ENGLISH VERSION.......

Structural conditioning factors of the installation of rooftop hvac equipment on existing load-bearing masonry buildings: Case study

Condicionantes estructurales de la implantación de instalaciones de climatización en cubiertas de edificios existentes de muros de carga: Caso de estudio

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Abstract

The growing interest in providing adequate Heating, Ventilation and Air Conditioning (HVAC) conditions for those public buildings in which they were not originally planned frequently leads to the need to install HVAC units of significant dimensions and weights in these buildings. Particularly in buildings located in urban centers, the unavailability of space to place those units has led to their installation in buildings' roofs.
From the case study of a remarkable brick masonry building located in the historical city center of Madrid, this article analyzes the structural aspects involved in the implementation of large-size HVAC units on the roof of existing masonry buildings, as well as the structural refurbishment typologies necessary for this purpose.
Thus, the study carried out focused, on the one hand, on the analysis of the HVAC new loads' impact on the previous masonry safety conditions, and the possible need to adopt strengthening actions to ensure an adequate future structural behavior, and, on the other hand, it focuses on the analysis of the aspects conditioning the design of the auxiliary support and fixing structure of those HVAC units.

Keywords: *Brick masonry, structural strengthening, HVAC units, change in use, structural assessment*

Resumen

El interés creciente por dotar de unas adecuadas condiciones de climatización a los edificios de uso público que no disponían en origen de éstas conlleva, en muchos casos, a la necesidad de implantar instalaciones de climatización de dimensiones y pesos significativos. Máxime en el caso de edificios situados en núcleos urbanos, la ausencia de superficie disponible para implantar dichas instalaciones ha motivado que se dispongan en sus cubiertas.
A partir del caso de estudio de un edificio notable de fábrica de ladrillo del casco histórico de Madrid, se analizan los condicionantes estructurales que supone la implantación de importantes aparatos de climatización en la cubierta de edificios existentes de muros de carga, así como las tipologías de actuación de acondicionamiento estructural necesarias al efecto.
Asimismo, el estudio realizado se centró, por una parte, en el análisis de la repercusión de la disposición de nuevas cargas sobre las condiciones de seguridad previas de la estructura y la necesidad de adoptar en ésta medidas de refuerzo que permitan asegurar unas adecuadas condiciones de seguridad futuras y, por otro lado, en el análisis de los condicionantes a tener en cuenta en el diseño de la estructura auxiliar de apoyo y sujeción de dichas instalaciones.

Palabras clave: Fábrica de ladrillo, refuerzo estructural, instalaciones de climatización, cambio de uso, evaluación estructural

1. Introduction

One of the main reasons to intervene historical buildings is the need to modernize and optimize their HVAC systems to improve their energy efficiency or meet the thermal comfort demands currently required for their users (Park, 1991) (Pérez-Lombard et al., 2008) (Ma Z et al., 2012) (Pisello et al., 2014). Originally, buildings located in urban centers did not have adequate HVAC conditions, and the lack of available surface area to install the necessary units to improve them has meant that often they are installed on the rooftops of the buildings, either supported on substructures placed on the rooftop surface or directly on the load-bearing structure of the buildings (AHRI, 1997). In addition, public buildings, due to their volume, generally require HVAC units of large dimensions and heavy weights to meet these requirements for improving their HVAC conditions (Alderson, 2009) (Westphalen and Koszalinski, 2001) (Westphalen and Koszalinski, 1999). This usually leads to the need to carry out a preliminary analysis of the impact on the nominal safety conditions of the structures to be intervened—in relation to the new loads to be applied—to determine whether it is necessary to adopt any structural strengthening measure to ensure adequate future safety and service conditions for the buildings after the installation. For the same reasons, a specific structural study is usually required to determine the conditioning factors of the buildings to be intervened on the design and location of the support and fixing substructures of these units.

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However, it is important to mention that in the reference bibliography, research on the layout of HVAC units in historical buildings is mainly focused on those aspects that condition the energy savings or efficiency or the indoor air quality achieved with the units to be installed (Webb, 2017) (Cabeza et al., 2018) (Krzemień et al., 2018). This study highlights the importance of structural limitations in the decision-making process regarding the choice of these units, taking into account the fact that they are generally units that present important loads and are installed on the rooftop of old buildings.

Based on a case study, this article addresses these problems applied to masonry buildings, analyzing both the structural conditioning factors involved in installing major HVAC units on the rooftop of old buildings with load-bearing masonry walls and the structural refurbishment solutions required for this purpose.

