Abstract. In the event of an earthquake, the perfect operation of hospital services is vital. The failure of the elevator system in this type of building may make the vertical transportation of patients impossible, and thus not allow medical care at such a crucial time. Therefore, this work intends to raise awareness to the importance of the seismic design of elevator systems, starting with a brief description of the various components of these systems and emphasizing seismic safety devices. Following that, is presented a retrospective analysis of damage resulting from seismic events based on the recording of systems performance in previous events. Such analysis reveals the derailment of the counterweight as the most frequent failure, exposing the rail-counterweight system as requiring more attention by a project to the seismic action. Since the elevators are non-structural elements and thus not considered to be part of the structural strength of the building where they are installed, there are only a few regulations developed by countries as USA and Japan where specific minimum safety requirements are defined for the various components. And although the European standard EN81-77, approved in 2013, has design and installation criteria against seismic action, Portugal still lacks seismic design methodologies. For this matter, these documents are approached and such methodologies are compared. The method recommended by EN81-77 is the one chosen to be confronted in the context of a case study based on the Barlavento Algarvio’s Hospital. For this, dynamic analyses are carried out to obtain the dynamic response of the car and counterweight guide rails.

Keywords. ASME17.1, Car, Counterweight, Earthquake safety device, Elevator/Lift, EN81-77:2013, Hospital, Seismic behavior

1. Introduction

Thanks to major advances in the building design and increasingly demanding regulations, there are fewer structural failures and collapses due to seismic events. On the other hand, the damages in the non-structural elements still stand out, being responsible for more than 50% of the total loss [8]. A non-structural element is not considered in seismic design due to the lack of resistance or its connection mode to the structure. However, after a seismic event, not only the building must withstand, but also all non-structural elements, such as elevators, must remain operational.

As such, nowadays there’s an increasing concern to create and improve safety rules for the construction and installation of these elements subject to seismic conditions. In the event of an earthquake, the importance of the normal operation of a hospital is recognized, and for this reason, elevators need to be operational since they allow the vertical movement of people and equipment. There are some regulations published by USA, Japan and, more recently, Europe to improve the seismic behavior of elevators. Although there’s this European standard presenting safety rules for lifts subject to seismic conditions, Portugal still lacks its own recommendations.
2. Elevator Systems

There are several types of elevators but, according to their mechanism of operation, they can be classified in two main types that are the most common in buildings: electrical traction and hydraulic. The traction elevators move along guide rails, usually made of steel, through a system of cables that pass through a traction sheave installed in the machine room. To counterbalance the lift, there is a cable-connected counterweight that allows lower energy costs and higher travel speeds than hydraulic lifts, and for these reasons, they are preferred for medium-to-high structures. The car and counterweight guide rails, fixed to the walls of the shaft by brackets, control the trajectory of these components, guaranteeing the linearity of their movement [9]. There is also an innovation of this system, that is the Machine Room Less (MRL) elevator, a system with no machine room.

Hydraulic lifts are installed in buildings up to 8 floors, being composed of an electric motor that increases the pressure of a fluid, usually an oil, so that it moves from the reservoir to the cylinder (upwards), causing the piston to move. To do this, the control valve is closed in such a way that the oil does not flow in the reverse direction. The car stops when the engine power is cut off. For the elevator to come down, the control valve opens, allowing the fluid to return to the reservoir. The piston pushes the car directly or through cables (roped). Also, the cylinder may be buried in the ground (in ground system) or installed laterally to the cabin (holeless).

There are seismic safety devices that can be installed in the lifts. A seismic detection system can help passengers quickly get out of the elevator by taking the cabin to the next floor. The seismic switch detects and measures the acceleration on three axes and must be able to detect P and S waves and act accordingly. The elevator will be out of service until a qualified technician inspects it and then restarts it. The installation area of this device is not consensual between some standards and even between suppliers and installation companies. The EN 81-77 standard [1], for example, indicates that if the sensor is used to transmit information to the elevator, it can be placed in the well. ASME 17.1 [2] indicates that the switch must be installed in the machine room. Another safety device is the counterweight derailment sensor that senses the displacements of this element relative to its normal location and is designed to avoid contact between the counterweight and the car.

3. Elevators Subjected to Seismic Conditions

3.1 Damages Resulting from Seismic Events

The damages suffered by elevators due to strong seismic events only began to be registered and compiled in a systematic way after the earthquake of San Fernando, California, in 1971.

