Strengthening of monuments under the effect of static loads, soil settlements and seismic actions – Examples

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1 GENERAL

Damage may be produced by increasing actions (forces, deformations, accelerations, etc.) change in the structural behaviour (removal of a wall or an arch, addition of a floor, etc.), reduction of the stregnth (decay of the material characteristics, etc.).

In this paper the problems related to the different kind of actions, which can be divided in three categories, will be discussed:

a) Mechanical actions. These are static and dynamic and their increase usually leads to increased stresses.

a.1) Static actions; these are of two kinds:

a.1.1) Direct actions (applied forces). These are always present and consist of applied loads, such as dead loads (dead weight, permanent loads) and live loads (furniture, people, etc.); these actions can be increased by a number of factors, including extension of the building, changes in the use of a structure, etc.

a.1.2) Indirect actions (imposed deformations). These are related to deformation or strain imposed on structures, such as soil settlement, thermal variations, viscosity or shrinkage of materials, etc.

These actions produce forces only when the deformations are contained or not free to develop; to avoid or reduce the generation of such forces, joints should be created to allow certain movement (as for example the thermal joints in bridges, etc.).

The most important of all indirect actions is soil settlement, which may even start to create new and significant stresses as soon as a construction is complete. Temperature is also an important factor in the creation of stresses and, consequently, cracks; the gradient between outer surfaces and the internal body can particularly produce superficial cracks that will accelerate decay.

a.2) Dynamic actions. The main result of these actions (earthquakes, wind, vibrating machinery, explosions, etc.) is an acceleration applied to the structure.

The intensity of the forces produced is related not only to the intensity of the acceleration, but also to the natural frequencies and the capacity of the structure to dissipate energy. The most significant dynamic action is usually caused by earthquakes.

Dynamic actions were rarely correctly taken into account in the original design of ancient buildings so that they often represent unexpected phenomena.

The remedial actions must be determined only after having identified the causes of damage and in particular the kind of actions that have produced it.

2 DAMAGE PRODUCED BY STATIC LOADS (DIRECT STATIC ACTIONS)

This is the most common situation and in general we can act following one or all of the following lines:
- strengthening of the material (injections of the masonry, etc.);
- stengthening of the main elements which a building is made of: stirrups to contain lateral expansion in pillars and walls; chanins or abutments to ensure the thrust in arches nd vaults; etc.;
- strengthening of the buildings as a whole.

Occasionally it can be more effective to improve the general overall structural behaviour of a building, as a whole, rather than deal with each single structural element of the building, reducing, for example the span of a floor or of an arcade by creating new supporting walls, etc.; this approach is usually followed when dealing with the actions that globally affect the structure, such as soil settlements and earthquakes. Whatever the case, it is important to ensure good connections between the walls and between them and the floor structures because eccentricities of the loads and thrusts of vaults are frequent and unavoidable. These connections can usually be achieved by means of the proper anchorage of the floor structures to the walls and the use of chains, ties, etc.

3 DAMAGE PRODUCED BY SOIL SETTLEMENTS (INDIRECT STATIC ACTIONS)

3.1 Soil settlements

Soil settlements belong to the category of indirect actions, that induce movement at the boundaries, i.e. the foundations of a building. The stresses thus produced may be large and can vary in value, depending on the real stiffness characteristics of the structure.

Soil deformation is one of the major causes of damage to buildings and therefore, although it is not our intention to enter into the complicated field of “soil mechanics”, it is essential to grasp the main concepts so that a general view of the various interdisciplinary problems and of the measures to be taken can be acquired.

The characteristics of deformability of the soil often cannot only be identified by specific investigations, as soil characteristics may have improved, due to the presence of loading over a long period of time, or its behaviour may have worsened, due to a new situation such as lowering of the water table, etc. Often the monitoring of the settlements, of the structural behaviour (cracks, tilting, etc.) and of the variation of the water table, provides the most important information. Often, most of the settlement of the soil as a result of the construction of the building occurs during the period of construction; it is therefore only some alteration in the soil conditions that has induced these phenomena. Clay and silt are the two soils most frequently associated with causing damage to buildings.

Soils settlement is mainly related to:
- a flow of the soil as a result of insufficient shear strength or,
- a reduction in pore volume, as a result of subsidence, consolidation, compaction, etc., or,
- a reduction in the grain volume, resulting in creep.

Only rarely are soil settlements uniform; the cause of non-uniformity and therefore of damage to buildings, is related to the pressures applied by the foundations, irregularities of the strata and the presence of water in different porous strata.

It is important to note that even if the pressure on the foundations is uniform, the stress distribution on the soil below is not uniform; this situation is aggravated by the asymmetric plan shapes of buildings.

The non-homogeneous nature of soil behaviour is mainly due to changes in the thickness of the strata or the presence of layers or trapped pockets of material; ancient buildings were often placed partly on the ruins of older constructions. The presence of water associated with differing porous materials also increases the potential for non-uniformity of the soil.

Linear deformations (Fig. 1) at the base of foundations induce rigid displacement and rotation of the building, which globally do not create internal stresses and damage; these movements, however, can affect the proper functioning of the building in terms of its local or overall stability, as in the case of beams that are displaced from their supports, etc. When foundations rotate and cause significant tilting additional stresses in the structure are generated by the eccentricities which in turn affect the vertical loads.

It should be noted that often the soil by itself would produce non-linear settlements and that these are converted into linear settlements due simply to the stiffness of the building; in these cases the pressure on the soil is modified, high stresses can be induced in some areas and unexpected cracks or more serious damage can suddenly appear especially in the pillars that became overloaded. Slight alterations, small increases of loading or low intensity earthquakes, which by themselves couldn't induce these effects, may instead become the cause of serious problems when associated with phenomena of this kind.

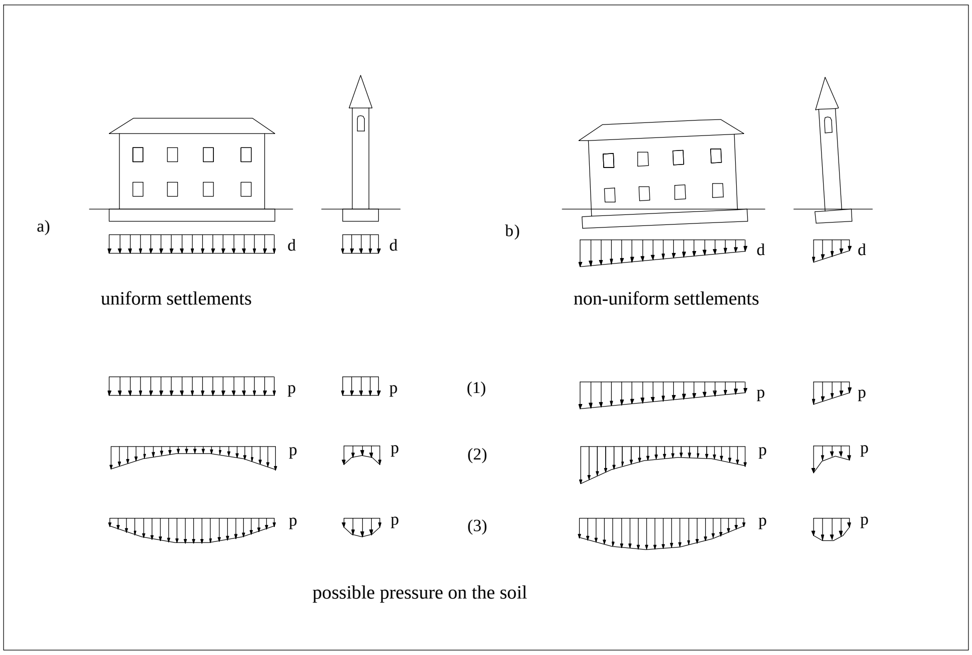

Figure 1

Minarets, towers and bell towers are structures particularly sensitive to soil settlements. Leaning effects may occur very easily because a very small original inclination it is sufficient to increase the pressures "downstream" and therefore to allow the phenomenon to develop. Significant cases can be seen in Samarkand where most of the minarets are leaning dangerously (Fig. 2).

