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The Colosseum: Quality and efficiency of construction

Giovanni Manieri Elia

The aim of this paper is to analyse certain specific aspects of the construction, structure and building site of one of the world's most studied monuments —perhaps the most studied— referring back to the ample extant biography for more general information. With this goal the study proceeded beginning from a thorough direct analysis of the monument and returning nevertheless to observe directly details already pointed out by various authors.[1]

The criterion for the interpretation of constructional and structural questions has been to reexamine the choices made by the ancient builders within the context of their way of reasoning and their method of organising the production process with well-defined objectives in mind, taking into consideration also the means at their disposal.

The duration of the construction works of the monument remains uncertain: according to some authors, the building works took about ten years, with a further two years for finishing-off;[2] according to others, the works were completed much sooner.[3] What is certain is that the period of execution was extraordinarily short and at the moment of the inauguration of the Colosseum, which took place in 80 AD, the construction was not yet completed in its current form, since almost certainly the attic and the greater part of the structure of the hypogea under the arena had still to be realised.

As noted many times, there are several indications that suggest that the construction work of the whole amphitheatre was a complicated operation, which was conceived, planned and carried out under constant and careful control in order to maintain a high level of productivity during the entire period of the building works, therefore taking into consideration always those aspects connected to efficiency — which was understood not only as speed of execution but also as qualitative productivity— as well as the structural solidity *(firmitas)* and long life expectancy of the building with the least expense possible.

From this point of view, we need to evaluate all those choices that were made during the period of construction to allow work to *proceed contemporaneously on many fronts* and in different places. The main problem in fact was represented by the logistical and organisational challenge posed by the need to have many hundreds of people work in the same place. As a matter of fact, the low level of mechanisation in those days entailed using a workforce that had a very high content of «slave labour». Since this sort of workforce was practically unlimited and low in cost, and given that there were no problems concerning the supply of materials that were easily available in the areas around Rome, the question of the *multiplication of the working spaces* of the building site was of primary importance, from which arose the necessity to distribute the works that were being carried out contemporaneously in different places.

Firstly, the blocks of travertine, but also those of tufa, arrived on the building site already squared, by way of the wide roads specially laid out to allow the

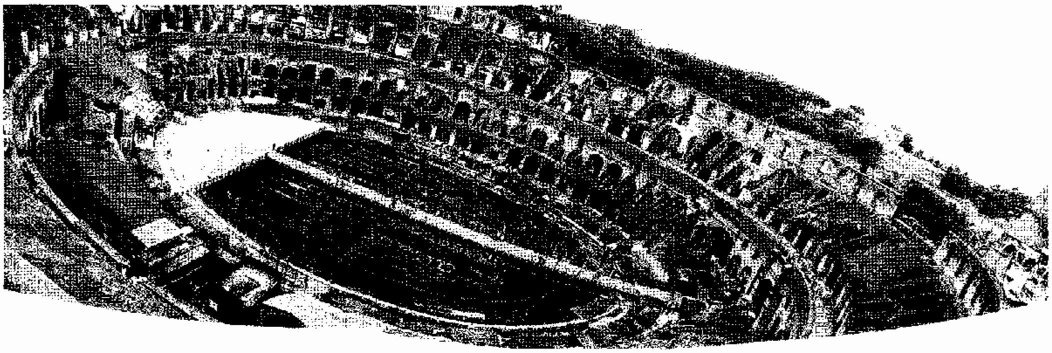

Figure 1
Wide angle panoramic view of the interior of the Flavian Amphitheatre in its current state

simultaneous transit of a large number of carts. Once the squared stones arrived on site, they were grouped according to their height in order that they could be laid in the same horizontal row. In fact the various stone courses do not have the same height in order to minimise the work of dressing the stones, making the blocks uniform and finishing-off.[4] A large volume of the work was therefore carried out off site, probably at the quarries where the material was extracted, cut and made regular. At the same time other large blocks of marble were in production with the sculptors for the execution of that great number of statues, which, once the structure was completed, would have been placed in every external arch.

The dimensions of the impressive scaffolding, of which traces remain in the points of support, also seem to indicate the necessity of being able to reach high positions with substantial loads —presumably consisting of men and heavy materials— before the conclusion or rather before the final structural solidity of the intermediate levels had been reached, with the evident intention, therefore, of working contemporaneously on several levels. There are those who carry this concept forward so far as to maintain that the «piers» in travertine, which are visible enclosed within the radial walls built in tufa or brick, were raised before the walling that contains them, in order to be able to build a ceiling in concrete above the piers as soon as possible, so as to allow several teams of workers to work contemporaneously on several levels.[5] In reality, certain constructional details, such as the scarcity of toothing between the load-bearing arches and the above-mentioned piers, combined with considerations regarding the execution of the work such as the difficulty of constructing a wall with large blocks of tufa that would have to be placed between pre-existent piers and with a ceiling above, which would have complicated greatly the lifting systems, make one tend rather towards the interpretation according to which these vertical elements in travertine, that pass through the walls in all their height, are intended to have the greater loads concentrated upon them, collecting together the forces of compression along predetermined preferential vertical alignments (Lugli, 1957, pp. 331–332; Giuffrè 1988, p. 126). (Fig. 2) Indeed, from a mechanical-structural point of view it is obvious that the loads concentrate on the most rigid structure constituted precisely by the piers in travertine, compared with the parts adjacent to this structure, which, relatively, are more compressible.