The most common damages in electrical traction elevators observed in several earthquakes since that time are as follows [3]:

- Damage in the guide rail brackets;
- Deformation of the guide rails and sliding devices;
- Counterweight derailment;
- Collision of the loose counterweight with the car;
- Displacement of the traction machine out of its attachment;
- Sliding of the generator motor out of the machine room;
- Damage to the cables due to projections and debris in the elevator shaft;
- Traction cables out from its trajectory;
- Break of the compensation cable;
- Failure of the seismic safety devices.
The counterweight is the heaviest component of a traction system weighing the same as the car plus about 50%, which means that it is subject to higher inertia forces. Its derailment is the most serious damage and is a serious problem because, once outside the guides, it can swing freely in the elevator shaft and collide against the car and other components, damaging the other components. In addition, being made up of blocks, if the counterweight jumps from its guides, they can fall into the shaft or even into the car.

From the records obtained, the most frequent damages, exclusive of hydraulic elevators, were [4]:

- Oil leakage;
- Cylinder and piston displacement;
- Leaks in hydraulic line;
- Reservoir overturned.

3.2 Codes and Standards

Currently, in Portugal, the elevators are designed according to existing European standards: EN81-1 for traction elevators [5] and EN81-2 for hydraulics [6] that lack methodologies of seismic design. Yet, there are some codes like ASME A17.1 and the Japanese Standard that define specific minimum safety requirements for the various components of an elevator system. In addition, there is the European Standard EN81-77, approved in 2013, which also presents construction and installation criteria for the seismic action.

Like ASME 17.1, EN81-77 establishes design equations considering the design acceleration, which is no longer the case in the Japanese standard. Like ASME 17.1. Taking into account that parameter, the European standard defines security requirements based on the classification of the elevator system (Table 1) for categories above 0.

<table>
<thead>
<tr>
<th>Category</th>
<th>Design acceleration (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$a_d &lt; 1$</td>
</tr>
<tr>
<td>1</td>
<td>$1 \leq a_d &lt; 2.5$</td>
</tr>
<tr>
<td>2</td>
<td>$2.5 \leq a_d &lt; 4$</td>
</tr>
<tr>
<td>3</td>
<td>$a_d \geq 4$</td>
</tr>
</tbody>
</table>

In the Annex B of this standard, you can find the formulae used to calculate this parameter that follows the methodology used by EN1998-1 for non-structural elements [7]:

$$a_d = S_a \times \left( \frac{Y_a}{q_a} \right) \times g \quad (1)$$

Where $Y_a$ is the factor of the element (equal to 1.5 for lifts installed in hospitals); $q_a$, the behavior factor of the non-structural element (equal to 2.0); $S_a$ is the seismic coefficient applicable to the element. This last coefficient can be determined by the following equation (see EN 1998-1:2004, Formulae (4.25)):

$$S_a = \alpha \times S \times \frac{3 \left( 1 + \frac{z}{H} \right)}{1 + \left( 1 - \frac{T_a}{T_1} \right)^2} - 0.5 \geq \alpha \times S \quad (2)$$

Where $\alpha$ is the ratio of the design ground acceleration on type A ground ($a_d$) to the acceleration of gravity $g$; $S$ the soil factor; $T_a$ and $T_1$ the fundamental vibration period of the non-structural element and of the building in the relevant direction, respectively; $z$ the height of the element above the level of application of the seismic action; $H$ is the building height measured from the top of foundation system. With this methodology, it's possible to take into account the most diverse aspects, thus introducing a high level of requirement:

- Resonance effect (when the ratio $T_a/T_1 = 1$);
• Importance of the equipment in the structure ($\gamma_a$) and the structure's own functionality;
• Type of soil (introduced by $S$);
• Location of the element in the structure (ratio $z/H$);
• Seismic zoning (introduced by $\alpha$).

The seismic action considered by the above expression is associated to the requirement of no Collapse - Ultimate Limit State, not ensuring a good performance and operability of the system after the earthquake (damage limitation requirement). The three elevator codes mentioned define constructive arrangements for the various components of an elevator system although the Japanese standard is the only that does not mention any requirement for the car and counterweight system. It is presented a summary of the requirements described in those codes [1] [10]:

**Car and counterweight systems:**

- The counterweight and car frames must be provided with position restraints (lower and upper) in order to prevent excessive displacements that may result in the undocking of one of these elements. These devices are designed to withstand a horizontal seismic force induced by the weight of the car or the counterweight;
- Minimum clearances between the car and the counterweight also between the counterweight frame and the shaft wall in order to prevent collisions.

**Guide rails system:**

The guide rails must be made of structural steel T sections and must withstand a seismic force induced by the mass of the counterweight or the car plus its rated capacity. The brackets and supports are also designed to resist the same action. To improve the performance of these elements, it can be installed intermediated supports.

![Fig. 2 – T-section [3]](image)

**Cables and sheaves:**

The sheaves must be provided with a cable retainer to avoid its displacement.

