AUTOMATIC DEFLECTION AND TEMPERATURE MONITORING OF A BALANCED CANTILEVER CONCRETE BRIDGE

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SUMMARY

There is a need for reliable monitoring systems to follow the evolution of the behavior of structures over time. Deflections and rotations are values that reflect the overall structure behavior. This paper presents an innovative approach to the measurement of long-term deformations of bridges by use of inclinometers. High precision electronic inclinometers can be used to follow effectively long-term rotations without disruption of the traffic. In addition to their accuracy, these instruments have proven to be sufficiently stable over time and reliable for field conditions.

The Mentue bridges are twin 565 m long box-girder post-tensioned concrete highway bridges under construction in Switzerland. The bridges are built by the balanced cantilever method over a deep valley. The piers are 100 m high and the main span is 150 m. A centralized data acquisition system was installed in one bridge during its construction in 1997. Every minute, the system records the rotation and temperature at a number of measuring points. The simultaneous measurement of rotations and concrete temperature at several locations gives a clear idea of the movements induced by thermal conditions. The system will be used in combination with a hydrostatic leveling setup to follow the long-term behavior of the bridge.

Preliminary results show that the system performs reliably and that the accuracy of the sensors is excellent. Comparison of the evolution of rotations and temperature indicate that the structure responds to changes in air temperature rather quickly.

1. BACKGROUND

All over the world, the number of structures in service keeps increasing. With the development of traffic and the increased dependence on reliable transportation, it is becoming more and more necessary to foresee and anticipate the deterioration of structures. In particular, for structures that are part of major transportation systems, rehabilitation works need to be carefully planned in order to minimize disruptions of traffic. Automatic monitoring of structures is thus rapidly developing.

Long-term monitoring of bridges is an important part of this overall effort to attempt to minimize both the impact and the cost of maintenance and rehabilitation work of major structures. By knowing the rate of deterioration of a given structure, the engineer is able to anticipate and adequately define the timing of required interventions. Conversely, interventions can be delayed until the condition of the structure requires them, without reducing the overall safety of the structure.

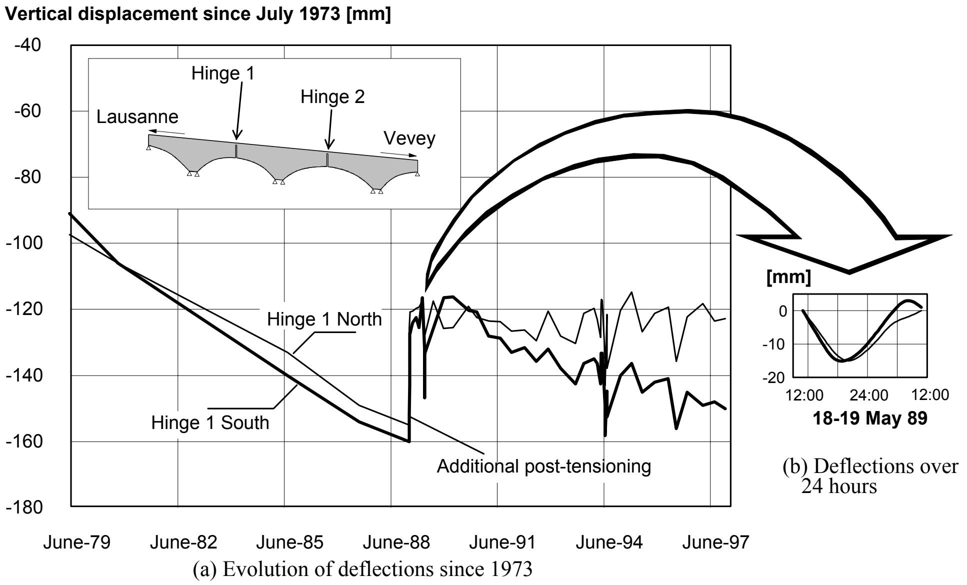
The paper presents an innovative approach to the measurement of long-term bridge deformations. The use of high precision inclinometers permits an effective, accurate and unobtrusive following of the long-term rotations. The measurements can be performed under traffic conditions. Simultaneous measurement of the temperature at several locations gives a clear idea of the movements induced by thermal conditions and those induced by creep and shrinkage. The system presented is operational since August 1997 in the Mentue bridge, currently under construction in Switzerland. The structure has a main span of 150 m and piers 100 m high.