Other elements that relate to the rationalization of the building site and therefore to the speed of execution, consist in the widespread use of modular elements in a building that in line with its oval form is anyway geometrically regular, repetitive and with few exceptions. All the steps of the stairs, for example, had the same measurements, as did the marble seats for the spectators which all had the same dimension of 57 centimetres each.[6]

The entire amphitheatre was then divided into sectors, each of which was entrusted to a different contractor. Every building firm, responsible for a sector, worked with his own workmen and could take advantage of a certain freedom of choice as regards technical solutions in the execution of the building; as proof of this, there exist in different places within the building notably different building techniques in parts which are architectonically the same, which, rather than second thoughts in the course of work, seem to be dictated by different and competing standpoints as regards the execution of the building.

One example is represented by the corbels present in the piers of the third tier of the external circle, which would have served to support the wooden structure of the scaffolding. (Fig. 3) In one sector of this circle (towards the Colle Oppio), the corbels are placed carefully at the same height, so much so that some have been chiselled painstakingly along their upper edge to remove a few centimetres in order to recover the established height for the support. (Figs. 4 and 5) Such an arrangement would lead one to

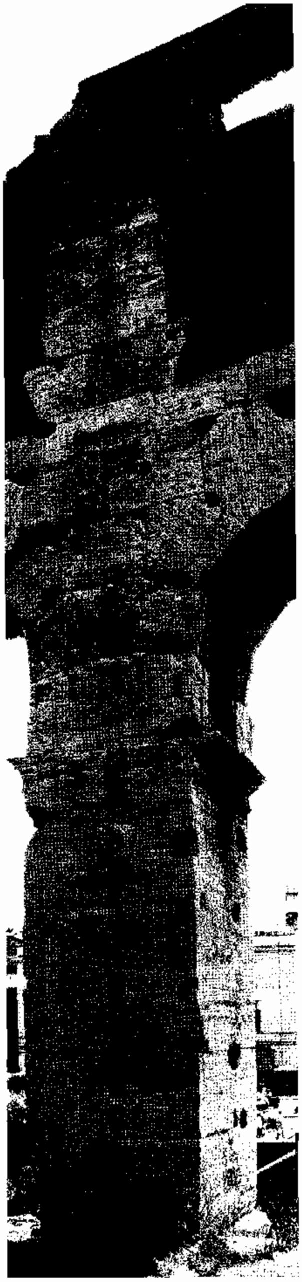

Figure 2
The structures in travertine were those most burdened by the loads, as confirmed by the presence of vertical cracks caused by crushing throughout the height of this pier, placed on the side towards the Celio

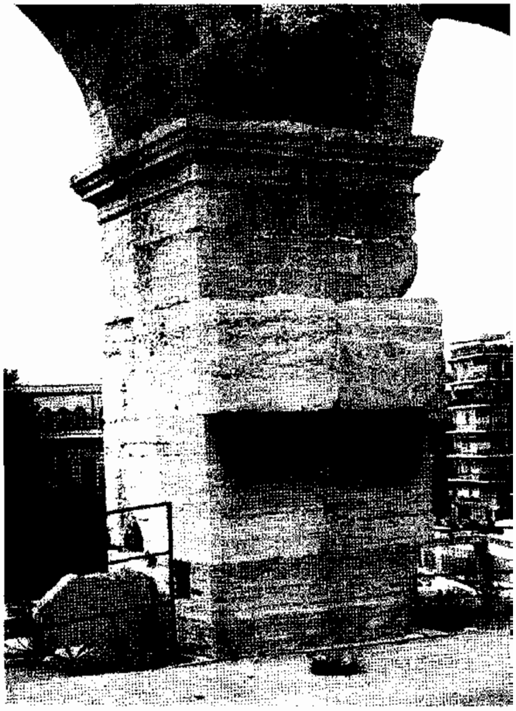

Figure 3
The corbels present on the internal face of the piers of the third tier would have been used to support the wooden structures of the scaffolding

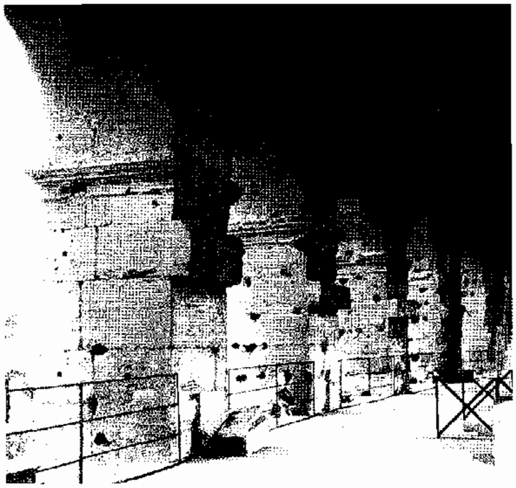

Figure 4
In some parts of the building (towards the Colle Oppio), the corbels are carefully placed at the same height

