Force Optimization for an Extradosed Bridge in Estonia

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Summary: The fulfilment of force and displacement boundary conditions in the process of bridge design and computation is a demanding task for an engineers mind. High effort is required ranging from precamber calculations for beam bridges over to prestress determination for cable-stayed bridges and even the iterative calculation of the shop form. The application of the SOFiSTiK module CSM (<u>C</u>onstruction <u>S</u>tage <u>M</u>anager) in this optimization process will be described in the following by the means of basic examples. As reference project the Smuuli bridge - the first extradosed bridge in the Baltic countries - will be presented.

Zusammenfassung: Für die Einhaltung bestimmter Kraft- und Verformungsrandbedingungen ist beim Entwurf und der Berechnung von Brücken der Ingenieurverstand im besonderen Masse gefordert. Von der Überhöhungsberechnung bei Balkenbrücken über die Abstimmung der Vorspannung bei Schrägseilbrücken bis hin zur iterativen Ermittlung der Werkstattform ist meist erheblicher Rechenaufwand notwendig. Die Anwendung des SOFiSTiK Moduls CSM (<u>C</u>onstruction <u>S</u>tage <u>M</u>anager) zur Vereinfachung dieses Optimierungsprozesses wird im Folgenden anhand von grundlegenden Beispielen erläutert. Als Referenzprojekt wird die Smuuli Brücke, die erste *extradosed bridge* des Baltikums, vorgestellt.

1 INTRODUCTION

1.1 Motivation for automatic optimization in the bridge design process

Many tasks in the bridge design process require advanced considerations regarding wanted forces or displacements, often this tuning is performed with the help of engineering experience or an iterative calculation in advance to the final computations.

When thinking of *displacements* it is necessary to consider and control the deflections of the structure in advance, not only when considering construction sequences like the balanced cantilever method, even cast-in-one systems might require precamber modifications to achieve a satisfactory serviceability or to fulfil aesthetic requirements. These modifications can be performed easily on linear systems, however some further considerations might be necessary with respect to the placing of the formwork for span-by-span or cantilever construction methods [1]. The possibilities of performing such calculations in order to achieve a ideally straight structure in a defined loadcase or construction stage is given as Precamber calculations in the SOFiSTiK module CSM. Even the application to nonlinear systems is possible with the CSM Precamber calculations.

However, often the fixed optimization target of an ideally straight system (i.e. the system as it was generated in the wanted shape) is not enough. Then the engineer needs tuning of several structural answers, as there are *forces*, forces and displacements or even coupling of different displacements in the structure. Here the need for a versatile optimization tool for such structural unknowns is given. The input should be the wanted *results* at discrete positions of the system, and as *primary unknowns* an equal number of *tuning/unit loadcases* shall be defined resulting in *coefficients* to set up a *linear equation system* which yields as answer the wanted *tuning factors* of the given loadcases. Furthermore the repeated application of this modifications should provide the possibility to perform automatic optimization on systems exhibiting nonlinear behaviour.

As the main objective was to help the engineer to perform such optimizations with as less input as possible and mostly the tuning loadcases are integrated into the (bridge) construction process the existing module CSM was enhanced to do such computations with the help of the so called CSM Equation system.

1.2 Precamber vs. Equation System

As stated before, the CSM Precamber calculation and the CSM Equation system follow the same objective in assisting the engineer to achive wanted structural answers. To pronounce the differences and to show possible combinations, the two principles of optimization shall be compared shortly. The main difference between the two calculation methods is the optimization target, the precamber calculation needs no additional information here, the wanted shape of the structure as it was input by the user is the target. The only additional information is the point of time when the wanted shape should be obtained. As no further information is required, the SOFiSTiK CADINP input for such a precamber modification is very simple, e.g. to calculate the precamber for a straight bridge in construction stage 35 the CSM input in the example file *csm26_precamber_spanbyspan* is one additional line:

```
CAMB CS 35
```

Yielding a additional calculation step in the construction stage calculation sequence generated by the CSM which evaluates the necessary precamber of the structure. After this calculation step the necessary predeformation of the formwork (here for a span-by-span erection) can be plotted:

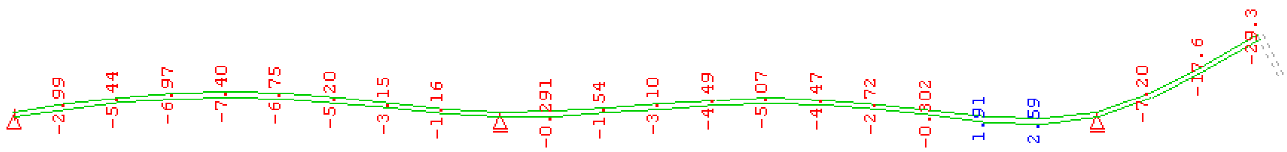

Figure 1: Precamber of formwork (nodal values in mm)

Further reference and examples for the CSM Precamber option can be found in the CSM Manual [6] and in [1].

CSM Precamber and Equation system: optimal forces and shape - with optimal effort

In contrast to the fixed optimization target, the CSM Equation system provides input possibilties for user defined force and displacement conditions as well as the input of the unit/tuning loadcases and the input of a target loadcase where these conditions should be fulfilled. Therefore the necessary CADINP input expands in *csm22_cable_stay_optimization* to:

```
EQLC 4092 TYPE    G     $ target loadcase
EQLC 5021,5022,5041,5042,5061,5062,5083,5087 TYPE FREE  $ unit loadcases
EQBE NO 1001 X 0 MY     0 ETYP BEAM
EQBE NO 1006 X 0 MY     0 ETYP BEAM  $ wanted pylon bending moment = 0.0
EQBE NO 1011 X 0 MY     0 ETYP BEAM
EQBE NO 331  X 0 MY  -800 ETYP BEAM
EQBE NO 536  X 0 MY  -800 ETYP BEAM  $ bending moments in superstructure
EQBE NO 126  X 0 MY  -800 ETYP BEAM
EQBE NO 741  X 0 MY  -800 ETYP BEAM
EQBE NO 746  X 0 MY -2000 ETYP BEAM
```

The basic elements of the input and the results of the CSM Equation system will be presented in the following. However a combination of the two methods is often advantageous when having a linear system where forces should be tuned with the help of the Equation system, here the deformations might be controlled adding a simple precamber step to the Equation systems input, achieving both objectives – optimal forces and shape - with optimal effort. To sum these points up a small table should provide the necessary information discerning both calculation methods:

	Precamber (CAMB)	***Equation System (EQST etc.)***
Target	To achieve an ideally straight system (i.e. the model/system as it was generated in the wanted shape) in a construction stage or final state.	Tuning of user defined structural answers like forces and displacements in a construction stage or final state.
Nonlinear Capability	Through repeated application of the precamber modification.	Through repeated solution of the optimization equation system.
Example Systems	Multi-span R/C or PSC beam bridges. Determination of the shop-form (nonlinear)	Cable stayed bridges Advanced linear and nonlinear force and displacement tuning
SOFiSTiK Example[1] [*.dat]	csm26_precamber_spanbyspan	csm22_cable_stay_optimization

Table 1: Comparison CSM Precamber and Equation system

2 USING THE CSM EQUATION SYSTEM

2.1 Input Elements

For the CSM Equation systems CADINP input, five input records are available, four defining the basic optimization targets and unit loadcases and one additional input to control an automatic nonlinear optimization. Here the basic input elements are given in sensible input order together with short information about the input records main objective. The input record items overview table found in the CSM Manual [6] is given as well.

- **EQLC: <u>EQ</u>uation <u>L</u>oad<u>C</u>ases**
  - Definition of target loadcase as TYPE G
  - Definition of the unit/tuning loadcases as TYPE FREE

1 To be found in the folder CSM.DAT of the SOFiSTiK installation folder

3.18. EQLC - Equation Load Cases

EQLC

Item	Description	Dimension	Default
NO	Load case number	-	!
TYPE	Type of load case: G permanent load case FREE uniform scalable load case	LIT	FREE

- **EQUU, EQPP, EQBE: EQuation boundary conditions/restrictions for displacements (UU), support forces (PP) and element forces (BE)**

  - Definition of the discrete optimization targets, optional together with Construction Stage
  - Possible coupling of conditions via ADD
  - Tolerance for nonlinear optimization via TOL

3.19. EQUU - Displacement Restriction

EQUU

Item	Description	Dimension	Default
NO	Node number	-	!
UX UY UZ PHIX PHIY PHIZ	Value of desired displacement	m/RAD	-
CS	Construction stage number	-	-
ADD	Addition factor to the previous condition	-	-
TOL	Tolerance for iteration end	-	-

3.20. EQPP - Reaction Restriction

EQPP

Item	Description	Dimension	Default
NO	Node number	-	!
PX PY PZ MX MY MZ	Value of desired reaction force	kN,kNm	-
CS	Construction stage number	-	-
ADD	Addition factor to the previous condition	-	-
TOL	Tolerance for iteration end	-	-

3.21. EQBE - Beam Force Restriction

EQBE

Item	Description	Dimension	Default
NO	Element number	-	!
X	Beam ordinate	m	0
N VY VZ MT MY MZ	Value of desired element force	kN,kNm	-
ETYP	Element type BEAM Beam elements CABL Cable elements TRUS Truss elements SPRI Spring elements	LIT	BEAM
CS	Construction stage number	-	-
ADD	Addition factor to the previous condition	-	-
TOL	Tolerance for iteration end	-	-

