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Adaptive procedure for camber control of forward cantilever structures

Procedimento adaptativo para controle de contra flechas durante a fase construtiva de estruturas em balanços sucessivos


M. F. L. O. SANTOS [a]
mariella.santos@ufpe.br

B. HOROWITZ [a]
horowitz@ufpe.br

Abstract

In forward cantilever structures, segments are built from previous ones, therefore construction loads must be carried by the partly completed structure. As the cantilever is moved forward deformations increase and corrections must be made during the construction phase. In camber control, corrective displacements are applied to compensate for deformations. The proposed procedure assimilates topographical survey data collected at each construction stage to update the structural model by minimizing the differences between real and computed displacements. Concrete material properties are used as design variables in an optimization process that drives them to values that better represent the material actually used in construction. This is an iterative process where new data are assimilated at each new structural deformed configuration. New camber values are computed and applied to segments that will be cast in the future in order to reach the desired final design profile. The use of the procedure leads to residual displacements of no greater than 5% of the total deformation without camber.

Keywords: forward cantilever, camber control, optimization.

Resumo

Na execução do Método dos Balanços Sucessivos, os segmentos são construídos a partir do anterior e os carregamentos de construção são suportados pelos segmentos anteriores. O balanço evolui e as deformações ocorridas aumentam, necessitando aplicar medidas corretivas ainda durante a fase construtiva. O uso de contra flechas introduz deslocamentos corretivos de modo a compensar essas deformações. O método proposto assimila os dados obtidos na leitura em cada etapa executada, e minimiza a diferença entre as deformações reais e previstas. Um programa de simulação utiliza propriedades do concreto como variáveis de otimização e desta forma, o material pode representar melhor aquele utilizado na construção. Esse processo é iterativo e novos dados são assimilados ao problema prevendo uma nova configuração deformada. Assim, novos valores de contra flechas são determinados e aplicados aos segmentos que ainda não foram executados, a fim de atingir a configuração de projeto. A aplicação do procedimento permite obter deformações residuais que não ultrapassam 5% da deformação total da estrutura sem contra flechas.

Palavras-chave: balanço sucessivo, contra flecha, otimização.

[a] *Departamento de Engenharia Civil, Universidade Federal de Pernambuco, Recife, PE, Brasil.*

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1. Introduction

The analysis of a project should not be restricted only to the working life of the structure. In some cases, loadings that occur during the construction period greatly influence both stability and the final configuration. Some construction techniques may require more elaborate design procedures requiring additional verifications. This is the case of structures built using the forward cantilever method. In this construction method, the structure is built in successive segments. Each new segment is cast from the previous ones, which must therefore withstand the corresponding construction loads. When the cantilever increases, deformations increase substantially making corrective measures necessary during the construction phase. The use of camber is a procedure whereby correction displacements are applied to compensate for the structure deformations in order to preserve the design profile.
In order to calculate camber values it is necessary to compute deformations at each construction phase as well as total displacements, since they are required for computing the necessary camber as described in Paim [15], Podolny and Muller [16] and Mathivat [11]. Deformation can be predicted by structural analysis of appropriate models and software. Time-dependent deformations must be taken into account since construction is carried out at different stages.
Deformations are monitored at each construction stage. Surveyed data are compared to predicted displacements. Values differ because the concrete properties actually used in construction are dependent on material proportioning, type of aggregate rock and a number of other factors that alter its composition.
Usually residual mismatch from the design profile occurs even when the design camber is applied. Stucchi [4] recommends corrections in camber values in the segments yet to be constructed. Oyamada [14] proposes a geometric correction in order that when new segments are cast they conform to the original design profile. Corrections may also be determined by integrating computer simulation and construction data monitoring. Lai and Wang [10] use data from deformation control to estimate real construction curves using linear regression analysis and thus adjusting camber values during execution. Jung [9] uses measured displacements and material models together with neural networks to tune time-dependent behavior of the actual concrete applied on site. The material model thus obtained is used to predict long-term displacements of the structure.

This work develops a procedure for camber control during the construction phase of forward cantilever structures that ensures proper final profile configuration to meet design requirements. Survey data collected at each construction stage are assimilated to the model using nonlinear least square, which minimizes the differences between real and predicted deformations. Design variables in the optimization process control both short and long-term deformations. The iterative procedure used to minimize displacement mismatch is automatically coupled to the structural analysis program. Taking into account the displacement computational model used by the structural software, the chosen design variables are the characteristic concrete strength at 28 days, fck, which directly influences the modulus of elasticity, and the relative humidity, RH, which influences the time-dependent creep and shrinkage deformations.
Through the proposed procedure, it is possible to better represent the properties of the material actually used in the structure. As survey readings are collected at each construction stage the iterative process allows for assimilation of new data gradually approaching the characteristics of the material actually employed. By using these updated material properties it is possible to better predict displacements and thus more effectively control the final desired configuration.

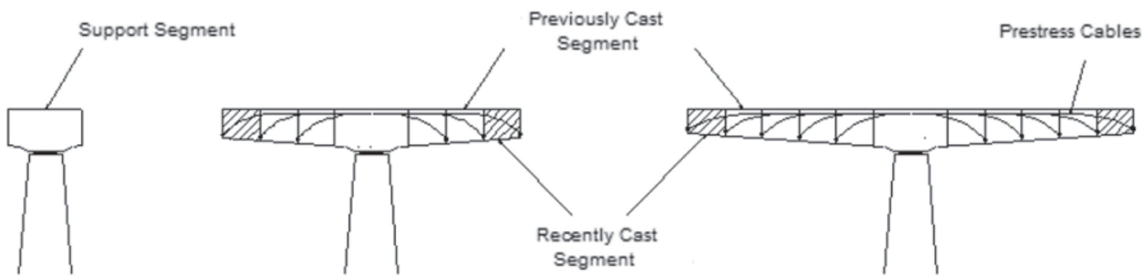
2. Behavior of bridges constructed by the forward cantilever method

To better understand the construction using the forward cantilever method, this technique is applied to the construction of bridges. Thus, it is possible to more easily grasp design procedures, the construction process and the consequences of mistakes made in some of those phases.

2.1 The construction technique

Cantilever construction consists of building a bridge deck in a succession of segments, where each segment placed carries the weight of the next segment and, on occasion, the weight of the formwork or of the construction plant [11].
This structure may be described as beam or frame bridge, which during construction uses a cantilever configuration. The weight on both cantilevers must equilibrate in order to make the structure feasible during construction (Figure 1).

