An alternative system for measuring displacements in bridges by using displacement transducers

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ABSTRACT: One of the most important controlling parameters in bridges are the vertical displacements. Measuring deflections is not only valuable at the early stages of the construction, but during the service lifetime of the structure also. Furthermore, vertical displacements are one of the most important indicators of the healthy state of the bridges among other structural health monitoring parameters used in the assessment of the structural response of the bridges and for foreseeing eventual damage or deterioration issues.

Bridges are often placed over watercourses or over accidentally terrain and normally load tests are carried out before starting its use with the purpose of evaluating the structural response. Measuring vertical displacements are always a challenge and many technics have been developed during the past few years. The present paper introduces a new system based on the use of LVDTs that enables the measurement of vertical displacements in structures when the access to reference points are limited. Also, this system offers a simple application and can be easily placed on site for measuring vertical displacements with both high sampling frequency rates and resolution.

1 INTRODUCTION

Measuring displacements in a structure, both during the construction phase and in later stages, is a key aspect in the construction industry. A very well-known example of this is the measuring of vertical deflections during load tests on bridges (Branco and de Brito, 2004; Ferreira and Branco, 2004; Ryall, 2010). Especially before a bridge starts in service, a load test is usually performed to validate the structural design by making a comparison between the real displacement values registered through a field test and the theoretical ones obtained by numerical models. Moreover, in some cases it is interesting to experimentally determine the influence line of the structure by carrying out a load test with a movable load crossing the bridge; however, that may only be possible if the measuring system allows an acceptable number of readings per second.

Measuring vertical deflections during load test on bridges can be easily conducted with Linear Variable Differential Transducers - LVDTs (Paultre et al., 1995), fibre-optic or other type of similar sensor (Vurpillot et al., 1998) mounted on a fixed support. The main disadvantage of these methods is the need of placing the sensor in contact with an auxiliary frame linked to a fixed point, usually the ground. Despite its high precision (order of microns) and high rates of reading acquisition (allowing to get lines of influence), these systems are difficult to implement when the bridge spans over a watercourse or when accidental terrain exists. Topographical methods can be used instead, regardless of the difficulty of access to fixed points, but they have low resolutions (normally millimetres), making it difficult to accurately characterize bridge deflections; besides, they do not provide a high a rate of readings, preventing its use for obtaining influence lines.

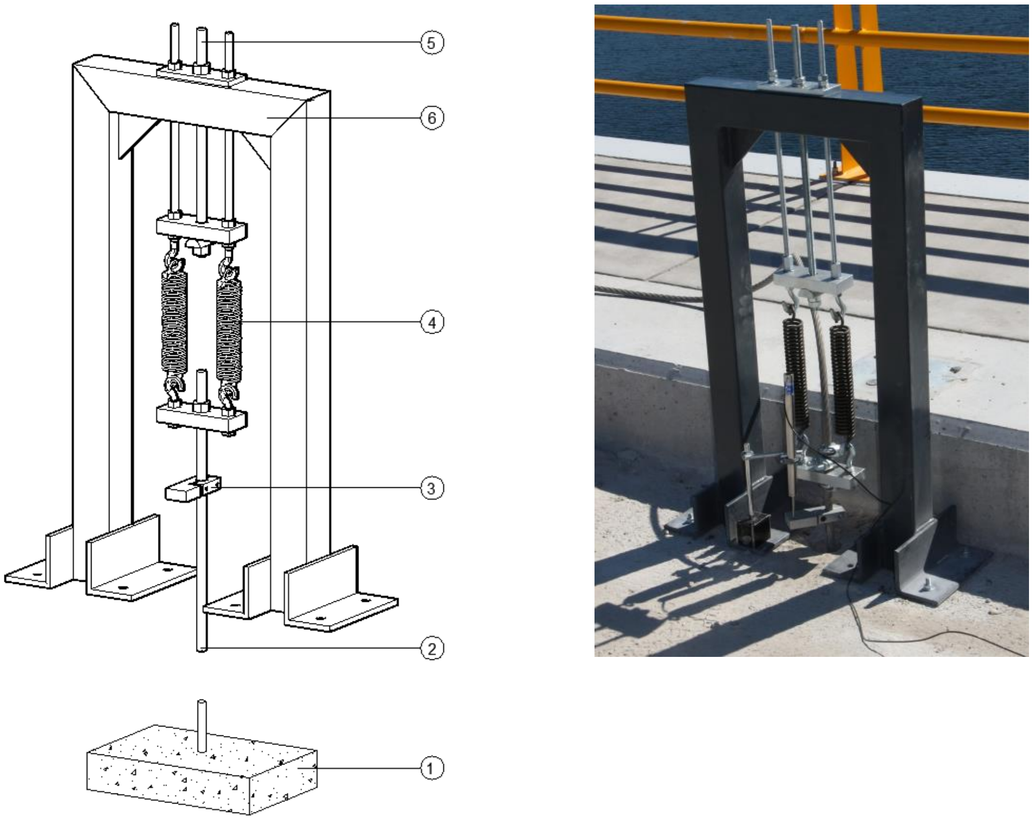
Other option is the use of hydraulic methods (Vurpillot et al., 1998) in which the displacements are measured based on the principle of communicating vessels, obtaining displacements as the difference in piezometric height between each point to be measured and a fixed reference point located outside of the structure. As the previous one, this method is capable of being implemented in any structure, regardless of the difficulty of accessing to fixed points; however it presents a low resolution (typically more than 1 mm) and effects of temperature may lead to errors in measurement. Moreover, it does not enable to render influence lines since it is not possible to obtain a high rate of readings due to the required stabilization of the fluid within the network.

