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Structural Problems Connected with Restoration and Strengthening

Problèmes structuraux liés à la restauration et au renforcement des bâtiments

Baustatische Probleme bei den Restaurierungs- und Verstärkungsarbeiten

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SUMMARY

The planning methods for the restoration of old buildings differ considerably from those applied to new buildings. Although there might be similarities in structural problems, each old building is a case of its own. The civil engineer should treat the building as a doctor would deal with his patient: anamnesis, diagnosis, therapy, prognosis. Careful restoration techniques and new research findings help to minimize the intervention and reduce the necessary repair and strengthening aids. Working with old buildings leads to a balance between theory and practice, experience and intuition.

RESUME

Les méthodes de planification utilisées lors de la restauration d'anciens bâtiments sont différentes de celles appliquées dans de nouvelles constructions. Malgré les problèmes structuraux souvent de même nature, chaque ancien bâtiment représente un cas particulier. Pour l'ingénieur civil, la meilleure façon de s'attaquer au problème d'un ancien bâtiment est celle du médecin traitant un patient: anamnèse, diagnostic, thérapie, pronostic. De nouvelles méthodes de restauration ménageant la substance combinées à des résultats de recherches récentes contribuent à minimiser l'intervention et à limiter l'emploi de matériaux modernes. Le travail de restauration et de renforcement représente une recherche de l'équilibre entre théorie et application, expérience pratique et esprit d'invention.

ZUSAMMENFASSUNG

Die Planungsmethoden für die Instandsetzung alter Bauten sind andere als für den Neubau. Altbauten sind, bei mancher Gleichartigkeit der baustatischen Probleme, jeder für sich ein Sonderfall. Am besten nähert sich der Bauingenieur dem alten Bauwerk wie der Arzt dem Patienten: Anamnese, Diagnose, Therapie, Prognose. Substanzschonende Sanierungstechniken und neuere Forschungsergebnisse helfen, die Eingriffe in den Bestand zu minimieren, die modernen Zutaten zu beschränken. Die Arbeit an den alten Bauten ist ein Feld des Ausgleiches zwischen Theorie und Praxis, Erfahrung und Erfindung.

Different planning methods for new buildings and building repair.

When we deal with new buildings as structural or civil engineers the architect himself tells us of his plans from the very beginning. The building is actually erected towards the end of our work. As it is designed by us it is also our product. Drawings, calculations and descriptions give information on all details. Of course we do not want to be confronted with damages on these buildings, so we construct them accordingly. Essentials for the planning and building process are laid down beforehand, we have personal contact with the soil engineer, the heating engineer and with the supervising architect. The amount of work and the fee involved can be estimated before signing the contract, the office organisation is arranged to suit the needs of the building task. Generally, we can base our calculations on codes and standards which are approved rules of architecture. We work with well-known materials, the quality of which we determine ourselves, and with bearing systems and structures, we have had much experience with. We apply well-established calculating methods, programs and formulas for rough estimating. We know about the building process and the techniques involved and the craftsmen are experienced in this field. Finally we are also able to determine the costs to a certain extent. On the whole when planning a new building we have many approved methods at our disposal.

When we repair an old building the structure already exists, its architect has been dead for a long time. He can describe to us neither the process of planning and development of the erection nor the finished product. We have to ascertain everything about it ourselves. The architect's plans no longer exist and reliable surveys of the building are seldom at hand. Structures added later have changed the substance.

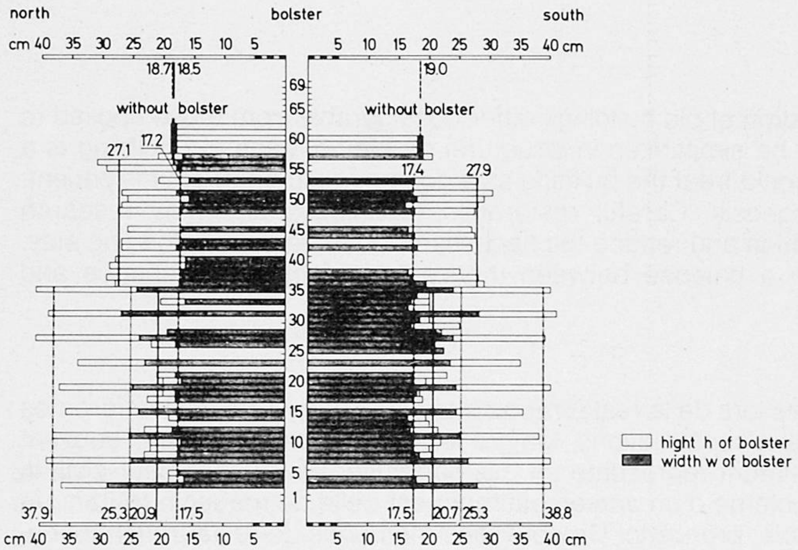

Fig. 1:

Minster of Freiburg

A survey and statistic valuation of the foot plate (bolster) cross sections in the roof of the nave helped discover the original system of tie beams. Most of the beams the rests of them being of larger size than the other plates were cut away when the vaults were built.

