Relación entre peculiaridades constructivas y comportamiento estructural en los edificios de Venecia

Relations between constructive peculiarities and structural behavior in Venice buildings

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RESUMEN

En este texto, se describen sintéticamente algunas peculiaridades de la edificación residencial de Venecia, analizando su relación con el abanico de problemas estructurales que caracterizan el comportamiento estructural del edificio a lo largo del tiempo. Se aventura la hipótesis que las construcciones venecianas y, en particular, algunos de sus detalles, concebidos específicamente para la laguna donde se enclava, han sido objeto de una adaptación evolutiva a través de la observación de los problemas estructurales de los edificios precedentes. Los alarifes venecianos aprendieron a tener en cuenta el comportamiento estructural posterior del edificio, que previeron en cierta medida. Este proceso ha llevado a perfeccionar algunos detalles constructivos exclusivos de Venecia que han perdurado en el tiempo, que han resistido impertérritos a mutaciones de estilo y de configuración arquitectónica, hasta constituir elementos esenciales de un aparato indivisible y adaptable cuya interpretación, fruto de la investigación desarrollada en la Universidad IUAV de Venecia, se expone aquí de manera sucinta.

Palabras clave: Venecia; construcción; comportamiento estructural; patología estructural; concepción estructural

SUMMARY

Here we are synthetically describing some constructive peculiarities of Venice civil buildings, analyzing the relation with the features of their structural decay and behavior in the long run. We suppose Venetian buildings, especially those parts which are conceived to suit the lagoon environment, to have undergone an evolution made of some adjustments, which were based on the observation of damages in previous buildings. That is we suppose ancient builders to rely on their awareness of the behavior of structures yet to come, and to be able to forecast it in part. This process brought some building contrivances to perfection, as exclusive and enduring features of Venice, overcoming changes in style and architectural layout, till they grew into essential elements of a whole and adaptable "device". This writing is meant for a concise interpretation of this device, which is the result of some research works carried out at Venice IUAV University.

Keywords: Venice; construction; structural behavior; structural damage; structural conception

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1. PREFACE

Venice has always been a strongly autonomous and self-conservative "technical milieu" whose traits, sporadically standing out, arouse heated debates about its peculiar nature, between people living in Venice, who have no need to explain each other their own mentality and deeply rooted technical customs, and those ones coming from outside the lagoon, who usually put this technical knowledge in discussion, after a comparison with their own one. An example of such discussions is the debate that arose before the rebuilding of the Palace of the Doges, in G. Lupo, (1).

Venice has been analyzed in different ways during the last two centuries. Despite this, is a singular thing the rarity of studies about the modes (2), materials and techniques which almost twenty thousand houses are built of, that is about the constructive "material culture" of Venice.

A series of studies, carried out at Venice IUAV University during the last years (3), tried to look at Venice building with a renewed objectiveness, searching those constructive principles which let them hold on with the passing of the time, adapting themselves to a particularly hostile environment, made of water immersion and soft ground. The different component parts were analyzed – wooden foundations, walls made of very small or very big bricks, floors with parallel beams... - in order to characterize them and underline the common traits and differences in comparison with other inland towns, like Padua and Verona. Several endemic peculiarities of Venice were deepened, such as buildings forms, materials and ways of building the different parts, searching for a non-usual link to the forms of structural disorder: the way the building reacted by adapting itself to the soft ground and lagoon environment was surveyed and classified. This comparison aims at verifying the hypothesis Venice construction to be a kind of device, which slowly gained perfection, taking account of the behavior of former buildings and adding those contrivances to re-address and make it better in the future, enacting a sort of technical evolutionism.

We don't expect this writing to explain all the solutions that "the Venice construction" had in the course of time, but to focus on its most evident - sometime exclusive - peculiarities, that came out from these studies. It deals with less gaudy characters, which were most of all revealed by a comparative examination, because they elude a simple observation of the pure architectural im-

age, even if they deeply contribute to give Venice "diversity" and uniqueness some substance.

2. DETECTING THE WAY OF BUILDING THROUGH THE OBSERVATION OF THE BEHAVIOR IN THE LONG RUN

Following the common sense, Venice main peculiarity is the fact it was built upon wooden stakes, sunk in the soft ground of the lagoon. However one doesn't know very much about this complex system of distributed support, because complete surveys and documentations and direct analysis of Venice foundations below the sea level are still rare.

Short and thick poles pounded in the ground are entrusted the task of constipating the ground and of acting as a base for thick and big larch planks, called *madieri*, which are often crossed each other and supporting the brick foundation, usually laid more than one meter deeper than the medium sea level and whose base is up to five times larger than the upper wall.