Towers and minarets are also subjected to earlier mentioned risk due to their stiffness, the deformations of the foundations are required to be linear even if the soil characteristics tend to produce non linear settlements; the pressure on the foundations, are therefore modified possibly producing high horizontal tensile stresses or vertical microcracks. These tensile stresses greatly reduce the compression strength.

It is possible that this was the true cause of unexplained collapses, such as the bell tower of St Marco in Venice at the beginning of the 20th century; it is also possible that these changes in foundation pressures, which are totally invisible and occur before any vertical cracks are produced in the masonry were, combined with the decay of the masonry, the underlying cause of the collapse of the Chor Minar in Bukara (Figures 3 and 4).

It takes experience and a lot of careful investigation to discover situations like these in advance of any serious damage occurring.

Due to a building's own stiffness, the very first phase of soil settlement under the foundations is always linear or very close to it. It is only when the intrinsic non-linearity of the soil deformation produces significant differences in the pressure distribution at the foundation level (consequently producing stresses which the construction is unable to resist) that cracks, movement and loss of continuity may occur; following this, the overall stiffness of the structure is progressively reduced and settlement becomes non-linear (Fig. 5).

The non-linearity of settlements depends on many factors, such as the ratio between deformability of the soil and the structure, the nature of the soil, the shape of the building and the efficiency of its internal connections and its load distribution, etc.

Figure 2

Figure 3

Figure 4

Often the presence of cracks, due to non-linear soil settlements, especially in masonry walls, which by their nature are very hyperstatic and of low tensile strength, are not dangerous because usually the structure has the capacity to adapt itself with new "independent column bearing capacities", "arch effects", etc. In other cases, however, typical of the tower mentioned above, these phenomena may considerably reduce the overall strength.

In a wall the crack pattern can indicate the two main types of behaviour that soil settlements induce: the "flexural" and the "shear" behaviour which depend on the ratio between height and length, the boundary conditions and the positions of the openings (doors, windows), etc.; usually the flexural behaviour (Fig. 5b) happens when the settlements are greater at the ends of the building, while the shear behaviour (Fig. 5a) occurs the other way around, with the greatest settlement at the centre: this is because with the greater thickness of the wall at its base, the friction between the foundations and the soil and, in some cases, the lateral thrust due to the embedding or trapping effect of the foundations, the tensile strength at the base increases, thereby also increasing the global flexural resisting capacity.

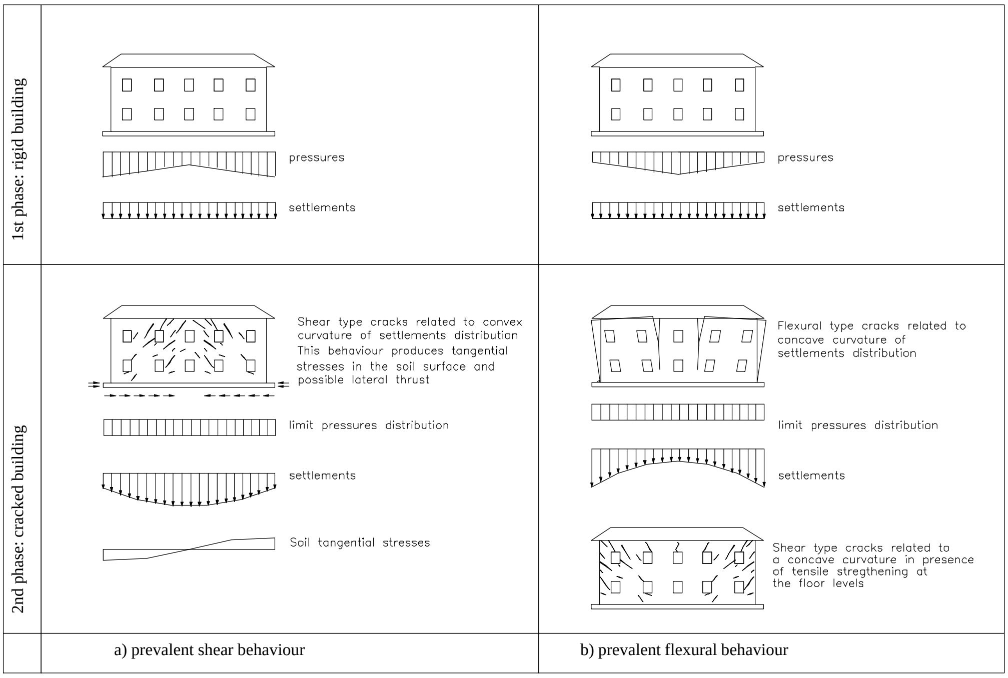

Figure 5

Another consequence of soil settlements is the horizontal movement that can occur at the upper storeys or levels, as a result of cracks in walls, movement of the joints in the walls and tilting of the foundations due to uneven soil pressure, etc.

Outward movement is much more dangerous than an inward one: in floors or roofs, beams can slip out supports; in arches and vaults the supporting thrust is reduced, tie chains may be broken and increased flexing effects associated with a loss of curvature are produced, which is potentially disastrous. The effect of cracks in the arches, however, providing the movement in the springers is small, only creates "hinges", which produce a new structural behaviour, closer to the isostatic one, where the thrust is then stabilised at a level similar to the original one; larger movement can cause the breakage of restraining chains if present.

In dry block arches it is the shear strength between the joints that can easily be exceeded, leading finally to loss of equilibrium and geometry (Fig. 6). In corbelled arches outward rotations of the base (Fig. 7) can create situations so severe that collapse often ensues. Inward rotations increase the thrust till sliding between the blocks occurs but the consequences are not usually so severe and new equilibrium conditions can usually be achieved.

The outward rotation of the columns supporting the drum and the dome (Fig. 8) was one of the causes of the cracks to the dome of the Basilica of St Charles in Rome which required correction.

In the Pantheon, whose dome is directly supported by the walls of the "Rotunda", ancient soil settlements induced tensile horizontal stresses in the walls and the lower zone of the dome, creating cracks in the dome itself and in the structures below (Fig. 9); the need to strengthen some of the architraves was the result of this phenomenon.

Figure 6

Figure 7

Soil settlements may also produce horizontal movements on flights of stairs, adversely affecting the bearing capacity provided by the development of ‘arch effects’, cracks over lintels, reducing the “arch effect” , and thus increasing the area of loading on the lintel itself, detachment of rigid facings such as marble from the walls, etc.

