Erection Control, TDV's unique tool solution for bridge design and construction

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Summary

Up to now, the erection control procedure of bridges exhibiting non-linear behaviour as well as being built in stages, has presented almost insoluble problems.

The missing structural engineering tool was the one, which gives the building contractor and consultant the ability to determine the effects – in terms of both deformation and force – of constraining the structure into a certain pre-defined position in any stage of construction. This missing erection control tool has finally been produced.

The erection control facility described in this paper accurately controls the position and the forces in the segments in non-linear (as well as linear) structures built using the stage-by-stage construction method.

The paper describes how the program provides various procedures for compensating the errors found on site and how it is used to apply the correction to subsequent construction stages - on a smear basis - spreading the error compensation to the pre-camber over all subsequent construction stages up to the end of the construction.

Keywords: Erection control, geometry control, pre-camber, construction condition, kink correction

1. Introduction

The method described in this paper can be used for both, bridge design analysis and for simulation of bridge construction sequence on site. The user can perform forward calculation, backward calculation, erection control or erection monitoring using the same method implemented in the software solution, also taking into account long-term effects like creep, shrinkage and steel relaxation.

Fig. 1 *Visible sagging of long stay cables highly influence forces in the stay cable*

The major usage is forward simulation of bridge construction sequence on site, combined with long-term effects and existing non-linear effects like cable sagging as shown in Figure 1.

In classical design mode the engineer is usually choosing the target geometry and a force/stress distribution in the service state. The new software solution 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.

In the erection control mode the method simulates the erection procedure using segment fabrication shapes and the stress free cable lengths given by design control lines. As additional result, erection control gives information if any force action is necessary to assemble the new segments. This allows determining any necessary equipment and possible construction problems already in the early design stage.

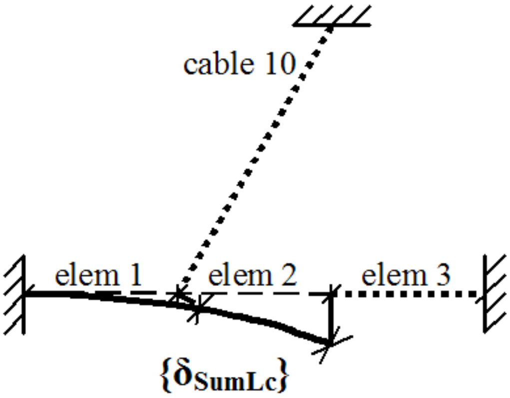

Fig. 2 *Missing geometric info while assembling cable 10 and element 3*

In the erection-monitoring mode, the new solution allows continuously monitoring the erection procedure on site. Any deviation from the predicted control line can be input in the software package and RM2006 [1] supports the engineer to fix the future changes in the erection steps by using the inbuilt optimisation tool.

It is important to note that both, linear and non-linear analyses are performed on the displaced structure in erection control mode, taking into account the exact geometrical lengths and rotations during the construction stages.

In the simple example in Figure 2 it is obvious that geometrical information is missing while assembling new element 3 and cable 10 to already assembled and loaded elements 1 and 2.

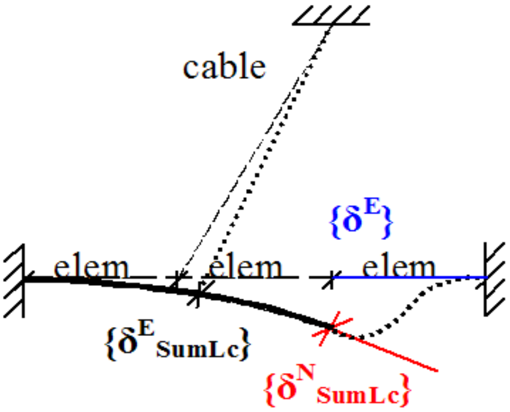

Fig. 3 *Automatic kink correction in erection control mode*

The missing geometric information is automatically updated in the erection control mode as shown in Figure 3. This feature, working with pre-cambering, gives the possibility of determining the effects, in terms of both, deformations and forces, constraining the structure into a pre-defined position at any stage of construction.

In this way the erection geometry and its effects can be carefully controlled, the effects of possible errors can be rapidly valuated and modifications for the following construction phases can be determined in order to minimize the final static and geometrical effects in the structure.

To this end, the deformed structure is used as the starting point for the calculations, taking in full account the position of each element in the space for the large deflection analysis where appropriate.

Using a novel solution based on displacement constraints [2], one generally applicable method has been found and implemented within a software package RM2006. This comprehensive solution simplifies design and erection control of the bridge, efficiently using the same procedure for all kinds of bridges from small concrete bridges to big stay cable bridges like Sutong Bridge in China, Stonecutter's bridge in Hong Kong and extra-large suspension bridges like Messina Bridge in Italy.

