Erection Control Analysis – Meeting the Demands of New Construction Techniques

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Summary

New bridge construction techniques such as the pre-cast segmental construction method yield special requirements for the design and proof checking process. In the case of stage-wise erection, an exact anticipate calculation of the bridge deformations arising throughout the construction schedule – and therefore the definition of the required pre-camber values and fabrication shapes – was for long time an almost insoluble problem.

An appropriate tool allowing for getting the ability to determine the effects of constraining the structure into a certain pre-defined position at any stage of construction has recently been provided. The respective erection control facility accurately controls the position and the forces in the segments in stage-wise built structures. The presented erection control tool also supports the definition of required compensation measures due to deviations from the scheduled position.

Keywords: Erection Control, geometry control, pre-camber, pre-cast segmental construction

1. Stress-less Geometry – Camber

A common requirement in bridge engineering is that the final bridge shape (after deformations due to permanent loads have occurred) should comply with the theoretical design shape. Therefore, in order to compensate the deformations, the main girders of bridge structures are usually “pre-cambered” during construction. In some cases this deformation compensation process is also applied to other structural parts, such as for instance the pylons of large cable-stayed bridges.

Whenever geometrically linear structural behavior can be assumed, the required camber values – commonly denoted camber-line – can be directly derived from the deflections calculated on the design structural system. An iterative procedure is required if the structural behavior is non-linear.

A new comprehensive approach, which can be used in both linear and non-linear analyses, has therefore been developed. This approach was first presented in [1] and is based on defining the required prefabrication shape as initial strain loading applied on the structural system in addition to the actual external loading. This initial strain loading is modeled with special load types describing element deformations as differential displacements or rotations of the element ends with respect to the connected structural node.

2. Erection and Geometry Control - Principles

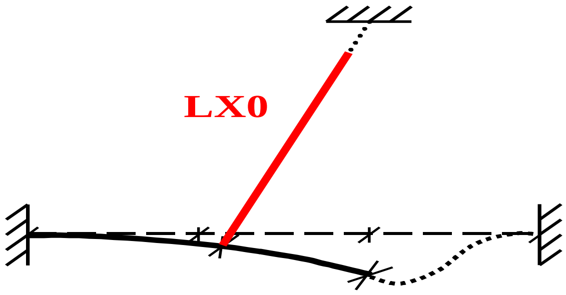
The erection geometry can only be seriously controlled using a precise structural analysis that considers all the structural stages occurring during the construction of the bridge as well as the effects from the pre-fabricated shapes (where applicable) of the elements.

The basic principle of classic structural analyses is that elements are connected to the common nodes, representing the degrees of freedoms in terms of displacements and rotations. Difficulties arise if the “face to face” connection is somehow modified in the construction process, or if the segment geometry is deviating from the design state.

Standard structural analysis codes can obviously not be used anymore after inserting displacement constraints at element faces. Element stiffness properties, including both linear and non-linear geometric terms, have to be transformed accordingly [3], and the local coordinate system of structural elements (defining local forces) is changed.

$$\left\{\delta_{Elem}^{I}\right\} = \left\{\delta_{Elem}^{I-1}\right\} + \left\{\delta_{Node}^{I-1} - \delta_{Elem}^{I-1}\right\} + \left\{\delta_{Elem}^{Kink\_Correction}\right\} \quad (1)$$

One of the most important application fields of the new method is the design process of cable-stayed bridges with optimizing the stay cable tensioning process, as the actual cable forces very much depend on the deformation behavior of the structure during construction. The "real" (stress free) fabrication shape of segments and cables has to be applied to the structure to get sufficiently accurate results. The fabrication shape of cables is purely the stress free length of the cable as shown in Figure 1.



Six input values are needed for defining the stress free fabrication shape of a beam segment as presented in Figure 6. With activating the option “Erection Control”, appropriate changing the structural system is done automatically by the software.