Steps on both sides make the foundation gradually taper and sometimes there is one stone layer or more, called *regoloni*, at the foot of the thinner wall placed higher. Following a study of 15th Century building accounts, one meter foundation needed 2.350 bricks, the equivalent of a bigger part of the building raising above.

Such foundations are just a peculiarity but they are not the sole features of Venice "specificity". On the contrary, we think the parts standing out of the ground are as peculiar and "different" as these foundations which they rest on, and the different parts together make up an unitary organism.

We can measure the "diversity" of Venice as well as its analogies and consonances by comparison, first of all with the inland and not too far towns as Padua, Verona, Treviso, but also with much more distant places in the Mediterranean, such as Constantinople, which had a lot of exchanges with Venice, especially in the Middle Ages.

No complete research of the "credits of constructive culture", that is of the one-sided or mutual influences, besides style and architectural references, has been performed so far but, anyway, such a study should begin from the deepest knowledge of the way of building in the course of time, in both cultural areas.

The first peculiarity applies to brickworks, the most widespread element the town is totally

made of, besides stone and wood. Few other places have such a range of bricks, with different dimensions, shape, mixture, color ..., and textures consequently. The reason can be found in the fact that Venice, which was rebuilt in brickwork between the 13th and 14th century, after the big fires that devastated it during the 12th century (5), wasn't able to manufacture bricks in a large scale; thus it was compelled to reuse brick coming from roman or byzantine ruined towns at first, and then to import them from far places as Padua and Ferrara, especially during those periods of intense building activity.

While Venice manufactured bricks were sized following local rules dated since the beginning of the 13th century, those ones coming from far places had shapes which were based on the customs of the town of origin.

Talking about Venice as a Babel, as what concerns bricks variety, is not an hyperbola, and it is almost impossible here, unlike other places, to elaborate a dimensional chronology, as an even meaningful attempt seems to prove: «Looking at the curve mensiochronology seems hardly to apply in Venice before the late Middle Ages, as the first brick-works show a great number of different shapes at the same time. (...) Things are even more confused in civil buildings, where the most distinctive brick is the *altinella* (...)». [translation from F. Varosio, (6)].

Besides the "picturesque", which is doubtlessly given the city by this wide range of bricks, especially when they are worn out by time and decay, we have an interest in following their contribution to the brickwork and to its evolution and progressive specialization.

After a first period of reusing bricks in masonry walls, which were necessarily irregular and provided with huge mortar layers, and that ceased during the 12th- beginning of the 13th century, during the 13th century new bricks got the upper hand, above all those small sized ones – the 14th century documents called "*ad mensuram parvam*" – among which there is a typical Venice brick, later called "*altinella*", whose dimensions were about 16x8x5 cm.(7). It was used during the 14th century to build accurate exposed walls, with well-finished mortar layers and it has often a grinding surface processing; but it is difficult to interweave these small bricks and the core of the wall is rather chaotic and rich in mortar.

Frequent wall parting, we ourselves observed, must have contributed to the relinquishment of this brick and of the wider and

rich-in-mortar wall which was connected to it, in favor of a thin and more specialized wall, with a wholly interwoven and homogeneous nucleus, made of bricks "*ad mensuram magnam*", the big bricks up to 28.5x8x14 cm, which a great part of the big gothic palaces of the 15th century were built of. (figure 1) It is worth notice that there is an almost six times difference in volume between the smallest and the biggest bricks and, in the middle, a great deal of halfway sizes for special use (for foundations, fireplaces, pits ...). But the prevalence of slim and well-interwoven walls with a modicum of mortar is the main consequence, after a period we suppose to have a byzantine ancestry, in which there were reused or small and slight bricks and thick mortar: a three or two heads thickness (40-42 and 26-28 cm) was usually adopted to raise walls up to 15 meters high.

This was also functional to reduce the loads weighing on the foundations, but some steadiness problems related to the thinness of walls raised.

If bricks are the connective tissue, the Istria stone (8), the compact limestone which Venice got indissolubly married to since 1260, was entrusted some special tasks in a wall that was specialized itself. Stone was usually given the function and placement as basement, opening contour, frame, *fiuba* head (we'll see the meaning of this term later), eaves, corner pieces, *barbacane* console and balcony; besides the fretwork multiple-windows.

