A LOW-COST PROCEDURE FOR QUICK MONITORING OF MONUMENTS AND BUILDINGS

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Abstract
A simple and reliable solution for structural monitoring of monuments and buildings, is presented. The system is based on the use of fixed instruments equipped with electric sensors and of a simple removable electric unit for periodical data acquisition. In this way the cost of the monitoring system can be greatly reduced without decreasing its reliability. In order to analyse the deformation behaviour of the structure, crack-gauges and long-base extensometers are generally installed as well as direct pendulums, clinometers and thermal-gauges. The flexibility of this monitoring system allows its use for the solution of any structural problem.
Two examples are presented:
the first one is referred to a long-term monitoring of a monument of great importance (the Church of SS. Giovanni and Paolo in Venice);
the second one is a short-term monitoring during the strengthening works of a church and a bell-tower (the Church of Angone in the Camonica Valley).

1. Foreword

Monitoring plays a significant role in the structural analysis of historical buildings. It is able to control the deformation behaviour of a structure during its life or to analyse the effect of rehabilitation and strengthening works. The real effectiveness of a restoration intervention on old buildings can be correctly evaluated only after a suitable period of observation of the deformation behaviour of the structure as a function of time and environmental conditions changes.
Monitoring should be widely used as a precious design tool before, during and after the rehabilitation works.
The design of a monitoring system can follow two different approaches:

a) use of fixed electrical transducer and automatic continuous data acquisition and recording system;
b) use of fixed or removable instruments and manual readings taken at fixed intervals of time.

The use of an automatic system is usually limited to important monuments or buildings or to delicate structural problems and rarely it is applied to structures with low historical and architectural importance. Moreover it requires efficacious protections for the cables and the acquisition equipment that can greatly increase the cost of the system especially in the case of execution of restoration or strengthening works.
In order to increase the use of monitoring also for buildings with lower historical and architectural significance, it is necessary to reduce the cost without decreasing the reliability and the accuracy of the measurements.
A reliable solution to this problem is presented in the paper which emphasizes the use of simplified monitoring systems based on the installation of fixed electrical sensors (of the same type used for automatic system) but with a very simple removable electric unit for periodical data acquisition. The reading unit can be easily installed and removed by the operator and it does not require the use of specialized technicians for periodical readings.
This kind of system is able to reduce the length of the cables because it does not require to collect all the instruments to a central unit; the reading equipment can be connected to several switching units which collect the groups of sensors installed in the different zones of the building.
The low cost of this monitoring system is due to several factors: rapidity of installation, low cost of the reading unit, reduction of the length of the cables, reduction of the cost for protection and maintenance of the system as well as for periodical data acquisition.
This kind of system can be used both for long-term monitoring to analyse the deformation behaviour as a function of time and temperature and for short-term monitoring during the execution of strengthening works as a design tool able to compare the original design with the real behaviour of the structure and to indicate the need of any change of the design solutions.
When the environmental conditions are so difficult that it is impossible to guarantee efficient protection for fixed instruments with electric transducers, the use of monitoring must not be neglected. In this case a monitoring system based on removable mechanical instruments can be used. This system is very cheap but the periodical readings require great care and more time in comparison with the use of a removable electric unit; moreover, the reliability of the measurements can be influenced by the hand of the operator.

2. Instruments and data acquisition system

In order to analyse the structural behaviour of a masonry building, the following main phenomena are measured:

Crack movements
Measuring the relative movements of the main cracks (opening and sliding) is by far the most simple and frequently applied method. Fixed electrical crack-gauges are installed, connected to the masonry by using special spherical devices that eliminate any bending effect on the sensor (see the particular of the crack-gauge in fig. 1).

Relative horizontal movements of vertical structures
Long-base extensometers are used to measure the relative horizontal movement of vertical structures (walls and columns). The instrument is equipped with invar wire, which is kept in tension by a weight, and with an electrical transducer (see the particular of the extensometer in fig. 1). As for crack-gauge, the high flexibility of this instrument allows an easy and quick installation. With the aid of climbers, the instruments can be installed without scaffoldings even in zones were the access is difficult.