- **EQIT: Maximum <u>IT</u>erations in the automatic nonlinear optimization**

3.22. EQIT - Construction Stage Iteration

EQIT

Item	Description	Dimension	Default
ITER	Number of iterations	-	-

3 BASIC EXAMPLES

3.1 Cable-stayed Bridge

For all types of bridges where cables are used as main structural elements, the need for the reliable determination of cable forces at the final stage is overcome by to need to determine appropriate cable jacking sequences or initial (i.e. stress-free) lengths to control the bending exposure of the whole structure. Mostly the construction sequence exhibits critical influence on the overall loadcarrying behaviour. As a first example a cable-stayed bridge shall be investigated, the example system of the bridge is simplified to focus on the main aspects of the input and its effects. However the construction sequence and therefore the chosen tuning loadcases – the cable stressing and additionally the hydraulic jacking of two supports to adjust the beam forces – are realistic (e.g. applied in the cable-stayed bridge described in [3]). The example systems layout is quite simple:

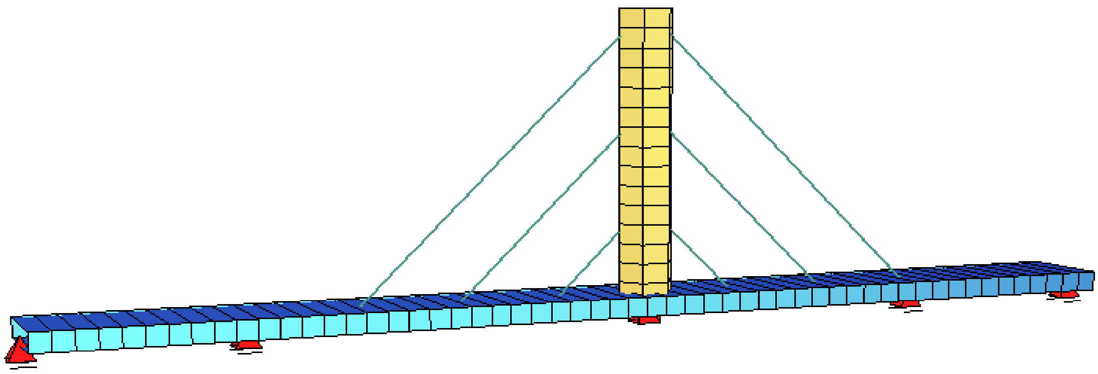

Figure 2: Example system cable-stayed bridge (csm22_cable_stayed_optimization.dat)

Tuning loadcases: the cable stressing and additional hydraulic jacking of two supports

It should be noted well, that in the context of an engineering approach (i.e. neglecting cable sag), the described system behaves *linear*. Therefore the main principle for the optimization of linear structural systems can be derived and explained here: **First adjust the wanted forces!** Displacements have no influence on the forces and can be set by an additional CSM Precamber run. This keeps the input effort low and makes the calculation less error prone and easier to check. In the sample file a first CSM run calculates the construction sequence using estimated pre-stress of the stay-cables. The CSM Equation systems input is done in a own block. The input for the CSM Equation system was given before in chapter 1.2. The two WinGRAF plots below show the qualitative differences in the beam bending moments of the deck without and with CSM Equation system optimization applied:

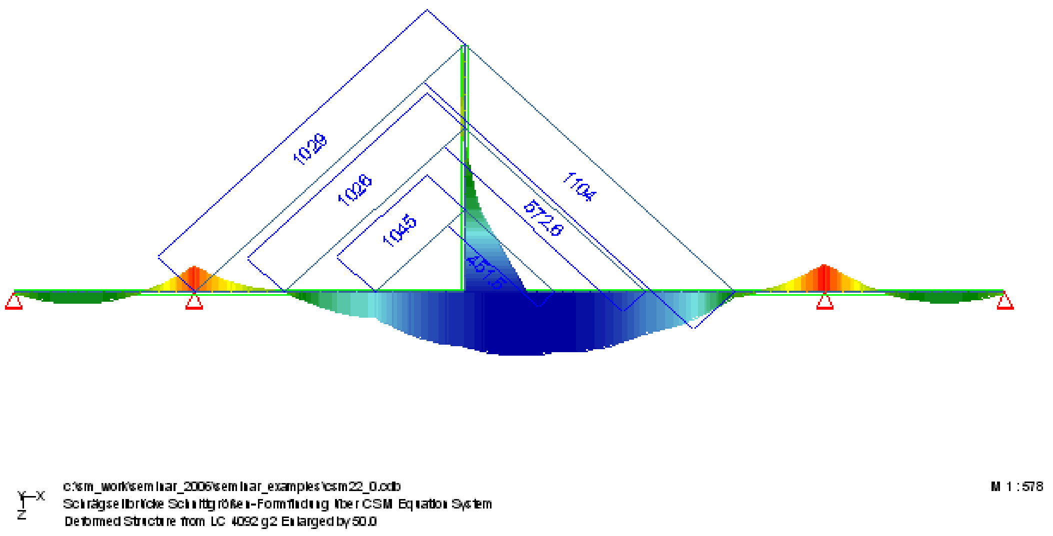

Figure 3: Bending moments and cable forces w/o CSM Equation system optimization

Optimization goal: pylon moment 0 with contiuous beam bending moments with hogging moments not exceeding -800kNm

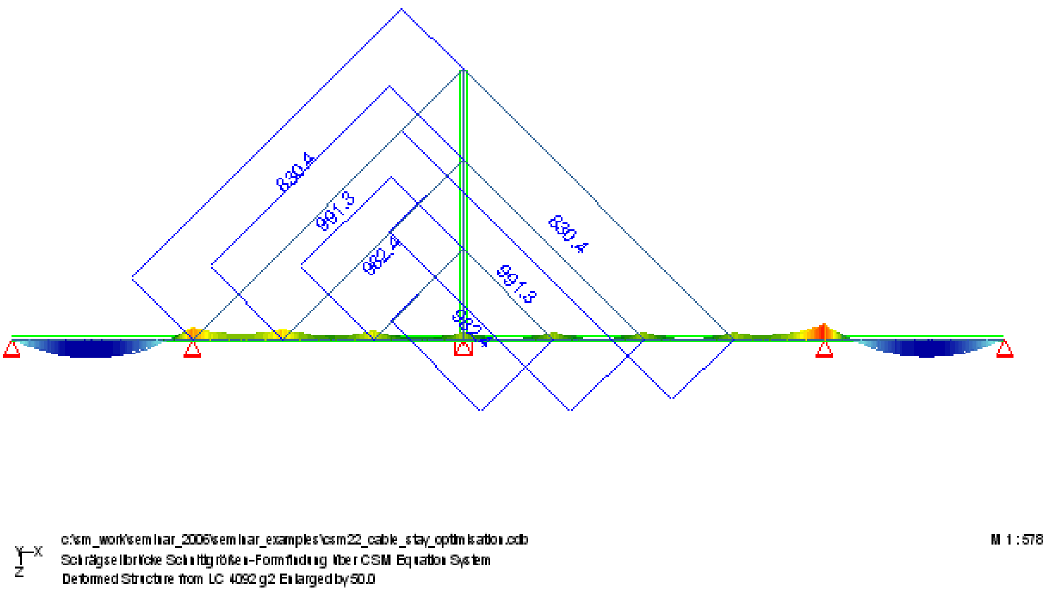

Figure 4: Bending moments and cable forces with CSM Equation system optimization

The plots above clearly show that the goal to achieve the bending moment distribution of a continuous beam with a hogging moment of -800kNm and -2000kNm in the right sidespan is fulfilled, also the pylon moment is reduced to 0 with all in all lower cable forces. One further point can be seen in the plots, the deformations of *both* calculations are zero as in both calculations the CSM Precamber was applied to set the deformations calculating appropriate initial deformations for the construction stages.

3.2 Suspension Bridge

As an example for the nonlinear automatic optimization, the construction sequence of a simple suspension bridge shall be considered. The nonlinearities of the structural system arise due to large deformations of the main cable, and therefore require a computation considering all geometric nonlinear effects (theory of 3rd order). As well as the computation, the optimization of the structure has to be performed iteratively. To carry out such calculations more easily and automatically the -23 generation of the SOFiSTiK structural analysis software has been enhanced in some points:

- Inline application of the CSM generated input files via the `+apply` statement, the automatically generated files **_csm.dat* and **_csmequ.dat* are inserted in the main **.dat* file at runtime, therefore automatically repeated calculations are possible. Also the output (one *.plb*) and the computation hava a more cast-in-one appearance.
- Iteration step no. output in SOFiSTiK WPS during the automatic optimization.
- Real-time qualitative display of residual forces during loadcase iteration in WPS.
- Input for optimization tolerance (`TOL`) and maximum number of iterations (`EQIT ITER`) in the CSM Equation system as described before.

The considered structural system is a simplified suspension bridge, the optimization goals shall be again zero bending moments in the pylons together with a straight deck at the end of the construction sequence. As unit loadcases the pre-stressing of the hanger cables together with additional pre-stressing of the side cables are defined. It should be noted that the output of the CSM equation system yields factors for the unit loadcases in every optimization step, so the pre-stress of the hangers can easily be transferred into a initial stress-free length.

