LONG TERM EFFECTS & SPECIFIC PROBLEMS IN CONCRETE & COMPOSITE BRIDGES

Dorian Janjic*, Martin Pircher**

*TDV Graz, Austria
Director

** University of Western Sydney, Centre for Construction Technology & Research
Research Associate

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Abstract: *Concrete and composite materials are widely used in bridge engineering. Creep and shrinkage long term effects combined with the specific structural behaviour of the bridge make it imperative that more accurate theories and tools are included in the design and analysis of such concrete/composite structures. Some of these problems and their solution in the process of the design and analysis phase of concrete and composite bridges are described in this paper. The basic theory needed for the numerical modelling of long term effects combined with the specific structural behaviour of the bridges are outlined. A consistent solution is made for both linear elastic theory and non-linear theory. The solutions presented have been implemented in a commercially available computer program. The implementation of the solution into the bridge design software is briefly described. The system takes into account all types of loading in the structural calculation including self-weight, pre-stressing, creep and shrinkage etc. The structural engineer has the ability, with such tools, to predict and follow the structural and material behaviour through all the steps of the bridge construction. The modern geometrical pre-processor and the powerful graphical post-processor facilitate the comparison of the behaviour and costs of different variants in a short time. Various bridges have already been designed and analysed using the presented solution and a commercial computer program. The bridges presented in this paper are provided to give insight into some specific problems that were encountered and solved in the design process using the presented solution. Extra focus will be given to comparing specific problems encountered from very long stayed cable bridges such as the Stonecutters bridge in Hong Kong (main span 1018m) with those from medium sized bridges such as Rach-Mieu bridge (main span 270m) in Vietnam.*

INTRODUCTION

1.1. Specific problems in concrete and composite bridges

Bridge design and analysis is an iterative process. During this process the engineer is looking for the best solution for given criteria by changing specific system parameters. Engineering experience helps to reduce the time required, but there will still be a need for many iteration steps until the design criteria are met. Computer programs nowadays should provide the best possible support for this design process.

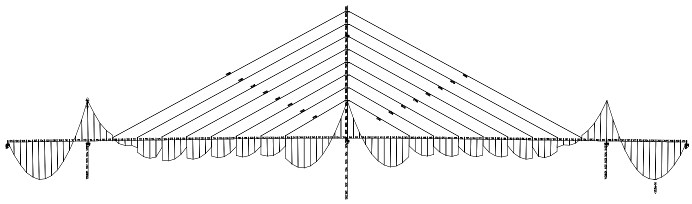

Figure 1: Target bending moment at the final stage should be achieved with construction sequence

The construction sequence combined with long-term effects has an influence on the target engineering design. Within structural analyses it is necessary to account for long-term effects in the calculation and to minimise[2] undesired influences.

1.2. Long-term effects

The occurrence of time dependent plastic strain is a material property of concrete. Total plastic strain consists of creep plastic strain and shrinkage plastic strain.

$$\varepsilon_p = \varepsilon_c + \varepsilon_s \tag{1}$$

The effect of the loading history on the strains in concrete is much more pronounced compared to the other materials. For instance, considerable strain changes (creep recovery) can continue for a very long time after removal of all loads. Fortunately the laws governing the behaviours of such creep are taken as linear in stress so that quasi superposition principles are valid.

National design codes for reinforced concrete, pre-stressed concrete or concrete in composite with steel take effects of the past loading history[4] into account. Starting with CEB FIB model regulation from year 1978, concrete creep models are generally defined by separated creep factors for each stress increment in the loading history. These creep factors depend of the loading time and of other factors like concrete quality, environment (humidity, temperature,…), section properties etc.

Rather complicated calculation of creep factors for each stress increment is impossible for hand calculation but presents no difficulty for computer implementation. The storage of each stress increments creates a huge amount of data which must be handled properly.

Shrinkage of concrete does not depend on the load. Even an unloaded element will shrink. The shrinkage coefficient can be determined without difficulties using the CEB-FIP rules or similar design code regulations. It depends of global parameters, section properties and the age of concrete.

