CRACKING OF THE APSE OF S. LORENZO IN CREMONA: STRUCTURAL INVESTIGATION AND MONITORING

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SUMMARY

The Basilica of St. Lorenzo in Cremona (Italy) dating back to XII century was investigated for the coming restoration. After a complex investigation, articulated at different levels and aimed to understand the historical evolution of the Basilica of S. Lorenzo at Cremona (Italy), its constructive techniques and the crack pattern in its spatial development, a strengthening intervention has started in the main nave. The results of the investigation carried out on the apse will allow to calibrate suitable analytical models in order to complete the structural diagnosis and to choose appropriate techniques for the preservation of the whole monument.

INTRODUCTION

The Basilica of S. Lorenzo in Cremona (Italy), no longer functioning as a church since the beginning of the XIX century, was also used as a gym in the thirties and shows all the formal contradictions deriving from centuries of continuous modifications of the load-bearing structures. The church reveals a complex palimpsest not easy to interpret, with many additions and variations that require investigation to understand its structural behaviour. The Basilica is affected by different kinds of damage including cracking of the vaults, rotation of one of the timber trusses constituting the roof, and tilting of the pillars.

A previous investigation, articulated at different levels (Anzani et al., 2007), was aimed to understand the state of damage through the knowledge of the historical evolution of the church, its constructive techniques, the materials characteristics and the crack pattern in its spatial development. A strengthening intervention has already started in the main nave only, given the project of the City of Cremona for re-using the church as an archaeological museum. In the presbytery, the vault shows many serious cracks probably due to the structure settlement. During the archaeological excavation carried out in the sixties to inspect the three-apsed ancient church standing underneath the present one, the cracks had already been repaired but re-opened; this motivated their monitoring in view of an extension of the strengthening intervention to the apse too.

In addition to archivistic information on the archaeological excavation, diagnostic techniques were recently applied to better understand the static conditions of the apse so to investigate:
- the masonry quality by sonic tests;
- the stress state and the stress-strain relationship by flat jack tests;

- the material characterization by physical, chemical and mechanical testing;
- the evolution of the crack pattern by long term monitoring.

The results of the experimental investigation are presented and commented in the following.

HISTORICAL EVOLUTION OF THE BASILICA

The area where the Basilica of S. Lorenzo rises was probably the place where the first Christian cults developed, since it is the only site where paleo-Christian tomb-stones were found in the city territory. During X century many monasteries were built in Cremona, including S. Lorenzo (Figure 1). Since 973, the Bishop of Cremona Olderico wanted the reconstruction of two churches, one of which was dedicated to S. Lorenzo Martyr. The primitive church was destroyed perhaps by an earthquake and a subsequent fire in 1113 (Figure 2).

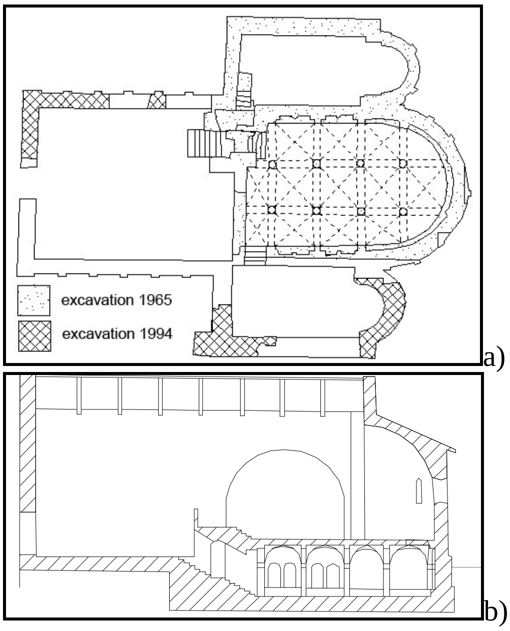


Figure 1. Plan and section of the church in X century.

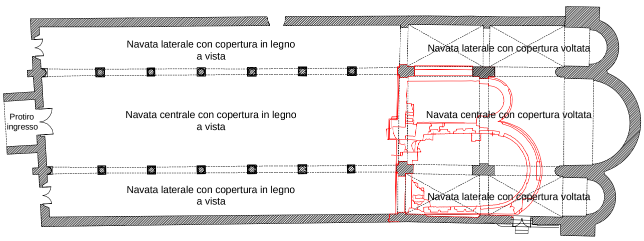


Figure 2. Plan of the church in XII century.

