CREEP EFFECTS AND STRESS ADJUSTMENTS IN CABLE-STAYED BRIDGES WITH CONCRETE DECK

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ABSTRACT

In construction stages of cable-stayed bridges with prestressed concrete deck, the influence of creep on stresses and strains is very important in order to foresee the final patterns of internal forces and displacements.

In cantilever construction, the concrete deck can be considered, in each stage, as a continuous beam resting on elastic restraints, which modify with successive additions of new segments, until the last one has been assembled. In these stages stress relaxation in concrete occurs as well as vertical displacements increase. Ehen structure has been closed by inserting midspan segment, stress redistribution begins, due to creep. Deformation and internal force development in construction and service life modify stay stresses such as deck and pylon final profiles.

It is necessary to prevent undesirable deformed shape of deck and pylon and to control the final stress pattern of deck and stays. The requested final geometry of the bridge is reached by adjusting stay axial forces during construction.

A study is presented in which, by taking into account creep effects, the optimization in terms of deck and pylon deformed shape can be achieved through a sequence of stay force adjustments during construction stages. The presented analysis is based on the theory of aging linear viscoelasticity in order to give a useful tool for the conceptual design of cable-stayed bridges with concrete deck.

The proposed procedure allows engineers to design by reducing and avoiding creep effects instead of calculating them with refined models since the first design step.

Keywords: Cable-stayed, Bridges, Creep, Stress adjustments, Staged construction

INTRODUCTION

Construction stages of a cable-stayed bridge are characterized by a sequence in which geometric configuration, restraints and consequently stress and strain patterns vary many times till the final arrangement is reached. Different topics have to be considered in construction stages in order to achieve the desired configuration: dead load bending moments into the deck, foundation deformability and pylons profile, stay forces and deformed shape for dead and live loads. Moreover materials imply different section and spacing of stays, internal forces distribution, construction sequences and technologies[1]. Apart from these items the influence of time-dependent phenomena has to be considered for prestressed concrete or composite decks and for concrete pylons. Creep and shrinkage of concrete as well as steel relaxation are liable for changing of stresses and strains during construction and service life. Great differences concerning creep and global behaviour have to be considered in cantilever construction with prefabricated elements or by casting in situ upon falsework. Cable-stayed bridges are generally non-homogeneous structures with respect to creep because they are composed of steel and concrete elements and their deck could be formed by segments of different ages. So, creep has an effect on the deformed shape of the structure in time and stress redistribution has to be expected, leading to possible overstressing of some elements by modifying the predicted behaviour. In literature it is well known the advantage to have the behaviour of a continuous beam on rigid supports, for that configuration called as the final "dead load configuration". In this case stay forces are found simply as the projection, on the stays direction, of rigid supports reactions. This approach does not take into account time-dependent phenomena in transient phases when concrete is young.
In the following, after a brief literature survey, the optimization of stay forces in construction stages are examined. The target is to find a convenient stay stressing procedure in construction phases, in order to obtain the predefined final design configuration and to minimize creep effects, in terms of stress and strain. The chosen approach allows engineers to avoid time consuming procedures in order to account these effects by numerical simulations and staged analyses from the beginning of design. It can be done by following the influence matrix method in order to reach a pattern close to that of a continuous beam on rigid supports for every construction stage and for the final one. A numerical application is presented to explain the proposed procedure.