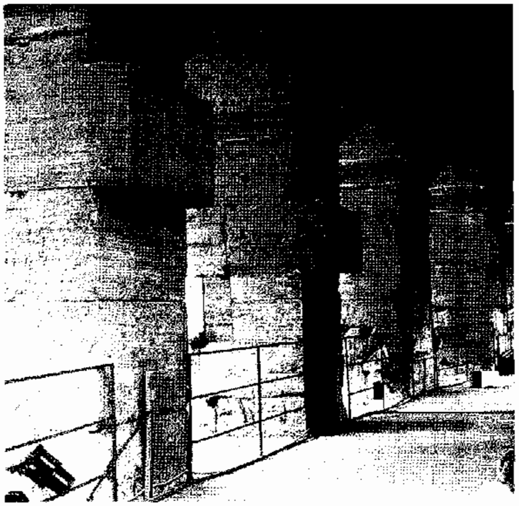

Figure 6
In other parts (towards the Fora), the corbels are placed at apparently random heights, or otherwise they are missing altogether

Figure 5
This block has been carefully chiselled by some centimetres along its top edge in order to recover the established height for the corbel

assume the positioning of a horizontal beam between them. In other sectors (towards the Fori Imperiali), however, the projecting blocks are placed in an apparently casual manner, or, in some cases, lacking altogether. (Fig. 6) The difference in height could be explained by the presence of oblique struts set in position on top of these (Cozzo, 1971, 46, fig. 28). The choice not to build the scaffolding directly on top of the roofing of the second level, thereby discharging the weight onto the piers below of the second circle, and instead to support the scaffolding on brackets projecting from the wall, allowed the builders to leave the floor completely free and therefore to build on top of this, without any obstruction, the structures of the second ambulatory of the third tier. (Fig. 7)

The junctions in which the parts realised by the workshops of different sectors meet are still clearly visible; it is precisely here that constructional inconsistencies, such as errors in the scansion of the architectural measure or in defining the height of the impost of the arches (Fig. 8), give rise to faults in the correspondence between the sectors which stand out in a very obvious manner. Examination of the structure in its current state reveals even quite notable irregularities but evidently, given the impressiveness of the whole, they do not disturb the original general architectonic effect. On the other hand, the correction of constructional incongruities of this type during the course of the works would have involved the remaking of substantial parts at a high cost, both in economic terms and in the time required for

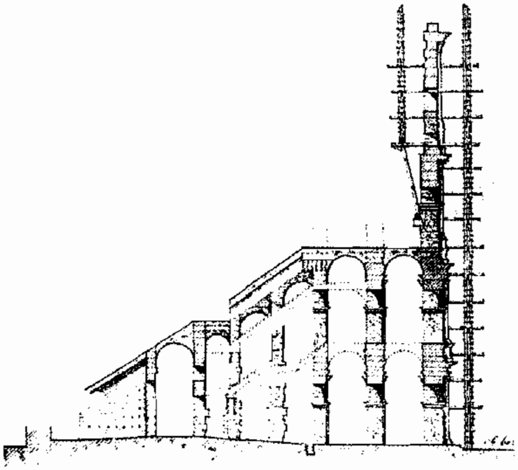

Figure 7
This diagram illustrates the theory advanced by Giuseppe Cozzo (1923) regarding the configuration of the internal wooden scaffolding supported on the corbels projecting from the wall. This solution enabled ample space to be left free on the second storey, thereby facilitating the work of the builders

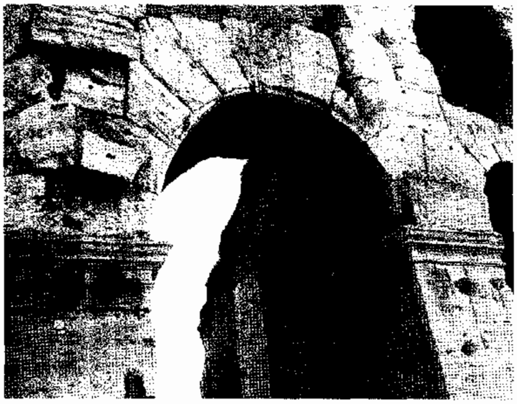

Figure 8
The irregularities in the architectural measure mark out the points at which the sections executed by the different building firms meet

execution. Also, the lack of a perfect vertical alignment between the piers of the superimposed orders in the façade, verified by surveys, demonstrates the determination to *sacrifice exactitude in execution to the productive efficiency* connected to the autonomy of the individual building teams (Conforto and Rea 1993, 73).