2. LONG-TERM MONITORING OF BRIDGES

As part of its research and service activities within the Swiss Federal Institute of Technology in Lausanne (EPFL), IBAP - Reinforced and Prestressed Concrete has been involved in the monitoring of long-time deformations of bridges and other structures for over twenty-five years [1, 2, 3, 4]. In the past, IBAP has developed a system for the measurement of long-term deformations using hydrostatic leveling [5, 6]. This system has been in successful service in ten bridges in Switzerland for approximately ten years [5,7]. The system is robust, reliable and sufficiently accurate, but it requires human intervention for each measurement, and is not well suited for automatic data acquisition. One additional disadvantage of this system is that it is only easily applicable to box girder bridges with an accessible box.

Occasional continuous measurements over periods of 24 hours have shown that the amplitude of daily movements is significant, usually amounting to several millimeters over a couple of hours. This is exemplified in figure 1, where measurements of the twin Lutrive bridges, taken over a period of several years before and after they were strengthened by post-tensioning, are shown along with measurements performed over a period of 24 hours. The scatter observed in the data is primarily caused by thermal effects on the bridges. In the case of these box-girder bridges built by the balanced cantilever method, with a main span of 143.5 m, the amplitude of deformations on a sunny day is of the same order of magnitude than the long term deformation over several years.

Instantaneous measurements, as those made by hydrostatic leveling, are not necessarily representative of the mean position of the bridge. This occurs because the position of the bridge at the time of the measurement is influenced by the temperature history over the past several hours and days. Even if every care was taken to perform the measurements early in the morning and at the same period every year, it took a relatively long time before it was realized that the retrofit performed on the Lutrive bridges in 1988 by additional post-tensioning [3, 7,11] had not had the same effect on both of them.



(b) Deflections over 24 hours

(a) Evolution of deflections since 1973

Figure 1: Long-term deflections of the Lutrive bridges, compared to deflections measured in a 24-hour period

Automatic data acquisition, allowing frequent measurements to be performed at an acceptable cost, is thus highly desirable. A study of possible solutions including laser-based leveling, fiber optics sensors and GPS-positioning was performed, with the conclusion that, provided that their long-term stability can be demonstrated, current types of electronic inclinometers are suitable for automatic measurements of rotations in existing bridges [8].

3. MENTUE BRIDGES

The Mentue bridges are twin box-girder bridges that will carry the future A1 motorway from Lausanne to Bern. Each bridge, similar in design, has an overall length of approximately 565 m, and a width of 13.46 m, designed to

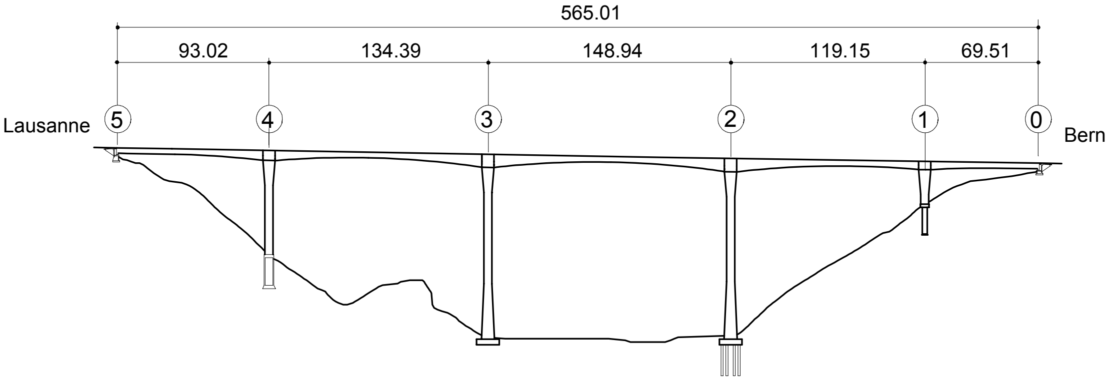


Figure 2: Elevation of the Mentue bridges

Figure 3: Pier 3 of the Mentue bridge during the free cantilevering

carry two lanes of traffic and an emergency lane. The bridges cross a deep valley with steep sides (fig. 2). The balanced cantilever design results from a bridge competition. The 100 m high concrete piers were built using climbing formwork, after which the construction of the balanced cantilever started (fig. 3).

4. INCLINOMETERS

Starting in 1995, IBAP initiated a research project with the goal of investigating the feasibility of a measurement system using inclinometers. Preliminary results indicated that inclinometers offer several advantages for the automatic monitoring of structures. Table 1 summarizes the main properties of the inclinometers selected for this study.

