Load Tests of a Cable-Stayed Bridge in Coimbra, Portugal

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Summary

Field load testing is an effective method to evaluate bridge performance and to calibrate structural models. This paper presents the load tests of the cable-stayed Rainha Santa Isabel Bridge which crosses the Mondego River near Coimbra, in Portugal. During these tests, several parameters were measured, like vertical displacements of the deck, horizontal displacements of the mast, rotations, strains and stay forces. Different types of equipment were used in order to get more accurate measurements. The experimental results are compared with the analytical values computed with a finite element model of the bridge.

Keywords: bridges; cable-stayed; load tests; instrumentation; finite element method.

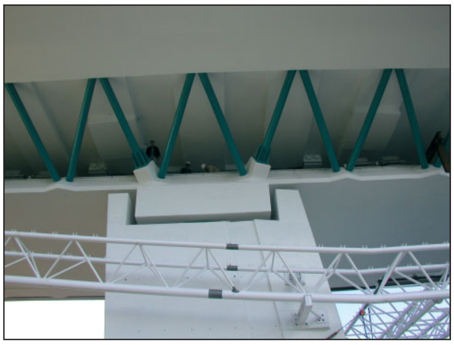
Fig. 2: Mast and deck support on pier P3

Introduction

Rainha Santa Isabel cable-stayed bridge is a road bridge that crosses the Mondego River near the city of Coimbra, in Portugal. This bridge was instrumented during the construction and its behaviour has been experimentally followed since then. Before it was opened to traffic, the new bridge was subjected to static and dynamic load tests.[1]

After a brief description of the structure, this paper presents the static testing procedures and the experimental equipment used. Some experimental results are presented and compared with the analytical values evaluated by the finite element model developed.

Rainha Santa Isabel Cable-Stayed Bridge

Rainha Santa Isabel Bridge is a cable-stayed bridge with a main span of 185,60 m and a total length of 330,30 m. Besides the main span, the bridge has two lateral spans on the left riverbank, with lengths of 45,30 m and 50,60 m and one lateral span on the right bank 45,3 m long. A general view of the bridge is presented in *Fig. 1*.

Peer-reviewed by international experts and accepted for publication by SEI Editorial Board

Paper received: April 18, 2007
Paper accepted: August 9, 2007

The main span is axially suspended from a single inclined mast by 19 pairs of stay cables. The mast has a height of 68 m above the deck and is of reinforced concrete up to the level of the first cable, and from there on consists of a steel-concrete composite structure. The equilibrium of the mast is assured by nine pairs of back stay cables, arranged in two planes, connected to two concrete anchorage blocks. The stresses at the mast are transmitted to the pier P3 through high damping rubber bearings (*Fig. 2*).

The bridge deck has a cross-section 30 m wide and 3,70 m high, formed by two pre-stressed concrete slabs connected by a three-dimensional steel truss, as shown in *Fig. 3*. The lower slab, 11,50 m wide, serves as pedestrian walkway (*Fig. 4*).

Instrumentation and Acquisition System

A structural monitoring system was installed during the construction of the bridge. Besides the measurement of vertical displacements and rotations in several sections, this system includes 36 vibrating-wire strain gauges to measure concrete strains, 22 resistance thermometers placed across the thickness of the concrete elements to obtain the thermal gradients, 80 resistance strain meters and 20 thermometers in the three-dimensional steel truss. In addition, a study of the creep and shrinkage of concrete has been carried out using specimens placed over both slabs of the deck, in several sections.

For load tests, additional equipment was installed to measure vertical


Fig. 1: General view of the bridge

Fig. 3: View of the bridge deck cross-section

Fig. 4: The pedestrian walkway in the lower slab

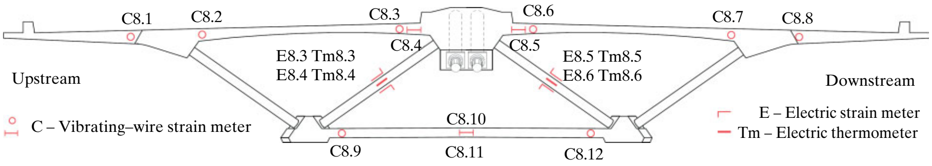

Fig. 6: Cross section S8

Fig. 7: Total station during load tests

displacement of the deck and horizontal displacement of the mast, besides stay cable forces. To measure the most reliable and redundant data, different types of sensors were installed. The general observation plan used during load tests is presented in *Fig*. 5. The distribution of the equipment in a deck cross-section is exemplified in *Fig*. 6.

