IMPROVED PREDICTION OF PRE-CAMBER OF POST-TENSIONED PRESTRESSED I-BEAM

(Date received: 22.11.2007)

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ABSTRACT

An improved method of calculating pre-camber prediction in prestressed concrete beam is presented. It has been found that the current method of estimation that is widely practiced by local engineers which is based on BS 8110 is over simplified and inaccurate. Accurate prediction of the upward deflection or pre-camber due to prestressing of prestressed concrete beams is always difficult to attain. Inaccurate estimation of pre-camber usually leads to complications in construction and may incur additional cost. This paper presents an improved pre-camber prediction of prestressed I-beam that adopts the equivalent weight method with the inclusion of concrete creep factor into the deflection equation. While creep is often ignored or underestimated, it is being considered in the calculation as it was identified to significantly increase pre-camber, even at an early age. Laboratory tests were conducted to obtain compressive strength, elastic modulus, creep and shrinkage of concrete. These properties were used in the evaluation of pre-camber. The accuracy of the prediction was compared against the actual pre-camber measured on four post-tensioned 'I' beam with overall height of 1.98m and 36m in length for a duration of 15 days after the application of prestressing force. Based on the comparison, the improved method seems to provide better results compared to the commonly adopted simplified method. The suitability of the concrete properties, especially creep coefficient recommended by various foreign standard codes - BS 8110, EC 2, ACI and AS 3600 for application on local concrete is also examined. The method presented is readily available for local engineers to adopt.

Keywords: *Creep Coefficient, Pre-Camber, Post-Tensioned Beam, Standard Codes*

1. INTRODUCTION

In a prestressed concrete beam, pre-camber or upwards deflection occurs due to the sustained eccentric compression force that induces negative moment in the section. A proper design of prestressing force can make this initial pre-camber to act as an offset to the downward deflection due to self weight and live load, reducing or eliminating the deflection and cracking of the prestressed member considerably. Ideally, this feature offers a means of controlling deflection and cracking, making it possible to design longer span members. However, one common problem usually faced by most local designers is the difficulty to accurately predicting the pre-camber development. The actual upwards deflection often deviates significantly from the estimated value, causing difficulty in the construction process, primarily in the construction of prestressed bridges [1].

Under the circumstances when the pre-camber is under or over predicted, various detrimental effects may take place. A typical example of the effect of an inaccurate prediction of pre-camber of prestressed bridge beam is uneven road profile and producing uncomfortable or even dangerous driving condition. An accurate estimation is also crucial to achieve a proper finished level of the bridge. Inaccuracy may results in the application of additional thickness of bituminous wearing course on the bridge deck in order to achieve the designed finish level. This inevitably results in additional dead load, compromising the safety of structure, incurs additional construction cost. In most cases, the contractors have to bear the additional cost. Besides that, misalignment at the jointing of segmentally constructed prestressed bridges may also occur when the vertical movement of each segment is not properly compensated. Considering the various damaging effects caused by pre-cambering, an accurate prediction value should not be taken lightly.

The common method of design estimation of pre-camber currently practiced by the local engineers is the equivalent weight method and the required concrete properties are taken directly from design codes such as BS 8110. A site study carried out indicated that this method was inaccurate. The results showed that the actual pre-camber measured on site was 48.6% higher than the predicted values and various reasons were identified as the cause of the vast differences [2]. The two main causes identified were the calculation method and the concrete properties such as elastic modulus, used in the equation which was normally based on the values recommended in standard codes and did not represent the actual properties of local concrete.

Having recognised the significant difference between the prediction and actual deformation, an improved calculation of pre-camber prediction of prestressed concrete beam is discussed. The suitability of adopting concrete properties from standard code's recommendation for local concrete is also examined. The accuracy of the currently practiced design prediction and the proposed improved calculation is verified by comparing with the actual pre-camber of post-tensioned 'I' beams measured on site. Beside the site measurement of pre-camber, laboratory tests were conducted to obtain the actual mechanical properties of concrete such as creep, shrinkage, elastic modulus and compressive strength which are required in order to predict the pre-camber more accurately.