LITERATURE SURVEY

Several studies about optimization of stay forces and adjustment sequences can be found in literature. For cantilever method, in most cases a backward analysis is performed, in which the bridge is considered in its final configuration, as a continuous beam on rigid supports with dead loads applied. Then the bridge is successively deconstructed by deleting the elements added in each construction stage[2,3]. Stay forces are evaluated for each deconstruction phase and they supply the stressing force to be given at that stage to the last stay[4]. So, backward analysis considers a unique stressing procedure for each stay. By cantilevering, it is very difficult to achieve the desired configuration with a single stressing of stays, because cable-stayed bridges are structures with a great number of redundancies and the mutual effect between stays is significant. On the other hand, a multiple stressing of each stay in different phases needs but it implies technological problems because every time a stress is given, strands in the anchorage are engraved and many stressing operations could damage them[5]. Some authors suggest to build deck section in more than one stage, by assembling in subsequent times different parts of the section and by a two-step stressing of stays. This methodology is effective for composite decks or wide concrete ones. Manterola and Fernandez[6] used it in the Barrios de Luna bridge. Schlaich[7] presented a survey of the most common methodologies to establish the final dead load configuration and to solve problems related to construction of composite girders with precast slabs. He provided some information to minimize effects of bending stress redistributions due to creep and to consider the influence of axial shortening due to creep and shrinkage into deck and pylons. In literature this problem has been faced by a forward analysis. In a first phase the backward analysis is used to establish the values of stay forces, then a more refined forward analysis is performed by following the real sequence of construction in which also creep effects in time are taken into account[2]. It is necessary because a time analysis can be only forward. The forces found in the first phase are successively modified by the results of the refined analysis. Many authors, in the second phase, take into account geometric non linearity due to cable sag and beam-column effect[8]. Optimization problems are faced by other authors in terms of stay forces in the final stage. The most common methodologies are three: i) making null dead load displacements in order to reach a predefined profile of the deck; ii) reaching the bending moment law of an equivalent continuous beam on rigid supports; iii) minimizing an opportune energetic function. Chen[9] suggests to determine the initial cable forces by the force equilibrium method. Xiao et al. examined the influence matrix method of cable tension optimization for long span bridges, considering an energetic function[10]. All these methods solve the problem only in the final stage, because in temporary stages they do not consider transient forces and deck deformations. Recupero[11] analyzed cable-stayed bridges with steel deck by the first two approaches and proposed a mixed method that considers a pre-defined configuration to be achieved in terms of deformed shape for dead loads and bending moments into the deck. Negrão and Simões[12] studied the general problem of optimization of cable-stayed bridges with three dimensional modelling. Cassity and He[4] pointed out the problem of sequential stressing of cable-stayed bridges erected on falsework. Kasuga[13] studied the optimum cable force adjustments by the influence matrix method. Khalil, Dilger and Ghali[14] considered creep effects in prestressed concrete cable-stayed bridges by a time-dependent analysis in which non-linearity due to cable sag has been included and the construction sequence has been followed. The results show the importance of heterogeneity, due to different cast ages and steel elements, on stress redistribution in time. Chiodi[15] presented a method to consider creep effects on construction stages by using the AAEM (Age Adjusted Effective Modulus) method and by taking into account cast heterogeneity. Chiorino, Mola et al.[16] established the "reduced relaxation" method for creep effects in structures with elastic restrains or in non-homogeneous structures with steel and concrete elements coupled. Mola and Giussani[17] applied these concepts on cable-stayed bridges. In these studies creep analysis is always based on prediction models given by codes (CEB MC90, ACI209,...).

CREEP EFFECTS ON CABLE-STAYED BRIDGES

During construction and service life the level of concrete stresses into the deck of cable-stayed bridges is generally below the 50% of concrete compressive strength; the most common cross-section is a hollow box composed of elements (slabs and webs) with similar