In the main span, vertical displacements were measured by an upgraded hydrostatic levelling system associated with pressure cells and by a total station, located over pier P4, at the lower slab (*Fig*. 7). At quarter and midspan, two pressure cells and two targets were placed, one on each side of the deck. The targets were automatically recognized, pointed and read by the total station. In the other spans, midspan and support sections were also instrumented with traditional mechanical apparatus as deflectographs.

Horizontal displacements at the top, middle and bottom of the mast were measured by another total station, located also over pier P4, but in the upper slab.

Accelerations were measured in seven stay cables to evaluate the cable tension from their vibration frequencies.[2,3]

Finally, nine automated data-acquisition systems *DataTaker DT515* were used to read general data. A *National Instruments* data acquisition equipment was installed for the acquisition of signals from the seven accelerometers.

Testing Procedure

Load tests were carried out in two phases: in the first one a concentrated load of 1777 kN, applied by a line of six loaded trucks, was used; the second phase of the tests was performed with 16 loaded trucks with a total weight of 4761 kN.

The use of a line of trucks as concentrated load allowed the experimental evaluation of influence lines, even though it was not a single axle load.[4] In effect, the structural response to the line of trucks, successively positioned at 11 locations, was acquired.

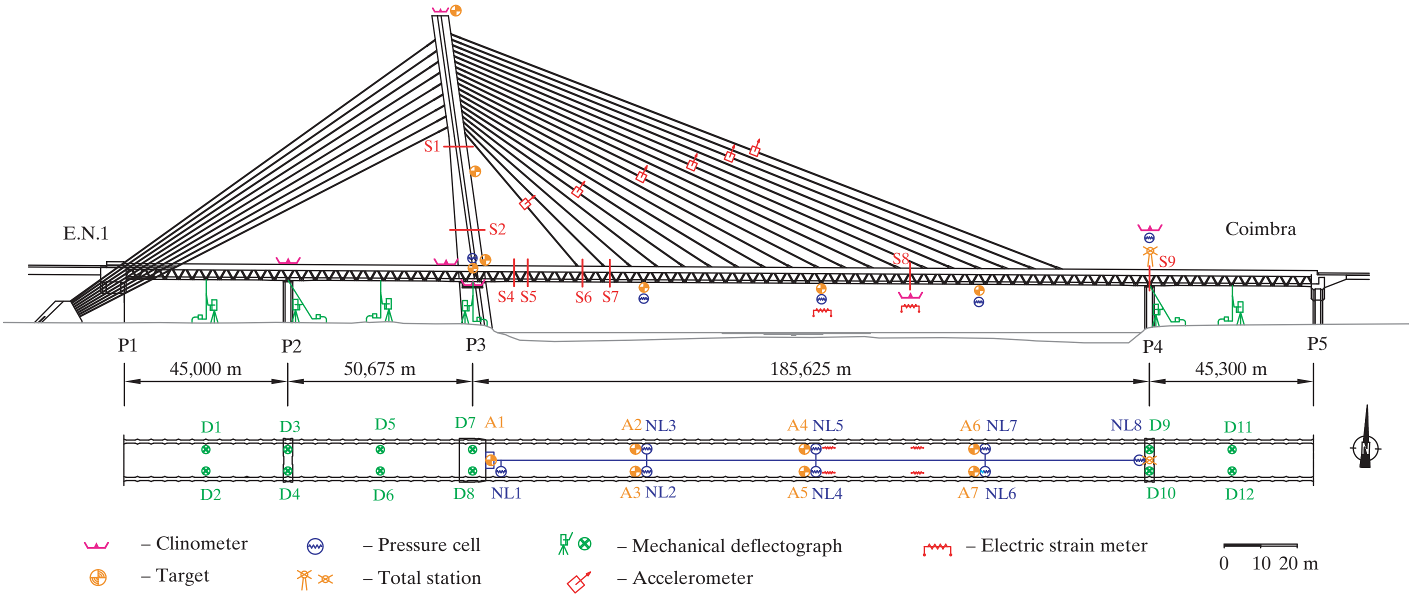

Fig. 5: General observation plan

The 16 loaded trucks were placed in six positions (*Fig. 8*), in accordance with the load plan that maximizes the most important effects in the structure, however without causing unwanted situations of early cracking in the structure.[5,6] *Fig. 9* presents the position of the trucks for main span load cases. Six eccentric load cases were considered, corresponding to the load cases 3–5, but loading only in the upstream lane or the downstream lane.

