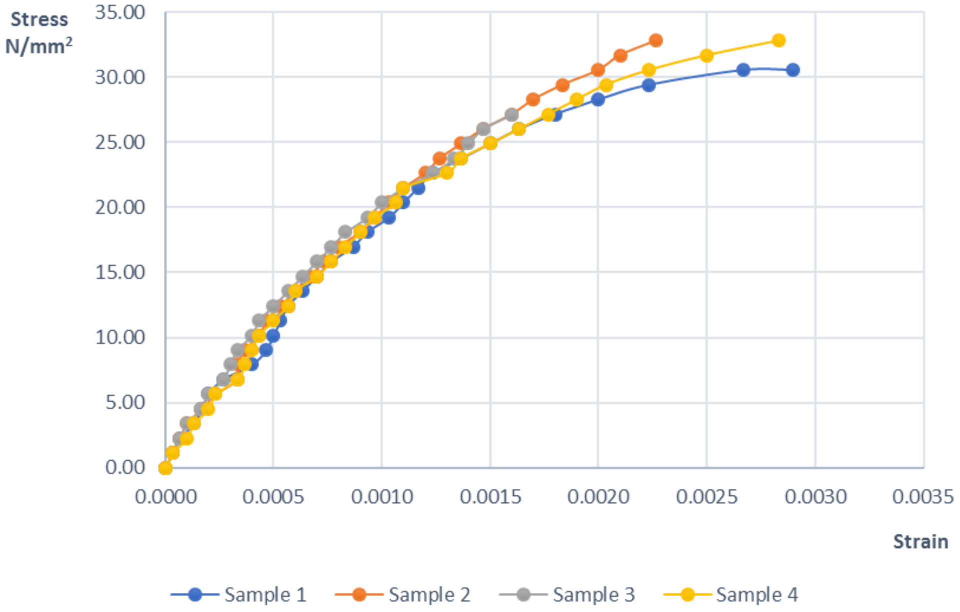


Figure 4.3.7– Stress Vs Strain diagram obtained for Sample 1,2,3 & 4.

The stress vs strain graph for concrete cylinder Sample 5,6 & 7 are shown in figure 4.3.8.

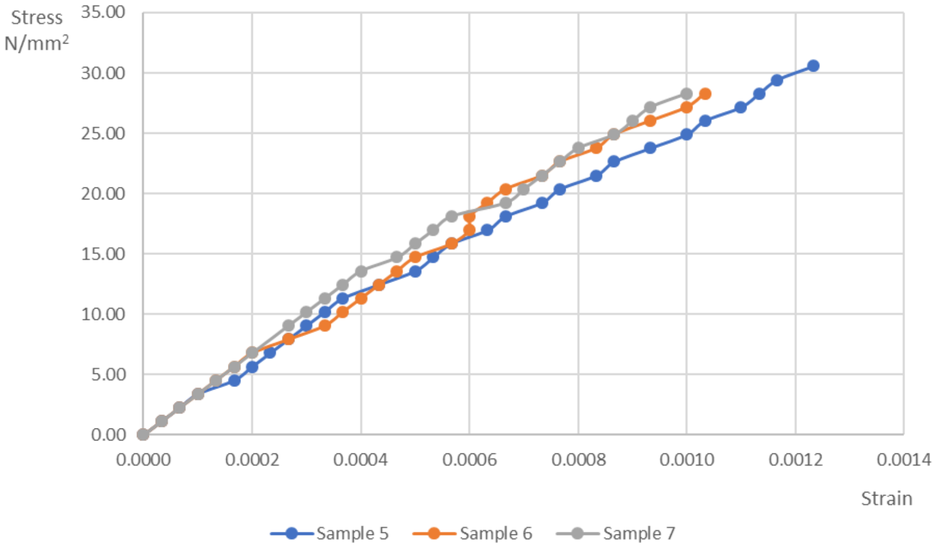


Figure 4.3.8– Stress Vs Strain diagram obtained for Sample 5,6 & 7.

From above graphs, the modulus of elasticity for each sample can be calculated. The modulus of elasticity values obtained are given in table 4.3.2 and table 4.3.3.

Table 4.3.2 – Modulus of Elasticity for Sample 1, 2, 3 and 4 (at 2 days of age, Transfer stage)

The concrete cylinder strength was converted to concrete cube strength by using Eurocode guide lines (Table 3.1 of BSEN 1992-1-1)

0.8 x Concrete cube strength = Concrete cylinder strength.

Sample number	Modulus of Elasticity (N/mm^2)	Concrete Cylinder Strength (N/mm^2)	Concrete Cube Strength (N/mm^2)
01	19.8×10^3	30.57	38.21
02	21.2×10^3	32.98	41.22
03	22.6×10^3	27.61	34.51
04	19.2×10^3	33.21	41.51

Therefore, the average Modulus of Elasticity at transfer stage = 20.7×10^3 N/mm^2

Therefore, the average Compressive Strength at transfer stage = 38.86 N/mm^2

Table 4.3.3 – Modulus of Elasticity for Sample 5, 6 and 7 (at 28 days of age)

Sample number	Modulus of Elasticity (N/mm^2)	Concrete Cylinder Strength (N/mm^2)	Concrete Cube Strength (N/mm^2)
05	28.3×10^3	50.74	63.4
06	29.4×10^3	42.2	52.75
07	29.7×10^3	48.8	61.00

Therefore, the average Modulus of Elasticity at age of 28 days = 29.1×10^3 N/mm^2

Therefore, the average Compressive Strength at age of 28 days = 59.05 N/mm^2

5.0 FIELD TESTS

5.1 Strain readings obtained at site before stressing the strands

Long line cast method was used in this precast yard as the construction method of precast prestressed slabs. The total length of precast bed is 100.0m. Six number of high strength strands were laid on pre-stress bed. The prestressed strands laying on the long line prestress bed is shown in the figure 5.1.1.

Figure 5.1.1 – Laying of strands on long line precast bed

Then six number of electronic strain gauges were installed in laid high strength strands to measure the strain developed in the strands during stressing and de-stressing processes. (One strain gauge in each strand). The electronic strain gauge installed in laid prestressing strand is shown in figure 5.1.2.

Figure 5.1.2 – Electronic strain gauge installed to strand

Then the electronic data logger was set and connected to strands before stressing of strands and the data logger reading was recorded for each strand to get the initial strain. The data logger connected to installed electronic strain gauge is shown in the figure 5.1.3 and the initial reading in data logger is shown in the figure 5.1.4.

Figure 5.1.3 – Data logger connected to electronic strain gauge.

Figure 5.1.4 – Observation of readings from data logger before stressing the strands.

The data logger readings before stressing the prestress strands are given in the table 5.1.1.

Table 5.1.1 - Data logger readings before stressing the strands

Strand Number	Initial reading (με)
1	-777
2	-771
3	-706
4	-570
5	-738
6	-1117

5.2 Readings obtained at site after stressing the strands

The stressing of strands was commenced one by one, and the stressing force was 133kN per strand. The Jacking dial gauge reading was recorded for each stressed strand and at the same time the elongation of strands was measured manually. The stressing of strands were done by using a hydraulic jack connected to strands as shown in the figure 5.2.1 and figure 5.2.2. The applied jacking force was observed from the jacking dial gauge as shown in figure 5.2.3. The elongation of strands was measured by marking the initial strand position and final strand position at jack end as shown in the figure 5.2.4 and figure 5.2.5.

Figure 5.2.1 – Hydraulic jack connected to strand.

Figure 5.2.2 – Application of jacking force to strand.

Figure 5.2.3 – Observation of applied jacking force from

Figure 5.2.4 Hydraulic jack connected to strand

Figure 5.2.5 – Initial strand location marked at the jacking end

The electronic data logger reading was also recorded to measure strain developed in strands. The data logger readings after stressing the strands are given in the table 5.2.1.

Table 5.2.1 - Data logger readings after stressing the strands

Strand Number	Reading after stressing (με)
1	5382
2	5226
3	4776
4	5257
5	4968
6	5045

The strain values developed can be calculated from the data logger readings obtained before and after stressing the strands**.** The calculated strain values can be tabulated as below.

Table 5.2.2 - The strain values developed at strands after stressing the strands

Strand Number	Initial reading (με)	Reading after stressing (με)	Strain developed
1	-777	5382	0.0062
2	-771	5226	0.0060
3	-706	4776	0.0055
4	-570	5257	0.0058
5	-738	4968	0.0057
6	-1117	5045	0.0062

Also, the strain values can be calculated by using the elongation values measured manually. The total length of prestressing strand is 100.0 m. This is the length between two edges of the prestressing bed.

Table 5.2.3 - The strain values developed at strands after stressing the strands (Using manual elongation measurements)

Strand Number	Pressure gauge reading (Bar)	Force (kN)	Elongation (mm)	Initial length (m)	Strain developed
1	420	133	575	100	0.0058
2	420	133	575	100	0.0058
3	420	133	560	100	0.0056
4	420	133	565	100	0.0057
5	420	133	565	100	0.0057
6	420	133	560	100	0.0056

From the values calculated in table 5.2.2 and table 5.2.3 the average strain values obtained can be calculated and compared for accuracy.

The average strain in strands (Using data logger readings) = 0.0059

The average strain in strands (Using data manual measurements) = 0.0057

Therefore, the strain values obtained from two different methods are approximately same and can be assumed as accurate strain values.

5.3 Readings obtained at site before releasing the strands

The spot levels were taken from six locations on the prestressed slab panel which was selected for testing by using level instrument. This spot levels were taken to get the developed camber values after releasing of strands. The spot level taking process is shown in the figure 5.3.1 and the spot level taken locations on prestress panel is shown in the figure 5.3.2

Figure 5.3.1 – Taking spot levels on prestressed panel before releasing the strands

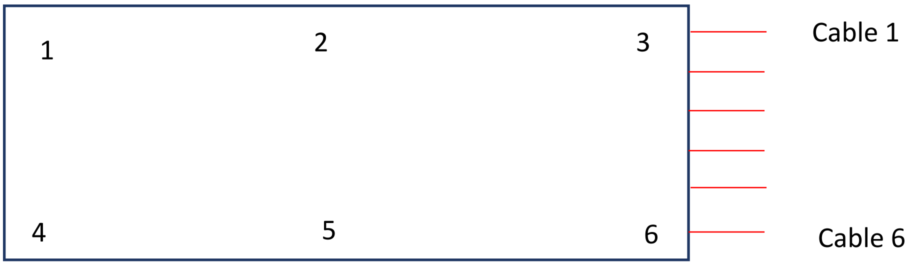


Figure 5.3.2 – Spot level locations on prestressed panel

Then the electronic data logger was set and connected to strands before releasing the strands. The data logger reading was recorded for each strand to get the developed strain in each strand as shown in the figure 5.3.3.

Figure 5.3.3 – Record data logger readings before releasing the strands

The data logger readings and calculated strain values in strands before releasing the strands are given in the table 5.3.1.

Table 5.3.1 - The strain values developed at strands before releasing the strands

Strand Number	Initial reading (με)	Reading before releasing trands (με)	Strain developed
1	-777	5347	0.0061
2	-771	4466	0.0052
3	-706	4361	0.0051
4	-570	4099	0.0047
5	-738	4899	0.0056
6	-1117	4995	0.0061

5.4 Readings obtained at site after releasing the strands

The spot levels were taken from the same locations on the prestressed slab panel which was selected for testing by using level instrument. The spot level taking procedure was continued in six steps, at the end of releasing of each strand. Then let the prestressed slab to develop camber and spot levels were taken 5 hours after releasing the all strands. From these spot levels taken before and after releasing strands the developed camber value was determined at the transfer stage.

The staff readings obtained at each strand releasing step are shown in table 5.4.1.

Table 5.4.1 - The staff readings before and after releasing strands

Location	Staff reading (cm)							
	Before releasing strands	After releasing strand no 6	After releasing strand no 1	After releasing strand no 5	After releasing strand no 2	After releasing strand no 4	After releasing strand no 3	5 hours after releasing of all strands
1	124.5	124.7	124.6	124.7	124.6	124.7	124.7	81.4
2	125.4	125.3	125.2	125.3	125.1	125.1	124.9	80.9
3	125.8	125.5	125.8	125.8	125.8	125.7	125.7	83.0
4	124.2	124.2	124.2	124.4	124.4	124.4	124.4	80.5
5	125.4	125.3	125.3	125.3	125.3	125.1	125.0	80.8
6	125.8	125.8	125.9	125.8	125.9	125.8	125.8	83.1

Then the electronic data logger was set and connected to strands after releasing of strands. The data logger was set on a platform so that, not to disturb during the strand releasing process as shown in the figure 5.4.1. Then the data logger reading was recorded for each strand to get the developed strain in each strand.

Figure 5.4.1 – Data logger set on a platform, not to disturb during strand releasing process

The data logger readings and calculated strain values in strands after releasing the strands are given in the table 5.4.2.

Table 5.4.2 - The strain values developed at strands after releasing the strands

Strand Number	Initial reading (με)	Reading after releasing (με)	Strain developed
1	-777	4865	0.0056
2	-771	4042	0.0048
3	-706	3957	0.0047
4	-570	3719	0.0043
5	-738	4443	0.0052
6	-1117	4503	0.0056

5.5 Readings obtained at site after placing the topping concrete on top of prestressed slab

The precast prestressed slab panels were placed on top of the precast load bearing walls and placed topping concrete on precast prestressed slab panels. The minimum topping concrete thickness was maintained as 75mm at the mid span of the slab. Then the spot levels were taken at six locations from the bottom side of the precast prestressed slab panel under observations. This spot levels were taken to determine the reduction of camber value due to the self weight of topping concrete and also to determine the actual volume of topping concrete used in the construction. The staff readings after placing the topping concrete on prestressed slab is given in the table 5.5.1.

Table 5.5.1 - The staff readings after placing the topping concrete on prestressed slab

Location	Staff reading (cm)
1	171.2
2	172.4
3	171.4
4	171.3
5	172.4
6	171.5

6.0 RESULTS AND DISCUSSION

6.1 Comparison of Material Properties

6.1.1 Comparison of Prestressing strand Material Properties

The prestressing strand material properties used in design process and the values obtained from laboratory tests are given in the table 6.1.1.

Table 6.1.1 - Comparison of Prestressing Strand Properties

	Design values	Laboratory test values
Modulus of Elasticity (N/mm^2)	200.00×10^3	196.11×10^3
Ultimate Tensile Stress (N/mm^2)	1860.00	1720.00

According to above results the Modulus of Elasticity value and Ultimate Tensile Stress value obtained from laboratory test is less than the value considered in design. The true properties of high strength strands can be obtained by using an effective gripping procedure during the tension test. The reduction in Modulus of Elasticity value and Ultimate Tensile Stress value can be due to not using an effective gripping method during the tension test.

