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Objekttyp: **Article**

Zeitschrift: **IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht**

Band (Jahr): **13 (1988)**

PDF erstellt am: **20.06.2024**

Persistenter Link: https://doi.org/10.5169/seals-13011

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Time and Temperature Effects in Prestressed Concrete Bridges

Performance dans le temps et effets de la température sur des ponts en béton précontraint

Zeit- und Temperatureinflüsse in vorgespannten Stahlbetonbrücken

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SUMMARY

This paper describes the observed serviceability behaviour and the analysis used to predict long-term performance, for a series of double cantilever 'T' structures built in Hong Kong during the early 1970's. The analysis incorporates creep, shrinkage and thermal strains for concrete, and prestress, relaxation and thermal strains for the prestressing steel. Temperature dependence of concrete creep and the daily and seasonal variations in bridge temperature distributions in depth are accounted for. The computer program also has provision for analysing the simultaneous effects of adding unbonded prestressing tendons to reduce the present unacceptable cantilever tip deflections.

RÉSUMÉ

L'article décrit le comportement en service et l'analyse utilisée pour prédire les performances à long terme de séries de structures construites à Hong Kong durant les années 1970. L'analyse prend en compte le fluage, retrait et les contraintes thermique pour le béton, et aussi la précontrainte, relaxation et contraintes thermiques pour l'acier de précontrainte. Le fluage du béton dépendant de la température, et des variations journalières et saisonnières des distributions de température en profondeur dans le pont sont considérées. Le programme informatique prévoit également l'analyse des effets simultanés des câbles de précontrainte à adhérence, pour réduire les flèches inacceptables aux extrémités de l'encorbellement.

ZUSAMMENFASSUNG

Diese Studie beschreibt das beobachtete Gebrauchsfähigkeitsverhalten, sowie die Analyse, welche angewendet wurde, um die Langzeitleistung für eine Reihe von Doppel-Ausleger-Strukturen (T), vorauszusagen, die in den frühen siebziger Jahren in Hong Kong gebaut wurden. Die Analyse beinhaltet Kriechverhalten, Schwinden und thermische Verformungen für Beton, sowie Belastungen, Lockerung und thermische Verformungen für Vorspannstahl. Die Temperturabhängigkeit des Betonkriechens und die täglichen und saisonbedingten Schwankungen der Brückentemperaturverteilung wurden berücksichtigt. Das Computerprogramm beinhaltet weiter eine Analyse der Gleichzeitwirkungen von zusätzlichen Spanngliedern ohne Verbund zur Reduktion der bestehenden unannehmbaren Abweichungen der Spitze des Auslegers.

1. INTRODUCTION

Between 1983 and 1986 a study was undertaken of a six span prestressed concrete bridge which had been constructed in Hong Kong in the early 1970's. The bridge consists of five 'T' units in which the 60 metre long cantilevers are integral with the piers but have no structural continuity between units. Observations and very limited monitoring prior to the study suggested that the tips of the cantilevers had deflected downwards excessively and concern was expressed that these deflections appeared to be increasing with time; Figure 3.

In order to investigate the behaviour in detail, vibrating wire strain gauges were surface mounted throughout the structure and thermocouples installed both inside and adjacent to the superstructure. The thermocouples were distributed to monitor both temperatures of the concrete box at various levels and the adjacent air temperatures and in addition to check on heat dissipation from the five 132kV electricity circuits carried through the superstructure box.

Once a month for over two years readings were taken from the strain gauges and thermocouples at hourly intervals during a 24hr period. During these monitoring periods precise levelling of the superstructure was carried out with the bridge closed to traffic at three times. Records were also obtained of the electrical load in the high voltage circuits. From these sessions typical variations in temperature, deflection and electrical loading were produced both for daily and yearly cycles. Figure 1 illustrates a typical set of readings obtained from the monitoring while Figure 2 and Table 1 show the yearly, seasonal and daily variations of temperature adopted for analysis.

In addition, traffic counts were undertaken with simultaneous reading of the strain gauges. This led to the production of a typical daily loading cycle and to an assessment of the loading growth since completion. It was concluded that the analysis should incorporate the full designed loading; Figure 4.