The actual Basilica, built in the 12th century on the remains of the previous one (Gualazzini, 1982; Mirabella Roberti, 1985; Voltini, 1987), is a three nave construction preserving the primitive column basis and capitels. In 15th century (Romanini, 1964; Pontiroli, 1967; Pontiroli, 1985) an important intervention introduced vaulted ceilings to the lateral naves and a monumental three-lobes chapel on the north-west corner (Figure 3).

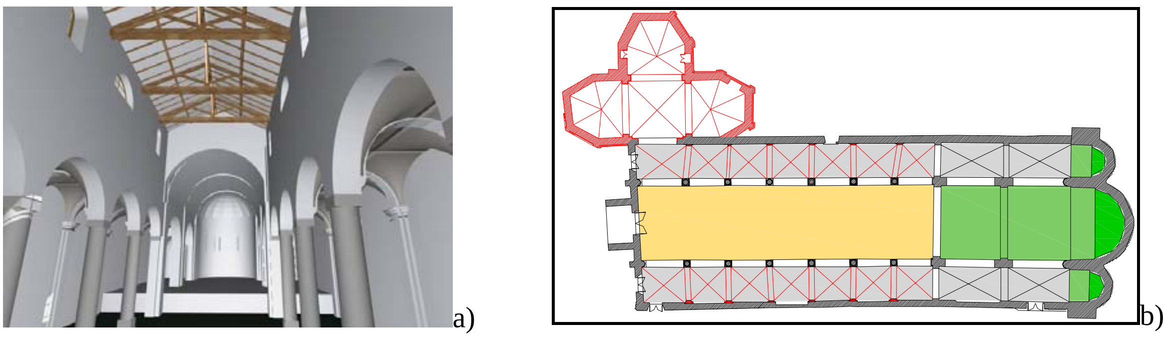
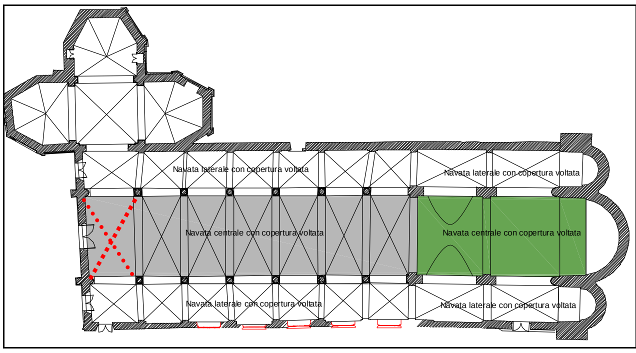


Figure 3. Reconstructed computer rendered view a) and plan of the church b) in XV century.

In the 18th century various interventions involving the facade and the interior were carried out (Romanini, 1964) including the construction of cross vaults on the central nave. During the 20th century the demolition of the vault covering the first bay of the central nave and the

accommodation of large windows on the south wall were performed (Figure 4b). Buttresses on the south side were probably added after an earthquake that hit Cremona in 1951.


a)


b)

Figure 4. Reconstructed computer rendered view a) and plan of the church b) in XX century.

Archaeological survey

In the sixties the church was subjected to numerous excavations; during the first works, digs were carried out in the apse and in the central and lateral naves, plaster was removed from the walls and the XIX century vault of the first bay was demolished to inspect the roof. During the excavation in the area of the main altar, the foundations of the previous church were found, therefore the hypothesis was made that S. Lorenzo had been founded on a previous construction (Figures 5 and 6). Nevertheless, these structures (Figure 5) appeared staggered of one nave, found in the courtyard close to the church. In this area, some tombs were found; they are probably more ancient than the paleo-christian walls, since these are resting on the tombs themselves.

In June 1962 strengthening interventions were carried out due to the presence of serious cracks on the main apse (Figure 7), during which part of the foundations of the apse were demolished. Having reached a stronger subsoil, more than 20 reinforced concrete piles were trusted in the ground, connected to a thick r.c. beam running all around the apses.

