Beyond the Limits of Erection Activities

Michel PETREQUIN
Engineering Mgr
Gec Alsthom
Grenoble, France

Michel Petrequin, born in 1960, obtained his degree in 1983 at the Arts et Metiers School of Eng. in Paris. He has worked with large French groups as an engineering mgr on important projects, gaining experience in design, manufacturing and erection of structural equipment. With Gec Alsthom, he was Eng. Mgr for the Storebaelt Project. At present he works as a private consultant.

Mario De MIRANDA
Consulting Eng.
DMA-Studio De Miranda
Milan, Italy

Mario de Miranda, born in 1954, obtained a degree in eng. in 1979 at the Politecnico di Milano. He is a partner of DMA, founded by professor Fabrizio de Miranda, and has worked on large projects on many aspects of design and analysis of bridges and in construction methods and equipment. Consultant for Gec Alsthom for erection of the Storebaelt Bridge.

Summary

The Storebaelt East Bridge has a total length of 6.8 km and includes a major suspension bridge with a 1,624 m. long central span.
While representing an exciting challenge for all the workers, technicians and engineers involved, its erection, which was recently completed, also required an approach which bordered upon the current limits in erection of large bridges using innovative solutions.
This paper illustrates some aspects and figures involved in erection of the bridge and discusses some of these limits and how they may be overcome.

1. Introduction

The Storebaelt Bridge Project appears in a book dated March 9, 1936. At that time, a bridge with a 400 m. long central span was planned. 62 years later, the bridge exists and is a 1,624 m. suspension bridge, the longest box girder suspension bridge in the world.
When its construction was started, no longer spans had ever been built and its erection called for going beyond the present limits.

The East Bridge is about 6.8 km long, running from Halsskov, on the Zealand side, to the small island of Sprogo, located at the centre of the Great Baelt channel and linked to Funen by the West Bridge, the concrete viaduct that completes the Storebaelt link.

The East Bridge includes the 2.7 km long suspension bridge and two approach viaducts with lengths of 2.54 km and 1.54 km respectively, each one formed by 193 m. spans, with continuous box girder superstructures. Details of the bridge are given in [1] to [6].

The erection of all the superstructure, including the intermediate phase of cable spinning, started in January, 1995, and was completed 34 months later, in December, 1997.

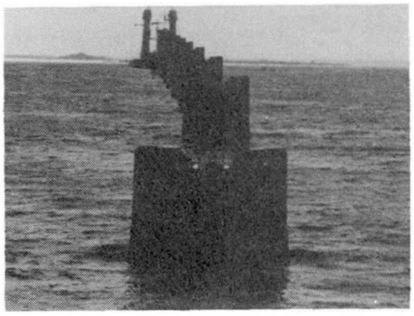


Fig. 1 - 2 - Before and after the erection work

The bridge was designed by a Joint Venture between COWIconsult, B. Hojlund Rasmussen and Ramboll & Hannemann (DK) for the final Client STOREBAELT A.S. [1].
STOREBAELT, split the East bridge contract between two main contractors: GBC (DK) for the civil works and COINFRA (I) for the steel structures [2], [3]. GEC ALSTHOM (F) obtained the contract for erection of the bridge from COINFRA. This included erection of the approach spans and of the suspended bridge that consisted in manufacturing the main cables and its hangers and deck erection. GEC ALSTHOM gained previous experience in building bridges with the erection of the Normandy Bridge (that was the longest cable-stayed bridge in the world) and therefore has skills in temporary works and welding activity. In order to face the challenge represented by erection of the Storebaelt Bridge, GEC ALSTHOM subcontracted work lots in order to obtain the complementary skills of other operators.
•SMIT MARITIM CONTRACTORS (NL) was in charge of transporting the girders by barge from Aalborg to the Halsskov site and of lifting the approach span sections and the two specific sections of the suspended deck at the anchor blocks using heavy crane barges.
•GIBSON (GB) was in charge of lifting the deck sections using the gantry lifting systems already used for the Tsing Ma bridge in Hong Kong.
•BM Contracting (DK) and GEC ALSTHOM Entreprise (F) were responsible for structural welding.
•COMAG (F), owing to its experience working in mountain conditions, was responsible for all activities connected to manufacturing of the main cables.
The company GEC ALSTHOM performed all engineering on erection methods, design and manufacturing of temporary equipment and chose DE MIRANDA Associati (I) as the structural engineering consultant, in order to have a good approach to the numerous technical problems involved.

