Venetian Buildings Are “of” and Not “on” the Lagoon

Paolo Foraboschi

Department of Architecture Construction Conservation; Università IUAV di Venezia, Dorsoduro 2206, 30123, Venice, Italy

Abstract: This paper demonstrates that Venetian architecture was the result of specifically conceived structural mechanics and construction techniques, which allowed structural design to take full advantage of materials. Venice witnessed the creation of “structural art” that drastically reduced the incidences of failure caused by extremely soft soils and aggressive environment, which extended the operating horizons of masonry and timber structural materials to the extent that very bold structures were obtained also before the preeminent materials of modern structures. While normal masonry constructions can be governed by Euclidean geometry, Venetian buildings are far more complex and elusive in form. Venice and its architecture can be interpreted and comprehended only in the remit of structural engineering, which played a central role in enabling the construction of the city. The fundamental determinants of Venetian building morphology—the underlying logic of form in architecture, entailed a tectonic form midway between the masonry construction and the skeletal structure.

Key words: Brackish water, skeletal masonry, soil settlement, space-saving structures, weight-saving structures.

1. Introduction

The concept of style to denote the idea that the art or architecture of a particular period shares a recognizable set of characteristics is relatively recent. It stems from the so-called “father of art history”, the German scholar Johann Joachim Winkelmann (1717-68) who proposed an influential biological conception of style as having a birth, maturity, decline, and eventually disappearance and death. In Winckelmann’s view the mature or classic phase offers the definition of a style.

The concept of style suits fine arts, whose products are to be appreciated only by sight and solely for their esthetic, intellectual or imaginative content, but instead does not suit arts whose products are employable manipulations of matter, form, and light, especially the arts that model in mass to enclose utilitarian space. It follows that style classification does not suit architecture, which is the manipulation of space, materials and components that change the environment in order to obtain utilitarian

constructions, and is primarily concerned with creating usable and comfortable interior space as well as inhabitable and durable refined mass. Then again, like all attempts to ground architecture in some absolute determinants, style classification offers a simple route to deal with architectural history.

The view of styles developed during the 20th century emphasizes that the history of architecture is a form of narrative or storytelling. That view makes it possible to develop a simplified didactic approach to architectural history for beginners in the field.

Although the idea that style is a version of a fiction is suited to secondary education and would be too simplistic or misleading for higher education and practitioners, it has however been adopted by universities. The view of styles in architecture that was developed in academia has dominated popular histories of architecture, and the academic attempts to classify past architectural styles have always had a far-reaching impact on the practice of architecture.

However, by divorcing form, appearance and image from structure, function and materials, architectural style classification has challenged central tenets of architecture to such an extent that it has had little capacity to understand and interpret architecture.

Corresponding author: Paolo Foraboschi, engineer–Ph.D., professor; research field: structural engineering. E-mail: paofo@iuav.it.

This paper is the second output of a research program devoted to submitting evidence that structural design is an all-pervading activity of architecture and that reading or interpreting a historical piece of architecture needs structural mechanics.

The first output has proven that the Renaissance was born when Filippo Brunelleschi carried out the structural design for the Santa Maria del Fiore dome in Florence (Italy), whose architectural project (concept) had remained unbuilt for more than 50 years because it was so demanding that it exceeded the expertise of the time [1]. Brunelleschi turned paper architecture into a buildable design and eventually the dome was constructed.

The Florentine dome is a Gothic building that terminated the Gothic period and started a new period, the Renaissance. Hence, the Renaissance—one of the most important revolutions in cultural history, and not just in architecture and not just in Italy—was born not as a new architectural style but instead as a new approach to architecture, based on intellectual theory rather than just craft practice and on the separation of design from construction.

The first research output has also proven that, before the pre-eminent materials of modern structures were made available and affordable (i.e., reinforced concrete and steel), no difference existed between architectural design and structural design. Examples have included a masonry dome that failed because the designer isolated the visible exterior form, without appropriate links established to the real building, which has confirmed that focusing on the image instead of the physical referent was (and is) a recipe for failure.

The separation between the two professions—architect and engineer—was institutionalized in France in 1747, while a growing separation between design and the practical craft of building had already initiated in the 17th century, especially in France. With the invention of Portland

cement (patented in 1824) and of the industrial process to turn iron into steel (the Bessemer process, patented in 1856), architecture and engineering initiated a process that has led the former to drift apart from the structural design, and the latter to outgrow safety assessment as the only objective.

By relieving walls of their load-bearing function, reinforced concrete and steel permitted the development of the combination called “skin and bones” architecture, which has progressively led architecture to split the Vitruvian triad (firmness, commodity, delight. An equivalent in modern English would be: robustness, utility, beauty). Critique, education, commentary, architects in academia and historians, keen to associate architecture with other forms of art, have been focusing mainly on “beauty”, while they have been disregarding “robustness” and “utility”. In doing so, they have eventually separated principles that conversely should represent three unifying concepts, which has impacted negatively on the contemporary architecture.

Few debates in architectural theory have been as vexed as those around the interrelationships of the Vitruvian triad. Arguing that “form follows function”, advocates of Functionalism believe that delight—or beauty—derives from firmness—or robustness—and commodity—or utility. Those debates involve structural engineering, which provides robustness and some facets of utility; further, the way that the structural system provides robustness and those facets of utility influences beauty and the other facets of utility.

This paper focuses on the architecture of Venice and proves that the standard mechanics of masonry had to be replaced by a mechanics specifically conceived for the lagoon. In Venice, the fact that “form ever follows function”, is not a belief but the inevitable consequence of paying proper attention to the structural requirements of a building.

This paper also describes the concern of Venetian architecture for place rather than space, to designing

and building in the nature of materials and environment.

2. Adverse and Restrictive Environment

Venetian lagoon is characterized by three specific features, which are extreme and radically affected the underlying logic of building form—morphology.