Absolute horizontal movements of vertical structures
The absolute horizontal movements at the top of walls and colums are measured by using a direct pendulum. A small cantilever is installed in the upper part of the structure to hang the pendulum wire while, at the bottom, a reading unit equipped with a telecoordinometer measures the two displacement components of the wire. The two electrical sensors of the telecoordinometer can be measured by means of a removable electric unit or by an automatic data acquisition system.
When a telecoordinometer cannot be installed, a simple and reliable pendulum can be used with a removable laser measuring unit which can be put on the vassel only during the reading phase. The particular of this pendulum is shown in fig 1.

Environmental conditions
The deformations of a structure are greatly influenced by the environmental conditions which are mainly temperature, radiation and wind. Temperature measurements are by far the most important due to their great effect on the deformation behaviour of the structure. By using electrical thermal-gauges, the air temperature inside and outside can be measured as well as the temperature gradient inside the masonry by drilling small diameter boreholes.

Differential settlements and tilting
When the building is affected by differential settlements due to foundation problems, an additional instrumentation may be required in order to examine the vertical settlements and the tilting of the foundation structures. The differential settlements are measured by using levelometric vessels, containing liquid and communicating each other. Inside each vessel, an electrical transducer measures the level of the liquid.
Tilting of vertical or horizontal structures can be measured by inclinometers provided with electrical sensors.

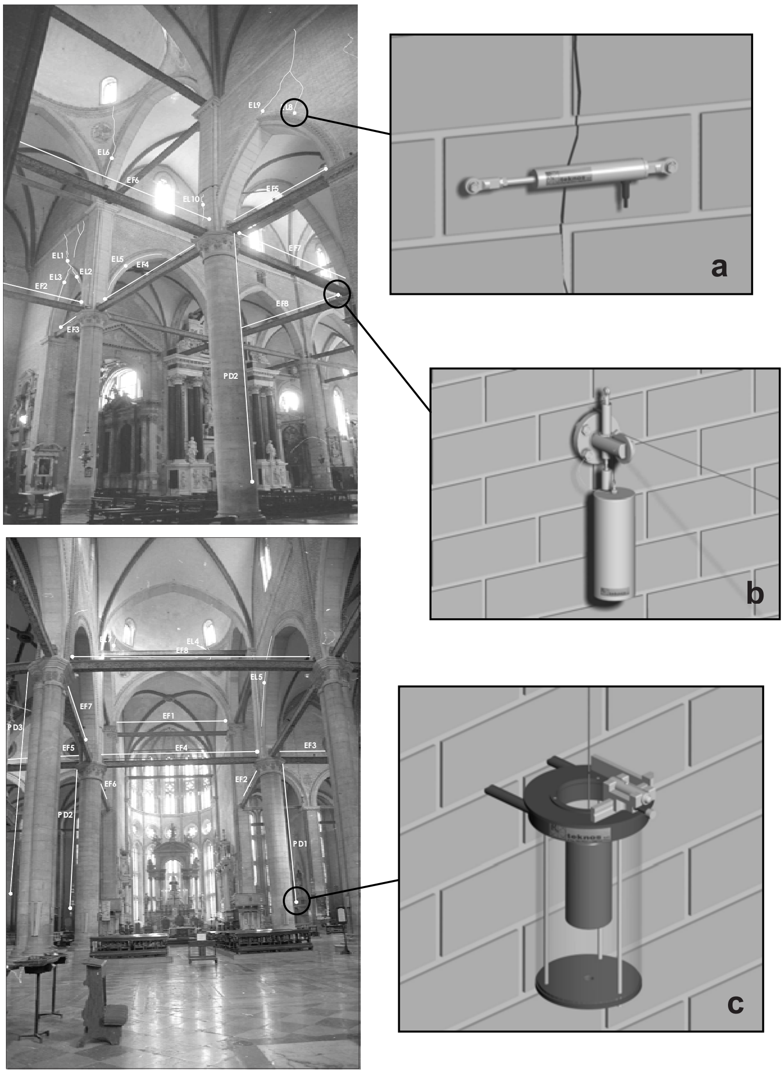

Fig. 1
Church of SS. Giovanni and Paolo in Venice
General layout of the instruments installed in the church and particular of the main instruments:

a- crach-gauge (EL)
b- long base extensometer (EF)
c- direct pendulum (PD)

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The use of this instrumentation, due to the high cost and to the difficulties of installation and interpretation of the data, is generally limited to structures of great

importance with serious geotechnical problems.

Removable electric reading unit
The monitoring system herein proposed is based on the use of a simple and cheap removable reading unit equipped with rechargeable battery. The electrical sensors of all the instruments above described are connected with small switching units on which the reading unit is connected during the periodical readings. In order to reduce the length of the electrical cables, several switching units are installed in the structure. The reading operation is very fast and simple and it does not require the use of specialized technicians. It must be pointed out that this monitoring system does not require permanent electrical connection for instruments alimentation; therefore the problems of protection of the sensors against fulmination are greatly reduced.
In case that in the future an automatic acquisition system should be required, all the peripherical switching units could be replaced by automatic peripheral units connected with a central unit where a computer can process the data or send them to a remote control centre. No modification is required for the instruments.

3. Long-term monitoring of an important structure (The Basilica of SS. Giovanni and Paolo in Venice)

The first example is referred to a structure of great historical and architectural importance which has to be controlled for a long period in order to examine its deformation behaviour as a function of time and temperature changes.
The Basilica of SS. Giovanni e Paolo in Venice is the most imposing example of sacred gothic architecture in Venice. It was built in 14th century and during its life it has undergone many restoration and strengthening works; the last important structural intervention was carried out in the period 1919-1922 when steel chains were installed between the columns.
In February 2000, under the supervision of Soprintendenza of Venice, a monitoring system was installed on the main supporting structures of the Basilica. The general layout of the instruments, shown in fig. 1, includes:

- 8 long-base extensometers to measure the relative displacements between the columns;
- 10 crack-gauges on the main cracks of the supporting structures and central dome;
- 1 thermal-gauge for measuring the temperature of the air inside the Basilica.

In May 2000, three direct pendulums, with laser measuring device, were installed in order to measure the absolute displacements of three columns with very high deviation from verticality. All the instruments were installed in a very short time (about 3 days) in the upper part of the masonry structures with the assistance of expert climbers, without any scaffolding (fig. 2).

Fig. 2
Church of SS. Giovanni and Paolo in Venice
Installation of crack-gauges and long base extensometers on the upper part of the columns with the aid of climbers.

The cables of the extensometers, of the crack-gauges and of the thermal-gauges were collected by two switching units where the removable electrical apparatus was connected for periodical readings (fig. 3).
The three pendulums, without electrical sensors, were measured by using a removable coordinometer provided with laser equipment to check the two displacements coordinates of the wire along two ortogonal axes.
The periodical measurements of all the instruments were taken with a frequence of 15 days and the data were plotted versus time and compared with the diagram of temperature. Fig. 4 shows the diagrams of some crack-gauges and long-base extensometers in the period Feb. 2000 – Sept. 2001. It can be observed that the relative movements of the columns as well as the movements of the cracks faithfully follow the temperature variations. No significant permanent deformations have been observed at the end of the first yearly thermal cycle.
By using the information obtained by direct pendulums and long-base extensometers, the absolute horizontal movements of the central columns were determined. These movements were analysed during two phases of the thermal cycle: during the temperature decreasing phase (July 2000 – Jan 2001) and during the increasing phase (Jan 2001 – July 2001). Fig. 5a shows the displacement vectors measured at the top of the columns in the temperature decreasing period; displacement values of about 1.1-1.2

mm were measured in the columns monitored by the pendulums PD1 and PD2 while smaller values were measured in the other columns. The displacement vectors measured in the same columns in the second thermal period with increasing temperature (see fig. 5b), show a clear inversion of the movements of the columns. The displacement values are very close to those measured in the temperature decreasing phase.