2. Erection and geometry control

2.1 The Real Problem

Significant displacements occur during the construction of bridges. They essentially depend on the erection sequence. In order to obtain the desired end-geometry of the bridge, these displacements are often compensated for with pre-camber and specific fabrication shapes of girder components.

The deformed structure is the start position for the calculation; therefore, full account of the current location in space is taken for the large deflection analysis. The whole procedure is repeated iteratively [3] until the predefined convergence criteria are achieved.

In the implemented method, the stress-free fabrication shape is applied as a loading, acting on the currently active structure. It will generally produce forces, stresses and deformations.

Since the fabrication shape is applied as a loading, the user can use this device to control and optimise the forces and displacements in the structure.

Structural assembly with the option to automatically correct the kink at the segment face can also be used to fully simulate certain construction conditions - each newly-active element is fully constrained with a face-to-face connection to the currently active structure in its displaced position.

It is also possible to fully control face-to-face connection by changing fabrication shape of new segments or to use kink correction on the connection face.

Fig. 4 *Segments waiting for errection*

Engineers may find, during the bridge construction, that the current position of the segment after installation does not correspond with the expected position in this stage.

The expected position is taken from the design calculation and is a postulated position, assuming that the material behaviour and length of time taken for construction up to that time are exactly in line with the assumptions made.

A precise structural analysis in construction stages is required to seriously control the erection geometry.

In the design process however, the optimisation of internal forces under permanent loads is the primary engineering task and the choice of erection situations are steps to reach it. The analysis is performed with a given starting geometry - usually the structure in its desired final geometry.

Fig. 5 *Typical constraction stage for stayed cable bridge*

Pre-camber is the geometry of the bridge required for assembly to reach the final geometry under given loading conditions.

Because the bridge structure is erected in segments, the pre-camber geometry is defined as the required coordinate offsets of the segment begin and end points.

The stress free segment shape for installation is the segment fabrication shape.

It is defined relative to the connection line between the current begin and end node position of the structural system.

This applies to the installation of cables as well as to the erection of beam segments. From the pre-camber geometry, the coordinates of cable start and end-points are extracted, whereas the fabrication shape of the cable is the fabrication-length of the cable, also known as the 'stress-free length'.

2.2 Usage of constraints

In classic static and dynamic FEM analysis, it is assumed that elements are connected to the common nodes. The common nodes consist of chosen degrees of freedoms (like displacements, strains, stresses or forces) and neighbour elements share all nodal degrees of freedoms included in the shared common nodes.

In reality, the structural segments are connected "face to face" and common nodes are only used to discretise the structural system. This concept works excellent if no changes occur in the "face to face" connection between the segments, free lengths between cable anchorage points and the segment geometry.

The difficulties arise immediately if "face to face" connection is manipulated during the construction or if the segment geometry or the total displacement of the structure is deviating from the design state.

On the one hand, the unassembled segments are not fitting into displaced geometry of the structure any more and on the other hand, the engineer has to find and optimise necessary future correction steps in the erection procedure in order to come close to the designed set of forces and displacements in time infinity.

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

Due to such changes in geometry the computer model of the structure based on "common nodes" is in general not accurate any more and should be updated as shown in equation 1. The first term represents the last known element displacement, the second term represents the difference between last known node and element displacement and the last term is user defined kink correction at element faces.

It is obvious that after inserting displacement constraint at element faces, the standard FEM code based on common node displacement can not be used any more. Element stiffness properties, including both linear and non-linear geometric terms, have to be updated [4], and the local coordinate system of structural elements (defining local forces) is changed.

The displaced geometry of the already assembled structure together with the geometry of the segments going to be assembled in the next erection step have to be geometrically updated.

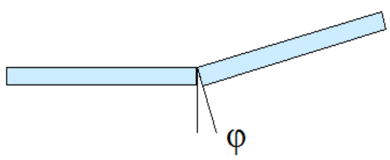

Fig. 6 *Kink correction between structural segment*

If the stress free geometrical shape of the new assembled elements does not fit into the geometry of already 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 and in 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.

2.3 The principles of the new TDV Erection control module

The main purpose of the TDV erection and geometry control module is to accurately control the position of the segments in a linear or non-linear bridge structure built with using the stage-by-stage construction method.

The whole procedure is repeated iteratively until the convergence criteria are achieved. The Fabrication Shape (stress free element shapes) is input as a load and is applied to the structure by calculation of the appropriate loading case.

The structural geometry of the segments and cables is defined by structural model and the individual shape of the segment elements and stress free lengths of the cables.

For the 1st iteration of the calculation, the "Erection Control" procedure uses the pre-deformed structure, i.e. the deflection line taken from a previous calculation.

