Seismic Safety Analysis of the Paço Ducal of Vila Viçosa

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Abstract

Paço Ducal is an important monument, historically and culturally, located in Vila Viçosa, which was owned and built by the family of the Dukes of Bragança, which would later become the Portuguese Royal Family.

Its walls are made of rammed earth, which is a construction technique that consists of using earth as a structural material. It is not a suitable material to resist seismic actions as it has a low tensile strength, which is often considered to be zero.

In this dissertation a seismic analysis is made to the Paço Ducal of Vila Viçosa in order to evaluate its safety against earthquakes.

The palace was modeled on the computer program SAP2000. From the data obtained in the program are analyzed the vibration modes, the base shear forces, the excessive stresses present in the walls and the relative and absolute displacements measured in different points of the palace.

Due to the uncertainty regarding the stiffness values of both floors and walls, a sensitivity analysis of the palace's seismic behavior for each of these properties is also performed.

Through these analyses it is possible to get a better understanding of the seismic behavior of the palace, namely which areas are most affected and which type of seismic action is the most serious for the safety of the palace and, finally, reach a conclusion regarding its seismic safety.

1 Introduction

Earthquakes are natural phenomena that have always occurred throughout human history.

The impact they have on human lives and existing structures leads to the study of their causes, characteristics and consequences, and these studies have evolved considerably in recent years.

Today it is not yet possible to predict the occurrence of earthquakes with a certainty that is sufficient to take preventive measures in the short term. However, it is essential that structures are adequately prepared to withstand such actions so that damage can be minimized, and especially human lives can be saved.

Therefore, there are currently norms for seismic design and safety checking of new structures as well as reinforcement of existing buildings.

The aim of this dissertation is to evaluate the seismic safety of the Paço Ducal of Vila Viçosa, through an analysis admitting the linear behavior of its materials. It is a palace whose main structural material is rammed earth, which constitutes its walls and it is an important monument, thus deserving such an analysis, as there is currently some uncertainty concerning its seismic safety.

For this analysis was created a model of the building that represents its structure, using *SAP2000*.

2 The palace, earth construction and the earthquakes

2.1 The Paço Ducal

The Paço Ducal is an important monument situated in Vila Viçosa. It belonged to the family of the Bragança Dukes that later became the Portuguese Royal Family.

Its construction was done in several phases and today it is the biggest building using rammed earth in all the Iberian Peninsula.

2.2 Earth Construction

Rammed earth, which constitutes the walls of the Paço, is not usually used in new constructions. Nevertheless, it is still present in many buildings spread all over the planet, and specifically in Portugal.

2.3 Earthquakes

One possible way to represent an earthquake compatible with the existing methodologies of structural analysis is the representation by a Response Spectrum [1].

In Portugal, the *Eurocode 8* defines two types of seismic actions, due to the need to consider two possible causes of earthquakes that can affect Portugal and, therefore, two distinct scenarios: the “distant” and the “near”.

The Type 1 seismic action represents the “distant” earthquake that has its origin in inter-plate movements caused by the convergence of the African and Eurasian plates.

The Type 2 seismic action characterizes an earthquake with its epicenter on geological faults in Portugal, thus being the “near” scenario. It is an earthquake of smaller magnitude than the Type 1 seismic action.

3 Modeling of the structure

A good modeling, which accurately simulates all aspects of a structure, both geometric and constituent materials, and the actions that act on it, implies a careful choice of all the values to be taken for the definition of the structure and the actions.

3.1 Structural elements

3.1.1 Floors

The floors were modeled in the program as s*hell* elements.

The flexural stiffness of the floors has been modeled to very high values so that the floors do not show flexural deformations. Otherwise, the first modes of vibration would all be associated with vertical floor movements and have very high natural periods. This would not even allow observing the vibration modes with frequencies of normal values for such a building and which are associated with the movement of the walls.

3.1.2 Walls

The walls were modeled as *frame* elements.

Each wall is represented by a *frame* element on its vertical axis, with its plan dimensions being defined in the characteristics of that element.

3.2 Structural materials

3.2.1 Timber

Timber can have different values in its properties depending on its origin, condition and considered direction, among other factors.

In this study, the timber’s own weight was modeled with the lowest value considered by the *EN 338*: $3{,}5\ kN\ /\ m^3$.

The floor material was modeled as isotropic and a shear modulus value was used based on studies of the rigidity of wooden floors.

The value of the equivalent shear modulus, G_{eq}, considered in the model for the floor material is $15\ MPa$.

However, at the roof level, the material was modeled with a shear modulus equal to half of the value of the floor shear modulus – $7{,}5 MPa$ - to take into account that the roofs do not provide the building with the same level of stiffness than the floors.

