Reinforced Concrete and Limestone: Rebuilding a Modern Church on Gothic Ruins

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ABSTRACT: The S. Domenico Church reconstruction (Cagliari, 1949-54, Arch. R. Fagnoni, Eng. E. Bianchini), almost completely destroyed by bombs in 1943, constitutes an interesting example of constructive mixture between historical structures and modern materials. A new additional church was set upon the limestone masonry ruins, after covering them with a reinforced concrete slab. The new church solved the difficult constructive problem of founding itself above fragile and damaged masonries: half-portal frames, rooted in only two points, supporting the entire vault weight of its structure. Beside the undoubted architectural result - with evident gothic echoes mindful to the ancient church - the structural system is certainly the most interesting aspect, along with its practical realization. The double curved covering, the parabolic dome, the intermediate slab and the external surface in bush-hammered concrete were really painstaking for employer and engineers, but allowed an appreciable example of reinforced concrete use in historical building.

AN AUTENTIC "TOTAL DESIGN"

The peculiar events during the S. Domenico Church rebuilding (1949, Cagliari, Sardinia) - even if not much known and until now not at all explored - is an interesting example of constructive mixture between historical structures and modern materials, composing limestone medieval masonries, reinforced concrete linear and plan structures, sandwich masonries with external stone blocks and pumice concrete inner filling. Moreover, it also represents more generally, a paradigmatic case of how Post Second World War European architectonical culture dealt with the problems of building restoration and town centres recovering from the bombing damages.
The ancient church, built around 1450 in gothic Aragonese style, was almost completely destroyed by bombs in May 1943: the sophisticated stellar vaults collapsed, the remaining covering was seriously damaged, masonries and arches were gravely unstable. It was immediately necessary to decide how to restore the religious site's dignity. The Dominican friars and the artistic heritage superintendent discussed about different choices: the possibility of an identical historical reconstruction, the fulfilment of a war memorial – with ruins *romantically* left as a warning and moving the church to a new residential suburb – or rebuilding a new church over the ancient settlement, but expressed in openly modern forms. Finally, this last option prevailed.
The Cagliari convent dependence by the Florence Dominican Province directed the choice toward the architect Raffaello Fagnoni (Florence, 1901-1996), a well-known architect very close to the ecclesiastic milieu. Together with his reliable structural engineer – Enrico Bianchini, with which he had a fruitful professional fellowship – Fagnoni conceived a very ingenious solution for a cultural, constructive, architectonical and structural problem: how to design a new church reminding to the gothic pre-existence and being, at the same time, a true current times expression? How to set up a self supporting hall only based upon the ancient structures in rag limestone? How can it be accomplished with maximum quality and minimum costs?
They applied to San Domenico an inventive line of thinking: as the original church floor was lower than street level and almost only the outside walls survived, the architect decided to cover it with a closely crossed nerved slab in reinforced concrete, obtaining a crypt exclusively reserved to friars (Fig. 6); upon it, preceded by wide steps flying from the street to the entrance level, he set the new church (Fig. 1). It is configured as a whole nave with a double-curved roof and a depressed floor, in order to produce a fluid and shell-shaped internal space (Fig. 2 right). In evidence on the side walls and standing out on the free-face rough stone sur-

faces, there are two ribs bundles opening in a beamed wattle supporting the ceiling (Fig. 8). It was indubitably thought with modern language and, in spite of it, it had some evident links to history, such as the large use of stone masonries, referring to the neighboring town fortifications, or the hint from the new reinforced concrete ribs to the primitive gothic vaults. The structural elements were really essential in the plan process, both in constructive and in linguistic terms, and Bianchini calculated the structures and supervised all the reinforced concrete building phases with peculiar technical ability, always in contact with Fagnoni, but also with the contractor delegate manager, Valerio Tonini.

