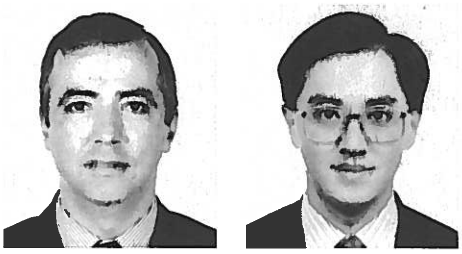
ANALYSIS AND OBSERVATION OF CREEP AND SHRINKAGE EFFECTS IN THE MACAU-TAIPA BRIDGE "PONTE DA AMIZADE"

José Manuel Catarino* and Chan Mun Fong**
* Investigador Principal, Chefe do Dep. de Materiais de Construção do LNEC
** Chefe do Dep. de Estruturas e Edifícios do Laboratório de Engenharia Civil de Macau, LECM



ABSTRACT

The Laboratory of Civil Engineering of Macau (LECM) monitored the Macau-Taipa Bridge, "Ponte da Amizade", to carry out its long-term observation. During construction, equipment was installed for measurement of strains, linear and angular displacements. The interpretation of results is based on a mathematical model for analysis of creep and shrinkage effects in prestressed reinforced concrete structures, integrating all available information in the observation study, i.e., construction sequence, loads, material properties, and environment conditions. A summary of the observation plan of this bridge, interpretation of measurements made and computational techniques used for this analysis are presented.

1 - DESCRIPTION OF THE BRIDGE

The new Macau-Taipa bridge, "Ponte da Amizade", has a total length of 4414 m. Starting from Areia Preta of Macau, the bridge can be divided into a North trestle, a North viaduct, an outer bridge, an inter-bridge viaduct, an inner bridge, a South viaduct, and a South trestle landing onto Pac On of Taipa island (Figure 1). The width of the bridge deck is 19,3 m with four 3,75 m wide traffic lanes, a central barrier, and two emergency walkways.

The construction was promoted by the Port and Bridge Office of Macau and the design was made by Câncio Martins. The contractor was a consortium of Construções Técnicas and Teixeira Duarte. Partex-CPS and Pengest made the supervision and LECM made the quality control of the construction, in Macau and in precast yards in GuangZhou. Being extinguished the Port and Bridge Office of Macau, the responsibilities related to the operation of the bridge have been transferred to DSSOPT, Direction of Soils, Public Works and Transportation.

The North and South trestles, with lengths of 912 m and 996 m respectively, are constructed from 12 m x 9 m precast slabs sitting on cast-in situ piers at 12 m apart. The three viaducts are 35 m spanned structures composed by precast piers and beams. The height of the piers varies and is achieved by mounting precast I-blocks, each with a maximum height of 4 m.

