Advantages of using raw materials in low cost sustainable structural solutions for single-family buildings

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ABSTRACT: In the last decades, the Portuguese housing building industry has been mainly focused on the construction based on reinforced concrete framed structures and non-structural clay brick masonry for exterior and interior partition walls. Recently, this industry started to include alternative structural materials, such as steel and timber. The earth based construction techniques and solutions still remains limited to individual cases, in which the owner and/or contractor have a particular concern and knowledge of these ecological solutions. Within this context was developed the present research work, in which a sustainable structural solution for a typical house using natural materials is proposed and studied. Two different structural solutions are defined, namely a reinforced concrete framed column-beam solution (designated by traditional solution) and a solution based on adobe masonry and timber structures for floors and roof (designated by sustainable solution). These two alternative structural solutions are then compared in terms of building costs, energy consumption and CO_2 emissions. All the main aspects related to the design of the sustainable solution, such as the design assumptions, structural models and behaviour parameters are described. Taking into account that the proposed sustainable solution is uncommon in the Portuguese building context, the difficulties faced during the design are also pointed out and commented.

1 INTRODUCTION

About half of the world population, nearly 3 billion people, over the six continents live or work in earth based buildings (Minke, 2005). In some countries with limited economic resources earth based construction might represent even more than half of the total building stock (Carvalho et al, 2008). Several existing earth constructions are classified as historical heritage (Cortés, 2009). Earth construction is a sustainable practice because earth is a natural material, recyclable and abundant anywhere, but also because the techniques used in the fabrication on those elements are usually simple, require a small amount of energy and have associated an inexpressive amount of toxic gases delivered to the atmosphere.

Moreover, the acquisition and application of the building materials currently used in the construction industry require a significant amount of energy consumption during the different stages of the process (extraction, transportation, manufacturing, application, demolition and disposal or recycling) and lead to pronounced release of noxious gases into the atmosphere.

This research work is focused on the viability analysis of the application of natural raw building materials, and traditional building techniques in the construction. Thus, earth based *adobe* masonry is proposed as structural load bearing elements, as an alternative to the traditional reinforced concrete (RC) frames. A typical Portuguese modern single family house was used as case-study, for which two different structural solutions were proposed, designed and compared: a traditional solution (ST) and a sustainable one (SS). The ST is a RC column-beam frame type main structure, with prestressed precast flooring structures and RC slabs in elements such as balconies and stairs, and partition walls made of ceramic brick masonry. The structural SS is based on load-bearing *adobe* walls and timber flooring structural systems. For each of these solutions, the overall building cost, the overall energy consumption and the overall atmospheric emission of noxious gases were quantified and compared. This led to the main conclusions here discussed, that the structural SS is obviously more advantageous both in terms of building cost as well as in what regards the environmental impact.

2 DESCRIPTION OF THE CASE-STUDY, DESIGN TOOLS AND METHODS

The building under study was idealized as being located in the city of Figueira da Foz, at an altitude of 100.00 m, in an urban area surrounded by small buildings. It is a typical of single family house suitable for a family of 3 or 4 people, with three bedrooms, which corresponds to one of the most common typologies in Portugal (around de 57% of the existing building stock, (INE, 1998). In Figures 1-2 can be observed the building architecture and spaces distribution of the studied building. The rooms are distributed in two floors: a ground floor mostly for social use and an upper floor (first floor) for private use. The overall construction areas for the ground and first floors are 285.00 m^2 and 106.5 m^2, respectively.

The ground floor consists of a living-room, a dining-room, a kitchen, a storage area, a toilet, an entrance hall and a corridor. There is also a porch which runs along two sides of the building. On the first floor there are two bedrooms (one of them with a private dressing room), an office, a bathroom, a landing and a veranda. The two floors are connected by stairs which links the entrance hall to the landing and the first floor. The roof at the first floor level is slightly sloped and covered with ceramic tiles. The roof at the second floor level is flat, inaccessible and covered with rolled pebbles. The main entrance faces towards east.

