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Strengthening of Building Structures — Therapy

Renforcement des structures de bâtiment — thérapie

Verstärkung von Bauwerken — Behandlung

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SUMMARY
Interventions involving the use of new structural materials in connection with aged materials must consider their mutual strength and deformability. Typical methods of repair and strengthening of timber, masonry and concrete structures are surveyed. It is emphasized that interventions on foundations and upper structures must be conceived under a global view. A large variety of methods is briefly presented.

RESUME
Les interventions impliquant l'usage de matériaux nouveaux à côté de matériaux anciens, doivent tenir compte de leurs résistances et déformabilités propres. Le rapport présente des méthodes classiques de réparation et de consolidation d'ouvrages en bois, en maçonnerie et en béton, et souligne que les interventions sur les fondations et les superstructures doivent être conçues dans une vision globale. Les différentes méthodes sont illustrées brièvement.

ZUSAMMENFASSUNG
Verstärkungen, welche neue Baumaterialien im Einklang mit alten beinhalten, müssen die Festigkeit und Verformung beider Materialtypen berücksichtigen. Typische Sanierungs- und Verstärkungsmethoden für Holz-, Mauerwerk- und Betonbauten werden besprochen. Es wird betont, dass Eingriffe an Fundationen und Überbauten global betrachtet werden sollen. Die verschiedenen Methoden werden kurz aufgeführt.

1. INTRODUCTION

1.1 Type and extension of any repair and/or strengthening work can only be decided after both origin and amount of structural inadequacy have been ascertained.

If, for example, the inadequacy is the result of a structural damage produced by an external action, the type of the intervention should aim at eliminating the causes, which might be either design or construction faults, while the extension of it should be concerned with the performance expected from the repaired structure.

Generally speaking, the 'optimal' degree of intervention should be outcome of an (explicit or not) cost-benefit analysis, under safety restraints. This latter aspect, in particular, is still largely dealt with on subjective bases, out of a rational framework of reliability analysis, with the frequent consequence of overly conservative design.

1.2 A further source of conservatism can be the lack of adeguate quality control policies. The two main aspects of this policy, which should be properly and consistently balanced, are: the evaluation of mechanical characteristics of old existing materials and structural elements through laboratory and in situ testing, and the control and surveillance during construction of the new materials employed, as well as of the compliance with design specifications.

In more detail control should be exercised on:
1) correcteness and effectiveness of the connections between old and new materials and elements
2) quality of the new material
3) correcteness in the placement of the new materials and of the selected repair technique.

The tasks above are to be carried out by personnel not involved in design or execution: specialized organisms exist in several Countries.

Finally,the fact cannot be passed without mentioning it that final reliability of the repaired structure and, hence, the 'succes' of the intervention, is essentially dependent in a correct evaluation of the design actions to be based, whenever the case, on probabilistic models.

The most common actions include:
1) gravity and other directly applied forces
2) stress states due to imposed deformations or temperature changes
3) inertia forces due to imposed accelerations
4) stress redistributions following modifications of the structural system.

Increased resistance to these actions can be achieved not only by means of strengthening measures, but also through liberation of the energy stored within the structure (case2), or by increasing the energy dissipation capacity of the latter (case 3).

1.3 A Key point of all repair or upgrading techniques is the connection between old and new materials.

A variety of situation can occur, the most common being replacement of the same material in a damaged element, for example a partially destroyed column.

In other cases new structural elements have to be added, as for example steel beams to be connected to columns, steel bracing, etc.

The modification of the resisting structural system with the ensuing new internal distribution of actions must be in all cases duly accounted for. It might happen that a new resisting structure is added, which is capable of resisting entirely (some of) the external actions: even in this case it must be cheklеd that the deformations required by the new structure be compatible with the integrity of the old one. Penalty for not complying with this criterion might be the partial collapse of the existing structure due to excessive deformations.

1.4 A very effective technique for achieving the desired distribution of the internal actions between old and new parts in the use of prestressing.

This technique is to be considered of fundamental importance in all Kinds of intervention: even permanent loads can be transferred from one element to another. The potentiality of prestressing in optimizating the performance of connected elements can be seen from simple considerations.

Let us indicate by 1 and 2 existing and added elements, respectively, and by Sa a superimposed load acting after the connection is made. Sa will be resisted by the two elements according to (see fig. 1):

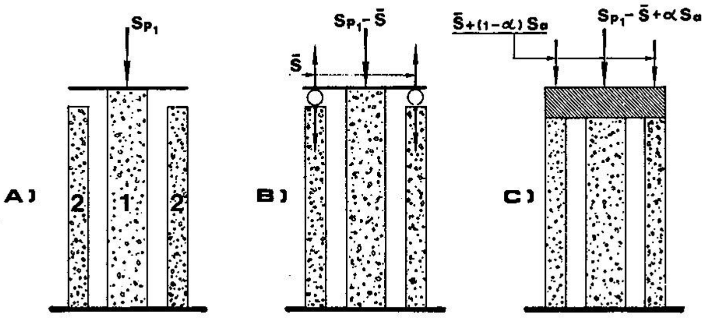


Fig. 1

$Sa = Sa1 + Sa2 = \alpha \cdot Sa + (1-\alpha)\ Sa$

with α depending on the relative stiffnesses.

If the first element was already carrying the load Sp1, the total load after connection will be:

$Sp1 + \alpha \cdot Sa$

Considering now the zero-resultant state of stress due to prestressing:

$\bar{S} = -\bar{S}$

the first element will be subjected to:

$Sp1 - \bar{S} + \alpha \cdot Sa$

and the new one to:

$\bar{S} + (1-\alpha)\ Sa$

Two independent parameters: α and $\bar{S}$, are available for achieving the best exploitation of the elements.

In a different context, prestressing can be used instead of normal reinforcement in masonry walls: the advantage is not so much in the increased resistance of the wall, but in being the prestressed steel immediately responsive to wall deformations.

1.5 It has been stated earlier that therapy is the final step which can only be accomplished based on the recognition of the causes which led to damages, or of the existance of a state of structural weakness.

A broad distinction of the types of intervention can be made between those necessary because of defects of the superstructure, and those originating from foundation inadequacy.

A merit of this classification is that it forces the designer to acquire a deeper insight about the real causes of the undesired effects. For instance, the visible symptoms due to uneven foundation settlements or to localized crushing of base walls are quite similar; also, creep deformations in the superstructure can sometimes be erroneously attributed to foundations.

Cases where statical deficiencies are present both in superstructure and in foundation are obviously more difficult to treat: the cure can often be that of strengthening the base of the building, so as to minimize the effects of foundations movements.

1.6 A classification of different nature would be that between the interventions limited to replacing or improving the existing materials, and those involving structural changes. These latter include for example creation of hinges to interrupt continuity, insertion of walls to resist horizontal actions, subdivision of the building into parts by means of joints, etc.

Clearly, in many cases both types of intervention would be used.

2. INTERVENTIONS ON STRUCTURAL ELEMENTS

2.1 Necessity of repair actions limited to structural elements can arise as a consequence of natural degrading due to aging, accelerated in some cases by aggressive external agents, or of specific damaging causes as for instance uneven soil settlements, earthquakes, explosions, fires, etc.

Structural modifications of elements may also be required following a decision of upgrading the building capacity in view of a different use.

The materials used for repair or strengthening purposes are similar to those for new constructions: the selection depends on the strength and deformability required for the modified structure. New types of materials, however, specific for adoption in existing structures, have been developed in recent times and a wide range of choice is now available.

The selection is particularly rich in the field of mortar additives, by which it is possible to obtain anything from a simple, no aggregate, fluid to fill the porosity of the old materials, to elaborate multi-purpose mixes to be pneumatically injected to fill the voids or to augment the size of the element.

Water-cement mixes in which cement particles are suspended in water are unstable because of the possibility of segregation.

Addition of bentonite increases stability, at the expense of strength.

Patented additives exist (ex.: Reoplast) which possess a number of favourable characteristics, such as greater fluidity, reduction of both shrinkage and swelling, and capability of retardation or acceleration of the setting process.

More effective, from the point of view of the strength attainable and of the ability to penetrate into the cracks, are the epoxy complexes. The mixtures are usual ly composed of one or more adhesive components, an hardener, and other particular additives.

When resin mixes are used to join together various elements, fillers are added to improve the adhesion between the adjacent surfaces.

Resin coats are also applied as a protection against aggressive agents on steel, wood and masonry surface. The method of application is frequently the so-called vacuum method, best suited for closing capillary fissures or for tighter penetration.

Epoxy resins and epoxy-mortars are most often applied in various form of injection techniques, whose aim is to eliminate voids or lack of continuity between parts of materials created by cracking or spalling.

The equipment for performing the injections consists of small rotative drillers which penetrate the material, and of mixers for the preparation of the mortar.

The strength of cement mortars to be injected may range from about 10 N/mm^2 for use in masonry elements to 50 N/mm^2 or above for concrete elements.

With epoxy resins compressive strengths of 100 N/mm^2 and tensile strengths of the order of about 1/3 can be obtained, though with the more common use of quartz sands the strengths are in the range of 10-50 N/mm^2.

Cement and epoxy-mortars can be used to form conglomerates with the addition of small-size aggregates. Resin conglomerates with polyesters are often preferred to normal conglomerates for the repair of concrete structures, because of their superior deformability.

Shotcrete, known also as 'gunite', is a means of strengthening structures by realizing strata of cement mortars having excellent adhesion to existing surfaces. Thicknesses of up to 20 cm can be obtained using mortars with aggregates of particle size less than 10 mm.

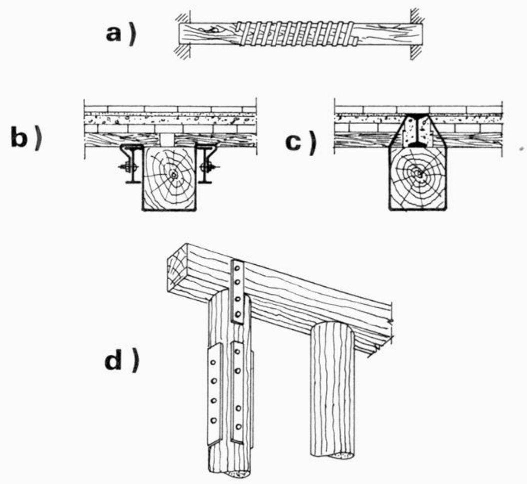
Frequently, the extra thickness to be realized contains a welded wire which is attached to the existing surface prior to the treatment.

2.2 Timber Elements

2.2.1 Strengthening of timber elements occurs frequently in the restoration of floor or roof systems; monumental or historic buildings have often precious timber roof structures which cannot be replaced by new ones.

Except in rural buildings, timber floor systems are generally replaced by concrete or steel floors.

2.2.2 Various examples of interventions on timber elements are illustrated in fig. 2. Fig. 2a shows a local strengthening obtained by binding metal sheets. Beams of greater importance can be relieved by inserting steel beams either in contact or joined with connectors (fig. 2b) or, if the appearance has to be maintained, by inserting the beams within the thickness of the plank, so as to make them not visible (fig. 2c). It is obviously imperative that the new elements be adequately anchored to the main walls.



Connections between elements can be improved by attaching metal plates with bolts or nails (fig. 2d).

Fig. 2

2.2.3 Timber trusses can be strengthened with steel elements as in the example shown in fig. 3, relative to a truss forming the roof of a stage in a theater. The loads from the structures below are transferred to the selected joints by means of prestressed steel bars.

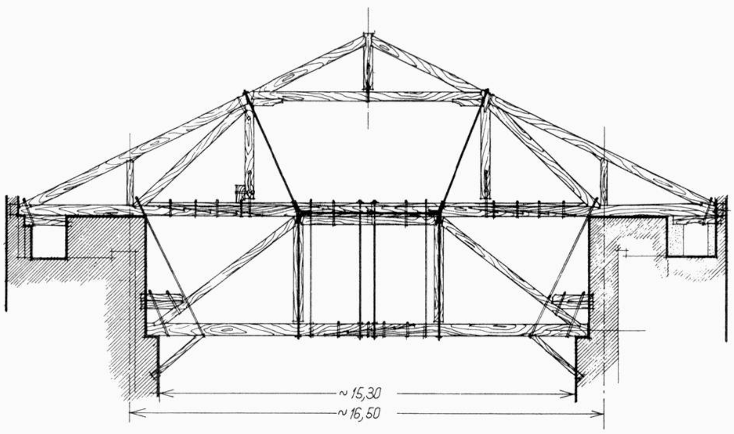


Fig. 3

2.2.4 Wooden structures of artistic importance are most conveniently repaired by using low-viscosity epoxy resins to be applied via impregnation (vacuum method), or by injection.

In some cases deteriorated parts of wood can be removed and epoxy mortars cast in situ to reintegrate them. This is frequently the case of the extremities of floor girders or trusses encased into niches of the walls and subject to humidity: the intervention can consist of the reconstitution of the degraded parts with epoxy resins, possibly with the addition of fiberglass, as shown in fig. 4.