The application of stress free fabrication shapes changes the stiffness matrix and adds additional loading terms. Structural assembling can easily be done using the option "Automatic Kink Correction". This option constrains each reactivated element to the displaced active structure.

3. Pre-cast Segmental – Segment Geometry

Producing bridge segments under constant and controlled environmental conditions in a factory increases the overall quality due to more possibilities for influencing the casting process. Therefore, in the case of pre-cast segmental erection it is essentially important to determine very accurate fabrication shapes because the prefabricated segments must fit together when they are assembled on site and later correction measures on already prefabricated segments are difficult to be performed.

4. Construction Engineering – Compensation Measures

Main application field of the erection control functionality is in construction engineering. When different parties using different analysis programs perform design and construction engineering as it is mostly always the case, required pre-camber values are given to the construction engineer in form of Excel tables or construction drawings. The construction engineer has to make sure, that those specifications are meaningful and fit into the intended design shape.

5. Application example – Stonecutters Bridge

The Stonecutters Bridge is a high level cable-stayed bridge which spans the Rambler Channel in Hong Kong, connecting Nam Wan Kok, Tsing Yi Island and Stonecutters Island. With a main span of 1018 m it will have the second longest cable-stayed span in the world after Sutong Bridge has been completed one year later. The RM has also been used for detailed pre-camber analyses for defining the exact shape of the individual segments and is now regularly used in the construction phase for checking any irregularities occurring during construction.

6. References

[1] JANJIC D, BOKAN H., Erection Control, TDV’s unique tool solution for bridge design and construction, IABSE Conference, Budapest 2006

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[3] JANJIC D., PIRCHER M., PIRCHER H., BRIDGE R.Q. “Towards a Holistic Approach to Bridge Design”, Proceedings: IABSE-Symposium 2002, Melbourne, pp. 236-237

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Summary

New bridge construction techniques such as the pre-cast segmental construction method yield special requirements for the design and proof checking process. In the case of stage-wise erection, an exact anticipate calculation of the bridge deformations arising throughout the construction schedule – and therefore the definition of the required pre-camber values and fabrication shapes – was for long time an almost insoluble problem.

An appropriate tool allowing for getting the ability to determine the effects of constraining the structure into a certain pre-defined position at any stage of construction has recently been provided. The respective erection control facility accurately controls the position and the forces in the segments in stage-wise built structures. The presented erection control tool also supports the definition of required compensation measures due to deviations from the scheduled position.

Keywords: Erection Control, geometry control, pre-camber, pre-cast segmental construction

7. Introduction

Whereas bearing capacity and safety issues formerly often were the sole design criteria, geometry constraints become more and more important, on the one hand for aesthetic reasons and achieving the required serviceability demands, and on the other hand for avoiding unacceptable constraints when fitting the segments into the boundaries.

Special attention must in this context be drawn to pre-cast segmental erection techniques, where it is essential that the individual segments have an appropriate fabrication shape for getting the intended design shape of the bridge after assembly. This requires a very accurate deformation analysis early in the design phase with accurately taking into account further governing parameters in addition to the general structural stiffness. These parameters are the construction sequence and creep and shrinkage behavior, and any geometrically non-linear behavior.

The presented tool for comprehensive camber control is part of the RM software suite of TDV Austria, a solution center of Bentley Systems Inc. The basic idea is to apply the stress-free fabrication shape as a loading to the currently active structure. This loading will generally produce forces, stresses and deformations in the structure. This approach also allows for simulating in the same manner any required compensation measures in case of deviations arising during erection.

8. Stress-less Geometry – Camber

A common requirement in bridge engineering is that the final bridge shape (after deformations due to permanent loads have occurred) should comply with the theoretical design shape. Therefore, in order to compensate the deformations, the main girders of bridge structures are usually "pre-cambered" during construction. In some cases this deformation compensation process is also applied to other structural parts, such as for instance the pylons of large cable-stayed bridges.

