EARTHQUAKE RESISTANCE OF DIFFERENT MASONRY MATERIALS

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ABSTRACT :

The present study is about calculating the earthquake resistance of a representative building made of 3 different masonry materials, vertically perforated clay block, sand-lime block, and aerated concrete (AAC) block. The calculation is done following the rules of the current European Codes EN1998-1 and EN1996-1-1. The underlying construction is a building of 3 stories with 3 meters each. For an easy but also meaningful comparison of the 3 varieties the shear wall portion amounts 4% in each excitation direction for all 3 alternatives. Rudimental for the comparison is, that all varieties do have the same Base Shear Coefficient (BSC = base shear force / building weight). The static system is a continuous beam with a field length of 5m. In the analysis and the comparison the maximum loaded middle-wall which has a thickness of 30cm is considered. For the building with the perforated clay bricks the natural frequency is estimated on basis of empirical values from in-situ measurements of typical masonry building constructions. Thus the effective stiffness of the equivalent linear oscillator is acquired. The effective stiffness of the other 2 varieties changes with the stiffness of the used materials, but it happens that the natural periods of all the 3 varieties stay within the constant spectral acceleration branch of the design spectra of EN1998-1. For comparing the efficiency of the earthquake resistance of the different materials the Resistance Excitation Ratio (RER) is introduced. The resistance is calculated using the characteristic shear strength and the area of the shear walls. The excitation is the seismic base shear force which is calculated using the lateral force method of analysis. The performed study shows how different materials affect the seismic performance of masonry buildings and it is also meant to be a guidance for the evaluation of the earthquake resistance according to the rules of the present European Standards.

KEYWORDS: Masonry, EN1998-1, EN1996-1-1

1. VERTICALLY PERFORATED CLAY BLOCK

1.1. General purpose masonry mortar

The mean compressive strength of the blocks $f_b = 12$ N/mm² and their bulk density $\gamma_{Bl} = 8$ kN/m³ are taken as given values by the producer. The density $\gamma_W \approx 10$ kN/m³ of the wall is estimated by adding 2 kN/m³ to γ_{Bl} (mortar, plaster, etc.). The characteristic compressive strength of masonry (here: Group 2 blocks and mortar M5) is calculated according to Eqn. 1.1 and gives $f_k =$ 4,15 N/mm² with $K = 0{,}45$.

$$f_k = K \cdot f_b^{0,7} \cdot f_m^{0,3} \tag{1.1}$$

The Dead Load is composed of 2,00 kN/m² (buildup) and 6,25 kN/m² (RC-Slab, 25cm) and gives $G_k = 8{,}25$ kN/m², while the Live Load is $Q_k = 3{,}00$ kN/m² (including partition wall addition). Eqn. 1.2 states the load combination for the loading case earthquake.

$$E_d = G_k + \psi_2 \cdot Q_k = 8,25 + 0,3 \cdot 3,00 = 9{,}15 \text{ kN/m}^2 \tag{1.2}$$

Thus the load for 3 floor levels is $P_{dSlab} = 27{,}45$ kN/m². Figure 1 depicts that the shear wall fraction is 4% in each of the two lateral directions, thus the walls take 8% of the base area and the load is $P_{dWall} = 7{,}20$ kN/m². The total load for the whole building therefore is $P_d = 34{,}65$ kN/m² and the total mass is $m = 3465$ kg/m².

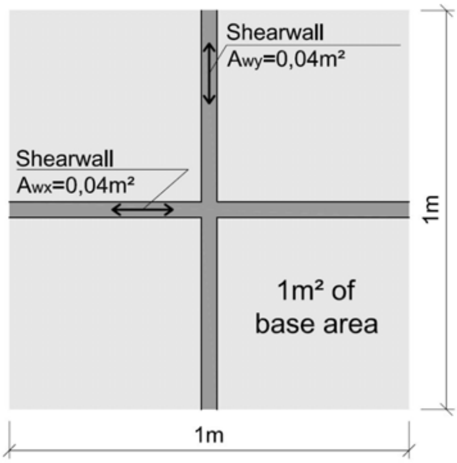

Figure 1 Shearwall area per m² base area

According to EC6 the short term modulus of elasticity is estimated as stated in Eqn. 1.3.

$$E_{GPM} = 1000 \cdot f_k = 4150 \text{ N/mm}^2 \tag{1.3}$$

As a representative natural frequency for the 3-story building made of vertically perforated clay blocks with general purpose mortar 3,0Hz (T=0,33sec) is assumed. With Eqn 1.4 the equivalent stiffness per m² base area is calculated.

