Nondestructive Load Testing of a Single-Span, Cable-Stayed Bridge: Testing Design, Instrumentation and Preliminary Results

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Key words: bridge monitoring, precise leveling, digital inclinometer, microwave interferometry, digital image correlation, FEM

SUMMARY

This paper presents the testing design, the instrumentation and preliminary results derived from a full-scale load test undertaken at a single-span, cable-stayed bridge using variant monitoring techniques. The primary objective of the project is to assess the level of structural integrity of the bridge based on systematic comparisons between analytical models and the parameters derived from the monitoring data for a multitude of specifically designed static and dynamic load tests. Also, a key objective of this work is to build a database of high capacity, multi-sensor bridge monitoring data to assist in research related to optimal sensor placement and sensor integration for bridge performance assessment. The deformation monitoring scheme consists of four independent systems used to provide complementary displacement data for the deck, the cables and the pylons. Deck monitoring is accomplished using a combination of ground-based microwave interferometry (GBMI), digital image correlation (DIC), digital inclinometers and precise leveling, whereas GBMI and DIC are used to track cable and pylon movements respectively. Currently, the field tests are underway, whereas data pre-analysis follows a stepwise and event-based process with preliminary results outlined in this article.

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1. INTRODUCTION AND OBJECTIVES

Nondestructive load testing of bridges has been used by civil engineers as an investigation tool to reveal the way in which loads are carried by and distributed through a bridge and, by extension in order to evaluate its structural response (Cai et al, 2012; Sousa et al, 2013). Nondestructive load testing can be further categorized in two types; static and dynamic. The goal of a static load test is usually to verify the capability of a structure to support heavy loads. Static tests are associated with the analysis of the materials and the design of a structure and ultimately aim at assessing the structural integrity of bridge elements (Gikas et al, 2013; Sanayei et al 2012). As a complement to static load tests, dynamic tests yield critical information about the actual behavior of the bridge under traffic and other ambient conditions such as variations in wind load and temperature (Gikas, 2012).

In recent years, the continuously increasing complexity in architectural designs and the need for periodic evaluation of the performance of existing (aged) bridges have greatly affected the evolution of new monitoring techniques, sensors and networks of sensors (Sanayei et al 2012). Current systems include traditional sensor types such as accelerometers, strain gauges and conventional optical systems as well as modern techniques including fiber-optic, vision-based and microwave interferometry systems. Moreover, depending on specific project goals, the choice of sensor types and the design of their placement configuration on the structure, in common with data acquisition strategy and the level of measurement integration adopted, are critical issues that can have a tremendous impact on the amount and the quality of raw data acquisition and final parameters estimation.

This paper presents the design and implementation of a multi-sensor system that was realized to fulfill a series of nondestructive load tests of a small-sized, cable-stayed bridge. The primary goal of the project is to evaluate the structural response of bridge elements under varying (static and dynamic) loads. This includes the development of a number of baseline finite element models (FEM) that would take into account the track history information of the bridge, the assessment of FE models against the parameters derived from the load tests and potentially the calibration of FE models as required. As the project seeks measurements of various types with high spatial resolution a multitude of independent monitoring systems were used to record the bridge kinematics of its various elements. Therefore, the monitoring setup used, in addition to its ability to provide comprehensive analysis results of the bridge performance, it allows for a thorough assessment of the sensors performance and their capabilities in field conditions. Also, it provides a test bed for the evaluation of alternative scenarios that would lead to "optimal sensor placement" configurations as well as the basis for research of sensor measurement integration that would lead to a more realistic mapping of bridge kinematic performance. Currently, the project is underway with most of the static load tests having completed. This paper presents the monitoring system, the loading testing procedures and preliminary results.