THE STRUCTURAL CONCEPTION

The reconstruction process started from the consolidation of the survived masonries, inserting into them a system of pillars, plinths and continuous foundation beams; it was necessary because their bearing capacity was very low and because the architect needed to introduce some autonomous structural elements, able to support the slab, super -elevation and the roof loads. The intermediate ceiling, lying upon the medieval walls, is a nerved slab created by closely crossed reinforced concrete diagonals, according to a narrow rhomboidal design (joists 12x45 cm, maximum span 60 cm, concrete topping 10 cm. Fig. 5 and 6).
The upper level – the effective church – is constituted by a single 20 m span nave. The fundamental static issue wasn't easy to solve: how to realize a roof system without intermediate supports, lying upon modern structures without involving the ancient limestone walls? The planners solved it with particular intelligence: the fundamental static mechanism was constituted by three different half portal frames, four times mirrored, whose beams crossed each others on the roof (Fig.1 and 2); it originated a grid structure completed by slab fields between the beams; the mesh was such as the largest slabs spam was always under 3.5 m.
The half portal system converged into a single point in each side of the church, therefore merging the group of six pillars into masonries (masonry thickness 100 cm, pillar section 110x80 cm, iron bars 18Ø22 on the tensile side and 12 on the other). Through this structural invention, the planners resulted to discharge all the roof loads in a single point autonomously founded on the ground, and to leave the outside walls of the new church totally unloaded but most of all, the gothic ones below. According to a similar principle, a different portal frame typology, four times mirrored to create the mesh, characterized the presbytery covering; it was only 11 m span, but complicated by the dome's circular base ring.
The dome itself was a fundamental structural element, denominated by the archive documents as "thin, well-balanced and rotation-solid shaped" (Fig. 3). Its parabolic profile closely followed the funicular shape, maintaining the loading curve inner to the slab and permitting to reduce its thickness to only 8 cm. Obviously, this hypothesis was valid only in abstract equilibrium conditions, without lateral forces, and so the structure was however armed to resist to the curve deviations provoked by wind, internal tensions due to thermal expansion or other actions not exactly foreseeable.

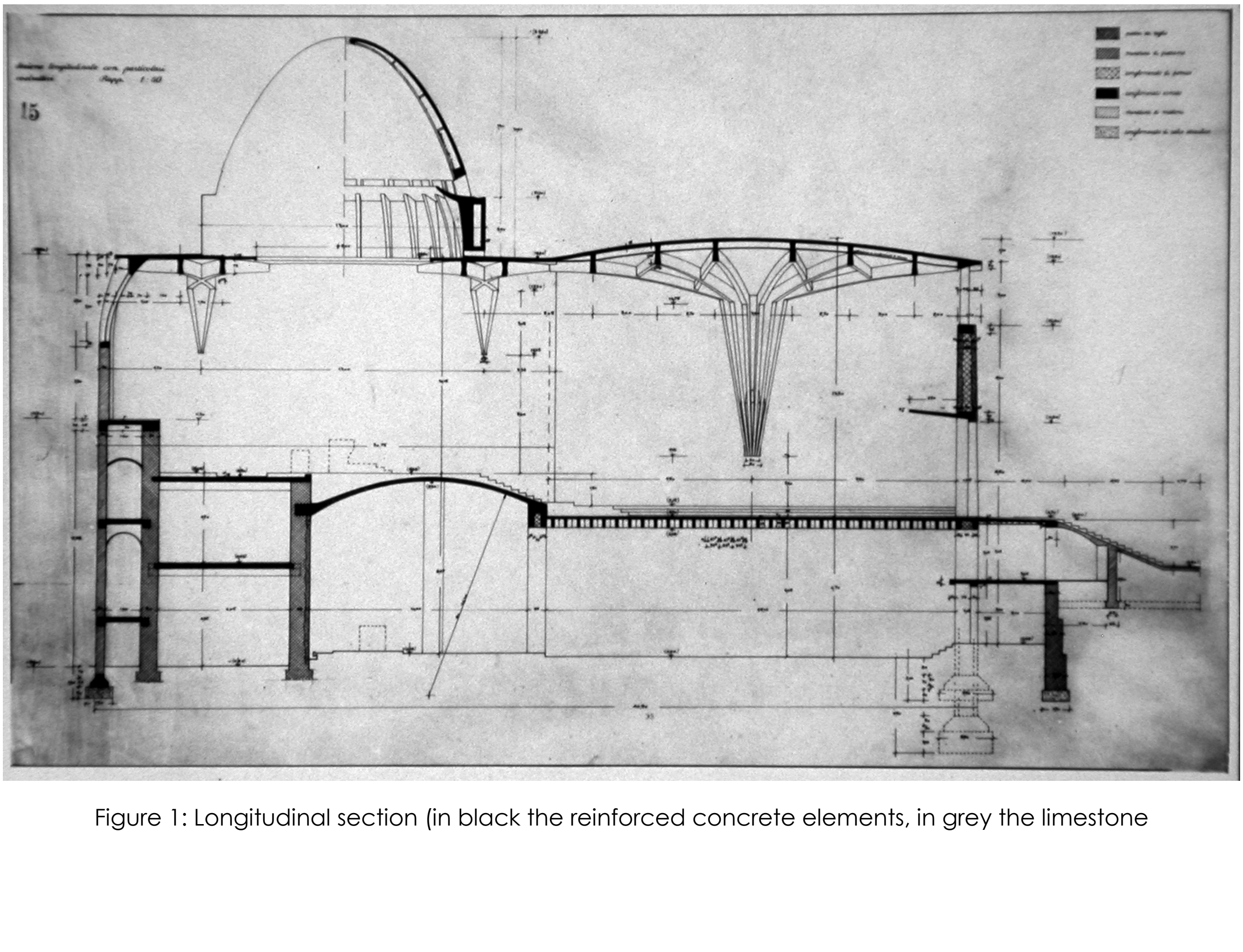

Figure 1: Longitudinal section (in black the reinforced concrete elements, in grey the limestone