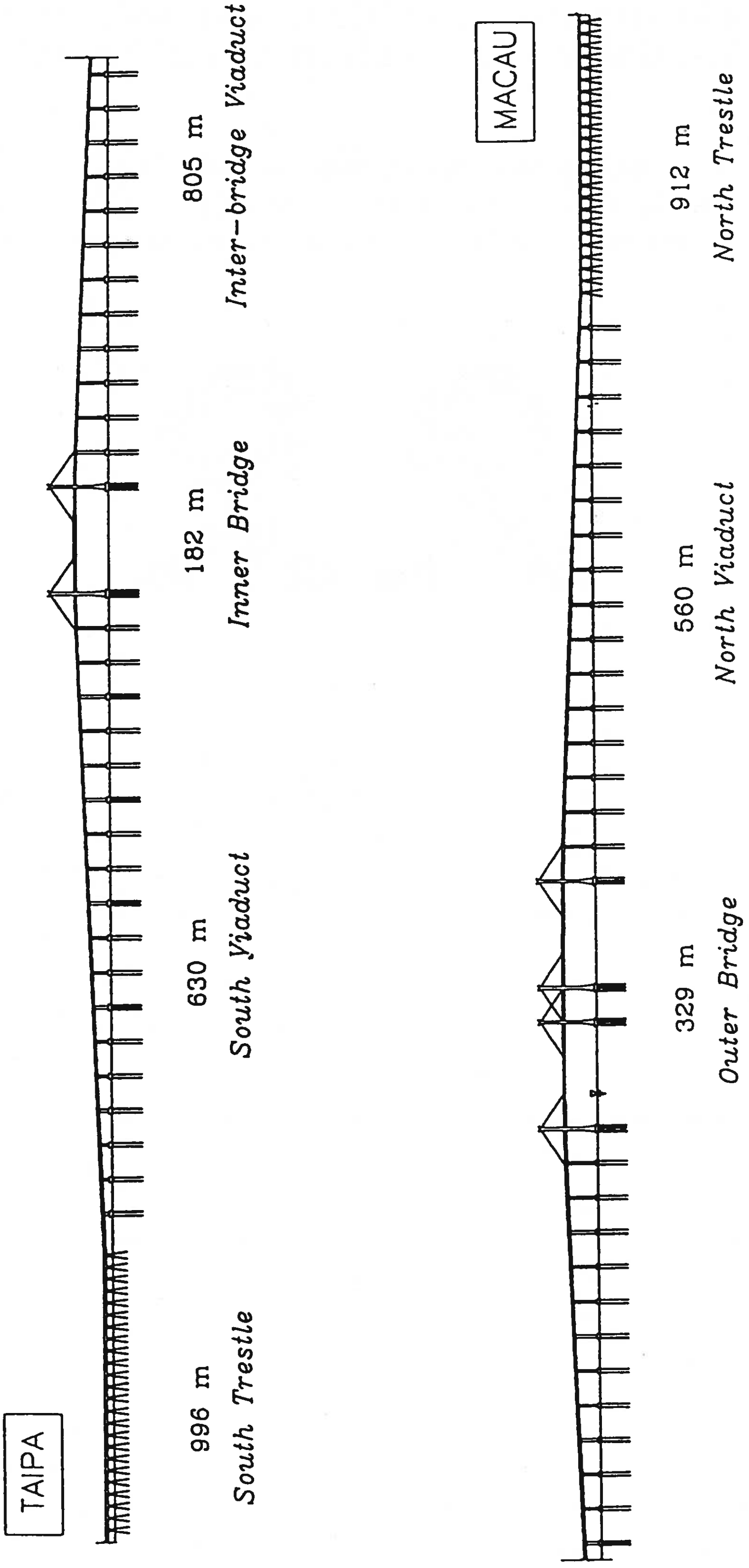
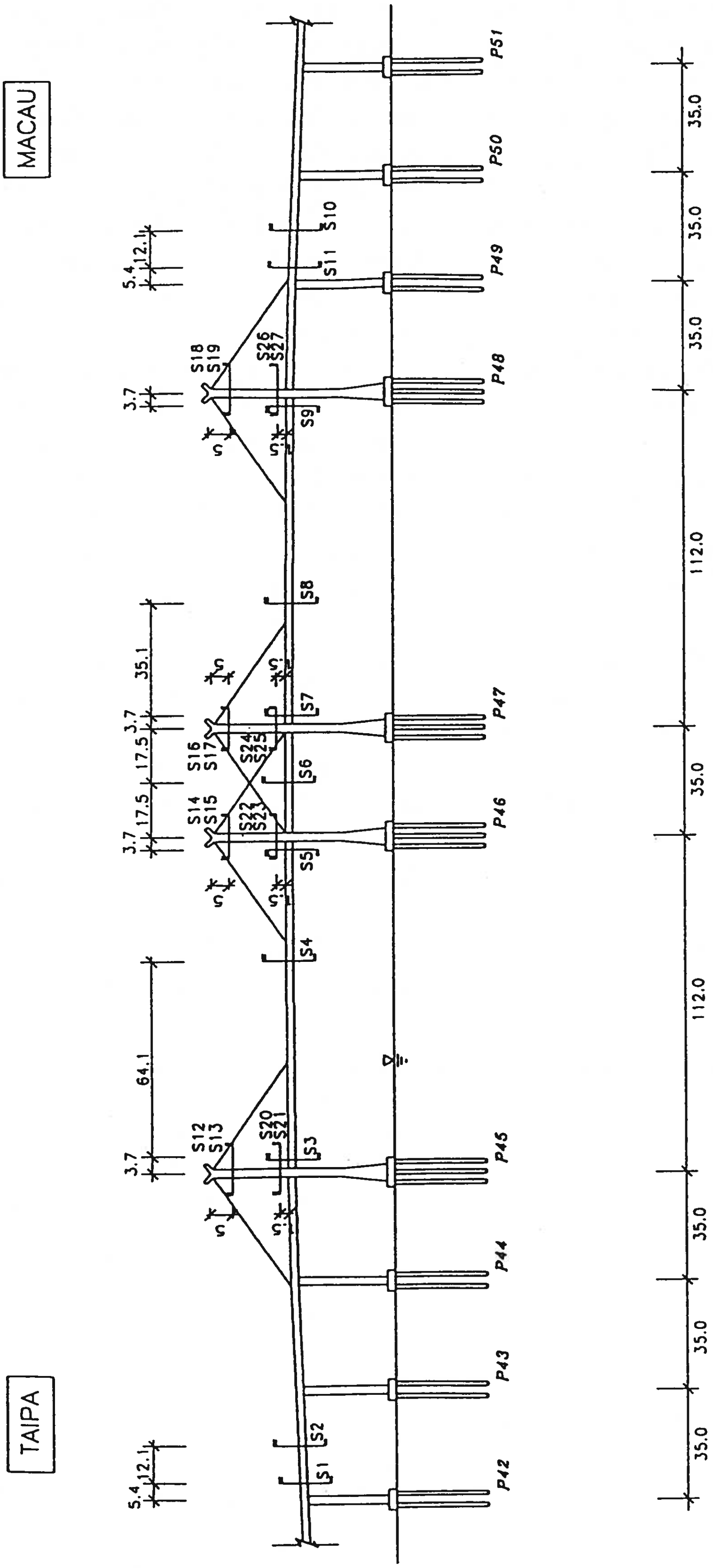


