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Construction evolution of medieval tuscan monasteries: The tie beam system in the Sant'Agostino monastery at Nicosia (Pisa)

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Restoration of the static and functional configuration of the Nicosia religious complex, a monastery erected near Pisa beginning in 1258, has been studied with particular regard to the historical and structural problems associated to the masonry tie beams fitted to its walls. Entrance to the main building is through a courtyard containing the remains of earlier buildings, the church and old infirmary. A cloister forms the ground floor, while the first floor has been divided according to the layout typical of such buildings: many small cells opening off both sides of three wide corridors. A series of cellars also occupies the partly underground basement floor. The goals of the planned restoration operations are to consolidate the monastery, while seeking to preserve the structure's historical identity through accurate historical analysis and the use of traditional techniques (Del Bufalo, 1981–Dezzi Bardeschi, 1981). From this standpoint, the tie beam system appears particularly relevant and interesting, as it reveals the evolution (Manna, 1980–Nascè, 1982) of the various stages of maintenance performed on several parts of the monastery from the time of the Medici up until the addition of the latest reinforcements in 1985. The anchorage system is substantially the same for all the tie beams: one (or two superimposed) diagonal, square cross-sectional rods acting to retain a similarly square cross-sectional beam; the only tie beam with a circular cross section is the most recent one, inserted in 1985.

In order to guide the choices to be made in planning the operations and test their practicability, we have conducted accurate analyses of the beams' make-up via metallographic optical-microscope examination, from which it has been possible to determine the type of cast iron used (dating back to the 18th century). Furthermore, analysis of the geometry of the various anchorage systems, supplemented by historical document research, has enabled determination of the successive stages of the monastery's construction and dating of the tie beams fashioned via traditional production techniques (Piccirilli et al 1994).

As it was impossible to execute tensile tests on iron specimens, a Vickers hardness test was used to determine the tensile strength values, while chemical and spectrographic analysis with the electron microscope confirmed that the beams could be joined via modern welding processes. Use of the minimally destructive technique of inserting a spinning cot in the middle of the beam has also been proposed in order to allow for regulation of the stress for safety reasons, i.e., to restrain the adjacent masonry walls during their disconnection and protect the original construction techniques used for the anchorages.

STATE OF THE ART-HISTORICAL REMARKS

Painstaking study of historical references, including bibliographical and cartographic sources, has allowed valuable materials to be uncovered for reconstructing the building's history, the alterations it has undergone, the historical contexts in which it evolved, and the constructive methods and techniques in use during each period of its development (which, except for rare, fortunate cases, has turned out to be rather sketchy) (Giuffrè, 1990) .

Four basic stages in the monastery's lifetime have been identified (fig. 1):

— The 13th century (original complex);
— The 15th century;
— The 17th century;
— The additions made during the 18th to 19th centuries.

The original structure is visible for the most part on the monastery's eastern side, beyond the right arm of the church transept. A seemingly reasonable hypothesis holds that the original entrance to the monastery had to be further down on the southern side, in correspondence to the point of arrival on a roadway dating back to the late middle ages, still usable today.

Initially, the building's highest elevation was probably along a section of its western flank, as testified to by the mixed masonry bearing structure, which reaches this maximum height only along said segment. Instead, the height of the northern and eastern portions did not generally exceed the plane of the current mezzanine floor.

During the 15th century the access road to the monastery was restructured and widened, along with the original cloister, which was enlarged to its current layout.

The cloister was then made taller, through addition of a floor above the parvis; this probably called for the addition of structural reinforcements, as testified to by the large masonry columns built around the slender stone pillars, which were inadequate to sustain the added weight of the upper floor.

Written references of further additions to the

Figure 1a/b/c/d
Construction phases of the S. Agostino monastery in Nicosia (PI)

building are scarce: documentation exists (1876) only for construction of a new kitchen. However, considering the type of workmanship, materials and construction techniques used on the other additions, these were probably erected sometime during the 18th and 19th centuries.

Regarding the ties, the main object of our study, a first step was to record all those present in the monastery. From their state of maintenance and the presence of cracking on adjacent walls, a number of hypotheses were formulated regarding their static state (Scillone, Di Segni, 2000–Tassios, 1995). Dating them was performed via experimentation through application of non-destructive analyses performed on samples of the materials making up the ties. The results, supplemented by a brief bibliographical research, has made it possible to establish, though only as a rough approximation, that a good number of these reinforcements date back the period between the 18th and the 19th centuries.[1]

A survey of the tie heads, all of the «pole type», led to identification of three different types: the first characterized by very long, slender rods, with well-finished eyelets and very small tightening wedges (fig. 2).