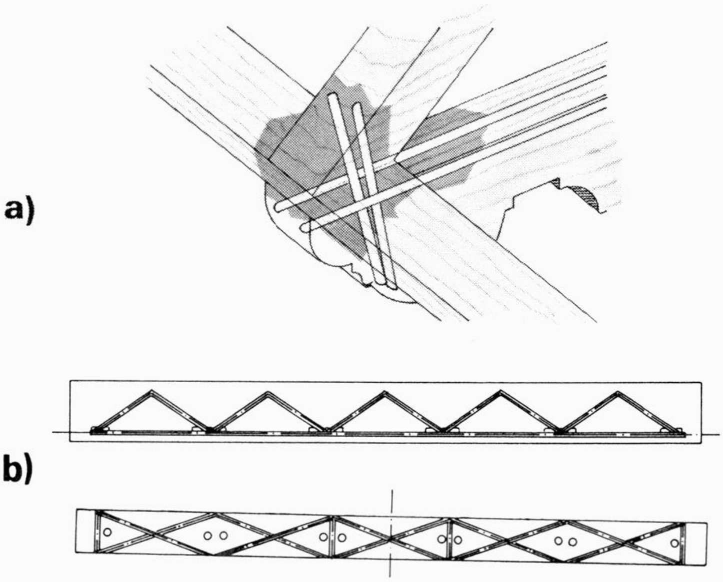


Fig. 4

2.3 Masonry elements

2.3.1 For damages of local nature, the "piece-by-piece" replacement procedure in fig. 5a, which is perhaps the oldest in use, may well keep its economical and technical validity. This is especially so for restricted cracked or disgregated areas of walls. The removed material can be replaced either by one of the same type, or by a concrete casting.

It is worth noting once more that the repair action cannot by itself eliminate the causes at the origin of the damages, which can be inherent to the overall structural organism.

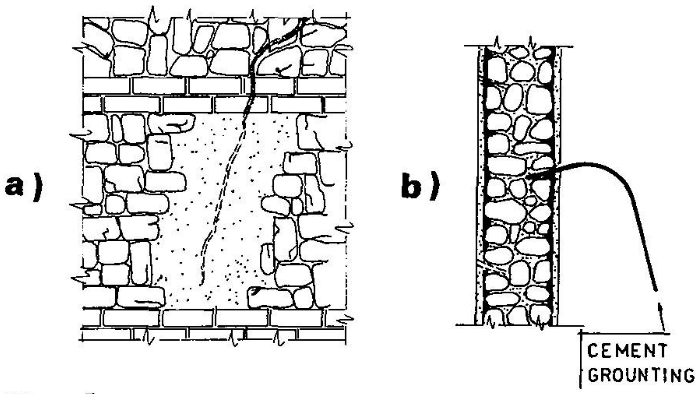


Fig. 5

2.3.2 More recent techniques involve the use of cement or epoxy mortars grouted into the masonry to increase its compactness and its strength (fig. 5b).

The technique is especially suited for irregular masonry made of coarse aggregates, since the volume of voids is far greater than in squared solid masonry. When the texture is very loose, containment of the injected material at the wall faces by means of cement plaster may be necessary, as shown in fig. 5b.

Before injection, the hole is accurately washed using slightly pressurized water, then dried with an air jet.

The humidity patches around the hole permit to evaluate the propagation distance of the mortar, from which the center-to-center spacing of the holes can be decided.

One sided injections whith half tickness hole length are usually performed for wall thicknesses up to 60 cm; greater thicknesses require double sided injections.

The injections begin at the lowest points in a wall, the pressure being gradually increased whith sufficient time allowed to penetrate: quartz sands are used in case the velocities are too low.

2.3.3 Fig. 6 shows the strenthening by means of injections of the corner pillar in the H.S. Chapel of the San Marco church in Venice. Although the masonry was in a very poor state, the type of restoration permitted to keep in place the original structural element.

2.3.4 A more effective version of the injection technique involves the use of reinforcement bars. The holes are drilled at an angle of about 45° with respect to the vertical plane of the wall and with alternate inclinations.

Before injected mortar hardens a deformed bar is inserted in each hole, as illustrated in fig. 7.

Since the reinforcing mesh can comprise bars in all directions a certain amount

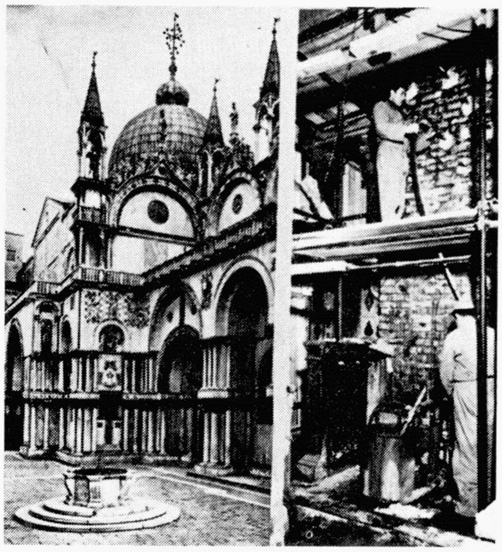


Fig. 6

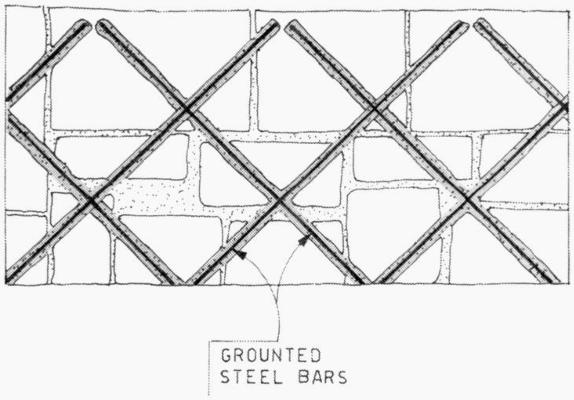


Fig. 7

of tensile and shear strength can be obtained in three dimensions. This result can be exploited in the form of bending strength, as for example in a simple lintel, but also for the realization of large deep beams, as it has been done over the arcades of S. Eugenio church in Arezzo, with the addition of Dywidag bars (fig. 8).

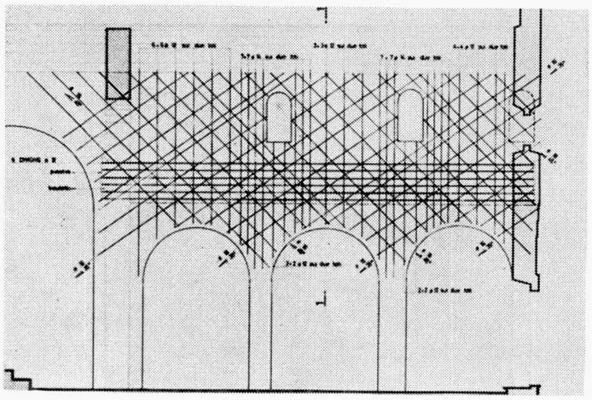


Fig. 8

In other cases the reinforcement bars are used within a certain height of wall across the floors, with the aim of realizing a sort of concrete boundary members.

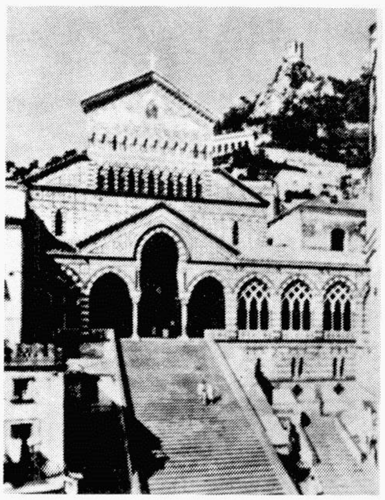


Fig. 9a

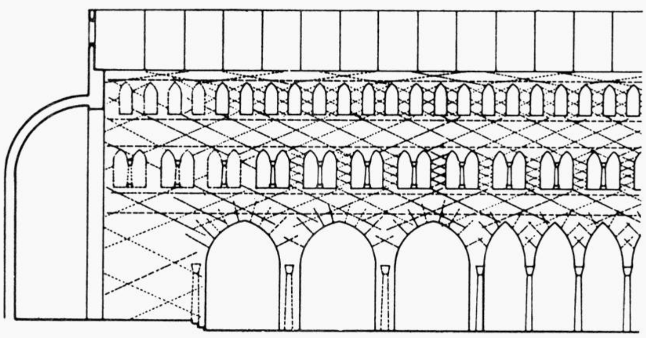


Fig. 9b

2.3.5 Fig. 9 illustrates the consolidation of the Duomo di Amalfi, in which injections were largely used to create reinforced masonry beams above and below the mullioned windows, so as to obtain a convenient distribution of the load on the columns.

2.3.6 An example of use of a reinforcemnt mesh is that on the vault of the S.Silvestro church in Rome, illustrated in fig. 10.

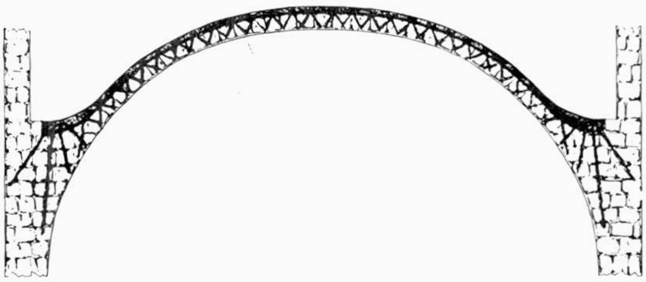


Fig. 10a

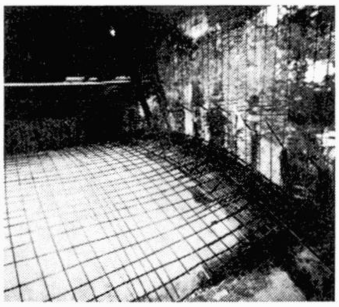


Fig. 10b

Foundation settlements had induced cracks in the vaults, which are made of tufaceous blocks only 30 cm thick. Reinforced holes cross the vault with the bars anchored in the topping gunite slab 10 cm thick shown in the figure.

2.3.7 The injection procedure can be integrated, if necessary, by reinforced coating of the type shown in fig. 11.

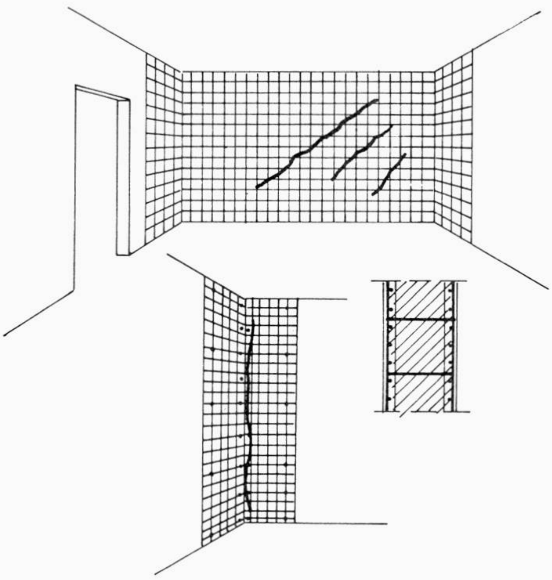


Fig. 11

These coatings can also be used autonomously, without recourse to injections.

Welded wire meshes are placed on both faces of the wall, and connected by steel ties running through holes transverse to the wall. Concrete mortar is then pneumatically applied on both faces, so as to 'sandwich' the wall. It is important that the steel used be ductile enough to accomodate the relatively large deformations characterizing the masonry structures.

An interesting case of effective integration of the two techniques of the injection and of the double coating illustred in fig. 12. Perpendicular walls detached at the corners can be reconnected by means of reinforcing bars, injections, and casting of mortar where large voids exist. The corners are then also sandwiched by means of reinforced cement plaster to further improve continuity.

2.3.8 Fig. 13 illustrates the case of the bell tower of the S. Ciriaco Cathedral, where a reinforcing framed system has been realized by placing reinforcement bars in the middle plane of the walls.

2.3.9 The connection between walls, in particular the exterior ones, which tend to displace outwards or even to rotate rigidly under the thrust exerted by the

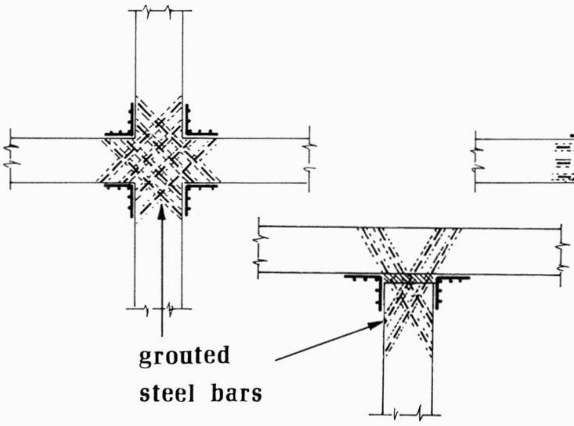


Fig. 12

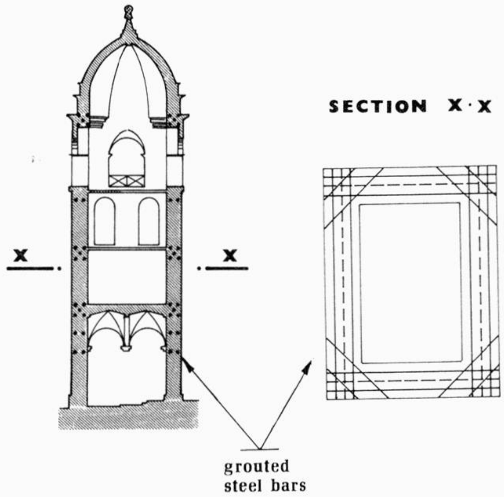


Fig. 13

roofs (see figs. 14a and 14b) has been traditionally obtained by means of tie rods adequately anchored at the extremities with steel plates.

