STRUCTURAL DESIGN ASPECTS IN MONUMENT PRESERVATION

by

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1. General consideration on the structural problems of monument preservation

The general problems of structural design and the connected trends of research are discussed in another paper of this publication (Structural Design and its Research). The paper has also been concerned with some general problems of monument preservation.

The present paper is devoted, rather than to structural research, to the modest aim of formulating simple, often seemingly primitive rules that are suitable to prevent the structural designer and the structural engineer engaged with monuments from making serious mistakes.

Of course, in the following only constructed monuments having load-bearing structures are discussed. It is often necessary to examine, strengthen or transform such constructions. These procedures are, however, not identical with similar procedures applied with new (a few decades old) structures. Looking into the reasons for these differences, we have found the following:

The structures of monuments

1. are generally made of materials having no tensile strength,
2. the quality of the material has deteriorated to an unknown extent,
3. there are often gaps in them,
4. their systems and dimensions cannot always be exactly estimated,
5. their strengthening, completion or transformation calls for methods based upon specific considerations.

The consequences of the above peculiarities are examined one by one in the following:

1.1 *Consequences of the absence of tensile strength*

Nowadays, materials without tensile strength are used only in construction of inferior structures. A modern architect will not find it a routine task to sense the distribution of forces of such structures, a problem that did not intrigue an architect in the past. Even if the education of architects gives—though scarcely—the necessary theoretical rudiments, it cannot offer any practical training. To acquire this "practice", an architect engaged with the structure of monuments is left to his own resources if he wishes to avoid mistakes. As a matter of fact, such knowledge would be most useful not only for structural designers and structural engineers but to the great number of architects specialized in monuments.

We have used the word "practice" in quotation marks as it is impossible to give anybody the practice of ancient architects and it would also contradict our present aspect of structure. Ancient architects built without calculations and often created structures that would not come up to the level when checked by simple calculations, and yet the building has been standing ever since. Here belong, for example, some shallow barrel vaults. Being checked as one-way structures not even the thrust line of the uniformly distributed load can always be kept within the vault. The structure is standing all the same and the explanation for it may be found only in the fact that it does not act as a one-way structure but like a cylindrical shell, shearing forces directing the thrust line inside the vault. The "practice" to judge structures without tensile strength often requires a thorough theoretical knowledge (in our case that of the theory of shells).

1.2 *Consequences of material quality losses*

If the quality of the material deteriorated uniformly, soundness could be established in a reliable way. However, the material of monuments exhibits strength properties reduced differently at each spot, a phenomenon generally difficult and often impossible to assess. The high number of destructive tests needed—even if they did not interfere with monument preservation considerations, — would involve inhibitive expenses.

Non-destructive tests (ultrasonic test, X-ray test etc.) are not suitable because of both the inhomogeneity of the material and the thickness of wall. Up to this day, there is no economical, reliable and generally applicable method of quality testing available.

1.3 Consequences of gaps

Gaps in monument structures can be detected in principle but in practice their survey in mostly irregular configurations is usually cumbersome and time consuming even when making use of photogrammetry. This is why the projects for strengthening or transforming monument structures cannot be as full and exact as those of new structures and more or less data are lacking as these can be established only in the course of construction. In structural design it is reasonable to compensate uncertain data by safer structures (e.g. of larger dimensions).

1.4 Consequences of the uncertainty of system and dimensions

It is often doubtful in what system the monument structures are built. Even if both surfaces of a thick wall are exposed and show bonding, it may happen that between the two wall layers in bond there is another layer unbonded or even of some other material. Upon an eventual discovering it may often turn out that the system is changing from spot to spot. Uncovering, however, cannot be applied too densely, because of risk of further deterioration.

If, on the other hand, only one surface of the wall (e.g. retaining wall) is exposed, even dimensions may be uncertain.

The peculiarities of monument structures and their consequences discussed so far make only dimensioning more difficult but affect indirectly the overall structural design. Major uncertainties can be offset by a pessimistic assessment of unknown data.

The last mentioned peculiarity makes, however, just the overall structural design rather difficult.

1.5 Reuqirements for respecting the monument character

Strengthening, completing or just preserving the state of monuments cannot be done by the observation of structural points only. Special monument considerations *a priori* exclude some materials, certain kinds or shapes of structures. Reduced possibilities are often concomitant with higher requirements. Thus, for example, around the Fire Tower in Sopron excavations have obviously reduced the stability of the tower. Excavations had other consequences, too. It has become impossible to walk around the Tower; it has lost its accustomed environment, the ruins have been left without frost protection and, in addition, there stood two monuments of various periods (and at various levels) side by side. The structural requirements consist in this case in eliminating all these faults and securing stability by opening the town gate earlier walled in (diminished).