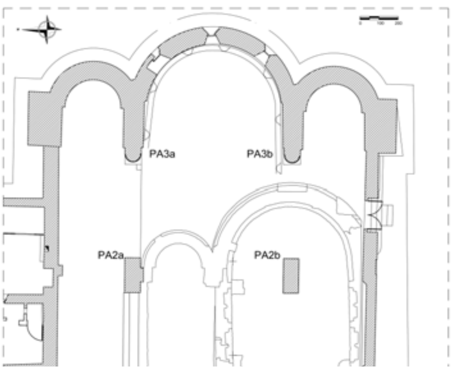


Figure 5.Plane of the Crypt.

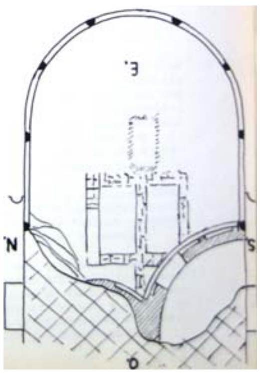


Figure 6.Sketch of main Apse


Figure 7. Particular of the external side of the main apse

In order to build this beam underneath the foundation of the three-lobes apse, a dig was excavated all along. It was found that the present apse was erected above a temple destroyed by a fire. Further excavations were carried out in 1965 to find the crypt; the remains of a

roman necropolis appeared. The soil was removed from the inner and the outer perimeter of the left apse and a floor in terracotta tiles was discovered (Figures 8 and 9). The archaeological survey continued in 1966 with excavations behind the apses up to 1,5 m depth, finding scarce roman remains and infill soil, and along the south perimeter of the church in an area 4,2 m wide and 2,5 m long. A roman brick floor appeared and the excavation continued up to 3.2 m depth, where roman brick fragments mixed with clayey soil were found (Archive of Archaeological Heritage Office).

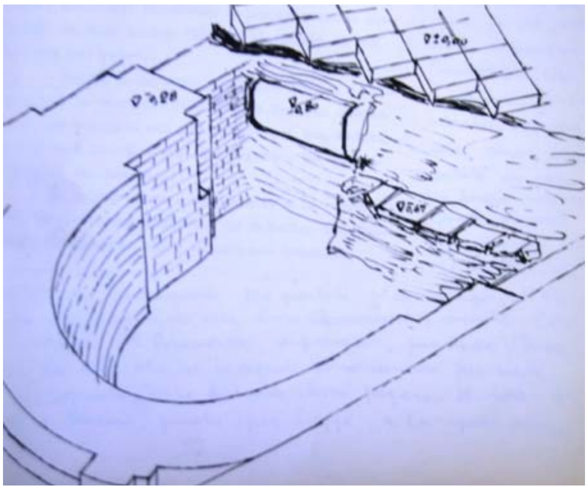
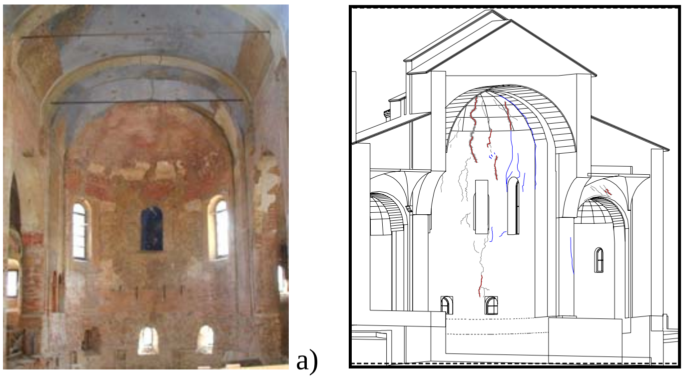


Figure 8.Sketch of the archaeological excavation (courtesy of the Archive of Archaeological Heritage office in Milan)

Figure 9. Archaeological remains.