2. THE DESIGN CALCULATION OF PRE-CAMBER IN PRESTRESSED CONCRETE BEAM

Pre-camber resulting from prestressing force can be calculated either on the basis of curvatures, moment-area method, or based on the equivalent weight method [3]. Deflections due to the dead and live loads are calculated as for any other flexural members, and to obtain the total deflection, the deflection due to prestressing force and all the deflections that are calculated separately are superimposed together. The common prediction method adopted by the local design engineers is the equivalent weight method in which the elastic modulus are usually taken directly from BS 8110 based on concrete strength. Only short term prestress losses are taken into account in this calculation.

According to the equivalent weight method, the upward deflection, δ_{pi} at the mid-span of a uniformly loaded simply supported beam is obtained using Equation (1), when the tendon profile is parabolic. The sagging of beam, δ_o is calculated based on Equation (1) with *Pe* being substituted by moment due to the dead load as given in Equation (2). The resultant short-term or instantaneous deflection is obtained by using Equation (3) in which the hogging produced by the prestressing force is deducted by the sagging due to the self-weight of the beam. Usually only the pre-camber at the mid span is obtained. Assuming that the deflection profile is a perfect parabolic curvature represented by equation $\boldsymbol{y = Ax^2 + Bx + C}$, the deflection at other locations can be easily obtained.

$$\delta_{pi} = \frac{5L^2}{48\, E_c\, I_c}\,(Pe) \qquad (1)$$

$$\delta_o = \frac{5wL^4}{384\, E_c\, I_c} \qquad (2)$$

$$\delta_{short\text{-}term} = -\,\delta_{pi} + \delta_o \qquad (3)$$

In Equations (1) and (2), the term L represents the beam span, E_c and I_c refers to elastic modulus of concrete and moment of inertia of section, respectively. *P* is the prestressing force after initial losses, *e* is the eccentricity of tendon at the mid-span and *w* is the self weight of the beam.

Generally in practice, this short term deflection is an important information for contractors to ensure a smooth construction process. However this crude calculation method adopted only provides an approximate estimation and only considers instantaneous deflections. Accuracy of this prediction is compromised due to the over simplified calculation method and based on Equations (1) and (2), it is observed that the reference to the concrete property is only on the elastic modulus. The usual practice adopted is that the elastic modulus is taken directly from the BS 8110 based on the concrete strength. The deviation of the recommended elastic modulus obtained from foreign codes based on concrete strength, from the actual local concrete properties, further intensify the digression.

3. SITE MEASUREMENT OF PRE-CAMBER OF PRESTRESSED CONCRETE

The monitoring of pre-camber development was conducted on four post-tensioned prestressed concrete I-beams with an overall height of 1.98m and 35.7m span over a duration of 15 days. The beams were cast with Grade 50 concrete and prestressing force was applied at the age of 28 days. Five points on the top of each beam with equal distance of 8.95 m were chosen as the leveling reference points, as shown in Figure 1(a). Figure 1(b) shows the cross-section of the beam. The maximum pre-camber was determined from the difference between point No. 3 to the average of point No. 1 and No. 5. The leveling points were measured at an interval of every two days using a theodolite and a reference datum was established to counter check for vertical movement or settlement of the beams during the period of monitoring. Details of site monitoring work are described in [2].