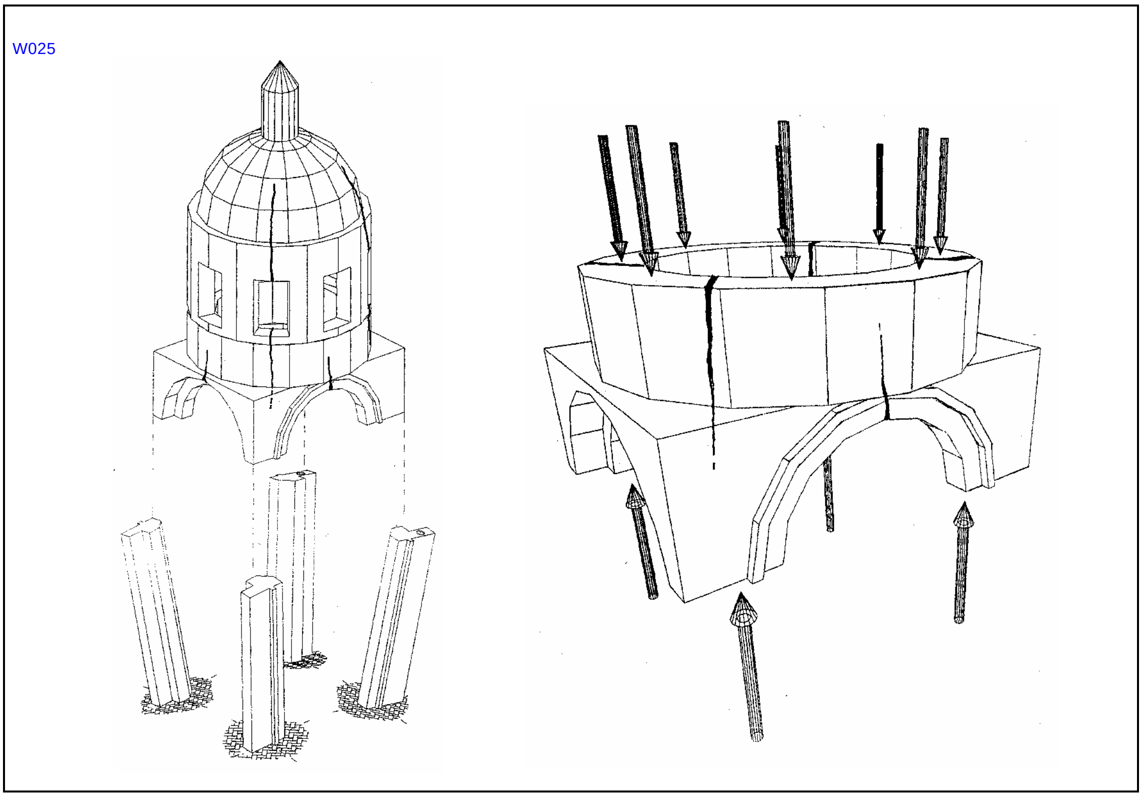

Figure 8

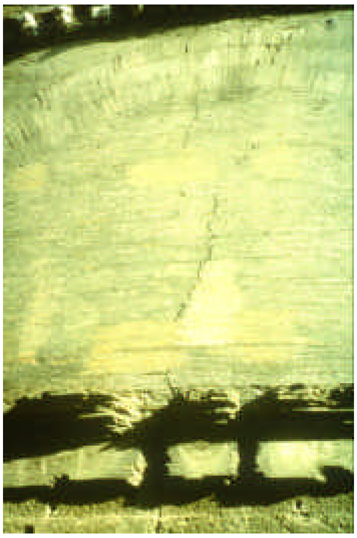

Figure 9

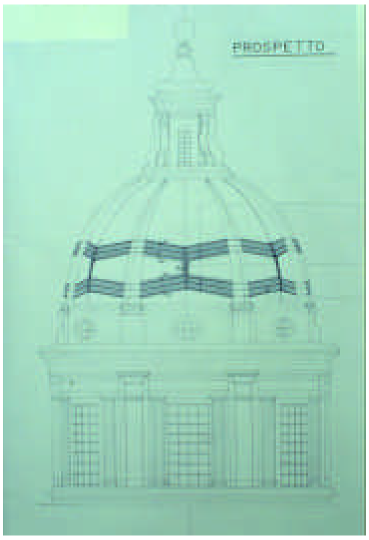

Figure 10

3.2 Damage to buildings

Damage to buildings can be produced by two very different situations:
a) Movement which has stabilised. Here, it is only necessary to repair the structure according to the general criteria laid out in paragraph 2. A situation of this kind occurred in the dome of St Charles in Rome where the settlement has now stabilised but the bearing capacity of the dome was reduced by the cracks so that reinforcement measures had to be taken (Fig. 10). It must be remembered that when permanent movement has taken place, even if no cracks or damage are produced, the induced tension stresses can reduce the bearing capacity of the structural elements; this can be particularly dangerous in seismic zones.
b) Current movement. This type of situation is very difficult to deal with and requires the utmost attention to detail. This type of problem does not usually occur in new buildings which are usually specifically designed to avoid settlement by the correct choice of foundations, etc.

The first step of any project is to organise *in situ* and laboratory research programmes to assess the mechanical properties of the materials in terms of strength and deformation parameters, the water conditions of the soil and any periodic variations, playing attention to the change of the water table which is usually the main cause of settlement.

A monitoring program of measurement of settlement, tilting of the structures, variation of the cracks and variation of the water table can also prove useful in providing an overall picture where investigation and mathematical models cannot provide reliable evaluations; in these cases it is useful if the monitoring system can acquire data before work starts and monitor the progress during the course of the work.

If it appears remedial action is required but not all the data and phenomena are yet fully understood, it may be useful to follow what is called the 'observational method' which consists of organising the work on a step-by-step basis, having initially carried out the most urgently-needed repairs, then monitoring the situation to see if further work is required and to provide guidance on the most suitable solutions. This method has the advantage of doing the least in the way of repairs yet achieving the required result.

3.3 Remedial measures

The strategy for remedial action on buildings, makes reference to Fig. 11, and can be divided into three main groups as follows:
- Actions to improve the soil's behaviour.
- Actions to modify the pressures under the foundations.
- Actions to improve the building's behaviour.

a) The remedial actions aimed at improving the soil conditions include:
- Improving the soil characteristics and in particular reducing the deformability.

- Regulation of site water conditions.
- Increasing the soil deformability in the zones under the foundations where settlements are smaller than in the others in order to reduce differential movements; what counts actually are relative settlements. A solution of this kind has been adopted for the tower of Pisa, as we'll see below.
- Protection and auxiliary works.

b) Modification of the pressure to the soil under foundations can be achieved following three main criteria which can often be carried out jointly:

- modification of the loads;
- enlargement of the actual foundation;
- transfer of the load to deeper strata (underpinning).

  Reduction of the loads acting on the soils can be simply achieved using procedures such as lightening of the construction by the demolition of floors, the removal of heavy walls and their substitution with lighter structures in steel or concrete, or the removal of soil internally and externally along sections of the perimeter walls and replacing it with lighter materials.

  Where different settlements and particularly tilting phenomena have occurred, it is possible to stabilise or even reverse these changes by altering the load distribution so as to increase pressures in some zones and reduce in others.

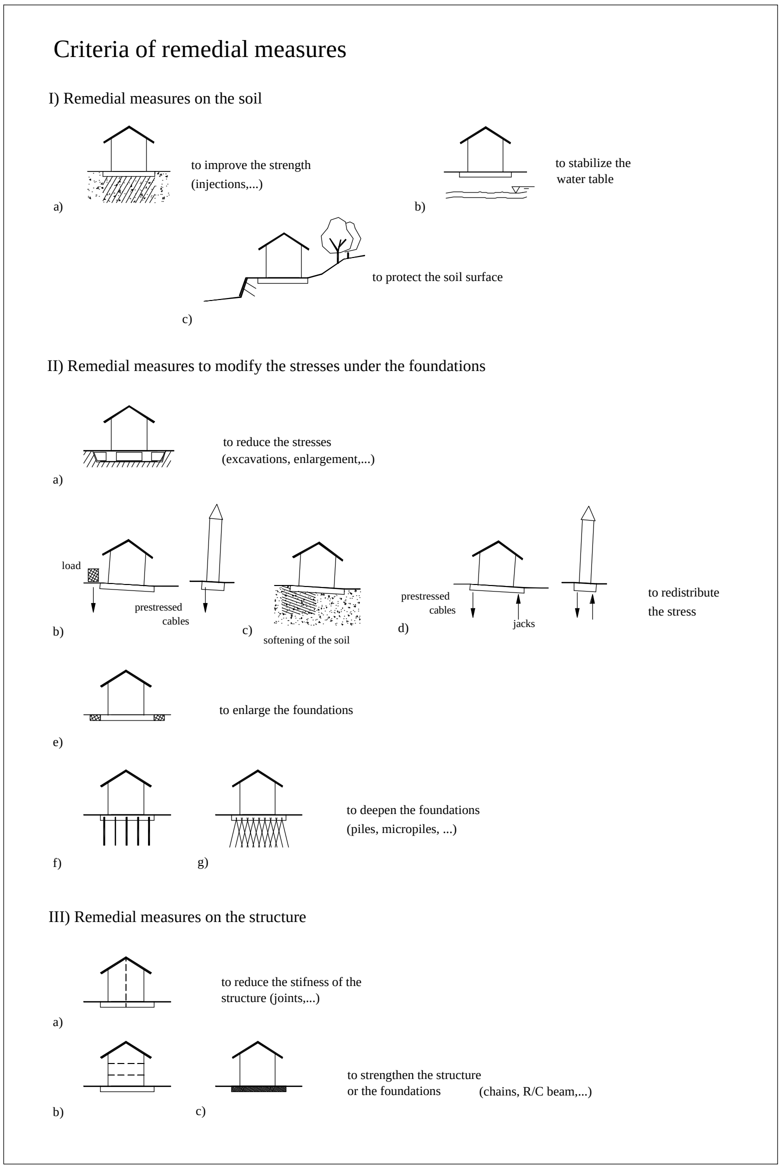

Figure 11

The measures on the 'upstream zone' can be achieved by applying new loads.

