Testing and monitoring for the control of strengthening interventions of Santa Maria Gloriosa dei Frari in Venice

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1 Introduction

The reconstruction of the Frari Basilica started in 1340 and was completed in the second half of the XV century. The bell-tower was built between 1361 and 1396 and it was designed as a separated body. The bell-tower, 65.00 m high and 9.50 m wide, shows a double pipe brick masonry structure, supporting the internal staircase. In 1432, the St Peter's chapel was constructed, leaned against the bell-tower, on its north-east side. The chapel's structure is nevertheless independent from both the bell-tower and the Basilica. The bell-tower showed the first documented signs of movements at the end of the XVI century. Its movements (settlement and tilting) continued progressively and at the end of 19th century it was observed a differential settlement of about 40 cm between the bell-tower and the walls of the Basilica. At that time, the deviation from verticality, measured at a height of 42.50 m, was about 76.50 cm toward outside.
The vertical settlement of the bell-tower induced severe crack pattern in the wall of the Basilica and in the vaults of the St. Peter chapel. In 1904, after the collapse of St. Mark bell-tower, a strengthening intervention was carried out on the bell-tower foundations. This intervention, consisting in widening of the bell-tower foundation base, was carried out only in the external side of the bell-tower and was not extended to the other sides. The strengthening project considered the traditional venetian soil strengthening technique, with the insertion of new timber piles (3.80 m long) covered by a two meters wide concrete bed, parallel to the side of the bell-tower (Figure 1).

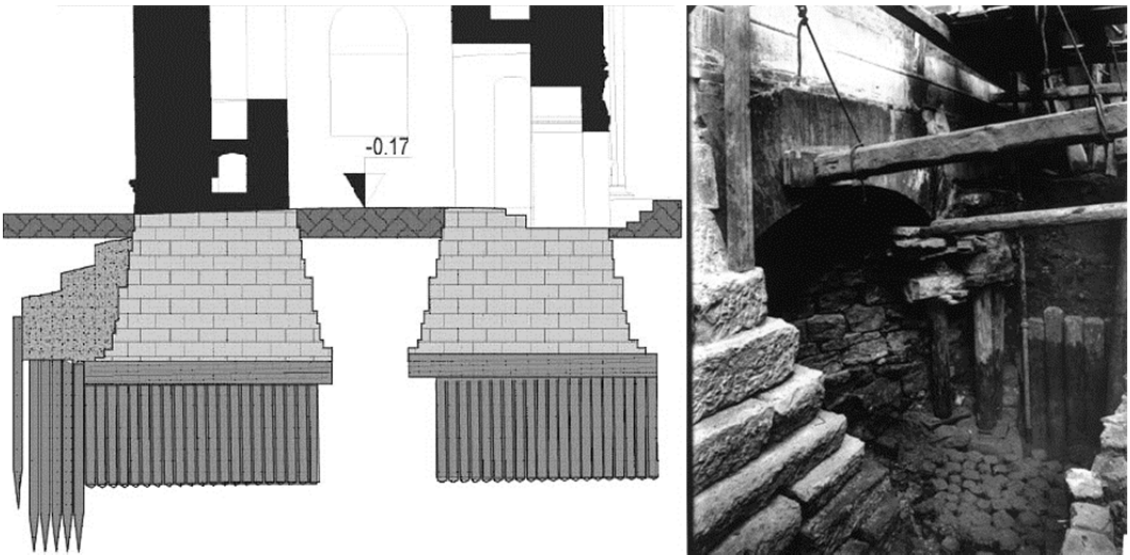

Fig. 1 Strengthening intervention on the foundations of the Frari bell-tower at the beginning of the 20th century..

During this intervention phase, the bell-tower and the St. Peter chapel, were strictly connected at the foundation level and at different heights on the perimeter wall. After this intervention on the external side, the bell-tower progressively inverted the tilting effect towards the internal structures of the Basilica. The effect of this movement was a large crack pattern on the wall which connects the bell-tower to the adjacent pillar of the Basilica, as well as in the supporting structures and vault of St. Peter chapel.
After the intervention of 1904, to the end of XX century, the estimated vertical settlement of the bell-tower was about 100 mm which means about one millimeter per year.

2 Structural diagnostic investigation

In 1990, subsequently to an extensive analysis of the structural behaviour of the Venice bell-towers, a diagnostic investigation on the Frari bell-tower started. In September 2000, some signs of structural

deterioration appeared: new crack patterns, especially in the St Peter chapel vaults, widening of already existing cracks, falling of small portions of plaster and bricks from the vaults. Emergency interventions were provided to the structures more affected by the deformation processes. In particular, the installation of a timber frame was required to support the stone arch which connects the bell-tower to the adjacent pillar of the Basilica.
In the period 2001-2003, detailed diagnostic investigations were carried out as well as the installation of a monitoring system able to check in real time the deformation behaviour of the structure.