- (1) Soft soils;
- (2) Brackish water and tidal actions;
- (3) Shortage of land.

Coastal lagoons are unstable environmental systems. Throughout centuries, a lagoon tends to turn into either a piece of sea or a piece of land. Venetian lagoon has escaped fate because of the constant and patient work of Venetians, who have always performed competent and skillful activity devoted to protecting and preserving the lagoon. Not only has the equilibrium been maintained although the system is highly unstable, but also the conditions of the lagoon have been improved throughout the centuries.

2.1 Soft Soils of the Venetian Lagoon

The stratigraphy of the lagoon is characterized by a layer of highly over-consolidated oxidized silty clay, near the ground surface, called “caranto”. The caranto begins 4-8 m below the mean sea level (2 m near the mainland, 10 m at Lido). The thickness of this layer is 2-3 m. The layer of caranto is discontinuous and in some areas it does not exist. Its strength and stiffness are very high. Notwithstanding, the layer is quite thin, so the caranto cannot bear high loads.

Strength and stiffness of the soils above the caranto are very low. The average strength and stiffness of the soils below the caranto up to 10-12 m are certainly greater than of the soils above, but only to a moderate extent.

Ultimately, neither the load-bearing capacity nor the compressibility of the soil allowed buildings more than one-two stories to rest on a shallow foundation, and not even on a deep foundation with depth lower than many meters.

2.2 Brackish Water Tidal Actions

Ancient bricks were highly porous, so they created the most favorable conditions for water infiltration.

Water infiltration increases the moisture content of bricks, which causes subflorescence and efflorescence and which significantly reduce compressive strength of bricks [2].

Salinity in the lagoon is substantial-brackish water. The salts contained in the water of the lagoon are the same salts contained inside the bricks. For that reason, the degree to which subflorescence and efflorescence can affect the portions of buildings in the tidal range has always been particularly high.

The above-described phenomena entailed that the brickwork portions of buildings submerged at high tides (high water) and exposed to air at low tides (low water) had to be protected against the infiltration of the lagoon water (the difference between high tide and ebb tide that may surpass 1.70 m).

2.3 Shortage of Land

The land of the lagoon is relatively small and was even smaller than now in the past. Yet despite shortage of land, Venice has always had a large population, which was around 20,000 in the 11th century and has always surpassed 150,000 since the 13th century (apart after plagues and the last decades). During the 14th century, Venice was one of the wealthiest cities in the world, maybe the wealthiest one. As a natural consequence, it was the most populous city in Europe, with 200,000 people who lived in the lagoon (180,000 in 1490 and more than 175,000 in the 19th century).

High population density necessitated exploiting the land to the maximum.

3. Foundation and Base of the Building

Venice posed three problems for builders tasked with constructing in the lagoon—namely, to allow a building: (1) to rest on very soft soil layers; (2) to endure the aggressive environment; and (3) to exploit

land.

The third problem could only be solved by adopting multi-story buildings, which however made the first problem more difficult to solve, because the more the stories the greater the contact pressure.

3.1 Soft Soils

Soft soils call for foundations supported by piles driven or drilled into the ground (deep foundations).

Technology for installation of timber piles available prior to the 16th century allowed builders to construct piles up to a maximum depth of just 2-3 m, and after up to 6-7 m. Those piles often reached the caranto, especially after the 17th century, when they could even pass the caranto (75% of the land lay less than 1.5 m above the sea level). However, those piles could not guarantee significant load-carrying capacity and stiffness, not even if they reached or surpassed the caranto.

Given that the piles that could be installed before the 20th century in the natural soils could not provide a foundation with adequate strength and stiffness, Venetians improved the soils. Ground modification technique improved the bearing capacity of the soils by increasing the relative compaction of the materials through densification. The relative density of the soils was increased by adding material, i.e. timber piles. Pile driving had thus, for its object, the consolidation of soils and not the transmission of surface loads to lower levels in the soil mass.

The larger the total cross-sectional area of the piles per square meter, the larger the volume of soil displaced to make room for the piles, and consequently the greater the compaction. The greater the bulk density, the higher the shear strength and the lower the compressibility of the artificially modified soils. Venetians took the mechanism of densification to the extreme. The typical density was 5-10 piles/m². The diameter of each pile was 0.10-0.30 m. The density of the piles was 0.3-0.7 the building footprint.

On one hand, ground modification technique by

increasing the compaction of the material through densification increased significantly the load-bearing capacity and stiffness of the soils. On the other hand, however, the load-bearing capacity and stiffness remained moderate.

3.2 Aggressive Environment

Builders had to enable the timber piles and the base of constructions to endure the lagoon water.

Two natural phenomena kept the timber intact for over 500-1,000 years. Timber rots only when both air and water are present, so in the oxygen starved environment of the water underneath the buildings, the timber was protected at least until the second phenomenon happened. The water of the lagoon carried an extremely large amount of silt and silty clay, and the timber was being blasted by that sediment for years, so timber adsorbed the sediment and quickly petrified into basically stone.

The base of the building was able to withstand extreme conditions and damage by virtue of the judicious selection of the best materials and techniques (i.e., pile caps, called “*madieri*”, a special waterproof clay, called “*tera da savon*”, a vertical layer of Istrian stones, continuous courses of Istrian stones, called “*cadene*”, hydraulic lime plaster) [2].

That construction technique was a viable means to protect buildings from brackish water and tides up to the first half of the 20th century. Unfortunately, because of the sea-level rise, now the lower parts of the walls are frequently submerged under the lagoon water.

4. Weight- and Space-saving Elements

According to Subsection 3.1, compaction allowed for construction of multi-story buildings provided that they were relatively lightweight. Therefore, buildings had to be composed of weight-saving construction elements.