The losses in steel stress directly depends on Modulus of Elasticity of steel. In this case the Modulus of Elasticity value obtained from laboratory test is less than the value considered in design. We can compare the difference in loss of stress in steel due to difference in design values and laboratory test values as follows.

Short term losses (Elastic shortening of concrete)

Loss due to elastic shortening of concrete, $\Delta p_{se} = \Delta f_{se} \times A_c$

$$\Delta f_{se} = n f_{co} = (E_s / E_c) f_{co}$$

where, f_{co} at mid span $= \{(Pj/A) + (Pj.e^2/I) - (Mo.\ e/I)\}$

f_{co} at support $= (Pj / A) + (Pj.\ e^2 / I)$

Therefore, decrease in Modulus of Elasticity of steel leads to reduction the prestress losses in steel and it will increase the effective prestress force.

The upward deflection (Camber) of prestressed slab due to prestress force is given by the equation,

Upward deflection due to prestress force $= - P_e \, e \, L^2 / 8E_{ci} \, I$

Therefore, when the effective prestress force increases, the upward deflection also increases.

In this study,

The percentage of reduction in short term losses compared to design value = (200-196.11) x (100/200) = 1.945 %

Long term losses (Shrinkage of concrete)

Loss due to shrinkage of concrete, $\Delta p_{ss} = k \, Es$

Shrinkage strain (k) = 300×10^{-6}

The percentage of reduction in loss due to shrinkage compared to design value

= (200 - 196.11) x (100/200)

= 1.945 %

Therefore, it is clearly observed that actual prestress losses due to elastic shortening and shrinkage are directly depend on Modulus of Elasticity of steel. In this research lesser laboratory test value in Modulus of Elasticity of steel leads to reduction in the prestress losses in steel and it increases the effective prestress force. Therefore, it will cause in higher camber value than design value.

6.1.2 Comparison of Concrete Material Properties

The concrete material properties used in design process and the values obtained from laboratory tests are given in the table 6.1.2.

Table 6.1.2 - Comparison of Concrete Properties

	Design values	Laboratory test values
Compressive Strength (N/mm^2) At Transfer stage (f_{ci})	35.0	38.86
Compressive Strength (N/mm^2) At age of 28 das (f_{cu})	50.0	59.05
Modulus of Elasticity (N/mm^2) At Transfer stage	27.0×10^3	20.7×10^3
Modulus of Elasticity (N/mm^2) At age of 28 das	30.0×10^3	29.1×10^3
$f_{amaxt} = 0.5 f_{ci}$ (N/mm^2)	17.5	19.43
$f_{amint} = -0.45(f_{ci})^{1/2}$ (N/mm^2)	-2.7	-2.8
$f_{amax} = 0.33 f_{cu}$ (N/mm^2)	16.5	19.5
$f_{amin} = -0.45(f_{cu})^{1/2}$ (N/mm^2)	-3.2	-3.45

The upward deflection (camber) in prestressed slab directly depends on Modulus of Elasticity of concrete. In this case the Modulus of Elasticity value obtained from laboratory test at both transfer stage and at the age of 28 days is less than the value considered in design.

The upward deflection (Camber) of prestressed slab due to prestress force is given by the equation,

Upward deflection due to prestress force $= - P_e e L^2 / 8E_{ci} I$

Therefore, when the Modulus of Elasticity of concrete decrease, the upward deflection also increase.

In this study,

The percentage of increase in upward deflection compared to design value (at Transfer condition) due to reduction in Modulus of Elasticity of concrete = **(1/20.7 - 1/27) / (1/27) X 100 = 30.4 %**

6.2 Analysis of strain values and prestress losses observed at site

6.2.1 Analysis of strain values and prestress losses before releasing strands

The summary of strain values obtained after stressing strands and before releasing strands are shown in the table 6.2.1.

Table 6.2.1 - The summary of strain values developed at strands after stressing and before releasing strands

Strand Number	Initial reading ($\mu\varepsilon$)	Reading after stressing ($\mu\varepsilon$)	Strain developed Reading after stressing	Reading before releasing strands ($\mu\varepsilon$)	Strain developed before releasing strands
1	-777	5382	0.0062	5347	0.0061
2	-771	5226	0.0060	4466	0.0052
3	-706	4776	0.0055	4361	0.0051
4	-570	5257	0.0058	4099	0.0047
5	-738	4968	0.0057	4899	0.0056
6	-1117	5045	0.0062	4995	0.0061

The average strain in strands (Reading after stressing) = 0.0059

The average strain in strands (Reading before releasing strands) = 0.00546

The Stress in strands (Just after stressing) = 133x1000/100

= 1330 Nmm^2

The Stress in strands (before releasing strands) = 1330x{0.00546/0.0059}

= 1230.8 Nmm^2

The actual loss in jacking force = (1330 – 1230.8) x100

= 9.92 kN per strand

Therefore, the actual percentage of loss in jacking force = 9.92 x (100/133)

= 7.45 %

But in the design, it is considered 10% loss of jacking force before releasing of strands. The actual loss in jacking force is less than the value considered in the design and that leads to increase in initial prestress force in strands. Therefore, due to the higher initial force than expected in the design, the upward deflection due to prestress force is increased.

6.2.2 Analysis of strain values and prestress losses after releasing strands

The summary of strain values obtained before releasing strands and after releasing strands are given in the table 6.2.2.

Table 6.2.2 - The summary of strain values developed at strands after stressing and before releasing strands

Strand Number	Initial reading (με)	Reading before releasing strands (με)	Strain developed before releasing strands	Reading after releasing (με)	Strain developed after releasing
1	-777	5347	0.0061	4865	0.0056
2	-771	4466	0.0052	4042	0.0048
3	-706	4361	0.0051	3957	0.0047
4	-570	4099	0.0047	3719	0.0043
5	-738	4899	0.0056	4443	0.0052
6	-1117	4995	0.0061	4503	0.0056

The average strain in strands (Before releasing strands) = 0.00546

The average strain in strands (After releasing strands) = 0.00503

The Stress in strands (before releasing strands) = 1230.8 Nmm^2

The Stress in strands (after releasing strands) = 1230.8 x {0.00503/0.00546}

= 1133.86 Nmm^2

The actual loss in initial force = (1230.8 – 1133.86) x100

= 9.69 kN per strand

Therefore, the actual percentage of loss in initial force = 9.69 x (100/123.08)

= 7.87 %

But in the design, it is considered 20% loss of initial force after releasing of strands. The actual loss in initial force is less than the value considered in the design and that leads to increase in effective prestress force in strands. Therefore, due to the higher effective force than expected in the design, the upward deflection due to prestress force is increased.

The upward deflection (Camber) of prestressed slab due to prestress force is given by the equation,

Upward deflection due to prestress force = $- P_e\ e\ L^2 / 8E_{ci}\ I$

Therefore, when the effective prestress force increases, the upward deflection also increases.

In this study,

The effective prestress force used at design stage = 562.5 kN

The Actual effective prestress force = 113.386 x 6 = 680.32 kN

The percentage of increase in upward deflection compared to design value (at Transfer condition) due to increase in effective prestress force = **(680.32 - 562.5) / (562.5) X 100 = 20.9 %**

On the other hand,

The actual effective prestress force required according to design = 561.7 kN

But actual effective prestress force obtained from 5 strands = 113.386 x 5 = 566.93 kN

Therefore, according to the experiment results it is possible to provide the required prestress force by using only 5 strands instead of 6 strands.

Therefore. the percentage of prestressing strands can be saved = (1/6) x 100

= 16.67 %

Therefore, if we provided the actual number of strands required, it is possible to save 16.67% amount from the high strength strand cost.

6.2.3 Effect on ultimate limit state flexure and shear due to prestressing force

6.2.3.1 Effect on ultimate limit state flexural capacity

The ultimate limit state flexural capacity with 6 strands and with 5 strands are calculated in the annexure A.

The ultimate limit state flexural capacity with 6 strands = 142.9 kNm

The ultimate limit state flexural capacity with 5 strands = 122.4 kNm

Therefore, when the effective prestress force increases, the ultimate limit state flexural capacity also increases. But this is not a linear increase.

6.2.3.2 Effect on ultimate limit state shear capacity

The ultimate limit state shear capacity in cracked section with 6 strands and with 5 strands are calculated in the annexure A.

The comparison of ultimate limit state shear capacity along the slab panel with 6 strands and with 5 strands are given in the table 6.2.3.

Table 6.2.3 - The summary of ultimate limit state shear capacity along slab panel with 6 strands and with 5 strands

X (m)	With 6 strands			With 5 strands		
	V_{co} (kN)	V_{cr} (kN)	V_c (kN)	V_{co} (kN)	V_{cr} (kN)	V_c (kN)
0.25	293.1	241.15	241.15	279.7	220.72	220.72
0.5	293.1	160.88	160.88	279.7	147.1	147.1
1	293.1	124.42	124.42	279.7	124.42	124.42
2	293.1	124.42	124.42	279.7	124.42	124.42
3	293.1	124.42	124.42	279.7	124.42	124.42
3.825	293.1	124.42	124.42	279.7	124.42	124.42

Therefore, when the effective prestress force increases, the ultimate limit state shear capacity also increases. But this is not a linear increase.

6.3 Analysis of deflection values obtained at site during and after releasing of strands

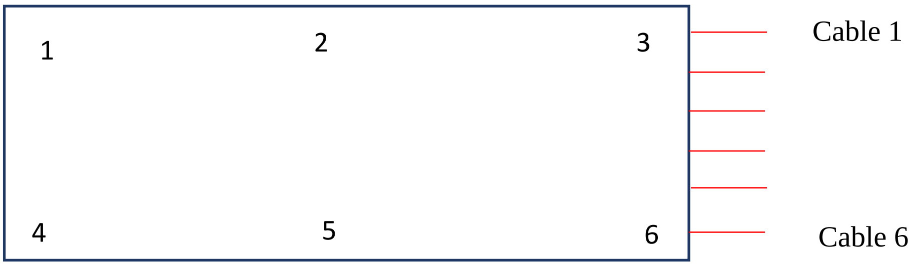


Figure 6.3.1 – Spot level locations on pre-stressed panel

The summary of upward deflection values calculated using spot levels during and after releasing of strands are given in table 6.3.1.

Table 6.3.1 - The summary of upward deflection values developed during and after releasing of strands

	strand 6 release	strand 1 release	strand 5 release	strand 2 release	strand 4 release	strand 3 release	After 5 hours of releasing all strands
Point 2	0.50 mm	2.50 mm	2.00 mm	3.50 mm	3.50 mm	5.50 mm	15.50 mm
Point 5	1.00 mm	1.50 mm	2.00 mm	2.50 mm	4.00 mm	5.00 mm	14.00 mm

Therefore, the average upward deflection developed at transfer stage = 14.75 mm

Although there is an upward curvature developed due to prestress force, it is necessary to keep the topping concrete top surface at same level because we have to place finishes such as tile and tile bedding on a levelled surface. Otherwise it is uncomfortable for the customer during service life of building. Therefore, we had to put extra amount of topping concrete thickness to maintain the minimum topping concrete layer thickness of 75 mm.

The volume of topping concrete required according to the design (Per slab panel) = 0.7183 m^3

The actual volume of topping concrete used (Per slab panel) = 0.7562 m^3

Therefore the percentage of extra amount of topping concrete used = (0.7562-0.7183)x(100/0.7183) = 5.27 %

Therefore, due to this excessive camber development, it increases extra 5.27% of topping concrete material cost.

During the stress releasing stage of the strands, releasing process was done one by one. Therefore, the stress releasing process is not symmetrical and the stress at strands vary during the releasing process. It can be clearly observed that the camber values at point 2 and 5 vary unevenly with the release of each strand. Due to this reason there can be a twist in the precast prestressed slab panel and the camber value also varies along a cross section considered.

Suggestion to avoid twist precast prestressed slab panel: Therefore, it is proposed to release all strands at same time to reduce the uneven camber development along a cross section and to avoid a twist in precast prestressed slab panel.

6.4 Redesign Calculation for Precast Prestressed Slab According to Experimental Data Obtained.

The precast prestressed slab panel was redesigned using experimental data obtained. The redesign calculation using experimental data is given in Annexure B.

7.0 CONCLUSIONS AND RECOMMENDATIONS FOR FUTUREWORK

7.1 Comparison of Literature Review Findings, Theoretical Calculations and Practical Observations

Comparison of Concrete Properties

The concrete material properties used in design process and the values obtained from laboratory tests are given in the table 7.1.1.

Table 7.1.1 - Comparison of Concrete Properties

	Design values	Laboratory test values
Compressive Strength (N/mm^2) At Transfer stage (f_{ci})	35.0	38.86
Compressive Strength (N/mm^2) At age of 28 das (f_{cu})	50.0	59.05
Modulus of Elasticity (N/mm^2) At Transfer stage	27.0×10^3	20.7×10^3
Modulus of Elasticity (N/mm^2) At age of 28 das	30.0×10^3	29.1×10^3

According to the literature review findings, precast prestressed elements tends to gain higher camber with higher specified concrete compressive strength. According to the values given in table 7.1.1 also, the actual concrete strength observed were greater than the values considered in the design and also it was observed that the actual camber value is higher than the design value.

According to the literature review findings, camber at prestress release is highly influenced by the modulus of elasticity of concrete. Therefore, using accurate values of modulus of elasticity of concrete leads to accurate prediction of camber value in precast prestressed slabs.

The upward deflection (camber) in prestressed slab directly depend on Modulus of Elasticity of concrete. In this case the Modulus of Elasticity value obtained from laboratory test at both transfer stage and at the age of 28 days is less than the value considered in design.

Therefore, when the Modulus of Elasticity of concrete decreases, the upward deflection also increases. In this study,

The percentage of increase in upward deflection compared to design value (at Transfer condition) due to reduction in Modulus of Elasticity of concrete = **(1/20.7 - 1/27) / (1/27) X 100 = 30.4 %**

Comparison of Prestressing Strand Properties

The prestressing strand material properties used in design process and the values obtained from laboratory tests are given in the table 7.1.2.

Table 7.1.2 - Comparison of Prestressing Strand Properties

	Design values	Laboratory test values
Modulus of Elasticity (N/mm^2)	200.00 x 10^3	196.11 x 10^3
Ultimate Tensile Stress (N/mm^2)	1860.00	1720.00

According to above results the Modulus of Elasticity value and Ultimate Tensile Stress value obtained from laboratory test is less than the value considered in design. The true properties of high strength strands can be obtained by using an effective gripping procedure during the tension test. The reduction in Modulus of Elasticity value and Ultimate Tensile Stress value can be due to not using an effective gripping method during the tension test.