Crack pattern survey

The crack-pattern survey was carried out with the aid of climbing technicians. The opening and the length of the main cracks were checked as well as the extension of the damaged zones, mainly concerning the detachment of the surface layer of the masonry wall. It was observed the presence of several cracks near the corners which is due to local stress concentration. Large areas involved by the detachment of the surface layer were also found, mainly in the pilaster strip.

Measurement of the state of stress

Flat-jack testing technique was used to measure the existing state of stress on the masonry structures of the bell-tower and of the adjacent structures of the Basilica (Figure 2). At the base of the bell-tower an average value of 1.92 MPa was measured on the external side, while on the inner part a mean value of 1.44 MPa was estimated. Very high values of compressive stress were measured at the top of the column sustaining the propped arch: 1.76 MPa at the external side and 3.20 and 3.04 MPa on the inner side.

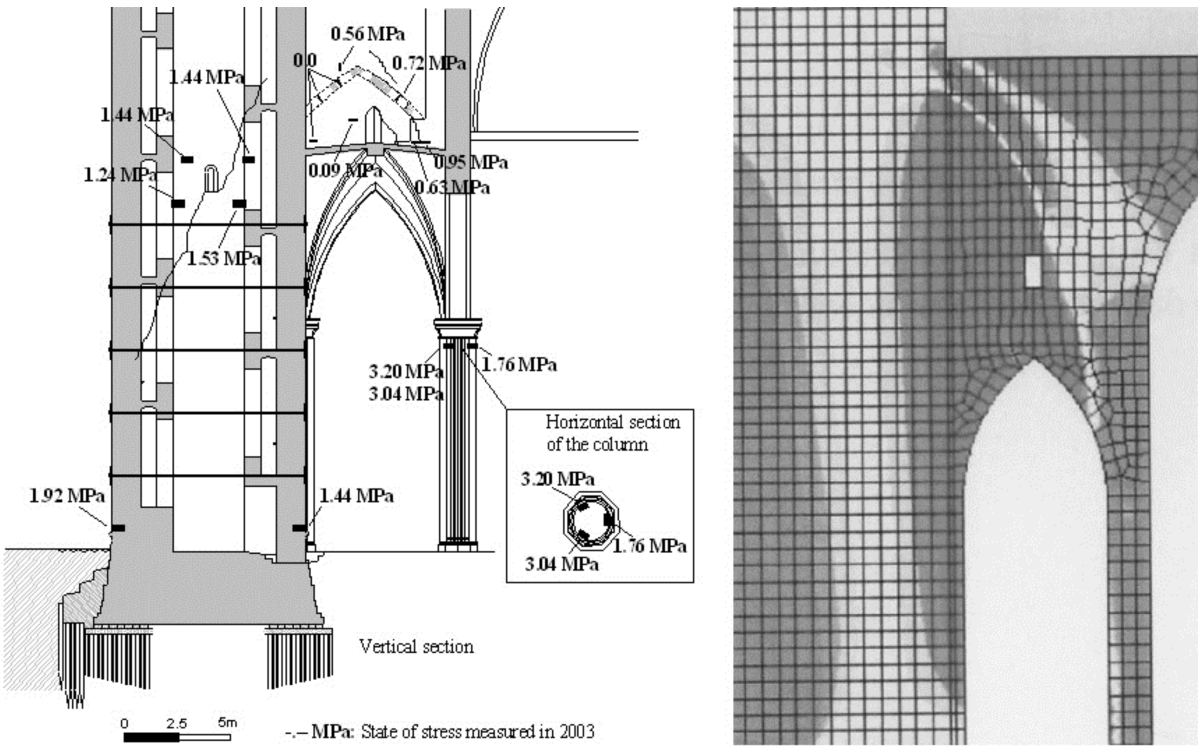

Fig. 2 Values of the state of stress measured by flat-jack test in the supporting structures of the Frari Basilica and bell-tower and comparison with the results of the numerical model.

Geotechnical investigation

An extensive geotechnical investigation campaign was carried out, including
- continuous vertical and inclined boreholes up to a depth of 25 m
- continuous coring into the foundation masonry
- static penetrometer tests with monitoring of pore water pressure (piezocone tests) up to a depth of 20 m;
- standard Penetration Tests (SPT), in boreholes;
- extraction of several soil and foundation samples, for the evaluation of physical and mechanical properties.