Each time we face structural damages, we are expected to provide a concept of restoration. The course of planning and constructing differs in each case depending on the nature and the size of needed repairing. Unfamiliar partners like conservators and restorators exert influence on our task. Being committed to the history of art they pay only marginal attention to the structures. Often we are called in too late which makes our task even more difficult because we must consider the restoration work already carried out which would better have been done after the structural repair. It is difficult to estimate the extent of our work and to fix the fee in advance. We are forced to do a lot of things ourselves, as designers and draftsmen cannot be employed as usual. Codes and standards which were not established for old buildings are seldom helpful. We have to deal with unfamiliar, aged materials of unknown qualities. We are not accustomed to the bearing systems and bearing structures. The common methods of calculation can be applied, at best, if they are modified. Little-known techniques must be used, so we depend on special firms. The other craftsmen are virtually inexperienced in the field of historical construction. To estimate the probable costs is difficult, takes a long time and is sometimes altogether impossible. All in all the working methods for the planning of new buildings are unsuitable for the restoration of old buildings.

Anamnesis, Diagnosis, Therapy, Prognosis

An old building is a patient with handicaps likely from congenital defects, damages from aging and wear, after-effects from early manipulating with the substance, injuries from accidents or wars to decrepitude. The civil engineer has to help this patient as a doctor would. It is therefore advisable to apply the doctors methods: anamnesis, diagnosis, therapy, prognosis.

In our context anamnesis means gathering information on the buildings history of illness and damage. Literature and old reports of defects have proven to be very helpful. For instance measuring results in expertises made by geodesists and geologists can be compiled to show in detail the behaviour of both the building and the foundation soil over the last decades.

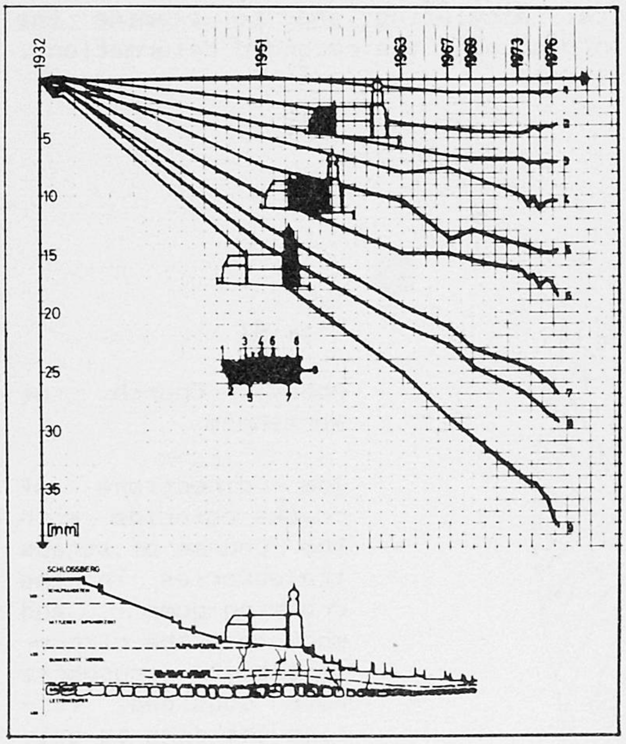

Fig. 2:

Collegiate church of Herrenberg

The results of geodesic measurements over a period of 5 decades show the gradual increase of subsidence from the choir to the tower and with the course of time as well.

Reports of damages and proposals for repair made in the past can help improve the judgement of the state the building is in today.

The better the anamnesis the more precise the diagnosis will be. Physicians point out that a good anamnesis can make for half of the diagnosis. It is similar with old buildings. But still, surveys of substance and damage have to be conducted on the site, drawings showing the course of cracks and deformations, high precision levelling and measurements of horizontal movements, observations carried out with plaster indicators as well as diagnostic operations such as exploratory drilling and samples taken from the building, foundation and soil to complete the examination of damages.

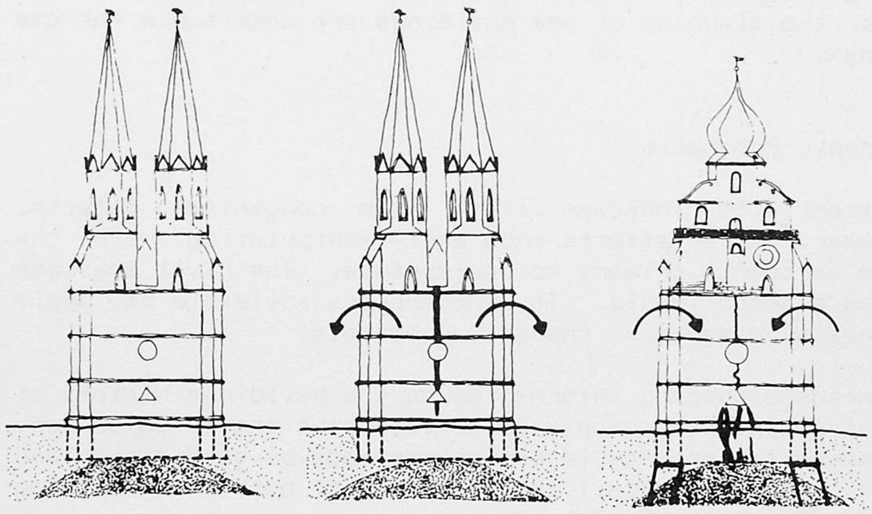

Fig. 3:

Collegiate Church of Herrenberg.
Crack damages, first in the upper and middle, then in the lower part of the tower, indicate saddle - supporting and subsequent underpinning which was confirmed by exploratory drilling.