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \rightarrow k = 4\pi^2 \cdot m \cdot f^2 = 1{,}2311 \text{ MN/m}^3 \tag{1.4}$$

The seismic base shear force F_b is calculated using the lateral force method of analysis. It is composed of the ordinate of the design spectrum S_d, the total mass of the building and a correction factor. With a design ground acceleration of $a_g = 1{,}0$ m/s², a behavior factor of $q = 1{,}5$ and a soil factor of $S = 1{,}2$ the ordinate S_d for the plateau section ($0{,}15 \leq T \leq 0{,}5$sec) is given in Eqn. 1.5 and the seismic base shear force per m² area in Eqn. 1.6.

$$S_d(T) = a_g \cdot S \cdot \frac{2,5}{q} = 1,0 \cdot 1,2 \cdot \frac{2,5}{1,5} = 2,0 \tag{1.5}$$

$$F_b = S_d(T_1) \cdot m \cdot \lambda = 2,0 \cdot 3465 \cdot 0,85 = 5{,}89 \text{ kN/m}^2 \tag{1.6}$$

Eqn. 1.7 states the Base Shear Coefficient (BSC) which gives the ratio of the seismic base shear force and the total weight of the building.

$$BSC = \frac{F_b}{P_d} = \frac{5{,}89}{34{,}65} = 0{,}17 \tag{1.7}$$

The static system for the loaded slab is a continuous beam with a field length of 5m as depicted in figure 2 and a center wall of 30cm in the ground floor is taken for the calculation. The total vertical load of $N = 198{,}6$ kN/m is composed of 171,6 kN/m from the slabs and 27,0 kN/m dead load of the wall. Thus the normal stress in the center wall is $\sigma_d = 0{,}662$ N/mm² and together with the initial shear strength of $f_{vk0} = 0{,}2$ N/mm² the characteristic shear strength of the masonry can be evaluated with Eqn. 1.8.

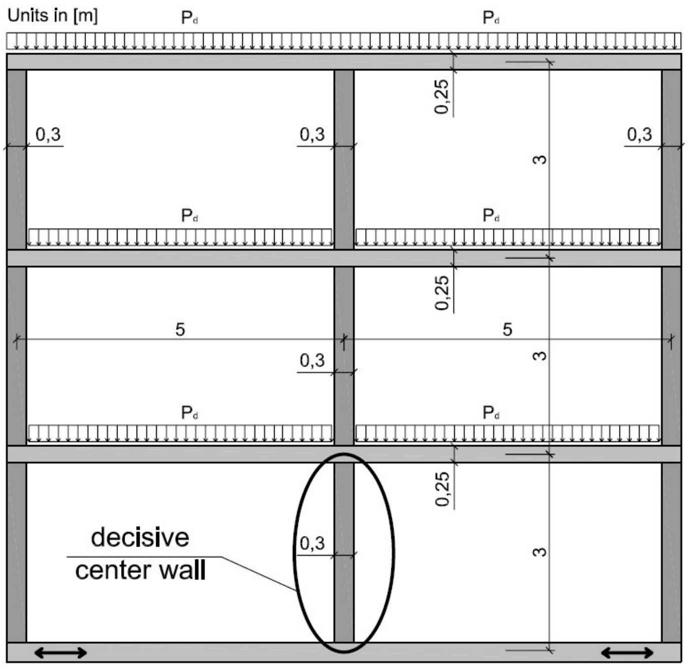

Figure 2 Cross section and decisive center wall

$$f_{vk} = f_{vk0} + 0{,}4 \cdot \sigma_d = 0{,}465 \text{ N/mm}^2 \quad (1.8)$$

A shear wall fraction of 4% in one excitation direction means that the area of walls per m² base area is 0,04 m² and the resistance, under assumption of full compression, is as stated in Eqn. 1.9. The ratio of resistance and loading is denoted as RER (Resistance Excitation Ratio) as stated in Eqn. 1.10.

$$F_v = f_{vk} \cdot A_s = 18{,}6 \text{ kN/m}^2 \quad (1.9)$$

$$RER = \frac{F_v}{F_b} = 3{,}16 \quad (1.10)$$

In the following sections the discrete calculation steps are analog to section 1.1.