The stratigraphic units are shown in Figure 3. The results of the geotechnical investigations were used for the numerical model of the soil foundation of the bell-tower

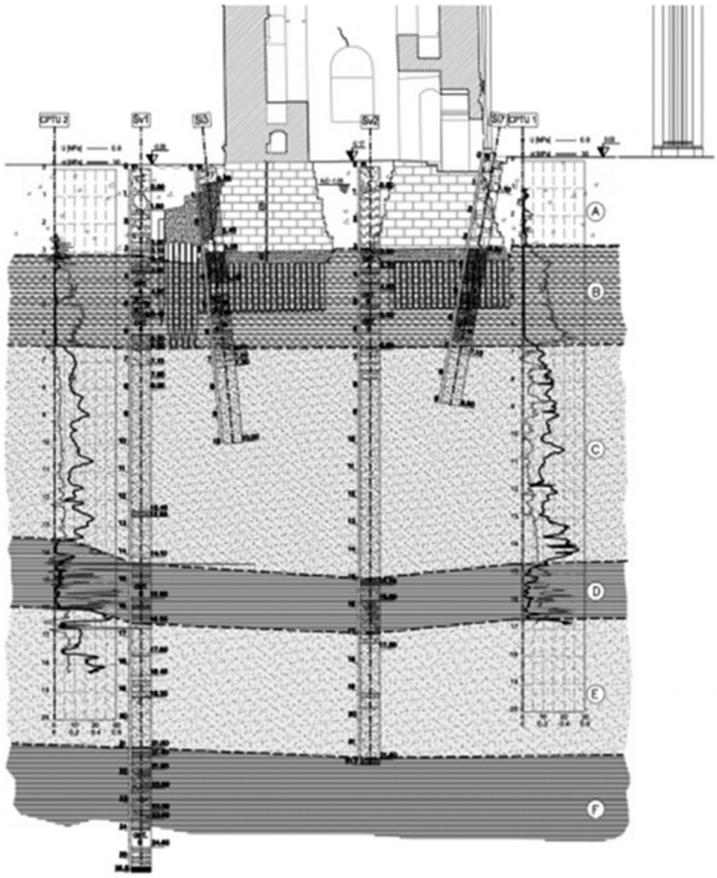

Fig. 3 Stratigraphy of the soil foundation of the Frari bell-tower.

The foundation of the bell-tower is made up of limestone (Pietra d'Istria) squared blocks, about 0.20-0.40 m thick, in a good state of preservation. Among the blocks, the original mortar was also locally found. Below the foundation blocks there is a wooden floor of squared larch boards, 0.40-0.50 m thick. Under the boarding, a thin layer of clean sand was found, probably used to prepare a uniform bedding plane for the foundation. Below the wooden floor, the typical wooden piles layer is made up of short (from 1.5 m to 2.0 m) consolidation piles, pushed into the fully saturated, soft clay, very close each other, often side by side, to make it denser and stronger.

<u>Numerical model</u>

A structural analysis of the bell-tower and the adjacent parts of Basilica was performed. The aim of the model was the identification, through the historical processes which led to the actual situation, of the masonry structures' present behaviour. The portion of structure which was reproduced in the model, includes the bell-tower and the adjoining parts of the church which were mostly affected by the interaction with the tower. For all the numerical simulations the only loading condition considered is the self weight. The load corresponding to some parts of the real structure not reproduced in the model (timber structure roof of the basilica, belfry), was imposed as external forces. The crossed vaults' filling was included as surface load. The mechanical properties chosen to describe the materials arise from the results of flat jack tests performed on the masonry structures. The material is considered homogeneous and isotropic and the analyses performed are linear elastic. This numerical model was used as a design tool for verifying the different phases of the strengthening interventions.

3 Monitoring system

After the end of the diagnostic investigations, an automatic monitoring system was installed to analyse the deformation behaviour and the structural conditions of the bell-tower and the adjacent portion of the Basilica during all the phases of the strengthening interventions.

The general lay-out of the instruments, includes:
- direct pendulum equipped with automatic telecoordinometer, for the measure of the absolute horizontal movements of the top of the tower.
- crack-gauges and long-base extensometers installed on the main cracks of the masonry walls.
- strain-gauges to measure the deformation of the steel cable installed in the bell-tower.
- thermal-gauges to measure the temperature of the internal and external air, and also inside the masonry at different depths from the outer wall.
- geotechnical instrumentation, installed into the boreholes drilled in the soil foundation, including electrical piezometer multibase extensometers and biaxial inclinometers.

All the instruments are connected to an automatic data acquisition and recording system which is equipped with a modem to transfer the data to a remote controller. This acquisition system was very precious during the phases of the strengthening works because it was able to follow in real time the effect of the works on the structures thus allowing to introduce appropriate variations of the intervention design.

In addition to the instruments connected to the automatic acquisition system, it was considered extremely important to measure the vertical movements of the bell-tower and of the adjacent portion of the Basilica. For this reason an high-precision manual levelling system was installed with several measuring points and the periodical readings were carried out during the most significant phases of the works.

