Elevator structures for seismic retrofit of old buildings
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Abstract
Old buildings' vulnerability to seism is definitely a matter of concern. Therefore, solutions that minimize the impact of seisms in these buildings are needed. Combined with the necessity of improving old construction' ineffective structural behaviour during seisms, the rehabilitation of historical centres is one of the main challenges European cities like Lisbon face. Despite the introduction of elevators in old buildings increases their economic value, they are not structurally prepared to have a lift system, which frequently implies the use of self-supporting structures. The present dissertation elaborates on the opportunity of using this type of elevator structures as seismic reinforcement in old buildings.
Elevator systems operation was studied and the lift structures usually adopted in building retrofit were characterized.
A computational model of a masonry building was created and six different lift structures were tested as well as their effect on the seismic behaviour of the building. The computational models used were three-dimensional finite elements and the analysis was linear elastic using a response spectrum. The non-linear behaviour was modelled using a behaviour coefficient.
A solution involving a global reinforcement of an old-stone masonry building ("gaioleiro") was also studied. This solution comprises a lift structure and the interior walls strengthening using shotcrete.
From all models considered, the best results respect to the three-dimensional metallic structure. It was possible to conclude that, generally, the implementation of self-supporting lift structures is insufficient to ensure the structural safety in relation to the seismic action. However, it helps the global performance of the building.

Key words: Elevator Structures; Lift structures; seismic reinforcement; old masonry buildings; lift shaft; building retrofit.

1. Introduction
A country's heritage in terms of real estate characterizes it, being an invaluable asset.

Given the importance of the built heritage, a concern about its conservation and appropriate performance facing natural phenomena is needed.

In an old country like Portugal, there is a high number of old buildings that are now requiring retrofit and structural improvements.

Changes in lifestyle as well as technology advances throughout the years make these old buildings unsuited to the needs of today's population. Interventions aiming these buildings' modernization should take into account that there are certain comfort and safety requirements to comply with.

Old constructions need more efficient means for vertical mobility which leads to the installation of lifts. Since these constructions are not usually prepared to have lifts, frequently self-supporting lift structures are used.

Currently, with technology evolution, this transportation system is easily accessible both in terms of acquisition and utilization costs. So it is common to use elevators in those buildings. Taking this option is often justified by the increased economic value of the building and by the greater convenience and speed of vertical mobility.

Today, building retrofit has an increasingly higher weight in the construction market, mainly
in European countries. So considering the use of an elevator structure as a means for the building structural reinforcement may become interesting.

Not only mobility is an issue in old buildings but also seismic reinforcement given their poor performance when seismic events occur.

The present dissertation elaborates on the opportunity of using this type of elevator structures as seismic reinforcement in old buildings.

2. Elevators systems

There are two types of elevation systems for buildings available in the market, traction and hydraulic lift structures.

A hydraulic elevator moves through a hydraulic circle where a fluid (currently oil) is compressed and expanded. This is possible due to a rotating motor that makes the piston moves in the vertical direction that, in its turn, makes the cab move.

The traction electric elevator is characterized by the use of electric and gravitational energy to move the cab and the counterweight through traction cables. The counterweight system is aimed at counterbalancing the cab’s weight.

The cab and the counterweight move in slide guides that generally are made of T-shaped cross sections upright positioned and fixed on the shaft walls with means of attachment.

The MRL (Machine Room Less) technology leads to a significant space reduction both in the case of traction electric elevators and hydraulic elevators. Solutions for construction and retrofit of low and medium-rise buildings are focusing on the use of this technology, generally in the case of traction motors.

The elevator systems are non-structural components of buildings, but they are affected by seisms and can cause human and material loss. Thus, these systems need to be prepared to react safely to a seismic action.

In order to reduce seismic impact in elevator systems some precautions need to be taken. Every elevator component needs to be restrained, anchored or have the ability to accommodate the movements caused by seisms.

So that the counterweight system, the most burdensome element, behaves adequately when a seism occurs, the counterweight slides themselves have to perform well in that situation to prevent the counterweight to derail and cause other problems in the system (FEMA, 2011).

