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Anamnesis, diagnosis, therapy, controls

Koen Van Balen & Els Verstrynge
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Damage observation and settlement mechanisms in the naves of the Cathedral of Milan

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ABSTRACT: The Cathedral of Milan is studied in relation to the observed damage and structural system configuration in the nave and aisles. The damage results from relevant events in the history of the construction, ageing of the structure, soil settlement, vibrations, environmental conditions, corrosion, etc. Information was gathered on damage in the vaults, arches and iron ties, on the basis of new observations compared to the documentation related to the repairs carried out in the 20th century. Based on the observation of compression, tension and sliding cracking (mechanisms or damage) the relevant settlement mechanisms are discussed. The data of the monitoring systems available since 1966 provide information about the foundation settlements and column verticality, caused by lowering of the water table in the 20th century and slowly continuing at present. The present damage in the structure has been compared to the corresponding damage of arches and vaults related to equilibrium load path calculations and settlement mechanisms in limit analysis theory. The results provide an interpretation of the causes of the damage and provide a basis for the planning of future monitoring and interventions.

1 INTRODUCTION

Interventions for the conservation of an historic building turn out to be as more appropriate, as more detailed is the knowledge of the construction and its current conditions. The full comprehension of its structural system, original materials, constructive techniques and past repair interventions is necessary.

Many studies and interventions have been dedicated along the centuries to the Duomo di Milano. Recently thorough structural interventions were carried out between 1965 and 1982 to avoid the danger of a dramatic collapse (Ferrari da Passano 1988). More ordinary repair works followed on the vaults. Constant maintenance activities continue to the present, the latest dedicated to the main spire and the iron ties of the Cathedral.

Along the history of the Duomo Leonardo da Vinci was challenged by the study of its damaged structures and the design of the Tiburio. In the Atlantic code he wrote about the importance of knowing the causes of the "malato Duomo" (diseased Duomo). He wrote: *the causes are to be found through careful study of the building and deep understanding of the mechanisms function as well as observation of its parts.* In the same years also Bramante divided the Cathedral in its parts to better understand the formal consistency of the building under construction (Patetta, 2001).

Following these principles in a recent research started on the Cathedral of Milan, the combination of experimental and analytical approaches is used to understand the present conditions and damage, and predict possible future events. The research develops considering different parts. This paper describes the research carried out on the first part of the nave built in time starting from 1415 and repaired between 1991 and 2001.

The aim of this paper is to understand the causes of the damage observed at present in the structures. This can provide an evaluation of the more appropriate maintenance and repair techniques and possibly future interventions.

2 PROBLEM DESCRIPTION

2.1 *The Cathedral of Milan*

At the end of the 14th century the building of a new Cathedral in Milan was undertaken by bishop Antonio da Saluzzo and the first Duke of Milan Gian Galeazzo Visconti (Ferrari da Passano, 1988). The gothic architecture of this building, composed of pink marble from the carries of Candoglia (near Lago Maggiore) has the shape of the latin cross with one nave and four aisles (Figure 1).

The cross dimensions in plan are 88 × 157 meters. The height of the nave is 45 m to the crown and its width is 19.2 m that is the double span compared to the two aisles, which are 30 m and 23 m high respectively. The separation of the main nave from the side aisle is effected by large pillars (3.2), 31meter high, nearly of octagonal shape with a diameter of 2.55 meter, except the four pillars that support the great cupola (tiburio) that have a diameter of 2.95 meter.

Figure 1. View of the Cathedral of Milan (Duomo di Milano).

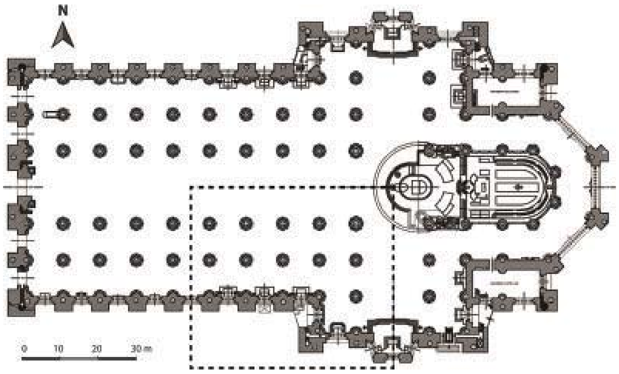


Figure 2. Plan with the area at study (dotted line).