3.2.2 Rammed earth

With the walls of the Palace representing most of the total weight of the structure, a careful choice of values regarding the material of the model walls is fundamental for a good seismic analysis of the palace.

The properties of rammed earth vary greatly depending on the quality of the material used, the construction process and the incorporation of other materials used, among other factors.

The volume weight adopted for the rammed earth in the model has a value of $21\ kN\ /\ m^3$. The choice of this value is due to the fact that the building under study is a palace, built by a noble family. Thus, it is assumed that all materials used in the palace are of high quality.

Regarding the stiffness, the values that the rammed earth can take are also very variable.

For the modulus of elasticity of the model, was adopted the value of $500\ MPa$.

3.2.3 Ground

The ground on which the palace is based on is made of marble, which is a material of very high rigidity. Therefore, the supports of the model are defined with full embedment, that is, they do not allow any type of displacement or rotation at these points.

Figure 1 shows the model of the Paço.

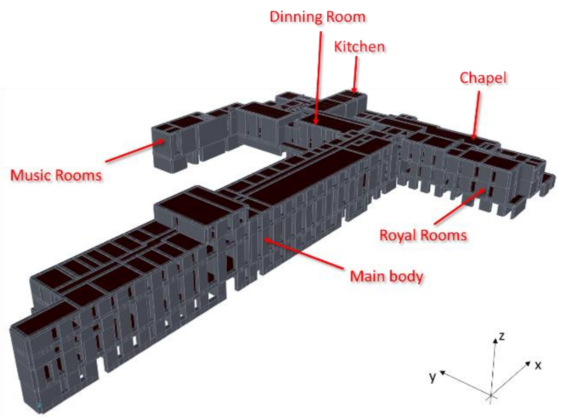

Figure 1 – Model of the Paço Ducal in *SAP2000*

3.3 Actions

3.3.1 Static actions

In all floors of the palace, except the roof, uniform loads corresponding to the permanent loads and the variable imposed loads, were applied to the model.

The value attributed to the variable imposed loads is in line with what *Eurocode 1* [2] defines for residential buildings: $2{,}0\ kN\ /\ m^2$.

The value of the permanent loads applied on the floors of is also a current value in residential buildings: $3{,}0\ kN\ /\ m^2$.

3.3.2 Seismic actions

For the analysis of the effects of a seismic action defined by response spectrum it is necessary to define the value of the behavior factor to be used. This value depends essentially on the ductility of the structure. Since the palace is largely made of rammed earth, which is a material whose tensile strength can be considered to be almost zero, its energy dissipation capacity should not be counted on. For this reason, the behavior factor is assumed to be equal to 1.

Regarding the ground type, since the palace is set in marble, the foundation ground was defined as Type A. Vila Viçosa belongs to seismic zone 5 and zone 4 for the seismic actions Type 1 and Type 2, respectively. In these zones the reference peak ground acceleration values, a_{gR}, are $0{,}6\ m\ /s^2$ for Type 1 seismic action and $1{,}1\ m\ /s^2$ for Type 2 seismic action, corresponding to actions with a return period of 475 years.

However, as the Paço Ducal is an existing building, it is justified that the seismic analysis should be carried out in accordance with *Eurocode 8.3*. The values to be used, which in the event of a safety check for the significant damage limit state correspond to a return period of 308 years, can be obtained by affecting the reference acceleration values by the coefficients of $0{,}75$ and $0{,}84$ for the seismic actions Type 1 and Type 2, respectively. Thus, the reference accelerations in the model have the values calculated in equations (1) and (2):

$$0{,}6 \times 0{,}75 = 0{,}45 ms^{-2} \tag{1}$$

$$1{,}1 \times 0{,}84 = 0{,}92 ms^{-2} \tag{2}$$

4 Seismic analysis

4.1 Vibration modes

The stiffness of the floors and walls were modeled, considering values within the range of possible values for these elements, aiming to obtain a vibration frequency associated with the first mode of oscillation of the main body in the y direction of about $2{,}0\ Hz$ (near an experimental value).

The Paço's first ten modes contain the first modes of vibration of almost every area of the palace.

Consider the modes with the highest mass participation in each direction - all modes with a mass percentage of 5% or more (rounded value).

Starting with the x direction, the most relevant modes of vibration in terms of mass participation are shown in Table 1.

Table 1 – Most important vibration modes in terms of mass participation ratios in the x direction

Mode	f (Hz)	U_x	U_y
7	2,11	0,37	0,00
30	3,20	0,06	0,00
10	2,38	0,06	0,00
4	1,99	0,05	0,00

The 7th mode corresponds to a movement of the main body of the Paço and the Dining Room, also oscillating the body of the Royal Rooms.