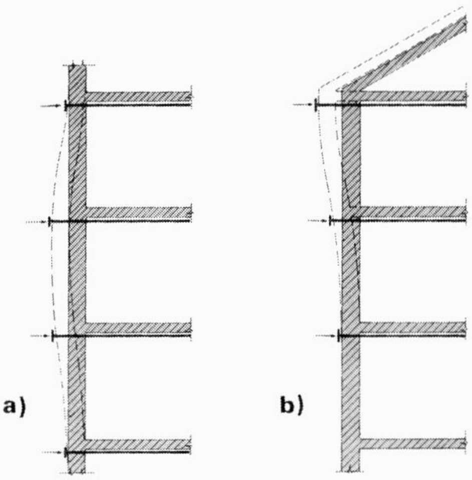


Fig. 14

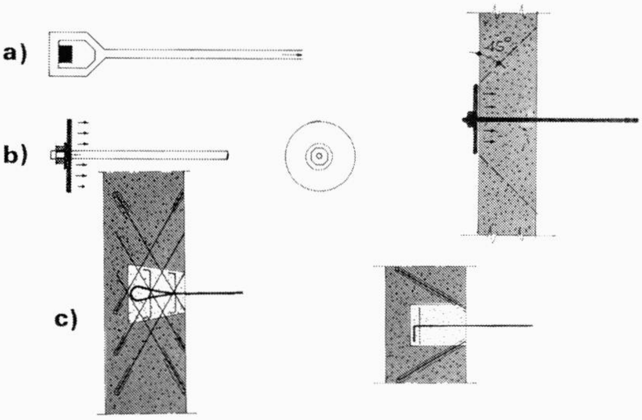


Fig. 15

To avoid seing the anchor plates, the tie rods can be terminated into blocks, sometimes wedge-shaped as in fig. 15c, connected to the adjacent masonry by means of reinforced injections.

Rods are always necessary to absorb thrust, as in the cases of vaults or arches when the abutments show signs of distress. Fig. 16 shows the application of tie rods in a building in Venice.

Concerning the strengthening of vaults and arches, mention has to be made to the idea of improving their stability by adopting fill material having different specific weight.

2.3.10 One often encountered problem in the restoration of masonry buildings is that of replacing the old wood floors with new ones made of steel or of reinforced concrete. What is required in those cases is to safely connect the new floors to the walls, without weakening these latter by carving large seats into them.

Fig. 16

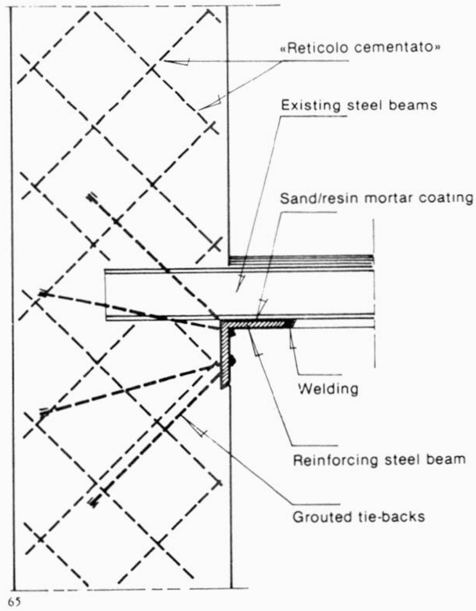
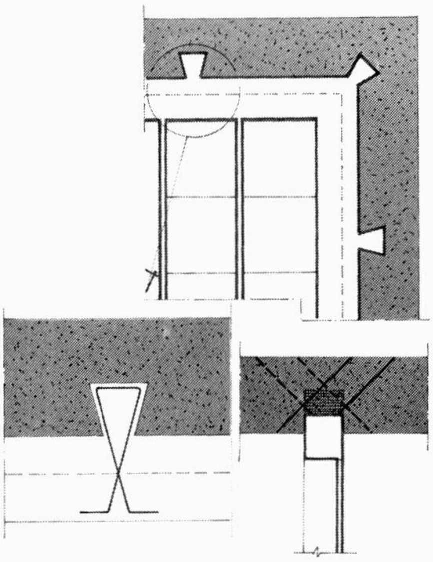


Fig. 17

Fig. 17 shows the anchorage of cantilevers to the wall by means of reinforced injections, for the support of steel girders.



One way to realize the floor-to-wall connection can be that illustrated in fig. 18: V-shaped keys at the floor ends allowing also for the crea tion of a continuous concrete boundary element only slightly encased into the wall.

Fig. 18

2.3.11 A further problem occurring very frequently in old buildings is the stren gthening of columns. The oldest system, much used in the past, consists of confining the columns by means of steel rings. Active (i.e., prestressed) confinement was obtained by heating the rings prior to their fastening.

Closed stirrups have been used in rectangular columns: their confining action is however much lower, as demonstrated for example by the case of the large stirrups used in the past for the rectangular pylons of the roman Colosseo (fig. 19). Cracking of the masonry has continued, so that recently the injection of cement and epoxy mortars has become necessary.

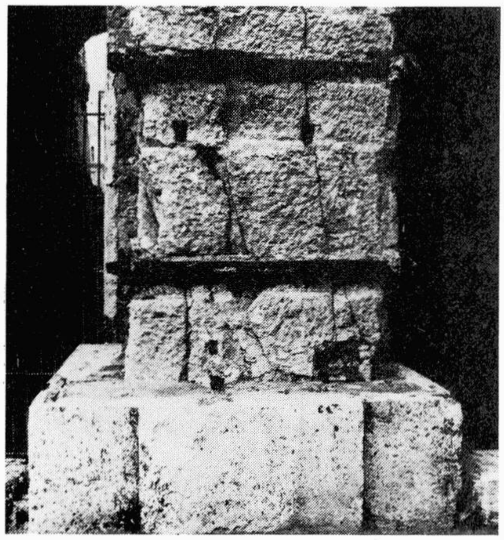


Fig. 19

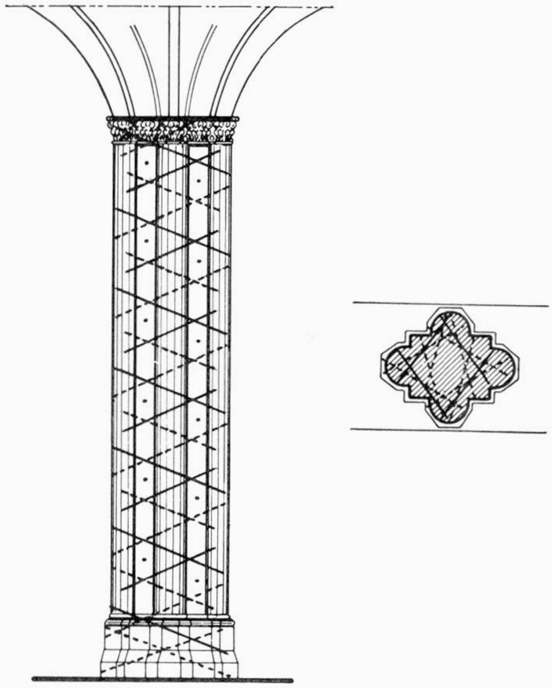


Fig. 20

2.3.12 Large pylons of any cross section can be strengthened by means of the reinforced injections technique, as in the case of the church of S. Lorenzo in Naples (Fig. 20).

The steel bars have been placed at the interior of the columns to form a double spiral, so as to achieve structural continuity both in the vertical and the horizontal directions.

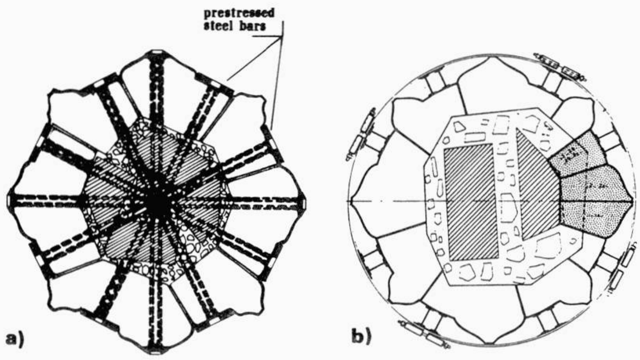


Fig. 21

Improvements can be obtained by adopting prestressed diametral bars, whose effect is equivalent to that of a perimetral confinement. An application of this type was studied for the columns of the tiburium in the Duomo of Milan, with diametral bars spirally arranged along the height of the columns (fig. 21a). A physical model was also prepared and tested at the I.S.M.E.S. laboratory in Bergamo (fig. 22).

Although the test results demonstrated the effectiveness of the new system, the decision was taken to follow the traditional one, already used for other columns in the Duomo.

It is worth to recall that as an emergency measure the pylons of the tiburium were initially encased into reinforced concrete hollow columns. The casing is now being removed and the original stone blocks gradually replaced according to the sequence in fig. 21

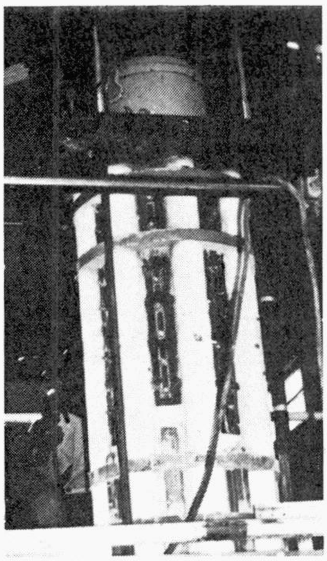


Fig. 22

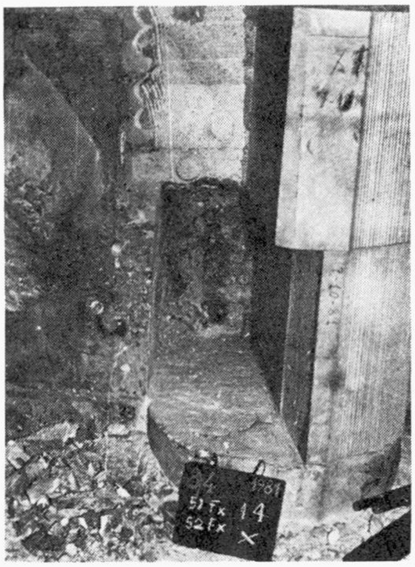


Fig. 23

The operations illustrated in fig. 23 have been carefully tested in order to ensure that the elastic deformations of the columns be conveniently limited.

2.3.13 Two notable examples of restoration of historic monuments have involved the use of steel elements.

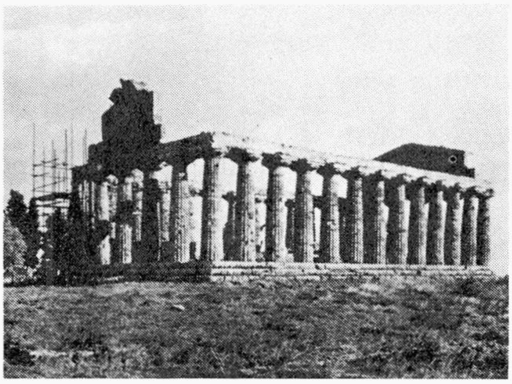


Fig. 24a

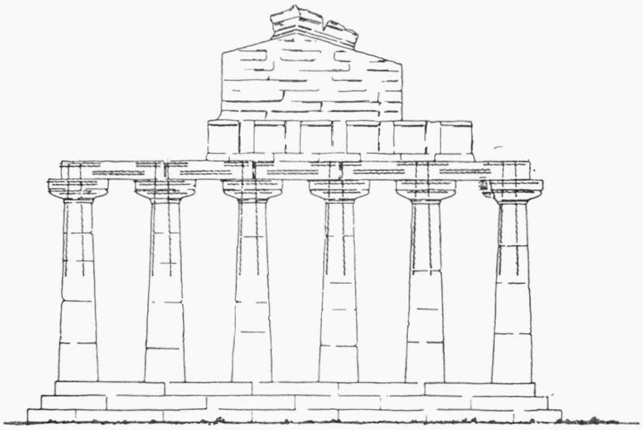


Fig. 24b

In the temple of Cerere at Paestum (fig. 24) the connection between vertical and horizontal elements has been ensured by drilling holes and inserting steel bars.

The second example is given by the pylons of the Arena of Verona (fig 25) which have been prestressed vertically in order to stabilize the entire structure principally against horizontal actions: wind and earthquake.

2.4 Reinforced concrete elements

2.4.1 Damages to concrete elements can be due to external actions such as earthquakes or fires, or can be of local origin, mostly from oxidization of steel, a phenomenon leading to crack formation.