notional sizes. In this case it is possible to assume cross section homogeneity, a one-dimension linear aging viscoelastic model for creep and the validity of superposition principle in time. Strains development can be modelled by the creep function $J(t,t_0)$ representing the total strain at the generic time t, due to a unit stress applied at time t_0, while creep coefficient $\varphi(t,t_0)$ represents the creep rate of the total strain. $J(t,t_0)$ is also called compliance function and it is given by creep prediction models adopted by codes. Stress development due to imposed strains is reciprocally modelled by the relaxation function $R(t,t_0)$ representing the total stress at the generic time t, due to a unit strain applied at time t_0. Analysis of homogeneous structures with invariable static scheme and rigid restraints can be based on the theorems of linear viscoelastic theory for aging materials. The 1st theorem states that for constant sustained loads, internal forces are constant too and they coincide with the elastic ones, while deformations increase amplifying the elastic values through the product $E_c(t_0)\cdot J(t,t_0)$. The 2nd theorem states that for constant geometric actions, strains are constant too and they coincide with the elastic ones, while internal forces vary in time, reducing the elastic values through the ratio $R(t,t_0)/E_c(t_0)$.
In case of static scheme changes for delayed restraints addition, under sustained loads and for structures on rigid supports, one or more delayed restraints applied at time $t_1 > t_0$ prevent the increasing of deformations due to creep that would occur in the section restrained if these restraints were not applied. For $t > t_1$ stress pattern evolves approaching the stress distribution corresponding to the application of sustained loads directly on the structure in its final static scheme[18]. For change of static scheme at time t_1, the law of the generic internal force[19] is written by introducing the redistribution function $\xi(t,t_0,t_1)$. It expresses the percentage of acquisition of the modified system stress. Codes provide values of the redistribution function in terms of tables or graphs. Creep effects on static scheme changes are considered by Arici and Granata[19]. An algebraic solution of creep integral equations and values of redistribution function can be found by applying the AAEM method, proposed by Bažant[20].
An important consequence of the first theorem of linear viscoelasticity regards homogeneous concrete structures statically determined for rigid external restraints and with additional elastic (e.g. steel) ones. If elastic restraints are introduced at the same time t_0 of sustained loads, or immediately after, and they are forced up to the values of the reactions for equivalent rigid restraints, the initial stress distribution is not affected by creep and remains unchanged. In this case in fact all the points restrained remain fixed at $t \geq t_0^+$ for that sustained load; as a consequence of the first theorem of linear viscoelasticity the initial stress distribution is not modified by creep[16,17]. This result is useful to reduce or avoid creep effects in cable-stayed bridges, by imposing the vertical component of the stay forces equal to the value of the vertical reactions of rigid supports. So, the final value of reactions is introduced from the beginning and it is not modified by creep for $t \geq t_0^+$.
In order to reach the stated target, it is possible to follow this strategy by giving the desired stay stresses for achieving the final dead load configuration as that of a beam on rigid supports, in which no changes due to creep are to be expected in time. After that, live loads will be applied but they do not cause time-dependent stress and strain. By this way, the scheme is forced to the final elastic one by minimizing the effects of creep, but it implies a forward analysis. Generally, two phenomena have to be considered in cable-stayed bridges: the application of sustained loads in a structure with elastic restraints (which implies relaxation of stress in concrete) and the redistribution of internal forces due to delayed restraints added during construction stages. In order to consider these phenomena, a

prediction of stress and strain evolution has to be done, based on the creep models given by codes. As a matter of fact the predictions of these models are often very different leading to a solution that varies within a large range of values. In the proposed approach, by reaching the configuration with rigid restraints at each stage through appropriate stay force adjustments, forces redistribution is strongly reduced and no evaluations of creep effects in time are necessary with prediction models, avoiding the related uncertainties. This is true for bending creep, i.e. the influence of creep on curvatures due to bending and then, to vertical displacements of deck and horizontal displacements of pylon, which influence the dead load configuration in terms of deformed shape and stay forces. Progressive shortening of deck and pylon in time due to axial forces and to creep and shrinkage effects on axial strains, remain and cannot be avoided[7]. For that reason deck and pylons must be built longer to compensate the axial shortening. The influence of prestressing into the deck has to be considered in the final state, at the same time of external sustained loads due to self-weight and superstructure.

CANTILEVER CONSTRUCTION OF CABLE-STAYED BRIDGES

Let us consider a cable-stayed bridge built by the cantilever method (building on falsework is not considered here). Bridge general configuration is self-anchored until the back span has reached its final length, then it could be partially earth anchored or not. In the following we will refer to a general 2-D symmetrical scheme, with a mixed fan-harp stays arrangement. Geometric non-linearity due to cable sag can be taken into account by performing an iterative procedure in which the modified Dischinger elastic modulus (by the Ernst hypothesis)[3,11,14] has to be computed. In case of short stays, geometric non-linearity can be neglected and the linear elastic solution is very close to the non-linear one[1,3]. Pylon foundation is assumed to be rigid and no foundation movements are taken into account here.

In cantilever construction, apart from self-weight and construction equipment, a centered temporary prestressing has to be considered to join the last segments built. The new stay is connected near the end of the last segment erected and dead load is applied only when the stay is in its position. This operation implies that the right initial position of the segment must be computed, because after dead load has been applied, a vertical displacement of the segment tip occurs. So, for each segment the initial position is determined by assembling it following the tangent at the tip of the previous one, just deformed[7]. The proposed strategy for taking into account time-dependent phenomena during erection consists of a forward staged construction analysis of the bridge in which at each stage the target is to reach the configuration of a partial beam on rigid supports under dead loads, construction equipment loads and temporary prestressing. To achieve the exact final configuration, a theoretic re-stressing of all stays in all stages would be done. In practical applications it is not possible to do that, because too many adjustments of stay forces make complicated the erection procedure[5].