According to the literature review findings, accurate estimate of elastic shortening losses at prestress release would allow for more accurate prediction of camber at release. Reduction in losses increases the effective prestress force. Therefore, it will cause in higher camber value than design value.

The losses in steel stress directly depends on Modulus of Elasticity of steel. In this case the Modulus of Elasticity value obtained from laboratory test is less than the value considered in design. we can compare the difference in loss of stress in steel due to difference in design values and laboratory test values as follows.

Short term losses (Elastic shortening of concrete)

Loss due to elastic shortening of concrete, $\Delta p_{se} = \Delta f_{se} \times A_c$

$\Delta f_{se} = n f_{co} = (E_s / E_c) f_{co}$

Therefore, decrease in Modulus of Elasticity of steel leads to reduce the prestress losses in steel and it will increase the effective prestress force.

In this study,

The percentage of reduction in short term losses compared to design value = (200-196.11) x (100/200) = 1.945 %

Long term losses (Shrinkage concrete)

Loss due to shrinkage of concrete, $\Delta p_{ss} = k Es$

Shrinkage strain (k) = 300×10^{-6}

The percentage of reduction in loss due to shrinkage compared to design value

= (200 - 196.11) x (100/200) = 1.945 %

Therefore, it is clearly observed that actual prestress losses due to elastic shortening and shrinkage are directly depend on Modulus of Elasticity of steel. In this research lesser laboratory test value in Modulus of Elasticity of steel leads to reduce the prestress losses in steel and it increases the effective prestress force.

Comparison of Prestress Loss Ratios Considered

According to the literature review findings, the design camber value is linearly varied with the jacking force. Therefore, accurate application of jacking force is important for a specified design camber value. The variation in actual prestress force with respect to the specified design prestress force will affect the accurate prediction of camber in precast slabs.

The summary of strain values obtained after stressing strands and before releasing strands are shown in the table 7.1.3.

Table 7.1.3 - The summary of strain values developed at strands after stressing and before releasing strands

Strand Number	Initial reading (με)	Reading after stressing (με)	Strain developed Reading after stressing	Reading before releasing strands (με)	Strain developed before releasing strands
1	-777	5382	0.0062	5347	0.0061
2	-771	5226	0.0060	4466	0.0052
3	-706	4776	0.0055	4361	0.0051
4	-570	5257	0.0058	4099	0.0047
5	-738	4968	0.0057	4899	0.0056
6	-1117	5045	0.0062	4995	0.0061

The average strain in strands (Reading after stressing) = 0.0059

The average strain in strands (Reading before releasing strands) = 0.00546

Therefore, the actual percentage of loss in jacking force = 7.45 %

But in the design, it is considered 10% loss of jacking force before releasing of strands. The actual loss in jacking force is less than the value considered in the design and that leads to increase in initial prestress force in strands.

The summary of strain values obtained before releasing strands and after releasing strands are given in the table 7.1.4.

Table 7.1.4 - The summary of strain values developed at strands after stressing and before releasing strands

Strand Number	Initial reading (με)	Reading before releasing strands (με)	Strain developed before releasing strands	Reading after releasing (με)	Strain developed after releasing
1	-777	5347	0.0061	4865	0.0056
2	-771	4466	0.0052	4042	0.0048
3	-706	4361	0.0051	3957	0.0047
4	-570	4099	0.0047	3719	0.0043
5	-738	4899	0.0056	4443	0.0052
6	-1117	4995	0.0061	4503	0.0056

The average strain in strands (Before releasing strands) = 0.00546

The average strain in strands (After releasing strands) = 0.00503

Therefore, the actual percentage of loss in initial force = 7.87 %

But in the design, it is considered 20% loss of initial force after releasing of strands. The actual loss in initial force is less than the value considered in the design and that leads to increase in effective prestress force in strands.

In this study,

The effective prestress force used at design stage = 562.5 kN

The Actual effective prestress force = 113.386 x 6 = 680.32 kN

The percentage of increase in upward deflection compared to design value (at Transfer condition) due to increase in effective prestress force = **(680.32 - 562.5) / (562.5) X 100 = 20.9 %**

7.2 Conclusion

The objective of this research project is to study the reasons for excessive camber development in precast prestressed slabs and suggestions to minimize the excessive camber development.

From the experimental values obtained from prestressing strand tests, the actual Modulus of Elasticity in prestressing strands used is slightly lower than the values considered in design. Therefore, decrease in Modulus of Elasticity of prestressing strands leads to reduce the prestress losses in prestressing strands and it will increase the effective prestress force and when the effective prestress force increases, the upward deflection also increases.

From the experimental values obtained for strain in the strands, it is clear that the actual losses in strands are less than the values assumed in design. during design process it was assumed 10% loss in jacking force and 20% loss in initial prestress force. But according to the experimental data obtained, the loss in jacking force is 7.45 % and the loss in initial prestress force is = 7.87 %. Therefore, due to the higher effective force than expected in the design, the upward deflection due to prestress force is increased.

In this research,

The percentage of increase in upward deflection compared to design value (at Transfer condition) due to increase in effective prestress force = **(680.32 - 562.5) / (562.5) X 100 = 20.9 %**

The actual effective prestress force required according to design is 561.7 kN and actual effective prestress force obtain from 5 strands is 566.93 kN (113.386 x 5 = 566.93 kN)

Therefore, according to the experiment results it is possible to provide the required prestress force by using only 5 strands instead of 6 strands. **Therefore, if we provide the actual number of strands required, it is possible to save 16.67% amount from the high strength strand cost.**

From the recalculation process by using the material properties and parameters obtained by experimental data, it is showed that it is adequate to use 5 number of strands instead of 6 number of strands.

From the experimental values obtained from concrete cylinder tests, the actual Modulus of Elasticity in concrete used is lower than the values considered in design. The upward deflection (camber) in prestressed slab directly depends on Modulus of Elasticity of concrete. Therefore, when the Modulus of Elasticity of concrete decreases, the upward deflection also increases.

In this study,

The percentage of increase in upward deflection compared to design value (at Transfer condition) due to reduction in Modulus of Elasticity of concrete = **(1/20.7 - 1/27) / (1/27) X 100 = 30.4 %**

Because of excessive camber development we had to put extra amount of topping concrete thickness to maintain the minimum topping concrete layer thickness of 75 mm. The volume of topping concrete required according to the design (Per slab panel) is 0.7183 m^3 and the actual volume of topping concrete used (Per slab panel) is 0.7562 m^3

Therefore, due to this excessive camber development, it increases extra 5.27% of topping concrete material cost.

During the stress releasing stage of the strands, releasing process was done by one by one and the stress releasing process is not symmetrical. Therefore, the stress at strands vary during the releasing process. it can be clearly observed that the camber values at point 2 and 5 vary unevenly with the release of each strand. Due to this reason there can be a twist in the precast prestressed slab panel and the camber value also varies along a cross section considered.

Suggestion to avoid twist precast prestressed slab panels: Therefore, it is proposed to release all strands simultaneously to reduce the uneven camber development along a cross section and to avoid a twist in precast prestressed slab panels.

7.3 Recommendation for future work

This research can be further extended in following directions.

1) The prestress losses can be varied with the concrete mix design also. Therefore this research can be extended with using different concrete mix designs.

2) According to the experimental results, the calculation was done by using 5 number of high strength strands. The experiment can be also performed by using 5 number of high strength strands at precast yard.

3) The tension test of high strength strands can be performed by using effective gripping method.

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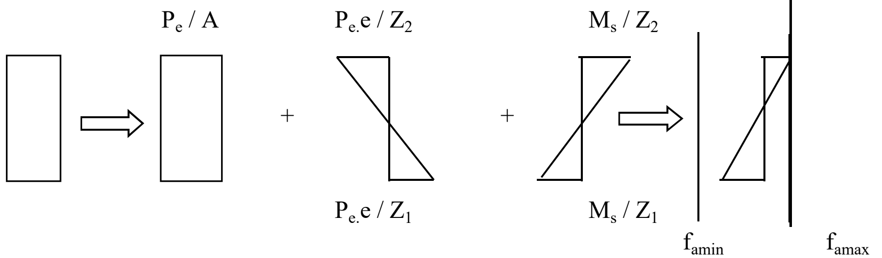
Ref	Calculations	Output
	This design was carried out according to British Standards.	
	The initial sizing and material properties are as following.	
	Slab panel length (Span) = 7.65 m Width = 1.2 m Thickness = 125 mm Concrete Grade, C50	
	Thickness of topping = 75 mm Topping Concrete Grade, C30	
	Diameter of High strength strands = 12.9 mm Strength of High strength strands = 1860 N/mm^2 Cross section area of High strength strand = 100 mm^2	
CL 4.1.3 BS8110:Part 1: 1985	Class of the slab according to amount of flexural tensile stress	
	Class 2 : Flexural tensile stresses but no visible cracking.	
CL 4.12.3 BS8110:Part 1: 1985	Cover requirement to pre stressing strands	
Table 4.8 BS8110:Part 1: 1985	Minimum cover requirement for moderate condition of exposure = 20 mm (Grade 50 concrete)	
Table 4.9 BS8110:Part 1: 1985	Minimum cover requirement for 1 hour fire resistance = 25 mm	
	Therefore provide 25 mm cover for pre stressed strands	
	Load Evaluation for Transfer Stage and Topping Concrete Placing Stage	
	Self weight of slab panel = 0.125 x 1.2 x 24 = 3.6 kN/m	
	Weight of topping concrete = 0.075 x 1.2 x 24 = 2.16 kN/m	
	Moment due to self weight of slab, M_o = 3.6 x 7.65^2 / 8 = 26.3 kNm	
	Moment due to self weight and topping concrete, M_{smax} = (3.6 + 2.16) x 7.65^2 / 8 (Stage of placing topping concrete) = 42.1 kNm	
	Sign convension	
	Tension - Negative Compresion - Positive	

Ref	Calculations	Output

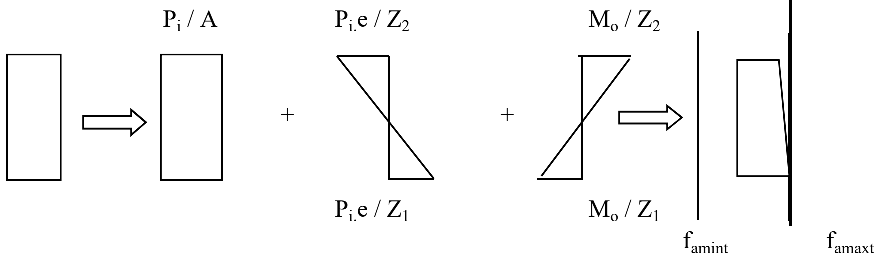
Selection of suitable section



At topping concrete placing stage

$$P_e / A - (P_e.e / Z_2) + M_s / Z_2 \leq f_{amax} \quad \text{———} \quad (A)$$

$$P_e / A + (P_e.e / Z_1) - M_s / Z_1 \geq f_{amin} \quad \text{———} \quad (B)$$



At limiting transfer conditions

$$P_i / A - (P_i.e / Z_2) + M_o / Z_2 \geq f_{amint} \quad \text{———} \quad (C)$$

$$P_i / A + (P_i.e / Z_1) - M_o / Z_1 \leq f_{amaxt} \quad \text{———} \quad (D)$$

Assume loss ratio, $\alpha = 0.8$

$$\alpha = P_e / P_i = 0.8 \quad (P_e = \alpha P_i)$$

$(A) - \alpha (C) \Longrightarrow$

$$(M_s - \alpha M_o) / Z_2 \leq f_{amax} - \alpha f_{amint}$$

$$Z_2 \geq (M_s - \alpha M_o) / (f_{amax} - \alpha f_{amint})$$

$\alpha (D) - (B) \Longrightarrow$

$$(-\alpha M_o + M_s) / Z_1 \leq \alpha f_{amaxt} - f_{amin}$$

$$Z_1 \geq (M_s - \alpha M_o) / (\alpha f_{amaxt} - f_{amin})$$

Ref	Calculations	Output
	Allowable stresses	
	At servisability condition	
	$f_{cu} = 50 \text{ N/mm}^2$	
CL4.3.4.2 BS8110:Part 1: 1985	$f_{amax} = 0.33 f_{cu}$ $= 0.33 \times 50 = 16.5 \text{ N/mm}^2$	f_{amax} = 16.5 N
CL4.3.4.3 BS8110:Part 1: 1985	$f_{amin} = -0.45(f_{cu})^{1/2}$ $= -0.45 \times (50)^{1/2} = -3.2 \text{ N/mm}^2$	f_{amin} = -3.2 N/
	At transfer condition	
	Assume $f_{ci} = 35 \text{ N/mm}^2$	
CL4.3.5.1 BS8110:Part 1: 1985	$f_{amaxt} = 0.5 f_{ci}$ $= 0.5 \times 35 = 17.5 \text{ N/mm}^2$	f_{amaxt} = 17.5 N
CL4.3.5.2 BS8110:Part 1: 1985	$f_{amint} = -0.45(f_{ci})^{1/2}$ $= -0.45 \times (35)^{1/2} = -2.7 \text{ N/mm}^2$	f_{amint} = -2.7 N
Stages upto topping concrete placing	$Z_1 \geq \{(42.1 - 0.8 \times 26.3) \times 10^6 \} / \{0.8 \times 17.5 - (-3.2) \} = 1.22 \times 10^6 \text{ mm}^3$ $Z_2 \geq \{(42.1 - 0.8 \times 26.3) \times 10^6 \} / \{16.5 - 0.8 \times (-2.7) \} = 1.12 \times 10^6 \text{ mm}^3$	
	Section properties at transfer condition	
	$I = (1200 \times 125^3) / 12$ $= 195312500 \text{ mm}^4$	
	$Z = I / y$ $= 195312500 / 62.5$ $= 3.125 \times 10^6 \text{ mm}^3$	
	$Z_1 = 3.125 \times 10^6 \text{ mm} > 1.22 \times 10^6 \text{ mm}^3$ $Z_2 = 3.125 \times 10^6 \text{ mm} > 1.12 \times 10^6 \text{ mm}^3$	
	Therefore selected section is adequate.	
	Magnel diagram (For Transfer stage and Topping concrete placing stage)	
	Area of section , A = 125 x 1200 $= 150000 \text{ mm}^2$ $1 / A = 6.67 \times 10^{-6} \text{ mm}^{-2}$	
	$I = 195312500 \text{ mm}^4$	
	$Z = 3.125 \times 10^6 \text{ mm}^3$	
	$e = 31.1 \text{ mm}$ $y = 62.5 \text{ mm}$	

Ref	Calculations	Output

From (A) $\Longrightarrow$ $6.67 \times 10^{-6} P_e - \{ P_e.e / 3.125 \times 10^6\} + \{42.1 \times 10^6 / 3.125 \times 10^6 \} \leq 16.5$

$(1 / P_e) \geq (20.84 - e) / (9.46 \times 10^6)$ —— (01)

From (B) $\Longrightarrow$ $6.67 \times 10^{-6} P_e + \{ P_e.e / 3.125 \times 10^6\} - \{42.14 \times 10^6 / 3.125 \times 10^6 \} \geq -3.2$

$(1 / P_e) \leq (20.84 + e) / (32.14 \times 10^6)$ —— (02)

From (C) $\Longrightarrow$ $(6.67 \times 10^{-6} P_e / 0.8) - \{ P_e.e / 0.8 \times 3.125 \times 10^6\} + \{26.3 \times 10^6 / 3.125 \times 10^6 \} \geq -2.7$

$(1 / P_e) \geq (20.84 - e) / (-27.8 \times 10^6)$ —— (03)

From (D) $\Longrightarrow$ $(6.67 \times 10^{-6} P_e / 0.8) + \{ P_e.e / 0.8 \times 3.125 \times 10^6\} - \{26.3 \times 10^6 / 3.125 \times 10^6 \} \leq 17.5$

$(1 / P_e) \geq (20.84 + e) / (64.8 \times 10^6)$ —— (04)

Then using equation 01,02,03 and 04, the magnel diagram for transfer stage and topping concrete placing stage were plotted on a drafting sheet. The magnel diagram for transfer stage and topping concrete placing stage is shown in the figure 4.1.