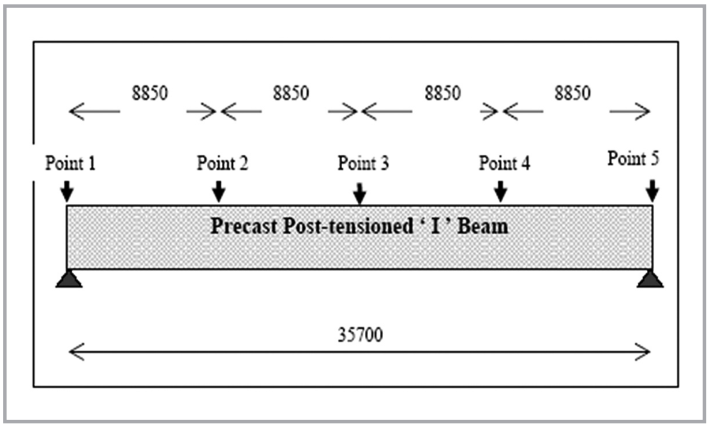

Figure 1(a): Schematic view of the experimental setup

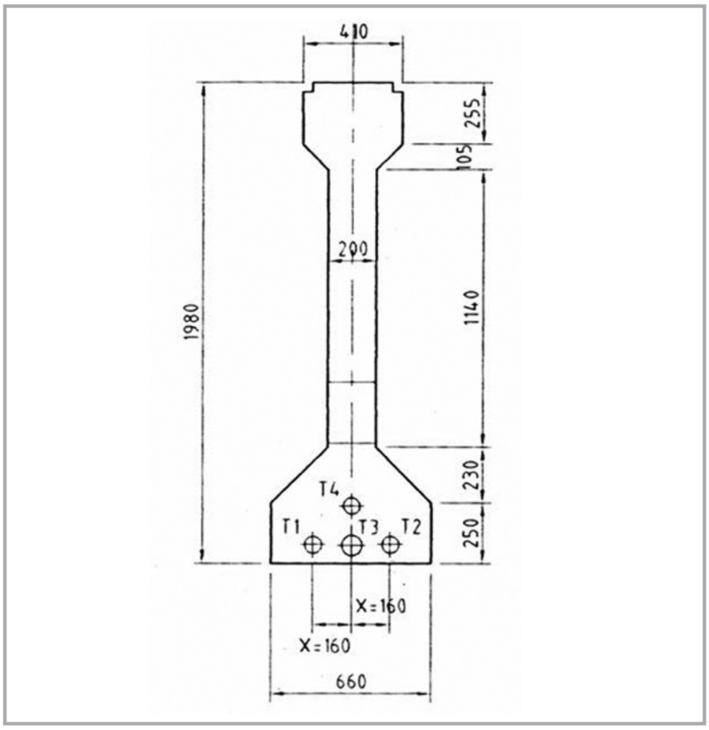

Figure 1(b): Cross section of I-Beam

3.1 COMPARISON OF ACTUAL PRE-CAMBER TO PREDICTION

Based on the measurement, it shows that the upward deflection of the four beams continue to increase after day one until day 15 as shown in Table 1. Immediately after prestressing, the mid-span pre-camber of the four beams ranges between 37mm to 57mm. 15 days after prestressing, pre-camber of the beams increased to an average of 63mm with a maximum of 75mm. It is observed from the results that substantial increase of the upward deflection occurred during the first three days after prestressing, and subsequently, it increases

Table 1: Comparison of Pre-camber Measured on Site and Predicted Value [2]

Day	Beam Pre-camber Measured on Site (mm)					Predicted Value (mm)	Difference* (%)
	Beam 1	Beam 2	Beam 3	Beam 4	Average		
1**	45	57	45	37	46.0	**42.4**	8.50
3	55	71	56	47	57.3	**42.4**	35.00
6	59	73	57	49	59.3	**42.4**	40.33
9	58	74	57	51	60.0	**42.4**	41.50
12	60	75	59	55	62.3	**42.4**	46.80
15	62	75	59	56	63.0	**42.4**	48.58