CRACK-PATTERN SURVEY

Different phenomena seemed to have caused the crack patterns visible in the presbytery and in the central nave. The cracks in the main apse depart from the centre of the semi-dome and develop along the wall (Figures 10 and 11); most of them had been repaired and re-opened. In order to gain a better understanding of the apse behaviour, and to formulate a strengthening project, the masonry quality and the state of stress has been assessed by sonic and flat-jack tests and a monitoring of the crack evolution has been carried out, as described in the following.



a) b)

Figure 10. Apse: a) interior, b) crack pattern.

Figure 11.Repaired crack in the apse.

STATE OF STRESS AND STRESS-STRAIN BEHAVIOR OF MASONRY

Different non-destructive and partially destructive tests were carried out on the load-bearing structures of the presbytery and the apse, investigating the brickwork masonry. Every flat jack tests was preceded by a check of the masonry morphology by means of sonic tests by transparency. In some cases, single flat jack tests were carried out on both sides of the structural element so to examine the possibly non uniform stress distribution. Some examples are illustrated in the following.

In Figures 12-15 the positions where sonic and flat-jack tests have been carried out on the apse are indicated. In both cases, sonic tests gave homogeneous results as shown; fairly high values of the sonic velocity were obtained, ranging between 1500 m/s and 2100 m/s.
The lowest values of sonic velocities were detected in some parts of the pillars (PA2a, PA3b) due to the presence of local interventions weakening the masonry.

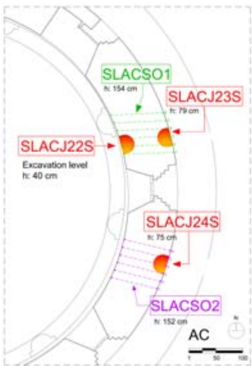
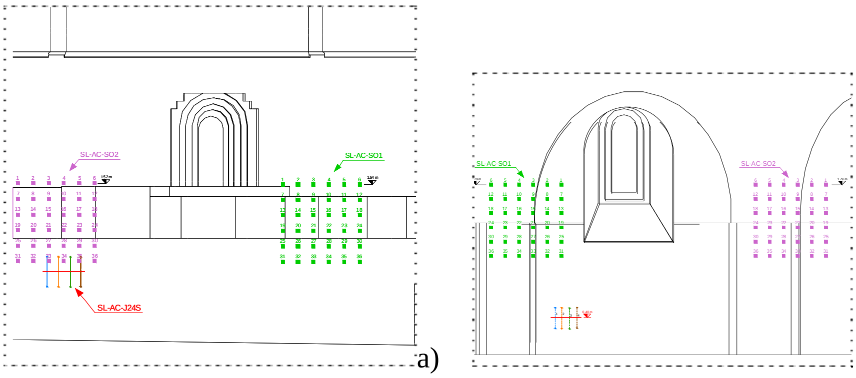
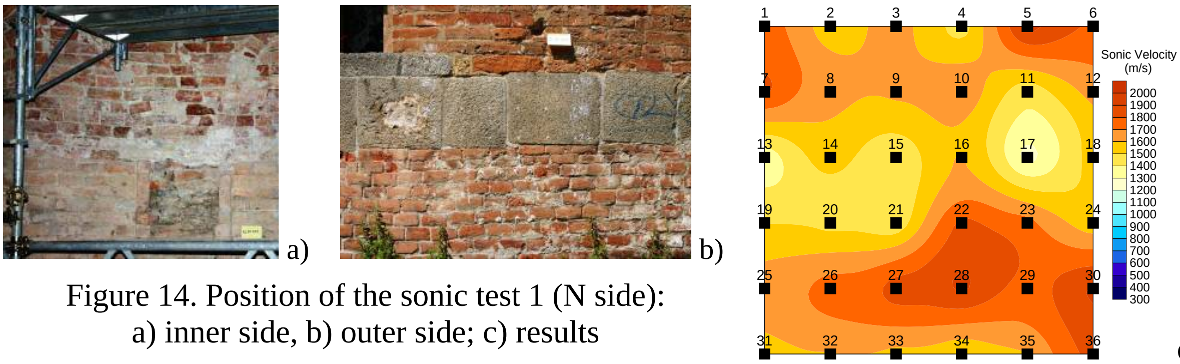


Figure 12. Position of sonic and flat-jack tests.



a) b)

Figure 13. Position of sonic and flat-jack tests: a) outer side, b) inner side.