Finite Element Model

A three dimensional, linear-elastic finite element model of the bridge was developed using SAP2000[7] to evaluate its response to load tests. This model includes 1680 beam elements, 1780 shell elements and eight link elements.

Steel tubes, cables and its anchorage beams were modelled with beam elements, while for other deck elements shell elements were used. To reproduce the element connection effect, "End Length Offset" property for beam elements were used.

Beam elements were also applied in the modelling of the piers and mast. The bearings between the deck and the piers were modelled with link elements, its stiffness coefficients were defined as 1×10^{11} kN/m, for the vertical direction, and 1×10^{8} kN/m for the fixed horizontal direction.

Fig. 8: Loaded trucks during tests

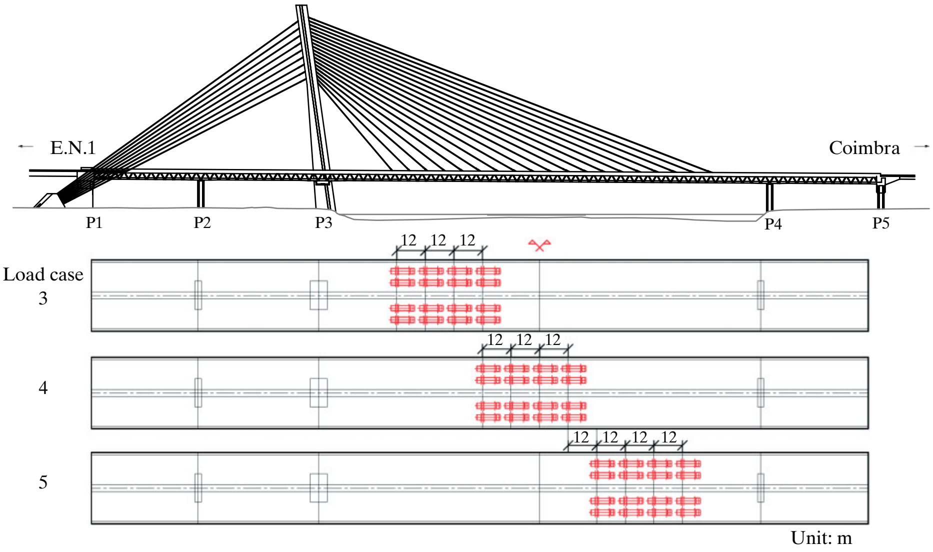

Fig. 9: Schematic positions of the trucks for load cases 3–5

The element section properties were defined according to the project. For the deck's concrete, the elastic modulus was taken as 40 GPa as for the mast's concrete it was 50 GPa.

The finite element model was calibrated after load tests, based on the experimental results several parameters were adjusted, such as the elastic modulus of concrete.[8] The calibrated model was also used for interpret the structural dynamic characteristics, identified from the dynamic tests.[1]

A general view of the developed finite element model is presented in *Fig. 10*.

Experimental Results

Vertical Displacements

The measurement of the vertical displacements of the deck was made in three different ways: hydrostatic levelling, a total station at main span and mechanical apparatus in the other spans.

For all load cases, a good correlation between values measured by different devices was achieved. In addition, numerical values show a good agreement with experimental ones.

The maximum vertical displacements of the deck occurred during load case 4, when 16 load trucks were placed at midspan. At that point, the values measured by the hydrostatic levelling were about 112 mm, the values measured by the total station were about 116 mm and the computed value was 117 mm, as presented in *Fig. 11*.

Horizontal Displacements of the Mast

The horizontal displacements at the three levels of the mast were measured by a total station placed at the upper slab, over pier P4. Experimental values measured when the concentrated load of six loaded trucks was applied can be presented like an influence line. This presentation is useful, besides the definition of the influence line.