Whenever geometrically linear structural behavior can be assumed, the required camber values – commonly denoted camber-line – can be directly derived from the deflections calculated on the design structural system. Camber values are just the negative values of the deflections to be compensated (equation 1). This also applies to stage-wise erect structures.

$$v_m^{camber} = (-1) \cdot \left(\sum_{i=1}^{n} v_i - \sum_{k=1}^{m-1} v_k \right) \quad (1)$$

Figures 1 and 2 show typical deflection and camber lines of a 3 span bridge built in three stages and additional dead load applied after completion.

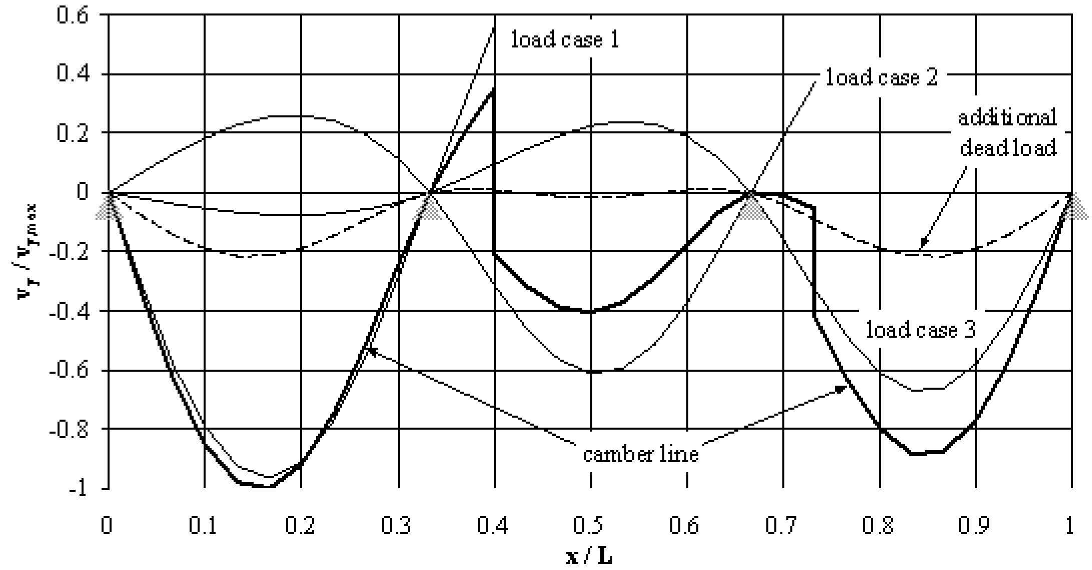

Fig. 1: Deflection lines for a three-span bridge

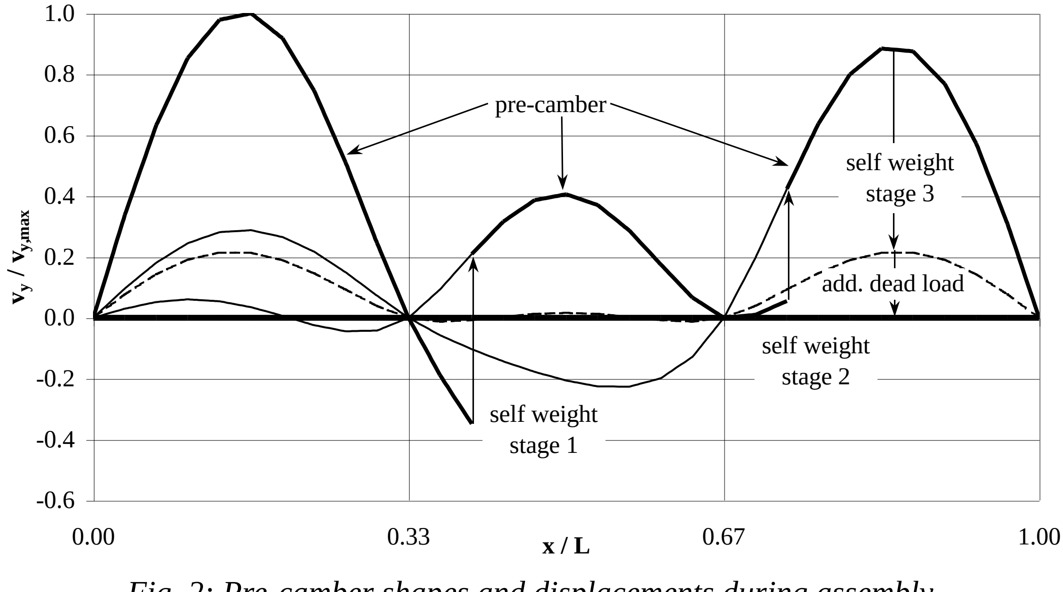

Fig. 2: Pre-camber shapes and displacements during assembly

An iterative procedure is required if the structural behavior is non-linear. A typical example of structural non-linearity with major influence is cable sagging effects typically occurring in stay cables of cable-stayed bridges.

A new comprehensive approach, which can be used in both linear and non-linear analyses, has therefore been developed. This approach was first presented in [1] and is based on defining the required prefabrication shape as initial strain loading applied on the structural system in addition to the actual external loading. This initial strain loading is modeled with special load types describing element deformations as differential displacements or rotations of the element ends with respect to the connected structural node.

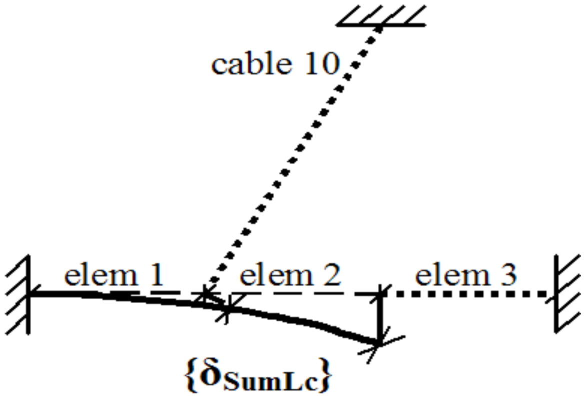

