Seismic design of elevator systems in base isolated structures

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Abstract

Elevator systems have a vital importance in the functionality of important buildings, for both public security and life protection. Exemplifying with hospital buildings, their functionality depends on the integrity of the vertical transport systems, in such a way that a failure of those systems can disable the medical services, which can be particularly critical in the aftermath of an earthquake event.

Base isolated solutions in buildings provide an improved performance and control of the seismic behaviour, minimising the resulting structural and non-structural damage, to an extent that these solutions may ensure the post-earthquake functionality of the building. Nevertheless, even in such buildings the elevator systems are subjected to the effects of the earthquake, thus requiring for explicit demonstration of the safety of these, considered as non-structural components.

The current structural design codes pay some attention to the damage control of the non-structural components, providing for formulas to compute the horizontal seismic forces that these components may be subjected to. However, those formulas do not consider the specific case of base isolated buildings, providing for an overly conservative calculation of the horizontal acceleration to which the non-structural components, such as those that compose the elevator system, are subjected to.

The main objective of this dissertation is to rationally derive the formulas for the computation of the horizontal seismic acceleration imposed on the non-structural components in base isolated buildings. These formulas provide for the estimation of the maximum design acceleration, as a function of the ratio between the isolated and the fixed base periods, $T_{isolated}/T_{fixed}$, also accounting for the different structural types.

Keywords: Elevator, Lift, Seismic design, Base isolation, EN 81-77:2018

1. Introduction

The observation on the seismic effects in the buildings allows to verify that, beyond the damage on structural elements, significant damages on the non-structural elements. Those damages can limit or stop the normal utilisation of the important buildings, for both public security and life protection. Exemplifying with hospital buildings, the perfect operation of hospital services is vital after a earthquake event. The failure of important non-structural elements, like 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.

Base isolation solutions in buildings provide an improved performance and control of the seismic behaviour, minimising the resulting structural and non-structural damage, to an extent that these solutions may ensure the post-earthquake functionality of the building. Nevertheless, even in such buildings the elevator systems are subjected to some level of earthquake effects, and still need to be designed, to resist the horizontal seismic acceleration.

Elevator systems are sensible to the seismic action, and their seismic design follows EN 81-77:2018 [5], articulated with Eurocode 8 [3]. Both standards do not give a formula to calculate the design acceleration in non-structural elements installed in base isolated buildings. The obtainment of the value design acceleration that the elements are subjected to is essential to a proper seismic design of the element.

This paper has the main objective of rationally deriving the formulas for the computation of the horizontal seismic acceleration imposed on the non-structural components in base isolated buildings.

2. Base Isolation

Seismic isolation has become an effective design strategy to mitigate seismic hazard.

2.1. Base Isolation Concepts

Base isolation solution in buildings consists in the introduction of a low stiffness horizontal layer between the superstructure and the base (foundation or substructure), constituted by isolators. By this separation the amount of energy that is transferred to the superstructure during an earthquake is reduced significantly.

Countless types of base isolation systems exist, but all consist in the same concepts. The first one is making the building more flexible in order to have a higher fundamental period of vibration. Another aspect is the increase of the damping level due the non-linear behaviour of the isolators.

In figure 1 it is illustrated for a typical base isolated structure, the spectral response acceleration and displacement, with reduction values due the damping of the base isolated structure and the transition of the fundamental period of vibration.

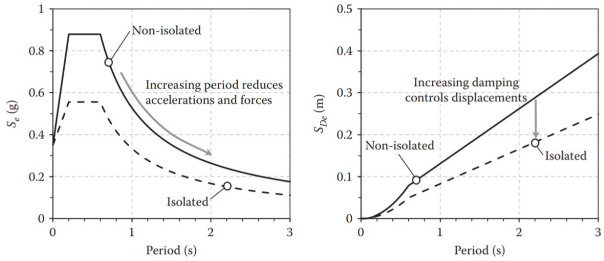

Figure 1: Effect of seismic isolation [9].

It is noticed the reduction of acceleration by the increasing of damping and the fundamental period. And also the increase of total displacements due the shift of fundamental period, but have some attenuation due the high damping. Concluding that increasing the period reduces the seismic forces transmitted to the superstructure, while increasing damping controls the displacements.

The shift between the base isolated period and the period considering the building as fixed base, $T_{isolated}/T_{fixed}$, is the primary measure of the efficacy of the base isolation system. In general this relation has values between 2 and 3.