**Electrical equipment support:**

The fastening devices and their screws used to secure the equipment to the structure shall be designed to withstand horizontal and vertical seismic forces generated by the design acceleration to prevent the displacement or overturning of the equipment.

**Safety devices:**

- Hydraulic lifts must be provided with a shutoff valve to avoid environmental problems related to oil leakage;
- In the event of a seismic event, class 2 and 3 lifts (EN81-77) shall automatically move to the nearest floor to avoid entrapment of passengers in the car;
- The elevators must be provided with a seismic switch and a counterweight displacement sensor, which is activated by its derailment;
- The seismic detection system should always be operational even in the event of a power outage, so it is provided with an emergency power supply;
- Each elevator must have an instant reset button installed on the control panel of the
machine room. This last device allows the restoration of the normal operation of the lift if the displacement sensor is not activated.

4. Case Study: Barlavento Algarvio's Hospital

The case study refers to an elevator system installed in the Barlavento Algarvio's Hospital in Portimão, where it is intended to analyze the response of the elevator guide rail system when requested to a seismic action defined according to EC8. For this, it is elaborated a numerical model of a part of the building, in SAP 2000 software. The objective of this analysis is not to evaluate if the elevators installed in the Hospital are well designed, but rather to employ and study the methodology recommended by EN 81-77. Restricted to the behavior of the counterweight and car guide rails, it is performed modal analysis by design spectrum (EC8), since these components are subject to global and local deformations.

4.1 Description of the Structure and Elevator System

The building is divided into 7 independent structural bodies and the object of study is the highest one with 7 upper floors and two buried and it is the one with vertical accesses (stairs and elevators). The structure is composed by reinforced concrete frames of C20/25 concrete grade and C12/15 for the foundations. The structure presents a fundamental frequency of 0.701 Hz.

The six elevators installed on this block are electrical traction lifts with machine room divided into two groups: the bigger ones for passenger and stretchers and the smaller ones for passengers only. For each elevator are two sets of T-section guide rails, destined to guide the car (T125B and T82A) and the counterweight (T70A and T50A). The guide rails have a total length of 33.8m, composed of mostly regular spans of 2.9 meters. The support and fixing of the guides is made by means of brackets and the sliding devices used are sliding guides. The vertical distance between the latter and the cab is 3.186m and 3.220m for the counterweight.

| Table 2 - Properties of the guide rail sections [11] |
|-----------------|---------|----------|----------|
| Mass (kg/m)     | Area (cm²) | Iₓ (cm⁴) | Iᵧ (cm⁴) |
| T50A            | 3.73     | 4.75     | 11.24    | 5.25     |
| T70A            | 7.47     | 9.51     | 41.3     | 18.65    |
| T82B            | 8.55     | 10.9     | 49.4     | 30.5     |
| T125B           | 17.9     | 22.83    | 151      | 159      |

4.2 Numerical Model

The numerical model was performed in the SAP 2000 where the structural elements (pillars, beams and walls) were modeled as frame elements. The interaction of the structural walls with the remaining structure is carried out by connecting it with rigid sections (with a very high modulus of elasticity).

Car and counterweight and counterweight guide rails were modeled with vertical frame elements in which the cross-sections correspond to those indicated in Table 2. The constituent steel is characterized by a modulus of elasticity of 210GPa and a Poisson coefficient of 0.3. The brackets which were represented by rigid bars of square section (0.1x0.1m). For this to be possible, the structural walls have been divided into several blocks to coincide the axis of the guide with the axis of the wall block where the connection is made. The modeling of this connection was made by assigning releases to each node of the frame element, the bracket. Thus, a monolithic bonding of this element to the concrete wall.
is considered, so there is no release; and the bending and torsion moments were released in the connection between the rail and the bracket.

In order to perform the dynamic analysis for X and Y directions, four load situations were assumed corresponding to three different behavior scenarios of the guide rails during a seismic action. In all cases, it is assumed that the elevator is stopped. For X direction, both guide shoes make contact with the guide rails so, for this direction, it is applied 2 masses (scenario 1). For Y direction, the car/counterweight can collide with the rails on both upper and lower guide shoe levels (scenario 1) or in just one level (scenario 2 - 1 mass applied).

According to the position of the center of mass of each component, the masses are multiplied by 1/2, for the car, 1/3 and 2/3 for the lower and upper counterweight guide shoes, respectively. These masses are applied in 31 different positions, corresponding to the brackets and middle span levels.

The analysis of the global behavior of the system of guides is divided in two different analyzes: the first one is related to the displacements between floors; and the second one is related to the local deformation of the guide rail due to the cab or counterweight. Thus, for the first part, it is used the numerical model, without including the masses, to determine the effects related to the deformation of the own structure when it subjected to a seismic action. In a second phase, the masses are applied at each point, accounting for the two aspects mentioned.

