

# Towards a Wholistic Approach to Bridge Design

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## Summary

The design of bridges is typically split into two, quite distinctly different stages. The design of the overall structure on the one hand, and the detailed design of the individual components on the other hand. Typically the overall design takes place on generalised and simplified models of the bridge structure. Section forces and displacements gained from such models are then used as boundary conditions for the much more detailed models used in the second stage. An integrated process whereby requirements for both design stages are incorporated into one model has in the past been made difficult or impossible by the lack of computing resources. This situation is about to change. Generally available computers will soon be powerful enough to allow such a wholistic approach. This paper outlines the strategies employed in a current research project which provides the scientific background for such an integrated design approach. The outcomes of this research project are directly incorporated into a state-of-the-art bridge design software package. First results of this research project are documented and future developments are explained in this paper

**Keywords:** bridge design, computer analysis, finite elements, construction schedule

## 1. Introduction

In recent years computers have become indispensable tools for the design and structural analysis of bridge structures. The oftentimes complex structural behaviour of bridges and the high number of loading conditions require the use of highly specialised software tools. As opposed to many other structural engineering problems the structural response of bridges is often time-dependent and non-linear which leads to very high demands towards software tools supporting the design process [eg. 1,2]. Very commonly, bridge design processes are partitioned into two quite distinctly different steps. Firstly, the analysis of the overall system and secondly, the detailed design of the individual components. In most cases the analysis of the overall system is based on the stiffness method and is performed on simplified models consisting of one-dimensional beam elements (*Fig. 1*). Such models allow for an adequate analysis of the general response of bridge structures but fail to deliver the exact response in places where restrictions of the beam elements are exceeded. Typical examples for such places are joints between piers and girders, localised load introduction points or stiffeners in orthotrope plates among many others (*Fig. 2*). Such details must be analysed with other methods - most commonly, the finite element method (FEM) - and results from the preliminary overall analysis are employed as boundary conditions. Such FE-analyses are very often extremely time-consuming and require large computer resources. Therefore, the FEM has in the past been deemed unacceptable for the overall analysis of whole bridges.

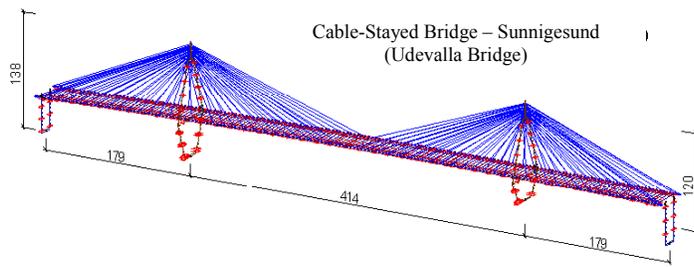


Fig. 1 Structural overall system of the Udevalla Bridge, Sweden.

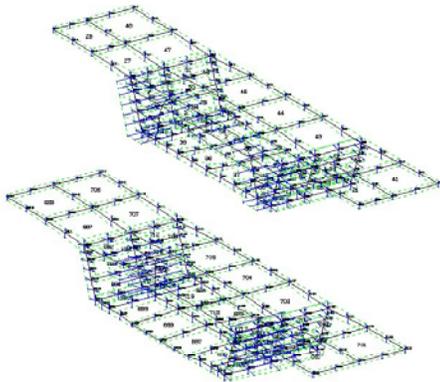


Fig. 2 FE-model of diaphragms and bearings.

## 2. Hybrid Bridge Models

In a current research project [3] the possibility of combining one-dimensional beam elements with finite elements in one and the same model of a bridge is being explored. The goal of this research project is to devise a software tool that allows for large portions of bridges still to be modelled with one dimensional beam elements, but where necessary, sub-models consisting of finite elements to be inserted (*Fig. 3*). Analysis of these hybrid models will be sufficiently fast and provide insights into the response of the overall structural behaviour as well as the response of particular details of the structure. A number of research topics have arisen from this concept and are currently being addressed.