Another type of tie is instead distinguished by much shorter, thicker rods, with a wedge-shaped extremity, probably for easing its insertion into the eyelet and whose tightening wedges are sometimes preceded by other metallic rods, with the function of tensing the tie and increasing the resistant section of the cross anchorage (fig. 3)

The ties on the northern façade belong to the third type encountered, whose geometry is intermediate between the two foregoing types, that is, they are quite long, and thick in cross section.

One interesting finding worth underscoring is the type of joint connecting the tie beams in the north-eastern area, at the height of the mezzanine level (fig. 4). This is a very long tie —made up of two square cross-sectional rods connected by means of a hook joint, which on one side is fitted to one of the pillars making up the system of arches along which it runs, while on the other, it is anchored to two different walls running parallel to each other. The area in which it is located was built up in the 17th century, a building extension clearly testified to by the varying thickness and types of masonry used.

It can be hypothesized, therefore, that two different systems of tension beams have been applied: a first type dating back to the 18th century, to add support to the walls of the old monastery complex, and a second one to sustain the building additions made in the 19th

Figure 2
Tie beam anchorage (type n.1)

Figure 3
Tie beam anchorage (type n.2)

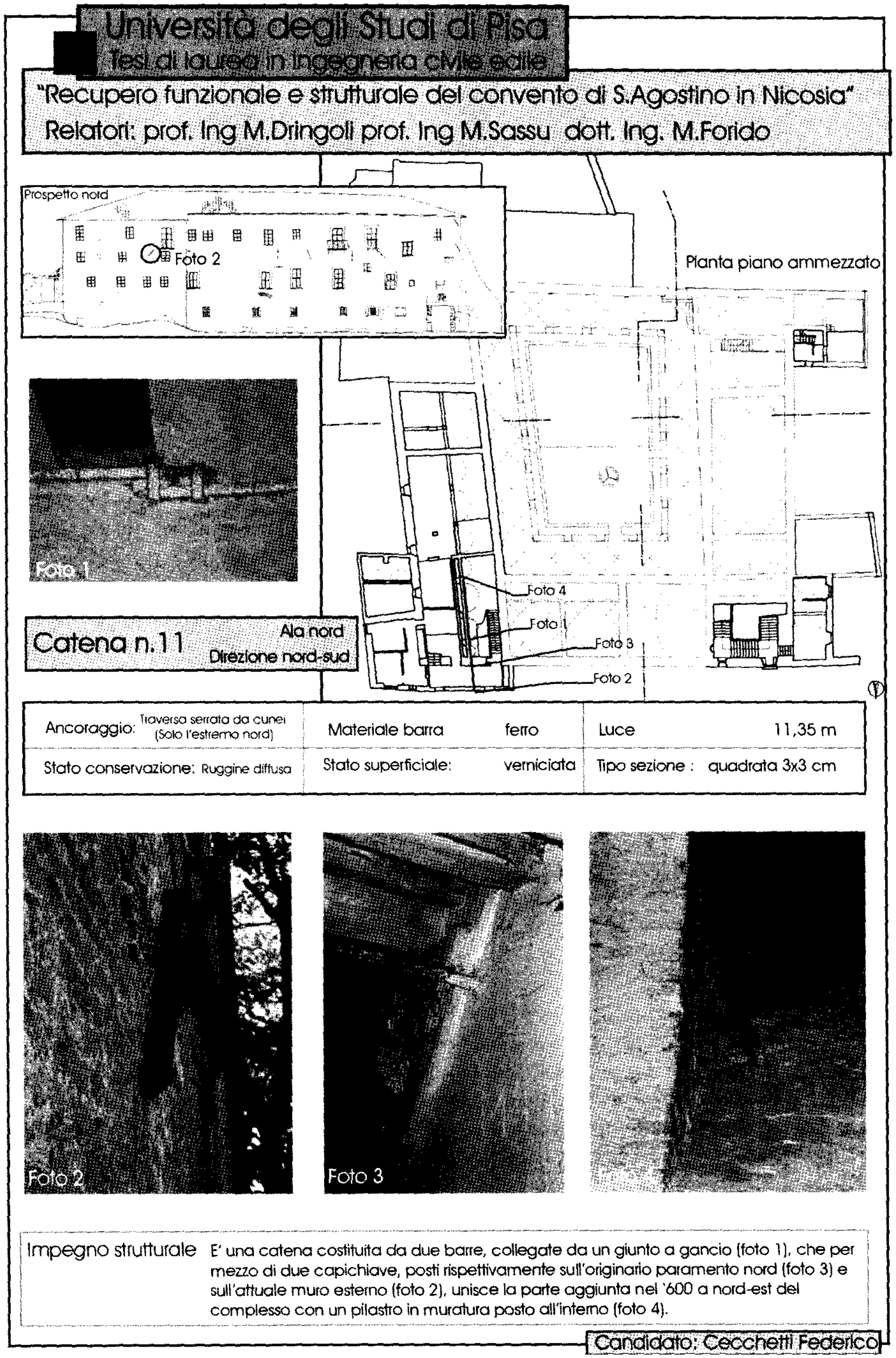

Figure 4