1.2. Thin layer masonry mortar

The density $\gamma_W = 9$ kN/m³ of the wall is estimated by adding 1 kN/m³ to γ_{Bl} (mortar, plaster, etc.) and the initial shear strength for thin layer mortar is $f_{vk0} = 0{,}3$ N/mm². Eqn. 1.1 changes to Eqn. 1.11 and gives $f_k =$ 3,99 N/mm² with $K = 0{,}7$.

$$f_k = K \cdot f_b^{0,7} \quad (1.11)$$

With an adapted load of the walls of $P_{dWall} = 6{,}48$ kN/m² the total load gets $P_d = 33{,}93$ kN/m² and the mass $m = 3393$ kg/m². Thus the short term modulus of elasticity is estimated as stated in Eqn. 1.3 and gets $E_{TLM} = 3990$ N/mm². By using the known ratio of the equivalent stiffness and the modulus of elasticity of the construction built with general purpose mortar (GPM, section 1.1), the equivalent stiffness per m² base area by application of thin layer mortar (TLM) is stated in Eqn. 1.12.

$$k_{TLM} = \frac{k_{GPM}}{E_{GPM}} \cdot E_{TLM} = 1{,}1837 \text{ MN/m} \quad (1.12)$$

The natural frequency is calculated with Eqn. 1.4 and gets $f = 3{,}0$Hz (T=0,33sec). As the periode still lies within the plateau section of the design spectrum the seismic base shear force gets $F_b = 5{,}77$ kN/m² and the Base Shear Coefficient stays at $BSC = 0{,}17$. As the dead load of the walls changes to 24,3 kN/m the total vertical load gets $N = 195{,}9$ kN/m. Thus the normal stress in the center wall is $\sigma_d = 0{,}652$ N/mm² and together with the initial shear strength of $f_{vk0} = 0{,}3$ N/mm² the characteristic shear strength of the masonry can be evaluated with Eqn. 1.8. and is $f_{vk} = 0{,}561$ N/mm². The resistance, under assumption of full compression is calculated with Eqn. 1.9. and gets $F_v = 22{,}44$ kN/m². The RER value therefore is $RER = 3{,}89$.

2. SAND-LIME BLOCK

2.1. General purpose masonry mortar

The mean compressive strength of the blocks $f_b = 20$ N/mm² and their bulk density $\gamma_{Bl} = 20$ kN/m³ are taken as given values by the producer. The density $\gamma_W \approx 22$ kN/m³ of the wall is estimated by adding 2 kN/m³ to γ_{Bl} (mortar, plaster, etc.). The characteristic compressive strength of masonry (mortar M5) is calculated according to Eqn. 1.1 and gives $f_k = 7{,}26$ N/mm² for blocks of group 1 with $K = 0{,}55$ and $f_k = 5{,}94$ N/mm² for blocks of group 2 with $K = 0{,}45$.

With an adapted load of the walls of $P_{dWall} = 15{,}84$ kN/m² the total load gets $P_d = 43{,}29$ kN/m² and the mass $m = 4329$ kg/m². Thus the short term modulus of elasticity is estimated as stated in Eqn. 1.3 and gets $E_{GPM} = 7260$ N/mm² for blocks of group 1 and $E_{GPM} = 5940$ N/mm² for blocks of group 2. Like in Eqn. 1.12 the equivalent stiffness and the natural frequency is obtained: $k = 2{,}1537$ MN/m and $f = 3{,}5$ Hz for blocks of group 1 and $k = 1{,}7622$ MN/m and $f = 3{,}2$ Hz for blocks of group 2.

Both natural periods are within the plateau section of the design spectrum and the base shear force therefore gets $F_b = 7{,}36$ kN/m² by evaluating Eqn. 1.6 and the BSC is still 0,17. As the dead load of the walls changes to 59,4 kN/m the total vertical load gets $N = 231{,}0$ kN/m. Thus the normal stress in the center wall is $\sigma_d = 0{,}770$ N/mm² and together with the initial shear strength of $f_{vk0} = 0{,}15$ N/mm² the characteristic shear strength of the masonry can be evaluated with Eqn. 1.8. and is $f_{vk} = 0{,}458$ N/mm². The resistance, under assumption of full compression, is calculated with Eqn. 1.9. and gets $F_v = 18{,}32$ kN/m². The RER value therefore is $RER = 2{,}49$.

