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Simulation and Consulting System for Bridge Construction

Système de simulation et de conseils pour la construction des ponts

Ein Simulations- und Beratungssystem für den Brückenbau

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SUMMARY

The computer program *Bridges* is used to determine the optimum shuttering geometry and predict the long-term displacements of long multispan concrete bridges. *Bridges* simulates each single construction step. When used during the design phase, *Bridges* is expected to help improve construction quality, extend the lifespan of the structure and reduce maintenance costs. The program, however, is also to be used in the construction phase as a consulting system. Each measured quantity, like displacement, temperature, humidity, etc. as well as unforeseen events, causing changes in the construction schedule can be taken into account at any time.

RÉSUMÉ

Le programme de calcul *Bridges* s'emploie à déterminer la géométrie optimale des coffrages et prévoir les déformations à long terme des grands ponts en béton armé et précontraint à travées multiples. Toutes les étapes de la construction sont intégrées dans un planning, puis simulées. Exploité durant la phase de projet, *Bridges* permet d'améliorer la qualité de la construction, d'assurer une plus longue durée de vie de l'ouvrage et de réduire les coûts d'entretien. Tout au long de la construction, le programme supervise son évolution et guide l'ingénieur dans les phases critiques sur la base des mesures effectuées sur l'ouvrage.

ZUSAMMENFASSUNG

Das Computerprogramm *Bridges* dient zur Bestimmung der optimalen Schalungsgeometrie und allfälliger Auflageranpassungen bei grossen vorgespannten und schlaff bewehrten Stahlbetonbrücken unter Berücksichtigung der zu erwartenden Langzeitverformungen. Dabei wird jede Phase des Bauprozesses simuliert. Eingesetzt bereits in der Projektierungsphase, erlaubt *Bridges* eine Erhöhung der Ausführungsqualität, eine Verlängerung der Lebensdauer und eine Reduktion der Unterhaltskosten. Während der Ausführungsphase steht dem Bauingenieur ein Beratungssystem zur Verfügung, welches den Baufortschritt überwacht und in kritischen Bauphasen Unterstützung leistet.

1 INTRODUCTION

The computer program *Bridges* is used to determine the optimum shuttering geometry and predict the long-term displacements of long multispan concrete bridges. These are strongly influenced by time-dependent deformations such as creep and shrinkage, temperature gradients and the stress relaxation of prestressing cables. *Bridges* simulates each single construction step taking into account all these effects.

The simulation program consists of three modules. The first one, the schedule manager, handles the timing of all building operations. The planned schedule can be updated at any time to accommodate unexpected events. The second module determines the distribution of the temperature and moisture in the transverse direction of the structure, under stationary and transient conditions. A set of state parameters defining the concrete's delayed behaviour are computed at each cross-section for each event defined in the schedule. The third module is a finite element code for the analysis of the structural deformations. Based on simple beam theory, the rates of change of physical and mechanical concrete properties are determined as a function of the state parameters mentioned above and included in the material laws. The resulting displacements can be compared with the deflections of the girders measured during construction.

The program is intended to be used daily on site. A consulting system is therefore coupled to the simulation module. If unexpected events occur (changes in the schedule, low material quality, special weather conditions, settlement of a pier, etc.) and the predicted displacements reveal unacceptable differences compared to the ideal state, the program suggests the required support adjustments, or even changes in the shuttering geometry, to be applied in order to achieve the desired final state.

When used during the design phase, *Bridges* is expected to help improve construction quality, extend the lifespan of the structure and reduce maintenance costs. Throughout the construction, the program monitors its evolution and guides the site engineer in the critical phases.

2 GEOMETRICAL DISCRETISATION

A unique geometrical description of the bridge is used throughout the 3 modules of the program. This discretisation has to consider the construction method in the definition of the girders and supports. The girders are described by a succession of beam elements, each being defined by two sections. These are generally different, thus the beam length has to be chosen so that a linear interpolation of all relevant section properties between them is a reasonable simplification. Each section is subdivided into subsections. The subsections are domains where the material parameters computed with a fine mesh can be assumed to be constant. The sections, consisting of subsections, generate subbeams which are assembled to build the beam elements (Fig. 1).

The geometry of the prestressing cables is defined by points in 3D space. The coordinates of the points are given by the construction plans. The high number of points generally needed to describe the exact cable position allows the use of a linear interpolation between them.

A 3D viewer allows the user to define the geometry of the bridge and check the accuracy of the consecutive construction steps.