From analysis of the constructional details of the entire building there seems to emerge a *general rule* to which the workmen had to conform: to *take care in the details only in the event that it proved inevitable.* Attention to detail, in fact, represented a cost, both in terms of economics and time, which increased enormously with the refinement of the execution of a building, that is, with the reduction of the approximations and tolerances that in fact are evident in the structure of the Colosseum. To employ resources for unnecessary refinements entailed a loss of efficiency, strictly to be avoided. There are many examples of the application of this rule in the finishing-off, but its application is also evident in structural elements. For example, there are some piers (Fig. 9) in which the vertical joints of the superimposed courses

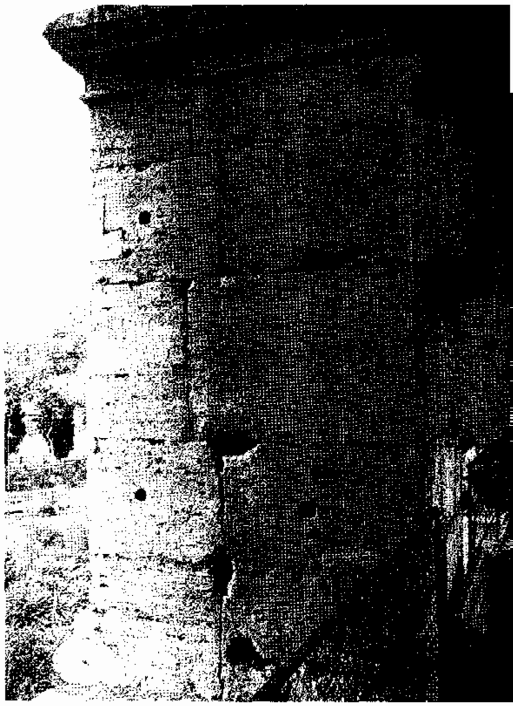

Figure 9
This travertine pier highlights the fact that just a slight staggering of the vertical joints between the external and internal blocks was considered sufficient

are staggered only very slightly. Evidently the Roman builders did not consider a substantial staggering of the joints essential, and the stability demonstrated by the age-old structure has proved them right. On the other hand, there were no exceptions to the painstaking care given to other details that were considered important. Analysing, for example, the attitude of the geological strata of the travertine, these are always parallel to one of the two side faces of the voussoirs (Giuffrè, 1988, 131, figs. 63-64). This manner of placing the stone was considered irremissible, clearly in relation to the Roman builders' knowledge that travertine was a material which was not at all isotropic.

As for the barrel vaults and groin vaults of the monument, as is the custom of the Romans, they are carried out with the use of *opus caementicium*, bedded down in horizontal layers on a wooden centring. A building technique that appears for the first time in the Colosseum (Rivoira, 1921, 116, figs. 98–99), which is still insufficiently studied but certainly to be evaluated from the viewpoint of a greater speed of execution and static efficiency, is the insertion of interconnected brick arches inside the *opus caementicium* forming the barrel vaults. (Figs. 10 and 11)

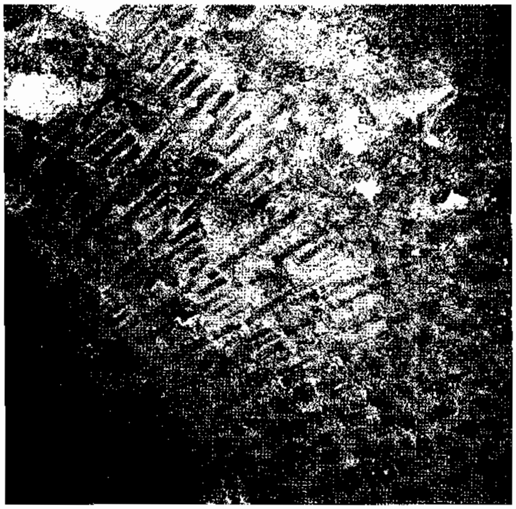

Figure 10
The presence of «ribs» inside the concrete of the barrel vaults, formed by brick arches interconnected by bipedal bricks, suggests that these too have their functional origin in the necessity of reducing the centring

Figure 11
Another theory to account for the brick ribwork, placed inside the concrete barrel vaults, could be that they were intended to distribute the shrinkage of the mortar constituting the concrete during the period of setting and hardening, in this way rendering the shrinkage negligible. On a large scale, in fact, the shrinkage could have caused dangerous cracking

There are various hypotheses regarding the function of these ribs: according to some, they would have served to make the structure more rigid, according to others to divide the mass of fresh concrete into sections; but the most credible theory is that this ribbing had the function of relieving the wooden centring and the props below, which consequently could be much more contained in size, since they had to support only little more than the weight of the ribbing and not all the weight of the mass of fresh concrete. Furthermore, the use of the ribs allowed the centring to be dismantled much more quickly. This constituted a saving in materials because as well as a reduction in the dimensions of the props, the fact that the props could be dismantled sooner also allowed the same centring to be reused several times; props that were simpler and slimmer were also more quickly and easily manageable. Moreover, and this seems to have been the most important thing, the sooner that a vault cast only a short time previously could be made functional, the more time was saved.

There is another measure, however, that with every probability was put to the test with the aim of simplifying the carpentry work, and this was the technique that anticipated the execution of a groove cut into the face of the travertine arches that were adjacent to the groin vaults in *opus caementicium*. On the inside face of the travertine arches on the third tier of the external circle, there is in fact a furrow or groove cut into the stone at a regular distance from the intrados or lower curve of the arch (Figs. 12, 13). According to an early interpretation, this operation would have been carried out to aid the adhesion between the concrete of the groin vault and the wall of the arch. It is possible to advance the theory, however, that this groove constituted the support for the planking of the centring, which as a result turned out perfectly formed and placed at the right distance from the lower edge of the arch and furthermore, it did not require complicated or robust props, which consequently here too became much reduced in dimension, much easier to make, and more straightforward and quick to erect and dismantle. To assist the adhesion of the concrete, it would have been sufficient and certainly much faster to break up the surface of the travertine at some points with a pick, even quite irregularly, in order to create some roughness on the surface. Furthermore, in an arch towards the Fori Imperiali, again on the third tier, there is a correction visible in the groove cut into the arch (Fig. 14), made in the course of the works. Obviously there would be no reason to make any such correction if this working of the stone was intended solely to favour the adhesion of the concrete and was destined to remain concealed.

