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A study on effects of creep and shrinkage in high strength concrete bridges

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Abstract

The last three decades have been marked by remarkable growth of high strength concrete applications in building and bridges. Both types of construction will benefit from the positif effetcs such as reductions in member sizes and amount of reinforcement, when using high strength concrete. However, bridges are often made with long spans resulting in significant dead weight which combined with the creep and shrinkage properties of concrete, leads to significant deformation and loss of prestressing force in the long term. In this study, the effects of creep and shrinkage of high strength concrete used for prestressed concrete bridge girder is investigated. The aim is to quantify the loss of prestress in high strength concrete bridge and to find justfications on increasing usage of high strength concrete for bridges. A continuous-span bridge built using span by span method (movable scaffold system) is chosen as a case study. Three grades of concrete strength are investigated, 40 MPa, 80 MPa, and 100 MPa, each representing normal, moderately high and high strength concrete. These are grades that can be routinely produced by concrete industry without significant alteration in current production/process technology. As part of this study, a literature survey has also been conducted. It suggests that high strength concrete requires modification of current creep and shrinkage code (applicable only for normal concrete). Thus, the initial part of this study deals with determination of proper creep and shrinkage code. Then, a finite element analysis of the bridge case is performed. The result indicates that reduction in girder size and amount of prestressing is not simply governed by concrete strength, but by the comlplex effects of strength, creep and shrinkage behavior of high strength concrete.

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Keywords: Creep; Shrinkage; High Strength Concrete.

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1. Introduction

Several researches have been conducted to study the material behaviour and the use of high strength concrete, particularly on the bridge structures. The high strength concrete has difference behaviour with the normal strength concrete, particularly in terms of the response to the creep and shrinkage. In addition to causing loss of pre-stressing force, the effects of creep and shrinkage that occurs can also lead to changes in the force distribution path that acting on the concrete element. The effects of creep and shrinkage are needed to be calculated and considered to control the quality of the structural elements.

ACI, CSA, and NZS standard provide requirements and formulations for normal strength concrete but do not provide codes for high strength concrete. CEB-FIP 1990 is a code/regulation which has been adopted by SNI (Indonesia National Standard) and generate the empirical equations to calculate the coefficient of creep and shrinkage, but the formulation can only be used for normal strength concrete (20 MPa - 50 MPa). Therefore, the modelling of creep and shrinkage in this study will follow the AASHTO-LRFD 2012 with the equations of creep and shrinkage that given can be used to confine the concrete compressive strength in between 20 MPa - 105 MPa.

In this research, a case study has been conducted on the use of high strength concrete on the cast in situ box girder. One drawback of the use of a cast in situ box girder is the pre-stress force can only be applied after the concrete has completely cured and reach its allowable strength. The stress and loss of pre-stress force due to creep and shrinkage in this method is relatively larger than the precast concrete.

2. Research Significance and Objectives

The main objective of this study is to determine the creep and shrinkage effects in high strength concrete, the required tendons for using high strength concrete, and the changes in stress distribution on bridge girder that is caused by creep and shrinkage.

In this research, three kinds of modelling variations of a cast in place bridge box girders have been conducted with Moveable Scaffold System (MSS) as the construction method. These three models consist of model A (40 MPa), model B (80 MPa), and model C (100 MPa). These bridges were modelled using Midas Civil software, which the formulation, creep, and shrinkage data can be inputted using a User-Defined tool.

A case study that has been performed was as follow: The bridge consists of five continuous spans, the length of each span is 40 meters, and the total length of the bridge is 200 meters. Each Bridge girder consists of one cell box with a width of 8750 mm and height of 2400 mm.

3. Modeling and Analysis

The bridge structures modelling can be divided into two conditions: transfer condition and service condition, where both of these conditions were reviewed for maximum moments that should be detained by pre-stressing the cables. The following tables show the allowable strength for compression and tension refer to AASHTO-LRFD 2012

Table 1. Allowable strength.