3 A SIMULATION TOOL

In *Bridges*, each single construction step is simulated. To handle this, a schedule manager coordinates the time-step decomposition of the whole construction process to be simulated by the two following modules: a finite element code for 2D analysis in the transverse direction for determining the temperature and moisture diffusion in the cross-sections and a finite element code for longitudinal 1D analysis of the structural deformations at each stage of the construction.

3.1 The schedule manager

The schedule manager keeps track of the timing of all the casting operations, removal of formwork (shuttering), tensioning of prestressing cables, special time-dependent load definitions, changes of support conditions, etc. A preliminary schedule is generally established by the contractor. This is the reference schedule, used to define the shuttering geometry. Due to unexpected events (e.g. strikes, lack of materials, extreme weather conditions, part of the construction area damaged), this schedule will inevitably evolve during the construction process. Therefore, the schedule manager, through an interactive graphical user interface, allows both for changes in the sequence of *events* and for modifications or definitions of new construction steps.

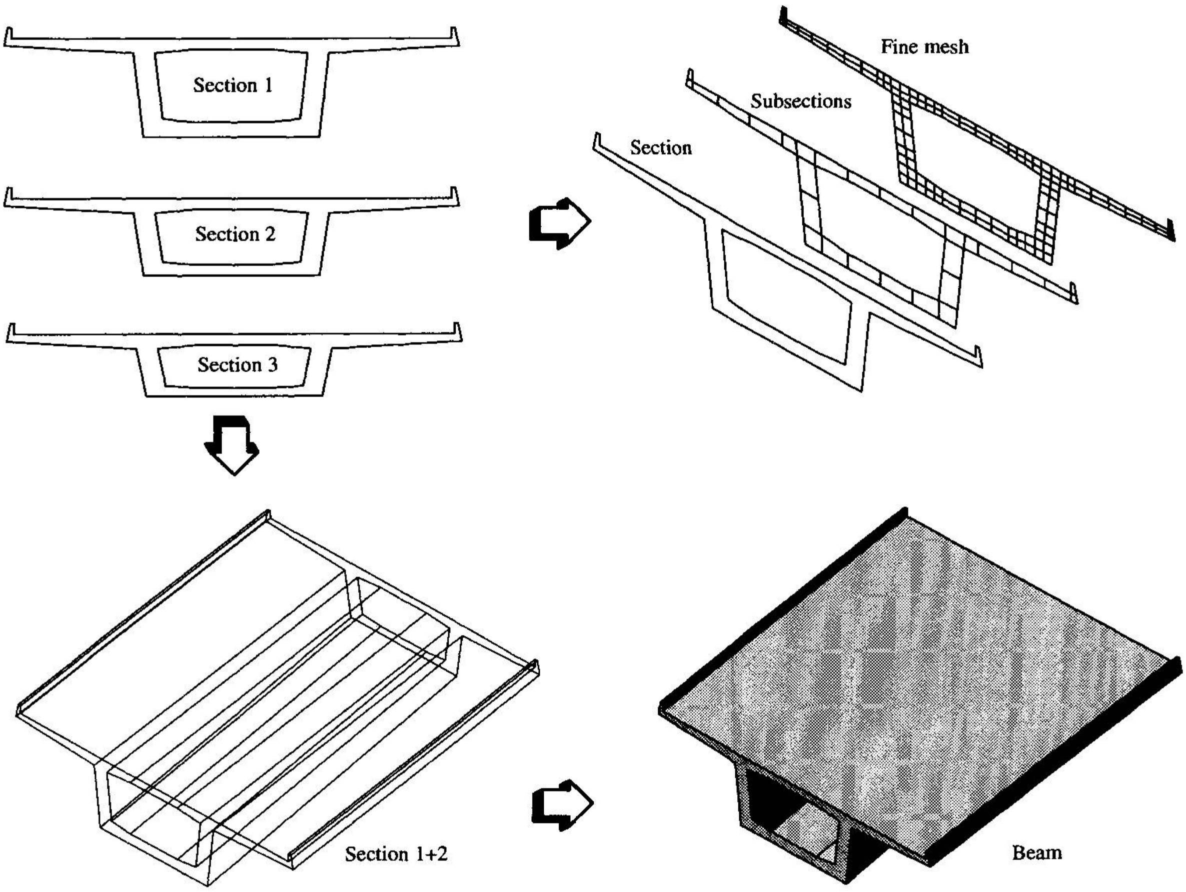

Fig. 1: Geometrical description of the bridge

The user does not have to define all the details of every construction operation. Since many procedures are repetitive, macro-events called *stages* are declared with starting and ending dates. The stages can be chained with several kind of relations such as "start n hours before end of stage B", "end with end of stage B", etc. If an absolute date of a stage is moved, all the relative stages are moved accordingly. Conflicts are automatically detected. Each stage is built of local events with a corresponding application date and a list of *actions*. At the beginning of a simulation, the stages are expanded and the global events are generated. For each local event's date mentioned, a global event is created, if necessary, and the local list of actions is appended to the global list for that event. This global event list determines the dates to be considered during the simulation process. The time-step values to be used later in the incremental equations are directly generated from this list.