Figure 1 – Construction by the forward cantiliver method



Field monitoring of deformations is carried out during all construction stages. Displacements due to casting of each segment are closely followed in order to avoid excessive deformations. Computation of displacements must consider prestressing, dead and construction loads, and creep and shrinkage.
Estimating immediate displacements, due to application of loads, as well as progressive deformations as a result of time effects helps control excessive displacements. Deformations, in order to reach the desired design profile, are compensated by using camber control, which is the application of intentional vertical displacements to the structure during the assembly of the formwork in the opposite direction of displacements due to loads.

2.2 Camber

Deformations of forward cantilever construction may achieve significant values and the application of camber is necessary to reach the desired design profile. The value of the camber is equal to total displacements due to dead loads [12].
The critical problem of in situ casting is the control of these deformations that should be considered when calculating displacements. Some displacements are not directly considered in this computation but must not be neglected as additional displacements due to formwork deformations.
Application of camber is controlled through field measurement during construction by using special spreadsheets. The monitoring is performed on all segments along the bridge deck either at daybreak or the end of the day in order to minimize thermal effects. These data allow necessary corrections to be made when level differences occur during construction in order to prevent casting problems.

2.3 CEB/FIP Code

Computation of deformations uses basic strength of material concepts as well as the CEB-FIP code [6] that is implemented in several structural programs, making it possible to consider time-dependent effects.

Computation of deformations according to CEB-FIP code

Total deformation may be computed by Equation (1) corresponding to the sum of immediate deformation that occurs on application of loads and time-dependent deformations due to creep and shrinkage.

$$\varepsilon_C(t)=\varepsilon_{Ci}(t_0)+\varepsilon_{CC}(t)+\varepsilon_{CS}(t)+\varepsilon_{CT}(t) \quad (1)$$

Where $\varepsilon_C(t)$ = total strain; $\varepsilon_{Ci}(t_0)$ = initial strain at loading; $\varepsilon_{CC}(t)$ = creep strain at time; $\varepsilon_{CS}(t)$ = shrinkage strain; $\varepsilon_{CT}(t)$ = thermal strain. The first two deformations are load-dependent while the remaining terms do not depend on loading.

2.4 Material properties

In order to compute deformation it is imperative to establish material properties that closely resemble those of the real structure. At the design stage, those parameters must be estimated based on CEB-FIP code equations derived from mathematical models of experimental research.

Modulus of elasticity

The modulus of elasticity is directly influenced by material strength and, therefore, factors that modify strength also affect it. Although not directly proportional, the modulus of elasticity increases with strength. Tangent modulus of elasticity, E_{Ci}, after 28 days, can be computed according to Equation (2):

$$E_{Ci}=E_{C0}\left[\frac{(f_{ck}+\Delta f)}{f_{cmo}}\right]^{\frac{1}{3}} \quad (2)$$

Where E_{C0} = 2,15x10^{4}MPa; f_{ck} = characteristic strength in MPa; Δf = 8MPa; f_{cmo} = 10MPa.
An increase of strength over time affects the modulus of elasticity. The change of modulus with time may be computed by:

$$E_{Ci}(t)=\beta_E(t)E_{Ci} \quad (3)$$

Where $E_{Ci}(t)$ = modulus of elasticity as a function of time; $\beta_E(t)$ = given by Equation (4):

$$\beta_E(t)=\left[\beta_{CC}(t)\right]^{0.5} \quad (4)$$

Where $\beta_{CC}(t)$ is given by Equation (5):

$$\beta_{CC}(t)=e^{\left\{s\left[1-\left(\frac{28}{t/t_1}\right)^{\frac{1}{2}}\right]\right\}} \quad (5)$$

Where s = depends on the type of cement; t = age of concrete in days; t_1 = one day.

Characteristic compressive strength

The characteristic compressive strength, f_{ck}, is measured at 28 days. Change of strength with time may be computed by Equation (6):

$$f_{cm}(t)=\beta_{CC}(t)f_{cm} \quad (6)$$

Where $f_{cm}(t)$ = concrete compressive strength at an age of t days; $\beta_{CC}(t)$ = given by Equation (5); f_{cm} = $f_{cm}=f_{ck}+\Delta f$ β_{CC} (t).

2.5 Time-dependent effects

Creep

Creep is the continuous increase of deformations due to a constantly applied stress [1]
According to CEB-FIP, creep coefficient is a linear function of stress as long as the limit, $|\sigma_c|<0.4f_{cm}(t_0)$, is satisfied. If this is true then creep deformation, $\varepsilon_{CC}(t,t_0)$, is given by Equation (7):

$$\varepsilon_{CC}(t,t_0)=\frac{\sigma_c(t_0)}{E_{Ci}}\phi(t,t_0) \quad (7)$$

Where $\sigma_c(t_0)$ = constant stress; $\phi(t,t_0)$ = creep coefficient, given by $\phi(t,t_0)=\phi_0\beta_C(t-t_0)$.
To compute the creep coefficient it is necessary to determine the theoretical creep coefficient given by Equation (8) and other parameters, such as the relative humidity influence on the coefficient, given by Equation (9), concrete strength influence on the coefficient, given by Equation (10), and influence of initial age of loading, given by Equation (11):

$$\phi_0=\phi_{RH}\beta(f_{cm})\beta(t_0) \quad (8)$$

$$\phi_{RH}=1+\frac{1-\frac{RH}{RH_0}}{0.46\left(\frac{h}{h_0}\right)^{\frac{1}{3}}} \quad (9)$$

$$\beta(f_{cm})=\frac{5.3}{\left(\frac{f_{cm}}{f_{cmo}}\right)^{0.5}} \quad (10)$$

$$\beta(t_0)=\frac{1}{0.1+\left(\frac{t_0}{t_1}\right)^{0.2}} \quad (11)$$

It is also necessary to compute the coefficient that models the increase of creep with time after initial loading, given by Equation (12), and the coefficient that models the time-dependent influence of relative humidity, given by Equation (13):

$$\beta_C(t-t_0)=\left[\frac{\frac{(t-t_0)}{t_1}}{\beta_H+\frac{(t-t_0)}{t_1}}\right]^{0.3} \quad (12)$$

$$\beta_H=150\left\{1+\left(1.2\frac{RH}{RH_0}\right)^{18}\right\}\frac{h}{h_0}+2\leq 1500 \quad (13)$$