Pillars are connected to each other by pointed arches, supporting the ribbed vaults over them. The horizontal thrust provided by the arches is balanced by iron ties and diaphragm walls and transferred to ground by the piers and an elegant buttressing system.

2.2 *The Tiburio construction*

The construction of the Cathedral started in 1386 from East to West with the apse and choir; in 1425 the pointed arches to support the Tiburio had been built, with the first bay of the nave. The construction of the nave and aisles proceeded in the following decades and ended in 1630. In 1452 Guiniforte Solari was appointed Architect of the Veneranda Fabbrica del Duomo di Milano and he judged that the existing pointed arches were insufficient to support the Tiburio and built new Roman arches above these (Ferrari da Passano1988; Coronelli et al. 2015). The decentering of the Roman arches broke the iron ties connecting the four main piers (4.2) caused lateral displacement of the four main columns in the diagonal direction and damaged the surrounding vaults. The construction was stopped for twenty years, as studies began for a solution, involving Leonardo da Vinci and Bramante amongst others. The final project was by Amadeo and Dolcebuono, who terminatd the Tiburio supported on Solari's arches in 1500, without ties to connect the four central piers.

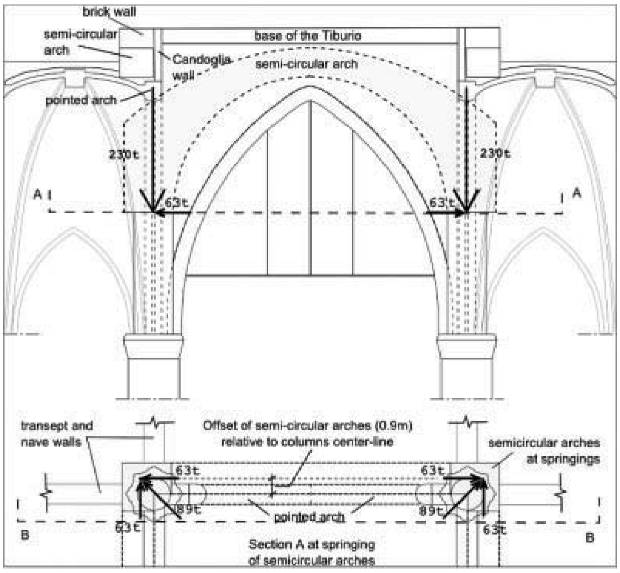


Figure 3. The effect of the Roman arches thrust in the nave and choir prior to Tiburio Construction, South West of the Tiburio.

2.3 *Soil subsidence*

The survey of the vaults around 1965 carried out by the Architect of the Veneranda Fabbrica Ferrari da Passano (Ferrari da Passano 1988) stated that the damage encountered was of ancient origin and traced back the causes to the construction of the Tiburio. The restoration interventions on the vaults that started in those years were interrupted due to new events that took place. In the second half of the 20th century with the soil subsidence due to lowering of the water table for industrial activities in Milan (Coronelli et al., 2014) caused redistribution of internal forces and heavy damage in a great number of piers, especially the ones located under the Tiburio, and in the vaulting. This is the second relevant event for the problem at study.

The water table lowering was stopped and the restoration of the columns carried out by Ferrari da Passano in 1982. The restoration of the vaults was continued by the new Architect of the Veneranda Fabbrica, Mörlin Visconti between 1991 and 2001.

The restoration works carried out in the Tiburio included the placing of new steel ties, to balance the lateral thrust, followed by intervention on the surrounding vaults covered with a reinforced concrete layer, as well as the insertion of a steel beam in the case of C1/C2 vaults in the NE-SW direction, in correspondence of the Tiburio thrust. The signs of restoration are not only visible from the extrados of the aisles vaults but also from their intrados, where the damaged stones units or part of them were substituted with new ones of the same material.

2.4 *Problem statement*

The prior discussion demonstrates that among other phenomena the Tiburio thrust and the soil subsidence are of particular importance.