Condition	Allowable tensile strength	Allowable compression strength
Transfer	$0.25 \sqrt{f_c}$	$0.6\ f_c$
Service	$0.5 \sqrt{f_c}$	$0.45\ f_c$

3.1. Preliminary Tendon

Preliminary tendon should also be considered on transfer condition. It is necessary to perceive the purpose of the additional tendons during construction. The loading stage on transfer condition is followed by the construction stage that use the span-by-span construction method by using under slung launching gantry where girder are supported on pillars and cantilever beam on the previous span.

The bending force determines the layout and number of tendons that are needed. Structural analysis needs to be performed to obtain box girder moment diagram at every conditions, and layout as well as the number of tendon can be determined. The following pictures show the beam moment force diagram on transfer and service conditions:

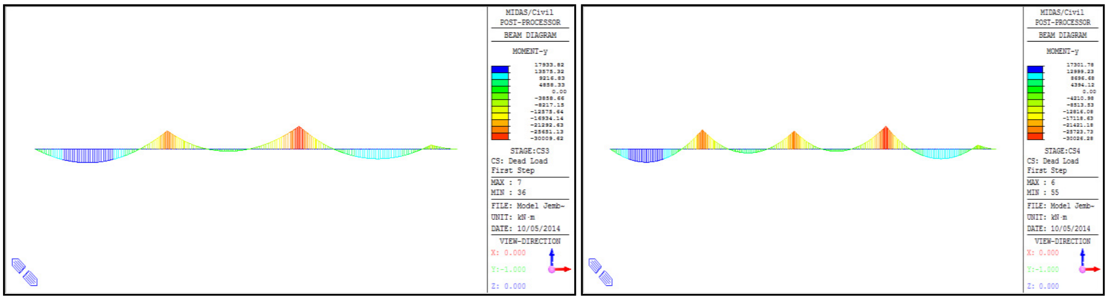

Fig. 1 Moment Diagram on Construction Stage 3 and Construction Stage 4

3.2. Creep and Shrinkage Model

The creep and shrinkage model that was used for this research is based on the study of literature from the previous research and existing code. AASHTO-LRFD 2012 states creep and shrinkage models that can be used, as follows:

- CEB-FIP 1990
  Concrete strength that can be used in the CEB-FIP 1990 is 20-50 MPa, the use of strength values outside the range as provisioned can reduce the accuracy of the use of formulations to obtain shrinkage strain and creep coefficient due to creep and shrinkage.
- ACI 209
  ACI 209 is one of the codes mentioned in the AASHTO-LRFD 2012 can be adapted to use with related to the analysis of creep and shrinkage. ACI 209.2R-8 performs some creep and shrinkage models, such as ACI209-92, Bazant-Baweja B3, CEB MC90, CEB MC90-99, GL-2000.

The creep and shrinkage parameters used for these bridges must follow the specified concrete strength range that can be accommodated by a certain code. Commonly, normal strength concrete often refers to CEB-FIP 1990, but to minimize any deviations that is not the main parameters to study, the research will refer to the same code that cover all concrete strength. From the previous research, there is no significant difference of creep coefficient and shrinkage strain between CEB-FIP 1990 and CEB-MC 90-99 that used 40 MPa. For this research, model A, model B, and model C will refer to CEB-MC 90-99 that have the concrete strength range in between 15 – 120 MPa. The following table was obtained from the study of literature before.

Table 2. Creep and shrinkage model.

Condition	ACI 209-92	Bazant-Baweja B3	CEB MC90	CEB MC90-99	GL 20000
F_{c28} (MPa)		17 – 70	20-90	15-120	16-82
a/c		2.5 – 13.5			
cement content (kg/m^3)	279 - 446	160 - 720			
w/c		0.35 – 0.85			0.4 – 0.6
Relative humidity (%)	40 – 100	40 - 100	40 - 100	40 - 100	20 - 100
Type of cement	R, RS	R, SL, RS	R, SL, RS	R, SL, RS	R, SL, RS