Shrinkage

Shrinkage is the decrease in concrete volume during the hardening process due to loss of pore water [1]. Development of shrinkage may result in cracking and increase of deleterious stresses.
Shrinkage strains, $\varepsilon_{CS}(t,t_S)$, may be computed by Equation (14):

$$\varepsilon_{CS}=(t,t_S)=\varepsilon_{CS0}\beta_S(t-t_S) \quad (14)$$

where ε_{CS0} is the theoretical shrinkage coefficient, computed by $\varepsilon_{CS0}=\varepsilon_S(f_{cm})\,\beta_{RH}$, with additional terms given by Equations (15) e (16):

$$\varepsilon_S(f_{cm})=\left[160+10\beta_{SC}\left(9-\frac{f_{cm}}{f_{cmo}}\right)\right]\times 10^{-6} \quad (15)$$

where β_{SC} depends on cement type, and is given by:

$$\beta_{RH}=\begin{cases}-1.55\beta_{sRH}, & se\ 40\%\leq RH\leq 99\%\\ \beta_{RH}=+0.25, & se\ RH\geq 99\%\end{cases} \quad (16)$$

Also, the relative humidity coefficient is given by: $\beta_{sRH}=1-\left(\frac{RH}{RH_0}\right)^3$

Development of shrinkage deformation with time is given by Equation (17) where t_s = concrete age at the start of shrinkage.

$$\beta_s(t-t_s)=\left[\frac{\frac{(t-t_s)}{t_1}}{350\left(\frac{h}{h_0}\right)^2+\frac{(t-t_s)}{t_1}}\right]^{0.5} \quad (17)$$

3. Data assimilation and history matching

With proper monitoring of displacements over time, it is possible to infer the characteristic concrete material properties actually applied to the structure. Material proportioning, type of aggregates and operational techniques of casting impair particular features to the concrete that may differ from parameters originally adopted at the design stage. This in turn may be conducive to differences between real and predicted behaviors.
Differences between real and predicted displacements should be

minimized in order to accomplish the desired design profile at the end of construction. Displacement monitoring coupled with an optimization process leads to more representative values of concrete parameters minimizing residual deformation along the construction stages.

The optimization process iteratively determines new values of material parameters and thereby computes new predicted structural displacements. Deformations are computed using SAP2000 [7] and the CEB-FIP code material modeling. Chosen design variables are concrete compressive strength, fck, which influences immediate deformations, and relative humidity, RH, which influences time-dependent deformations. The particular choice of these parameters derives from the adopted structural analysis code and its time-dependent modeling of concrete deformations.

Once design variables are chosen the optimization may be stated as follows:

$$\begin{aligned} &Minimize \quad f(x)=\sum_{i=1}^{no} f_i^2(x) \\ &Subject\ to: \quad x_j^L \le x_j \le x_j^u \qquad j=1,2 \end{aligned} \tag{18}$$

Where *no* = number of observations; *x* = vector of unknown material parameters; x_i^L and x_i^U = lower and upper bounds of the two material parameters: f_{ck} and *RH*. Parameter bounds are set to values that bracket the material properties of the real structure. In the examples of this study bounds on the compressive strength, f_{ck}, are set to 20MPa and 50MPa. For relative humidity, which appears in Equation (16), the adopted values are 40% and 99%.

The mismatch functions $f_i(x)$ correspond to the difference between predicted and measured structural displacements at the ends of each segment, at each construction stage, as shown in Equation (19). In order to take into account possible negative values $f_i(x)$ is squared in the final objective function *f*(*x*).

$$f_i(x)=\frac{yp_i(x)-yr_i}{yr_i}=\frac{yp_i(x)}{yr_i}-1 \tag{19}$$

where i = observation index; $yp_i(x)$ = predicted displacement, and yr_i = actual surveyed displacement values.

Usage of actual field measurements characterizes this problem as model parameters-fitting problem. Therefore, Nonlinear Least Squares technique is suitable to effectively solve it. The nonlinear relationships between displacements and material parameters make it necessary to adopt a nonlinear solver.

3.1 Nonlinear least squares algorithm

In general, the least squares technique seeks to find a vector x that minimizes an objective function comprising the sum of the squares of mismatching terms. This is exactly the form of function *f* in Equation (18). It is a very useful technique in practical problems because it can determine model parameters that best fit a given set of experimental results. If the mathematical model of the problem is adequate, the minimum value of the objective function may be expected to be small. If it is assumed that the value of the objective function is negligible in the solution a very efficient algorithm based on Newton's method can be developed. In fact, in this case second order derivatives may be computed using first order derivatives only.

The objective function in Equation (18) may be rewritten as:

$$\begin{aligned} &f(x)=\frac{1}{2}\sum_{i=1}^{no}\left[f_i(x)^2\right]=\frac{1}{2}F(x)^T F(x), \\ &with\ F(x)=\left[f_1(x)\ldots f_{no}(x)\right]^T \end{aligned} \tag{20}$$

Newton's method solves the problem by equating to zero the gradient of function *f*. This results in a nonlinear system of equations. Equation (21) expresses the gradient of *f* in terms of the Jacobian matrix *J*(*x*) of vector function *F*(*x*):

$$\nabla f(x)=\sum_{i=1}^{no} f_i(x)\nabla f_i(x)=\left[J(x)\right]^T F(x) \tag{21}$$

The Hessian matrix of *f* is given by:

$$\nabla^2 f(x)=\sum_{i=1}^{no}\nabla f_i(x)\nabla f_i(x)^T+\sum_{i=1}^{no} f_i(x)\nabla^2 f_i(x) \tag{22}$$

Assuming that the value of *f* in the solution approaches zero, it is possible to neglect the second term of the right-hand side of Equation (22). Then, as can be seen from Equation (23), due to the special structure of the problem it is possible to compute second derivatives with first order information only.

$$\nabla^2 f(x)=\sum_{i=1}^{n}\nabla f_i(x)\nabla f_i(x)=\left[J(x)\right]^T J(x)=H(x) \tag{23}$$