Figure 12

In some cases what is really necessary is not to substantially change the global load, but to increase and reduce the loads, and then the pressures, in different areas of the soil in order to reduce the differential settlements. A current technique is the use of a hydraulic jack acting against piles or new foundations provinding an upward reaction. To stop the increasing settlements at the Tilla Kari Mosque in Samarkand, where deformations have also created large cracks in the structures (Fig. 12) it is proposed to combine the effects of jacks on the side of the major settlements with an enlargement of the foundations (Fig. 13). In addition to eliminate the high stresses produced in the connections between the heavy central dome and the two lateral wings, as clearly shown by a mathematical model (Fig. 14), two joints are proposed to separate these zones (Fig. 15).

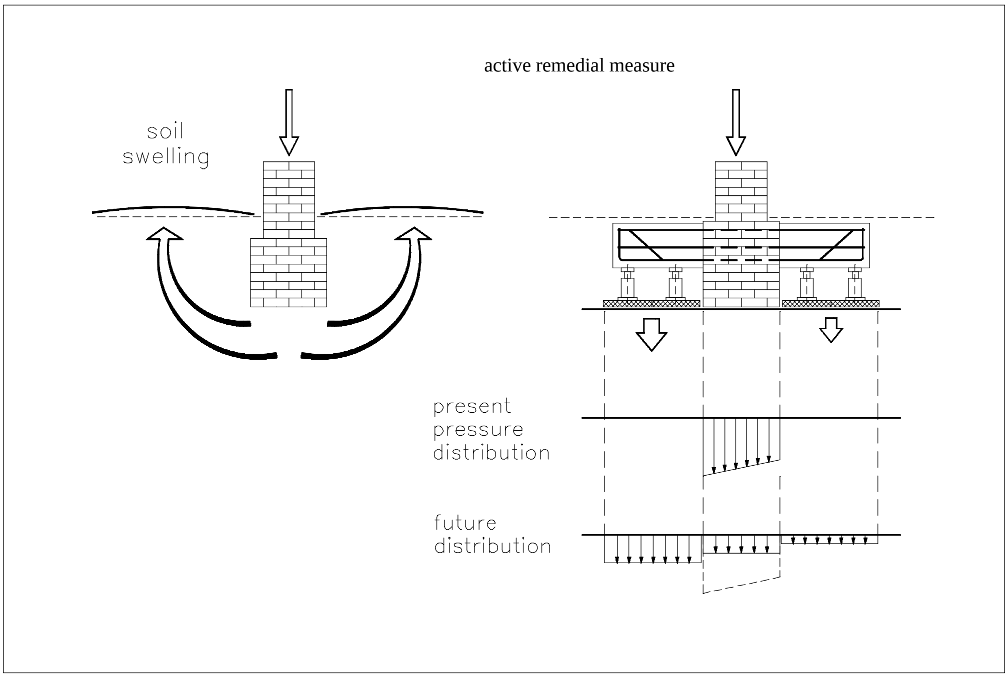

Figure 13

In general 'upstream' actions are sufficient when the structure behaves as a rigid body, like a tower or a minaret, whilst in more articulated structures it is usually necessary to act on both upstream and downstream sides.
Hydraulic jacks and other mechanical systems are very useful tools in regulating the forces transmitted between the ancient building and new foundation structures.

Reduction of the pressure can be achieved by widening the foundation base in order to obtain the redistribution of loads over larger surfaces (Fig. 5.28 IId).

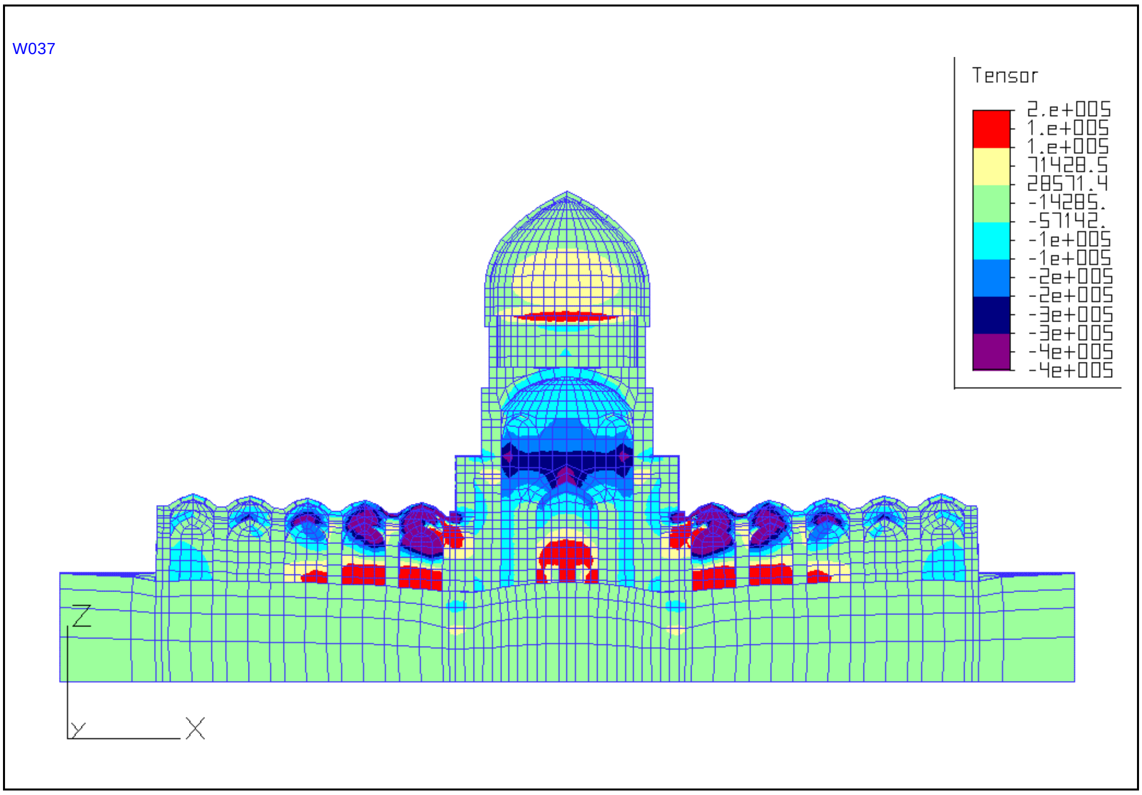

Figure 14

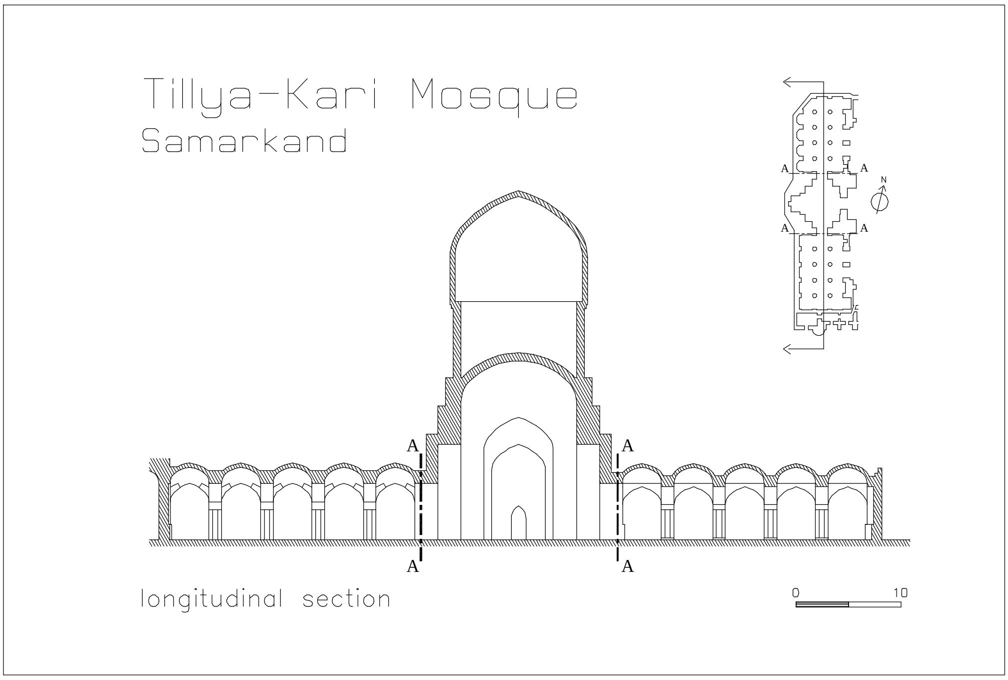

Figure 15

In order to obtain maximum benefit from this type of procedure, it is important to check the stratigraphy of soil and in particular for the presence of large compressible strata under the building. In fact this solution is not very effective where settlement is caused by the high compressibility of deep stratum; wider foundations (created by connecting a new raft to an ancient plinth or wall, etc.) do not significantly modify the intensity and the overall arrangement of the pressure pattern in the deep strata, which are the real culprits responsible for the settlement of the construction.