Radar interferometry (Gentile and Bernardini, 2010; Kuras et. al, 2011) is also another possibility; it consists of a broadcasting system of electromagnetic waves (in the frequency range of microwaves) which, upon finding an obstacle in its path, are reflected to the transmitting antenna. This method is capable of monitoring the displacement at various points of the bridge structure and its resolution rounds the order of 10 microns, reaching an acquisition rate up to 100 readings per minute. However, this system present a high initial cost and the vertical displacements are not directly measured (system only measure the distance between the transmitter antenna and the targets reflectors, and based on this data, vertical displacements should be obtained) which makes it difficult its application and use.

With the aim of facing the disadvantages that typical techniques and methods present, in this paper a new alternative system is presented to measure displacements in bridges. The proposed system has been tested both in lab environment and on field for assessing its performance. As it will be shown, the developed system uses LVDTs for measuring the displacements, reaching both high accuracy and rate of acquisition, while needs neither a direct access to the terrain on which the bridge is located, nor the use of any auxiliary structure. It is interesting to mention that even though the new system has been specially designed to measure vertical displacements during load tests in the case of bridges that span over watercourses, it can be easily adapted to measure any other kind of displacement in bridges or in any other structure.

2 DESCRIPTION OF THE PROPOSED SYSTEM

The proposed system is a stand-alone device designed to be used without the necessity of other additional equipment or material. It is developed to measure, by means of LVDTs, vertical displacements during load tests on bridges (as well as any kind of displacements in structures) when the access to fixed points (e.g. ground surface) is difficult or when the structure spans over a watercourse. The system is easily and quickly installed and is comprised of the following main elements, depicted in Figure 1: (1) a dead weight for locking a cable; (2) a steel cable; (3) a LVDT linked to the system and in contact with the bridge deck at the measuring point; (4) a set of springs; (5) a stretcher used for prestressing the steel cable; and, (6) a steel frame which allows fixing and tensioning the springs.



(a) (b)

Figure 1. Proposed system: (a) Schematic representation; (b) Prototype used *in situ* testing.

For installing the system the steel cable is locked to a dead weight placed on fixed ground (in the case of watercourse, the river bench) and then it is prestressed by the stretcher; this procedure also introduce a tension in the spring. Finally, a LVDT is placed in contact with both the measuring point and the steel cable. After this simple procedure the system is ready to measure displacements. Thanks to the use of a LVDT, the system can present resolutions on the order of microns and a data acquisition rate greater than 100 readings per minute (thus allowing to get influence lines).