The analyzed building was built in the 18th century. It is a remarkable public building located in the historical center of Madrid. Its structure is made up of one-way slabs consisting of steel joists supported on brick masonry walls (Figure 1). It was decided to carry out a generalized improvement of the HVAC systems in this building. To do so, it was necessary to install different units on the rooftop of the building: air treatment units, chillers, heat pumps, stand-alone equipment, among others.

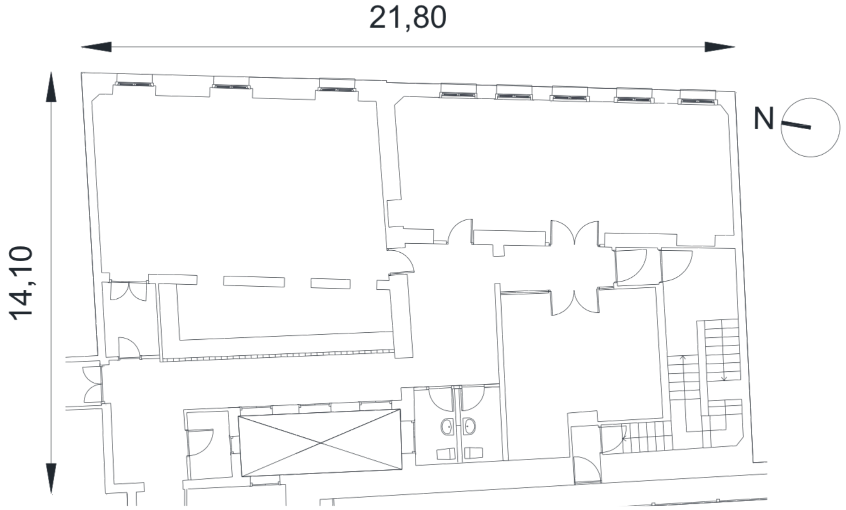


Figure 1. *Partial sketch of the roofed area of the building under analysis, corresponding to the building area where two air treatment units are proposed to be installed*

2. Previous research

2.1 Inspection work

A first inspection of the building was carried out to determine the existence of any damages or anomalies that would show anomalous structural behavior. According to the inspection results, the building showed no signs of anomalous behavior in its structure.

2.2 Campaign of test cuts in the structure

After the damage inspection, a campaign of test cuts was carried out on the rooftop (Figure 2) and on some sections of the load-bearing masonry walls underneath it to determine their configuration.

Figure 2. *General views of the building rooftop*

The most significant aspects of this research were the following:

- The lining of the roof structure is composed of 20 cm high checkered brick walls on top of which different layers of rooftop finishings are laid out (thin hollow bricks, waterproofing sheets, etc.) until reaching a total height of about 30 cm. (Figure 3).

Figure 3. *View of one of the test cuts on the rooftop of the building*

- The roof slabs are unidirectional, formed by steel joists type IPN 160, with an interaxis of 75 cm and a small masonry vault of brick rowlock and a distribution area between 2 cm and 3 cm.
- The load-bearing walls are made of brick and are between one foot and two feet thick.

2.3 Structural impact analysis of the new loads to be placed on the rooftop

Based on the information obtained in the campaign of cut tests in the structure and the technical documentation available on the building, safety checks were carried out on the resisting elements that would be over-requested after the planned intervention to determine the structural refurbishment measures that might be necessary to undertake in the building to ensure adequate future safety conditions of the building after the installation.

It is important to mention that, taking into account that it was a rooftop with a lining made up of checkered brick walls, on which the loads to be placed could not be directly supported, a solution was proposed to support the units to be placed on the rooftop, to direct the loads of the units to the existing load-bearing walls. In this case, it was not necessary to check the horizontal rooftop structure against these loads.

Regarding the wall sections affected by the planned intervention, a stress analysis was carried out for the new loads to be placed on the rooftop. However, this analysis did not indicate the need to undertake strengthening *measures in the wall sections requested by these loads since the surface area occupied by the metal grids supporting the units to be installed was important, as it was necessary to bring their supports to the position of the masonry. Thus, the new stress states in the affected wall sections were similar to the previous ones due to the use overload on the rooftop corresponding to those surfaces.*

3. Unit support solution proposal

As mentioned above, various HVAC units were required in different sections of the rooftop under analysis: several air treatment units (ATUs), chillers, heat pumps, stand-alone equipment, among others. It should be noted that, taking into account that the solution chosen for the layout of the units was to direct the new loads to the existing walls using metal grids designed for this purpose. Their geometry and configuration were conditioned by the distribution of the masonry structure, the location of the supports of the units to be placed and the alignments of a metal structure that had been previously installed on the rooftop.