3.3. Creep and Shrinkage Model – CEB MC90-99 (ACI 209 Committee Report)

CEB MC90-99 on ACI 209 Committee Report state that the range of compressive strength that can be used for the model is between 15-120 MPa, the of normal strength concrete (< 70 MPa) is applicable for model A, and the use of high strength concrete (> 70 MPa), is applicable for model B and model C. Input parameters for this model are given as follows:

Table 3 Creep and shrinkage parameter

Condition	Unit	Model A	Model B	Model C
Mean 28 Day (f_{cm28})	MPa	48	88	108
Strength constant (f_{cm0})	MPa	10	10	10
Mean 28 day elastic modulus	MPa	36267.60	44388.04	47524.01
Cement type		N	N	N

The following tables contain the creep coefficient and shrinkage strain based on CEB MC90-99 model

Table 4 Creep coefficient and shrinkage strain based on CEB MC90-99 model

T (days)	Model A		Model B		Model C	
	$\Phi_{28\ (t,to)}$	$\varepsilon_{sh\ (t,tc)}$ x 10^{-6}	$\Phi_{28\ (t,to)}$	$\varepsilon_{sh\ (t,tc)}$ x 10^{-6}	$\Phi_{28\ (t,to)}$	$\varepsilon_{sh\ (t,tc)}$ x 10^{-6}
7	0	-37.9	0	-78.4	0	-95.3
14	0	-75.6	0	-117.3	0	-135.7
28	0.59	-106.8	0.35	-153.2	0.3	-174.4
90	0.94	-169.0	0.57	-218.2	0.48	-241.2
180	1.15	-212.8	0.69	-256.3	0.59	-277.9
365	1.34	-262.7	0.8	-293.4	0.68	-310.8
1000	1.55	-337.5	0.92	-362.4	0.78	-351.1
10000	1.73	-446.5	1.02	-410	0.86	-404.4

Based on the model CEB MC90-99 analyse for varies compressive strength, among other 25 MPa, 40 MPa, 80 MPa and 100 MPa. The analysis was performed on the same specimen dimensions (V / S), the early age shrinkage of concrete and same loading age. The following graphs show the relation between creep coefficient and shrinkage strain and compressive strength of concrete:

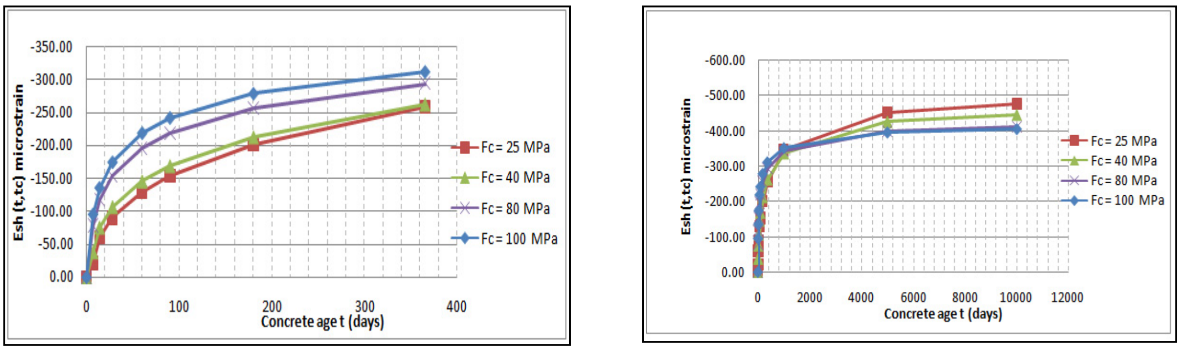

Fig. 2 The comparison of shrinkage strain versus concrete age based on model CEB MC90-99

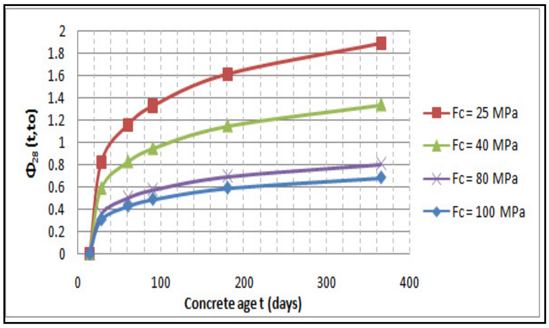

Fig. 3 The comparison of creep coefficient and concrete age based on model CEB MC90-99