This analysis confirms that in the first yearly thermal cycle the deformation behaviour of the supporting structures of the Basilica is only depending on temperature variation and no significant permanent displacements related to other causes have been observed.

The example herein presented clearly shows that the proposed monitoring system is able to analyse with great accuracy and reliability the deformation behaviour of a monumental building with a very low cost for periodical acquisition and processing of the data and for the maintenance of the system.

Fig. 3
Church of SS. Giovanni and Paolo in Venice
Removable electric unit for periodical acquisition of the data

4. Short-term monitoring during strengthening works (The Church of Angone in the Camonica Valley)

This second example shows the precious aid of monitoring during the execution of strengthening works on a structure which was seriously damaged by an external cause.

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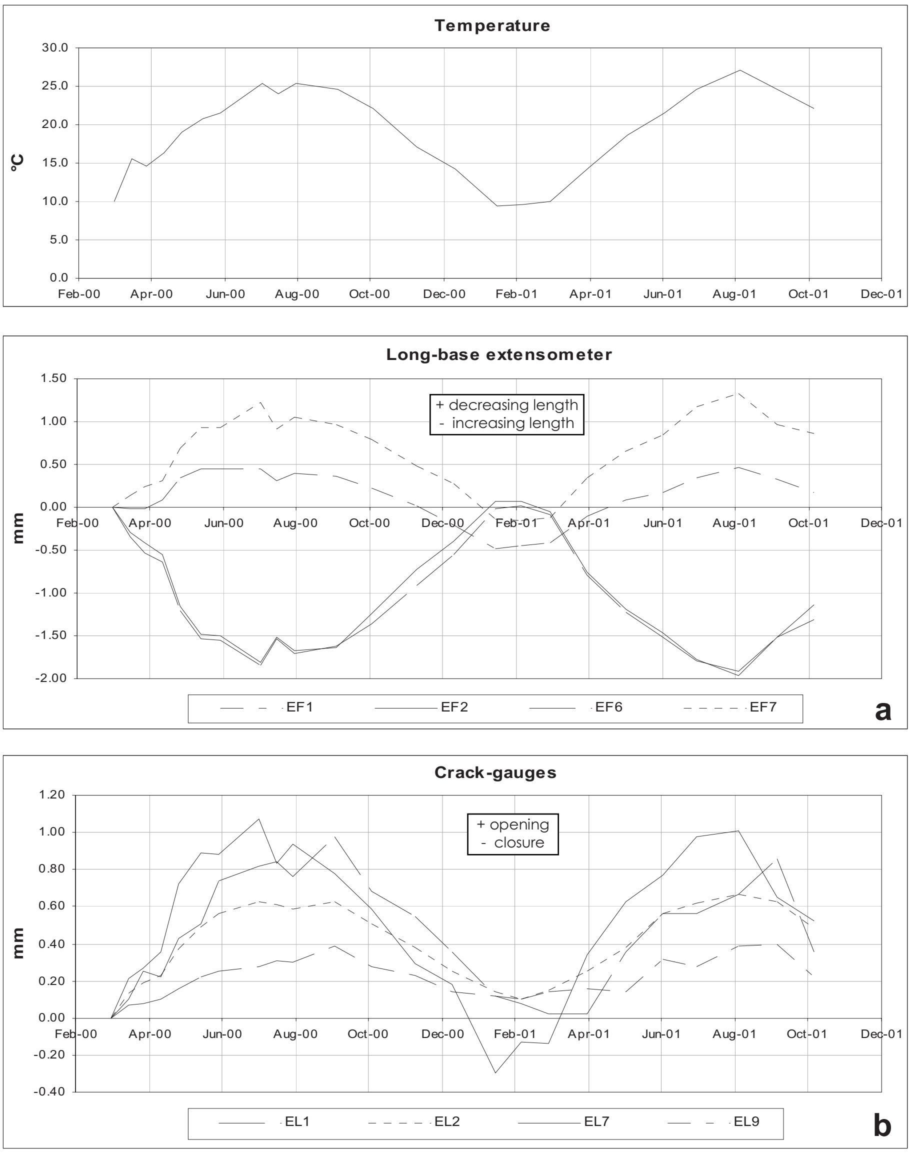