Fig. 3: Missing geometric info when assembling cable 10 and element 3

The software fits the structure into the target position and constrains the chosen force/stress distribution by calculating segment fabrication shapes, stress free lengths of the cables, section shop-forms and a pre-camber line and control-lines for each stage. As additional result, erection control gives information if any force action is necessary to assemble the new segments. This allows specifying any required equipment and construction problems already in the early design stage.

In the "erection control" mode the method simulates the erection procedure using segment fabrication shapes and stress free cable lengths given by design control lines. In the "erection-monitoring mode", the program function allows for continuously monitoring the erection procedure on site. Any deviation from the predicted control line can be input in the database [2], supporting the engineer to fix the future changes in the erection steps by using the inbuilt optimization tool.

When looking at the simple example in Figure 3 we can easily see that geometrical information is missing when the new element 3 and cable 10 are assembled to previously activated and loaded elements 1 and 2.

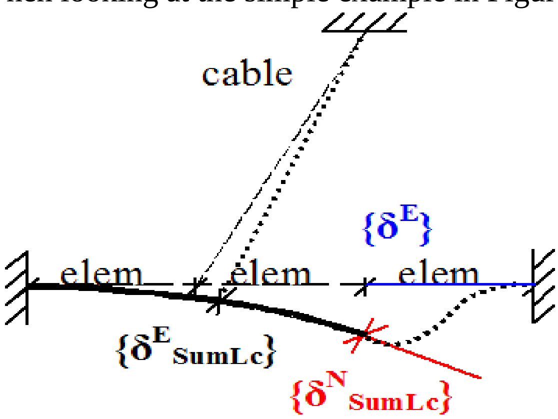

Fig. 4: Automatic kink correction in erection control mode

In the erection control mode the missing information is automatically updated. This is shown in Figure 4. This feature gives the possibility for determining the deformations and forces resulting from constraining the structure into a pre-defined position at any stage of construction.