Creep and shrinkage model based on MC90-99 CEB can be used for model A, B, and C with user – defined which has been provided by Midas Civil Software. The user - defined, facilitate to input creep function for every loading age manually. For this research, 1, 3, 7, 14, and 28 days of loading age is done. The following figures show the steps to input MC90-99 models into the software

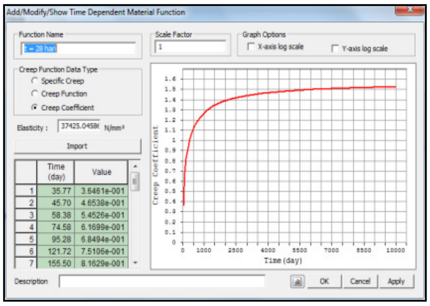

Fig. 4 Creep function on user defined (loading age = 28 days)

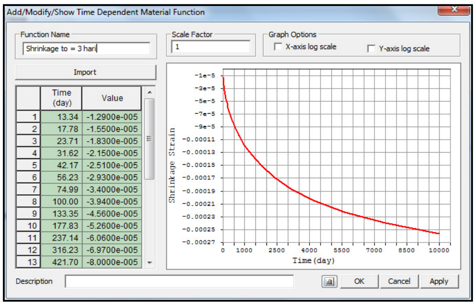

Fig. 5 Shrinkage function on user defined

4. Results and Discussion

4.1. Final Tendon Layout

By doing analysis based on the working loads on the construction and service phase, layout and number of tendons was obtained from the allowable stress as follows:

Table 5 Allowable stress

Model	Allowable Stress - Transfer (MPa)		Allowable Stress – Service (MPa)	
	Compression	Tension	Compression	Tension
A	21.13	1.5	18	3.16
B	142.26	2.1	36	4.47
C	52.83	2.35	45	5

The iteration of strand number for every tendon was performed to attain the optimum number of strand for every model. The following table illustrates the comparison of the strands number that used in each model

Table 6 The comparison of the strands number in each model

Model	Total Strand
A	1114
B	898
C	812

In order to appreciate the significant of using high strength concrete, an analysis showing the reduction of tendon number is performed. The reference case is model A. From table 6, model B could reduce up to 19% of the tendons that were used in model A, meanwhile the reduction for model C is up to 27% of the tendons that were used in model A.

Another simpler analysis can also predict the reduction in the following way

$$\frac{\sigma_{allowable1}}{\sigma_{allowable2}} = \frac{\frac{P_1}{A_1}}{\frac{P_2}{A_2}} \tag{1}$$

$$\frac{0.25\sqrt{fc_1}}{0.25\sqrt{fc_2}} = \frac{\frac{P_1}{A_1}}{\frac{P_2}{A_2}} \tag{2}$$

$$\frac{\sqrt{fc_1}}{\sqrt{fc_2}} = \frac{n_2}{n_1} \tag{3}$$

From these equations, the percentage of reduction in the number of tendons that were used can be calculated by the following equations

$$\text{Reduction in the number of tendons } (\%) = 1 - \frac{n_2}{n_1} = 1 - \frac{\sqrt{fc_1}}{\sqrt{fc_2}} \tag{4}$$

The following table compares the difference in reduction the number of tendons based on the two analysis above. The more rigorous analysis give lower percentage of reduction compared to the simple analysis. In other word, the simpler analysis can overestimate tendon reduction.

Table 7 The comparison of the strands number in each model

Model	Reduction in the number of tendons (%)	
	Analysis	Simple Equation
B	19.38	29.3
C	27.11	36.75

4.2. Tendon Time Dependent Losses

Tendons time dependent losses display the amount of effective force acting on the tendon. Effective force was calculated from the initial jacking force (0.75 fpu) which has been reduced by the immediate losses and time-dependent losses that occur in the tendon. The effective pre-stress force in tendons may be produced in the form of graphs or animations for each construction stage / step. Instantaneous pre-stress loss and time dependent pre-stress loss may be reviewed. The instantaneous pre-stress loss represents the difference between the pre-stress force at the time of tensioning the tendon and the pre-stress force in tendon in the immediately subsequent construction stage.