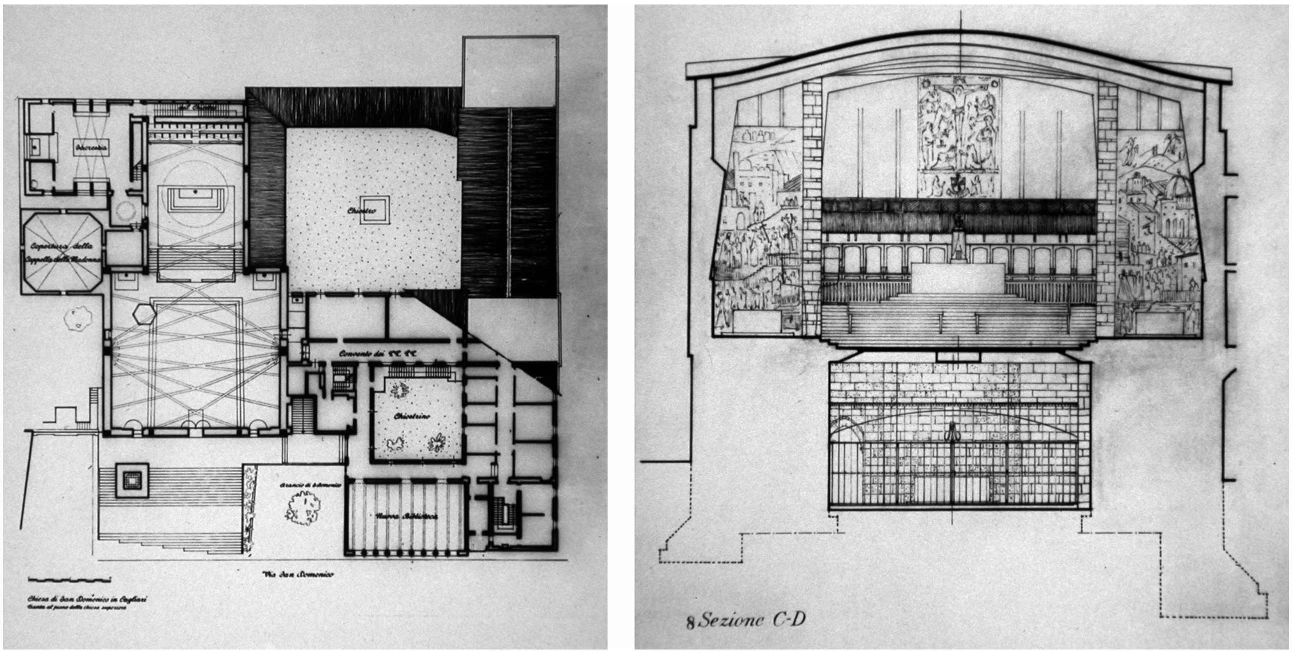

Figure 2: Upper church and monastery level plan, with roof ribs projection (left); transversal section (right)