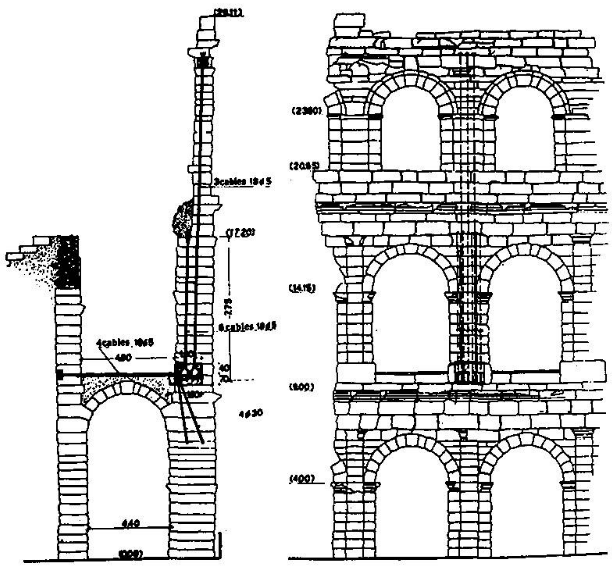


Fig. 25

Degradation due to oxidization is a very frequent problem in old structures:the specific volume of steel can increase up to ten times the original one,causing spalling of the concrete cover, while the net section of the bar decreases notably.

When the situation is not too advanced, the remedy consists in removing the concrete wherever signs of rust are visible, in polishing the bars by means of sand jets, and in applying some anti-corrosion chemical.

When the steel section has been reduced by corrosion of more than 5% the residual capacity of the element has to be checked analytically and, if found insufficient, adequate additional bars must be welded to the existing ones.

Before proceeding to any type of intervention, a check has to be made of the level of carbonation reached by the concrete, and of its rate. If the activity is such to yield values of ph under 7 there can be no guarantee for the steel to be protected, and the concrete has to be replaced. This fact occurs more frequently with porous concretes, porosity being a characteristic sometimes more dangerous than a state of cracking.

2.4.2 Cracking remains however an undesiderable state, because it weakens the structures and is a potential cause of corrosion.

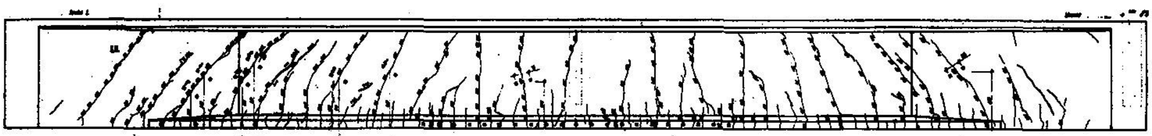


Fig. 26

In several instances cracks form in the webs of long span beams having T sections with relatively thin webs, classical examples being the roof girders of industrial plants. Since in these cases the ratio between total and permanent loads is near to unity, the tensile principal stresses in concrete remain permanently at values near to the maximum admissible ones, which makes formation of cracks more likely. If the beams are subjected to dinamic actions the cracks pattern is more diffuse, as shown in fig. 26, relative to a beam subjected to forced vibrations.

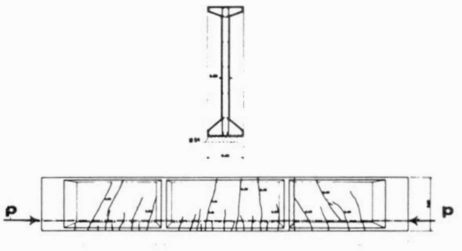


Fig. 27

If the design of the beams is correct, i.e., made according to code specifications, stability problems should normally not arise; larger-than-average cracks, however, if they appear, should be closed in order to ensure the expected service life of the element.

An effective means to close the cracks is the use of prestressing, which has the additional effect of strengthening the structure. Fig. 27 shows an example of a beam whose existing cracks were completely closed by introducing prestressing cables along its sides.

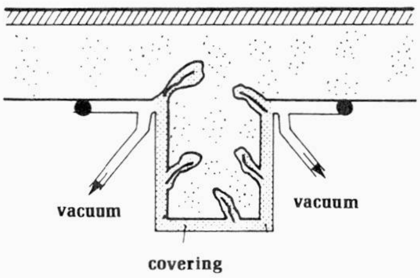


Fig. 28

A different concept is that of simply protecting the cracked elements by filling the cracks with epoxy resins, using the vacuum method as shown in fig. 28, or by applying a gunite plaster reinforced with a welded wire mesh (see fig. 11).

2.4.3 Fire is a further source of damages. Repair of structures subjected to fire is advisable only after careful inspection and testing of materials. Concrete cores and steel samples extracted from critical points should be checked in laboratory for strength and deformability.

The steel can be assumed undamaged only if the temperatures during the fire remained moderate: in this case the repair can be limited to the concrete. It can involve demolition of the external crust of concrete burnt by the fire, and shotcreting to reconstitute the size of the element.

2.4.4 Considerating damages produced by external actions to r.c. elements, repair and strengthening can be required either locally or for the entire element.

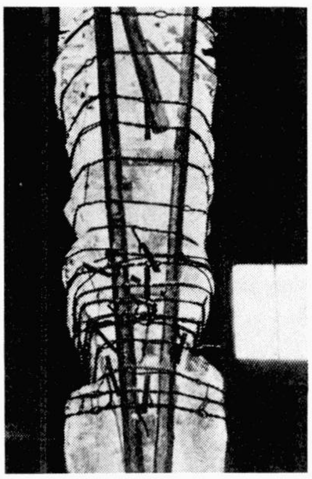


Fig. 29

In the latter case the size of the element can be increased by a shotcrete coating or by encasing the beam into a larger one.

For columns, once loose concrete is removed, a provisional binding can first be applied (fig. 29), then new concrete is cast externally (fig. 30). For strength and bond purposes, a mesh of vertical and horizontal reinforcement is included in the new part of the section.

For beams similar procedures can be adopted; if a bending strength increase is the only purpose, the added stirrups can be of reduced height (fig. 31a), while they must en-

encircle completely the element if extra shear strength is also required (fig. 31b).

Replacement material must possess no-shrinkage and adhesive properties, in order to ensure satisfactory bond whith the in-place material.

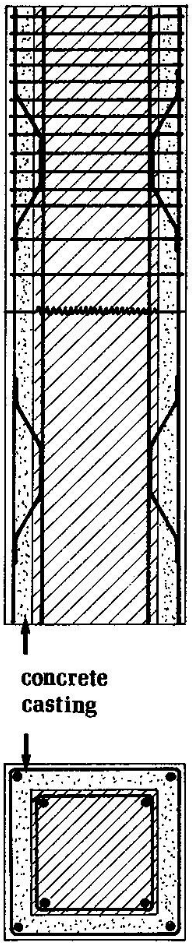
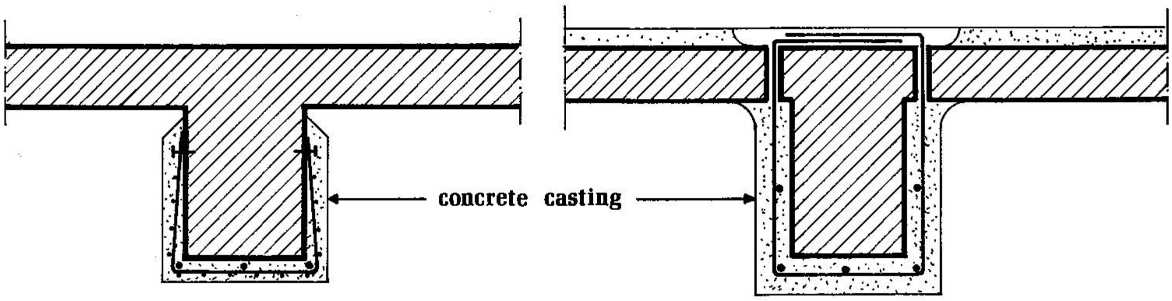


Fig. 30

Fig. 31



2.4.5 A strengthenig method which has had wide applications is the so called 'beton plaqué'.

It consist in gluing steel plates on the element surface, using proper resin mixes. The adhesion between plates and concrete can be improved by treating the surface with acids. The main problem is the transmission of shear stresses within the concrete cover: to this purpose the plates are anchored into the body of the element by means of large connectors (fig. 32).

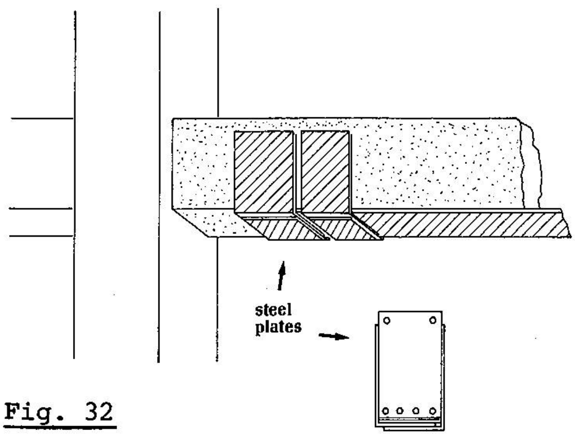


Fig. 32

2.4.6 Concrete slabs containing hollow tiles have in some cases to be stiffened and/or strengthened. Satisfactory results can be obtained by increasing the slab thickness having previously removed some of the tiles: small concrete blocks are thus created which act as keys improving the transmission of shear stresses (fig. 33). The extra thickness of the slab can be made variable with maximum at midspan, to save material and weight.

A very simple and cheap way of strengthening one-way hollow-tile slabs is to remove alternatively one row of tiles and to replace it with reinforced concrete ribs. (fig. 34).

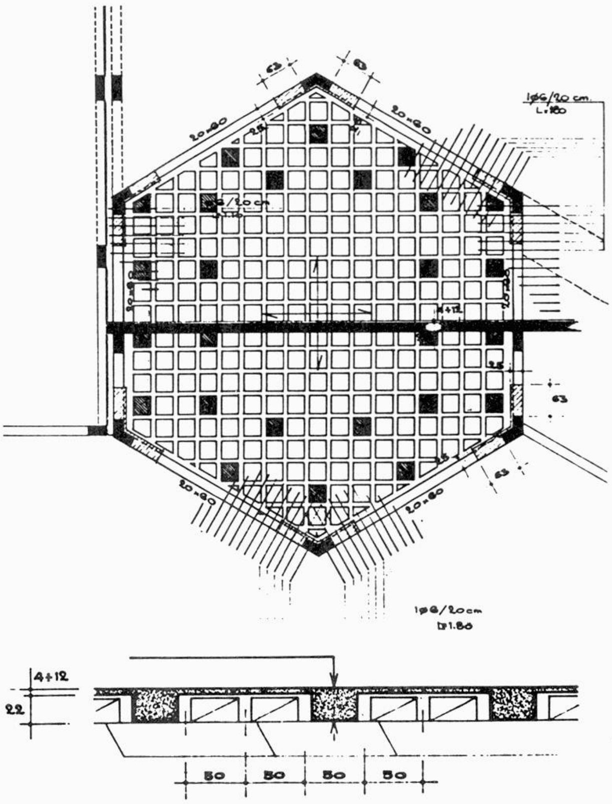
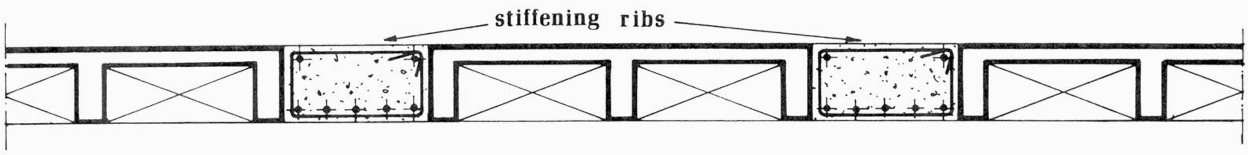


Fig. 33

Fig. 34



3. INTERVENTION ON THE STRUCTURAL SYSTEM

The more frequent reason for structural system modification is a change in the loading pattern, as for example when a certain level of earthquake resistance is required to a not seismically designed building. This latter requirement arises every time seismic zones are enlarged.

A modification of the structural system may also be necessary to eliminate undesired zero-resultant states of stress due to imposed deformations: an example could be the transformation of a continuous beam having undergone uneven settlements into a series of simply supported beams.

Differential settlements are quite likely in large buildings founded on soft soil, and the corresponding states of stress may well lead to cracks formation. The distress can be halted by introducing joints between parts the buildings.

Fig. 35a

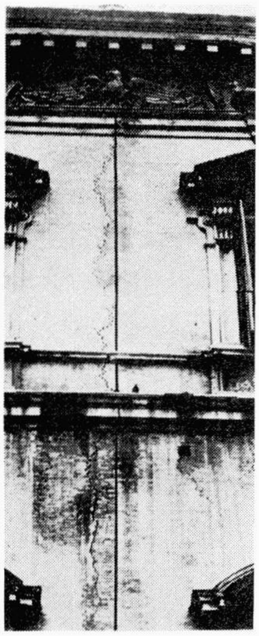


Fig. 35b

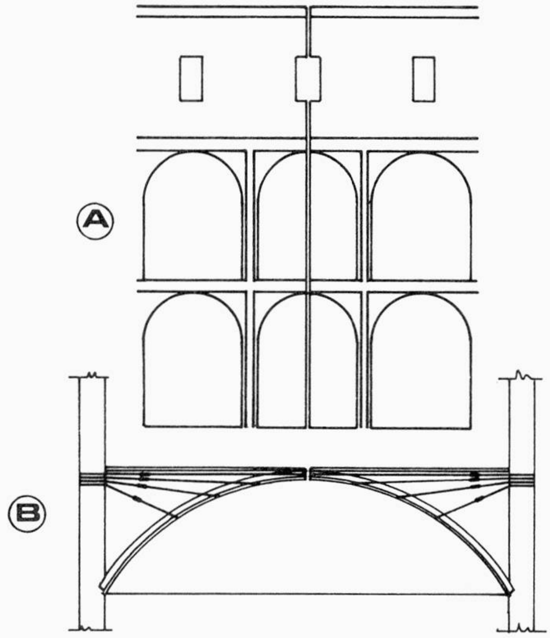


Fig. 35c

3.2 The differential settlements are obviously larger in case of nonhomogeneous subsoil. An example is provided by the Palazzo Ducale in Modena (fig. 35a), where a joint had to be inserted in correspondence to the variation of soil type (35b). In this case differential settlements were also due to subsidence phenomena. It is visible in the figure the cut crossing a vault (35c).