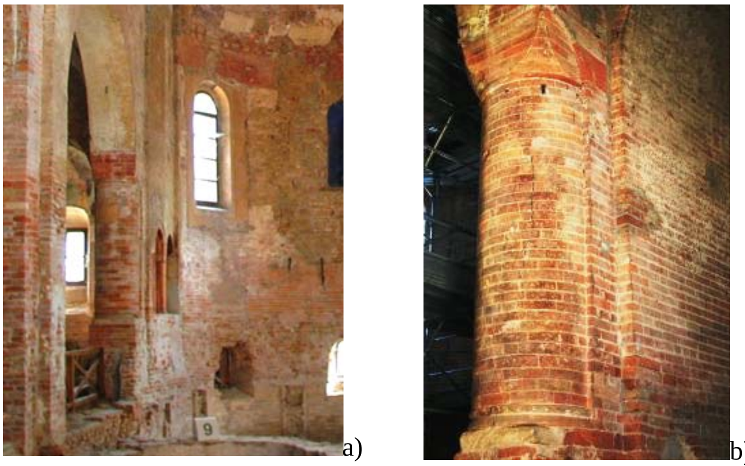


a) b) c)

Figure 14. Position of the sonic test 1 (N side): a) inner side, b) outer side; c) results

Figure 15 shows a vertical crack recently opened on pillar PA3b between the apse and the naves. In Figure 16 the sonic tests on pillar PA3b are illustrated. Also in this case a single flat jack test was carried out. As shown in Table 1, fairly high values of sonic velocity for a brick masonry have been obtained, the lowest value corresponding to pillar PA3b at church level. Particularly high values of stress have been recorded on pillars PA3a and PA3b in the apse, and on the large pillars in the presbytery, with values around or higher than 1 N/mm^2. A non uniform stress distribution has to be highlighted in the case of the apse at point 1 N side (see Table 2) and in the case of pillar PA2b (see Table 1); this is in agreement with the results of verticality loss and tie rod stress commented below. Results of double flat jack tests are shown in Table 1, where values of E are indicated for pillar PA2a and PA1b. Values of the results of the assessment are also illustrated in Figure 17.

Figure 18 show a crack indicating a rotation of the south wall above the presbytery.



a) b)

Figure 15. Pillars of the main apse: a) PA3a and b) PA3b.