Magnel diagram for equation 01 , 02 , 03 and 04.

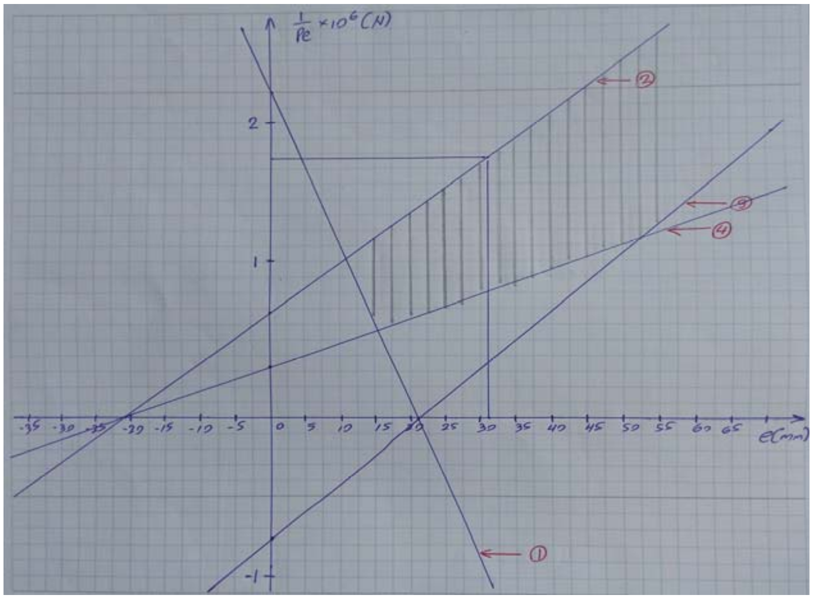


Figure A.1 : Magnel diagram for transfer stage and topping concrete placing stage

Ref	Calculations	Output

Tendon arrangement

Use 12.9 mm diameter high strength strands with characteristic strength of 1860 N/mm^2

Stress factor = 0.7

Jacking force, P_j (per strand) = $0.7 \times 1860 \times 100 \times 10^{-3}$ = 130.2 kN

Assume loss , 10% of jacking force

P_i = 0.9×130.2 = 117.1 kN

α = 0.8

P_e = 0.8×117.1 = 93.7 kN

Practrical situation, e = {125/2 - (25 + 12.9/2)} = 31.1 mm

$1 / P_e$ = 1.78×10^{-6} (From magnel diagram)

Total effective force = 561.7 kN

Therefore number of strands needed = 561.7 / 93.7 = 5.9

Therefore provide 6 number of 12.9 mm high strength strands.

Check the panel for service condition (Composite section)

Weight of finishes and partitions = (0.85 + 1.35) x 1.2
= 2.64 kN/m

Imposed load = 1.5 x 1.2
= 1.8 kN/m

Moment at service stage, M_{smax} = $(3.6 + 2.16 + 2.64 + 1.8) \times 7.65^2 / 8$
= 74.6 kNm

Characteristic strength of Prestressed slab = 50 N/mm^2

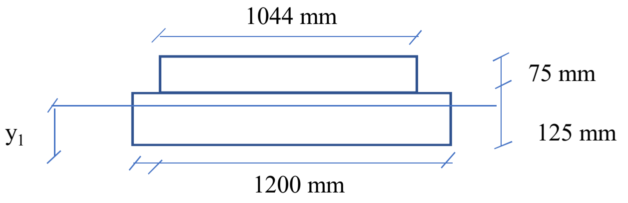
Elastic modulus of Prestressed slab = 30 N/mm^2

Characteristic strength of topping concrete = 30 N/mm^2

Elastic modulus of topping concrete = 26 N/mm^2

Elastic modulus of C30 concrete / Elastic modulus of C50 concrete = 26/30 = 0.87

Therefore the effective width of topping concrete layer = 0.87 x 1200 = 1044 mm
(equivqlent to C50 concrete)



Ref	Calculations	Output

Area of section , A = 228300 mm^2

$1/A = 4.38 \times 10^{-6} \text{ mm}^{-2}$

$I = \{(1044 \times 200^3)/12 + (156 \times 125^3)/12\} = 720414062.5 \text{ mm}^4$

$y = 96.8$ mm mm

$e = 96.8 - (25 + 12.9/2) = 65.35$ mm

$Z_2 = I/y_2 = 720414062.5 / (200 - 96.8) = 6.98 \times 10^6 \text{ mm}^3$

$Z_1 = I/y_1 = 720414062.5 / 96.8 = 7.44 \times 10^6 \text{ mm}^3$

From (A) $\Longrightarrow$ $4.38 \times 10^{-6} P_e - \{P_e.e / 6.98 \times 10^6\} + \{74.6 \times 10^6 / 6.98 \times 10^6\} \leq 16.5$

$(1/P_e) \geq (30.57 - e)/(40.57 \times 10^6)$ —— (05)

From (B) $\Longrightarrow$ $4.38 \times 10^{-6} P_e + \{P_e.e / 7.44 \times 10^6\} - \{74.6 \times 10^6 / 7.44 \times 10^6\} \geq -3.2$

$(1/P_e) \leq (32.59 + e)/(50.8 \times 10^6)$ —— (06)

Then using equation 03,04,05 and 06, the magnel diagram for transfer stage and service stage were plotted on a drafting sheet. The magnel diagram for transfer stage and service stage is shown in the figure 4.2.

Magnel diagram for equation 03 , 04 , 05 and 06.

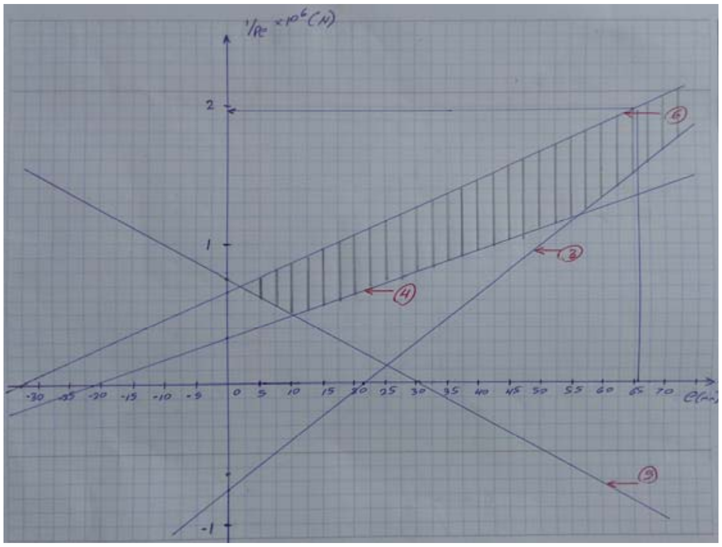


Figure A.2 : Magnel diagram for transfer stage and service stage

For composite section

e = 65.35 mm

$1/P_e = 1.97 \times 10^{-6}$

Required P_e = 507.6 kN

Therefore required total effective pre stress force = 507.6 kN

(For composite section)

Provided total effective prestress force = 6 x 93.75

= 562.5 kN

Therefore composite section is adequate

Ref	Calculations	Output

Prestress losses

Short term losses

CL 4.8.3 (01) Elastic shortening of concrete
BS8110:Part 1: 1985

Jacking force is transferred to the neutral axis as following.

Jacking force , P_j = 130.21 kN (per strand)

At level of wires

$f_{co} / E_c = \Delta f_{ps} / E_s$

$f_{co} = \{ (P_j / A) + (P_j.e^2 / I) - (M_o. e / I) \}$

Total P_j = 6 x 130.2 kN
= 781.2 kN

At midspan $f_{co} = \{ (781.2 \times 10^3 / 125 \times 1200) + [781.2 \times 10^3 \times 31.1^2 /(1200 \times 125^3/12)]$

$- [26.3 \times 10^6 \times 31.1 / (1200 \times 125^3/12)] \}$ = 4.88 N/mm^2

At support $f_{co} = \{ (P_j / A) + (P_j.e^2 / I)$
$= \{ (781.2 \times 10^3 / 125 \times 1200) + [781.2 \times 10^3 \times 31.1^2 /(1200 \times 125^3/12)]$
= 9.07 N/mm^2

Average f_{co} = (4.88 + 9.07)/2
= 6.975 N/mm^2

$\Delta f_{ps} = n f_{co}$
$= (E_s / E_c) f_{co}$

CL 7.2 (At transfer) $E_{ci} = Ko + f_{ci}$
BS8110:Part 2: 1985 = 20 + 0.2x35
= 27 kN/mm^2

Δf_{ps} = (200 / 27) x 6.975 x 10^{-3}
= 0.052 kN/mm^2

Δp_{se} = 0.052 x 100 x 6
= 31.2 kN

Ref	Calculations	Output
	Long term losses	
	(01) Steel relaxation	
CL 4.8.2 BS8110:Part 1: 1985	Δp_{sr} = P_j x Relaxation factor x 1000h relaxation test value	
Table 4.6 BS8110:Part 1: 1985	For relaxation class 2 (prestressing), Relaxation factor = 1.2	
CL 4.8.2.2 BS8110:Part 1: 1985	1000h relaxation value = 2.5 %	
	Δp_{sr} = 6 x 130.2 x 1.2 x 2.5 / 100	
	= 23.44 kN	
CL 7.2 BS8110:Part 2: 1985	(02) Losses due to creep of concrete	
	Prestress losses due to creep, Δp_{sc} = $\emptyset f_{co} E_s / E_{ci}$	
	E_{ci} = Ko + f_{ci} = 20 + 0.2x50 = 30 kN/mm^2	
	Ambient relative humidity = 80% and $\emptyset$ = 0.8	
	E_s = 200 kN/mm^2	
	f_{co} = 6.975 N/mm^2	
	Δp_{sc} = (0.8 x 6.975 x 10^{-3} x 200 / 30) x 10^3 x 100 x 6	
	= 22.3 kN	
CL 4.8.4 BS8110:Part 1: 1985	(03) Losses due to shrinkage	
	Stress due to shrinkage of concrete = kE_s	
	Skrinkage strain (k) = 300 x 10^{-6} (For indoor exposure condition)	
	Therefore prestress loss due to shrinkage	
	Δp_{ss} = 300 x 10^{-6} x 200 x 10^3 x 6 x 100	
	= 36 kN	
	Total long term losses = Δp_{sr} + Δp_{sc} + Δp_{ss}	
	= 23.44 + 22.3 + 36	
	= 81.74 kN	
	Initial force (P_i) = P_j - short term losses	
	= (781.2 x 0.9) - 31.2	
	= 671.9 kN	
	Effective force (P_e) = P_i - long term losses	
	= 671.9 - 81.74	
	= 590.14 kN	
	Actual loss ratio = (590.14 / 671.9) X 100 = 87.8 %	

Ref	Calculations	Output

Assumed $\alpha < \alpha$ actual

Therefore prestress plank is adequate for considered loading.

Deflection check

$P_e = 562.5$ kN

$E_{ci} = 27$ kN/mm^2

$I = 195312500$ mm^4 (At transfer)

Deflection due to pre stress (δ_{ps})

$$\delta_{ps} = - P_e\, e\, L^2 / 8E_{ci}\, I$$

$$= - 562.5 \times 31.1 \times 7650^2 / (8 \times 27 \times 195312500)$$
$$= - 24.26 \text{ mm}$$

Deflection due to self weight of slab (δ_{sw})

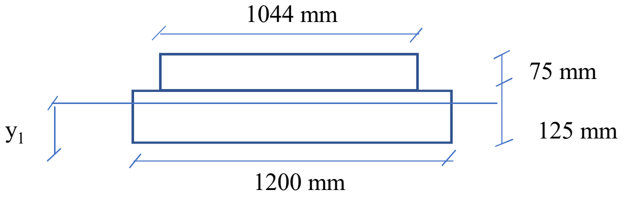
$$\delta_{sw} = 5\, w\, L^4 / 384\, E_{ci}\, I$$

$$= 5 \times 3.6 \times 10^{-3} \times 7650^4 / (384 \times 27 \times 195312500)$$
$$= 30.4 \text{ mm}$$

Net deflection = -24.26 + 30.4
= 6.14 mm (At transfer condition)

Ref	Calculations	Output

Ultimate limit state flexure design (With 6 strands)