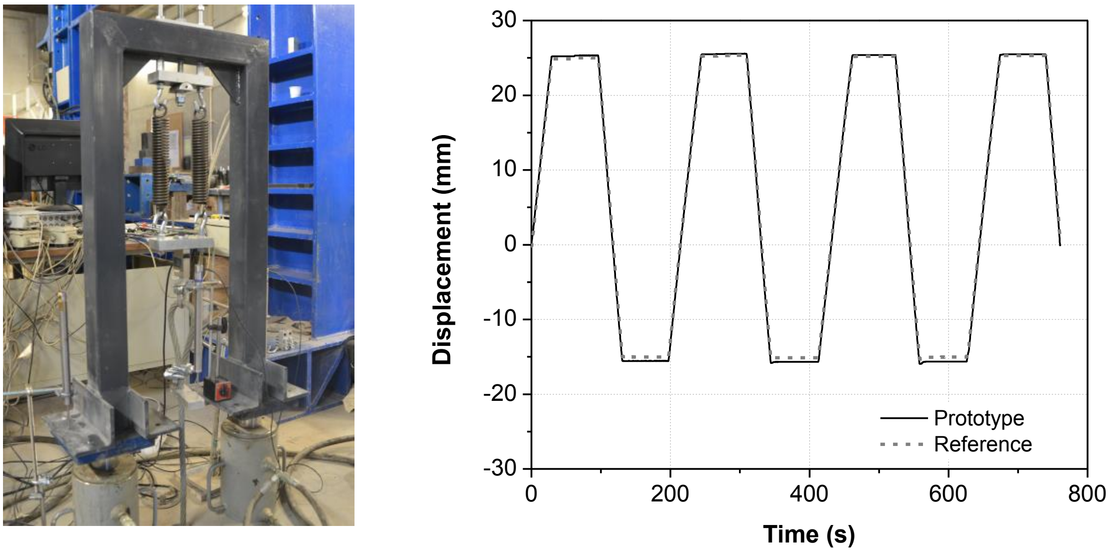
It should be mentioned that small holes should be drilled in the bridge deck to implement the designed system. Nevertheless, due to their reduced dimension (less than 50 mm), it is not expecting that drilling these holes results in any complex operation, neither lead to any mechanical damage and durability degradation issues. Alternatively, a temporary extension of the deck might be carried out (e.g. by using steel profiles attached to the bridge).

3 APPLICATIONS

3.1 Lab testing

Before the use of the new developed system, some lab tests were carried out to assess the proper work and behaviour of the proposed system. These tests were conducted in the Structural Laboratory of Civil Engineering of the University of Minho (LEST).

The first test was related to the behaviour of the designed system under imposed displacements. For this evaluation the system was mounted over two hydraulic jacks which moved simultaneously and cyclically, representing potential movements of a bridge's deck. As Figure 2 shows, there existed a very good match between the actual value imposed by the jacks (denoted as "Reference" – average value of the displacements measured by the jacks) and the value registered by the developed system. It should be mention that the present test was designed to have a maximum deformation of the cable (during the cycles) of 0.1 mm.



(a) (b)

Figure 2. Imposed displacement test: (a) Test setup; (b) Values registered.

With the aim of evaluating the eventual relaxation of the system, a second test was performed. The proposed system was tested in a climatic chamber with constant temperature (+20 °C) and relative humidity (50 %) during 110 hours with an applied load of 1.5 kN. After that time, results (Figure 3) showed that there was no evidence of relaxation in the system.

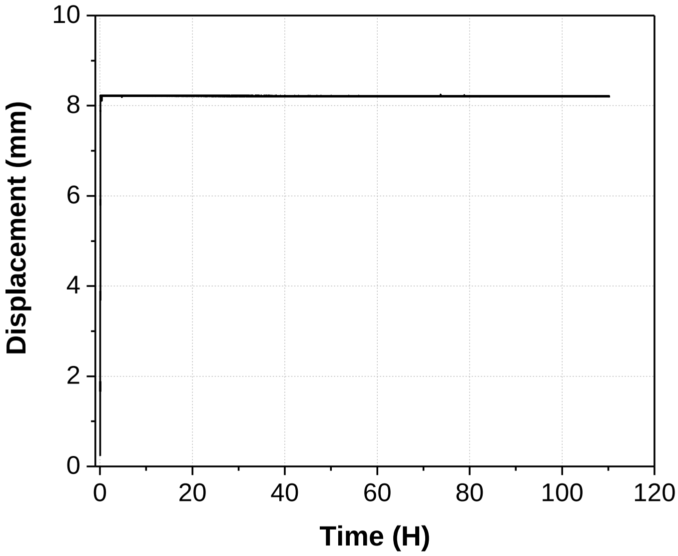


Figure 3. Relaxation test under constant temperature and humidity.

Finally, the developed system was subjected to a series of thermal cycles to analyse the influence of the temperature on it. Similar to the previous test, the proposed system, with an applied load of 1.5 kN, was introduced in a climatic chamber and submitted to a temperature variation from –15 °C to +40 °C during around 235 hours. Figure 4 displays the thermal cycles as well as the displacements registered by the LVDT along the time. As can be observed, temperate has a moderate influence in the proposed system (actually, it was determined that temperature had slight influence in both the springs and the LVDT), which experiments a variation of about 0.35 mm for the total thermal amplitude studied (55 °C). It interesting to note that, due to the behaviour of the LVDT, when temperature is positive, registered displacement is negative. Based on the obtained results, a linear regression was performed establishing the effect of temperature according to Equation 1:

$$\Delta d = 0.03 - 0.007 \cdot \Delta T \quad (1)$$

where ΔT is the temperature variation respected to the initial one (in degrees Celsius), and Δd the expected variation to be registered in the LVDT of the system (in millimetres).