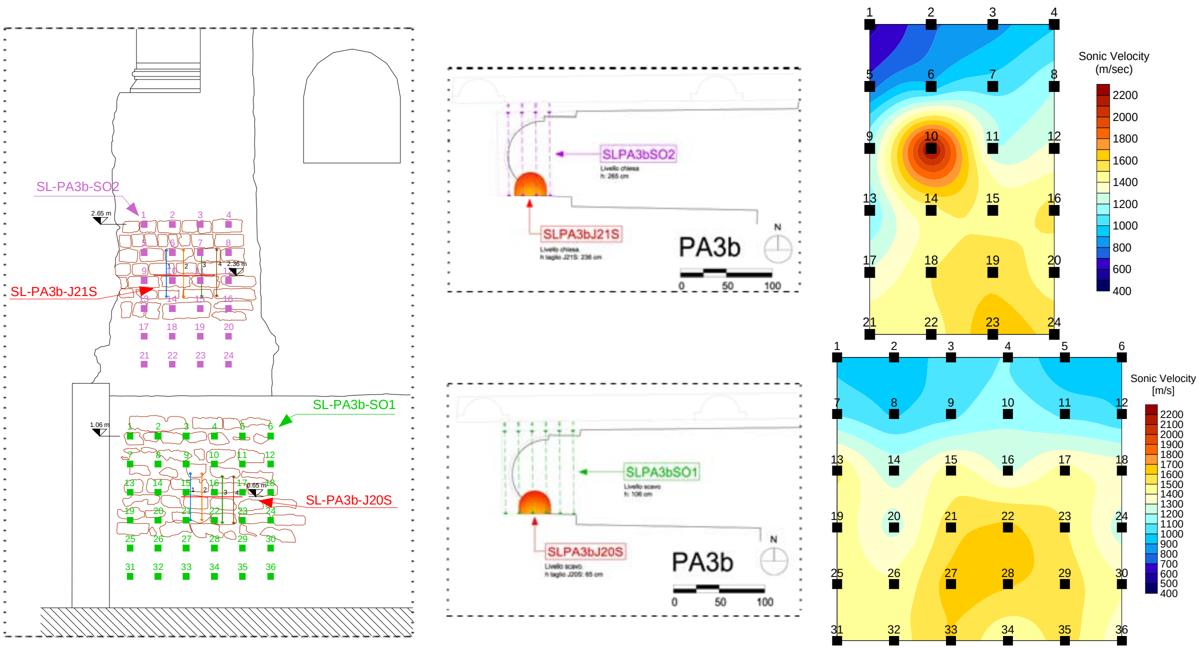


Figure 16. Sonic tests on pillar PA3b

Table 1. Results of sonic and flat jack tests on the pillars in the presbytery.

Pillar	Sonic velocity (m/s)	σ_v North side (N/mm^2)	σ_v South side (N/mm^2)	E North side (N/mm^2)	E South side (N/mm^2)
P A1a	1592.1	0.66	0.85	-	-
P A1b	1502.4	0.36	0.54	2131	3058
P A2a	1347.3	0.91	0.81	3986	-
P A2b	1512	0.27	1.21	-	-
P A3a	1556.2	1.05	-	-	-
P A3b, excav. level	1311.7	-	0.39		
P A3b, church level	1276.4	-	1.34	-	-

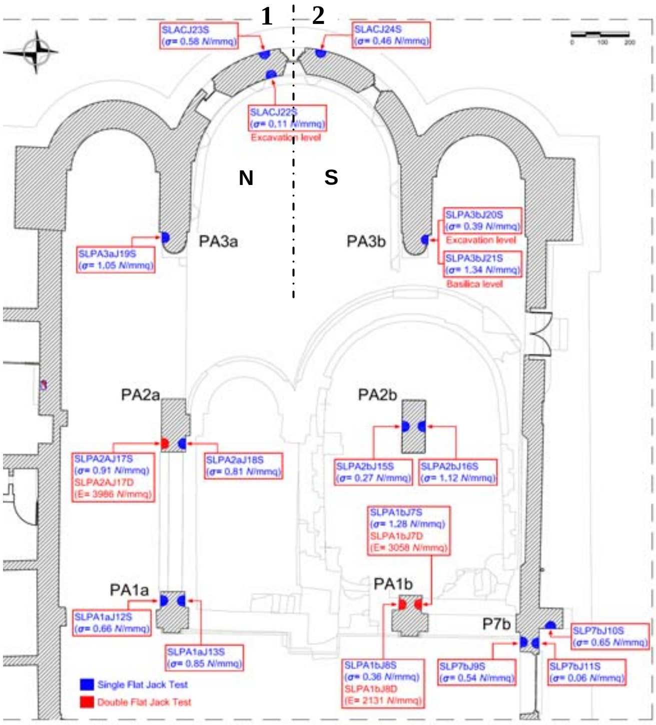


Figure 17. Results of single and double flat-jack tests.

Table 2. Results of sonic and flat jack tests on the apse.

Apse	Sonic velocity (m/s)	σ_v outer side (N/mm^2)	σ_v inner side (N/mm^2)
Point 1, N side	1629.4	0.58	0.11
Point 2, S side	1628.5	0.46	-

Figure 18. Crack and rotation of the south wall above the presbytery.

TIE RODS TENSION

Free vibration dynamic tests were carried out on the tie rods of the main and south nave and of the apse, measuring their tension as a function of the frequency corresponding to the first vibration mode, assuming the tie rods are vibrating cords. The apparatus consists of a piezoelectric accelerometer having a sensitivity of 1.00 V/g and working in a range of 0.5 to 1000 Hz. The tests were performed by exciting the rods, characterized by a rectangular cross section, with an impulse and reading the accelerations at the mid span.

