Design Guide

for midas Civil

Prestressed Concrete Girder Design

to AS 5100.5-2017

April 2019

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Contents

Chapter 1 Introduction

The PSC design function can be applied to both non-composite and composite prestressed concrete girder and can be used to check if the PSC section can satisfy the requirements of AS 5100.5: 2017. It does not provide an automatic optimization of tendon arrangement / profile.

In the design of prestressed concrete girders, the program calculates the design moment, shear and torsion using load combinations which are compared with the bending strength and shear strength combined with torsion at the ultimate limit state based on AS 5100.5: 2017.

For the design of crack control, the incremental stresses in the tendon or reinforcement are calculated based on decompression force and compared with the limit value specified in the code.

Input and output data can be presented graphically on the model, in tables, or on the excel sheet prepared for each section of the element.

The design algorithm of the PSC design function refers to AS 5100.5: 2017 and RMS Amendments to Clause 8 of AS5100.5-2017 - November 2018.

Organization

This guide is designed to help you quickly become productive with the design options of AS 5100.5-2017.

Chapter 1 provides the introduction and organization of this book.

Chapter 2 provides detailed descriptions of the input data of prestressed concrete girders for design to AS 5100.5-2017.

Chapter 3 provides detailed descriptions of the design algorithm and design outputs of prestressed concrete girders for strength and serviceability to AS 5100.5-2017.

Objective

The objective of this design guide is to outline the design algorithms which are applied in midas Civil finite element analysis and design system. The guide aims to provide sufficient information for the user to understand the scope, limitations and formulas applied in the design features and to provide relevant references to the clauses in the design standards.

The design guide covers prestressed box girder and precast composite girder as per AS 5100.5-2017. It is recommended that you read this guide and review corresponding tutorials, which are found on our website, http://www.MidasUser.com, before designing. Additional information can be found in the online help available in the program's main menu.

Chapter 2 Input Data for Design

This chapter provides an overview of the basic assumptions, design preconditions, and some of the design parameters that affect the design of prestressed concrete girders.

2.1 Load Combinations

The load combinations are used for defining the various combinations of the load cases for which the prestressed concrete girders need to be checked.

In order to perform PSC design function, load combinations should be defined in the *Concrete Design* tab. The load combinations defined in the *General* tab can only be used to view the analysis results.

Design load combinations can automatically be generated based on AS 5100.2: 2017 for the roadway and pedestrian bridge type. Load factors and load cases can be modified by the user if the auto-generated load combinations are not appropriate for a specific project.

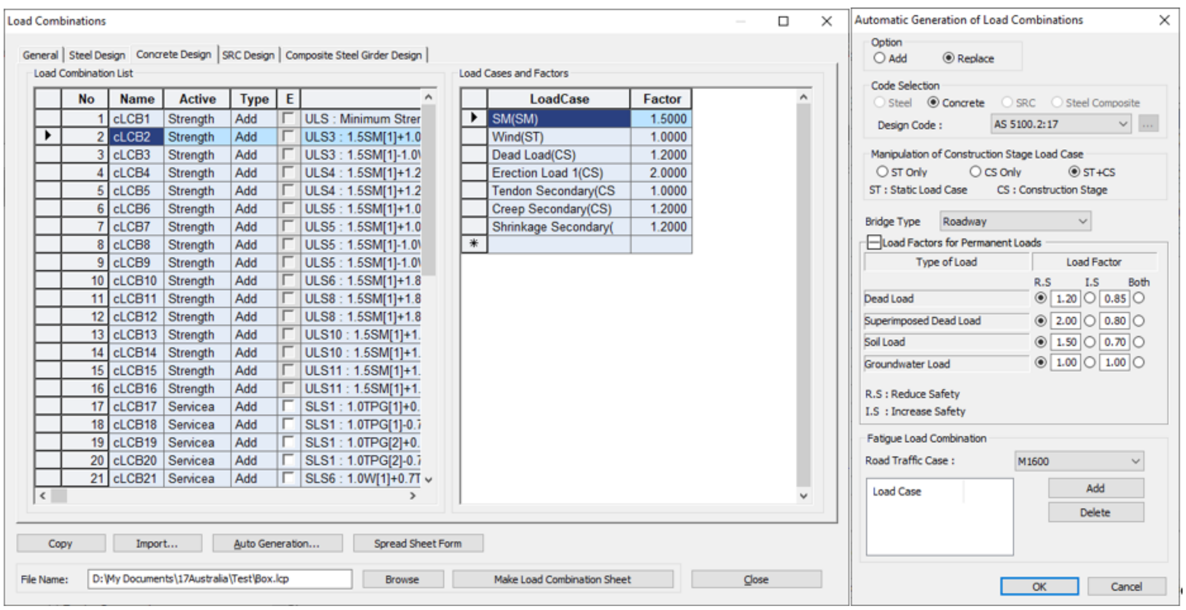


Figure 2- 1 Load Combination

Auto-generation is performed based on the load type which is defined in the *Static Load Cases* dialog box.

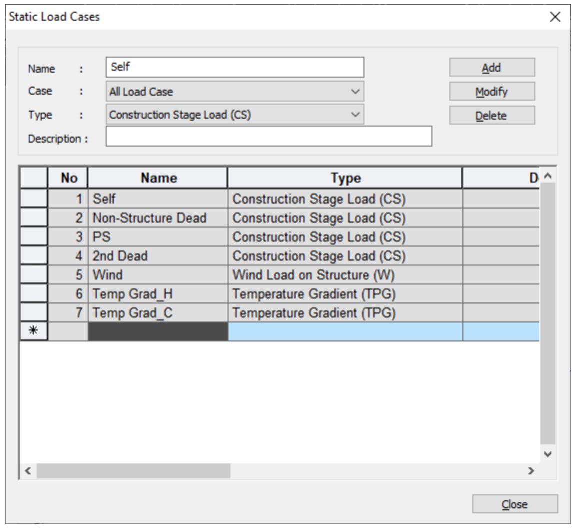


Figure 2- 2 Load Type

For the load cases whose type is *Construction Stage Load (CS)*, the load type will be further divided into CS: Dead Load, CS: Erection Load, CS: Tendon Primary, CS: Tendon Secondary. When a load case, *Self*, is defined as *Construction Stage Load (CS)* and activated in a construction stage, the program automatically produces *CS: Dead Load* which includes the effects of the load case, Self.

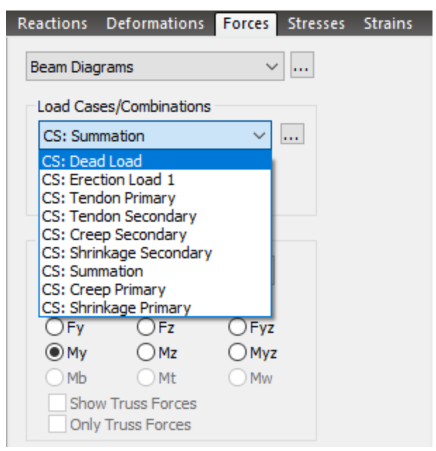


Figure 2- 3 Construction Stage Load Cases

If another load case, 2nd Dead, defined as *Construction Stage Load (CS)* is activated in a construction stage, the effects of the load case will also be included in *CS: Dead Load*. In order to separate the effects of the two load cases, i.e. Self, 2nd Dead and apply different load factors for the auto-generation of load combination, the program provides CS: Erection Load so that the user can assign the load case, 2nd Dead as CS: Erection Load and define the load type using the *Load Cases to be Distinguished from Dead Load for C.S. Output* option in the Construction Stage Analysis Control Data dialog box.

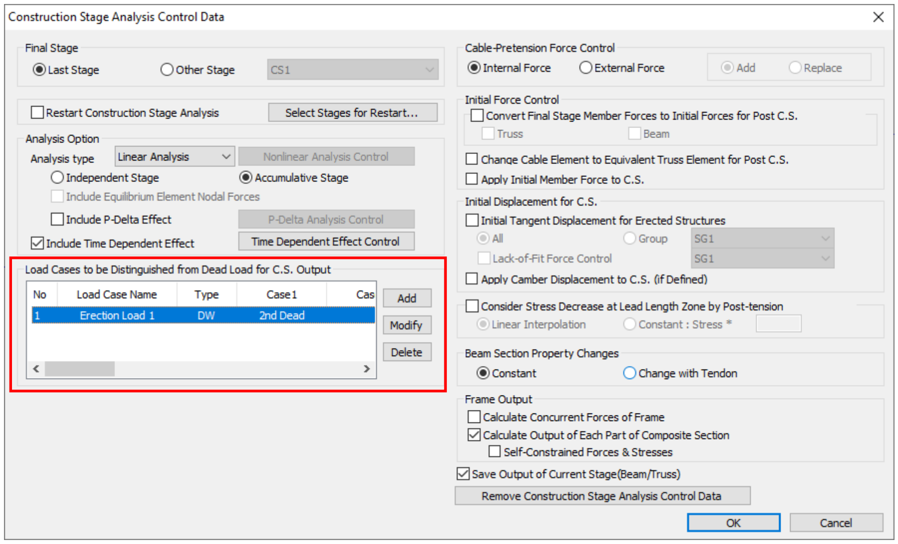


Figure 2- 4 Erection Load Case

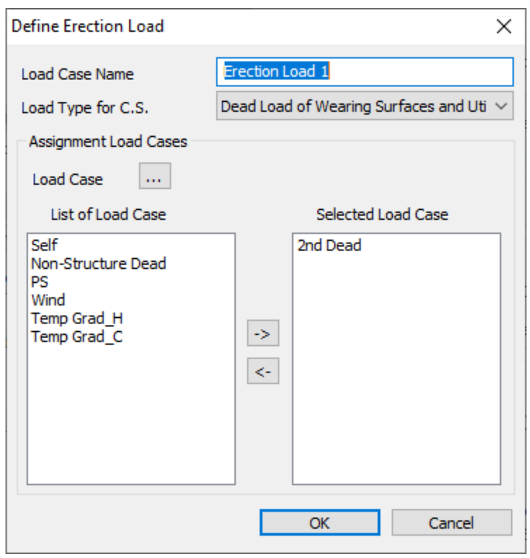


Figure 2- 5 Load Type of Erection Load Case

When a moving load case is included in the load combination, the program automatically produces sub-combinations using maximum, minimum, absolute maximum values of moving load analysis results. Load Combination (max) is the sum of the results of static load cases and maximum results of moving load case and Load Combination (min) is the sum of the results of static load cases and minimum results of moving load case.

2.2 Identifying Girders

By default, any elements created on the global XY plane are taken as a girder. If an element is vertically inclined and has a significant slope, the element will not be designed. In this case, the element can be designed by assigning member type as *Beam* using the *Modify Member Type* function.

▶ Design>Common Parameter>Modify Member Type

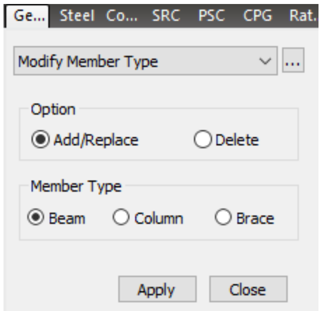


Figure 2- 6 Modify Member Type

2.3 PSC Design Parameters

In the PSC Design Parameters, the user selects a design code and design outputs for which PSC Design will be performed. Also, the maximum nominal aggregate size needs to be entered. See AS 5100.5-2017 Clause 8.2.4.2 for more details.

▶ PSC>Design Parameter>Parameters

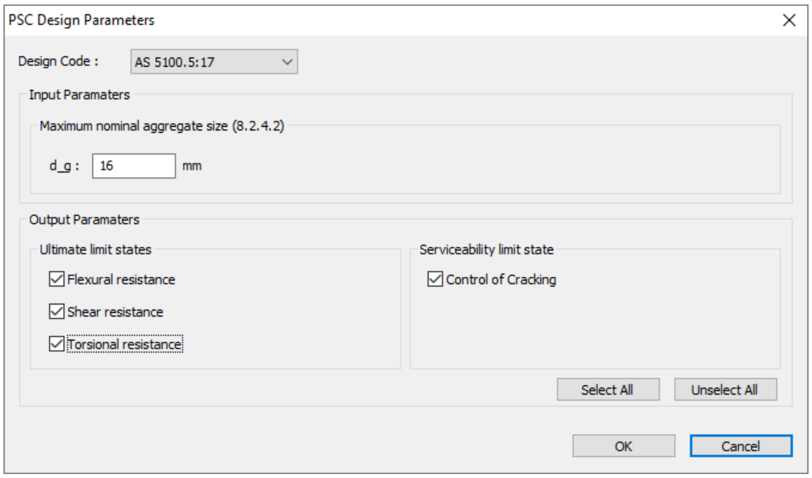


Figure 2- 7 PSC Design Parameters

2.4 PSC Design Material

Design strength of materials of concrete and reinforcement can be defined or modified here. This is explained in details in Chapter 3 Section 3.5 Material Properties for Design.

▶ PSC>PSC Design Data>PSC Design Material

2.5 Design/Output Position

By default, the program performs PSC design and produces excel report for all the elements. The positions and number of elements for PSC design and excel report output can be selected separately to reduce the waiting time in case where a lot of elements are included in the model.

▶ PSC>PSC Design Data>Design/Output Position

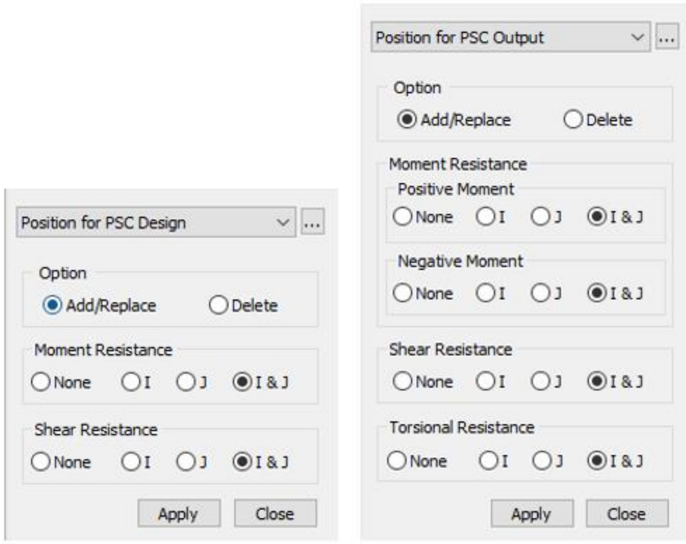


Figure 2- 8 Design/Output Position

2.6 Exposure Class

Exposure classification can be defined for top and bottom of each element to check crack control.

▶ PSC>PSC Design Data>Exposure Class

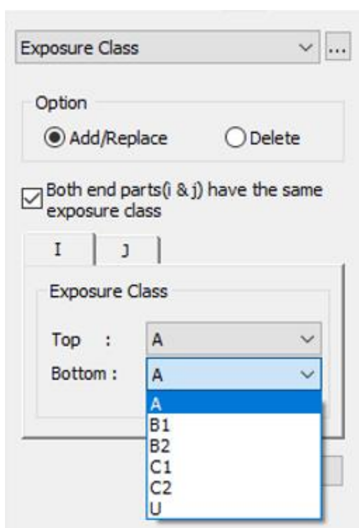


Figure 2- 9 Exposure Classification

2.7 Preference

Default design code for PSC design and material code of reinforcement can be defined from the Preference dialog box.

▶ Tools>Setting>Preferences

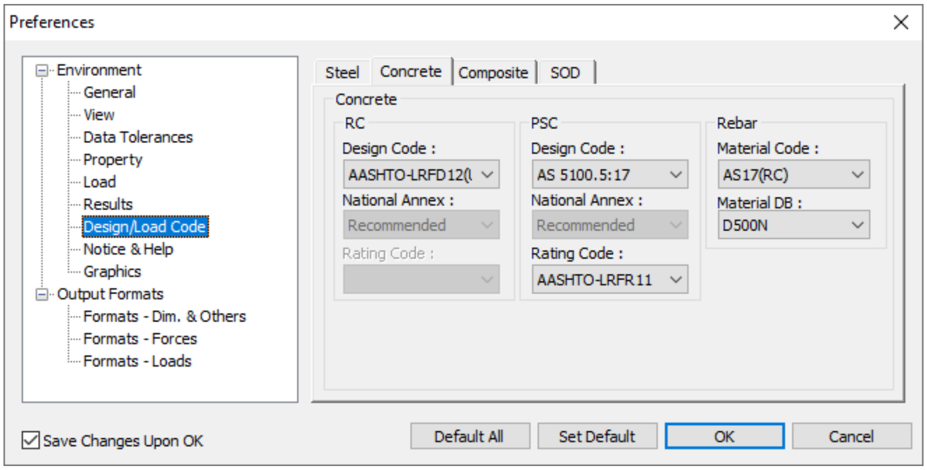


Figure 2- 10 Preferences

The type of reinforcement diameter in *Section Manager* can be set or changed to Australian standard by selecting AS17(RC) for the *Rebar Material Code* in *Preferences* dialog box.

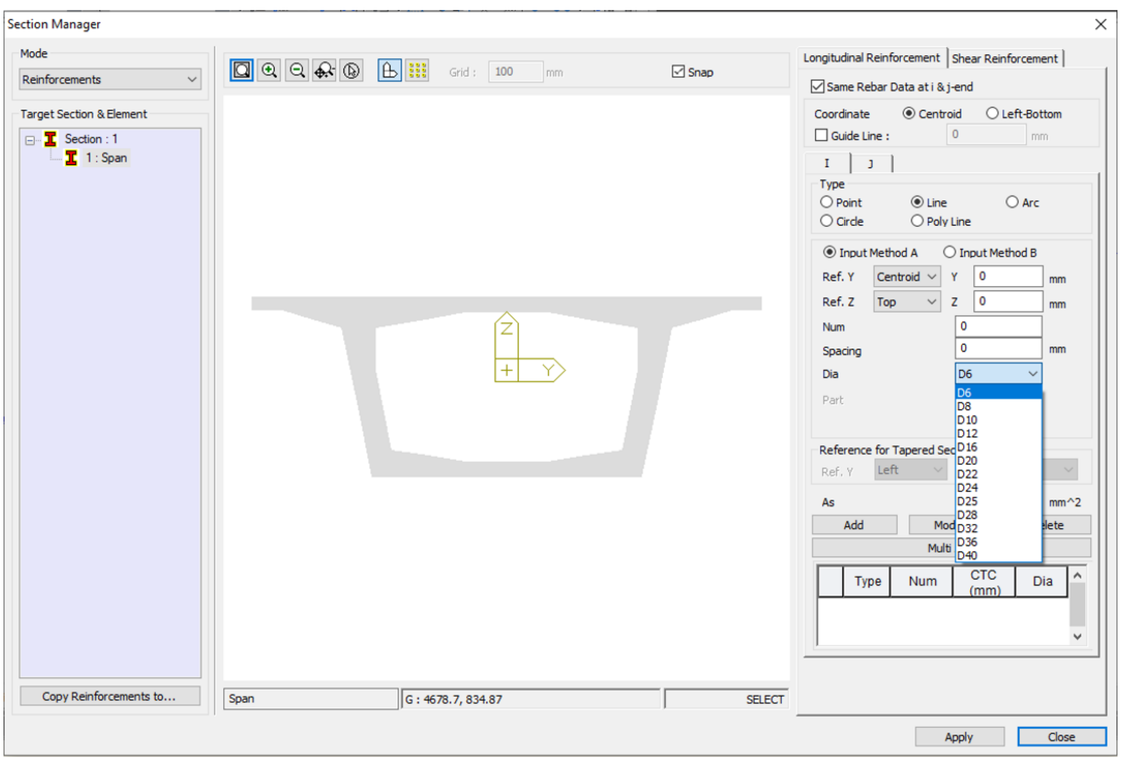


Figure 2- 11 Reinforcement of Section Manager

2.8 Design of Girders

In the design of PSC girders, in general, the program calculates and reports the ratio of demand and strength for flexure, shear, and torsion and limit stress for crack control based on the user-defined input data such as cross-section, tendon profile, and reinforcement. The code check results are provided for the user-defined number of elements along the span.

All girders are designed for major direction flexure, shear, and torsion only. Effects resulting from any axial forces except prestress are taken into account for the shear and torsion design and crack control, but not for the flexural design. Effects resulting from minor direction bending that may exist in the girders must be investigated independently by the user.

In checking the flexural strength for the major moment, the steps involve the determination of the maximum factored moments and the determination of the design bending strength. The beam section is designed for the maximum positive and maximum negative factored moment envelopes obtained from all of the load combinations.

In checking the shear strength for the major shear, the steps involve the determination of the factored shear force, the determination of the shear force that can be resisted by concrete, the determination of shear force that can be resisted by reinforcement steel, and the determination of vertical component of prestress force to carry the balance.

In checking the combined shear and torsion strength for the major shear and torsion, the steps involve the determination of the factored concurrent shear force and torsion, the determination of the shear force that can be resisted by concrete, the determination of shear force that can be resisted by reinforcement steel, the determination of vertical component of prestress force, and the determination of torsion that can be resisted by transverse reinforcement.

For the crack control of the cracked section, the steps involve the determination of effective prestress, decompression force, and the determination of the location of neutral axis and section properties of the cracked section, and the incremental stress in the tendon.

Chapter 3 Design Algorithm

3.1 Assumptions / Limitations

The following general assumptions and limitations exist for the current implementation of AS 5100.5-2017 within the program. Limitations related to specific parts of the design are discussed in their relevant sections.

- The design for fatigue is not supported.
- The strength check of a prestressed beam at transfer is not supported.
- Shear design for the regions near discontinuities and interface regions is not supported. Shear design is provided only for the flexural regions based on the sectional design method (AS 5100.5-2-17 Clause 8.2.3).
- Longitudinal shear in composite and monolithic beams is not supported.
- Deflection of beams is not supported.
- Vibration of beams is not supported.
- Slenderness limits for beams is not supported.
- The design value of the modulus of elasticity of steel reinforcement, E_s, is assumed to be 200×10^3 MPa (AS 5100.5-2017 Clause 3.2.2).

3.2 Design Load Combinations

The program creates a number of default design load combinations for a prestressed concrete girder design. Users can add their own design load combinations as well as modify or delete the program default design load combinations.

AS 5100.2-2017 specifies load combinations to be considered in AS 5100.2 Clause 23.3 for ultimate analysis and in AS 5100.2 Clause 23.4 for serviceability analysis.

3.2.1 ULS Load Combinations

The following load combinations are considered in the program.

(a) Minimum strength and stability.
(b) PE + road traffic loads.
(c) PE + pedestrian, cyclist path and maintenance traffic loads.
(e) PE + collision load.
(g) PE + earth pressure from traffic load.
(h) PE + earthquake effects.
(i) PE + water flow forces.
(j) PE + wind load.
(k) PE + thermal effects

The load combinations (d) PE + minimum restraint load, (f) PE + road traffic barrier load, (l) PE + fire effects are not considered in the auto-generation of load combinations.

For minimum strength and stability [Item (a)], the following load combination is considered in the program.