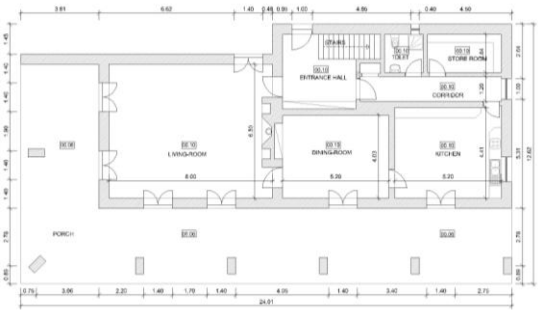
Figure 1. Architectural plan – Ground floor

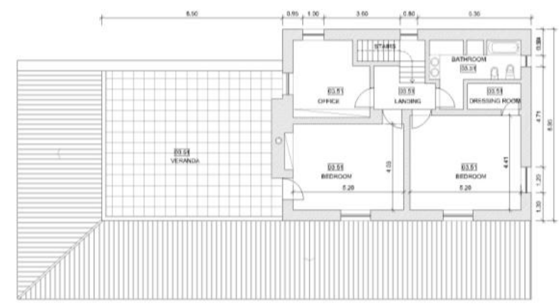
Figure 2. Architectural plan – First floor

For the design of the structural ST commercially-available software programmes were used. The computer program allowed for dynamic modal analysis, consideration various vibration modes, and allows for the determination of the structural response to seismic loadings based on response spectra analysis. The wind load is quantified automatically, considering the building location, the rugosity associated and the global dimensions of the building. Spreadsheets were developed to check and analyze the numerical results obtained from the structural computer program. Specific spreadsheets were also used for the design of isolated structural elements, such as stairwells.

For the structural SS design, and due to the lack of computer programs devoted to the automatic calculation of the *adobe* masonries, specific spreadsheets based on the provisions of standards [5, 6] were developed. For the timber structural elements design (beams and stairs), the provisions in Eurocode 5 (CEN, 1998) were adopted and also specific spreadsheets were worked up for the SS design.

3 TRADITIONAL SOLUTION

In accordance with (REBAP, 1983), it was adopted a concrete type C25/30 for all the RC structural elements (columns, beams, stairs and foundations). S400NR steel was used for reinforcing bars and S500EL steel was used for electro-welded wire mesh reinforcement in slabs. Exterior walls and interior partition walls are basically masonry made of hollow ceramic bricks. For exterior walls, the outer curtain have a thickness of 0.15 m and the inner curtain 0.22 m, both with mortar at the joints and a 0.10 m wide insulation space between them. The interior walls are single-leaf with a thickness of 0.15 m also with mortar at the joints. The structural system of floors is basically made of precast prestressed slabs. These floorings system are unidirectional and considered simply supported by RC beams.

For the building structural analysis, it was considered for the dead load the self-weight of the structural and non-structural elements. Variable loads comprised live, wind and earthquake actions.

For the weight of the structural elements, the following specific reference weights were adopted: 78.50 kN/m^3 for the steel and 25.00 kN/m^3 for RC elements. Floor and wall coverings were considered with 2.00 kN/m^2 and 3.00 kN/m^2, respectively. For live loads, in accordance with (RSA, 1985), 2.00 kN/m^2 was considered for the living areas, 1.00 kN/m^2 for the inaccessible terraces and 3.00 kN/m^2 for the access areas. For the quantification of the wind load, also in accordance with (RSA, 1985), it was considered that the building is located in Zone B and a type II rugosity. In terms of earthquake load, in accordance with (RSA, 1985), calculations were made on the basis of a class C seismic zone, type II soil, a seismic coefficient value of 0.50, a damping coefficient of 5% and a behaviour factor of 2.0 was assumed. For the foundation soil capacity, a value of 200 kPa was considered.

After quantifying the loads and their combinations, according to (RSA, 1985), the safety and design of the structure was then developed. All structural element sections were designed according to the ultimate and serviceability limit states philosophy, using for this purpose the provisions of (REBAP, 1983). The design of the ST solution adopted for the building under study results in the structural system represented in Fig. 3-6.