The 30th mode essentially affects the Music Rooms, also moving the Chinese Porcelain Room and the Dining Room.

The 10th mode corresponds to the movement of the Royal Rooms body and the 4th vibration mode is associated with the movement of the Dining Room.

Regarding the main modes, in terms of mass participation, in the y direction, Table 2 shows all modes in this direction that have a mass participation of 5% or more (rounded value).

Table 2 – Most important vibration modes in terms of mass participation ratios in the x direction

Mode	f (Hz)	U_x	U_y
1	1,66	0,00	0,28
17	2,72	0,00	0,06
9	2,22	0,00	0,05

Paço Ducal's first vibration mode is the one that moves the most mass of the building in the y direction (28.4%). Corresponds to the transverse movement of the main body.

The 17th mode concerns the movement in the y direction of the Dining Room and the ninth mode is once again the movement of the main body of the palace with transverse displacements of the left and right zones of the main entrance taking place in opposite directions, that is, a "second mode" of transverse vibration.

4.2 Base shear forces

Base shear forces are the global horizontal reactions that acts on the building due to earthquakes.

The base shear forces obtained in the palace model, due to Type 1 and Type 2 seismic actions (significant damage) are shown in Table 3.

Table 3 – Base shear forces on the model

Seismic Action	F_x (kN)	F_y (kN)
Type 1	16 122	13 194
Type 2	22 092	17 250

In terms of base shear forces, the Type 2 seismic action is clearly the worse for the palace structural behavior, as it is due to this action that the base shear forces are greatest. The values of the forces due to the Type 1 seismic action are about $^3/_4$ of the values of the base shear forces due to the Type 2 seismic action. This can be explained by the response spectra of the two seismic actions.

Figure 2 shows the spectra corresponding to the two seismic actions and, in shading, the spectral zone where the natural periods of the vibration modes are located, corresponding to an accumulated mass ratio of at least 90% in both horizontal directions. This area covers vibration periods between $0{,}12\,s$ and $0{,}60\,s$ ($1{,}67$ to $8{,}33\,Hz$).

The graph shows that the Type 2 seismic action for the Paço range of natural periods causes greater accelerations than the Type 1 seismic action, except for vibration period values greater than $0{,}53\,s$ (point which corresponds to the intersection of the two spectra). However, this higher period spectral zone includes only the first four modes of the palace, with an accumulated mass ratio of 32% in the y direction, not reaching 1% in the x direction. Thus, generally, the Type 2 seismic action is more severe for the Palace than the Type 1.

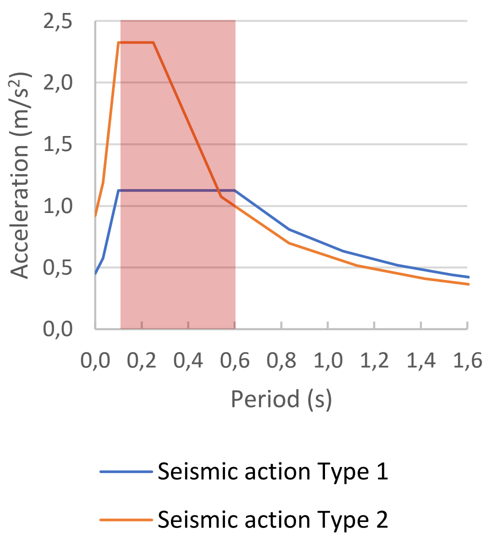

Figure 2 – Response spectra of the seismic actions and range of natural periods of the model

4.3 Excessive stresses

The equivalent forces acting on the structure, corresponding to the accelerations induced by the seismic actions also cause stresses in the walls of the palace.

Analyzing the behavior of the palace when the different combinations of actions act on it, the compressive stresses that appear on the walls are never higher than $1{,}2\,MPa$, even in the most compressed areas, where the moments caused by earthquakes aggravate the compressions caused by the static loads.

Now, according to Delgado and Guerrero [3], the only case in which rammed earth does not resist compressions to this value corresponds to one without any stabilization and with low resistance.

Since it is assumed that the quality of the material in the walls is good, the value of its compressive strength will surely be no less than $1{,}2\ MPa$. Therefore, the palace stress analysis only focusses on tensile stresses.

Figure 3 graphs all tensile stresses that appear on the walls of the Palace when each type of seismic action acts on it. The x axis orders all the walls in descending order of the value of their maximum traction, which reads on the y axis.