By this procedure it is easily possible to rapidly assessing the effects of the erection geometry. Any modifications for the ensuing construction phases required for minimizing the final static and geometrical effects in the structure can be determined.

It is important to note that in the erection control mode linear as well as non-linear analyses are performed on the displaced structure, taking into account the exact geometrical lengths and rotations during the construction stages. The deformed structure is used as the starting point for the calculations, considering the exact position of each element in the space for the large deflection analysis where appropriate.

9. Erection and Geometry Control - Principles

9.1 The Problem

The erection geometry can only be seriously controlled using a precise structural analysis that considers all the structural stages occurring during the construction of the bridge as well as the effects from the pre-fabricated shapes (where applicable) of the elements.

Erection control and pre-camber work hand-in-hand – where the pre-camber shape is correctly calculated and specified and where the segments are manufactured and installed exactly in accordance with these specifications there is no need for any correction or modifications of forces and stresses. They will be exactly in accordance with the original design calculations. Use of the erection control facility will in this case indicate that no additional forces result from the erection procedure and that the pre-fabricated shape has exactly compensated the deformation due to loading.

9.2 Use of constraints

The basic principle of classic structural analyses is that elements are connected to the common nodes, representing the degrees of freedoms in terms of displacements and rotations. In reality, the structural segments are connected “face to face” and common nodes are only used to discretize the structural system. This concept works excellent if no changes occur in the “face to face” connection between the segments.

However, difficulties arise if the “face to face” connection is somehow modified in the construction process, or if the segment geometry is deviating from the design state. On the one hand, the unassembled segments possibly do not fit into the displaced geometry of the structure and on the other hand, the engineer has to find and optimize necessary future correction steps in the erection procedure in order to come close to the designed set of forces and displacements.

$$\left\{\delta_{Elem}^{I}\right\} = \left\{\delta_{Elem}^{I-1}\right\} + \left\{\delta_{Node}^{I-1} - \delta_{Elem}^{I-1}\right\} + \left\{\delta_{Elem}^{Kink\_Correction}\right\} \qquad (2)$$

Such changes of the structural geometry essentially require an extension of the computer model of the structure based on “common nodes” and the displacement relation must be updated as shown in equation 2. The first term represents the known element displacements of the previous step, the second term is the difference between the previous node and element displacements and the last term represents any user defined kink correction at element faces.

Standard structural analysis codes can obviously not be used anymore after inserting displacement constraints at element faces. Element stiffness properties, including both linear and non-linear geometric terms, have to be transformed accordingly [3], and the local coordinate system of structural elements (defining local forces) is changed.

9.3 Principles of the new approach

The new procedure is based on the concept of applying the “Fabrication Shape” (stress free element shape) as an initial strain loading. This loading is applied to the structure by calculating the corresponding load cases. In addition, the structural stiffness of the elements is updated accordingly. I.e. element stiffness matrices are calculated with taking into account these initial deformations. The solution is therefore an iterative process, even in a linear analysis.

In the 1st iteration step the "Erection Control" procedure uses the pre-deformed structure, i.e. the deflection line taken from a previous standard calculation. This enables both, a linear calculation or a full large displacement analysis to be performed. Structural assembling with the option "Automatic Kink Correction" is commonly used in this mode - where each newly activated element is fully constrained by a face-to-face connection with the currently active displaced structure.

In the special case, when the stress free shape exactly matches the theoretical deflection shape (i.e. is in full accordance with the pre-camber calculation), there will not arise additional constraint forces and deformations in the structure. However, in general, the application of the stress free fabrication shape of a segment to the currently active structure will produce additional forces, stresses and deformations. Since the stress free shape is applied as a loading, the user can easily control and optimize the forces in the structure by appropriately varying this load input.