Similarly difficult and equally challenging problems of structural design are often encountered in connection with monuments.

In conclusion it can be assumed that the problems of monument structures differ from those of any other structure, and are more difficult both as regards structural design and dimensioning.

Let us have a closer look at these problems.

2. Problems of various structural elements

2.1 Foundations

When having to do with a monument, generally no surveying documentation is available, likely to deliver accurate data concerning the depth, material and dimensions of the foundation. In the case of major complexes of buildings, for instance castles, foundations built at various times may be not uniform and the differences can only be detected after excavating.

The excavation of foundations means to lower the ground level. This lowering may change the stress state of the building and lest the greatest precaution is applied, the stability of the structure is compromitted. This is why the greatest circumspection is needed in excavating, with due regard to the following points:

a) The lowering of the ground level must invariably be started at the parts situated higher.

b) Exploring trenches and pits must be constructed so that no water is drained towards the base or the wall.

c) The excavated state must not be kept up for long. The soil layers protecting the ground must be filled up to one metre above ground level as soon as possible or the ground must be protected in some other way.

d) Excavating beyond the bottom level of foundation is strictly forbidden as a rule. If it is still required by archeological considerations, the suitable method shall be consulted with an expert.

Be it the strengthening, reconstruction of an existing building or some other structural problem, foundations must not be excavated but partially.

There may be a break-through in the foundation at a few metres from the spot of excavation as required by a secret tunnel (e.g. *Máré* Castle). It can happen that part of the foundation rests on a slanting rock (e.g. *Eger* Castle) or it may have been built on the wall stubs of some earlier construction (*Sopron:*

Fire Tower). There are even cases, when it may be supposed that no foundations were made at all, if, say, the ground was rocky *(Hollókő)*.

Whatever the foundation of the monument under examination, great care must be taken that it should not be further weakened, for not to endanger this way the stability of the superstructure.

As regards planning, it is always the possible worst state conceived upon excavation that must be taken into consideration.

2.2 Walls, pillars

It often happened that the wall of a castle was thickened by building another wall next to it. The two walls are in no structural connection, are not walled in bond, and yet, if they are topped with a common cornice, they give the impression of a homogeneous wall. Castle walls were often repaired omitting to connect structurally the old and new parts.

The state of the wall core is often (in fact nearly always) different from its outside, being much poorer. Proceeding downwards, the rate of deterioration is generally increasing. The quality of the wall changes also in the horizontal, depending on the corner of the compass and on the prevailing wind direction.

In short, the wall material is generally inhomogeneous to an unknown extent. This mostly appears by visual examination (e.g. *Máré* Castle). Thus, if exact tests are impossible, it should be kept in mind that stress conditions in the walls must not get worse. This applies to the design of excavating, preserving, strengthening, transforming or pulling down operations.

In this respect some further general rules can be put down to complete those mentioned in connection with foundations:

a) Care shall be taken not to increase the level difference bilaterally of the wall and to avoid sign change. This must be stressed even if at the reconstruction of monuments the ground level would be lowered to the original. The layers inside and outside may, namely, differ in thickness but even if they were identical, in its poor condition the wall may not be safe against the same loads as it was when sound.

b) When the ground level has been lowered to the top of the wall foundation, this state must be carefully examined for danger of instability.

c) In case of very slender walls, it must be thought over whether it is necessary to lower the ground and make thereby the wall even more slender. The worst enemy of wall is water. So the following must always be remembered:

Water drainage out of the wall must never be hampered by state conserving procedures either. If, for example, on one side of the wall there is a soil layer transmitting water, provisions shall be made on its other side contacting open air for not to hinder drainage. Water that has penetrated the wall and cannot leave it has a most harmful effect.

In case of a wall contacting the soil, if there is a means (e.g. ground lowering and subsequent refilling) it is advisable to impermeabilize the wall at its side contacting earth.

If the wall or pillar is in a condition dangerous to life and it is impossible to strengthen it, it must be pulled down. When doing so, care shall be taken not to interfere with the stability of the remaining building parts. (The removal of a poor supporting pillar, for example, may compromit the stability of the wall or vault let intact.)

In transformations, in addition to monumental points, also structural aspects shall be observed. Walls and pillars must be able to bear eventual load increments.