2. BRIDGE DESCRIPTION AND TEST LOAD SCENARIOS

2.1 Description of the bridge

The bridge under investigation is a roadway cable-stayed bridge, which overpasses "*Attiki Odos*" high-speed tollway in the motorway section connecting Athens, Greece to the city international airport (Figure 1). The bridge consists of a steel-composite deck, double-plane cables and two Λ–shaped pylons. The suspended span is 58.3 m long and bears two traffic lanes and two pedestrian walkways. The deck is formed by two main longitudinal steel girders running at each side of the deck at between distances varying from 13.40 m to 16.50 m and 20 steel cross-girders spaced every 2.5 m. Girder and floor beams are composite with a concrete slab of variable thickness 0.20 m to 0.40 m. The compressed and tensile legs of the Λ–shaped towers are made of prestressed concrete and steel respectively, whereas the two pylons are connected near the top. The stay cables are made of strands in varying number; 19 for the shorter ones and 42 for the other two.

Figure 1. Bridge overview

2.2 Testing Scenarios and Procedure

The bridge monitoring investigation plan includes a number of tests and inspections from which the most significant part refers to static and dynamic load tests. Also, in addition to visual technical inspection, thermographic surveys were carried out on the stay cable anchor heads and bridge pylons to further examine structural surfaces integrity and to identify areas of potential invisible discontinuities.

The focus of static load tests involves measuring the bridge settlements under live load. For this purpose a three-axle track, weighting 300 kN (total mass of 30metric tons) was used. The test track was placed according to the six different arrangements shown in Figure 2, left to provide six live load cases. Also, in order to induce maximum deck settlements the track was placed by the sidewalk curb at the cross sections passing through the cable anchor points. Finally, in addition to deck measurements, a limited number of horizontal deflection measurements were undertaken at the top of the pylon. Dynamic tests shall include a variety of kinematic scenarios also realized using the test track. Specifically, these tests are scheduled to involve the track crossing the bridge deck at various speeds, breaking and passing through wooden beams. At present time, only the static tests have been completed whereas dynamic tests are scheduled after analysis of static tests has been completed.

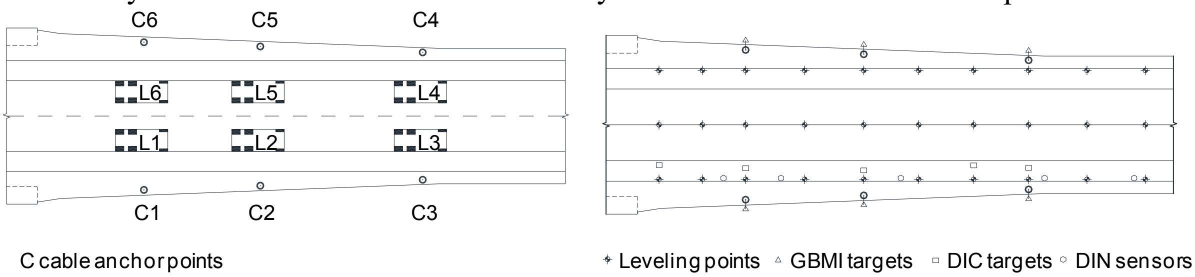

Figure 2. Loading scenarios (left) and sensor placement (right)

3. OBSERVATION GEOMETRY AND MONITORING SYSTEMS

As already stated, a key objective of the bridge monitoring strategy is to provide a dense network of observation points through a combination of a number of heterogeneous sensors. Therefore, a complete description of bridge elements kinematics would be derived to allow advanced studies of their structural response alone and their interaction. To this effect four independent monitoring systems were used: (a) precise leveling, (b) a range of digital inclinometers, (c) a videometry system, and (d) a ground-based microwave interferometry system. Figure 2, right shows the type of sensors and their distribution in the three (deck, pylon, cables) bridge elements.