The isolated period values are considered optimum around the 2s [8], and generally are in the interval between 2 and 3s.

2.2. Base Isolation Devices

The base isolation effect primarily depends on the type of isolator device to use. Nowadays are multiples types of isolator devices, but the ones how stand out are the elastomeric bearings and sliding systems.

From the elastomeric bearings devices is highlighted the High Damping Rubber Bearings (HDRB) and the Laminated Rubber Bearings (LRB). Those devices are constituted with elastomer made of either natural rubber or neoprene [1]. A rubber-bearing typically consists of alternating laminations of steel plates and thin rubber layers, attached together to offer vertical rigidity and lateral flexibility [1]. Those bearings are very strong and stiff in the vertical direction, but also flexible in the lateral direction. Vertical rigidity ensures the isolator will support the structure's weight, while horizontal flexibility transforms destructive horizontal shaking into smooth movement. The difference between this types of bearings is that HDRB is made with a high damping elastomer, having damping value between 10 and 15%. The LRB are made with low damping elastomer but the damping is assure by a insertion of lead core inside the bearing, that gives the damping of the device, leading to higher damping values almost 30%.

The second type of base isolation system is typified by the sliding system, most common used is the Friction Pendulum System (FPS). This device are constituted by an articulated friction slider, a spherical concave sliding surface, and an enclosing cylinder for lateral displacement restraint. During the ground motion, the structure is free to slide on the bearings. Since the bearings have a curved surface, the structure slides both vertically and horizontally [1].

2.3. Simplified Model

It is possible to model the base isolation system, in an approximate way, only with base in the following parameters: effective horizontal stiffness, K_{eff}, and the effective damping, ξ_{eff}, of the base isolation system. The effective stiffness takes the secant value of the stiffness relative to total design displacement of the system. And the effective damping can be expressed by the cycles dissipation of energy with a frequency in the interval of frequencies of the modes considered.

With the effective horizontal stiffness and with the total mass of the superstructure it is possible to calculate the fundamental period of vibration, denominated effective period, considering the superstructure as rigid body, by equation 1.

$$T_{eff} = 2\pi\sqrt{\frac{M}{K_{eff}}} \tag{1}$$

3. Elevators Systems

Elevator system have the function of establishing vertical connection in the buildings. This article focus only in electrical traction elevators because it is the most common use and the other types of elevators are not adequate for installation in base isolated structures.

3.1. Components

For a better understanding how an earthquake can affect a elevator system, it is illustrated in figure 2 the principal parts of an elevator.

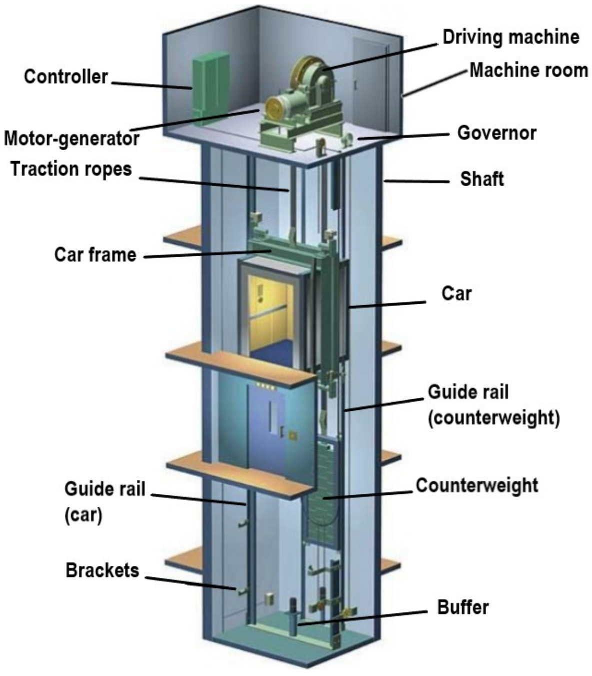

Figure 2: Electrical traction elevator components [2].

The car and counterweight are the elements in the system with more mass, and they are the ones how generate large inertia forces due the horizontal acceleration in a seismic event.
One of the principal components of the system and also normally the most affected by the seismic action is the guide rail system. The design requires additional verification in order to guarantee the guide rails remains without some level of permanent deformation. This is crucial for all the system remains operational after the earthquake.