It is part of the diagnosis to do statical calculating and to examine the present stability of the building taking into account the recorded deformations.

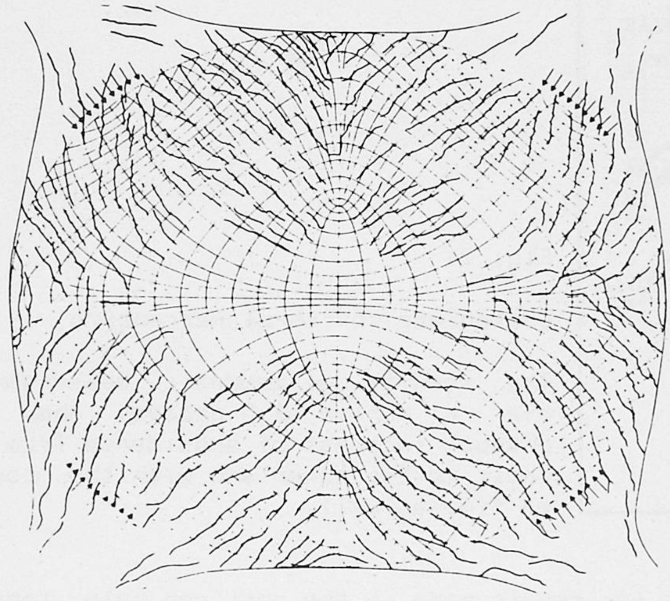

Fig. 4:

Abbey Church of Neresheim

The directions of cracks coincide with the course of stress trajectories in the crossing-dome and show that the circumferential supports have subsided, forcing the dome to settle on the four crossing-piers.

The therapy concept often results very obviously from the anamnesis and diagnosis made. Significant advice as to what repair and strengthening aids might be adequate in type and form can be drawn from the building's history. Our assisting measures must fit into the old building structure. It does not suit the building to arrange them according to statical and constructional needs only.

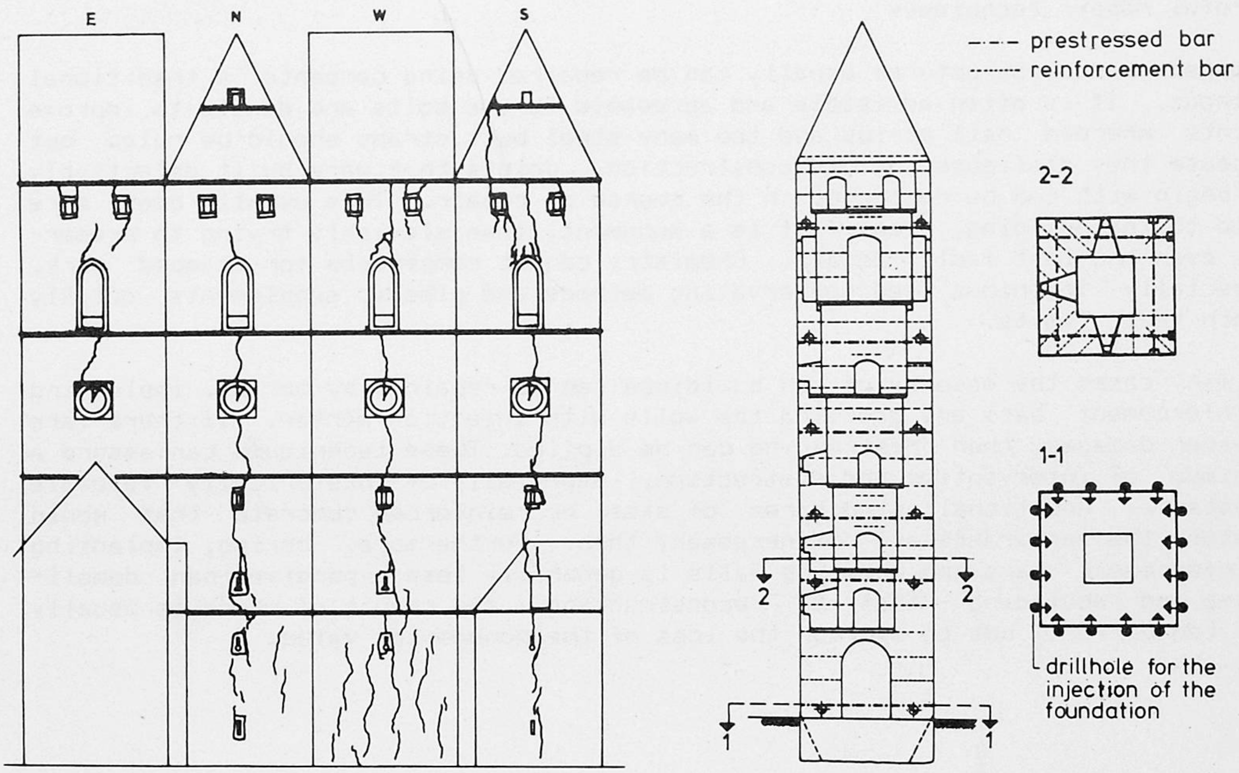

Fig.5:

Church steeple of Weitingen

The masonry which was torn apart on all sides and separated into four corner sections (left) now functions as a structurally complete unity after prestressing, inserting reinforcement bars and injecting cement (right).