Figure 1 – Macau-Taipa Bridge, "Ponte da Amizade"



Remarks: S12, S14, S16, S18, S20, S22, S24, S26 - on East side of the bridge

S13, S15, S17, S19, S21, S23, S25, S27 - on West side of the bridge

Figure 2 – Sections Monitored with Strain Gauges

On top of the I-block is a cross capping beam which forms the supports for six 34,7 m span precast I-beams. The deck of the viaducts is of cast-in situ concrete.

The outer bridge is 329 m long with two 112 m spans over the exterior port of Macau in order to provide the necessary clearance for free shipping passages. The inner bridge is 182 m long and has only one 112 m span over the interior port of Macau for shipping passage. Both bridges have a height clearance of 30 m above sea level. The 112 m span is obtained by using triangular cable stayed structure. Cables are tied at one end to the top of cast-in-situ pylons which rise to a maximum height of 59 m above sea level. The other end of each cable is connected to precast longitudinal girders with one end resting on a supporting pier and the other end as cantilever. Cross girders were then placed on the cantilever end of the longitudinal girders to serve as bearing for precast I-beams similar to those used in the viaducts. A cast-in-situ deck is put on to complete the structure.

2 - MONITORING PLAN

Upon request of the Consortium of Construções Técnicas and Teixeira Duarte, LECM prepared the observation plan of “Ponte da Amizade” (Dinis, 1991). During the construction some adjustments had to be made in the original proposal to arrive at the final form of the observation plan (Chan, 1994). The final plan covered observation of the behaviour of the bridge during construction and for a period of one year after its completion. Within the one year monitoring period, five tri-monthly data recording have been performed. The observation plan can be divided into two parts: topography survey and instrumentation program.

The topographic survey involves the use of theodolite Wild TC 200 to monitor the deflections at selected locations of the structure during construction, in order to provide early detection of any abnormality that might have occurred.

The instrumentation program is designed to observe the performance of the outer bridge, a portion of the North viaduct, and a portion of the inter-bridge viaduct. Parameters such as strains, angular rotations, and joint displacements are of interest. For interpreting made measurements, it is important to observe its development with time and construction sequences.

The strain in structural elements is measured by vibrating wire strain gauges embedded inside concrete. Four types of structural elements are monitored, namely, precast I-beams, the cast-in-situ deck, precast longitudinal girders, and cast-in-situ pylons. The locations of monitored elements are shown in Figure 2. Vibrating wire strain gauges were installed in sections S1 to S5 and S7 to S11. Details of a typical section are illustrated in Figure 3. In section S6, only the longitudinal girders are monitored. The longitudinal girders are also monitored in sections which align with S3, S5, S7, and S9. Two gauges are put on each monitored section of the longitudinal girders. In each of sections S12 to S27 in the pylons, four gauges are installed.

For measurement of strain, compensating gauges for creep and shrinkage are used in order to obtain information concerning the behaviour of the bridge under dead and live loads. Shrinkage compensating gauges are placed inside 20 cm x 20 cm x 75 cm concrete prisms properly protected from the sides to simulate the actual exposure of the elements in site. For creep compensation, a vibrating wire strain gauge is embedded in the 20 cm x 20 cm x 75 cm concrete prism. A flat jack system, with regulator to maintain constant pressure of 10 MPa on the prism, is used. The set up is placed inside a steel frame which works as a reaction frame. Exposure condition is the same as that for shrinkage compensating gauge. Such a creep compensating device is designed and patented by LNEC.