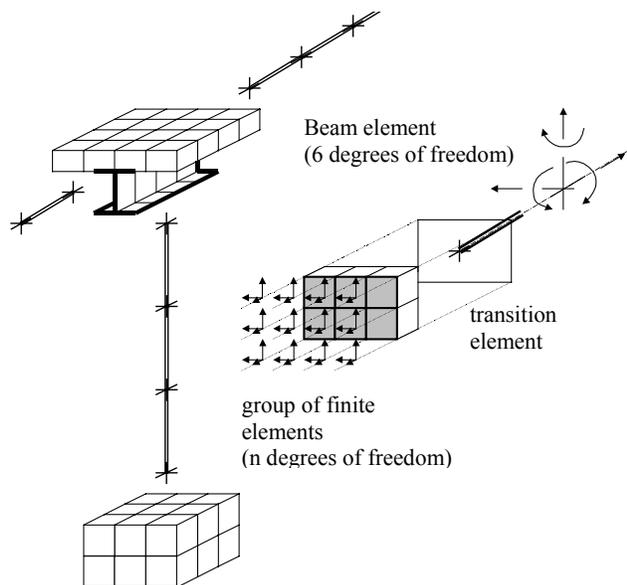


Fig. 3 Part of a bridge model consisting of beam elements, finite elements and transition elements.

Furthermore, in most design codes the results gained from simplified overall models are the basis for the required design checks (ultimate load check, shear capacity check, etc.). These checks are often based on stresses in idealised fibres within, or on the surface of, beam elements. Results from the overall analysis allow simple formulations of these checks whereas results gained from FE-analyses are not compatible with most design checks as required in most codes.

This paper outlines the strategies for the development of computer software supporting an integrated design approach. The issue of combining traditional beam elements with a comprehensive finite element concept is one of the core targets of this project. Along with an innovative program architecture the resulting software package will advance computer aided bridge design and provide an efficient tool for practising engineers.

### 2.1 Transition Elements

Beam elements are defined by six degrees of freedom. Where complicated cross-sections of bridge components are modelled with finite elements, the number of degrees of freedom invariably will be greater than six. Therefore, at points where FE-sub-models connect with beam elements the number of degrees of freedom differ and special transition elements must be devised to couple the two components (*Fig. 3*). Smart integration over the stresses within the cross-section on the FE-side of the transition elements provides the desired reduction from stresses to section forces.

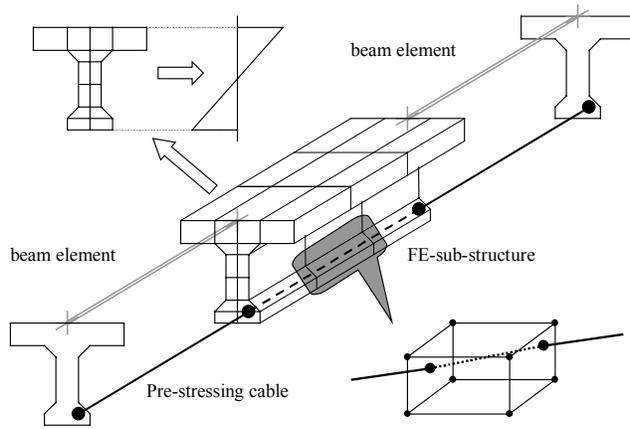


Fig. 4 Combined beam and FE-model of a pre-stressed girder.

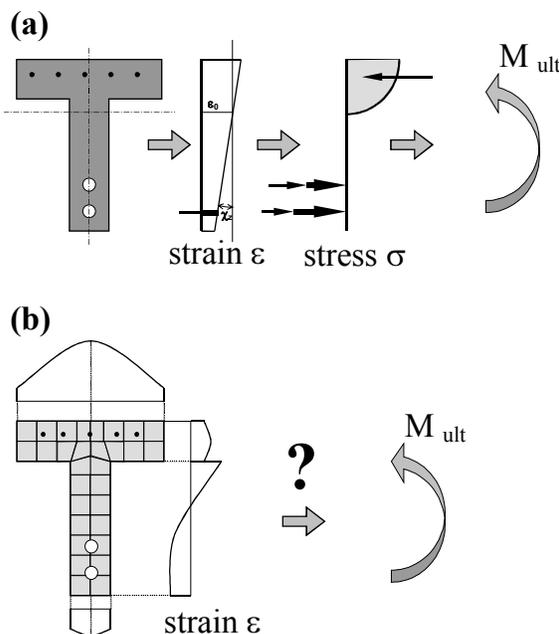


Fig. 5 Ultimate moment check for a beam element and a cross-section through finite elements.

