Structural and Material Characterization of a Haussmann Building Complex at *La Madeleine*, Paris. The First Step Before Sustainable Rehabilitation and Strengthening

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Abstract: - Haussmann buildings architecture spread throughout the city of Paris. Nevertheless, those buildings are nowadays submitted to heavy operations of use change, conservation and rehabilitation, justified by several reasons, among others are building aging and the increasing demand for hotel rooms in Paris. In this paper, a structural and material characterization of a Haussmann building complex located at *La Madeleine* in Paris is presented. This characterization is the result of several technical visits realized during construction works stage relative to use change, rehabilitation and strengthening which take place between 2015 and 2017. The present study allows identifying the existing structural system, the materials and the geometry of the principal structural elements in a structural engineering view. The knowledge from this study could be very useful for the development of sustainable rehabilitation and strengthening methodologies, helping at the same time to preserve this important legacy or similar ones existing in other countries.

Key-Words: - Traditional buildings, Haussmann buildings; rehabilitation; structural characterization; strengthening; sustainability.

1 Introduction

Paris Haussmann buildings are actually subjected to a huge quantity of use change, rehabilitation and strengthening works. These buildings being old, since built or rebuilt around the 19th century, [1], present nowadays several pathologies affecting their main structural behavior. Besides, the codes regarding structural and fire safety, thermal and sound insulation, have changed since those buildings were built, an upgrade is therefore necessary to meet the new standards. Additionally, the environmental issue related to energy consumption for cooling and heating make them obsolete. Beyond that, the Paris Haussmann buildings are a valuable building heritage. This construction technique [2], was implemented until the introduction of concrete and steel in the 20th century. It is of vital importance to preserve and protect this legacy. Furthermore, there is a huge demand for hotel rooms in the city of Paris due to a growing tourism activity. All the reasons presented previously justify the urgent need to realize conservation and rehabilitation works. This article characterizes the main structure and the materials of a Haussmann building complex, [2, 3], located at *La Madeleine*, near the *Saint Marie Madeleine Church*. Figure 1 shows the complex implantation and Fig. 2 shows a front view of the existing facade.

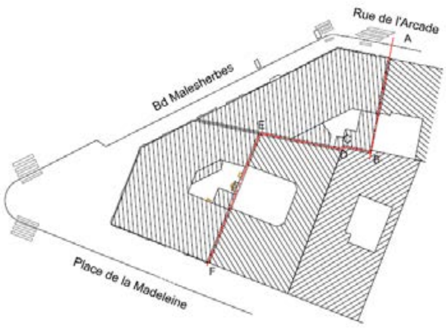

Fig. 1 – Complex implantation

Fig. 2 – Facade front view

This article is original since the material and structural characterization is realized from a structural engineering point of view and is based in investigations realized in site during the rehabilitation and strengthening work performed between 2015 and 2017 with the objective to turn it in a hotel of 54 rooms. This article is supported by several photographies, an assessment of the geometric characteristics of some structural elements was realized and a foundation investigation was performed. Besides, the first author was also the rehabilitation, strengthening and underpinning project designer during the construction stage.

We believe this article will allow to better understand the materials and the structural behavior of Haussmann buildings allowing to better identify the best sustainable [4], rehabilitation, and strengthening techniques that should be applied to other Haussmann buildings or similar buildings around the world. This article is structured as follow: first the Haussmann complex is defined, secondly, the main structure, the ceiling, the floors, the walls, the basement floor and the foundations are characterized and simultaneously data related to the materials and to the geometry are given. Finally, conclusions relative to the characterization results and sustainable building issues are presented.

2 The Haussmann building complex

The building complex is constituted by two Haussmann buildings, built between 1830 and 1841. Malesherbes building on the left and Madeleine building on the right in Fig. 1-a). Malesherbes building as a gross floor area of 365 m^2 and 7 stories and Madeleine building as a gross floor area 416 m^2 and 6 stories. The ground floor, Fig.3, of the two buildings has a commercial use and the basement is used as a storage and to the technical equipment.

Fig. 4 – Ground floor

The other are office floors. The main Haussmann facades are made of dressed stone, excepted the two upper floors which are made with a timber frame solution. The facades located in the backside are made with a timber frame or steel frame solution. Fig. 4 shows Madeleine building building facade viewed from *Place Madeleine*, this is a typical Haussmann facade.