- 1.35 dead load + 1.35 superimposed dead load

For PE + road traffic loads [Item (b)] and for PE + wind load [Item (j)], the thermal effects shall be included in these combinations with a load factor of 1.0 if they produce a more severe loading. The program generates the following four combinations.

- PE + road traffic loads
- PE + road traffic loads + 1.0 thermal effects
- PE + wind load
- PE + wind load + 1.0 thermal effects

For PE + road traffic loads [Item (b)], the wind load shall be included in the combination using a design wind speed of 35 m/s in all locations. The program generates the following two combinations. The program does not identify the wind load whose wind speed is 35 m/s and hence the wind load case should be modified by the user.

- PE + road traffic loads
- PE + road traffic loads + wind load

For PE + collision load [Item (e)], the road traffic loads shall be included in the combination with a load factor of 1.0 if they produce a more severe loading. The program generates the following two combinations. The traffic loads will be added regardless of vehicle type and hence it should be modified by the user when the vehicle type is not SM 1600.

- PE + collision load
- PE + collision load + 1.0 traffic loads

For PE + water flow forces [Item (i)] and for PE + thermal effects [Item (k)], the road traffic loads shall be included in these combinations with a load factor of 1.0 if they produce a more severe loading, unless it can be demonstrated that the structure will be closed to traffic under ultimate conditions. The program generates the following four combinations. The traffic loads will be added regardless of vehicle type and hence it should be modified by the user when the vehicle type is not SM 1600.

- PE + water flow forces
- PE + water flow forces + 1.0 traffic loads
- PE + thermal effects
- PE + thermal effects + 1.0 traffic loads

Table 3- 1 ULS Load Combinations Generated by Program

No.	Load Combination	Table D3 of AS 5100.2-2017
cLCB1	1.35cDL+ 1.35cEL1	A Minimum Strength and Stability
cLCB2	1.2cDL+2.0cEL1+1.0cTS+1.2cCR+1.2cSH+1.5SM+1.8LL	B Road Traffic
cLCB3	1.2cDL+2.0cEL1+1.0cTS+1.2cCR+1.2cSH+1.5SM+1.8LL+1.0TPG	B Road Traffic
cLCB4	1.2cDL+2.0cEL1+1.0cTS+1.2cCR+1.2cSH+1.5SM+1.8LL+1.0W	B Road Traffic
cLCB5	1.2cDL+2.0cEL1+1.0cTS+1.2cCR+1.2cSH+1.5SM+1.8LL-1.0W	B Road Traffic

cLCB6	1.2cDL+2.0cEL1+1.0cTS+1.2cCR+1.2cSH+1.5SM+1.0W	J Wind
cLCB7	1.2cDL+2.0cEL1+1.0cTS+1.2cCR+1.2cSH+1.5SM-1.0W	J Wind
cLCB8	1.2cDL+2.0cEL1+1.0cTS+1.2cCR+1.2cSH+1.5SM+1.0W+1.0TPG	J Wind
cLCB9	1.2cDL+2.0cEL1+1.0cTS+1.2cCR+1.2cSH+1.5SM-1.0W+1.0TPG	J Wind
cLCB10	1.2cDL+2.0cEL1+1.0cTS+1.2cCR+1.2cSH+1.5SM+1.25TPG	K Thermal
cLCB11	1.2cDL+2.0cEL1+1.0cTS+1.2cCR+1.2cSH+1.5SM+1.25TPG+1.0LL	K Thermal

Note:
cDL: CS: Dead Load representing self weight of the structure
cEL1: CS: Erection Load 1 representing superimposed dead loads
cTS: CS: Tendon Secondary representing secondary effects of prestress
cCR: CS: Creep Secondary representing secondary effects of creep
cSH: CS: Shrinkage Secondary representing secondary effects of shrinkage
SM: Settlement
LL: Traffic load
TPG: Thermal load
W: Wind

Concurrent Forces and Concurrent Reactions of Moving Load Analysis

By default, the moving load analysis provides maximum and minimum member forces for a cross-section of each element considering all possible combinations of vehicle positions applied on the bridge. For beam elements, six maximum beam forces and six minimum beam forces can be checked by MV load case (max) and MV load case (min), respectively as shown below. These values are the most critical force for each component but not the concurrent forces. They cannot happen at the same time. The design results based on these non-concurrent forces would be conservative but not economical.

Elem	Load	Part	Axial (kN)	Shear-y (kN)	Shear-z (kN)	Torsion (kN*m)	Moment-y (kN*m)	Moment-z (kN*m)
3	M1600(max)	I[3]	0.00	0.00	302.17	1958.59	9718.52	0.01
3	M1600(min)	I[3]	-0.00	-0.00	-1869.93	-1958.59	-1483.50	-0.01

Figure 3- 1 Beam Forces of Moving Load Analysis

By selecting the *Normal + Concurrent Force/Stress* option in the *Moving Load Analysis Control Data* dialog box, the program provides concurrent forces.

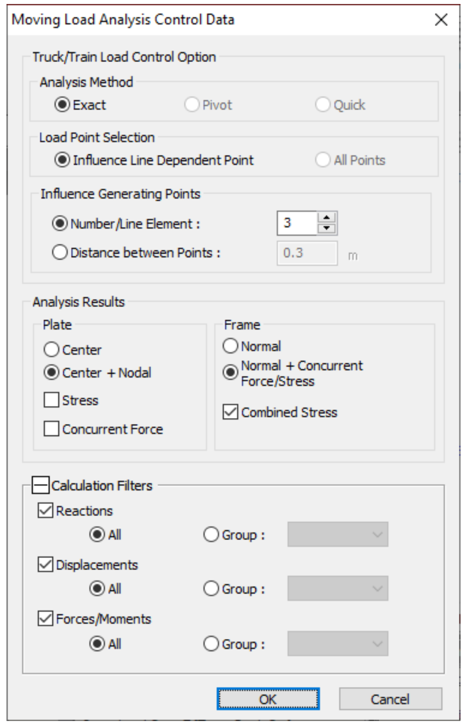


Figure 3- 2 Moving Load Analysis Control

The concurrent forces can only be viewed in a table format. In the Beam Force result table, right-click the mouse and select View by Max Value Item.

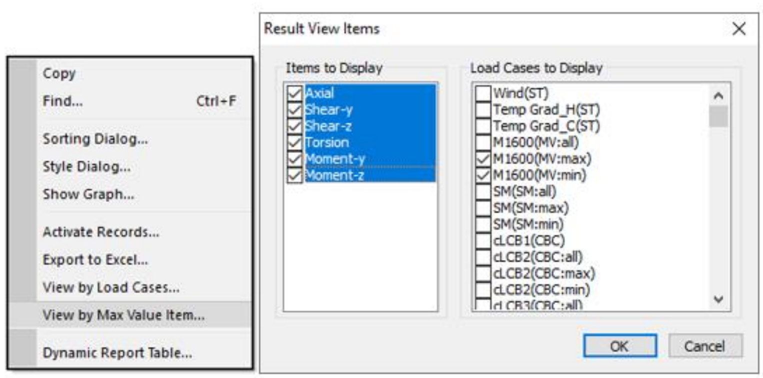


Figure 3- 3 View by Max Value Item

Total twelve sets of concurrent forces can be viewed. If the *Normal + Concurrent Force/Stress* option is selected, these concurrent forces will be used for the PSC design. Otherwise, non-concurrent forces will be applied.

Elem	Load	Part	Component	Axial (kN)	Shear-y (kN)	Shear-z (kN)	Torsion (kN*m)	Moment-y (kN*m)	Moment-z (kN*m)
3	M1600(max)	I[3]	Axial	0.00	-0.00	296.70	0.01	-1483.50	0.01
3	M1600(max)	I[3]	Shear-y	-0.00	0.00	-751.07	-156.92	4983.83	-0.01
3	M1600(max)	I[3]	Shear-z	0.00	-0.00	302.17	-0.77	-1335.33	0.01
3	M1600(max)	I[3]	Torsion	-0.00	-0.00	-972.21	1958.59	6343.04	0.00
3	M1600(max)	I[3]	Moment-y	-0.00	-0.00	-1698.00	347.88	9718.52	0.00
3	M1600(max)	I[3]	Moment-z	0.00	-0.00	15.29	9.96	-76.47	0.01
3	M1600(min)	I[3]	Axial	-0.00	-0.00	-1275.93	-276.12	6555.16	0.01
3	M1600(min)	I[3]	Shear-y	0.00	-0.00	15.29	9.96	-76.47	0.01
3	M1600(min)	I[3]	Shear-z	-0.00	-0.00	-1869.93	-379.86	9349.65	0.00
3	M1600(min)	I[3]	Torsion	-0.00	-0.00	-972.20	-1958.59	6343.02	0.00
3	M1600(min)	I[3]	Moment-y	0.00	-0.00	296.70	-0.01	-1483.50	0.01
3	M1600(min)	I[3]	Moment-z	-0.00	0.00	-751.07	-156.92	4983.83	-0.01

Figure 3- 4 Concurrent Beam Forces

3.2.2 SLS Load Combinations

The following load combinations are considered in the program.

PE + (*serviceability design load* for one transient load or thermal effect)

+ *k* (*serviceability design load* for one or more other transient load or thermal effect)

where

k = 0.7 for *one additional* effect

= 0.5 for *two additional* effects

The load factors to be applied to the SLS design loads shall be in accordance with the relevant clauses of this Standard.

Table 3- 2 SLS Load combinations Generated by Program

No.	Load Combination	Type
cLCB1	1.0cDL+1.3cEL1+1.0cTP+1.0cTS+1.0cCR+1.0cSH+1.0LL+0.7W	PE+TL1 +0.7TL2
cLCB2	1.0cDL+1.3cEL1+1.0cTP+1.0cTS+1.0cCR+1.0cSH+1.0LL-0.7W	
cLCB3	1.0cDL+1.3cEL1+1.0cTP+1.0cTS+1.0cCR+1.0cSH+1.0LL+0.7TPG	
cLCB4	1.0cDL+1.3cEL1+1.0cTP+1.0cTS+1.0cCR+1.0cSH+1.0W+0.7LL	
cLCB5	1.0cDL+1.3cEL1+1.0cTP+1.0cTS+1.0cCR+1.0cSH-1.0W+0.7LL	
cLCB6	1.0cDL+1.3cEL1+1.0cTP+1.0cTS+1.0cCR+1.0cSH+1.0W+0.7TPG	
cLCB7	1.0cDL+1.3cEL1+1.0cTP+1.0cTS+1.0cCR+1.0cSH-1.0W+0.7TPG	
cLCB8	1.0cDL+1.3cEL1+1.0cTP+1.0cTS+1.0cCR+1.0cSH+1.0TPG+0.7LL	
cLCB9	1.0cDL+1.3cEL1+1.0cTP+1.0cTS+1.0cCR+1.0cSH+1.0TPG+0.7W	
cLCB10	1.0cDL+1.3cEL1+1.0cTP+1.0cTS+1.0cCR+1.0cSH+1.0TPG-0.7W	
cLCB11	1.0cDL+1.3cEL1+1.0cTP+1.0cTS+1.0cCR+1.0cSH+1.0LL+0.5TPG+0.5W	PE+TL1 +0.5(TL2+TL3)
cLCB12	1.0cDL+1.3cEL1+1.0cTP+1.0cTS+1.0cCR+1.0cSH+1.0LL+0.5TPG-0.5W	
cLCB13	1.0cDL+1.3cEL1+1.0cTP+1.0cTS+1.0cCR+1.0cSH+1.0W+0.5TPG+0.5LL	
cLCB14	1.0cDL+1.3cEL1+1.0cTP+1.0cTS+1.0cCR+1.0cSH-1.0W+0.5TPG+0.5LL	
cLCB15	1.0cDL+1.3cEL1+1.0cTP+1.0cTS+1.0cCR+1.0cSH+1.0TPG+0.5W+0.5LL	
cLCB16	1.0cDL+1.3cEL1+1.0cTP+1.0cTS+1.0cCR+1.0cSH+1.0TPG-0.5W+0.5LL	

Note:

cDL: CS: Dead Load representing self weight of the structure

cEL1: CS: Erection Load 1 representing superimposed dead loads

cTP: CS: Tendon Primary representing primary effects of prestress

cTS: CS: Tendon Secondary representing secondary effects of prestress

cCR: CS: Creep Secondary representing secondary effects of creep
cSH: CS: Shrinkage Secondary representing secondary effects of shrinkage
LL: Traffic load
TPG: Thermal load
W: Wind
PE: Permanent loads
TL: Transient loads

3.3 Loss of Prestress in Tendons

Immediate loss of prestress

The calculation of immediate loss of prestress is different between pre-tension and post-tension.

- Pre-tension type
  The immediate loss is calculated only from the elastic deformation of concrete at transfer. The immediate loss due to curing conditions such as steam curing of a prestressed member is not handled.

- Post-tension type
  The immediate loss consists of the losses due to friction and anchorage slip. The loss due to elastic deformation of concrete is only calculated from each stage of stressing for multi-stage stressing.

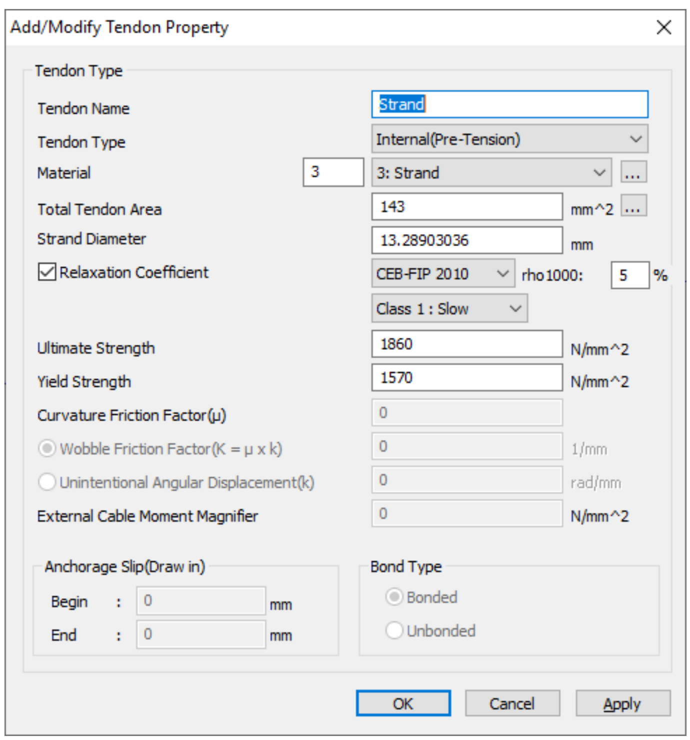


Figure 3- 5 Tendon Property (Pretension Type)

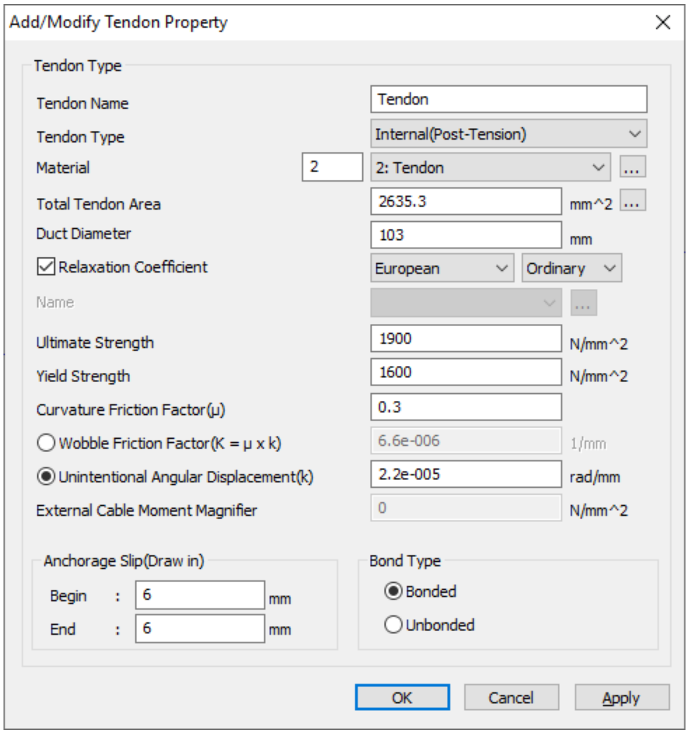


Figure 3- 6 Tendon Property (Post-tension Type)

Loss of prestress due to elastic deformation of concrete

Calculation of the immediate loss of prestress due to elastic deformation of the concrete at transfer is based on the value of modulus of elasticity of the concrete at that age. The development of modulus of elasticity of the concrete can be defined using the *Time Dependent Material (Comp. Strength)* function.

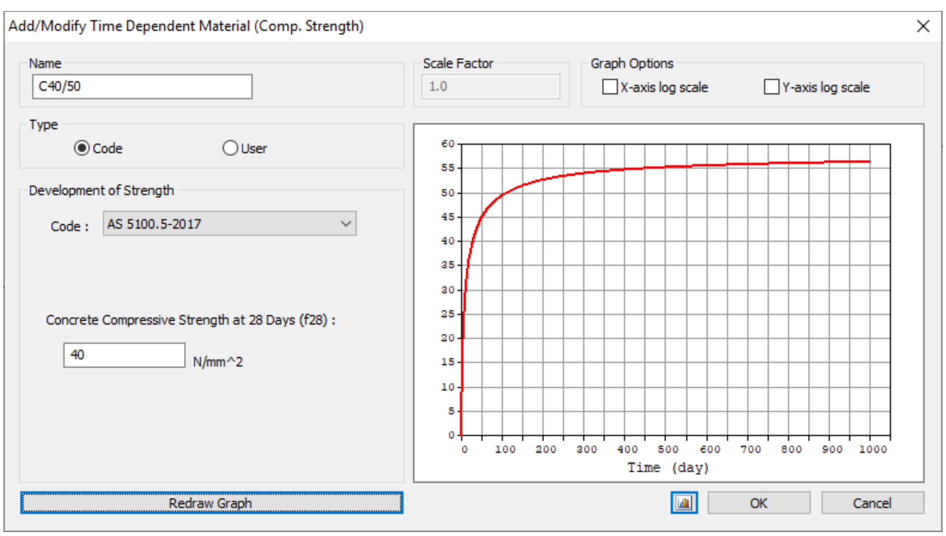


Figure 3- 7 Time Dependent Material (Comp. Strength)

The modulus of elasticity of concrete (E_{cj}) at the age j, in days, is taken from AS 5100.5-2017 Clause 3.1.2 as follows:

(i) $(\rho^{1.5}) \times \left(0.043\sqrt{f_{cmi}}\right)$ (in MPa) when $f_{cmi} \leq 40$ MPa or
(i) $(\rho^{1.5}) \times \left(0.12 + 0.024\sqrt{f_{cmi}}\right)$ (in MPa) when $f_{cmi} > 40$ MPa

The development of compressive strength of concrete at the age t, in days, is taken from AS 3600-2009 as follows:

$$f(t) = \frac{1.452 \times t^{0.75} \times f_c'}{t^{0.75} + 5.5}$$

Loss of prestress due to friction

The stress in the tendon at a distance (*a*) measured from the jacking end (σ_{pa}) is taken as

$$\sigma_{pa} = \sigma_{pj} e^{-\mu(\alpha_{tot} + \beta_p L_{pa})}$$

There are two ways of considering the loss due to wobble friction in the program. Either β_p in the equation above should be entered using *Unintentional Angular Displacement (k)* or $\mu\beta_p$ should be entered using *Wobble Friction Factor (K=μ x k)*.

Loss of prestress during anchoring

In a post-tensioned member, allowance is made for loss of prestress when the prestressing force is transferred from the tensioning equipment to the anchorage. For the details of calculation method, the p. 368 *Loss due to anchorage slip* in the Analysis Reference manual should be referenced.

Time-dependent losses of prestress

Prestress loss due to creep and shrinkage can be taken into account by defining Time Dependent Material (Creep / Shrinkage).

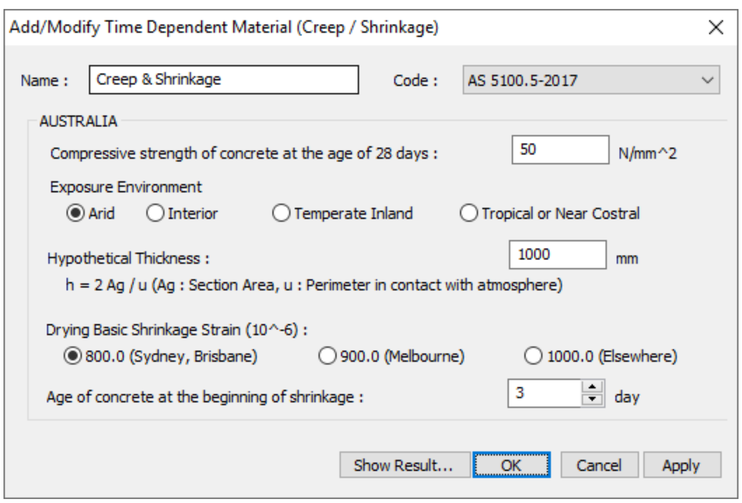


Figure 3- 8 Time Dependent Material (Creep/Shrinkage)

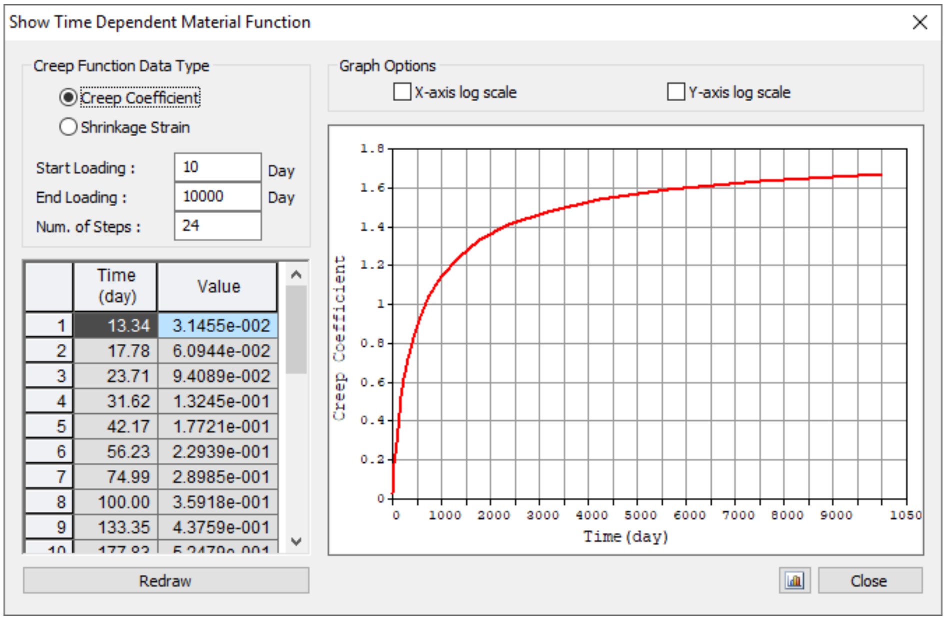


Figure 3- 9 Creep Coefficient

Loss of prestress due to shrinkage of the concrete

The loss of prestress in the tendon due to shrinkage of the concrete is taken as $E_p\varepsilon_{cs}$, where ε_{cs} is determined in accordance with AS 5100.5-2017 Clause 3.1.7.2. The shrinkage restraint effects of the reinforcement can be calculated using the *Consider Re-Bar Confinement Effect* option. The restraint force/stress can be viewed using CS: Shrinkage Secondary. However, the effects of reinforcement on the loss of prestress is ignored. The loss of prestress will not change regardless of the option. It should be noted that the restraint effect of the reinforcement will only be working when the *Consider Reinforcement for Section Stiffness Calculation* option is turned on.

