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Preserving the Original Static Scheme in the Consolidation of Old Buildings

Sauvegarde de l'équilibre existant dans la consolidation de vieux bâtiments

Bewahrung des vorhandenen Zustandes bei der Konsolidierung alter Gebäude

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F. Lizzi originated in 1952 the «palo radice» (root pile), first example of micropile, initially used for underpinning and afterwards for solving difficult foundation problems. At about the same time he introduced the «reinforced masonry» technique for the consolidation of upper structures.

SUMMARY

There is no reason to consider a «living reality» such as an existing building, even though it may be in a precarious static condition, as an inert material to call to new life by the introduction of artificial forces. The possibility of increasing the safety factor of the building, within the framework and with full respect to the present equilibrium, should be the guiding principle for a correct static restoration work. According to this essential principle some original techniques are presented.

RESUME

Un bâtiment, même en mauvais état du point de vue statique, reste une «réalité vivante»: il n'y a aucune raison pour le considérer comme une matière inerte à raviver, moyennant des forces externes, et qui vont altérer l'équilibre actuel. Un travail de restauration, dans le but d'améliorer la stabilité d'un vieux bâtiment doit être basé sur le respect absolu de cet équilibre. Sur la base de cette philosophie ont été développées des techniques d'intervention, couramment utilisées.

ZUSAMMENFASSUNG

Ein Gebäude ist immer eine lebende Wirklichkeit, auch wenn es nicht mehr standfest ist. Es besteht kein Grund es als totes Material zu betrachten, das man durch äussere Einwirkungen, die den gegenwärtigen natürlichen Zustand verändern könnten, ins Leben zurückrufen kann. Ein Konsolidierungsprojekt, das dazu bestimmt ist die Stabilität eines alten Gebäudes zu verbessern, muss den vorhandenen natürlichen Zustand beachten. Auf dieser Grundphilosophie sind Interventionstechniken entwickelt worden, die dargestellt sind.

INTRODUCTION

This paper deals with some aspects of the consolidation of old masonry constructions.
The static equilibrium of such constructions is based essentially on the compressive strength of the masonry, as well as on the overall structural continuity of the building. The ability to resist tensile forces, peculiar to modern reinforced concrete structures, is completely lacking in old masonry fabrics.
The genius of the Old Architects of the Past was, therefore, fully engaged in absorbing horizontal thrusts, transmitted by arches, vaults etc., through original schemes, in which vertical additional loads would prevent the development of tensile stresses in the masonry.
Only in exceptional cases they resorted to "tie-backs", perhaps reluctantly, because such a device could not be considered on a satisfactory technical level; furthermore it was, generally, an unsightly addition from the aesthetic point of view.

1. THE CRACKS IN AN OLD BUILDING.

The symptoms of a possible state of crisis of the static equilibrium of an old building are the cracks, which appear in the structures as a clear evidence of the lack of tensile strength of the masonry.
At any rate the presence of fissures in a building does not necessarily imply a state of danger: old masonry buildings enjoyed, during the construction period and for some time after, of states of plasticity which allowed, generally, a compensation for some minor unforeseen deformations in the foundation soil, as well as in the upper structure.
In these evolutive phases, the intervention of Nature was instrumental in redistributing the loads and, when necessary, in opening natural joints (cracks) where the continuity of the masonry was not sufficient for absorbing tensile stresses. Generally, in these cases, the reduction or the elimination, dictated by Nature, of the redundant bonds peculiar to old constructions, are to be considered a relief more than a damage.

2. THE STATIC CRISIS IN OLD FABRICS.

When, on the contrary, there is clear evidence, in an old building, that the existing cracks are progressing and, furthermore, that some new fissures are appearing, then a state of danger has to be presumed.
At any rate, also in these critical cases, it should be remembered that the structure is still in equilibrium; its Safety Factor defined, as customary, as the ratio of the stabilizing forces to the disturbing forces, may be approaching the minimum value of one but, for the time being, it is not less than one. There exists a precious safety margin not to be wasted.

2.1 The importance of the tensile resistance in the masonry.

The cracks in the masonry are the most conspicuous evidence of a state of crisis for the structure; but they are only the effects, consequent to several different causes. Therefore the most important step to be taken for the static restoration of an old building is the elimination of the original disturbing causes.

That is not enough; there are secondary adjustment movements to be feared, and the possibility that the original causes may act again (e.g. seismic events).

All the above causes entail the development of tensile forces which cannot be resisted by the masonry; therefore the latter needs an appropriate reinforcement.

Finally, there are cases in which the essential and only cause of the crisis is a general weakness of the masonry, which requires the introduction of reinforcing elements to absorb tensile stresses.

In conclusion, no serious restoration works can be carried out without a correct reinforcement of the building to counteract possible tensile forces.