Also, four metallic structures were proposed, as grids, consisting of rolled steel frames type IPE 180, IPE 160, IPE 140 and HEB 140, raised above the rooftop, and supported either on supports of reduced length—made up of 100 mm x 100 mm x 5 mm tubular frames—, which, in turn, rest on the existing masonry under the rooftop, or anchored through plates and rods to the sections of the wall that were above the grid level (raised walls, parapets, etc.) It was also intended that the floor alignments of the designed grids should be approximately orthogonal between the frames and that the connections between these elements should be welded. In addition, the perimeter of the HVAC units was proposed to have platforms with tramex-type metal grids for their maintenance and conservation. Two solutions were proposed to connect the beams to the walls. One is welding the beam to the anchor plate, and the other is using dowels to free the walls from possible horizontal thrusts.

Thus, taking into account the existing conditioning factors for the design of the support solutions for the aforementioned HVAC units, the following grid types were proposed:

Grid 1: *A single metal grid is proposed for the support of chillers, heat pumps and stand-alone equipment, made up of frames type IPE 180, IPE 160and IPE 140, taking advantage of the supports of a metal structure previously installed on the roof—giving continuity to its alignments—and creating five additional support points in the existing wall sections under the grid (Figure 4). To do this, it was proposed to drill holes in the floor slab at certain points to make fillings until reaching the sections of the wall under the roof where the grid could be supported. The rest of the support points are provided by anchoring plates to the masonry, whose upper level is above the grid. It is important to mention that a cantilever is created from the new supports (support points) on the sections of wall under the roof at the end of this structure*

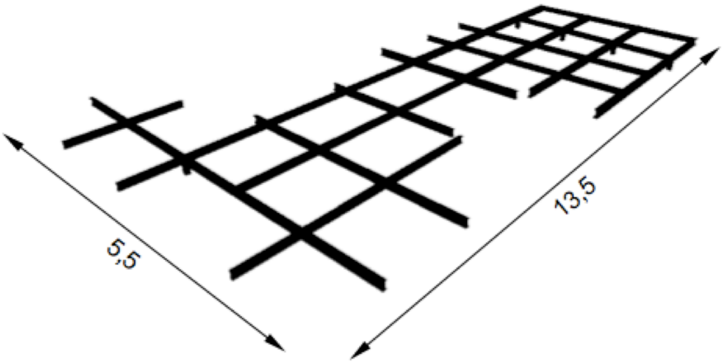


Figure 4. *Graphical representation of the configuration of Grid 1*

Grid 2: *Consisting of three frames type IPE 160, with supports on plates directed to the raised walls, and transverse frames type IPE 140 (Figure 5), on which the platform and the supports of an air treatment unit will rest in operation.*

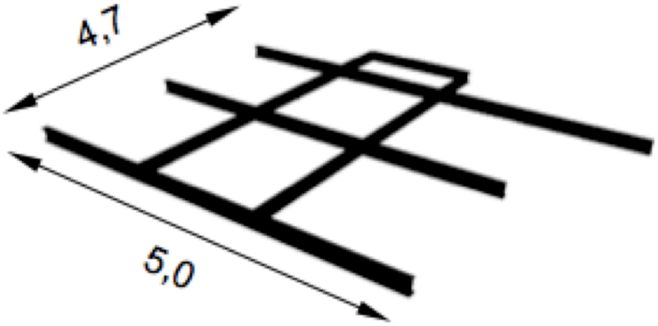


Figure 5. *Graphical representation of the configuration of Grid 2*

Grid 3: *It is built with two frames type IPE 160, directed to the raised wall sections through anchor plates, and two transverse frames type IPE 140(Figure 6), on which the platform and the supports of another ATU and the heat pumps will rest in operation.*