9.4 Practical implementation in the software package

One of the most important application fields of the new method is the design process of cable-stayed bridges with optimizing the stay cable tensioning process, as the actual cable forces very much depend on the deformation behavior of the structure during construction. The "real" (stress free) fabrication shape of segments and cables has to be applied to the structure to get sufficiently accurate results. The fabrication shape of cables is purely the stress free length of the cable as shown in Figure 5.

The system length of a cable element is generally defined as the straight distance between the start and end-points before applying any transverse loading. Changing the stress-free length results in a length differing from the system length of the element.

The initial strain required for producing the elongation characterized by the difference between the specified length and the system length is automatically calculated. This strain is applied to the cable element in the same manner as a uniform temperature change. There is an alternative possibility to define the jacking force in the cables instead of the stress free element length.

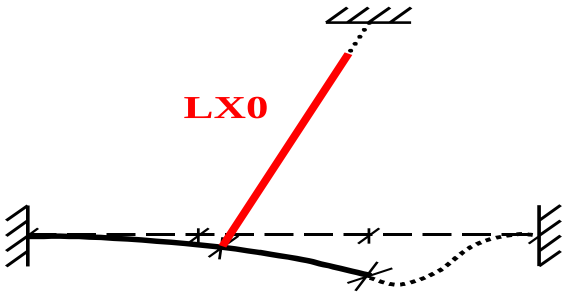

Fig. 5: Stress free length is constrained to the current distance between the nodes

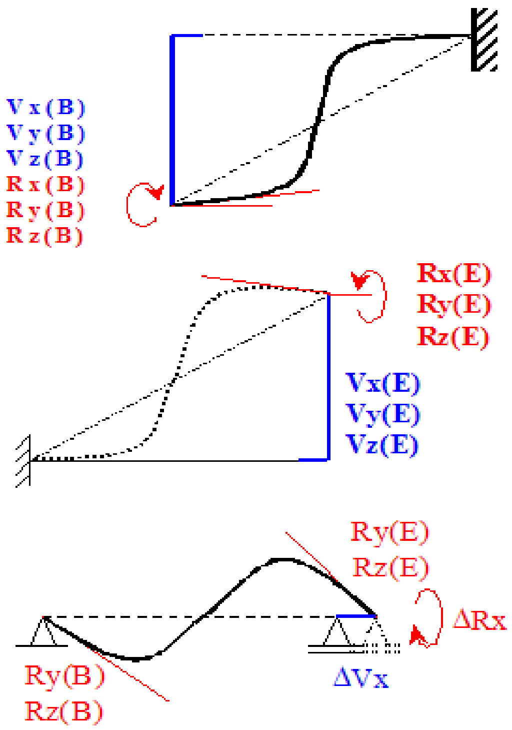

Fig. 6: Fabrication shape of a beam in terms of element end rotations

Six input values are needed for defining the stress free fabrication shape of a beam segment as presented in Figure 6. With activating the option “Erection Control”, appropriate changing the structural system is done automatically by the software.

The application of stress free fabrication shapes changes the stiffness matrix and adds additional loading terms. Structural assembling can easily be done using the option "Automatic Kink Correction". This option constrains each reactivated element to the displaced active structure.

The 1st iteration of a recalculation is started with the last known deflection line updated with a given fabrication shape and kink correction for the new stage. The displaced geometry of the already assembled structure together with the geometry of the segments to be assembled in the next step has to be geometrically updated.

If the stress free geometrical shape of the new assembled elements does not fit into the geometry of the ady assembled structure and the structural system is fully or partially constrained, this will result in additional forces and stresses. This is an indication that additional equipment, such as a hydraulic press, is necessary to assemble those elements on site.

Even the simple calculation with equilibrium at the non-deformed system, like linear and 2nd order theory analysis, is influenced by displacement constraints. In this case, the non-linear terms in stiffness matrix are not present, but the analysis will result in additional element displacements, forces and stresses if the deformation is constrained. For composite and steel structures, the method can detect frozen stresses in composite parts and give information about necessary equipment.