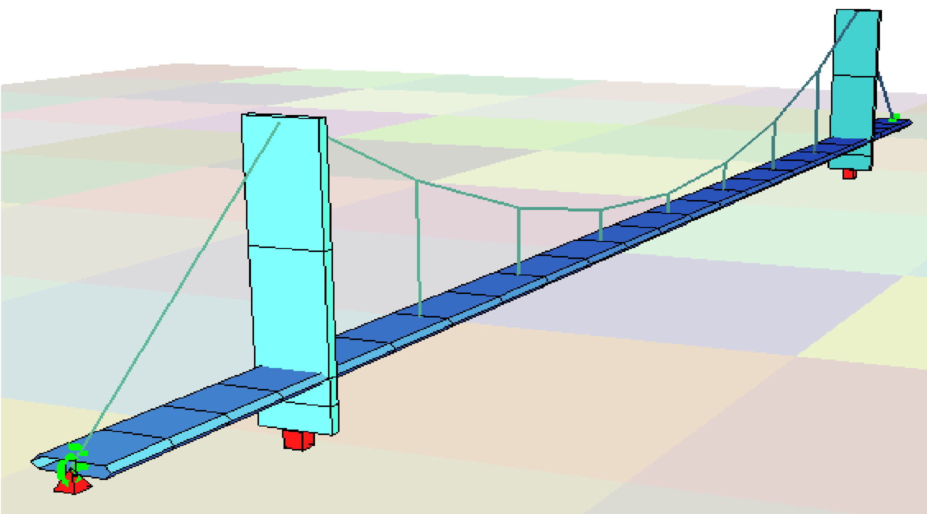

Figure 5: Example suspension bridge

The CADINP input for the automatic optimization including the inline application of the generated input reads:

```
+PROG CSM
HEAD Optimization
$ Computing required factors of unit loadcases
EQLC 4095 TYPE    G  $ target loadcase

EQLC (5025 5055 10) TYPE FREE  $ variabel gesuchte Vorspannungslastfälle
EQLC (5085 5095 10) TYPE FREE  $ variabel searched unit loadcases

EQBE NO 1001 X  0 MY 0 TOL 50.0 ETYP BEAM $ gewünschtes Pylonmoment am
Anschnitt = 0.0
EQBE NO 1002 X  0 MY 0 TOL 50.0 ETYP BEAM $ wanted pylon bending moment = 0.0

EQUU NO (102 105 1)  UZ  0 TOL 0.05 $ 0.05 m Tolerance

EQIT 10 $ 10 optimization iterations

$ Zur Iterationskontrolle kann auch noch während der Iteration
$ die wps-Datei .prt geöffnet werden und nach den Strings
$ "CSM EQUATION ITERATION" durchsucht werden.
$ For iteration check also during the iteration the
$ wps-file .prt can be opened and searched for string
$ "CSM EQUATION ITERATION".
UNIT 0 0 0 0 0 0 0 0 0  $ no plots during iteration
END

+apply $(NAME)_csmequ.dat
```

During the automatic optimization run the number of the current iteration step is printed in WPS, and in the *.prt* file of the calculation the factors and convergence checks of the CSM Equation system can be found for each iteration step, e.g. for step 4:

```
 CSM EQUATION ITERATION   4
  Restriction type number   x     CS    target act.value tolerance fulfilled?
    1   beam   MY   1001   0.000   95     0.000  -247.868  > 50.000 no
    2   beam   MY   1002   0.000   95     0.000    68.067  > 50.000 no
    3  node    UZ    102           95     0.000     0.006  <  0.050 OK
    4  node    UZ    103           95     0.000     0.010  <  0.050 OK
    5  node    UZ    104           95     0.000     0.041  <  0.050 OK
    6  node    UZ    105           95     0.000    -0.042  <  0.050 OK
    loadcase    last factor     new factor
        5025        2.375179       2.433804
        5035       73.376015      72.064659
        5045       56.735054      65.950233
        5055      190.951141     181.488937
        5085        0.534482       0.514303
        5095        0.524737       0.518421
```

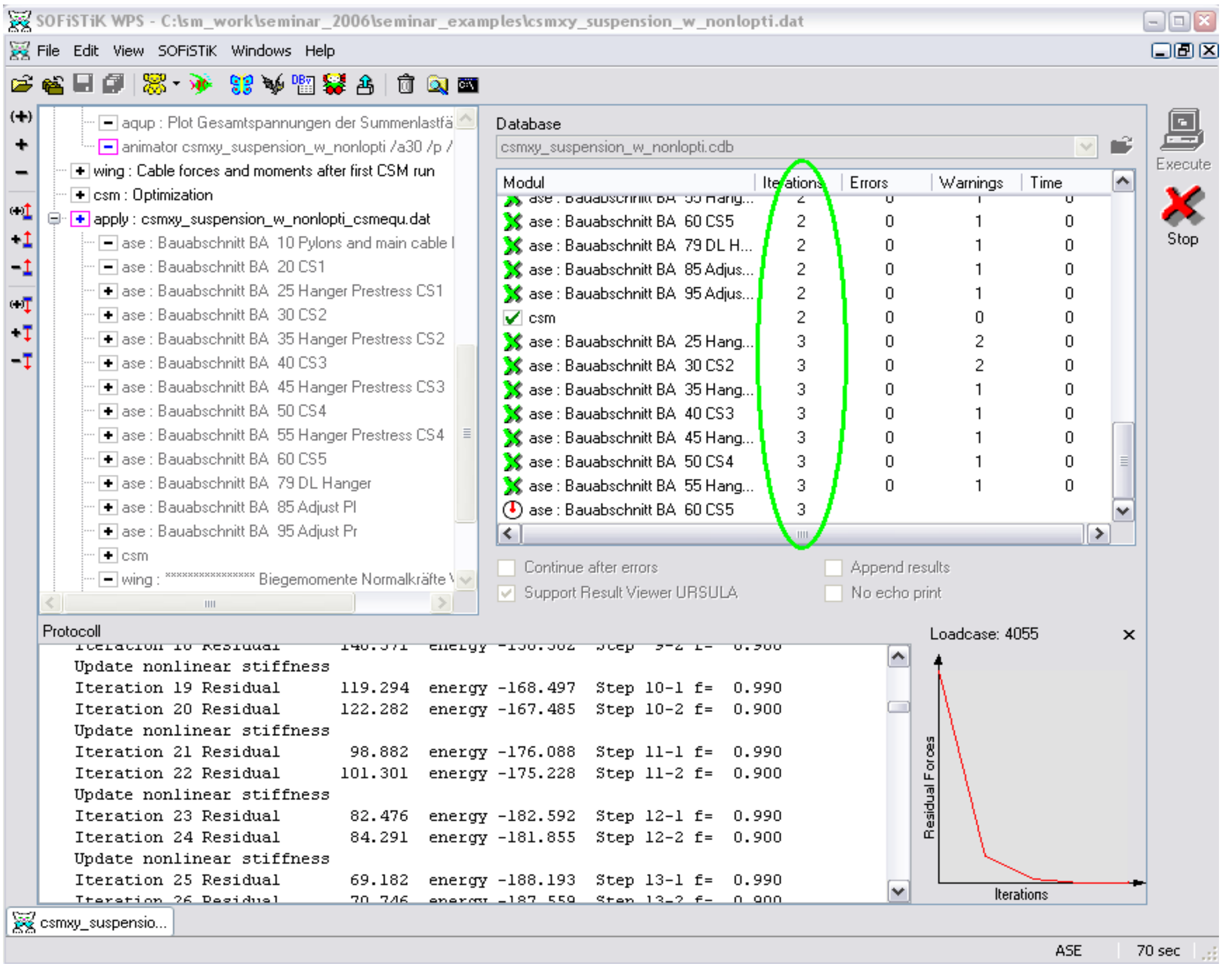

Figure 6: SOFiSTiK WPS during optimization iteration

The following plots shall visualize the convergence of the optimization objectives during the seven - here required - optimization iterations.

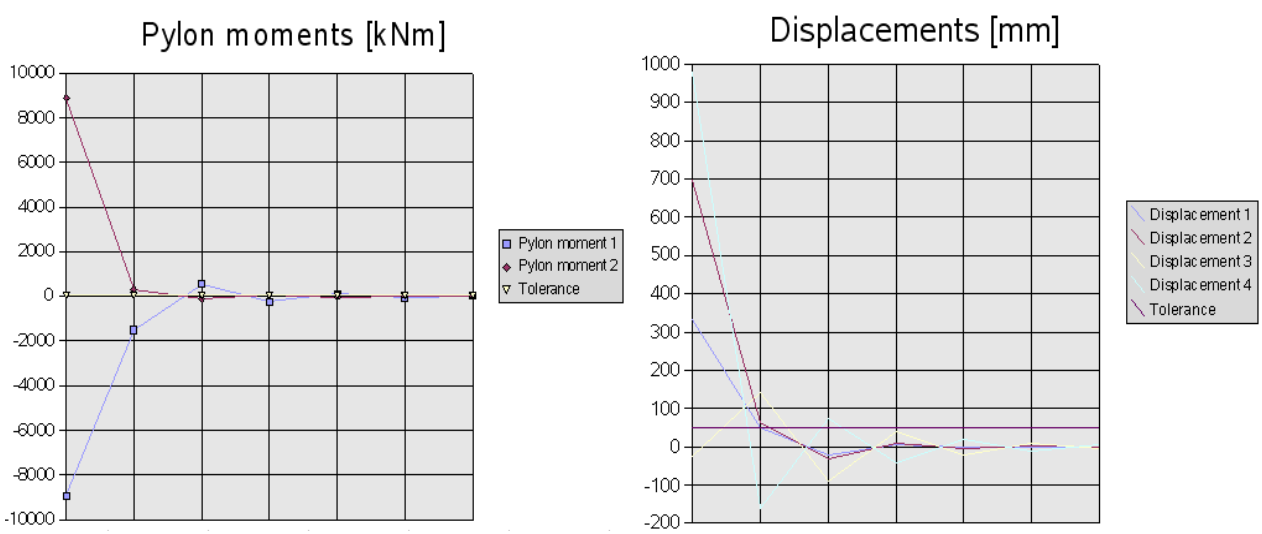

Figure 7: Convergence behaviour of the objetives during optimization (7 Iterations)

The results of the CSM Equation system calculation of the suspension bridge construction sequence show the wanted straight shape of the bridge deck together with zero pylon moments. As the bending stiffness of the bridge deck was arbitrarily chosen and no further consideration w.r.t. the bending moments of the deck were performed the moment line might not be optimal for a suspension bridge, however further modfications like beam hinges etc. will solve this task. In looking at the final results and the consistent construction stage results it can be shown, that the optimization with the help of the CSM Equation system provides a powerful alternative to the conventional approach of formfinding without introducing artificial stiffness factors, and the results of the construction sequence are obtained as well.