3.1 Precise leveling and digital inclinometers

Regarding traditional monitoring techniques, precise leveling and inclination measurements were used to monitor the response of the deck under live static loads. Deck settlements were measured using an optical level sensor (Leica DNA03) of ultra high accuracy (0.3 mm/km$^{0.5}$ @ 1σ). Because of the relatively short (< 60 m) observation distances, high accuracy settlements was possible to obtain through the deck. In total, spirit level measurements were collected at 30 points established over the cross girder deck locations which are distributed into three axes along the span; two along the outer part of the sidewalks and the third one along the road axis (Figure 2).

Digital inclination measurements were taken to obtain information about the rotation of individual points of the deck. Such information is independent and different in nature from other measurements and can be used to enhance our understanding of bridge deck kinematics. Specifically, a range of five high precision (0.001 mrad) digital inclinometers (Leica Nivel 220) were fixed along the outer side of a sidewalk at locations for which maximum torsional variations were expected (Figure 3). The sensors were operated through a laptop and aligned so that the measured inclinations reflect the bridge response in the longitudinal and transversal directions.

3.2 Radar microwave interferometry and digital image correlation systems

As opposed to standard static test load scenarios, dynamic tests necessitate high sampling rates and ultra-high accuracy monitoring observations. Clearly, in this study this requirement also applies for static load tests, as the project seeks to study the bridge response for the complete sequence (i.e. from the time the track enters the bridge to the time it drives away) of the static loading process. In order to overcome known limitations of conventional surveying methods alternative monitoring techniques were adopted for measuring the static and dynamic bridge deflections.

In this study the ground-based microwave interferometry (GBMI) technique was used to monitor the deck settlements and cable vibrations during the static / dynamic and dynamic load tests respectively. The operating principle of the method relies on the computation of scattering object displacements using the phase information obtained by a radar sensor from repeated electromagnetic pulse transmissions (Benedettini et al, 2011; Dei et al, 2013, Gikas, 2012; Pieraccini, 2013). Specifically, the radar system used (IDS IBIS-S) consists of a radar sensor module, a control PC and a power supply unit. It radiates at a central frequency 17.20 GHz and provides radial dynamic displacements at a maximum sampling frequency 200 Hz and displacement accuracy better than 0.1 mm. Deck displacements were monitored at six locations using metallic reflectors fixed at the cable-deck anchor points.

Figure 3. DIC targets, digital inclinometer (left) detail of digital inclinometer (center) and GBMI sensor (right)

To complement radar measurements, video-based observations were taken to compute deck and pylon displacements using digital image correlation (DIC) principles (Lee et al, 2011; Olaszek ,1999; Yigit et al, 2010). Specifically, the videometry system used (Imetrum Video Gauge) analyzes sequences of video pictures (at maximum 15 Hz) to provide 2D displacements of predefined points and specifically designed targets on the deck with absolute accuracy better than 0.1 pixel. The system was used to compute deck settlements simultaneously along both sidewalks of the bridge using two cameras. Also, for a limited number of tests the system shall be used to record the horizontal deflections at the top of the pylons.

4. FIELD CAMPAIGNS AND PRELIMINARY RESULTS

4.1 Data acquisition

As already stated, the project aims at full scale load testing of the bridge structure and thus it calls for a large number of simultaneously operating monitoring systems. Therefore, data acquisition planning required detail discussions with structural engineers regarding the content and sequence of monitoring scenarios, the sensor configuration setup, their placement and other issues.

At a preliminary stage, detailed topographic surveying measurements were taken to pre-construct the optimal observation geometry between sensors and targets required for the operation of the radar and viedometry systems. In order to minimize the effects of variations in environmental conditions on measured data, field work was undertaken strictly at night hours. Furthermore, in order to facilitate better comparisons in the bridge parameters obtained from the FEM analyses and those derived from measurements the ambient temperature was measured throughout the tests. Regarding sensor synchronization, the GPS time tagging method was used to provide a common time reference of all systems. Data acquisition planning involves data collection in two phases. Firstly, static tests which are currently about to complete and, secondly dynamic tests to be undertaken after preliminary analysis of the static tests has been completed.