3.2. Seismic Design under EN 81-77:2018

Design of elevator systems under seismic conditions are followed by EN 81-77:2018 [5] articulate with the Eurocode 8. This standard defines rules of additional security, and are composed by both prescriptive and performance-based measures, dividing in seismic elevator categories, and those depended on the seismic design acceleration, as show in table 1.

The measures and the verification in the structural elements also depends on the design acceleration too.

Both EN 81-77:2018 and Eurocode 8 prescribe formulas to calculate the design acceleration in the element, but this formulas do not consider buildings with base isolation.

Table 1: Seismic elevator categories.

Category	Design acceleration (m/s^2)
0	$a_d \leq 1$
1	$1 < a_d \leq 2.5$
2	$2.5 < a_d \leq 4$
3	$a_d > 4$

One of the components of the seismic design is that of designing the guide rails, of the car and counterweight, for the seismic forces resulting the clash of the car or the counterweight in the guide rails in the seismic event, as illustrated in figure 3.

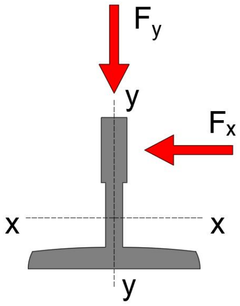

Figure 3: Resulting seismic forces on guide rail.

The formula of calculus of those forces are given in EN 81-77:2018, and primarily depends on the design acceleration, a_d, that the systems are subjected, and others variables in conciliation with the standard EN 81-50:2014 [4]. All the variables considered for the explicit seismic design, are presented in the table of load cases in the standard, in the particular load case of seismic condition.

3.3. Elevators Systems in Base Isolated Structures

In buildings that have the base isolated plan between floors and the elevator system as continuity through floors, leads to taking some measures to protect the system to the high displacements at the base isolation level. As show in figure 4 one technical solution to protect the elevators is to suspend the elevator shaft on the superstructure.

This solution leads that the elevator shaft is isolated, having the same displacements as the superstructure. Referring that it only function if the shaft is separated to the substructure, guaranty the necessary gaps to accommodate the displacements of the building.

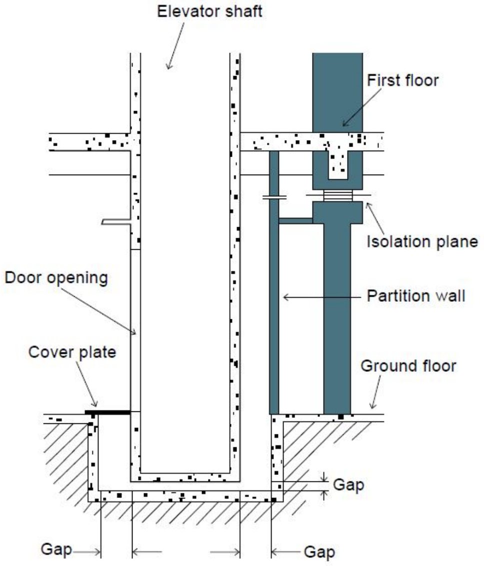

Figure 4: Section through a elevator shaft in a base isolated building [6].

4. Numerical Model

The numerical model for obtainment the results that lead to a set of formulas of calculus of design acceleration, consist in a plane model with concentrated masses on the floors levels and was programmed in the language Python.

The buildings model has a variable number of floors, N, between 2 and 10 floors, because this values reflects the current isolated buildings. It is assumed that the vertical structural elements have the same dimensions in all floors of the building, conducing that the stiffness per floor, $EIfloor$, is the same in all floors.

Figure 5 show the models for superstructure and base isolated structure.

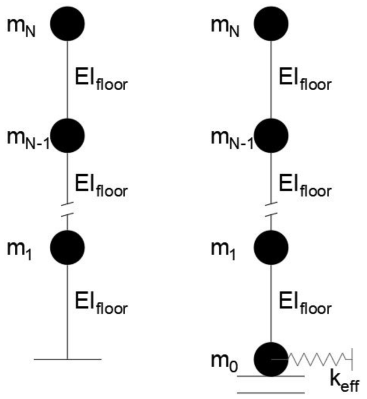

Figure 5: Model with concentrated masses at floors levels: Fixed base and Isolated base.