Fig. 4
Church of SS. Giovanni and Paolo in Venice
Analysis of the deformation behaviour of the church as a function of time and temperature changes:
a- diagrams of the relative movements between some columns
b- diagrams of the movements of the main cracks

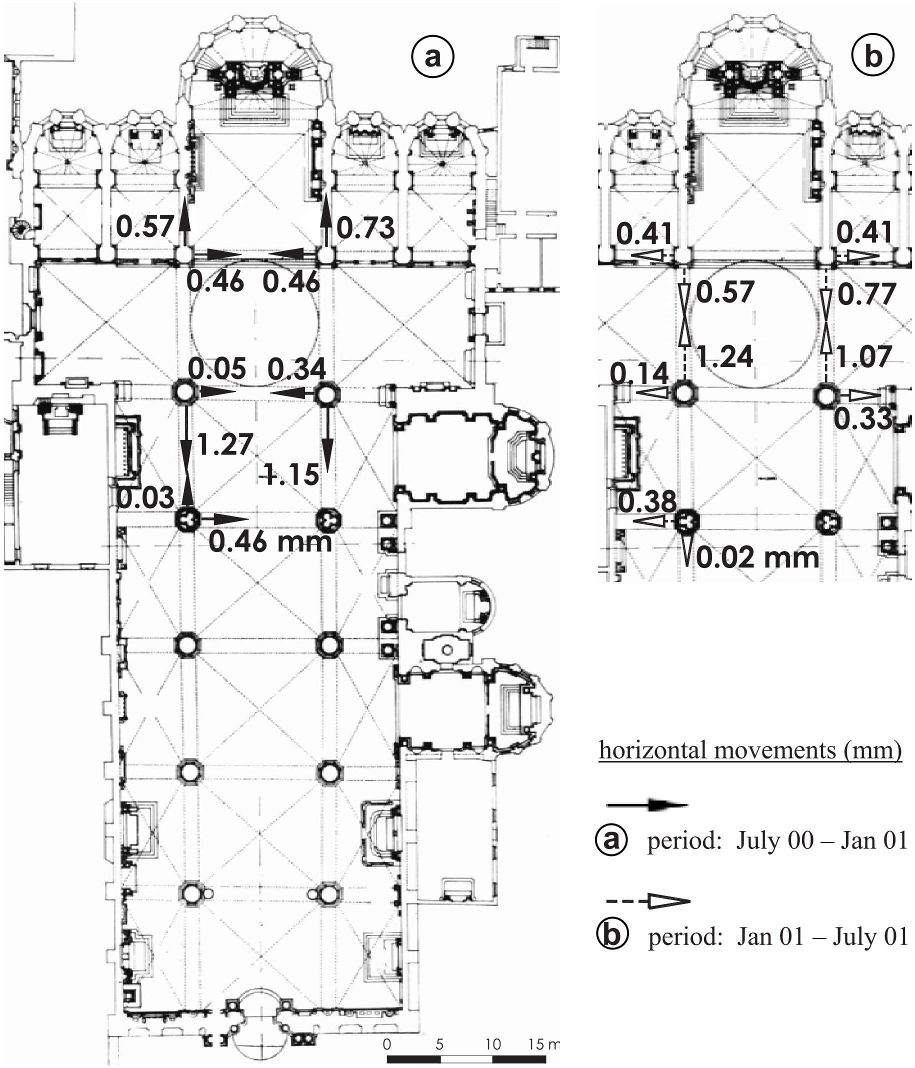

Fig. 5
Church of SS. Giovanni and Paolo in Venice
Absolute horizontal movements at the top of the central columns in two different periods:

a- decreasing temperature
b- increasing temperature

The Church of Angone was involved, after a severe raining period, in a differential settlement of soil foundation which induced a tilting effect on the bell tower and right side wall. In the night of 24th Dec. 2000, the steel chain of the triumph arch, adjoining to the bell tower, suddenly collapsed.
Provisional strengthening chains were rapidly installed and a geotechnical investigation was carried out which showed the presence of soft soil layer on the right side of the church.
In Feb. 2001, a monitoring system was installed, including 2 long-base extensometers, 4 crack-gauges and one thermal-gauge. All the instruments were connected to a switching unit for periodical readings with the removable equipment. In fig. 6a the general layout of the instruments is shown.

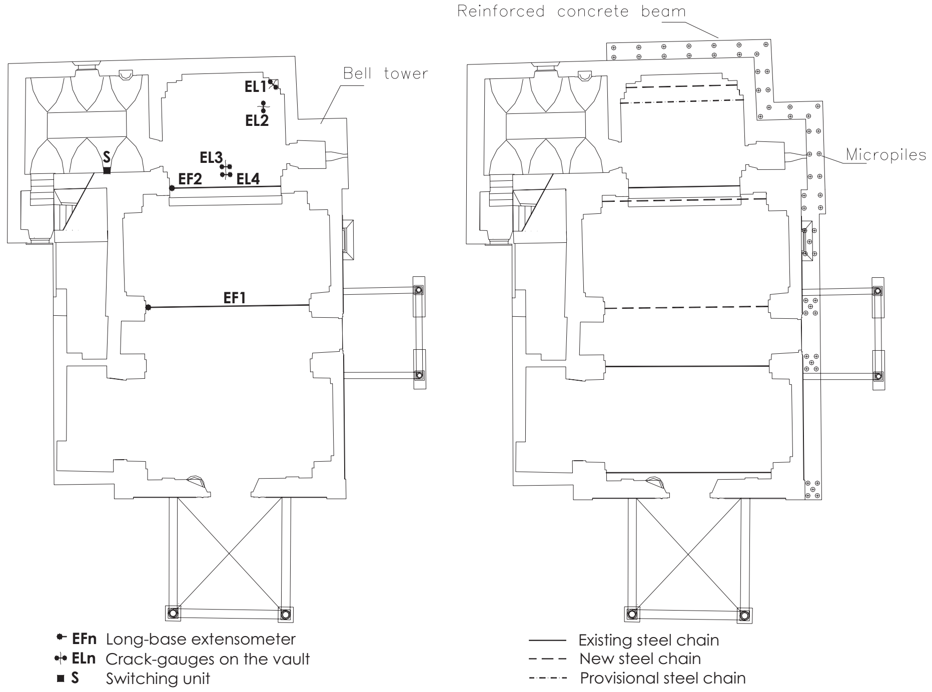

Fig. 6
Church of Angone in the Camonica Valley
a- general layout of the instruments installed during the strengthening works
b- scheme of the strengthening interventions on the foundation and on the supporting masonries.

During the first period of observation, from Feb. to Apr. 01, a progressive movement of the bell tower was observed, which means that the settlement process of soil foundation was continuing (see diagram of extensometer EF2 in fig. 8).