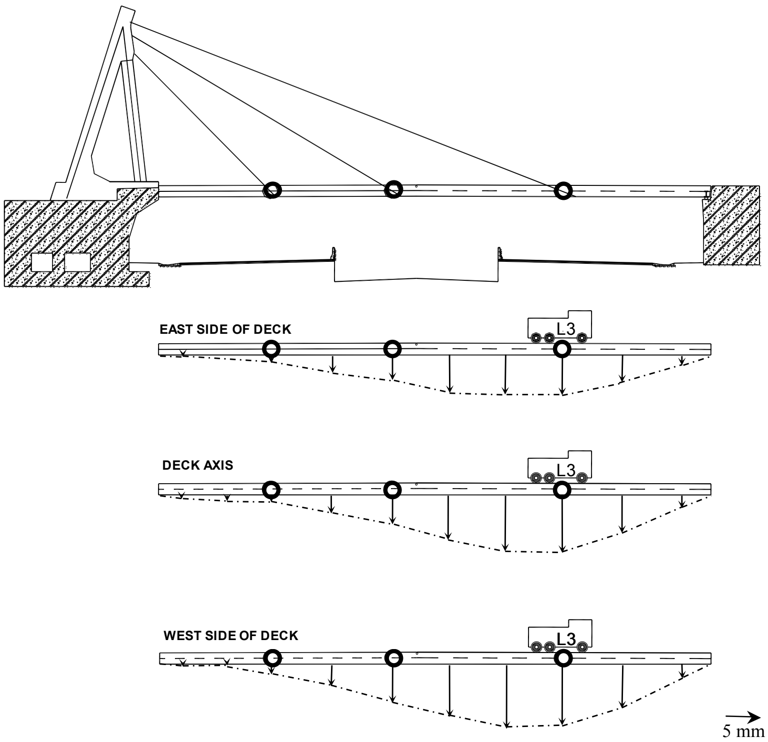

Figure 4. Deck settlements derived from precise leveling for test load L3, see Fig. 2

4.2 Data pre-analysis and preliminary results

As the project is currently underway, in this article only preliminary results of the analyses undertaken will be shown. These results are typical examples extracted from a sample dataset aiming to examine the consistency (precision) of individual systems as well as their performance in absolute terms (accuracy) through comparisons of parameters obtained independently from heterogeneous sensors.

Figure 4 shows the deck settlements obtained at all 30 leveling points for the static load case L3 (see Figure 2). As expected, maximum displacements occur in the deck area in the vicinity of the track location. From the same figure is evident that deck settlements decrease gradually towards the ends of the span.

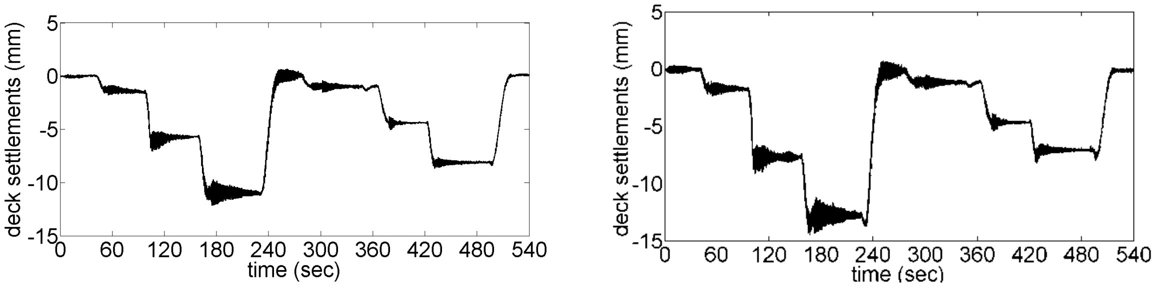

Figure 5. Deck settlements at third (longer) cable anchor point area obtained by DIC and GBMI systems for all load test positions