** Between predicted value and average pre-camber of 4 beams measured on site*
*** Immediately after prestressing*

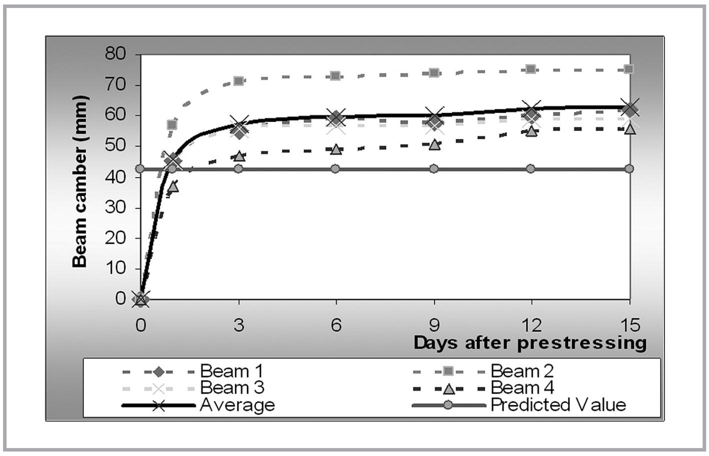

Figure 2: Pre-camber of beams at different days after prestressing [2]

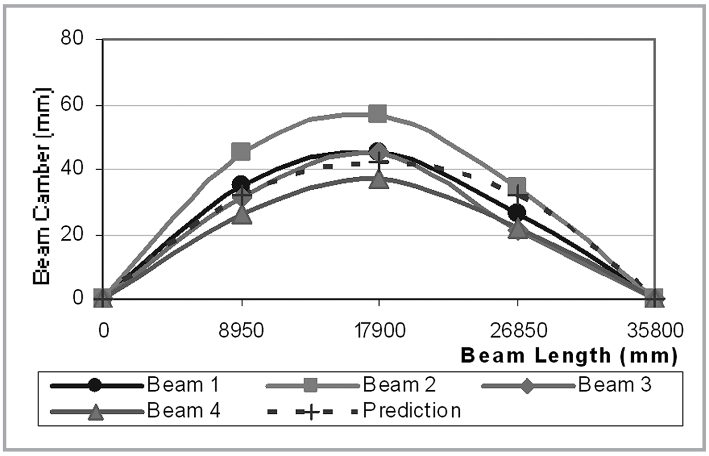

Figure 3: Pre-camber of beams measured immediately after prestressing [2]

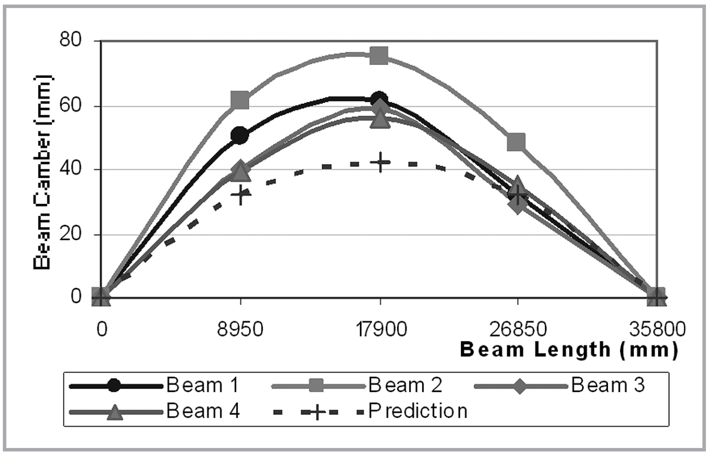

Figure 4: Pre-camber of beams measured 15 days after prestressing [2]

steadily within a small margin. The pre-camber of the four beams at different time after prestressing is plotted in Figure 2. The steep increment at the initial stage is due to the effect of elastic strain of concrete when prestressing force is first applied. Thereafter, the rate of increment is lower under the influence of time-dependent deformation of creep and shrinkage. The standard deviation of all the pre-camber measurement obtained from the four beams is within the range of 8.3mm to 10.0mm, with the coefficient of variation is between 13.3% and 17.9%. Statistically the data collected on site can be considered as relatively consistent and acceptable as far as concrete testing is concern.