When carrying out the therapy concept in measures to secure and repair the building it is necessary for the engineer to be on the site as much as possible to be able to adjust planning to the actual situation of the building. Most of the decisions necessary for this can only be made on the site.

To give a prognosis on how long our stabilizing efforts will prevail is difficult. Statistical considerations and the theory of probabilities can usually be eliminated as aids to assess the time. We would need too much data and information on the building and the soil. But by careful investigation of the building's present condition and with the help of the experience we have had to date with securing techniques, we can at least come to a rough estimate of the probable durability of the repairs, so as to extrapolate our experience into the future. To assess the cost-benefit-ratio of our repair suggestions this prognosis is appropriate in any case, even though it is based on an estimate.

Careful repair techniques

Damaged wooden structures usually can be repaired using carpenter's traditional methods. It is often advisable and agreeable to use bolts and dowels to improve joints whereas nail strips and too many steel butt straps should be ruled out because they disfigure the old construction. Joints that were built defectively to begin with can be corrected in the course of repair. This usually does more good to the building, even if it is a monument, than slavishly trying to preserve even the last faulty detail. Chemistry cannot compensate for scamped work. Especially ingenious wood conservating methods and plastic supplements quickly reach their limits.

In many cases the masonry of old buildings can be repaired by boring, implanting reinforcement bars and grouting the walls with injection mortar. If there are greater damages, then prestressing can be applied. These techniques can assure a minimum of intervention and destruction, especially of historically valuable substance. Additional structures of steel or reinforced concrete that would disturb the appearance are not necessary then. Furthermore, boring, implanting reinforcement bars and grouting walls is generally less expensive than demolishing and rebuilding - that is: reconstructing - the result of which is usually far too perfect, not to mention the loss of the monumental value.

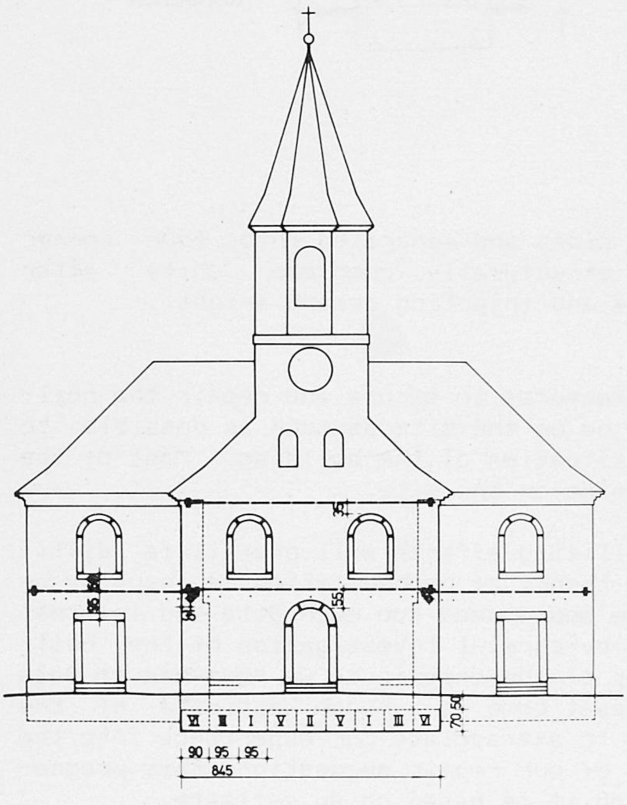

Fig. 6:

Village Church of Spielberg

Inexpensive repair of the torn walls, whose foundations were not deep enough, by underpinning, prestressing, implanting reinforcement rods, grouting and installing an upper peripheral tie beam.

Damaged masonry vaults are often stabilized by applying shotcrete. If possible the shotcrete should be restricted to the spots of damage or to small bearing strips. This way the effect on the temperature gradient in the vaults and on the resistance to diffusion of vapour is minimal. This is especially important if there are paintings on the ceiling underneath. Only if it would be insufficient to mend the joints or to just apply shotcrete partially, should it be considered to strengthen the complete surface of the vaults with a shell of reinforced shotcrete on top. Besides, it usually pays to examine the statical behaviour of the vaults more closely by taking three-dimensional-bearing systems into account. This can be done according to diagramms of the contourlines and by checking the load transfer in the downlines. By doing so, expensive repair measures were avoided in several cases. This would not have been possible without precise information on the flow of forces within the vaults.