Using Taylor series expansion of function *f* at $\bar{x}$ and using Equations (20), (21) and (23), then:

$$\begin{aligned} &f(x)=\frac{1}{2}F(\bar{x})^T F(\bar{x})+(x-\bar{x})^T\left[J(\bar{x})\right]^T \\ &F(\bar{x})+\frac{1}{2}(x-\bar{x})^T\left[J(\bar{x})\right]^T J(\bar{x})(x-\bar{x}) \end{aligned} \tag{24}$$

The first order necessary optimality condition requires that the gradient vanished at the solution, x^*. Using Newton's method to solve the system $\nabla f(x^*) = 0$ results in the iterative process shown in Equation (25).

$$x_{k+1}=x_k-\left[J(x_k)^T J(x_k)\right]^{-1}\cdot\nabla f(x_k) \tag{25}$$

3.2 Optimization using MATLAB optimization toolbox

The optimization process is implemented using MATLAB Optimization Toolbox [13]. New values for the design variables, which are the two material properties f_{ck} and RH, are obtained by minimizing the differences between predicted displacements using the SAP2000 model and real measured deformations. This automatic iterative process allows for computation of new material parameters that best fit the real behavior up to the current construction stage and are inserted into the structural model to predict new displacement curves for future stages.

MATLAB Function lsqnonlin

MATLAB function *lsqnonlin* is the tool of choice to solve the minimization problem of Equation (18). This function uses a Nonlinear Least Squares technique to solve the problem:

$$\min_{x} \sum_{i} f_i^2(x) = \min_{x} F(x)^2 \quad (26)$$

Function syntax is:
[x, resnorm, residual, exitflag, output] = lsqnonlin (fun, x0, lb, ub, options)

where the output components at in the solution are: *x* = solution vector of design variables; *resnorm* = value of the objective function which is sum of the squares in individual; *residual* = residual values; *exitflag* = describes solution status; *output* = output structure detailing the optimization history. The input components are *fun* = name of the function that returns each individual residual shown in Equation (27) (sum of squares should not be informed); *x0* = initial vector of design variables; *lb* and *ub* = vectors of lower and upper bounds on design variables; *options* = structure containing option specifications for the solver.

$$f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ \ldots \\ f_n(x) \end{bmatrix} \quad (27)$$

In order to compute the residual values one must have real and predicted values for structural displacements. SAP2000 model is used to compute the predicted displacements and is automatically called from inside the supplied function subroutine *fun*.

3.3 Computing displacements with SAP2000

Computation of predicted displacements with SAP2000 requires a structural model template. Design variables are fed into the template to create an input file for analysis. The input file activates the export of output displacement in EXCEL spreadsheet format. The MATLAB interface reads the spreadsheet file and creates the necessary displacement vectors for the optimization process.
This process is iterative and automatic. A result of the optimization process updated values of the design variables, f_{ck} and RH, are computed by assimilating field measurements and producing deformation curves that better fit actual structural behavior.

4. Camber computation and correction

Displacement control is an essential serviceability requirement for

Figure 2 – (a) Deformation diagram and (b) Camber diagram

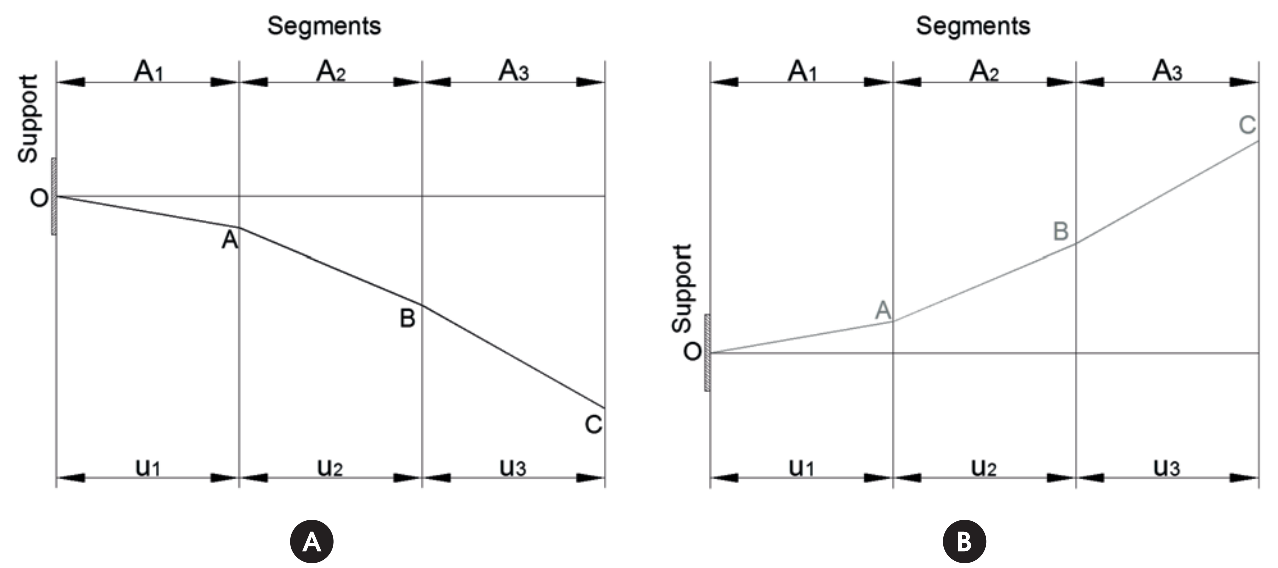
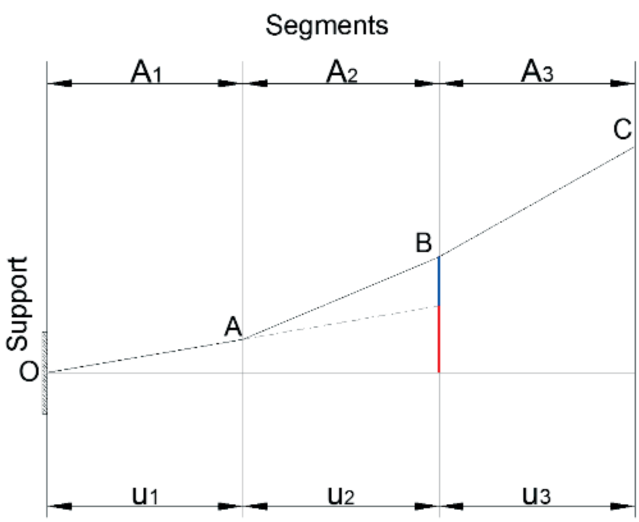


Figure 3 – Relative camber applied to the projetion of previous segment



all structures. Those built by the forward cantilever technique require camber control, which is applied through corrective displacements that compensate for cantilever deformations so that final design profile is achieved.