Fig. 4 - Madeleine building facade

3 Description of the existing structure

It is a composite structure conceived essentially with local materials. The materials used for the facades are dressed stone; timber for the floors, for some beams, for the interior timber frame walls and for the stairs; limestone rubble for the timber frame infill; ceramic bricks for some interior walls, a plaster revetment for the walls and ceiling cover, Fig.5.

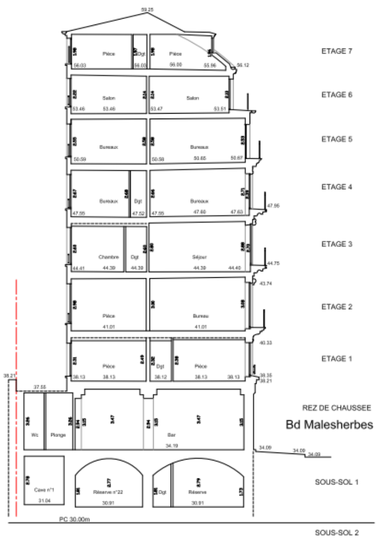

Fig. 5 - Malesherbes Building

Nevertheless, some floors are realized with metallic IAO profiles, being in some cases supported by a metallic beam structure, a plaster infill is present between the IAO profiles. Cast-iron is present in some ground floor columns of Madeleine building.

The ground floor is supported by the limestone masonry vaults and the limestone masonry walls of the basement floor as illustrated in Fig. 5 and relative to Malesherbe building. Figure 5 indicate also that the structural elements are aligned along vertical lines, a demonstration of the simplicity associated with the resistant structures of that period.

3.1 The facades

The facades existing prior to the advent of Haussmann buildings were made of timber frame structure with limestone rubble, [2]. The Haussmann facades, Fig. 3, are made with a 55 cm width dressed stones supported by the limestone walls located beneath them, on the basement floor. The last storey of Madeleine facade, under the ceiling, is made of a timber frame structure, as the two uppers stories of Malesherbes. For both facades, the last storey is made of a curved timber frame structure. The backside facades are, from the bottom to the top made of a timber frame structure full with limestone rubble or a metallic frame structure full with bricks.

3.2 The interior walls

Along the Haussmann building complex, there is an interior timber frame wall going parallel to the main facades and approximately located at the middle distance between the front and the backside facade. This interior timber frame wall supports the floors. The other solution present in this building complex consists of a clay brick walls. The timber frame structure is made of oak tree with an infill, of clay bricks, Fig. 6.

Fig. 6 - Clay bricks infill

Another solution is the use ok limestone rubble for the infill, Fig. 7. At the ground floor level, the timber frame wall is interrupted and supported by masonry columns.

During the investigations, the width and the thickness of the posts and also the thickness of the plaster revetment relative to timber frame walls was evaluated.

Fig. 7 - Limestone rubble infill

Eight timber frame walls located at the 4th, 5th, 6th and 7th floor of Malesherbes building and two timber frame walls located at the 4th and 5th floor of Madeleine building were analyzed.
The results are indicated in Table 1.

Table 1 – Timber framing elements dimensions

Building	Timber frame wall posts (cm)			Plaster (cm)
	Width	Thickness	Spacing	Thickness
Mal.	9-18 (13.3)	10-13 (11.4)	13-29 (19.5)	3-6/3-7 (3.6/4.3)
Mad.	8-10 (9)	10-11 (10.5)	14 (14)	6/5 (6/5)

These results indicate that the posts have a width that varies 9 to 18 cm with a mean value equal to 13.3 cm, a thickness that varies from 10 cm and 13 mm and a mean value equal to 11.4 mm, the spacing between the posts varies from 13 cm to 29 cm width a mean value equal to 19.5 cm. The plaster thickness existing in each face of the walls varies between 3 and 7 cm with a mean value equal to 4 cm. In Table 1, the average values are indicated in brackets.

It is interesting to compare this typology of interior walls with tabique walls typology present in the Alto Douro Wine Region, in Portugal, [5]. In fact, the timber structure is similar but the infill is completely different, Haussmann interior walls are filled with limestone rubble or clay bricks while tabique walls are filled by an earth-based material

[6]. There is no dough, the solution adopted is dependent on the existing local raw material [7].