The influence line of displacement measured at the top of the mast, obtained with a concentrated load of six

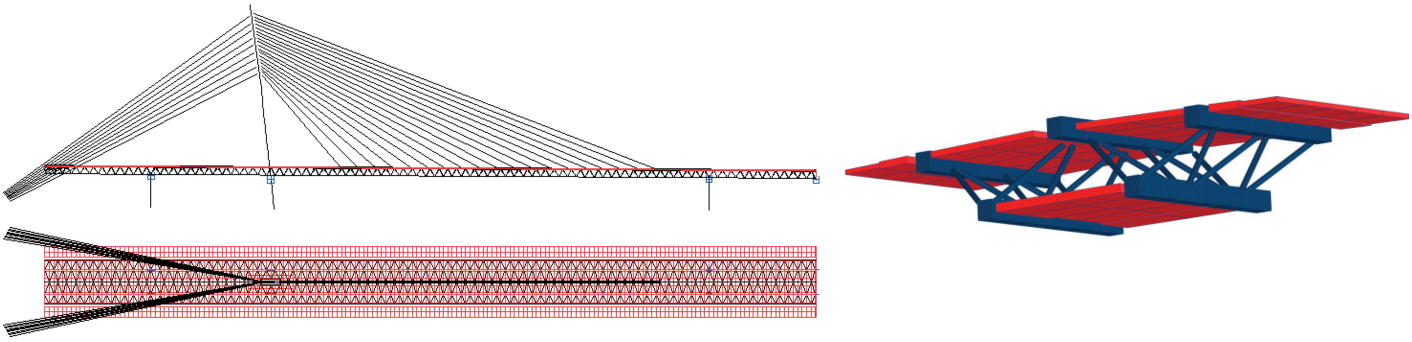

Fig. 10: Finite element model

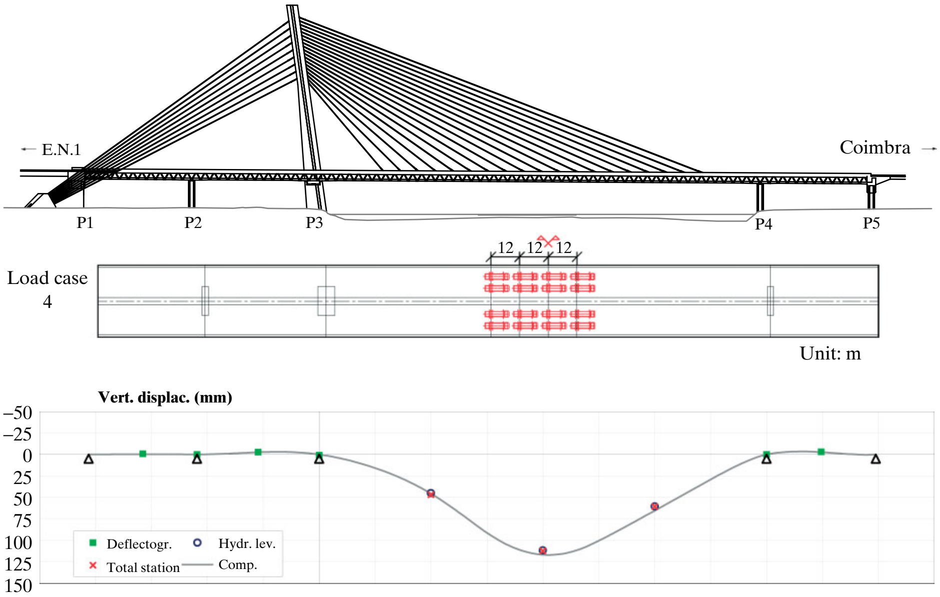

Fig. 11: Deck deformations for trucks at mid-span (Load case 4)

trucks, is presented in *Fig. 12(a)*. In this chart the continuous line is obtained from the numerical model and the points corresponding to the experimental values.

The maximum displacement at the top of the mast was 19 mm, from EN1 to Coimbra, measured during load case 4.

Rotations

Transversal and longitudinal rotations were measured by six two-axis gravity-referenced inclinometers, located at the top of piers P2, P3 and P4, at the top and bottom of the mast and at the deck section S8. The use of the concentrated load allows the acquirement of very interesting influence lines, as the one presented in *Fig. 12(b)*, where the high positive correlation between experimental and numerical results is obvious.

The highest longitudinal rotation was 16,5 × 10^{-3} rad, measured in section S8, during load case 4.

Cable Forces

The measurement of cable forces was done with the vibration method.[2] For this purpose, seven accelerometers were used on different stays. The influence line of one of them, stay cable 5, is presented in *Fig. 12(c)*, and, once more, a high positive correlation between experimental and numerical values has been achieved.