2. Erecting the Storebaelt East Bridge

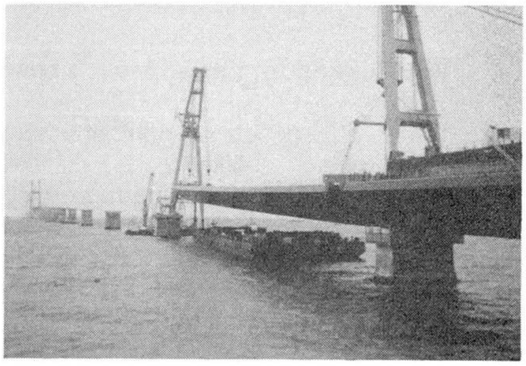
The approach spans

Girders were of the box section type, 6.7 m. deep, with two side slanting webs and a central vertical web. The structural weight of the standard 193 m long girders is about 2,400 t.
The continuous girder deck was built in the following basic phases [4]:
_Loading of full-length girders onto a barge and transportation from Aalborg to the site, 300 km by sea.
_Positioning and mooring of the barge and of an auxiliary floating crane, and lifting of the girder by means of a fixed crane installed on the previously erected girder and of the floating crane.
_Placement of the girder on temporary bearings: the rear end section remained suspended from the fixed crane aligned to the previous section, while the front section was placed on a 4.5 m. high bearing structure, in order to give the necessary angle between adjacent girders before welding.
_After section length cutting to fit with the pier axis distance, the section was finally matched by jacking and welded.
_Lowering of girder on the front support, thereby applying a negative bending moment to the section at the preceding pier which, when combined with the bending moments of all successive construction steps, provided the necessary final bending moment at the pier.
Instead of the usual progressive step-by-step lowering with jacks and shims, a more drastic system was chosen: the use of a floating crane to hold the girder end temporarily, lift it to free the support structure, slide it forward by means of cantilever guides and lower the girder onto supports.

The suspension bridge

The box girder had a flat trapezoidal shape with sharp edges, with a total width of 31.20 m. and a total depth of 4.34 m. Each standard girder section is 48 m. long and is formed of three 16 m. long welded segments.The structural weight of a standard section is about 530 t.
The girder is vertically supported over the entire length by hangers. No vertical supports are present at the pylon; only transversal restraints.
In order to optimise distribution of the bending moment, the designer provided moment adjustment at the pylon sections and near the anchor blocks, to be achieved by girder pre-stressing during erection.

After all cable work was completed, girder erection could take place, in the following basic phases:
_Installation of four special gantry cranes on the main cables, capable of running on the cables, to accurately position and lift the sections, with a lifting capacity of 600 t. each. Two cranes and four lifting points were provided for each segment. After the load out and the transport of two sections simultaneously, the barge is moored by anchoring for a section lifting.
_Picking up the section using two spreader beams and special anchoring devices, and its lifting from the barge up to the final elevation.
_Bringing the lifted section close to the adjacent one, and precise positioning to match them at deck level.
_Joining the sections by means of temporary connections.
_Installing the hanger sockets in their anchor blocks and then transferring the section load from the gantry crane to the final hangers.
_Welding of section when joints closed the rotational gap, which had remained open up to that stage.
_Applying pre-stressing moments, where required, by de-shimming some hanger sockets, thereby allowing the deck to shift along the hanger up to the final anchor position. The deck at these hanger locations was previously installed at an elevated position by means of proper shims.
All erection phases were analyzed by extensive progressive computer analysis able to define both the evolution of structure forces and the sections displacements in order to allow the correct matching of sections. This last task required a special effort mainly to compute the exact shimming heights when considering that bridge deflections were of the order of meters during the evolution of the erection phases while the precision required to match the sections to be butt welded was of the order of few millimetres.