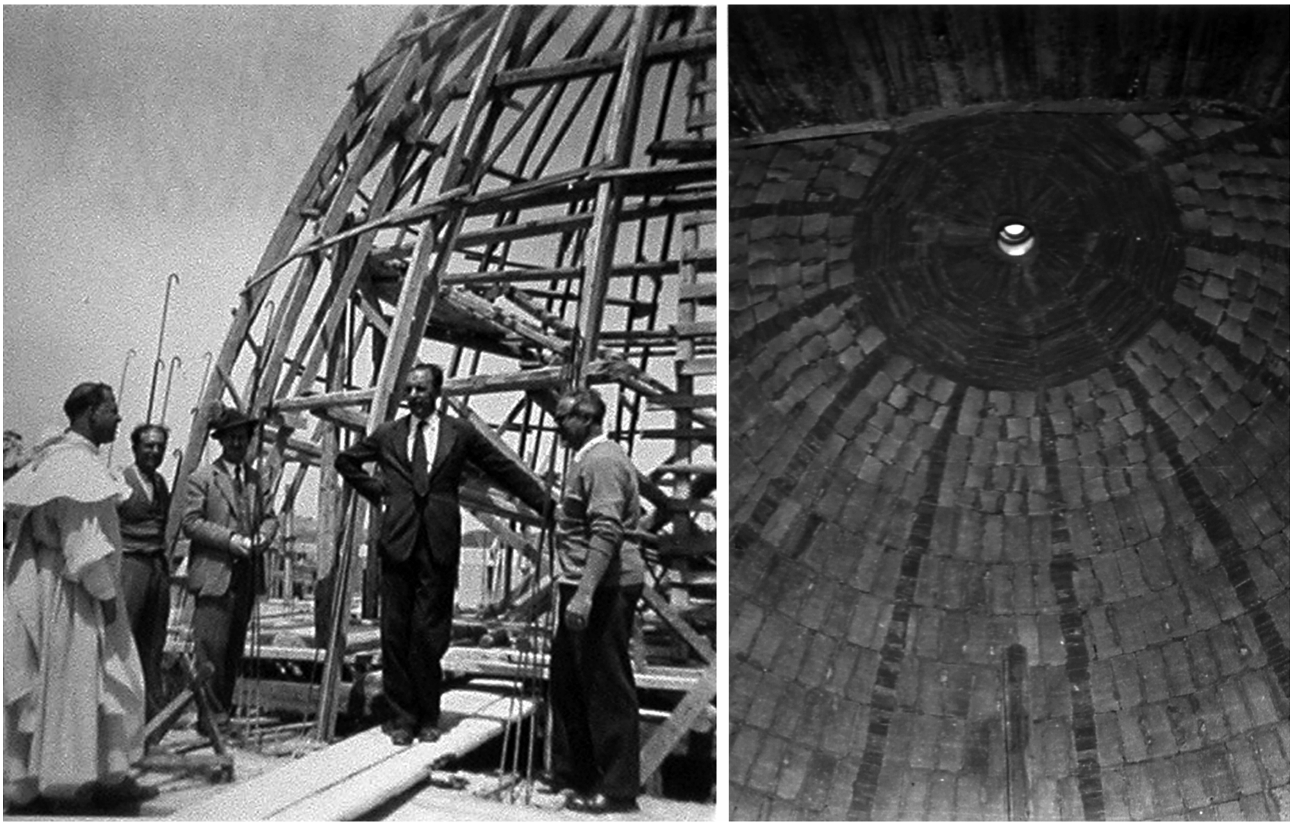

Figure 3: Fagnoni (in profile on the right side) examines the wooden scaffolds (left); the unfinished dome (right)

THE CALCULATION

The calculation process, as referred by the archive documents, started illustrating the half portal system, specifying its general geometry, the shape details and the static hypothesis.

> The dimensions and consequently the inertia moments, both of the beam and of the pillar constituting the basic frame, are very much reduced beside the support; even better, the beam raises the bearing with very small dimensions (almost a pendulum). It is then to be excluded every kind of fixed support, and only hinge or free bearing support is possible. The pillar foot is very tapered and only fixed joint or hinge can be considered a possible solution; a sliding bearing is to be absolutely excluded.

After this preamble, the calculator proceeded to verify the only three possible bonding conditions: fixed joint-hinge, hinge-hinge and fixed joint-support, always maintaining strictly orthogonal to the beam-pillar node to ensure a stiffly monolithic frame. Comparing the results, he derived that the first solution produced a lower moment in mid-span, but a foot thrust higher than the others two, and it could create some inconvenience because of the difficulty to accomplish an actual perfect fixed joint. Then he excluded this fist case.

> In the other two cases, the highest positive moment corresponds to the last condition (and it reassures us in case of imperfect accomplishment of the fixed one or others constraints). We have to get as near as possible to the III case and that is to say: to assume in mid span a high bending moment; to make especially flexible the C support [at the end of the beam. N.d.A.]; [we have] not to be too worried if a little thrust raises for an inexact realization of the fixed joint or of the C support because the intersection between opposite portals make the pillars collaborating to absorb it. We can also eliminate the thrust with a proper tie conducted trough the ceiling thickness (because of the particular fan-shaped disposition and of the symmetrical crossing, which transform the thrust in a tensile stress along the nave axe).