2. NUMERICAL SOLUTION

2.1. Stepping in the time domain

The numerical solution is accomplished step by stepping in the time domain. Let time t_1 corresponds to the start and time t_2 to the end of a given time step.
It can be assumed that complete load/response history is known (including all stress increments) from time equal to zero up to the start (time t_1) of the time step. Basic unknowns are stresses and strains (or corresponding integral forces and displacement) at the end of time step (time t_2).

$$\varepsilon^2 = \varepsilon^1 + \Delta\varepsilon \;,\; \Delta\varepsilon = \int_{t_1}^{t_2} \frac{\partial\varepsilon}{\partial t}\cdot dt \tag{2}$$

$$\sigma^2 = \sigma^1 + \Delta\sigma \;,\; \Delta\sigma = \int_{t_1}^{t_2} \frac{\partial\sigma}{\partial t}\cdot dt \tag{3}$$

The total strain increment Δ□ can be divided into elastic and plastic part. It can be assume that elastic strain depends linearly on the stress state.

$$\Delta\varepsilon = \Delta\varepsilon_e + \Delta\varepsilon_p \tag{4}$$

The total plastic strain increment consists of three parts.

$$\Delta\varepsilon = \sum_{i=1}^{n}\int_{t1}^{t2}\frac{\sigma_i}{E}\cdot\frac{\partial\varphi_i(t)}{\partial t}\cdot dt + \int_{t_1}^{t_2}\frac{\partial\varepsilon_s}{\partial t}\cdot dt + \int_{t1}^{t2}\frac{1}{E}\frac{\partial\sigma}{\partial\tau}\cdot\left(1+\varphi^*(\tau,t)\right)\cdot d\tau \tag{5}$$

The first part is a plastic strain increment due to the creep of all stress increments occurring before time t_1.
The second part is a plastic strain increment due to shrinkage of concrete. Those two terms are basically known and can be evaluated in closed form at any time t.
The third part of the plastic strain is produced by creep of additional elastic strain increments which continuously occur within the time step (between time t_1 and time t_2). This part together with corresponding elastic strain increment is unknown and needs to be determined. It is obvious that the third integral term produces major difficulties.

Instead of determining the continuous change between time t_1 and time t_2 it is advantageous to look only for the final solution at the end of the time step (at time t_2). Linear change of elastic strain within time step according to the "finite differences" theory will be assumed.

$$\varepsilon = w_1\varepsilon_e^1 + w_2\varepsilon_e^2 \;,\; w_1 + w_2 = 1 \tag{6}$$

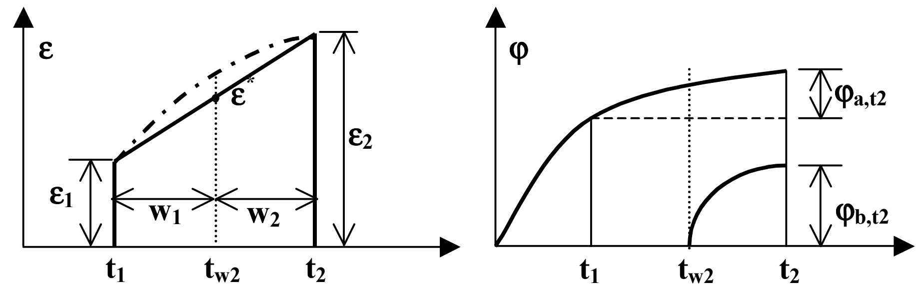

Figure 2: Elastic strain increment and creep coefficient over time

Additionally it can be assumed that the third integrand can be approximated by the following simplified term:

$$\int_{t1}^{t2} \frac{1}{E} \frac{\partial \sigma}{\partial \tau} \cdot \left(1 + \varphi^{*}(\tau, t)\right) \cdot d\tau \approx \left(1 + \varphi_{w2}\right) \cdot \int_{t1}^{t2} \frac{1}{E} \frac{\partial \sigma}{\partial \tau} \cdot d\tau \tag{7}$$

The final expression is then given by:

$$\Delta\varepsilon = \sum_{i=1}^{n} \frac{\sigma_i}{E} \cdot \left(\varphi_i(t_2) - \varphi_i(t_1)\right) + \left(\varepsilon_s(t_2) - \varepsilon_s(t_1)\right) + \left(1 + \varphi_{w2}\right) \cdot \frac{\Delta\sigma}{E} \tag{8}$$

The solution is now straightforward. There are two basic possibilities. The First option is to establish the new stress/strain relation using an equivalent E-modulus and solving by stress increment. This solution is very elegant but has the disadvantage that it cannot be combined with further non-linear effects like p-delta effects, large displacements etc. A more appropriate solution is to iterate the corresponding plastic strain due to the additional elastic strain increment within a general Newton/Raphson procedure. This solution is implemented in TDV the software RM2000/RM2004 in a closed and consistent algorithm.

2.2. Logarithmic time stepping

The described solution in the time domain has an approximate nature. The number of time steps has to be increased in order to get a more accurate solution.