It is assumed as well that the floor masses are a discrete system of concentrated masses. And was taken the option of fixing the mass per floor, included the mass at the base level, taking the value of 500 ton, for all the oscillators calculated. Because is intended that each oscillator has a determined fundamental period of vibration. So fixing the mass value it is only necessary finding the floor stiffness, EI_{floor}, which satisfies that condition.

The height between floors, h, is all the same and equals to 3.2m. The base isolation system is modelled with an association of a horizontal spring in the model of the base isolated structure. And the spring have the same stiffness as effective stiffness of the system of the base isolation considered, K_{eff}.

This model was build to incorporate differents structural types, with the criteria based on the Eurocode 8. Considered adequate in a base isolated building these types: frame system, dual system frame equivalent, dual system wall equivalent and ductile wall system. Each type of structure was satisfied in the numeric model introduction a parameter that reflects one ratio between the contribution of frames and structural walls in the total stiffness per floor.

It is presented in table 2 the distribution of the basal shear force in percentage, between frames and structural walls, for each structural type considered.

Table 2: Structural types considered.

Structural type	$\%V_{frames}$	$\%V_{walls}$
Frame system	80	20
Frame equivalent	60	40
Wall equivalent	40	60
Wall system	20	80

5. Results

This section aim to rationally derive the formulas for the computation of the horizontal seismic acceleration imposed on the non-structural components in base isolated buildings.

Those formulas depends on the spectral acceleration and in one factor of amplification (β_{global}), that leads to transform the spectral acceleration for the fundamental mode in the maximum acceleration in the building.

It is presented the results obtained of global amplification, separating the analyse in two components: spectral amplification (β_1) and amplification due to accounting the superior modes of vibration (β_2).

All the curves in the next figures with the results, were obtained with a continuous approximation of the 50 discrete points. And refer that in this document it is only present some of the results obtained, and the rest is in the MSc Dissertation [7].

5.1. Spectral amplification (β_1)

To consider the difference between the spectral acceleration and the maximum acceleration in the building it is presented the spectral amplification, β_1, and it is obtained by equation 2.

$$\beta_1 = P_{1x} \cdot \phi_{1N} \tag{2}$$

- P_{1x} the modal participation factor for the first mode;
- ϕ_{1N} the modal amplitude for the fundamental mode at last floor, floor N.

5.1.1 Variation in the number of floors - Wall system

Figure 6 show the results of amplification factor in function of relation between fundamental effective period and fixed base period, T_{eff}/T_{fixed}, for buildings with the structural type wall system and for the numbers of floor 2, 4, 7 and 10.

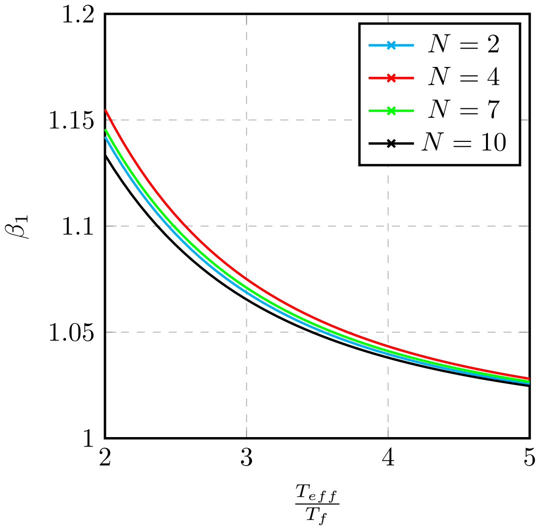

Figure 6: Amplification factor β_1 in function of T_{eff}/T_f, for structural type wall system and varying the number of floors.

As observed the influence of variation number of floors do not reflect a signification change in spectral amplification, being buildings with 4 floors leading to higher values in relation to the cases considered.

5.1.2 Variation of structural types - N=4

In figure 7 it is fixed the number of floors in 4 and the structural types are varied.

The influence of the increasing of the stiffness of the walls in the system is reflected in the values of spectral amplification. Increasing the stiffness of the walls of the system increases the amplification values. For the particular case $T_{eff}/T_f = 3$, for the frame system the value is 5.2% and for the wall system is the 7.5%.

Concluding that for the values of amplification β_1 the buildings with 4 floors and structural type wall systems, leads to higher values of amplification.