3.3 Global upgrading of buildings involving modification of the structural scheme can consist in the addition of framed structures working in parallel with the existing ones, and dimensioned to absorb the totality of horizontal actions.

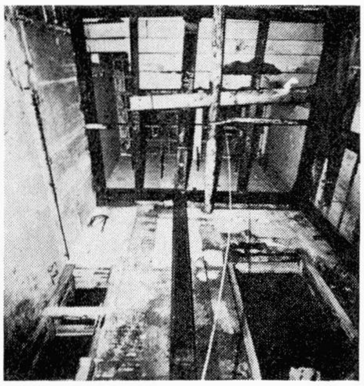


Fig. 36

Masonry buildings damaged by earthquakes are often strengthened using reinforced concrete or steel frames, the latter composed of vertical elements supporting beams which run below the floors (fig. 36).

Reinforced concrete buildings can be strengthened by inserting steel diagonal bracing (fig. 37a) so as to form reticular composite walls able to resist the horizontal actions.

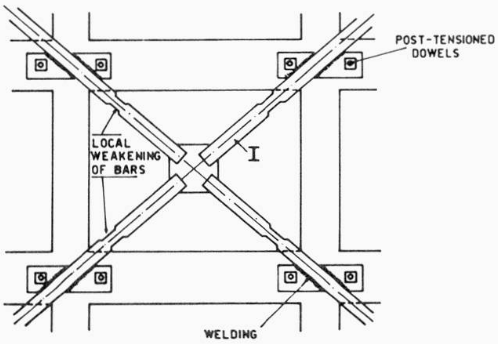


Fig. 37a

In the design of the strengthening elements and structures, account must be taken of the relative deformabilities of the new and existing structures. The deformation of the new structure must also be compatible with the deformation capacity of the old one, so that this latter can keep its integrity and ability to carry the vertical loads. This ne cessary requirement often dominates the dimensioning of the strengthening structures, and it may be met for instance by means of a truss structure as the portal in fig. 37b.

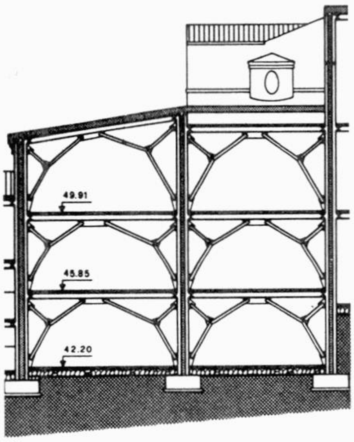


Fig. 37b

3.4 Reinforced concrete buildings can also be in some cases effectively and economically strengthened by infilling the frames with accurately laid good quality masonry. The infill walls can be limited to the lower floors, or can be extended to the entire height.

Under increasing lateral forces the infill wall behaves initially as monolithic; after the principal tensile stress reaches the tensile strength of the fill material, diagonal struts form in the panels (fig. 38) so that the wall becomes equivalent to a truss system.

It is to be verified that the corners of the framing structures are able to absorb the thrust exerted by the diagonals: it is very frequent to observe damages due to this cause at the ends of columns chich were not designed to resist this action. The phenomenon is more easy to occur in corner columns, so that greater care must be devoted to them.

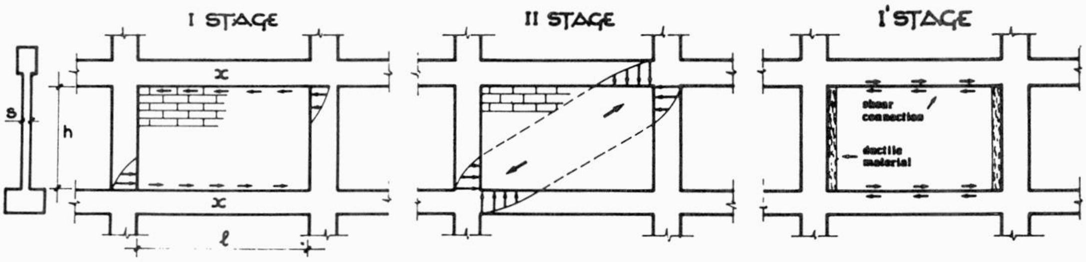


Fig. 38

Since the stiffening and strengthening effect of the infill walls is very desirable, a way of utilizing it while avoiding the danger of column distress could be that of separating the panels from the column faces, and at the same time trying to obtain a perfect adhesion of the panels with the upper and lower beams (fig. 38c).

This result can be practically achieved by denting the beam surfaces to improve transmission of shear, and by inserting strips of weaker masonry adjacent to column faces.

The presence of new shear walls in a building obviously modifies the previous distribution of forces among the resisting elements: the verification of the new statical system has to be extended down to the foundations.

During the repair works in a damaged building, attention has to be paid when removing some apparently non structural elements, as light walls or partitions, because the distress of the main resisting system could have transferred some essential statical function to these elements.

Modifications of the structural system occur also in case prestressing cables are used to strengthen flexural elements, to close cracks, etc. Prestressing actually introduces new forces and corresponding deformations, and the whole deformability of the structure can be altered.

3.5 A notable example of total alteration of the structural scheme and of the use of prestressing is found in the restoration and consolidation of the Palazzo della Zisa in Palermo, dating back to year 1100.

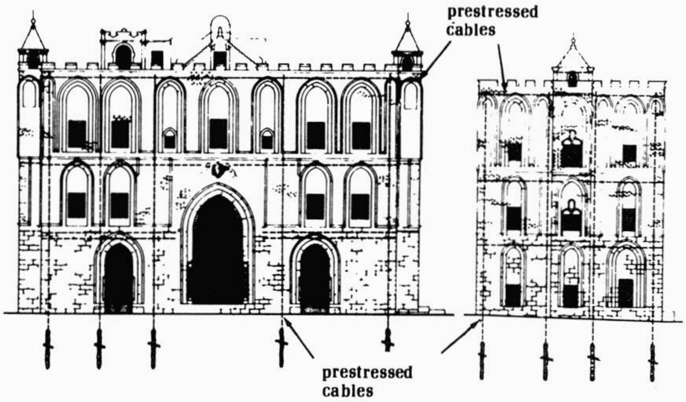


Fig. 39

The walls are of sandwich type with outer tufaceous blocks and poor filling material inside.

Reinforced injections were used throughout, but the main operation consisted in a complete vertical and horizontal prestressing of the building, such as to make it monolithic under seismic action (fig. 39). The vertical cables have been anchored in the foundation soil.

4. INTERVENTIONS ON FOUNDATIONS

4.1 The stability of foundations of a construction may be affected by alterations rising either in the soil or in the contruction itself.

Among the former are the phenomena of natural subsidence (settlements in young soils) or artificial subsidence (due to loading or digging the ground, to lowering the water table by pumping), as well as dynamic effects of natural actions (earthquake) or artificial actions (road and rail traffic).

Among the latter are the action variations on the foundation, due to variations of external actions or to structural redistributions of action effects.

In both situations there are soil-foundation and foundation-upper structure interactions, that have to be carefully considered in order to plan proper repairs and strengthenings.

The analysis of the interaction, particularly the second type, allows one to unstand the influence of relative stiffness of base and upper structure, and of the position of the global centroid, on the stability of the construction with regard to tilting.

Fig. 40 sketches the typical cases of the interaction: the first one represents predominant stiffness of the upper part, the third-one of the base, while the second, representing two infinitely stiff parts, may correspond to a block construc

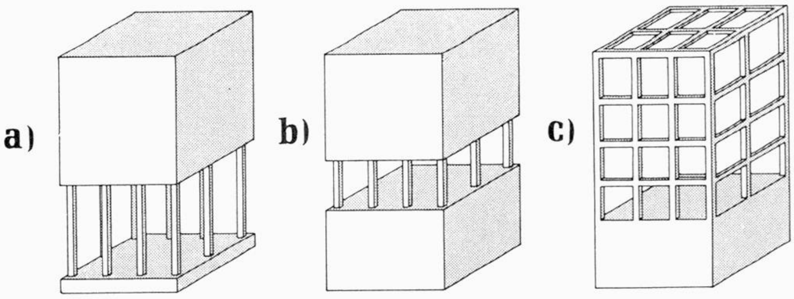


Fig. 40

tion with no differentiation between upper and basement structure.

When one faces a situation of damage, one has to ascertain first which case the construction is falling in, then the suitability of acting on the construction, or the soil. Rarely it will be convenient acting on both. Acting on the construction means varying the mutual stiffness of the said structural parts, and make it shift from one case to another in fig. 40. Whereas acting on the soil means either to induce artificial subsidence or to build sub-foundations, able to involve a larger effective volume of soil.

Especially a study of the interactions is required in seismic areas, since the soil must be considered in its twofold function of transmitting the seismic action and of sustaining the construction: if a firm rock soil maintains its bearing capacity, on the other hand it also transmits to the construction the entire excitation; instead, a loose soil reduces its bearing capacity under the dynamic response of the building, but it has higher damping characteristics.

The alternative choice arise of fastening the construction to the soil, or not. The choice depends on the type of construction, too, but in general it can be said that it is worth to realize a tight connection with firm rock soils; whereas, in presence of loose soil it is convenient, when technically possible, to approach the third scheme in fig. 40, suitably complemented.

Indeed, it is a rather frequent error after on earthquake to subfoundate buildings lying on loose soils with piles that reach down the bed-rock. Eventually, at a next earthquake the building would perform worst.

4.2 The procedure for strengthening foundations may be classified as follows:

(4.2.1) Direct interventions

(4.2.1.1) Variation of the stiffness of the basement structure

(4.2.1.2) Widening of the contact interface for shallow foundations

(4.2.1.3) Deepening of the transmission zone by means of piles

(4.2.2) Indirect interventions

(4.2.2.1) Variation of the stress/strain state of the soil with local artificial subsidences:

a) by loading or digging it;
b) by altering the water table;
c) by altering the soil consistency by means of injections or electro-osmosis.

The following may be observed concerning the above points, respectively.

4.2.1 (Direct interventions)

4.2.1.1 The option of altering the structural stiffness leads quite always to the third case in fig. 40, i.e., to provide a base structure rigid and strong with respect both to the ground and to the upper structure, forming a stiff partition preventing differential settlements in the building. The evaluation of the stiffness ratio between foundation and ground may be based on interpretation of the coefficient of Borowica

$$K_r = \frac{E_b \, J_b}{E_t \, b \, l^3}$$

where E_b, J_b are the elastic modulus and the moment of inertia of the global bending-resistant structure, respectively; E_t the modulus of the soil, b and l the width and the length of the contact surface along the bending direction.

For $K_r > 0.5$ the structure may be considered infinitely stiff with respect to the ground.

The stiffness ratio between base and upper structure (see fig. 40), if the respective horizontal dimensions are the same, may be assumed as

$$K' = \frac{J_f \, E_f}{\Sigma \, J_e \, E_e}$$

being $J_e E_e$ the sum of the stiffnesses of all the storeys. This ratio, where the deformability of the ground is not contained, is only valid for a rough global analysis.

4.2.1.1.1. Masonry buildings, yet rather stiff, may be stiffened at the base by increasing the wall depths with reinforced concrete sheets, as it has been seen for the upper structures, too.

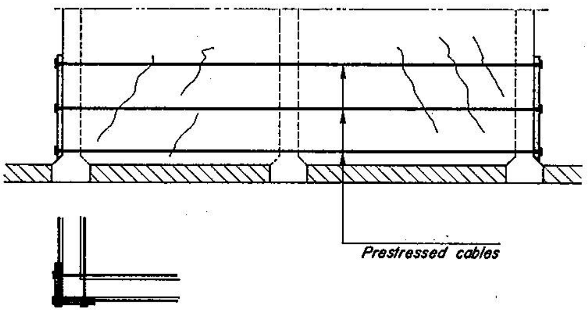


Fig. 41

The sheets may be sprayed on one or both faces of the wall. Reinforcement must be able to resist stresses deriving from non uniform distribution of the reaction (e.g. according to Winkler's model).

Particularly suited are the prestressed tendons, laid as in fig. 41, offering the advantage of continuity. Non prestressed reinforcement would require large deformation and cracks in the masonry, before giving significant force contribution.

4.2.1.1.2 Reinforced concrete framed structures allow for an effective stiffening of the basement, by replacing the infill masonry of the first storey with reinforced concrete walls, tightly connected to the columns, as sketched in fig. 42.

The effect of the stiffness variation is greater than in masonry buildings, as the upper structure is generally not stiff, disregarding the weak fill panels.