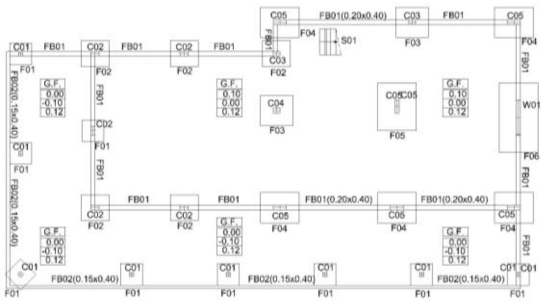

Figure 3. ST: Foundations

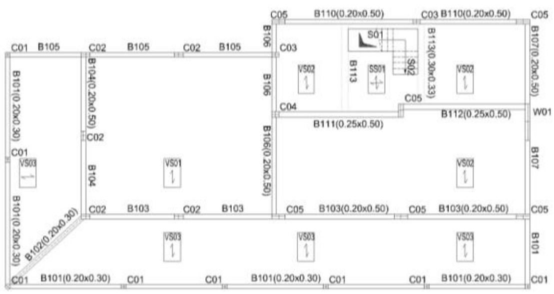

Figure 4. ST: First floor

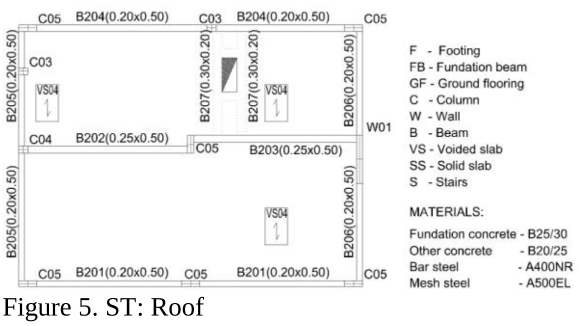

Figure 5. ST: Roof

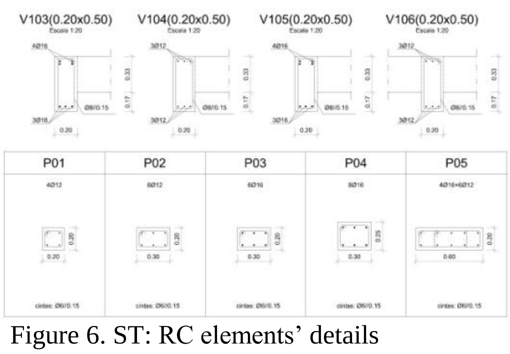

Figure 6. ST: RC elements' details

4 SUSTAINABLE SOLUTION

For the structural SS, pre-dimensioning of the structural elements was carried out based on the minimum allowable dimensions for each of these elements, as specified in EC6 (CEN, 1995) and EC5 (CEN, 1998). All elements were designed using specific spreadsheets developed.

The load-bearing walls are made of adobe, with a compressive strength of 4.0 MPa and bed joints with a class M5 (5.0 MPa) mortar, in accordance with EC6 (CEN, 1995). For structural elements at the first floor, for the roof and for the stairs, wood beams of E class, *pinus pinaster* pine, were considered, in accordance with EC5 (CEN, 1998). The load-bearing walls foundations are continuous, made of solid limestone blocks. These materials were chosen because is natural, local and abundant in the building's location area.

The structural analysis of the SS followed the same loading parameters as the considered for the ST, described in detail in the previous section. For the specific weight of the earth blocks it was considered a value of 18.00 kN/m^3, and 5.80 kN/m^3 for the wood. The other loading actions, as stated previously, were computed analogously to those defined in the previous section for the ST.

The wooden floor structural elements were designed in bending and shear, based on the provisions of EC5 (CEN, 1998). These floor systems are supported directly by the load-bearing adobe masonry walls, which were designed according to the specifications of (RSA, 1985) and EC6 (CEN, 1995).