In order to verify the efficiency of the past interventions mentioned above and to evaluate the eventual

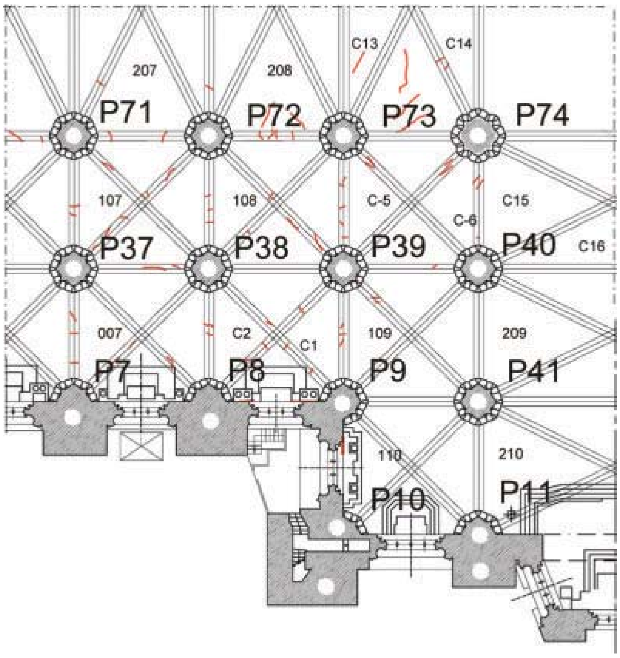


Figure 4a. Crack pattern survey of the South vaults near pillar 74 of the Tiburio.

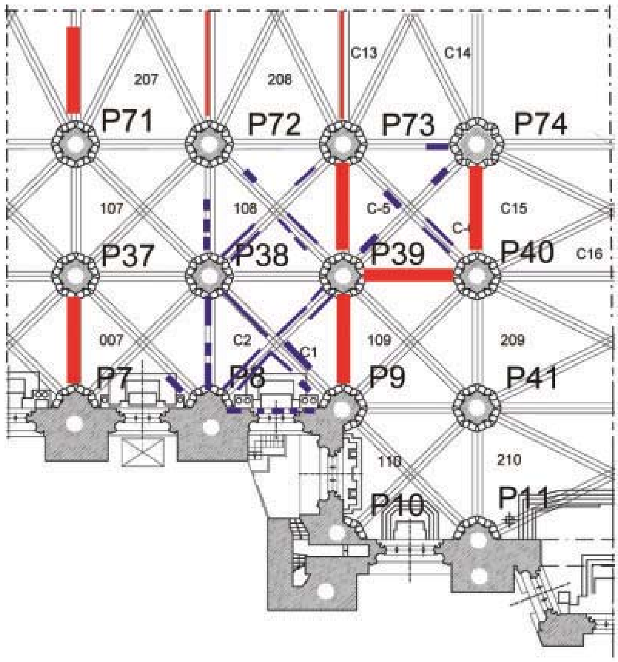


Figure 4b. Schematic representation of the replaced damaged stone units (in dark colour) of the vaults near pillar 74 of the Tiburio with the indication of higher stressed tie rods (thick red lines).

presence of new damage, a survey of the cathedral structures conservation state recently started within this research.

Amongst the surrounding zones of the Tiburio (four zones) the attention is focused on the one extended in the South-East, but nearly the same logic could be used for the four of them. From the archive of Veneranda Fabbrica documents it comes out that its construction started in 1415 (later on in this paper we will refer only to this zone).

The structural defects on the vault ribs and arches, repaired in the last two decades can be seen with the naked eye. In section 3 the first observations are presented.

3 SURVEY AND INTERPRETATION OF DAMAGE

A visual inspection of the naves of the cathedral has been started. The results, here presented, consist of the crack pattern survey of the vaults near one of the four main Tiburio pillars: P74, South-West oriented. The vaults are named C1/C2, C007, C108 and C107 (Figs. 2 and 4).

The major cracks visible in the above mentioned vaults are located in some arches and ribs but no cracks are visible on the vaults bays (Fig. 4a).

The crack pattern survey is also correlated with a survey of the repaired arches, realized with the substitution of damaged stones units. Figure 4b shows how the concentration of repaired stones is exactly oriented near the Tiburio, along its diagonal thrust. Other important data available from the monitoring of the columns base settlement and their verticality are also taken into consideration.

Figure 5. Small visible transversal cracks on the C1/C2 vault ribs and substituted stone units (the lighter colored units). The Tiburio is localised top left.

The vault C1/C2 along the diagonal thrust of the Tiburio presents an extremely high number of replaced stones, consequence of a serious occurred damage, that also justified the strengthening intervention visible on the extrados with r.c. structures, made about twenty years ago, as mentioned in section 2. Nevertheless, the arches and ribs still present few but new very thin transversal cracks mainly localized on the rib along the diagonal of the Tiburio thrust (Fig. 5).

Also the vault C5/C6, the closest to Tiburio pillar 74, heavily restored, presents a high number of replaced units in its arches but also few and very thin short longitudinal cracks on the stone units.