Furthermore, in Madeleine building seven perforated brick walls were analyzed, located at the 3rd, 4th, 5th and 6th floor. In Table 2, the brick wall thickness and the plaster revetment thickness existing in each face are indicated. The average values are indicated in brackets.

Table 2 – Brick walls dimensions

Building	Brick wall thickness (cm)	Plaster thickness (cm)
Madeleine	15-22 (17.3)	2-4/2-5 (3.1/3.1)

The average value thickness of the walls is equal to 17.3 cm while the average plaster thickness value is equal to 3.1 cm.

3.3 The floors

The site observations realized during the rehabilitation work [8] allowed to identify two types of floors. Floors made with timber elements [5, 8], Fig. 8, and floors realized with IAO metallic profiles, the existing metallic profiles prior to the actual IPE/IPN profiles. Malesherbes building has only timber floors while Madeleine building has timber floors until the second floor. The uppers floors of Madeleine building are made with metallic profiles and this technique is clearly an evolution from timber floors to metallic floors.

Fig. 8 - Timber floors view

It is possible to verify that the timber floors do not have more the required resistance and stiffness to safely carry the loads. Several beams present hight deformations or have extensive cracks. A weakening due to attacks by wood-eating insects and fungi is also evident. Furthermore, the floorboards are clearly deformed by the natural deterioration. The timber beams are made of massif oak. The floors are made with resistant timber beams, below the beams and attached to it there is the floor ceiling made with laths and plaster and under the beams, laths and a mortar layer support the floorboard revetment, as shown in Fig. 9.

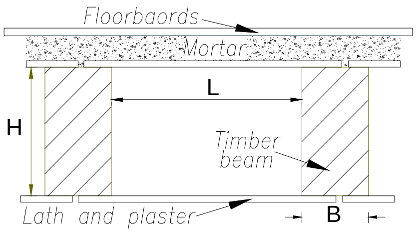

Fig. 9 - Timber floor detail

The analyze of several timber floors allow identifying different typologies along the same floor and along the stories. We identified more than sixteen type of floors, varying the dimensions of the timber beams and their spacing. The spacing (L) between beams varies 16 to 30 cm, the width (B) of the beams varies between 7 cm and 12 cm and can exceptionally reach 24 cm and finally, the beam height (H) varies from 15 cm to 26 cm.

Starting on the 3rd floor of Madeleine building, the floors are realized with metallic beams constituted of IAO cross-sections, Fig. 10.

Fig. 10 - Metallic pavement view

Between those beams, plaster elements (*augets*) are set and plaster joist (*lambourdes*) support the floorboards, Fig. 11. Regarding the metallic IAO profiles, the technical observations indicated hight deflections and plaster cover deterioration. Furthermore the design calculations indicate that those floors do not have the necessary resistance to withstand the new loads rising from the actual regulations, [9], and due to the new used given (hotel).

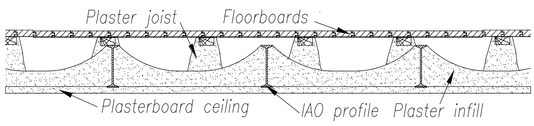

Fig. 11 - Metallic pavement view

Table 3 is relative to the cross-section dimensions of the IAO profiles existing in the 4th and 5th floors of Madeleine building.

Table 3 – IAO cross-section dimensions

Floor	Cross-section dimensions (cm)		
	Flanges width	Height	Spacing
4th	6	16	63
5th	6	16	60
	6	16	58

The flanges width of the IAO profiles is equal to 6 cm, the height to 16 cm and the spacing between beams varies from 58 to 63 cm. Beyond that tensile tests ordered to Veritas office regarding IAO cross-section beams indicated a tensile yield strength varying from 258 MPa and 283 MPa and a Young modulus varying from 179 to 187 GPa. These results indicate that the metallic profiles still present good mechanical characteristics, in fact, the actual minimum tensile yield strength for metallic profiles is 360 Mpa and the Young modulus is 200 GPa, [10]. The plaster infill The protection given by the existing plaster infill around the metallic profiles certainly justifies those values [6].

3.4 The basement floor

This building complex has one basement floor. This floor is realized with limestone masonry vaults, Fig.12. The vaults are supported by interior and exterior limestone rubble masonry walls. The interior walls have a thickness varying from 40 cm to 65 cm and the exterior walls have a thickness equal to 80 cm. This was the main structural system since concrete was not yet used and because timber elements could not be used in the basement which has high humidity levels.