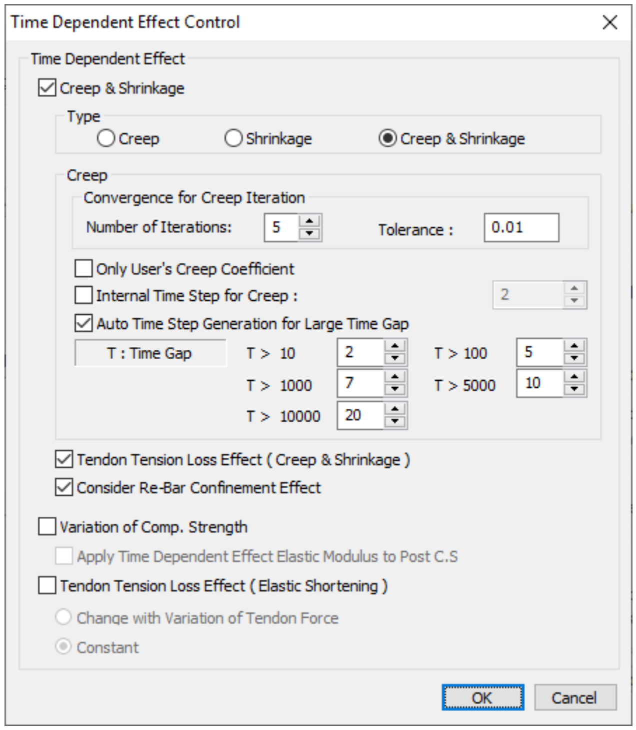


Figure 3- 10 Time Dependent Effect Control

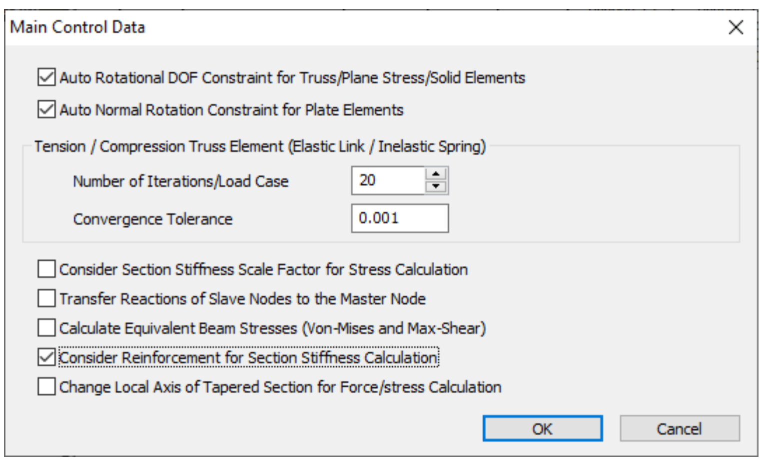


Figure 3- 11 Main Control Data

Loss of prestress due to creep of the concrete

The loss of prestress due to creep of the concrete is calculated from an analysis of the creep strains in the concrete. The creep coefficient φ_{cc} is determined in accordance with AS 5100.5-2017 Clause 3.1.8.3.

Loss of prestress due to tendon relaxation

The current version does not support the calculation of relaxation loss to AS 5100.5-2017 Clause 3.3.4.3. However, it can be defined by the user-defined relaxation function.

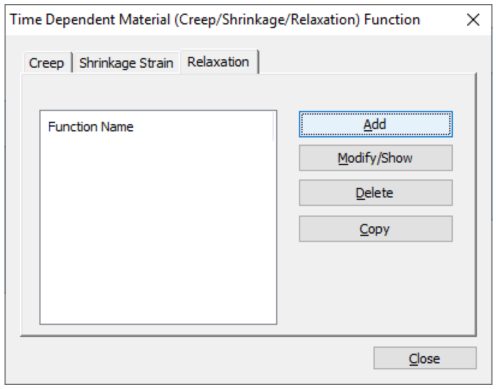


Figure 3- 12 Time Dependent Material (Relaxation)

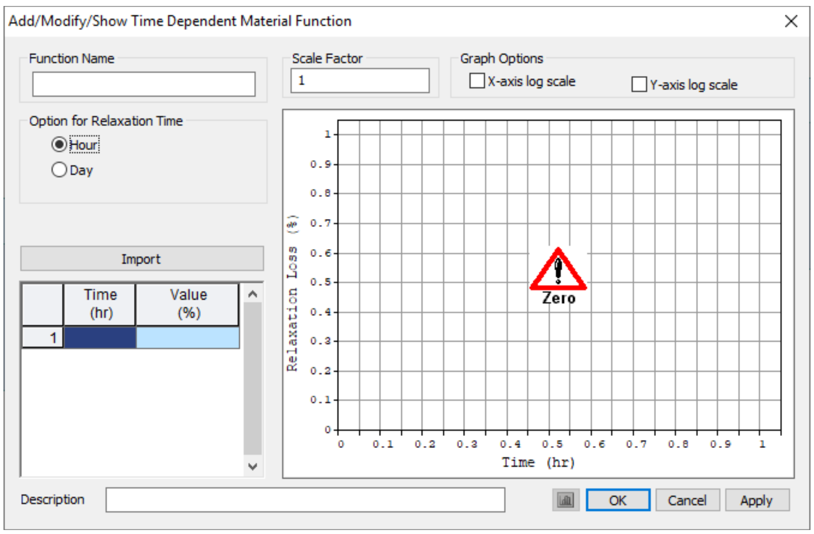


Figure 3- 13 User-defined Relaxation Function

After analysis, the prestress losses can be found in the Results>Tendon>Tendon Loss table.

Elem	Part	Stress (After Immediate Loss) : A (N/mm^2)	Elastic Deform. Loss : B (N/mm^2)	Stress(Elastic Loss)/ Stress(Immediate Loss)	Creep/Shrinkage Loss (N/mm^2)	Relaxation Loss (N/mm^2)	Stress(After All Loss)/ Stress(After Immediate Loss)	Effective Num.
The Loss of tendon group [A1] at the stage of [CS4]								
Tendon		A1	Stage	CS4	Apply			
1	I	1094.6	5.11	1.00	-86.6	-128.3	0.808	2.0
1	J	1121.8	5.97	1.01	-91.9	-136.5	0.802	2.0
2	I	1121.8	5.99	1.01	-91.9	-136.4	0.802	2.0
2	J	1152.0	7.78	1.01	-95.5	-146.0	0.797	2.0
3	I	1151.9	7.80	1.01	-95.5	-146.0	0.797	2.0
3	J	1183.9	9.90	1.01	-97.8	-156.7	0.793	2.0
4	I	1183.8	9.91	1.01	-97.8	-156.6	0.793	2.0
4	J	1209.1	11.81	1.01	-99.1	-165.6	0.791	2.0
5	I	1209.0	11.82	1.01	-99.0	-165.5	0.791	2.0
5	J	1178.7	12.53	1.01	-97.2	-154.9	0.797	2.0
6	I	1178.6	12.52	1.01	-97.2	-154.9	0.797	2.0
6	J	1149.5	12.26	1.01	-94.0	-145.2	0.803	2.0
7	I	1149.5	12.26	1.01	-94.0	-145.2	0.803	2.0
7	J	1129.5	11.66	1.01	-91.7	-138.8	0.806	2.0

Tendon Loss (Stress) | Tendon Loss (Force)

Figure 3- 14 Tendon Loss Table

3.4 Material Properties for Design

- Concrete and reinforcement

The material properties of various concrete grades used in the program are as shown below.

Table 3- 3 Material Properties of Concrete

	C20	C25	C32	C40	C50	C65	C80	C100
Elasticity (MPa)	24,000	26,700	30,100	32,800	34,800	37,400	39,600	42,200
Poisson Ratio	0.2							
Thermal Coeff. (1/°C)	10×10^{-6}							
Weight Density (kN/m^3)	23.54							

These values such as modulus of elasticity or weight density can be modified by the user after changing Standard from *AS17(RC)* to *None* in the *Material Data* dialog box.

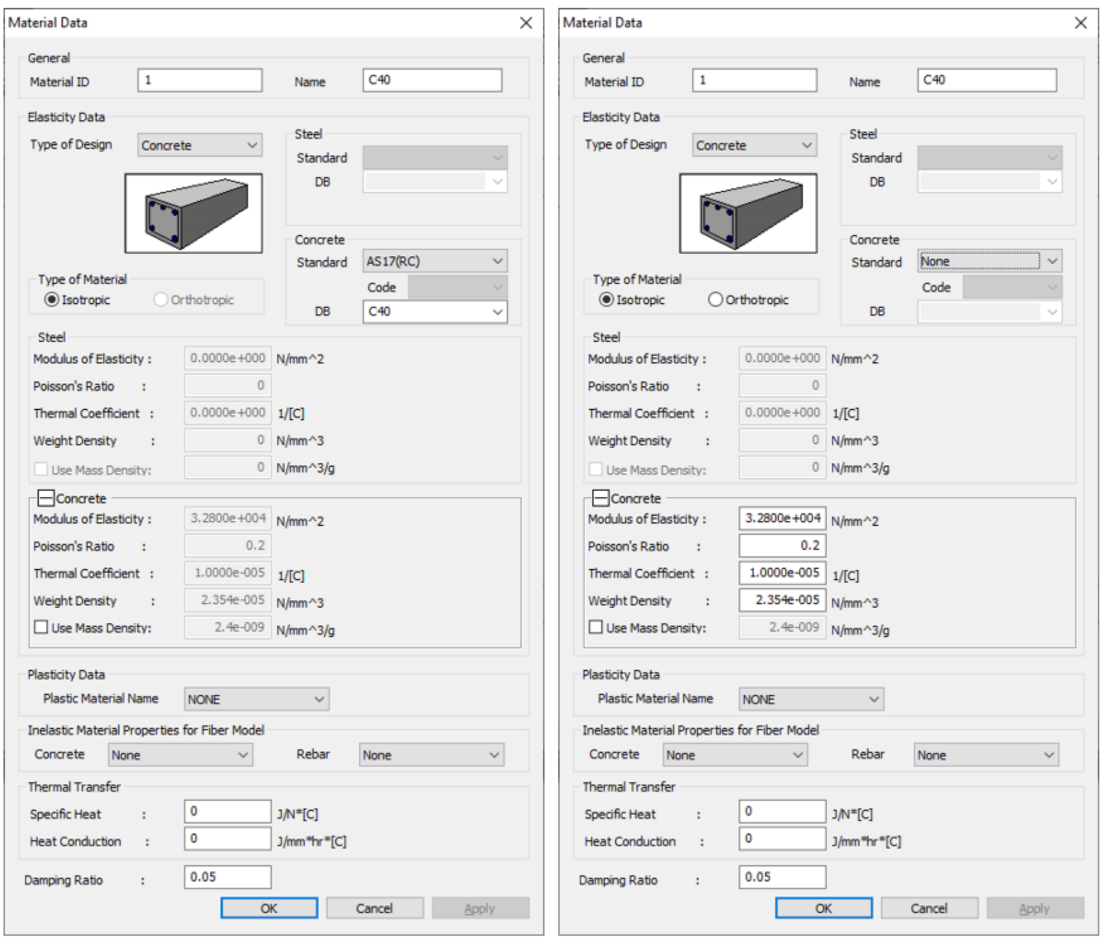


Figure 3- 15 Material Data

The material properties of reinforcement used in the program are as shown below. In the current version, these properties cannot be modified by the user.

Table 3- 4 Material Properties of Reinforcement

	D500L	D500N	D500E	D500LP
Elasticity (MPa)	200,000			
Thermal Coeff. (1/°C)	12 x 10^{-6}			

The design strengths of concrete and reinforcement to be used in PSC design can be entered or modified from the PSC>PSC Design Data>PSC Design Material. The strength can be checked for the selected material grade according to the selected material code. When "None" is selected in Code field, the strength of concrete and reinforcement can be directly entered.

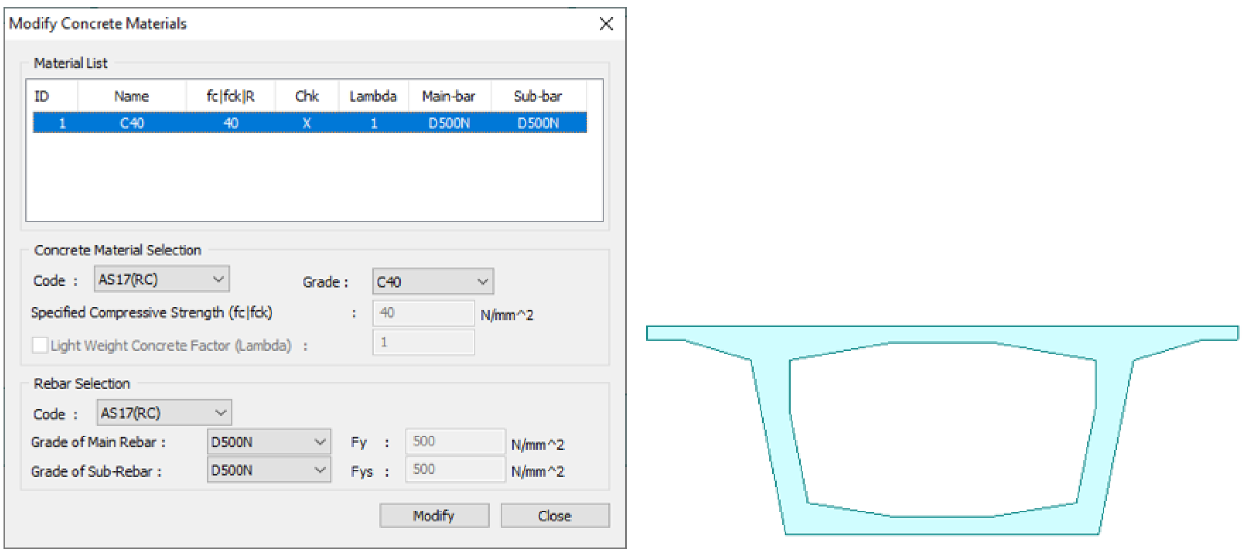


Figure 3- 16 Modify Concrete Material (Non-composite Box Section)

For the composite type PSC sections, the Design Material window changes to allow users to define the material properties of the slab. The concrete and rebar material properties entered for slab are used for every calculation such as the neutral axis calculation.

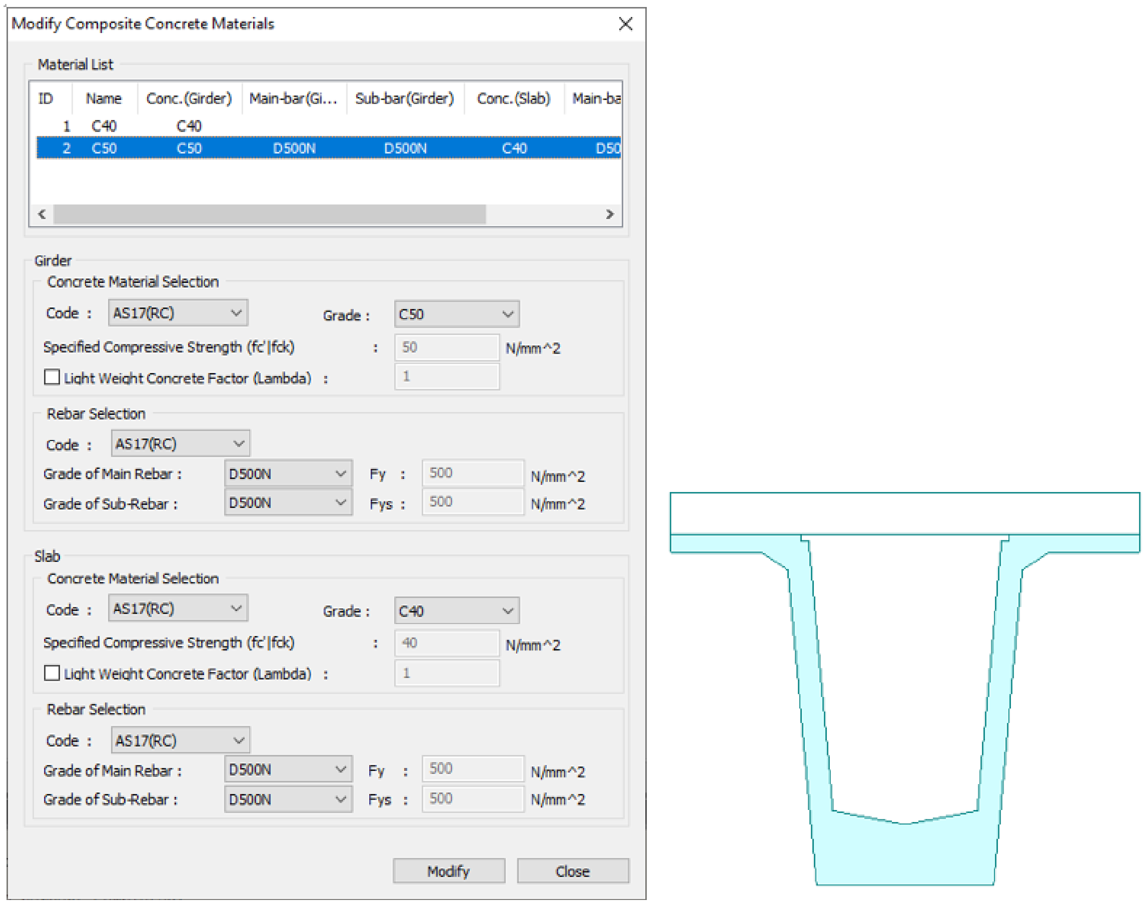


Figure 3- 17 Modify Concrete Material (Composite Section)

The development of compressive strength of concrete at the age t, in days, is taken from AS 3600-2009 as follows:

$$f(t) = \frac{1.452 \times t^{0.75} \times f_c'}{t^{0.75} + 5.5}$$

- Tendon

The modulus of elasticity of the tendon can be defined by selecting material for tendon from the *Tendon Property* dialog box. Yield strength and tensile strength of tendon can also be defined here.

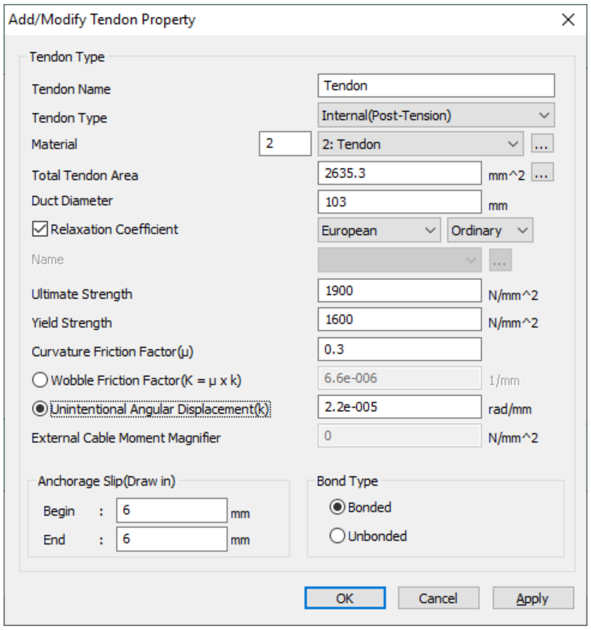


Figure 3- 18 Tendon Property

3.5 Strength of Beams in Bending

3.5.1 Reinforcement and Tendon profile

Input reinforcements to be used in the calculation of resistance in the dialog box below.

▶ *Model*>Properties>Section Manager>Reinforcements

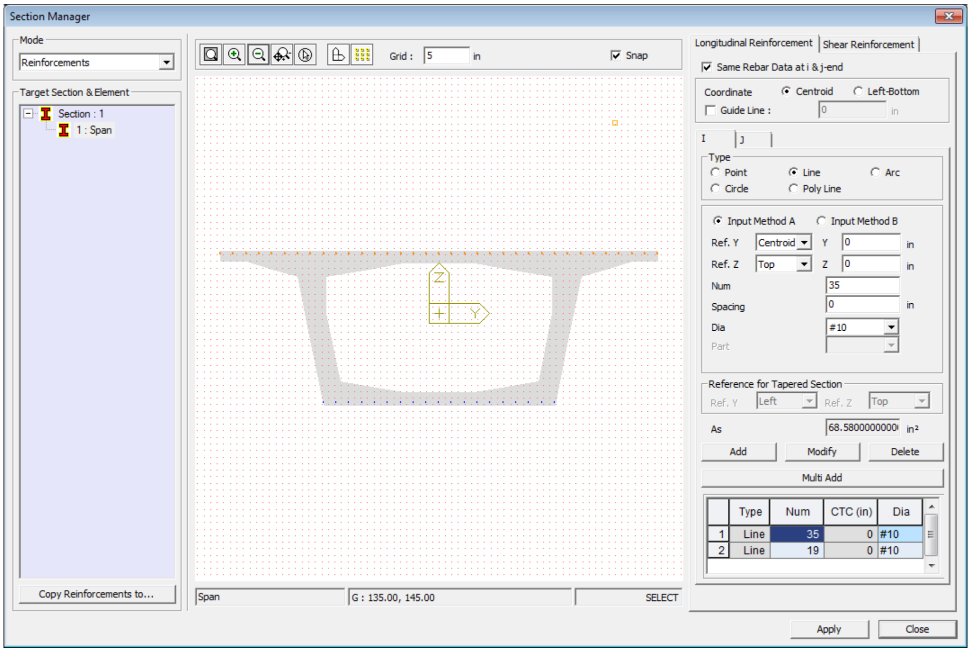


Figure 3- 19 Longitudinal Reinforcement

Once reinforcement is entered at the PSC section, the rebar which is placed at the closest position to the extreme compression fiber will be used to calculate the strain. In short, the rebar at the bottom most is used under the sagging moment. And the rebar at the top most is used under the hogging moment.

Input tendon profile to be used in PSC design in the dialog box below.