STAY STRESSING PROCEDURE

In order to achieve the desired target, a two-step procedure is proposed herein:

- in each stage two stays are stressed: the new one and the previous one, reaching the stay force values, close to that of the continuous beam on rigid supports (figure 1*a*);
- in the final configuration, when the structure is completed, all stays are re-stressed and

adjusted to achieve the final "dead load configuration", by considering all permanent loads, definitive prestressing, creep and shrinkage effects on axial shortening (figure 1*b*).

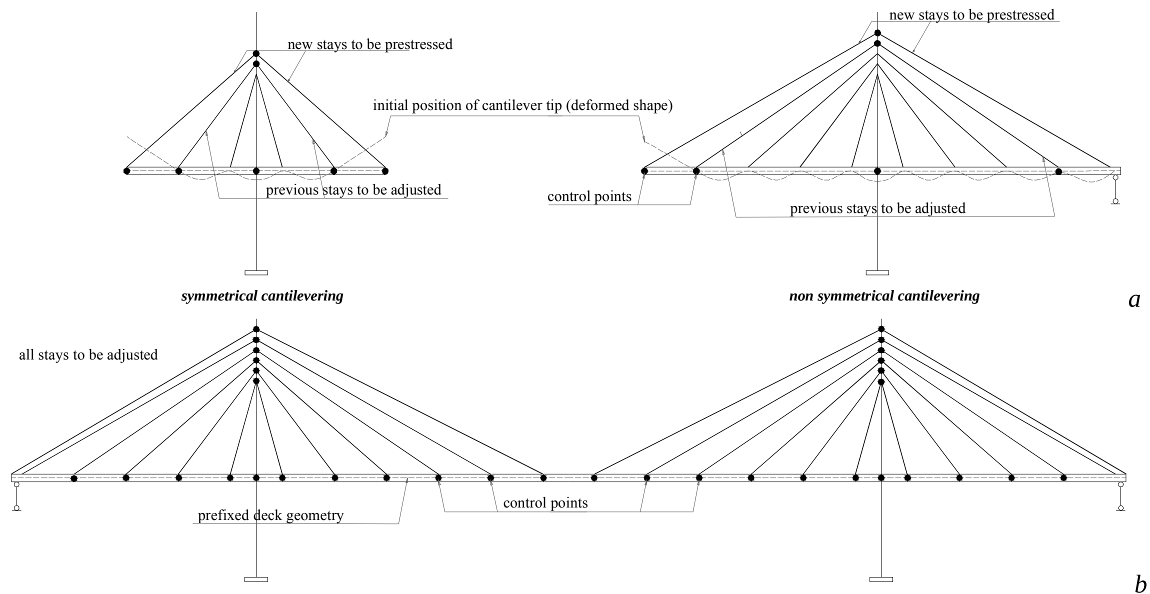


Fig. 1 – *a*) Stressing sequence during construction and deformed shape. *b*) Final geometry with adjustments.

At the end of this procedure deformed shape and bending moments into the deck are very close to those of the continuous beam on rigid supports and consequently the final values of stay forces are determined. No backward analysis has to be performed. In each phase of the procedure, the first unknown is the value of stressing to be given to the new stay introduced into the structure and the adjustment value of the previous one. Here, the influence matrix method has been applied, by making stays behaviour linear, through the Ernst modulus, for each step of the iterative non-linear procedure. By considering as direct unknown variables the specific imposed strains of stays due to stressing, cable elongations and forces will be indirect unknowns. Therefore maximum number of unknowns will be the same as stays number to be stressed. It is important to choose the smallest number for a good conditioning of the mathematical problem, by considering the smallest number of control points in which an assigned displacement is imposed. These are the vertical displacements of the deck stay anchorage points and the horizontal ones of the pylon. With n stays to be stressed and m displacements to be controlled, the influence matrix $\boldsymbol{D}$ can be obtained by evaluating the displacement δ_{ij} of the j-th control point ($j \leq m$) due to the unit imposed strain of the i-th stay ($i \leq n$). Considering the m-dimensional vector $\boldsymbol{d}$ of displacements of profile control points and the n-dimensional vector $\boldsymbol{e}$ of imposed strains, it can be written[11]:

$$\boldsymbol{d} = \boldsymbol{D}\,\boldsymbol{e} + \boldsymbol{d}^{*} \tag{1}$$

where $\boldsymbol{d}^{*}$ is the vector of displacements induced by loads applied at that stage in the control points. Because of $\boldsymbol{D}$ is not a square matrix, to obtain the strains $\boldsymbol{e}$, by making null total displacements $\boldsymbol{d}$, the following relation has to be considered (zero displacement method):

$$\boldsymbol{D}^{\mathrm{T}}\boldsymbol{D}\,\boldsymbol{e} + \boldsymbol{D}^{\mathrm{T}}\boldsymbol{d}^{*} = \boldsymbol{0} \tag{2}$$

from which, the strains $\boldsymbol{e}$ can be found, by inverting the square matrix $\boldsymbol{K_D} = \boldsymbol{D}^{\mathrm{T}}\boldsymbol{D}$.

In this way a configuration close to that on rigid supports, can be achieved at each construction stage. For the 1st theorem of linear viscoelasticity, no stress redistribution due to creep is induced in every partial structure. After erection end the same procedure can be followed for the final configuration, by considering all dead loads, definitive prestressing and axial shortening due to creep and shrinkage. So, the configuration of a beam on rigid supports can be definitely achieved, before live loads are applied.

REMARKS FOR CONCEPTUAL DESIGN

In order to reach the desired result in terms of geometric profile and internal forces through the described procedure, the influence of following phenomena has to be considered:

- construction methodology (cast in situ or precast segments) and creep heterogeneities due to different cast ages into the deck;
- temporary prestressing in construction and final prestressing tendons distribution;
- shortening of deck and pylon due to shrinkage and axial creep.

About construction methodology and creep heterogeneity due to cast, a more relevant internal redistribution is induced by the cast in situ technique where creep deformations of young concrete are more important with respect to precast segments, which are generally stocked and cured. In order to take into account this heterogeneity a staged construction technique based on the AAEM method can be done, in which a fictitious elastic modulus is used for each segment[15]. Alternatively a more refined computer analysis, which involves all the different creep functions of each segment, could be performed. When cast ages are not so different an average value of the load application time t_0 (and of the related concrete elastic modulus) can be taken into account, considering an average homogeneous structure. This assumption can be always acceptable for the conceptual design of the bridge. In case of cast in situ technique the right placement of the segment and consequently the correct geometry is achieved by positioning the formwork along the tangent to the last segment end, just deformed, and by stressing the stay attached to the tip of the formwork (fig. 1*a*). In case of precast segments they are assembled by positioning the point of the stay anchorage higher than the final position, by computing the vertical displacement of that point for loads that will be applied[7].

Temporary prestressing has to be taken into account, because the shortening due to it could affects the values of displacements of control points in each stage, but its influence is often small. Final prestressing instead could affect the displacements significantly and it needs a careful evaluation of bending moments due to tendon configuration, which is generally the typical one of a continuous beam, based on diagrams of maximum and minimum internal forces due to moving loads. By inserting the displacements of deck and pylon control points due to loads into the vector of displacements $\boldsymbol{d}^*$ in order to make null the total displacements $\boldsymbol{d}$ in the final stage, the solution $\boldsymbol{e}$ that gives the correct values of stay elongations adjustment is found by equation (1).

Axial shortening can modify the configuration at the age of erection end. At that age, it is convenient to have a shape higher than the desired one, because with time, a downward vertical displacement occurs, bringing the configuration towards the desired dead load deformed shape. The value of this pre-camber can be found by estimating axial creep and shrinkage through prediction models. It is convenient to consider different models, in order to compute an average value that can be reliable in practice.