Returning to the ribbing, it should be pointed out that in its early days the technique of constructing vaults in concrete counted on a preliminary structure

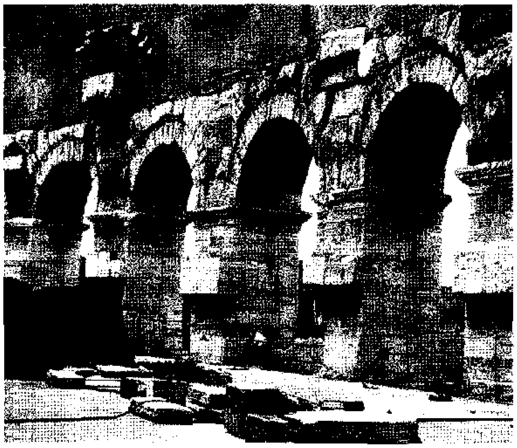

Figure 12
On the inside of the travertine arches on the third tier, note the grooving around the arches

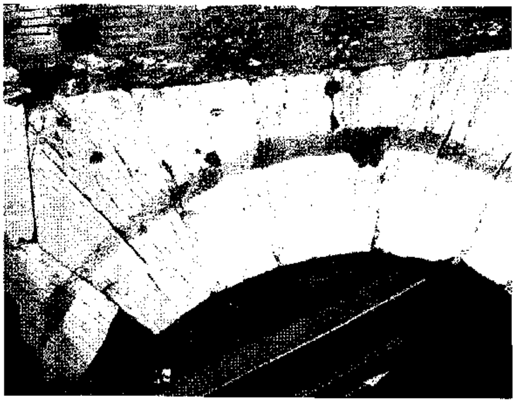

Figure 13
We can put forward the hypothesis that these grooves provided the support for the planking of the centring, which as a result was more easily realised

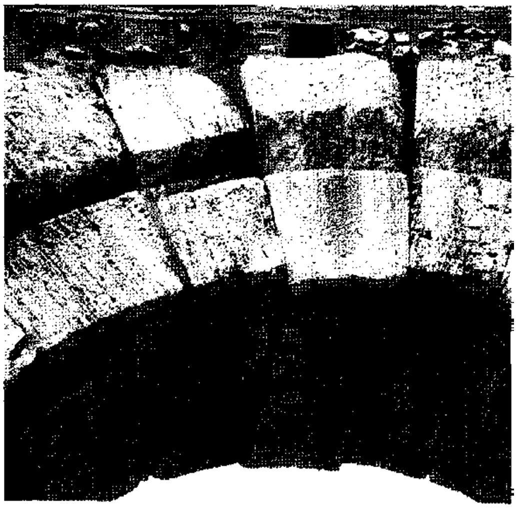

Figure 14
In an arch located towards the Fora, again on the third tier, there is a correction in the groove cut into the face of the arch, made during the course of the works. Obviously there was no reason to make such a correction if this operation was carried out exclusively to aid the adhesion of the concrete and therefore would have remained concealed

made up of large slivers of calcareous stone, placed on the centring and arranged radially, which remained embedded inside the concrete; therefore the insertion into the vaults of brick elements in the form of arches results from the technological evolution relating to the use of brick. It is not to be excluded that another function of the ribs, with respect to those already illustrated, could be to channel the forces within the most rigid and resistant elements, that is precisely the arches in brick, resulting in a concentration of the loads on the most rigid parts of the structure, as already shown with regard to the travertine piers present inside the tufa walling, but also because of the shrinkage of the mortar during the setting and hardening phase, which caused a concentration of the loads on those parts whose volume remains unchanged with the passing of time.

It is clear that the Romans were aware that the lines of force that run through masonry masses, due to vertical loads and horizontal stresses, both in the elevations and in the concrete vaults, never diffuse in a random, indifferent manner, but rather they follow very precise rules. Load-bearing arches, ribbing, piers in a more solid stone inserted within the walling, the carefully arranged horizontal positioning of the stones and of the fragments inside the concrete are all proof of such a knowledge, which, if not exactly scientific, was certainly technological.