3. Lift structures for building rehabilitation

When implementing an elevator in a building, an empty space where it can circulate is needed. That void is called lift shaft.

In recent buildings with a reinforced concrete structure, using the lift shaft for structural purposes is common and this is generally the most robust element of the building.

In some situations, the shaft is only responsible for supporting the elevator, receiving the actions coming from its operation and providing the conditions that enable its good performance.

Sometimes, introducing elevators in old buildings is complex and can involve severe difficulties. Many old buildings were not designed to have these elevation systems so structures that are capable of supporting and transmitting to their foundations all actions developed by themselves are used. Conceiving these structures, called self-supporting structures, implies assessing the required conditions of the building for their installation and operation.

One of the main restrictions considered when installing elevator systems in old buildings is the space needed, not only for the cab but also for the equipments. The space needed depends on the type of elevator and consequently on the manufacturer. For instance, while the structure of a traction electric elevator has to include space for the counterweight system, the structure of an indirect hydraulic drive elevator has to involve the space needed for the hydraulic system.

The building has to have a free space for the installation of the lift shaft. This space can be inside or outside the building. In old building, it is very common to install the lift shaft in the existing stairwell, taking advantage of the free space (Figure 1). However, in many cases, restructuring the stairs and sometimes some walls is needed. Another option is installing the elevator on the outsider, not causing any perturbation inside the building.

Frequently old buildings have their structural systems degraded. The installation of an elevator in these conditions can negatively contribute to the stability of the building. Thus, in the majority of the cases, self-supporting structures are used since they are capable of
autonomously absorbing the stresses generated by the elevator systems.

The elevator’s height reach can also pose a difficulty to the structure conception. This is because for a higher reach, the structure has to handle more stresses and has to be stiff. The result is a more robust structure that requires more space.

The construction process should be simple. Currently, structures that are easily assembled and quickly concretized are chosen. One factor that affects structure conception is the difficult realization of foundations inside buildings.

Actions developed by hydraulic elevators and by traction electric elevators are obviously different since the loads transfer from the system to the structure is realized distinctively. Forces developed depend on loads and on possible dynamic effects originated by the cab’s movement.

4. Elevators structures as seismic elements of old buildings

4.1. “Gaioleiro” buildings’ characterization and seismic behaviour

In the present section, the performance of many elevator structures is studied as well as their applicability as a seismic reinforcement element in “gaioleiro” buildings.

Usually, a building is composed by masonry walls made of stone and brick, and by wooden floors. The amount of old building is Portugal is significant, in particular in historical centres of urban centres, like the case of Lisbon (Gomes, 2011).

Old buildings present a high seismic vulnerability today they need structural interventions in order to reduce the impacts caused by a seism. Many buildings are subjected to retrofit interventions but many times those do not include any type of seismic reinforcement (Lopes, 2009).

In what concerns structural behaviour, Lisbon old buildings are grouped in many types. In the present study, the chosen type of building is “gaioleiro”.

These buildings were built in the end of 19th century and in the beginning of 20th century along with the demographic expansion of the city towards north. They stopped being built in the end of the third decade of the 20th century when the reinforced concrete surged (Branco, 2007).

“Gaioleiro” buildings were taken as model for the following reasons: worse structural
behavior; high number of these buildings in Lisbon, significant number of floors and relevant dimensions in plant; lack of structural retrofit due to the fact that most of them are for living.

“Gaioleiro” buildings can both be included in blocks or be isolated. They are essentially rectangular and elongated, in which the smaller sides are the main façade and wall-backing. This type of buildings frequently present one or more vertical openings (interior patio). These are normally formed by masonry walls located in the interior of the building (Appleton, 2005).

The external walls have an approximate width 80 cm and they are made of ordinary stone masonry, with limestone and hydraulic lime. The internal walls can be of two types: main interior walls (with widths of 30 cm and masonry that is equal to the external walls or brick masonry) and dividing interior walls (with widths of 15 cm, composed by brick masonry or wooden partitions (Appleton, 2005).