▶ Load>Temp./Prestress>Section Manager >Tendon Profile

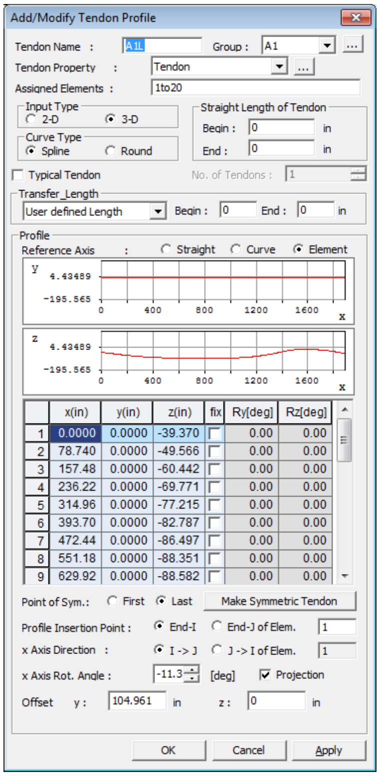


Figure 3- 20 Tendon Profile

3.5.2 Neutral Axis Depth at Ultimate Strength

The neutral axis depth at the ultimate strength is determined by the iteration approach as shown in the figure below.

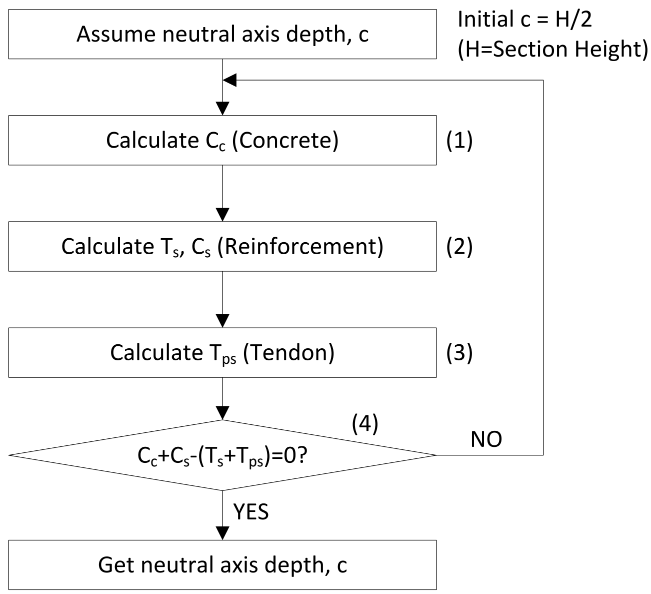


Figure 3- 21 Flow chart to calculate neutral axis depth, c

(1) Calculate compressive force of concrete, C_c.

In the program, the relationship between stress and strain of concrete is considered as the equivalent rectangular concrete compressive stress block. The compressive strain limit of concrete, ε_{cu} is 0.003, and a uniform compressive stress on the concrete is α_2 f_c'. The neutral axis is located at a distance γ k_u d from the extreme compressive fiber.

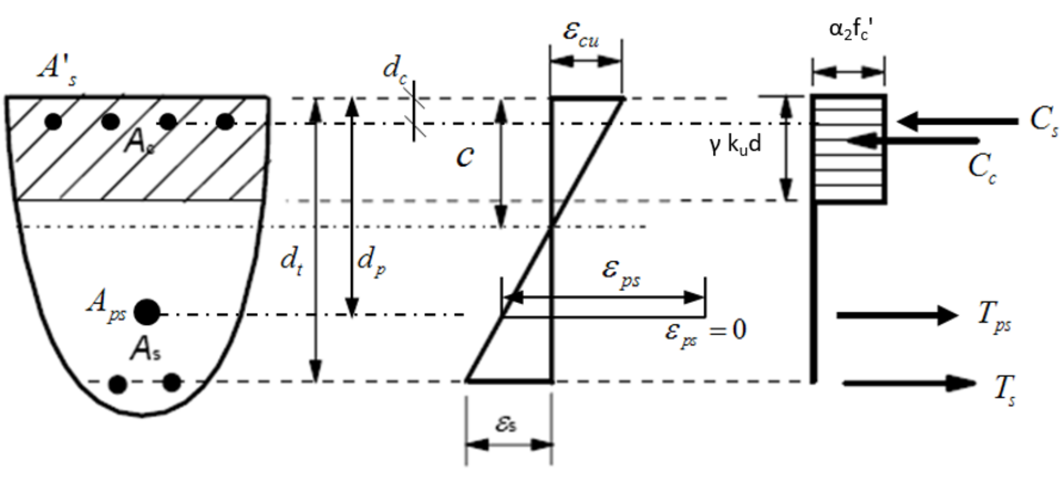


Figure 3- 22 Calculate force of concrete, Cc

$$C_c = \alpha_2 f_c' A_c$$

Where,

f'_c : Specified compressive strength of concrete for design. Compressive strength to be used in PSC design is defined in PSC Design Material dialog box.
$\alpha_2 = 1.0 - 0.003 f_c'$ (within the limits of $0.67 \le \alpha_2 \le 0.85$)
$\gamma = 1.05 - 0.007 f_c'$ (within the limits of $0.67 \le \gamma \le 0.85$)
A_c : Concrete area of compressive zone

When the neutral axis of a composite section under positive moment is located below the slab, the lower value of f_c' between slab and beam is applied for the calculation of α_2 and γ.

(2) Calculate force of reinforcement, T_s, C_s.

Tensile stresses in the longitudinal reinforcement (T_s) and compressive stresses in the compression reinforcement (C_s) are calculated as shown in the following equation.

$$T_s = A_s f_s, \quad C_s = A_s' f_s'$$

Where,
A_s, A_s' : the cross sectional area of tensile and compressive reinforcement
It is entered in Section Manager>Reinforcements as shown in the Fig1. 2.
f_s , f_s': the stress of tensile and compressive reinforcement

In order to calculate the tensile stress of reinforcement, the program calculates the corresponding strains as per the strain compatibility condition. And then the related tensile stresses are calculated by the stress-strain relationship. The equation is as follows.

▪ **Strain**

$$\varepsilon_s = \frac{d_t - c}{c}\varepsilon_{cu}, \quad \varepsilon_s' = \frac{c - d_c}{c}\varepsilon_{cu}$$

Where,
ε_s : the strain of tensile reinforcement.
ε_s' : the strain of compressive reinforcement.
ε_{cu} : the ultimate compressive strain in the concrete. (ε_{cu} = 0.003)
c : the neutral axis depth.
d_t : Distance from the compression fiber of concrete to the extreme tensile fiber of reinforcement
d_c : Distance from the compression fiber of concrete to the extreme compressive fiber of reinforcement

▪ **Stress**

If the tensile stress of reinforcement reaches its yield stress limit, tensile stress will be applied as yield stress. If not, the tensile stress will be calculated as "ε_s x E_s".

$$f_s = \begin{cases} \varepsilon_s E_s & (f_s \le f_y) \\ f_y & (f_s > f_y) \end{cases}, \quad f_s' = \begin{cases} \varepsilon_s' E_s & (f_s' \le f_y) \\ f_y & (f_s' > f_y) \end{cases}$$

Where,

E_s : Modulus of elasticity of reinforcement

f_y : Yield tensile stress of reinforcement

(3) Calculate force of tendon, T_{ps}.

Tensile stress in the prestressing steel, T_{ps}, is calculated as shown in the following equation.

$$T_{ps} = \sum A_p f_{ps}$$

Where,

A_p : the cross sectional area of tendon.

f_{ps} : the stress of tendon.

▶ Load>Temp./Prestress>Section Manager>Tendon Property

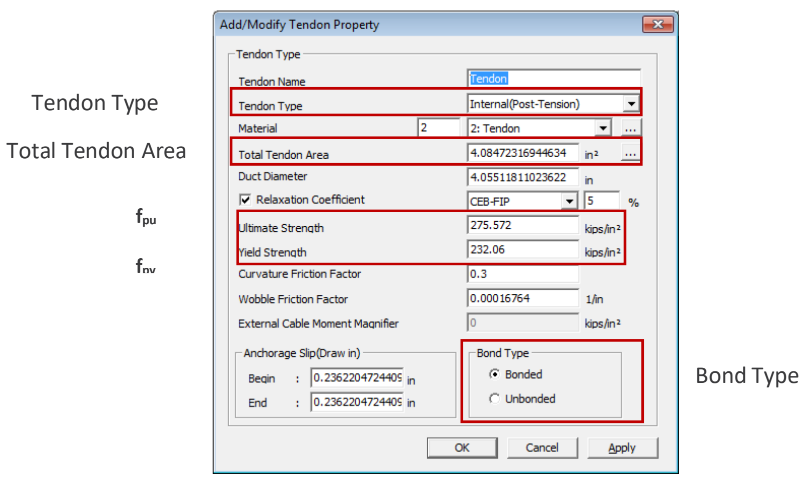


Figure 3- 23 Tendon Property Dialog box

▪ **Tendon Type**

Internal (Pre-Tension)

Internal (Post-Tension)

External

▪ **Bond Type**

Bonded: Section properties reflect the duct area after grouting.
When tendon type is specified as Internal (Pre-Tension), bond type will be taken as Bonded Type.
Unbonded: Section properties exclude the duct area.
When tendon type is specified as external, bond type will be taken as Unbonded Type.

Table 3- 5 Applicable Bond Type by Tendon Types

Tendon Type	Bond Type
Internal (Pre-tension)	Bonded
Internal (Post-tension)	Bonded
	Unbonded
External	Unbonded

▪ Total Tendon Area

Enter the tendon area (A_p). Click [...] to select the number of strands and diameter in order to calculate the tendon area automatically. Tensile stress of prestressing steel f_{ps} is calculated as follows.

▪ Stress in bonded tendons at ultimate strength

When bending strength is calculated, the stress in the prestressing tendon is calculated by the stress-strain relationship which is represented by bilinear curve.

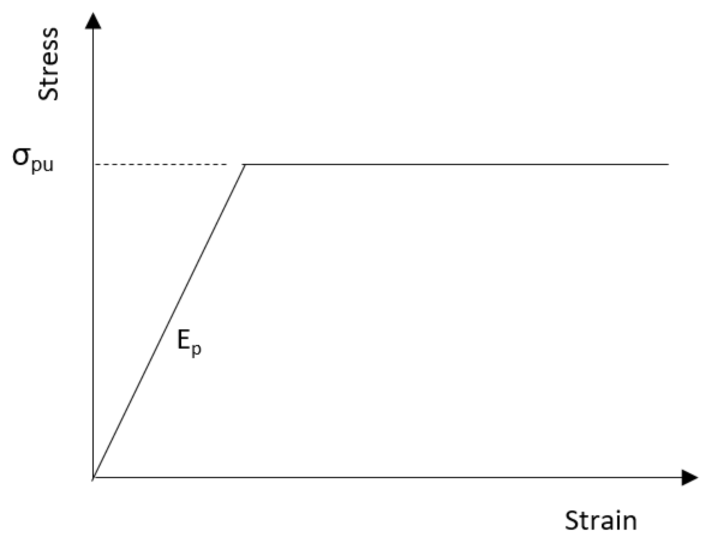


Figure 3- 24 Stress-Strain Relationship of Tendon

The maximum stress that would be reached in bonded tendons at ultimate strength σ_{pu} is taken as

$$\sigma_{pu} = f_{pb}\left(1 - \frac{k_1 k_2}{\gamma}\right) \qquad \text{(AS 5100.5 8.1.7(1))}$$

where

$k_1 = 0.4$ if $f_{py}/f_{pb} < 0.9$ or
$k_1 = 0.28$ if $f_{py}/f_{pb} \geq 0.9$
$k_2 = \frac{1}{b_{ef} d_p f'_c}\left[A_{pt} f_{pb} + (A_{st} - A_{sc}) f_{sy}\right]$

▪ **Stress in unbonded tendons at ultimate strength**

$$\sigma_{pu} = \sigma_{p.cf} + 6200\left(\frac{d_p - k_u d}{L_{pc}}\right) \qquad \text{(AS 5100.5 8.1.8(1))}$$

(4) Determination of neutral axis depth

In order to find the neutral axis, the iteration analysis will be performed until compressive strength ($C=C_c+C_s$) becomes equal to the tensile strength ($T=T_s+T_{ps}$).

The convergence criterion is applied as shown in the following equation.

• Convergence condition:

$$\left|\frac{C}{T} - 1.0\right| < 0.001 \ (Tolerance)$$

3.5.3 Calculate ultimate bending strength M_u

Once the neutral axis is determined, the ultimate bending strength is calculated by multiplying the distance from the neutral axis.

$$M_u = C_c a_c + C_s a'_s + T_s a_s + \sum\left(T_{ps} a_{pi}\right)$$

where,

*a_c, a_s, a_s', a_{pi} : the distance from neutral axis depth, **c** to concrete, reinforcement rebar, tendon.*

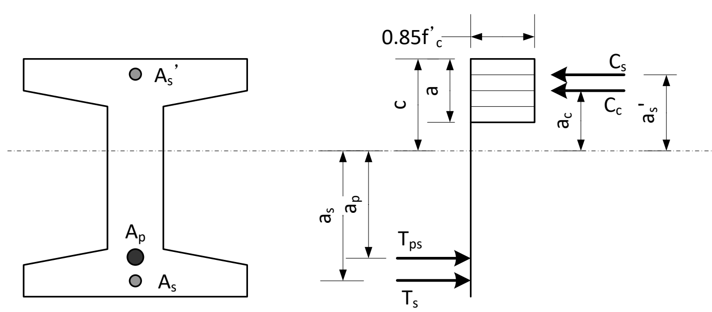


Figure 3- 25 Forces and Distances from Neutral Axis Depth for M_n

If a tendon is located at the upper part of the neutral axis under the positive moment, the bending strength will have (-) sign and it will reduce the total moment resistance.

$$M_u = C_c a_c + C_s a_s' + T_s a_s + \sum\left(T_{ps} a_{pi} - T_{ps}' a_{pi}'\right)$$

3.5.4 Design Strength in Bending

The design strength in bending of a section shall be taken as not greater than ϕM_{uo}. M_{uo} is the ultimate strength in bending and ϕ is the capacity reduction factor and determined as follows:

$$0.6 \le \phi = (1.19 - 13\,k_{uo}/12) \le 0.8 \qquad \text{(AS 5100.5 Table 2.3.2)}$$

According to AS 5100-2017 Clause 8.1.5, sections with k_{uo} greater than 0.36 and $M^* > 0.6M_{uo}$ shall be used only when—

(a) the structural analysis is carried out in accordance with Clauses 6.2 to 6.6; and

(b) compressive reinforcement of at least 0.01 times the area of concrete in compression is used and restrained by fitments as specified in Clause 10.7.4.

The current version of the program does not check this requirement.

3.5.5 Minimum Strength Requirements

The ultimate strength in bending (M_{uo}) at critical cross-sections shall be not less than $(M_{uo})_{min}$, the minimum required strength in bending at a critical cross section, and calculated using the following equation:

$$(M_{uo})_{min} = 1.2\left[Z\left(f'_{ct.f} + P_e/A_g\right) + P_e e\right] \qquad \text{(AS 5100.5 8.1.6.1(1))}$$

where

Z = section modulus of the uncracked cross-section, referred to the extreme fiber at which flexural cracking occurs

$f'_{ct.f}$ = characteristic flexural tensile strength of concrete at 28 days

P_e = total effective prestress force allowing for all losses of prestress

e = eccentricity of the prestressing force (P_e), measured from the centroidal axis of the uncracked section

3.5.6 Check Design Moments

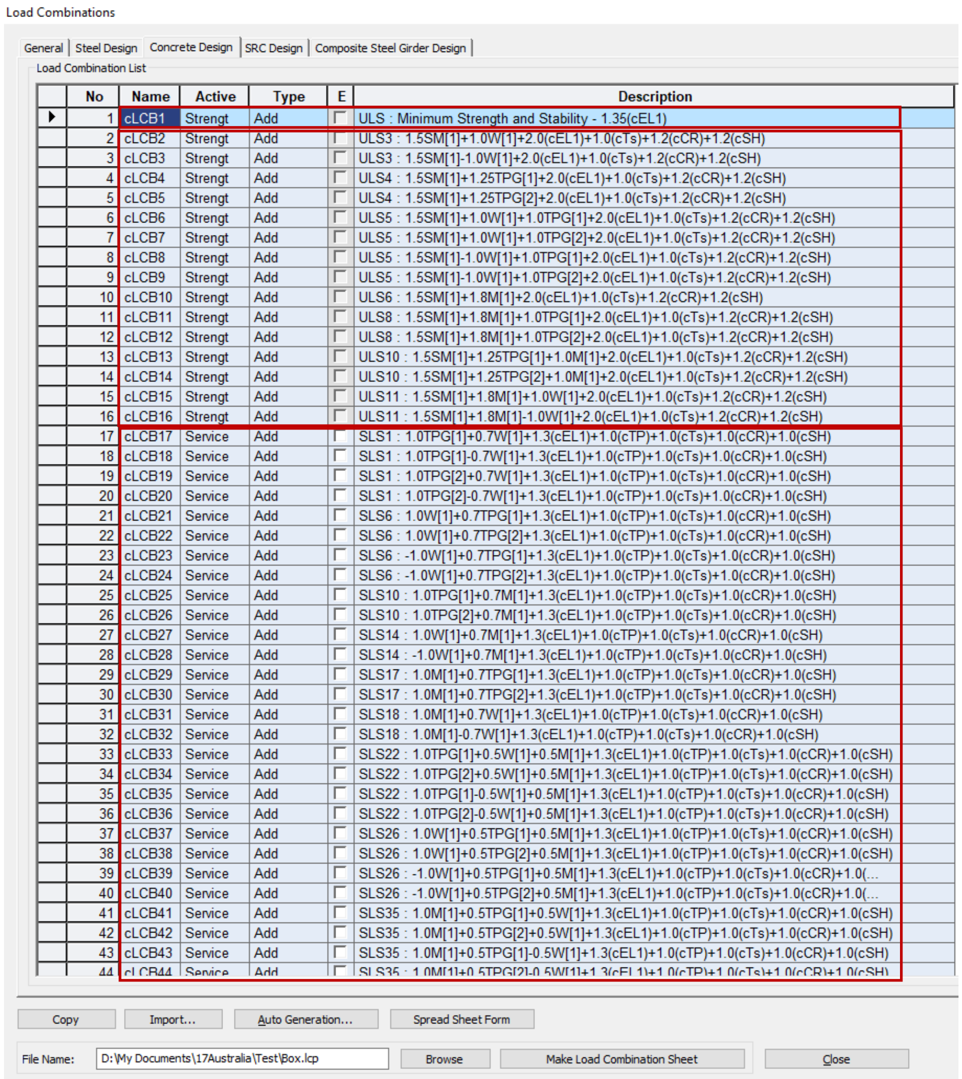
In the program, factored moment is obtained from load combinations specified in Load Combinations dialog box. In AS 5100.5-2017 specification, load combinations need to be generated as shown below.

(a) Minimum strength and stability.

(b) PE + road traffic loads.
(c) PE + pedestrian, cyclist path and maintenance traffic loads.
(e) PE + collision load.
(g) PE + earth pressure from traffic load.
(h) PE + earthquake effects.
(i) PE + water flow forces.
(j) PE + wind load.
(k) PE + thermal effects

In the program, load combinations can be automatically generated by clicking [Auto Generation…] button. The load combinations need to be generated in concrete design tab. The most critical load combination among *Strength* type load combinations will be used to obtain factored moment, factored shear force, and factored torsional moment to verify ultimate limit state. The *Service* type load combinations will be used to verify the serviceability limit state or crack control.

▶Results>Load combinations>Concrete Design tab



No	Name	Active	Type	E	Description
1	cLCB1	Strengt	Add		ULS : Minimum Strength and Stability - 1.35(cEL1)
2	cLCB2	Strengt	Add		ULS3 : 1.5SM[1]+1.0W[1]+2.0(cEL1)+1.0(cTs)+1.2(cCR)+1.2(cSH)
3	cLCB3	Strengt	Add		ULS3 : 1.5SM[1]-1.0W[1]+2.0(cEL1)+1.0(cTs)+1.2(cCR)+1.2(cSH)
4	cLCB4	Strengt	Add		ULS4 : 1.5SM[1]+1.25TPG[1]+2.0(cEL1)+1.0(cTs)+1.2(cCR)+1.2(cSH)
5	cLCB5	Strengt	Add		ULS4 : 1.5SM[1]+1.25TPG[2]+2.0(cEL1)+1.0(cTs)+1.2(cCR)+1.2(cSH)
6	cLCB6	Strengt	Add		ULS5 : 1.5SM[1]+1.0W[1]+1.0TPG[1]+2.0(cEL1)+1.0(cTs)+1.2(cCR)+1.2(cSH)
7	cLCB7	Strengt	Add		ULS5 : 1.5SM[1]+1.0W[1]+1.0TPG[2]+2.0(cEL1)+1.0(cTs)+1.2(cCR)+1.2(cSH)
8	cLCB8	Strengt	Add		ULS5 : 1.5SM[1]-1.0W[1]+1.0TPG[1]+2.0(cEL1)+1.0(cTs)+1.2(cCR)+1.2(cSH)
9	cLCB9	Strengt	Add		ULS5 : 1.5SM[1]-1.0W[1]+1.0TPG[2]+2.0(cEL1)+1.0(cTs)+1.2(cCR)+1.2(cSH)
10	cLCB10	Strengt	Add		ULS6 : 1.5SM[1]+1.8M[1]+2.0(cEL1)+1.0(cTs)+1.2(cCR)+1.2(cSH)
11	cLCB11	Strengt	Add		ULS8 : 1.5SM[1]+1.8M[1]+1.0TPG[1]+2.0(cEL1)+1.0(cTs)+1.2(cCR)+1.2(cSH)
12	cLCB12	Strengt	Add		ULS8 : 1.5SM[1]+1.8M[1]+1.0TPG[2]+2.0(cEL1)+1.0(cTs)+1.2(cCR)+1.2(cSH)
13	cLCB13	Strengt	Add		ULS10 : 1.5SM[1]+1.25TPG[1]+1.0M[1]+2.0(cEL1)+1.0(cTs)+1.2(cCR)+1.2(cSH)
14	cLCB14	Strengt	Add		ULS10 : 1.5SM[1]+1.25TPG[2]+1.0M[1]+2.0(cEL1)+1.0(cTs)+1.2(cCR)+1.2(cSH)
15	cLCB15	Strengt	Add		ULS11 : 1.5SM[1]+1.8M[1]+1.0W[1]+2.0(cEL1)+1.0(cTs)+1.2(cCR)+1.2(cSH)
16	cLCB16	Strengt	Add		ULS11 : 1.5SM[1]+1.8M[1]-1.0W[1]+2.0(cEL1)+1.0(cTs)+1.2(cCR)+1.2(cSH)
17	cLCB17	Service	Add		SLS1 : 1.0TPG[1]+0.7W[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
18	cLCB18	Service	Add		SLS1 : 1.0TPG[1]-0.7W[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
19	cLCB19	Service	Add		SLS1 : 1.0TPG[2]+0.7W[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
20	cLCB20	Service	Add		SLS1 : 1.0TPG[2]-0.7W[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
21	cLCB21	Service	Add		SLS6 : 1.0W[1]+0.7TPG[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
22	cLCB22	Service	Add		SLS6 : 1.0W[1]+0.7TPG[2]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
23	cLCB23	Service	Add		SLS6 : -1.0W[1]+0.7TPG[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
24	cLCB24	Service	Add		SLS6 : -1.0W[1]+0.7TPG[2]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
25	cLCB25	Service	Add		SLS10 : 1.0TPG[1]+0.7M[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
26	cLCB26	Service	Add		SLS10 : 1.0TPG[2]+0.7M[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
27	cLCB27	Service	Add		SLS14 : 1.0W[1]+0.7M[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
28	cLCB28	Service	Add		SLS14 : -1.0W[1]+0.7M[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
29	cLCB29	Service	Add		SLS17 : 1.0M[1]+0.7TPG[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
30	cLCB30	Service	Add		SLS17 : 1.0M[1]+0.7TPG[2]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
31	cLCB31	Service	Add		SLS18 : 1.0M[1]+0.7W[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
32	cLCB32	Service	Add		SLS18 : 1.0M[1]-0.7W[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
33	cLCB33	Service	Add		SLS22 : 1.0TPG[1]+0.5W[1]+0.5M[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
34	cLCB34	Service	Add		SLS22 : 1.0TPG[2]+0.5W[1]+0.5M[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
35	cLCB35	Service	Add		SLS22 : 1.0TPG[1]-0.5W[1]+0.5M[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
36	cLCB36	Service	Add		SLS22 : 1.0TPG[2]-0.5W[1]+0.5M[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
37	cLCB37	Service	Add		SLS26 : 1.0W[1]+0.5TPG[1]+0.5M[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
38	cLCB38	Service	Add		SLS26 : 1.0W[1]+0.5TPG[2]+0.5M[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
39	cLCB39	Service	Add		SLS26 : -1.0W[1]+0.5TPG[1]+0.5M[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(...
40	cLCB40	Service	Add		SLS26 : -1.0W[1]+0.5TPG[2]+0.5M[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(...
41	cLCB41	Service	Add		SLS35 : 1.0M[1]+0.5TPG[1]+0.5W[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
42	cLCB42	Service	Add		SLS35 : 1.0M[1]+0.5TPG[2]+0.5W[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
43	cLCB43	Service	Add		SLS35 : 1.0M[1]+0.5TPG[1]-0.5W[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)
44	cLCB44	Service	Add		SLS35 : 1.0M[1]+0.5TPG[2]-0.5W[1]+1.3(cEL1)+1.0(cTP)+1.0(cTs)+1.0(cCR)+1.0(cSH)

Figure 3- 26 Load Combinations dialog box

3.5.7 Post-processing for Bending Strength Verification

3.5.7.1 Result Tables

The results can be checked as shown in the table below.