Doors and windows bring out the contribution of stone frames to the architectural and structural layout, as well as the role of confining stresses at the edge of the thin walls (9), channeling them and making the loads-and-reactions self-locking effect easier, through three-quin arches. However the structure can keep some adaptability, warping without losing its efficiency against foundation differential subsiding. The monolithic sides of windows and the frames themselves act as ribs in the thin walls, which help in contrasting their potential disbandment.

Venice technical endemism, compared to the nearby towns, is stronger just in relation to the feedback about this problem – that is the stabilization of thin overhanging façade walls.

We observe tens, or rather, hundreds of thousands *fiube* (10) (11) in Venice houses, such stone heads with metal hooks connecting front walls and wooden floors inside (figure 2), while we can count on the fingers of one hand the examples of this structural tie in the inland towns, most of

1. There is almost six times difference in volume between the smallest brick, called *altinella* (16.5x8x5), which was mostly used in Venice in the 14th century masonries, and the biggest one (28.5x14x7.5), which was used in 15th century buildings. Between these two extremes, a great variety of intermediate shaped bricks was used in the course of time.

2. The typical Venetian iron and Istria-stone connection, between the facades and inner floors, called *fiuba*, is often subject to oxidization.

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3. In this ancient building (Palazzo Zane in Campo Santa Maria Mater Domini, end 13th-beginning of the 14th century) the white stone head of the three fiube are included in the decorations made of sculpted paterae and Byzantine crosses, above the multiple window.

4. One of the latest cases of fiube following the venetian tradition in a 19th-20th century building with concrete structures.

which were commissioned by Venetians. The term *fiuba*, which means buckle in the ancient venetian language, has been used since the 14th century to name the stone and metal head connecting the external wall, in which it is built, with the inner wooden floors.

This technique doesn't obviously come from the nearby *terra firma*, where it is a really rare feature: it could also be influenced by even more distant Mediterranean or over the Alps towns, or it could come from ship-building; or, again, from the lost wooden framework houses.

The fact is that this is a peculiar building feature of Venice construction, whose role as a stabilizer of thin walls is essential.

The head of the *fiuba* is made of a rectangular 15-20 cm high, 50-70 cm wide and 20-30 cm deep Istria-stone quoin, which is linked and often fixed with lead to a wrought iron hook, lying in an hollow along the lower or upper side. It is sometimes visible from outside (these details kept on varying in the course of time) and gets through the wall, turning into about a meter long blade, fixed to the planks and beams of the wooden floor by means of drop-forged nails.

The stone piece is built together with the wall itself right from the beginning, and, in this way, it proves to be linked to the inner floor, whose beams usually don't rest on the façades but only on the side and inner walls.

The first applications of this device we know are in "double-case" bell towers, such as St.Salvador's and the Jesuits, former Cross-bearers church, both of them built in the first years of the 13th century, a few years after the conquest of Constantinople by the Venetians (1204). Their appearance in the most ancient civil buildings, dating between 13th and the beginning of the 14th century, (figure 3) is a nonstop presence, steadily enduring without big changes for over six centuries, till the edge of the 20th century, when it appears in concrete buildings too (Figure 4).

Another peculiarity of *fiube* is the position in the building: mainly, but not solely, they lie on the façade and on the inner front, on which no floor beam is usually resting. By the corner *fiube* are made of couples of stone quoins, linked to the adjoining walls and placed a little far from the inner walls. Every clear stretch of the façade, corresponding to an inner room, is connected by

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two intermediate *fiube*, placed in axis with the multiple windows, or at the opposite ends of the windows or of the inner fireplace, that is in those points where the vertical load gathers and the stone block jammed in the wall is more effective. It's a peculiar thing that these connections are far from the junction between façade and inner bearing wall, which is usually – but we don't know how frequently – disconnected, that is they are simply leaning against each other.

This is another Venice peculiarity, which apparently controverts the persistent presence of *fiube* connections. Synthetically, the façade walls are linked to the wooden floors, that are themselves connected with the inner bearing walls, which they are resting on: floors are the mutual indirect connecting element between external walls and the inner "body" of the building.

Why did they pervasively connect walls and floors and, on the other side, why did they avoid any link between walls, that is the first rule following the usual constructive principles?

Perhaps we can find an answer in the fact that facades had different foundations, often deeper and built on a channel, making up a kind of "structural-and-hydraulic enclosure" for the building, differing from the inner wall foundations, which were less wide and deep, thus bound to a stronger subsiding, sinking lower than the external walls.

A reason to avoid the link with the facades is just the widespread differential subsiding of inner bearing walls (Figure 5): it was probably taken for granted or even meant to happen since the beginning of the building, and the structural disorder was simply made easier, letting the inner bearing walls sink and almost slip off, without cracking too much and, above all, without giving rise to any discharge-arching thrust (Figure 6).