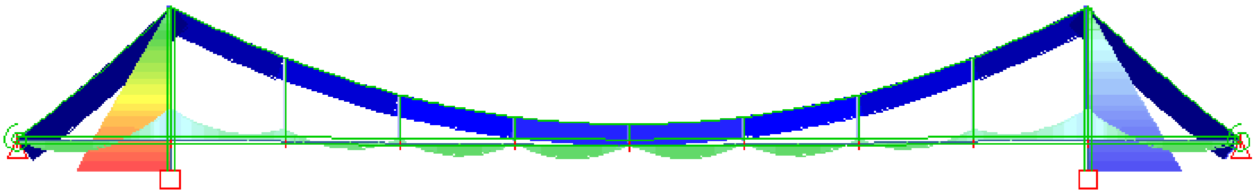

Figure 8: Beam and cable forces on the built-in-one system

CSM Equation system - a powerful alternative to the conventional approach of formfinding

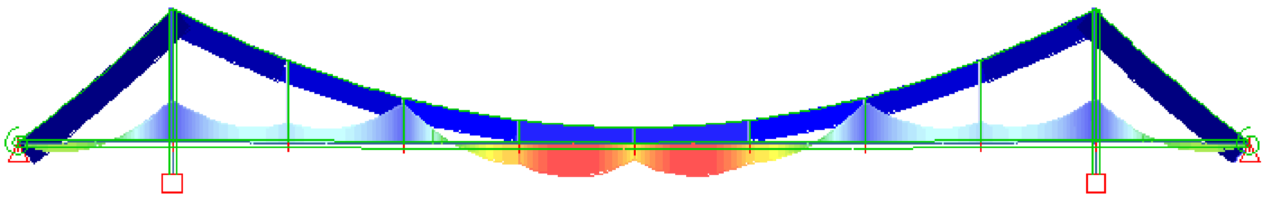

Figure 9: Beam and cable forces after CSM Equation system optimization

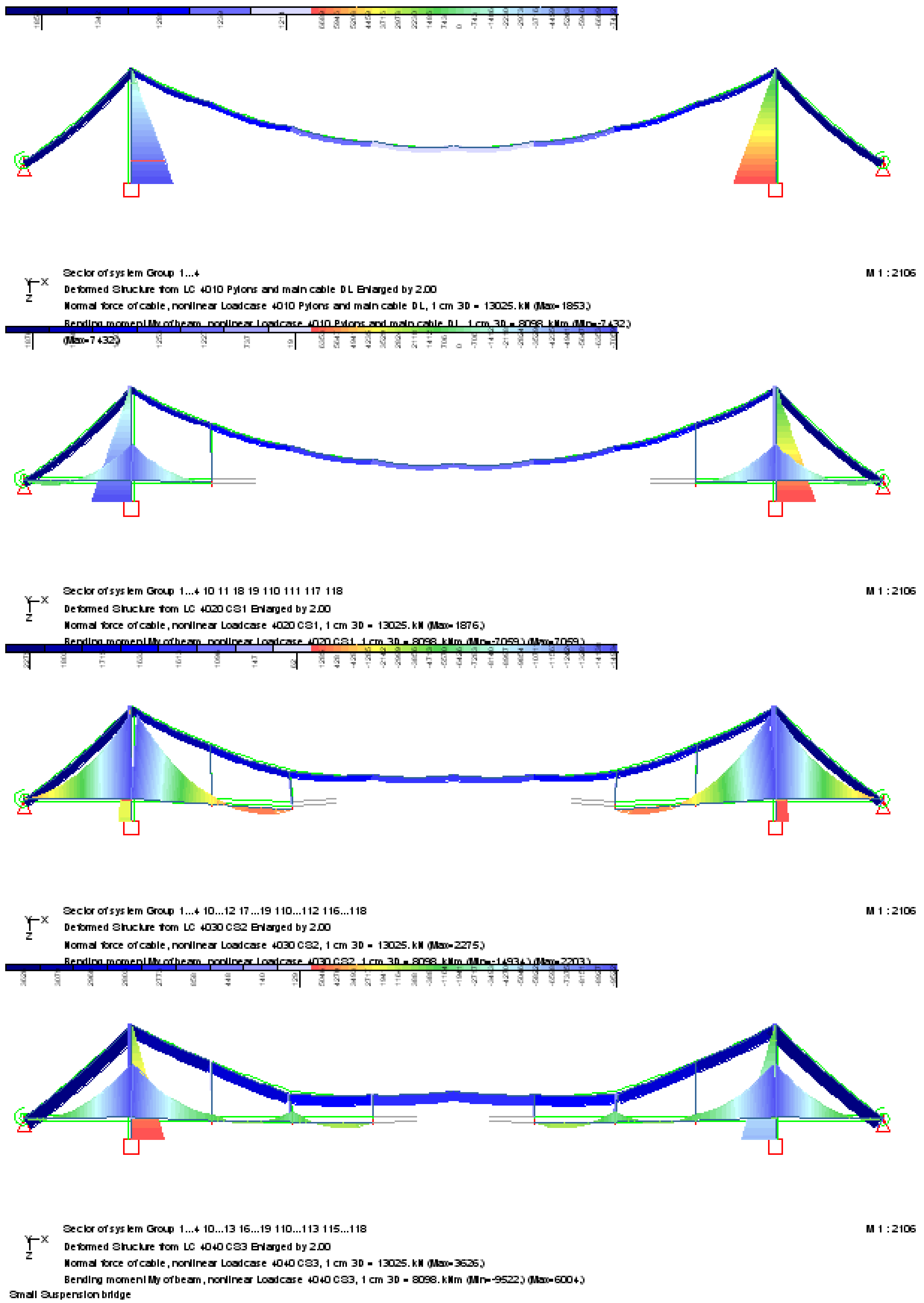

Figure 10: Optimized construction stages 1-4 of the suspension bridge

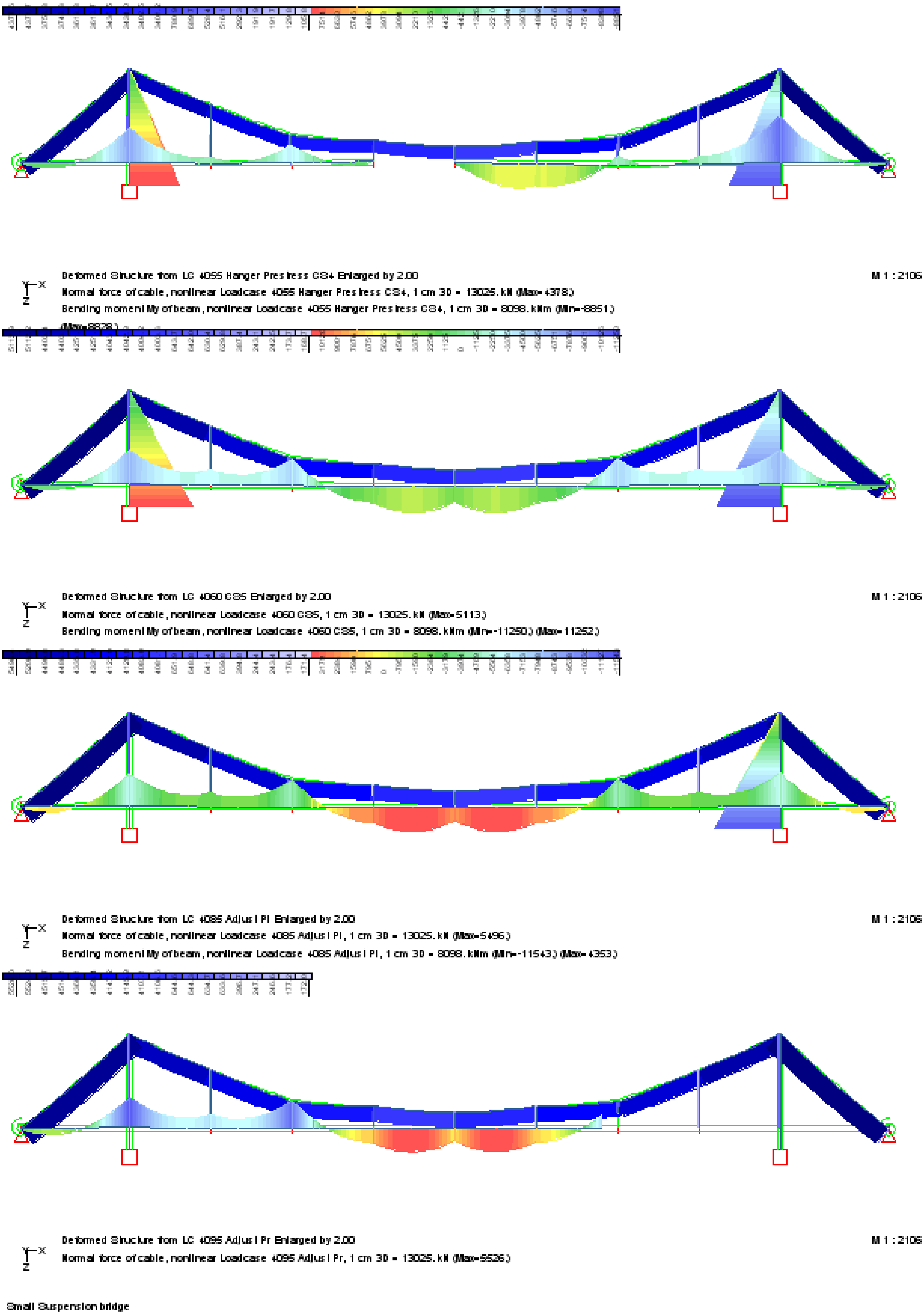

Figure 11: Optimized construction stages 5-8 of the suspension bridge

3.3 Further Examples

Two further examples for the CSM Equation system shall be mentioned here, one showing the differences between the combined application of the Precamber and the Equation system and the pure application of the Equation system. Here also the input for a symmetric cable stayed bridge with cantilver construction requires the coupling of two displacments:

```
$ cantilever last segment: incl. deadload of last segment condition:
$ in CS 60       displacement107 = displacement108
$ =>            displacement107 - displacement108 = 0.00
$ => factor ADD for node 108 => ADD -1
EQUU NO 107         UZ      0    CS 60
EQUU NO 108         UZ      0    CS 60 ADD -1
```

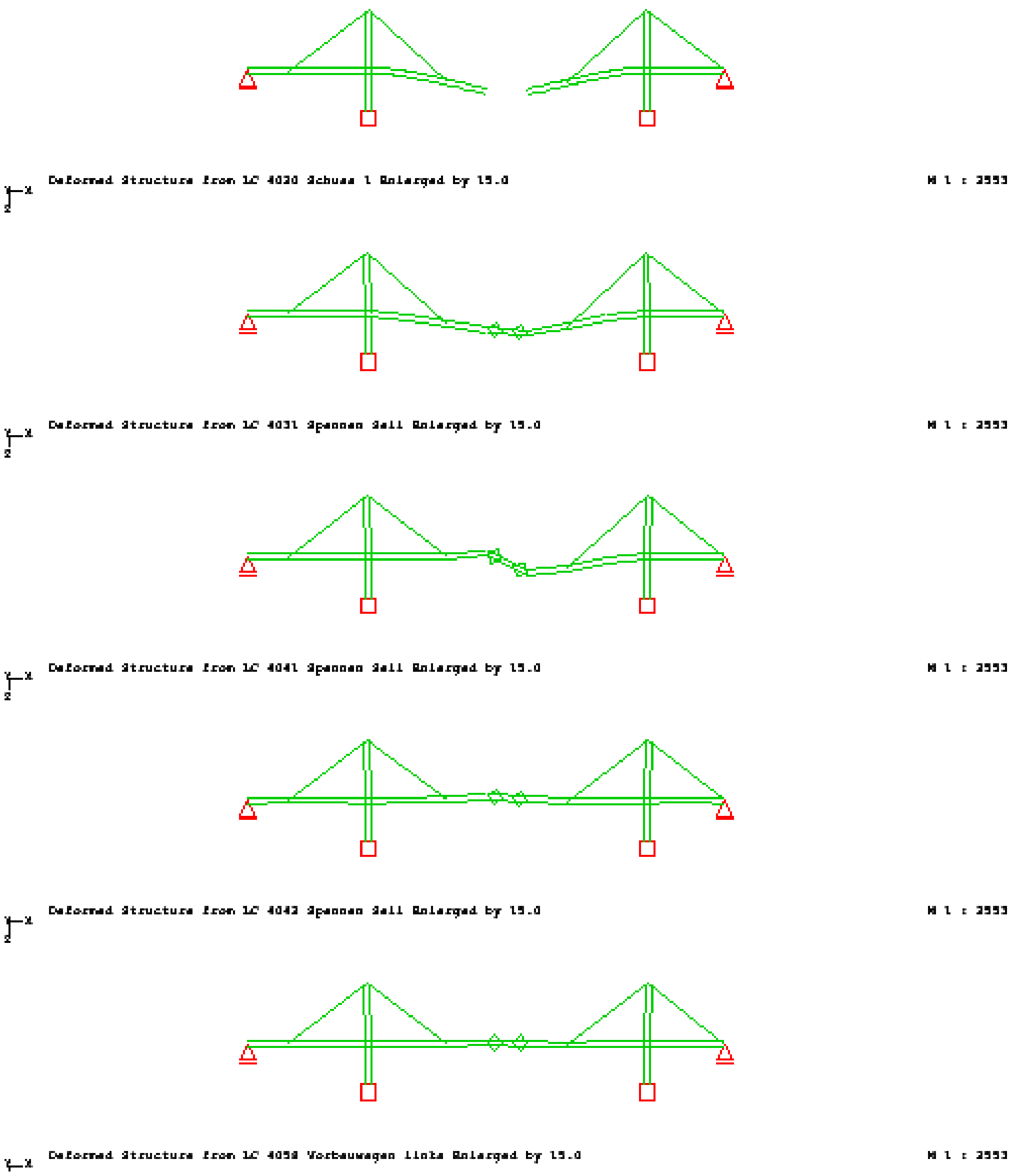