4 The role of monitoring during the strengthening intervention phases

Owing to the deep connection between structural and geotechnical aspects, it was clear that, in order to guarantee the safety of the complex Basilica and bell-tower, it should have been necessary to find a suitable technological solution able to realize gradual strengthening interventions with a strict control during the execution of the works, by adopting the so called “Observational Method”. The only way to obtain a strict control during the execution of the works is represented by the structural and geotechnical monitoring system. The complexity of the problems required the set up of an interdisciplinary group of technicians including experts in structural and geotechnical engineering, diagnosis and monitoring, chemistry and wood conservation.

4.1 Phase A – Temporary strengthening intervention

The first intervention was required by the considerable deformation induced on the column of the Basilica by the thrust of the bell-tower. A provisional intervention was carried out in order to guarantee the safety of this portion of the Basilica. A steel cable was positioned connecting the stone ashlars just above the capital of the column to the bell-tower structure at a height of 14.40 m. This steel cable aimed at support part of the horizontal thrust acting on the column. The structural scheme of this intervention is shown in Figure 4. Two strain-gauges were installed on the steel cable and the tension was continually controlled during the whole intervention period.

4.2 Phase B – Soil-fracturing intervention

From the results of the experimental and numerical simulation it emerged that the bell-tower and the interacting structures of the Basilica could not bear, without serious consequences, further differential settlements. It was evident the need of an intervention, at the level of the foundations, aimed at reducing the settlements of the bell-tower thus obtaining that the entity of vertical displacements of the complex basilica/bell-tower should be in the same range. A special technique able to improve the mechanical characteristics of the foundation soil with the respect of all the prescriptions above described, was chosen. An interesting result was obtained by using grout injections with soil-fracturing technique.

The soil-fracturing technique consists in installing special injection tubes in the foundation soil, with valves at different depths. The careful and slow-rate injections of suitable cement and bentonite mixtures is repeated at successive stages, to obtain progressive increments in terms of mechanical characteristics, according to the above-mentioned “observational method”. The final outcome is a reinforced soil, made up of the original material and a mesh of thin layers of injected grout, as can be observed in the particular of Figure 5.

The soil is confined by these thin layers of injection mortar and subjected to an increased stress state. An increment in terms of deformation modulus of the consolidated soil (with subsequent creep reduction) and an improvement of the soil shear resistance, is obtained.

With the aim of validating and calibrating this rather innovative strengthening method, a full-scale test site was arranged on the northern corner of the bell-tower, inside the Basilica by installing a special monitoring system including several piezometers and multibase extensometers.

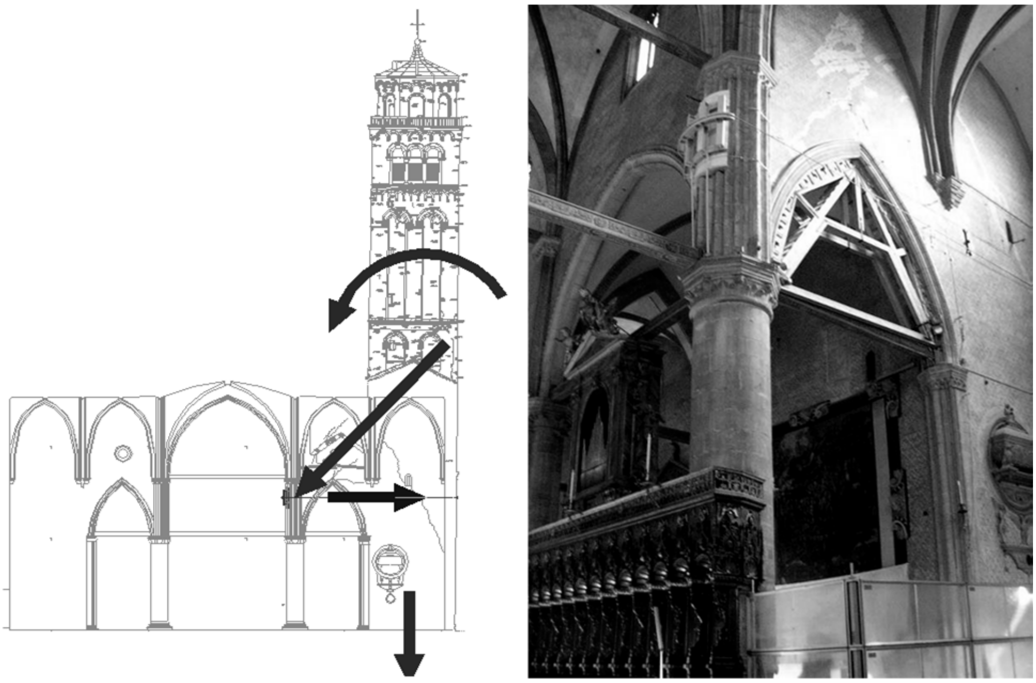

Fig. 4 Temporary intervention with steel cable to support part of the horizontal thrust acting on a column of the Frari Basilica.