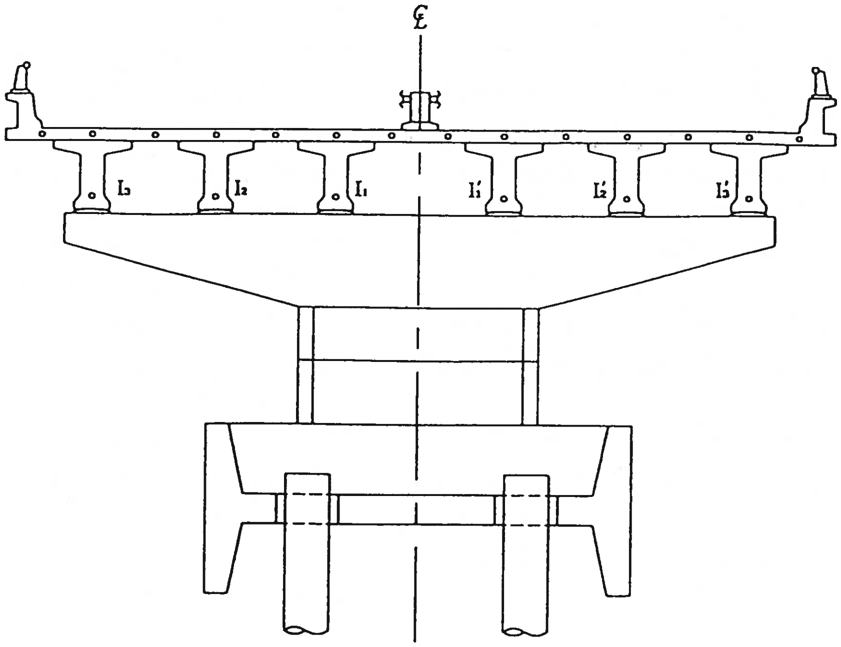


Figure 3 – Location of Strain Gauges

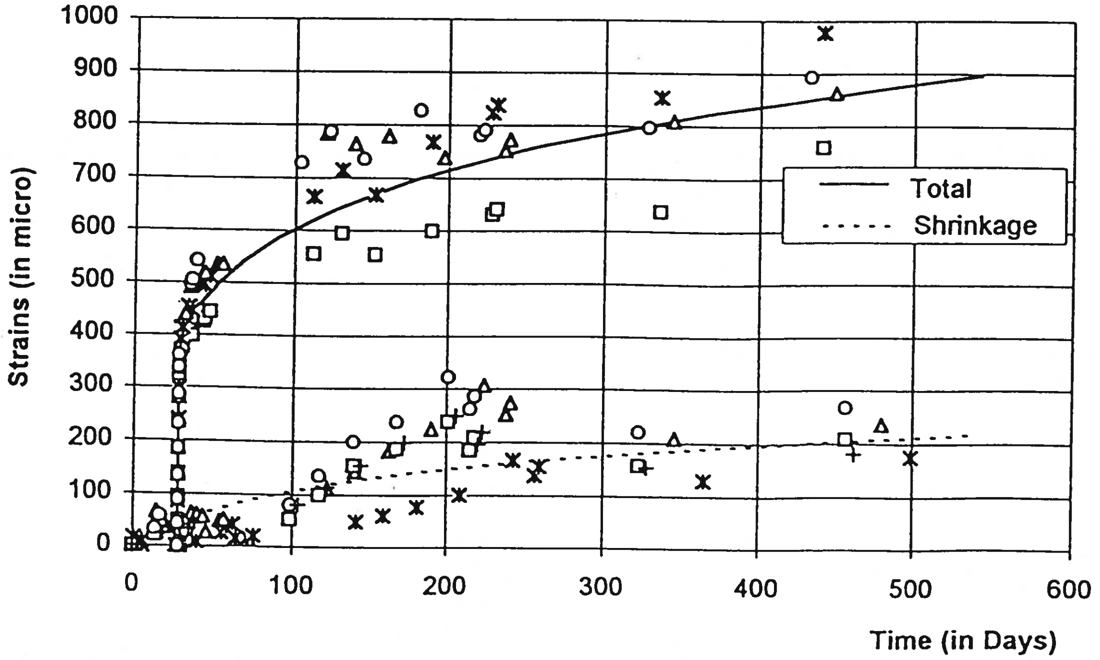


Figure 4 – Measured and Predicted Total and Shrinkage Strains

In this monitoring plan, 4 creep compensating gauges are used for the I-beam, 3 for the deck, and 2 for the pylon. For shrinkage compensation, 12 gauges are used for the I-beam, 18 for the deck and 3 for the pylon. The measured strains for the creep and shrinkage prisms of I-beam are plotted in Figure 4.

For measurement of angular rotations, 63 tiltplates are used to obtain bi-directional rotation of the deck. For the pylon, 3 resistance type inclinometers are installed in each pylon of the outer bridge giving a total of 24 inclinometers.

For expansion joint displacement, special made vibrating wire jointmeters are installed at six expansion joints in the North viaduct, the outer bridge, and the inter-bridge viaduct.

3 - CONSTRUCTION SEQUENCE

This paper deals mainly with the analysis of development of strains along time in a structural element. To achieve that, the construction sequence must be considered, based on good record of all important events experienced by structural elements.

For discussion, the measured total strains in I-beam and deck of S1 and S2 are shown in Figure 5 and Figure 6. The I-beam has gone through the following construction sequence:

a) casting of the beam in GuangZhou, China;
b) in precast yard, first prestressing of two cables in the beam, each with a prestressing force of 2340 kN, minimum strength of concrete at prestressing shall be no less than 70% of the designated B35 grade concrete;
c) in Macau site, the prestressing of a third cable with the same 2340 kN prestressing force;
d) positioning of the beam onto cross capping beam;
e) setting up of formwork and casting of deck;
f) removing formwork;
g) placement of asphalt surface.