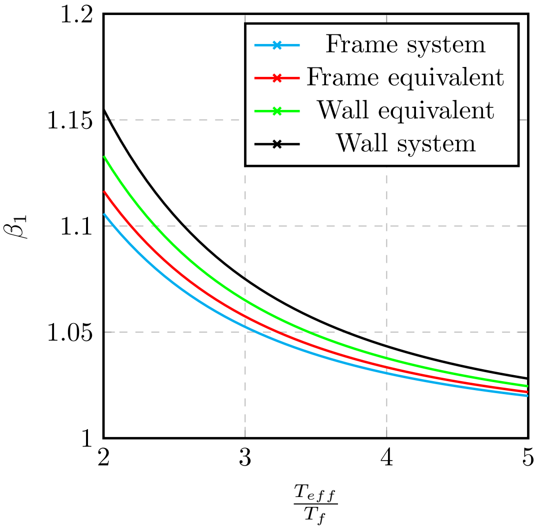

Figure 7: Amplification factor β_1 in function of T_{eff}/T_f, for buildings with 4 floor and varying the structural type.

5.2. Amplification due accounting of higher modes (β_2)

The amplification due the accounting of higher modes it is translated by the ratio between the maximum acceleration in top with all modes combined, using a Complete Quadratic Combination, and the acceleration in the top of the building for the fundamental mode. And it is translated by equation 3.

$$\beta_2 = \frac{a_N^{CQC}}{a_N^{mode1}} \tag{3}$$

The seismic action influences the results of the amplification β_2, because it is calculated the spectral acceleration for all modes. The results were obtained for action Type 1, as described in the Portuguese National Annex of Eurocode 8. The action Type 2 was disregarded because for high period structures (such as those base isolated) action Type 1 leads to increased action effects.

5.2.1 Variation in the number of floors - Wall system - $T_{eff} = 2s$

In figure 8 it is presented the amplification factor in function of relation between fundamental effective period and fixed base period, T_{eff}/T_{fixed}, for buildings with the wall system structural type, for the numbers of floor 2, 4, 7 and 10 and for a T_{eff} equal to 2s.

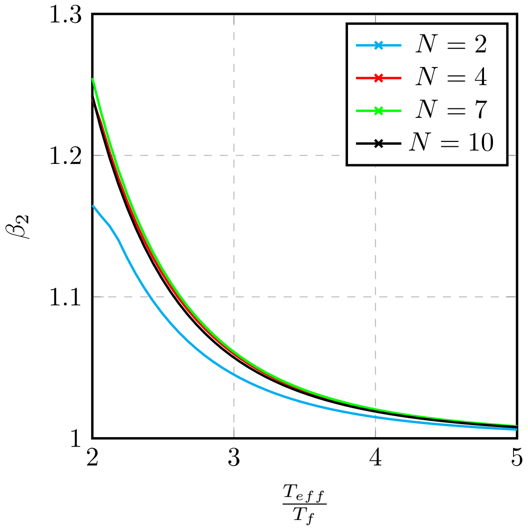

Figure 8: Amplification factor β_2 in function of T_{eff}/T_f, for structural type wall system with $T_{eff} = 2s$ and varying the number of floors.

For this case, and focusing in values of T_{eff}/T_f higher than 3, the amplification values are not significantly high. For the case of T_{eff}/T_f equal to 3 the value of amplification is around 6%.
The curve relative to the case of buildings with 2 floors present smaller values, is because those buildings has less modes of vibration, 3 in total, and in comparison with other curves, with more modes of vibration associated, leads to a smaller values of β_2.

5.2.2 Variation in the number of floors - Wall system - $T_{eff} = 3s$

In figure 9 it is presented the amplification factor in function of relation between fundamental effective period and fixed base period, T_{eff}/T_{fixed}, for buildings with the wall system structural type, for the numbers of floor 2, 4, 7 and 10 and for a T_{eff} equal to 3s.

Considering a T_{eff} equal to 3s results in higher values of amplification in comparison to the values for T_{eff} equal to 2s. It is explained by the fundamental period in those cases are more to the right of spectral, leading to a smaller spectral value, and the superior modes continues in the constant level of the spectrum or near by. Resulting in higher difference for the spectrum values of the superior modes in relation to the spectral value for the first mode, leading to higher values of amplification.
For the case of T_{eff}/T_f equal to 3 and for the curve relative to buildings with 7 floors, the amplification reach the value of 30%.