4.1 Methods of camber computation

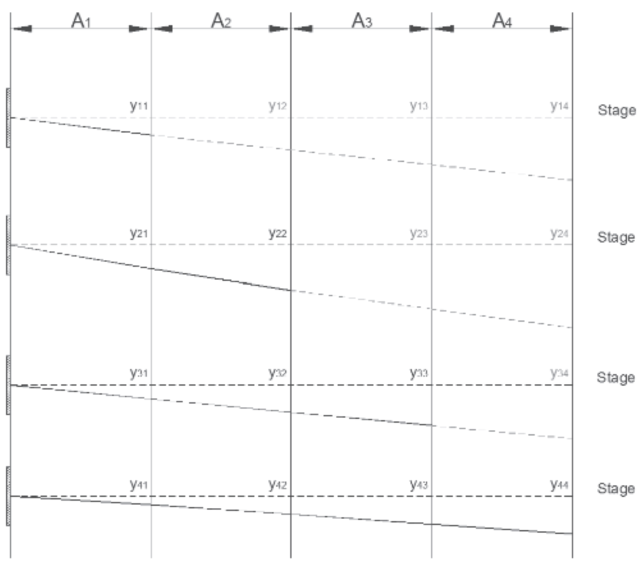
It is essential to estimate structural displacements. Camber curve is the sum of deformations as a result of casting successive segments, i.e., it is the mirror image of total displacements [16] (see Figure 2).

Use of camber diagrams may cause problems since its applications depend on constructor experience. Absolute coordinates are not used because the system changes at each construction stage. It is, therefore, advisable to use relative camber which is imposed displacements relative to the previously cast segment.

Figure 3 presents the relative camber applied to section B at casting time of segment A2, which corresponds to the blue portion of the vertical line through B. Relative camber is positioned over the projection of the axis of segment A1 that is represented by the red portion of the vertical line. Absolute camber is the sum of the two portions, blue and red, and equals the summation of all displacements at section B.

Modified Paim [15] methodology is used to compute the necessary camber. Construction stage index is denoted by i, whereas j denotes the end section of segment j. Hence, the displacement at section j due to isolated action of loads pertaining to stage i only is denoted by yij. In those segments still to be constructed, these values are defined by tangential extension of the deformed axis, as illustrated in Figure 4.

Figure 4 – Beam constructed by cantiliver method



Using the isolated displacements it is possible to compute the accumulated displacements, Yaij, at end j, at each construction stage i, as given by Equation (28):

$$Ya_{ij} = \sum_{k=1}^{i} y_{kj} \tag{28}$$

Total displacement, Y_j, is the sum of all isolated displacements over the total number of construction stages, n, as given below:

$$Y_j = \sum_{k=1}^{n} y_{kj} \tag{29}$$

In order to compute the relative camber for the casting of a new segment, it is necessary to know the position of node *j*, yet to be executed, according to the tangential extension of the previous segment, (*j*-1), at stage (*i*-1). It is then necessary to compute the position of node j up to casting of the previous stage, (*i*-1). The position of segments during construction is the accumulated displacement curve, including relative camber application, computed by Equation (30):

$$\begin{pmatrix}\text{Accumulated displacement}\\ \text{including relative camber}\\ \text{at stage }(i-1)\end{pmatrix} = \begin{pmatrix}\text{Accumulated displacement}\\ \text{at stage }(i-1)\end{pmatrix} + \begin{pmatrix}\text{Sum of relative}\\ \text{camber up to}\\ \text{stage }(i-1)\end{pmatrix}$$

$$Z_{(i-1)j} = Ya_{(i-1)j} + \sum_{k=1}^{(i-1)} cf_{kj} \tag{30}$$

where $Z_{(i-1)j}$ = accumulated displacement at node j, including camber, up to stage (i-1), stage preceding the one being considered; $Y_{a(i-1)j}$ = accumulated displacement at node j up to execution of

stage (i-1), and $\sum_{k=1}^{(i-1)} cf_{kj}$ = accumulated relative camber at node j up to execution of stage (*i*-1).
At the execution of the first segment, since there are no previous displacements, Z_{1j}=0.
Knowing the present position of node *j* it is possible to determine the relative camber to be applied to this node at stage *i* to honor the design profile from the displacements that will occur in the future, from stage *i* onwards, through Equation (31):

$$\begin{pmatrix}\text{Accumulated displacement}\\ \text{including camber}\\ \text{at stage } (i-1)\end{pmatrix} + \begin{pmatrix}\text{Relative camber}\\ \text{at stage i}\end{pmatrix} + \begin{pmatrix}\text{Residual displacement}\\ \text{yet to occur}\\ \text{from stage i onwards}\end{pmatrix} = 0$$

$$Z_{(i-1)j} + cf_{ij} + \sum_{k=i}^{n} y_{kj} = 0 \quad (31)$$

Where cf_{ij} = relative camber at node *j* at stage *i*; $\sum_{k=1}^{(i-1)} cf_{kj}$ = residual displacement still to occur from stage *i* onwards.
Therefore, it is possible to compute the relative camber at node *j* at the execution of stage *i* using Equations (30) and (31), as:

$$cf_{ij} = -\left(Z_{(i-1)j} + \sum_{k=i}^{n} y_{kj}\right) = -\left(Ya_{(i-1)j} + \sum_{k=1}^{(i-1)} cf_{kj} + \sum_{k=i}^{n} y_{kj}\right) \quad (32)$$

Using Equation (28) the accumulated displacement corresponding to the previous stage, $Ya_{(i-1)j}$, can be computed as:

$$Ya_{(i-1)j} = \sum_{k=1}^{(i-1)} y_{kj} \quad (33)$$

Substituting Equation (33) into (32) and using Equation (29), then:

$$cf_{ij} = -\left(\sum_{k=1}^{(i-1)} y_{kj} + \sum_{k=1}^{(i-1)} cf_{kj} + \sum_{k=i}^{n} y_{kj}\right) = -\left(\sum_{k=1}^{(i-1)} cf_{kj} + \sum_{k=1}^{n} y_{kj}\right) = -\left(\sum_{k=1}^{(i-1)} cf_{kj} + Y_j\right) \quad (34)$$