The ultimate pre-camber of 42.4mm, obtained from the simplified calculation method given by Equations (1) to (3) discussed earlier is also shown in Table 1. The calculation is based on the site data as given in Appendix A. This ultimate calculation refers to the final pre-camber at transfer before service load is applied. However the time frame for the structure to stabilise to that stage is ambiguous. Therefore for comparison purpose, the predicted value of 42.4mm is set constant from day 1 to day 15 without any demarcation, as shown in Table 1. A better assessment of the accuracy of the prediction is to compare it to actual pre-camber at day 15, when the actual pre-camber has almost stabilised. The difference between the predicted pre-camber and the initial pre-camber of the four beams at different times after prestressing is also plotted in Figure 2.

The pre-camber profile of the four beams immediately after prestressing and the calculated design value is shown in Figure 3. Even though the predicted profile is within the range of the measured pre-camber, a better assessment of the accuracy is when the pre-camber has almost stabilised. A vast difference is observed when the calculated 42.4mm pre-camber is compared to the actual deflection at 15 days, when the pre-camber is more constant as plotted in Figure 4. On average, the actual pre-camber is higher than the estimated pre-camber in the range between 8.50% to 48.58% and the values are given in Table 1. Through this site measurement, the approximate calculation method currently being practiced is proven to be inaccurate and under- predicts the actual pre-camber.

Referring to Figures 3 and 4, it is observed that the pre-camber for the four beams are different although they are designed to be the same. The difference in deformation may be due to the influence of various intrinsic and extrinsic factors. Therefore properties and performance of concrete play an important role in prestressed concrete members. Accurate estimation of pre-camber cannot be obtained without a rational account of prestress losses and an accurate prediction of the concrete properties [4].

4. IMPROVED PRE-CAMBER ESTIMATION

According to Nawy [1], the best estimate of pre-camber should be based on accumulated experience, and a correct choice of elastic modulus of concrete. The accuracy of pre-camber is very much dependent on the prediction of concrete properties such as elastic modulus and prestress losses, especially due to creep and shrinkage. The difficulty in estimating the total prestress losses affects the task to precisely estimate the magnitude of expected pre-camber.

Therefore better accuracy can be achieved when creep factor is considered in the initial deflection prediction and creep is considered in prestress losses [5]. Creep strain affects the deflection in two opposite ways. While it produces loss of prestress force, hence reducing the pre-camber, creep strains in the concrete usually increase negative curvatures and hence, increase the pre-camber. Generally the second effect predominates and pre-camber increases with time, in spite of the reduction of prestress loss [3].

When the creep coefficient and prestress losses are considered, the upward deflection is given as Equation (4), as proposed by Nilson [3], where δ_{pe} is the midspan deflection due to prestressing after considering prestress losses and ϕ is the creep coefficient.

$$\delta_{upwards} = -\delta_{pi} + (\delta_{pi} - \delta_{pe}) - \frac{\delta_{pi} + \delta_{pe}}{2} \cdot \phi \tag{4}$$

Both δ_{pi} and δ_{pe} in Equation (4) above are calculated based on Equation (1) for prestress beam with parabolic tendon profile. The first term in Equation (4) is the initial negative curvature and the second term is the reduction in that initial curvature because of the loss of prestress. The third term is the increase in negative curve because of concrete creep. In Equation (4), the important approximation is made that creep occurs under a constant prestress force, equal to the average of the initial and final values, as expressed in the third term.