Figure 12: Construction sequence of csm23_cable_stayed_opti_displacements.dat

The complete input including additional comments can be found as *csm23_cable_stay_opti_displacements.dat* in the folder CSM.DAT of the SOFiSTiK Installation directory.

To demonstrate the nonlinear capabilty of the CSM Equation system, the tuning of a hogging moment in a two span beam with the help of a hydraulic jack shall be demonstrated. The hogging moment occurs due to force redistributions caused by creep after the connection of two single span precast elements with the in-situ slab only, and is therefore physically nonlinear. The complete input can be found as *csm24_equation_iteration.dat.*

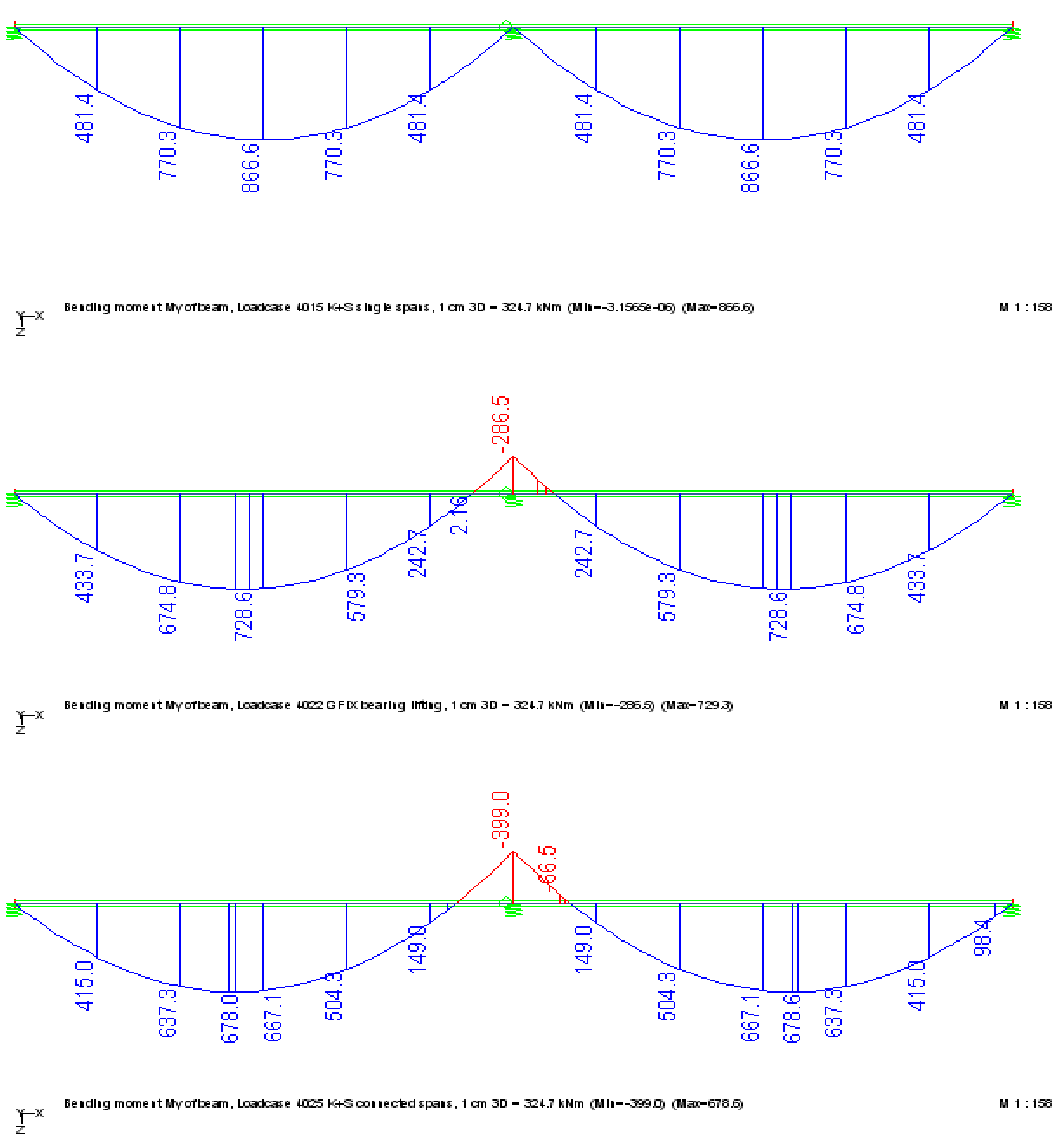

Figure 13: Bending moments of a precast girder system; Hogging moment limited to 400kNm due to CSR with the CSM Equation system

4 SMUULI EXTRADOSED BRIDGE

4.1 Introduction and Background

Estonia has experienced an amazing economical development from 1990 on. Two of the main projects have been the development of the Tallinn harbour in Muuga and the construction of the Tallinn ring road. The construction engineering community is quick in applying trends and new systems to their projects and it was just a question of time until the first cable stayed bridge got realized.