The action of enlarging the foundations is more effective when widening the raft beyond the external edge of the construction as the pressure bulb will also be spread over a larger area of the soil, thus reducing stresses and settlements in the deeper stratum.

Transferring loads to the deeper and more resistant strata of the soil by means of underpinning can represent the only reliable solution when it is not possible to stop the settlement in any other way. Underpinning ancient buildings must always be considered as a last ditch solution. This solution, when adopted for shallow foundations, can give problems during the boring phase, as softening of the soil can occur during the course of the works, as some parts are underpinned whilst others are still on deformable soil.

If settlement in large buildings is only concentrated in certain zones, it could be dangerous to limit the underpinning only to that zone, since unfavourable "rigid" areas may be created, increasing the difference between the settlements in the various zones, which is the real problem; in fact it must be born in mind not only the structural zones on the boundaries of large and small settlements are affected by increasing stresses, but also the zones where the settlement is less are affected by increased pressures from the foundations, causing possible crushing phenomena on pillars and walls. In these cases, a detailed study of possible differential behaviour must be made and if these are not compatible with the structural capacities then it will be necessary to extend the underpinning to the whole of the construction.

In old masonry buildings, it may often be easier to carry out the underpinning by means of small diameter short bored piles (micro-piles), as the drill equipment requires only limited space and drilling through the existing foundations is much easier.

c) Action to a modify the building's behaviour

When, from a technical or economic point of view, it proves too difficult to prevent settlement, it is possible to act on the structure so as to minimise or to annul the effects connected with the differential settlements.

There are two main but opposing strategies that can be followed:

- to reduce or to annul the stiffness in some zones or joints.
- to improve the strength and stiffness of the building.

3.4 Measures to follow settlements

This concept follows the first philosophy and is based on the creation of joints and the 'disconnection' of structural elements; one example is the proposed joints in the Tilla Kari mosque discussed above.

Generally the joints in the walls can be made using rotary saws, or special high resistance steel wires.

Sometimes, in order to avoid problems making complete cuts over all the construction, "potential" joints being partially-cut or weakened zones may be created.

The idea of creating movement joints in walls, although simple in concept, can become difficult in practice as natural cracks are never exactly vertical or horizontal, but oblique and curved, intersecting the construction in a complex way. It is only possible therefore to embark on a programme of joint cutting after extensive study of the building and its spatial arrangement, including the analysis of the stability of elements such as vaults, ceilings and stairs after the continuity has been altered.

In the Ducal Palace of Modena, (Fig. 16), the building has been cut along the lines of the main cracks so as to create new "homogeneous" independent blocks. The joints have been cut in the main walls (Fig. 17) and in the vaults with the stability of the latter being ensured by using a system of stays.

Figure 16

3.5 Strengthening to counter the settlement

This concept follows the second philosophy and is based on the strengthening of the structure, which may be achieved in the following ways:

- The formation in the basement of a series of boxes or honeycomb-type arrangements, usually in reinforced concrete, with solid or perforated walls to form a strong resistant box-construction to reinforce the building.
- The insertion of braces and ties to walls or ceilings; ties are very useful for masonry buildings when there is a tendency for front walls to move out. This type of action is particularly efficient in towers, etc., where the ratio between the height and the base magnifies the effects of any small rotations in the foundations.
- A general stiffening of the construction as a whole, using additional reinforcement, inserted, for maximum efficiency, at various levels.

4 DAMAGE PRODUCED BY SEISMIC ACTIONS (DYNAMIC ACTIONS)

4.1 Damage

Seismic actions belong to the category of dynamic actions inducing accelerations and movement in the structure. This action creates either larger or smaller forces or more precisely, stresses in the structure, dependent on the natural period or frequency of the building and its ability to dissipate part of the energy provided by the earthquake.

Seismic action is often the main cause of damage and collapse of historical buildings; the purpose of this paragraph is to lay out, in a qualitative and plain way, the basic principles and to provide a clear understanding of the most appropriate methods of strengthening and restoration.

The effect of earthquakes is often amplified by earlier structural damage and by soil settlement in particular.

Damage and collapse are progressively produced during earthquakes; the building becomes more and more disconnected and cracked as each of about a hundred shocks sequentially hit the building, although only a few are of high intensity. Fortunately this usually reduces the overall stiffness of the structure so that the natural period increases and thereby lower forces are induced; in many cases, the safety margin is therefore not reduced and is very different to that which occurs in very rigid buildings.

The earthquake's length and the number of additional shocks are important factors.

After the earthquake the building can remain affected by permanent damage which can include disconnections, cracks and out-of-plumbness, etc., which all combine to reduce the global resistance and accelerate the deterioration processes.

This permanent damage can induce collapse decades and sometimes centuries after the earthquake has happened; the significant out-of-plumbness and cracks produced in certain pillars of the Colosseum by the earthquakes that occurred throughout the centuries has been the main cause of the decay process that have caused large-scale damage and collapse.

The characteristics of the soil, as mentioned above, can produce two main effects on the structures:

- possible non-uniform amplification in all the structures and consequently increase of stress;
- differential settlement leading to supplementary stresses whose distribution, in some aspects, is similar to that induced by earthquakes and which reduce the global bearing capacity.

In addition, we want repeat that the seismic resistance can be reduced by additional stresses produced in the structure by other effects (soil settlement, etc.) even when there are no other cracks or other signs visible.

4.2 Remedial measures

Seismic actions are often the largest actions that affect a building, not only because of the intensity of the forces involved but especially because usually the structures are not designed to take account of horizontal forces.

The main structures of monuments and historic buildings are usually made of masonry; masonry also has very small tensile resistance or strength, so that this material is by far the most important to be studied. However, as concrete structures also begin to acquire a historical value, a few indicators should be given on the subject.

The criteria to be followed as preventive or remedial measures do not substantially differ each other; the latter however are easier to establish because the analysis of the damage, and particularly of the crack pattern, may provide a clear picture of what the structural behaviour was; this observation therefore represents the best starting point for a programme of repair and strengthening, although it is always necessary to bear in mind that, even in areas without apparent damage, additional stress due to permanent deformations, caused, for example, through soil settlement, may reduce the overall resistance. Remember, therefore, that remedial action may not only be required to repair defects but also to prevent damage and failures.

The decision and the choice of preventive measures or repairs must be the result of global analysis and investigation, first of all to evaluate the present safety levels and then the levels expected to be achieved as a result of the action; the mathematical analysis, especially with regard to the seismic behaviour of ancient buildings is often only partially reliable and the theoretical analysis should always be interpreted hand-in-hand with accurate site observation and practical experience.

In historic buildings, interventions are a compromise between carrying out as little work as possible, so as not to interfere with the original concept of the building and the need to ensure safety requirements; in addition, the work must be determined and carried out in accordance with a detailed analysis of the specific techniques and technologies that were originally used in the construction.

These measures, which must ensure adequate continuity and connections between all the main structural elements of walls, floors and roofs can take two routes (Fig. 16):

- to improve the structural behaviour;
- to reduce the seismic effects.