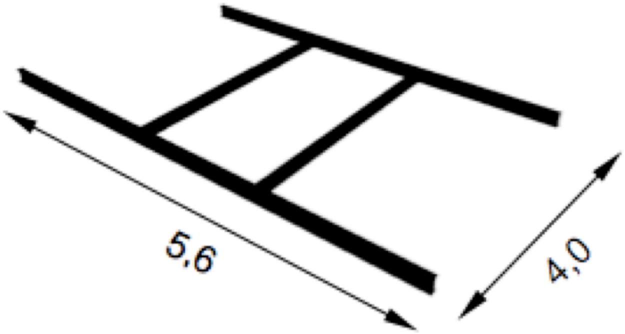


Figure 6. *Graphical representation of the configuration of Grid 3*

Grid 4: *Consisting of frames type IPE 160 and IPE 140, it supports two ATUs. It is also raised above the rooftop and rests either on reduced-length supports, which, in turn, rest on the existing load-bearing masonry walls under the roof or anchored by plates and rods to the perimeter masonry walls above the grid level (Figure 7). It also has a frame type HEB 140, which rests on the head of a slightly raised rooftop wall—anchored to it through plates and rods—, which coincides with the dividing wall support of the two ATUs to be installed on this structure. Given the configuration of the walls under this grid, it should be noted that it is also necessary to create a cantilever at the northeast end of the grid, starting from the supporting points on the walls of the new supports and the frame type HEB 140.*

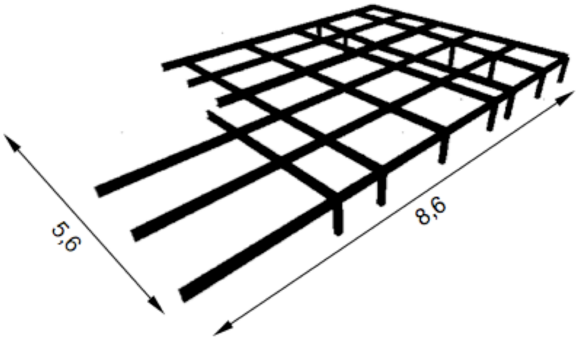


Figure 7. *Graphical representation of the configuration of Grid 4*

4. Calculation checks

Based on the solutions described in the previous section, which were proposed for the four metal support structures for the different HVAC units to be installed on the rooftop, the necessary calculation checks for their design were carried out.

4.1 Grid Design

Checks were carried out using the METAL 3D® structural calculation software tool of CYPE INGENIEROS (Figure 8), verifying that the frames proposed in the pre-design of the grids (see the previous section) were in line with the dimensioning requirements with respect to the actions foreseen on them. Regarding the frame deformations, it was also verified that the relative deflections obtained were less than 1/250 of the span in all cases.

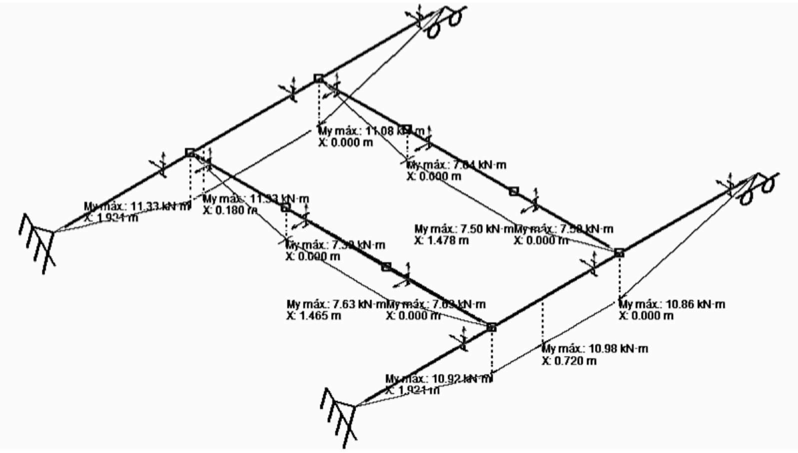


Figure 8. *Bending moment laws of Grid 3*

4.2 Anchor Fastening Design

The anchor fastening design of the grids to the raised masonry walls of the building was carried out in conformity with the anchor fastening design and testing criteria established in the HILTI® anchor fastening technical guide (HILTI, 2019). Also, taking into account the valid solutions for the actions obtained from the previous structural calculation results, and adopting conservative resistance characteristics for the existing masonry walls of the building, depending on subsequent verification tests, it was necessary to use Ø12 HIT-V anchor rods with HIT-HY 270 chemical anchor.

However, since no detailed information was available on the resistant characteristics of the anchor support material, it was also considered appropriate to carry out in situ tensile and shear tests—which are described in the following section—to guarantee an adequate in-service performance of the designed anchors.

5. Testing campaign

Before installation, the anchors designed for the support and fixing of the grids were tested to verify their suitability through a campaign of tensile and shear tests (Figure 9) on anchors of the same type as those designed for the grids, in conformity with the test requirements described in (EOTA TR 053, 2016).