2.2. Thin layer masonry mortar

The density $\gamma_W = 21$ kN/m³ of the wall is estimated by adding 1 kN/m³ to γ_{Bl} (mortar, plaster, etc.) and the initial shear strength for thin layer mortar is $f_{vk0} = 0{,}4$ N/mm². Evaluating Eqn. 1.11 gives $f_k = 10{,}21$ N/mm² with $K = 0{,}8$ and an exponent of 0,85 for blocks of group 1 and $f_k = 5{,}29$ N/mm² with $K = 0{,}65$ for blocks of group 2. With an adapted load of the walls of $P_{dWall} = 15{,}12$ kN/m² the total load gets $P_d = 42{,}57$ kN/m² and the mass $m = 4257$ kg/m². Thus the short term modulus of elasticity is estimated as stated in Eqn. 1.3 and gets $E_{TLM} = 10210$ N/mm² for blocks of group 1 and $E_{TLM} = 5290$ N/mm² for blocks of group 2.

Like in Eqn. 1.12 the equivalent stiffness and the natural frequency is obtained: $k = 3{,}0289$ MN/m and $f = 4{,}2$ Hz for blocks of group 1 and $k = 1{,}5693$ MN/m and $f = 3{,}0$ Hz for blocks of group 2.

Both natural periods are within the plateau section of the design spectrum and the base shear force therefore gets $F_b = 7{,}24$ kN/m² by evaluating Eqn. 1.6 and the BSC is still 0,17.

As the dead load of the walls changes to 56,7 kN/m the total vertical load gets $N = 228{,}3$ kN/m. Thus the normal stress in the center wall is $\sigma_d = 0{,}761$ N/mm² and together with the initial shear strength the characteristic shear strength of the masonry can be evaluated with Eqn. 1.8. and is $f_{vk} = 0{,}704$ N/mm². The resistance, under assumption of full compression, is calculated with Eqn. 1.9. and gets $F_v = 28{,}16$ kN/m². The RER value therefore is $RER = 3{,}89$.

3. AERATED CONCRETE

3.1. General purpose masonry mortar

The mean compressive strength of the blocks $f_b = 5$ N/mm² and their bulk density $\gamma_{Bl} = 6$ kN/m³ are taken as given values by the producer. The density $\gamma_W \approx 8$ kN/m³ of the wall is estimated by adding 2kN/m³ to γ_{Bl} (mortar, plaster, etc.). The characteristic compressive strength of masonry (mortar M5) is calculated according to Eqn. 1.1 and gives $f_k = 2{,}75$ N/mm² with $K = 0{,}55$.

With an adapted load of the walls of $P_{dWall} = 5{,}76$ kN/m² the total load gets $P_d = 33{,}21$ kN/m² and the mass $m = 3321$ kg/m². Thus the short term modulus of elasticity is estimated as stated in Eqn. 1.3 and gets $E_{GPM} = 2750$ N/mm². Like in Eqn. 1.12 the equivalent stiffness and the natural frequency is obtained: $k = 0{,}8158$ MN/m and $f = 2{,}5$.

The natural period lies within within the plateau section of the design spectrum and the base shear force therefore gets $F_b = 5{,}65$ kN/m² by evaluating Eqn. 1.6 and the BSC is still 0,17. As the dead load of the walls changes to 21,6 kN/m the total vertical load gets $N = 193{,}2$ kN/m. Thus the normal stress in the center wall is $\sigma_d = 0{,}644$ N/mm² and together with the initial shear strength of $f_{vk0} = 0{,}15$ N/mm² the characteristic shear strength of the masonry can be evaluated with Eqn. 1.8. and is $f_{vk} = 0{,}408$ N/mm². The resistance, under assumption of full compression, is calculated with Eqn. 1.9. and gets $F_v = 16{,}32$ kN/m². The RER value therefore is $RER = 2{,}89$.