3. ESSENTIAL REQUIREMENTS FOR A CONSOLIDATION WORK: THE "QUICK RESPONSE".

A consolidation work must be technically adequate, long lasting and, what is most, when completed, it has to give a "quick response" to any further displacement of the structure, however small.

The very restricted residual limits of "time" and of "deformations", available for the restoration works to be carried out and to start being operative, must be the subject of very careful and responsible attention from the Designer.

Also in cases where propping structures are to be provided for, the allowable limits of time and of deformations, both for the struts and for the building, have to be considered. All of that within the framework of the present and future equilibrium of the fabric.

4. THE CONSOLIDATION OF OLD MASONRY BUILDINGS: DIFFERENT APPROACHES

The consolidation of old buildings can be carried out according to two different approaches:

- "Active intervention" by which additional external forces are introduced in the structure and in the subsoil, under the form of constraints.
- "Passive intervention", based on reinforcing elements introduced in the soil and in the structure, without any constraints, in order to ameliorate the existing state of equilibrium, increasing the Safety Factor.

5. THE "ACTIVE INTERVENTION".

The active intervention, with the introduction of external prestressing, is intended to partially counteract the acting forces and, possibly, in some cases to reverse the deformations.

The active intervention is dictated by the fear that further deformations could be fatal to the overall stability of the construction.

This is the case of:

- underpinning by means of precast or cast-in-place piles forced against the upper structures;
- introduction of states of stress in the subsoil immediately below foundation level, in order to accelerate its consolidation;

- introduction in the masonry of tie-backs, steel bars and/or cables to be prestressed in order to provide concentrated tensile strength, where necessary.

Practically, according to this type of intervention (active), a new additional system of forces is superimposed to the present static scheme, considered no longer sufficient for guaranteing the stability of the building.

The soil and the masonry are partially surcharged beyond the present levels: this is a risk which cannot be underestimated by the modern designer, entrusted with a restoration work.

As a matter of fact, one should not forget that the problem of consolidating an old building is completely different from the problem of a new construction:

- In modern constructions, the materials are well known as far as their strength and elasticity are concerned; they are capable of accumulating a well calculated elastic reserve (as with prestressing); their response to the acting forces, in terms of unit stresses and deformations, can be very reliably assessed using the most recent calculation methods.
- On the contrary, the problem of consolidating an old building is completely different: the materials are heterogeneous and brittle; the forces/deformations ratio is practically unknown because the deformations have already taken place; their response to new forces cannot be reliably assessed. Also, in case of extensive grouting of the masonry, the possible presence of weak spots due to inadequacies of the treatment can reduce or nullify any local prestressing intervention. The only most important data to consider is that the building is standing, hence it is in a state of natural equilibrium, however precarious; any change to its static scheme entails a very serious unwarranted risk.

  In a consolidation work "what" the Engineer wants to do must be subordinate to "how" he wants to do it.

6. "PASSIVE INTERVENTION"

For all the above, it seems more logical to consider the present state of equilibrium of the building as the starting point for the consolidation works; the present Safety Factor is preserved and should be increased by the new restoration works.

According to this philosophy, in a passive intervention the consolidating works are aimed at providing additional resources for a "living" structure, within the framework of the existing state of equilibrium, without modifying its static scheme and, what is more, without worsening the present critical state of stress, both in the masonry and in the subsoil.

On the other hand, the requirement of giving a "quick response" to any further displacement of the structure must not be forgotten.

The essential features and the means for a passive intervention are described in the following paragraphs, both for foundation strengthening (underpinning) and for masonry reinforcement, where the possibility of giving a "quick response" is duly stressed.

6.1 Underpinning by means of "pali radice" (root piles).

This special type of pile (micropile) was developed by the Author of the present paper about thirty years ago; its use for underpinning, as well as for other

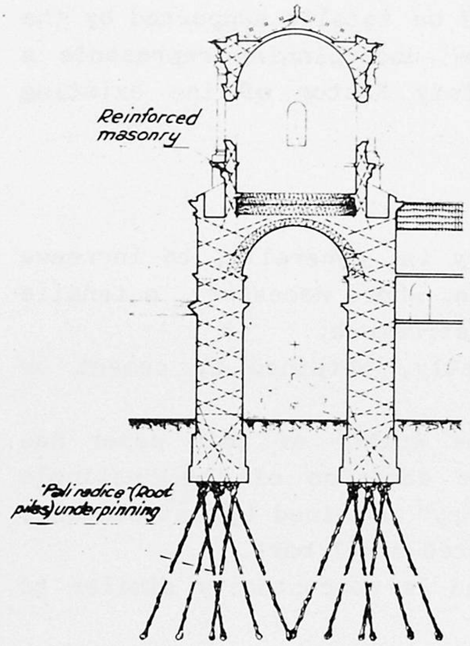

Fig. 1 - Typical strengthening of an old building.

engineering purposes, is described and discussed at length in technical literature.
A typical underpinning by means of root piles is shown in Fig. 1; where the "reinforced masonry" technique for the upper structure is also indicated.
For the purpose of the present paper, the two essential characteristics of a "palo radice" are recalled:

- The pile is drilled "through" the existing masonry; therefore, it is automatically connected to the upper structure and becomes operative as soon as the concrete has set ("quick response" in terms of time).
- The "palo radice" is essentially a friction pile and therefore its settlement under load is very reduced ("quick response" in terms of deformations).