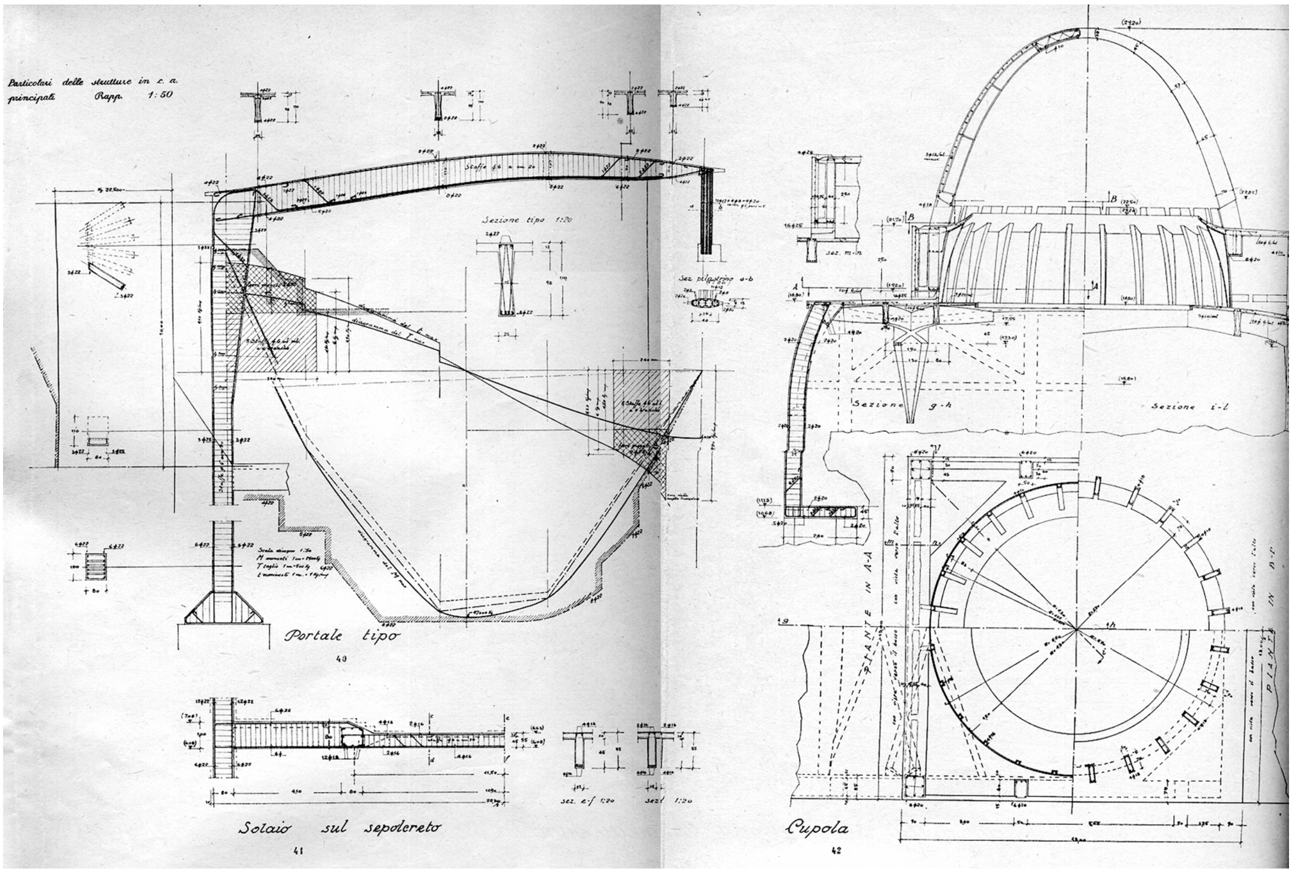

Figure 4: Resuming drawing of the principal reinforced concrete structures

The calculator quickly resolved the loads analysis for the roof ceiling and the correspondent measuring, establishing a 12 cm structural thickness, alternating reinforced concrete and pumice blocks in order to lighten it, with 10Ø6/m iron bars; then he passed to the less obvious analysis of the main frame.
The nave roof calculation consisted in only three half-portal typologies (Fig. 4 left) every one intersecting three times the corresponding frames on the other side (Fig. 2 left, ribs plan projection). The beam crossing deflections were prearranged in order to determine stress entities, supposing beams solidarity in their intersection points. The calculator deduced nine singular values of the total bearing loads, each one corresponding to a single node, and starting from them, he calculated the bending moments and the shear stresses trough the graphic method. A T-shape section was assumed for the beams, composed by the intrados ribs (whose height varied between 110 and 60 cm, base 25 cm) and by 75 cm of the correspondent slab. The iron bars in tensile zone were variable between a maximum of 8Ø22 in mid span to a minimum of 4 in the less stressed sections beside the supports.
The dome calculation (Fig. 4 right) started from this assumption: "the dome meridian profile is calculated as a permanent load funicular curve, increased by a 150 kg/m^2 incidental overloads, acting vertically and uniformly disposed all over the span line." The loads resting on different portions of the meridian profile were calculated with the graphic method - excluding thrust variations and parallel stresses except in the circular ring closing the apex - so deducing the vertical and horizontal vectors in the dome impost slice. Hypothesizing just permanent loads, it was possible to expect "very weak compressive or tensile actions in the rings and surely

lower stresses in the meridians." Coherently, the effective values analytically calculated, gave back an insignificant stress condition in parallel rings and so easily absorbed by the structure internal cohesion itself.
In order to foresee the full load conditions, it was supposed a wind uniform strength - 120 Kg/m^2 - acting on half dome always orthogonal to the external surface. The graphic method allowed calculating the stresses on the meridians and parallels, resulting surely higher in this case. The structural measuring ordered an 8 cm thick slab, reinforced with a diagonal iron net with 3Ø12/m.
The analysis went on with the dome base ring, the big quadrangular tambour beams (with a reinforced concrete section of 100x250 cm and a consistent stirrups mesh) and a complicate system of pillars and concrete trusses. This particular combination of elements, drowned into the masonry body that are no longer visible, is charged by the entire dome load; it is canalized trough the pillars, autonomously founded, directly to the ground without involving masonries, both the ancient and the recent ones, as expressly wanted by the planners. (All the quotations in this paragraph were extracted from the "Calculation Book", Folder 36, Raffaello Fagnoni Fund, State Archive, Florence, Italy)

