Intervention methodology on historical structures subject to distortions

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ABSTRACT: Differential subsidence in the ground causes phenomena of interaction between ground and structures which implies continuous modifications of the structures and their static schemes. Static strengthening works must secure the safety of the structures and accordingly be compatible with the unrelenting progress of distortions imposed by the ground. The present paper illustrates some methodology of interventions recently executed on Palazzo Poggi/Ca’ Grande dei Malvezzi, site of the Bologna University.

1 INTRODUCTION

The recurrent problems afflicting historical buildings are normally related to a variety of factors, such as antiquity of the structures, modifications and alterations made over the centuries, structural adjustments due to continuous usage and so on. The presence of differential subsidence in the ground further contributes to the deteriorating process, in that such phenomena apply distortions to the structures with an impact depending on their hyper-static condition.

The diagnosis procedure and subsequent choice of intervention strategies are subject to the need to identify the causes of structural damage, which is appropriately done by distinguishing causes related with gravitational cases from those due to differential movements imposed to the structure by the ground; the latter category of problems, the effects of which are often predominant, has been scarcely investigated in the technical literature. The reason for this lies probably in the fact that analytical procedures fail to describe these phenomena, which are associated with significant movements ultimately capable of disconnecting the structures.

In such cases the understanding of the structural behaviours should necessarily be guided by the analysis of a ‘conceptual model’ aiming to produce static suggestions that would fully explain the phenomena observed. This approach implies that static calculation is often inessential. The construction and the elaboration of the model takes place mainly during the phases of survey and investigation.

Structural strengthening and repair works must also safeguard the structural conditions over time, and accordingly the coexistence of structures and ground settlements. This end may be achieved making sure
that the structural schemes remains compatible with the deformation process imposed by the ground.

It goes without saying that every single structural intervention must comply with the architectural and historical constraints which necessarily determine what remedial methods may suitably be applied to buildings of monumental value.

2 MONUMENTAL BUILDINGS HOUSING THE UNIVERSITY OF BOLOGNA: HISTORICAL OVERVIEW AND STATIC CONDITIONS

The historical site of the University is among the oldest building complexes in Bologna, Figure 1. Its starting point was the conversion of the sixteenth-century Palazzo Poggi, formerly the private residence of Cardinal Giovanni Poggi, into the House of the Istituto delle Scienze in 1714 (Cavinà, 1988). An elaborate extension plan followed in subsequent years. The Astronomical Observatory Tower was realised in 1725 (Carlo Francesco Dotti); the University Library was built in 1756; the fifteenth-century palace Ca’ Grande dei Malvezzi was integrated in 1827 after major internal restructuring. The building which now houses the Istituto Giuridico completed the façade along Via Zamboni in 1931. Around the same years Paolo Arata designed the University Hall, which was subsequently annexed to Palazzo Poggi to make room for a library (Hall II). At present the complex stretches without structural break over the area bounded by Via Belmeloro, via Zamboni and Borgo di S. Giacomo, Figure 2.

The realisation of the University Museum in the Palazzo Poggi and Ca’ Grande Malvezzi (1999–2001) entailed intervening on a large section of the structures of the historical complex, according with the architectural design by Prof. Romeo Ballardini (†), Corrado Tossani and Roberto Scannavini. The restoration works repropose the old ‘Istituto delle Scienze’, the eldest University in Europe. In fact the structures were affected by the recurrent static problems that grew critical due to the differential subsidence characterising the ground in the north-eastern area of Bologna. Subsidence in the Bologna area concerns ground measures as deep as 100 meters, and the phenomenon is constantly being monitored through a topographical levelling network (Folloni, 1996). Some historical buildings have been monitored for over twenty years by means of a local network connected to the general survey network (Alessi, 1985; Alessi and Raffaglì, 1994). The state of affairs and related effects of the differential subsidence are illustrated in Figures 3 and 4.

Figures 5 and 6 show respectively the plan of the structures on the first floor (site of the museum) and on the second floor. The drawings focus on the most seriously damaged area, where the two buildings were originally joined together and give an overview of the information available on the complex of the structures.
Furthermore, keeping in mind the presence of distortions imposed to the structures by the ground, the analysis of these drawings would also facilitate the understanding of the main deformation behaviours. As a result, some typical static issues of the structures may be singled out as follow:

- the variable stiffness of the floor structures on their middle plane – this depends on their layout in plan and on the intrinsic stiffness of the various structural elements. As a result the static behaviours of the various parts of the building are different between each other.