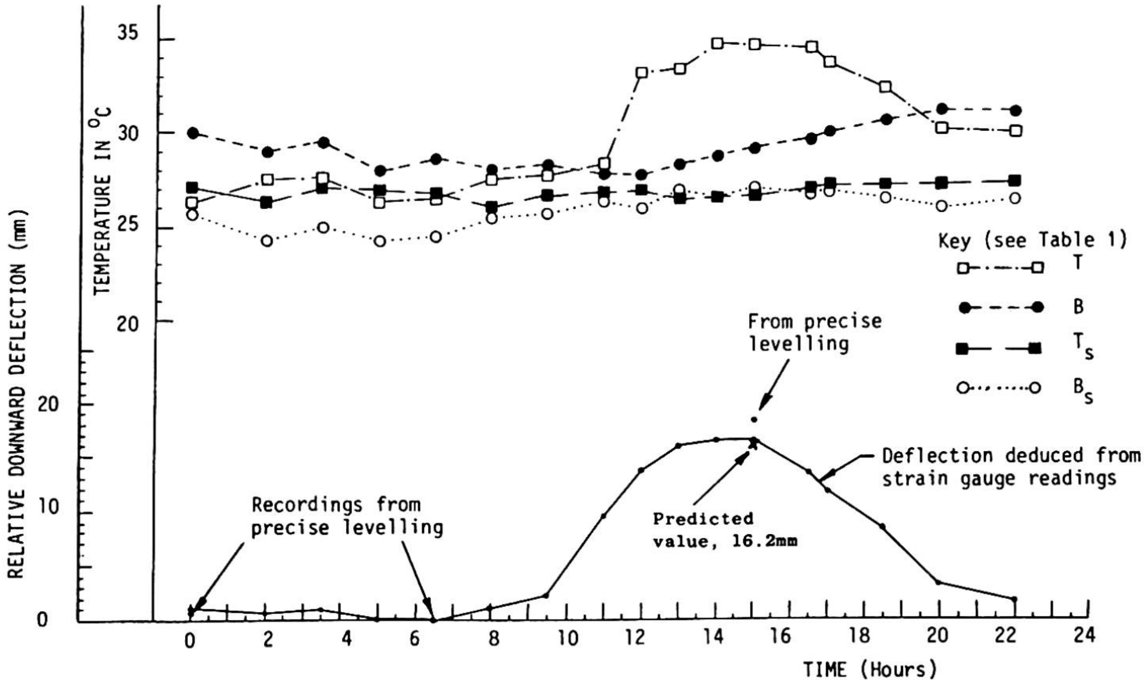


FIGURE 1. **Temperature and cantilever tip deflection records during 24hr period on 11/11/84**