3.2. Thin layer masonry mortar

The density $\gamma_W = 7$ kN/m³ of the wall is estimated by adding 1 kN/m³ to γ_{Bl} (mortar, plaster, etc.) and the initial shear strength for thin layer mortar is $f_{vk0} = 0{,}3$ N/mm². Evaluating Eqn. 1.11 gives $f_k =$ 3,14 N/mm² with $K = 0{,}8$ and an exponent of 0,85. With an adapted load of the walls of $P_{dWall} = 5{,}04$ kN/m² the total load gets $P_d = 32{,}49$ kN/m² and the mass $m = 3249$ kg/m². Thus the short term modulus of elasticity is estimated as stated in Eqn. 1.3 and gets $E_{TLM} = 3140$ N/mm².

Like in Eqn. 1.12 the equivalent stiffness and the natural frequency is obtained: $k = 0{,}9315$ MN/m and $f = 2{,}7$ Hz. The natural period is within the plateau section of the design spectrum and the base shear force therefore gets $F_b = 5{,}52$ kN/m² by evaluating Eqn. 1.6 and the BSC is still 0,17.

As the dead load of the walls changes to 18,9 kN/m the total vertical load gets $N = 190{,}5$ kN/m. Thus the normal stress in the center wall is $\sigma_d = 0{,}635$ N/mm² and together with the initial shear strength the characteristic shear strength of the masonry can be evaluated with Eqn. 1.8. and is $f_{vk} = 0{,}554$ N/mm². The resistance, under assumption of full compression, is calculated with Eqn. 1.9. and gets $F_v = 22{,}16$ kN/m². The RER value therefore is $RER = 4{,}01$.

4. DIAGRAMS AND FINDINGS

Due to the same Base Shear Coefficient of the different alternatives, they can easily be evaluated by means of the RER value. The comparison is done by applying the lateral force method of analysis according to the rules of EN 1996-1-1:2006 and EN 1998-1:2005.

The stiffness augments more than the mass by using sand-lime blocks, therefore the natural frequency raises in comparison with the construction built of perforated clay blocks. The construction built of aerated concrete shows a different behavior. The stiffness decrease is greater than the mass decrease, thus the natural frequency is lower than the one from the construction with the perforated clay blocks. The difference of the base shear forces is simply due to the different masses of the alternatives, because all the ordinates of the design spectrum lie within the plateau section. The resistance per m² base area on one hand depends on the material parameter of the initial shear force and on the other hand on the mass and therefore of the normal stress in the masonry construction. The construction built of perforated clay blocks and general purpose mortar has a 28% better performance as the one built of sand-lime blocks (group 1 and 2) and a 10% better performance as the construction of aerated concrete. The behavior of all alternatives by application of thin layer mortar is almost the same.