One interesting property of measuring a structure's rotations, is that, for a given ratio of maximum deflection to span length, the maximum rotation is essentially independent from its static system [8]. Since maximal allowable values of about 1/1,000 for long-term deflections under permanent loads are generally accepted values worldwide, developments made for box-girder bridges with long spans, as is the case for this research, are applicable to other bridges, for instance bridges with shorter spans and other types of cross-sections. This is significant because of the need to monitor smaller spans which constitute the majority of all bridges.

Table 1 : Main properties of inclinometers

Property	***Description***
Absolute measurement	The measure is absolute, relative only to the initial position. In case of failure of an instrument, the information given by the others is still usable.
Easy connection to data acquisition systems	Inclinometers are electronic instruments that produce electric signals easily captured by standard data acquisition systems. The inclinometers used for this project include an industrial network interface (RS 485) which greatly reduces cabling.
Principle of measurement applicable to all kinds of bridges	The amplitude of rotations is essentially independent of the static system or the cross section of a bridge. Because of their reliability, inclinometers can be located in hard to reach places, and are thus suitable for all kinds of cross sections.
High accuracy	The high accuracy of inclinometers opens possibilities for measurements of very small movements, such as those that occur within a couple minutes.
Easy installation and operation	Inclinometers are very compact instruments that require only a minimal space. The selected model includes automatic temperature compensation. The sensors can be easily replaced and are reusable.
Cost	Although relatively high, the cost of inclinometers is competitive with comparable systems, and the cost of installation is rather low.

The selected inclinometers are of type Wyler Zerotronic ± 1° [9]. Their accuracy is 1 *microradian* (μrad), which corresponds to a rotation of one millimeter per kilometer, a very small value. For an intermediate span of a continuous beam with a constant depth, a mid-span deflection of 1/20,000 would induce a maximum rotation of about 150 μrad, or 0.15 *milliradians* (mrad).

One potential problem with electronic instruments is that their measurements may drift over time. To quantify and control this problem, a mechanical device was designed allowing the inclinometers to be precisely rotated of 180° in an horizontal plane (fig. 4). The drift of each inclinometer can be very simply obtained by comparing the values obtained in the initial and rotated position with previously obtained values. So far, it has been observed that the type of inclinometer used in this project is not very sensitive to drifting.

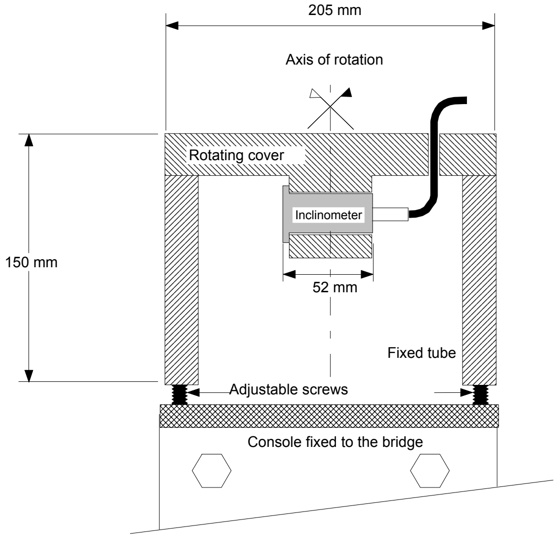


Figure 4: Rotation system for the correction of drifting over time

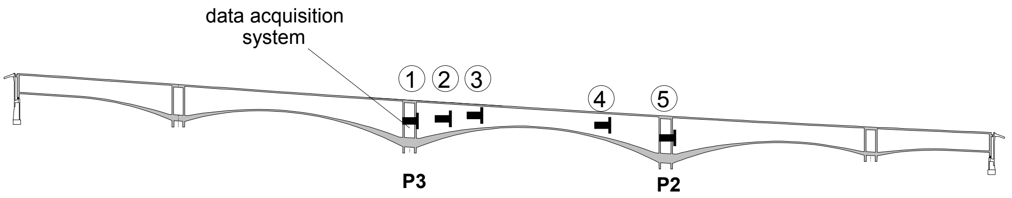
5. INSTRUMENTATION OF THE MENTUE BRIDGES

Because a number of bridges built by the balanced cantilever method have shown an unsatisfactory behavior in service [2, 7,10], it was decided to carefully monitor the evolution of the deformations of the Mentue bridges. These bridges were designed taking into consideration recent recommendations for the choice of the amount of post-tensioning [7,10,13]. Monitoring starting during the construction in 1997 and will be pursued after the bridges are opened to traffic in 2001. Deflection monitoring includes topographic leveling by the highway authorities, an hydrostatic leveling system over the entire length of both bridges and a network of inclinometers in the main span of the North bridge. Data collection is coordinated by the engineer of record, to facilitate comparison of measured values. The information gained from these observations will be used to further enhance the design criteria for that type of bridge, especially with regard to the amount of post-tensioning [7, 10, 11, 12, 13].