Most significant force variations occurred during the loading of the main span: 360 kN in cable 1 (load case 3), 326 kN in cable 5 (load case 3), 368 kN in cable 10 (load case 4) and 229 kN in cable 10 (load case 5).

Concrete Strains

Strains inside the concrete were measured by 50 vibrating-wire strain gauges, placed in two sections of the mast and three sections of the deck (S4, S8 and S9). For the load test only, eight electric strain gauges were positioned in the midspan and S8 sections of the deck in order to measure strains at the concrete surface. An example of an influence line of concrete strains is presented in *Fig. 12(d)*. This figure includes the strains measured in section S8 when the line of six loaded trucks was placed in different positions on the deck.

The maximum values measured in this section were –14 × 10^{-6} in the upper slab, and 59 × 10^{-6} in the lower slab, measured during load case 5. The values acquired during this load case are presented in *Fig. 13*, which also includes the values measured during load case 4. In both charts and particularly in the chart of load case 5, the flexural behaviour of the slabs is quite obvious.

Strains in Steel Truss

Strains in the three-dimensional steel truss were measured, by resistance strain meters, in 40 truss tubes from six sections of the deck.

The influence line of strains, measured in the tubes of sections S6, is presented in *Fig. 12(e)*. The eight strain gauges mentioned are placed in different tubes. As it is a three-dimensional truss, all the strain meters with odd numbers are placed in front tubes and strain meters with even numbers are placed in back tubes (*Figs. 2–4*).

The highest values of strains achieved during load tests were measured in this section during the eccentric load case 3: –322 × 10^{-6} and 256 × 10^{-6} in strain meters E6.1 and E6.2, respectively.

Temperatures

To avoid the effects of temperature changes, testing procedures include several intermediate measurements with the bridge unloaded. In addition, during testing the temperature was measured by 40 resistance thermometers placed inside the concrete, and by 40 other resistance thermometers placed in the steel truss. This procedure verified that no significant temperature changes occurred during tests, especially between two consecutive measurements of the unloaded bridge.

Conclusion

The Rainha Santa Isabel cable-stayed bridge was subjected to load tests, performed at the end of its construction and before it was opened to traffic. During these tests, the existent structural health monitoring system and the additional equipment installed for these tests allowed the measurement of vertical displacements of the deck, horizontal displacements of the mast, stay cable forces, concrete and steel truss strains and temperature. Load tests were carried out with sixteen loaded trucks with a total weight of 4 761 kN. A total of 27 load cases were considered.

The use of different types of sensors allowed the validation of the experimental results. The large number of sensors used, more than 200, assures the reliability of the measured values. The consistency of these values is particularly obvious in vertical displacements of the deck, measured at the same points by a hydraulic levelling system and by a total station with the similar results.

The experimental results acquired during the load tests were used to validate the numerical model developed and to assess the structural behaviour of the bridge, which proved to be linear for all the load cases conducted. In general, differences between the measured and computed values were less than 5%. The calibration of the structural model was a significant outcome of the tests.

The information collected in the tests concerning the structural behaviour of the Rainha Santa Isabel cable-stayed bridge was an important contribution to characterizing its actual condition.

Acknowledgements

The authors would like to acknowledge the cooperation of the Portuguese Roads Institute, and all technicians of the National Laboratory for Civil Engineering (LNEC) who participated in the load tests presented in this paper.

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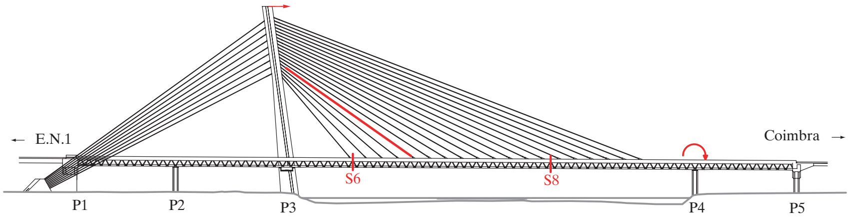
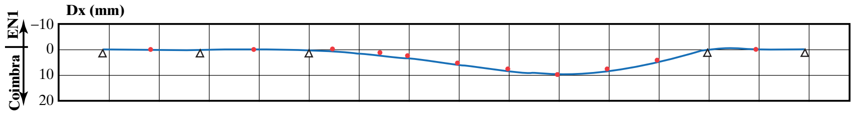
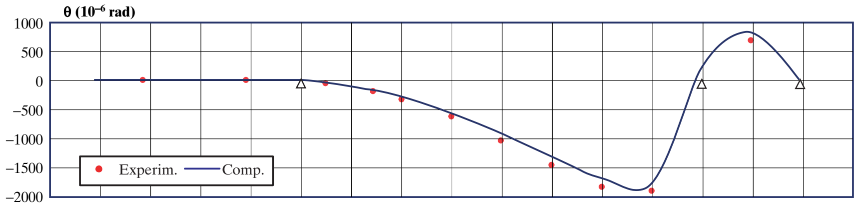