Typical survey form – (photo n.1 with an intermediate tie beam anchorage)

century. The arrangement of the ties is however not very effective statically and probably the result of successive additions over time, as can be seen, for instance, on the northern face where two tie heads have been placed side by side.

RESTORING THE TIE CONNECTIONS AND EXPERIMENTAL MEASUREMENTS

In deciding upon a maintenance programme for the ties, we considered the case of the connecting rods currently under tension and hypothesized intervening to replace the intermediate tightening mechanism (photo 1, fig. 4) with a new mechanism that would enable the tensional stress to be maintained in the tie. Actually, a common finding in historical ties is that degradation has involved only the terminal or intermediate junctions, so that it is often possible to proceed by reinforcing the junctions alone, without having to remove the rod itself. This, however, calls for detailed knowledge of the tie's metallographic composition, so that the type of reinforcement to apply can be decided upon (welding, gluing, friction tightening).

In the case at hand, we decided to design a device to unload a segment spanning the joint (fig. 5), and

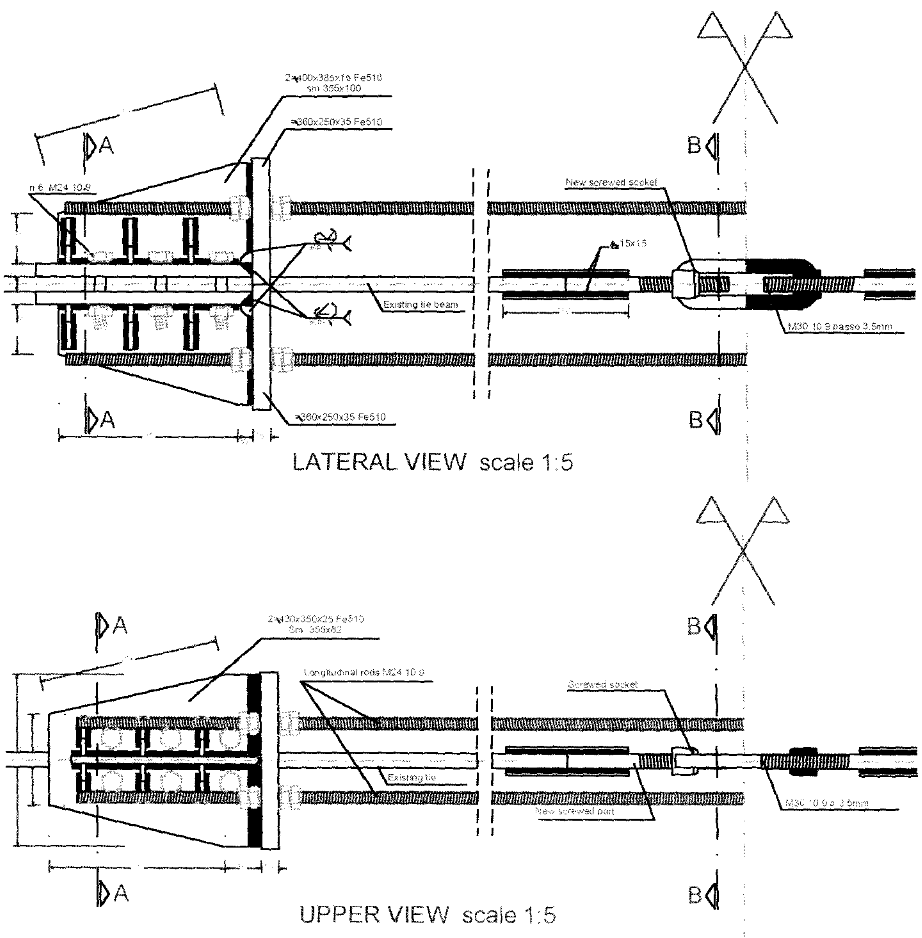

Figure 5
Device to repair tie beams maintaining the originary traction force

then cut and weld on a threaded sleeve, which will allow tensing and regulating of the tie. Thus, preliminary experimental metallographic and hardness testing was performed in order to determine the tie's historical value and check whether it could tolerate welding.

