1st Conference on Structural Dynamics (DinEst 2018)
Madrid, 20-21 June

ANALYSIS OF THE LIFTING PROCESS OF BRIDGE SEGMENTS

Luis M. Lacoma, Javier Rodríguez, Francisco Martínez and Joaquín Martí

Principia
Velázquez 94
28006 Madrid, Spain
e-mail: luis.lacoma@principia.es

Abstract. The paper deals with the dynamics of the lifting of deck segments for constructing a bridge over water, with segments being brought by barge and lifted by an erection traveler while the barge and the bridge are undergoing the motions induced by the sea state and the wind. To investigate the process, a model was generated that included the barge and the mooring system, the supporting plinths, the bridge segment, the lateral restraints, the lifting strands, the erection traveler, and the bridge deck with its associated stiffnesses. Nearly 400 simulations were conducted, covering combinations of wave, wind, and current forces, as well as other aspects like the deck length and the cracked or uncracked state of the section. The analyses allowed establishing whether the success criteria were being satisfied, the influence of the various parameters, and the potentially more hazardous phases of the lifting process.

Key words: Bridges, Dynamics.

1 INTRODUCTION

The construction of a bridge over water, with segments being brought by barge and lifted into position, gives rise to complex dynamic phenomena. The segments are being lifted by cables while the barge and the bridge are undergoing the motions induced by the sea state and the wind. The authors were involved in conducting the necessary calculations, first for the bridge "Constitución de 1812" across the Bay of Cádiz and then for the Queensferry Crossing in Scotland. The present paper describes the problem, the methodology used and the results obtained for the latter bridge.

2 DESCRIPTION OF THE PROBLEM

2.1 Structural components

The barge may carry one or two bridge segments. Fig. 1 shows a view of the barge with two segments, a configuration termed S407; that with one segment is S408, and that with none is S414. Barge length is 91.5 m and beam is 24.4 m. The drafts forward and aft are a function of the configuration, as is the barge displacement and the location of its center of gravity.

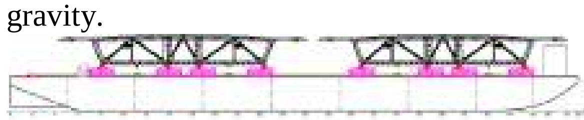

Figure 1: View of the barge with two bridge segments

During the lifting process the barge is moored with four lines. The stiffness and mass matrices representing the barge and its mooring system were determined by previous hydrodynamic simulations, as were the motions (during 1 h) caused by an uplift force of 7760 kN and a moment of 183 MNm. The Rayleigh damping coefficients were also estimated.

The supporting plinths for the segments and the restraint system are shown in Fig. 2. The segments have a weight of 792 t for the short and long deck, and 737 t for the medium deck. Their moments of inertia with respect to the three axes X, Y and Z are respectively 18.6, 95.9, and 120.0 (units are 10^3 t.m^2).

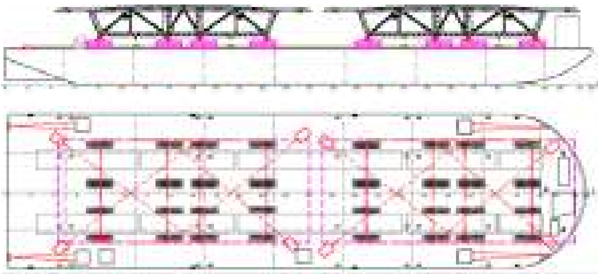

Figure 2: Segment support and restraint

Longitudinally, the plinths are centered 21.87 m from the bow; their offsets are +/- 2.55 m and +/- 13.10 m. Transversely, the plinths are centered on the barge centerline with offsets of 7.40 m, 1.25 m, -3.00 m, and -7.25 m, where positive refers to starboard and negative to port. The vertical stiffness of the plinths is 4878 kN/m. The restraint system is made of 36 mm diameter cables, with a stiffness times area of 62,000 kN, pretensioned to 10 t.

The lifting strands have an initial length of 72 m, diameter of 0.10 m and mass per unit length of 63.19 kg/m. Their stiffness times area is 1.55×10^6 kN. The lifting strands are connected 8.54 m above the top of the road segment, which corresponds to the height of the lifting tackle. The erection traveler has a weight of 730 kN. Its vertical stiffness is 10^5 kN/m and its rotational stiffness is 17.45 kNm/deg. Lifting takes place at a rate of 1 cm/s.