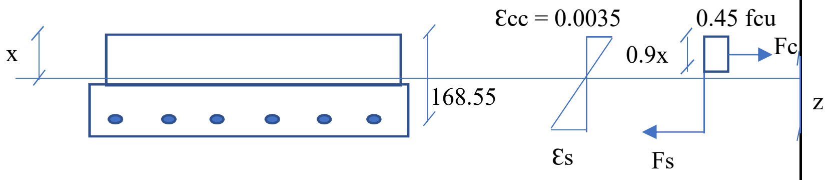


Area of section , A $= 228300\ \text{mm}^2$

I $= \{(1044 \times 200^3) / 12 + (156 \times 125^3) / 12\} \quad = 720414062.5\ \text{mm}^4$

y $= 96.8$ mm mm

e $= 96.8 - (25 + 12.9/2) \quad = 65.35$ mm



Characteristic strength of high strength strands $= 1860\ \text{N/mm}^2$

$0.8\, f_{pu} / y_m \quad = 0.8 \times 1860 / 1.15$

$= 1293.9\ \text{N/mm}^2$

$f_{pu} / y_m \quad = 1860 / 1.15$

$= 1617.4\ \text{N/mm}^2$

The stress strain curve for prestressing strands is shown in figure 4.3

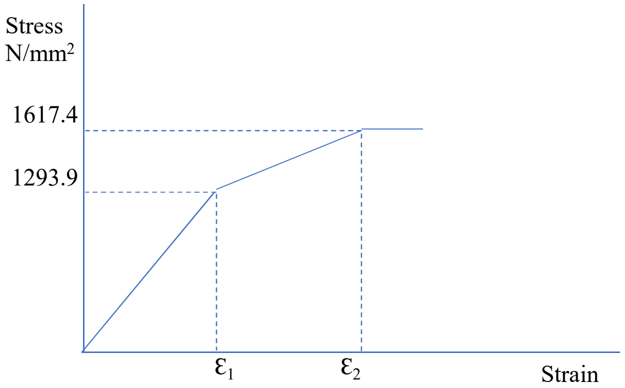


Figure A.3 - Stress strain curve for the prestressing strands

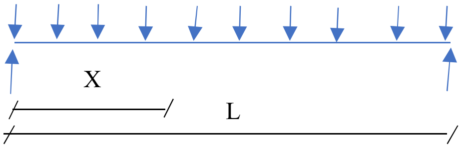
Ref	Calculations	Output
	ε_1 = 1293.9 / 200 x 10^3 = 0.0062 ε_2 = 0.0062 + 1617.4 / (200 x 10^3) = 0.0143 Stress in the strands after losses = 93.75 x 1000/100 = 967.5 N/mm^2 Strain in the strands after losses = 937.5 / 200 x 10^3 due to prestress force = 0.0047 < ε1 Ultimate moment of resistance, Mu = Fc. Z = Fs. Z Final strain in strands = prestress strain + Bending strain εs = ε1 + ε's = 0.0047 + {(168.55 - x) / x} . εcc = 0.0047 + {(168.55 - x) / x} 0.0035 Assume x = 45.7 mm εs = 0.0047 + {(168.55 - 45.7) / 45.7} x 0.0035 = 0.0141 Stress in strands = 1293.9 + {(1617.4 - 1293.9)/(0.0143 - 0.0062)}x(0.011 - 0.0062) = 1609.8 N/mm^2 < 1617.4 N/mm^2 Therefore the strands are not yielded Force in strands, Fs = 6 x 100 x 1609.8 = 965.9 kN Therefore force in concrete, Fc = 0.45 f_{cu} b (0.9x) = 0.45 x 50 x 1044 x (0.9 x 45.7) = 966.1 kN Therefore, Fc ≈ Fs Ultimate moment of resistance, M_{ur} = Fs x (d - 0.45x) = 965.9 x (168.55 - 0.45x45.7)/1000 = 142.9 kNm Moment at ultimate limit stage, M_{max} = {1.4 x (3.6 + 2.16 + 2.64) + (1.6 x 1.8)} x 7.65^2 / 8 = 107.1 kNm < M_{ur} = 142.9 kNm Therefore ultimate limit state flexural capacity is adequate.	

Ref	Calculations	Output
	Ultimate limit state shear design (With 6 strands)	
	Section uncracked in flexure	
CL 4.3.8.4	Maximum principal design tensile stress, f_t $= 0.24 (f_{cu})^{0.5}$	
BS8110:Part 1: 1985	$= 0.24 (50)^{0.5}$	
	$= 1.69$ N/mm^2	
	Design compressive stress at the centroidal axis $= Pe / A$	
	due to prestress, f_{cp} $= 562.5 \times 1000 / 228300$	
	$= 2.46$ N/mm^2	
	Design ultimate shear resistance of the section $= 0.67 b_v h \{ f_t^2 + 0.8 f_{cp} f_t \}^{0.5}$	
	V_{co} $= 0.67 \times 1044 \times 168.55 \times \{ 1.69^2 + (0.8 \times 2.46 \times 1.69)$	
	= 293.1 kN	
	Section cracked in flexure	
CL 4.3.8.5	Design ultimate shear resistance of the section, V_{cr} $> 0.1 b d (f_{cu})^{0.5}$	
BS8110:Part 1: 1985		
	$0.1 b d (f_{cu})^{0.5}$ $= 0.1 \times 1044 \times 168.55 \times (50)^{0.5}$	
	= 124.4 kN	
	Vcr $= \{(1 - 0.55 f_{pe} / f_{pu}) v_c b d +(M_0 V/M) \}$	
	f_{pe} / f_{pu} $= 937.5 / 1860 = 0.504$	
	100 A_s / bd $= 100 \times (6 \times 100) / (1044 \times 168.55)$	
	= 0.34	
Table 3.9	v_c $= 0.54 (50/25)^{(1/3)}$	
BS8110:Part 1: 1985	$= 0.68$ N/mm^2	
	f_{pt} $= P_e \{ 1/A + e y_b / I \}$	
	$= 562.5 \times 10^3 \{ (1/ 228300) + (65.35 \times 96.8 / 720414062.5) \}$	
	$= 7.4$ N/mm^2	
	M_0 $= 0.8 f_{pt} Z_1$	
	$= 0.8 \times 7.4 \times 7.44 \times 10^6$	
	= 40.04 kNm	
	Vcr $= \{(1 - 0.55 f_{pe} / f_{pu}) v_c b d +(M_0 V/M) \}$	
	$= \{(1 - 0.55 \times 0.504) \times 0.68 \times 1044 \times 168.55/ 1000 + (40.04 V/M)\}$	
	$= 86.4 + 40.04 V/M$	

Ref	Calculations	Output

Uniformly distributed load at ultimate limit state $= \{1.4 \times (3.6 + 2.16 + 2.64) + (1.6 \times 1.8)\}$

$W = 14.64$ kN/m



$Mx = WLX - WX^2$

$Vx = WL/2 - WX$

$Vx / Mx = (L - 2X) / (LX - X^2)$

CL 4.3.8.2
BS8110:Part 1: 1985

$V_{max} = WL/2$
$= (14.64 \times 7.65) / 2$
$= 56.0$ kN

$v_{max} = 56.0 \times 1000 / (1044 \times 168.55)$
$= 0.318$ N/mm^2

$0.8 (fcu)^{0.5} = 0.8 \times (50)^{0.5}$
$= 5.65$ N/mm^2 $>$ v_{max} OK

The ultimate shear capacity of uncracked section, ultimate shear capacity cracked section, Critical shear capacity and shear force along the slab is given in the table 4.1

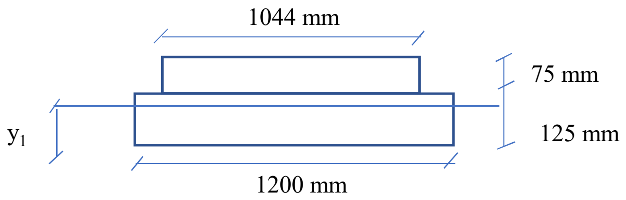
Table A.1 - Summary of shear capacities and shear force at ultimate limit state

X (m)	V_{co} (kN)	V_{cr} (kN)	V_c (kN)	V (kN)	
0.25	293.10	241.15	241.15	52.34	$V < 0.5\ V_c$
0.5	293.10	160.88	160.88	48.68	$V < 0.5\ V_c$
1	293.10	124.42	124.42	41.36	$V < 0.5\ V_c$
2	293.10	124.42	124.42	26.72	$V < 0.5\ V_c$
3	293.10	124.42	124.42	12.08	$V < 0.5\ V_c$
3.825	293.10	124.42	124.42	0.00	$V < 0.5\ V_c$

Therefore no need to provide shear reinforcement.
Shear capacity at ultimate limit state is satisfactory.

Ref	Calculations	Output

Ultimate limit state flexure design (With 5 strands)

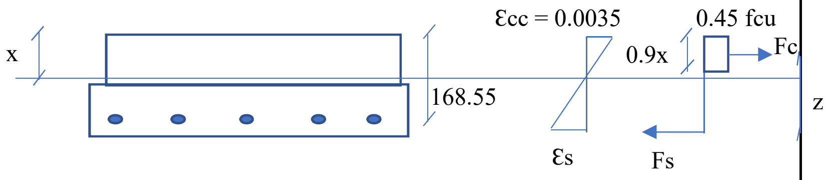


Area of section , A $= 228300\ \text{mm}^2$

I $= \{(1044 \text{ x } 200^3) / 12 + (156 \text{ x } 125^3) / 12\} = 720414062.5\ \text{mm}^4$

y $= 96.8$ mm mm

e $= 96.8 - (25 + 12.9/2) = 65.35$ mm



Characteristic strength of high strength strands $= 1860\ \text{N/mm}^2$

$0.8\ f_{pu} / \gamma_m = 0.8 \text{ x } 1860 / 1.15$

$= 1293.9\ \text{N/mm}^2$

$f_{pu} / \gamma_m = 1860 / 1.15$

$= 1617.4\ \text{N/mm}^2$

The stress strain curve for prestressing strands is shown in figure 4.3

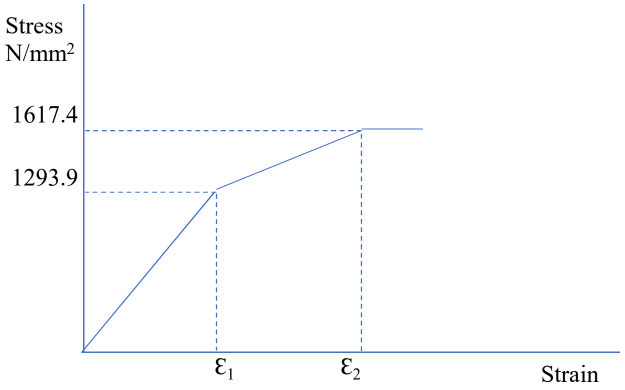


Figure A.4 - Stress strain curve for the prestressing strands

Ref	Calculations	Output

$\varepsilon_1 = 1293.9 / 200 \times 10^3 = 0.0062$

$\varepsilon_2 = 0.0062 + 1617.4 / (200 \times 10^3) = 0.0143$

Stress in the strands after losses $= 93.75 \times 1000/100$

$= 967.5\ \text{N/mm}^2$

Strain in the strands after losses $= 937.5 / 200 \times 10^3$

due to prestress force $= 0.0047 < \varepsilon 1$

Ultimate moment of resistance, Mu = Fc. Z = Fs. Z

Final strain in strands = prestress strain + Bending strain

$\varepsilon s = \varepsilon 1 + \varepsilon' s$

$= 0.0047 + \{(168.55 - x) / x\} \,.\, \varepsilon cc$

$= 0.0047 + \{(168.55 - x) / x\}\ 0.0035$

Assume x = 39.85 mm $\quad \varepsilon s = 0.0047 + \{(168.55 - 39.85) / 39.85\} \times 0.0035$

$= 0.016 > 0.0143$

Therefore the strands are yielded

Stress in strands $= 1617.4\ \text{N/mm}^2$

Therefore the strands are not yielded

Force in strands, Fs $= 5 \times 100 \times 1617.4$

$= 808.7$ kN

Therefore force in concrete, Fc $= 0.45\, f_{cu}\, b\, (0.9x)$

$= 0.45 \times 50 \times 1044 \times (0.9\, X)$

Therefore $\quad X = 38.25$ kN

Ultimate moment of resistance, $M_{ur} = Fs \times (d - 0.45x)$

$= 808.7 \times (168.55 - 0.45 \times 38.25)/1000$

$= 122.4$ kNm

Moment at ultimate limit stage, $M_{max} = \{1.4 \times (3.6 + 2.16 + 2.64) + (1.6 \times 1.8)\} \times 7.65^2 / 8$

$= 107.1\ \text{kNm} \quad < M_{ur} = 122.4\ \text{kNm}$

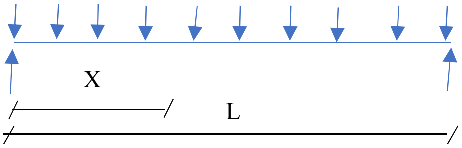
Therefore ultimate limit state flexural capacity is adequate.

Ref	Calculations	Output
	Ultimate limit state shear design (With 5 strands)	
	Section uncracked in flexure	
CL 4.3.8.4 BS8110:Part 1: 1985	Maximum principal design tensile stress, f_t $= 0.24 (f_{cu})^{0.5}$ $= 0.24 (50)^{0.5}$ $= 1.69 \text{ N/mm}^2$	
	Design compressive stress at the centroidal axis due to prestress, f_{cp} $= Pe / A$ $= 468.75 \times 1000 / 228300$ $= 2.05 \text{ N/mm}^2$	
	Design ultimate shear resistance of the section V_{co} $= 0.67\ b_v\ h\ \{ f_t^2 + 0.8\ f_{cp}\ f_t \}^{0.5}$ $= 0.67 \times 1044 \times 168.55 \times \{ 1.69^2 + (0.8 \times 2.05 \times 1.69)$ $= 279.7 \text{ kN}$	
	Section cracked in flexure	
CL 4.3.8.5 BS8110:Part 1: 1985	Design ultimate shear resistance of the section, V_{cr} $> 0.1\ b\ d\ (f_{cu})^{0.5}$	
	$0.1\ b\ d\ (f_{cu})^{0.5} = 0.1 \times 1044 \times 168.55 \times (50)^{0.5}$ $= 124.4 \text{ kN}$	
	$Vcr = \{(1 - 0.55\ f_{pe} / f_{pu})\ v_c\ b\ d + (M_0 V/M) \}$	
	$f_{pe} / f_{pu} = 937.5 / 1860 = 0.504$	
	$100\ A_s / bd = 100 \times (5 \times 100) / (1044 \times 168.55)$ $= 0.28$	
Table 3.9 BS8110:Part 1: 1985	$v_c = 0.59 (50/25)^{(1/3)}$ $= 0.62 \text{ N/mm}^2$	
	$f_{pt} = P_e \{ 1/A + e\ y_b / I \}$ $= 468.75 \times 10^3 \{ (1/ 228300) + (65.35 \times 96.8 / 720414062.5) \}$ $= 6.17 \text{ N/mm}^2$	
	$M_0 = 0.8\ f_{pt}\ Z_1$ $= 0.8 \times 6.17 \times 7.44 \times 10^6$ $= 36.72 \text{ kNm}$	
	$Vcr = \{(1 - 0.55\ f_{pe} / f_{pu})\ v_c\ b\ d + (M_0 V/M) \}$ $= \{(1 - 0.55 \times 0.504) \times 0.62 \times 1044 \times 168.55/ 1000 + (36.72\ V/M)\}$ $= 78.8 + 36.72\ V/M$	