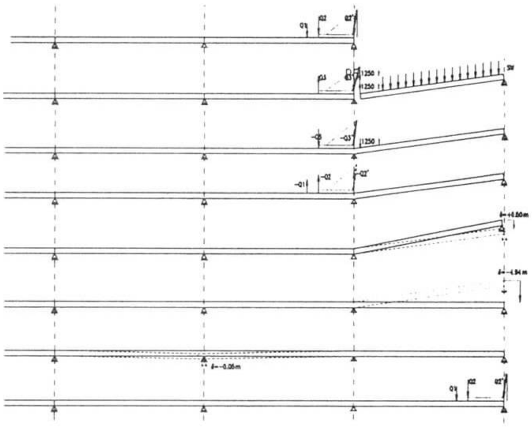
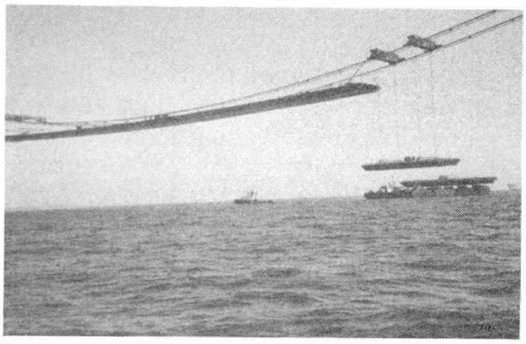


Fig. 3 - 4 - Approach spans: Lifting, front end lowering, typical span erection phases



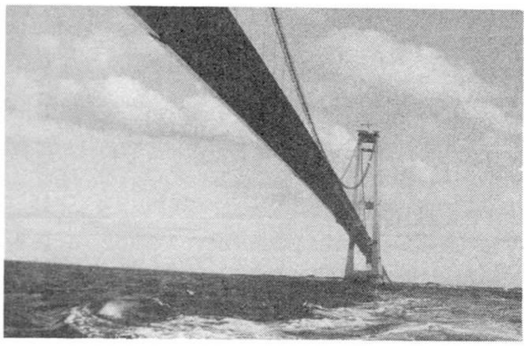


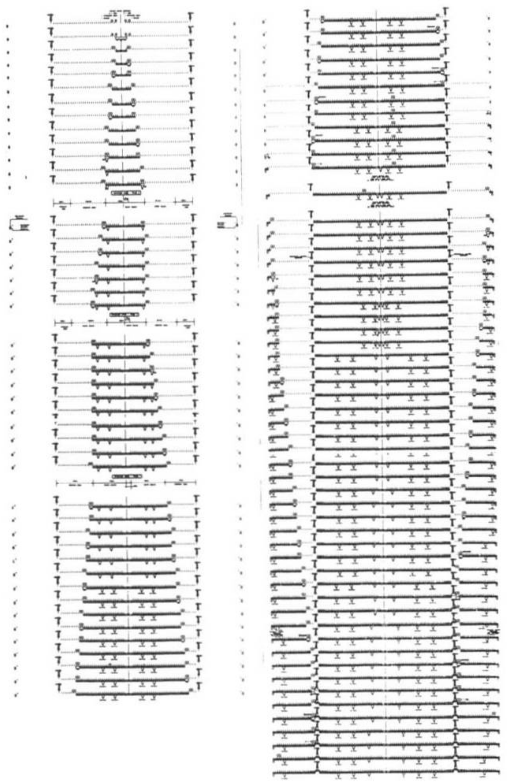
Fig. 5 - 6 - Installing suspension bridge sections

3. Wind, waves and thermal influence

Vortex shedding at approach spans

Wind effects played an important role in erection activities.
Vortex shedding soon appeared to be a possibly decisive load condition, since the structural frequencies at various stages of construction were close to the critical frequencies related to the design wind speed for erection conditions. A vibration damping system was therefore studied.
Wind tunnel tests on both sectional models and on the full bridge model were available and gave useful data on structural response and consequent actions.
However, certain results of the wind tunnel tests were contradicted by observation of the vibrations which actually occurred in the first spans, when the damping system had not been yet installed, at a different wind speed to the one predicted by the wind tunnel results.
Discrepancies were mainly attributed to the large difference in the Reynolds number between the tested model and the actual full-scale section [5], [6].