Although, from a theoretical point of view, to strengthen the structure or to dissipate seismic energy can result in equivalent safety-level improvements, from a practical point of view, very often the former route of 'improving the structural behaviour 'is not only more reliable but also easier to carry out, rather than the latter.

Attention must be paid to the stability of non-structural elements, such as entablatures, cornices, ridges, spires, etc. using, if need be, specialised connections, such as dowels, cramps, pins. etc.

a) Strengthening of structural elements

In masonry structures repairs follow the general criteria described above; bearing capacity of pillars and walls in particular can be increased by stirrups to contain the lateral expansion.
Walls are the elements which play the principle role. Repairs, if damage is present, can be based on the type of physical damage distribution present and by the crack pattern. A preliminary analysis of the walls can be useful to identify whether 'flexural' or 'shear' behaviour is the weaker one or they may even be both equally present.

The repairs should concentrate on the following aspects (Fig. 17):

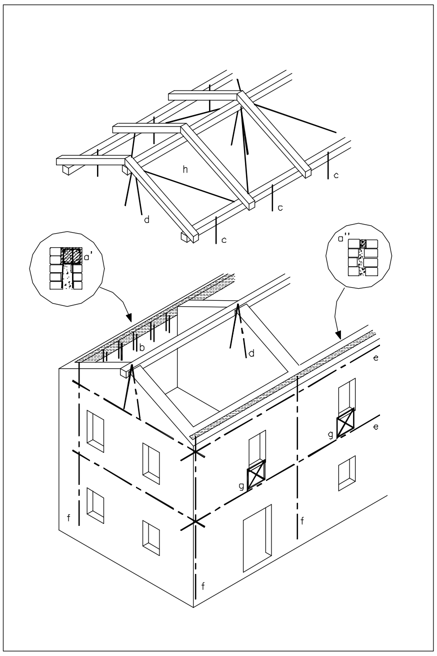

Figure 17

- to assure the soundness of the wall materials using injections, etc., and then eliminating, if necessary, any weakness that has been created by holes for equipment, etc., in the building as a whole.
  The wall areas under floor timber beam supports, being potential points of weakness, must be carefully checked and consolidated; in this regard, small stone corbels as bearing to the floors are preferable as they do not affect the soundness of the wall;
- the "flexural" behaviour of the walls is characterised by cracks mainly concentrated under and over the windows (Fig 18); the wall behaviour can be improved by ensuring good horizontal connections at floor level. This can be done by using "kerbs" formed with steel or synthetic bars injected in the masonry. Concrete "kerbs" can be structurally useful but often incompatible with the historical appearance and can be difficult to insert in the building; their use must therefore be limited to situations where it is not possible to ensure safety levels in more acceptable ways; it is always better, anyway, to lose the kerbs in the thickness of the masonry. Small x-frame steel braces can be inserted in the zones under the windows, which are often weak. Vertical bars or cables, often prestressed, may be placed through drilled holes ideally near the corners of the masonry to eliminate vertical tensile stresses produced in the walls by high seismic actions.
- the "shear" behaviour of the walls is characterised by cracks mainly concentrated between the windows (Fig. 19); it is more favourable than the "flexural" behaviour and usually only occurs where the floor level connections have been reinforced.

Figure 18

Figure 19

- to improve the "shear" behaviour it is necessary to strengthen the masonry panels between the windows. This is generally a more difficult task as usually it requires major works which tend to affect the architectural value of the building. It usually involves the insertion of vertical or inclined bars or cables. In exceptional cases high strengthening may be obtained sandwiching the panel between two thin concrete slabs; this however should be regarded only as an extreme measure, to be used only when there is no other way of saving the building. Fortunately, if the masonry is of good quality, the resistance of these panels is sufficiently high by itself or if inadequate, can be improved simply by consolidating the material.
- In the "arch effect" behaviour, the weakest zones are near the corners and under the roof, where the weight may be insufficient to ensure a vertical thrust; the insertions of bars, cables or of small kerbs may be required to provide an adequate "thrust".

Arches and vaults usually require to be strengthened generally in two situations: where there is a very flat central zone of the arch or vault and where any large movements of the springers can occur. In the first case, local shear forces and bending moments may compromise the stability.
In the second case chains, ties, buttresses or similar reinforcement to stiffen the springers may be required to ensure an adequate thrust.
Besides ensuring the strength of each element it is usually necessary strengthening the building as a whole. The general policy is to ensure the proper working of all structural connections and to improve the general tensile strength in the critical zones (Fig. 17).

5 CASE HISTORY

5.1 The Leaning Tower of Pisa

The problems of the tower

The tower has suffered, since its construction (13th century), a progressively increasing tilt, getting close to the collapse, as the eccentricity of the resultant force (about 5,5 meters at the top) has reached its limit value.

Also the stresses in the structure have, therefore, largely increased, significantly reducing the safety levels.

5.1.1 Provisional safeguard measures

Provisional measures have regarded both the stability of the foundation and of the structure.
Fig. 3 gives a picture of different safeguard systems. The first (20a), which can be realized both imposing deformations through vertical anchorages or applying forces through some weights, is the simplest but also the least effective, not producing any benefit on the structure and inducing further compression on the soil.

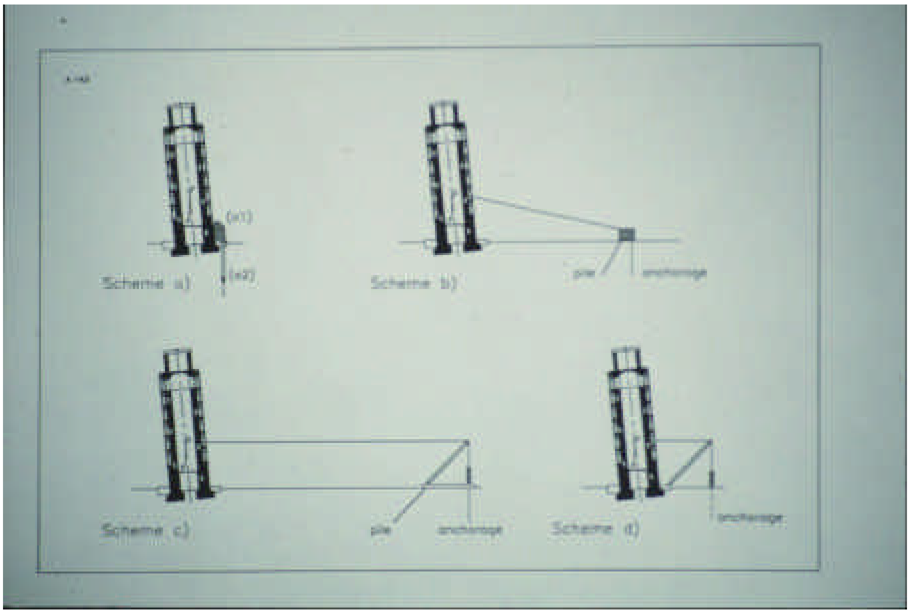

Figure 20

In 1993, anyway, about 600 tons of lead blocks (afterwards increased till about 900 t) where applied on a provisional reinforced concrete ring realized over the foundation (Fig. 21), creating a first even if small recover of the tilting.

This intervention was been associated with a provisional strengthening of the structure through a series of external circumferential prestressed cables.

In 1998 it has been decided to adopt some further more efficient measures to implement the safety margins during the final works of consolidation.

Between the three possibilities shown in Figures 20b, c, d, it has been decided to chose the solution d (Figures 22), where the anchorages are not visible from the area of the tower; personally, however, I would have preferred the solution (20c) with two struts, much more efficient, inducing pure bending moments without any shear force on the soil at the b
asis of the tower.

Figure 21

5.1.2 The final measures

The stabilization of the foundation

The stabilization of the foundation is obtained through a new technique, called "underexcavation".

This technique consists on pulling out, about 5 meters under the upstream border of the foundation, little bits of soils,through a series of casings drilled into the soil (Fig. 23). This operation causes little cavities which progressively close due to the pressure, producing then little artificial settlements and a tilt on the opposite side respect the present one.