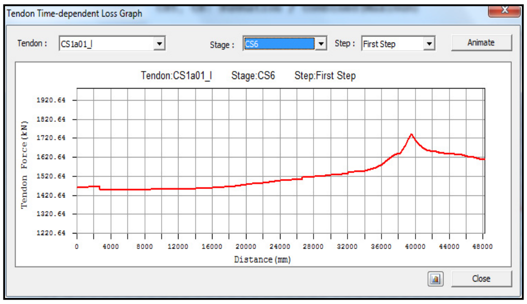

Fig. 6 Tendon time-dependent loss graph CS6 first step

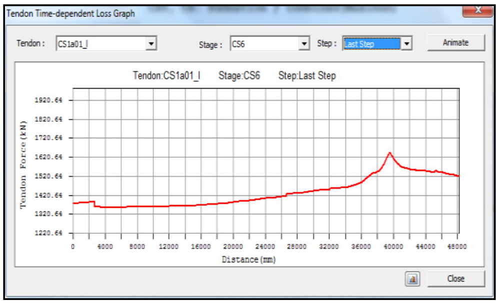

Fig. 7 Tendon time-dependent loss graph CS6 last step

The table 8 shows tendon time-dependent losses that occur in some tendons on three variations of bridge material The table shows that the immediate losses for different concrete strength is on the same value, but the time-dependent loses to different concrete strength produce different values. Losses appear larger for the low strength concrete, whereas for the high strength concrete, the losses that occur reduced on the other words, tendon pre-stress force is more effective. The magnitude of losses that happened in tendon also affected by the tendon layout which has been applied. The parabolic tendon layout produces the higher pre-stress losses compared to the constant eccentricity tendon layout. Bigger tendons curvature would causes higher losses in pre-stress.

Table 8 Tendon time-dependent losses – support and span

Tendon Grup	Model	CS	Immediate losses (%)		Time dependent losses (%)		Effective prestress force (%UTS)	
			Support	Span	Support	Span	Support	Span
CS1a01-L	A	1	21.20	18.59	22.76	21.61	57.93	58.79
	B	1	21.20	18.59	22.74	21.26	57.95	59.06
	C	1	21.20	18.59	22.53	21.11	58.10	59.16
CS1a01-L	A	6	21.20	18.59	31.13	31.13	51.65	51.66
	B	6	21.20	18.59	28.75	28.32	53.44	53.76
	C	6	21.20	18.59	28.00	27.39	54.00	54.66
Top1-R	A	1	13.96	12.10	15.32	13.17	63.51	65.12
	B	1	13.96	12.10	15.31	13.15	63.52	65.14
	C	1	13.96	12.10	15.18	13.14	63.62	65.14
Top1-R	A	6	13.96	12.10	24.25	21.23	56.82	59.08
	B	6	13.96	12.10	21.96	19.41	58.53	60.45
	C	6	13.96	12.10	21.09	14.10	59.18	64.43

5. Conclusion

The following conclusions were drawn from the analysis:

- The model that covers the range of concrete strength considered in this study is CEB MC90-99
- Shrinkage tends to be higher initially for high strength concrete, however the ultimate shrinkage strain is larger for normal strain concrete. The behavior is no found for creep. Higher concrete strength produces less creep at all ages.
- High strength concrete (>70 MPa) could reduce the number of tendon up to 19%, more significant reduction is obtained for concrete with $f_c' = 100$ MPa. The reduction of tendon number can not be predicted using simple equation by comparing allowable compressive stress. Instead a rigorous analysis such as the numerical analysis in this study is necessary.
- The magnitude of losses that happened in tendon also affected by the tendon layout which is used. The parabolic tendon layout produces the higher pre-stress losses compared to the constant eccentricity tendon layout. Bigger tendons curvature would causes higher losses in pre-stress.

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