Abstract. Haussmann buildings are representative of Paris urban architecture. However, those buildings being centenarians, present several pathologies which is preventing their adequate use. Moreover, an upgrade regarding users security, acoustic, thermal and fire requirements is, among others, urgently needed to meet the new standards. Additionally, there is actually, in Paris, an increasing demand for hotel rooms. For those previous reasons, Haussmann buildings are nowadays submitted to heavy operations relative to use changes, conservation, rehabilitation and strengthening. 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 a survey realized during the construction stage occurred between 2015 and 2017, relative to use change, rehabilitation and strengthening. The present study allows identifying the existing structural system, the materials and the geometry of the principal structural elements. The knowledge from this study would be very useful for the development of sustainable rehabilitation and strengthening techniques and at the same time helping to preserve this important heritage or similar ones existing in other countries.

Key words: Haussmann buildings, rehabilitation, structural characterization, sustainable construction.
1. Introduction
A huge quantity of use changes and rehabilitation works are being done actually in Paris Haussmann buildings. In fact, those buildings are aging rapidly, since built or rebuilt around the 19th century (Jordan, 2004; Keegan et al., 2017), presenting nowadays a very poor state of conservation and several pathologies adversely affect their main structure. Besides, the regulations regarding structural and fire safety, thermal and sound insulation (Ter Minassian, 2011), among others, have changed since those buildings were built, therefore an upgrade is necessary to meet the new standards. Furthermore, the environmental issue related to energy consumption for cooling and heating make them obsolete. Beyond that, Haussmann buildings are representative of the Paris architecture (Jordan, 2015; Jomber, 1764), the construction techniques associated were used until the introduction of concrete and steel in the 20th century. It is therefore of vital importance to preserve and protect this heritage and demolition can’t be a solution. Additionally, 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 rehabilitation, strengthening and underpinning works.

This article is devoted to characterizing the main structure and the construction materials of a Haussmann building complex (Lepoutre, 2010), located at La Madeleine near the Saint Marie Madeleine Church, subject to heavy a transformation, rehabilitation, strengthening and underpinning works between 2015 and 2017, with the main objective to turn it in 54 rooms’ hotel. The Fig. 1 shows an aerial view of the complex implantation and Fig. 2 shows a front view of the existing Haussmann façade before the intervention.

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 stage.

This article is supported by several photographies and an assessment of the geometric characteristics of the 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 rehabilitation, strengthening and underpinning techniques (Tuppurainen, 1990; Versaci, 2016), 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, Fig. 1. 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. Fig. 3 shows Malesherbes and Madeleine buildings facades viewed from Malesherbes Boulevard, this is a typical Haussmann facade.

![Fig. 3. Malesherbes and Madeleine building façade.](image)

The ground floor of the two buildings is for commercial use and the basement is used as storage and to the technical equipment, the others floors are used for offices and housing. The main Haussmann facades are made of dressed stone (Corradi et al, 2003), excluding 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 presents an elevation of the building complex.

![Fig. 4. Building complex elevation.](image)

Fig. 4 shows also that structural elements are aligned along vertical lines, a demonstration of the simplicity associated with the resistant structures of that period.

3. Description of the existing structure
It is a composite structure conceived essentially with local materials (Tavares et al., 2014). The materials used for the facades are dressed stone (Binda et al., 2000), timber for the floors (Branco et al., 2011), 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. 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. 4 (Schmid and Testa, 1969).

3.1. The facades

The facades existing prior to the advent of Haussmann buildings were made of timber frame structure with limestone rubble (Rowland, 1999). The Haussmann facades of this building complex, Fig. 4, are made with a 55 cm width dressed stones (Quelhas et al., 2014) supported by the limestone walls located beneath them, on the basement floor. The last story of Madeleine facade, under the ceiling, in made of a timber frame structure, as the two uppers stories of Malesherbes building. 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 to the interior walls consists of a clay brick masonry. The timber frame structure is made of oak tree with an infill of clay bricks, Fig. 5 or limestone rubble, Fig. 6. 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.

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.

![Fig. 5. Clay bricks infill.](image)

![Fig. 6. Limestone rubble infill.](image)

<table>
<thead>
<tr>
<th>Building</th>
<th>(A)</th>
<th>(B)</th>
<th>(C)</th>
<th>(D)</th>
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<tbody>
<tr>
<td>Malesherbes</td>
<td>9-18</td>
<td>10-13</td>
<td>13-29</td>
<td>3-6/3-7</td>
</tr>
<tr>
<td>Madeleine</td>
<td>8-10</td>
<td>10-11</td>
<td>14</td>
<td>6/5</td>
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</tbody>
</table>

The results, presented in Table 1, indicate that the posts have a width (A) that varies 9 to 18 cm with a mean value equal to
13.3 cm, a thickness (B) that varies from 10 cm and 13 mm and a mean value equal to 11.4 mm, the spacing (C) between the posts varies from 13 cm to 29 cm width a mean value equal to 19.5 cm. The plaster thickness (D) existing in each face of the walls varies between 3 and 7 cm with a mean value equal to 4 cm.

It is interesting to compare this typology of interior walls with tabique walls typology present in the Alto Douro Wine Region, in Portugal (Cardoso, 2013; Cardoso et al., 2011; Cardoso et al., 2015a) or similares ones in Turkey. 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 (Cardoso and Pinto, 2015b). There is no dough, the solution adopted is dependent on the existing local raw material (Hegyi et al., 2016).