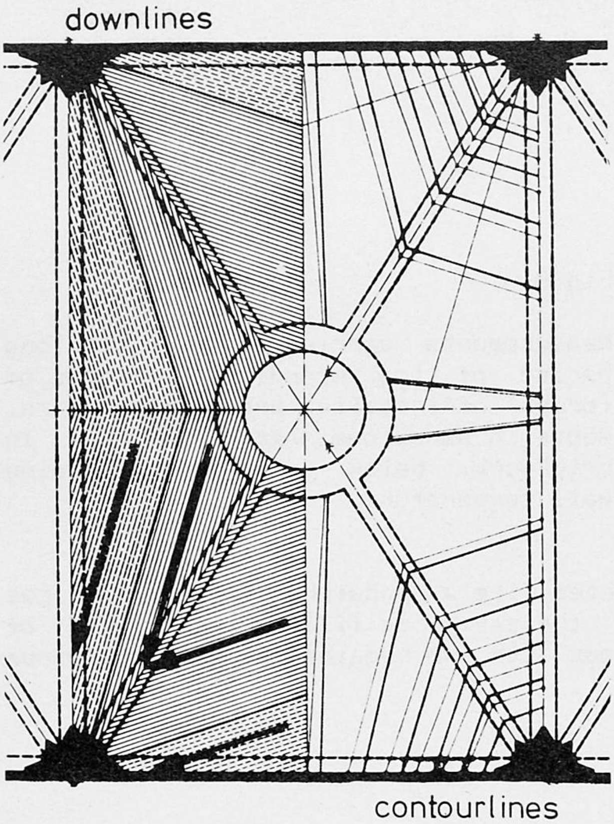

Fig.: 7

Minster of Freiburg

Contourlines and downlines of a cross-ribbed vault. 65% of the load are transfered to the cross rib, 25% to the transverse arch and 10% to the wall arch.

New research results

To complement the methods for improving masonry which were derived from practical experience, research has now supplied results that are applicable in practice.

For prestressing masonry in historical buildings data has been compiled concerning the permissible partial surface pressures underneath anchor plates; the flow of forces in walls can now be described; information is given on the size of the splitting tensile forces. There are also specifications on the loss of prestressing forces in course of time and several other special problems are dealt with.

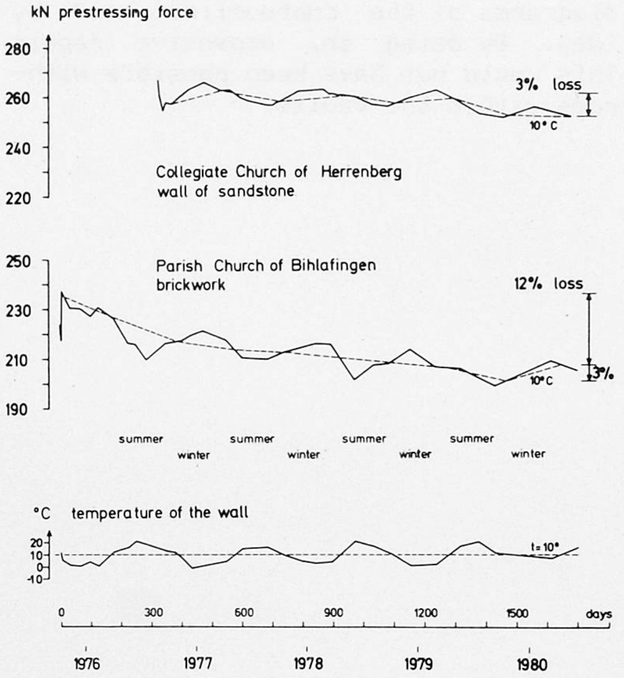

Fig.8:

Measurements carried out over a long period of time recording the losses of forces of installed prestressed bars. Above in sandstone masonry, centre in brickwork, below is the corresponding wall temperature.

Walls in old buildings are often constructed like a sandwich: The outer slices are more or less built in masonry bond, the cavity is filled with pieces of stone, sand, at best mortar but at times with the remains of the previous building.

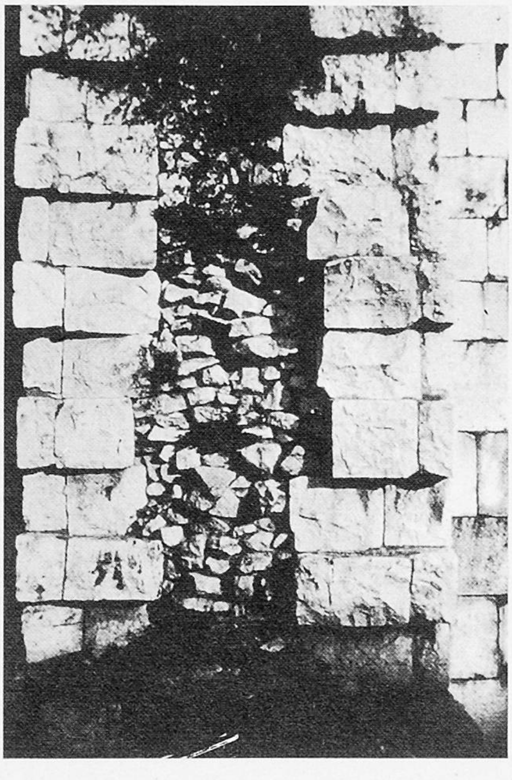

Fig.9:

Diocletian palace in Split
sandwich walls

The bearing capacity of such sandwich masonry is small because of the lack of rigidity towards transverse stress. Test results now show how much the load at cracking and the ultimate load of sandwich brickwork can be increased by inserting reinforcement rods to connect both outer sclices of the wall and by grouting the wall, especially the loose centre with mortar. The achievable increase in loading capacity is considerable.The significance this has for practice is that less old masonry has to be demolished and replaced because it can be improved sufficiently by inserting reinforcement rods and grouting. This can also be done at less cost than by demolition and reconstruction.