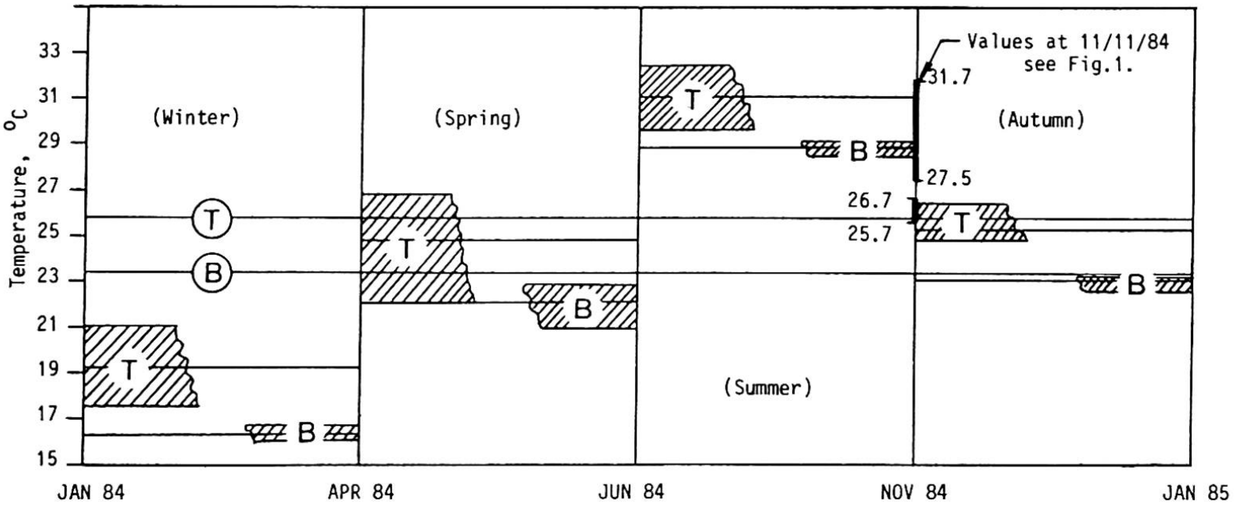


FIGURE 2. Mean upper and lower flange bridge temperatures: Yearly average; Seasonal average; and seasonally averaged Daily maximum and minimum variations.

2. ANALYSIS

A numerical step-by-step analysis in time was undertaken using a computer model of one of the cantilevers of a 'T' unit. The span was divided into 18 segments horizontally for which the section properties (e.g. dimensions, prestress, eccentricity) were known for each of the 19 bounding sections; Figure 3. Equilibrium and compatibility (plane section theory) equations for each segment were formulated such that creep, shrinkage and thermal strains of the concrete, and prestressing, relaxation and thermal strains of the steel could be incorporated in a general 'initial' strain formulation. This permitted a 'standard' numerical calculation to be performed at every step of the analysis, to determine average values of centroidal strain, $\mathcal{E}$, and curvature, χ , for each segment. Numerical integration of these values along the span revealed the cantilever tip extensions and vertical deflections.

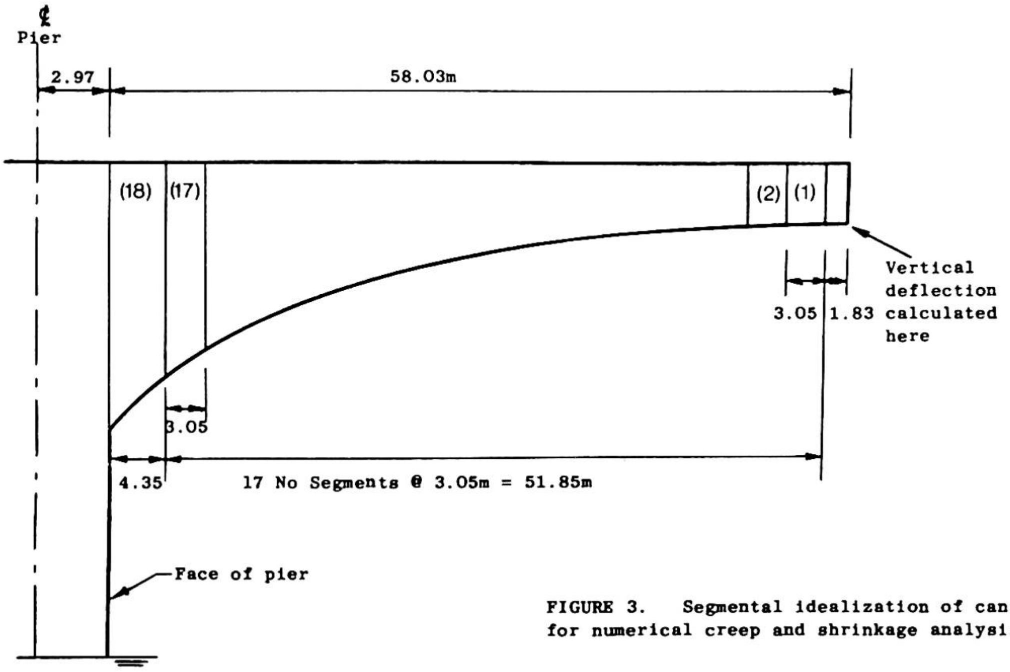


FIGURE 3. Segmental idealization of cantilever for numerical creep and shrinkage analysis.