3.2 The diffusion module

In this module, the bridge is analysed in the transverse direction for simulating transport phenomena such as mass flow (gas, liquid) and energy (heat) diffusion under stationary and transient conditions. The analysis is applied at each previously defined cross-section defining a beam's end for each event defined in the schedule. The time-dependent temperature distributions due to the liberation of concrete hydration heat is predicted. Nonlinear moisture transport as a function of time is also simulated. In this way shrinkage-induced deformations and stresses can be computed and assessed. Phenomena like internal and external condensation can also be taken into account.

The concrete model implemented [1] is based on the following set of so-called state parameters at the microstructural level:
- degree of hydration α (describes the chemical hydration process)
- maturity M (describes the time-dependence of the mechanical properties)

and at the physical level:
- temperature T
- relative humidity H

It is assumed that the rates of change of physical and mechanical properties of concrete are fully determined by these parameters. A second fundamental assumption is that the thermo-mechanical coupling, such as the liberation of thermal energy in the fracturing process, can be neglected. This means that the evolution of the state parameters can be determined independently of the mechanical behaviour of the structure.

The evolution of these state parameters is computed by solving a set of coupled nonlinear differential equations modelling temperature and humidity diffusion.

The program then builds a state parameter table at each construction stage (*event*) for all subsections.

3.3 The simulation module

This module is called to compute the structural deformations according to the material data and loading at each *event*. From the schedule manager, the program fetches the external and internal loads as well as the corresponding state parameters and computes the deformations incrementally. Both ordinary reinforcement and prestressing are included in this computation.

All physical and mechanical properties depend on the state parameters determined in the previous module, each providing its own contribution to the total strain rate.

In this last module, the program follows the whole process of the construction and delivers the deformations of the bridge after each *event*. The result is a simulated deflection line (profile) which can be compared with the measured deflections of the girders (i.e. the effective construction state) and the ideal line. Changes in the schedule, settlements and others unexpected events, as well as the introduction of material data based on in-situ tests influence the deflections. If the predicted deflection line reveals unacceptable differences compared with the ideal one, the user can assign special degrees of freedom to some girders or supports (rotation of the girder, adjustment of the bridge bearing) and ask for a (computer) consulting session. The longitudinal analysis is started again and, taking into account the new degrees of freedom, the program attempts to:
- determine the required rotations of the girder in order to obtain the best possible deflection line without any changes in the shuttering geometry
- propose the required adjustments of the bridge bearing (e.g. after a settlement) to obtain the optimum deflection line (in spite of this settlement)
- suggest the minimum corrections to the shuttering geometry

At the end of the session, a new simulated deflection line is presented with the corrections used to obtain it (Fig. 2).

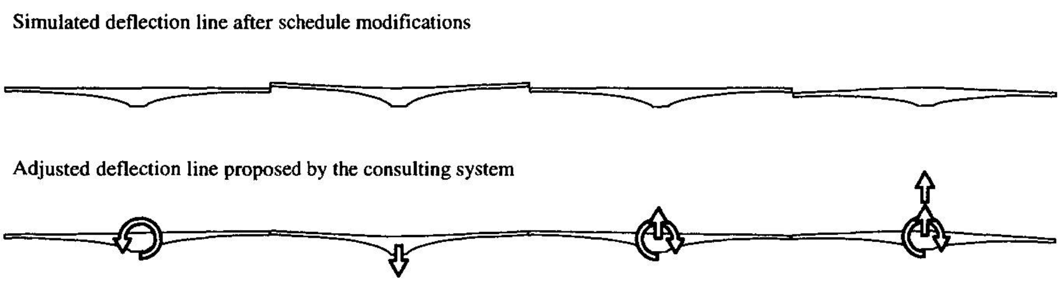

Fig. 2: Result of a consulting session

4 THE CONCRETE MODEL

As mentioned in section 3.2, the concrete model used in *Bridges* depends on the evolution of a set of microstructural and physical state parameters. The value of these parameters along the whole construction process is calculated by solving a set of coupled nonlinear and nonstationary differential equations [2] modelling temperature and humidity diffusion:

The energy (thermal) balance is expressed by:

$$C_{TH}\,\dot{H} + C_{TT}\,\dot{T} - C_{Ta}\,\dot{a} = \nabla\left(k_{TH}\,\nabla H + k_{TT}\,\nabla T\right) \tag{1}$$

The mass (hydrous) balance is given by:

$$C_{HH}\,\dot{H} + C_{HT}\,\dot{T} + \left(C_{Ha} + P\right)\dot{a} = \nabla\left(k_{HH}\,\nabla H + k_{HT}\,\nabla T\right) \tag{2}$$

The hydration rate is evaluated using:

$$\dot{a} = F_1\!\left(a, \tfrac{w}{c}\right) F_2(H) \exp\left(\frac{Q}{R}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right) \tag{3}$$

where ∇ represents the gradient operator; a dot indicates differentiation with respect to time; C_{HH} and C_{TT} are the hydrous and thermal capacity; C_{Ta}, C_{Ha} and P are material parameters which depend essentially on the type of cement; a is the degree of hydration; k_{HH} and k_{TT} are the hydrous and thermal permeability coefficients; C_{TH}, C_{HT}, k_{TH} and k_{HT} are the coupling matrices. The function F_1 takes the influence of the degree of hydration and the concrete composition into consideration; F_2 describes the influence of pore humidity on the rate of hydration. The influence of the degree of hydration, temperature and relative humidity on the hydration rate is given by (3). The parameters of these equations are extensively discussed in the reference [1].

An average value for each state parameter is evaluated at each subsection for each event. For the longitudinal analysis, these parameters are integrated for determining the strains and stresses. Thus, the following contribution to the total strain rate can be described, with c_1, c_2 and c_3 representing known constant values:

$$\dot{\varepsilon}_{Total} = \dot{\varepsilon}_T + \dot{\varepsilon}_H + \dot{\varepsilon}_{CH} + \dot{\varepsilon}_{VE} \tag{4}$$

Thermal deformation: $\dot{\varepsilon}_T = c_1\,\dot{T}$ (5)

Hygral shrinkage: $\dot{\varepsilon}_H = c_2\,\dot{H}$ (6)

Chemical shrinkage: $\dot{\varepsilon}_{CH} = c_3\,\dot{M}$, if $M \leq 24$ *hours* (7)

$\dot{\varepsilon}_{CH} = 0$, if $M > 24$ *hours*

Viscoelastic deformation: $\dot{\varepsilon}_{VE} = C^*\,\dot{\sigma}$ (8)

The shrinkage and thermal dilatancy rate are directly computed from the physical state parameters. The rate of elastic and creep strain are combined and related to the stress rate by means of specially developed constitutive relations C^* [1]. The stress evolution is then obtained by time integration.

5 A DESIGN TOOL

Most computer programs in the construction industry are dedicated to the structural safety (i.e. calculation of the ultimate load, simulation of the collapse mode, etc.). Today, however, a substantial and increasing amount of money is invested for maintaining and repairing poorly designed structures. These costs can be drastically reduced if more care is taken during the design phase. It has become increasingly apparent over the last decade that temperature effects due to the hydration of cement contribute substantially to the early-age cracking of concrete. These cracks can result in a serious decrease of the load-bearing capacity of unreinforced concrete elements (e.g. breakwater blocks). They can also have a major impact on the serviceability and durability of reinforced concrete structures through a lack of watertightness and corrosion of the reinforcement, respectively. *Bridges* is capable of predicting the time-dependent temperature distributions due to the release of concrete hydration heat with a high degree of accuracy. The deformations are computed and the risk of cracks due to arbitrarily restrained volume changes is efficiently detected. As a result, damage cases can be studied and the effects of structural or technological measures for improving the structure (e.g. artificial cooling system) can be investigated. With the implemented concrete model, the temperature influence on the development of structural concrete properties can be predicted. When used during the planning of construction work, *Bridges* helps the designer make decisions for critical phases and determine the suitable times for prestressing and removal of formwork.

6 CONCLUSION

An early version of this program has been successfully used on the Størebælt West Bridge in Denmark [3][4][5]. It was used daily on site and exhibited a high degree of accuracy for the predicted girder deflections. *Bridges* is able to help the site engineer make decisions and suggest the required adjustments throughout the construction process. As a design tool, *Bridges* is a useful adviser to reduce both construction and maintenance costs, and thus to enhance the quality of the structure.

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