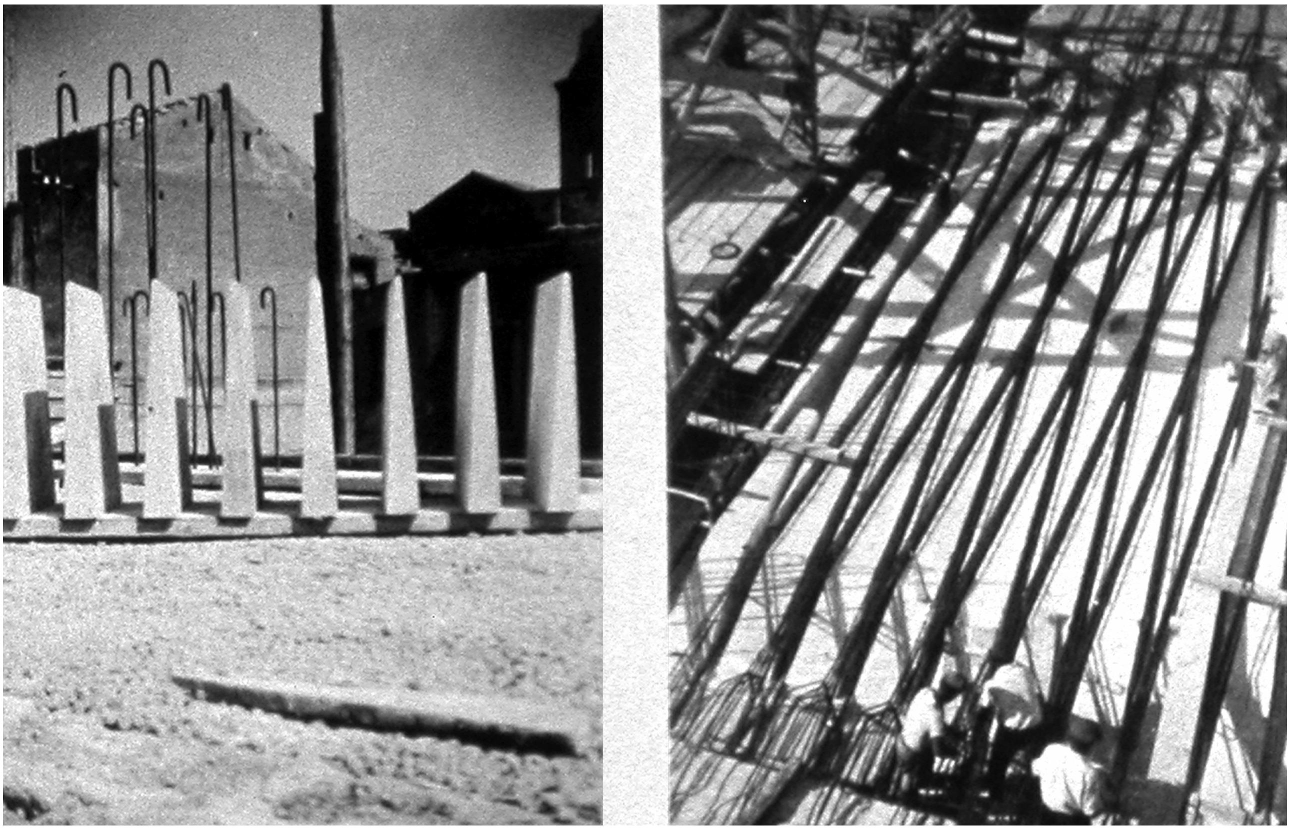

Figure 5: Two different building phase for the intermediate ribbed slab

THE BUILDING YARD AND THE CONSTRUCTION PROCESS

The innovative structural idea brought inevitably a similar constructive difficulty. In the San Domenico building yard the perfect cast execution is particularly notable, witnessing the ability of planners, contractor and workers. The concrete appears smooth and compact, homogeneously mixed, without any imperfections as gravel segregations or aggregate irregularities. The cast restarting is rightly executed only by horizontal levels, correctly prepared for the structural connection and such as to not compromise the global image of the wide fair-face surfaces. That is why the entire building is almost perfectly conserved today. The reinforcement corrosion is very rare, such as the concrete cover spalling, indicating the negligible conglomerate porosity and consequently the scarce humidity penetration possibilities.
The ribbed slab and the nave roof greatly tested the builder's skill. The horizontal slab covering the old church (Fig. 6) – at first named cemetery and now called crypt - is characterized by the close sequence of crossing joists, high and slim, with very acute angular intersection.