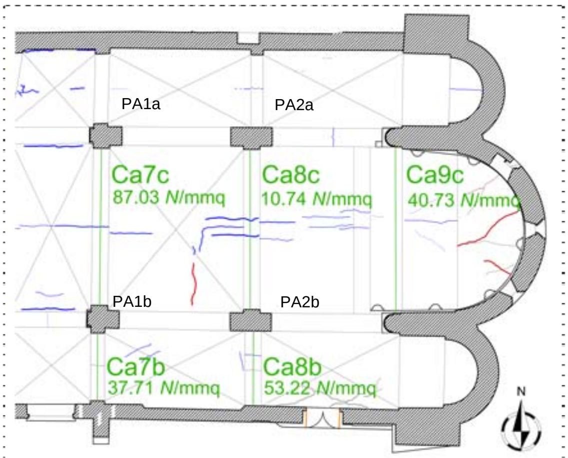


Figure 19.Tie rod tension.

Figure 20.Verticality loss of pillars in the presbytery.

The rods of the central nave resulted generally more stressed than those of the south nave. In particular, the highest and lowest values correspond respectively to rod CAC7c and CAC8c in the presbytery (Figure 19). The corresponding rods CAC7b and CAC8b are those showing the highest stress of the southern aisle. This is in agreement with the hypothesed settlement of the southern side of the church, one of the effects of which is the crack and rotation shown in Figure 18. This is also in coherence with the recorded verticality loss of the large pillars in the presbytery (Figure 20) and with the results of flat-jack tests highlighted above.

It should be taken into account in order to better understand the movements, that the archaeological excavation eliminated most of the soil covering the foundation, leaving only 1 m of soil depth. So that the constraint for the foundation seems to be very weak, allowing probably the pillars tilting.

MONITORING OF CRACK OPENING

The evolution of the extensive crack pattern on many of the vaults has been studied continuously through the monitoring of 36 cracks. The cracks have been chosen considering their path, thickness and position relatively to the geometry of each vaults. The monitored cracks are shown in Figures 21-24.

The monitoring has been carried out placing couples of inox steel basis with conical holes (Figure 23a) and reading their distance every month through a millesimal removal dial gauge (Figure 23b).

Ambient temperature has also been recorded in the same periods: results of the variation of crack thickness and of the corresponding temperature monitored on seven cracks of the apse are shown in Figure 24. As it appears from the diagrams, the crack thickness' trend is opposite to the temperature's trend, except for A4, A6 and A7 which show a rather remarkable trend of opening after 22 months (between 90 and 150 μm). This indicates that the apse movements are still active, showing that a soil settlement is proceeding despite the r.c. piles and beam.

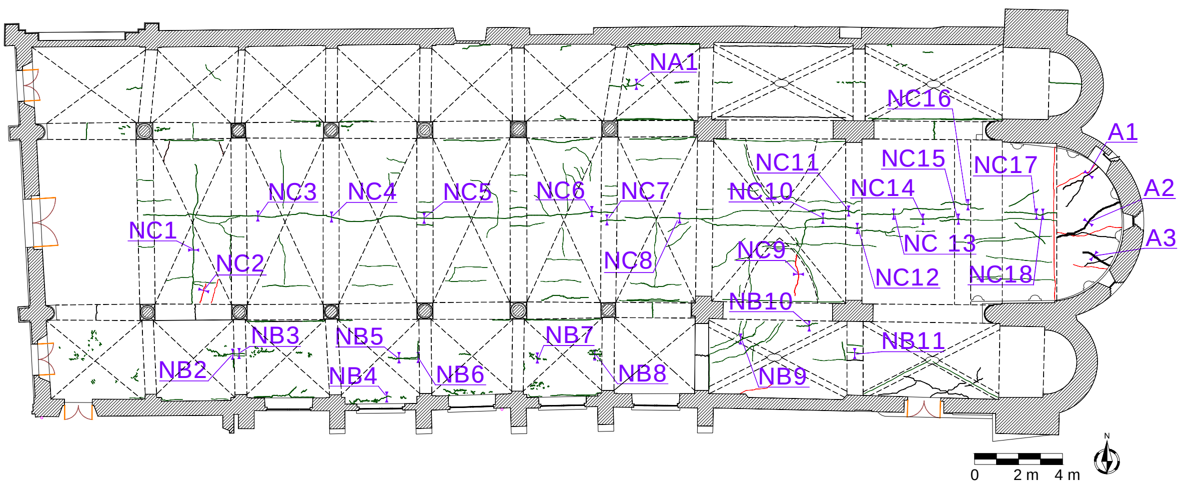


Figure 21. Monitored cracks along the central nave, plane (NC=central nave; NA and NB=lateral aisles; A=apse).