At the beginning of April, it was decided to start the consolidation works of the foundations by using micropiles (length 11 m) and a reinforced concrete beam connected to the existing foundation structures. The scheme of the consolidation works is shown in fig. 6b which also indicates the existing steel chains and the new ones. Fig. 7 shows the transversal section of the church with the indication of the consolidation intervention under the bell tower and the right side wall, as well as the position of extensometers EL1 and EL2 which were used to control all the phases of the consolidation works. The monitoring system was particularly precious to adapt the procedures of execution of the works to the real behaviour of the church and to correct an anomalous procedure for the execution of micropiles. In fig. 8 the diagrams of the deformations measured by the extensometers EL1 and EL2 are shown during all the phases of the strengthening works.
At the beginning of the drilling phase for micropiles, 5 boreholes were drilled close to the bell-tower without grouting the steel tubes. During this phase a sudden movement of 1 mm was measured by the extensometer EL2. The procedure for the execution of micropiles was then rapidly changed and strictly controlled by the monitoring system in order to avoid dangerous movements of the bell tower. A second sudden

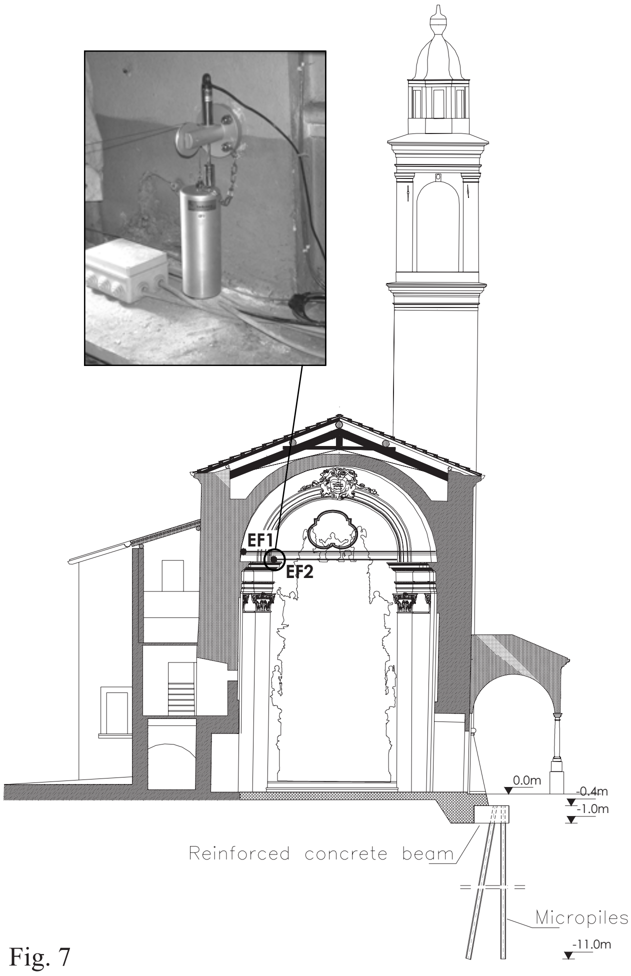

Fig. 7
Church of Angone in the Camonica Valley
Transversal section of the church with the indication of the two long-base extensometers (EL1, EL2) and the foundation consolidating works. A particular of the long-base extensometer EL2 is shown.