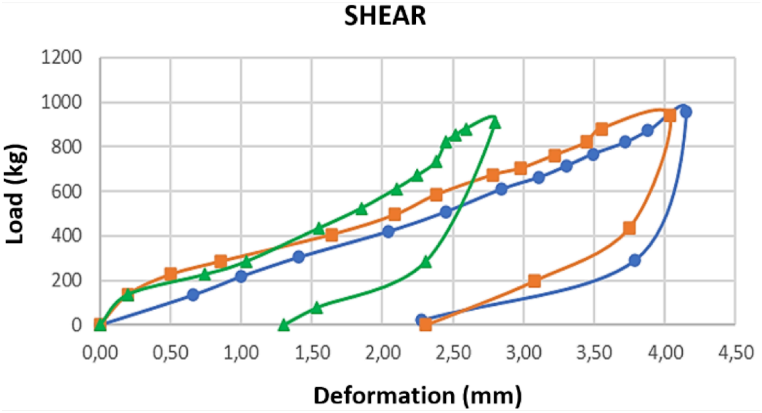
Figure 9. Tensile and shear testing of anchors

The acceptance criterion for the tests was that they would be valid for tensile loading values higher than 3 kN and shear values higher than 6 kN.

(Table 1) below shows the results obtained in the tests performed. (Figure 10) also shows the load-deformation behavior graphs obtained.

Table 1. *Results obtained in shear and tensile tests on anchors*

Test	Test Load (kN)
E1 – Tension	4.11
E2 - Shear	9.55
E3 - Tension	6.43
E4 - Tension	3.16
E5 - Tension	4.06
E6 - Tension	4.06
E7 - Shear	9.40
E8 - Shear	9.10



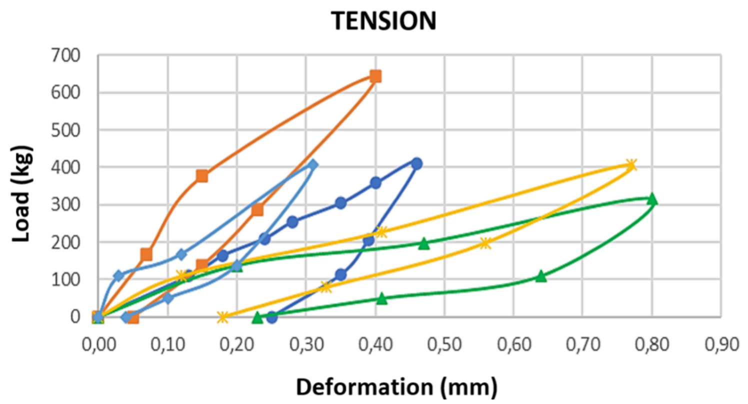


Figure 10. *Behavior curves obtained in the shear and tensile tests*

The results obtained in the tests confirmed the validity of the proposed solution, as the minimum tensile load (3.0 kN) and shear load (6.0 kN) required to absorb the service loads to which the anchors will be subjected were exceeded in each test

6. Assembly control

After the design verifications for the support and fixing solutions for the units and the verification tests of the existing structure, to guarantee an acceptable behavior of both the units to be installed and the structures on which they will rest, it is equally important to verify in situ the adequacy of the assembly of the units to what was previously defined (Figure 11).

This control also makes it possible to verify that they are arranged in the appropriate form and in conformity with the quality requirements previously established for the same, particularly with regard to the position of their supports, and that their characteristics are in line with their technical requirements. It is important to point out that, in densely populated urban areas such as the one under analysis, these assembly operations have the extra difficulty of being carried out at night, and the equipment is lifted by crane from the first floor.

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Figure 11. *Distribution of two ATUs after assembly*

7. Conclusions

The case study investigated in this article highlighted the existence of different conditioning factors that influence, to a greater or lesser extent, the decision-making process regarding the feasibility of installing major HVAC units on the rooftop of old buildings for public use, and which must therefore be checked. Some of these factors include: (i) the configuration and type of the existing structure; (ii) the existence of damage showing anomalous structural behavior of the building; (iii) the need to carry out tests to characterize the structure; (iv) the repercussion of the new loads to be placed on the previous safety conditions of the structure; (v) the configuration and design of the auxiliary support structures for the equipment to be installed; (vi) assembly adequacy.

The analysis of these aspects is also decisive for developing structural refurbishment solutions for these buildings to ensure adequate safety and service conditions for both their structure and the equipment to be installed on the rooftop.

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