The unloading device. As designed, the mechanism absorbs (by the effects of friction) the stress resulting from disconnection of the rod, and transmits it —via the tension rods— from one extremity of the tie to the other. It should be emphasised that in order to render the device versatile, the tension rods adopted were threaded throughout their entire length, so that they could be adapted-via a system of nut and lock-nut to the various spans that may be encountered in various parts of the tie system of the monastery complex.

The tie-sleeve connection. In order to verify the feasibility of welding the new elements to the existing ones, a series of analyses has been conducted on the type of iron making up the existing ties. In order to avoid damaging the tie itself, this was performed by removing small portions of the metal and performing only those tests and analyses possible with such small samples. The samples have thus been subjected to the following:

— Brinell hardness tests;
— metallographic examination with the optical microscope;
— spectrographic analysis via the electron microscope;.
— chemical analysis.

The Brinell Hardness test is the only mechanical check possible on such small quantities of material. The tensile resistance of the constituent material of the ties, an indispensable parameter for planning restoration, can be deduced by virtue of a relation between the Brinell hardness and the limit tensile stress. The tests, whose results are reported in Table 1, were conducted in the laboratories of the departments of chemical (lab 1) and structural (lab 2) engineering.

Upon metallographic examination all the samples exhibited macro-inclusions at first visual inspection,; these are probably attributable to incomplete decarbonisation during the iron production process.

Table 1 Brinnell hardness test

Specimen	Lab. 1	Lab. 2	Brinnell hardness	Strength {Mpa]
A	149	143	146	438
B	123	133	128	384
C	85	89	87	261

The exams moreover revealed that the samples all have a rather large grain (see fig. 6), indicating a high concentration of impurities [2].

This exam enabled a first hypothesis regarding the metal's chemical composition to be formulated, in that observation by the optical microscope revealed that it is not composed of a two-element, iron-carbon alloy, such as steel, but soft iron with low carbon content.

Electron microscope examination confirmed the previously forecasted chemical composition of the metals examined: via spectrographic analysis of the digital images furnished by the electron microscope, we were able to determine the chemical composition of the analysed metal at a single point, as well as along a line and within a region.

The chemical analysis yielded the percentages of all elements present in the metal. The conclusions that can be drawn from the results of the analyses performed are that the tie beams are essentially made of a soft grade of iron, probably produced in an old

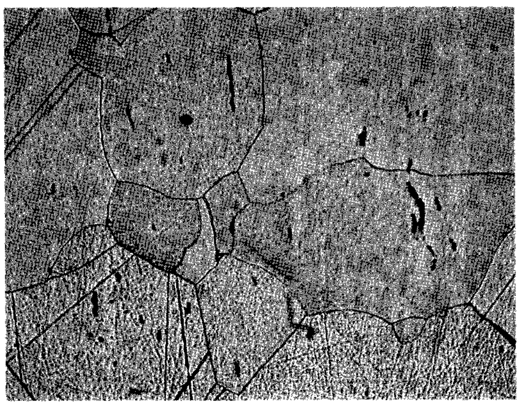

Figure 6
Metallographic view

iron mill by puddling[3] and can be welded perfectly only through forge welding.[4]

Iron with such a low concentration of carbon (Table 2, specimens A and B) is easily worked, and for this reason the rods in the monastery, if removed, could easily be threaded by lathing to allow direct insertion of the tensing sleeves, of course contingent upon verification of the beams bearing capacity.

Table 2 Spettroscopic test

Specimen	Carbonium	Silicium	Potassium	Sulphur	Tin
A	0,0100	0,1440	10,4157	0,0108	0,0094
B	0,0610	0,0970	10,3077	10,1212	0,0031
C	0,2160	0,2150	0,0046	0,0028	0,0086