On the contrary, the near vault C007 does not present replaced stone units, informing us that most

Figure 6. Longitudinal cracks and crushing of the stone units (indicated by the arrow) on the C007 vault ribs.

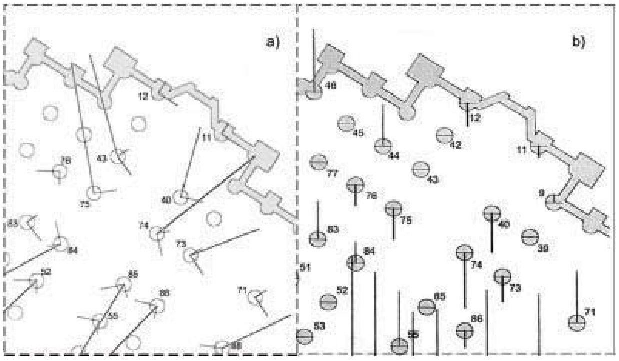


Figure 7. Ongoing monitoring in the Cathedral around Tiburio area: a) pillars out of plumb (1981–2013), with pillar 73 in evidence (segment length represents 2 mm), and b) soil settlements (1966–2014) in the same area (segment length represents 0.8 mm) (Lab. Gicarus 2015).

likely there was not damage on it, during the past repairing works of the near vaults. However this vault is now presenting: a) longitudinal thin cracks along the ribs and b) localized crushing of stone units. The arrows in figure 6 show the localization of the crushing effect at the contact of some ribs stone units. Both phenomena indicate a high level of compression of the ribs mainly visible towards the South.

It does not appear evident that these ribs could have been already damaged twenty years ago and not repaired. It is most likely that a new redistribution of stress has started, due not only to the extensive strengthening intervention of the Tiburio and of the vaults, but also to the continuous leaning of the pillars and soil settlement below the South part of the Tiburio, as monitored by Gicarus Laboratory (Lab. Gicarus 2015) of Politecnico di Milano (Fig. 7).

Another aspect, useful to understand the stress distribution in the vaults of the South-West of the Tiburio, deals with the iron tie rods. The evaluation of the tie rods tensioning was carried out in 2013 by the Laboratory of Materials Testing of Politecnico di Milano (Vasic et al., 2013, 2014; Vasic, 2015). This analysis was not carried out on all the tie rods, but the ones in

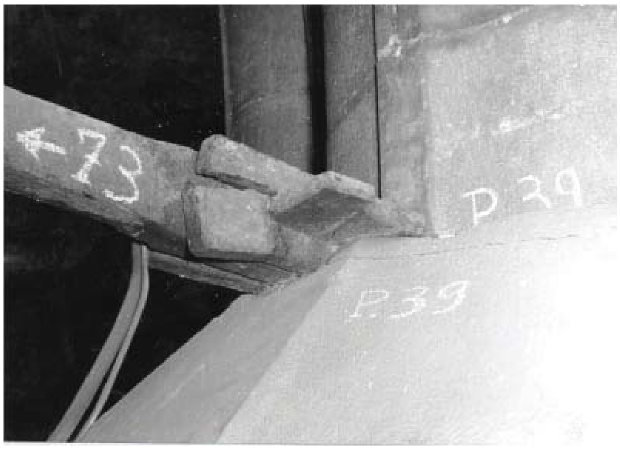


Figure 8. Survey in 1960 showing the failure of the tie rod anchorage on the South aisle between pillars 73 and 39.

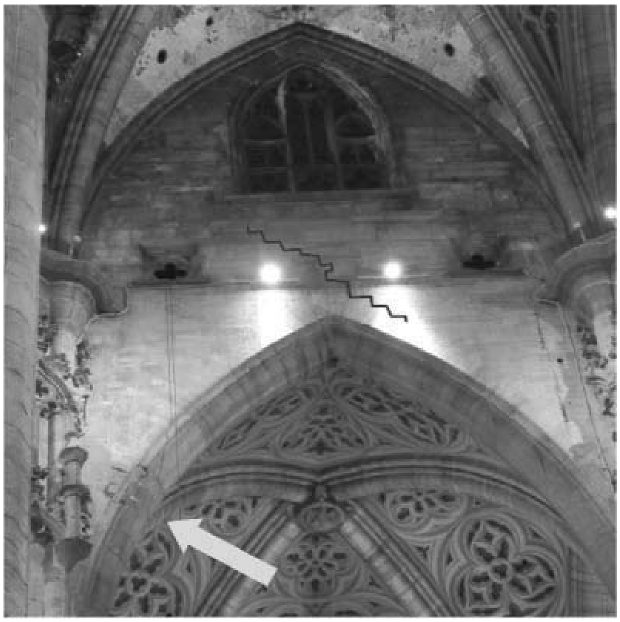


Figure 9. Damaged arch between the two South aisles near Tiburio (P37-P38) and diagonal crack on the upper wall.

the area analyzed here, (between pillars 39-9 and 37-7), are the ones presenting the highest tension values in all the cathedral (Fig. 4b).