Furthermore, such a position of fiube let them begin to pull when both floors sloped downwards, despite a partial retaining near the façade, and inner walls bearing the beams, sunk. This combined, so-called "self-locking" action (Figures 7a-7b) was meant to hinder effectively the deformation of the slim façades as if they were sails, that is the dangerous tendency to warp free outside.

Another Venice peculiarity is the widespread presence of inward leaning buildings. We have been wondering about the origin and nature of such shapes (12) mostly with 1,5-2 cm/m slope but sometimes they reach such huge inclination as 4-5 cm/m and the façade seems to lean on the inner walls and floors.

We aim at the cognitive and diagnostic objective (13) of estimating, for Venice buildings, which one of these three hypothesis we can rely on best:

1. The inward leaning shape is a deformation coming from a structural damage after building;
2. It is, on the contrary, the result of an intentional geometrical shape given the building since the beginning of the building process.
3. It is an hybrid outcome of an evolution in deforming through the time, which is related to the structural damage of a building that had an irregular geometry since its origin.

In the supposition it is an almost partially original arrangement, we have to wonder if it is an intentional artifice (hypothesis 2a), and what its purpose is, or if it is an unintentional building inaccuracy (hypothesis 2b).

We don't know about any general treatise existing about this constructive geometrical aspect, that certainly is not a Venice exclusive, but that is particularly widespread in this town.

Following the results of the research, testing some meaningful buildings, we aimed at clearing up the edges and links between construction and structural disorder, between physiological, or typical of the building, and pathological, that is the result of a wrong and potentially dangerous behavior.

5. The bearing wall structural disorder is a process due to a greater compliance of the foundations-ground system, that gives rise to a vertical translation and to an arch-shaped cracking pushing the facades outside.

6. The so-called "arching thrust" structural damage seen on a bearing wall in Ca' Zusto. The lower part of the wall is not connected to the façade while the upper part seems to be.

8a

8b

7a and 7b. The “self-locking effect” of *fiube*, before and after the vertical translation of the bearing walls, as it was outlined by Michele Bondanelli.

We need to understand the diagnostic border line between the initial shape and the contribution of a structural disorder; to develop a sort of case history tracing the evolution of the building first shape, of the following and mutually related structural damages and maybe, of the past repairs. Usually, the effects of a structural disorder are analyzed making a survey of cracks and deformations (14), that is a description and measure of the gap in reference to the regular geometry coming from the rules of good building (uprightness and flatness of walls, horizontal floors, and so on). In this case the “rule” should be “suspended”, waiting for some elements coming out of the research and explaining which was the initial “regular” geometry: this is a pre-diagnostic passage which is necessary to measure the following modifications.

It was deemed necessary for this in-depth examination to prove at least some of these inward-leaning shape to be intentional (hypothesis 2a), as a consequence of an initial and conscious constructive device.

This cannot dismiss the idea that other inward leaning buildings could be only a result of a structural damage (hypothesis 1), but they could also be related to the hypothesis 3 (building-and-damage hybrid genesis).

A large scale survey brought a first ranking of the geometrically irregular shapes which

were outlined by means of sections across the façade (Figure 8) and surrounding conditions:

- type a) constantly inward leaning outline;
- type b) broken line shape with an initial vertical segment and an inward leaning upper segment;
- type c) broken line shape with an initial overhanging segment and an inward leaning upper segment.

These most common shapes can be added to:

- type d) vertical shape till the first floor and then inward leaning, and again vertical shape;
- type e) external step-tapered inward leaning (only one case that came out of an architectural adjustment of a previous inward leaning building);
- type f) inward leaning shape from the ground floor to the first roof and upper vertical shape.

We focused on a) and b) outline buildings, as we think the c) type is the result of a damage process of a type b) building or even of a vertical one, that is one of those existing regular buildings whose façades are not off plumb.

From a logical and methodological point of view, we think the demonstration should be based on several concordant factors:

- In the negative, we must prove the inward leaning to be partially, if not totally, incompatible with a structural disorder;
- In the positive, we must pinpoint the existing building elements showing the willingness to obtain an inward leaning geometry.

Some buildings were chosen for an in-depth examination, as they had an high stratigraphic-and-constructive legibility, that is their surfaces and architectural elements let us detect the presence of evidences pointing to the initial condition, as well as to the following changes, and damages and repairs as well.

These buildings are still keeping initial stone elements almost intact or just subjected to some recognizable transformations.