Three lengths of bridge deck are considered. The vertical stiffnesses are 155,560 kN/m for the short deck, 5720 kN/m for the medium deck, and 2410 kN/m for the long deck. The transverse stiffness is assumed infinite. The rotational stiffness depends on whether the section is taken as cracked or not: 69,813 kNm/deg for the uncracked section and 24,435 kNm/deg for the cracked section.

The equivalent concentrated mass at the cantilever end of the medium deck is 6485 t and 10,160 t in the case of the long deck. The dashpot constant governing energy dissipation was taken as 72 kNs/m.

2.2 Actions and acceptance criteria

The external actions considered arise from waves and winds. For waves, wave heights and periods were known at the site; given the operating envelope, the more significant scenarios were those of 0.05 m and 0.15 m waves with 2.5 s period, and that of 0.35 m waves with 3.5 s period. For wind, displacements and rotations were given for wind velocities up to 15 m/s for both the medium deck, with a 6.7 s period, and the long deck, with 12.5 s.

Some 400 simulations were conducted combining barge configurations (S407, S408, S414), wave heights and periods (0.05 m and 2.5 s, 0.15 m and 2.5 s, 0.35 m and 3.5 s), current headings with respect to the barge (150º, 180º, 210º), wind speeds (0 m/s, 4 m/s, 15 m/s), and deck lengths (short, medium and long).

The lifting process must satisfy: misalignment of supports below 50 mm in X direction and 300 mm in Y; plinth loads below 834 kN; uplift in erection traveler below 200 kN; dynamic load factor below 1.20; strand bundle load, when the other strand load is nil, below 750 kN; load in restraints below 500 kN; loads on strands below 5400 kN.

3 METHODOLOGY

To analyze the lifting process a model was generated (Fig. 3) that includes the barge and the effects of its mooring system, the plinths, the bridge segment, the lateral restraints, the lifting strands, the erection traveler, and the bridge deck with its associated stiffnesses.

The barge and its mooring system are represented with the corresponding mass and stiffness matrices. The transported segment is modelled with its mass and rotational moments of inertia. Truss elements are used for the lateral restraint system; the cables are active in tension but not in compression. Connector elements are used to model the plinths, with their compressional stiffness and damping. The barge is defined as a rigid body to which the plinths are attached. All the restraint cables have one end attached to the barge and the other to the segment being carried.

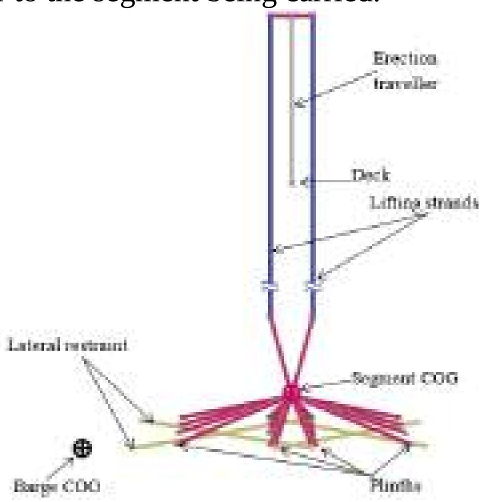

Figure 3: Schematic view of the model

The lifting strands are modelled with connector elements that allow lifting the segment by pulling up the strand. They are attached to the erection traveler, represented with a connector element with the appropriate stiffness. The erection traveler is also connected to the bridge deck, characterized with its stiffness, inertia, and damping, in respect of both translation and rotation. The deck is only allowed to translate vertically (Z direction) and to undergo torsional movements (rotation around the Y axis).

The external loads due to the waves are introduced at the center of gravity of the barge. The loads due to the wind are applied to the deck as concentrated loads.

After extracting the natural modes, the lifting process was studied. For this, the histories of the barge and bridge deck motions were converted into histories of forces, i.e.: the vertical displacements and the Y-rotations, whether caused by the waves or the wind. Those force histories, together with those of the other components of the motions, were introduced in the model and the time varying solution was obtained by implicit integration. The calculations proceeded for a duration equivalent to 1.5 times the separation time of the segment from the barge. The program used in the analyses was Abaqus (SIMULIA, 2014).

4 RESULTS AND DISCUSSION

The natural modes of the system were identified before any separations start to take place. This was done for the three deck lengths, for both uncracked and cracked sections. While the first mode corresponds to the rotation of the segment in the case of the short deck (0.226 Hz), for the medium and long decks it reflects the vertical translation of the deck (0.149 and 0.077 Hz, respectively).