According to Subsection 2.3, buildings had to make optimal use of both the footprint and volume, with the purpose of saving land and exploiting to the maximum

the internal space. Therefore, buildings had to be composed of space-saving construction elements.

A building made of traditional construction materials (i.e., masonry and timber) is composed of weight- and space-saving elements only if the following five criteria are met (Fig. 1).

- (1) Masonry walls are thin and perforated.
- (2) Brick is preferred to stone.
- (3) Columns are employed as opposed to load-bearing walls wherever possible.

(4) Floors and roof are made of timber structures, and not of masonry vaults.

(5) The footprint makes the best use of land, and the distribution of rooms makes the best use of the allotted space.

Builders met those criteria as close as possible. In so doing, buildings implicitly followed a format, which not only drastically influenced the construction technique but also gave a specific morphology and character to buildings (Venetian architectural style).

Fig. 1 Gussoni-Grimani palace (building on the right in the photo). Façade of the palace, which overlooks Canal Grande. This building fulfills all five criteria: (1) External walls are both thin and largely perforated, and internal walls are very thin; (2) Load-bearing walls are made of brick units; (3) Columns are used where possible (façade and lower stories), while load-bearing walls and partitions are made coincident with each other to minimize weight and volume of the inactive materials; (4) The structures of floors and roof are made of timber; (5) No inner space is left unused or wasted. As in many other Venetian buildings, manufactured stone (stone veneer) was used as a protective and decorative covering for the lower part of the façade.

Fig. 2 Typical Venetian building: thin walls pierced with large openings. The number of openings in the external walls is high and the total span of the openings is relatively long. Thinness and high void-solid ratio lent lightness to walls. Masonry lintels do not work over those spans, so the building is pierced by arched windows. In this case the windows are spanned by pointed jack arches, which exert lower lateral thrust (the greater the rise of the arch the lower the springing thrust). The vertical stone elements in the façades are not columns but mullions. The load-bearing walls are made of bricks.

Fig. 3 Venetian load-bearing masonry walls are an assembly of brick units, while the connections between the external walls are frequently made of stone blocks (Istrian stone), which resist soil settlements and movements more than brick units. The columns are often made of stone as well, including the capitals. Columns are often slender, and capitals exhibit very high void-solid ratio, so the stone is necessary to carry the stresses (thin columns and perforated capitals entail high stresses, which bricks could not bear).

4.1 Thin and Perforated Walls

Walls were kept as thin as possible (Figs. 1 and 2). Builders used the minimum number of wythes of masonry units that enabled each wall to bear the load. That was a novel and unique approach to masonry construction, since masonry walls had never been shaped in response to the force at work.

External walls and some internal walls were pierced by large openings (Figs. 1-3). Builders achieved the highest void-solid ratios possible. As a result, Venetian walls were both weight- and space-saving construction elements with respect to typical walls.

Many openings were wide. Since the widths that could be spanned by a masonry lintel or a transom were limited, wide openings were spanned by a masonry arch (jack arch).

Many openings were also tall, besides being wide, which implied that the two vertical portions of wall on the sides of those openings were tall too. Those masonry portions were the abutments of the jack arches that spanned the openings. While the lintel exerted only a vertical force, the masonry jack arch also exerted an outward horizontal (lateral) thrust onto the abutments.

However, the lateral thrust that the abutments of a

tall opening could withstand was low (especially the openings at the upper stories). For that reason, builders introduced the pointed arch, which exerted a thrust lower than the semi-circular arch and much lower than the segmental (shallow) arch.

Lots of openings were so large that not even the pointed arch could bring the thrust down to a smaller amount which could be withstood by the abutments. In those cases, builders used windows of two or more lights separated by mullions (ranging from single to quadruple mullions used not decoratively but as columns, dividing the window into from two to five equal/not-equal elements).

The combination of pointed arch and mullioned window allowed the openings to be decidedly wide and tall, so that the void-solid ratio of the walls reached very high values.

In order to further reduce the void-solid ratio of walls, capitals of columns and abutments were often pierced as well (Fig. 3).

4.2 Bricks versus Stones

The unit used by builders for masonry structures was the brick, while the stone was used only for specific structures. There are only two exceptions to that general rule (apart from some walls of the

Prison’s Palace, for obvious reasons).

The first exception occurred in the case of the columns whose shaft was subjected to high stresses, where the stone was preferred to the brick since the latter minimizes the weight but the former the volume, which was the preferred option for columns. The most apparent examples are the columns included in many façades, which are slender. The stone was even more necessary for their capitals, which often were perforated (Fig. 3).

The second exception encountered to the rule was the connection of external walls. Buildings had to accommodate large differential displacements between walls, due to great differential settlements of soil. Only strong connections between the longitudinal and transverse external walls avoided splitting the building into separate walls. Accordingly, the intersections between orthogonal external walls were often made of stone. Stone could not prevent the connection from cracking locally but prevented cracks from propagating along the entire connection (Figs. 2 and 3).

Another kind of exception was the stone used as cladding (stone veneer) of external walls, especially at the lower level of buildings (Fig. 1).

Stone cladding on a brick wall entailed an extra-weight. However, builders dressed brick walls with a very thin revetment of stone, thereby only slightly increasing the total weight. In so doing, bricks were protected from the environment and buildings were generally more aesthetically pleasing. Considering that the brickwork was several times thicker than the stonework, in effect cladding consisted in a non-load-bearing envelop.

Thus, what appear to be stone load-bearing walls are, in reality, brick load-bearing walls with a protective and ornamental facing of stone, excluded from the above general rule.

To put it briefly, brick walls were often finished in thin stone veneers, which bear no relation to the

underlying structure, whereas they bear direct relation to the construction, since they protect the buildings from the environment.