▶Design>PSC Design>PSC Design Result Tables>Check Flexural Strength…

Elem	Part	Positive/ Negative	LCom Name	Type	CHK	M* (kN*m)	PhiMu (kN*m)	M*/PhiMu	(Muo)min (kN*m)	As,min (m^2)	As (m^2)
1	I[1]	Negative	cLCB5	FY-MAX	OK	-238.7446	40362.4862	0.0059	40885.7505	0.0047	0.0110
1	I[1]	Positive	cLCB1	-	OK	0.0000	56582.6728	0.0000	47786.5850	0.0047	0.0060
1	J[2]	Negative	cLCB5	FY-MIN	OK	0.0000	34348.2743	0.0000	36406.2331	0.0047	0.0110
1	J[2]	Positive	cLCB4	FY-MAX	OK	11895.1798	63154.5017	0.1884	53054.1432	0.0047	0.0060
2	I[2]	Negative	cLCB5	FY-MIN	OK	0.0000	34348.3076	0.0000	36406.3208	0.0047	0.0110
2	I[2]	Positive	cLCB4	FY-MAX	OK	11892.2849	63154.5017	0.1883	53054.8024	0.0047	0.0060
2	J[3]	Negative	cLCB5	FY-MIN	OK	0.0000	28578.8145	0.0000	31669.4378	0.0047	0.0110
2	J[3]	Positive	cLCB4	FY-MAX	OK	21588.3915	69916.9856	0.3088	58656.8037	0.0047	0.0060
3	I[3]	Negative	cLCB5	FY-MIN	OK	0.0000	28578.8133	0.0000	31669.2452	0.0047	0.0110
3	I[3]	Positive	cLCB4	FY-MAX	OK	21585.6542	69916.9856	0.3087	58656.6280	0.0047	0.0060
3	J[4]	Negative	cLCB5	FY-MIN	OK	0.0000	23997.6696	0.0000	27759.5480	0.0047	0.0110
3	J[4]	Positive	cLCB4	FY-MAX	OK	29670.1753	75281.8842	0.3941	63512.7227	0.0047	0.0060
4	I[4]	Negative	cLCB5	FY-MIN	OK	0.0000	23997.6673	0.0000	27759.4520	0.0047	0.0110
4	I[4]	Positive	cLCB4	FY-MAX	OK	29667.5805	75281.8842	0.3941	63512.4361	0.0047	0.0060
4	J[5]	Negative	cLCB5	FY-MIN	OK	0.0000	20642.7471	0.0000	24832.4475	0.0047	0.0110
4	J[5]	Positive	cLCB4	FY-MAX	OK	36140.5297	79104.5020	0.4569	67299.0981	0.0047	0.0060
5	I[5]	Negative	cLCB5	FY-MIN	OK	0.0000	20642.6942	0.0000	24832.4606	0.0047	0.0110
5	I[5]	Positive	cLCB4	FY-MAX	OK	36139.2834	79104.5020	0.4569	67298.1251	0.0047	0.0060
5	J[6]	Negative	cLCB5	FY-MIN	OK	0.0000	18631.9955	0.0000	23096.5747	0.0047	0.0110
5	J[6]	Positive	cLCB4	FY-MAX	OK	41000.8063	81400.7632	0.5037	68741.2277	0.0047	0.0060
6	I[6]	Negative	cLCB5	FY-MIN	OK	0.0000	18631.9218	0.0000	23096.7679	0.0047	0.0110
6	I[6]	Positive	cLCB4	FY-MAX	OK	41001.5367	81400.7632	0.5037	68739.1804	0.0047	0.0060
6	J[7]	Negative	cLCB5	FY-MIN	OK	0.0000	17974.2390	0.0000	22612.5658	0.0047	0.0110
6	J[7]	Positive	cLCB4	FY-MAX	OK	44251.5049	82162.0155	0.5386	68635.7906	0.0047	0.0060
7	I[7]	Negative	cLCB5	FY-MIN	OK	0.0000	17974.1997	0.0000	22612.7069	0.0047	0.0110
7	I[7]	Positive	cLCB4	FY-MAX	OK	44252.2705	82162.0155	0.5386	68634.5386	0.0047	0.0060
7	J[8]	Negative	cLCB5	FY-MIN	OK	0.0000	17959.6599	0.0000	22694.1573	0.0047	0.0110
7	J[8]	Positive	cLCB4	FY-MAX	OK	45890.6499	82160.3888	0.5585	68054.7010	0.0047	0.0060
8	I[8]	Negative	cLCB5	FY-MIN	OK	0.0000	17959.6438	0.0000	22694.2365	0.0047	0.0110
8	I[8]	Positive	cLCB4	FY-MAX	OK	45891.6951	82160.3888	0.5586	68054.1353	0.0047	0.0060
8	J[9]	Negative	cLCB5	FY-MIN	OK	0.0000	17940.0497	0.0000	22788.4045	0.0047	0.0110
8	J[9]	Positive	cLCB4	FY-MAX	OK	45918.5210	82162.1015	0.5589	67390.1236	0.0047	0.0060
9	I[9]	Negative	cLCB5	FY-MIN	OK	0.0000	17940.0232	0.0000	22788.5355	0.0047	0.0110

Flexure Strength

Figure 3- 27 Result Table for Bending Strength

Elem : Element number

Part : Check location (I-End, J-End) of each element.

Positive/Negative : Positive moment, negative moment.

LCom Name : Load combination name.

Type : Displays the set of member forces corresponding to moving load case or settlement load case for which the maximum stresses are produced.

CHK : Flexural strength check for element

M : Design moment*

PhiMu : Design bending strength

M/ PhiMu : Bending resistance ratio, The verification is satisfied when it is less than 1.0.*

(Muo)min : Minimum required strength in bending

3.5.7.2 Excel Report

Detail verification results can be checked in MS Excel report as shown in the figure below.

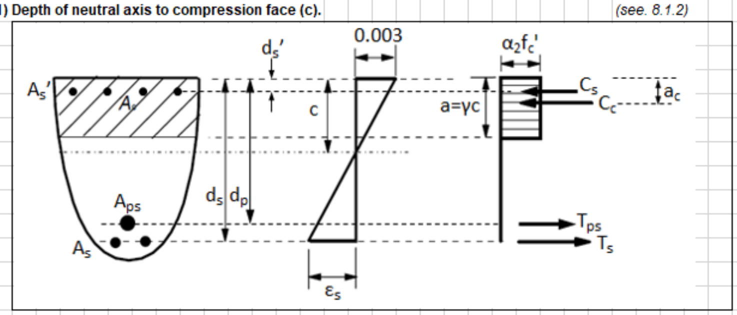
▶ Design>PSC Design>PSC Design Calculation…

2.Flexure design for a section

■ **Moment Direction : Positive**

- Method of calculation : Strain compatibility
- Maximum strength limit load combination : cLCB1
- Maximum strength limit load combination type : MY-MAX
- Maximum factored moment (M^*) : 12322.80 (kN·m)

1) Depth of neutral axis to compression face (c). *(see. 8.1.2)*



Axial force in concrete (compressive zone)					
$c = k_u d$	$a=\gamma c$	A_c	a_c	$C_c=\alpha_2 f'_c A_c$ (kN)	$C_c(c-a_c)$ (kN·m)
221.484	170.543	341085.94	85.27	11596.92	1579.65

Axial force in reinforcement steels			
tensile zone		compressive zone	
$T_s=A_s f_{sy}$ (kN)	$\Sigma A_s f_{sy}(d_s-c)$ (kN·m)	$C_s=A'_s f_{sy}$ (kN)	$\Sigma A'_s f_{sy}(c-d'_s)$ (kN·m)
0.00	0.00	0.00	0.00

No.	Axial force in tendons(Bond) by strain compatibility				
	Tendon name	ε_{ps}	f_{ps} (MPa)	$T_{ps}=A_{ps} f_{ps}$ (kN)	$A_{ps} f_{ps}(d_p-c)$ (kN·m)
1	S_strand_039	0.021375	1763.29	252.15	313.55
2	S_strand_038	0.021375	1763.29	252.15	313.55
3	S_strand_037	0.021375	1763.29	252.15	313.55
4	S_strand_036	0.021376	1763.29	252.15	313.55
5	S_strand_035	0.021376	1763.29	252.15	313.55
6	S_strand_034	0.021376	1763.29	252.15	313.55
7	S_strand_033	0.021376	1763.29	252.15	313.55

Figure 3- 28 Excel report for moment resistance

3.6 Strength of Beams in Shear

3.6.1 General

Shear resistance can be checked according to the following steps:

1) Calculate the ultimate shear strength excluding shear reinforcement (V_{uc}).
2) Compare the factored shear force (V^*) with the limit in order to decide whether the transverse shear reinforcement is required or not.
3) Calculate the ultimate shear strength ($V_u = V_{uc} + V_{us} + P_v$)
4) Calculate the ultimate shear strength limited by web crushing failure ($V_{u.max}$)
5) Determine the final design shear strength and compare it with V^*.
6) Check minimum transverse shear reinforcement.
7) Check maximum longitudinal spacing of transverse shear reinforcement.
8) Proportioning longitudinal reinforcement on the flexural tension side.
9) Proportioning longitudinal reinforcement on the flexural compression side.

The design shear strength of a beam without consideration of effects of torsion shall satisfy the following condition.

$$\phi V_u \geq V^* \qquad \text{(AS 5100.5 8.2.3.1(1))}$$

Where, capacity reduction factor for shear, ϕ=0.7.

Refer to the clause 3.8 **Strength of Beams in Shear and Torsion** for the verification of shear resistance where the effects of torsion are required to be considered.

3.6.2 Parameters for shear

3.6.2.1 Effective Web Width

Effective web width b_v is taken as the minimum web width in a horizontal plane across the web. For PSC single or multi-cell box girders, the web width is automatically taken as a summation of the widths for all webs. When determining the effective web width, the presence of prestressing ducts is not accounted for. This value can be entered by the user directly as shown in the figure below.

▶ Property > Section Property > Section >PSC

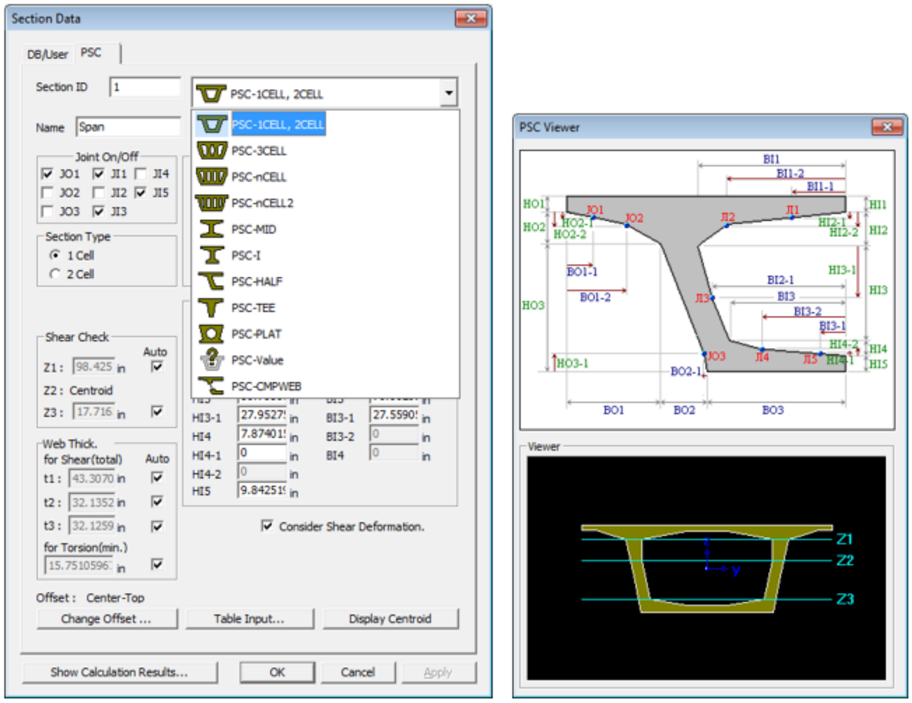


Figure 3- 29 Consideration of Effective Web Width

1) When the user directly enters values for web thickness

Apply the minimum value among the entered web thickness values.

2) When "Auto" option is selected

Apply the minimum web thickness among t1, t2, and t3. These values are automatically taken as a summation of thickness for both webs at the vertical position of Z1, Z2, and Z3.

3.6.2.2 Effective Shear Depth

The effective shear depth d_v shall be taken as the distance between the resultants of the tensile and compressive forces due to flexure but not less than the greater of 0.72D or 0.9d, where d is taken as the distance from the extreme compression fiber to the centroid of the longitudinal tension reinforcement in the half-depth of the section containing the flexural tension zone.

In the program, the effective shear depth d_v is calculated as shown in the equation below.

$$d_v = \min\left(\frac{M_n}{A_s f_s + A_{ps} f_{ps}}, 0.72D, 0.9d\right) \qquad \text{(AS 5100.5 8.2.1.9)}$$

Where,

D : Overall depth of a cross-section

d: Distance from the extreme compression fiber to the centroid of the longitudinal tension reinforcement in the half-depth of the section containing the flexural tension zone

$$d = \frac{A_{ps} f_{ps} d_p + A_s f_s d_s}{A_{ps} f_{ps} + A_s f_s}$$

d_p : Distance from extreme compression fiber to the centroid of the prestressing tendons

d_s : Distance from extreme fiber to the centroid of nonprestressed tensile reinforcement

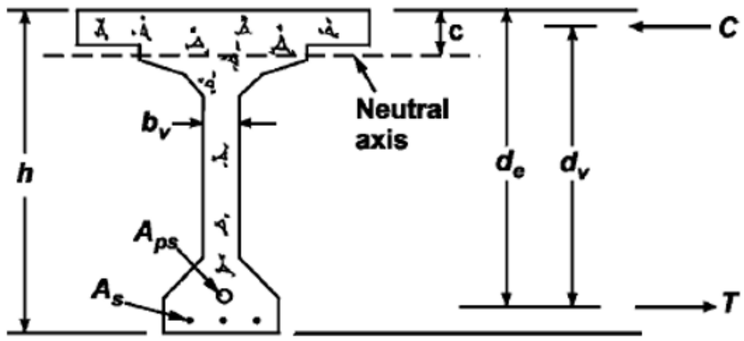


Figure 3- 30 Effective Shear Depth

Requirements for transverse shear reinforcement

The transverse shear reinforcement is provided in all regions where:

$V^* > 0.5\phi(V_{uc} + P_v)$ (AS 5100.5 8.2.1.6(a))

3.6.3 Ultimate Shear Strength

The ultimate shear strength of a beam V_u shall be determined as the lesser of:

$V_u = V_{uc} + V_{us} + P_v$ (AS 5100.5 8.2.3.1(2))

$V_{u.max} = 0.55 f'_c b_v d_v \left(\frac{\cot\theta_v + \cot\alpha_v}{1 + \cot^2\theta_v}\right) + P_v$ (AS 5100.5 8.2.3.3(1))

Where,

V_{uc} : ultimate shear strength excluding shear reinforcement

V_{us} : contribution by shear reinforcement to the ultimate shear strength

P_v : vertical component of prestress crossing the section under consideration. In the program, shear resistance due to prestressing force, Pv, includes primary prestress force. The secondary effects from prestressing shall be included in the design shear force obtained from the load combinations.

$V_{u.max}$: ultimate shear strength limited by web crushing failure

b_v: Effective web width taken as the minimum web width within the depth

d_v: Effective shear depth

θ_v : angle between the axis of the concrete compression strut and the longitudinal axis of the member

α_v : angle between the inclined shear reinforcement and the longitudinal tensile reinforcement

3.6.3.1 Ultimate shear strength by concrete

The shear strength by concrete is determined by the equation below.

$$V_{uc} = k_v\sqrt{f_c'}b_v d_v \qquad \text{(AS 5100.5 8.2.4.1)}$$

Where $\sqrt{f_c'}$ shall not exceed 8.0 MPa and k_v shall be determined in accordance with either general or simplified procedure based on modified compression field theory. The simplified procedure is for the non-prestressed components and thus the general procedure is applied in the program.

Where,
b_v: Effective web width taken as the minimum web width
d_v: Effective shear depth

Determination of k_v and θ_v

The value of k_v is calculated as follows:

(a) For sections with transverse reinforcement less than minimum shear reinforcement ($A_{sv} < A_{sv.min}$)

$$k_v = \left[\frac{0.4}{(1+1500\varepsilon_x)}\right]\left[\frac{1300}{1000+k_{dg}d_v}\right] \qquad \text{(AS 5100.5 8.2.4.2(1))}$$

where

(i) $f_c' \leq 65$ MPa

$k_{dg} = \frac{32}{(16+d_g)}$ but not less than 0.80

where d_g = maximum nominal aggregate size

(ii) $f_c' > 65$ MPa

$k_{dg} = 2.0$

Provided the maximum nominal aggregate size (d_g) is not less than 16 mm, k_{dg} may be taken as 1.0. In the program, the value of k_{dg} can automatically be calculated using the value of d_g entered by the user in the Design Parameter dialog box. k_{dg} can be taken as 1.0 by entering 16 mm for d_g.

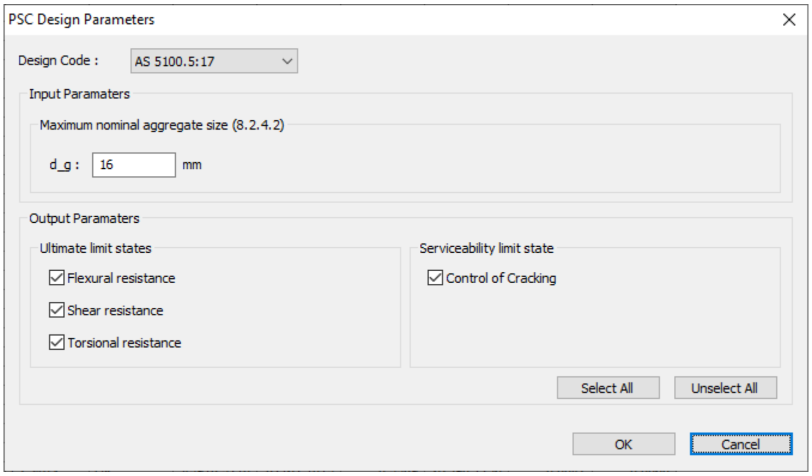


Figure 3- 31 PSC Design Parameter

(b) For sections with transverse reinforcement equal or greater than minimum shear reinforcement ($A_{sv} \geq A_{sv.min}$) —

$$k_v = \left[\frac{0.4}{(1+1500\varepsilon_x)}\right] \qquad \text{(AS 5100.5 8.2.4.2(4))}$$

The angle of inclination of the concrete compression strut and the longitudinal axis of the member (θ_v) is calculated as follows:

$$\theta_v = (29 + 7000\varepsilon_x) \qquad \text{(AS 5100.5 8.2.4.2 (5))}$$

Longitudinal strain in concrete for shear

The longitudinal strain ε_x in the concrete at the mid-depth of the section is calculated as follows:

$$\varepsilon_x = \frac{|M^*/d_v + V^*| - P_v + 0.5N^* - A_{pt}f_{po}}{2(E_sA_{st} + E_pA_{pt})} \qquad \text{(AS 5100.5 8.2.4.3(1))}$$

ε_x shall be taken within the following the limits:

$\varepsilon_x \geq 0$

$\varepsilon_x \leq +3.0 \times 10^{-3}$

In the program, where ε_x is negative (i.e. tension), ε_x is taken as zero.

where

(a) V^* and M^* are absolute values and $M^* \geq (V^* - P_v)d_v$.
(b) N^* is taken as positive for tension and negative for compression.
(c) A_{st} and A_{pt} are the areas of reinforcing bars and prestressing tendons in the half-depth of the section containing the flexural tension zone.

In the program, f_{po} is taken as $0.7f_{pb}$ for bonded tendons and σ_p for unbonded tendons.

For sections closer than d_o to the face of the support, the value of ε_x calculated at d_o from the face of the support may be used in evaluating θ and k_v. There is no consideration about this in the program.

If the axial tension is large enough to crack the flexural compression face of the section, the resulting increase in ε_x shall be taken into account. In lieu of more accurate calculations, ε_x calculated from the equation shall be doubled. There is no consideration about this in the program.