Fig. 2 summarizes how the "quick response" problem is solved with a "pali radice" underpinning.
Chart a) shows the assumed evolution of the foundation settlement with time; this diagram could be obtained from the study of the previous movements of the building; "m" is the value of settlement corresponding to the period of time considered still available for carrying out the underpinning (point T).
In presence of provisional struts, the value "m" (generally no more than a few millimetres) can be taken as the value for which the propping structures are assumed to become fully loaded.
Chart b) shows the Load/Settlement curve for the selected "palc radice". This diagram can be drawn on the basis of previous experience or derived by direct, unexpensive, load tests. The working load P to be entrusted to the single pile of the future underpinning is the value corresponding to settlement "m", as indicated in diagram a).
For all the above, a "pali radice" underpinning does not introduce any alteration in the existing overall equilibrium of the structure and, at the same time, it can readily become operative and give a gradually increasing support to

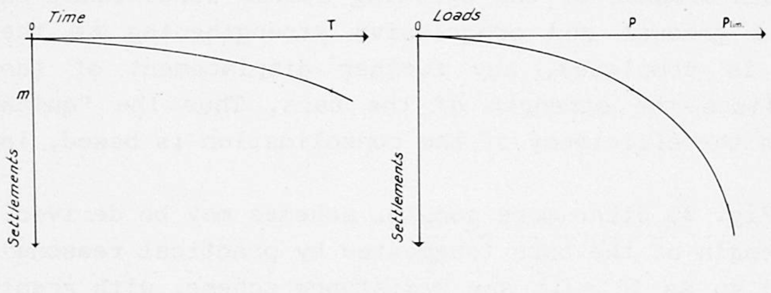

Fig. 2 - The problem of the "quick response".

the existing foundation.
The transfer of the loads from the building to the "pali radice" underpinning takes place gradually, according to the further settlement of the structure, if any. It is possible that the settlement will stop well before reaching the maximum value of "m", for which the building would be totally supported by the new foundation; that means that the "pali radice" underpinning represents a substantial addition to the fully preserved Safety Factor of the existing foundation.

6.2 "Reinforced masonry".

The purpose of the consolidation of an old masonry is, generally, to increase its resistance to compressive forces and to provide, where necessary, a tensile strength which cannot be displayed by the original structure.
The increase of compressive strength is, currently, obtained by cement or chemical grouting.
As regards the resistance to tensile forces, the Author of this paper has fostered, over the past thirty years or so, the adoption of the "reticolo cementato" which is some sort of "reinforced masonry" obtained by introducing, in the very thickness of the wall, a series of grouted steel bars.
"Reinforced masonry", therefore, is inspired by and is conceptually similar to reinforced concrete.
The basic element of "reinforced masonry" is a steel bar (2÷3 metres long), cement or resin grouted in small holes, drilled to appropriate slopes through the masonry wall, from face to face. The grout (injected at very low pressure) provides the necessary bond between the bars and the surrounding masonry.
A series of such bars, adequately overlapped, provides the masonry with the required tensile strength; therefore, positions, length and number of reinforcing bars must be designed according to the tensile forces to be resisted, just like for reinforced concrete.
Fig. 3 shows, in an horizontal cross-section of a wall, an elementary scheme of a series of bars (the so called "overlapping scissors"); the scheme, formed by two rows (at different levels) of slanting bars, supplies a chaining for resisting a tensile force T; it is worth noting that the reinforcement can be extended to any length of wall.
The efficiency of the chaining is based on the steel/masonry adherence as can be easily checked by unexpensive in-situ tests. As a rule, a tensile force is not entrusted to a single chaining: normally, the walls are engaged for a substantial height by several series of "overlapping scissors", adequately staggered.
It is to be stressed that the construction of such a bolting system in the masonry does not entail any disturbance of the existing static conditions; on the contrary, it represents a gradual and progressive strengthening of the structure. When the bolting is completed, any further displacement of the masonry, however small, mobilizes the strength of the bars. Thus the "quick response" requirement, on which the efficiency of the consolidation is based, is perfectly fulfilled.
From the elementary scheme of Fig. 3, other more complex schemes may be derived. Due to the relatively short length of the bars (suggested by practical reasons) the boltings can be positioned so as to suit any resistance scheme, with great flexibility; no substantial alteration of the external appearance of the

Fig. 3 - The "overlapping scissors".

structures is involved.