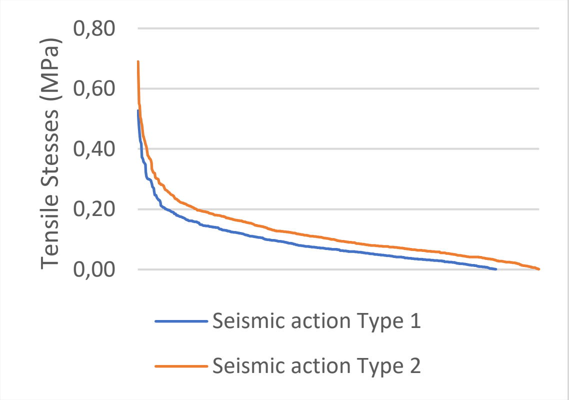

Figure 3 – Tensile stress values on all the walls of the palace

Although the graph does not match the same walls for the two types of seismic action, it can be seen that the Type 2 seismic action causes higher tensile stresses than the Type 1 seismic action. On average, the values of the curve representing the stresses due to the Type 1 seismic action correspond to about 79% of the values that constitute the stress curve caused by the Type 2 seismic action.

This brief analysis allows us to know the range of tensile stress values on the walls throughout the palace for each type of seismic action.

Seismic level supported by the Paço

If the values used as the reference peak acceleration regarding the two types of seismic actions were to be reduced, all results obtained on the analyses would also be reduced and in the same proportion, since the analyses made are linear analyses.

With this in mind, it is considered that the walls can withstand tensile stresses up to $0{,}10\ MPa$, as suggested by the New Zealand Regulation [4].

Take as a reference the average value of tensile stresses greater than $0{,}10\ MPa$ across the palace. This value is $0{,}15\ MPa$ for Type 1 seismic action and $0{,}17\ MPa$ for Type 2 seismic action.

If these average values are to be reduced to the maximum allowable traction value according to the New Zealand Regulation, lower seismic levels need to be considered.

Through the results obtained in the model it is possible to reach maximum reference acceleration values that the two types of seismic action can have so that the palace supports these actions without presenting considerable damage. For the Type 1 seismic action, this value is $0{,}34\ m/s^2$ and for the Type 2 seismic action is $0{,}68\ m/s^2$.

Equations (3) and (4) relate these reference acceleration values to the significant damage limit state (SD) reference accelerations for Type 1 and Type 2 seismic actions, respectively.

$$\frac{0{,}34\ m/s^2}{a_{gR,1,SD} = 0{,}45\ m/s^2} = 0{,}76 \qquad (3)$$

$$\frac{0{,}68\ m/s^2}{a_{gR,2,SD} = 0{,}92\ m/s^2} = 0{,}74 \qquad (4)$$

That is, these reference accelerations correspond to about 74% and 76% of the reference accelerations associated with the significant damage limit state for the Vila Viçosa zone for Type 1 and Type 2 seismic actions, respectively.

Eurocode 8 - Part 3 also defines coefficients that affect the reference accelerations of seismic actions associated with the near collapse and damage limitation limit states.

The coefficients related to the near collapse limit state (NC) take values of $1{,}62$ and $1{,}33$ for the reference acceleration of the Type 1 and Type 2 seismic action, respectively, in mainland Portugal. These values correspond to a return period of 975 years.

For Vila Viçosa, the reference accelerations related to the near collapse limit state for the Type 1 and Type 2 seismic action take the values calculated in equations (5) and (6):

$$a_{gR,1,NC} = 1{,}62 \times a_{gR,1} = 0{,}97\ m/s^2 \qquad (5)$$

$$a_{gR,2,NC} = 1{,}33 \times a_{gR,2} = 1{,}46\ m/s^2 \qquad (6)$$

Where $a_{gR,1}$ $(= 0{,}60\ m/s^2)$ and $a_{gR,2}$ $(= 1{,}10\ m/s^2)$ are the reference accelerations defined by *Eurocode 8 - Part 1* for Vila Viçosa , for Type 1 and Type 2 seismic actions, respectively.