It may happen that the transformation of a floor structure done with unsufficient foresight will reduce the dead load on a wall or pillar and just this load reduction will make the wall or pillar unable to take up lateral thrusts.

2.3 Retaining walls, buttresses

They had been built for high lateral thrusts due to either internal soil pressure or horizontal loads transmitted by the building structure (e.g. buildings overroofed by a barrel vault).

The vertical load on the retaining wall can, in most cases, not be reduced without reducing at the same time the horizontal load. On the other hand, it is generally possible to increase the vertical load.

On the contrary, horizontal loads can, in general, not be increased without simultaneously increasing the vertical load as well. It is, however, nearly always feasible to reduce the horizontal load. If the horizontal load is due to soil pressure, it is advisable, if feasible, to remove part of the earth. It may happen that a new fill is necessary near the retaining wall. In such cases the use of a plastic sheet may save the retaining wall from lateral pressure due to the backfill. The details of the process suggested are illustrated in Fig. 1.

2.4 Floors

Floors are discussed in two categories, as plane floors and vaults.

2.41 Plane floors

In ancient buildings, plane floors had been generally made of wood. These floors, especially in heavily ruined buildings, are present only in traces as they have become uncovered in most of the cases and perished quickly.

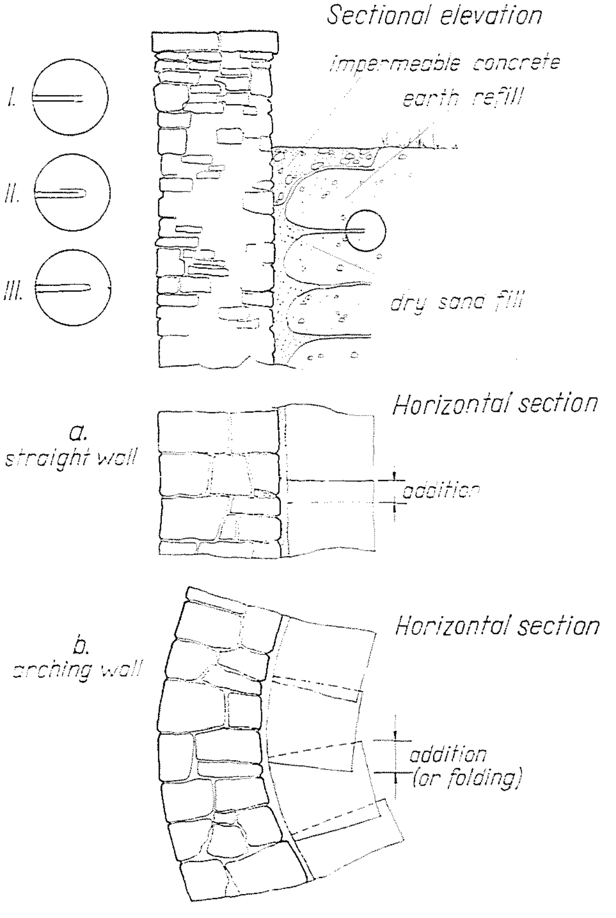

Fig. 1. Strengthening old walls

In reconstruction, the designer must have in mind the possibility of an ulterior replacement. It is advisable to design timber surfaces exposed to water as small as possible and in addition, to conserve the uncovered timber structure, for example by an impermeable coat. This coat shall be made jointless and interacting with the timber.

Such a protective coat can be made by fixing a wire-mesh on the floor top, densely nailed on with U-nails on both sides of the joint between the planks, and applying a smearable and hardening impermeabilizer. The mesh will partly restrain the movement of the planks, and partly keep the protective coat on the timber structure in case of displacement.

2.42 *Vaults*

The other major group includes vaults. They fail, crack or collapse by horizontal displacement of springings, rather than by material deterioration. With minor repairs the vault can generally be preserved if the springing displacement can be eliminated or minimized.

Strengthening may be by buttresses, tie rods or else depending on the condition and structure of the vault.

2.5 *Towers*

In our ancient buildings, towers played an important part and their structural problems well deserve attention.

In the case of towers, first of all the existing parts have to be structurally surveyed. Strength conditions of the tower govern the decision whether it will be reconstructed or only conserved the part that has been left (cf. *Diósgyőr*, Fig. 2).