θ_v and k_v may be determined from AS 5100.5-2017 Clause 8.2.4.2 using a value of ε_x that is greater than that calculated from the equation in this Clause. ε_x shall be taken as not greater than 3.0×10^{-3}. User-defined value of ε_x is not available in the program.

In order to apply concurrent moment M^* and shear V^* for the calculation of ε_x, the concurrent force option should be selected in the Moving Load Analysis Control Data dialog box.

3.6.3.2 Ultimate Shear Strength by shear reinforcement

The contribution to the design shear strength (V_u) by shear reinforcement in a beam (V_{us}) shall be determined from the following equations:

For perpendicular shear reinforcement:

$$V_{us} = (A_{sv} f_{sy.f} d_v / s)\cot\theta_v \qquad \text{(AS 5100.5 8.2.5.2(1))}$$

For inclined shear reinforcement:

$$V_{us} = (A_{sv} f_{sy.f} d_v / s)(\sin\alpha_v \cot\theta_v + \cos\alpha_v) \qquad \text{(AS 5100.5 8.2.5.2(2))}$$

where

α_v = angle between the inclined shear reinforcement and the longitudinal tensile reinforcement

The transverse reinforcement for shear can be defined from *Section Manager*.

▶Model>Properties>Section Manager>Reinforcements

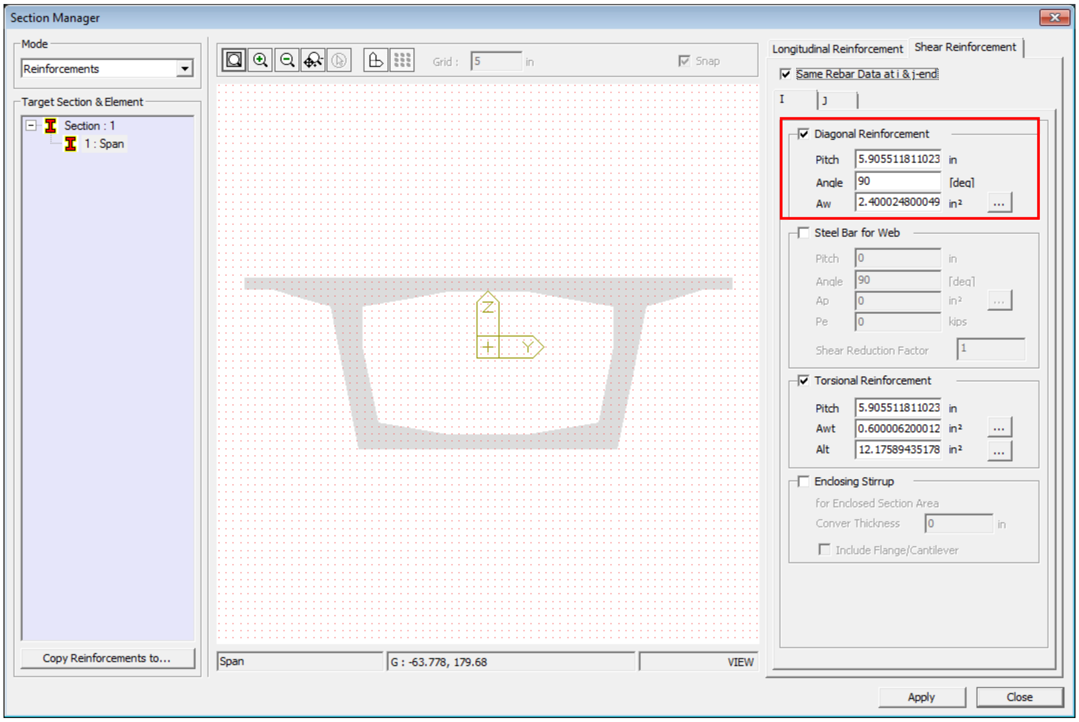


Figure 3- 32 Transverse Reinforcement

The required input data for transverse reinforcement are as follows:

- Pitch: Enter the longitudinal spacing of transverse shear reinforcement.
- Angle: Enter the angle of inclination of transverse shear reinforcement.
- A_w: Enter the area of transverse shear reinforcement within distance pitch crossing all the webs in a cross-section

3.6.3.3 Vertical component of prestress

Where the vertical component of the prestressing force (P_v) at the section under consideration is greater than the minimum design shear force (V^*_{min}), the following additional design action shall be considered:

$$V^* = 1.2P_v - V^*_{min} \qquad \text{(AS 5100.5 8.2.1.3)}$$

where

V^*_{min} = minimum design shear force for all load combinations

In this case, P_v shall be taken as zero for the determination of the shear capacity.

The current version does not take this provision into account. The vertical component of the prestressing force (CS: Tendon Primary) either increase or decrease the shear strength of a beam depending on the direction of the vertical component of the prestressing force.

3.6.4 Proportioning Longitudinal Reinforcement

3.6.4.1 Flexural Tension Side

Additional longitudinal reinforcement and tendons on the flexural tension side of a beam section shall be proportioned such that the additional force is greater than or equal to ΔF_{td}, calculated as follows:

[Shear without torsion]

$$\Delta F_{td} = \left[\left(V^* - \gamma_p P_v\right) - 0.5\phi V_{us}\right]\cot\theta_v \qquad \text{(AS 5100.5 8.2.7(2))}$$

where V^* is the absolute value of shear force.

Additional reinforcement (ΔA_s) and/or additional tendons (ΔA_p) shall be fully anchored and proportioned such that the following is satisfied:

$$\Delta A_s f_{sy} + \Delta A_p \sigma_{pu} \geq \Delta F_{td}/\phi \qquad \text{(AS 5100.5 8.2.7(3))}$$

where ϕ = 0.7

In the program, the additional force ΔF_{td}, is calculated and additional reinforcement (ΔA_s) is provided assuming that additional tendons (ΔA_p) is zero using the equation below.

$$\Delta A_s f_{sy} \geq \Delta F_{td}/\phi$$

At simply supported end supports, the longitudinal reinforcement and tendons on the flexural tension side of the beam shall be capable of resisting a tensile force of $(\Delta F_{td} + 0.5N^*)/\varphi$. There is no consideration about this in the program.

3.6.4.2 Flexural Compression Side

Additional longitudinal reinforcement on the flexural compression side of the beam section shall be proportioned such that the additional force is greater than or equal to the force ΔF_{cd}, calculated as follows:

[Shear without torsion]

$$\Delta F_{cd} = \left[\left(V^* - \gamma_p P_v\right) - 0.5\phi V_{us}\right]\cot\theta_v - F_c^* \qquad \text{(AS 5100.5 8.2.8(2))}$$

where F_c^* is the absolute value of the design force in the compressive zone due to flexure and axial actions.

Additional reinforcement (ΔA_s) and/or additional tendons (ΔA_p) shall be anchored and proportioned such that the following is satisfied:

$$\Delta A_s f_{sy} + \Delta A_p \sigma_{pu} \geq \Delta F_{cd}/\phi \qquad \text{(AS 5100.5 8.2.8)}$$

where ϕ = 0.7

In the program, the additional force ΔF_{cd}, is calculated and additional reinforcement (ΔA_s) is provided assuming that additional tendons (ΔA_p) is zero using the equation below.

$$\Delta A_s f_{sy} \geq \Delta F_{cd}/\phi$$

3.6.5 Extension of longitudinal reinforcement and tendons

At every section, the longitudinal reinforcement and tendons shall be designed to resist the flexural design force determined in AS 5100.5-2017 Clause 8.1.5 and additional longitudinal forces caused by shear and torsion as specified in AS 5100.5-2017 Clause 8.2.7, Clause 8.2.8

For members not subjected to significant direct tension or torsion, these requirements may be satisfied by extending the flexural tension reinforcement and tendons to develop the flexural tensile force beyond the location required by flexure alone as follows:

(a) Where transverse reinforcement is not required, a distance D.

(b) Where transverse reinforcement is required, a distance $d_o \cot\theta_v$.

where D and d_o are taken at the section under consideration.

In the program, the required longitudinal reinforcement and tendons are determined only to resist flexural design force determined in AS 5100.5-2017 Clause 8.1.5. The additional longitudinal reinforcement required by shear and torsion as specified in AS 5100.5-2017 Clause 8.2.7, Clause 8.2.8 is only provided but not used to check the strength of the cross-section.

3.6.6 Detailing for Transverse Shear Reinforcement

3.6.6.1 Maximum Spacing for Transverse Shear Reinforcement

Shear reinforcement shall be spaced longitudinally not further apart than 0.5*D* or 300 mm, whichever is less.

3.6.6.2 Minimum Transverse Shear Reinforcement

The cross-sectional area of minimum shear reinforcement ($A_{sv.min}$) provided in a beam shall be calculated from the following equation:

$$A_{sv.min} = 0.08\sqrt{f_c'}b_v s/f_{sy.f} \geq 0.35 b_v s/f_{sy.f} \qquad \text{(AS 5100.5 8.2.1.7)}$$

where

s = centre-to-centre spacing of shear reinforcement, measured parallel to the longitudinal axis of the member

3.6.7 Check Design Shear Forces

The program checks the shear strength limit state for the V_{max} and V_{min} cases among the active strength load combinations, which are defined in the *Load Combinations* dialog box.

3.6.8 Post-processing for Shear Strength Verification

3.6.8.1 Result Tables

The results can be checked as shown in the table below.

▶ Design>PSC Design>PSC Design Result Tables>Check Shear Strength…

Elem	Part	LCom Name	Type	CHK	N* (kN)	M* (kN*m)	V* (kN)	PhiVu (kN)	V*/PhiVu	Vuc (kN)	Vus (kN)	Pv (kN)	Vu.max (kN)	Asv (m^2)	Asv.min (m^2)
1	I[1]	cLCB4	FY-MAX	OK	1801.7935	-238.7446	-5506.3968	13035.8834	0.4224	3064.1387	14770.6639	1464.6260	18622.6905	0.0015	0.0002
1	J[2]	cLCB4	FY-MAX	OK	1801.7935	11895.1798	-4200.7428	12668.9054	0.3316	4458.9633	16089.9123	1656.3441	18098.4363	0.0015	0.0002
2	I[2]	cLCB4	FY-MAX	OK	1824.9485	11892.2849	-4200.7596	12668.9253	0.3316	4458.9633	16089.9123	1656.3725	18098.4647	0.0015	0.0002
2	J[3]	cLCB4	FY-MAX	OK	1824.9485	21588.3915	-3556.1256	12545.6670	0.2835	4458.9633	16089.9123	1480.2893	17922.3815	0.0015	0.0002
3	I[3]	cLCB4	FY-MAX	OK	1846.7578	21585.6542	-3556.1254	12545.6493	0.2835	4458.9633	16089.9123	1480.2639	17922.3561	0.0015	0.0002
3	J[4]	cLCB4	FY-MAX	OK	1846.7578	29670.1753	-2911.4914	12975.8649	0.2244	4719.3815	17029.6164	1134.5851	18536.9499	0.0015	0.0002
4	I[4]	cLCB4	FY-MAX	OK	1867.4441	29667.5805	-2911.4966	12975.8526	0.2244	4719.3815	17029.6164	1134.5675	18536.9323	0.0015	0.0002
4	J[5]	cLCB4	FY-MAX	OK	1867.4441	36140.5297	-2266.8626	13322.6327	0.1702	4952.4309	17870.5615	770.6158	19032.3325	0.0015	0.0002
5	I[5]	cLCB4	FY-MAX	OK	1877.3091	36139.2834	-2266.9262	13322.6173	0.1702	4952.4309	17870.5615	770.5937	19032.3104	0.0015	0.0002
5	J[6]	cLCB4	FY-MAX	OK	1877.3091	41000.8063	-1622.2922	13413.4715	0.1209	5092.3726	18375.5334	384.3605	19162.1021	0.0015	0.0002
6	I[6]	cLCB4	FY-MAX	OK	1871.5497	41001.5367	-1622.3043	13413.4578	0.1209	5092.3726	18375.5334	384.3410	19162.0826	0.0015	0.0002
6	J[7]	cLCB4	FY-MAX	OK	1871.5497	44251.5049	-977.6703	13280.4613	0.0736	5138.9276	18543.5244	22.6780	18972.0876	0.0015	0.0002
7	I[7]	cLCB4	FY-MAX	OK	1865.4242	44252.2705	-977.6688	13280.4608	0.0736	5138.9276	18543.5244	22.6774	18972.0869	0.0015	0.0002
7	J[8]	cLCB5	FY-MIN	OK	1865.4242	34043.4169	343.9499	13262.5159	0.0259	5138.8285	18543.1666	2.5926	18946.4513	0.0015	0.0002
8	I[8]	cLCB5	FY-MIN	OK	1857.0863	34044.4621	343.9375	13262.5159	0.0259	5138.8285	18543.1666	2.5926	18946.4513	0.0015	0.0002
8	J[9]	cLCB5	FY-MIN	OK	1857.0863	32378.8256	988.5715	13262.5430	0.0745	5138.9328	18543.5433	2.9388	18946.4900	0.0015	0.0002
9	I[9]	cLCB5	FY-MIN	OK	1844.1894	32380.4428	988.5581	13262.5430	0.0745	5138.9328	18543.5433	2.9388	18946.4901	0.0015	0.0002
9	J[10]	cLCB5	FY-MIN	OK	1844.1894	29103.2552	1633.1921	13274.5917	0.1230	5138.1060	18540.5598	17.3224	18963.7024	0.0015	0.0002
10	I[10]	cLCB5	FY-MIN	OK	1826.2181	29105.5067	1633.1748	13274.5914	0.1230	5138.1060	18540.5598	17.3219	18963.7019	0.0015	0.0002
10	J[11]	cLCB5	FY-MIN	OK	1826.2181	24216.7771	2277.8088	13323.4264	0.1710	5142.5222	18556.4952	70.8021	19033.4663	0.0015	0.0002

Shear Strength

Figure 3- 33 Result Table for Shear Resistance

Elem : Element number

Part : Check location (I-End, J-End) of each element

LCom. Name : Load combination name.

Type : Displays the set of member forces corresponding to moving load case *or settlement load case for which the maximum stresses are produced.*

CHK : Shear strength check for element

N :*

M : Bending moment for the LCom which has Vu*

V : Maximum shear force among Strength/Stress load combinations*

PhiVu : Nominal Shear resistance.

V/PhiVu*

Vuc : Shear resistance of concrete.

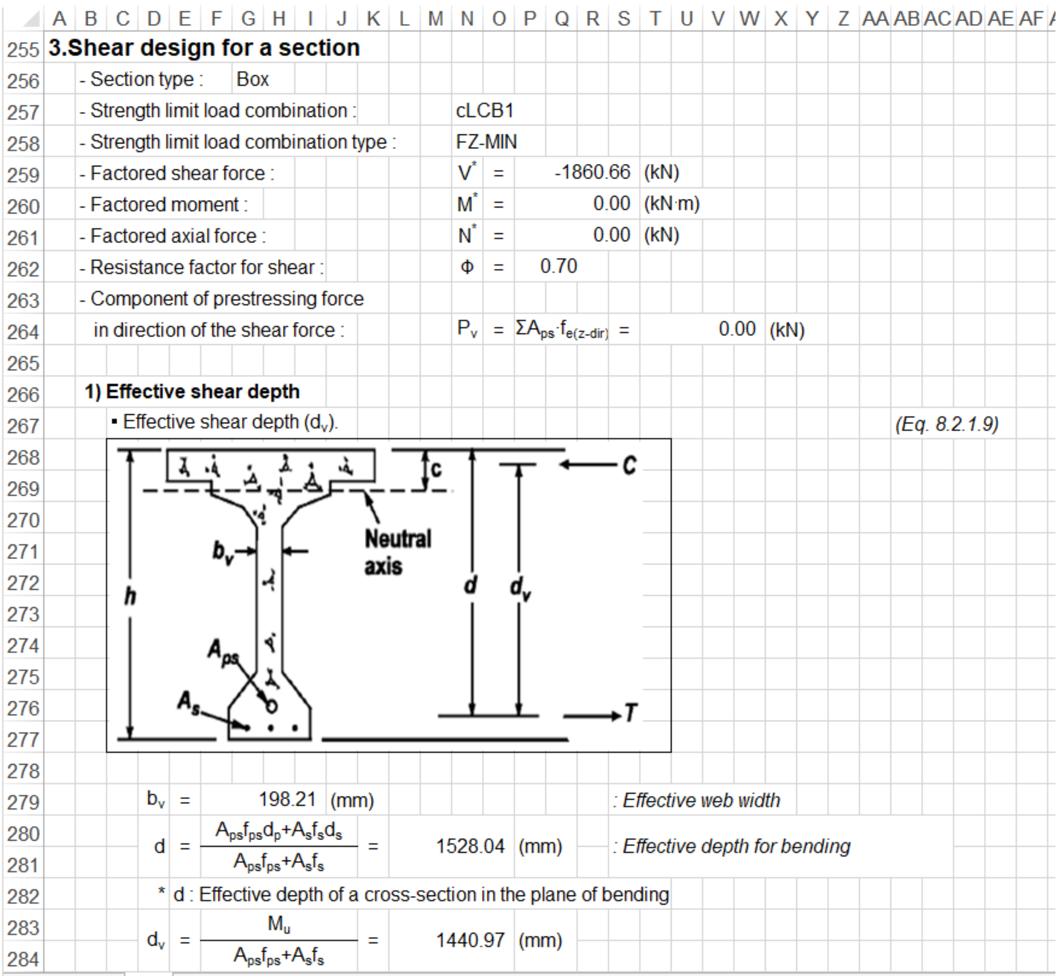
Vus : Shear resistance of shear reinforcement.

Pv : Shear force of the effective prestressing force.

3.6.8.2 Excel Report

The detailed results, which contain the calculations, are produced in the Excel Report.

▶ Design>PSC Design>PSC Design Calculation…



255 **3.Shear design for a section**

256 - Section type : Box

257 - Strength limit load combination : cLCB1

258 - Strength limit load combination type : FZ-MIN

259 - Factored shear force : $V^* = -1860.66$ (kN)

260 - Factored moment : $M^* = 0.00$ (kN·m)

261 - Factored axial force : $N^* = 0.00$ (kN)

262 - Resistance factor for shear : $\Phi = 0.70$

263 - Component of prestressing force

264 in direction of the shear force : $P_v = \Sigma A_{ps} \cdot f_{e(z\text{-dir})} = 0.00$ (kN)

265

266 **1) Effective shear depth**

267 ▪ Effective shear depth (d_v). *(Eq. 8.2.1.9)*

279 $b_v = 198.21$ (mm) *: Effective web width*

280–281 $d = \dfrac{A_{ps}f_{ps}d_p + A_s f_s d_s}{A_{ps}f_{ps} + A_s f_s} = 1528.04$ (mm) *: Effective depth for bending*

282 * d : Effective depth of a cross-section in the plane of bending

283–284 $d_v = \dfrac{M_u}{A_{ps}f_{ps} + A_s f_s} = 1440.97$ (mm)

Figure 3- 34 Excel Report for Shear Resistance

3.7 Strength of Beams in Shear and Torsion

3.7.1 General

For sections subjected to combined shear and torsion, the transverse reinforcement that is provided shall be at least equal to the sum of that required for shear and that required for the coexisting torsion. Combined shear and torsional resistance can be checked according to the following steps:

1) Calculate the torsional cracking moment (T_{cr}).
2) Compare the factored torsional moment (T^*) with the limit in order to decide whether the effect of torsion should be considered or not.
3) In case where the torsional effect should be considered, calculate the design shear strength and compare it with V*.
4) Calculate the design torsional strength and compare it with T*.
5) Check minimum torsional reinforcement.
6) Check web crushing due to combined shear and torsion.
7) Proportioning longitudinal reinforcement on the flexural tension side.
8) Proportioning longitudinal reinforcement on the flexural compression side.

3.7.2 Dimension of section for torsion

The dimensions of section that are required for checking torsion are as follows:

A_o : Area enclosed by the shear flow path, including any area of holes therein
midas Civil uses the area of the closed section enclosed by the torsion reinforcement, instead of the shear flow path.
p_h : Perimeter of the centerline of the closed transverse torsion reinforcement
A_{cp} : Total area enclosed by outside Perimeter of the concrete section
p_c : The length of the outside perimeter of concrete section

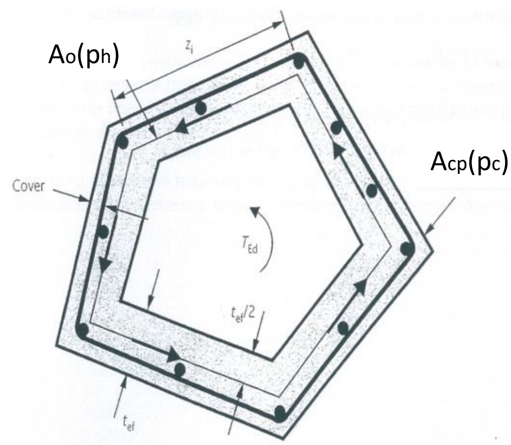


Figure 3- 35 Dimension of Section for Torsion

**Additional information for the torsional area A_o and circumference p_h calculation of the composite section.

In the program, when A_o is applied for the composite section, the girder and slab sections are calculated separately and then added. The value of p_h is calculated based on the same approach but the value of 2 x b_w is substracted in order to consider the contact area between the girder and slab.

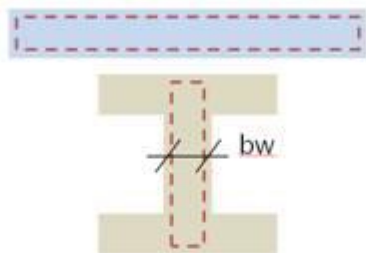


Figure 3- 36 Composite Section

3.7.3 Condition for Torsion Design

3.7.3.1 Condition

Except for slabs less than 300 mm thick, walls and footings, transverse shear reinforcement shall be provided in all regions where:

$$T^* > 0.25\phi T_{cr} \quad \text{(AS 5100.5 8.2.1.2(1))}$$

Where,

ϕ = capacity reduction factor for torsion(=0.7)

3.7.3.2 Torsional Cracking Moment (T_{cr})

$$T_{cr} = 0.33\sqrt{f_c'}\frac{A_{cp}^2}{p_c}\sqrt{\left(1+\frac{\sigma_{cp}}{0.33\sqrt{f_c'}}\right)} \quad \text{(AS 5100.5 8.2.1.2(2))}$$

Where,

A_{cp}: total area enclosed by outside perimeter of concrete section
T_{cr}: torsional cracking moment
p_c: the length of the outside perimeter of concrete cross-section
σ_{cp}: average intensity of effective prestress in concrete at the centroid, or at the junction of the web and flange when the centroid lies inside the flange

where T^* is calculated on an uncracked sectional analysis.