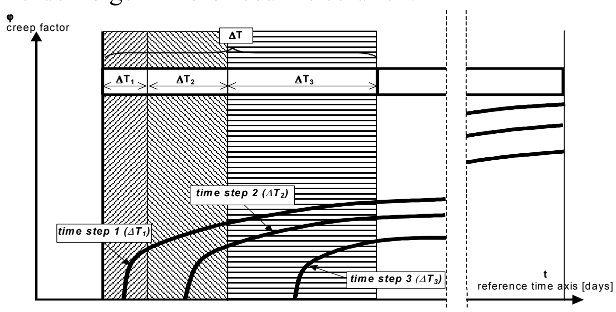

Figure 3: Logarithmic subdivision of time step into three sub steps

The use of equal time steps is inappropriate because creep functions have an exponential characteristic. Therefore it is useful to make equal time steps in the logarithmic time domain. Experience has shown that the calculation of end creep (up to time infinity) can be done using 3-4 time steps in the logarithmic time domain. Smaller creep intervals within the construction schedule only need (on average) one time step. Bending moment due to the final creep can have differences of about 12% to 18% between solution with 1 time step and 3 logarithmic sub steps (Figure 4).

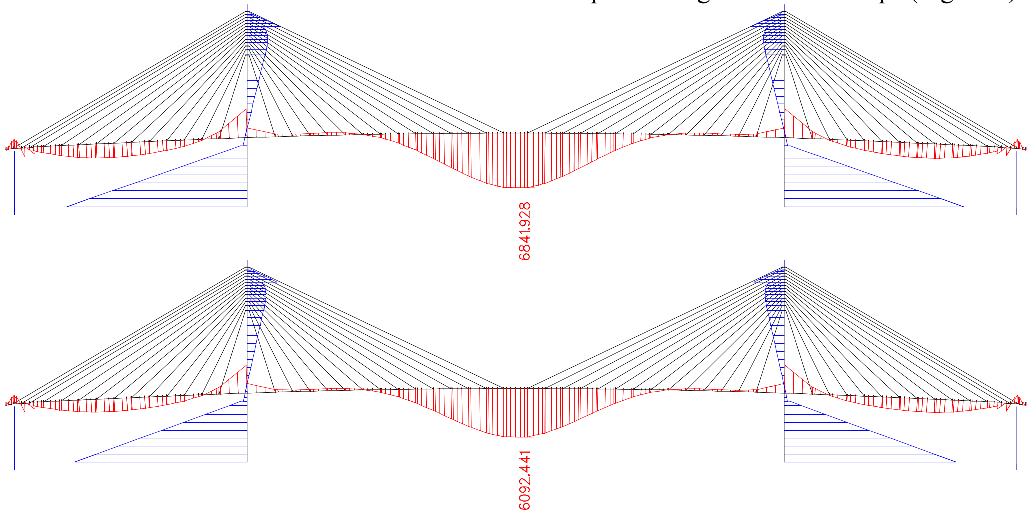

Figure 4: Rach Mieu Bridge (project engineers TEDI, Vietnam) – bending moments for final creep

2.3. Primary and secondary effects

If concrete is constrained with steel in a composite section or grouted with internal tendons additional stresses in the concrete occur even in statically determinate structures. In such composite sections the presence of non-creep material (steel or prestressing steel) constrain the stress free straining of concrete.

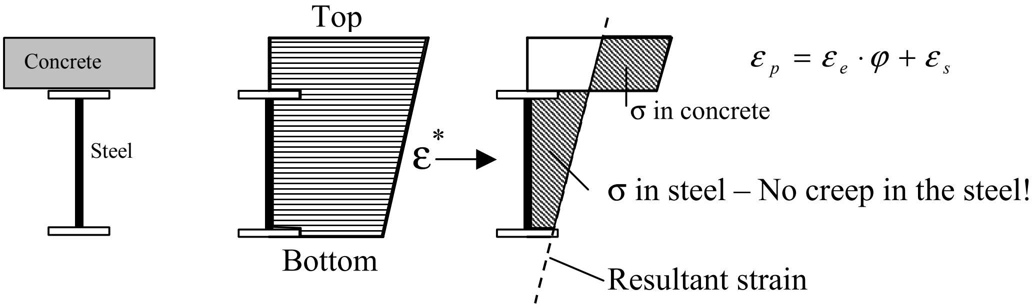

Figure 5: Primary effects in concrete/steel composite section

The resultant strain plane "Primary effects" and corresponding stresses in the concrete and steel are determined using the equilibrium equation. As the only loading is creep and shrinkage plastic strain, "primary effects" are always in equilibrium:

$$N_x = \int_{Concrete} \sigma \cdot dA + \int_{Steel} \sigma \cdot dA \equiv 0$$
$$M_y = \int_{Concrete} \sigma \cdot z \cdot dA + \int_{Steel} \sigma \cdot z \cdot dA \equiv 0$$
$$M_z = \int_{Concrete} \sigma \cdot y \cdot dA + \int_{Steel} \sigma \cdot y \cdot dA \equiv 0 \qquad (9)$$