One of the local contractor from Tallinn is Merko. Merko was the first to use external pre-stressing on the Muuga bridge and also the first to install pre-stressed plates for buildings in Tallinn. An extradosed bridge is a new challenge for all involved parties in Estonia and the designer was asked to do an as simple as possible design. 3Bau from Switzerland developed the general concept for Merko. Once the solution proposed was awarded by the local authority, ABES from Austria was invited to join the design team. The joint venture started in late October 2005.

4.2 The project

The Smuuli bridge with a span arrangement of 42.0m + 85.0m + 42.0m as the first extradosed bridge in the Baltic countries is currently under construction. 3 approach spans at both sides of 40.0m each lead to the main structure providing a link of the city of Tallinn with the Muuga harbour. The Smuuli bridge passes over the local railway line which determines the construction method since free passage at any time must be provided for the trains.

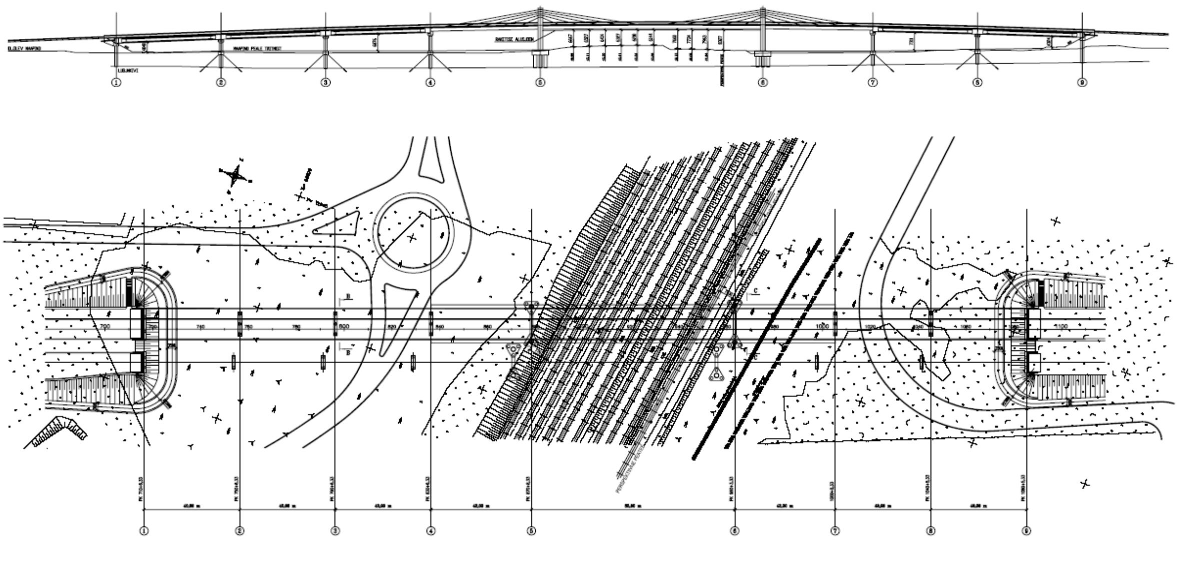

Figure 14: Plan and elevation view of the project

The free cantilever method was chosen and a slender girder was wanted. This led to the idea to hold the tip of the girder with cables transferring the forces over a pylon to the cable-anchorages in the side spans. An important detail requiring specific attention in the modelling and analysis part are the rigid connections of the pylon to the foundation and between the pylon and the main girder. The moment transferred between pylon and girder as well as between pylon and foundation were limited, based on the capacity of these connections. During the preliminary design on the finale state bridge it was found that the moment limit for the pylon-foundation connection required a modification of the general concept.

"As simple as possible" structure - requirement for the construction of the bridge, not necessarily for the analysis

4.3 The general bridge concept

The wish of having an "as simple as possible" structure was a requirement for the actual construction of the bridge only and not necessarily for the analysis and design part. The cross-sections for the main span had to be a Tee-beam shape since the specific formwork was available. The cantilevering of the main span was done in 5 steps. For each step an individual construction stage was considered and the whole segment of this stage was cast in one go. Figure 15 shows the structural model with the stages of the main span.

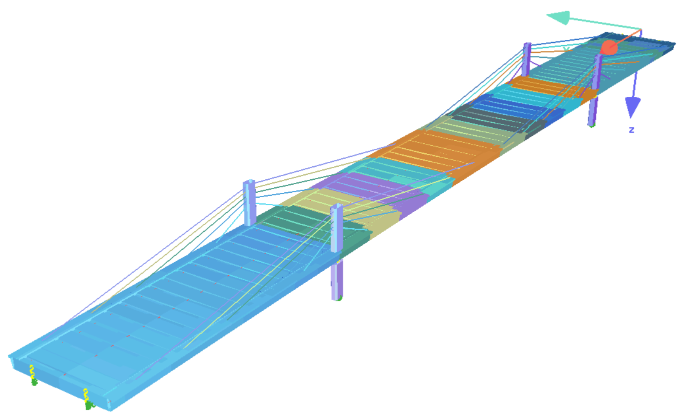

Figure 15: Structural model of the main bridge

For the approach spans many different concepts were evaluated. The most economical solution of casting the side spans on site was not chosen in order to allow Merko to try a new technology. Pre-cast pre-tensioned beams were chosen, first creating a series of simple supported beams. The casting of the roadway slab then created a continuous girder over 3 spans. The approach spans are separated from the main extradosed part by expansion joints.

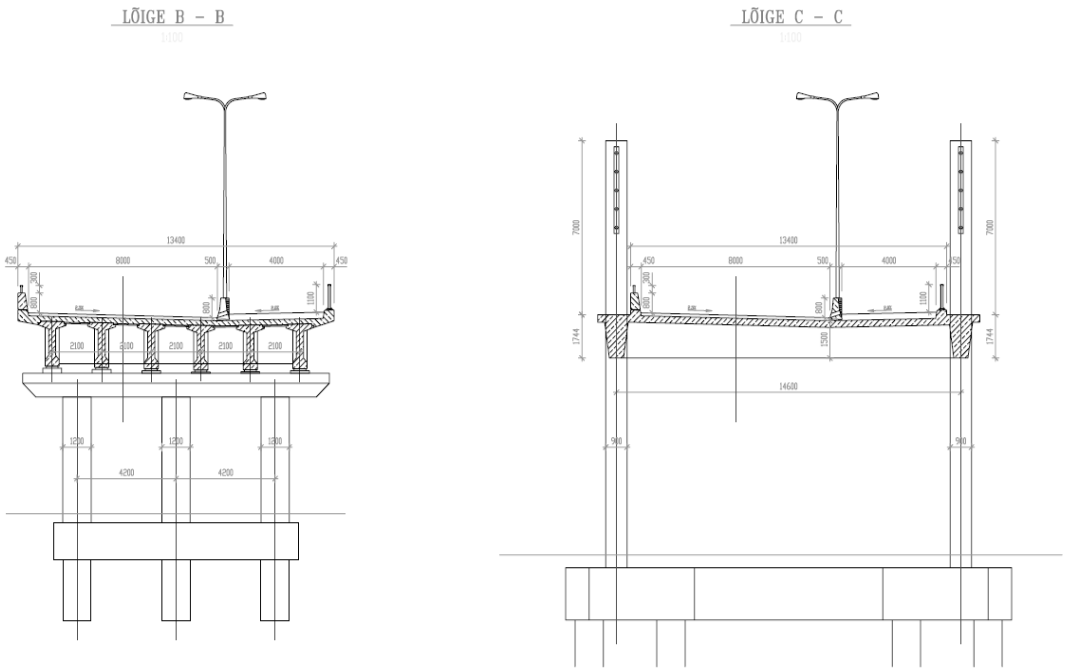

Figure 16: Cross-sections of approach and main span

4.4 The erection sequence

In November 2005 the piles were drilled on site, the foundations were completed just before Christmas 2005. The foundations design for the main span was submitted by end of November as well and were already based on a structural analysis containing a rough construction sequence. The piers for the approach viaducts were erected parallel to the main span pylon foundations.

The precast pre-tensioned beams were into position at the end of January 2005 and the erection of the pylons was supposed to be started in March.

During the months February and March the design of the main span was carried out. As already mentioned the calculation brought up a few issues that required modification of the basic concept.

One issue was the maximum moment capacity of the pylon-foundation connection. The basic erection concept was to build the side spans and to segmentally cantilever the main spans from both sides.