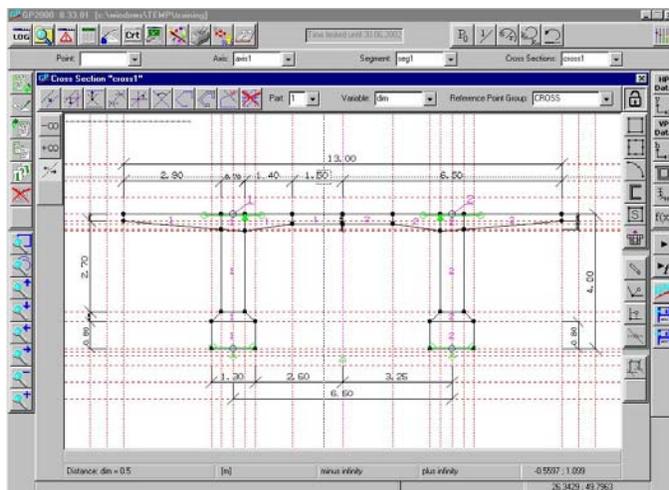


Fig. 6 Input of a double-Tee cross-section.

## 2.2 Pre-Stressing and Post-Tensioning

Pre-stressing and Post-tensioning are common load cases during the erection of bridges. When portions of bridge girders are modelled with finite elements, a unique loading situation arises. Solutions for this loading type exist for beam elements [eg. 4] but have to be derived for two- and three-dimensional finite elements (Fig. 4).

## 2.3 FE-Sub-Models and Design Checks

Most design checks in bridge design codes are based on section forces in beam elements (eg. shear capacity, ultimate moment check) (Fig. 5a). Results for finite elements are given as strains in the so-called Gauss-points within each element (Fig. 5b). These strain fields also include effects which are not normally accounted for in beam elements (eg. warping, shear lag). Non-linear material behaviour (eg. Cracked concrete) is commonly included at this level and the software performing the design checks must take these effects into account.

In order to be able to support automated design checks in FE-sub-structures, procedures have to be devised which allow the definition of cuts through sub-structures and support the integration over stress-components into section forces along these cuts taking into account the respective non-linear material properties. Special consideration must be given to composite cross-sections in this context.

## 2.4 Pre- and Post-Processing

Bridges are often complex three-dimensional structures. The generation of computer models with the exact geometry of such structures must be supported by powerful CAD-like tools in order to be practical (Fig. 6). Visualisation of results is another important issue that must be addressed and the inclusion of FE-sub-models emphasises the need for efficient pre- and post-processing even further.

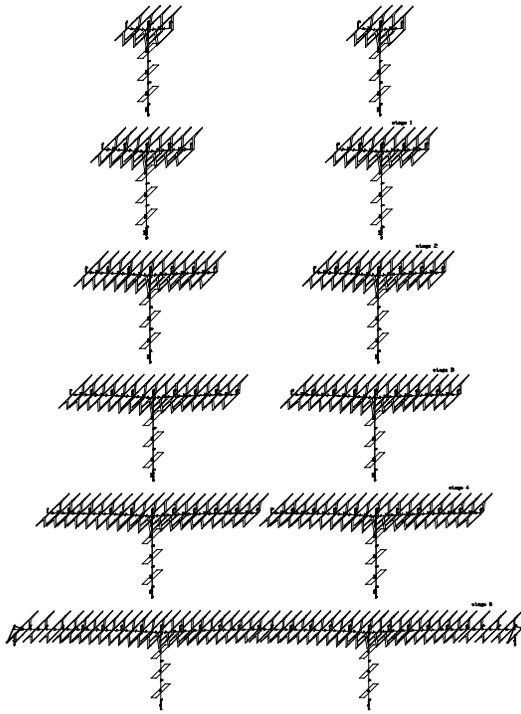


Fig. 7 Construction stages of a balanced cantilever.

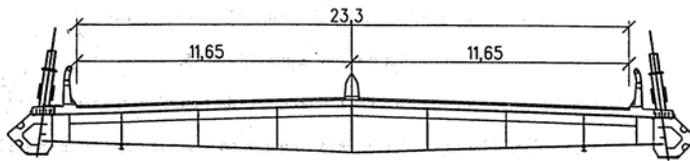


Fig. 8 Composite cross-section.

## 2.5 Construction Schedule

The importance of modelling the construction process of bridges has been well recognised [5,6]. Fabrication and erection procedures often critically determine the stress state in bridges and the changes thereof during the various construction stages. Time dependent effects such as re-distribution of section forces due to creep & shrinkage or cable relaxation are strongly dependent on the changes in the structural system and the amount of time the structure remains in each partly completed state during erection. In order to analyse the structural response of a bridge throughout its construction, the precise erection history must be described and simulated by the mathematical model of the bridge (Fig. 7).