In addition to these two analyzes that use the building model, it is necessary to use a separate model of the guide, to obtain the fundamental periods of this system for each position mentioned. In this way, the guide is modeled with frame elements, as horizontal continuous beam, with geometric and physical properties identical to those considered in the other model.

4.3 Results Analysis

The parameters evaluated were the following: horizontal accelerations, horizontal displacements, bending moments and bending stresses for the four T-section guide rails. In the following figures, it is presented some of the results.

![Fig. 4 – Representation of the guide rail with applied masses](image)

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![Fig. 5 – Accelerations along T125B section due to seismic action type 1 – Y direction (scenario 2)](image)
Since they rely on vibrations induced by the structures, the guide rails present a similar behavior for the acceleration graphs of the systems without masses applied. It is noticed that there is an increase in the accelerations of the guide T125 to the guide T50 due to the decrease in stiffness of the sections and increase of mass. As for the accelerations of the systems with masses, the behavior of the guides with counterweights is emphasized in which the lower guide shoe, with greater mass applied mass, displays greater accelerations. The graphs for EN81-77 show a linear evolution of the accelerations along the guide and, although with much higher values, follow the trend verified in the guides systems without masses applied. Such linearity is less pronounced in the counterweight guides not only because of the mass increase but also because of the vertical distribution of the same in the various positions that affect the fundamental periods of the system.

The displacements due to the seismic action are the difference between the displacements resulting from the two analysis (with masses minus without masses), multiplied by the behavior factor. As expected, the maximum displacements are observed for the middle span zones and the displacements obtained by the dynamic analysis do not exceed, in any case, the values calculated by the standard. Those values are very high, especially in the T50 and T70 guides, of the counterweight system, not only due to the large masses but also to much lower inertia values.

The counterweight guide rails exceed the maximum allowable displacement (40 mm) recommended by EN81-77.

It is to be noted that the displacements obtained by the European approach do not consider the effect associated with the movement of the floors of the building and the local deformation of the guide.
The moments associated with the rail local deformation are obtained by the difference between the moments resulting from the analysis of the guide model with and without the elevator ($M_2 - M_1$). As shown for the displacements, this last component is affected by the factor behavior when, in reality, they are the efforts generated by the displacement between floors and, therefore, must be multiplied by $q$. Thus, the final moments are obtained by the following equation:

$$M = M_1 \times (q - 1) + M_2$$  \hspace{1cm} (3)

It can be seen that the worst scenario corresponds to that of the lower guide and for counterweight systems, the values determined by the standard are exceeded in several points, whereas for car systems this occurs less frequently.

As for bending stresses, in the counterweight sections, the values obtained are evidently higher than the yield strength of the material (370 MPa). Generally, by decreasing the section area, the values obtained by the design spectrum analysis
surpass more frequently the ones obtained by the Standard.

5. Conclusions

The operability of elevators in a hospital is critical after a seismic event, when it is expected to be a greater influx of people in need of care. For this reason, the vertical transport of patients must be ensured.

Due to the research of the earthquakes registered in previous years, there is no record of fatalities in the elevators during this event, for which it is verified that these systems present a favorable behavior to the human protection. However, the material damages observed in the various components compromise the functionality of the system and may even cause serious economic and social consequences.

The retrospective analysis of damages in elevator systems, due to seismic events, allowed to indicate the counterweight derailment as the most frequently observed, which shows the importance of the existence of specific regulations for the seismic design of the various components.

The results obtained by the dynamic analyzes carried out, proved the conditioning behavior of the counterweight system during a seismic action due essentially to the high loads as well as to the vertical distribution of the same. Furthermore, in doing this analysis for four different guide sections, it has become obvious that the sections of minor inertia are inadequate to resist this action and that the yield stress of the material is largely exceeded.

The discrepancies between the two dynamic analyzes through SAP2000 and the one recommended by the standard, are evident and such can be justified by the consideration of different values of behavior factors - the structure behavior factor for X and Y directions and the behavior factor of the non-structural element - which reflect the nonlinear response of the structure or elevator. Also the European standard does not fully account for the effects associated with the movement of the floors and the consequent local deformation of the guide rail.

However, it is to be reinforced the idea that the results obtained come from a single case study.

Finally, in order to contribute to a possible manual of seismic design of elevator systems, it was performed the Portuguese territory zoning, taking into account the methodology adopted by EN81-77. Thus, for each county or island of the country, it is possible to know more quickly which seismic category the elevator is inserted in, considering the importance class and the type of soil.

6. References


![Fig. 11 – Portugal zoning for seismic lift categories for importance class III and soil type A](image)