The resulting "strain plane" is then applied to the overall structure in a similar way to temperature loading (initial strain). The response of the overall structure to this application of the "strain plane" results in the "Secondary effects".

2.4. Tstop

Interesting effects occur when a structure has repeated spans. Time effects due to the closure between parts with different age are rather high. Therefore, structures with repeated spans have to be fully modelled and optimisation of closure sequences is necessary to produce a good design.

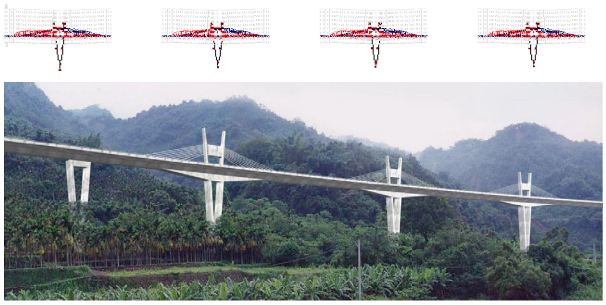

Figure 6: Computer model in construction stage before closure and finished project

A special extension called "TStop" (time stop) can be added to the presented creep solution. Within the computer model repeated structural parts are built all at the same time. Before closure, the time is stopped for newer parts and creep duration is different for older and newer structural parts. TStop allows the preparation of only one construction schedule for all repeated structural parts and highly simplifies the design and analysis process.

3. COMPUTER IMPLEMENTATION AND APPLICATION EXAMPLES

The software[3] is centred around an object-orientated data base (Figure 7). Various pre- and post-processing tools support the input into the system and the processing of results from the system. Most importantly, all functionality is provided to exactly define the planned construction schedule including all changes in the structural system and the exact time frame for all actions relevant for the structural behaviour of the structure. A large number of pre-defined material models for time-dependent behaviour (eg. CEB/FIP and derivatives) can be complemented by user defined models. A powerful solver module is provided to analyse the structural data and generate results which are again stored into the central data base. Various interface functions allow the import and export of data from the data base for use with other computer programs such as spread sheet software or CAD-packages. The graphic user interface follows the common conventions of modern interactive computer programs.

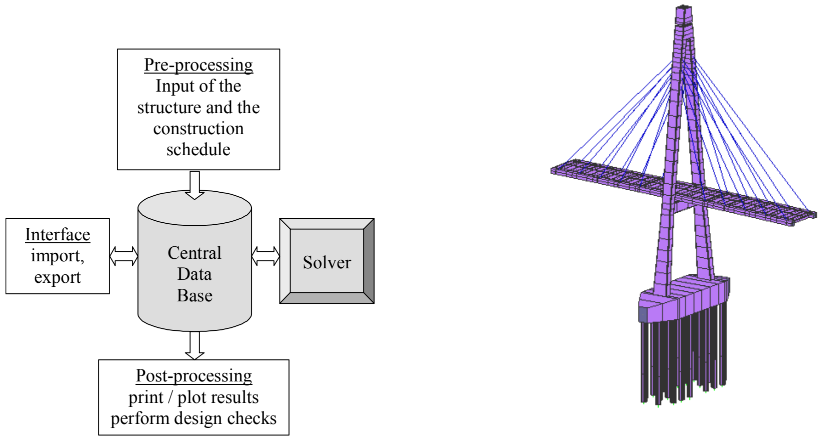

Figure 7: Structure of the bridge design software *RM2000/RM2004 with visualisation example*

The solver module has been designed to perform geometrically non-linear, time-dependent structural analyses. RM2000/RM2004 uses a Newton-Raphson algorithm for the geometric non-linearities and the described extended Newmark time integration [1] for the time dependent portion of the analysis. If less sophisticated types of analyses are sufficient for a specific problem, then this can be achieved simply by dis-activating the appropriate portions of the analysis process.

The central data base manages all the input data and also all the result data generated by the solver. Time-dependent behaviour is automatically taken into account according to the specifications made with regards to the construction schedule and the material properties. Section forces and displacements due to time dependent effects are treated in the same way as any other results and pose no exception. Various load management functions allow the storage of results from individual loading cases and the selective combination thereof.