Hence, the relative camber to be applied at node *j*, at construction stage *i*, may be computed by:

$$\begin{pmatrix}\text{Relative camber}\\ \text{at stage i}\end{pmatrix} = -\left[\begin{pmatrix}\text{Tangential extension}\\ \text{of the relative camber}\\ \text{up to stage } (i-1)\end{pmatrix} + \begin{pmatrix}\text{Total}\\ \text{displacement}\end{pmatrix}\right]$$

As execution of segment *j* occurs at stage *i=j*, the tangential extension at nodes starting form (j+1), for stages form *i* to *n*, is a linear function of the relative camber applied to node *j*, as given by Equation (35):

$$cf_{ij} = \frac{cf_{ii}}{u_i} \sum_{k=i}^{j} u_k \quad if\ j > i \quad (35)$$

where cf_{ii} = is the relative camber at the end of the executed segment at stage *i*, i.e., when *i=j*; u_i = length of segment *i*.
Similar methodologies for camber computation can be found in [11] and [16].

4.2 Camber adjustment during construction

Residual deformation with respect to design profile occurs even with application of camber specified in the design documents. Problems during construction or mischaracterization of materials actually employed result in differences between predicted and real displacements. Field monitoring of displacements allows for identification of camber correction needs for segments yet to be executed. Therefore methods for possible correction of camber values during construction should be developed.

4.3 Proposed procedure for camber control during construction

A procedure for adaptive camber adjustment during construction using the Nonlinear Least Squares technique is proposed below to refine the estimation of displacements. Field survey data of displacements are assimilated and material properties values are refined allowing for better deformation prediction and thus improved camber specification. The sequence of steps of the proposed procedure is given below:
1. To construct the structural model of the forward cantilever bridge computing the original design values of displacements in EXCEL spreadsheet format;
2. To determine the original design camber values based on the modified Paim methodology given above.

Next procedure steps comprise an iterative process for camber adjustment after the execution of each new segment. Therefore, the number of steps depends on the number of segments.
3. To execute segment j (j=1..n) and measure displacement at the

Table 1 – Accumulated displacements for execution up to j = 3

Stage	Node 1	Node 2	Node 3	Node 4
1	Ya_{11}	–	–	–
2	Ya_{21}	Ya_{22}	–	–
3	Ya_{31}	Ya_{32}	Ya_{33}	–
4	–	–	–	–

Table 2 – New accumulated displacements for execution up to j = 3

Stage	Node 1	Node 2	Node 3	Node 4	Node 5
1	Ya_{11}	–	–	–	–
2	Ya_{21}	Ya_{22}	–	–	–
3	Ya_{31}	Ya_{32}	Ya_{33}	–	–
4	Ya_{41}	Ya_{42}	Ya_{43}	Ya_{44}	–
5	Ya_{51}	Ya_{52}	Ya_{53}	Ya_{54}	Ya_{55}

ends of all previously built segments. Isolated displacements that occur up to execution of current segment are computed. Accumulated displacements are determined according to Equation (28) and are assimilated through the optimization process. Table 1 illustrates an example of accumulated displacements for execution up to the third segment;

4. To assimilate displacement data up to segment j. This step makes use of the optimization procedure implemented in MATLAB. Displacement data are processed minimizing deformation mismatch and, thereby, obtaining new refined values for material properties, fck and RH that are more representative of the actual applied concrete;
5. New refined values of material properties are automatically fed into the structural model;
6. The new model is analyzed and a new accumulated displacement configuration is predicted for the whole structure (see Table 2);
7. To determine new camber values for segment j+1. Table 3 presents isolated displacements considering the updated model, in black, displacements that have already taken place, in red, and tangential extensions for the yet to be cast segments, in gray.
   It is possible to compute new values of total displacements already incorporating actual measured deformations using Equation (29). By applying these results in Equations (34) and (35) it is possible to compute new camber values, in blue, and their tangential extensions, in gray, as illustrated in Table 4. In these calculations actual values of camber applied to already cast segments must be kept unchanged, in red.
8. On execution of the last segment, corrections can no longer be made and final values of material properties should be more repre-

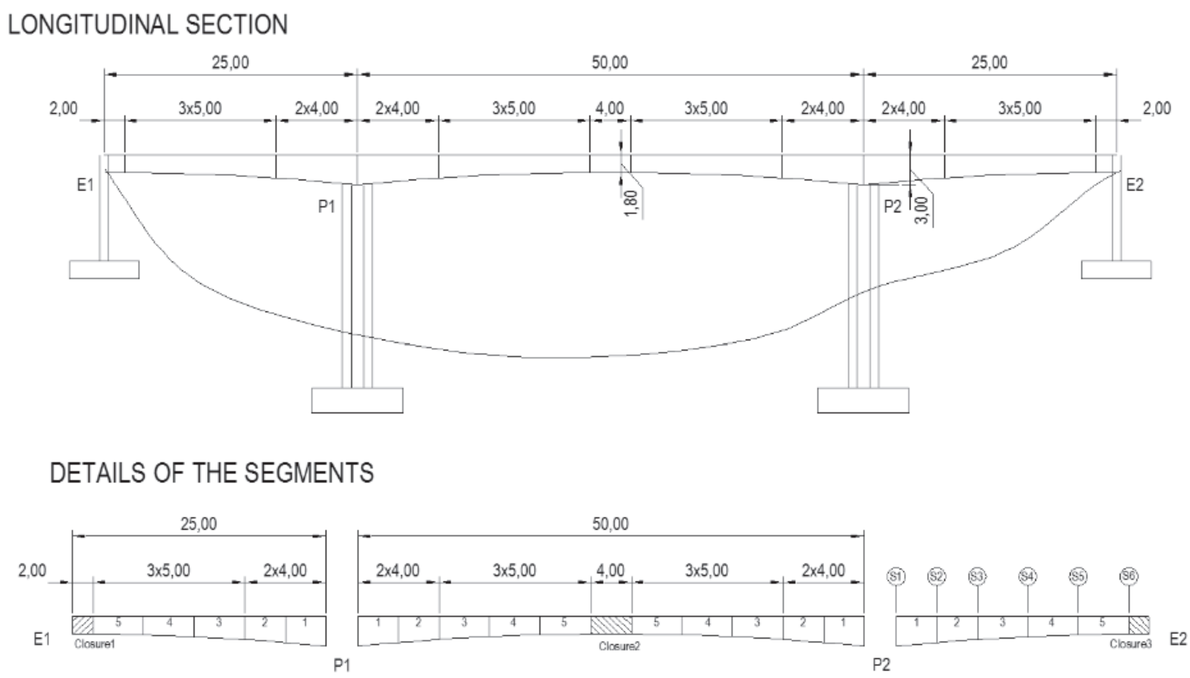
Table 3 – Isolated displacements for the updated model