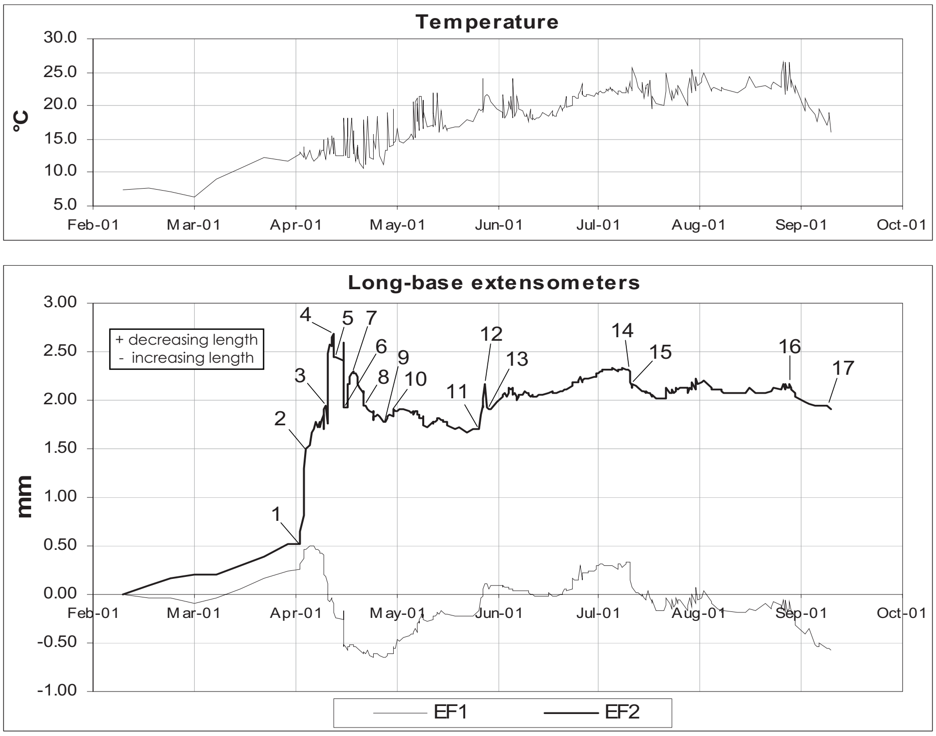

Fig. 8
Church of Angone in the Camonica Valley
Diagrams of the relative movements of the lateral walls (extensometers EL1, EL2) during all the phases of the strengthening works.
1 start of borehole drilling for micropiles; **1-2** five boreholes were drilled close to the bell-tower without grouting the micropiles; **2-3** during this phase each micropile was grouted just after drilling; **3-4** the effect of five additional micropiles induced a further rotation of the bell-tower; a crack appeared between the bell-tower and the lateral wall which inverted its tilting (see extensometer EF1); **4-5** a provisional reinforcing steel chain was installed; **5-6** the tension of the chains was increased **6-7** a further rotation due to five new micropiles was observed; **7-8** two new provisional reinforcing steel chains were installed; **8-9** the tension of the new steel chains was gradually increased; **9-10** a residual movement induced by the last four micropiles was observed; **10** the reinforced concrete beam which connects the micropiles heads to the bell-tower and presbiterial walls, is completed; **10-11** the consolidation of the lateral wall of the church is completed; **11-12-13** unloading and reloading test to verify the effect of the steel chains tension; **13-14** only the temperature increasing is affecting the deformation behaviour; **14-15** final tensioning of the steel chains close to extensometers EL1 and EL2; **16-17** the effect of temperature decrease is clearly evidenced by the measurements of extensometers EL1 and EL2.

movement (0.70 mm) occurred during the execution of other micropiles and a new crack appeared in the right wall between the anchoring points of the instruments EL1 and EL2. As a result of this crack it was observed that the part of the wall regarding EL1 was non collaborating any more with the remaining part of the wall and the bell tower. In fact the diagram of EL1 in fig. 8 shows an inversion of the movement while EL2 continues its movement in the same direction. After this crack occurred, provisional steel chains were installed and tensioned under the control of the monitoring system.
Fig. 8 describes in detail all the phases of the works and it can be observed how promptly the instruments are able to evidence the effect of all the operations on the deformation behaviour of the church.
Also the crack-gauges gave very useful information during the working phases and their measurements were in good agreement with those of the long-base extensometers.
The monitoring system was controlled several times per day directly by the technicians involved in the direction of the works and was able to promptly follow quasi in real time the effect of the strengthening works with a cost much lower than that of a complete automatic monitoring system.

6. References

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