4. CONCLUSION

Using a finite difference in the time domain the presented algorithm includes coupled effects of the creep, shrinkage and steel relaxation within overall structural non-linear analysis. Cable sagging, p-delta effects, large displacements or even contact problems can be combined with long term effects within consistent analysis. The proposed method for the numerical analysis can satisfactorily predict long term effects up to the time infinity; it is generally suitable for the investigation of all kinds of bridges with reinforced concrete, pre-stressed concrete or composite sections. Figure 8 shows the target final state for the Stonecutter's Bridge (SCB), Hong Kong

(Project engineers: Ove Arup, Hong Kong). The main span of 1018m is a steel girder while the back span is done in concrete and the towers which are almost 300m high are composite. In Figure 9 and Figure 10 the construction stage analysis with and without long-term effects are compared.

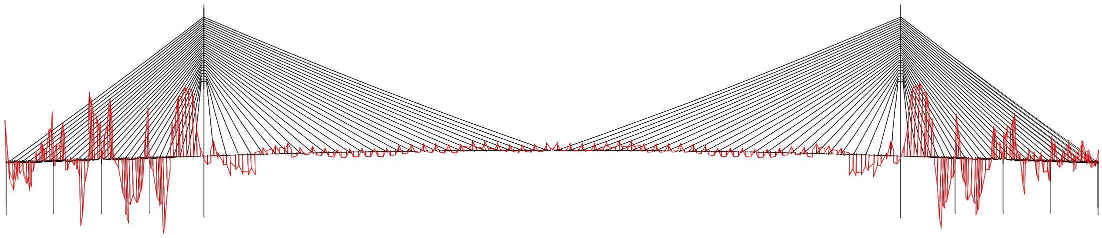

Figure 8: SCB - Final state analysis.

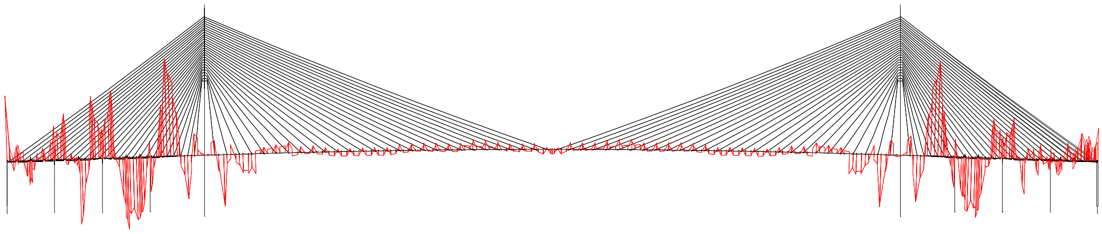

Figure 9. SCB - Construction stages analysis (without creep and shrinkage).

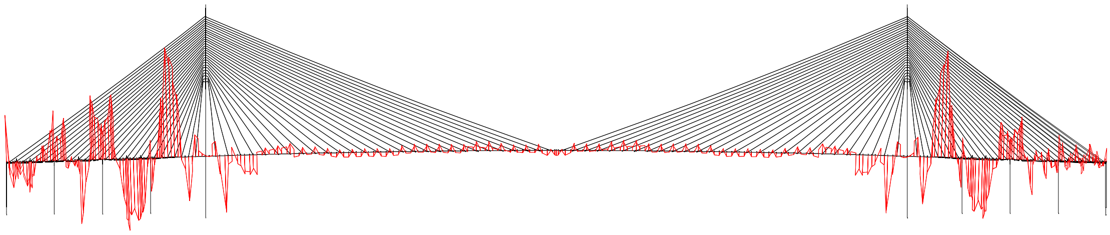

Figure 10. SCB - Construction stages analysis (including creep and shrinkage).

REFERENCES

[1] O.C. Zienkiewicz: “The Finite Element Method”, 3rd ed., McGraw-Hill, 1977

[2] JANJIC D., PIRCHER M., PIRCHER H., “Optimisation of Cable Tensioning in Cable-Stayed Bridges”, *Journal of Bridge Engineering, ASCE*, v8, n3, pp 131-137

[3] TDV GesmbH. (2001) *RM200 – Technical Description*, Graz, Austria

[4] CRUZ P.J.S., MARI A.R., ROCA P., “Nonlinear Time-Dependent Analysis of Segmentally Constructed Structures“, *Journal of Structural Engineering, ASCE*, v124, n3, 1998, pp 278-287