10. Pre-cast Segmental – Segment Geometry

Producing bridge segments under constant and controlled environmental conditions in a factory increases the overall quality due to more possibilities for influencing the casting process. Preparation of reinforcement and pouring is accelerated, because there is more room for workers and material. Since casting of segments can already be started when the piers are still under construction, this is another possible acceleration of the construction time.

However, the price to be paid for these advantages is that no immediate survey of the newly cast segments at the construction site is possible. Therefore, the casting process is susceptible to small errors and precise survey and control mechanisms must be established in order to be able to detect errors already in the casting yard.

These errors can be corrected when casting the next segment. Therefore, the ideal situation is that the forerun of segment casting is kept small in order to allow for compensation measures in the casting process if major deviations from the intended shape are detected during erection.

The applicability of such a survey-correct loop depends on the possibility to obtain the necessary corrections of the casting geometry in a straight and forward manner in the casting yard. To this end, the designer must provide the theoretical 3D casting geometry. This data is used at the casting yard to setup the mould. Then the surveyed as-cast geometry must be measured and compared with the theoretical one, and corrections must be calculated. These corrections must be immediately considered when casting the following segments. Finally the segments are delivered together with the corrected control lines to the construction site, where they are assembled and final survey is performed.

Therefore, in the case of pre-cast segmental erection it is essentially important to determine very accurate fabrication shapes because the prefabricated segments must fit together when they are assembled on site and later correction measures on already prefabricated segments are difficult to be performed. In general, the computation model with calculated pre-camber values shall be used during the casting process for governing the position of the different formwork components for the different segments.

Supplying information directly to the casting (manufacturing) yard considerably eases the construction process. A facility that provides all the necessary information of the relative 3-D positions of each critical point on the segment compared with the control points on the segment has been implemented and is currently being extensively tested in pilot projects in order to allow for official release later this year.

11. Construction Engineering – Compensation Measures

Main application field of the erection control functionality is in construction engineering. When different parties using different analysis programs perform design and construction engineering as it is mostly always the case, required pre-camber values are given to the construction engineer in form of Excel tables or construction drawings. The construction engineer has to make sure, that those specifications are meaningful and fit into the intended design shape.

The proposed procedure is to establish an appropriate mathematical model and to enter the prescribed camber values as actions on this structure. This is performed with using the same load types as automatically created with the schedule action LsCamb described above. Performing the analysis in the erection control mode will then show whether the intended geometry can be achieved with these setting without applying major additional constraints.

During the construction of the bridge it may be found that the actual position of the segment after installation does not correspond with the expected stage position as taken from the design calculation and being a postulated position assuming that the material behavior and length of time for construction up to that point are exactly in line with the assumptions made.

The program provides various procedures for compensating the error and applies the correction to subsequent construction stages – on a smear basis – spreading the error compensation to the pre-camber over all the subsequent construction stages up to the end of the construction. The procedure for making error compensation adjustments to unformed segments during the construction period includes:

- Manipulate the existing structure up to the end of the current stage using any available method to manipulate the structural model such as applying different E-Modulus or modifying the individual fabrication shapes such that the end of the structure coincides exactly with the position on site.
- Activate and apply a fabrication shape as a loading case to the next element to bring it into the correct position. (The macro allows the user to spread this adjustment over more than one element)

- Apply Erection Control

The ways available for modifying the camber on site during construction using a segment that has already been manufactured are limited:

- The next segment can be installed in a position stepped up or down from the previous segment (aesthetically and often practically unacceptable)
- The contractor can adjust the rotation angle between the old and the new segment. This adjustment is subject to certain practical and design restrictions depending on whether the segment is pre-cast or manufactured in steel.
- Application of eccentric jacking forces against the two segments on either side of the closure segment(s) can ensure correct relative alignment of the two cantilever halves.
- Modifying the stay cable stresses (where applicable)
- The resulting forces from making these modifications can again be easily checked by modifying the end rotations in the “Stress free fabrication shape” and using the Erection Control facility. The result of applying the “Individual segment shapes” as a load will be forces stresses and deformations in all the elements of the structural model.