Ref	Calculations	Output

Uniformly distributed load at ultimate limit state $= \{1.4 \times (3.6 + 2.16 + 2.64) + (1.6 \times 1.8)\}$

W $= 14.64$ kN/m



$M_x = WLX - WX^2$

$V_x = WL/2 - WX$

$V_x / M_x = (L - 2X) / (LX - X^2)$

CL 4.3.8.2
BS8110:Part 1: 1985

$V_{max} = WL/2$
$= (14.64 \times 7.65) / 2$
$= 56.0$ kN

$v_{max} = 56.0 \times 1000 / (1044 \times 168.55)$
$= 0.318$ N/mm^2

$0.8 (f_{cu})^{0.5} = 0.8 \times (50)^{0.5}$
$= 5.65$ N/mm^2 $>$ v_{max} OK

The ultimate shear capacity of uncracked section, ultimate shear capacity cracked section, Critical shear capacity and shear force along the slab is given in the table 4.1

Table A.2 - Summary of shear capacities and shear force at ultimate limit state

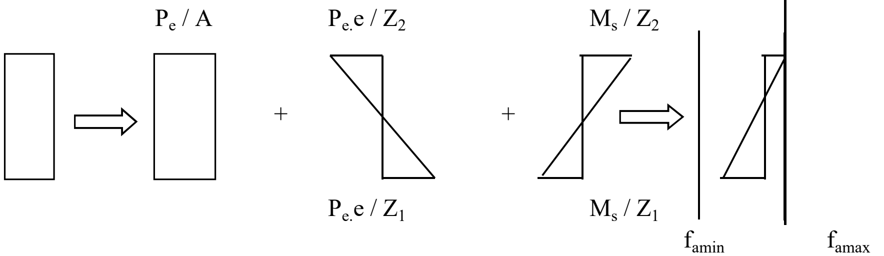
X (m)	V_{co} (kN)	V_{cr} (kN)	V_c (kN)	V (kN)	
0.25	279.70	220.72	220.72	52.34	$V < 0.5 V_c$
0.5	279.70	147.10	147.10	48.68	$V < 0.5 V_c$
1	279.70	124.42	124.42	41.36	$V < 0.5 V_c$
2	279.70	124.42	124.42	26.72	$V < 0.5 V_c$
3	279.70	124.42	124.42	12.08	$V < 0.5 V_c$
3.825	279.70	124.42	124.42	0.00	$V < 0.5 V_c$

Therefore no need to provide shear reinforcement.
Shear capacity at ultimate limit state is satisfactory.

Ref	Calculations	Output
	This design was carried out according to British Standards.	
	The initial sizing and material properties are as following.	
	Slab panel length (Span) = 7.65 m	
	Width = 1.2 m	
	Thickness = 125 mm	
	Concrete Grade, C50	
	Thickness of topping = 75 mm	
	Topping Concrete Grade, C30	
	Diameter of High strength strands = 12.9 mm	
	Strength of High strength strands = 1720 N/mm^2	
	Cross section area of High strength strand = 100 mm^2	
CL 4.1.3 BS8110:Part 1: 1985	Class of the slab according to amount of flexural tensile stress	
	Class 2 : Flexural tensile stresses but no visible cracking.	
CL 4.12.3 BS8110:Part 1: 1985	Cover requirement to pre stressing strands	
Table 4.8 BS8110:Part 1: 1985	Minimum cover requirement for moderate condition of exposure = 20 mm (Grade 50 concrete)	
Table 4.9 BS8110:Part 1: 1985	Minimum cover requirement for 1 hour fire resistance = 25 mm	
	Therefore provide 25 mm cover for pre stressed strands	
	<u>Load Evaluation for Transfer Stage and Topping Concrete Placing Stage</u>	
	Self weight of slab panel = 0.125 x 1.2 x 24 = 3.6 kN/m	
	Weight of topping concrete = 0.075 x 1.2 x 24 X (1.0527) (with extra topping concrete weight) = 2.27 kN/m	
	Moment due to self weight of slab, M_o = 3.6 x 7.65^2 / 8 = 26.3 kNm	
	Moment due to self weight and topping concrete, M_{smax} = (3.6 + 2.27) x 7.65^2 / 8 (Stage of placing topping concrete) = 42.9 kNm	
	Sign convension	
	Tension - Negative Compresion - Positive	

Ref	Calculations	Output

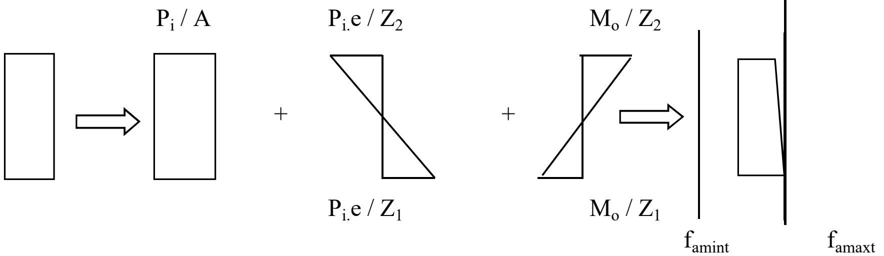
Selection of suitable section



At topping concrete placing stage

$$P_e / A - (P_e.e / Z_2) + M_s / Z_2 \leq f_{amax} \quad \text{——} \quad (A)$$

$$P_e / A + (P_e.e / Z_1) - M_s / Z_1 \geq f_{amin} \quad \text{——} \quad (B)$$



At limiting transfer conditions

$$P_i / A - (P_i.e / Z_2) + M_o / Z_2 \geq f_{amint} \quad \text{——} \quad (C)$$

$$P_i / A + (P_i.e / Z_1) - M_o / Z_1 \leq f_{amaxt} \quad \text{——} \quad (D)$$

Assume loss ratio, $\alpha = 0.8$

$$\alpha = P_e / P_i = 0.8 \quad (P_e = \alpha P_i)$$

$(A) - \alpha (C) \Longrightarrow$

$$(M_s - \alpha M_o) / Z_2 \leq f_{amax} - \alpha f_{amint}$$

$$Z_2 \geq (M_s - \alpha M_o) / (f_{amax} - \alpha f_{amint})$$

$\alpha (D) - (B) \Longrightarrow$

$$(-\alpha M_o + M_s) / Z_1 \leq \alpha f_{amaxt} - f_{amin}$$

$$Z_1 \geq (M_s - \alpha M_o) / (\alpha f_{amaxt} - f_{amin})$$

Ref	Calculations	Output
	Allowable stresses	
	At servisability condition	
	$f_{cu} = 59\ \text{N/mm}^2$	
CL4.3.4.2 BS8110:Part 1: 1985	$f_{amax} = 0.33\ f_{cu}$ $= 0.33 \times 59 = 19.5\ \text{N/mm}^2$ $f_{amax} = 19.5\ \text{N/mm}^2$	
CL4.3.4.3 BS8110:Part 1: 1985	$f_{amin} = -0.45(f_{cu})^{1/2}$ $= -0.45 \times (59)^{1/2} = -3.45\ \text{N/mm}^2$ $f_{amin} = -3.45\ \text{N/mm}^2$	
	At transfer condition	
	Assume $f_{ci} = 39\ \text{N/mm}^2$	
CL4.3.5.1 BS8110:Part 1: 1985	$f_{amaxt} = 0.5\ f_{ci}$ $= 0.5 \times 39 = 19.5\ \text{N/mm}^2$ $f_{amin} = -3.45\ \text{N/mm}^2$	
CL4.3.5.2 BS8110:Part 1: 1985	$f_{amint} = -0.45(f_{ci})^{1/2}$ $= -0.45 \times (39)^{1/2} = -2.8\ \text{N/mm}^2$ $f_{amint} = -2.8\ \text{N/mm}^2$	
Stages upto topping concrete placing	$\left\{ \begin{array}{l} Z_1 \geq \{(42.9 - 0.9 \times 26.3) \times 10^6\} / \{0.9 \times 19.5 - (-3.45)\} = 0.915 \times 10^6\ \text{mm}^3 \\ Z_2 \geq \{(42.9 - 0.9 \times 26.3) \times 10^6\} / \{19.5 - 0.9 \times (-2.8)\} = 0.833 \times 10^6\ \text{mm}^3 \end{array} \right.$	
	Section properties at transfer condition	
	$I = (1200 \times 125^3) / 12$ $= 195312500\ \text{mm}^4$	
	$Z = I / y$ $= 195312500 / 62.5$ $= 3.125 \times 10^6\ \text{mm}^3$	
	$Z_1 = 3.125 \times 10^6\ \text{mm}^3 > 0.915 \times 10^6\ \text{mm}^3$ $Z_2 = 3.125 \times 10^6\ \text{mm}^3 > 0.832 \times 10^6\ \text{mm}^3$ Therefore selected section is adequate.	
	Magnel diagram (For Transfer stage and Topping concrete placing stage)	
	Area of section , A = 125 x 1200 = 150000 mm^2 $1 / A = 6.67 \times 10^{-6}\ \text{mm}^{-2}$	
	$I = 195312500\ \text{mm}^4$	
	$Z = 3.125 \times 10^6\ \text{mm}^3$	
	$e = 31.1$ mm $y = 62.5$ mm	

Ref	Calculations	Output

From (A) $\Longrightarrow$ $6.67 \times 10^{-6} P_e - \{ P_e.e / 3.125 \times 10^6 \} + \{42.9 \times 10^6 / 3.125 \times 10^6 \} \leq 19.5$

$(1 / P_e) \quad \geq \quad (20.84 - e) / (18.0 \times 10^6)$ —— (01)

From (B) $\Longrightarrow$ $6.67 \times 10^{-6} P_e + \{ P_e.e / 3.125 \times 10^6 \} - \{42.9 \times 10^6 / 3.125 \times 10^6 \} \geq -3.45$

$(1 / P_e) \quad \leq \quad (20.84 + e) / (32.1 \times 10^6)$ —— (02)

From (C) $\Longrightarrow$ $(6.67 \times 10^{-6} P_e / 0.9) - \{ P_e.e / 0.9 \times 3.125 \times 10^6 \} + \{26.3 \times 10^6 / 3.125 \times 10^6 \} \geq -2.8$

$(1 / P_e) \quad \geq \quad (20.84 - e) / (-31.5 \times 10^6)$ —— (03)

From (D) $\Longrightarrow$ $(6.67 \times 10^{-6} P_e / 0.9) + \{ P_e.e / 0.9 \times 3.125 \times 10^6 \} - \{26.3 \times 10^6 / 3.125 \times 10^6 \} \leq 19.5$

$(1 / P_e) \quad \geq \quad (20.84 + e) / (78.5 \times 10^6)$ —— (04)

Then using equation 01,02,03 and 04, the magnel diagram for transfer stage and topping concrete placing stage were plotted on a drafting sheet. The magnel diagram for transfer stage and topping concrete placing stage is shown in the figure 8.1.

Magnel diagram for equation 01 , 02 , 03 and 04.

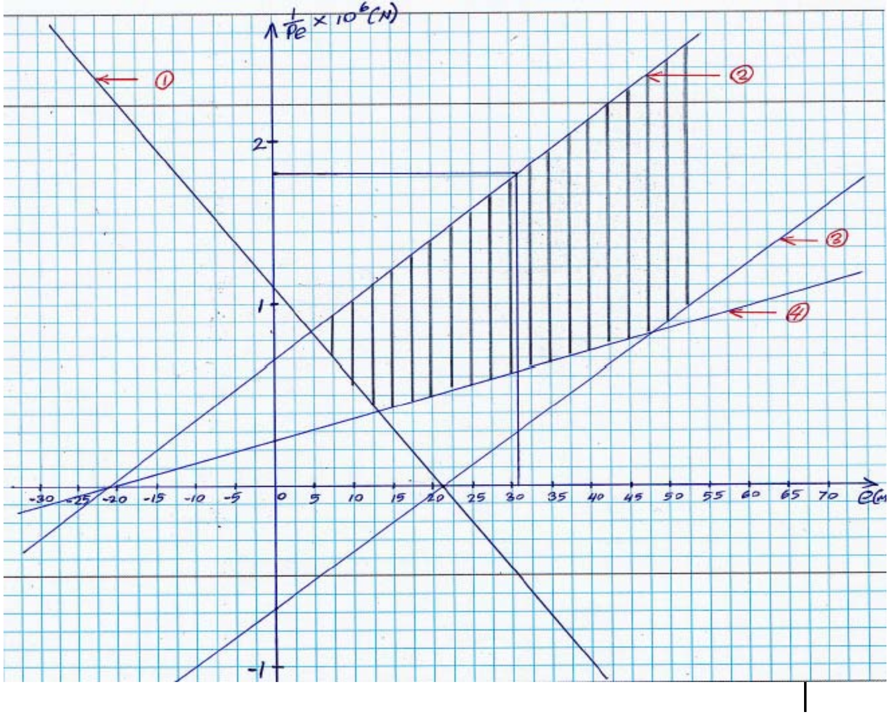


Figure B.1 : Magnel diagram for transfer stage and topping concrete placing stage

Ref	Calculations	Output

Tendon arrangement

Use 12.9 mm diameter high strength strands with characteristic strength of 1720 N/mm^2

Jacking force, P_j (per strand) = 133 kN (Used in the site)

Experimental loss , 7.45% of jacking force

P_i = 0.9255 x 133 = 123.1 kN

α = 0.9213 (Experimental loss ratio)

P_e = 0.9213 x 123.1 = 113.4 kN

Practrical situation, e = {125/2 - (25 + 12.9/2)}
= 31.1 mm

$1 / P_e$ = 1.81×10^{-6} (From magnel diagram)

Total effective force = 552.5 kN

Therefore number of strands needed = 552.5 / 113.4
= 4.87

But provided 6 number of 12.9 mm high strength strands.