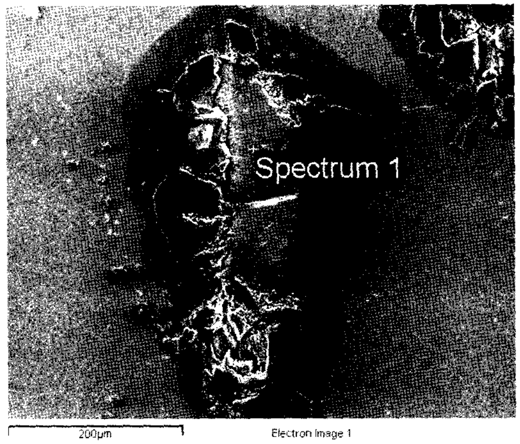

Figure 7
Iron impurity by electron microscope

The solution proposed instead calls for insertion of a threaded steel sleeve (Table 2, specimen C): the connection is to be made by angle bead welding. It should be noted that the temperatures attained in this welding process may provoke partial melting of the adjacent iron. In such situations, the considerable sulphur and potassium content of the impurities, could bond with the iron and give rise to composites that would weaken the connection. Therefore, the procedure must be planned with the widest possible margin of safety. However, it seems that such a drawback can be minimised if the welding is executed with particular care.

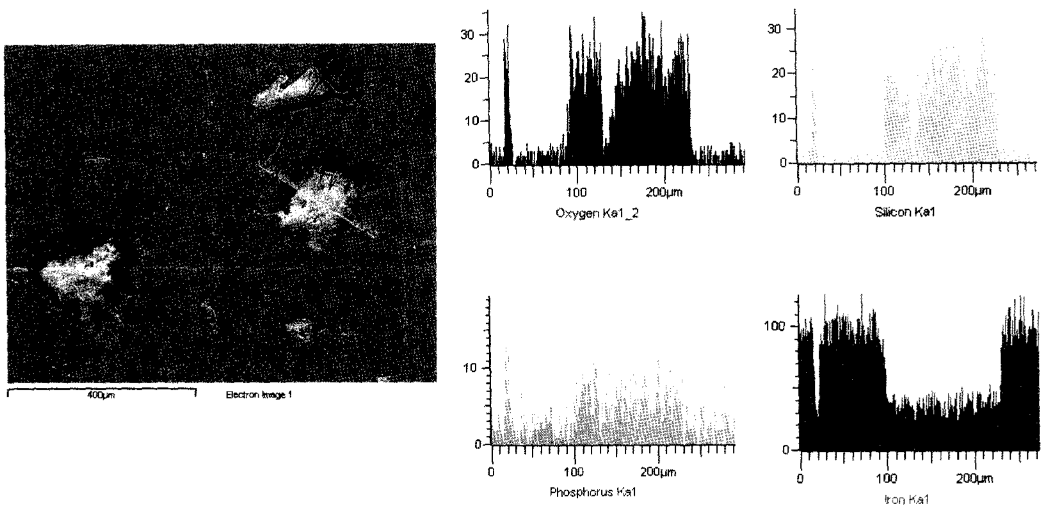

Figure 8
Example of spectrographic analysis on impurities

Conclusions

Many Tuscan buildings, in particular the numerous monasteries set on high ground or embankments, are often fitted with tension rods to reinforce their external walls. Researching their histories, including chemical-physical analysis, constitutes an important step in their safeguard and maintenance from the perspectives of both their static equilibrium and historical configuration. Moreover, any consolidation or reinforcement operations must be performed, as far as possible, through techniques that take into account the structures' geometric properties and consitituent materials.

Notes

1. The only indications come from the research conducted by Alessandro Del Buffalo for the History of Architecture course at the University of L'Aquila. An illustrated chart shows six different types of capichiave(?)head rod), each indicated with the period of its most wide-spread use. Cfr A. Del Bufalo in «Metodo storico di schedatura per interventi di restauro» drawn from «La Conservazione dei Monumenti-Metodologie di ricerca e tecniche di consolidamento contro il degrado», ed. Kappa, 1981, Rome, fig. 1 p. 172.
2. Actually, a certain variability was observed in the grain sizes. This is probably attributable to the different processes adopted in the ironworks that produced the rods. Some of the samples may in fact have a finer grain because during production they also underwent a lamination process, which would have considerably compacted the metallographic structure, with a consequent improvement in its mechanical properties, especially the tollerance for welding, which at the time was only done by forge welding.
3. With this production method the cast iron, set on a silica base, is heated at high temperatures and decarbonated by the air aspirated by the flame in particular types of forges. However, a fundamental aspect of the procedure is the puddling process, by which the product was stirred into a pasty iron mass, easily worked subsequently by drop-hammering/forging/pressing(?)maglio).
4. In this welding technique, used by blacksmiths to weld soft iron, the pieces are heated in an oven or forge until they take on a pasty consistency, and then hammered together.

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