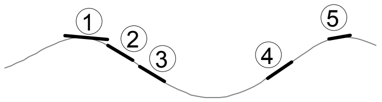
The automatic monitoring system is driven by a data acquisition program that gathers and stores the data. This system is able to control various types of sensors simultaneously, at the present time inclinometers and thermal sensors. The computer program driving all the instrumentation offers a flexible framework, allowing the later addition of new sensors or data acquisition systems. The use of the development environment LabView [14] allowed to leverage the large user base in the field of laboratory instrumentation and data analysis. The data acquisition system runs on a rather modest computer, with an Intel 486/66 Mhz processor, 16 MB of memory and a 500 MB hard disk, running Windows NT. All sensor data are gathered once per minute and stored in compressed form on the hard disk. The system is located in the box-girder on top of pier 3 (fig. 5). It can withstand severe weather conditions and will restart itself automatically after a power outage, which happened frequently during construction.

6. SENSORS

Figure 5(a) shows the location of the inclinometers in the main span of the North bridge. The sensors are placed at the axis of the supports (① and ⑤), at 1/4 and 3/4 (③ and ④) of the span and at 1/8 of the span for ②. In the cross section, the sensors are located on the North web, at a height corresponding to the center of gravity of the section (fig. 5a). The sensors are all connected by a single RS-485 cable to the central data acquisition system located in the vicinity of inclinometer ①. Monitoring of the bridge started already during its construction. Inclinometers ①, ② and ③ were installed before the span was completed. The resulting measurement were difficult to interpret, however, because of the wide variations of angles induced by the various stages of this particular method of construction.



(a) location of the inclinometers in the main span of the North bridge



(b) principle for the determination of the deflected shape from measured rotations

Figure 5: Location of the inclinometers in the main span and principle for the reconstruction of deformations

The deflected shape will be determined by integrating the measured rotations along the length of the bridge (fig. 5b). Although this integration is in principle straightforward, it has been shown [8, 16] that the type of loading and possible measurement errors need to be carefully taken into account.

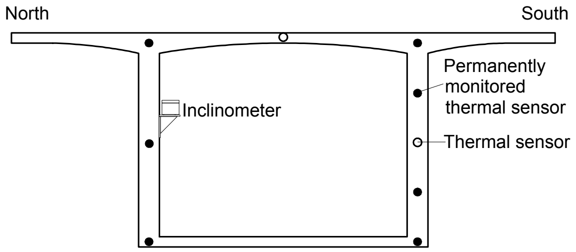


Figure 6: Location of thermal sensors in the main span

Thermal sensors were embedded in concrete so that temperature effects could be taken into account for the adjustment of the geometry of the formwork for subsequent casts. Figure 6 shows the layout of thermal sensors in the main span. The measurement sections are located at the same sections than the inclinometers (fig. 5). All sensors were placed in the formwork before concreting and were operational as soon as the formwork was removed, which was required for the needs of the construction. In each section, seven of the nine thermal sensor (indicated in solid black in fig. 6) are now automatically measured by the central data acquisition system.

7. RESULTS

Figure 7 shows the results of inclinometry measurements performed from the end of September to the third week of November 1997. All inclinometers performed well during that period. Occasional interruptions of measurement, as observed for example in early October are due to interruption of power to the system during construction operations. The overall symmetry of results from inclinometers ① and ⑤ as well as ③ and ④ seem to indicate that the instruments drift is not significant for that time period. The maximum amplitude of bridge deflection during the observed period, estimated on the basis of the inclinometer's results, is around 40 mm. More accurate values will be computed when the method of determination of deflections will have been further calibrated with other measurements. Several periods of increase, respectively decrease, of deflections over several days can be observed in the graph. This further illustrates the need for continuous deformation monitoring to account for such effects. The measurement period was "busy" in terms of construction, and included the following operations: the final concrete pours in that span, horizontal jacking of the bridge to compensate some pier eccentricities, as well as the stressing of the continuity post-tensioning, and the de-tensioning of the guy cables (fig. 3). As a consequence, the interpretation of these measurements is quite difficult. It is expected that further measurements, made after the completion of the bridge, will be simpler to interpret.