Figure 5 shows the time-series of vertical displacements obtained for all load positions for the GBMI corner reflector and the DIC target located in the proximity to anchor point of cable 3 (see Figure 2). A number of points are directly evident from these diagrams. Firstly, all phases of load testing are clearly identified; starting from load test L0 (empty bridge), followed by track locations L1 to L6 and, finally after the track departs off the bridge, L7. Secondly, as expected the observed displacements for load positions, L1, L2, L3 are more significant compared with those obtained for track locations L4, L5, L6. Also, the high sampling rate and accuracy of both systems reveal the dynamic part of the displacements induced every time the track moves. Finally, comparison of the GBMI results with those derived from the DIC indicates an extremely good agreement suggesting a high accuracy performance of both systems.

So far, several tests have been undertaken in order to examine further the results obtained from different sensors. One of the tests involves comparisons of displacements obtained from different systems at neighboring locations and for the same load positions. Figure 6 depicts the deck settlements obtained from precise leveling and from the GBMI sensor targets fixed in the proximity of the track location for load cases L6 (top) and L3 (bottom). Figure 6 indicates very similar results for both systems and for both track locations. Specifically, the level sensor and the GBMI show settlements of the same magnitude for symmetrically load conditions. Also, the relatively higher settlements observed at precise leveling points compared to those derived at the GBMI reflectors is explained as the leveling points are much closer to the track position.

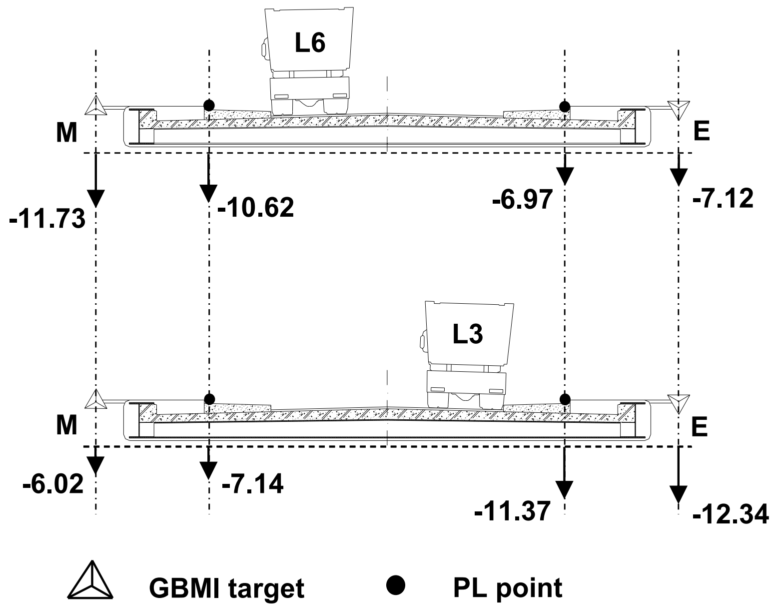

Figure 6. Deck settlements in millimeters obtained at the GBMI and DIC targets located in the proximity of track position for load cases L6 (top) and L3 (bottom)