The deflection due to self weight is also modified by creep and may be obtained by applying the creep coefficient to the instantaneous value. Thus the downward deflection is obtained through Equation (5) with δ_o being calculated based on Equation (2).

$$\delta_{downwards} = \delta_o (1 + \phi) \tag{5}$$

The total member deflection is obtained based on principle of superposition after consideration of losses and creep, effective prestress and self weight is given by equation (6).

$$\delta_{total} = -\delta_{pe} - \frac{\delta_{pi} + \delta_{pe}}{2} \phi + \delta_o (1 + \phi) \tag{6}$$

Equation (6) is formulated based on principle of superposition from Equations (4) and (5).

4.1 CONCRETE PROPERTIES

Besides a better calculation formula, accurate concrete properties prediction is important to contribute towards a better pre-camber prediction of prestress beams. The formulae described above require the properties of concrete such as strength, elastic modulus and creep coefficient to be taken into account. Therefore, laboratory testing were conducted on cube and cylinder specimens prepared using the same batch of concrete that has been used to cast the prestressed beams to obtain the actual compressive strength, elastic modulus, creep and shrinkage. The compressive strength was obtained from tests carried out on 150mm cubes at 7 days and 28 days. Test on elastic modulus, creep and shrinkage were conducted on 100mm diameter x 300mm cylinders at the age of 28 days. The creep and shrinkage testing were carried out according to ASTM C512-87, under the ambient of 27 ± 4°C and RH of 70 ± 10% to simulate the tropical climate condition. The elastic modulus test was conducted in accordance to ASTM C469-87a. Full details of the laboratory testing are reported in [6].

The results of concrete properties obtained from laboratory testing and standard codes are tabulated in Table 2 for comparison. The recommended values of modulus of elasticity and creep coefficient obtained from each code and their respective clauses are also indicated in Table 2. The creep strain, ε in Table 2 is calculated based on Equation (7) below. σ is the applied stress due to prestressing force applied on the beam, as given in Appendix A.

The comparison reveals that the magnitude obtained from laboratory tests are within the range provided by various design codes. It should be noted that elastic modulus and creep coefficient provided by BS 8110 shows a significant difference from the tested values. This is one of the reasons identified for the significant difference between estimated pre-camber based on BS 8110 and the site measurement. The modulus of elasticity given by BS 8110 and ACI 209 are both comparatively low compared to the actual values. However it is worth noting that the E_c of 30 kN/mm² represents the mean recommended value and actually BS 8110 allows E_c to be taken in the range of 28 kN/mm² to 36 kN/mm² for concrete Grade 50. Therefore in the prediction of pre-camber, the value of 34 kN/mm² is adopted by the contractor as indicated in Appendix A.

$$\varepsilon = \frac{\phi}{E_c} \times \sigma \tag{7}$$

As appear in the Table 2, BS 8110 does not recommend equivalent cylinder strength for the corresponding cube strength. As for ACI 209 and AS 3600, both codes are based on concrete cylinder strength, therefore no equivalent cube strengths are given. These are reflected in Table 2. It should be noted that the correlation of G50 cube strength to G40 cylinder strength is recommended by EC2. The accuracy of cube-cylinder strength conversion especially for Malaysian concrete has not been fully established and further investigation should be initiated.

It is interesting to observe the closeness between the creep coefficient values provided by EC2 and the test values, which indicates that EC2 may be a suitable replacement to BS 8110 in the near future for Malaysia.

Table 2: Concrete properties results from experiment and standard codes

Concrete Properties	Experiment	BS 8110 [7]	EC 2 [8]	ACI 209 [9]	AS 3600 [10]
f_{cu} *cube* (N/mm²)	59	50	50	–	–
f_{cu} *cylinder* (N/mm²)	42	–	40	40	40
Elastic Modulus, E_c (kN/mm²) *(ref. Clauses)*	35.1	30 *(Pt. 2, Cl. 7.2)*	35 *(Cl. 3.1.3)*	29.9 *(Cl. 2.2.2)*	32.7 *(Cl. 6.1.8)*
Creep Coefficient at 15 days, ϕ *(ref. Clauses)*	0.725	0.375 *(Pt. 2, Cl. 7.3)*	0.723 *(Cl. 3.1.4)*	0.567 *(Cl. 2.4)*	0.954 *(Cl. 6.1.8)*
Creep Strain, ε, at 15 days (μ strain)	342.6	250.0	332.7	302.8	482.4