The stairwell in “gaioleiro” buildings length is usually one quarter of the building length. Commonly, the stairs are made of wood and present 3 flights with two steps.

The seismic behaviour of masonry buildings relies on main factors: building dimensions and shape in plant, number of floors, vertical arrangement, masses distribution, construction quality, materials, construction processes, and year of construction. Due to the walls' dimensions and orientation, “gaioleiro” buildings are characterized by having high vibration frequencies (Braga, 2007).

Seismic resistance depends on its capacity of transmitting inertia forces provoked by the seismic, through the walls towards foundations. To be able to transmit these forces, walls need to have both flexural and shear strength. The collapse mechanisms of the walls subjected to horizontal actions have two orientations: the walls' plane and out of the walls' plane. The collapse in the wall plane can occur due to three mechanisms: diagonal cracking, sliding or unsymmetrical bending (Sabatino, et al., 2011).

The out-of-plane collapse is a rupture type that is common in masonry buildings. It is acknowledged that it is only possible to obtain a reasonable seismic behaviour in masonry buildings if this collapse is prevented. In order to have the wall resistance in their own plan, the building has to behave like a “box” and that only happens when the floors behave similarly to undeformable diaphragm and when the walls are linked to the floor and between themselves.

The undeformable diaphragms are also responsible for a better distribution of inertia forces throughout the building walls (Modena, et al., 2009).

In the present work, it is assumed that walls’ behaviour beyond the walls plane is not allowed and that the ground behaves like an undeformable diaphragm. Solutions to transform the grounds in undeformable diaphragms have been studied by many authors.

4.2. Non-linear behaviour modelling

Modelling masonry as an element with linear elastic behaviour is not realistic. Therefore, it is important to take into account its non-linear behaviour. To do that, a three-dimensional elastic analysis with non-linear behaviour modelling through a behaviour factor. To quantify it, two standards were used: the European Standard (CEN EC8-3, 2005) and the Italian Standard (OPCM 3274, 2003). The OPCM 3431 standard comprises the criteria defined in EC8 but it is more wide-ranging in terms of building structures safety verification.

According to CEN EC8-3 (2005), the behaviour factor to adopt is 1.50 in the case of simple masonry structures. On the other hand, the Italian Standard OPCM 3274 (2003) takes advantage of masonry structures' capability of behaving non-linearly, establishing a higher behaviour factor of 3.00.

Due to the mixed effect in a structure made of both masonry and steel or in a structure of both masonry and reinforced concrete, the behaviour factor was only applied in the stresses assessment in the masonry structure. Despite the non-linear behaviour of steel and reinforced concrete structures were not modelled, it was possible to verify that these materials performed an elastic behaviour.

4.3. Numerical model and adopted hypothesis

In order to study how using a lift structure as retrofit in “gaioleiro” buildings affects their performance, a fictitious building was modelled. This comprises the main characteristics of “gaioleiro” buildings except for the dimensions in plant. Despite the elongated shape of these buildings, it was decided that only the influence area of the retrofit structure was going to be studied which resulted in a compact building, with 5 floors above the ground.

It was modelled using a finite elements method, recurring to the automatic calculation software SAP2000™.
The rigid floor was modelled using the diaphragm constraints that the software provides. Taking this option prevents relative displacements between points on the horizontal plane.

It is through the rigid diaphragm effect that the elevator structures join the building.

It is possible to observe in Table 1 the modulus of elasticity used for masonry.

![Figure 3- Floor type of building model and representation of the walls analysed](image)

Table 1- Masonry elastic modulus (Branco, 2007)

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_{eff}$ - elastic modulus [GPa]</th>
<th>$E_{crack}$ - elastic modulus (cracked) [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alvenaria de Pedra</td>
<td>3.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Alvenaria de Tijolo</td>
<td>1.00</td>
<td>0.50</td>
</tr>
</tbody>
</table>

In what regards the materials of the retrofit structure, in the metallic structures the steel S235 was assumed, with a modulus of elasticity of 210 GPa; and the reinforced concrete is C25/30 with a modulus of elasticity of 30 GPa.