This enables both, linear calculation or a real 3rd order theory analysis. 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.

Using the erection control facility, the stress free fabrication shape is applied as a load to the structure. In general, the application of the stress free fabrication shape of a segment to the currently active structure will produce forces, stresses and deformations. The special case where the stress free shape is in exact conformity with the position of the existing structural parts (i.e. all in accordance with the pre-camber calculation) will produce no forces stresses and deformations in the structure.

Since the stress free shape is applied as a loading, the user can, using this device, control and optimise the forces in the structure.

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.

Possible procedure for making error compensation adjustments to unformed segments during the construction period:

Manipulate the existing structure 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 corresponds (position and orientation-wise) 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 and go to the next step.

Procedure for making error compensation adjustments to already formed segments during the construction period:

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), etc.

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.

2.4 Implementation in the software package RM2006

For both, calculation with equilibrium at the non-deformed system (linear and 2nd order theory analysis) and calculation with equilibrium at the deformed system (theory of large displacement) there is the same calculation procedure.

The "real" (stress free) fabrication shape of segments and cables has to be applied to the structure.

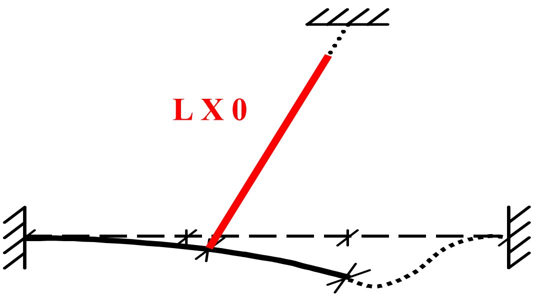

Fig. 7 *Stress free length of the cable is constrained in current length between anchorage at begin/end*

Fabrication Shape of cables is pure stress free length of the cable as shown in Figure 7.

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 length differing from the system length of the element.

The initial strain required for producing the elongation characterised by the difference between the specified length and the system length is automatically calculated.

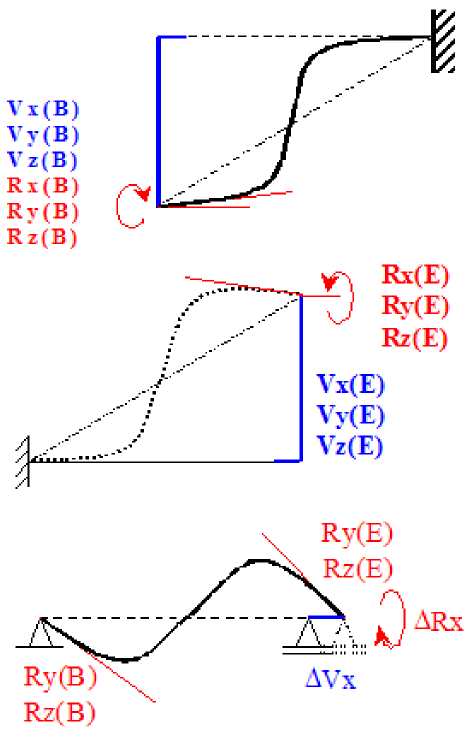

Fig. 8 *Fabrication shape of structural segments input as equivalent cantilever or simple span beam*

This strain is applied to 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.

For a beam segment, six input values are needed to define the stress free fabrication shape. Figure 8 shows the input as equivalent cantilever or simple beam.

The changing of the structural system is done automatically by the software by activating an option "Erection Control".

The application of stress free fabrication shapes changes the stiffness matrix and adds additional loading terms.

The 1st iteration of a recalculation is started with a last known deflection line updated with a given fabrication shape and kink correction for the new stage. This enables a true 3rd order theory analysis. In this mode, structural assembling can easily be done using the option "Automatic Kink Correction" by which each reactivated element is fully constraint to the displaced active structure.

3. Application example

The below shown application example for the presented method is the pre-camber and control line calculation for bridge 4C over Brunswick River.

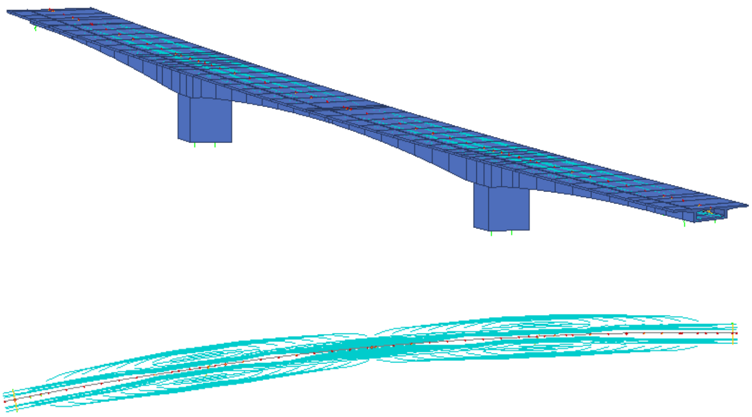

Fig. 9 *Brunswick bridge VSL(specialist), Abigroup (contractor), SMEC(consultant).*

The bridge is built using the balanced cantilever method. Segments are cast in-situ using the VSL modular form-traveller.