Check the panel for service condition (Composite section)

Weight of finishes and partitions = (0.85 + 1.35) x 1.2
= 2.64 kN/m

Imposed load = 1.5 x 1.2
= 1.8 kN/m

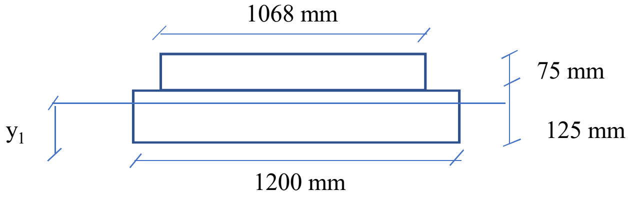
Moment at service stage, M_{smax} = $(3.6 + 2.27 + 2.64 + 1.8) \times 7.65^2 / 8$
= 75.4 kNm

Characteristic strength of Prestressed slab = 59 N/mm^2 (Experimental value)
Elastic modulus of Prestressed slab = 29.1 N/mm^2 (Experimental value)

Characteristic strength of topping concrete = 30 N/mm^2
Elastic modulus of topping concrete = 26 N/mm^2

Elastic modulus of C30 concrete / Elastic modulus of C59 concrete
= 26/29.1 = 0.89

Therefore the effective width of topping concrete layer = 0.89 x 1200 = 1068 mm (equivqlent to characteristic strength of concrete = 59 N/mm^2)



Ref	Calculations	Output

Area of section , A = 230100 mm^2

1 /A = 4.34×10^{-6} mm^{-2}

I = {(1068 x 200^3) / 12 + (132 x 125^3) / 12} = 733484375 mm^4

y = 97.3 mm mm

e = 97.3 - (25 + 12.9/2) = 65.85 mm

Z_2 = I / y_2 = 733484375 / (200 - 97.3) = 7.14×10^6 mm^3

Z_1 = I / y_1 = 733484375 / 97.3 = 7.53×10^6 mm^3

From (A) $\Longrightarrow$ $4.34 \times 10^{-6} P_e - \{ P_e.e / 7.14 \times 10^6\} + \{75.4 \times 10^6 / 7.14 \times 10^6 \} \leq 19.5$

$(1 / P_e) \geq (30.98 - e) / (63.83 \times 10^6)$ —— (05)

From (B) $\Longrightarrow$ $4.34 \times 10^{-6} P_e + \{ P_e.e / 7.53 \times 10^6\} - \{75.4 \times 10^6 / 7.53 \times 10^6 \} \geq -3.45$

$(1 / P_e) \leq (32.68 + e) / (49.42 \times 10^6)$ —— (06)

Then using equation 03,04,05 and 06, the magnel diagram for transfer stage and service stage were plotted on a drafting sheet. The magnel diagram for transfer stage and service stage is shown in the figure 8.2.

Magnel diagram for equation 03 , 04 , 05 and 06.

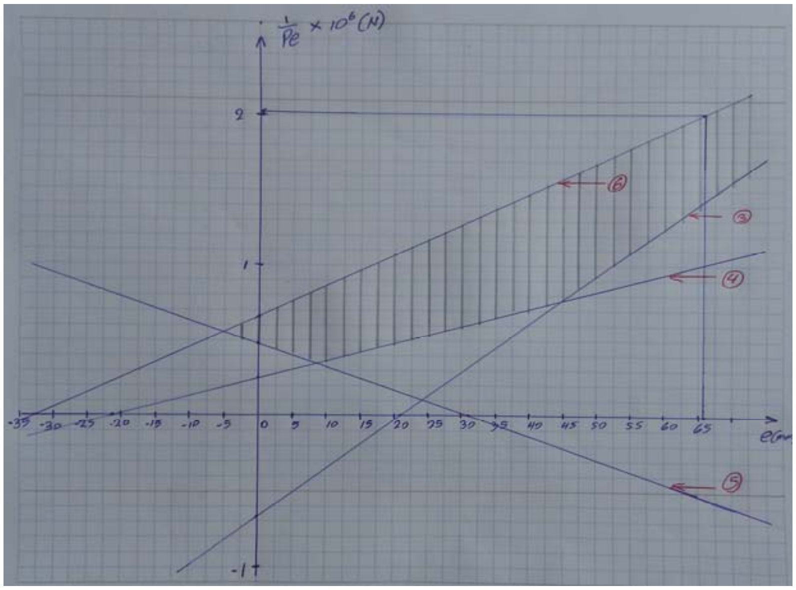


Figure B.2 : Magnel diagram for transfer stage and service stage

For composite section

e = 65.85 mm

$1 / P_e$ = 2.02×10^{-6}

Required P_e = 495.05 kN

Therefore required total effective pre stress force = 495.05 kN

(For composite section)

Provided total effective prestress force = 6 x 113.4

= 680.4 kN

Therefore composite section is adequate

Ref	Calculations	Output
	Prestress losses	
	Short term losses	
CL 4.8.3 BS8110:Part 1: 1985	(01) Elastic shortening of concrete	
	Jacking force is transferred to the neutral axis as following.	
		
	Jacking force , P_j = 133.0 kN (per strand)	
	At level of wires	
	$f_{co} / E_c = \Delta f_{ps} / E_s$	
	$f_{co} = \{ (P_j / A) + (P_j.e^2 / I) - (M_o. e / I) \}$	
	Total P_j = 6 x 133 kN = 798kN	
	At midspan $f_{co} = \{ (798 \times 10^3 / 125 \times 1200) + [798 \times 10^3 \times 31.1^2 /(1200 \times 125^3/12)]$ $- [26.3 \times 10^6 \times 31.1 / (1200 \times 125^3/12)] \}$ = 5.08 N/mm^2	
	At support $f_{co} = \{ (P_j / A) + (P_j.e^2 / I)$ $= \{ (798 \times 10^3 / 125 \times 1200) + [798 \times 10^3 \times 31.1^2 /(1200 \times 125^3/12)]$ = 9.27 N/mm^2	
	Average f_{co} = (5.08 + 9.27)/2 = 7.17 N/mm^2	
	$\Delta f_{ps} = n f_{co}$ $= (E_s / E_c) f_{co}$	
CL 7.2 BS8110:Part 2: 1985	(At transfer) E_{ci} = 20.7 kN/mm^2 (Experimental data)	
	$\Delta f_{ps} = (196.11 / 20.7) \times 7.17 \times 10^{-3}$ = 0.068 kN/mm^2	
	Δp_{se} = 0.068 x 100 x 6 = 40.8 kN	

Ref	Calculations	Output
	Long term losses (01) Steel relaxation	
CL 4.8.2 BS8110:Part 1: 1985	Δp_{sr} = P_j x Relaxation factor x 1000h relaxation test value	
Table 4.6 BS8110:Part 1: 1985	For relaxation class 2 (prestressing), Relaxation factor = 1.2	
CL 4.8.2.2 BS8110:Part 1: 1985	1000h relaxation value = 2.5 %	
	Δp_{sr} = 6 x 133 x 1.2 x 2.5 / 100 = 23.94 kN	
CL 7.2 BS8110:Part 2: 1985	(02) Losses due to creep of concrete	
	Prestress losses due to creep, $\Delta p_{sc} = \phi f_{co} E_s / E_{ci}$	
	E_{ci} = Ko + f_{ci} = 20 + 0.2x59 = 31.8 kN/mm^2	
	Ambient relative humidity = 80% and ϕ = 0.8 E_s = 196.11 kN/mm^2 f_{co} = 7.17 N/mm^2	
	Δp_{sc} = (0.8 x 7.17 x 10^{-3} x 196.11 / 31.8) x 10^3 x 100 x 6 = 21.2 kN	
CL 4.8.4 BS8110:Part 1: 1985	(03) Losses due to shrinkage	
	Stress due to shrinkage of concrete = kE_s	
	Skrinkage strain (k) = 300 x 10^{-6} (For indoor exposure condition)	
	Therefore prestress loss due to shrinkage	
	Δp_{ss} = 300 x 10^{-6} x 196.11 x 10^3 x 6 x 100 = 35.3 kN	
	Total long term losses = $\Delta p_{sr} + \Delta p_{sc} + \Delta p_{ss}$ = 23.94 + 21.2 + 35.3 = 80.44 kN	
	Initial force (P_i) = P_j - short term losses = 798 - 40.8 = 757.2 kN	
	Effective force (P_e) = P_i - long term losses = 757.2 - 80.44 = 676.76 kN	
	Actual loss ratio = (676.76 / 757.2) X 100 = 89.4 %	

Ref	Calculations	Output

Assumed α < α actual

Therefore prestress plank is adequate for considered loading.

Deflection check

P_e = 680.4 kN

E_{ci} = 20.7 kN/mm^2

I = 195312500 mm^4 (At transfer)

Deflection due to pre stress (δ_{ps})

δ_{ps} = - P_e e L^2 / 8E_{ci} I

= - 680.4 x 31.1 x 7650^2 / (8 x 20.7 x 195312500)
= - 38.3 mm

Deflection due to self weight of slab (δ_{sw})

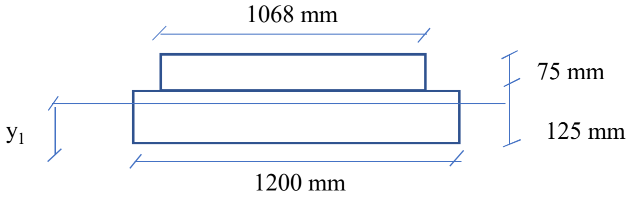
δ_{sw} = 5 w L^4 / 384 E_{ci} I

= 5 x 3.6 x 10^{-3} x 7650^4 / (384 x 20.7 x 195312500)
= 39.7 mm

Net deflection = -38.3 + 39.7
= 1.4 mm (At transfer condition)

Ref	Calculations	Output

Ultimate limit state flexure design

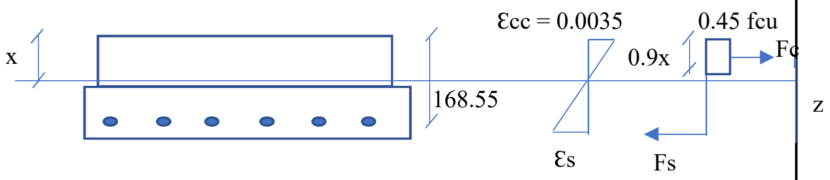


Area of section , A = 230100 mm^2

I = {(1068 x 200^3) / 12 + (132 x 125^3) / 12} = 733484375 mm^4

y = 97.3 mm mm

e = 97.3 - (25 + 12.9/2) = 65.85 mm



Characteristic strength of high strength strands = 1720 N/mm^2

$0.8\ f_{pu} / \gamma_m$ = 0.8 x 1720 / 1.15
= 1196.5 N/mm^2

f_{pu} / γ_m = 1720 / 1.15
= 1495.6 N/mm^2

The stress strain curve for prestressing strands is shown in figure 8.3

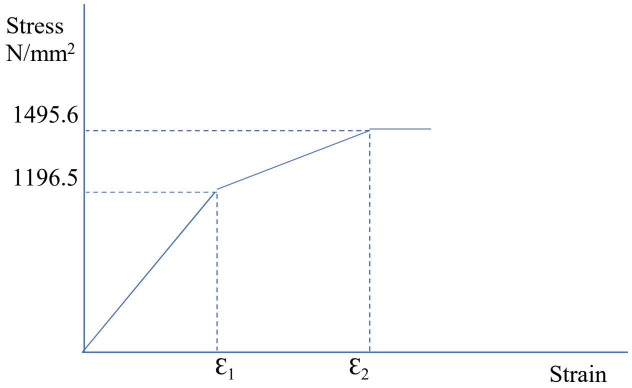


Figure B.3 - Stress strain curve for the prestressing strands

Ref	Calculations	Output

ε_1 = 1196.5 / 196.11 x 10^3 = 0.0061
ε_2 = 0.0061 + 1495.6 / (196.11x 10^3) = 0.0137

Stress in the strands after losses = 113.4 x 1000/100
= 1134.0 N/mm^2

Strain in the strands after losses = 1134.0 / 196.11 x 10^3
due to prestress force = 0.0058 < ε1

Ultimate moment of resistance, Mu = Fc. Z = Fs. Z

Final strain in strands = prestress strain + Bending strain
εs = ε1 + ε's
= 0.0058 + {(168.55 - x) / x} . εcc
= 0.0058 + {(168.55 - x) / x} 0.0035

Assume x = 45.7 mm εs = 0.0058 + {(168.55 - 45.7) / 45.7} x 0.0035
= 0.0175

Stress in strands = 1196.5 + {(1495.6 - 1196.5)/(0.0137 - 0.0061)}x(0.011 - 0.006
= 1646.9 N/mm^2 > 1495.6 N/mm^2

Therefore the strands yielded
Therefore x should be less than assumed value (x < 45.7 mm)

Force in strands, Fs = 6 x 100 x 1495.6
(Strands yielded condition) = 897.4 kN

Therefore force in concrete, Fc = 897.4 kN
= 0.45 f_{cu} b (0.9x)
897.4 = 0.45 x 59 x 1068 x (0.9 x)
Therefore, x = 35.2 mm < 45.7 mm

Ultimate moment of resistance, M_{ur} = Fs x (d - 0.45x)
= 897.4 x (168.55 - 0.45x35.2)/1000
= 137.0 kNm

Moment at ultimate limit stage, M_{max} = {1.4 x (3.6 + 2.27 + 2.64) + (1.6 x 1.8)} x 7.65^2 /
= 108.22 kNm < M_{ur} = 137.0 kNm

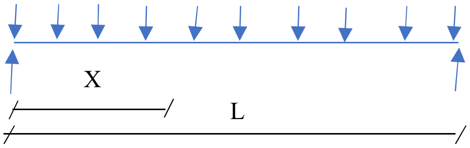
Therefore ultimate limit state flexural capacity is adequate.