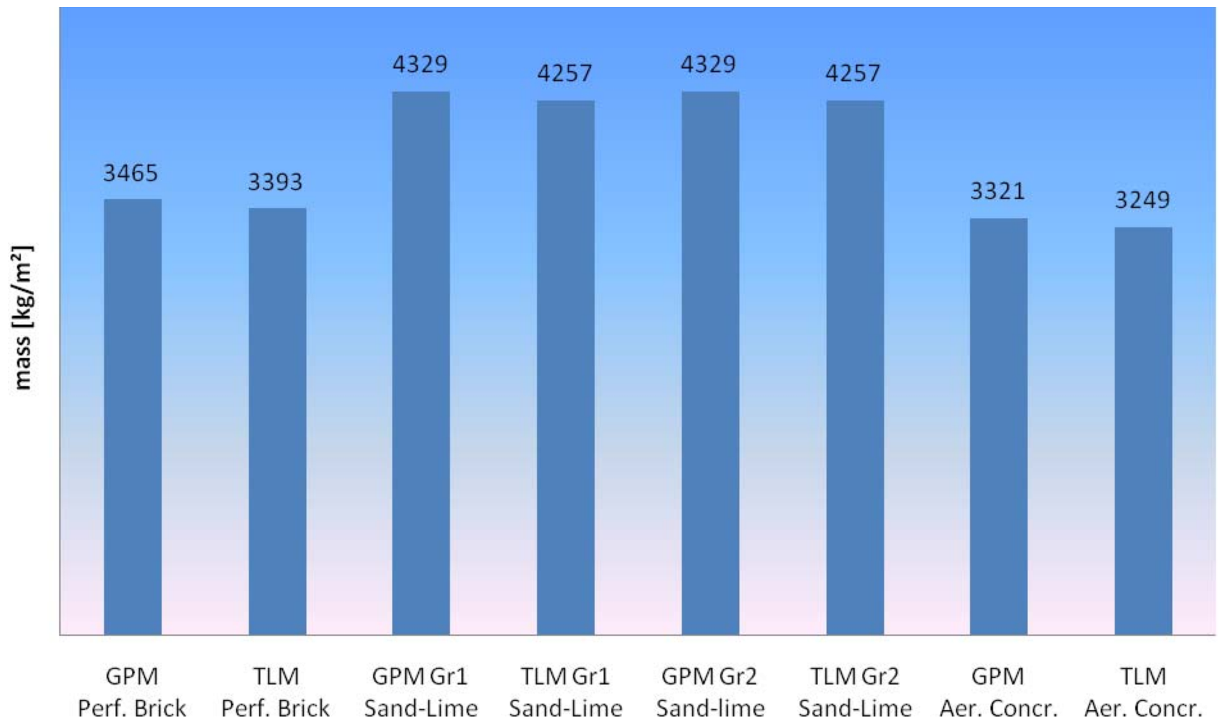

Figure 3 masses of different alternatives

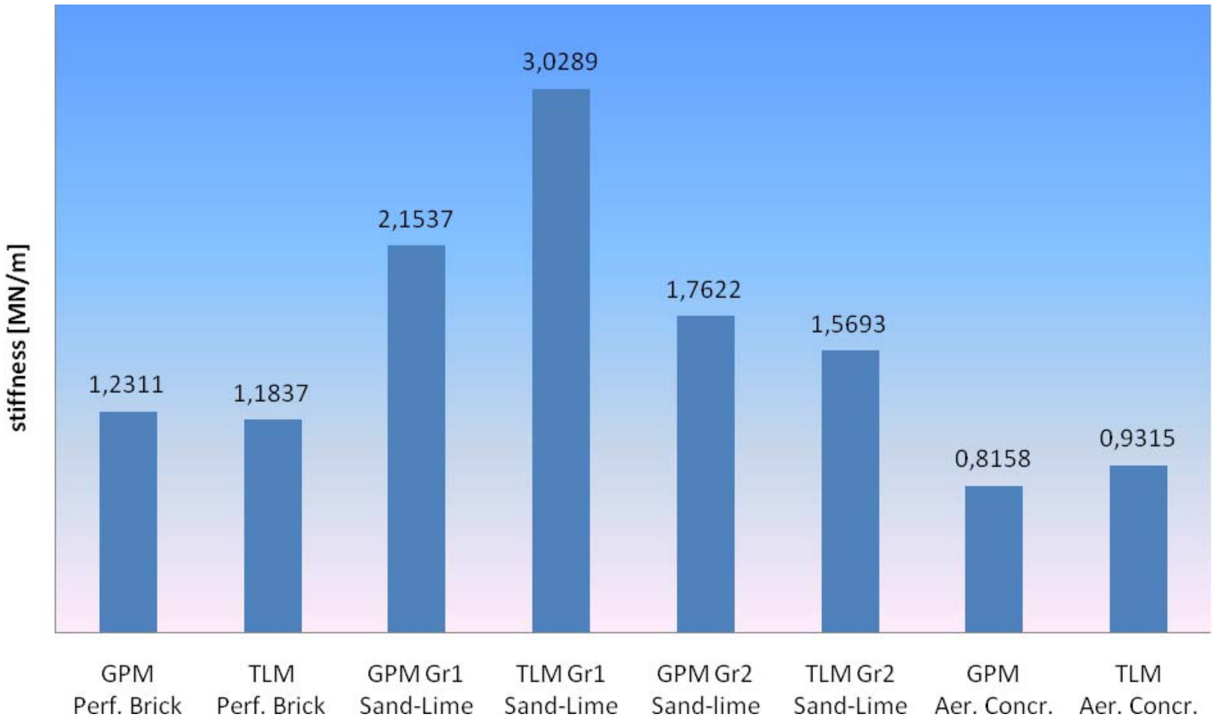

Figure 4 equivalent stiffness of different alternatives