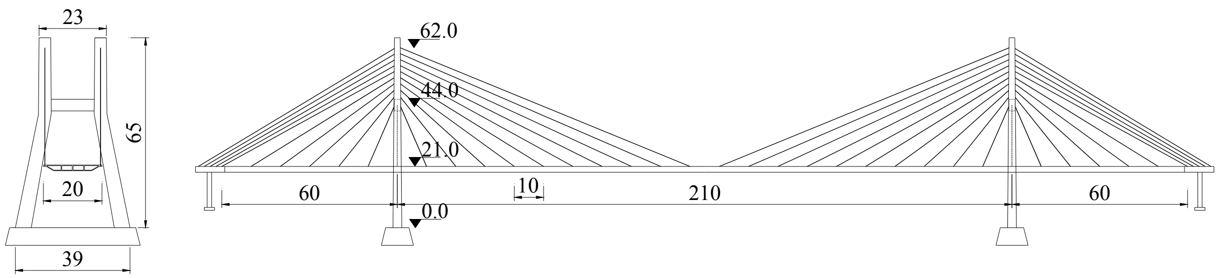


Fig. 2 – Geometry of the bridge.

NUMERICAL APPLICATION

A numerical application is here presented on a model of a partially earth-anchored cable-stayed bridge. The main geometric characteristics are illustrated in figure 2, while the construction sequence is showed in figure 3. The main span is 210 m long while side spans are 60 m long. The stay arrangement is mixed (harp and fan) with two symmetric planes of stays anchored at the edges of a multi-cellular box 20 m wide and 2 m high. The bridge is built by symmetrical cantilevering till the back span has been completed. The other back stays are then anchored on a flexible pier which allows for longitudinal movements.

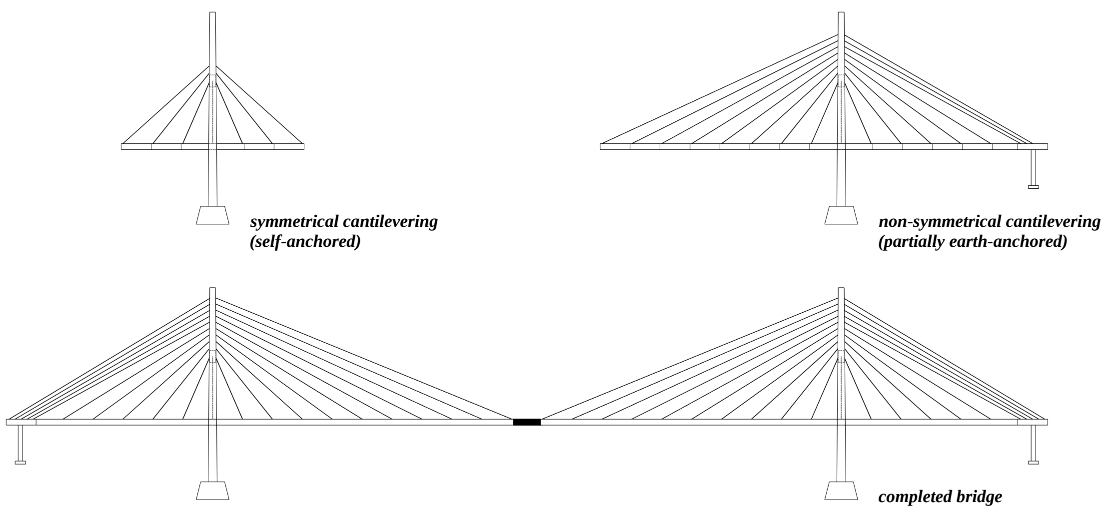
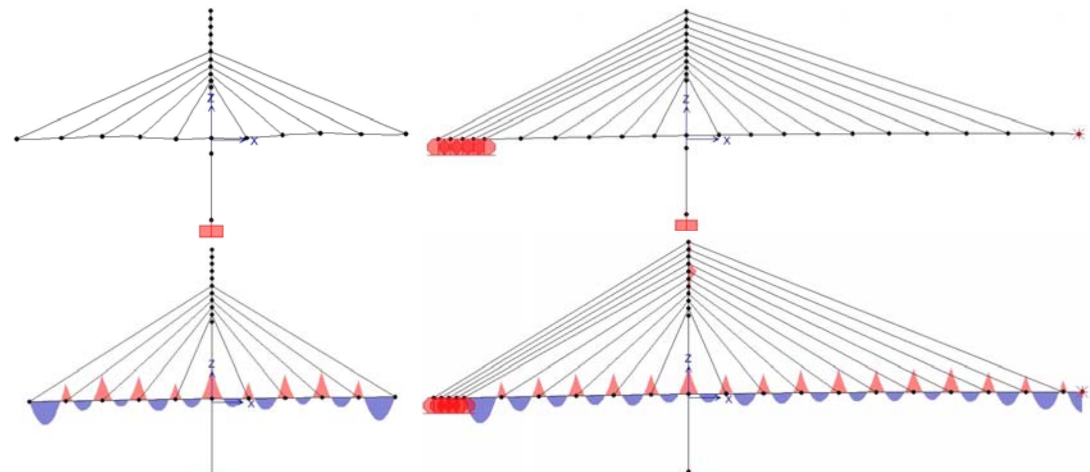