4.2.1.1.3 When very long buildings show damages due to differential soil settlements, the length l in the Borowica's coefficient becomes predominant, and it is difficult to make K_r great enough by acting on the moment of inertia, obviously

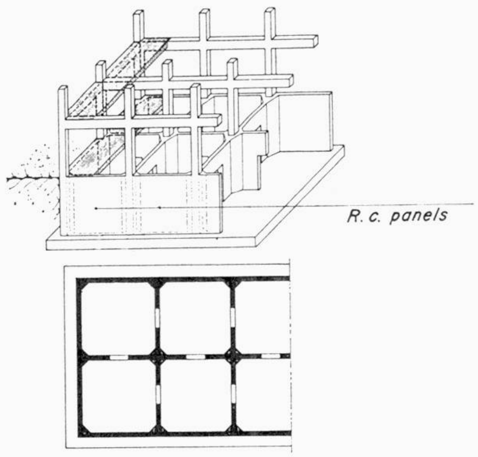


Fig. 42

limited by size reasons. It is then convenient to act on the length l, and to reduce it by cutting structural joints, extended to the whole height of the building.

A joint may be even a good solution for rendering parts of buildings independent if falling on different kinds of soil, as it has been done for the above said ducal palace of Modena: the two disengaged parts settle now independently across the joint.

4.2.1.1.4 A noticeable example of stiffening the foundation is given by the "Palazzo di Giustizia" (Court House) in Rome, which lies on a clay soil on one side, and on a sandy soil on the other, subject to variations in the water table level due to the close Tiber river (see fig. 43); the building has been undergoing differential settlements since its construction (1900).

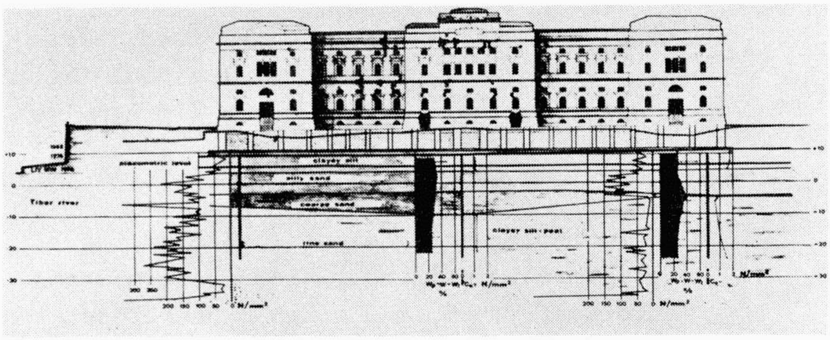


Fig. 43

The contact compression stress, about 0.4 N/mm^2, has been reduced by 10% by removing 4m of earth fill over the basement mat. The walls, thus uncovered, have been stiffened with reinforced concrete side walls making a box girder grid which covers the whole foundation, as shown in fig. 44.

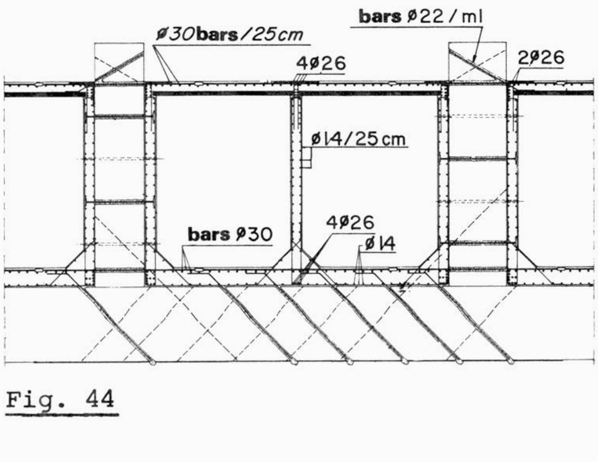


Fig. 44

A diagonal joint up to the top of the building will be set, following a series of breaks risen since the beginning of the construction.

Other cases occur of stabilization by lightening the loadings of buildings having direct foundations. E.g., in a tall building in the Abruzzi region (Italy), have been replaced all the heavy floor pavements, made of marble, with light linoleum ones, and the upper storey has also been demolished. Thus, 30% reduction of the weigth acting on the foundation has been obtained.

4.2.1.2 The solution of widening the contact surface of a shallow foundation has uncertain issues.

In fact, if the settlement is due to deep layer of soil, the stability can be improved yet by reducing the total load, not the bearing stress: thus, the benefit would be negligible.

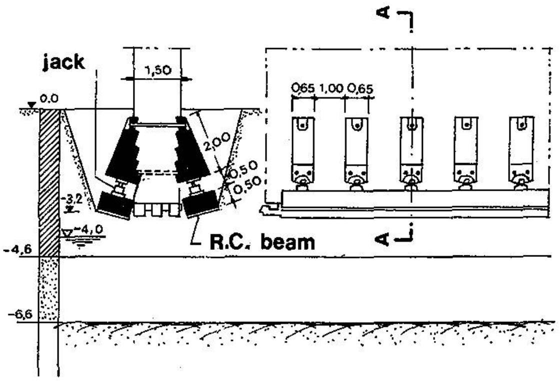


Fig. 45

On the other hand, if the superficial layers are weak, widening the base may be useful for supporting additional loads. However, the new surface produces a sensible reaction only after a certain settlement. This implies the shortcoming of settlements, possibly differential, even in the original foundation.

The widening of a shallow foundation may be rendered valid with a prestress that must be controlled during the necessary time for the settlement, and may be realized by means of jacks as in the case in fig. 45.

4.2.1.3 More effective for that purpose is the transmission of the actions to deeper layers, by means of piles, that can either implement a shallow foundation or integrate an existing foundation.

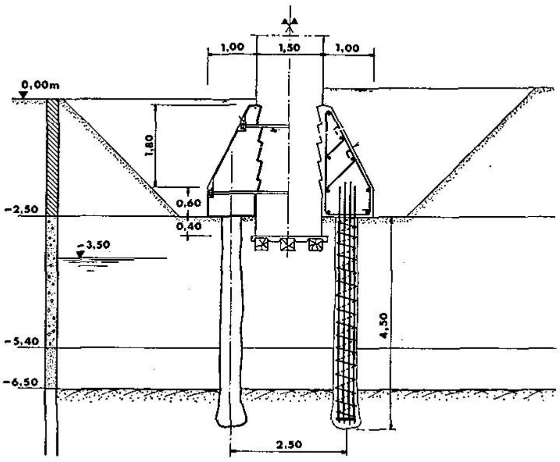


Fig. 46

Large diameter pile are often used, as it will be shown for some examples, but their use is difficult beside the buildings, yet impossible inside, due to the cumbersome outfit.

In addition, transfer of load from the structure is difficult, requiring systems like in fig. 46, and often a prestress, too, in order to compensate the relevant initial settlements.

4.2.1.3.1 Fig. 47 shows a remarkable intervention on a building on piles, where a wing suddendly had settled down ca. 30 cm, sinking over the formation of an underground hole.

R/C cantilever beams have been grouted underneath columns, each supported by a pair of piles 50 m long and based on the bed-rock. By means of a series of jacks centrally monitored, the columns have been lifted up after having been cut (fig. 48); the operation has obtained the re-closure of all the cracks in the upper structure.

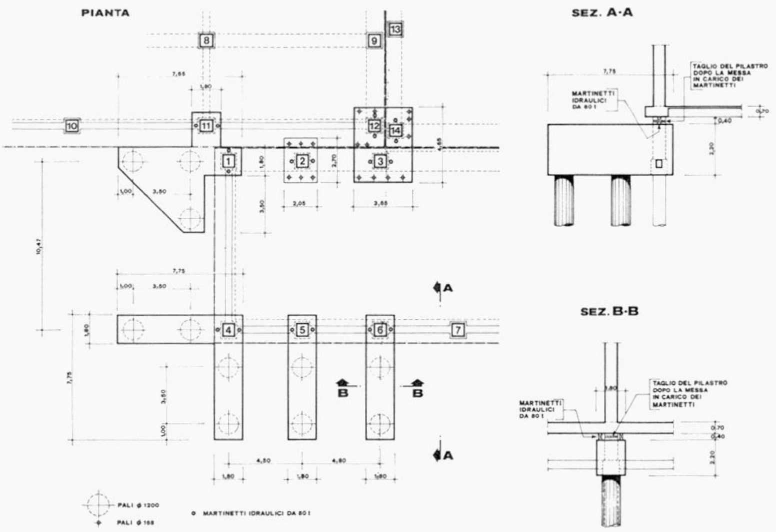


Fig. 47

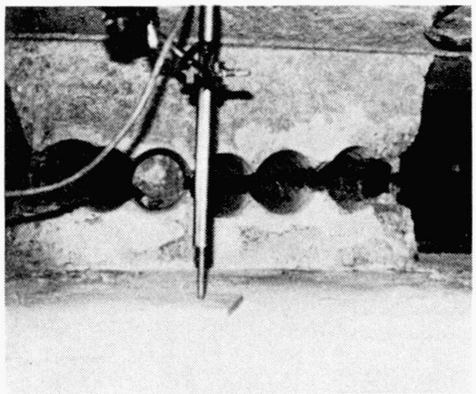


Fig. 48

4.2.1.3.2 Rather than large diameter piles, often in strengthening and repair works use in made of micropiles (fig. 49a), which were patented in Italy (1952) with the name of "pali radice" (root piles). They have 12 to 20 cm diameter, are reinforced with a steel bar or a suitably holed pipe and realize a sort of injection in the soil. Cement mortar, injected at heavy pressure, penetrates into the soil and the more it expands the weakest are the layers. The root pile can be easily connected with the structure (see fig. 49) by piercing a segment of it, whence its name.

Due to their flexibility and ductility they are particularly suited for seismic areas, where they can be strongly reinforced.

Micropiles may be loaded by means of jacks, too, but this is less necessary than for large piles, since they mainly resist by lateral friction, thus require less settlement before offering consistent reaction.

A type having an expanded base (see fig. 50) may be used when the bearing capacity has to rely mainly on deep layers.

Micropiles can be easily connected to reinforced concrete structures. In fig. 51, some structures for strengthening footings and foundation girders are pictured.

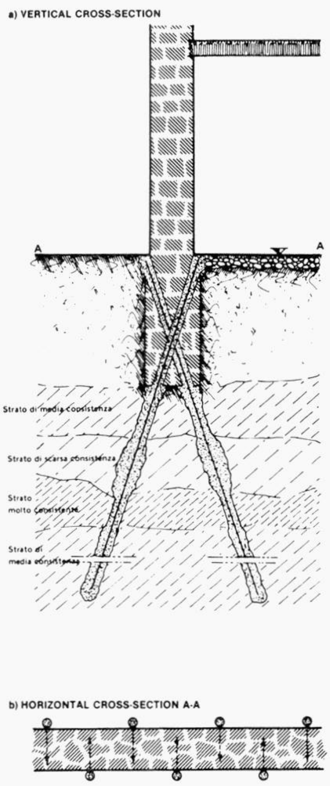


Fig. 49

4.2.1.3.3 Fig. 52 shows one of the first applications in a strengthening work i.e. for a town door of York (Boothern Bar), that had visibly settled due to traffic vibration.

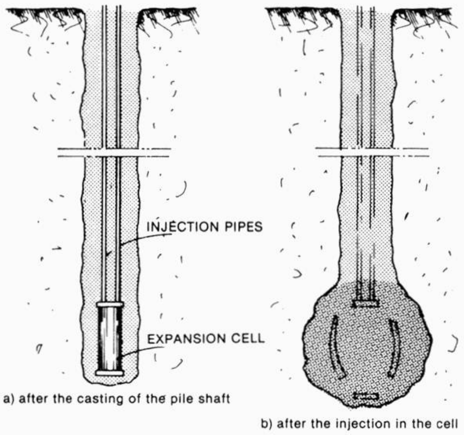


Fig. 50

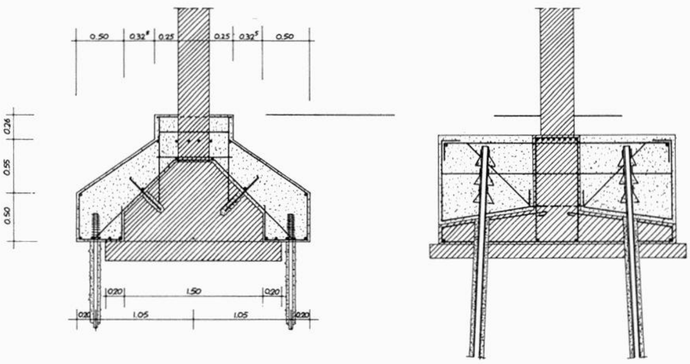


Fig. 51

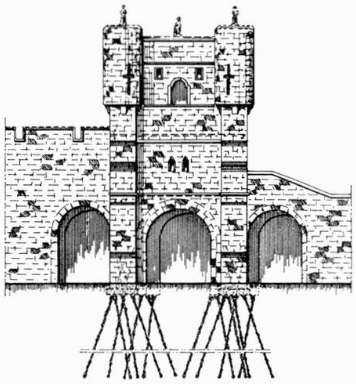


Fig. 52

4.2.1.3.4 Fig. 53 a) depicts the subfoundating whith root piles of the bell-tower in the Isle of Burano, and (fig. 53b) an interpretation of the equilibrium of the whole tower-soil mass after the operation.

The tilting stability is improved by the weight of the soil connected to the piles, which lowers position of the overall centroid (fig. 50b).