Since the design of these structural elements (adobe and timber) is still punctual in the Portuguese construction context, and the structural design commercial software do not include tools for the design of these types of structural materials, a 3D finite element structural model was developed, using shell and frame elements, to calculate the stresses distribution in the structural elements composing the building, for each loading case and for their combination.

From the design strategy adopted for the structural SS for the building under study, were obtained the results represented in Fig. 7-10.

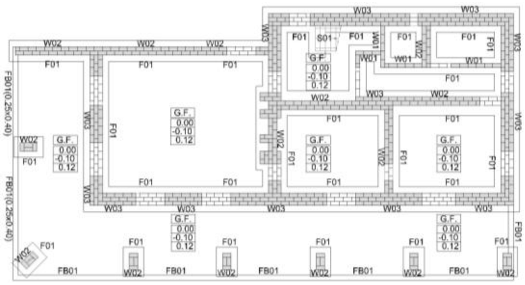
Figure 7. SS: Foundations

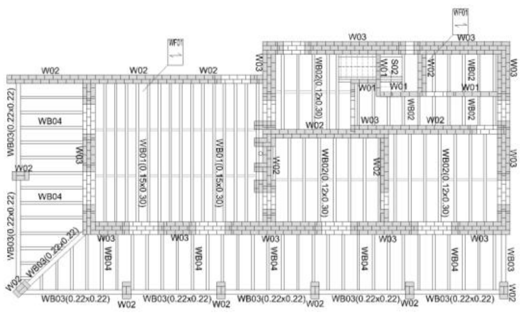
Figure 8. SS: First floor

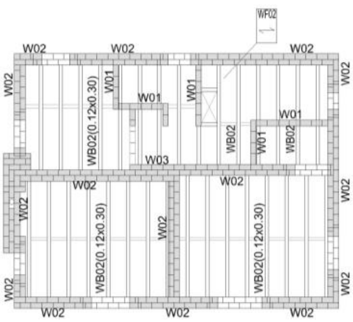
Figure 9. SS: Roof

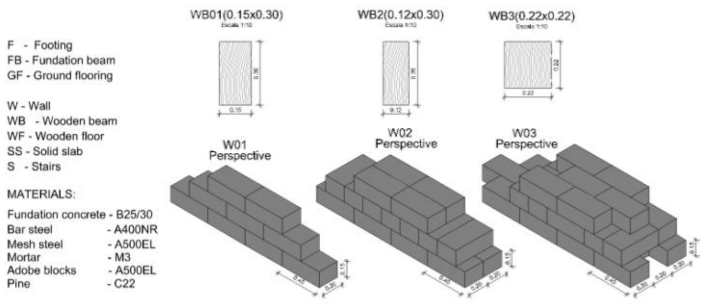

Figure 10. SS: Structural details

5 RESULTS ANALYSIS

Each building material has associated a specific cost, an energy consumption in its production and a quantity of noxious gases released into the atmosphere, resulted from all the phases, namely its extraction from the raw material, transportation, transformation, building process, maintenance, demolition and recycling.

It is possible to estimate the quantity all the environmental parameters associated associated to each phase of the complete life-cycle of the materials, as done per example in (KangHee et al, 2007), (PRE, 2009) and (Baird et al, 1997).

Table 1 presents the values of energy consumption for the building materials which are considered in this research work, following the procedures proposed by different authors ((KangHee et al, 2007), (PRE, 2009) and (Baird et al, 1997)). Comparing the values obtained by the different approaches, it is noticed an expressive difference among them. According to (Baird et al, 1997), this fact may be related to the different approaches used by each author concerning different period of time for the material life-cycle and/or different fabrication techniques. In this study, the values of energy consumption proposed by (KangHee et al.2007) were adopted and the current building Portuguese market unit costs were used (see Table 2).