Well-known examples showing that stone cladding consisted in pure dressing of raw construction (i.e., permanent wallpaper) are the Doge’s Palace and St Mark’s Basilica. In the former case, the thin stones that compose the upper level of the façade are manifestly not structural as the building put upside down the logic of form. In the latter case, the condition is marked by confessed rivets used to fix thin panels of stones to the walls.

Some bridges included stone, but this was not an exception because bridges usually had not to save weight or space. In those cases, stone was preferred over brick for the durability performance and esthetic. Sometimes, the barrel vault of the bridge was composed of two stone arches at the edges and a brick arch in the middle.

The typical stone was the Istrian stone (Figs. 1-3), which is a limestone with very low porosity (high compactness), thereby extremely durable.

No structures, without any exception, were made of masonry with rubble core (sandwich masonry), since it did not save weight or space (it was only a labor saving and cheap masonry type).

Some utilitarian buildings in poor neighborhoods included walls made of timber, which not only were both weight- and space-saving but were also cheap.

4.3 Columns in Lieu of Walls

Builders used columns in lieu of walls wherever possible, supported by the self-evident proposition that the column is weight-saving and space-saving with respect to the wall (Fig. 4).

Columns were made of either Istrian stone or brick.

A masonry construction composed of many columns as well as of thin and perforated walls is midway between the masonry wall structure and the skeleton, as addressed in Section 6 (Fig. 4).

4.4 Timber Floors and Roofs in Lieu of Vaults and Domes

Almost all the floors and roofs were made of timber (Fig. 5), while masonry vaults were used only in the exceptions hereinafter defined, since a curved masonry system weighs much more and occupies much more space than a timber floor over the same span [4].

More specifically, masonry weighs more than timber. A vault needs the fill on the extrados to obtain a flat floor, which adds weight and subtracts space. Due to the strength asymmetry of masonry material, curved masonry structures crack even under the dead load, and turn into thrusting structures. The thrust—namely, the horizontal force transferred through the springing sections to the abutments—can be resisted only if the masonry abutments are heavy

and thick. Ergo, curved masonry structures call for massive abutments to accommodate the outward thrust, save those in succession, which press against each other, and those with the tie-rod, which do not press (but the tie-rod was usually not compatible with occupancy).

Nevertheless, in patrician palaces, builders could build curved ceiling without using curved masonry structures (Fig. 6). The curved floors consisted of members having the appearance of an arch or vault, though not of arch or vault construction (false vaults). Vault-like constructions were made of wattle and daub, and hung from timber curved elements which, in turn, hung down from the timber beams of the floor. The wattle and daub surface was plastered. This system occupied little space, was lightweight, and transmitted no horizontal thrust to the walls.

Fig. 4 Wherever possible, builders used columns as opposed to external and internal walls. The photos show buildings where the skeleton forms not only the bones but also the skin. Venice gave birth to the earliest buildings that abandoned load-bearing walls in favor of a framework of columns and beams (the former made of masonry, the latter of timber), which allowed lightweight buildings to be obtained. As such, those structures were the archetype of the “skin and bones architecture” and of the framed structures.

Fig. 5 Largest room of the Doge’s Palace, called “Sala del Maggior Consiglio” (53.8 m long, 26.2 m wide, and 15.5 high), whose ceiling and roof are supported by larch lattice trusses and purlins. Each timber tie-beam consists of four pieces joined by “Jupiter dart” connections. On the mainland, those rooms were often roofed by masonry vaults.

Fig. 6 False vaults: vault-like construction. The floor is composed of timber flat structures—namely, timber beams and timber boards, the latter nailed to former (single boards or double boards), plus a timber component between wall and floor, called “rema” (but no spandrel fill). In its turn, the ceiling is composed of wattle and daub, and it hangs from curved timber elements, which hang down from the floor. The curved timber elements have no structural role, so the false vault exerts no thrust and thus the system does not require thick abutments. The wattle and daub surface is plastered and, in some cases, painted.

In the case of roofs, especially church roofs, another way to obtain a vault-like construction was to build a wooden curved ceiling resembling the hull of a ship turned upside down. That ceiling was supported by the main timber structure, so it played a marginal structural role. Hence, it was indeed a vault-like construction (Fig. 6).

There were only two exceptions to the above-stated general pattern. Builders made a first exception for rooms containing highly inflammable materials (storages, warehouses, fondaco buildings, some mezzanine floors) or devoted to activities that could start a fire (workplaces, workshops, kitchens, cells and corridors of the Prison’s Palace). In those cases, the masonry vault was sometimes preferred over the timber floor, as safety measure to decrease fire risk and fire effects. However, those rooms were small and the vaults thin, so the structural system was not massive.

Where possible, builders arranged a compartmentalization of specialized rooms, so that those vaults were next to each other. The structure of that enfilade consisted of an arcade, which was highly efficient because the outward thrusts of the successive arches pressed against each other, and needed no buttressing and no thick abutments, except for the first and last ones. Nevertheless, those vaults constituted the lower floor of multi-story buildings, so that the weight of the upper walls and of the floors that rested

on those walls helped the first and last abutments in resisting the outward thrust [3, 4].

The second exception was made for some churches. Contrary to the first one, this second exception proves the rule. In order to roof the churches with domes and vaults, builders either adopted shapes different than the basilica, which is characterized by large spans, or reduced the spans of the basilica shape, which led to relatively small churches. According to the former option, which was frequently adopted, the plan tended to be centralized; it was symmetrical about a central point, as is a circular, square or octagonal (polygonal) plan, or also a Greek cross. Those plans were roofed by domes (Fig. 7). The masonry dome exerts a thrust much lower than a masonry vault, as long as the brick pattern is built according to specific construction rules [4]. Builders knew those rules, thereby those masonry domes did not need thick drums.

Likewise, when the basilica shape is characterized by relatively small spans, vaults can be used to roof the nave and sometimes the aisles, and a dome or a vault to roof the apse and the transept.