Therefore each I-beam has to be compared with its corresponding analytical model separately, in order to reflect the actual dates of the construction sequence. In Figs. 5 and 6, the measured data of one beam are presented.

For the deck, the most important change in loading takes place during construction, is in placement of the asphalt surface. The average strains measured in the deck of sections S1 and S2 are also plotted in Figs. 5 and 6.

4 - STRUCTURAL ANALYSIS ALONG TIME

In prestressed reinforced concrete structures composed of linear parts, several types of rheological effects can occur in concrete sections, which can be classified as follows:

type I	due to different drying conditions of concrete;
type II	due to compatibility of concrete, steel reinforcement and prestressing steel;
type III	in sections made of several parts with different ages, thickness and exposure conditions, due to the compatibility between these parts.

All these rheological effects have, as consequence, increases of strains and internal coaction states of stress which, in statically indeterminate structures, produce redistributions of internal and bearing forces. In linear pieces, it is commonly adopted the assumption of plane cross sections.

Rheological effects along the smaller dimension of a concrete part due to different drying conditions (type I) can be estimated by finite element analysis, taking into consideration the evolution of boundary conditions and concrete creep and shrinkage laws for all possible histories of relevant parameters.

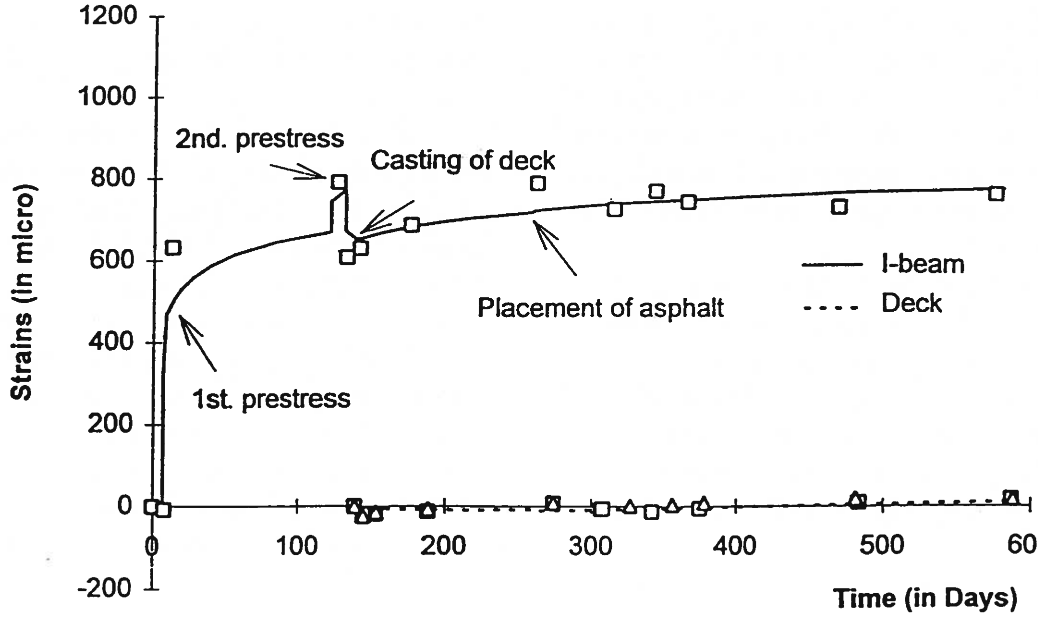


Figure 5 – Strains at I-beam and Deck of S1

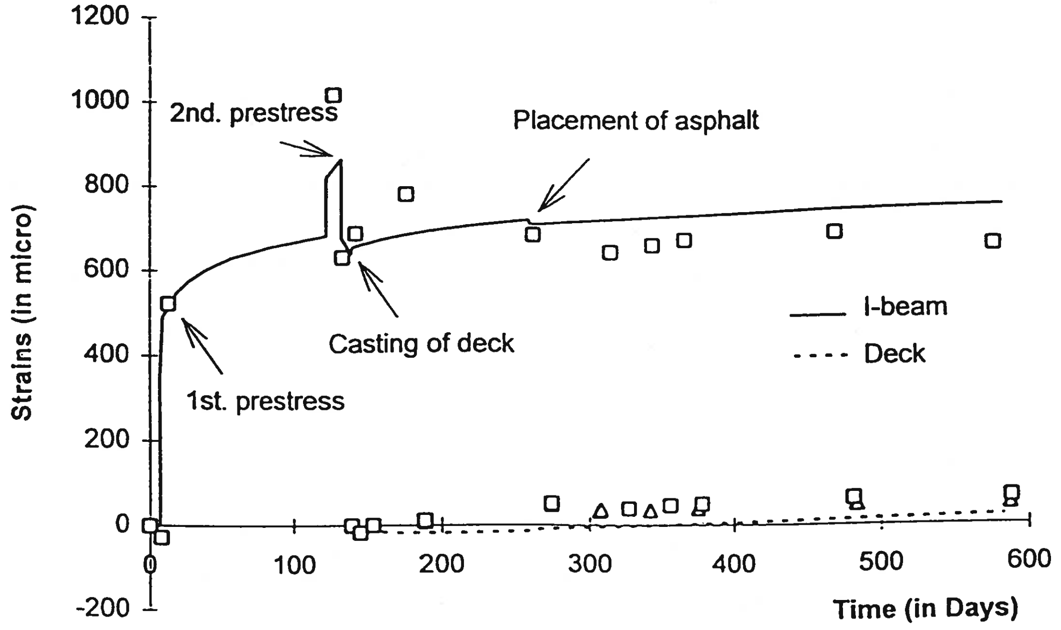


Figure 6 – Strains at I-beam and Deck of S2

There is not yet available enough experimental data to calibrate the behaviour of concrete in variable conditions of temperature, humidity and applied stresses. So, only some extrapolations based on well known concrete response permit this type of analyses.

For the structural analysis along time of "Ponte da Amizade", a mathematical model based on (Catarino, 1986) has been used, making possible the interpretation of measured strains and displacements, as this model has the following possibilities:

a) step by step analysis along time with consideration of concrete and prestress steel rheology in cracked or uncracked sections;
b) skyline and Cholesky method for storage of rigidity matrix and resolution of the system of equations;
c) consideration of construction phases;
d) composed concrete sections with parts cast in different dates;
e) change of support conditions;
f) imposal of internal forces and strains;