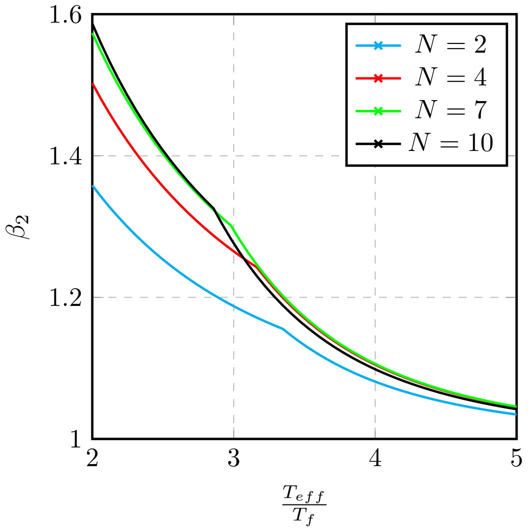

Figure 9: Amplification factor β_2 in function of T_{eff}/T_f, for structural type wall system with $T_{eff} = 3s$ and varying the number of floors.

5.2.3 Variation of structural types - N=4 - $T_{eff} = 3s$

In figure 10 it is presented the amplification factor in function of relation between fundamental effective period and fixed base period, T_{eff}/T_{fixed}, for buildings with number of floors equal to 4, varying the structural types and for a T_{eff} equal to 3s.

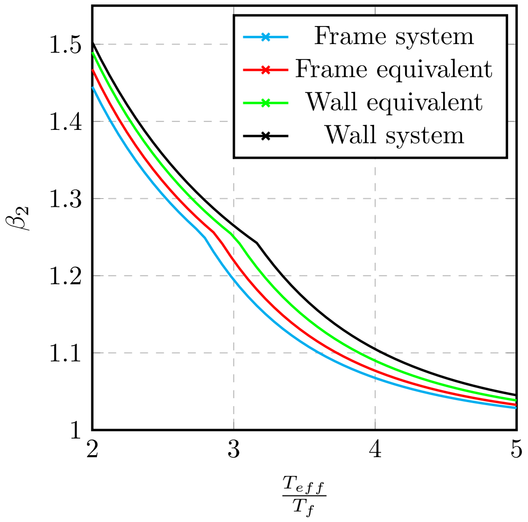

Figure 10: Amplification factor β_2 in function of T_{eff}/T_f, for buildings with 4 floors with $T_{eff} = 3s$ and varying the structural type.

Structural types with more influence of the structural walls lead to higher values of amplification, it is explained by the superior modes of this structural types have bigger modal participation factor for superior modes.

5.3. Global Amplification (β_{global})

The global amplification are a combination of spectral amplification and the amplification due the accounting the superior modes, and is describe by equation. 4.

$$\beta_{global} = \beta_1 \cdot \beta_2 \tag{4}$$

5.3.1 Variation of structural types - N=4 $T_{eff} = 2s$

In figure 11 it is presented the global amplification factor in function of relation between fundamental effective period and fixed base period, T_{eff}/T_{fixed}, for buildings with number of floors equal to 4, varying the structural types and for a T_{eff} equal to 2s.

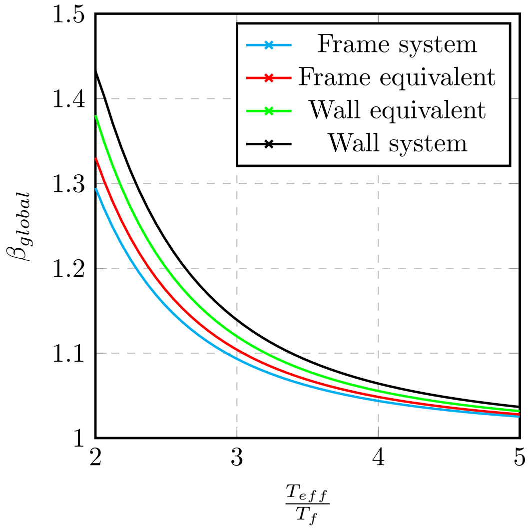

Figure 11: Global amplification factor β_{global} in function of T_{eff}/T_f, for buildings with 4 floors with $T_{eff} = 2s$ and varying the structural type.

As expected, like the factor β_1 and β_2, the amplification value increases with the more participation of the structural walls in relation to the frames.
For the case of T_{eff}/T_f equal to 3, for frame structural type the global amplification takes the value of 9% and for the wall structural type takes 14%.