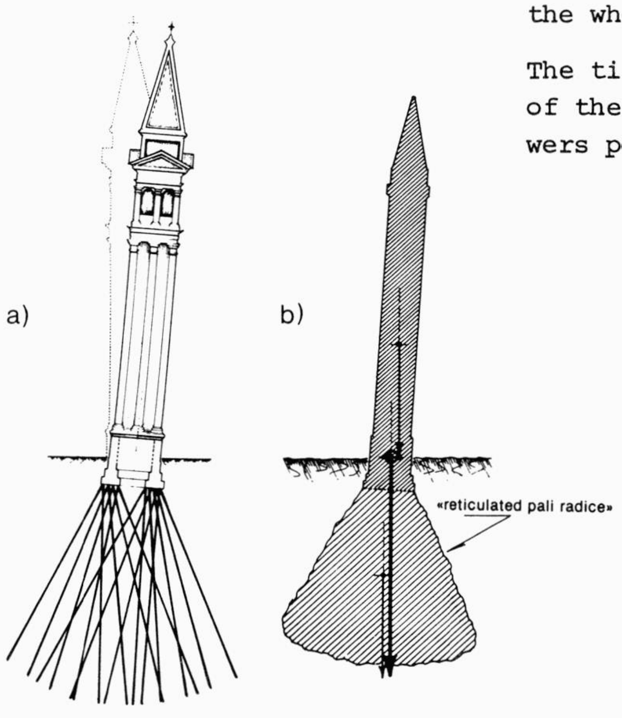


Fig. 53

4.2.1.3.5 Another type of pile having the advantage of easy connection to existing structures, is the one shown in fig. 54 ("Mega" pile) made of precast concrete or steel segments.

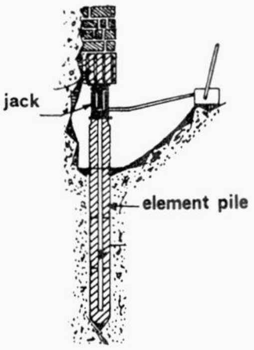


Fig. 54

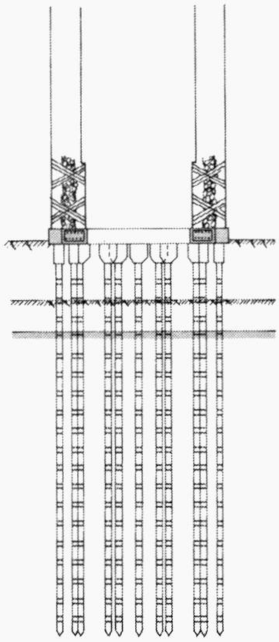


Fig. 55

The jack driving the pile, this being progressively assembled in situ, counteracts on the structure itself.

Thus, the initial settlement is automatically compensated when the upper pile segment is fixed under pressure to the structure.

Fig. 55 shows the sub-foundation of the bell tower Concordia Sagittaria in Venice, where that type of pile has been extensively used.

4.2.1.3.6 Frequent interventions have been done in order to tilt up monuments or buildings having undergone a rigid rotation without damage for the structure.

As above seen, sometimes it has been tried to stabilize the situation at a limited angular distorsion. Thus, in the competition for the stabilization of the Tower of Pisa, participants proposed various solutions, using micropiles or large diameter piles, often after freezing the soil.

4.2.1.3.7 A remarkable case of tilting up a six-buildings complex has been faced in Rome. The buildings were originally founded on piles not long enough. After the completion, and earth embankment was erected beside, and the buildings

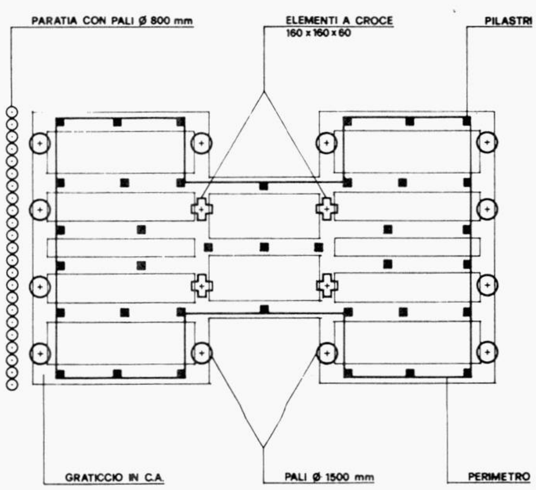


Fig. 56

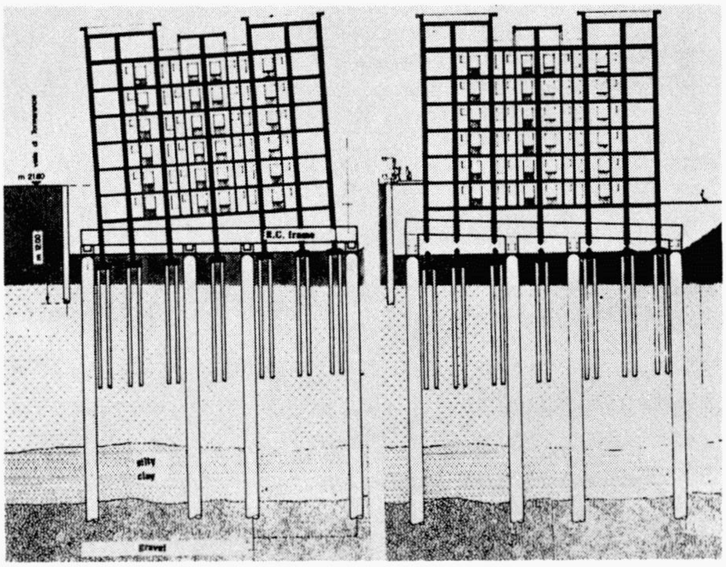


Fig. 57

tilted as much to become unpracticable. Instead of demolishing them, a tilting up work has been studied, that has already succeded for two of them. As shown in fig. 56-57 large diameter piles, 40 m long, were first prepared around the building, and cross sheet walls inside; then, a large horizontal frame was grouted, connected to all the columns. Then the new piles were loaded by jacks counteracting on the frame, and the columns were cut below it. Thus freed from the old foundation, the building has been tilted up by means of the same jacks and, finally, the frame has been fixed in the corrected position.

4.2.1.3.8 Among the cases of stabilization and partial tilting up by simple means, the one of the Lubeck Cathedral must be cited (fig. 58): after the strengthening of the masonry edge, a local pressure has been applied, counteracting on ad hoc piles.

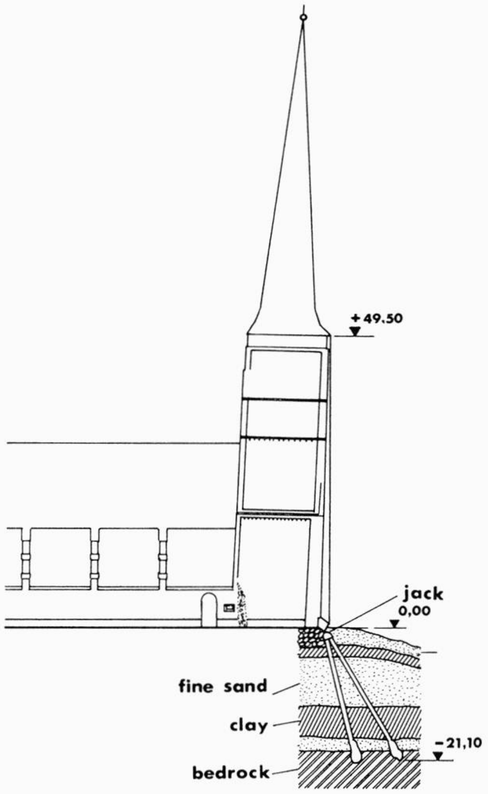


Fig. 58

4.2.2 Indirect interventions

4.2.2.1 The stabilization of buildings under slow movement for soil settlements may be obtained by directly acting on the soil, without modifying the foundation structure, i.e., by creating artificial subsidences.

4.2.2.1.1 Various cases are given of tilting up buildings by loading the ground uphill the inclination. For example, a sensible tilting was possible of a U-shaped building by filling up with earth the enclosed courtyard.

Taking advantage of modern technology, the loading may be obtained by means of prestressing ties, anchored in the deep bed-rock on one end, and in large concrete slabs on the surface, as in fig. 59; naturally, water drains facilitate the consolidation of the soil.

In accordance with the same principles even though in different form, are some proposals for stopping the rotation of the Tower of Pisa, which shows presently a top deviation of 6.8 m, increasing by 1 mm per year.

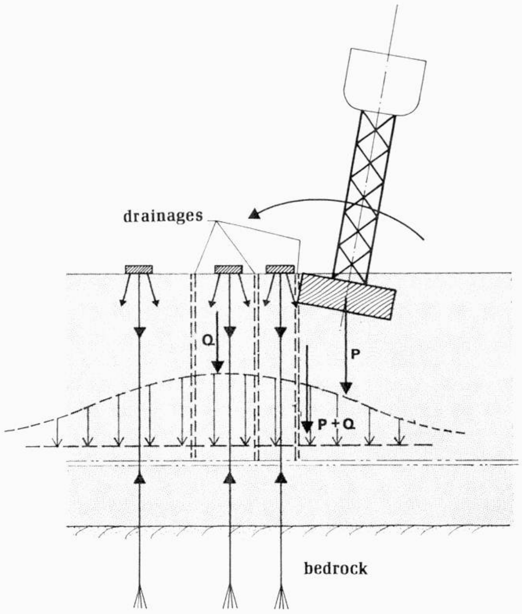


Fig. 59

The proposal depicted in fig. 60 plans the setting of a plate uphill the inclination, with prestressing ties anchored in the consolidated sand at the depth of 50 m, complemented with some drains. The ties permit to control the pressure on soil, thus the degree of tilting up of the tower.

One typical case is a building in Pescara which underwent a 2% inclination. The foundation was a mat-type one, resisting on a silty-clay soil with high water content, whose SPT was as low as N = 5.

First, some 20 m deep drains were drilled through the mat (fig. 61) then this has been loaded with

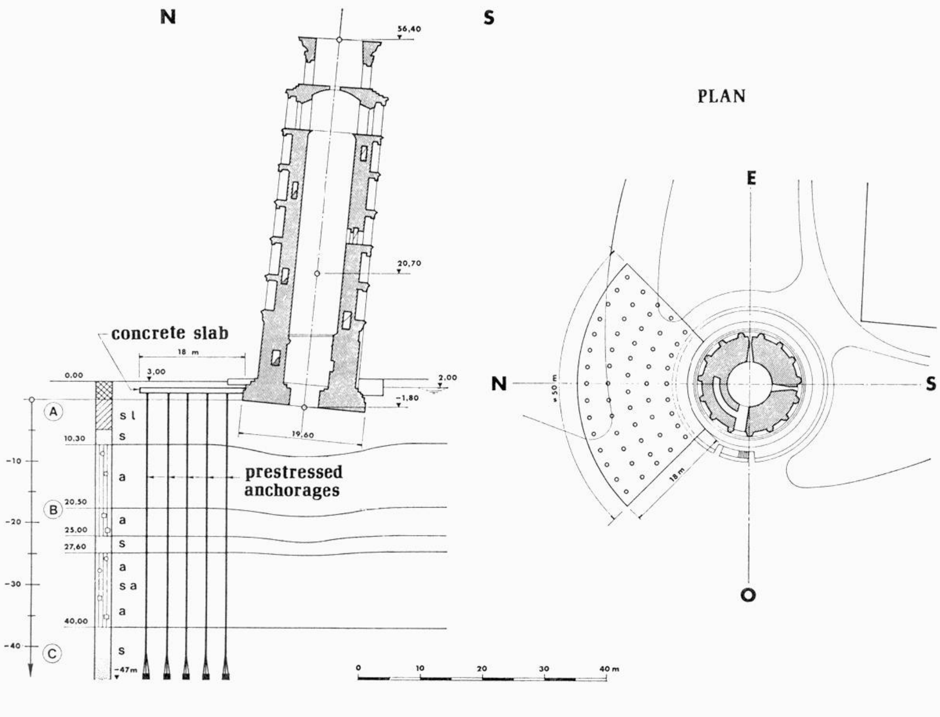


Fig. 60

bulk sand laid in non uniform depth, in order to favour the tilting up. This has been gradually obtained during the operation, as it appears from the curves in the fig. 62. Finally, the drains have been closed.