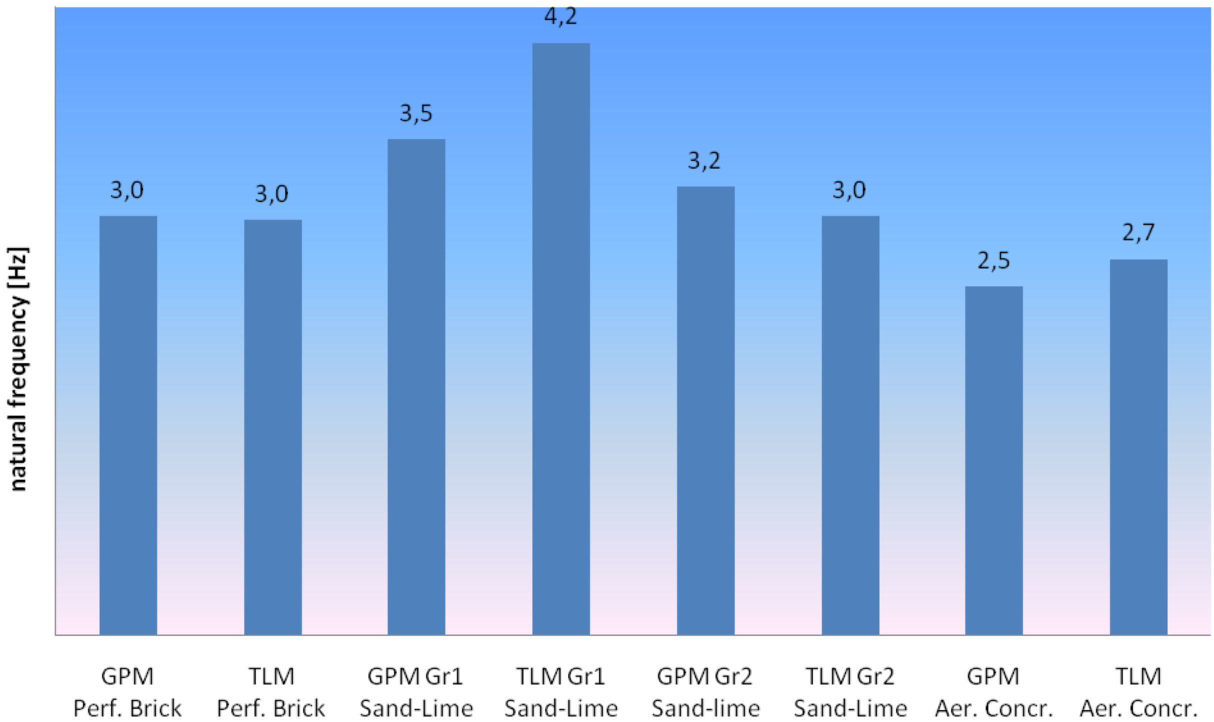

Figure 5 natural frequency of different alternatives

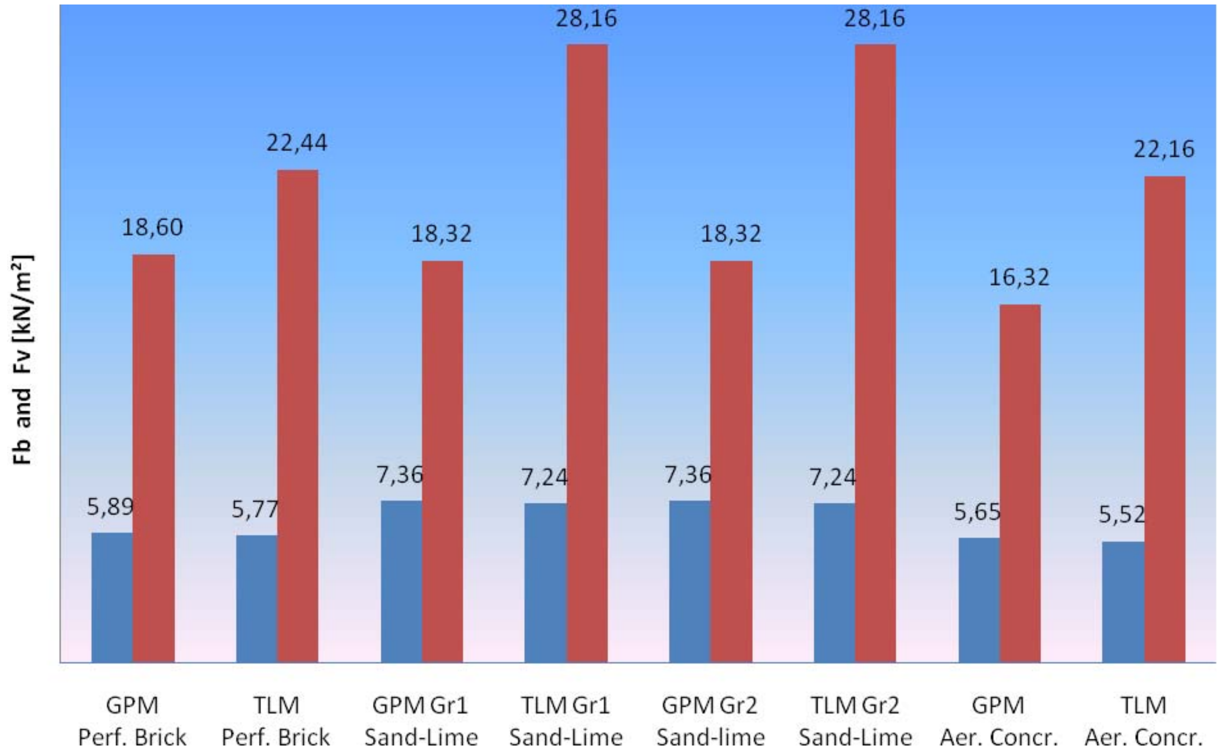

Figure 6 base shear force and resistance