- the non-existent continuity in plan for a number of inside walls – e.g. walls perpendicular to the front, or walls belonging to various buildings in their boundaries, or walls facing the main corridors, etc. Here the movement imposed by the ground is not contrasted by structural stiffness, and this gives rise to large movements. Thus attending phenomena may occur, such as (1) the bending of the transverse walls, which typically exhibit vertical cracks (2) the concentration of actions in the vaults, which are subject to local deformations and (3) the concentration of stresses in the heads of the wooden beams, and so on.

- the impact of walls built on the vaults – these walls have no structural continuity on the level below.

Such structures obstruct the free deformation of the vaults, and damage them much more than their own load. All the phenomena outlined above are signalled by typical localised cracks.
Figure 7. Crack patterns on the intrados due to the interaction of ground and structures.

Figure 8. Via Zamboni arcades, deformation of the tie bars (compressed).

Figure 9. Fissures on the walls and the vault due to the interaction between ground and structures.

Figure 10. Fissures on the cloister vault covering the Hall IV (second floor, intrados).

Figure 7 schematically sums up the most relevant crack patterns observed (looking at the intrados) in the horizontal structures of the first floor. The crack patterns mainly reveal tensile flows due to the interaction between ground and structures (Figures 8, 9 and 10) and, in some cases, also the cracks due to the load. It often happens that the overlap of further crack patterns occurs, such as cracks due to either structural peculiarities (e.g. flues, plugged hatches, etc.) or building practices (e.g. variable thickness of masonry structures, presence of ties, etc.). In some cases the cracks resulting from the above significant phenomena are puzzling and complicated to interpret. Familiarity with the structures as may be acquired through investigation and adequate knowledge of historical building practices – especially local practices – contributes to the correct interpretation of the cracks patterns observed.

Conservative techniques were employed for the structural repair and static strengthening of the overall building structure. Where required, specific interventions were designed to solve the problems of interaction between buildings inadequately connected, as illustrated below (paragraph 3); further local interventions concerning individual structures were designed to secure their compatibility with the distortions (paragraph 4).

3 ‘OVERALL’ INTERVENTIONS

Some complete structural joints have been realised in the areas where the historical structures were inadequately joined together with a view to restore their original static behaviour. Figure 11 shows the joint G1, which disconnects the two historical palaces Poggi and Ca’ Grande Malvezzi. The joint has been executed by cutting the additions detailed in Figure 2, without
affecting the older ones: the horizontal structures of the floor have been cut and appropriately supported, either by redoubling the bearing structures, or by realising sliding supports for the beams resting on historical walls. Subsequent to the execution of joint G1, the two edges of the disconnected walls got instantly closer by ca. 2 cm (measurements were taken on the level of the first floor). Furthermore effects of noticeable compressions were also observed on the ground floor pavement. The observation of these phenomena gave a qualitative indication of the high co-actions which affected the cut structures. In fact the structures were subject to compression stress generated by contrasting the ground settlements.

4 'LOCAL’ STRENGTHENING AND REPAIR WORK

4.1 Intervention on the exhibition halls dedicated to the explorer Ulisse Aldrovandi

The sixteenth-century core of Palazzo Poggi was built at an oblique angle with the front of via Zamboni (see Figure 12). As was customary at the time, an additional wall was built along the main front wall in order to normalise the shape of the interior. In this case, as result of the noticeable length of the Hall, this inside wall was progressively shifted from the front wall and rested on the subjacent vaults of the via Zamboni arcades (Figure 13). This determines the static importance of the wall. To make matters worse, the wooden trusses of the roof (Figure 14) appeared deteriorated in their bearing points, and moved down significantly (ca. 10 cm); furthermore, it also emerged that their bearing point had long been shifted form the front wall on the inside wall by way of temporary remedial work for safety sake. The same trusses support also the great roof vault of the hall by means of wooden suspension ties. The structure of the vault, consisting of the reed wattle vault and the wooden centings, appeared seriously deformed and

Figure 11. Structural joint G1 disconnecting the historical palaces Poggi and Malvezzi. Joint G2 disconnecting the Istituto Giuridico. Joint G3, to be executed in further works.

Figure 12. Ulisse Aldrovandi Hall. (a) Structures on the first floor level and (b) roof wooden structures and decorative reed wattle vault.

Figure 13. Section S1.
cracked as a result of the abovementioned movements of the trusses.

The following intervention works were planned and carried out:

- the bearing point of trusses was restored to its original position i.e. on the front wall. To that end, steel structures, lever functioning (Figures 15 and 16), were placed on the ends of the wooden tie-beams of the roof trusses. This levering action brought back the beams to their original level. The load on the arcade vaults was noticeably reduced, as shown by the decreased tension of their intrados tie-bars, which were monitored with strain gages in the course of the execution of the works.