This means that the Palace verifies safety against the near collapse limit state if the seismic actions do not have spectral accelerations greater than 35% and 47% of the seismic accelerations defined by *Eurocode 8 - Part 3* for this limit state. The equations (7) and (8) present the necessary calculations to obtain these values:

$$\frac{0{,}34}{a_{gR,1,NC}} \times 100 = 35\% \qquad (7)$$

$$\frac{0{,}68}{a_{gR,2,NC}} \times 100 = 47\% \qquad (8)$$

Consider now the damage limitation limit state, whose multiplicative coefficients of the reference seismic action are $0{,}29$ and $0{,}47$ for the Type 1 and Type 2 seismic action, respectively. These values correspond to a return period of 73 years. The corresponding reference acceleration values are given in equations (9) and (10) for Type 1 and Type 2 seismic actions, respectively:

$$0{,}29 \times a_{gR,1} = 0{,}17\ m/s^2 \qquad (9)$$

$$0{,}47 \times a_{gR,2} = 0{,}52\ m/s^2 \qquad (10)$$

These values are lower than those previously calculated as the maximum reference acceleration values of the Type 1 and Type 2 seismic actions that can act on the Palace so that it can withstand the seismic forces without considerable damage. Thus, the palace checks the safety regarding the damage limitation limit state.

It is important to note that due to these reference accelerations, for both types of seismic action, the maximum values of compressions in the palace walls, which were about $1{,}2\ MPa$, also decrease, but remain above the unit, which, according to the New Zealand standard, exceeds the compressive strength of rammed earth. However, as it was considered that the material of the walls has an above average quality, these compression values, slightly higher than $1\ MPa$, should not be excessive for the rammed earth in the Paço Ducal.

4.4 Displacements

The analysis of the horizontal displacements of the palace is made in two different ways: the displacements of the floors in different areas of the palace and how they evolve in height; and the relative displacements between points on the roof.

In terms of displacements of the floors, these always increase with height. That is to say, higher floors have higher absolute displacements, which could be easily predicted.

In general, the absolute displacements and the relative displacements between floors are higher in the case of the seismic action Type 2.

Regarding the relative displacements between different points on the roof, the values obtained are very low, always below $1\ cm$, with just one exception: the relative displacement in the y direction between two points in the main body (one in each facade) reaching $4\ cm$, due to the seismic action Type 1, which is still a low value, considering the distance that separate the two points (about 15 meters).

This suggests that the stiffness attributed to the floors and roof is sufficient for the walls to be in phase with each other.

4.5 Influence of Floor Stiffness

After analyzing various data, this subchapter is intended to analyze the influence that the stiffness of the floors has on the behavior of the Paço Ducal.

The necessity of this analysis is related to the fact that the exact stiffness of the floors is not known.

For this purpose two more palace models are tested: one whose equivalent shear modulus of the floors, G_{eq}, is $5\ MPa$ and the roof is $1\ MPa$; another whose G_{eq} of both floors and roof is infinite.

4.5.1 Vibration modes

Predictably, by increasing the stiffness of the floors, the overall stiffness of the palace increases as well. Thus, the palace has higher natural frequencies than when the stiffness of the floors is lower.

This corresponds, in the Type 2 seismic acceleration spectrum, to higher acceleration values, while the

Type 1 seismic spectral acceleration values vary little in the ranges of the three models.

Thus, the stiffness of the floors negatively influences the behavior of the structure regarding the Type 2 seismic action, at least in terms of spectral accelerations.

4.5.2 Base shear forces

The values of base shear forces in the palace as a function of floor stiffness are shown in Figure 4 (Type 1 seismic action) and Figure 5 (Type 2 seismic action).

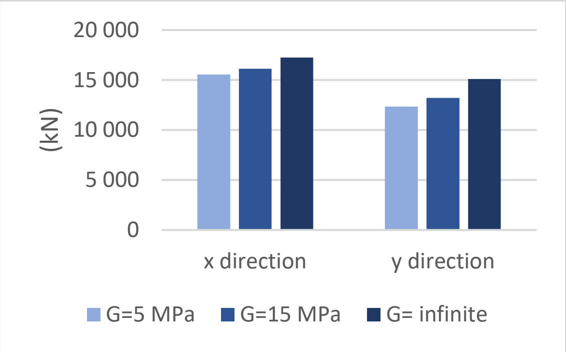

Figure 4 – Base shear forces as a function of the floor stiffness, seismic action Type 1

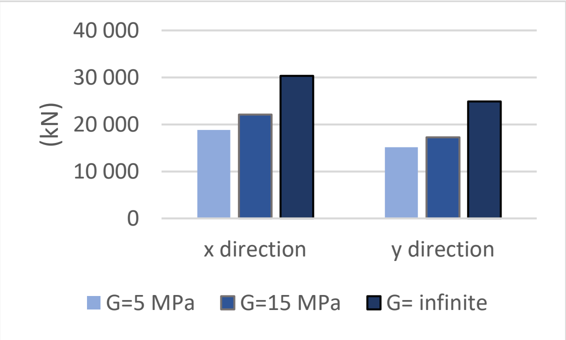

Figure 5 – Base shear forces as a function of the floor stiffness, seismic action Type 2

Predictably, shear forces increase as increasingly rigid floors are considered. As the stiffness of the floors increases, thus increasing the overall stiffness, the vibration modes tend to have higher natural frequencies. This corresponds to higher values in the acceleration response spectra. However, these accelerations increase sharply in Type 2 seismic action, while for Type 1 seismic action, in the natural period intervals of the three models, the accelerations remain approximately constant.