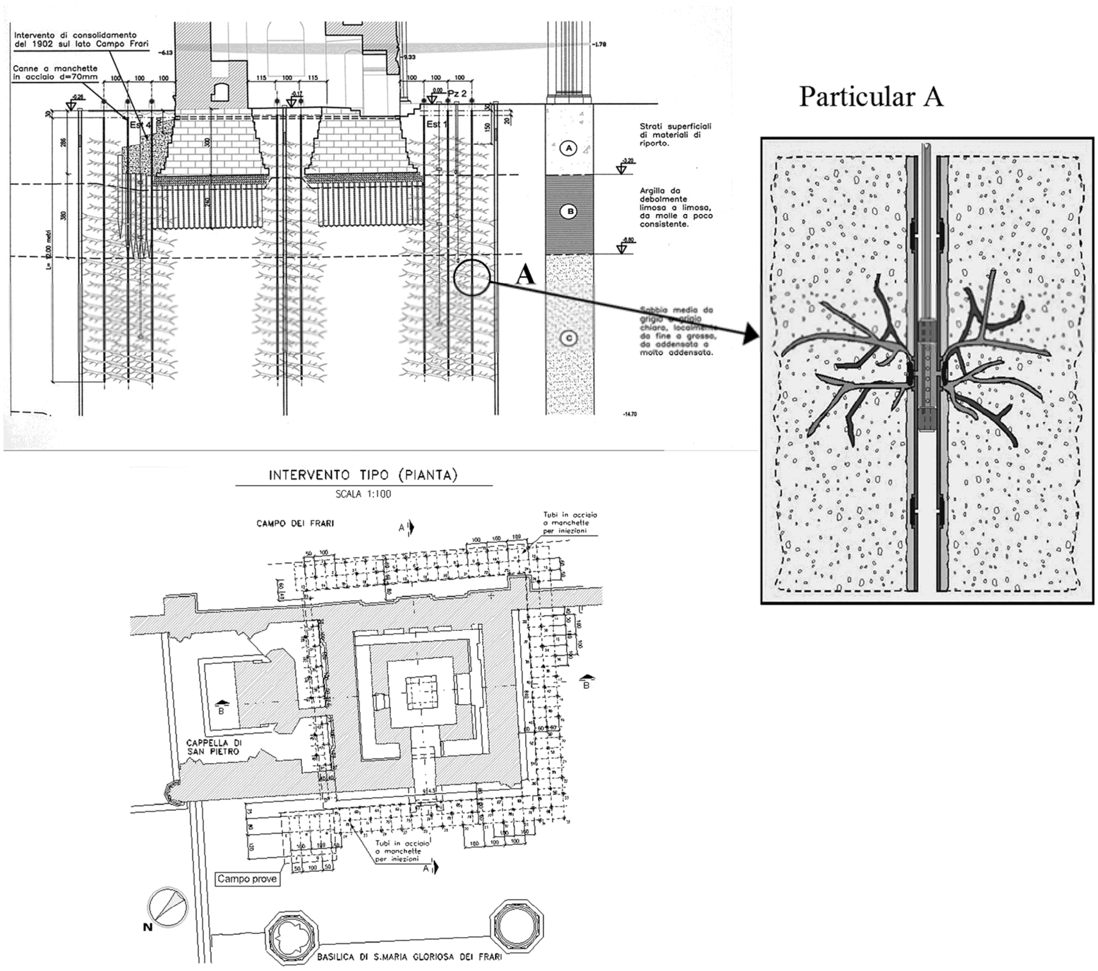

Fig. 5 Scheme of the soil-fracturing technique for the consolidation of the soil foundation of the Frari bell-tower. The position of the full-scale test is also indicated.

After the positive answer of this full-scale test, the soil-fracturing intervention was decided and the scheme of the intervention is shown in Figure 5 where the planimetry and the cross section of the intervention is shown. Around the foundation basement, 88 injection tubes (length 12 m, diameter 88.9 mm. distance 500 mm) with special valves at a distance of 500 mm each other, were installed in two or three lines. A grouting mortar with pozzolanic cement, water, bentonite and limestone filler, was used with a grouting pressure of about 5 bars in the clay levels and 25 bars in the sand ones. The grouting processes were carried out very slowly through a continuous control of the movements and at the end of the intervention about 100 cubic meters of mortars were injected.