Furthermore, there is an inward leaning wall in at least two adjoining sides of these selected buildings, a fact that makes the hypothesis of a roto-translation as a “rigid-block” of the whole at an angle rather unconvincing, even if this shifting movement can sometimes occur.

For example, the facade of Ca' Corner de la Frescada, (Figures 9 and 10) a gothic building dated the first half of the 15th century, is from 34 to 38 cm constantly leaning inward (outline type A), that is in a ratio of 2 and 3% with relation to its height; the side wall is leaning as well but only 18 cm, that is 1%. We could dismiss the phenomenon of the rigid rotation of the whole building, as the ancient floors are still laying flat, and structural disorder is moderate, a fact that makes the role of the inward leaning of the facades marginal. The gothic windows, with their well-preserved stone elements, let us observe a particular constructive device, placed where the stone pillars rest on the sill; these ones are made up of a big monolithic element, and have a carefully manufactured oblique relief, whose purpose is forming a perpendicular support to the axis of the jamb which follows the inward leaning façade.

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We were doubtful about the fact that these oblique reliefs could be the result of a jamb reworking to reduce the surface and ease the outflow of rainwater. Yet, if we observe the side of the gothic jamb, the upper stripe of the frame has a constant height and is often outward leaning itself: so we can dismiss, in the examined cases, the idea that the leaning reliefs on the window jambs can be the consequence of a rework to lower the stone.

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We think the particular stereotomy of the window jambs (Figure 11), that since their origin are so molded as to let windows follow the leaning facade wall, is a sure sign that the inward leaning shape is intentional; the flatness of the floor and the absence of considerable cracks, let us exclude structural damage as the main component of this phenomenon. On the contrary, such elements support the hypothesis the inward leaning façade on the channel of Ca' Corner della Frescada to be initial and intentionally performed.

The three adjoining fronts of the 13th century Soranzo Pisani palace in S. Agostin (Figure 12) have a type B) outline, that is vertical till the first level and then strongly inward leaning, above the big gothic stone portal, which has a vertical arrangement

8. Outline schemes of the observed inward leaning arrangements.

9. Ca' Corner de la Frescada. Inward-leaning amounts (A type outline, constant leaning) of the facade (from 38 to 34 cm.) and of the side wall (18 cm).

10. Ca' Corner de la Frescada. Inward-leaning amounts (A type outline, constant leaning) of the facade (from 38 to 34 cm.) and of the side wall (18 cm).

11. Palazzo Soranzo in S. Stin (14th century). The constructive sloping relief of the plane gothic window-sill provides the inward leaning window-pier with a perpendicular base.

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12. Palazzo Soranzo in S. Stin (14th century). The constructive sloping relief of the plane gothic window-sill provides the inward leaning window-pier with a perpendicular base.

13. The inner oxidization of the metal element of an ancient fiuba (14th century) brings about the ejection and the separation of part of the external brick wall. Such phenomena show the connection between wall and floors, which is an essential feature of venetian construction, is going to be lacking.

14. Ca' Corner de la Frescada. See the position of stone-headed visible fiube, which are situated on the corner or in a trait of the facade between two perpendicular walls, and that one of the iron-headed tie-rods, which were put in afterwards on the corner or by the sides of the bearing walls.

and is placed crosswise on the short middle side, which is as large as the door. Some stratigraphic surveys were carried out and it turned out the portal with the big carved stone relief above, the stone-and-brick corner pieces connecting the cross side to the two main fronts to belong to the initial constructive phase. The bricks themselves, which are small ("altinelle") and homogeneous, can be related to the period the sculpted slab was made.

The three fronts, (whose survey was made by IUAV Photogrammetry Laboratory), were outlined and an inward leaning between 12 and 47 cm was detected, that is more than 3%. The three incident fronts being from the first level inward leaning, engender a sort of truncated pyramid resting on a prism.

This arrangement make us exclude the inward leaning to be mostly caused by a structural disorder, that is a partial or "rigid-block" roto-translation of the building: the short crosswise façade has a strongly trapezoid shape, 284 cm wide by the portal lintel and 268 cm next to the eaves.

As the enlargement due to the lintel cracking is 40 mm at most, and it is well detectable, because the lintel is a big as wide as the front stone element; and as the upper wall can't be compressed – it can enlarge because of cracking, but it cannot decrease very much – then the differential can't be caused by anything but the initial constructive shape.

In addition, the trapezoid shape of the mould stone quoin next to the slab (mm 305 at the bottom and 282 mm on top) is a confirmation, as the stone surface has never been reworked.