Only the short deck results will be discussed. Two figures are provided as an example of the type of results obtained in the simulations. They correspond to an S408 configuration, with 0.35 m waves, 150º current, and cracked section in the bridge. Fig. 4 shows the forces in the lifting strands and Fig. 5 describes those in the support plinths.

A total of 12 simulations were conducted with 0.05 m waves for the short deck. The results allowed comparisons with all the acceptance criteria adopted; with this relatively small level of wave action, all the acceptance criteria are satisfied in all the cases analyzed. Additionally, 60 simulations were carried out for the same deck length when the wave height is increased to 0.15 m. Once again, all the acceptance criteria are satisfied. Finally, another 60 simulations were conducted for the same deck length when the wave height is increased to 0.35 m. Most of the acceptance criteria were again satisfied, except for the misalignment in the X direction; this parameter is in principle limited to 50 mm, a value that was exceeded in about 20% of the cases analyzed. The average value of the maxima, however, satisfies the limitation imposed. The uplift reaction at the erection traveler reaches a maximum value of 171.0 kN, lower but not too far from the limit of 200 kN. All the cases with the current at 180º satisfy all the conditions; the problems only arise with currents at 210º and 150º.

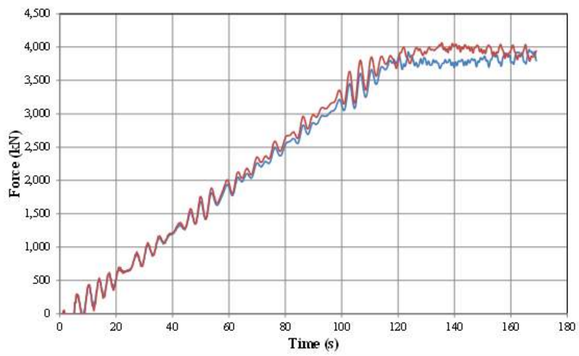

Figure 4: Forces in the strands for the long deck

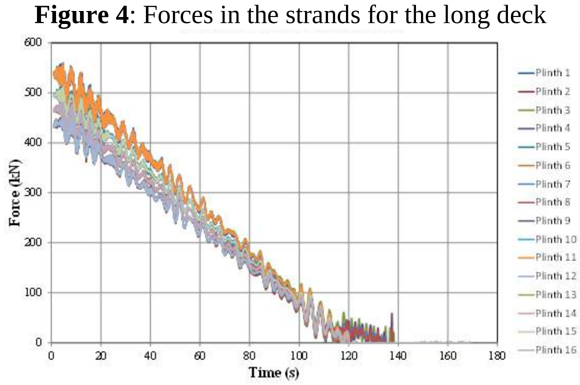

Figure 5: Forces in the plinths for the long deck

For the three deck lengths, a total of nearly 400 simulations were conducted, covering a large variety of operating conditions. All the acceptance criteria were satisfied in the large majority of them. The only exception is the misalignment in the X direction, with the 50-mm limit being exceeded in specific cases for the three deck lengths, with 0.35 m waves and misaligned currents (150º and 210º). It was presumed that this limit could be exceeded, given the large dimensions of the plinths. In any case the average of the maxima always satisfied the limit.

The 0.35 m wave height is rather demanding from other viewpoints as well. With those waves, the maximum uplift reaction at the erection traveler reached 199.4 kN in one of the simulations, with the allowable limit at 200 kN. Another significant observation is the role played by the direction of the current: no problems are experienced with the current at 180º, the extreme values arise for 210º and 150º. In comparison, the wind effects are relatively unimportant.

Finally, the more demanding phase of the lifting occurs when the segment is about to lose, or has just lost, contact with the barge. It is then that impacts and other undesirable effects can be triggered. Hence, this phase should be as brief as reasonably possible. Analyses performed halving the lifting rate to 0.5 cm/s, showed consistently worse results. Hence it may be advisable to forego balancing or other delays during this phase of the process.

5 CONCLUSIONS

As conclusions, practically all acceptance criteria are satisfied for all the combinations of parameters studied.

No problems are experienced with any of the criteria when the current is at 180º. The wind plays a relatively unimportant role within the range of conditions analyzed; the effect of the waves is far more significant.

The more critical phase is that in which the segment is about to lose, or has just lost, contact with the barge; this phase should be kept as brief as reasonably possible.

Finally, it must be highlighted that the lifting process operated without problems and the bridge was opened in September 2017.

REFERENCES

[1] SIMULIA (2014) "*Abaqus Analysis User's Guide*", Version 6.14.