5. EVALUATION OF IMPROVED PRE-CAMBER ESTIMATION

Using the improved pre-camber calculation method as given by Equation (6), and with concrete properties taken from Appendix A, the magnitude of predicted pre-camber 15 days after prestressing is 69.31 mm. This result is 38.8% higher than the value obtained from Equation (3). Comparison of the new predicted value and the pre-camber measured on site is presented in Figure 5. With the inclusion of the effect of creep, the new predicted values are closer to the average site

Table 3 Experimental creep coefficient used for prediction

Days	Experimental Creep Coefficient
0	0
1	0.261
3	0.406
6	0.455
9	0.533
12	0.599
15	0.725

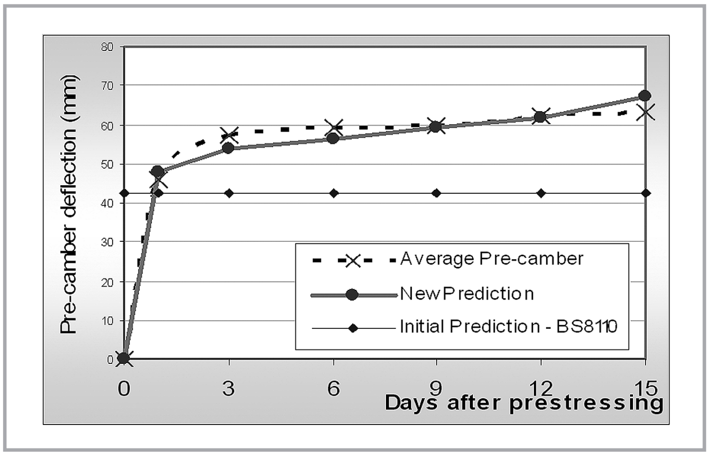

Figure 5: Comparison of average site measurement to the prediction values

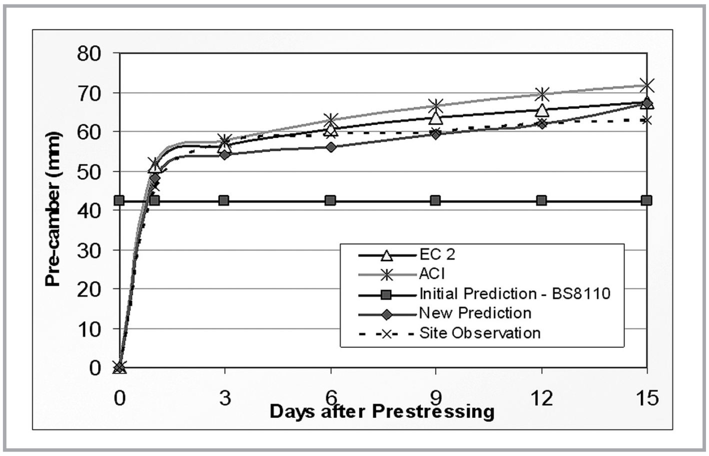

Figure 6: Estimated precamber using different values of creep coefficient

measurement. This drastic improvement compared to the initial prediction that stays at 42.4mm reveals the important effect of this time-dependent deformation. This new prediction is within the range of 5.76% lower and 6.56% higher than the actual pre-camber of the beams.

The creep coefficient value, ϕ which is used in equation (6) is obtained from laboratory creep testing and the values for 15 days are given in Table 3.