Each segment was subdivided in depth and the stress associated with each slice (concrete) and prestressing steel (where appropriate) was derived from the calculated values of and together with the non-elastic strains appropriate to the step of the analysis being performed. The stresses were then used to determine the appropriate creep strains for the next step of the analysis; which then repeated but with changed values for the non-elastic strain components.

The prestress at the end of construction (November 1974) together with dead load, superimposed dead load, effective average live load and average yearly temperatures (Figure 2) defined the start of the time-dependent analysis. The effects of daily and seasonal temperature variations were computed from thermo-elastic analyses for temperature differences from average yearly values and were superimposed on the main time-dependent response as appropriate.

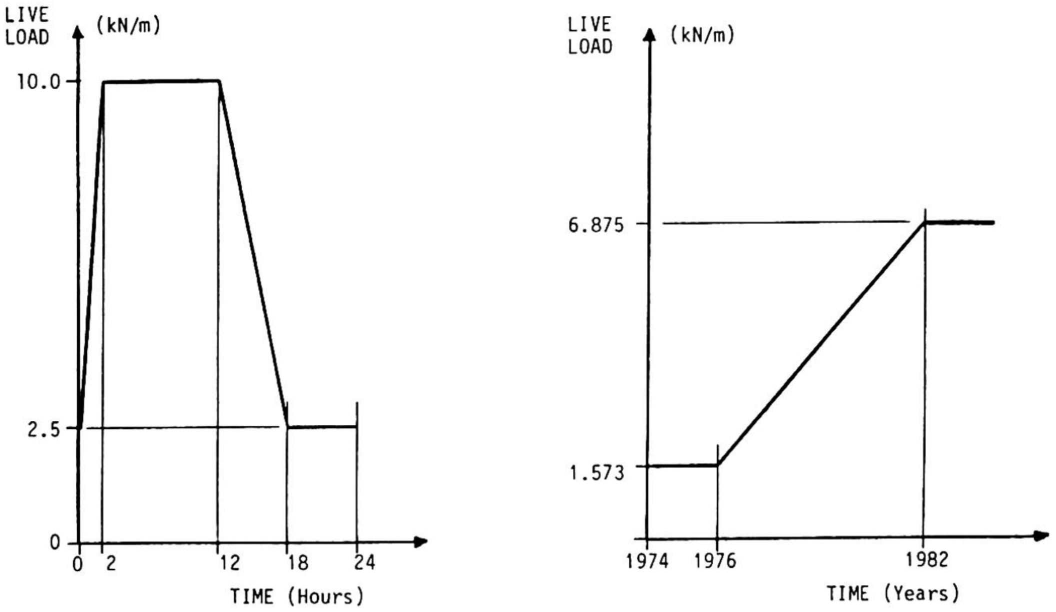


FIGURE 4. (a) Representative daily load cycle, 1982
(b) Mean daily live load variation since 1974. Design values.

3. MATERIAL DATA

The analyses were first performed using creep and shrinkage data extrapolated from tests carried out at the time of construction. Later, a survey was carried out and more recent data for Hong Kong concrete indicated that higher creep and shrinkage values should be adopted in design. The analyses were consequently repeated using these enhanced values. The temperature dependence of creep was taken into account by assuming a linear dependence on temperature in degrees Celcius. Table 2 shows the results of analysis and illustrates the separate significance of creep and shrinkage strains on tip displacements in the long term. The recorded tip displacement during 1984 is shown also for comparison.

4. DISCUSSION

The nature of the time-dependent analysis allows for the easy introduction of data which themselves change with time, e.g. live load (Figure 4), temperature and even the late introduction of additional prestress. A further benefit of the analysis is the ability to study the separate contributions to bridge deflections of prestress, temperature, loading (dead and live) and shrinkage; and thereby gain an appreciation of the sensitivity to particular parameters. Such knowledge is of importance for assessing the suitability of any remedial prestressing designed to reduce the long-term tip deflection.