g) rheologic models of materials based on CEB Model Code (CEB, 1978) or other available data.

In this mathematical model, taking into consideration the construction sequence, the behaviour of used materials, all relevant dates with variations of loads and measurements in equipment used, time is divided in intervals for step by step analysis. During each interval of time stresses are assumed as constant, and increments of strains are computed in concrete sections at the end of the time interval, based on "superposition principle". After this, the compatibility of materials inside sections is "re-established" and variations of stresses in concrete sections are computed, as well as a system of "fictitious forces" that return the structure to the same shape of the beginning of the time interval. Finally, the instant analysis of the whole structure is done, based on the actual geometry, materials parameters, environment conditions, removal of fictitious forces and appliance of other loads.

This mathematical model estimates rheological effects due to the compatibility of materials and different parts of concrete sections (types II and III above described). Type I effects can be analysed separately because, in most cases, results can be superposed. However, classical methods of measuring strains in situ can not detect type I effects, but only mean values of strains along the thickness of a concrete part. Because of this, it is always necessary to have separate analysis of the referred rheological effects.

In several long term observations made by LNEC, the interpretation of measured strains and displacements has been tried through this computer program (TINTIN). After discovering the relevant parameters that permit the approach to experimental data, a better understanding of the behaviour of the structure becomes possible, as well as the elimination of erroneous information.

The same computer program has been used for modelling the effects of creep and shrinkage in concrete sections with components of different thickness. (Catarino, 1993) presents the method used for this analysis. Basically it consists in subdividing section in parts of same thickness, and treat it as a plane frame structure with rigid bars to impose linear total strains in each section.

5 - INTERPRETATION OF MEASURED STRAINS

5.1 - Creep and Shrinkage Strains

Figure 4 includes comparisons made of creep, shrinkage and total strains in compensators for measurements made in the bridge deck.

The analysis of measured strains has been based on the rheologic models of concrete of CEB Model Code (CEB, 1978).