For cellular structures:

$$\frac{A_{cp}^2}{p_c} \le 2A_o b_v \qquad \text{(AS 5100.5 8.2.1.2(3))}$$

where
A_o: area enclosed by shear flow path, including any area of holes therein
b_v: effective width of the critical web

3.7.4 Ultimate Shear Strength

The ultimate shear strength of a beam V_u is determined as follows:

$$V_u = V_{uc} + V_{us} + P_v \qquad \text{(AS 5100.5 8.2.3.1(2))}$$

Where,
V_{uc} : ultimate shear strength excluding shear reinforcement
V_{us} : contribution by shear reinforcement to the ultimate shear strength
P_v : vertical component of prestress crossing the section under consideration. In the program, shear resistance due to prestressing force, P_v, includes primary prestress force. The secondary effects from prestressing shall be included in the design shear force obtained from the load combinations.

3.7.4.1 Ultimate Shear Strength by Concrete

The shear strength is determined by the equation below.

$$V_{uc} = k_v \sqrt{f'_c} b_v d_v \qquad \text{(AS 5100.5 8.2.4.1)}$$

Where $\sqrt{f'_c}$ shall not exceed 8.0 MPa and k_v shall be determined in accordance with either general or simplified procedure based on modified compression field theory. The simplified procedure is for the non-prestressed components and thus the general procedure is applied in the program.

Where,
b_v: Effective web width taken as the minimum web width

d_v: Effective shear depth

Determination of k_v and θ_v

The value of k_v is calculated as follows:

a) For sections with transverse reinforcement less than minimum shear reinforcement ($A_{sv} < A_{sv.min}$)

$$k_v = \left[\frac{0.4}{(1+1500\varepsilon_x)}\right]\left[\frac{1300}{1000+k_{dg}d_v}\right] \quad \text{(AS 5100.5 8.2.4.2(1))}$$

where

i) $f_c' \le 65$ MPa

$k_{dg} = \frac{32}{(16+d_g)}$ but not less than 0.80

where dg = maximum nominal aggregate size

ii) $f_c' > 65$ MPa

$k_{dg} = 2.0$

Provided the maximum nominal aggregate size (d_g) is not less than 16 mm, k_{dg} may be taken as 1.0. In the program, the value of k_{dg} can automatically be calculated using the value of d_g entered by the user in the Design Parameter dialog box. k_{dg} can be taken as 1.0 by entering 16 mm for d_g.

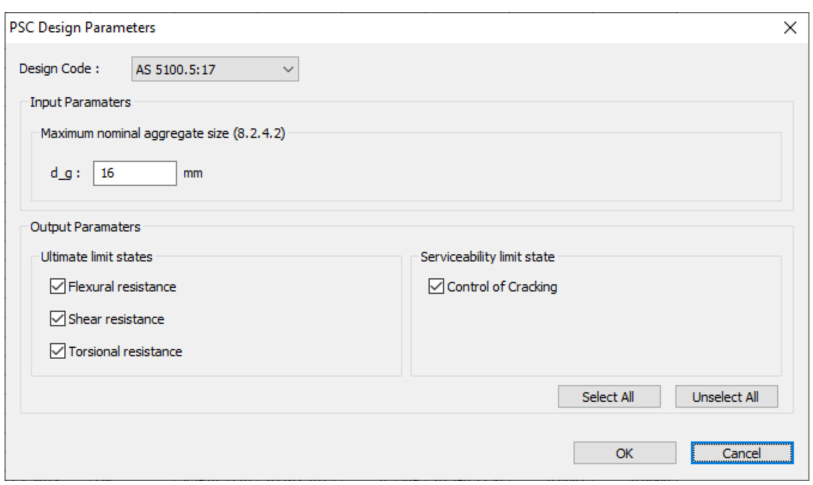


Figure 3- 37 PSC Design Parameter

b) For sections with transverse reinforcement equal or greater than minimum shear reinforcement ($A_{sv} \ge A_{sv.min}$) —

$$k_v = \left[\frac{0.4}{(1+1500\varepsilon_x)}\right] \qquad \text{(AS 5100.5 8.2.4.2(4))}$$

The angle of inclination of the concrete compression strut and the longitudinal axis of the member (θ_v) is calculated as follows:

$$\theta_v = (29 + 7000\varepsilon_x) \qquad \text{(AS 5100.5 8.2.42(5))}$$

Longitudinal strain in concrete for combined shear and torsion

The longitudinal strain ε_x in the concrete at the mid-depth of the section subjected to shear and torsion shall be calculated as follows:

$$\varepsilon_x = \frac{M^*/d_v + \sqrt{(V^* - P_v)^2 + \left[\frac{0.9T^* u_h}{2A_o}\right]^2} + 0.5N^* - A_{pt} f_{po}}{2(E_s A_{st} + E_p A_{pt})} \qquad \text{(AS 5100.5 8.2.4.4(1))}$$

ε_x shall be taken within the following the limits:

$$\varepsilon_x \geq 0$$

$$\varepsilon_x \leq +3.0 \times 10^{-3}$$

In the program, where ε_x is negative (i.e. tension), ε_x is taken as zero.

where

(a) V^* and M^* are absolute values and

$$M^* \geq d_v \sqrt{(V^* - P_v)^2 + \left[\frac{0.9T^* u_h}{2A_o}\right]^2} \qquad \text{(AS 5100.5 8.2.4.4(3))}$$

(b) N^* is taken as positive for tension and negative for compression.

(c) A_{st} and A_{pt} are the areas of reinforcing bars and prestressing tendons in the half-depth of the section containing the flexural tension zone.

In the program, f_{po} is taken as $0.7f_{pb}$ for bonded tendons and σ_p for unbonded tendons.

For sections closer than do to the face of the support, the value of ε_x calculated at do from the face of the support may be used in evaluating θ and k_v. There is no consideration about this in the program.

If the axial tension is large enough to crack the flexural compression face of the section, the resulting increase in ε_x shall be taken into account. In lieu of more accurate calculations, ε_x calculated from the equation shall be doubled. There is no consideration about this in the program.

θ_v and k_v may be determined from AS 5100.5-2017 Clause 8.2.4.2 using a value of ε_x that is greater than that calculated from the equation in this Clause. ε_x shall be taken as not greater than 3.0 × 10−3. User-defined value of ε_x is not available in the program.

In order to apply concurrent moment M^* and shear V^* for the calculation of ε_x, the concurrent force option should be selected in the Moving Load Analysis Control Data dialog box.

3.7.4.2 Ultimate Shear Strength by shear reinforcement

The contribution to the design shear strength (V_u) by shear reinforcement in a beam (V_{us}) shall be determined from the following equations:

For perpendicular shear reinforcement:

$$V_{us} = (A_{sv} f_{sy.f} d_v / s)\cot\theta_v \quad \text{(AS 5100.5 8.2.5.2(1))}$$

For inclined shear reinforcement:

$$V_{us} = (A_{sv} f_{sy.f} d_v / s)(\sin\alpha_v \cot\theta_v + \cos\alpha_v) \quad \text{(AS 5100.5 8.2.5.2(2))}$$

where

α_v = angle between the inclined shear reinforcement and the longitudinal tensile reinforcement

3.7.5 Ultimate Torsional Strength

The ultimate torsional strength shall be determined from the following equation and should meet the condition $T^* \le \phi T_{us}$.

$$T_{us} = 2A_o \frac{A_{sw} f_{sy.f}}{s} \cot\theta_v \quad \text{(AS 5100.5 8.2.5.6)}$$

Where,
A_o: 0.85 A_{oh}

The reinforcement data used for the torsion check are as follows:

▶ Model>Properties>Section Manager>Reinforcements

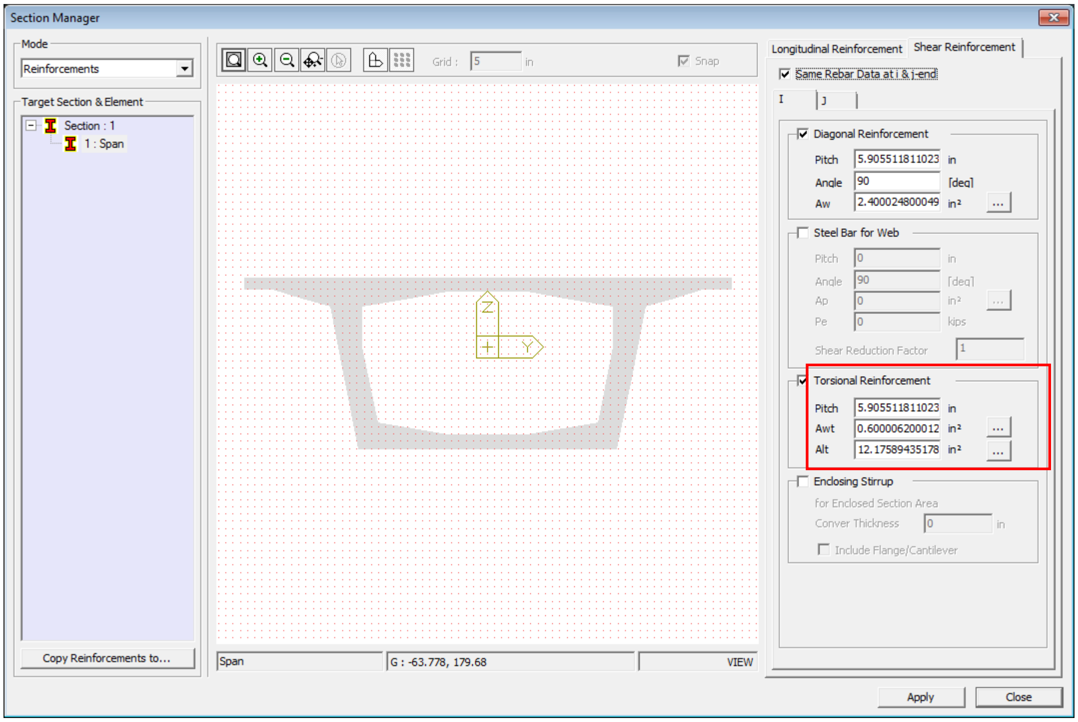


Figure 3- 38 Reinforcement Input for Torsion

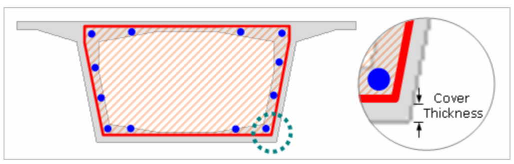


Figure 3- 39 Reinforcement Close against Outer Closed Stirrup

- Pitch : longitudinal spacing of transverse reinforcement for torsion

- A_{wt} : area of transverse reinforcement for torsion crossing a single web within distance *pitch*.

- A_{lt} : area of longitudinal torsional reinforcement. The area of all reinforcing steels ● which are close against the outer closed stirrups. In the current version, this data is not used in the design checks. However, the program provides the required area of longitudinal reinforcement due to torsion.

3.7.6 Minimum torsional reinforcement

Minimum torsional reinforcement shall consist of the following:

(a) Closed tie reinforcement, satisfying the lesser of—

(i) $T_{us} \geq T_{cr}$ and

(ii) $\frac{A_{sw}}{s} \geq \frac{0.2y_l}{f_{sy.f}}$

where y_l is the larger dimension of the closed tie.

(b) Longitudinal reinforcement in accordance with Clauses 8.2.7, 8.2.8 and 8.2.9.

In the program, additional longitudinal reinforcement in accordance with AS 5100.5-2017 Clauses 8.2.7, 8.2.8 is provided. However, the comparison with the area of longitudinal reinforcement entered by the user is not performed.

3.7.7 Web crushing due to combined shear and torsion

The wall thickness (t_w) to avoid crushing from combined shear and torsion shall be calculated as follows:

(a) For box sections:

(i) Where wall thickness $t_w > A_{oh}/u_h$

$$\frac{V^*-P_v}{b_v d_v}+\frac{T^* u_h}{1.7A_{oh}^2}\le\frac{\emptyset V_{u.max}}{b_v d_v} \qquad \text{(AS 5100.5 8.2.4.5(1))}$$

(ii) Where wall thickness $t_w \le A_{oh}/u_h$

$$\frac{V^*-P_v}{b_v d_v}+\frac{T^*}{1.7t_w A_{oh}}\le\frac{\emptyset V_{u.max}}{b_v d_v} \qquad \text{(AS 5100.5 8.2.4.5(2))}$$

(b) For other sections:

$$\sqrt{\left[\frac{V^*-P_v}{b_v d_v}\right]^2+\left[\frac{T^* u_h}{1.7A_{oh}^2}\right]^2}\le\frac{\emptyset V_{u.max}}{b_v d_v} \qquad \text{(AS 5100.5 8.2.4.5(3))}$$

where

A_{oh}: area enclosed by centre-line of exterior closed transverse torsion reinforcement, including area of holes (if any)

u_h: perimeter of the centre-line of the closed transverse torsion reinforcement

$V_{u.max}$: ultimate shear strength limited by web crushing failure, in accordance with Clause 8.2.3.3

In the program, the user can define the distance from outer surface to the center-line of exterior closed transverse torsion reinforcement using the *Enclosing Stirrup* option in *Section Manager*.

3.7.8 Proportioning longitudinal reinforcement

3.7.8.1 Flexural Tension Side

Additional longitudinal reinforcement and tendons on the flexural tension side of a beam section shall be proportioned such that the additional force is greater than or equal to ΔF_{td}, calculated as follows:

[Shear with torsion]

$$\Delta F_{td} = \sqrt{\left[\left(V^* - \gamma_p P_v\right) - 0.5\phi V_{us}\right]^2 + \left[\frac{0.45T^* u_h}{2A_o}\right]^2} \cot\theta_v \qquad \text{(AS 5100.5 8.2.7(1))}$$

where

γ_p = 0.9 when P_v reduces the shear;
= 1.15 when P_v increases the shear.

Additional reinforcement (ΔA_s) and/or additional tendons (ΔA_p) shall be fully anchored and proportioned such that the following is satisfied:

$$\Delta A_s f_{sy} + \Delta A_p \sigma_{pu} \geq \Delta F_{td}/\phi \qquad \text{(AS 5100.5 8.2.7(3))}$$

Where ϕ = 0.7

In the program, the additional force ΔF_{td}, is calculated and additional reinforcement (ΔA_s) is provided assuming that additional tendons (ΔA_p) is zero using the equation below.

$$\Delta A_s f_{sy} \geq \Delta F_{td}/\phi$$

At simply supported end supports, the longitudinal reinforcement and tendons on the flexural tension side of the beam shall be capable of resisting a tensile force of $(\Delta F_{td} + 0.5N^*)/\varphi$. There is no consideration about this in the program.

3.7.8.2 Flexural Compression Side

Additional longitudinal reinforcement on the flexural compression side of the beam section shall be proportioned such that the additional force is greater than or equal to the force ΔF_{cd}, calculated as follows:

[Shear with torsion]

$$\Delta F_{cd} = \sqrt{\left[\left(V^* - \gamma_p P_v\right) - 0.5\phi V_{us}\right]^2 + \left[\frac{0.45T^* u_h}{2A_o}\right]^2} \cot\theta_v - F_c^* \qquad \text{(AS 5100.5 8.2.8(1))}$$

but not less than zero.

Where F_c^* is the absolute value of the design force in the compressive zone due to flexure and axial actions.

Additional reinforcement (ΔA_s) and/or additional tendons (ΔA_p) shall be anchored and proportioned such that the following is satisfied:

$$\Delta A_s f_{sy} + \Delta A_p \sigma_{pu} \geq \Delta F_{cd}/\phi \qquad \text{(AS 5100.5 8.2.8}$$

Where ϕ = 0.7

In the program, the additional force ΔF_{cd}, is calculated and additional reinforcement (ΔA_s) is provided assuming that additional tendons (ΔA_p) is zero using the equation below.

$$\Delta A_s f_{sy} \geq \Delta F_{cd}/\phi$$

3.7.9 Check Design Shear and Torsion Forces

The program checks the combined shear and torsional strength limit state for the concurrent shear and torsion forces among the Active: Strength/Stress load combinations, which are defined in Fig.1.12 Load Combinations dialog box. The following three cases are reviewed and most critical case is provided in the design report.

1) V_{max}, and co-existing T
2) V_{min} and co-existing T
3) T_{max} and co-existing V

3.7.10 Check the Combined Shear and Torsion Design Results

3.7.10.1 Result Tables

The results can be checked as shown in the table below.

▶ Design>PSC Design>PSC Design Result Tables>Check Combined Shear and Torsion Strength…

	Elem	Part	LCom Name	Type	CHK	N* (kN)	M* (kN*m)	V* (kN)	T* (kN*m)	0.25PhiTcr (kN*m)	Tcr (kN*m)	PhiVu (kN)	V*/PhiVu	PhiTu (kN*m)	T*/PhiTu	Tus (kN*m)
	14	I[14]	cLCB1	FZ-MIN	OK	0.0000	10191.5277	-552.6156	745.5241	65.1473	372.2706	1518.7792	0.3639	1391.3925	0.5358	1987.7035
	14	J[15]	cLCB1	FZ-MIN	OK	0.0000	10052.1465	-468.8664	657.0720	65.2047	372.5981	1646.0589	0.2848	1486.1421	0.4421	2123.0602
	15	I[15]	cLCB1	FZ-MIN	OK	0.0000	10052.1465	-468.8664	657.0720	65.2047	372.5981	1646.0589	0.2848	1486.1421	0.4421	2123.0602
	15	J[16]	cLCB1	FZ-MIN	OK	0.0000	9848.2509	-389.6100	568.6200	65.2238	372.7073	1807.6349	0.2155	1596.6912	0.3561	2280.9875
	16	I[16]	cLCB1	FZ-MIN	OK	0.0000	9848.2509	-389.6100	568.6200	65.2238	372.7073	1807.6349	0.2155	1596.6912	0.3561	2280.9875
	16	J[17]	cLCB1	FZ-MIN	OK	0.0000	9615.7829	-316.2504	564.4080	65.2047	372.5981	1858.3760	0.1702	1629.0280	0.3465	2327.1829
	17	I[17]	cLCB1	FZ-MIN	OK	0.0000	9615.7829	-316.2504	564.4080	65.2047	372.5981	1858.3760	0.1702	1629.0280	0.3465	2327.1829
	17	J[18]	cLCB1	FZ-MIN	OK	0.0000	9276.9617	-243.1716	560.1960	65.1473	372.2706	1933.6834	0.1258	1674.8556	0.3345	2392.6509
	18	I[18]	cLCB1	FZ-MIN	OK	0.0000	9276.9617	-243.1716	560.1960	65.1473	372.2706	1933.6834	0.1258	1674.8556	0.3345	2392.6509
	18	J[19]	cLCB1	MY-MAX	OK	0.0000	12150.0005	355.2840	387.5040	65.0517	371.7240	1701.8044	0.2088	1525.5564	0.2540	2179.3663
	19	I[19]	cLCB1	MY-MAX	OK	0.0000	12150.0005	355.2840	387.5040	65.0517	371.7240	1701.8044	0.2088	1525.5564	0.2540	2179.3663
	19	J[20]	cLCB1	MY-MAX	OK	0.0000	11840.1004	466.6920	383.2920	64.9176	370.9574	1752.6604	0.2663	1560.3537	0.2456	2229.0767
	20	I[20]	cLCB1	MY-MAX	OK	0.0000	11840.1004	466.6920	383.2920	64.9176	370.9574	1752.6604	0.2663	1560.3537	0.2456	2229.0767
	20	J[21]	cLCB1	MY-MAX	OK	0.0000	11351.4004	662.3400	294.8400	64.7447	369.9695	1977.4958	0.3349	1700.3146	0.1734	2429.0209

Figure 3- 40 Result Table for Combined Shear and Torsion

Elem : Element number
Part : Check location (I-End, J-End) of each element
Max./Min.: Maximum torsion/shear, minimum torsion/shear
LCom Name: Load combination name.
Type: Displays the set of member forces corresponding to moving load case or settlement load case for which the maximum stresses are produced.
CHK: Shear and torsion strength check for element

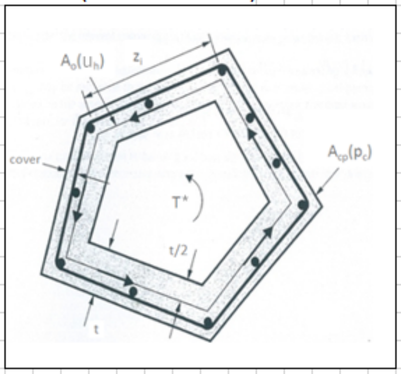
3.7.10.2 Excel Report

Detail verification results can be checked in MS Excel report as shown in the figure below.

▶ Design>PSC Design>PSC Design Calculation…

4. Torsional design for a section

■ Notation (Shear and Torsion)



A_{oh} = Area enclosed by centre-line of exterior closed transverse torsion reinforcement, including area of holes (if any).
= 9.061E+05 (mm^2)

u_h = Perimeter of the centerline of the closed tranverse torsion reinforcement.
= 12802.96 (mm)

A_{cp} = Total area enclosed by outside Perimeter of the concrete section.
= 9.061E+05 (mm^2)

p_c = The length of the outside perimeter of concrete section.
= 12087.90 (mm)

- Section type : Nonsegmental-Box
- Strength llimit load combination : cLCB1
- Strength llimit load combination type : FZ-MIN
- Factored torsional moment : T^* = 1137.24 (kN·m)
- Factored shear force : V^* = -1860.66 (kN)
- Factored moment : M^* = 0.00 (kN·m)
- Factored axial force : N^* = 0.00 (kN)
- Resistance factor for shear : Φ = 0.70 *(see. Table 2.3.2-c)*
- Component of prestressing force in direction of the shear force : P_v = $\Sigma A_{ps} \cdot f_{e(z\text{-}dir)}$ = 0.00 (kN)

1) Checking Torsional Effects

▪ Torsional cracking moment (T_{cr}).

$$T_{cr} = 0.33\sqrt{f'_c}\frac{A^2_{cp}}{p_c}\sqrt{\left(1+\frac{\sigma_{cp}}{0.33\sqrt{f'_c}}\right)} = 344.88 \text{ (kN·m)}$$ *(Eq. 8.2.1.2-2)*

where,

A_{cp}^2/p_c = min [A_{cp}^2/p_c , $2A_ob_v$]= min [6.22.E+07 , 3.59.E+08] = 6.22.E+07 (mm^3)

$_{cp}$ = *Compressive stress in concrete due to effective prestress only.*

$$= \frac{\Sigma A_{ps} \cdot f_{e(x\text{-}dir)}}{A_g} + \frac{\Sigma A_{ps} \cdot f_{e(x\text{-}dir)} \cdot e_p \cdot y_{joint}}{I_y} = 8.71 \text{ (MPa)}$$

T^* = 1137.24 (kN·m) > $0.25\Phi T_{cr}$ = 60.35 (kN·m) *(Eq. 8.2.1.2-1)*

∴ $T^* > 0.25\Phi T_{cr}$, Consider torsional effects.