- the reed wattle vault was reinforced by using traditional techniques, and subsequently suspended on the trusses by means of steel tie-rods, supported by thin beams (Figure 17), which were pre-tensioned in the assembly phase. The point of this operation was to limit the effect of eventual structural settlements on the reed wattle vault, since the pre-tensioned beams can restore the imposed deformations and offset the settlements.

All the structures added, assembled and pretensioned through screws may also be adjusted if required.

4.2 The strengthening of vaults covering the main entrance at 33, Via Zamboni

The roof vaults covering the main corridors in the entrance at 33, Via Zamboni are divided into regular bays separated by decorative arches (Figure 5). The geometry of the vaults varies in the different bays from barrel vault to ribbed vaults. The vaults showed crack patterns at their intrados. Their causes were difficult to interpret until the execution of the works. Once all floorings and fillings were removed (Figure 18), the vaults appeared to be the result of (1) early modifications of a unique barrel vault, which was divided into sectors through the insertion of the abovementioned arches, and (2) the reconstruction of some sectors by ribbed vaults. The majority of the arches were built of masonry and had tie-bars inserted at the extrados, whereas the two decorative arches placed over the monumental stairway of the Observatory Tower were built with sandstones appropriately shaped at the intrados.

Such features of the vaults fully account for the crack patterns observed. These were more evident due to the distortions imposed by the ground and to the large subsequent movements as allowed by the lack of continuity of the transverse walls.

The effects of the large deformations imposed are mainly (1) the relative translation and (2) the differential settlement of the springers of the vaults.
behaviours of the vaults, depending on their geometry. While the curvature of barrel vaults can change regularly, the rigid geometry of ribbed vaults forced them into disconnection, and sandstone arches must undergo deformations moving towards a cusp shape. We observed that this peculiar deformation of the stone arches had gradually uplifted the marble flooring (‘alla veneziana’) above. This latter damage phenomenon has been satisfactorily explained through the adoption of this model of structural deformations.

(b) the vertical translation of the springers (Figure 20) causes the arches to buckle and the extrados tie-bars to bend as a consequence of the opposition that the arches offer to their free movements. The effect is significant because the tie-bars (tie-plates) are placed on the plane of their maximum stiffness.

Work execution entailed that the old tie-bars were cut and replaced by new tie bars located on the plane of their minimum stiffness and spaced out by the structures and the finishes. Once cut, the tie-bars gave back the deformation impressed (Figure 21), and revealed a significant translation of the cut edges. This provided a clear indication of the relevant cutting-action constantly produced by the tie-bars on the masonry arches.
4.3 The cloister vaults of the Hall IV roof

The sequence of cloister vaults in the roof of Hall IV (Figure 6) were affected by complicated crack patterns, mainly concerning the horizontal mortar joints (Figure 10). The analysis of topographical surveys showed that the outer walls were subject to differential settlements which warp the ‘ideal’ spring plane (Figure 22). Cloister vaults are rigid structures which cannot follow the deformation of their spring plane and therefore they crack.

The phenomenon appears alongside the meridian lines corresponding to mortar joints, whose tensile strength is weak.

Therefore the only conservation works concerned re-pointing mortar joints, for no further reinforcement work involving an increase of stiffness was deemed compatible with the deformation conditions.

5 CONCLUSIONS

Old building structures have been able to survive precisely thanks to their attitude to endure deformations, which allow the structures to modify their structural scheme even through fissuring or cracking. We believe that strengthening and repair works must be undertaken in observance of the natural behaviour of the structures. It is with this philosophy in mind that the works on Palazzo Poggi here illustrated have been carried out avoiding an increase of the structural stiffness.

In fact the risk of brittle failures is increased when structures are strengthened, because they are hindered from releasing their tensile stress along with the unrelenting progress of the settlements. The behaviour of vaulted structures in particular imply that brittle cracks may be more treacherous than the formation and development of fissures. We should observe that the fissures, do indeed put into plain sight the structural problems, but in many cases do not involve immediate risk, unless the translations of the edges of the fissures themselves became incompatible with the thickness of the vaults.

We should note, if we may, that interventions which privilege an increase of stiffness are improperly done on historical structures, especially on those subject to distortions. In that sense we have to remark the inadequacy of alleged ‘innovative’ interventions which increase the stiffness of the structures through gluing of reduced-elasticity fibres. We should finally note that repairing the damages does not imply a solution of their causes.

REFERENCES