The nature and dimension of the cracks on the crosswise basement (whose amount doesn't exceed 40 mm or so, as we said before) cannot explain the considerable inward leaning of the side fronts (from 21 to 47 cm). Nor are there cracks on the upper wall made of altinelle.

Such observations, together with the particular morphology coming from the polygonal layout, let us suppose the inward leaning shape of the three adjoining fronts to be an initial and intentional constructive arrangement, and admit only a limited contribution by structural disorder.

Perhaps we've not prove it yet, but at least we think we have highlighted some meaningful arguments in support of the hypothesis the inward leaning to be initial and intentional, showing some constructive details that we found in several other buildings afterwards.

Yet this arrangement is not a "rule", its extent is variable and it is bigger in Veneto-byzantine and gothic buildings however. We have to acknowledge we have not been able yet to explain the reasons persuasively why builders adopted it in the old time and then they gradually mitigated it, without completely abandoning it.

Maybe it is an arrangement in order to hinder the most frightful effect in advance, that is the sloping out of plumb. This arrangement allowed buildings, especially those ones looking on a channel, to have a bigger load on the inner part of the foundation, which was less subject to the water. It also let the load on the external walls be almost axial, as their thickness went on decreasing step by step on the inner side at any level. But we haven't any complete and careful surveys of the actual wall section, net of inner plasters and brick-covers to straighten up the inner side.

The matter seems more complex if we consider that the type b) outline – straight basement and inward leaning façade from the first level upward – has engendered, in Venice buildings, a particularly unfavorable load distribution, where loads gather on the inner side of the wall and make it buckle under a pressure-flexure mechanism.

The fiube can only partially hinder the outward displacement as, by the first level, they are also subject to rising damp that makes the iron rod oxidize till a complete corrosion (Figure 13).

In the course of time thousands of tie rods with external metal heads, have been applied and are still being applied on the front walls, to hinder one of the most insidious and diffused damage-mechanisms in Venice buildings, that is the bulging of the part of the façade next to the first floor (Figure 14). The type c) outline, where the basement up to the first floor is out of plumb and the upper part is strongly leaning inward, seems to be the pathological evolution of an irregular but intentional type b) outline.

A change occurs with regard to the position of the tie rods, which were applied after that fiube deteriorated or as a reinforcement pursuant to a structural disorder: they are longer, still nailed into the lower side of the wooden floor, but they are mostly placed next to the corner and the inner bearing walls, which the fiube used to stay far from. Venice buildings are places where structural devices have been stratified in the course of time, functionally replacing or complementing the former ones, but never removing them.

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They are also the evidence of a careful “structural maintenance”, that is able to catch the alarm signs in the course of time and capable of a prompt intervention, as if the idea of the “way of functioning” of the house would not have concerned only the initial builders but as if it were a sort of consciousness coming from a widespread mind-set on the part of the owners and inhabitants as well.

But we have much to clarify about the reasons (maybe functional ones) that may have lead to raise type B or “broken line” inward-leaning buildings intentionally, which were subject to turn into the dangerous type C shape – that can be present in plumb-line buildings as well, but with a different and recognizable geometry (Figure 15).

We think the awareness of the expected behavior, by means of the observation of the active damages, biased the choices of venetian builders and their improvements in the course of time, giving them this firm consciousness, which became steady and that comes out clearly in the way repairs/strengthening were conceived and applied in the past.

For example, the leaded metal forks connecting two contiguous stone pillars and hindering their displacement, look like a careful and mutual assistance between elements (Figure 16); or the tie rods looks like “strained piston rod” which are applied to a corner pillar or to an abutment and locked on a stone inserted in the wall at a certain distance.

These devices grant the system some levels of freedom, without stiffening it needlessly and making those displacements possible, which are deemed not dangerous; thus they reveal a full comprehension of the acting mechanism and the awareness of the necessary and sufficient mean to contrast it, mobilizing the building resistant resources to help the stressed point.

It is important to note that these devices exceed, somehow including it, the pure repair of damages occurred and they act as a corrective integration of the initial arrangement, which is in condition to prevent the future progress of the damage or of the mechanism.

These interventions, that are almost naturally displayed, are a typical venetian way, not very much diffused in other places, nor in the inland parts of Veneto, to neutralize the structural disorder “stone with stone” by means of metalwork. It is the counterpart,

in the shape of a tie rod, of the “crutch” which John Ruskin preferred as a means to contrast the decay.

Going back to Venice constructive peculiarities, we can investigate roofs (15) and wooden floors (16). The wooden horizontal elements in Venice – there are vaulted ceilings – are usually very well manufactured and have a considerable section, which is bigger in proportion to the terra firma, where, indeed, the huge amount of coniferous woods came from – most of all fir and larch – necessary for the buildings of the city.