On the contrary, Venetian churches with basilica shape characterized by large spans were roofed with timber structures and a flat ceiling (bold and expensive timber systems).

4.5 Expansions of Venetian Buildings

Venice has always been a densely populated city

Fig. 7 Internal view of Baldassarre Longhena’s masterpiece, the Church of Santa Maria della Salute, at the entrance of the Canal Grande in Venice (started in 1631; completed in 1687). The drum is thin and consists of segmental windows with mullions. As almost every masonry dome, this dome cracked and is split into arches, which exert a springing thrust. Such a lightweight drum can resist the outward thrust of the cracked dome because every arc of dome whose endpoints are two consecutive meridian cracks subtends a large central angle. That is, the resisting thickness of those arches is great (the greater the resisting thickness of an arch the lower the springing thrust exerted by that arch). The resisting system was the result of the brick pattern (loxodromic curves arranged in a herringbone pattern). Altogether, the weight-to-volume ratio of this dome is relatively low. It is to note that the intrados has a shape different than the extrados of the dome, because there is a timber frame between, which is supported by the former and, in turn, supports the latter, creating a wide gap.

and the lagoon was fast consumed by urban development, so that Venetians soon run out of inhabitable space (Subsection 2.3).

Land exploitation entailed that the perimeter of a building should almost coincide with the boundary of the ground plot that the building was erected onto. Since the ground plots were irregular polygons, the perimeters of many buildings were irregular polygons too. Because of that, the neighboring buildings either were in contact to each other along their boundaries or left very narrow space between for the alleyways.

Courtyard houses were widely adopted throughout the Venetian history, also because the courtyard allowed the staircase to be placed externally (Gothic staircases), whereas an internal stair would have been a nuisance to be accommodated in compliance with the other four criteria.

Venetian building forms also made the best use of inner space, not only because of the space-saving construction elements, but also because of space allotted for large medium and small rooms around the tripartite layout of the main façade. The vast central

hall, called the “portego”, connected rooms; that is, rooms were connected to each other via a shared hall or en suite, and not via corridors, so as to save space.

The excess of “form follows function” that characterized Venetian buildings from the flexibility perspective suggests that there was remarkably little latitude for building modifications. Actually, exploitation of land and inner space entailed that no allowance was made for new developments of buildings over time.

The Getto provides a clear example. The strong demographic increase of the Getto in the 16th century entailed growing demands for housing, retail and workspace, as well as the demands of new social needs, which could be satisfied only by creating novel real estate space. Those demands led to construction of new buildings very tall for Venice (up to 7-8-stories). Moreover, since rearrangement of inner space was nearly impossible, those demands also led to the insertion or addition of new stories, obtaining lower interstories or higher buildings. In some buildings in the Getto, the writer found masonry walls or columns close to failure by crushing.

5. Serviceability Limit States

Satisfaction of what in modern terminology is called “serviceability limit states” constituted a serious problem for Venetian builders.

5.1 Double Function of the Venetian Terrazzo

Terrazzo is a form of mosaic flooring made by embedding chips in a matrix and polishing, which was created when Venetian mosaic workers discovered a way to reuse marble remnants. Nevertheless, it was the evolution of works of art attributed to the first Roman age, according to a Greek procedure.

With odd-size chips, Venetian builders began to construct terraces around living quarters. Then, terrazzo went beyond its simple beginnings and evolved into a flooring system for both rich and ordinary buildings, and we find terrazzo in many buildings.

Terrazzo was laid onto the timber boards of the floor, which rested onto the timber beams (boards and beams were nailed together). The thickness of terrazzo was never less than 130 mm and often surpassed 200 mm, even up to 250 mm (sometimes more, especially when the terrazzo was poured onto warped floors).

The unit weight of terrazzo ranged from 3.2 kN/m² to 4.5 kN/m², sometimes even 6.0 kN/m². Namely, not only was terrazzo really heavy, but above all it was drastically heavier than all the other non-load-bearing components of the Venetian building. Thus, terrazzo seems to be in flat contradiction to the weight-saving goal. That contradiction prompted some research, which has proven that terrazzo played a paramount role in the structural behavior of the floor [5].

If the structure had consisted of the timber system only, almost all the floors would have not guaranteed adequate stiffness. But conversely, the terrazzo slab was (and is) not structurally independent from the timber system, since interlocking and friction transmitted shear stresses at the interface between the former and the latter, so that the timber-terrazzo floor is a composite structure. As a result, the stiffness of

the whole floor was substantially greater than that of the individual timber system and allowed the floor to satisfy the deflection limit. Still, terrazzo provided the floor with an extra load-carrying capacity greater than its weight.

Also the terrazzo floorings that were first built in Venice are still in existence today—a testament to terrazzo’s durability and strength.

Ultimately, Venetian builders considered terrazzo a load-bearing component, while literature has always included terrazzo in the non-load-bearing components. Altogether, the total weight of the timber elements plus the terrazzo slab is not high, as those elements simultaneously compose the structural floor and the flooring system.

5.2 Soil Settlement and Moisture

Although the Venetian foundation system and the weight-saving elements had substantially decreased soil settlements, differential settlements between vertical structures could not be reduced to such a level that could be accommodated without deep cracking. Builders knew that differential settlements needed specially devised construction methods.

In some buildings, the internal transverse walls (at an angle of 90° to the façade) were deliberately not connected to the longitudinal walls (parallel to the façade, i.e. parallel to the canal faced by the building).

In so doing, gaps were created between orthogonal walls. A gap in a masonry structure consists in a structural joint. In its turn, a joint in a masonry structure consists in a purpose-built crack in lieu of natural cracking; while the latter produces meandering cracks, the former consists in a regular, straight, and even fissure between two unconnected walls. That device provided the best esthetic quality, since it allowed the relative movements to occur opening or closing the gaps, without causing any cracks.