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 (A) and the plaster revetment thickness (B) existing in each face are indicated.

<table>
<thead>
<tr>
<th>Building</th>
<th>(A)</th>
<th>(B)</th>
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<tbody>
<tr>
<td>Madeleine</td>
<td>15-22</td>
<td>2-4/2-5</td>
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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 works allowed identifying two types of floors. Timber floor joists (Branco et al., 2014), Fig. 7, and floors realized with metallic IAO profiles, the existing metallic profiles prior to the actual IPE/IPN profiles. Malesherbes building has only timber floors while Madeleine building has timber floor joists until the second floor. The uppers floors of Madeleine building are made with metallic IAO profiles, this distribution clearly indicates a technical evolution from timber floors to metallic floors.

It is possible to verify that the timber floor joists (Biscaia et al., 2017) do not have more the required resistance and stiffness to safely carry the loads (Adem et al., 2006). Several beams present high deformations or have extensive cracks. A weakening due to attacks by wood-eating insects and fungi is also evident (Murta et al., 2011). Furthermore, the floorboards are clearly deformed by the normal decay.

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. 8.

The analysis of several timber floor joists allows for identifying different typologies along the same floor and along the stories. We identified more than sixteen types of floors, varying the dimensions of
the timber beams and their spacing. The results indicate that 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. 9.

Between those beams, plaster elements (augets) are set and plaster joist (lambourdes) support the floorboards, Fig. 10.

Regarding the metallic IAO profiles, the site observations indicated high deflections and plaster cover deterioration. Furthermore, the design calculations also indicate that those floors do not have the necessary resistance to withstand the new heavier loads rising from the actual regulations, according to EN 1991-1-1, and due to the projected hotel use.

The dimensions of IAO profiles located on 3rd, 4th and 5th floor were analysed. The Table 3 is relative to the cross-section dimensions results. The flanges width (A) of the IAO profiles is equal to 6 cm, the height (B) to 16 cm and the spacing (C) 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, according to EN 1993-1-1:2. The plaster infill The protection given by the existing plaster infill around the metallic profiles certainly justifies those values (Cardoso et al., 2016).

### Table 3. IAO cross-section dimensions.

<table>
<thead>
<tr>
<th>Floor</th>
<th>(A)</th>
<th>(B)</th>
<th>(C)</th>
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<tbody>
<tr>
<td>3rd</td>
<td>6</td>
<td>16</td>
<td>63</td>
</tr>
<tr>
<td>4th</td>
<td>6</td>
<td>16</td>
<td>60</td>
</tr>
<tr>
<td>5th</td>
<td>6</td>
<td>16</td>
<td>58</td>
</tr>
</tbody>
</table>

3.4. The basement

This building complex has one basement floor, Fig. 11. This floor is realized with limestone masonry vaults supported by
interior and exterior limestone rubble masonry walls with a thickness equal to 80 cm. Fig. 11, shows the vaults existing in the basement. This was, at that time, the main structural system since concrete hasn’t been yet discovered and because timber elements could not be used due to basement high humidity levels.

3.5. 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, Fig. 12.

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. 13.

The depth of those foundations walls varies between 15 cm and 1 meter. Besides, some walls have limestone masonry or concrete strip footings to support them, in those cases, the footings have a height varying between 3 cm and 40 cm, Fig. 14.

In those cases, the width extending beyond the walls internal surface varies between 4 and 13 cm.

4. Sustainability versus rehabilitation and strengthening techniques design

There is growing consensus among organizations that appropriate actions are needed to make building construction more sustainable (Tweed and Sutherland, 2007). Besides, the sustainable building approach (Akadiri et al., 2012) has a high
potential to make a valuable contribution to sustainable development, therefore buildings should be designed to reduce the overall impact of the built environment (Legian et al., 2018), on human health and the natural environment. The use of raw and local materials in existing structures (Cardoso et al., 2017), as Haussmann buildings, clearly indicate a sustainable choice of materials (Lopes et al., 2017), since local materials are in general lower in embodied energy and toxicity than man-made materials requiring less processing and being less damaging to the environment (Moatassem et al., 2018), wood, for instance, is theoretically renewable material. When those materials are incorporated into building products, the products become more sustainable (Pinto et al., 2011). Furthermore, often local materials are better suited to climatic conditions. When, for any reason, rehabilitation and strengthening works are undertaken (Li, 2014), the design techniques should optimize the use of locally-available materials (Saradj et al., 2017), and maintain, by reusing, the biggest part of existing raw material structures (Pinto et al., 2012). For the Haussmann building complex here characterized, the investigations undertaken during the construction stage have shown that strengthening the floors by connecting to the main structure a concrete slab was the adopted solution (Cardoso, 2018). Besides, some structural elements were maintained, as the dressed stone main facade and a few timber frame walls.

5. Conclusions

The investigations realized during the construction in a Haussmann building complex, have shown that the materials are: limestone rubble, wood, plaster, steel and cast-iron with 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 in the basement floor, these vaults support the ground floor level. 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 in 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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REFERENCES
Jomber C. (1764), Moderne Architecture or the good construction art for all types of persons [in French], Tome premier de la construction, Librairie du Génie et de l’Artillerie, rue Dauphine Notre-Dame, Paris, France.