Table 2 shows the recorded tip deflection in 1984 as being intermediate between the predictions based on 'extrapolated' creep and shrinkage test data and current 'design' strain values; the design values leading to a more pessimistic estimate. Table 3 shows calculated values for the average daily variations to tip deflection due to temperature changes during the four seasons of the year. Additionally the maximum recorded daily deflection changes are shown for comparison. In order to predict the tip deflection for a particular day it is necessary to know the amount by which the maximum and minimum temperatures of that day differ from the seasonally averaged maximum daily values, and to then superimpose the deflection appropriate to these changes on the calculated values of Table 3. This exercise leads to good agreement with recorded values; a typical example comparison is given in Figure 1. These data highlight the need to recognise short term thermal displacement changes when taking on-site measurements for long-term performance. The predicted average daily change amounts to approximately 10mm, while the maximum daily change can exceed 20mm.

5. CONCLUSIONS

Within the limits of available data and the duration of the study, generally good agreement between predictions and on-site measurements has been obtained.

For the cantilever tip deflection calculations the incorporation of 'design' creep and shrinkage data has led to an overestimate, i.e. safe, whereas the use of 'extrapolated' test data led to underprediction.

The comparisons between measured and predicted deflections resulting from maximum daily temperature changes throughout the bridge depth were generally excellent.

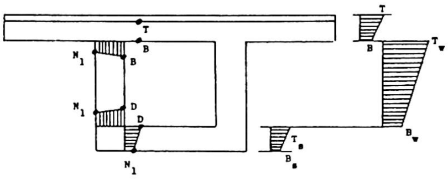
In carrying out a site study of long-term bridge behaviour it is essential to give proper recognition to short-term (daily) temperature deflections, since these can mask completely the slow development of deflections due to concrete creep and shrinkage, and tendon relaxation.

SEASON		T	B	T_w	B_w	T_s	B_s
Winter		19.55	18.86	17.46	16.35	16.63	16.06
Spring		25.30	24.32	23.15	22.13	22.28	21.98
Summer		31.03	30.96	29.55	28.79	29.43	28.14
Autumn		25.00	25.58	24.03	23.13	23.79	22.47
Year Average		26.05	25.71	24.33	23.40	23.86	22.95
Winter	Min	16.40	18.50	17.05	16.05	16.50	15.60
	Max	23.30	18.80	17.75	16.70	16.70	16.70
Spring	Min	20.80	23.50	21.85	20.95	21.70	20.20
	Max	29.30	24.30	23.85	22.90	22.40	23.40
Summer	Min	28.50	30.70	29.15	28.50	29.40	27.60
	Max	34.10	30.70	29.80	29.10	29.30	28.90
Autumn	Min	22.90	25.70	23.65	22.65	23.70	21.60
	Max	28.00	24.80	23.85	23.25	23.60	22.90

Average seasonal temps.

Seasonally averaged daily temp variations.

TABLE 1. Yearly, seasonal, and daily temperature variations throughout bridge section. Temps in degrees Celcius



Data used in Analysis	Tip Deflection below Piers, mm			
	1974	1984	2016	2098
Extrapolated creep and shrinkage values	111.0	179.2	185.5	190.6
Extrapolated creep and design shrinkage values	-	197.3	206.5	213.9
Design creep and extrapolated shrinkage values	-	216.6	250.3	276.4
Design creep and design shrinkage values	-	249.3	288.5	320.3
Measured deflections	103.0	215.0		

TABLE 2. Comparison of Cantilever tip deflections as influenced by creep, shrinkage and temperature of concrete, and tendon relaxation. Ratios of 'design' to 'extrapolated values are; creep, 4·45; shrinkage, 1·60.

Season	Daily Change in Cantilever Tip Deflection (mm)		
	Calculated - averaged over 1984 season	Recorded	
		Max	Min
Winter	10.4	21.4	5.0
Spring	9.4	16.4	8.7
Summer	7.6	31.0	10.5
Autumn	5.7	20.0	6.8

TABLE 3. Daily changes in cantilever tip deflections.