Seismic action was quantified through EC8-1. Only type 1 seismic and type A soil were assumed and the damping coefficient adopted was of 5%.

Safety verification of the masonry structure was realized by comparing acting shear forces in the walls $V_{rd}$, both globally and in each floor, with the respective resistance shear forces that correspond to a Mohr-Coulomb model $V_{rd}^m$. In this model, the resistance force $V_{rd}^m$ relies on masonry cohesion $C_u$, on the angle of friction $\varphi$ and on the vertical forces $N$ level that the wall is exposed to:

$$V_{rd} = N \times \tan(\varphi) + A \times C_u$$

The design values of resistance adopted are:

$$\tan(\varphi) = 0.233$$

$C_u = 0.033 \text{ MPa}$

These were divided by a confidence level of 1.20 and by safety material factor of 2.00. Characteristic values were retrieved from experimental results obtained by Milosevic, et al. (2013).

4.4. Testing elevator structures

The stairwell is located in a free space inside the building which can be used for the elevator and its structure.

Five metallic (MS1 to MS5) and one reinforced (RCS) concrete structures were used.

**MS1 - Metallic Structure 1**

This is a three-dimensional structure composed by four flat gantries, comprising cross-beams, columns and bracings, in which cross sections are of commercial type. The distance between columns’ axis is the same in the two directions, being 1.50m. This choice was based on the existing structures in the market which justifies this being the first approach to address the problem.

Bracing systems are only possible in three of the four planes of the elevator structure. Since using the lift requires openings in the plane of the elevator doors (Vierendeel type structure). The bracings only support traction forces.

**MS2 - Metallic Structure 2**

This structure is similar to the MS1 with respect to the geometric positioning. However, MS2 involves more robust cross sections and bracings made of commercial metallic cross sections. These work with tension and compression like a Warren truss. The distance between columns is 1.75m in both directions.

Using bigger elements than in MS1, an increase in the retrofit structure stiffness is expected. As a consequence, the global
stiffness of the building should increase leading to a relief in acting stresses in masonry.

**MS3 – Metallic Structure 3**

Given its poorer performance when exposed to horizontal forces, the Vierendeel type structure, when compared with a braced structure, the solution adopted was to strengthen the plane of the non-braced gantry by increasing cross beams’ flexural stiffness (Figure 6). For this purpose, cross beams were extended and built-in masonry walls.

The chosen section for the MS3 was *IPE* 300.

**Figure 5- Elevator Metallic structure MS 3**

This reinforcement is expected to lead to a more symmetric behaviour than the previous MS. Nonetheless, this is only possible if the masonry wall is rigid enough in vertical direction.

**MS4 - Metallic Structure 4**

In this case, the main goal was to increase not only axial stiffness in truss chords but also flexural stiffness in Vierendeel plane. In order to achieve this goal composite columns of steel and concrete were used.

Except for the composite columns, this structure is very similar to MS2.

**EM5- Estrutura metálica 5**

This structure encompasses two componentes: the three-dimensional interior structure, similar to MS2 located in the stairwell; and a three-dimensional exterior structure, located next to the stairwell walls. These two structures are connected by cross beams in the plane of the elevator doors.

**RCS – Reinforced concrete structure**

This structure comprises a C-shaped reinforced concrete element, located in the stairwell. This shaft’s walls width is 25cm and the external dimensions are 1.70x1.80cm.

**Figure 6- Elevator Metallic structure MS 5**

4.5. Results

A modal behaviour of a not reinforced building is characterized by translational motions along x and y-directions. It is the x-direction that represents the fundamental mode of the structure so this is the direction with the lowest stiffness.

Forces caused by the seismic action in the base along the x-direction are 4541.48 KN, of which the exterior walls absorb 76.61%. Along the y-direction forces equal 4199.92 KN, 85.32% of which are absorbed by the exterior walls.