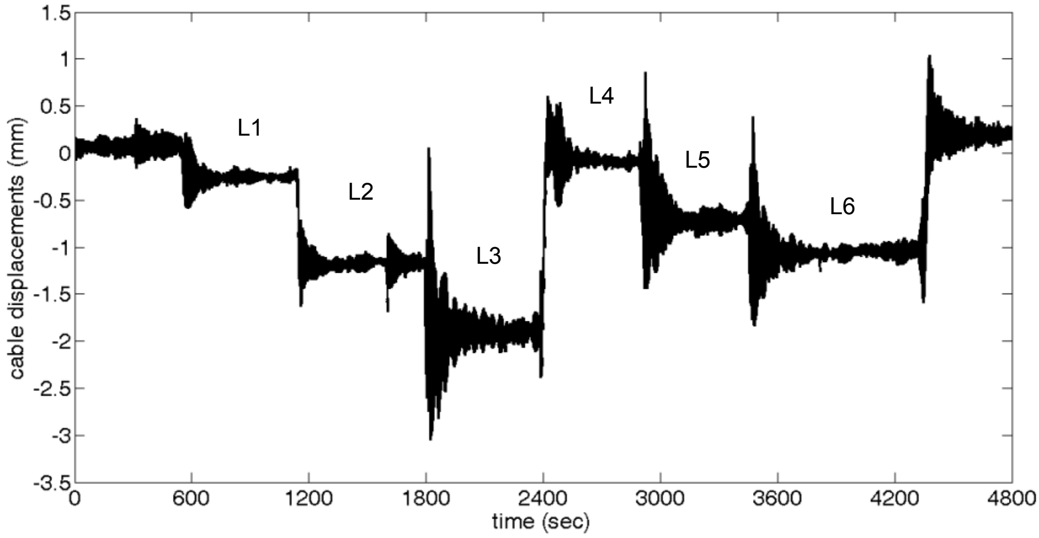

Figure 7. Displacements of the third (longer) cable perpendicular to the cable axis at distance approximately at one third of cable length measured from the top of the pylon

Finally, Figure 7 shows the response of the third (longer) cable obtained by the GBMI system for all (L0 through L7) live load positions. Particularly, it shows the cable displacements obtained at the direction perpendicular to the cable axis and at a distance about one third of cable length measured from the top of the pylon. From this diagram the displacement pattern reveals clearly the test load phases as well as the dynamic part of the measurements.

5. CONCLUDING REMARKS AND FUTURE WORK

This paper summarizes the test design, instrumentation and some preliminary results obtained from a nondestructive bridge load test project. Analysis of the displacement results obtained so far for the deck and the cables due to static live loads justify fully the monitoring strategy adopted and confirm the precision and accuracy of the various systems used.

For the time being most of the static tests have been executed and once analysis is completed dynamic tests will follow. Also, at the next analysis stage a number of baseline FE models will be constructed and detailed comparisons between the analytical and computed (from measurements) parameters will be attempted. Particular attention will be place in dynamic scenarios and studying the interaction of the structural response among the bridge elements, whereas a FE model calibration shall be decided at a later stage. Finally, the multi-sensor data of this project will also serve the basis to conduct independent research towards optimal sensor placement strategies and sensor fusion for bridge dynamic monitoring.

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BIOGRAPHICAL NOTES

Vassilis Gikas received the Dipl. Ing. in Surveying Engineering from the National Technical University of Athens, Greece and the Ph.D. degree in Kalman filtering and Geodesy from the University of Newcastle upon Tyne, UK, in 1992 and 1996, respectively. He is currently an Associate Professor with the School of Rural and Surveying Engineering at the National Technical University of Athens, Greece. In the past (1996–2001) he served the offshore and land seismic industry in the UK and the USA as a navigation and positioning specialist and, more recently (2001–2005) he served the private sector in a series of surveying and transportation engineering projects under the same capacity. His principal areas of research include sensor fusion and Kalman filtering for navigation and mobile mapping applications as well as engineering surveying and structural deformation monitoring and analysis.

Phaedon Karydakis received the Diploma Degree in Civil Engineering from the National Technical University of Athens (NTUA), Greece (1974), the D.I.C. Master Diploma from Imperial College, UK (1975), the MSc in Applied Statics from London University, UK (1975) and the Ph.D. from the NTUA (2011). He is an expert in steel and composite structures design running his own civil engineering firm. In his professional career he has contributed in the realization of many pioneering civil engineering projects like the rotation of the Athens Olympic Stadium pylons and the designing of several composite structures. He is also working as a scientific collaborator in the Laboratory of Steel Structures of the Civil Engineering Department, NTUA.

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