The main peculiarity of wooden floors is the single-frame structure, that is made up of a single series of parallel beams resting on both walls (Figure 17).

This “comb-like” arrangement, crowded with beams is advantageous for Venice, because it allows an homogenous distributions of loads on the inner and side walls, as the main facades are usually left free.

By the fulcrum of big beams there are no concentrated loads pushing. We have to say that single-frame floors make the bearing wall parallel and straight, in order to keep the span constant and not too wide, that is shorter than double-frame floors are able to allow.

This choice certainly concurred to that “celled” organization, with long and narrow cells which are the fundamental architectural-structural element of Venice buildings of a ripe age.

In lieu of a row of bricks under the beams, a thin larch joist, called rema, is often included in the wall (that must be straight); and beams are nailed down on the “rema”, that acts as a mutual anchorage between beam and wall, for a further partition of an already distributed load, or as a shrinkable structure making masonry somehow tensile.

Two or three layers of big and pervasively nailed planks lay upon the beams and, together with the thick mortar bed of the flooring superimposed, they allow the floor to act effectively as a plate with a little warp in its plane. A very useful element connecting walls mutually, even by means of the fiube applied on the façade, but that is able to absorb the differential sinking of the walls resting on it, as it keeps deformable with regard to the strains acting out of its plane.

Roofs have peculiar features as well. They are generally four-pitched hip-roofs and they are supported by a thick series of tres-

15. Palazzo Zane in Campo Santa Maria Mater Domini (13th-14th century). The C type outline (out-of-plumb till the first floor and inward-leaning upper part) is probably due to a structural disorder in a building that had an initial B type outline (that is vertical till the first floor, with an intentional inward leaning in the upper part). In the course of time this damage process, which was widespread in Venice, was contrasted by means of several iron-plate or stake tie-rods.

16. An old metal “forked” cramp was applied with lead to the quoins in order to contrast the movement of the corner.

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17 Palazzo Grimani in Santa Maria Formosa. The 15th century single-framed wooden floor in the 18th century decorated hall.

18. Drawing by Michele Bon-danelli showing the wooden roof structures and the two main wooden floors of Palazzo Pisani in Santa Marina. The fiube metal connections, which were observed or detected by a geo-radar inner inspection, are underlined.

ties which look like trusses apparently, but they have no lower chain or restraining element, as they rest on the upper floor, that is – in Venice but not in the inland – placed at the same level as the eaves (Figure 18). The inclined struts of the roofing structure are connected to some chain-stretches which rest and are nailed down into the last floor. In this way the floor is able to absorb horizontal thrusts and to act both as a floor and as a structural part of the roof, which is almost joining and merging together with the floor itself. The floor also partially gathers loads coming from the roof, reducing the flexion of the struts as well as the thrusts against the eaves stone elements, by means of some short wooden pillars called “colon-nelli”, which looks like posts but have another function actually.

We wonder which “constructive device” and whole “structural conception” – reminding the Italian translation of Eduardo Torracca’s writing title (17)- all the solutions we noticed are referring to (18).

First of all, between load concentration and load distribution, the maximum distribution is prevailing, both where the whole building rests on the soft ground and as for floors and roof settled on the walls.

Usually there are stone elements by the points and lines where loads gather, and the use of stone is precise and specialized, first of all from a structural point of view, more than with respect to the architectural ornament.

On the other hand, walls are rather specialized than undifferentiated as well, often they are thin and slim in comparison with those ones in the inland and in the rest of Italy, which are usually made of two stone or brick leaves with a masonry nucleus inside. The specialization is not initial but comes after the former and more disordered masonry-work was left behind and it enables a lighter load weighing on the foundations; the fiube with their hooks act as a thick net of restraining points, with a self-locking effect, just in order to prevent thin walls from warping and getting unstable: when the inner walls sink, and they often sink, front walls turn out to be efficiently fastened.

We usually think about masonry-work as highly rigid structures, so stiff as to make breaking unlikely, that is a fragile way of breaking anyway.

In Venice, masonry-works have a rigid-and-fragile behavior, as well, but many of the devices and solutions we’ve seen are meant to allow warping behaviors, as if they pursued an overall ductility, in order to follow, even through some cracks and adaptations, the differential ground sinking.