Pre-camber values are required to define the casting curve; control lines are required to validate the as-built conditions during erection.

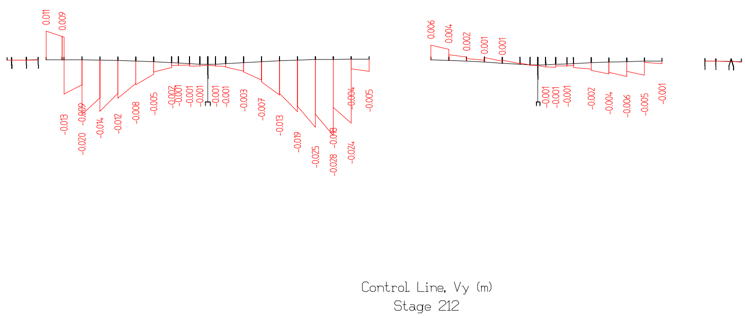

Fig. 10 *Fabrication shape of structural segments input as equivalent cantilever or simple span beam*

Bridge 4, part of the state highway 10, consists of 3 individual bridges (A, B and C) spanning over Brunswick River. The three bridges run parallel to each other, each a 3-span structure with an 84.5m long main span and 50m side spans.

Each bridge deck is a single box section with variable deck slab width. The piers are arranged with an angle of approximately 60° to the deck. The pier table is monolithically connected to the pier.

The four cantilevers of a bridge are built simultaneously. Temporary props are installed on the side span side next to the pier to provide additional stability for out-of-balance construction stages such as form-traveller launching or casting of a segment.

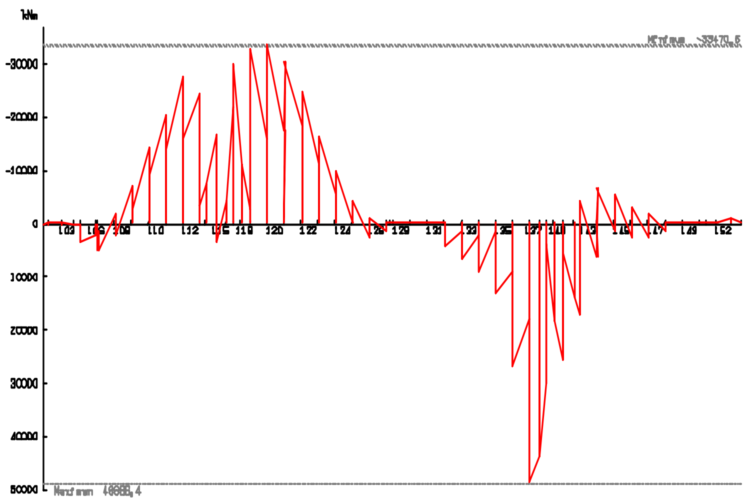

Fig. 11 *Intermediate results at stage 212*

The out-of-balance moment acts always towards the side span, since the props cannot take tension.

The load in the temporary props is monitored and adjusted in order to avoid loads other than the ones resulting from out-of-balance moments.

4. Conclusion

Bridges are in general designed with a specific pre-camber in order to compensate deformations occurring during the construction. The erection procedure is based on the bridge design and usually optimised by the contractor in order to minimise time and costs needed for performing the construction in accordance with available equipment and resources. During the erection of the bridge, it is necessary to compensate the deviation of the bridge geometry compared to the design geometry and to optimise future changes in the construction sequence in order to get the final geometry as well as design forces and stresses in the structure.

The derivation of the exact pre-camber shapes is a time consuming task for the design office, especially for 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 bridge design, constraints are based on forces and not on displacements. In the classical design, pre-cambering and fabrication shape is treated as additional future correction, which will fit the structure in the target final geometrical position. This fabrication shape is not considered in structural analysis. Therefore, there are usually different sets of results for the final state analysis and for the stage-by-stage (construction) analysis.

On the other hand, in bridge construction the main goal is to follow the construction procedure on site step by step. All segments are defined by their fabrication shapes, and the cables are defined by stress free lengths for each stressing sequence of the cable.

In order to compensate deviations from design line, produced by different material quality and different loading on site, it is necessary to add additional corrections, like kinks between segments, to reach the final design state.

5. References

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