Figure 3- 41 Excel Report for Combined Shear and Torsion

3.8 Crack Control for Flexure in Prestressed Beams

3.8.1 General

Flexural cracking in a prestressed beam shall be deemed to be controlled if, under SLS load combinations, the resulting maximum tensile stress in the concrete does not exceed $0.25\sqrt{f_c'}$ and $0.25\sqrt{f_{cp}'}$, or, if this stress is exceeded, by providing reinforcement or bonded tendons, or both, near the tensile face with a centre-to-centre spacing not exceeding 200 mm and limiting either

(a) the calculated maximum flexural tensile stress under SLS load combination, including transfer limited to $0.5\sqrt{f_c'}$ and $0.5\sqrt{f_{cp}'}$; or

(b) the increment in steel stress near the tension face must be limited to 160 MPa, as the load increases from its value when the extreme concrete tensile fiber is at zero stress to the SLS load combinations values.

In the current version, the crack control at transfer is not supported and the stress limit in the concrete and steel cannot be modified. The crack control of the precast composite section under negative moment is not supported.

Procedure to calculate incremental stress:

- Non-composite section.

1. Calculate the effective stress in the tendon after losses, $f_{p1} = f_{pe}$.

$$f_{p1} = f_{pe} = P_e/A_p$$

2. Find the increase in stress in the tendon f_{p2} as the member passes to a decompression stage.

$$\varepsilon_{p2} = \frac{P_e}{A_c E_c}\left(1 + \frac{e^2}{r^2}\right) \qquad f_{p2} = E_p \varepsilon_{p2}$$

3. Determine decompression force F needed to produce the decompression stage.

$$F = A_p\left(f_{p1} + f_{p2}\right)$$

4. Apply an equal and opposite force F to the member, in combination with the moments due to dead and live loads. The resultant force R=F has an equivalent eccentricity.

$$\bar{e} = (M_t - Fe)/R$$

Where M_t.is the external moment due to self weight, superimposed dead loads and live loads excluding Tendon Primary.

5. Assume the neutral axis depth y of the cracked section.
6. Calculate the stress at the neutral axis due to R.

$$\sigma_{NA} - \frac{R}{A_{ct}} + \frac{Re^{*}(y - c_{top}^{*})}{I_{ct}}$$

7. Repeat step 5 and 6 until the stress at the neutral axis is zero.
8. Find the section properties $A_{ct}, I_{ct}, c_{top}^{*}$ of the cracked section.
9. Determine incremental stress f_{p3} in the tendon.

$$f_{p3} = n_p \left[-\frac{R}{A_{ct}} + \frac{Re^{*}(d_p - c_{top}^{*})}{I_{ct}} \right]$$

Worked example 1: Non-composite section

Reference: Flexural stresses after cracking in partially prestressed beams by Arthur H. Nilson in PCI Journal /July-August 1976

Data

The partially prestressed T-beam shown in the figure below is subjected to superimposed dead and service live load moments of 52 kN-m and 259 kN-m in addition to a moment of 113 kN-m due to its own weight.

An effective prestressing force of 547 kN is applied using six 12.7 mm diameter strands which are lumped into one tendon in this example (A_p = 556.77 mm^2). Two nonprestressing steel #8 bars are located close to the tension face of the beam.

The elastic moduli for the concrete, tendon steel, and bar steel are, respectively 24,900, 186,000, and 200,000 N/mm^2. The modulus of rupture of the concrete is 3.5 N/mm^2.

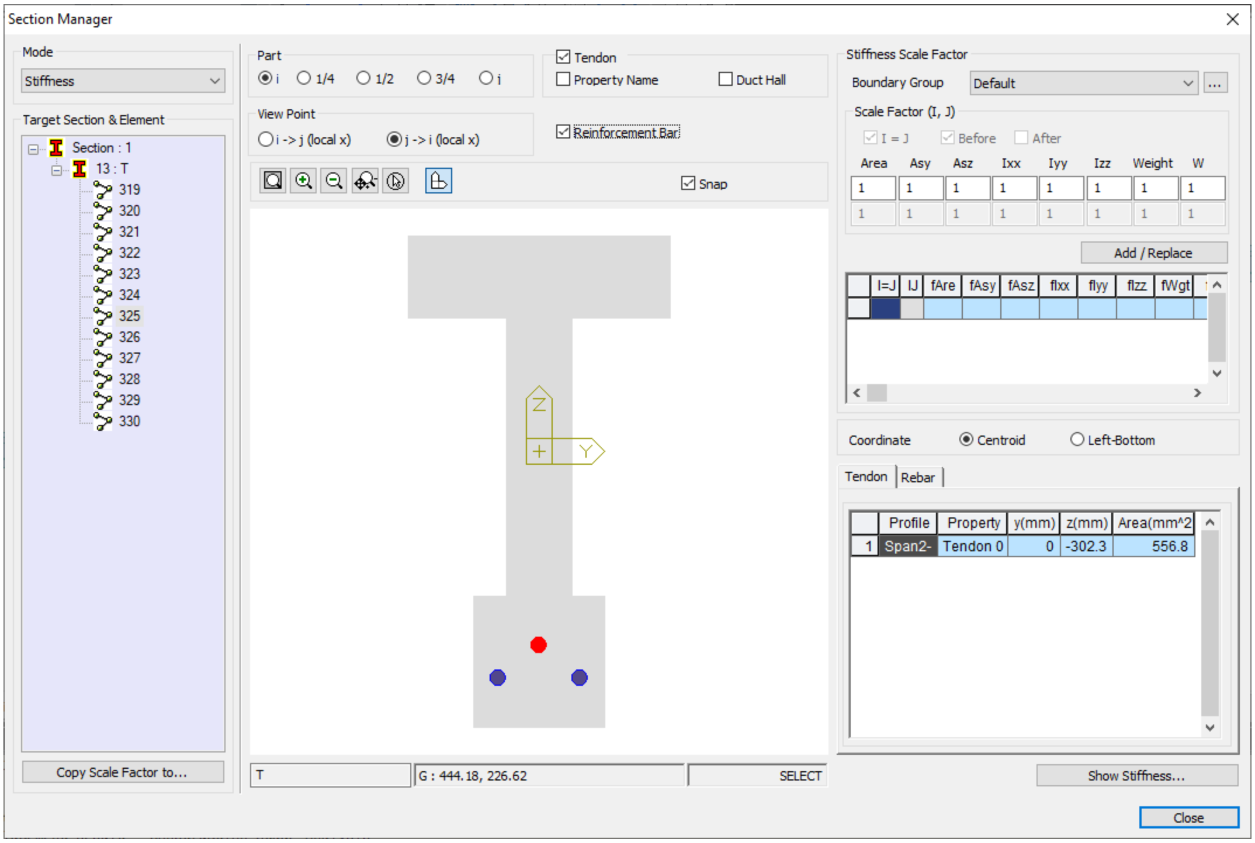


Figure 3- 42 Cross-Section

Required

Find the stress in the concrerte, prestressing steel, and bar reinforcement at the full service load.

Solution

First, the tensile stress in the concrete at the bottom of the beam will be checked, assuming the member is uncracked. The properties of the uncracked section are

$A_c = 1.368\times10^5$ mm^2 $\quad c_{top} = 332.74$ mm
$S_{top} = 2.727\times10^7$ mm^3 $\quad c_{bot} = 429.26$ mm
$S_{bot} = 2.114\times10^7$ mm^3 $\quad r^2 = 66451.5$ mm^2

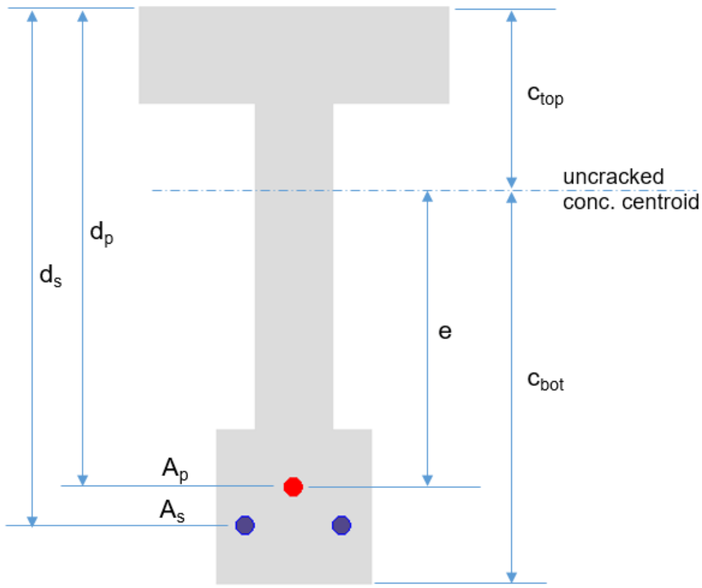


Figure 3- 43 Uncracked Cross-Section

Then the tensile stress in the concrete at the bottom of the beam f_{bot} is

$$f_{bot} = -\frac{P_e}{A_c}\left(1 + \frac{ec_{bot}}{r^2}\right) + \frac{M_t}{S_{bot}} = 8.177\ \text{MPa}$$

where *e* is the eccentricity of the prestressing force, *r* is the radius of gyration of the concrete section.

This stress greatly exceeds the modulus of rupture, indicating that the section has indeed cracked. The effective stress in the tendon when P_e acts alone is

$$f_{p1} = f_{pe} = P_e/A_p = 985.95\ \text{MPa}$$

The change in strain in the tendon as the section is decompressed is the same as that in the concrete at that level, and can be calculated on the basis of the uncracked concrete section properties.

$$\varepsilon_{p2} = \frac{P_e}{A_c E_c}\left(1 + \frac{e^2}{r^2}\right) = 0.0004$$

Thus the corresponding increase in the tendon is

$$f_{p2} = E_p \varepsilon_{p2} = 74.46\ \text{MPa}$$

To obtain decompression of the concrete, the fictitious external tension F = $A_p(f_{p1} + f_{p2}) =$ 591.6 kN must have been applied to the tendon. This is now cancelled by applying an equal and opposite force F. This force acting together with the total moment of 424 kN-m, is equivalent to a compressive force R=591.6 kN applied with eccentricity $\bar{e} = (M_t - Fe)/R = 412.75$ mm above the centroid of the uncracked concrete, or 80 mm above the top surface of the member.

With $n_p = 186000/24900 = 7.48$ and $n_s = 200000/24900 = 8.03$ the transformed areas of the tendon and the bars are, respectively, 4167.7 and 8135.5 mm^2. The effective cross section of the cracked beam, with neutral axis dimension y still unknown is shown in the figure below.

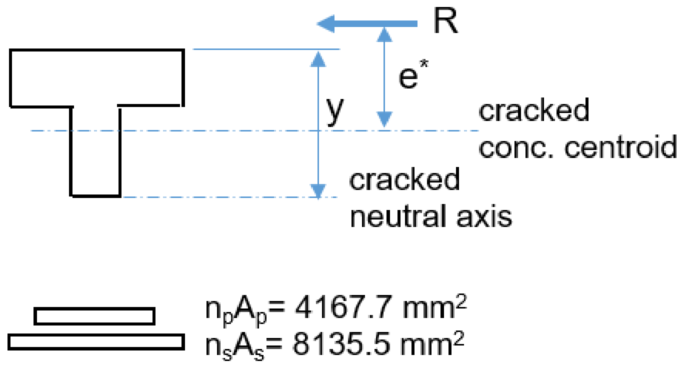


Figure 3- 44 Transformed Cracked Cross-Section

The stress at the neutral axis should be zero.

$$-\frac{R}{A_{ct}} + \frac{Re^*(y - c^*_{top})}{I_{ct}} = 0$$

Through the iteration, the neutral axis depth y = 340.36 mm is obtained.

With y known, the location of the centroid of the cracked transformed section is a routine matter. Taking moments of the partial areas about the top surface locates the centroid c^*_{top}=193.55 mm from the top of the section. Section properties of the cracked section are

$$A_{ct} = 85806.3 \text{ mm} \quad I_{ct} = 3.843 \times 10^9 \text{mm}^4$$

The eccentricity of the force R with respect to the centroid of the cracked transformed section is

$$e^* = 273.56 \text{ mm}$$

Now the incremental stress in the concrete and steel can be found as follows:

- Concrete (top)

$$f_{c3} = -\frac{R}{A_{ct}} - \frac{Re^* c^*_{top}}{I_{ct}} = -15.0 \text{ MPa}$$

- Tendon

$$f_{p3} = n_p\left[-\frac{R}{A_{ct}} + \frac{Re^*(d_p - c^*_{top})}{I_{ct}}\right] = 87.6 \text{ MPa}$$

- Bar reinforcement

$$f_{s3} = n_s\left[-\frac{R}{A_{ct}} + \frac{Re^*(d_s - c^*_{top})}{I_{ct}}\right] = 111.0 \text{ MPa}$$

- Composite section

For composite sections, the situation is more complicated. The prestress and some dead load bending are usually applied to the bare non-composite beam. This creates stress in the bare beam, but not in the composite slab. This causes a discontinuity in stress and strain at the interface and this discontinuity remains while additional loads are applied to the composite beam.

How does one find a section property of a cracked composite section when some of the forces and moments were applied to a different bare beam section? The solution is to work with section properties of the composite beam and apply all forces and moments to the composite section. This requires modifying the forces and moments applied to the bare beam to an equivalent force and moment applied to the composite beam. This equivalent force and moment must produce stresses in the bare beam portion of the composite beam that are equal to the actual stresses in the bare beam.

Worked example 2: Composite Section

Reference: Analysis of Cracked Prestressed Concrete Sections: A Practical Approach by Robert F. Mast PCI Journal July-August 1998

Consider a 305 x 610 mm beam shown in the figure below, subjected to a prestress force P of 1281 kN at an eccentricity of 203 mm, and a bare beam bending moment M_{bb} of 195.3 kN-m.

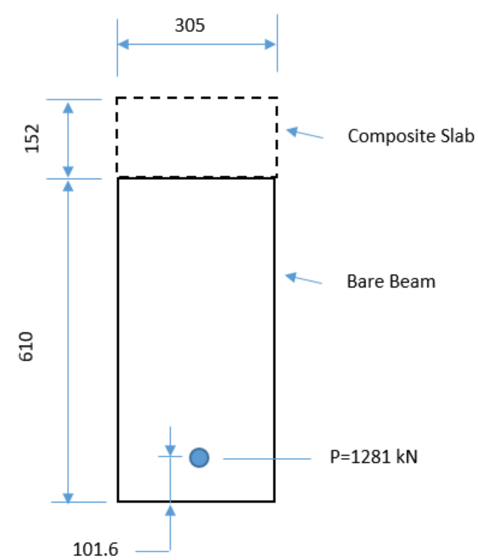


Figure 3- 45 Composite Section

This produces stresses in the bare beam as shown in the figure a below. The beam is then made composite with a 152 mm slab of 305 mm width of the same concrete strength. It is now necessary to find the equivalent forces and moments applied to the composite section that will produce the same stresses in the bare beam portion of the composite beam.

This operation may be accomplished by extending the stress diagram for the bare beam up through the composite slab, as shown in the figure a. This produces a fictitious force F in the slab, as shown in the figure b. This fictitious force is combined with the prestress force P to produce the equivalent force P_e at a resultant location to be applied to the composite section. The magnitude and location of P_e combined with M_{bb} produce the desired stress in the composite section, as shown in the figure c. In this explanation, the increase in stress in the tendon f_{p2} for the bare beam as the member passes to a decompression stage is ignored for simplicity, but the program includes it in the calculation of decompression force.

The stresses shown in the figure c are then combined with the stresses shown in the figure d due to moments M_{cb} applied to the composite beam. The fictitious stresses in the composite slab are subtracted in order to obtain the true stress in the composite slab. The final stresses are shown in the figure e, and they are identical to stresses calculated in the usual manner.

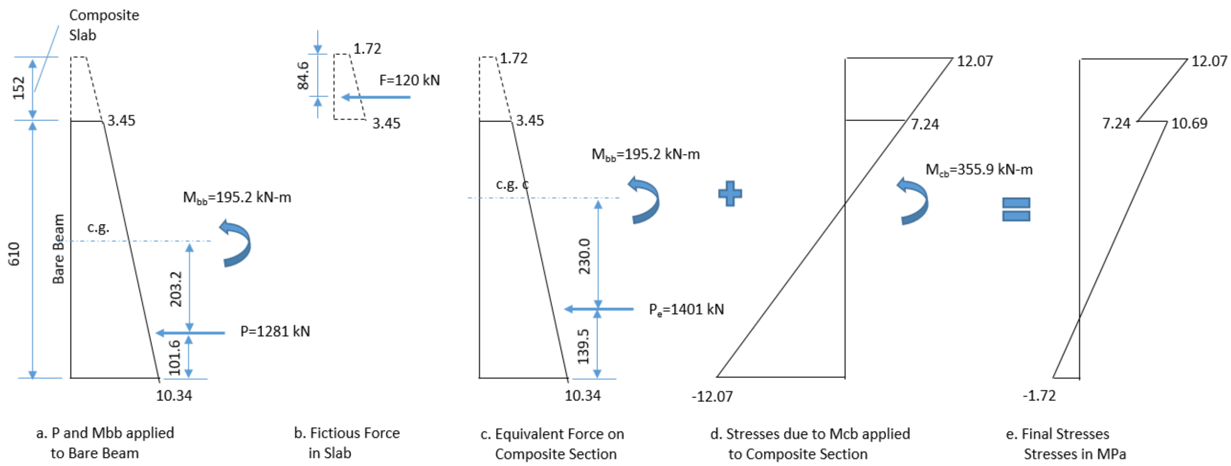


Figure 3- 46 Incremental Stress of Composite Section

The analysis of a cracked composite beam is similar to that of a cracked non-composite beam, with the additional step of including the fictitious force in the composite slab due to bare beam stresses.

Procedure to calculate incremental stress:

- Cracked composite section

1. Calculate the stresses of the bare beam for the moments applied to that beam.
2. Extend the stress gradient in the bare beam upward to the top of the future composite slab.
3. Find the magnitude and location of the fictitious force F.
4. Determine the magnitude and location of the equivalent force P_e by combining the fictitious force F and the decompression force P.
5. Assume the neutral axis depth y of the cracked composite section.
6. Calculate the stress at the neutral axis which is the sum of the stress of the bare beam due to P_e and M_{bb} and the stress of the composite section due to M_{cb}. Where M_{bb}.is the external moment due to self weight acting on the bare beam and M_{cb} due to superimposed dead loads and live loads acting on the composite section.
7. Repeat step 5 and 6 until the stress at the neutral axis is zero.
8. Find the section properties $A_{ct}, I_{ct}, c^*_{top}$ of the cracked composite section.
9. Determine incremental stress in the tendon.

3.8.2 Segmental members at unreinforced joints

Under all SLS load combinations, the residual compression at the joint shall be not less than 1.0 MPa. In the program, there is no consideration about this requirement.

3.8.3 Prestressed members in exposure classification B2, C1, C2 or U

For exposure classifications C1, C2 or U, the concrete at the level of each tendon shall be in compression under a SLS load combination that comprises permanent effects plus 50% of the transient serviceability load(s).

For exposure classification B2, the concrete at the level of each tendon shall be in compression under a SLS load combination that comprises permanent effects plus 25% of the transient serviceability load(s).

In the program, the reduction of the transient serviceability load is automatically taken into account.

3.8.4 Crack control in the side face of beams

For crack control in the side face of beams where the overall depth exceeds 750 mm, longitudinal reinforcement, consisting of 12 mm bars at 200 mm centers or 16 mm bars at 300 mm centers, shall be placed in each side face.

In the program there is no consideration about this requirement.

3.8.5 Crack control at openings and discontinuities

Reinforcement shall be provided for crack control at openings and discontinuities in a beam.

In the program there is no consideration about this requirement.

3.8.6 Check the Crack Control Design Results

3.8.6.1 Result Tables

The results can be checked as shown in the table below.

▶ Design>PSC Design>PSC Design Result Tables>Check Crack Control for Flexure at Service Loads…

	Elem	Part	Top/Bottom	LCom Name	Type	CHK	ft (N/mm^2)	fb (N/mm^2)	0.25*sqrt(fc') (N/mm^2)	0.5*sqrt(fc') (N/mm^2)	s (mm)	s_max (mm)	fs (N/mm^2)	fsa (N/mm^2)
▶	28	I[28]	Bottom	cLCB35	MY-MAX	OK	-5.1612	0.7636	1.5811	3.1623	244.4444	200.0000	-69.7207	160.0000
	28	I[28]	Top	cLCB35	MY-MIN	OK	-3.0721	-2.3373	1.5811	3.1623	246.4706	200.0000	-14.3414	160.0000
	28	J[29]	Bottom	cLCB35	MY-MAX	OK	-4.8225	0.3867	1.5811	3.1623	244.4444	200.0000	-103.1864	160.0000
	28	J[29]	Top	cLCB35	MY-MIN	OK	-2.7898	-2.6303	1.5811	3.1623	246.4706	200.0000	-16.0577	160.0000

Figure 3- 47 Result Table for Crack Control

3.8.6.2 Excel Report

The detailed results, which contain the calculations, are produced in the Excel Report.

▶ Design>PSC Design>PSC Design Calculation…

237	**4.Crack check**									
238	**■ Bottom**									
239	- Exposure class :		B1							
240	- Maximum service limit load combination :		cLCB3							
241	- Maximum service limit load combination type:		FX-MAX							
242	- Stress at bottom surface (Concrete)									
243	fb	=	6.92	(MPa)						
244										
245	**1) Crack control for flexure in prestressed beams (General)**									
246	▪ Maximum stress analysis at surface									*(see. 8.6.2.1)*
247	$f_{surface}$	=	6.92	(MPa)	>	$0.25\sqrt{f'_c}$	=	1.77	(MPa)	
248	∴ Since maximum tensile stress is exceeded, spacing check consideration is needed.									
249										
250	▪ Maximum spacing for reinforcement or bonded tendons.									
251	- Closest steel reinforcement bar at the surface (s):		Rebar							
252	s	=	63.50	(mm)	≤	s_{max}	=	200.00	(mm)	
253	∴ Since s doesn't exceed 200 mm, the additional check will be considered.									
254										
255	▪ Stress limitation check									
256	$f_{surface}$	=	6.92	(MPa)	>	$0.5\sqrt{f'_c}$	=	3.54	(MPa) ; or	
257	f_s	=	115.00	(MPa)	>	f_{sa}	=	160.00	(MPa)	**OK**
258	* f_s is the tensile stress of bar(extreme fibre at surface) under service limit state									
259	c_{na}	=	520.58	(mm)	distance from extreme compression fiber to neutral axis					
260	f_{cr}	=	32.33	(MPa)	concrete stress at reinforcement location					
261	A_{cr}	=	545852.26	(mm^2)	area of a cracked section					
262	Z_{cr}	=	1348.96	(mm)	centroid of a cracked section					
263	I_{cr}	=	4.5754E+10	(mm^4)	second moment of area of a cracked section					
264										
265	**2) Prestressed members in exposure classification B2, C1, C2 or U**									
266	∴As exposure classification is either A or B1, the clause 8.6.2.3 is not considered.									*(see. 8.6.2.3)*

Figure 3- 48 Excel Report for Shear Resistance