Based on the results of the structural design for the ST and SS, the estimated quantities of each building material are presented in Table 3. The noxious gases estimative has been converted into CO_2 and for the functional working unit was considered the overall construction area which is 391.50 m^2 in this case. The total cost, the total energy consumption and the total CO_2 emissions associated to both the structural ST and SS solutions studied are presented in Table 4, comparing also the inherent gains estimated.

Table 1. Energy consumption (MJ/kg).

Material	KangHee (KangHee et al, 2007)	Leiden (PRE, 2009)	Baird (Baird et al, 1997)	Alcorn (Baird et al, 1997)
Concrete	2.5	0.98	2.01	0.79
Bar steel	3.0	1.18	2.01	0.79
Mortar	3.0	1.18	3.28	1.29
Brick	3.0	1.18	3.28	1.29
Earth *adobe*	3.0	1.18	3.28	1.29
Gravel	3.0	1.18	3.28	1.29
Pine wood	3.0	1.18	3.28	1.29
Sand	3.0	1.18	3.28	1.29
Cement	3.0	1.18	3.28	1.29
Earth	3.0	1.18	3.28	1.29

Table 2. Parameters of the materials.

Material	Unit	Unit Cost (€)	Energy Consumption (MJ/Unit)	Emission (CO_2/Unit)
Concrete	m^3	50.25	1292.24	99.43
Bar steel	kg	0.63	38.66	3.72
Cement based mortar	m^3	50.45	961.40	63.91
Ceramic brick	un	0.31	14.78	1.11
Stone	m^3	15.00	365.26	26.90
Earth *adobe*	un	0.15	1.45	0.09
Earth based mortar	m^3	48.88	931.48	61.92
Pine wood	kg	0.44	4.44	0.38

Table 3. Quantities of each building material.

Material	Unit	ST	SS
Concrete	m^3	120.25	28.00
Bar steel	kg	6480.00	455.00
Cement based mortar	m^3	24.80	-------
Ceramic brick	un	12969.00	-------
Stone	m^3	39.00	128.60
Earth *adobe*	un	-------	18000.00
Earth based mortar	m^3	-------	48.20
Pine wood	kg	-------	16211.05

Table 4. Comparison of the two proposed structural solutions.

Parameter	Unit	ST	SS	Better solution	Reduction (%)
Cost	€/m^2	40.82	38.73	SS	5.14
Energy consumption	MJ/m^2	1623.69	622.60	SS	61.66
CO_2 emission	kg-CO_2/m^2	135.64	47.77	SS	64.78

From Table 4, it is evident that the structural SS offers a better solution considering all the three parameters analysed. In fact, the structural SS allows for a reduction of 5.14%, in building cost, a reduction of 61.66% in energy consumption and a reduction of 64.78% in CO_2 emissions. In this case, these results show that although the structural SS may not offer a significant financial benefit, it is much more environmental friendly.

6 MAIN CONCLUSIONS

It was noticed that there is still a certain lack of experience in applying the current regulations for the design of structural solutions based on natural raw materials, as well as a lack of commercial computer programs for the design of structural elements made of natural materials, as earth based building products.

Two structural solutions were studied, defined, designed and compared, namely a ST and a SS solution, for a typical Portuguese single family house. Structural building details are proposed for both structural solutions studied. The building details defined for the structural SS have an additional relevance because there is still a lack of experience in this field.

There are several research works focused on the quantification of unitary values of energy consumption and noxious gases released into the atmosphere, for different building materials. However, these values may differ considerably among those works. This fact may be associated to different approaches and assumptions made in the measurement of the life-cycle time periods and in the considered fabrication processes.

The environmental parameters considered it the comparative analysis of the two structural solutions studied are the energy consumption and the noxious gases released into the atmosphere (converted into CO_2 emissions). The comparison of the two structural solutions has shown that the structural SS is clearly more favourable, in financial terms, but mainly in environmental terms. The results plainly demonstrate the advantages of using natural materials in the Portuguese construction context in general, and the use of adobe load-bearing walls in particular in the construction of single family houses. These results may be generalized for many other civil engineering construction works, and can contribute for a more sustainable world.

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