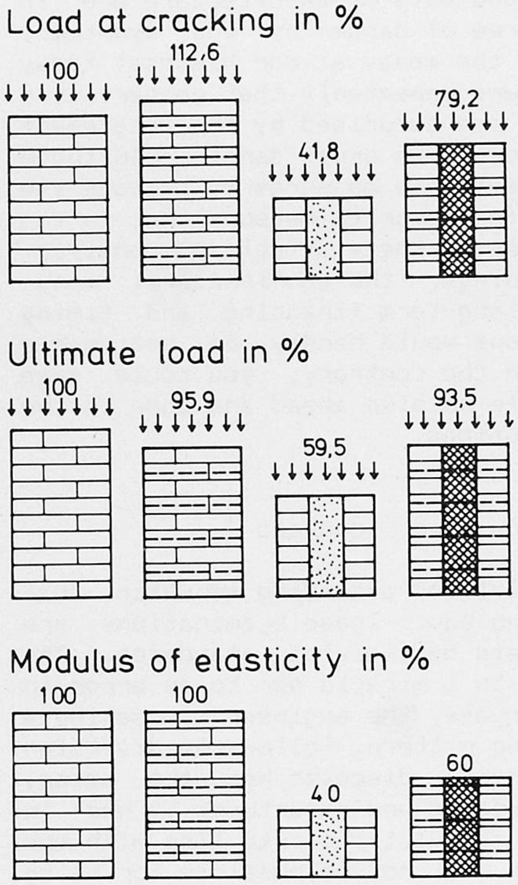

Fig.10:

Tests on brick masonry

From left to right:
one-slice masonry
one-slice masonry including reinforcement rods, grouted
sandwich masonry, ungrouted
sandwich masonry including reinforcement rods, grouted

Standards for old buildings?

The question has often been raised whether the practical experience and the results of scientific work on securing old buildings could be embodied in standards so that a wider circle of experts could have free access to them. The answer can only be: for heaven's sake, no. Every old building and each defect is a special case of its own. During any statical and constructional restoration the techniques applied have to be specially chosen to meet the requirements of the particular building. Therefore the structural engineer must take great care in advance and study the existing structure and the special features of the building. His diagnosis and therapy-concept should be established for this special object. If there were standards for everything then the engineer would easily be tempted to meet these standards primarily - if not even feel obliged to do so as we can experience with other standards we have - and to neglect the special situation of the specific project. For those who try to find the best possible solution to fit the needs of the particular building those standards would be more an obstacle than a help.

The causes of damage and the symptoms

In my experience as consultant and proof engineer, I have found that checks and restoration concepts often do not go beyond repairing the worst and most visible damages. You must be careful not to simply cure the symptoms and ignore the causes. In most cases the hidden causes are dangerous, not the symptoms. The size of the damage is not necessarily important: small defects at sensitive spots within the structure can have grave consequences whereas large damages at less important places need not be of any danger.

Many old buildings need help, many important monuments of architecture are in danger. In most cases you cannot tell the degree of danger by the symptoms. Because funds for repairs are becoming smaller, the money at our disposal today should be directed to specific objects. It occurs repeatedly that conservators or the state, community or church as proprietor are surprised by the statement that a certain building has very grave damages or is in great danger. In those cases the financial planning is swept over by inevitable measures to salvage the building. In the haste, steps are often taken for security reasons that go too far. If precautionary examinations were to be made of the statical and constructional condition of a top group of historic buildings, the architectural monuments, then there would be a basis to set up long-term financing and timing schedules. The expenses for these investigations would hardly be noticeable compared to the costs of securing measures. On the contrary, you could save money by setting priorities and by then being able to plan ahead and come to the technically and financially most appropriate solutions.

What about an old building that should have fallen apart long ago ?

From time to time I come to read statical calculations according to which that particular building should have fallen apart long ago. These examinations are usually supported by computer results and by lists of violated standards. The fact that it has not fallen apart is neither due to a miracle nor to an error in its bearing behaviour. The calculation is inadequate, the engineer was making a mistake. We have to find out the real load-bearing pattern, follow the diversion of loads from failing building components to others, discover how the aging, ailing building helped itself and what hidden systems and structures it has in reserve. We must also try to bring the statical calculations into line with the damage record. If we do not do all this then it will not be possible for us to give reliable information on the danger the building is in.

Help for a hundred years, not for a thousand

In my therapy-concepts I try to bring as little changes as necessary to the substance and to the soil. I try to keep risks low and try to find ways to support the building's self-help mechanisms.