All these data are strictly connected with the ongoing measurements of the out of plumb together with the settlement at the base of some pillars, measured by Gicarus Laboratory of Politecnico di Milano. This monitoring shows clearly (Fig. 7) that there are still small but active movements in the pillars and consequently on the vaults arches of all this area. Two trends are observed in the vertical settlements: the first is a descent towards the center of the Tiburio and the second is a differential settlement between the Tiburio piers, with the southern part descending.

Considering in particular the Tiburio pillar 74, as well as the nearby pillar 73, both showed a high rotation outwards in the South-West direction also before the extensive strengthening interventions in the ‘80s. Ferrari da Passano observed in the ‘60s the break of the tie rod between pillar 73 and 39 in South direction

Figure 10. Cracks of a replaced stone unit in an arch of the aisles near Tiburio.

(Fig. 8). Today those pillars are still moving slightly toward South, as confirmed by the still high tension of the new tie rod between pillars 73 and 39, as well as of the tie rods around Tiburio pillar 74.

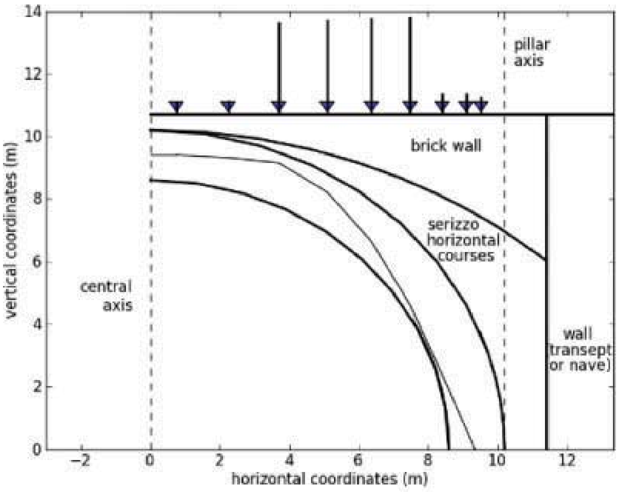
The area at study is characterized by significant differential settlements. One of those effect is the diagonal crack visible on the longitudinal wall between the two South aisles (the C007 vault and the adjacent C107 vault) and the damage of the below arch, visible in figure 10.

The combination of these small but constant and differential movements could be the main causes of the new observed damage that should be constantly monitored, starting at least with the visual but periodical inspection. As an example, a new crack has formed again where stones units were replaced (Fig. 10); this is one of the first signals to be observed of the current movements. Similar cracks are visible on the new stone units of vault C5/C6 repaired in 1993.

4 LIMIT ANALYSIS

Limit analysis (Heyman, 1995; Giuffrè, 1991; Como, 2013) is here used to obtain first level approximate solutions, providing interpretation of the damage described in the previous section. Two causes are analysed, the thrust of the Tiburio on the surrounding structures, and the soil settlements. The former is studied using the static and the latter a kinematic approach; both analyses are worked out with the aid of experimental information from surveys.

The number of bays in the nave in the different historical periods must be taken into account to define the portion of the structure at study moving West from the Tiburio. The first bay was terminated in 1425, the sixth bay in 1550 and the last in 1630 (Coronelli et al., 2015). Two bays of the arcade are shown in Fig. 12 as a possible configuration in 1460. The wall is enclosed between the vertical shafts of the columns reaching to the top and limited at the bottom by the arches spanning East-West.



position (m)	0.7	2.2	3.7	5.1	6.3	7.4	8.3	9.1	9.5	9.6
load (ton)	14.6	15.9	147.9	151.2	154.5	157.2	29.0	28.0	24.1	16.6
			tiburio	tiburio	tiburio	tiburio				

Figure 11. Funicular line in the Tiburio Roman arches, minimum thrust in Phase II (Coronelli et al., 2015).