The evolution of the tilt from the time of the construction is represented in Fig. 24a, whilst Fig. 24b, in a different scale, shows the recover obtained when the lead blocks were applied (1993) and then the positive answer to the first phase of the undeexcavation (beginning 1999).

The underexcavation is expected to recover about 10% of the present inclination, going therefore back at the situation of the tower in the middle of the 17th century; we think the newly acquired safety levels will eliminate the geotechnical risks for many centuries as it is very likely that, if further inclination is produced, its speed will be much lower than the present one.

These favourable expectations will be verified through a sophisticated monitoring system so that any final decision will only be taken at the end of the underexcavation works, presumably by the end of the year 2000.

The strength of the structure

The stresses in the structure are largely increased due to the leaning. A concentration of stresses in particular is produced at the level of the first balcony, where the structure is weakened by the passage of the staircase.

Another important aspect is related to the seismic actions which largely increase the stresses in the masonry; an important role under these actions is played by the little columns (Fig. 25a), and the cracks visible on the little architraves and the vaults of the balconies are probably related to that.

Figure 22

Figure 23

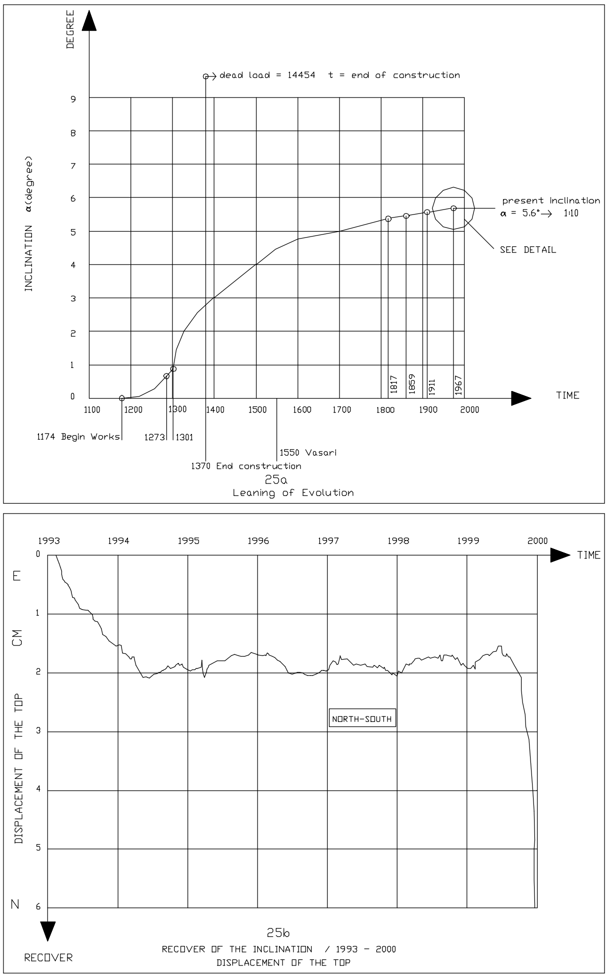

Figure 24

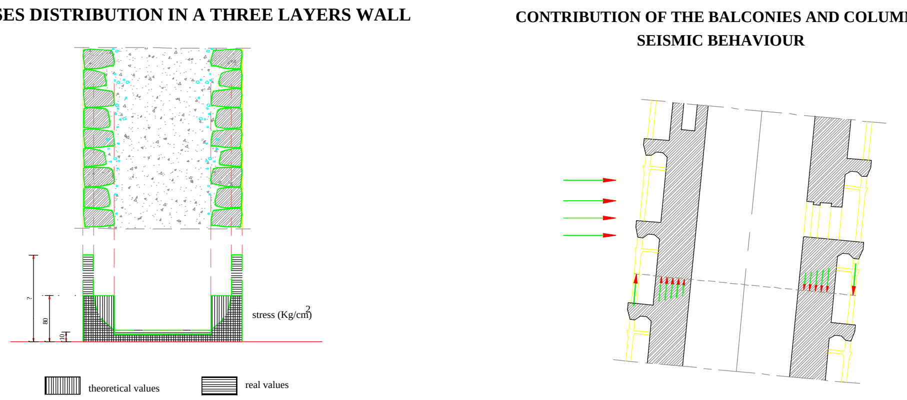

Figure 25

The strengthening measures have been decided on the basis of the various investigations (endoscopic, ultrasonic, thomographies tests, etc.) and mathematical models, taking into account the specific nature of the masonry made of two facing walls with stones of excellent quality and a concrete fill much less resistant (Fig. 25b).

The stresses on the facing walls reach about 80 Kg/cm^2 whilst in the fill their value is about 10 Kg/cm^2. It is very difficult to ascertain the actual strength of a wall of such kind starting from the strength of its elements (the stone of the facing walls (about 1000 Kg/cm^2) and of the fill (between 40 and 70 Kg/cm^2) especially in relation with the detachment between the two different materials, the presence of voids and cavities, etc.

The strengthening involves only the more stressed zones and consist on grouting, (to fill the voids of the masonry), on the insertion of little transversal bars (to connect the two facing walls), on the application of a circular chainage at the level of the first and second balcony and finally on the position of radial tie bars to strengthen the little architraves.

5.1.3 Conclusions

After a very long time of studies, researches, thousands of projects, the strengthening and stabilization of the tower of Pisa is going to be successfully concluded and will soon be handed the tower over again to the joy of the tourists and of the citizen of Pisa.

5.2 The Basilica of St Francis of Assisi

5.2.1 History, damage and collapse

Many earthquakes in its history hit the Basilica of St Francis, built in the 13th century. Earthquakes stronger than that of 26 September 1997 probably occurred in 1279, 1328, 1703, 1747, 1781, 1799, 1832, 1859, 1917, 1979, and yet no one produced damage as large as that: the destruction of the vaults close to the façade, of the vaults close to the transept, of a portion of the left transept (Fig. 26) and production of large cracks and permanent deformation all over the vaults of the Basilica, letting them in a very precarious and dangerous situation.

Besides the different impact that earthquakes of different characteristics may have produced on the Basilica, other factors have increased the vulnerability respect the past.

As regards the tympanum, made of a cavity wall with two faces and an inner fill, the cause of the partial collapse (the first damage was produced the 26 September, but it was the quake of 7 October to create a large hole in the wall) was the decay of the mortar which linked the stones of the external face with the inner fill; the reduced cohesion and bond could not prevent single stone blocks to progressively detach each other and fell down.

As regards the vaults the collapse was produced by a large volume of fill, mainly broken tiles and other loose materials accumulated over centuries of roof repairs in the springer zones. Under seismic actions this fill, without any cohesion, alternatively acts only on one side, whilst on the other side the fill is detached; what is more the lose fill follows the movement of the vaults opposing their recovery and facilitating therefore increasing permanent deformations. When the quake of 26 September hit the Basilica it is very likely that permanent deformations, reducing the curvature and therefore the bearing capacity, were accumulated as consequence of the previous earthquakes.

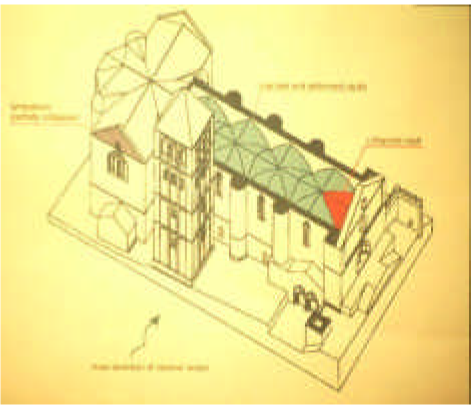

Figure 26

A general model and a global stress analysis of the Basilica has been carried ou; in para non linear model of the vaults has confirmed the decisive role of the fill (Fig. 27); when the horizontal acceleration reaches about 0,2 g, relevant tensile stresses are produced.The deformation shown by the mathematical model is perfectly in agreement with the failure mechanism of the vaults filmed by Umbria Television, resulted from the progressive loss of curvature of the ribs, then a “hinge” was produced in the middle and finally the rib collapsed drawings the vault down with it (Fig. 28).