Finally, we feel we can advance the hypothesis that the ribs and the links between them in bipedal bricks (a two-foot square brick) could also have the function of distributing as much as possible the effects of the shrinkage of the mortar, which if subdivided into many different sectors would be negligible, while for large single volumes it could create serious problems of cracking in the concrete block. It is to be believed that the Roman builders must have been particularly aware of this problem, since a careful observation cannot miss the fact that the solutions adopted to remedy the problem reached high levels of refinement and perspicacity. But, furthermore, it is perhaps from this viewpoint in fact that we can also explain the use (not yet sufficiently justified) of *opus reticolatum* placed at 45°, not present in the Flavian Amphitheatre but widely diffused in the following decades.[7]

Even the procedure of which mention has been made of realising the vault with sheets of bricks in several layers —a solution moreover adopted at the Colosseum (Fig. 15)— would support the theory of the necessity of lightening the load-bearing function of the wooden centring and of simplifying it. In fact just as soon as the first layer of the vault was realised, which was very light and quick to execute since it was carried out with a quick-setting mortar and with a minimal centring, work proceeded to get the second layer under way, which could already make use of the support and the shape provided by the layer beneath, together with which it constituted a heavier and more robust structure as well. The same counted for the third layer, until a vault capable of supporting the weight of the mass of fresh concrete placed on top of it was obtained, the whole procedure achieved with a centring that, practically speaking, had the measurements necessary for just a thin sheet vault.

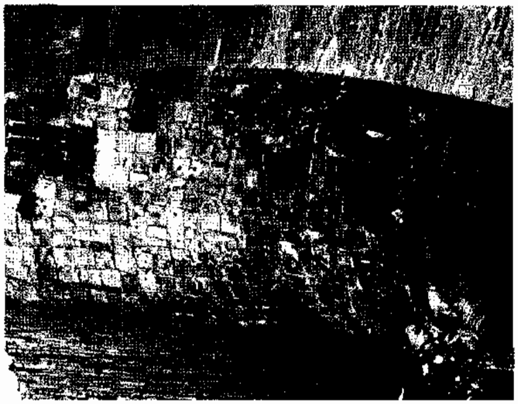

Figure 15

A barrel vault, on the first tier, with bricks laid in sheets on the intrados of the vault. These bricks probably formed a preliminary vaulted structure, allowing a reduction to be made in the dimensions of the wooden centring

Probably the frequently used superimposed arches (with two arches placed one above the other and sometimes more)[8] also follow the same criteria: only the first arch was intended to be carried on the wooden centring, which, therefore, could have much reduced dimensions. Furthermore, the bipartite and tripartite horizontal division did not diminish the carrying capacity of the structure since it was completely compressed, unlike that which would have happened in the case of trabeated systems.

Similarly, for the execution of the foundations —comprised of an impressive oval *platea* (greater diameter 188 metres, smaller diameter 156 metres) with an oval hole in the centre of an average depth of 13 metres— work proceeded in such a way as to save a considerable amount of time in the execution. In fact the foundations were not executed by means of excavation, which would have necessitated an enormous operational undertaking, but by building upwards, then filling in the adjoining areas with soil and rubble brought from the surrounding zones (Cozzo, 1971, 24; Giuffrè, 1988, 123). This structure, in concrete with fragments of hard volcanic (leucitic) stone, which was particularly solid, dense and impermeable, took the place of a natural trough that was occupied —as is well-known— by a small basin that collected water coming from the hills, the so-called «Nero's Pool». The Neronian structures, porticoes and buildings that rose up around the pool were buried in the made land around the perimeter. The foundation platform, bounded at its edges by a mighty wall in concrete and brick some three metres thick,[9] constituted a very solid and impressive base in relation to the particularly yielding, marshy ground, which over the centuries has caused differential subsidence in the part towards the Celio.

The piers of the first order do not rest directly on the foundation *platea* but on high stone plinths buried in the foundation. These plinths are noticeably wider than the piers set upon them and as a matter of fact, on the ground storey the offset that these create is visible at floor level.[10] Between the interred plinths and the piers, there is an adjustment of some centimetres, from which it can be deduced that only at the moment of realisation of the part above ground, was attention given to the accurate measurement and placing of the piers. Once again it is apparent that attention and care were given only where and in the moment in which they were considered necessary, or rather in the parts of the building that were in sight.

Another question which can be analysed from the viewpoint of the builders' desire to simplify the construction process wherever possible in order to achieve greater building efficiency is that of the planimetric layout of the geometry of the monument. Some hypotheses consider the geometry of the Colosseum to be an elliptical form; others consider it more probable that it is a polycentric, ovoid curve. The distinction is not simple to make since, in the Flavian Amphitheatre, these geometries are superimposable but for a few tens of centimetres. Certainly the polycentric curve is easier to lay out, easily manageable on the building site and more compatible with the fact that the ambulatories have a constant width. Even the laying out of the radial walls turns out to be more immediate. With the use of a geometry governed by polycentric curves, all of the construction, and therefore the positioning of every single block, on the superimposed levels as well, turns out to be more easily controllable from positions and sights placed at particular points.[11] (Fig. 16) What motive could the Romans have had to prefer a more complex form if it differed so slightly from another that was more easily manageable? Furthermore, the most precise surveys have confirmed the polycentric nature of the curvature.[12]

Another aspect that we should point out here is the static efficiency of the morphological configuration chosen for the façade. The presence of external offsets between the superimposed orders is, in fact, particularly appropriate to the objective of a greater solidity. It is apparent from the graphic renderings of the sections, but even to the naked eye observing the curved façade tangentially, that the line of the façade of every order is set back by a few tens of centimetres with respect to the order below. This configuration, which is also canonical in the superimposition of the orders, guarantees as far as possible that the vertical loads, to which are added the horizontal outward thrusts due to the vaults and, in the event of earthquake, those due to the horizontal accelerations, exert stress on the piers, at their base, in the most axial manner possible and therefore in the manner in which they offer the maximum solidity, thereby averting the eventuality of triggering mechanisms of collapse by overturning or the eventuality of exceeding the resistance of the material owing to the narrowing of the active section due to eccentric loading. As a result the external circle is braced towards the inside by the radial walls and towards the outside by this slightly stepped configuration of the façade, as well as by the curved form of the plan. In the case of the Flavian Amphitheatre, the offsets —which in buildings are generally present towards the inside so as not to be visible and in order to have a flat façade— reinforce the external walls and enhance the effect of solid stability which Piranesi grasped so well in his striking representations of the Colosseum.