12. Application example – Stonecutters Bridge

The Stonecutters Bridge is a high level cable-stayed bridge which spans the Rambler Channel in Hong Kong, connecting Nam Wan Kok, Tsing Yi Island and Stonecutters Island. With a main span of 1018 m it will have the second longest cable-stayed span in the world after Sutong Bridge has been completed one year later.

Fig. 7 Artists view of the Stonecutters Bridge in Hong Kong

Construction commenced on April 27th, 2004 and completion is scheduled for 2009. The concept is for a twin aerodynamic deck wit three lanes each, suspended from two 295 m high single pole towers. These towers have bases measuring 24 m x 18 m tapering to 7 m diameter at the top. The deck will allow a navigation clearance of 73.5 m over the full entrance to the container port.

Consultant Ove Arup is responsible for detailed design and construction supervision ober the whole Route 8 project, working with Cowi on the detailed design of the Stonecutters Bridge. Arup used TDV’s program RM including the wind dynamics module for the design analysis of the structure.

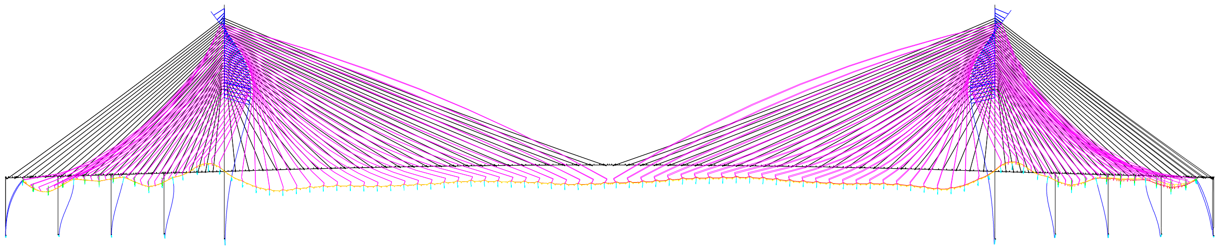

Fig. 8 Deflection shape of the Stonecutters Bridge to be compensated by pre-cambering

Once the mathematical model had been established, the program has also been used for detailed pre-camber analyses for defining the exact shape of the individual segments. The erection monitoring module is now regularly used in the construction phase for checking any irregularities occurring during construction. This direct link between design engineering and construction engineering is applied with great success, allowing for designing effective compensation measures as soon as deviations from the nominal condition are detected.

13. Conclusion

Pre-cambering of bridges is generally adopted for various reasons. The purpose of the camber is to compensate for the deflections of the structure under permanent loading and to bring the final position of the structure within acceptable limits for the structure's intended function.

Modern construction techniques for minimizing time and costs, such as free cantilevering or pre-cast segmental, require considering exact pre-camber shapes. Although determining the required pre-camber shape is a standard procedure for simple linear structures, it is very time consuming and error-prone when considering large structures with multiple construction stages and complicated loading history.

A methodology to cover the needs of the design office and the contractor within one computer program has been implemented and is presented in this paper. The technical background is outlined. The computer program automatically follows the bridge erection procedure and predicts the exact geometric position of structural segments taking into account the construction method, the construction sequence, the loading history, pre-stressing and post-tensioning, changes in support conditions and geometry and time-dependent effects.

In practice deviations from the theoretical deformation shape can always occur due to various reasons, e.g. deviant material quality, different loading on site or time delays causing additional creep. It is often necessary to add additional corrections for compensating these deviations, like kinks between segments. The presented method also allows for easily determining the required compensation measures and taking them into account in the analysis.

14. References

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