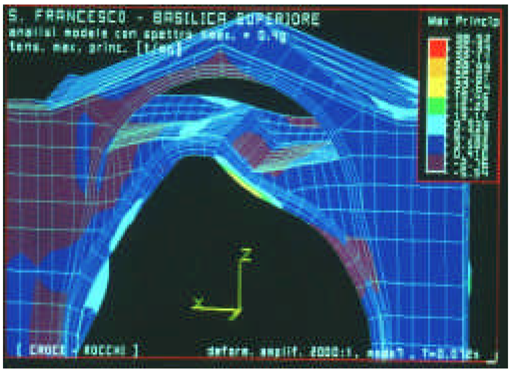

Figure 27

Figure 28

The collapses were concentrated on these specific zones because, being the direction of the seismic action mainly perpendicular to the nave axis, it behaved globally like a "beam", where a kind of restraint at the ends was provided by the stiffness of the façade and the transept. The results was that high normal and shear stresses where produced there, in addition to the "local stresses" resulting from the weight of the fill (Fig. 29).

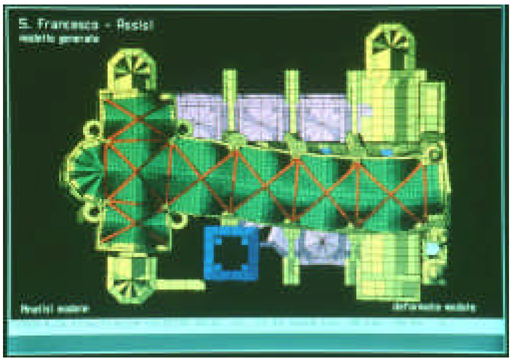

Figure 29

5.2.2 Urgent measures

Urgent measures were required immediately after the earthquake to prevent the global collapse of the tympanum and of the vaults. The survived vaults were all affected by large cracks distributed both on the intrados and the extrados (Fig. 30); curvature, as already said, was lost in several zones.

Figure 30

The danger that the standing vaults might collapse, and the consequent risk to the human life, precluded the possibility of supporting the vaults from the ground level. Instead, a platform was suspended from the roof above the vaults with the double function of inspection and of providing a base for working over the vaults (Fig. 31).

The urgent measures taken in the first month after the main earthquake can be synthesised as follows:

- removing the huge load represented by the fill in the springer zones of the vaults,
- filling cracks with a salt free mortar to limit possible damage to the frescoes, first taking the precaution of inserting a strip of polyurethane in the larger cracks to prevent the mortar from flowing out,
- applying bands of synthetic fibres over the cracks of the extrados,

- suspending the vaults from the roof with a system of tie bars, having first inserted two springs to maintain the force at the design value, independent of thermal effects and minor vibrations (Fig. 32)

The cracked ribs were suspended from the roof as well with a system similar to the previous one after having placed underneath a kind of steel cradle filled with soft rubber in order not to damage the frescoes.

Figure 31

Figure 32

As regard the tympanum the risk was that if it had collapsed it would have destroyed the roof of the chapel below, causing the loss of frescoes and works of art of inestimable value. After long reflections it was decided to use a huge crane, 50 m tall.

But such a crane could not get through the narrow gate into the inner yard. This problem was resolved by using two cranes; a first one outside the Basilica complex lifted the second one over the roof of the building and deposited it in the inner courtyard.

Organizing this operation involved anchoring two cantilever steel trusses on the two walls of the transept. The trusses were designed to support a 4,5 steel frame structure in the shape of the tympanum, a triangle 8 m high and 17 m at the base.

In the period of time between the 10^{th} and the 14^{th} of October all the operations were completed: the steel structures were built; two cranes arrived on the square in front of the Basilica; the first crane lifted the second one into the courtyard; the two cantilever steel trusses were lifted over the roof of the transept and were anchored to the lateral walls, ready to receive the steel frame.

After some attempts hindered by heavy rain and wind, the crane succeeded on lifting the steel tympanum over the brackets.

The following day the empty spaces and big holes were filled with polyurethane foam to provisionally stabilize the masonry.

5.2.3 The consolidation and restoration project

Strengthening

The problem of the definitive restoration and consolidation of the Basilica, expecially as regards the vaults, has immediately appeared to be very delicate, because, due to the presence of the frescoes, it was impossible to recover the deformations and to re-establish, therefore, an adequate curvature and autonomous bearing capacity.

Different studies, researches and mathematical models have been carried out to decide which solution would have been the most appropriate to strengthen the vaults and secure their stability over the time, without risking to damage the frescoes and without compromizing the historical value of the original vaults structure. Finally the choice has been to realize on the extrados a series of little ribs, following a pattern typical of Gothic structures (Fig. 33), letting clearly visible the original structure.

Figure 33

These ribs are made up of a composite material with aramidic fibers bedded in epoxy resins and a central timber nucleus; this material is light, very strong (the tensile strength of the aramidic fiber is 30.000 Kg/cm2 and that of the fiber with resins is about 14.000 Kg/cm2) and less stiff of the steel (the elasticity modulus is respectively 1.200.000 Kg/cm2 and 600.000 Kg/cm2).

Aramidic fibers, besides, haven't brittle behaviours and present a good ductility.

The ribs are built in situ, so that it is possible to follow the deformed shape of the vaults: whilst the width of the ribs remains constant (8 cm), the high has an average value of 20 cm, but it increases or is reduced in relation with the deformation of the vaults, because the extrados of the ribs follows a regular curve parallel to the original ideal surface of the undeformed vaults.

As regards the cracks, which have compromised the continuity of the vaults, it has been decided to complete the first injections realized in the emergency situation using a mortar able to satisfy very specific and severe conditions. This mortar, produced by MAPEI, is salt-free and compatible with the frescoes, sufficiently fluid to penetrate and diffuse in all the cracks and microcracks able to be injected in dry masonry (no use of water is allowed) and finally has good strength and bond capacity so that a structural continuity through the cracks can be established.

A further intervention regards the masonry arches, which sustain the roof; their base actually simply stands on little arches, which insist over the springers of the vaults without any structural connection and with a certain eccentricity respect the ribs of the vaults and the pillars.

It has been therefore decided to anchor the base of the arches at the walls and the towers behind, which in this very peculiar Italian Gothic have the function of abutments. The anchorage is realized with a steel belt and prestressed horizontal bars.

Reconstruction

The reconstruction of the collapsed vault has been another major problem. Fortunately after a painstaking piece of research several frescoed bricks that could be reused to rebuild the vaults have been identified.

The operation has been particularly successful as regard the pieces of ribs, although having felt down from 25 metres, had maintained a good bend between the bricks.

It has therefore been possible to assemble in laboratory the broken parts of ribs in such a way to create a sort of voussoirs about 40 - 60 cm long; these voussoirs are then placed on a provisional centring to rebuilt the ribs.

It hasn't been possible instead to recover significant elements of the webs, so that new bricks, expressly built to have the same constituents and similar characteristics of the original ones, are going to be used.

The reconstruction of the vaults has taken into account the problem of re-establishing not only a structural, but also a stress, continuity between the new and the original portions of the vaults; a system of jacks has been foreseen for this purpose, placed in a provisional joint on the crown of the new vaults, to compensate the deformation, including the shrinkage of the mortar, and to calibrate the stress distribution.

The restoration of the Basilica has been completed with the reconstruction of the collapsed portion of the left tympanum and the recovery of the deformations that both tympanum have suffered; stones coming from the same original quarry have been used. To reduce the seismic actions transmitted to the tympanum, which even if consolidated remains a delicate structure, the connection between it and the roof, is realized by interposing special steel devices made with “shape memory alloys” able to dissipate a certain amount of energy.

The Basilica was reopened to the public 29 November 1999, 2 years and 3 months after the earthqualke.

5.2.4 Conclusions

The operations carried out, firstly to save and then to consolidate and restore the Basilica of St Francis of Assisi, have all followed the same philosophy: to place the most up-to-date techniques and technologies at the service of the culture in order to respect the historic value of the ancient building and to obtain adequate safety levels, changing as little as possible the original conception. Some of these technologies, never applied before in the restoration field, have expressly been studied for this occasion, offering new interesting possibilities for the safeguard of the architectural heritage.