Ref	Calculations	Output
	Ultimate limit state shear design	
	Section uncracked in flexure	
CL 4.3.8.4	Maximum principal design tensile stress, f_t $= 0.24 (f_{cu})^{0.5}$	
BS8110:Part 1: 1985	$= 0.24 (59)^{0.5}$	
	$= 1.84$ N/mm^2	
	Design compressive stress at the centroidal axis $= Pe / A$	
	due to prestress, f_{cp} $= 680.4 \times 1000 / 230100$	
	$= 2.95$ N/mm^2	
	Design ultimate shear resistance of the section $= 0.67 b_v h \{ f_t^2 + 0.8 f_{cp} f_t \}^{0.5}$	
	V_{co} $= 0.67 \times 1068 \times 168.55 \times \{ 1.84^2 + (0.8 \times 2.95 \times 1.84$	
	$= 335.28$ kN	
	Section cracked in flexure	
CL 4.3.8.5	Design ultimate shear resistance of the section, $V_{cr} > 0.1 b d (f_{cu})^{0.5}$	
BS8110:Part 1: 1985		
	$0.1 b d (f_{cu})^{0.5} = 0.1 \times 1068 \times 168.55 \times (59)^{0.5}$	
	$= 138.26$ kN	
	Vcr $= \{(1 - 0.55 f_{pe} / f_{pu}) v_c b d +(M_0 V/M) \}$	
	f_{pe} / f_{pu} $= 1134 / 1720 \quad = 0.66$	
	$100 A_s / bd$ $= 100 \times (6 \times 100) / (1068 \times 168.55)$	
	$= 0.33$	
Table 3.9	v_c $= 0.53 (50/25)^{(1/3)}$	
BS8110:Part 1: 1985	$= 0.67$ N/mm^2	
	f_{pt} $= P_e \{ 1/A + e y_b / I \}$	
	$= 680.4 \times 10^3 \{ (1/ 230100) + (65.85 \times 97.3 / 733484375) \}$	
	$= 8.9$ N/mm^2	
	M_0 $= 0.8 f_{pt} Z_1$	
	$= 0.8 \times 8.9 \times 7.53 \times 10^6$	
	$= 53.6$ kNm	
	Vcr $= \{(1 - 0.55 f_{pe} / f_{pu}) v_c b d +(M_0 V/M) \}$	
	$= \{(1 - 0.55 \times 0.66) \times 0.67 \times 1068 \times 168.55/ 1000 + (53.6 V/M)\}$	
	$= 76.8 + 53.6 V/M$	

Ref	Calculations	Output

Uniformly distributed load at ultimate limit state $= \{1.4 \times (3.6 + 2.27 + 2.64) + (1.6 \times 1.8)\}$

W $= 14.79$ kN/m



$$M_x = WLX - WX^2$$

$$V_x = WL/2 - WX$$

$$V_x / M_x = (L - 2X) / (LX - X^2)$$

CL 4.3.8.2
BS8110:Part 1: 1985

$$V_{max} = WL/2$$
$$= (14.79 \times 7.65) / 2$$
$$= 56.57 \text{ kN}$$

$$v_{max} = 56.57 \times 1000 / (1068 \times 168.55)$$
$$= 0.314 \text{ N/mm}^2$$

$$0.8\,(f_{cu})^{0.5} = 0.8 \times (59)^{0.5}$$
$$= 6.14 \text{ N/mm}^2 \quad > \quad v_{max} \quad \text{OK}$$

The ultimate shear capacity of uncracked section, ultimate shear capacity cracked section, Critical shear capacity and shear force along the slab is given in the table 8.1

Table B.1 - Summary of shear capacities and shear force at ultimate limit state

X (m)	V_{co} (kN)	V_{cr} (kN)	V_c (kN)	V (kN)	
0.25	335.28	283.96	283.96	52.87	$V < 0.5\, V_c$
0.5	335.28	176.50	176.50	49.18	$V < 0.5\, V_c$
1	335.28	138.26	138.26	41.78	$V < 0.5\, V_c$
2	335.28	138.26	138.26	26.99	$V < 0.5\, V_c$
3	335.28	138.26	138.26	12.20	$V < 0.5\, V_c$
3.825	335.28	138.26	138.26	0.00	$V < 0.5\, V_c$

Therefore no need to provide shear reinforcement.
Shear capacity at ultimate limit state is satisfactory.

ANNEXURE C: LABORATORY TEST RESULTS

Table C1 – Readings obtained for strand Sample 01

Load (kN)	Elongation (mm)	Stress (N/mm^2)	Strain
0	0.000	0	0
-0.1	0.000	-1	0
0.2	0.005	2	0.00001
1.7	0.042	17	0.00008
3.1	0.077	31	0.00015
4.6	0.114	46	0.00023
5.95	0.147	59.5	0.00029
6.9	0.171	69	0.00034
7.7	0.191	77	0.00038
8.05	0.199	80.5	0.00040
8.4	0.208	84	0.00042
8.65	0.214	86.5	0.00043
9.4	0.233	94	0.00047
9.8	0.242	98	0.00048
10.4	0.257	104	0.00051
11.3	0.279	113	0.00056
10	0.247	100	0.00049
12.3	0.315	123	0.00063
13.9	0.356	139	0.00071
15.35	0.394	153.5	0.00079
16.75	0.429	167.5	0.00086
18.05	0.463	180.5	0.00093
19.25	0.494	192.5	0.00099
20.45	0.524	204.5	0.00105
21.7	0.556	217	0.00111
24.2	0.621	242	0.00124
26.95	0.691	269.5	0.00138
29.85	0.765	298.5	0.00153
33.05	0.847	330.5	0.00169
36.25	0.929	362.5	0.00186
39.55	1.014	395.5	0.00203
40.6	1.041	406	0.00208
45.85	1.176	458.5	0.00235
50.1	1.240	501	0.00248
54.15	1.340	541.5	0.00268
58.1	1.438	581	0.00288
62.1	1.537	621	0.00307
60.2	1.490	602	0.00298
66.9	1.656	669	0.00331
72.55	1.796	725.5	0.00359
77.85	1.927	778.5	0.00385
83	2.054	830	0.00411

Load (kN)	**Elongation (mm)**	**Stress (N/mm^2)**	**Strain**
88.05	2.179	880.5	0.00436
93	2.302	930	0.00460
97.9	2.448	979	0.00490
102.7	2.568	1027	0.00514
104.35	2.609	1043.5	0.00522
110.75	2.840	1107.5	0.00568
116.45	2.971	1164.5	0.00594
121.75	3.090	1217.5	0.00618
126.85	3.203	1268.5	0.00641
131.75	3.327	1317.5	0.00665
136.4	3.444	1364	0.00689
137.6	3.475	1376	0.00695
143.75	3.686	1437.5	0.00737
148.4	3.805	1484	0.00761
152.4	3.908	1524	0.00782
155.9	4.018	1559	0.00804
158.8	4.114	1588	0.00823
160.1	4.169	1601	0.00834
163.7	4.285	1637	0.00857
166.35	4.378	1663.5	0.00876
168.3	4.476	1683	0.00895
169.5	4.556	1695	0.00911
172.15	4.653	1721.5	0.00931
174	4.703	1740	0.00941
175.35	4.871	1753.5	0.00974
175.9	4.886	1759	0.00977
43.75	1.215	437.5	0.00243

Table AC – Readings obtained for strand Sample 02

Load (kN)	Elongation (mm)	Stress (N/mm^2)	Strain
0	0	0	0
1.05	0.028	10.5	0.00006
5	0.132	50	0.00026
8.35	0.220	83.5	0.00044
10.1	0.266	101	0.00053
11.95	0.314	119.5	0.00063
14.95	0.396	149.5	0.00079
18.7	0.495	187	0.00099
23.2	0.614	232	0.00123
27.9	0.742	279	0.00148
32.75	0.866	327.5	0.00173
37.7	0.997	377	0.00199
42.9	1.141	429	0.00228
48.35	1.293	483.5	0.00259
51.75	1.362	517.5	0.00272
59.2	1.574	592	0.00315
65.55	1.725	655.5	0.00345
71.85	1.911	718.5	0.00382
78	2.086	780	0.00417
84.2	2.239	842	0.00448
90.35	2.416	903.5	0.00483
96.55	2.547	965.5	0.00509
99.15	2.637	991.5	0.00527
106.65	2.852	1066.5	0.00570
113.9	2.997	1139	0.00599
120.85	3.180	1208.5	0.00636
127.6	3.358	1276	0.00672
133.8	3.559	1338	0.00712
137.8	3.684	1378	0.00737
139.2	3.762	1392	0.00752
145.5	3.954	1455	0.00791
150.65	4.139	1506.5	0.00828
153.05	4.228	1530.5	0.00846

Load (kN)	**Elongation (mm)**	**Stress (N/mm^2)**	**Strain**
158.05	4.366	1580.5	0.00873
161.3	4.481	1613	0.00896
164.75	4.602	1647.5	0.00920
166.75	4.710	1667.5	0.00942
166.95	4.716	1669.5	0.00943

Table C3 – Readings obtained for Concrete Cylinder Sample 01 (at 2 days of age, Transfer stage)

Dial gauge reading	Load (kN)	Stress (N/mm^2)	Strain
0	0	0.00	0.0000
1	20	1.13	0.0000
2	40	2.26	0.0001
4	60	3.40	0.0001
5	80	4.53	0.0002
6	100	5.66	0.0002
8	120	6.79	0.0003
12	140	7.92	0.0004
14	160	9.05	0.0005
15	180	10.19	0.0005
16	200	11.32	0.0005
17	220	12.45	0.0006
19	240	13.58	0.0006
21	260	14.71	0.0007
23	280	15.84	0.0008
26	300	16.98	0.0009
28	320	18.11	0.0009
31	340	19.24	0.0010
33	360	20.37	0.0011
35	380	21.50	0.0012
37	400	22.64	0.0012
41	420	23.77	0.0014
45	440	24.90	0.0015
49	460	26.03	0.0016
54	480	27.16	0.0018
60	500	28.29	0.0020
67	520	29.43	0.0022
80	540	30.56	0.0027
87	540.3	30.57	0.0029

Table C4 – Readings obtained for Concrete Cylinder Sample 02 (at 2 days of age, Transfer stage)

Dial gauge reading	Load (kN)	Stress (N/mm^2)	Strain
0	0	0.00	0.0000
1	20	1.13	0.0000
2	40	2.26	0.0001
3	60	3.40	0.0001
5	80	4.53	0.0002
7	100	5.66	0.0002
10	120	6.79	0.0003
10	140	7.92	0.0003
11	160	9.05	0.0004
13	180	10.19	0.0004
14	200	11.32	0.0005
16	220	12.45	0.0005
18	240	13.58	0.0006
20	260	14.71	0.0007
22	280	15.84	0.0007
24	300	16.98	0.0008
27	320	18.11	0.0009
29	340	19.24	0.0010
31	360	20.37	0.0010
33	380	21.50	0.0011
36	400	22.64	0.0012
38	420	23.77	0.0013
41	440	24.90	0.0014
44	460	26.03	0.0015
48	480	27.16	0.0016
51	500	28.29	0.0017
55	520	29.43	0.0018
60	540	30.56	0.0020
63	560	31.69	0.0021
68	580	32.82	0.0023
	582.8	32.98	0.0000

Table C5 – Readings obtained for Concrete Cylinder Sample 03 (at 2 days of age, Transfer stage)

Dial gauge reading	Load (kN)	Stress (N/mm^2)	Strain
0	0	0.00	0.0000
1	20	1.13	0.0000
2	40	2.26	0.0001
3	60	3.40	0.0001
5	80	4.53	0.0002
6	100	5.66	0.0002
8	120	6.79	0.0003
9	140	7.92	0.0003
10	160	9.05	0.0003
12	180	10.19	0.0004
13	200	11.32	0.0004
15	220	12.45	0.0005
17	240	13.58	0.0006
19	260	14.71	0.0006
21	280	15.84	0.0007
23	300	16.98	0.0008
25	320	18.11	0.0008
28	340	19.24	0.0009
30	360	20.37	0.0010
33	380	21.50	0.0011
37	400	22.64	0.0012
40	420	23.77	0.0013
42	440	24.90	0.0014
44	460	26.03	0.0015
48	480	27.16	0.0016
	487.9	27.61	0.0000

Table C6 – Readings obtained for Concrete Cylinder Sample 04 (at 2 days of age, Transfer stage)

Dial gauge reading	Load (kN)	Stress (N/mm^2)	Strain
0	0	0.00	0.0000
1	20	1.13	0.0000
3	40	2.26	0.0001
4	60	3.40	0.0001
6	80	4.53	0.0002
7	100	5.66	0.0002
10	120	6.79	0.0003
11	140	7.92	0.0004
12	160	9.05	0.0004
13	180	10.19	0.0004
15	200	11.32	0.0005
17	220	12.45	0.0006
18	240	13.58	0.0006
21	260	14.71	0.0007
23	280	15.84	0.0008
25	300	16.98	0.0008
27	320	18.11	0.0009
29	340	19.24	0.0010
32	360	20.37	0.0011
33	380	21.50	0.0011
39	400	22.64	0.0013
41	420	23.77	0.0014
45	440	24.90	0.0015
49	460	26.03	0.0016
53	480	27.16	0.0018
57	500	28.29	0.0019
61	520	29.43	0.0020
67	540	30.56	0.0022
75	560	31.69	0.0025
85	580	32.82	0.0028
	586.9	33.21	0.0000

Table C7 – Readings obtained for Concrete Cylinder Sample 05 (at 28 days of age)

Dial gauge reading	Load (kN)	Stress (N/mm^2)	Strain
0	0	0.00	0.0000
1	20	1.13	0.0000
2	40	2.26	0.0001
3	60	3.40	0.0001
5	80	4.53	0.0002
6	100	5.66	0.0002
7	120	6.79	0.0002
8	140	7.92	0.0003
9	160	9.05	0.0003
10	180	10.19	0.0003
11	200	11.32	0.0004
13	220	12.45	0.0004
15	240	13.58	0.0005
16	260	14.71	0.0005
17	280	15.84	0.0006
19	300	16.98	0.0006
20	320	18.11	0.0007
22	340	19.24	0.0007
23	360	20.37	0.0008
25	380	21.50	0.0008
26	400	22.64	0.0009
28	420	23.77	0.0009
30	440	24.90	0.0010
31	460	26.03	0.0010
33	480	27.16	0.0011
34	500	28.29	0.0011
35	520	29.43	0.0012
37	540	30.56	0.0012
	896.7	50.74	0.0000

Table C8 – Readings obtained for Concrete Cylinder Sample 06 (at 28 days of age)

Dial gauge reading	Load (kN)	Stress (N/mm^2)	Strain
0	0	0.00	0.0000
1	20	1.13	0.0000
2	40	2.26	0.0001
3	60	3.40	0.0001
4	80	4.53	0.0001
5	100	5.66	0.0002
6	120	6.79	0.0002
8	140	7.92	0.0003
10	160	9.05	0.0003
11	180	10.19	0.0004
12	200	11.32	0.0004
13	220	12.45	0.0004
14	240	13.58	0.0005
15	260	14.71	0.0005
17	280	15.84	0.0006
18	300	16.98	0.0006
18	320	18.11	0.0006
19	340	19.24	0.0006
20	360	20.37	0.0007
22	380	21.50	0.0007
23	400	22.64	0.0008
25	420	23.77	0.0008
26	440	24.90	0.0009
28	460	26.03	0.0009
30	480	27.16	0.0010
31	500	28.29	0.0010
	746.4	42.24	0.0000

Table C9 – Readings obtained for Concrete Cylinder Sample 07 (at 28 days of age)

Dial gauge reading	Load (kN)	Stress (N/mm^2)	Strain
0	0	0.00	0.0000
1	20	1.13	0.0000
2	40	2.26	0.0001
3	60	3.40	0.0001
4	80	4.53	0.0001
5	100	5.66	0.0002
6	120	6.79	0.0002
8	160	9.05	0.0003
9	180	10.19	0.0003
10	200	11.32	0.0003
11	220	12.45	0.0004
12	240	13.58	0.0004
14	260	14.71	0.0005
15	280	15.84	0.0005
16	300	16.98	0.0005
17	320	18.11	0.0006
20	340	19.24	0.0007
21	360	20.37	0.0007
22	380	21.50	0.0007
23	400	22.64	0.0008
24	420	23.77	0.0008
26	440	24.90	0.0009
27	460	26.03	0.0009
28	480	27.16	0.0009
30	500	28.29	0.0010
	863.8	48.88	0.0000