Therefore, base shear forces due to Type 1 seismic action do not vary widely from the most flexible to the most rigid model. The base shear force in the x direction if the floors that have a $5\ MPa$ shear modulus corresponds to about 90% of the value of the palace's base shear force when all floors are infinitely rigid. In the y direction this ratio is about 82%.

However, as regards the Type 2 seismic action, these differences are more pronounced. At the x direction the base shear force in the model with $G_{eq} = 5\ MPa$ is worth only 62% of the shear force in the stiffer model. And in the y direction, the shear force in case the floors are the most flexible is about 61% of the shear force in the stiffer model.

4.5.3 Excessive stresses

In terms of stresses present on the walls, in general, there is a clear difference between seismic action Type 1 and the Type 2.

Figure 6 shows the distribution of all tensile stresses on the palace walls, in descending order, in the three cases, for type 1 action.

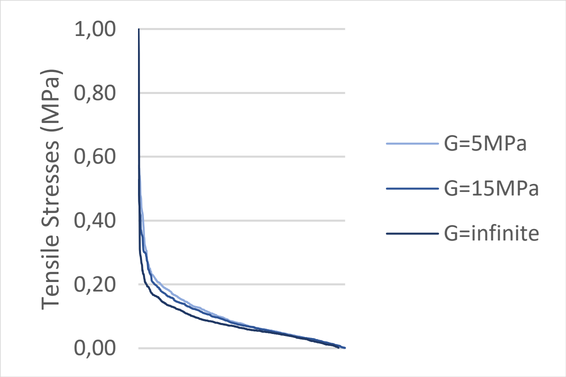

Figure 6 – Tensile stresses on walls, seismic action Type 1

The graph shows that, when acting on the Type 1 seismic action, the tensile stresses that appear on the palace walls, for the most part, decrease as the stiffness of the floors increases.

In fact, a building with very flexible floors, will have its floors transmitting the loads to the vertical elements depending on the influence areas of these elements. In other words, the forces are transmitted by the floors to the nearest vertical elements.

Thus, there may be vertical elements, which in this case are the walls, with low stiffness that receive forces equal to or even greater than the forces that more rigid walls receive. This results in high stresses on the walls.

However, this is not what happens when the stiffness of the floors is increased as regards the Type 2 seismic action. In this case this trend is the opposite. Note the graph in Figure 7:

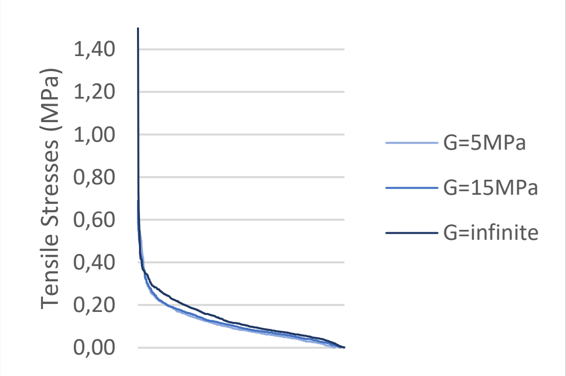

Figure 7 – Tensile stresses on walls as a function of the floor stiffness, seismic action Type 2

Most stresses are higher if the stiffness of the floors is infinite.

The reason is the same that causes base shear forces to vary more for Type 2 earthquake than for Type 1: spectral accelerations increase sharply in Type 2 seismic action as natural period values decrease.

Therefore, although theoretically a higher stiffness of the floors is beneficial for structural behavior, allowing the forces coming from the floors to be transmitted to the vertical elements proportionally to their stiffness, in the case of the Paço Ducal, increasing the stiffness of the floors will aggravate the structural behavior of the palace against Type 2 seismic action.

4.5.4 Displacements

By analyzing the displacements of the different floors in the chosen alignments it is possible to understand what rising the stiffness of the floors does to the deformations of the palace.

With an infinite value to the floors and roof stiffness, the displacements are naturally smaller than in the model with the less rigid floors and roof. But this improvement of the structural behavior regarding the displacements, when the stiffness of the floors and roof is increased, is clearer when acting the seismic action Type 1. Which makes sense because, as seen before, when the stiffness of floors and roof is increased, the natural frequency range of the palace corresponds to higher values of acceleration regarding the seismic action Type 2. For this reason, although rigid floors are better for the structural behavior of a building, on the other hand, in this case, it also increases the global stiffness of the palace which means higher base forces, hence higher stresses and displacements.