4.1 *Thrust of the Tiburio*

The four Roman arches thrust laterally onto the surrounding structure, buttressed by the walls above the arcades in the choir, transepts and nave (Fig. 3 for one arch spanning East to West). Two historical periods are considered: (I) 1460 with the decentering of the Roman arches, without the Tiburio loads on top; (II) with the Tiburio and main spire built, until the placing of new ties in this zone around 1970. Considering the constructive phases, the thrust ranges from (a) minimum to (b) maximum.The horizontal and vertical reactions H and V obtained from static calculations (Coronelli et al., 2015) are:

Ia) $H = 67$ ton; Ib) $H = 204{,}1$ ton ($V = 220$ ton)
IIa) $H = 278$ ton; IIb) $H = 745$ ton ($V = 739$ ton)

The funicular line for minimum thrust in case IIa is shown in Fig. 11 (Coronelli et al., 2015).

For the arch thrust transfer into the nave South wall a static solution is proposed in the following. Similar analyses can be formulated for all four corners of the Tiburio connected to the North nave arcade, transepts North and South and choir to the East. The resultant D, with components H and V is shown in Fig. 12b. The thrust is divided into components along different lines, depending also on the geometric constraints imposed by the windows in the wall (Fig. 12b). A first steep line of action (Fig. 12a) reaches the top of the first column (P74). A less inclined line can be drawn, reaching the first arch (P74-P73) at the side of the tiburio and through this the pier suport. A third line is directed to the second arch and third column (P72).

Inclined cracking is observed in the wall between P74 and P73 (Fig. 13b) related to diagonal force transfer; the same damage is found in all eight walls at the four corners of the Tiburio. It is assumed that the shear resistance of the wall is reached; considering the vertical load given by its weight, using a Mohr-Coulomb

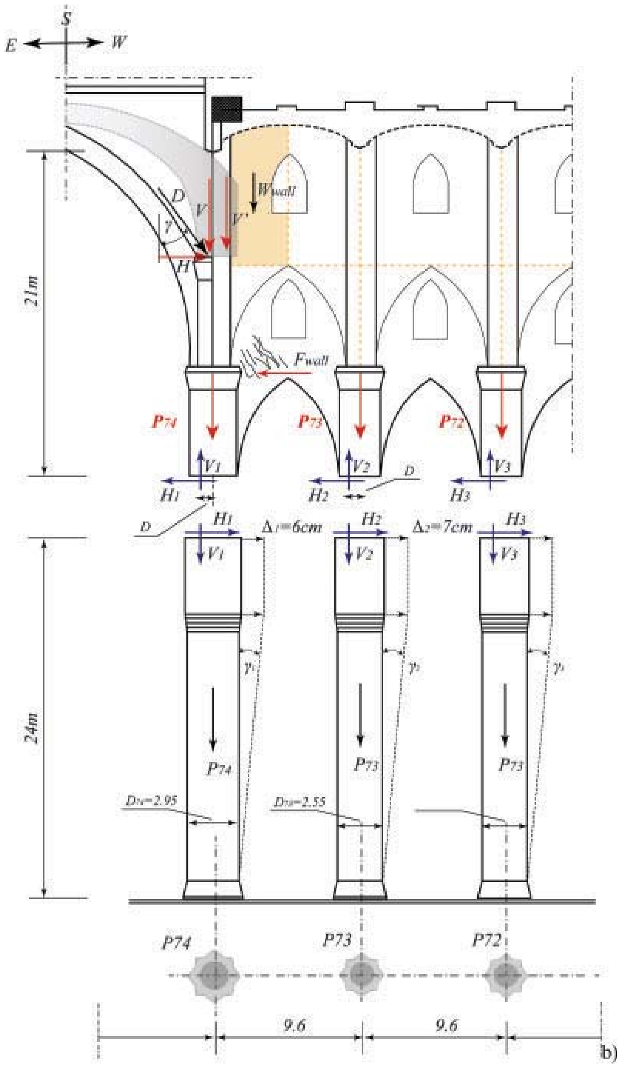


Figure 12. Roman arches reactions (minimum thrust) and equilibrium with forces at the top of the columns.

failure criterion the force transfer in the cracked panel to the right of P74 is a horizontal component of 65 ton, with a vertical component of 86 ton. The remaining force transfer is solved by equilibrium, given the loads in the system (not shown for the sake of brevity).