On one hand, cracking is not esthetically pleasing. On the other hand, however, cracking breaks the connection between the walls only to a certain degree,

so the walls maintain the restraints (only rarely a crack cuts the connection from the bottom to the top of the building and through the entire thickness of the wall). Thus, that device implied that no connection existed between the walls, so each unconnected edge was a free boundary instead of a restrained boundary.

When the longitudinal walls were particularly slender or wide, metal tie-rods were placed beneath the terrazzo to compensate for the lack of connection between transverse and longitudinal walls. So, the tie-rod prevented the out-of-plane collapse mechanism of the external wall from occurring.

Ultimately, the transverse external walls were firmly connected to the longitudinal external walls, while sometimes the transverse internal walls were not connected to the longitudinal external walls. In that way, buildings could cope with large differential settlements between longitudinal and transverse walls.

Satisfaction of serviceability limit states also included devices for coping with moisture, which damaged not only brickwork but above all timber. The floor-system comprised a timber beam (rema), placed at each edge of the floor, between floor and wall, to protect the floor from the rising damp.

In addition, builders often applied a special plaster onto walls, currently called “polished Venetian plaster”, which concealed surface moisture.

In Venetian buildings, architecture, construction and ornament were inseparable. Ornament was something conceived as integral to design, and must not be seen as a secondary element applied to the design.

6. Tectonic Form

The Venetian building structurally considered does not belong to any common structural type; it properly belongs neither to the masonry wall structure nor to the skeleton, in the normal acceptance of those terms. The Venetian building implies a particular sense of the collocation “masonry construction”, while the generally recognized meaning is unfitting.

6.1 Typical Masonry Construction versus Skeleton

The vertical structures of a masonry construction are composed of masonry walls and may include some masonry columns, while the horizontal structures may be composed of either curved masonry structures or flat timber structures. The vertical structures of a skeleton are composed of columns, while the horizontal structures may be composed of either slabs or beams plus floors.

A masonry-wall structure (i.e., the system of vertical structures) has multiple functions – namely, to support the dead, live, and environmental loads, to form the periphery of the building and the rooms, and to provide insulation. Accordingly, the cross-sections of a masonry-wall structure are dictated by the area of the building and rooms that the vertical structures have to surround and the spaces that they have to divide, enclose, and protect.

A skeletal structure, as opposed to a masonry construction, has one function only—namely, to support the dead, live and environmental loads. Accordingly, the cross-sections of a skeletal structure are dictated by the materials that they are made of and by the loads that they have to bear.

The masonry cross-sections that are necessary to shelter a building and to separate one internal area from another entail compressive stresses drastically lower than the compressive strength (crushing strength) even under severe vertical loads. It follows that failure by crushing is impossible, apart from masonry with rubble core or uncoursed masonry, subjected to earthquakes or high vertical loads.

Even though masonry cross-sections are large, tensile stresses reach the tensile strength even under just barely the dead load or small differential settlements. Hence, cross-sections cannot prevent cracking from happening, so that masonry structures bear the ultimate load in the cracked state. It follows that failure by cracking does not dictate the load-carrying capacity.

Being that masonry cannot fail by crushing and that the ultimate load stems from a cracked resisting system, failure occurs only when the masonry structure becomes an unstable kinematic collapse mechanism composed of blocks joined to one another by pins at (near) the edges of some cross-sections (or friction hinges). Stresses and masonry mechanical properties only marginally influence equilibrium and ultimate behavior. As a result, the kinematic collapse mechanism acts as an assembly of pinned rigid blocks, and the load-carrying capacity of a masonry structure is the load that triggers the weakest rigid block collapse mechanism. That result gives a necessary and sufficient condition. For a masonry structure to be in equilibrium with the applied load there must be a line of thrust contained entirely within the masonry sections (lower bound theorem) [3, 4].

Conversely, the cross-sections of a skeletal structure are designed to exploit the structural materials, and stresses are as high as possible, in order to reduce the dimensions to a minimum. It follows that the failure modes of skeleton structures are dictated by strength of materials. Given that skeletons can fail by crushing, fracture, yielding or softening, and the ultimate behavior depends on stresses and material's mechanical properties, a failure mode consists in an assembly of rigid blocks joined to one another by plastic hinges. It follows that the necessary and sufficient condition involves not only the geometry but also the ultimate internal actions. For a skeleton to bear the applied load the internal actions of every cross-section must fall within the interaction diagrams of that section (moment, axial force, and shear internal actions).

The lower bound theorem implies that masonry structures can simply be scaled up and down in size. Conversely, the interaction diagrams together with inelasticity imply that the proportions of skeletal structures have to change according to their size and materials (as is the case with animal skeletons).

To conclude, a masonry-wall structure that satisfies

the architectural requirements always resists the design vertical loads. On the contrary, masonry buildings often resist only moderate horizontal loads, especially are vulnerable to seismic actions.

Conversely, a skeletal structure resists vertical and horizontal loads owing to its size together with type and amount of materials. Thus, the load-carrying capacity of a skeleton depends on its structural design.

6.2 Venetian Masonry Buildings

Venetian buildings did not include curved masonry vaults or domes, apart from some churches (Section 4.4). According to the Italian code, Venice has a low level of seismic hazard. Those conditions may suggest that Venetian buildings satisfied (and satisfy) every structural requirement.

That statement would have been true if the buildings had been constructed on the mainland, but instead was (and is) wrong for buildings constructed on the Venetian lagoon. Oversizing of masonry walls met an exception: buildings in sites where the soil was soft and the space available for constructing was limited. Venice met both those conditions.