The most useful information for the analysis of the behaviour of the structure during the soil-fracturing works are coming from direct pendulum and from altimetric precision levelling. Also the crack-gauges installed in the arch which connects the bell-tower to the adjacent column, gave precious information concerning the interaction between the two structures. During the soil-fracturing intervention (between April 2005 and March 2006) the monitoring system was used to define the velocity of the intervention phases as well as all the parameters of the grouting procedures (pressure, flow rate, etc). A notable movement of the bell tower during this intervention phase was observed. The component of movement in x direction shows a movement toward the abse of about 9.0 mm and a movement in y direction of about 5.0 mm toward the Basilica. After the end of the soil-fracturing, the velocity of the bell-tower movement shows a quick reduction, reaching a value which is lower than the one observed before the soil-fracturing intervention. Also the movements of the cracks in the stone arch which connects the bell-tower to the Basilica, show a marked increase during the soil-fracturing and a rapid decrease at the end of the operation.

After the end of the soil-fracturing intervention, the vertical settlements show a marked decrease of the velocity of settlements in comparison with the values measured before the intervention. It was estimated a decrease of this settlement velocity from about 1.0 mm/year to about 0.5 mm/year. This can be considered a very satisfactory result in spite of the temporary movements induced by the soil-fracturing intervention.

4.3 Phase C – Structural joint execution

About two years after the end of consolidation works of the soil foundation by soil-fracturing technique, it was decided to introduce a new structural intervention aiming at modifying the boundary conditions of the bell-tower and to reduce as much as possible its interaction with the adjacent structures of the Basilica. At the beginning of June 2008, a structural joint was created between the bell-tower and the Basilica in the position shown in Figure 6. The effect of this intervention was a marked change of the direction of the thrust applied by the bell-tower to the adjacent column. The direction of this thrust, before and after the execution of the structural joint, is shown in Figure 6, together with the corresponding numerical models.

The execution of the structural joint was very slow and lasted about 6 months. During this period a detailed analysis of the information obtained by the monitoring system allowed to carry out the different steps of the intervention with a continuous check of the structural behaviour, so avoiding to induce damages to the bell-tower and to the supporting structures of the Basilica.

In order to follow with special care the deformation behaviour during the execution of the structural joint, new crack-gauges were installed as well as new long-base extensometers. In Figure 7, the lay-out of the deformation sensors is shown, with the values of the deformations measured during the whole structural joint intervention. In the same figure, also the movements measured by the direct pendulum are shown, as well as the settlements of the soil foundation measured by altimetric levelling. It was observed a marked movement of the bell-tower (10.40 mm) in y direction, towards the adjacent column of the Basilica. This movement is only partly related (about 50%) to the differential settlements of the foundation, while the remaining part is due to deformation processes of the bell-tower itself. The analysis of the deformations shown in Figure 7, indicates a closure of the structural joint of 6.72 mm and appreciable movements of the cracks in the masonry wall which connects the bell-tower to the Basilica, while small movements and deformations are observed on the masonry walls of the bell-tower.

In order to follow with particular attention the modification of the thrust between the bell-tower and the Basilica, special flat-jacks were installed. It can be observed a decrease of the state of stress in the upper part of the wall between the bell-tower and the Basilica which is a clear confirmation of the lowering of the thrust applied by the bell-tower.