> Cemetery slab: we are preparing it and cast it any day now. It is difficult and very expensive work. We prepared the entire horizontal level made by wooden boards. Over it, we built the crossed joist moulds in hollow clay blocks (Fig. 5 right). These moulds were plastered and then stuccoed by gypsum. The bottom surfaces were also stuccoed by gypsum. The acuminated ends constituting the beams intersection males, whose formworks were first prepared in steel plates, seemed to be unsatisfactory. We had to form 128 new gypsum points un-mounted (Fig. 5 left), 60 cm long and 45 cm high; we used four gypsum main forms, derived from another gypsum model preventively executed. These 128 points are located on the wood sur-

face and linked up with the brick formworks. A large and skilful roman plasterer team is now at work. The iron bars positioning, with such thin spaces between the plastered forms, also required a lot of accuracy and is very onerous (Fig. 5 right). When everything will be assembled, the cast will be executed in whole, without any interruption. We have kindly asked the assistant chief engineer to ensure you accurate information on the preparation and execution of this particular work.

These words by Eng. Tonini, delegated for the local building firm, widely testify the difficulties and precision needed by the accomplishment of this intermediate slab, whose surfaces are still perfectly smoothed. The intrados was bush-hammered in the joists lower face, so giving a grain contrast between the inner and external parts of each rib.

Figure 6: Detail of the lower church, with the gothic masonry arches and the concrete slab

The whole building yard went on for progressive elevations, mixing the limestone parts, the fair face concrete sides and the pumice conglomerate intermediate filling. When the last edge beam level was reached (15,80m, starting from the old gothic church floor) they started to lay out the more complicated formworks for the half portals and the overhanging slab. They chose to use metal formworks (Fig. 7 left) for the ribs, left fair faced without any further superficial work; they were made by one meter square panels, blocked by gripping jaws to continuous wooden bottom planks defining the beams spatial lay out. Each half portal was comprised in a single different vertical plan and the beams had curved paths and variable transversal sections so constituting a complex bending roof surface (Fig. 7 right).
The roof intrados was formed by pumice in order to assure lightening and thermic insulation to the different layers; it was built before the structural final reinforced concrete cast. A particular care was taken to the roof monolithicity by dividing the whole surface into four portions; each one cast without any interruption.
The intrados was taken in particular care with a lot of specific preliminary tests, not only to have a perfect beams execution, but also because the architect pretended to apply to all the slab inner surface a continuous carpet of star shaped tiles, stuck and painted one by one. The tiles had two different purpose: the first was mainly aesthetic – to uniform the ceiling fields, otherwise too much different one from each others – and the second one linked to technical and building reasons, in order to hide or dissimulate eventual micro cracking caused in the intrados by casting shrinkage effects. The result was proportionate to the effort spent for it and to the lot of hypothesis and tests that prepared the final resolution and brought, trough an outspoken and intense exchange of views between the chief engineer and the firm delegated, until the best solutions, individuated by mediating the different needs and dispositions.
All the reinforced concrete elements were calculated by the engineer Enrico Bianchini and carried out by the SACIP firm, from Florence (Società Anonima Costruzioni Ingegner Poggi, directly derived by the Attilio Muggia firm, one of the first Hennebique patent agent for Italy), whose technical director and governing manager was Biachini himself. The intense and lasting cooperation between Fagnoni and Bianchini (both with a double scholastic education, technical and humanistic) led to produce many appreciable works, starting from the

1920s until the 1950s, everyone characterized by a deep coherence between idea and practical realization, architectural conception and structural inspiration. Among them, the San Domenico Church constituted certainly an excellence in work.
The entire church design was dominated by an explicit mediation intention, mixing traditional and innovative construction techniques or historical and modern building materials: the reinforced concrete portals emerged from walls in the same limestone of the ancient town fortifications; the modern architectural language, with horizontal windows and the innovative ovoidal dome, resulted to allude to the gothic vaults without falling into mimetic historicism but rather giving them an interesting re-interpretation. It is difficult to say about it if architecture or structure idea, project or building process were better resolved, but it is indubitably clear that it found its key in the masterly use of reinforced concrete.