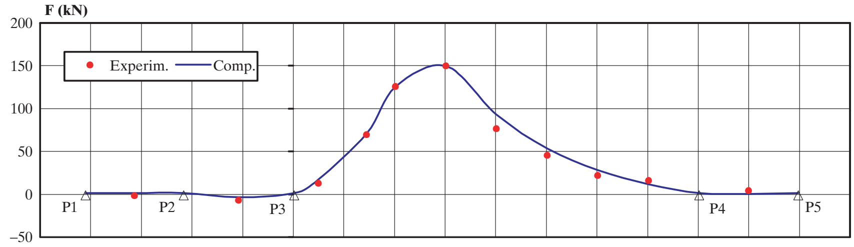
(a) Horizontal displacements at the top of the mast



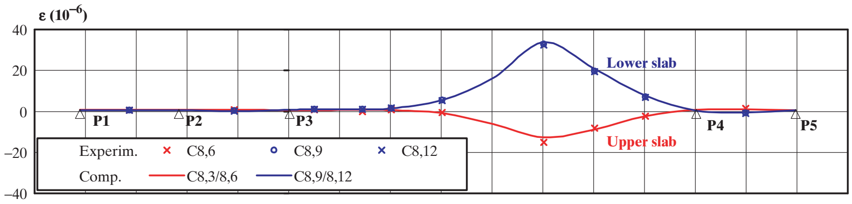
(b) Longitudinal rotations at the top of pier P4



(c) Variation of force at stay cable 5



(d) Concrete strains at section S8



(e) Steel truss strains at section S6

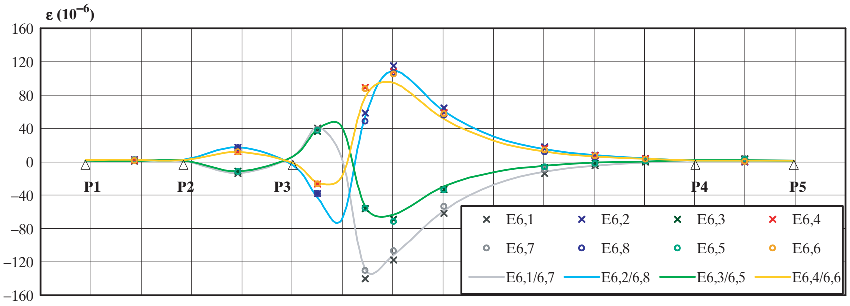


Fig. 12: Experimental and numerical influence lines; (a) Horizontal displacements at the top of the mast (b) Longitudinal rotations at the top of pier P4 (c) Variation of force at stay cable 5 (d) Concrete strains at section S8 (e) Steel truss strains at section S6

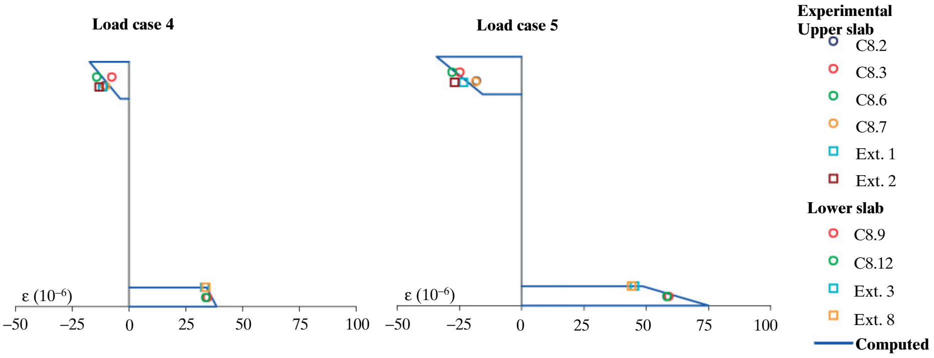


Fig. 13: Experimental and numerical strains in concrete (S8)