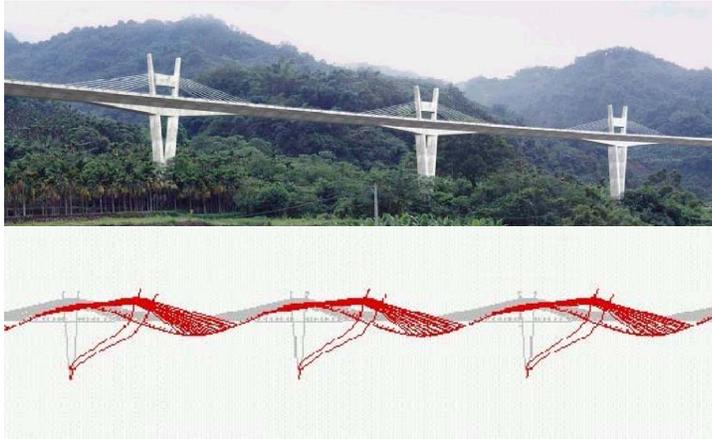
## 2.6 Composite Structures

Many bridge structures are built from a mixture of materials, most commonly steel and concrete (Fig. 8). Different parts of the composite cross-sections are erected at different times and locked-in stresses and displacements occur. Bridge design software packages must include algorithms to take into account the effects resulting from these locked-in stresses and displacements. Again, time-dependent processes play an important role and must be accounted for.

## 3. Analysis Functionality

Certain problems in the design of bridges require a relatively high standard of analysis in order to take into account effects which are not usually encountered in other types of structures. Linear elastic analysis is often not adequate to describe the structural behaviour of large bridge structures, especially when cable stayed or suspended structural systems are involved. This leads to the requirement of geometrically non-linear analysis approaches which take into account the effects of cable sag, second order theory or large displacements. Not so long ago this was still accomplished by painful hand calculations [7] but more recently computers have become powerful enough so that geometrically non-linear algorithms can be implemented into bridge design software packages. However, once these tools are being used another complication arises due to the fact that simple superposition of loading cases is not permissible anymore. An elegant way to overcome this problem is presented in [6] paving the way to use non-linear algorithms on the one hand but still accumulate results throughout the various construction stages on the other hand.

The time dependent material properties of concrete (creep & shrinkage) and steel (relaxation) often lead to considerable re-distributions of section forces and to changes in the displacements of bridges. The inclusion of these time-dependent effects is especially important in pre-stressed and post-tensioned structures. Modern material models such as the CEB/FIP90 model for concrete also take into account the time of load application which in turn leads to the absolute necessity of concise book keeping of changes in loading conditions and structural system.



The requirements for dynamic design have become much more stringent in recent years, especially in areas with high earthquake probability. Response spectrum analysis, time-history simulations of previous earthquake events, moving load and moving mass analyses are requirements often expected from state-of-the-art bridge design software packages (*Fig. 9*).

*Fig. 9 Dynamic analysis of a high-speed railway bridge in Taiwan.*

Automated design checks according to various national standards reduce the work load for design engineers immensely. Surprisingly, many design codes are still based on models which are well suited for hand calculations but which are very impractical when design checks are to be performed automatically by computer programs. These problems increase when numerical models include elements other than one-dimensional beam elements. These models produce stress fields as results which have to be reduced to section forces in order to comply with design procedures. At this stage there is very little guidance in any national design standards on how this reduction should be performed. Basic research is needed to develop design rules are compatible with modern analysis techniques.

Optimisation of the construction process is also an important issue. The computation of pre-camber shapes, the optimisation of post-tensioning sequences [8] or the optimisation of the pre-stressing lay-out in incrementally launched bridges [10] are only a few examples. More and more, modern software packages are not only supporting the analysis of structures but are also expected to assist the optimisation of erection processes and the choice of the optimal structural system.

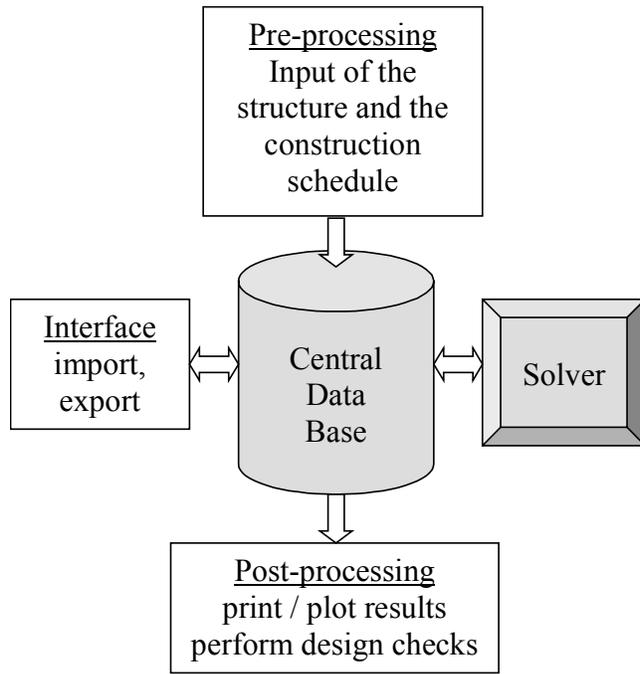


Fig. 10 Structure of the bridge design software.