Stage	Node 1	Node 2	Node 3	Node 4	Node 5
1	y_{11}	(y_{12})	(y_{13})	(y_{14})	(y_{15})
2	y_{21}	y_{22}	(y_{23})	(y_{24})	(y_{25})
3	y_{31}	y_{32}	y_{33}	(y_{34})	(y_{35})
4	y_{41}	y_{42}	y_{43}	y_{44}	(y_{45})
5	y_{51}	y_{52}	y_{53}	y_{54}	y_{55}

Table 4 – New relative camber after update the model

Stage	Node 1	Node 2	Node 3	Node 4	Node 5
1	cf_{11}	(cf_{12})	(cf_{13})	(cf_{14})	(cf_{15})
2	–	cf_{22}	(cf_{23})	(cf_{24})	(cf_{25})
3	–	–	cf_{33}	(cf_{34})	(cf_{35})
4	–	–	–	cf_{44}	(cf_{45})
5	–	–	–	–	cf_{55}

Figure 5 – Geometry of bridge



sentative of the actual concrete used in the bridge.
Use of the material properties for a longer-term prediction of displacements may require more elaborated material models.

5. Results and discussion

The proposed procedure is applied to a synthetic case. The structure is a bridge built according to the forward cantilever technique adapted from Oyamada [14].

5.1 Problem definition

Geometry

The bridge has a total length of 100m, consisting of three spans 25m, 50m, and 25m (see Figure 5). Side spans are divided into five segments of different lengths, two 4m long and three 5m long. Closure segments are cast in situ linking the structure to the abutments. The central span is divided into ten segments plus closure. Segment arrangement for each half-span is identical with side spans. The deck is 7.5m wide and the cross-section is variable, as can be seen in Figure 6.

Materials

Design material specifications are given below:
1. Characteristic compressive strength: f_{ck} = 30MPa
2. Normal hardening cement: α = 2
3. Relative humidity: *RH* = 70%

Figure 6 – Cross section of the segments

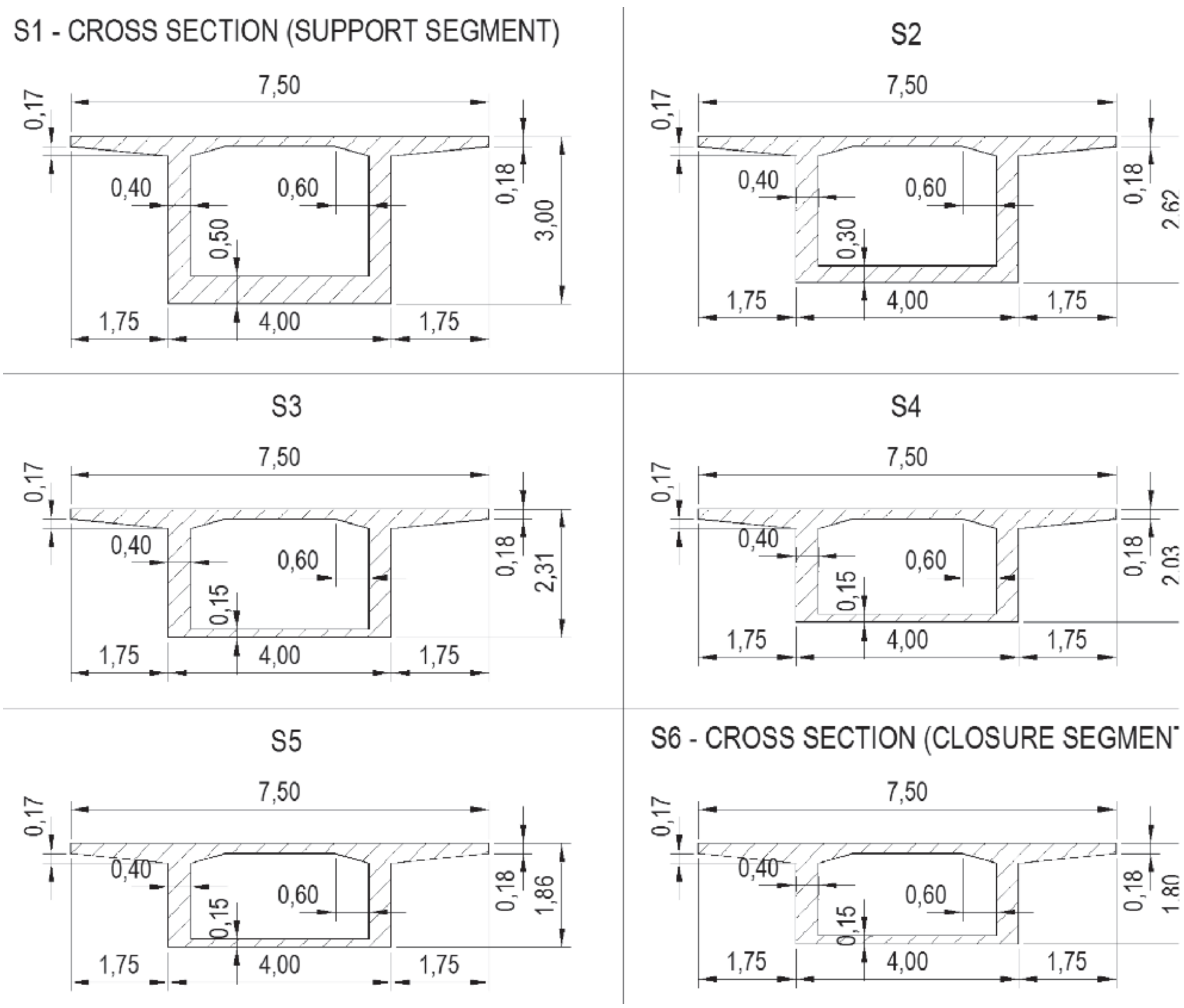


Table 5 – The initial design camber values (cm)

	Node 1	Node 2	Node 3	Node 4	Node 5
Camber	cf_{11} = 0,12	cf_{22} = 0,30	cf_{33} = 0,74	cf_{44} = 1,30	cf_{55} = 2,48

4. Prestressing steel: CP190RB
5. Cables: 10 ϕ 12.5mm

Loads

The model considers four loading cases and takes into account the time-dependent effects of creep and shrinkage.