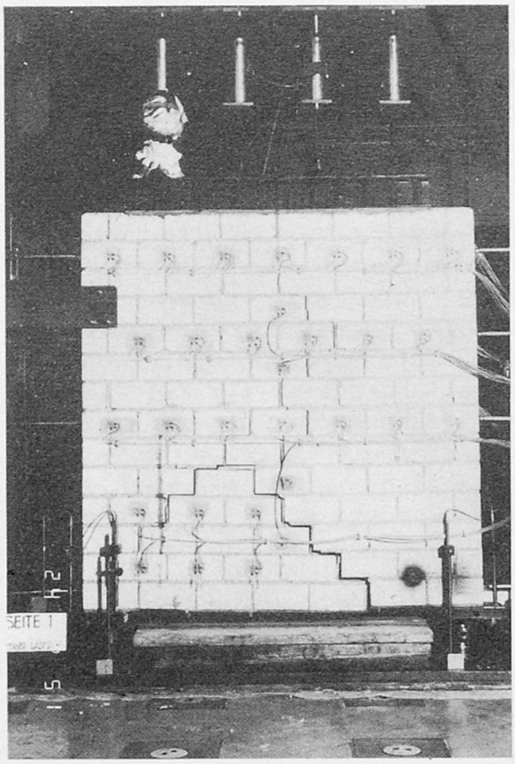

Fig.11:

Sheet action as a self-help mechanism above openings and weak spots in masonry walls. Results from tests (picture) and FE-calculation

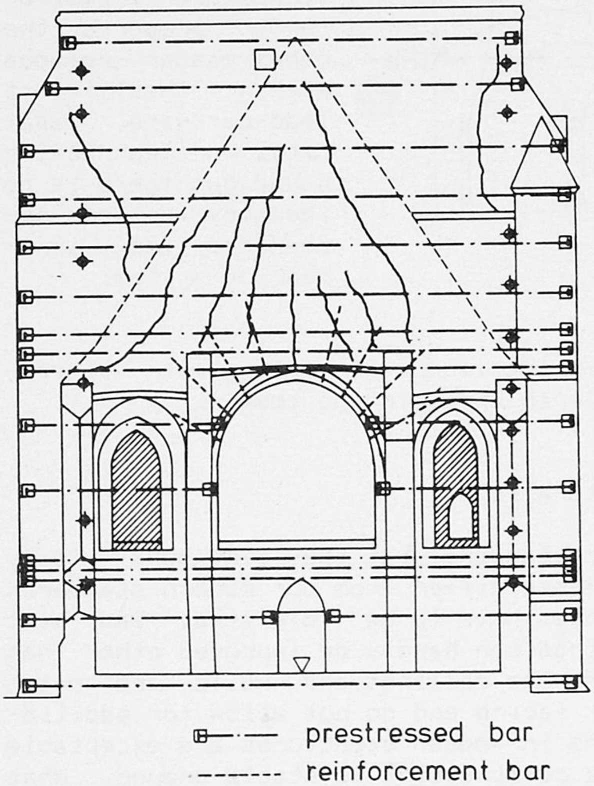

Fig.12:

Collegiate Church of Herrenberg

The prestressed masonry diaphragm spanning the big opening to the tower makes visible supporting structures of steel or reinforced concrete superfluous.

The durability of the repairs has to be estimated for each case separately. Modern imperceptible therapy methods can be helpful at crucially sensitive spots of historical buildings for a hundred years, to give a rough estimate. You could double the period for less delicate areas. It would be irresponsible to promise more at the present stage of science and technology. Future generations will and should have to deal with the surviving monuments. To think we could and should free our descendants from such care and concern once and for all would be presumptuous.

A typical example for the question, how far an engineer should go in planning his securing constructions, is the underpinning of subsiding walls with the help of piles. It is often sufficient not to preload the piles, that is not to press them with jacking force against the wall load above. Otherwise the walls could easily be damaged additionally. The not preloaded pile foundation represents a cushioning support which is activated only when the walls sink further. They are then supposed to settle onto the support and gradually transfer their loads to the piles. The bit of subsequent subsidence has to be accepted. There are cases, though, where it can be advisable to already redistribute the flow of force within damaged walls during restoration work, to take the weight off weak spots in the structure and transfer loads to a few new supports such as preloaded piles.

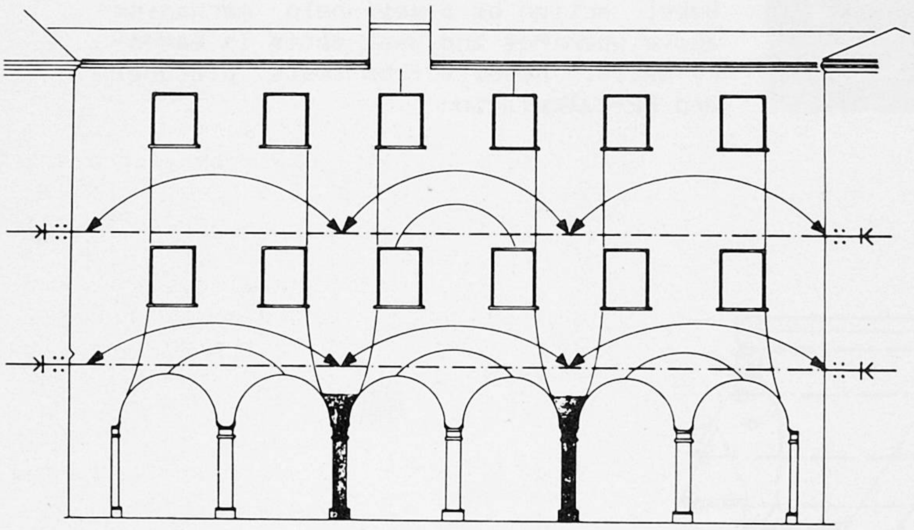

Fig.13:

Laupheim Castle

Prestressing the wall in two horizons and inserting two new columns of reinforced concrete that are pressed against the wall load above with jacks make it possible to preserve the other masonry columns with insufficient load-carrying capacity. Technically sound but there is no identity between appearance and inner bearing system.