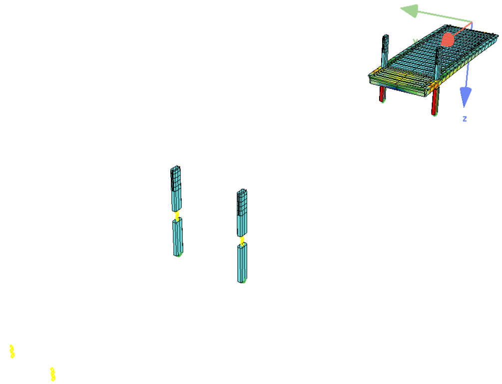

Figure 17.1: stage 1

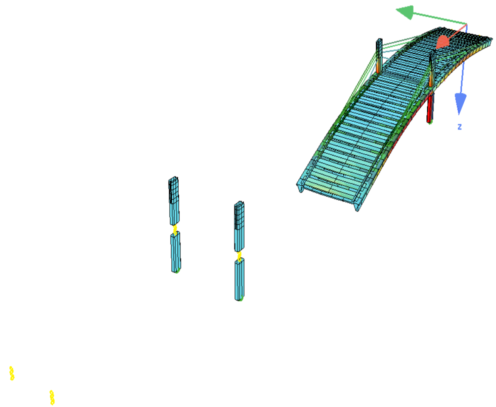

Figure 17.2: stage 5

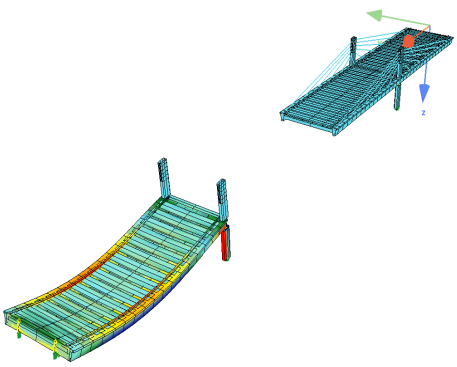

Figure 17.3: stage 6

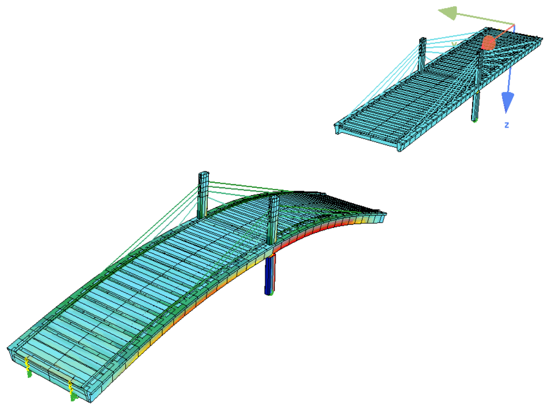

Figure 17.4: stage 9

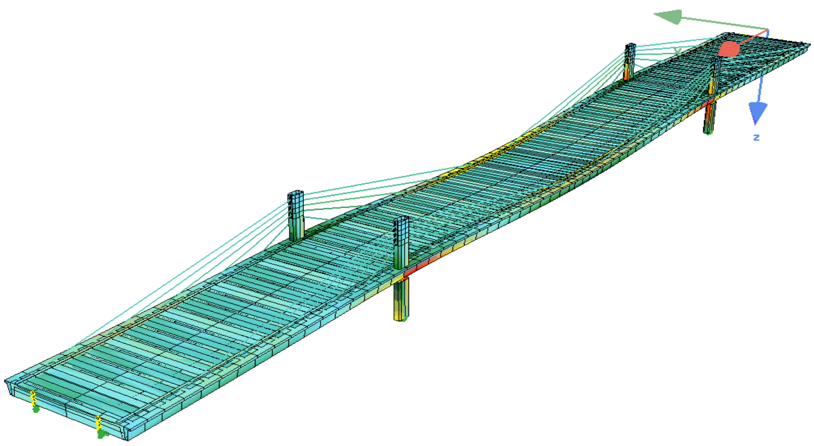

Figure 17.5: stage 12

4.5 The cable stressing sequence

Using the cables as adjustment force either the deflection and moments in the main girder or the moment in the pylon could be controlled. Considering both limitations with jacking each cable only once was not possible. Introducing each cable force as one available variable in the system and in the forward calculation in combination with the introduction of an estimated pre-camber of the main girder the resulting moment in the foundations was about 20% above the moment limit considering the permanent part of the loads only.

Two options were evaluated to overcome this problem: One idea was to install a hinge at the pylon-foundation connection during the main girder erection and to create the rigid connection only for the finalized situation, the other idea was to install one additional cable for the 3rd, 4th and 5th construction stage. This temporary stay cable was not anchored in the back span, but in the ground near the abutment. The contractors choice was the temporary cable, as a manipulation of the pylon footing was not wanted.

4.6 The cable and tendon layout

The longitudinal pre-stressing is located in the two edge beams. Additional longitudinal tendons are installed in middle of the roadway slab. The cross-beams being located at each cable anchorage point had transversal pre-stressing. This transverse post-tensioned girders also carry the thin roadway slab.

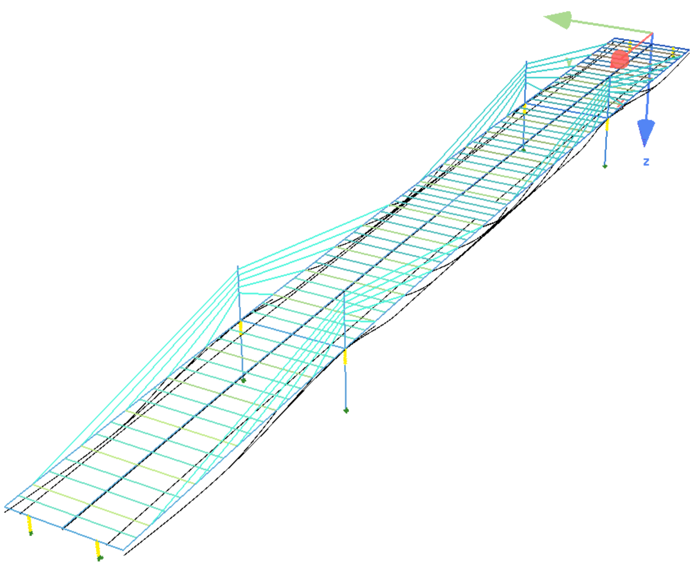

Figure 18: Pre-stressing layout in main girders

The details of the cable deviation at the pylon had to be as simple as possible. The anchorages of the stay cables to the main girders was a located at the bottom of the girder and represented a build-in connection. The cable are stressed at the edge of the cantilever in the mid span.

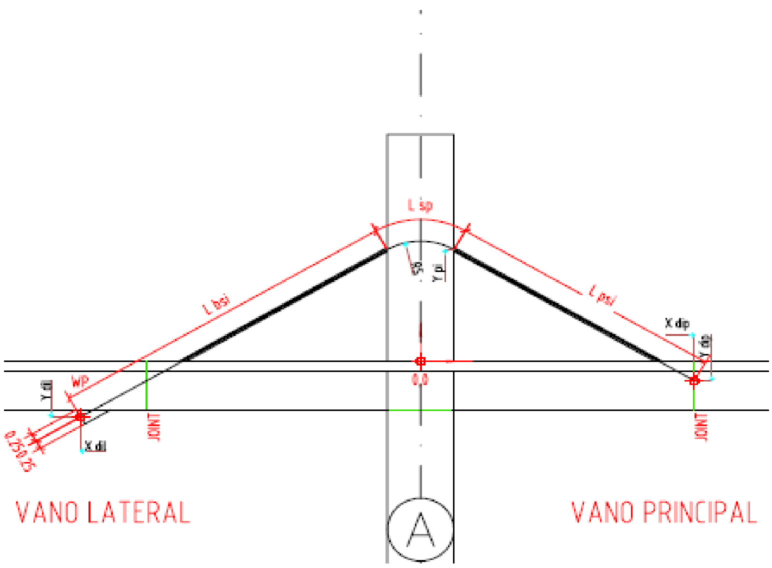

Figure 19: AutoCAD detail of cable anchorages

4.7 The structural model

A set of AutoCAD files was available at the beginning of the structural analysis showing the structural system and the cross-sections. The modelling was started in October/November 2005 and was fully done in SOFIPLUS. The system was defined as a beam structure, the roadway slab as a grillage composed by transversal and one addition longitudinal girder in the middle between the two edge beams. Not only was the system defined in SOFIPLUS, but also all loads including traffic and other additional loads.