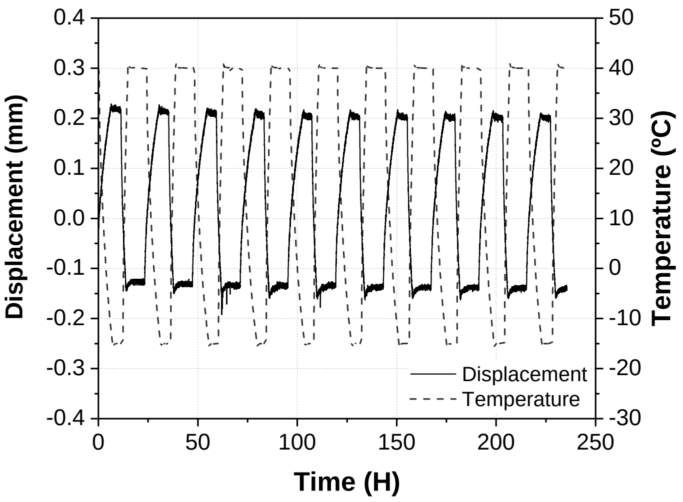


Figure 4. Thermal cycles test.

3.2 In-situ testing

After conducting the previous tests on lab, the proposed system was tested on field at mid-span of the new bridge over Dão River near Coimbra (Portugal). The bridge was designed by *Armando Rito Engenharia, Lda*. company and built by *Casais, S.A.* company. As shown in Figure 5, it consists of a three span prestress concrete box girder bridge, with span lengths equal to 120 m, 170 m and 100 m, respectively, a cross-section height varying from 4 m to 10 m, and a deck of 15 m of width. Piles are formed by two parallel U-shape shells made of prestress concrete, with a height of around 11 m monolithically connected to the bridge deck and at a footing located on the water level, which transmits all stresses to the ground placed under water by nine pilots of 2 m of diameter. The bridge was built by segments, starting simultaneously from the piles and the abutments. At the present, the structural part of the bridge is completely finished and load tests are being conducted.

Hence, the developed system was transported to the bridge and installed at mid-span (i.e. at a section placed 205 m from the “Viseu” abutment) for its evaluation (see Figure 1b). A dead weight of 10 kN was placed at the bottom part of river bed to lock the steel cable (see Figure 1a). Once the system was ready, a truck of 445 kN crosses the bridge twice: (i) first in direction Viseu-Coimbra and afterwards (ii) in opposite direction. During this period of time the LVDT installed in the system registered the vertical deflection at mid-span, which is showed in Figure 6. As can be observed, the truck stopped at mid-span twice, especially in the second cross, when it stopped for 5 minutes. As expected, during this stop no significant creep deformation of the bridge was measured. It should be note that this test was performed in a windy day, what explains the small oscillations observed in the graph.