Another factor relevant to the speed of the works was the mechanisation of the building site. The

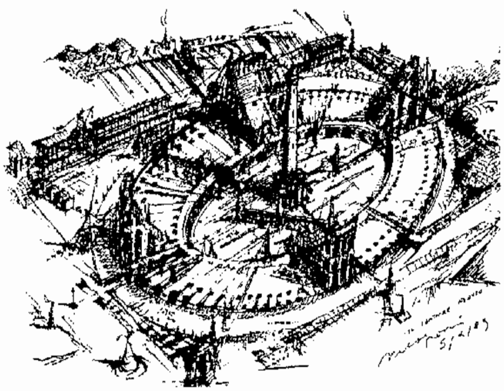

Figure 16
The ancient Flavian valley of the Colosseum. (Illustration 1989 and text by Piero Meogrossi)

This «reconstruction» of the Colosseum illustrating a possible but imaginary situation, circa 73–74 AD, depicts the valley (and its older drainage system supplied with natural springs) transformed by Vespasian's project and completed by Titus, who put into practice their desire to cancel out the previous Neronian structures and therefore also the memory of Nero's Domus Aurea itself.

The initial building works for the Flavian Amphitheatre appear to have taken into consideration, as important pointers, the topographical and urban landmarks of ancient Rome.

The Augustan *Meta Sudans*, the lowest point of Rome's water level, was intended by the Flavian engineers to become a fountain at a height that allowed water to be brought to the first storey of the Colosseum; while the *Sacellum Streniae*, a sacred site which marked the beginning of the Via Sacra, was probably maintained in connection with the outer limits of the site which would later be occupied by the Arch of Constantine.

These elements, which are fundamental and sustain the area of the amphitheatre, are in practice a series of sacred places which still remain bound together today by a greater topographical rule, the geometric measurement of which is consistent with the seasonal sun date of the XI *Calendas Maja* (which corresponds to the current 21 April, the anniversary of the foundation of Rome.)

For this reason it seemed important to preserve such signs or pointers and to link them together in order to determine the new relationships which moved around the topographical structure of the Colosseum itself.

In the drawing one notes the oval geometry that forms the Flavian monument under construction, the design of which must have been based physically on a central point set in position upon four focuses, all corresponding to as many towers linked in their turn to a central «betilum» tower (which probably was already present at the centre of the Neronian valley), a sort of solar clock reused as a base for the topographical control and three-dimensional construction of the building.

In the drawing one observes the ideal reconstruction of the four sectors, which advance progressively into the space and make use three-dimensionally of the wooden guide structures that serve to control the dimensions of the oval as it grows; at the same time, those instruments, put together on the building site according to a law based on the relationship 3–4–5, ensure mobility inside the area and the many related measurements that mark out a geometry made of regular lines that allowed the various corridors of the amphitheatre to be laid out.

Many working machines (the so-called *polyspastoses*) move all over the place in order to transport heavy materials and to raise the fabric of the Colosseum, while inside as outside the valley, which is not yet completely organised, there appear buildings of a public nature which represent an ample piazza organised on three sides with a portico or *porticus* on three levels.

The geometry and the distribution of such a *porticus triplex miliarensis* (as it was recalled by Tacitus) represent the appearance of a public architecture that exceeded by far the Neronian valley, which once had been characterised by its private nature and for having at its centre the private lake of Nero's palace.

The drawing shows the foundations of the Colosseum (about 13 metres high, a continuous oval enclosure which filled in the former Neronian lake leaving only a central hole) and it shows how the four towers for measuring the building site have been mounted artificially so as to make it possible to control the raising up of the different sectors of the building in accordance with the geometrical design.

By continuously measuring at different heights, these towers made it possible to remain perfectly in line with the topographical rule that crossed the entire valley and to maintain the Pythagorean relationship 3–4–5 that created the oval form of the Colosseum. Several fires placed at a distance marked out the sacred rule through Rome and allowed the construction to follow the principal topographical measure that crossed the valley and designed the *forma urbis*. (Meogrossi, 1993, 81–90).

Romans were capable of building complex machines for the raising of the blocks, which, even if made only of wood, through a system of levers, winches and hoists allowed even quite considerable loads to lifted. Most probably the inclined surfaces constituted by the top of the radial walls that supported the cavea, as well as slopes built up with filling material and rubble, provided surfaces along which building materials could be drawn upwards and thereby played their part in the transport and lifting of the blocks.