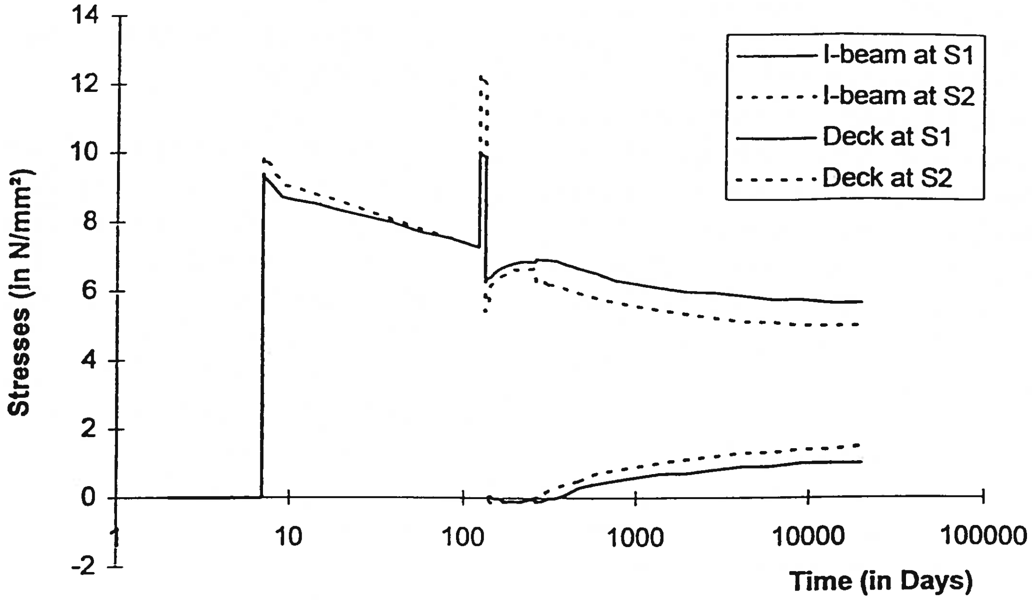


Figure 7 – Computed Stresses of I-beams and Decks at S1 and S2

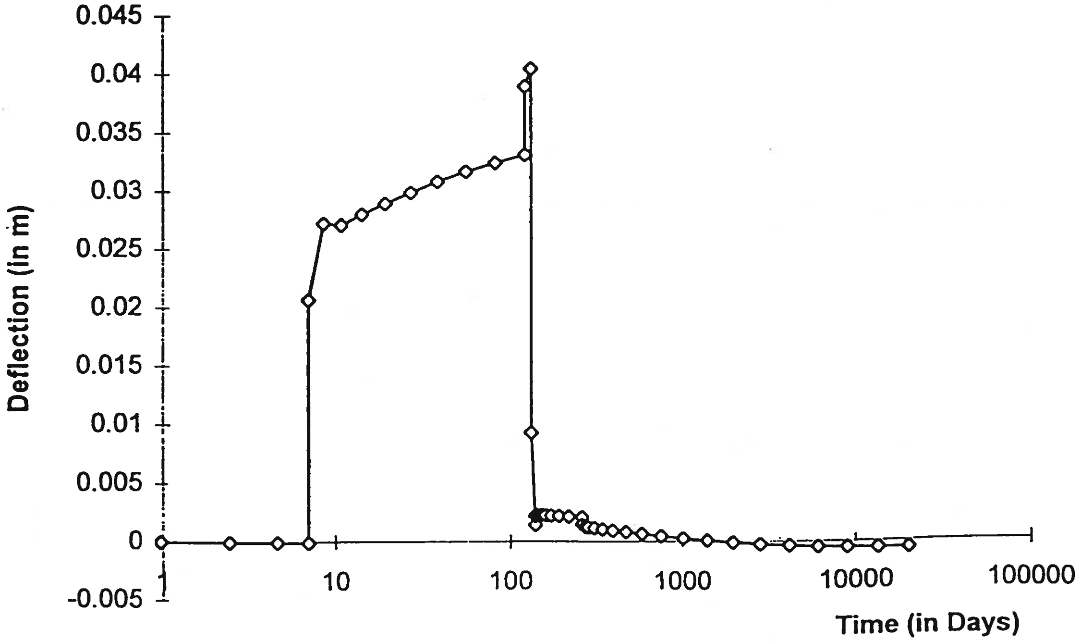


Figure 8 – Computed Deflection of I-beam at S2

The purpose of this analysis is the calibration of well known material models to a group of experimental data, so that, in the structural analysis, the same models can be extrapolated for all existing situations. The procedure used consists of combining the possible values of parameters of those models which influence elastic and rheological properties, in order to optimise the approach between measured and computed strains.

5.2 - Beam and Deck Strains

Figs. 5 and 6 include comparisons made of strains measured in I-beam and Deck of sections S1 and S2 of the bridge, referring the most important construction phases for this part of the structure. The four cases included in these figures show very good correlation, much better than in analysis of this type made in other structures. Part of this achievement is due to the simplicity of the structural system used.

6 - ESTIMATION OF OTHER PARAMETERS

After achieving a reasonable approach between measured and computed strains in a part of the bridge deck, it is very reliable to estimate other parameters like stresses, deflections, shortenings and rotations in the same instrumented areas and, with an inferior degree of reliability, it is possible to estimate the evolution of the same parameters for the life time of the bridge.

6.1 - Stresses

Figure 7 shows the evolution of stresses in sections S1 and S2 during the period of observation and its extrapolation for a life time of 50 years. The stresses have been computed at the same locations of the installed gauges.