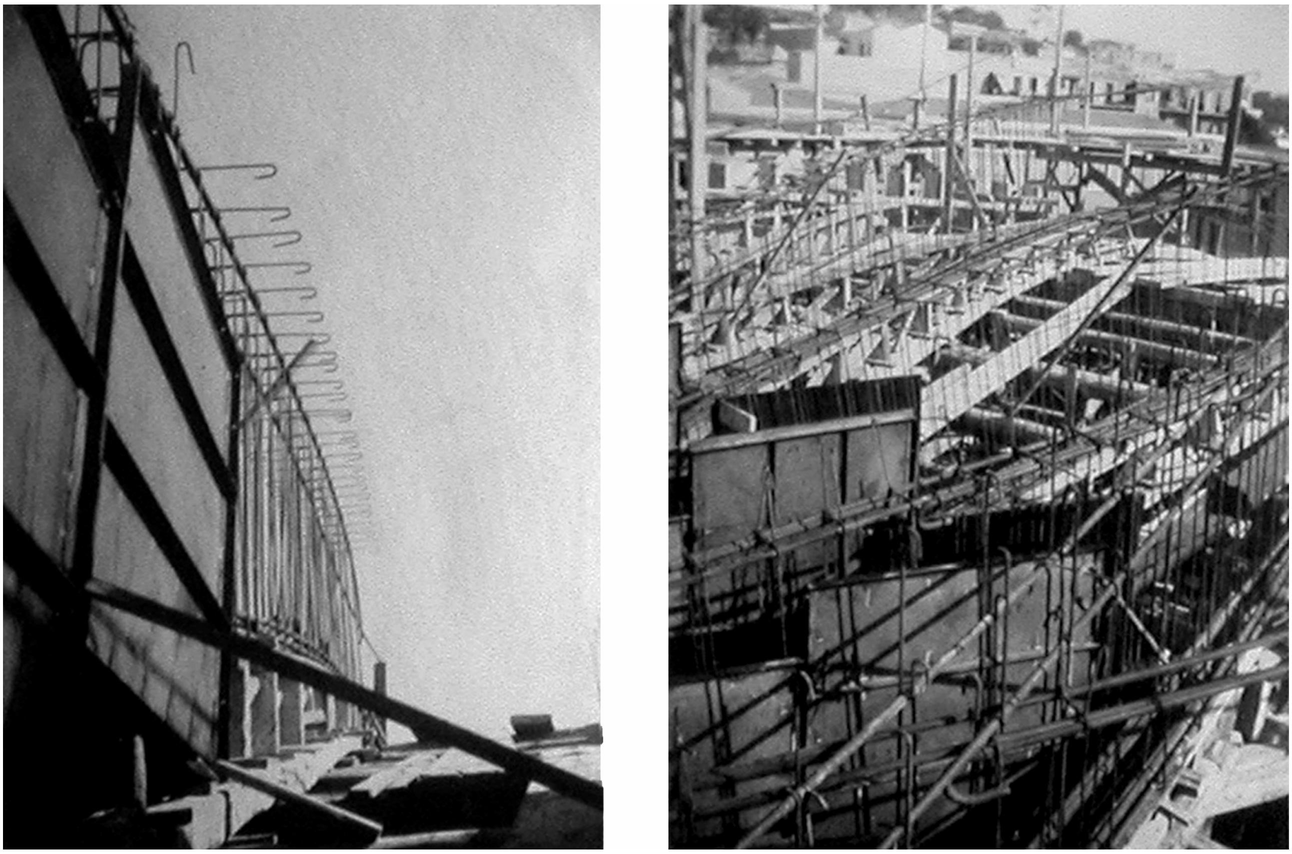

Figure 7: Wooden and metal formwork and reinforcement disposition for the main nave roof beams

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ACKNOWLEDGMENTS

The author wants to particularly thank those who helped her during the research about the San Domenico church reconstruction. First, arch. Piermatteo Fagnoni and arch. Raffaella Fagnoni, for their expressed kindness and for receiving me in Florence to talk about their grandfather and his works. Then, all the State Archive employees, in particular dott. Roberto Fuda e dott. Cecilia Ghelli, careful custodians of the Fagnoni and Bianchini

archives. A special thanks also to the Dominican prior and friars of the Cagliari Convent, so helpful during my numerous visits and surveys to the church.
This research is part of a wider one belonging to the National Interest Research Program (PRIN) funded by the Italian University and Scientific Research Ministery (MURST), called *La costruzione dell'architettura in italia nel dopoguerra (1945-65). Modi e tecniche di conservazione e* recupero [*Architecture construction in Italy after Second World War (1945-65). Manners and techniques for its recovering and conservation*], directed by prof. S.Poretti for the national coordination, and by prof. A.Sanna for the local unit of Cagliari's Architectural Department.

Figure 8: Inner view of the just finished superior church

Figure 9: Aerial view of the church and monastery complex inserted in the medieval neighbour