A vibration damping system was then designed on the basis of the field data and proved to be effective, since no more vibrations occurred.
This system was mainly based on the frequency tuning concept, i.e. increasing the natural frequency of the system to increase the critical wind speed accordingly.
This was achieved by means of steel cables, with proper cross section, stretching force and position, anchored to weight tuned concrete blocks dropped onto the seabed.
The system was designed to increase the critical speed beyond frequent wind speed values and to reduce the maximum forces and bending moments applied to the girder structure when resonance occurred at higher wind speeds and concrete blocks tended to lift. In this condition, the non-linearity of the system proved to be effective in significantly reducing the maximum response on the first two advancing, and more stressed, girders.



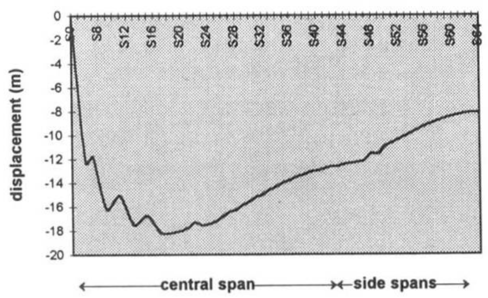


Fig. 7 - Diagram of analysis phases of the suspension bridge

Fig. 8 - Vertical displacements of cables at midspan during erection steps

The influence of the wind on the erection sequence of the suspension bridge

The erection sequence adopted consisted of starting from the mid-span of the central span and going towards the pylons; then starting from the anchor blocks and completing the deck toward the pylons.
Different sequences were actually possible, but wind stability considerations governed the decision. It was, in fact, only possible to guarantee a critical flutter speed higher than the design wind speed considered for erection activities by starting from the mid-span.
During deck erection, the critical speed is generally lower than that occurring for the completed deck, dropping to only 40% of the speed for the completed deck when about 20% of the deck is erected, then rising to near the final value, depending on the actual torsional stiffness of the deck.
To achieve the required flutter speeds, the torsional stiffness of the deck when only temporary connections were installed was extensively studied and temporary connections were designed which

fulfilled torsional-flutter requirements, but also remained functional and efficient according to the erector's needs.

The influence of the wind and waves on lifting

The maximum lifted weight was the central section, weighting about 900 t.
Standard sections were installed at an average rate of about one section per day, with cases of two sections per day when favourable conditions allowed it.
Static and dynamic loads are applied to the gantry crane and all lifting equipment during lifting.
The main dynamic load occurs when lifting starts, when the section is still on the barge and is subject to the actions of the waves moving together with the barge.
If the barge and its load drop in a wave at this point, when the section has almost been taken off the barge, large dynamic effects occur.
The dynamic amplification factor related to this effect was studied through dynamic analysis of large, non-linear displacements for the design wave conditions.
Data was also obtained to examine the problem of possible re-contact between the section and the barge due to the combined effect of slow lifting speed and wave motion.
Von Karman Vortex and buffeting effects were found to be of minor importance in lifting operations, giving lower DAFs and allowable response.

Buffeting and flutter requirements on temporary joint connections

While flutter conditions required sufficient torsional stiffness of the temporary connections between installed sections, wind buffeting governed their capacity to transmit longitudinal forces.
The average wind action gives low bending moments for all stages in which the deck is simply suspended to the cables, without transverse restraints at the pylons.
When transverse restraints are used, a significant increase in bending moments occurs. The deck is therefore kept unrestrained until the welding of joints has been completed.
However, turbulent wind action and its dynamic effects on the deck are the main source of horizontal bending moments during the construction stages. The innovative temporary connections were designed to fulfil the dual needs of keeping sections in position while allowing significant rotation on the vertical plane and allowing simple section connection.
They also had to be able to transmit longitudinal forces related to horizontal bending moment and shear due to dynamic wind action, vertical shear force given by erection loads and torsional moments still due to buffeting action. Torsional stiffness, as said, was a further condition.
Various types of finite element analysis were carried out to support and address the design of temporary connections, as well as of all temporary equipment and structures, including local stress analysis, dynamic analysis for wind buffeting action and step-by-step analysis of the progressively erected structure.