**Figure 7- Main vibration modes of original building**

The modal behaviour of the lift structure MS1 (Table 2) is very similar to the model without reinforcement but with a slightly higher stiffness. The MS1 only equalizes 1.04% and 1.22% of the basal force.

The higher dimensions of the cross-sections and the longer spacing in the MS2 increases the global stiffness of the building (Table 2). 19.14% of the total basal force along the x-direction and 20.27% in the y-direction is balanced by the elevator structure.

Masonry’s stiffness exploited by the MS3 makes it more rigid along the x-direction, even though it is not a significant increase (Table 2).
Additionally, MS4 presents a reduced improvement when compared with the other structures. This is due to the non-linear behaviour performed by reinforced concrete that leads to an irrelevant increase in stiffness.

In what concerns MS5, it is the most rigid one thanks to an increase of resistant elements and to trusses with longer spans. It is possible to notice higher stiffness by the increase in frequency of vibration modes (Table 2). It was possible to verify that the elevator structure absorbed 30.98% of the basal force along the x-direction and 29.50% along the opposite direction.

With respect to the building retrofit using a RCS, an improvement in global stiffness occurred, being 25.78% (x-direction) and 20.36% (y-direction) of total basal forces supported by the reinforced concrete structure.

**Table 2: Frequency of the main vibration modes [Hz]**

<table>
<thead>
<tr>
<th></th>
<th>Translation x</th>
<th>Translation y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Building</td>
<td>1.97</td>
<td>2.38</td>
</tr>
<tr>
<td>MS 1</td>
<td>1.98</td>
<td>2.39</td>
</tr>
<tr>
<td>MS 2</td>
<td>2.06</td>
<td>2.45</td>
</tr>
<tr>
<td>MS 3</td>
<td>2.07</td>
<td>2.45</td>
</tr>
<tr>
<td>MS 5</td>
<td>2.18</td>
<td>2.49</td>
</tr>
<tr>
<td>RCS</td>
<td>2.06</td>
<td>2.42</td>
</tr>
</tbody>
</table>

It was concluded that while exterior walls comply with safety requirements when the behaviour factor recommended by the Italian Standard is used (q=3), safety is not ensured when the European Standard is used.
Interior walls are excessively requested in relation to their resistance capacity (Figure 11). Due to their dimensions and reduced dynamic characteristics, these walls do not comply with safety requirements. It was by comparing acting axial forces $N_{ed}$ with resistant axial forces $N_{rd}$ that the metallic reinforcement structures were verified (Figure 12).

As referred in the previous section, from all lift structures studied, the most efficient one facing a seismic event is the metallic structure MS5. This structure is composed by two modulus, an interior metallic structure that includes the elevator and an exterior metallic structure that includes both the stairs and the elevator. This was the structure chosen for the present analysis. However, cross sections of some metallic components were reduced.

A structural reinforcement solution was studied in the walls of interior patio. Reinforced shotcrete was used with a 10cm layer. This option increased building’s resistance and, consequently, its safety. The results of the structural model study are presented and discussed. The study implied taking the following steps:

1\textsuperscript{st} Step: Building – a model of the building itself, without any type of reinforcement
2\textsuperscript{nd} Step: Building + Elevator – building with elevator structure reinforcement
3\textsuperscript{rd} Step: Building + Elevator + Interior Patio – building with the two reinforcements mentioned above.

### Table 3- Frequency of the main vibration modes

<table>
<thead>
<tr>
<th></th>
<th>Translation x</th>
<th>Translation y</th>
<th>Torsion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>2.01</td>
<td>3.35</td>
<td>3.42</td>
</tr>
<tr>
<td>Step 2</td>
<td>2.15</td>
<td>3.42</td>
<td>3.43</td>
</tr>
<tr>
<td>Step 3</td>
<td>2.31</td>
<td>3.46</td>
<td>3.46</td>
</tr>
</tbody>
</table>

The increase of the global stiffness through retrofit has more impact along the x-direction (Table 3). This is the most vulnerable direction in terms of resistance which is justified by the lack of resistant walls along the lowest direction. Along the y-direction, the building presents high stiffness thanks to the amount of walls and the reduced number of openings in them.