On one hand, knowledge and practice derived from direct observation of constructions allowed builders to make full use of structures without undermining their load-bearing capacity, although being made of thin brick walls, many slender columns, and had high void-solid ratios. On the other hand, however, with their privileging of emptiness and lightness, compressive stresses were not far from the compressive strength of materials (crushing strength).

Although the soil had been compacted, differential soil downwards displacements were large. Those soil movements lessened the effectiveness of the connections between orthogonal walls, and their ability to prevent walls from out-of-plane overturning. Besides impairing the connections, those movements also increased the compressive stress level, because cracking always prevents stress diffusion in masonry walls.

To sum up, saving weight and space entailed that buildings were provided with just a small margin of safety against collapse under gravity loads. Nevertheless, the skill acquired by a long period of practical experience allowed builders to balance between saving both weight and space on one side, and providing structures with adequate capacity on the other side.

However, that balance was true for the past, not for the present. A recent research [2] has demonstrated that moisture and salts cause damage to masonry further than subflorescence and efflorescence—namely, ingress and diffusion of lagoon water into masonry have substantially affected the crushing strength of bricks. Compressive strength of bricks with high moisture and high salt contents can be half the value of dry bricks.

That effect, added to the effects of crystallization, i.e. subflorescence and efflorescence (Subsection 2.2), implies that now compressive masonry strength may be substantially lower than in the past [2].

Not a few Venetian buildings can just barely support the loads that are applied, while they cannot even resist the loads that are called on to support (service load, i.e. superimposed load), let alone the ultimate load prescribed by the Italian structural code.

High stress levels imply that structural safety assessment of Venetian masonry buildings must include stress analysis together with the mechanism analysis. Relating forms and materials to maximum strength and no-tension behavior entails satisfying the requirements of both a masonry construction and a skeletal structure.

6.3 Masonry Skeletal Structure

The morphology of a masonry building that fulfilled the five criteria set out in Section 4 implied that Venetian buildings were, and are, governed by a specific structural mechanics, which overturned masonry mechanics and that needed specially devised construction techniques.

In a normal masonry construction, the load-carrying capacity is dictated by the weakest rigid block collapse mechanism. Consequently, the vast majority of the dead load belongs to the resisting system, so that the load system is only composed of the live load and a minor part of the dead load [1, 4].

In a Venetian masonry building, the load-carrying capacity was dictated by the bearing capacity of the soil (ultimate pressure). Consequently, both the dead and live loads belonged to the load system. In addition, the greater the dead load the greater the amount of space occupied by the structure, while buildings had to save space as well. Accordingly, design and construction of Venetian buildings aimed at minimizing the dead load, which is exactly the opposite of what is done in normal masonry structures. As a result, the structural system of the Venetian building exploited to the maximum masonry strength. Thus, equilibrium was (and is) only a necessary condition for a Venetian building to be safe, but not a sufficient condition.

The eye at once deduces the scheme behind the design of many Venetian buildings, which is closer to a skeleton than to a masonry-wall structure (Fig. 8). Nevertheless, that skeleton provided not only the load-bearing system, but also the cladding and partition systems; skin plus bones architecture, as the skeleton composed not only the latter but also the former.

Conversely, reinforced concrete and steel skeletons provide the load-bearing system only; skin and bones architecture, as the latter is provided by the skeletal system while the former by the cladding and partition systems.

Builders learned from experience that, contrary to mainland masonry constructions, Venetian masonry constructions were not governed only by Euclidean geometry and proportions, but also by the strength of masonry material.

Hence, the Venetian building is a skeletal masonry construction. In the light of the definition of a masonry structure, “skeletal masonry construction”

Fig. 8 Procuratie Vecchie, on the north side of St. Mark’s Square in Venice, which were rebuilt after a fire in the 16th century. The façade is formed from three superimposed Renaissance arcades of which the lowest, which is open, has fifty arches, whilst the upper two each have 100, containing windows. The façade, with its concentration of loads into points and lines of support, creates a vivid impression of the play of structural forces. With its vast network of columns and arches, this building exemplifies the idea of tectonic.

seems to be a combination of contradictory and incongruous words, since a skeleton should relieve walls of their load-bearing function, while that skeleton imposed the burden of bearing the loads on the claddings. But conversely, it is a special case within masonry construction, not a contradiction or an incongruity. Then again, that exception was the only way to solve the exceptional structural problems of the lagoon.

While the Venetian building structurally considered is a masonry skeleton, the Venetian building architecturally considered cannot be considered to be a skeleton. Skeletons are characterized by no strict interrelationship between the outer form and inner structure, whereas the exterior of Venetian buildings is not autonomous from the interior. While the skeleton epitomizes the ideal of the free plan, the skeletal masonry construction does not allow the spatial possibility of the free plan.

6.4 Tectonic Form

The analysis presented above stresses how all the parts of a Venetian building reinforced the overall structural idea. The collocation that can be invoked to describe both the structural and architectural facets of the Venetian building is “tectonic form”.

The idea of tectonic form signifies an approach based on the rational expression of structure and construction of which the Venetian gothic presented a potent paradigm.

The word tectonic assumes a broader meaning in Venice and tectonic can be invoked to describe the interrelationship between the form and structure. Masonry skeletal structure, with no distinction between structure and cladding, typifies the contemporary understanding of tectonic expression as construction made manifest. Tectonic expression is also seen in the process of suppressing secondary elements, in order to base architectural expression on the essential element of a structure, and to eliminate visual clutter; it is seen in the juxtaposition of timber and brick as well.

The specific mechanics that underpinned the construction of that tectonic form and dictated the architecture blends the structural behavior of a masonry structure and a skeletal structure.

The tectonic superstructure of a skeletal masonry with timber floors enables a fresh synthesis to be produced. A normal masonry structure can be governed by accommodating a possible line of thrust within the geometry. In order to assess the safety of a masonry structure, it is sufficient to prove that at least one thrust line, which is in equilibrium with the external load, lies everywhere within the boundaries of the masonry structure.