The need for good weather windows

Generally speaking, mechanical erection activities are not heavily dependent on weather conditions.
Work is not stopped until the wind speed reaches 20 to 25 m/s. The influence of windy, rainy or icy conditions on work progress and efficiency may lie more in the fact that working comfort is lower. This fact can be partially compensated when designing the equipment by considering ergonomics.
Maritime activities, on the other hand, are closely linked to weather conditions, so criteria were defined during the study phase to analyse feasibility of the activity.
These criteria (wind, current speed and direction, wave height and period) are used to analyse barge movement when the sections are being transported or lifted off the barge. If local weather statistics are known, it is possible to construct an activity program and to check that all the technical solutions envisaged are correct.
On the actual day of activity, it is the responsibility of the crane barge captain alone to decide whether or not to commence activity. The non-rational aspect of his decision may sometimes cause dismay, but serves as a useful reminder that a certain degree of forbearance is required on this type of project.

4. Concluding Remarks

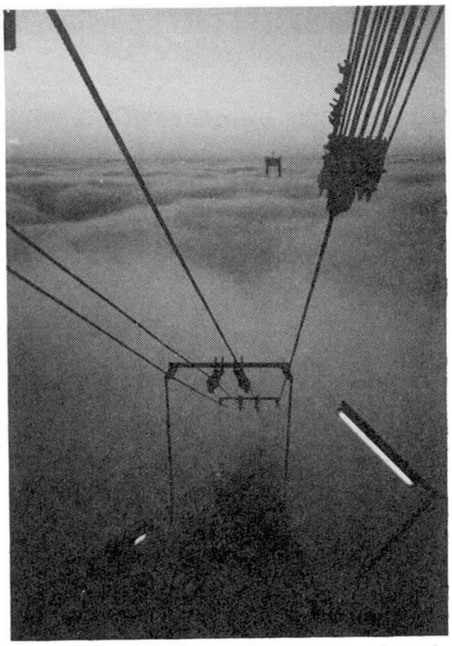


Fig. 9 - Good weather at top level

The erection of the approach spans brought to light the particular problems involved in transporting, lifting and matching 200 m. long sections.
These problems quickly increase with span length, but seem to be mainly limited to the capacity and availability of transporting and lifting equipment.
Wind must be taken into account, but is not a critical factor in this case.

Erection of the suspension bridge demonstrated and confirmed that both sea conditions and wind effects, together with thermal effects, can constrain and severely limit erection activities.
The present uncertainties in predicting wind effects, together with the short amount of time available for some activities, also place certain limits on activity.
As stated, certain welding activities require very quick action, so it could be difficult to join very large sections in the amount of time available, even if not too large problems should arise in transporting and lifting sections weighing more than 1,000 t.
Critical flutter speed during the first phases of erection are well below the speed for the bridge in service.
Taking into account the fact that the critical flutter speed decreases when the span length increases, and that the accuracy of the theoretical prediction of wind effects can be reduced on very large-scale structures, new solutions should be used to erect longer spans safely:
- Although active mechanical and aerodynamic control devices [7], [8] have not yet been tested on actual large structures, they will undoubtedly help to achieve these aims. A system which increases flutter speed would also allow the erector to chose the best procedure from a logistic point of view.
- Another option is to erect faster. This should be possible by lifting larger elements, like two sections already assembled. For this the lifting devices should have an active system of load control and section structure and attachments should be designed consequently.

In any case it appears essential that the most detailed definition and analysis of erection methods be carried out at the same time and as part of the bridge design.

6. References:

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