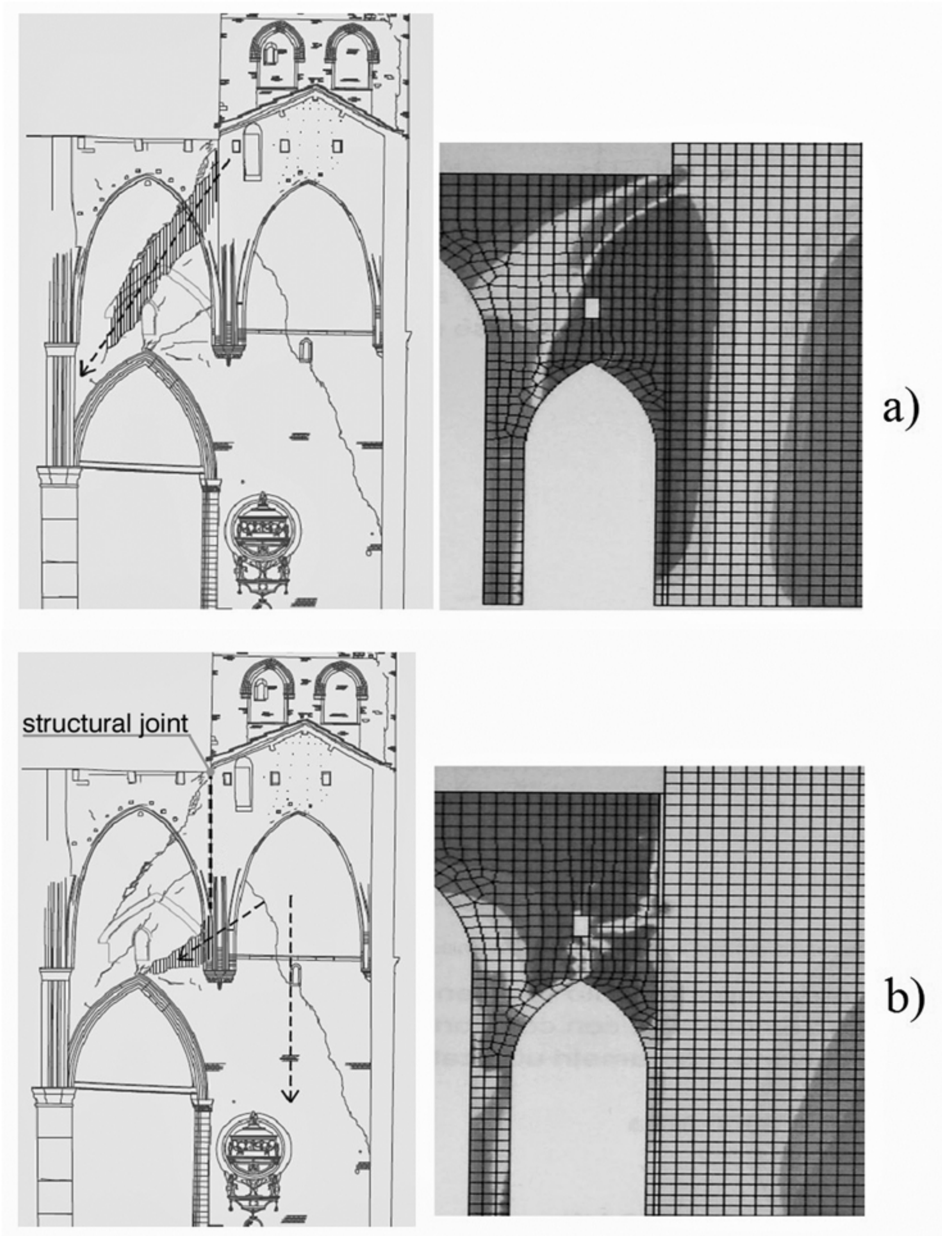

Fig. 6 Direction of the thrust between the bell-tower and the Basilica and comparison with the numerical model results: a) – before the structural joint execution, b) – after the structural joint execution.

The complete history of the two components of the movements measured by the direct pendulum is shown in Figure 8, where the soil-fracture intervention and the structural joint execution are indicated. It can be observed a great influence of the soil-fracturing on the displacement component in x direction, while during the structural joint execution the effect on the component in y direction is more evident.

After the end of the structural joint execution and after the complete removal of the temporary steel cables and of the timber prop system, the deformation behaviour was observed during a period of about 3 year During the period of three years after the end of the structural joint execution, the average differential settlement of the bell-tower relative to the Basilica was about 0.40 mm/year. This value is considerable reduced in comparison with the value of about 1.0 mm/year which was measured before the interventions. The actual rate of the differential settlement of the bell-tower must be carefully controlled in the future in order to analyse its evolution during the time.

It can also be observed that the presence of the structural joint between the bell-tower and the Basilica reduces the interaction between the two structures with consequent reduction of the risk of cracks under static or seismic loads.