4.6 Influence of Wall Stiffness

In this section it is analyzed the influence that the rigidity of the walls has on the seismic behavior of the palace. This analysis is similar to the analysis made about the influence of floor stiffness on the seismic response of the building.

The modulus of elasticity of the rammed earth was modeled with the value of $500\ MPa$. However, some authors consider different values.

Thus, modulus of elasticity of $200\ MPa$ and $800\ MPa$ were chosen to compare the results with that of the original model.

4.6.1 Vibration modes

Once again, varying the stiffness of structural elements of the palace, in this case, the walls, varies the overall stiffness of the structure. As a result, in the graph of the response spectra of the two types of seismic action, the palace's natural period range shifts to the left if the stiffness of the walls increases and to the right when the stiffness of the walls decreases.

4.6.2 Base shear forces

Considering the response spectra of both types of seismic actions and the natural frequency values on each model, the base shear forces evolve, with the variation of the wall stiffness, as it could be predicted. Figure 8 shows the values of the shear forces obtained in the three models for the Type 1 seismic action. Due to the Type 2 seismic action, the shear forces obtained are shown in Figure 9.

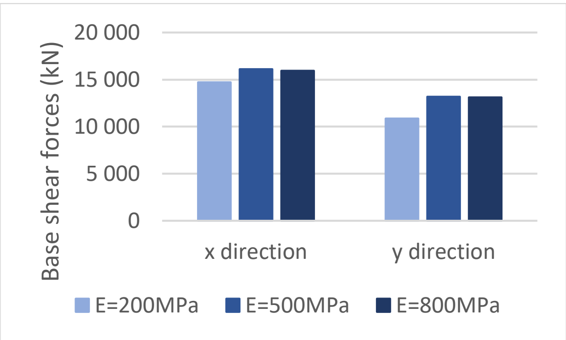

Figure 8 – Base shear forces as a function of the wall stiffness, seismic action Type 1

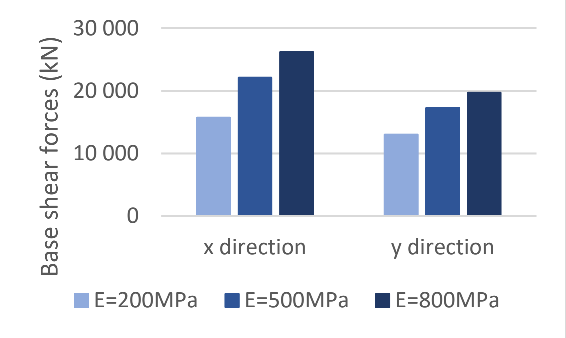

Figure 9 – Base shear forces as a function of the wall stiffness, seismic action Type 2

4.6.3 Excessive stresses

The maximum tensile stress values, as a function of the elasticity modulus of the palace walls, in the case of acting on the Type 1 seismic action, are in the three curves shown in the graph in Figure 10. If acting the Type 2 seismic action, the maximum tensile stress values in the three models are presented in Figure 11.

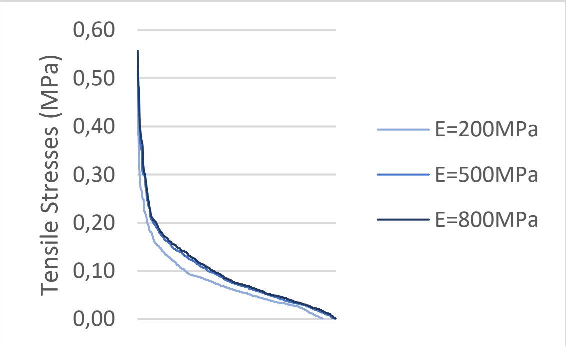

Figure 10 – Tensile stresses on walls as a function of its stiffness, seismic action Type 1

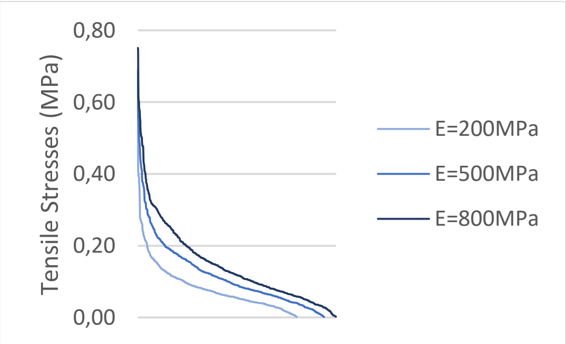

Figure 11 – Tensile stresses on walls as a function of its stiffness, seismic action Type 2

With this analysis, it is quite clear that the increase in wall stiffness causes the palace to increase seismic forces and increase wall stresses. There are no areas of the palace that escape this trend nor does this trend vary depending on the type of earthquake under consideration.