One should generally be careful preloading piles if one is dealing with vulnerable walls whereas this procedure is the rule in underpinning towers.

Proving stability before and after the restoration

Our ancestors did not build according to standards but they did have widely recognized rules of their building craft. These differ from our modern standards in a few points and some of these differences have to be tolerated. Bad heat insulation for instance in historic buildings can hardly be improved other than in radiator niches or in the attic because the ceilings and walls are often decorated with plaster, paintings or brick facing and do not allow for additional layers. Large impressions and deflexions in wooden structures are exceptable if the wood is healthy otherwise and if the construction is stable enough. What if this security is not given? Securing measures for vaults, columns and walls that are aimed at achieving todays permissable stresses often lead to a great loss of historical substance and shape. What is to be done if what should be saved will be lost by the securing measures?

In those cases I begin with the ascertainment that the building although there are damages has survived till today. Because of this it will receive the safety factor 1,0. If the building's condition has been recorded reliably - which is a requirement - and if it can be proven that statical and constructive helping measures can improve safety at the most crucial points by, say, 50% to 1,5, then this is - if it cannot be done otherwise - a confirmatory strength report which I do as engineer and which I recognize as proof engineer and which I recommend to my colleagues.

I am sorry to have to say that there are proof engineers in structural statics as well as building administrators who insist on having the standards for new buildings observed to the letter and who therefore encourage destruction rather than preservation of substance. It is absolutely necessary for a larger number of engineers and proof engineers to get acquainted with the statical and constructional problems of old buildings. The questions concerning statics and construction are especially difficult with those buildings. I am always grateful to encounter colleagues while working at these tasks who co-operate in finding a safe and adequate structure.

Building-related physics

An important task for engineers and proof engineers during the restoration of old buildings is consulting in matters concerning building-related physics. The engineer is becoming more and more responsible for planning and supervision of the protection from heat, cold, noise, moisture, rot, timber pests and corrosion since the architect lacks the necessary technical knowledge to an ever greater extent. His co-operation is especially important in matters of precautionary fire protection. Adequate measures are not always possible, just think of historical staircases or long hallways in monasteries. But there are always ways to erect fire-resisting walls where old weakend framework walls are removed or to replace damaged wood-beam floors with a solid construction and thereby create fire compartments. In such cases we must proceed carefully but decisively.

Work on old buildings leading to a balance between theory and practice, experience and intuition

The engineering work as part of restoration activity is neither ideal for theory-minded calculation specialists nor for colleagues who try to make their construction job appear a bit more scientific by verbally complicating trivial matters nor for those who work according to the motto: "we have always done it that way". Instead, working with old buildings leads to balancing theory and practice, experience and intuition.
We are to deal with works of the building craft to which we are to make careful contributions. These contributions can improve in quality the more we look into the history of architecture, arts and crafts - all of which are subjects that were not part of our specialized curriculum. In this sense, engineering work on old buildings means continuous studies.

Balance between conservation and renewal

While dealing with the restoration of old buildings we engineers or proof engineers face co-operation with conservators. We must describe the building's constructive condition. We are to show in a sound and understandable manner why or why not restoration is feasible. It is equally terrible to clear away a monument of architecture as to repair it at any expense. This is where the engineer can contribute to a reasonable balance between the conservation and the renewal of our building substance. To repair old buildings can only mean to put further decay under control. It can never be completely stopped. If it is reasonable to repair a building then we are expected to recognize its value and to work carefully and to find solutions that fit organically into the existing substance.

Why I become involved with old buildings

To conclude, please let me make a personal statement. When asked why I get involved with old buildings so often, several answers come to my mind: First of all I like to investigate the work of previous masterbuilders. Again and again I am surprised by the clarity and simplicity of many a structural concept, their effectiveness by being confined to only a few building materials and the evidence of solidity, well demonstrated by the age of the monuments. Our old buildings undoubtedly represent a positive selection, we can surely learn quite a bit from them. This in mind, I become more pensive and more cautious when I deal with the variety of modern means and possibilities, more frugal in designing my own structures.

Another answer to the question concerning the reasons for my dealing with old buildings is that very often historically interesting buildings are connected with interesting people. For instance the abbot of a monastery who is more at home in architecture and engineering and in the history of arts than some of our expert colleagues; or the administrator of public archives who asked to preserve the holes of the swift when grouting the walls of the church steeple; or say the conservator who spent many hours of his spare time in the Carolingian building he had done his graduation report on 50 years ago and who continued doing research on it his whole life long. Those are all people who looked after these buildings and it is really very rewarding to get acquainted with them.

Finally, I must also say that it is fun to apply new engineering methods to old buildings because in these cases there are not all those many standards and regulations which have prevented so many of our engineer colleagues from using their minds and have degraded them instead to "book-keepers of reinforcement", as somebody once put it. But seriously, as I have to take on more responsibility myself in work on repair of old buildings, my task as engineer is more satisfactory and rewarding than it can be with many a new building.

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