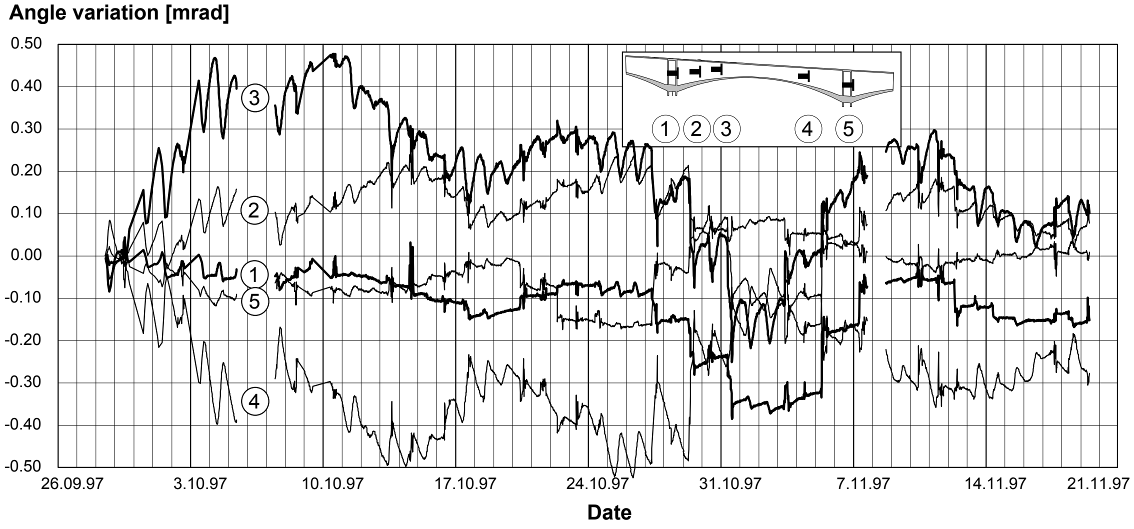


Figure 7: Measured angle variations from the end of September through November 1997

Figure 8 shows a detail of the measurements made in November, while figure 9 shows temperature measurements at the top and bottom of the section at mid-span made during that same period. It is clear that the measured deflections correspond to changes in the temperature. The temperature at the bottom of the section follows closely variations of the air temperature (measured in the shade near the north web of the girder). On the other hand, the temperature at the top of the cross section is less subject to rapid variations. This may be due to the high elevation of the bridge above ground, and also to the fact that, during the measuring period, there was little direct sunshine on the deck. The temperature gradient between top and bottom of the cross section has a direct relationship with short-term variations. It does not, however, appear to be related to the general tendency to decrease in rotations observed in fig. 8.