As to the enormous blocks of travertine, these were assembled with the use of lifting machinery of various types: in almost all the blocks there are conspicuous holes to allow them to be hooked up. Before laying every single stone in position, the surface of the block underneath was smeared with a thin layer of liquid lime mortar: this fluid layer aided the sliding of the masses one against the other and, at the same time, rendered the parts in contact more cohesive (Lugli, 1957, p. 243). Furthermore, this mortar layer clearly also had the important function of distributing the loads on the entire horizontal section, thereby avoiding dangerous concentrations on limited areas due to the fact that the corresponding faces of the blocks were not always perfectly flat. Moreover, metal pins were placed in appropriate slots cut into the faces of the blocks. Finally, the positioning completed, molten lead was poured into special channels carved into the lower block that conveyed the lead to the pins already positioned inside, which by this means were fixed effectively in place. That multitude of holes currently visible on all of the travertine façade of the monument are the traces of the laborious operation carried out during the Middle Ages to retrieve the metal materials which were particularly sought-after in that period. But for what motive did the Romans occupy themselves with such care to pin every single block? What important compensation did such a precise and widespread operation have? Was the strong friction owing to the high loads in play at the point of seizure between the blocks not sufficient to render the masonry sound?

According to some authors, the ties avoided relative shifts between the blocks during the phase of construction when, in the absence of loads above and in the setting and aligning of the upper blocks, unwanted displacement was still possible. But this theory loses its force if one considers the method of assembling and aligning through the use of lifting instruments and also the facilitation constituted by the liquid mortar of which mention has already been made. The objective of achieving a static reinforcement of the structure would seem to be excluded as well, taking into account the high values of the friction.

The only situation in which the effect of the friction could diminish to the point of failing is in the event of earthquake. The subsultory oscillations can, in certain instances, diminish the effect of the weight force and the vibrations of the structure can make the adhesion or bond between the faces of the blocks fail, even if for very brief periods of time. In these situations the effects of the undulatory oscillations can cause single blocks to become dislodged with respect to the blocks around them. It is clear that the presence of the pins could have had the precise function of preventing such circumstances from happening, in so much as they exercised an effective tie, which, resisting the shearing stress, opposed the relative horizontal displacement. Put more simply, it can be assumed that the Romans had observed the effects of earthquake on the masonry of older monuments in *opus quadratum* and, consequently, they opportunely found, or at least used in a systematic fashion, the most effective measure to prevent the occurrence of such serious damage, which was moreover irreversible once it had happened.

NOTES

1. This paper fits within the compass of the research undertaken by the author for the Doctorate in *Tecnologie dell'Architettura* at the Univerisità «La Sapienza» of Rome with a final thesis entitled *Interventi di restauro sul patrimonio archeologico romano: tecnologie e metodologie*, as well as in the sphere of the *Gruppo per la Ricerca Storica sul Colosseo* commissioned by the *Soprintendenza archeologica di Roma* to the *University of Roma Tre*.
2. From 71–72 AD until 80 AD, the year of the inauguration. See Lugli (1971), 11.
3. The alternative suggestion that the duration of the works was three to four years, from 76 AD to 80 AD, is improbable. See Cozzo (1923), 275.
4. Cozzo (1971) has pointed out how the travertine was worked as little as possible on the building site to speed up the execution of the works. For this reason, the stone courses have different heights and the blocks intended to be buried have very irregular dimensions. See Cozzo (1971), 29–30. On the working of the blocks on site, see also Lugli (1957), 1: 332.

5. Lugli hypothesizes an initial huge framework of pilasters and arches in travertine «enorme ingabbiatura di pilastri ed archi in travertino» (Lugli 1957, 1: 331–332)— on which it was possible for work to proceed with different teams of builders working contemporaneously.
6. All the measurements were made using a module (or *modulo)* and fractions were avoided wherever possible. See Pearson (1975), 88.
7. «The most fitting justification seems to be, however, that which begins from the consideration that the arrangement of the blocks set at 45° ensures that every «casing» owing to the shrinkage of the mortar during the period of its setting, is easily aided and compensated for by small, gradual vertical shifts in the structure, assisted by the load itself, which recompacts the masonry before the mortar hardens, without the formation of vertical cracks. More simply, one could say that the diagonal disposition at 45° generates an effect of horizontal precompression of the structure, which averts the formation of vertical cracking during the phase of setting and hardening». See Giovanni Manieri Elia 2002.
8. Among the many examples, we can cite the *Terme di Caracalla*, or the load-bearing arches at the *Pantheon* in Rome or at the *Terme di Cellomaio* at Albano.
9. On the form, location and materials of the foundations, see Coarelli et al. (1999), 104.
10. With regard to the «pillars of foundation», see Cozzo (1971), 22 25.
11. Piero Meogrossi, within the context of a polycentric geometric configuration, the principal axes of which identify precise and significant directions that relate to the form and history of the city, suggests the presence during the phase of construction of a «torre-obelisco-traguardo e regia, alta e centrale», that is, a tall centrally-placed tower used for taking sights in order to control the geometric layout of the building. See Meogrossi 1993.
12. This is the conclusion arrived at by the group of researchers coordinated by Mario Docci. See Docci 1999.

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