5.3.2 Variation of structural types - N=4 - $T_{eff} = 3s$

In figure 12 it is presented the global amplification factor in function of relation between fundamental effective period and fixed base period, T_{eff}/T_{fixed}, for buildings with number of floors equal to 4, varying the structural types and for a T_{eff} equal to 3s.

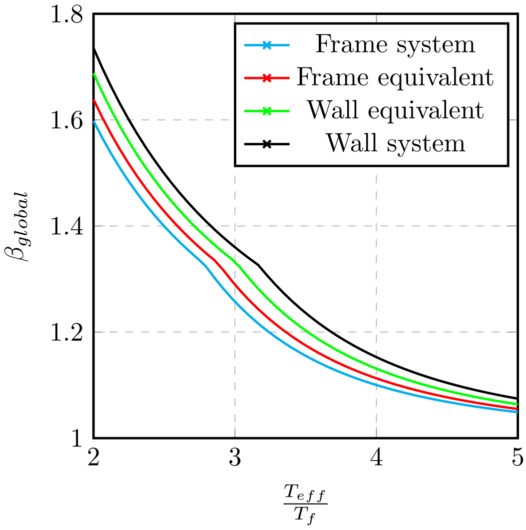

Figure 12: Global amplification factor β_{global} in function of T_{eff}/T_f, for buildings with 4 floors with $T_{eff} = 3s$ and varying the structural type.

Similarly to the one described in the previous figure, the amplification values varies the same way with the structural type, but with the T_{eff} equal to 3s the values are much more higher.
For the case of T_{eff}/T_f equal to 3, for frame structural type the global amplification takes the value of 25.8% and for the wall structural type takes 36%.

5.4. Proposed Formulas

It is rationally derive the formulas to estimate the global amplification in form of equation 5. These equations are interpolated for a building with 4 floors, structural type of wall system, with a effective damping in base isolation system equal to 15%.

$$\beta_{global}\left(\frac{T_{eff}}{T_f}\right) = a \cdot e^{-b\left(\frac{T_{eff}}{T_f}\right)} + c \tag{5}$$

For all structural types and for the cases of T_{eff} equal to 2 and 3s, it is given in tables 3 and 4 the values of coefficients a, b and c to substitute in expression 5.

Table 3: Interpolation coefficients for all structural types, T_{eff}=2s.

Structural type	a	b	c
Frame system	3.993	1.359	1.026
Frame equivalent	4.501	1.361	1.028
Wall equivalent	5.144	1.356	1.032
Wall system	5.630	1.331	1.036

Table 4: Interpolation coefficients for all structural types, T_{eff}=3s.

Structural type	a	b	c
Frame system	3.317	0.845	0.992
Frame equivalent	3.223	0.797	0.99
Wall equivalent	3.112	0.741	0.983
Wall system	3.001	0.690	0.980

The figures 13, 14, 15 and 16 are a graphic representation of the interpolation formulas, with the gray triangular marks representing some of the exact values β_{global}.

With the global amplification value calculated follow the calculus of the design acceleration, and it is given by equation 6.

$$a_d = S_e(T_{eff}, \xi_{eff}) \cdot \beta_{global} \cdot \frac{\gamma_a}{q_a} \tag{6}$$

Being γ_a and q_a respectively, the importance factor and the behaviour factor of the element. It is assumed that the importance and behaviour factor takes a unitary value, as explained in [7] and [10].

Expression 7 gives an approximation of the acceleration for other equipments that are not in highest floor of the building, so they are subjected to a smaller value of acceleration, $a_d^{'}$, and depends on the height of the building H and height that are installed the equipment Z, those parameters are calculated in relation to above the level of application of seismic action.

$$a_d^{'} = S_e(T_{eff}, \xi_{eff}) \cdot (1 + (\beta_{global} - 1) \cdot \frac{z}{H}) \tag{7}$$

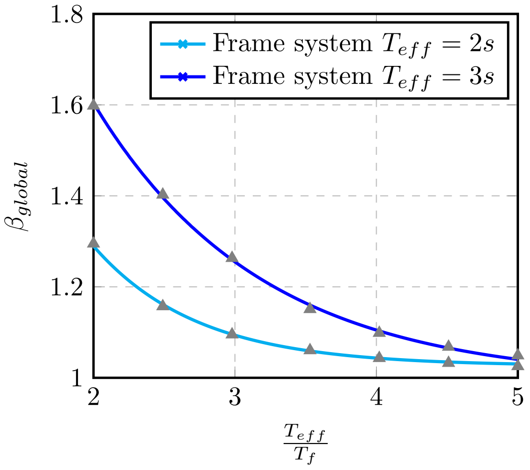

Figure 13: β_{global} for frame systems.