force of different alternatives

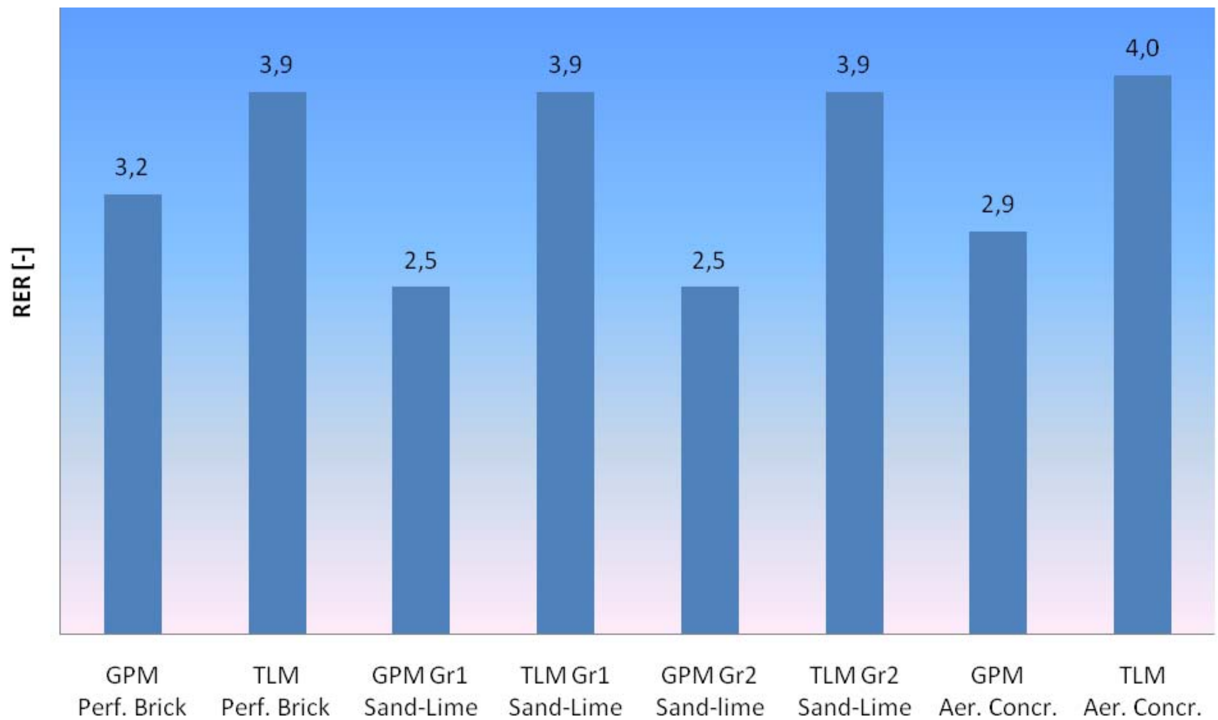

Figure 7 RER values of different alternatives

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