Figure 22. Monitored cracks in the apse zone.

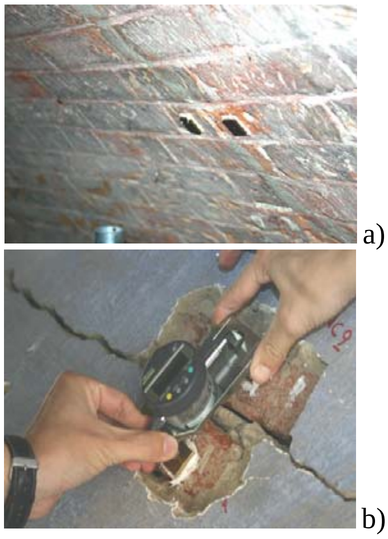


Figure 23. Crack monitoring: a) inox steel basis; b) millesimal dial gauge.

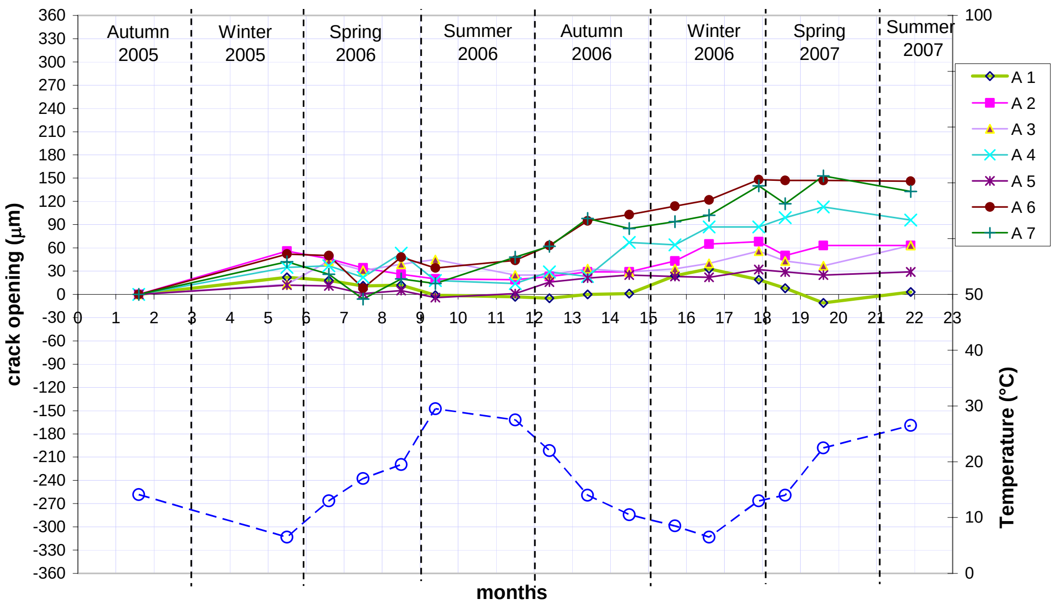


Figure 24. Results of crack monitoring of the central apse: S. Lorenzo Basilica (CR).

CONCLUSIONS

An articulated investigation was carried out on the medieval church of San Lorenzo in Cremona (Italy); here the results of this investigation on the apse are reported, because affected by crack patterns mainly due to soil settlement but also to the archaeological dig. The evolution of the church in the centuries was reconstructed and its influence on the behaviour and on the damage of the building was found. Flat-jack tests revealed the non-uniform stress distribution in pillars and walls. The crack monitoring carried out for 22 months put forward that the apse movement is still active and the results of flat-jacks and tie rod tests show a still active complex movement of the presbyter pillars and walls. The interpretation of the translational and rotational movements of the naves and the presbytery still need more research and modelling. The results of the investigation will allow to calibrate suitable analytical models in order to complete the structural diagnosis and to choose appropriate

techniques for the preservation of the monument as a whole.

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