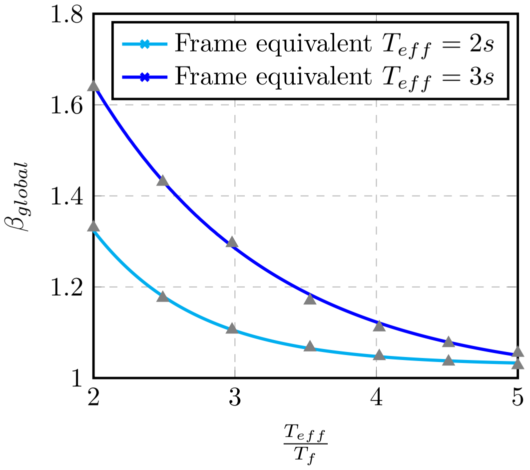

Figure 14: β_{global} for frame equivalent systems.

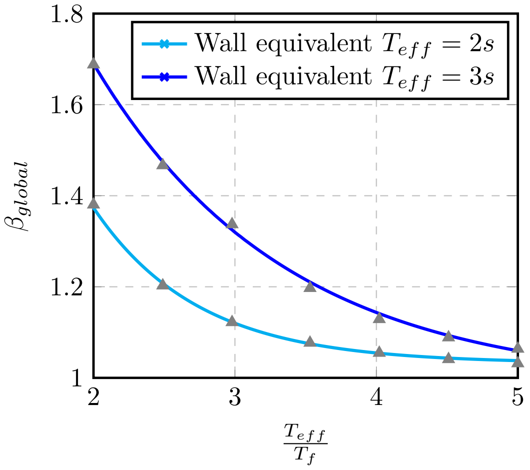

Figure 15: β_{global} for wall equivalent systems.

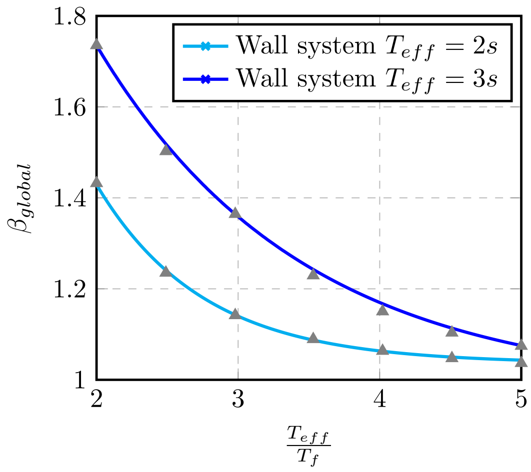

Figure 16: β_{global} for wall systems.

5.5. Simplified Formula Proposed

Considering the possibility that the designer of the elevators system not have the dynamic parameters of the building, it is proposed a simplified formula of calculus. Using a T_{eff} equal to 2s, T_{eff}/T_f equal to 3, and using the global amplification curves for a building with structural type wall system with number of floor equal to 4. The global amplification factor takes the value of 1.14. This assumptions leads to a conservative value of design acceleration.

$$a_d = S_e(2s, 15\%) \cdot 1.14 \cdot \frac{\gamma_a}{q_a} \tag{8}$$

With this simplified formula was calculated for all Portugal counties the design acceleration and the seismic elevator category, the results are show in the MSc Dissertation [7]. And it is conclud that in many regions of the country the elevator systems installed in base isolated buildings are still need seismic design.

6. Conclusions

A set of formulas that gives the design acceleration in a base isolated building is achieved. This is a contribution for seismic design of elevator system in this types of structures, and not only, this expressions can be used for seismic design of other non-structural elements.

With simplified formula derived, and the respective values of design acceleration obtained for all Portugal counties, and with that conduces to a seismic elevator category given by EN 81-77:2018, it is conclud that in many regions of the country, it is still necessary to design the elevator systems for the seismic action in buildings with base isolation.

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