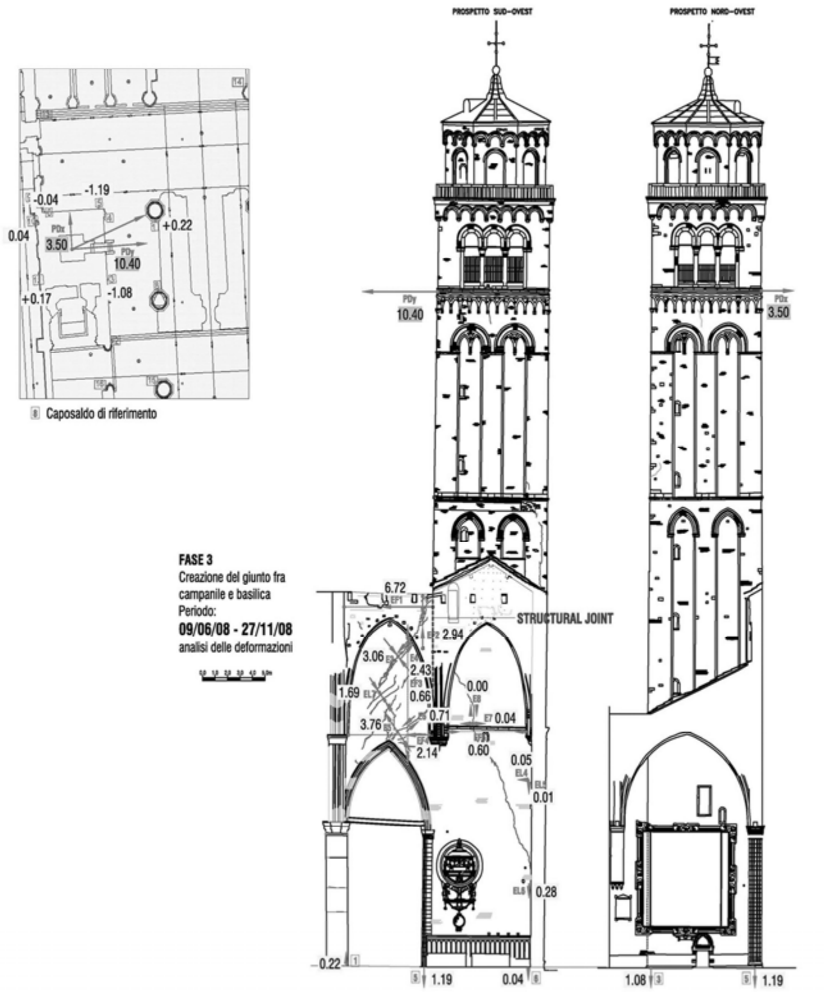

Fig 7 Analysis of the deformations induced by the structural joint execution.

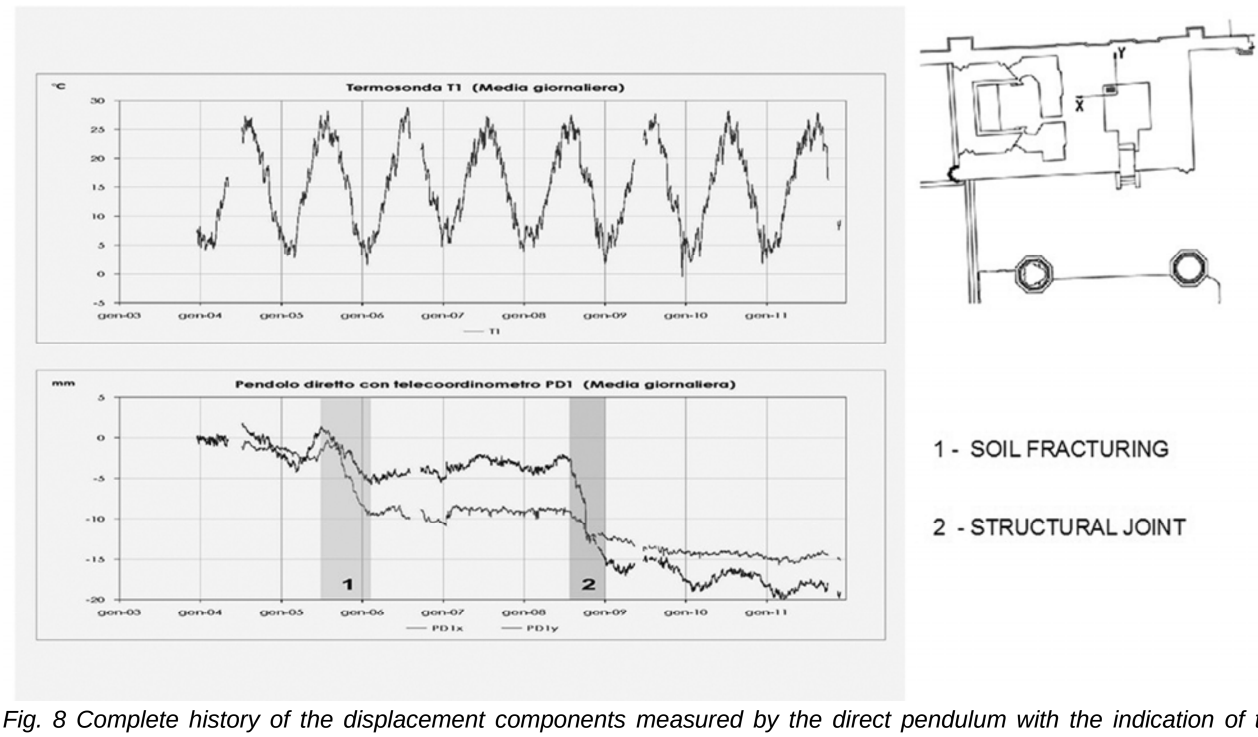

Fig. 8 Complete history of the displacement components measured by the direct pendulum with the indication of the intervention phases (soil-fracturing and structural joint execution)

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