1. Dead Loads – Self-weight;
2. Prestressing – Initial presstressing force of 2888kN per cable;
3. Formwork – For segments 1 and 2 = 200kN vertical force and 400kN-m moment; other segments = 200kN vertical force and 500kN-m moment.
4. Wet Concrete – temporary weight of cast concrete applied to the previous adjoining segment. It becomes dead load after concrete hardening.
5. Creep and Shrinkage – CEB-FIP model is used to compute time-dependent displacements as well as prestressing loss.

Construction stages

The main characteristic of this structure is staged construction and this is taken into consideration in the model.
Once the design model is concluded and analyzed the initial design camber values are shown in Table 5.

5.2 Simulation data for "real" displacements

In order to simulate field measurements, regarded here as "real" displacements, two cases with different pairs of f_{ck} and RH values, different from the original design data, are considered as detailed below:
Case A: f_{ck} = 36MPa; *RH* = 80%.
Case B: f_{ck} = 26MPa; *RH* = 60%.
Case A represents the situation where actually applied concrete in the bridge is stronger and relative humidity higher than the original design data. Case B represents the opposite situation where concrete strength and relative humidity are lower than considered in the original design.

Case A

The camber control process is started with original design values for f_{ck} and RH. Displacement at each construction stage is assimilated and new values for these two properties are obtained. Subsequent displacement predictions are based on the updated values, simulating real construction camber control. Design variables at the execution of the last segment are fck = 32,2 MPa and RH = 83,7%.
A study comparing the results of the application of the corrected and original uncorrected design camber is discussed in the sequel. Table 6 presents values of residual displacements that occur after application of both camber strategies, Z_{nj}. Percent ratio between residual displacements and structural total displacements, Y_j, is presented for both uncorrected and corrected cambers. . It can be seen that, as construction advances, residual deformation decreases so that it is lower than 3% for corrected camber whereas reaches 12% for the uncorrected case, at the last node.

Case B

A similar study is carried out. At the execution of the last segment refined property values are f_{ck} = 24,7 MPa and RH= 50%. Comparative values of residual displacements are presented in Table 7. Results are similar to those of Case A with slightly better accuracy. For the last node the residual displacement percent ratio for uncorrected camber is 0.10%, while for the uncorrected case it is 7.93%.

6. Conclusions

Structures built by the forward cantilever technique require camber control in order to achieve the design profile. The computation of camber, in turn, requires refined prediction of displacements during the staged construction. Design displacements are based on assumed material properties, which depend on the kind of aggregate and proportioning details that are generally not available at the design stage. The proposed procedure adaptively refines the material properties based on the monitoring of field displacements and an optimization

Table 6 – Camber, residual deformation and residual percentage to Case A

		Node 1	Node 2	Node 3	Node 4	Node 5
Design	Camber (cm)	cf_{11} = 0,12	cf_{22} = 0,30	cf_{33} = 0,74	cf_{44} = 1,30	cf_{55} = 2,48
	Residual deformation (cm)	Z_{51} = 0,01	Z_{52} = 0,07	Z_{53} = 0,24	Z_{54} = 0,51	Z_{55} = 1,01
	Residual percentage (%)	9,09	14,89	15,38	13,21	12,02
Proposed procedure	Camber (cm)	cf_{11} = 0,12	cf_{22} = 0,30	cf_{33} = 0,69	cf_{44} = 1,12	cf_{55} = 2,17
	Residual deformation (cm)	Z_{51} = 0,01	Z_{52} = 0,07	Z_{53} = 0,19	Z_{54} = 0,23	Z_{55} = 0,19
	Residual percentage (%)	9,09	14,89	12,18	5,96	2,26

Table 7 – Camber, Residual deformation and Residual percentage to Case B

		Node 1	Node 2	Node 3	Node 4	Node 5
Design	Camber (cm)	cf_{11} = 0,12	cf_{22} = 0,30	cf_{33} = 0,74	cf_{44} = 1,30	cf_{55} = 2,48
	Residual deformation (cm)	Z_{51} = - 0,01	Z_{52} = - 0,05	Z_{53} = - 0,18	Z_{54} = -0,41	Z_{55} = - 0,81
	Residual percentage (%)	7,69	8,47	9,09	8,58	7,93
Proposed procedure	Camber (cm)	cf_{11} = 0,12	cf_{22} = 0,30	cf_{33} = 1,01	cf_{44} = 1,23	cf_{55} = 2,60
	Residual deformation (cm)	Z_{51} = - 0,01	Z_{52} = - 0,05	Z_{53} = - 0,09	Z_{54} = - 0,06	Z_{55} = - 0,01
	Residual percentage (%)	7,69	8,47	4,55	1,26	0,10

process that uses the Nonlinear Least Squares Technique to minimize the mismatch between predicted and real displacements.
The presented synthetic example corroborates that as more data are assimilated by the proposed procedure the closer the unknown material parameters approach the actual properties of the applied concrete. Therefore, the proposed tool allows concrete properties to be better characterized for the given structural software through a learning process as construction progresses.
The procedure assumes that differences between real and measured displacements are due to material model inaccuracies. If major formwork misalignment is detected during construction additional corrective measures should be applied.
With the proposed corrective procedure for camber control, it is possible to reach the desired design profile with high accuracy. As demonstrated by the synthetic example in the first stages residual deformations may reach 10% of the total structural displacements. This is not particularly detrimental because those are very small displacements. As construction progresses and more data are assimilated material properties are updated and residual displacements are lower than 5% of total displacements. This is significant because those are the sections undergoing the largest deformations. The proposed camber correction procedure produces smaller residual deformation than the original design uncorrected values.
The considered material model is adequate for camber control during the construction phase. In order to use the final refined values for long-term displacement predictions more refined material models must be adopted.

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