However, it is important to note that, for the seismic behavior of a structure, it is no better that the rammed earth constituting its walls has a reduced modulus of elasticity. It is true that this will allow the stress values due to earthquakes to be lower. However, a smaller modulus of elasticity means that the rammed earth is of inferior quality. That is, the model with an elasticity modulus of $800\ MPa$ for the walls may be subjected to higher stresses than those appearing in a model whose walls are less rigid. However, this rammed earth is of better quality and will have a higher strength than the less rigid rammed earth. Thus, although the less rigid rammed earth is subject to lower stresses, it will also have lower resistances.

4.6.4 Displacements

The displacements vary, as a function of the stiffness of the walls, again in a very predictable way: the displacements are smaller when considering stiffer walls.

Once again, just as the analysis of the floor stiffness allowed to conclude, the relative displacements between points on the roof is very low. Therefore, these displacements are irrelevant for the analysis of the wall stiffness.

5 Conclusions

Throughout the analyses made in this dissertation, the model used to represent the Paço Ducal of Vila Viçosa proved to be adequate for the purpose.

By analyzing vibration modes, base shear forces, excessive stresses along the walls of the palace and absolute and relative displacements on both walls and floors, it was possible to understand how the palace behaves in response to the seismic actions defined by *Eurocode 8*.

The purpose of the dissertation was to evaluate the seismic safety of the palace and, after the analysis made it is possible to draw conclusions in this regard. The results show that Type 2 seismic action is the most conditioning one for the Paço Ducal. This seismic action corresponds to an earthquake originated by geological faults in mainland Portugal and has its maximum accelerations corresponding to values of smaller periods comparing with the seismic action Type 2.

Having observed all the analyses made it is safe to say that Paço Ducal is not prepared to support the forces of an intense earthquake that could happen in Vila Viçosa.

It was estimated the maximum intensity of an earthquake that the Paço could withstand without its walls collapsing, globally or locally. It was concluded that the palace does not verify seismic safety for significant damage nor near collapse limit states, but only for damage limitation. Regarding the earthquakes recommended by *Eurocode 8 - Part 1*, the palace resists, without considerable damage, to an earthquake with accelerations of about 60% of the earthquake accelerations defined for Vila Viçosa. These values are only approximations. However, they are sufficiently expressive to make it possible to state that an earthquake with the characteristics of one of the two types of seismic actions defined by *Eurocode 8*, would have a very large impact on the structure of the Paço Ducal, at least in some areas.

However, the possibility of some kind of reinforcement intervention that improves the palace's seismic behavior seems to be an unrealistic scenario. Wall reinforcements are rarely used in rammed earth walls as they do not work well and, if they are effective, will also be an expensive solution.

At floor level, increased stiffness does not seem to be a good solution either. Indeed, through the sensitivity analysis of the stiffness of the floors it is possible to draw two conclusions in this regard.

The first is that a possible reinforcement to increase the stiffness of the floors would generally decrease the tensile stresses in the Palace against seismic action Type 1, but would increase, in almost all areas of the building, the tensions due to the seismic action Type 2. Since it is not possible to know the characteristics of future earthquakes affecting the Paço Ducal, such a reinforcement could both help the palace withstand seismic forces or could even worsen its response behavior if the acting earthquake was similar to the seismic action Type 2.

The other conclusion that can be drawn from the sensitivity analysis of the stiffness of the floors is that even if localized reinforcements were made on the floors, only in areas that improve their behavior for both types of earthquake, their stresses would never decrease to acceptable values in rammed earth. Because one of the models tested had an infinite value for the stiffness of the floors. That is, as much as the reinforcement increased the stiffness of the floors, this stiffness would never exceed that of the tested model. And this model, although showing tensions improvements in some areas of the palace for both types of earthquake, these still exceed the maximum stresses supported by the rammed earth.

It would remain, as a theoretical solution to analyze, the introduction of elements that, locally, could confer some ductility to the structure, or devices that would allow, also locally, to guarantee some energy dissipation. However, the practical implementation of such solutions is not easy, although it may be the subject of possible future studies.

It is therefore expected that in a relatively intense earthquake situation damage will occur in some areas of the Paço Ducal of Vila Viçosa.

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