Fig. 12 – Basement walls

3.5 Basement barrel vaults

The vaults observed in this Haussmann complex are masonry barrel vaults. A survey was performed to obtain the vaults dimensions, Fig.13, and three parameters were considered, the distance between the vault footer and the keystone which define the rise and the free span and the rise to span ratio.

Fig. 13 – Basement vault

Eleven vaults were measured and grouped in 6 categories according to the free span value, as represented in Table 4.

Table 4 – Barrel vaults geometry

free span (m)	Rise (m)	Rise/ Span
2.80 (1)	0.79	0.28
3.00 (1)	0.95	0.32
3.76 (1)	1.48	0.39
3.91 (3)	0.99, 0.89, 1.12	0,23-0.29
4.80 (1)	1.09	0.23
5.20 (4)	1.05, 0.77, 1.10, 0.98	0.15-0.20

From table 4 it is possible to conclude that the rise to span ratio varies from 0.15 to 0.39. According to [11] the critical rise-to-span ratio is equal to 0.2 since the shallower the vault, the greater is the horizontal reaction, as already perceived at least in the 1st century BCE, and reported by Vitruvius within De Architectura, [12], [13], [14].

3.6 The foundations

In order to identify the foundations, a survey was realized in three foundation points of investigations. The foundations were manually dug with a shovel, to a depth between 0,40 and 1,20 meters. The results clearly indicated that the foundations of the building complexes are usually obtained by extending the limestone rubble masonry walls below the ground, Fig. 14 and Fig. 15.

Fig. 14 – Wall fondation

The depth of those foundations walls varies between 15 cm and 1 meter.

Fig. 15 – Foundation by wall extension

Besides, some walls have limestone masonry or concrete strip footings to support them, Fig. 16 and Fig. 17.

Fig. 16 – Limestone masonry strip footing

In those cases, the footings have a height varying between 3 cm and 40 cm, Fig. 16 and Fig. 17 and the width extending beyond the walls internal surface varies between 4 and 13 cm.

Fig. 17 – Limestone masonry strip footing

4 Strenghtening techniques

Several structural strengthening techniques used in this construction site will be the scope of further articles, [8]. These techniques allow maintaining structural elements like floors, walls and the entire Haussmann facade, which clearly indicates that it is possible to update technical characteristics regarding the actual regulations with rehabilitation and strengthening works, thus avoiding the complete demolition of structural elements. Strengthening techniques can, therefore, be used as a way to achieve sustainability in building construction, [15], [16], [17].

5 Conclusions

The investigations realized during the rehabilitation of a Haussmann building complex, have shown that the materials are: limestone rubble, wood, plaster, steel and cast-iron corresponding to a a predominant use of raw and local materials. Five solutions were found for the walls, which are: a timber frame with infill, a metallic frame with infill, brick masonry, dressed stone or limestone rubble masonry. The floors are made from timber joists or metallic IAO profiles. The foundations are essentially obtained by extending the basement walls under the ground and sometimes a strip footing can be observed. Several limestone rubble masonry vaults are placed on the basement floor, these vaults support the ground floor level. The rise to span ratio varies from 0.20 to 0.39, in one case this ratio was found to be 0.15. The resistant structure is very simple, with the structural elements aligned along vertical lines. The investigations allowed also to verify that this building complex is very damaged by the normal material decay. Deformations and cracks are visible on the floors, in the timber stairs, on the walls and there is water infiltration in the basement. The actual regulations regarding structural and fire safety, thermal and soundproof insulation, persons with disabilities are no longer respected. The rehabilitation works realized will eliminate those pathologies and enhanced, by strengthening techniques, among others, their mechanical characteristics regarding current standards.

The organizations worldwide are being faced with sustainable concerns, therefore strengthening and rehabilitation techniques design should reuse the most quantity of existing materials in order to minimize waste material, pollution and maximize energy saving, preserving this building heritage in a sustainable way. This approach should be the scope of further studies. If the right choices related to rehabilitation and strengthening techniques are proposed, the final product will achieve a high sustainability degree, associating rehabilitation and strengthening works with sustainable construction, a different scenario that the one which is nowadays associated with the concrete and metal-based building industry.

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