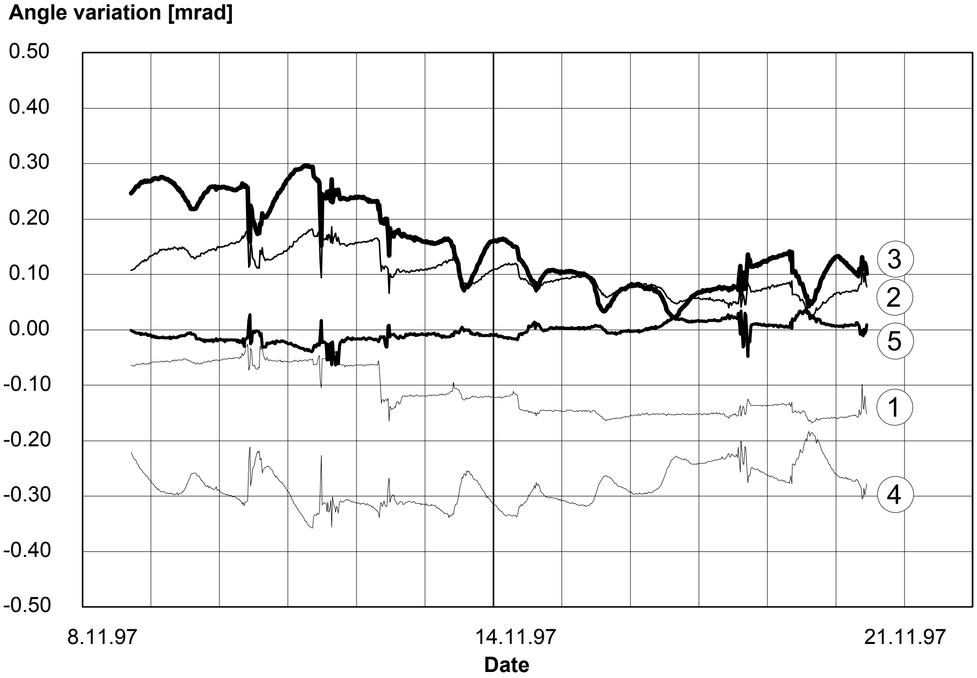


Figure 8 : Angle variations in November 1997

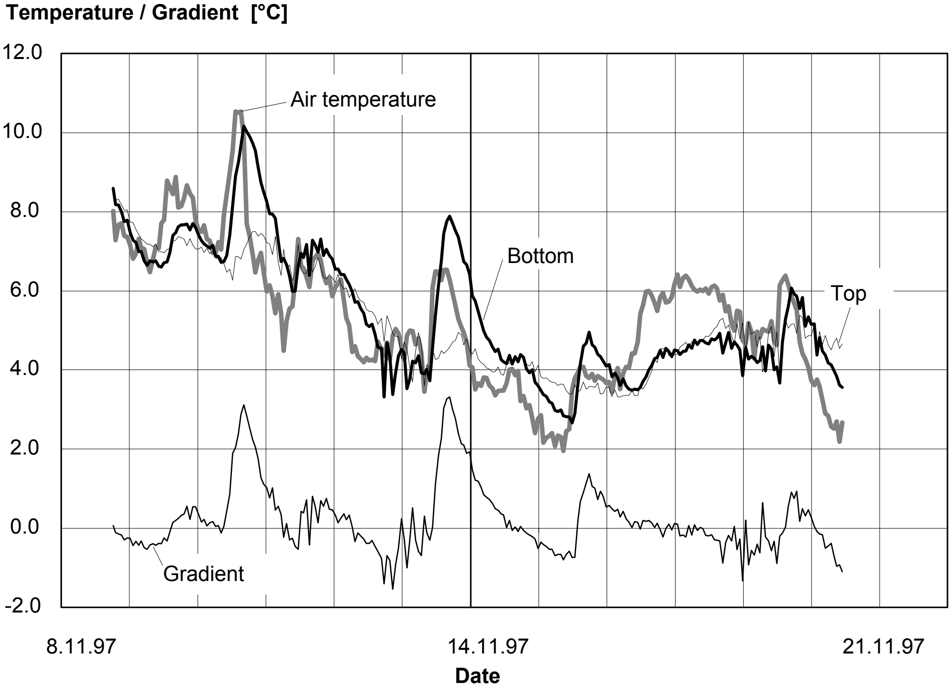


Figure 9: Temperatures in November 1997

8. FUTURE DEVELOPMENTS

Future developments will include algorithms to reconstruct deflections from measured rotations. To enhance the accuracy of the reconstruction of deflections, a 3D finite element model of the entire structure is in preparation [15]. This model will be used to identify the influence on rotations of various phenomena, such as creep of the piers and girder, differential settlements, horizontal and vertical temperature gradients or traffic loads.

Much work will be devoted to the interpretation of the data gathered in the Mentue bridge. The final part of the research project work will focus on two aspects: understanding the very complex behavior of the structure, and determining the most important parameters, to allow a simple and effective monitoring of the bridge's deflections.

Finally, the research report will propose guidelines for determination of deflections from measured rotations and practical recommendations for the implementation of measurement systems using inclinometers. It is expected that within the coming year new sites will be equipped with inclinometers. Experiences made by using inclinometers to measure deflections during loading tests [16, 17] have shown that the method is very flexible and competitive with other high-tech methods.

As an extension to the current research project, an innovative system for the measurement of bridge joint movement is being developed. This system integrates easily with the existing monitoring system, because it also uses inclinometers, although from a slightly different type.

9. CONCLUSIONS

An innovative measurement system for deformations of structures using high precision inclinometers has been developed. This system combines a high accuracy with a relatively simple implementation. Preliminary results are very encouraging and indicate that the use of inclinometers to monitor bridge deformations is a feasible and offers advantages. The system is reliable, does not obstruct construction work or traffic and is very easily installed. Simultaneous temperature measurements have confirmed the importance of temperature variations on the behavior of structural concrete bridges.

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