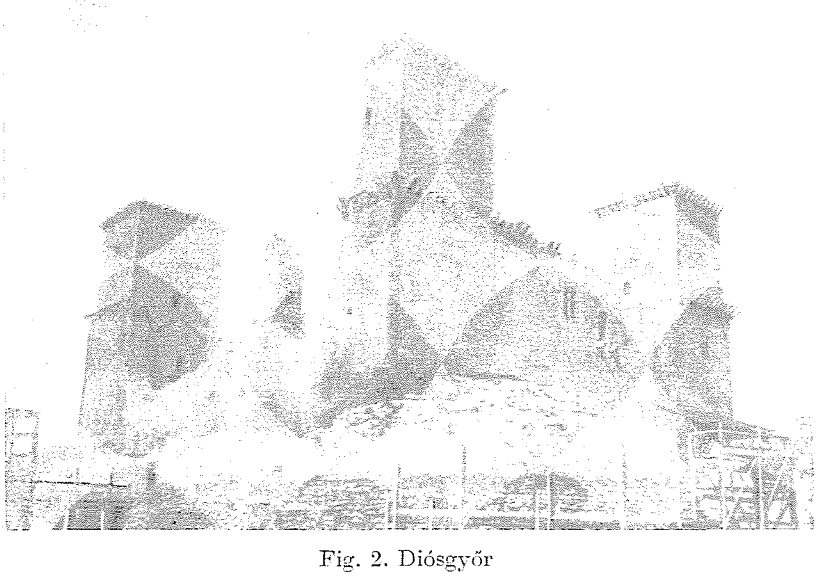

Fig. 2. Diósgyőr

In case of reconstruction it should be kept in mind that the complemented surface will be more exposed to wind. Hence, the load capacity of the walls must be checked with due attention paid to the increased wind pressure.

The restoration of towers is a requirement encountered mainly in castles. Often it is only possible to get a view over the surroundings from the top of the tower that plays thus the role of a lookout tower as well (e.g. *Hollókő*. Fig. 3).

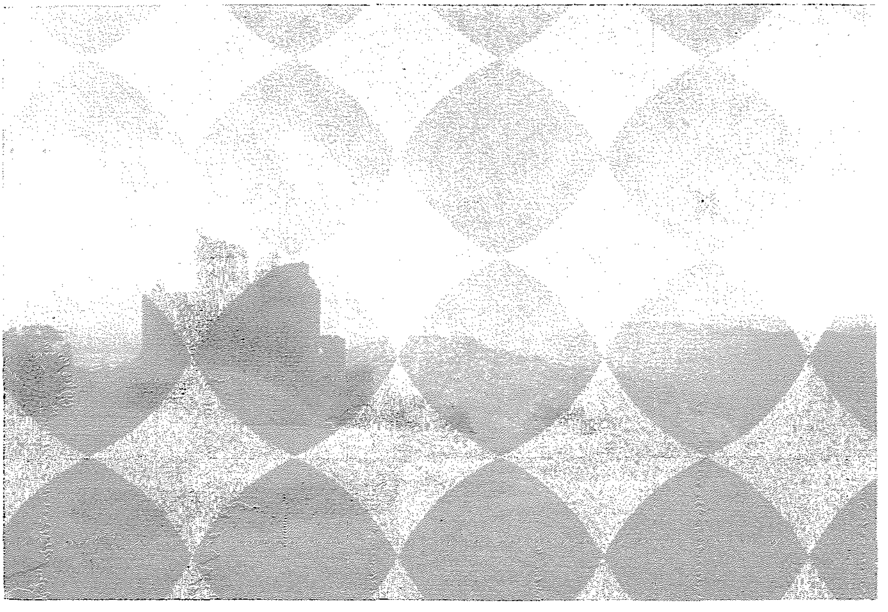

Fig. 3. Hollókő

Keeping this in mind, reconstruction must provide for a means to reach the top, a convenient top floor and intermediate floors. If trueness to style is attempted, floors are to be made of timber, according to the same principles as discussed in section 2.4.

All that has been said in this paper about the problems of structural design in monument preservation is just a sampling of the complex. A discussion in full details is only possible by presenting more actual instances and relevant designs. Structural research in the field of monument preservation, development of up-to-date methods of excavation, restoring strength of deteriorated materials, etc. are problems to be discussed in themselves.

Summary

The presented simple rules are likely to save structural designers and structural engineers engaged in monument preservation from serious mistakes.

Monument materials are characterized by lack of tensile strength, with its consequences on reductions in quality. Structures exhibit deficiencies and their systems and dimensions are uncertain, all these affect the stability of the monument. Co-ordination of the aspects of monument preservation and of structural design raises special problems.

Simple rules of universal validity can be formulated likely to be of help in the most frequent problems encountered in connection with the structural elements of monuments.