On the contrary, a Venetian masonry structure must be governed by accommodating the geometric boundaries far away from the real line of thrust. In order to assess the safety of a Venetian masonry structure, it is necessary to prove that the real thrust

line lies everywhere within the interaction diagrams associated with materials and geometry.

Ultimately, the tectonic form of Venetian buildings is midway between the masonry construction and the skeleton.

7. Conclusions

A work of Venetian architecture can be understood as possessing intrinsic laws—of geometry, structure, proportion, choice of materials, relation between its members and so on—that are determined not only by the occupancy (the reason why it is constituted), but also by the natural condition of the lagoon (the specific circumstances of the site). This is analogous to an organism, which responds to both its internal constitution and its external circumstances.

The idea that a work of art is analogous to a natural organism in its interdependence of parts to form a whole goes back to Aristotle’s *Poetics* and gained new momentum in German thought in the 18th and 19th centuries, playing a vital role in the ideas of Kant and Hegel, and preoccupying Göthe.

This paper has proposed two aspects to the formation of Venetian buildings: the law of inner nature, according to which each construction was constituted (intended use), and the law of outer circumstances, by which the Venetian type was modified during the first Venetian age until reaching a type that could cope with the lagoon (environment).

The architecture of early Venice was almost entirely made of timber (as such, very little remains). As the city flourished and at its peak became the most prosperous city in Europe, Venetian masons became a renowned community of practice, and architecture modified towards multi-story (high-rise) masonry buildings. However, that evolution was a trial and error (or success and failure) story for improving buildings.

During the first centuries of the Venetian history, constructions evolved like natural organisms—namely, by natural selection and not by adaptation to their environment. The power of Venetian art of building

lay first in discovering, in order to eliminate, what failed in the Venice although it worked on the mainland, then in defining novel techniques that worked in the unique situation of the Venetian lagoon. Hence, Venetian architecture began as a succession of attempts to integrate building and site.

Once found a type that worked, it became a strict format that was followed with few and justified exceptions. In so doing, Venetian buildings could rise above common masonry constructions. Accordingly, Venetian buildings, which are distinct from all other constructions and structural systems present in the world, exhibit the defining property of “teleonomy”. This means that they are endowed with a purpose of project which they display in their structure and carry out through their performance.

So, the origin of Venice and the process of evolution are the result of chance, which dictated the buildings that survived, while Venice as we know it is the result of both a functional fitness-for-purpose and underlying morphological rules.

Ultimately, in Venice all forms were a creation of necessity: nature was so powerful in the lagoon that form had to follow function without any exception; i.e., necessity prescribed certain forms for certain qualities. Venetian building’s forms were determined entirely by their purpose—which was structural and environmental. Therefore, it is always possible to infer the qualities from the forms, the purpose from the shape.

This paper has analyzed the architecture of Venice in the remit of structural engineering, which offers a unique perspective of comprehension and interpretation. Understanding Venetian architecture as “the art of building” does not derive from the recognition of the status of master masons, but from the fact that the distinction between “architecture” and “building” as well as the reworking of historical styles are misrepresenting. Seeking to ground architecture in the craft employed in its making, this paper contrasts what architectural theory, criticism, and histories of architecture have often written about Venice.

Venetian architecture was a complete building system which bounded all the elements into a structurally expressive esthetic unity: a tectonic form. In plain words, the essence of the Venetian architecture was not the creatress of space but lay in the tectonic assembly of elements of construction.

The contrast between a lightweight superstructure and a water-bound base epitomizes tectonic expression of Venetian architecture, which displays no contradiction between form and function. Essentially, function was the consequence of, not only individual need, but also environmental need, while form was the consequence of establishing a relationship with environment.

Venetian buildings are masonry constructions. But whereas typical masonry constructions—their columns apparently swelling under load—suggest a responsive acceptance of gravity, Venetian buildings soar in defiance of it, dissolving into a profusion of slender shafts and delicate trceries. Buildings were soundly built yet some buildings may look flimsy and precarious. What is called “Venetian Gothic style”, which is emblematic of the city and gives Venice its unique appearance, is actually not an architectural style but the only way to build in the lagoon (Venetian skeletal Gothic style).

It can be argued that, in Venice, Gothic never died out, continuing in the practice of builders, whose primary goal was to minimize the weight and size of structures, which tacitly kept alive the Gothic style.

In each epoch, Venetian architecture was not the will of that epoch “translated into space”, but the response to context. Venetian style could change only when the preeminent materials and techniques of modern structural engineering were made available and affordable, i.e. from the second half of the 19th century onwards.

Every Venetian building was enmeshed in its context, and buildings can only be understood when seen as fully integrated in the lagoon. Venetian buildings are “of” and not “on” the Venetian lagoon.

References

- [1] Foraboschi, P. 2016. “The Central Role Played by Structural Design in Enabling the Construction of Buildings that Advanced and Revolutionized Architecture.” *Construction and Building Materials* 114 (July): 956-76.
- [2] Foraboschi, P., and Vanin, A. 2014 “Experimental Investigation on Bricks from Historical Venetian Buildings Subjected to Moisture and Salt Crystallization.” *Engineering Failure Analysis* 45 (October): 185-203.
- [3] Blasi, C., and Foraboschi, P. 1994. “Analytical Approach to Collapse Mechanisms of Circular Masonry Arch.” *Journal of Structural Engineering—ASCE* 120 (8): 2288-309.
- [4] Foraboschi, P. 2014. “Resisting System and Failure Modes of Masonry Domes.” *Engineering Failure Analysis* 44 (September): 315-37.
- [5] Foraboschi, P., and Vanin, A. 2015. “Mechanical Behavior of the Timber-Terrazzo Composite Floor.” *Construction and Building Materials* 80 (April): 295-314.