Fig. 3 – Construction sequence by cantilevering and final configuration with the central joint..

Spacing of stay anchorages is 10 m in the deck and 2 m in the pylon. The framed pylon has two vertical arms transversally joined by a rigid concrete element. Concrete strength is f_{ck} = 50 MPa. Vertical stays have been anchored at the deck to avoid rigid restraints next to the pylons. Self-weight of the deck is q_d = 350 kN/m. Superstructure load is q_s = 60 kN/m. Geometric characteristics of deck are: A = 10.694 m^2, J = 6.265 m^4, y_G = 0.796 m (centroid position). Equivalent steel diameter of stays is ϕ_p = 0.09 m, while earth anchored stays have the diameter ϕ_b = 0.13 m. The pylon has a mean cross section A_p= 13.92 m^2 and J_p = 15.3 m^4. A parabolic profile is assumed for the deck with a maximum camber in the midspan of 1.60 m with respect to bridge accesses. Fig. 4*a* shows the deformed shape of a symmetrical cantilevering stage and the relative bending moment diagram, by considering dead loads and temporary prestressing. Fig. 4*b* shows the dead load configuration and the bending moment diagram of the completed bridge.



a *b*

Fig. 4 – Deformed shape and bending moments. *a*) Symmetrical cantilevering stage. *b*) Final configuration

The solution considers self-weight, superstructure loads, prestressing and axial shortening due to creep and shrinkage. Table 1 reports values of stay forces in each stage, for stays (11-21) and backstays (1-10) of the half bridge.

Table 1 – Stay forces in construction stages [kN]. Stages I-V: symmetrical cantilevering, stages VI-X: non symmetrical cantilevering, stage XI: final adjustment.

stay \ stage	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
1										50	4239
2									130	7491	6757
3								1192	6879	6423	6203
4							1792	5582	5079	4630	5530
5						1538	3835	3336	2837	2397	2765
6					1410	3628	3458	3274	3090	2929	4140
7				1267	3260	3082	2995	2899	2804	2721	3434
8			1104	2852	2675	2582	2559	2533	2507	2484	2999
9		984	2512	2343	2266	2245	2251	2257	2263	2268	2649
10	750	2001	1842	1798	1799	1810	1818	1826	1834	1843	2054
11	2125	1812	1762	1794	1831	1857	1870	1880	1889	1897	2150
12	743	1981	1823	1782	1784	1796	1805	1809	1808	1801	2170
13		973	2483	2320	2247	2227	2230	2239	2246	2248	2509
14			1090	2810	2639	2546	2510	2506	2515	2526	3034
15				1257	3203	3022	2911	2860	2846	2852	3404
16					1405	3606	3412	3284	3215	3189	3848
17						1521	3963	3752	3601	3511	4233
18							1619	4310	4075	3895	4552
19								1695	4651	4378	4888
20									1742	5011	5238
21										1748	5387

CONCLUSIONS

A procedure of stay stressing and adjustments has been proposed for cantilever construction of cable-stayed bridges. The target is to find a convenient construction sequence, in order to obtain the predefined final design configuration and to minimize creep effects on that configuration, in terms of stress and strain. The chosen approach follows the influence matrix method for reaching a pattern close to that of a continuous beam on rigid supports for every construction stage and for the final one. The main topics related to construction and service life have been analyzed by taking into account time-dependent phenomena. The procedure proposed herein allows designers to face creep phenomena in cable stayed bridges by reducing or avoiding its effects instead of calculating it since the phase of conceptual design. A numerical application has been presented to show the results.

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