The forces at the base are in the same order of magnitude in both directions and between the adopted reinforcements.

Attaching the metallic structure to the building caused a relevant reduction of the walls’ level of request (Figure 14). Nevertheless, the walls studied only verify safety requirements along the y-direction. Only reinforcing the lift structure was not sufficient to satisfy safety verification since walls along the x-direction are highly requested. Reinforcing the interior patio results in a better distribution of forces throughout the walls, enabling the request stresses at the walls of the main façade to be lower than its resistance capacity.

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**5. Seismic study of a strengthened building “gaioleiro”**

The present section focuses on the deployment of an elevator structure in a “gaioleiro” building in Lisbon (Monteiro, 2012).

The building preserves the main properties of “gaioleiro” buildings and it is rectangular-shaped in plant (Figure 13). Modelling and material characteristics were beforehand mentioned. It is a linear analysis using a response spectrum and the non-linear behaviour was modelled using a behaviour factor $q=1.50$. 

![Figure 13- Building plan study (Monteiro, 2012)](image)

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![Figure 12- Steel structures](image)

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<table>
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The metallic structure keeps behaving elastically, meaning that modelling its non-linear behaviour using the behaviour factor it is not necessary.

6. Conclusions

Elevator structures may have several different purposes beyond sustaining the elevator such as the elevation system protection or increasing building resistance.

Having mentioned the main constraints that this type of structures implies, it was shown that the need for space is the main issue.

Many structures available in the market were analysed either made of steel or concrete. It was concluded that metallic structures are the most common due to their effectiveness and easy assembly.

In section 4, the influence of lift structures on old buildings using a computational model (finite elements) of a fictitious “gaioleiro” building was studied. A three-dimensional elastic analysis was performed and non-linear behaviour was modelled using a behaviour factor. The mechanic characteristics of the materials assumed in the model were based in real buildings of Lisbon and they were established based on scientific articles.

The five metallic structures studied as well as the reinforced concrete structure aimed at increasing the global building resistance by improving building global stiffness.

The first hypothesis tested was a metallic braced structure, conventional type. About its impact on the global structure, it was possible to verify that there is no impact. A more robust structure was required. Moreover, other lift structures were created to be tested.

These comprised metallic structures composed by gantries. They were different from the previous one in, for instance, metallic components sizes and gantries width, and so on.

A composite structure, of steel and concrete was analysed. However, the improvements in this case were not interesting.

An important conclusion is that when there is an increase in metallic structures stiffness, the acting forces and the building displacements are lower. The best performance obtained corresponds to a structure with high dimensions and that exploited the space previously used for the stairwell.

The studied concrete structure was cross-section “C” type and it was implemented in the stairwell. The impact of this option is not very different from the metallic structures.

Safety verification of the masonry walls used Mohr-Coulomb criteria for the exterior and interior walls. Despite safety was not ensured, in some cases the implementation of a reinforcement structure it was possible to verify safety requirements in some masonry buildings.

Another important conclusion is that metallic reinforcement structures are less requested comparing with their maximum capacity, performing elastically.

This analysis enabled to understand that the metallic structure needs to be highly stiff and that the resistance level would be excessive.

In section 5, a 5-floor “gaioleiro” building was studied. This building had two vertical openings, an interior patio and a stairwell. A solution involving the interior patio walls and a metallic elevator structure was studied.

With the introduction of reinforcement elements, the behaviour of the building improves expressively not only in terms of displacements but also in terms of resistance. Nevertheless, in terms of resistance, the lower dimension walls do not verify shear safety. These walls belong to the back façade so a structural intervention would be easy. The remaining walls are interior walls that need resistance.

Generally, an elevator structure is not sufficient for safety verification according to the defined criteria. The impact of elevator structures can positively contribute to the building behaviour. When a global reinforcement occurs, this structure can be used as a complemental reinforcement, bringing benefits to the building performance. However, in order to actively participate in the building behaviour, they have to present high stiffness which can only be achieved with very robust elements or long snaps between columns.
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