4.2.2.1.3 Finally, among the systems for consolidating soils, mention is made of the injections with concrete mortars, is in the case in fig. 63 or with silicates, for fine-grained soils, and of systems which come even to dry up the clays by electro-osmosis. Another system, by the japanese company Konoike, consists in consolidating the soil subsequently in a series of adjacent cylinders,

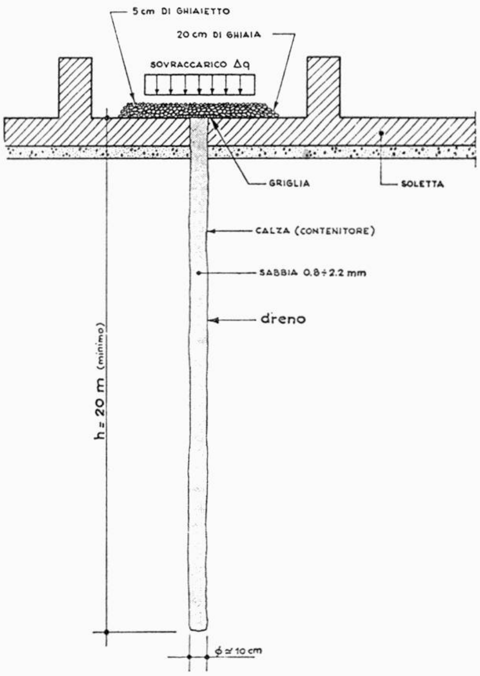


Fig. 61

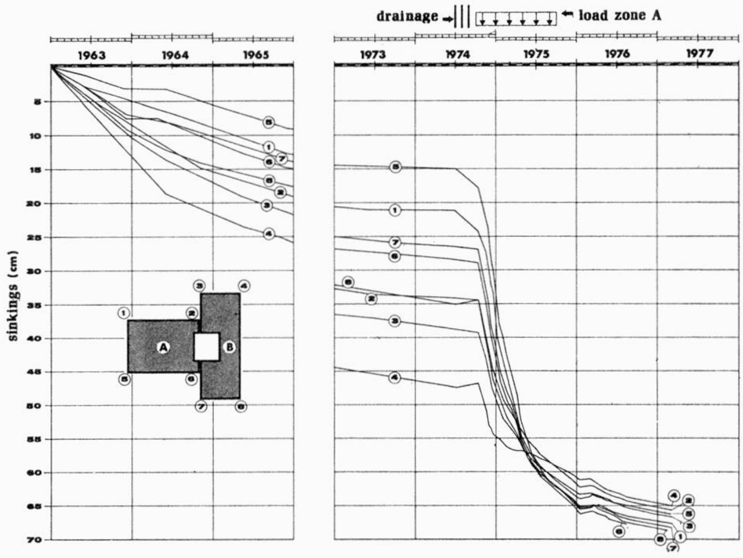


Fig. 62

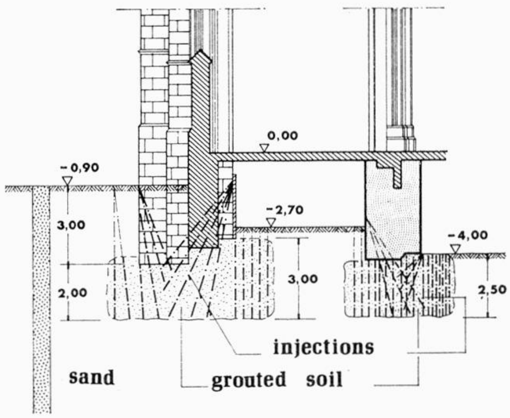


Fig. 63

where first the cohesion is destroied by means of water jets, then it is restored with resin glues, thus obtaining strengths up to 10 N/mm^2.

4.3 Interventions along slopes

4.3.1 The stability of buildings or complexes of buildings may be affected by earth slips.

In most cases it is possible to intervene with drains that lower the water table, since water is the main cooperator of gravity in provoking fast or slow movements.

By means of suitably distributed drains, it was made possible to stop slippings that had produced damages to buildings over long periods. Particularly, large urban areas in Assisi and in Ancona were stabilized with drains.

4.3.2 In stabilizing slopes, drains can be effectively complemented with retaining structures relying on rock anchors. Fig. 64 shows a barrier that became

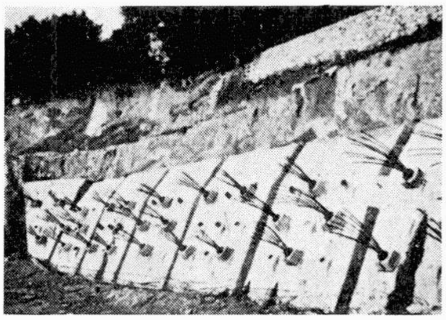


Fig. 64

necessary after a slope of sandy soils started slipping, due to the excavation of a large area, where an important building complex was to be located, near Montecarlo. The barrier is made of heavy concrete plates, tied to rock anchors of the capacity of 1200 KN each.

Fig. 65 shows a sheet wall of piles made for stopping earth slide phenomena threatening the stability of a building complex. Atop every couple of piles, a tie is placed, anchored at depth of 20 m.

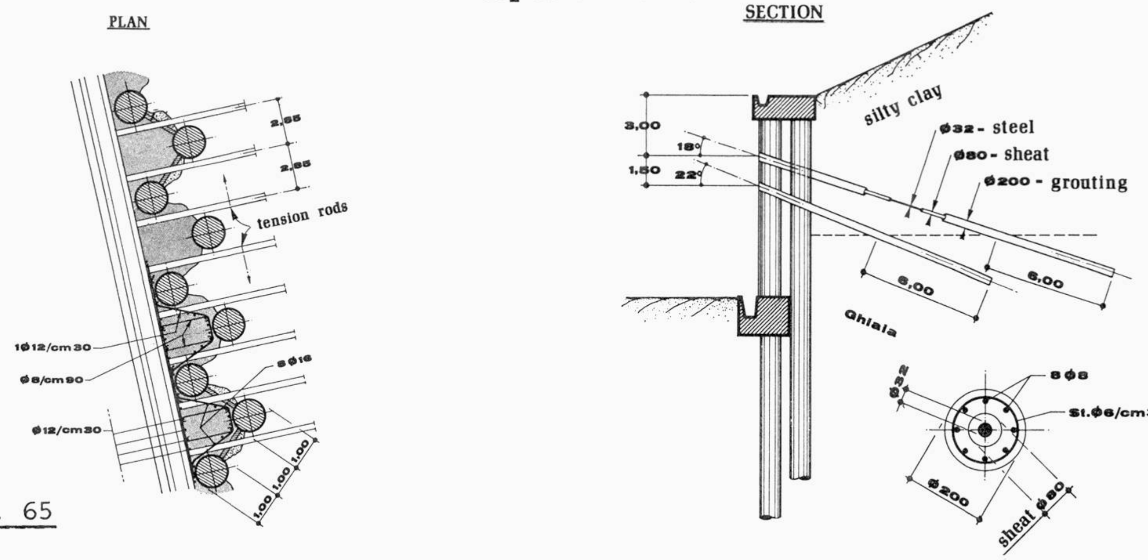


Fig. 65

4.3.3 Anchors are employed even for consolidating entire rocks, as for instance the town of Orvieto, represented in the ancient print in fig. 66, which is located on a rocky cliff, like many towns in Italy. Given the presence of buildings on the edge, their conservation requires the prevention of further spalling and sliding of cliffs, whose degradation is due to both natural and human action.

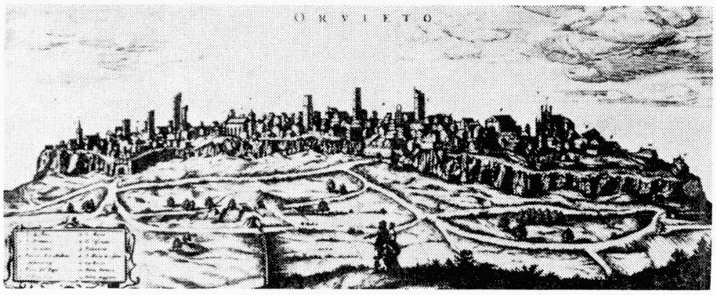
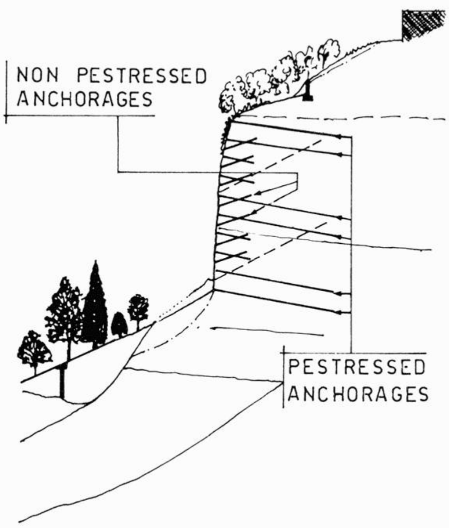


Fig. 66

Presently the most endangered areas are being consolidated with rock anchors. As it is shown in fig. 67a, short ties acting as nails are patterned as to consolidate the crust; among these, some long ties are driven up to the sound rock; the latter are only partially tensioned, i.e., not at the actual permissible steel stress, but in accordance with the long term capacity of the anchoring tuff rock.

In several areas, where slides of loose rock occurred, retaining walls as in fig. 67 b have been erected, also tied with rock anchors.

4.3.4 Fig. 68 shows the similar case of consolidation of Portovenere, where, instead of using rock anchors, the intervention has been performed whith micro-



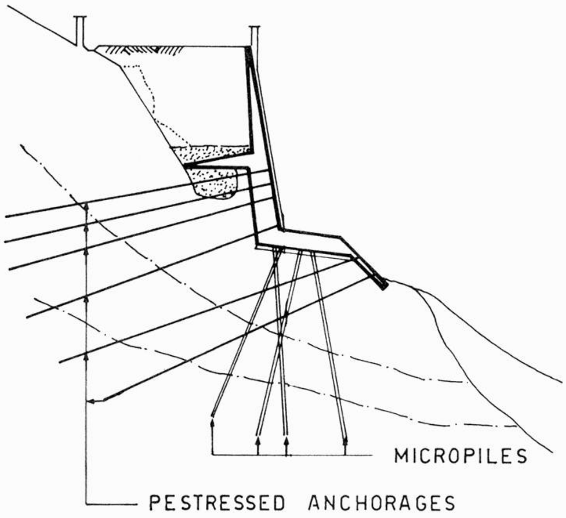


Fig. 67

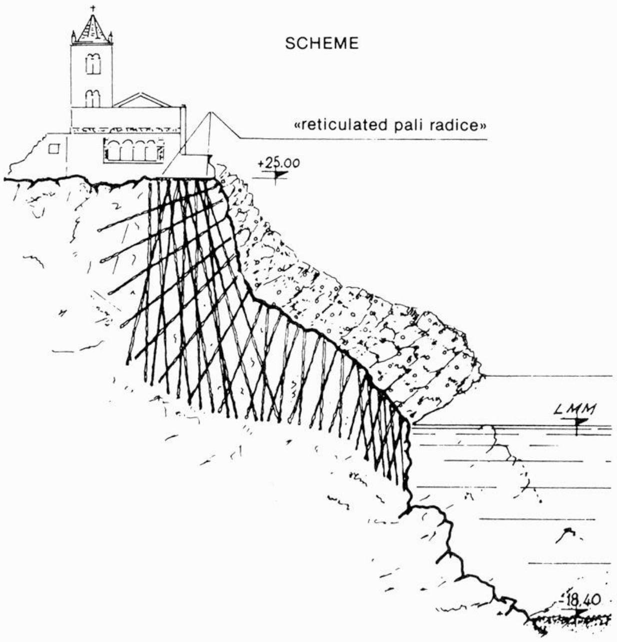


Fig. 68

piles, forming a truss which makes a sort of reinforced earth crust, as a permanent stabilizator of the rock.

4.4 Protection from vibration

Another problem of foundations protection concerns vibrations, that can derive from road and rail traffic (especially of metropolitan railway nets), or frc other sources, as for instance machineries of industrial plants.

Mainly historical buildings suffer processes of degradation due to the dynamic actions from the soil.

A noticeable example of intervention is given by the protection realized for the Farnesina Palace in Rome, by means of a special road foundation on the adjacent river bank, able to cut traffic vibrations: underneath the road pavement two grids of prestressed concrete beams have been cast, with a layer containing dam-

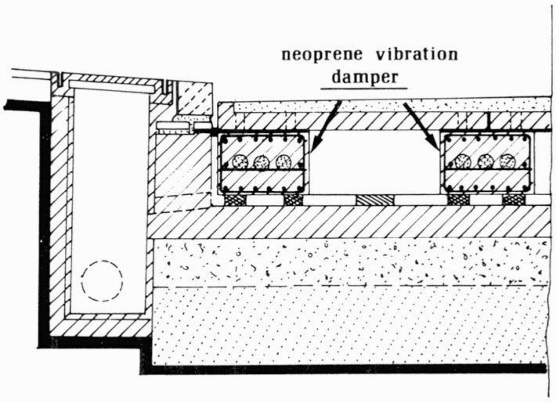


Fig. 69

ping neoprene elements in between (fig.69).

Another isolation system consists in lengthening the wave path enough to obtain the required damping.This can be done by digging trenches in the ground (fig.70). In fact hollow trenches are the best solution, but, considering some side - difficulties, among which the presence of water - which is a very good wave conductor - often sheet walls of damping material are preferred.

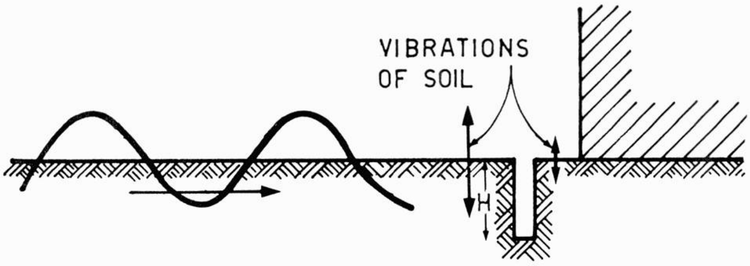


Fig. 70

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