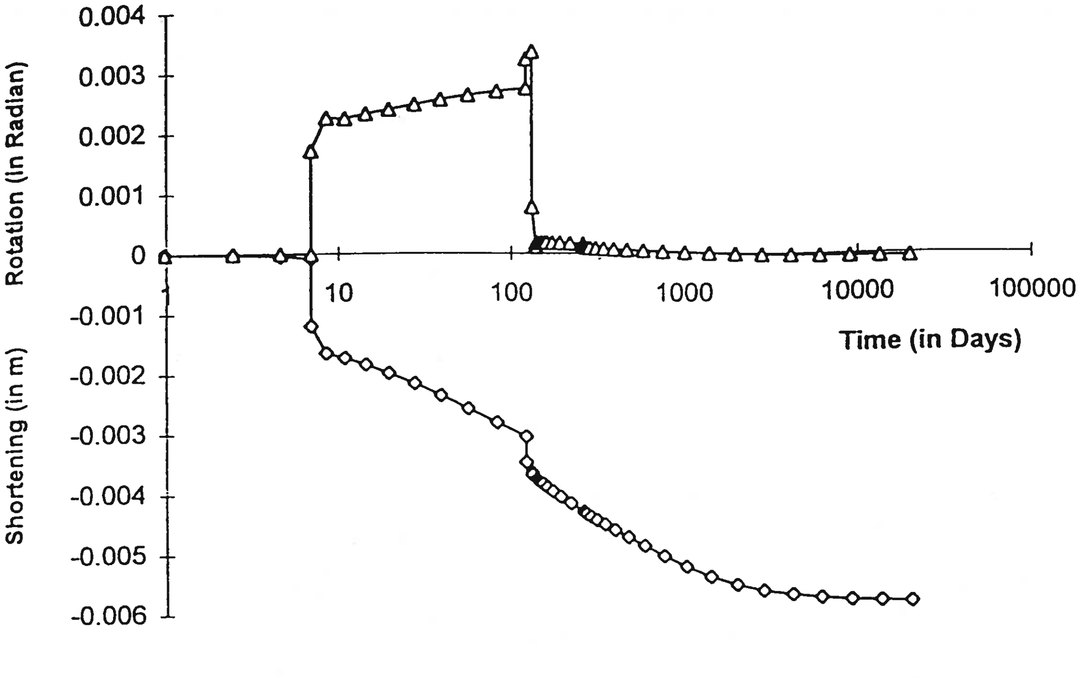


Figure 9 – Computed Shortening and Rotation of I-beam at A1

The estimated stresses in I-beams and Deck have adequate ranges of values in accordance with age and class of concrete.

6.2 – Deflections

Figure 8 shows the evolution of deflection in section S2 (middle span) during the period of observation and its extrapolation for a life time of 50 years.

This figure demonstrates the very good balance adopted in design between permanent loads and prestress, important for the long term performance of the bridge deck.

6.3 - Shortenings and Rotations

Figure 9 shows the evolution of shortening of the I-beam and rotation in section S1, during the period of observation and its extrapolation for a life time of 50 years.

The plotted shortening refers only to the left part of the I-beam, with a length of 5 m. The comment made for deflection in S2 is also applicable to estimated rotation in section S1.

7 - CONCLUSIONS

The information presented in this paper is only a small part of a systematic analysis of all measurements made in the New Macau-Taipa Bridge, "Ponte da Amizade", which is being carried by the Laboratory of Civil Engineering of Macau (LECM).

Although the type of structure of this bridge is few sensitive to concrete rheological effects, even in this case is indispensable the use of a mathematical model with the above described possibilities for the interpretation of measured strains, angular and linear displacements.

After achieving a reasonable approach between measured and computed parameters in all possible situations, it is very reliable to estimate other parameters not easily measurable, like stresses, strains and displacements in some parts of the structure. With an inferior degree of reliability it is certainly capable to estimate the evolution of all parameters for the life time of the bridge.

From the measurements and analysis already made, it can be stated that the structural behaviour of this bridge, verified since the construction and estimated for its life time, seems quite satisfactory. In particular the balance adopted in design between permanent loads and prestress prove to be excellent in terms of long term evolution of deflections of the deck.

REFERENCES

Catarino, J.M. (1986), “Comportamento Reológico de Estruturas de Betão Armado Pré-esforçado - Análise e Observação”, LNEC, thesis

Catarino, J.M. and Silveira, P. (1993), “Creep and Shrinkage Effects in Concrete Sections with Components of Different Thickness”, RILEM ConCreep 5, Barcelona

CEB, Comité Euro-International du Béton (1978), “Code Modele CEB-FIP pour les Structures en Béton”, Bulletin d'Information nº 125, CEB

Chan, M.F. and Lam, C.L. (1994), “Monitoring of New Macau-Taipa Bridge - Instrumentation Part, LECM report nº 543

Dinis, V.M.S. (1991), “Proposta para Observação do Comportamento Estrutural da Nova Ponte Macau-Taipa”, LECM report nº 188