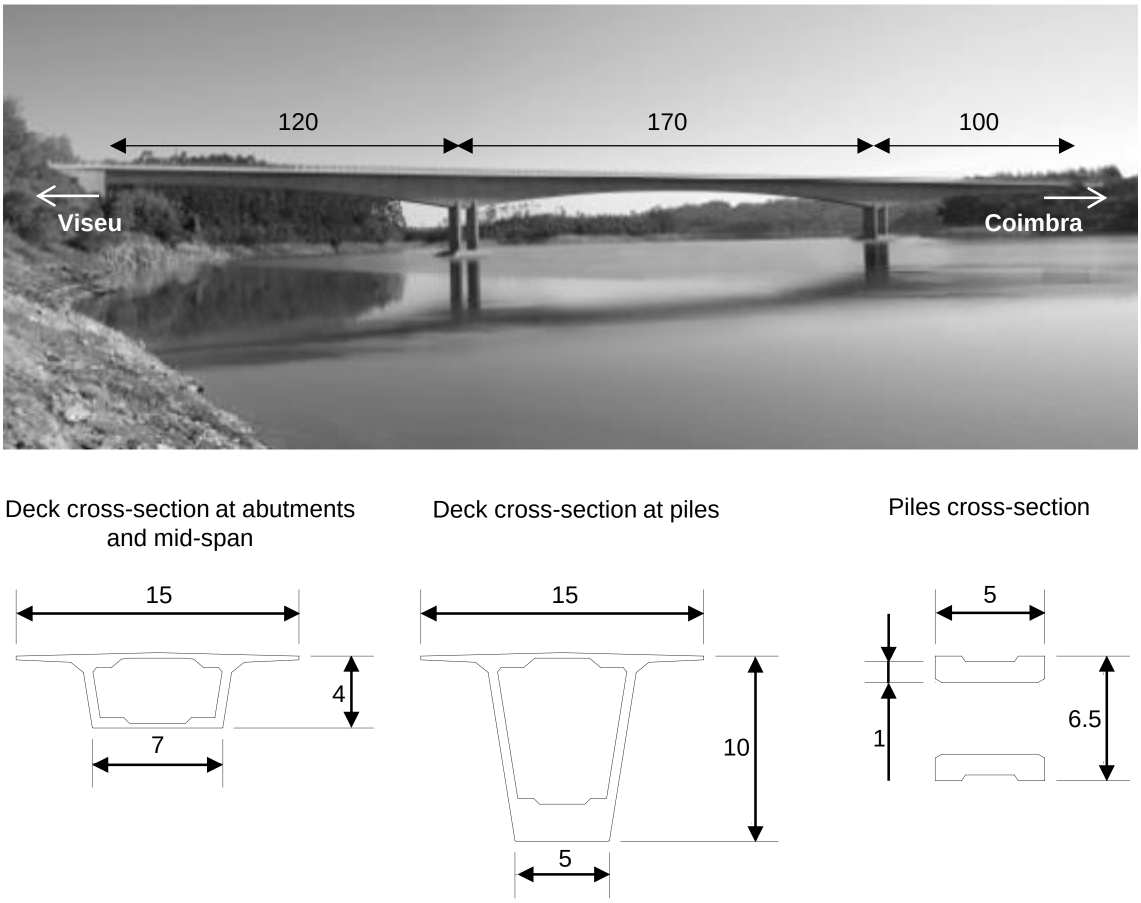


Figure 5. New bridge over Dão River near Coimbra, Portugal (all dimensions are in meters).

4 CONCLUSIONS

This paper has presented a new system for measuring displacements in structures where the access to a fixed point is difficult. Especially, the proposed system has been designed for measuring the vertical deflections registered in a bridge during a load test, for that cases where the bridge spans over a watercourse or other similar situation that makes it difficult the access to a fixed point.

The proposed system is composed of 6 main elements: (1) a dead weight for locking a cable; (2) a steel cable; (3) a LVDT linked to the system and in contact with the bridge deck at the measurement point; (4) a set of two parallel spring; (5) a stretcher, used for prestressing the steel cable; and, (6) a steel frame which allows fixing and tensioning the springs.

In order to validate the developed system, a series of lab tests have been conducted. These tests have shown that the proposed system is able of registering displacements with a high precision. The temperature effect on the system (including the LVDT) has been also assessed and a mathematical expression has been obtained for taking into account this aspect.

Finally, the developed system has been tested in real conditions. The new bridge over Dão River near Coimbra (Portugal) was chosen for carrying out that testing. A truck of 445 kN crossed the bridge while the developed system was registering the vertical deflection at mid-span of the central span of the bridge. As expected, the proposed system was able to perfectly capture the influence line of the bridge.

The good results registered in both lab and field tests give rise to stating that the new proposed system is able of being used for controlling deflections during the load tests carried out in bridges which span over a watercourse or are place in an accidentally terrain. Moreover, the developed system can be used for measure any kind of displacement in any other structure, being recommended for that cases where the access to a fixed point is difficult or nearly impossible.

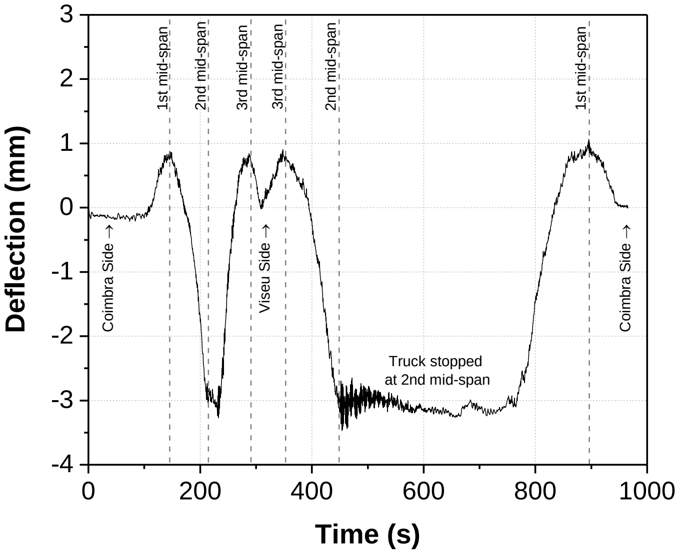


Figure 6. In-situ test.

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