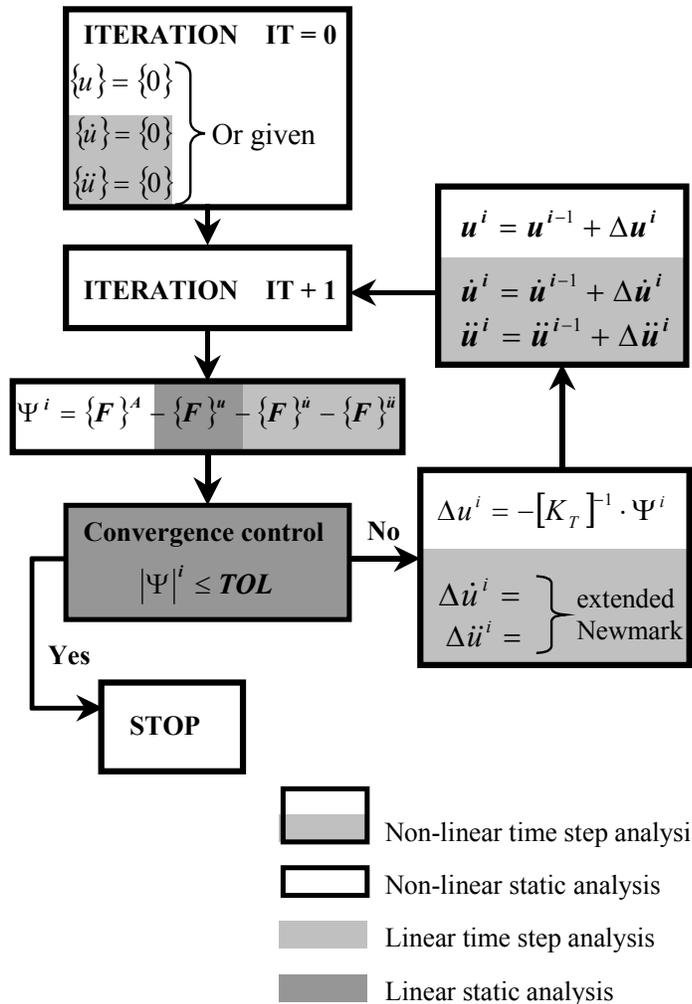


Fig. 11 Flow chart of the solver.

## 4. Implementation

Over the past four years the principles described in section 2 and section 3 have been implemented into a well established bridge design software package called *RM2000* [9]. The software is centred around an object-orientated data base (Fig. 10). Various pre- and post-processing tools support the input into the system and the processing of results from the system. At any point during data generation the existing model can be analysed by a solver module which then stores the generated results into the 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.

The solver module has been designed to perform geometrically non-linear, time-dependent structural analyses (Fig. 11). It uses a Newton-Raphson algorithm for the geometric non-linearities and an extended Newmark time integration for the time dependent portion of the analysis. If less sophisticated types of analysis are sufficient for a problem, then this can be achieved simply by deactivating parts of the analysis process as indicated in Fig. 11.

Currently the program is restricted to one-dimensional elements (beams, cables etc.). The research and development work which is being carried out as part of an international research project aims at the inclusion of finite elements into the program. A library of plate, shell and brick elements will be implemented and transition elements will be devised to couple the sections of the structure which are modelled with conventional beam elements with the sections modelled with finite elements.

## 5. Conclusions

A concept for the functionality and architecture of structural bridge design software has been presented. The challenges to be met by such software include the analysis of geometrically non-linear systems, time-dependent and non-linear material behaviour, automated design checks and solutions to common optimisation problems in bridge design. The inclusion of general finite elements into such a software package poses some interesting problems. In a recent research project these problems are being identified and tackled. It is the intention to find solutions to these challenging problems and implement them into a state-of-the-art bridge design software package. This paper gives a first overview over the intended scope of this research work and about some progress that has already been made.

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