In the occasion that the laboratory testing for creep is not feasible to be conducted, the improved calculation method can still be applied to obtain an acceptable prediction. This is made possible with the reference to other standard codes for creep coefficient values. The suitability of foreign codes prediction for creep coefficient is presented in Figure 6. The creep coefficient from EC 2 and ACI 209 that caters for surrounding relative humidity of 80% is used to replace the experimental creep coefficient. The result, as given in Figure 6 reveals that the prediction is more accurate than the initial predicted values that ignoring the effect of creep. By taking creep coefficient and concrete properties from EC2, the pre-camber is within 1.73% lower and 11.1% higher than the actual deformation. ACI 209 on the other hand overestimates the pre-camber up to 14% higher than the actual magnitude. Therefore it can be concluded that the concrete properties recommended by EC 2 are better to be applied to our local concrete than the ACI recommendation.

6. CONCLUSIONS

Based on this study, it can be concluded that:-

1. The pre-camber of the 36m I-beam measured on site is between 37 mm to 57 mm immediately after prestressing and it increases to between 56mm to 75mm after 15 days due to time-dependent deformation.
2. The results of this study reveals that the actual beam pre-cambers measured are 8.5% to 48.6% higher than the design estimation based on BS 8110. This shows that the current simplified pre-camber prediction based on BS 8110 is inaccurate and may cause complications during construction.
3. Creep factor has to be taken into account in the pre-camber estimation for a more accurate prediction. The proposed design calculation with consideration of creep factor is found to be simple for application and provides a closer prediction to the actual site measurement.
4. With the limited creep data for local concrete, the creep coefficient catered for RH of 80% derived from foreign standard codes is sufficient to achieve a good pre-camber prediction. The EC 2 has proven to provide the best result for local concrete properties under the condition when laboratory testing is not feasible.
5. More laboratory test data is still required in order to develop a comprehensive and reliable set of creep coefficient for local tropical concrete. ■

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APPENDIX A

<u>PRE-CAMBER CALCULATION (Site data)</u>

<u>Section Properties</u>

Concrete cross section area	A_c	=	628000	mm^2
Centroid of beam from bottom	y_b	=	862	mm
Centroid of beam from top	y_t	=	1120	mm
Area of tendon	A_{ps}	=	98.77	mm^2/strand
Tendon elastic modulus	E_s	=	190	kN/mm^2

<u>Materials Properties</u>

Concrete elastic modulus,	E_c	=	3.4E+07	kN/m^2
Length of beam,	L	=	35.7	m
Beam self weight,	W	=	15.072	kN/m
Moment of Innertia,	I	=	0.275	m4

<u>Prestressed Forces</u>

Total Initial Prestress,	P_i	=	7590	kN
Total Prestress after initial losses,	P	=	7255.4	kN
Eccentricity (mid-span)	e	=	0.742	m

<u>Pre-camber calculation</u>

Hogging due to prestress $\quad d_i = \dfrac{5L^2}{48E_cI_c}(Pe)$

$= 76.87$ mm

Sagging due to S/W $\quad d_o = \dfrac{5wL^4}{384E_cI_c}$

$= 34.48$ mm

Beam deflection at transfer $\quad d_{short\text{-}term} = d_i - d_o$

$=$ **42.4** mm

PROFILES

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Engr. Assoc. Prof. Dr Wahid bin Omar is an Associate Professor at the Faculty of Civil Engineering, UTM. He graduated with B.Sc (Civil) from University of Strathclyde, Scotland (1986), obtained his MSc in Bridge Engineering from University of Surrey (1989) and PhD from University of Birmingham (1998). Currently he is working on time-dependent deformation of Malaysian concrete with funding from CIDB. His other research at present is to study the possibility of using low cost steel strap to improve the ductility of high-strength concrete.

TAN PUI LAI
Tan Pui Lai conducted her doctorate research on time-dependent deformation of concrete in the tropical climate in Universiti Teknologi Malaysia. She is currently a consulting engineer in Parsons Brinckerhoff Pte. Ltd. while she completes her doctorate part-time.

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