This analytical scheme is confirmed by the surveys. The westward out of plumb of these columns in 1965 was 6 cm for P74 and 5cm for P73. The monitoring of lateral displacements (Fig. 7a) between 1981 and 2015 shows a westward component for the top of P74 and P73. The lateral loading of the arches to the side of the Tiburio is confirmed by damage at the crown, observed for instance at the side of P75 (Fig. 15).

4.2 *Equilibrium with column reactions and ties*

Fig. 12 shows horizontal equilibrium with thrust H balanced by the column horizontal reactions H_P. In a static analysis scheme the maximum possible values of the column horizontal reactions H_i depend on the vertical force on the columns V_i summed to their weight

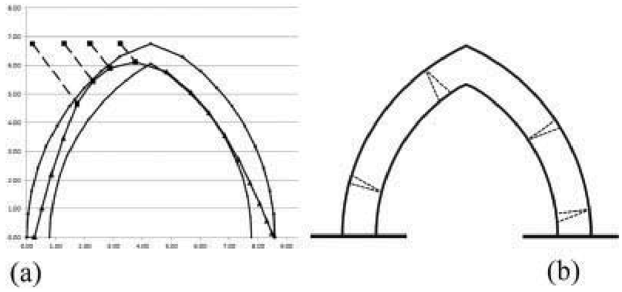


Figure 13. Calculated thrust lines and theoretical mechanism for lateral loading in the longitudinal arches (50% of thrust H').

P_i, their height h and half the dimension of the column cross-section b ($H_i^{max} = V_i b/h$ Como 2013).

Load path calculations (Ferrari da Passano, 1988) show that with the load of the Tiburio the forces at the basis of the columns are approximately 3000 ton (P74) and 1500 ton (P73, P72). The height of the columns from the base to the supports of the arches (line A in Fig. 13) is $h = 25$ m, and cross-sections have a diameter of 2.95 m (P74) and 2.55 m (P73, P72), $H_p^{\max}$ is equal to $1.5/25 \times 3000 = 180$ ton (P74) and $1.275/25 \times 1500 = 76.5$ ton. The first three columns provide sufficient resistance for the minimum thrust H. As the construction of the nave proceeded more columns became available to balance the final thrust. Similar calculations lead to the same conclusion for the configuration of year 1460.

This balance was possible though with lateral drift producing damage to the stone masonry on the west side of the columns, shown by several surveys in the 20th century. The drift of the columns of the arcade aligned with the thrust H is confirmed also by some failures of the ties connecting these members to the outer line of columns between the aisles; an example is shown in Figure 8.

Steel ties, each over 40 m long, were placed connecting the tiburio piers around year 1970, anchored at each end in two points to the side of the two lower windows (bottom row of windows in Fig. 12b). The future evolution of the structural system will require the study of their efficiency in buttressing the Tiburio together with the walls analysed here.

4.3 *Vault damage in the diagonal direction*

Considering that the thrust H on the walls in the corners of the Tiburio had two orthogonal components in the horizontal plane (Fig. 2), there was a diagonal resultant. Hence the corner column (P74) moved along the diagonal towards buttress P8 and the nearby P7 and P9. The structure along this line is made of the vaults with their diagonal ribs. The portion of the lateral thrust balanced by these parts being acted upon is small, in first approximation. The mechanisms corresponding to a passive thrust involves cracking of the diagonal ribs. This is confirmed by the survey, where these vaults evidently show the most damage in the ribs (Fig. 4–6).

Figure 14. Damage with stone sliding at the crown of an arch.

4.4 *Arches with lateral load*

The thrust D (Fig. 12) loads laterally the pointed arches near the Tiburio. Using the static approach the thrust line in these arches is obtained (Fig. 13a) under the gravity load and the shear force in the cracked wall, previously calculated. Figure 13b following a kinematic approach shows a possible mechanism related to the lateral loading.

This type of mechanical damage has been shown in the survey in many elements of the zone analyzed here. Diagonal ribs in the vaults have similar damage, indicating the passive thrust state given by the Roman arches thrust. Further interpretation will be given considering soil settlements in the following.

4.5 *Soil settlement*

The four tiburio piers (eg. P74) and the surrounding columns (eg. P73 and P40) are increasing their out-of-plumb outwards (Fig. 7), approximately along the diagonals. The cause of the out-of-plumb is undoubtedly the thrust of the tiburio analysed above.