There are joints between facades and inner bearing walls where discontinuity is planned, such joints making respective translations easier; as well as it’s no coincidence the permanence in Venice of arched openings till the 17th century, a century over than in the inland, where they had already been replaced by lintels. As two-dimensional structures, acting in the same plane of the wall, arches can re-address vertical loads, concurring to engender the self-locking system; the prevailing structure of the three-pieces arch, that is a constant in venetian-byzantine, gothic, Renaissance and seven-teenth-century windows, let them adjust to the differential sinking, opening one or

more of the joints between the stones or at the base, that are four hinges, and deforming the arch without breaking its stone pieces; this system, which is tightened by the brickwork resting on it, does not lose its overall structural functionality. Thus, doors and windows arches are highly adaptable structures, which are able to fit themselves to the deformation acting in the plane of the walls they belong to, walls that they keep on restraining themselves, despite the structural disorder.

The façade walls are thin and furthermore they often contain a fireplace, placed between the two main windows, and drain pipes as well. Inevitably, they behave as fragile structures, going beyond both the elastic and plastic response threshold, this last one being very important in brickworks (19); though they keep most part of their efficiency even after they've reached the breaking point: both in their plane, thanks to the windows and arch frames; and perpendicularly, by means of the thick net of retaining *fiube*. There is a kind of overall "ductile behavior" of the structure, that has a sort of "granted but controlled adaptability", even after the structural disorder has gone over the threshold the walls and single elements behave as fragile structure and break.

In the light of these and some others remarks, more than masonry boxes made of rigid diaphragms, venetian buildings look like a whole of horizontal and vertical "membranes", mutually linked by means of a thick net of punctual connections; deformation is granted, but only if mitigated and confined, and this fact protracts the maintaining of the efficiency, even in the case of collapse. As if, besides a structural resistance, there were a kind of resilience, that is the capacity of a natural system to recover its own vital organization, even after it has undergone a severe external upset.

Behavior in the course of time, structural disorder and resettlement (20) seem to be connected and complementary aspects.

Two cases of partial collapse of buildings placed on a channel by Campo S. Barnaba, which occurred during the last twenty years, can support this hypothesis (21).

In both cases, the lower part of the facade fell almost completely down into the channel, overturning but forming a long arch that enabled the upper part of the front to hang without collapsing.

Besides the causes of the collapse, we suppose to be related to the erosion of the foundation poles, as we can see in some pictures, it is amazing how so a severe collapse could stop without leading the two buildings to a

complete ruin. Maybe it was a stroke of luck or a sort of miracle deserving a traditional *ex-voto*; but the fact is that both the collapses, which very similar one another, just begun but then they were kept under control and interrupted by *fiube*, anchor-elements and distributed loads, so far as to avoid causing damages to people and to make a complete rebuilding possible. The two houses were repaired, rebuilding the stretch of foundation and the lower part of the façade.

In conclusion, we can do some remarks.

The Venetian buildings have such marked constructive peculiarities, so as to distinguish themselves both from the housing on *terra firma* and from the buildings of other Italian towns

Among these distinctive features, we can point out particularly:

- The exclusive use of slight and well connected brickwork, forming thin and slender walls;
- The wide net of devices keeping the facades steady and made of stone-and-iron elements which are connected to the wooden floors (*fiube*);
- The utmost distribution of the loads coming from roofs (by means of thin structures at close range) and wooden floors (with a peculiar single-direction arrangement of the beams) on the masonry walls;
- The presence of bearing-walls which are intentionally disconnected from the façade (whose percentage of diffusion we don't know), so as to allow inner walls to sink most;
- The use of Istria-stone frames to channel and concentrate the loads, allowing the presence of wide doors and windows on the facades;
- The presence, up to the 16th century at least, of an inward leaning of the facades, which is supposed to be intentional and whose rate and reasons we don't exactly.

A set of structural damages corresponds to such peculiar features, distinguishing itself by the presence of some diffused forms (the inner bearing-wall strongly sinking, a horizontal translation of the corner, a "broken line" layout of the facade, with the basement being off-plumb and the upper part inward leaning) and by the rarity of other kinds of structural damage (for example the façade or corner being entirely out of plumb).

The weakening of the connections between the floors and the facades, because of the physical decay of metal, gives rise to a strong concern, as they play an essential role in the balance keeping, obviously together with

the dangerous damage of the foundation, and with the decay of the brickwork, once it is subjected to the aggressive seawater.

This “constructive device”, which is “flexible but soft” turned out to be able to fit the environment, in good part preserving

its efficiency in the course of time. This is the reason why it's advisable for our restoration and strengthening interventions to be conceived as a “structural maintenance”, repairing the damaged elements and contrasting the structural decay without radically changing the behavior of the whole.

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