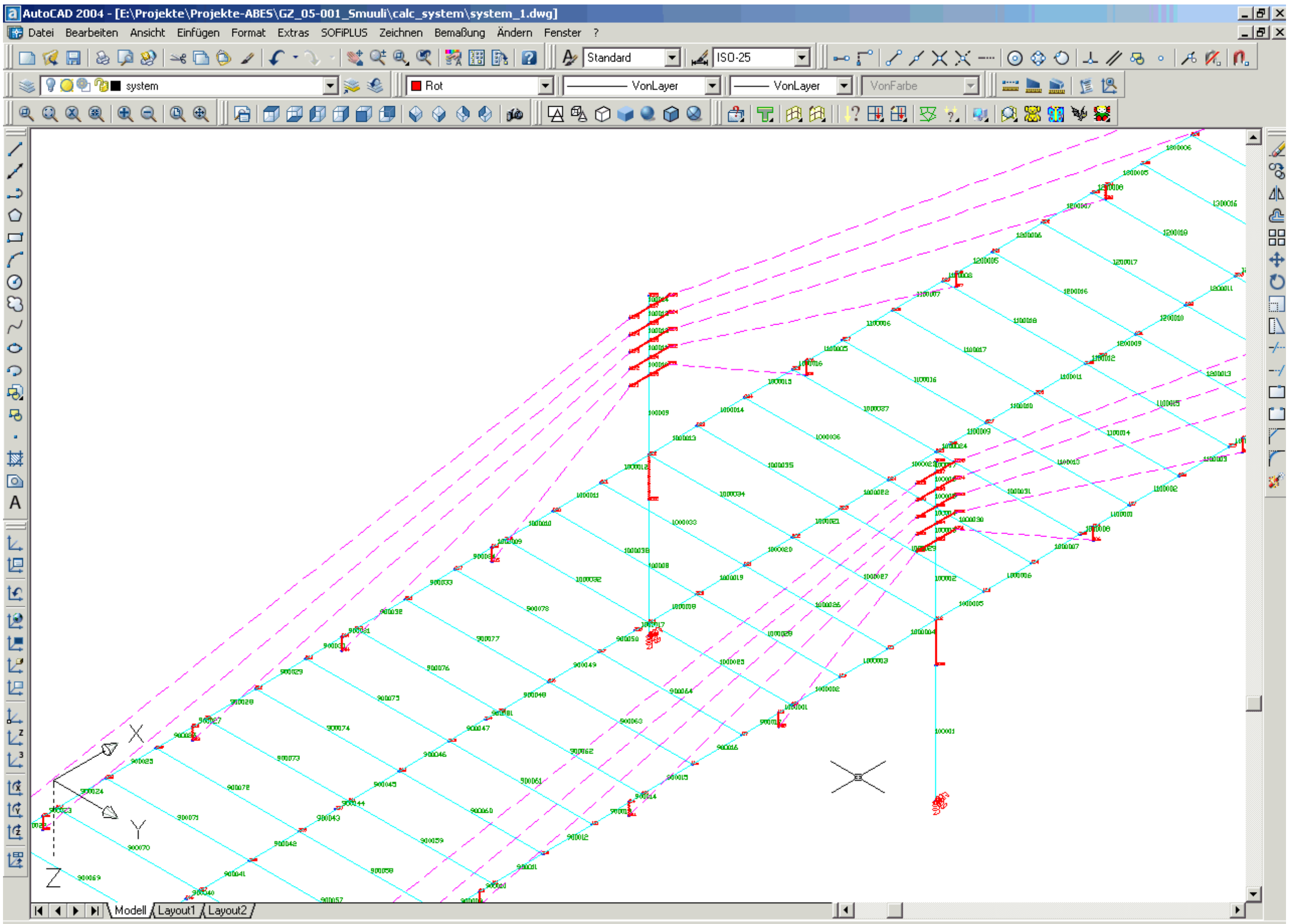

Figure 20: Structural model in SOFiPLUS (element and node numbers)

As part of the structural system only the pre-stressing in the edge beams, the slab and in the transversal beams has been done within CADINP.

CSM allowed accurate modelling of the erection sequence considering all time dependent effects

The SOFiSTiK construction stage manager CSM allowed an accurate modelling of the erection sequence considering all the time dependent effects. An important factor was the eccentricity introduced by the cable anchorages at the bottom of the main girder. In combination with the high normal forces in the cables of about 4200 kN a moment almost as big as the actual main girder bending moment due to permanent load resulted.

4.8 The superstructure design

During January and February 2006 the construction work was stopped due to difficult climatic conditions. Before starting the construction of the pylon in March 2006 the detailed design had to be completed. In order to fulfil the EC3 design requirements for both the SLS and ULS checks a two-step stressing sequence of the cable stays was developed using the new SOFiSTiK CSM Equation system. The design condition to be achieved was the maximum moment capacity of the main girder. This condition was controlled by stressing the permanent cables a first time when installing each cable and by jacking the cables a second time before installing the pavement and other permanent load.

The stressing of the temporary stay being tied back to the abutment was used to control the pylon moment during the erection sequence. The impact of each stay cable on the structure is not the same when looking at the situation for the final structure and the individual construction stages. The structural systems are different and the effect introduced by the cables is different, too. Each cable representing one variable within the system of equations allows the adjustment of one specific component, but effects all other structural parts as well. The full history of construction must be available within the complete system of equation. In order to achieve a certain wanted final condition the necessary initial stressing force on the cable results from the SOFiSTiK CSM Equation system considering all intermediate changes during the erection sequence.

For the first run all cables were stressed with a “unit“ force of “100.0 kN“. Applying the wanted condition (moment shape in main girder) the factors for each cable result. The following overview shows the change of the force in the cable being installed in the third construction stage:

Cable force	***Action on the structure***
1058.3 kN	Initial force after installation
958.5 kN	Pre-stressing in the main girder
1032.0 kN	Creep & Shrinkage (14 days) until next stage
2522,0 kN	Self weight of next segment
.... next stages	.... next stages
3868.0 kN	Application of additional dead load after closure
4572.0 kN	2^{nd} stressing of cable, open for traffic
4188.0 kN	Creep & Shrinkage until time infinity

As each cable to be installed in the Smuuli bridge the cable is installed with its stress free length. Due to the structural configuration and considering all loads applied on the structure up to this time an initial force of 1058.3 kN is in the cable. The cable force at the time of opening the bridge for traffic will be 4572 kN.

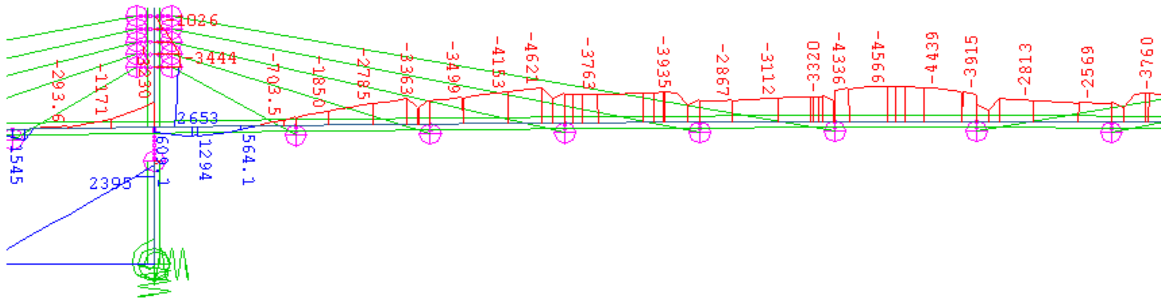

Figure 21: Moment shape in girder before additional load application

The figure 21 (above) shows the selected condition (My of the main girder) to be achieved with the stressing strategy. Each stage had to be checked whether for stresses. The figure 22 below shows the stresses in the total stage 9 where the left pylon cantilever is completed (and creeping) and the third cable for the right pylon cantilever is being installed.

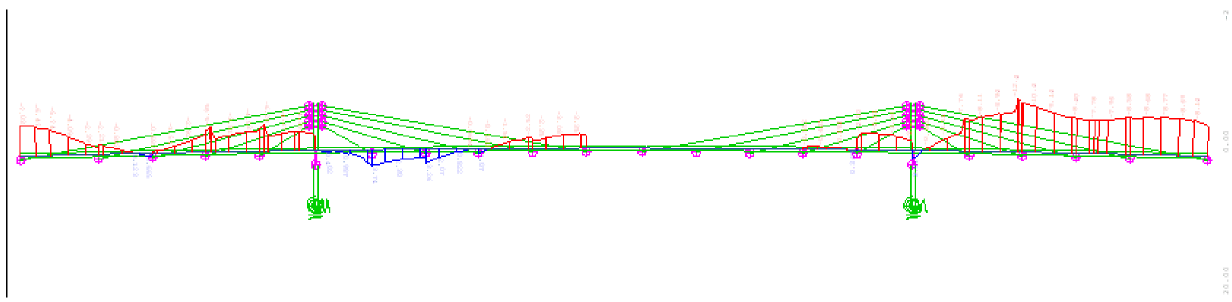

Figure 22: Stresses in main girder at Stage 9

4.9 The current situation

Currently the traveller and the formwork for the first main girder segment are being installed. The midspan closure is supposed to happen in June and the structure will be opened for traffic in September/October 2006.

Structure will be opened for traffic in September/October 2006

4.10 Special feature and future applications

Cable stayed and extradosed bridges require careful treatment of the construction stages. In many cases it is necessary to consider both, the often high normal forces introduced in the girder and the vertical deflections of the girder in the analysis process. SOFiSTiK allows finding the appropriate stressing strategy by using both the forward and the backward calculation. The only restriction is that for the backward calculation creep & shrinkage is considered using the user defined negative creep coefficients. An important detail and an outstanding feature of SOFiSTiK is the possibility of having several equation systems within one construction sequence. This allows to adjust the calculation according to a new situation on site. In many cases the construction work does not follow the defined pre-camber. There are many reasons for that such as difference between model and site regarding the time table, differences of concrete quality and others.

In case a difference between the calculated values and the measured values on site is detected the calculation has to be adjusted and as a first step the situation on site needs to be reproduced. In order to do this a geometry correction loading case might be introduced in the CSM part. This loading case should correct the geometry of the system, but should not create any stresses or forces. Once the model geometry matches with the site situation the construction sequence is repeated. New system conditions are set up, less cables(variables) remain for achieving these conditions. The CSM Equation system runs the construction stages, but does not restart from the actual beginning, but at the time when the geometry adjustment has been done.

Structural parts optimized in shape and design resulted in a very economical construction

4.11 Conclusions

The CSM Equation system is one of the recent developments within the SOFiSTiK software package. It makes SOFiSTiK an even more versatile tool for bridge engineering and gives the engineering the possibility to control the structural behaviour for both the final situation and the construction stages. The Smuuli bridge has been the first application of the new CSM Equation system on a real bridge structure.

For the contractor the advantage of having several options and modifications available within only a few working days was very important. The fact that all structural parts have been optimized in shape and design resulted in a very economical construction.

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