The general trend of the ongoing vertical foundation settlements, provided by the monitoring started in the 1960s, shows an increase in the vertical settlement moving from the side walls to the tiburio piers; this depends on the foundation soil characteristics and the position of the maximum forces on the foundations (Coronelli et al., 2014), reaching over 3600 tons, the double of the nave piers and three times the piers between the aisles. The measurements are available only for the past 50 years (1966–2016), but it is reasonable that the trend due to the soil subsidence, started in the early 20th century, continued in time, though with a lower rate.

In figure 7 column P74 shows the highest settlement, and the differential settlements of the foundations and out-of-plumb in the area at study are high. Relative movements of P73 with respect to P39 were the cause of the tie failure in figure 8. The surveys and repair operations show that most past and present damage is in the vaults between P74 and P7-P8-P9.

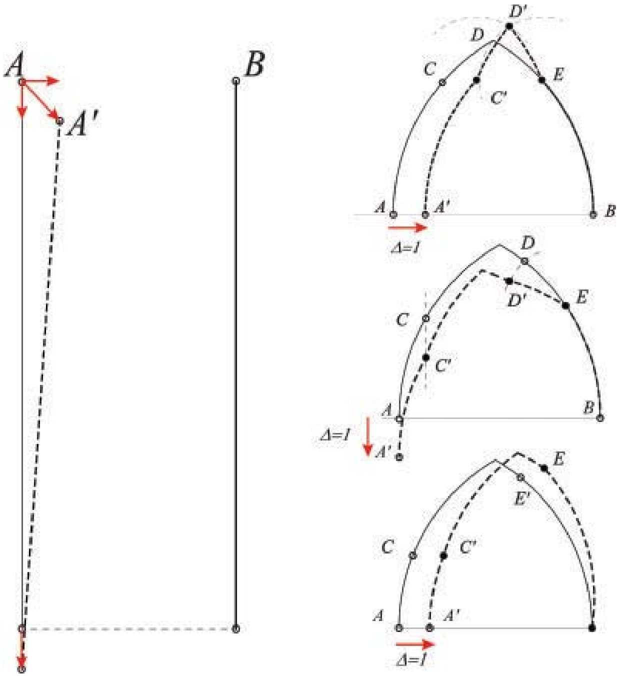


Figure 15. Settlement and rotation of a pillar (left) and settlement mechanisms in the arches (right).

With the kinematic method of limit analysis, the settlement mechanisms associated to these measurements are described by the relative vertical displacement at the base and horizontal displacement at the top of the columns (Fig. 14); these are reflected in arch settlement mechanisms with the prevailing possibility of damage with extrados compression; the load calculations are not shown for brevity.

The superposition of these settlement effects with the effect of lateral force analysed previously provides damage distributions corresponding to those observed experimentally. Stone crushes with cracks parallel to the compression. The arch and rib cross section have a round shape at the intrados and a wider top flange at the extrados. High compression stresses at the extrados create damage showing at the top sides of the cross section, while at the intrados the central part of the block is affected. This is reflected in the stones replaced in the repairs of the 20th century.

5 CONCLUSIONS

The damage of a part of the vaults of the Cathedral of Milan was here analyzed, considering the action of the Tiburio loads and soil settlements on the South aisles.

Visual inspection showed a new crack pattern, following the strengthening interventions realized during the second half of the XX century. Cracks are still very thin but localized in defined points showing that kinematic mechanisms are active. The ongoing monitoring of the pillars confirms that there are slow but continuous movements causing differential settlements and pillars rotation. Limit analysis described the static effects and corresponding mechanisms of the load transfer from the Tiburio on the area at study.

The mechanisms related to soil settlement have been described. The superposition of the two sets of effects corresponds to the observed damage identifying its causes.

The study presented here is an attempt to take into account the complex events that determined the present state of conservation of the structural elements, together with the new active causes of damage. The analysis, here in its beginning phase, should consider important aspects: the crack pattern survey on all the building, the evaluation over time of the tie rods tension, related to the pillars movements measured for more than 60 years, together with the inspection of their state of conservation, in order to avoid unforeseen failures. Another point is the evaluation of the real efficiency of the strengthening intervention with modern structures made in the second half of the XX century, in relation to the continuing soil settlement.

The regular substitution of the damaged stones elements guarantees the constant maintenance of the structural elements but is not sufficient to avoid further damage, if not correlated with the crack pattern analysis. The constant monitoring of some selected cracks should be carried out over time, together with the already active monitoring of some pillars, increased with other new selected survey points. These data could be used for the structural analysis in order to monitor constantly the cathedral's state of conservation, to help during repair interventions and to predict the maximum displacements admitted before failure could occur.

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