6.2.1 Examples of "reinforced masonry".

Fig. 4 shows the horizontal cross-section of a reinforced masonry cross-wall. The reinforcement is intended to provide resistance to Traction as well as to Bending Moment, which can affect the wall. The shadowed lines indicate the resistance paths on which the reinforcement can be relied upon.

Fig. 5 shows the reinforcement for the upper wall of a colonade. The reinforcement is intended to form some sort of "reinforced masonry" long beam, overhanging the colonade, in order to compensate out-of-balance effects which can be generated by possible differential settlements of the columns.
The dotted lines represent, schematically, tensile chainings formed by several series of "overlapping scissors".
The complete network forms a reinforced beam, with a double horizontal steel reinforcement (sections A-A and B-B) and the slanting bars C-C as stirrups.
Also in this case, no disturbance is introduced in the equilibrium of the structure which is gradually reinforced and, at the end, behaves like a proper beam.

Another example is the reinforcement of a column shown in Fig. 6: the bars are arranged according to a double helix, tangent to an ideal internal core; the complete network provides a reinforcement both in vertical and in horizontal sections, like in a reinforced concrete column provided with vertical reinforcement and stirrups.
The work is to be carried out step by step with good workmanship, having care not to create any disturbance, even if temporary.
If necessary, it is advisable to provide for a provisional strut formed by cables fastened around the column under light tensioning.

6.3 "Reinforced masonry" and the earthquakes.

One of the characteristics of "reinforced masonry" is the possibility of spreading the reinforcement over large wall surfaces instead of concentrating it on single areas or elements. This enables a reinforced wall to display an overall tensile strength.
Consequently, the energy introduced by an earthquake can be dissipated without a substantial loss of strength, because the continuity of the masonry can be preserved also in case of diffused cracking. Practically the ideal knots formed at the crossings of the bars behave like "plastic hinges" which keep the masonry together under any unfavourable emergency.

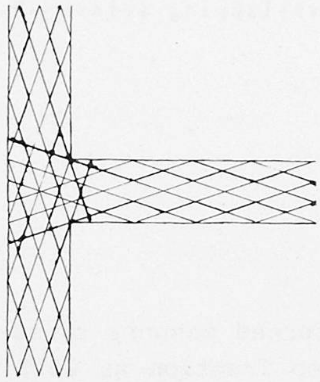

Fig. 4. Reinforced cross-wall.

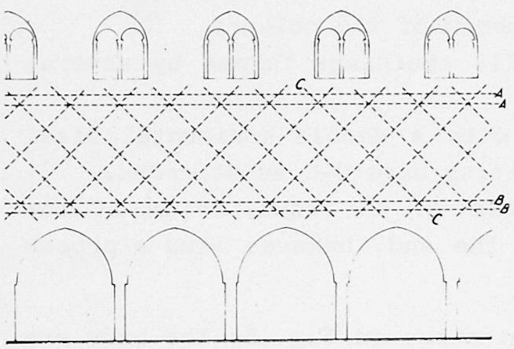

Fig. 5. Reinforcement of a colonade upper wall

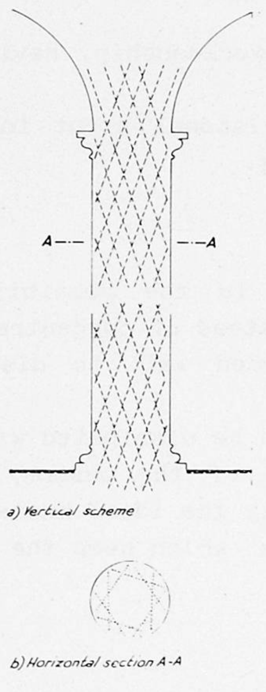

Fig. 6. Column reinforcement.

CONCLUSIONS.

Additional stresses, introduced in the subsoil and/or in the upper masonry of a building in critical static conditions, are to be feared, in the Author's opinion, more than further slight foundation settlements and/or upper structures deformations; the displacements can be accepted or, alternatively, prevented by temporary struts.

A correct consolidation work should be carried out in full respect of the existing static equilibrium, aiming to increase the Safety Factor of the building. This may be best obtained by the "passive intervention" approach. Experience gained by the Author, who was responsible for the static restoration of several hundreds Old Buildings and Monuments in various parts of the world, indicates that both the "pali radice" underpinning and the "reinforced masonry" technique are reliable and efficient tools for the preservation and strengthening of old fabrics.

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