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Sustainability of Masonry and Reinforced Concrete Frame Structures. Case Studies.

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Abstract

Structures of buildings are generally not known as sustainable parts of the buildings, their impact being often neglected, even if important economies could be made in the use of the limited limestone resources and in the negative impact of the large quantity of energy on the environment. When establishing the appropriate structural solution for the given theme the main optimization criteria are the realization cost and the construction time, but also the aesthetics of the structure as well as other architectural impacts might count. The paper aims establishing relationship between the studied structural solutions and their environmental impact: reinforced concrete frame structures with masonry infill walls and load bearing masonry walls with reinforced concrete tie-beams and pillars. The paper presents a comparative study on buildings of three to seven stories, generally used for residential applications. For the same building with variable number of stories two different structural solutions are used, obtaining a total of 8 structures to be designed according to the valid Romanian norms. For the structures the environmental impact is assessed, considering the necessary materials for the realization of the studied structures including internal and external walls. Also cost analyses are performed for the obtained results, in order to obtain the correspondence between the environmental impact and the cost of each solution. Results are emphasizing the environmental impact and cost evolution of buildings with increase of stories for the two structural solutions. It can be followed as the environmental impact varies also with the number of stories. Differences appear in all the main LCA indicators considered in the comparison: energy, solid emissions in air and water, natural resources consumption and waste generation. Comparing the results the more sustainable structural solution with less environmental impact can be concluded.

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Keywords: structural sustainability; masonry walls; reinforced concrete frame; environmental impact; LCA; cost analysis.

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1. Introduction

In practice of current social and public buildings reinforced concrete frame structures with masonry infill walls are frequently used due to the technological advantages and calculation simplicity the solution presents. From structural point of view load bearing masonry walls with reinforced concrete tie-beams and pillars might emphasize advantages when displaced in seismic region, but from point of view of material use there are no significant differences. Differences appear mainly in the way the different materials are considered to work together. The structural solution might be influenced by several technical conditions, as seismic conditions, layout and geometry, technological conditions etc., but in the decision making also personal preferences of the structural designers are having important role. Technically the design process of the structures is ruled by the existing structural codes, norms and standards, but also the essential requirements stated in the Council Directive 89/108/EEC [1](implemented into the specific laws) have to be permanently considered. The essential requirements are including the "hygiene, health and environment" as well as the "energy economy", but for structural engineers there are no practical tools for complying with the mentioned ones. The dilemma is even greater if there exists a real commitment of the designer for reducing the environmental impact of the resulting structure. Even if worldwide concern and responsibility of the specialists is increasing towards obtaining sustainable structures with reduced environmental impact, the generally applicable methods are still missing despite the existence of the theoretical tools for identifying and controlling the environmental impact and for improving the environmental performance represented by the ISO 14000 standard family [2]. The most efficient methodology for obtaining a sustainable structural system is by assessing its impact using Life Cycle Analysis (LCA), emphasized in studies performed by Danatzko [3], Gonzales [4] and others. In the method based on the LCA the impact of the structures are considered for the entire life cycle of the evaluated structure, for the whole cradle to grave process - which is preferably turned into a cradle to cradle circle (Fig. 1) -, as regulated by European framework standards EN 15643-1:2010 [5] and EN 15643-2:2011 [6].

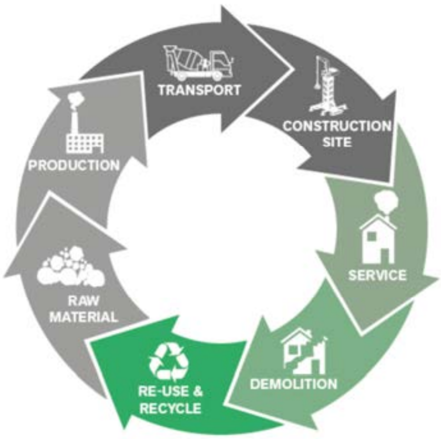

Fig. 1. Desired life cycle of the construction materials. [7]

Another shortcoming in the sustainability assessment of structures is represented by lack of absolute values for reading the results since results are evaluated only by comparison, which presumes possibility of choosing of the best option from a set of assessed solutions [8]. The environmental impact of a structural solution is determined by the type, quantity and quality of used materials, the realization processes, service period, maintenance needs and end-of-life processes [9] [10],[11]. Existing studies (Danatzko [12], Puskas [13] [7], Naik [14], Struble [15] and others) are emphasizing the effect on the environmental impact of the used structural system, but also the high influence of the used materials [16] on the overall sustainability of the specific structure.

2. Design specifications and the studied structure

In order to realize a comparison of the structural systems and to establish the influence of the stories on the economic and environmental impact a typical architectural layout of the levels is considered (Fig. 2). For the given layout – in order to catch the influence of the floor number increase – the number of levels has been considered to be three to seven (Fig. 3).

It is always a dilemma for the structural designer to choose between a reinforced concrete frame structure with masonry infill walls and a load bearing masonry wall structure with reinforced concrete tie-beams and pillars. Differences appear in realization cost, necessary technology, construction time and architectural conditions. Reduced environmental impact of the structural solutions is not yet a common condition in design.

Advantages in design are often turned into inconveniences in the execution phase. Differences in the structural quantities are mainly results of the applicable design codes [8].

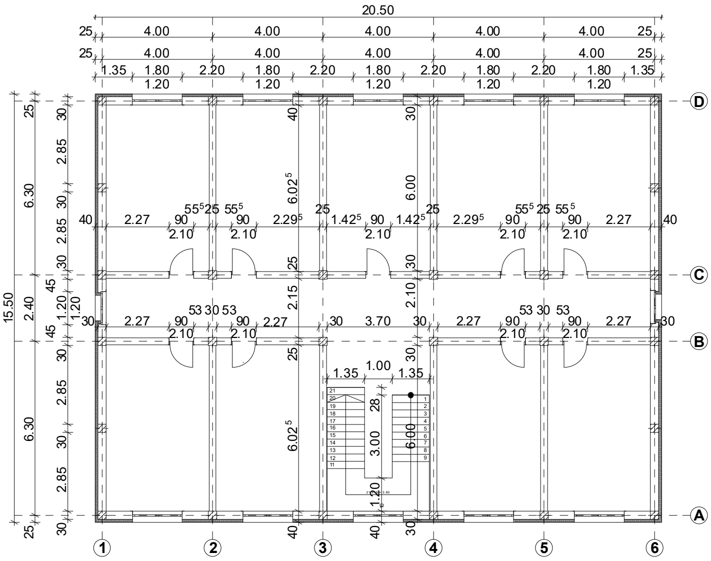

Fig. 2. Architectural layout of the levels [7].

A complete structural design process has to be performed for both structural solutions, for the further evaluation of the results. In order to have fair comparison also in the case of the reinforced concrete frame structure masonry internal and external walls have been used, even if lightweight partitioning walls with reduced impact might be used. Differences appear also due to the differences in the applicable norms for the different structural systems. In case of the masonry different wall thicknesses are used for the two structural types due to their structural role also.

For the study the building has been placed in a seismic area characterized by the upper limit of the period of the constant spectral acceleration branch of T_c=0.7 sec and the design ground acceleration a_g=0.15g. The ductility class established for the design is medium ductility. The loads (permanent and variable) are taken with the same value, differences being result only of the differences in the own weight of the structure.

The quality of the used materials is also considered unchanged during the study, even if the material quality change can cause important differences both economic and environmental point of view [8].

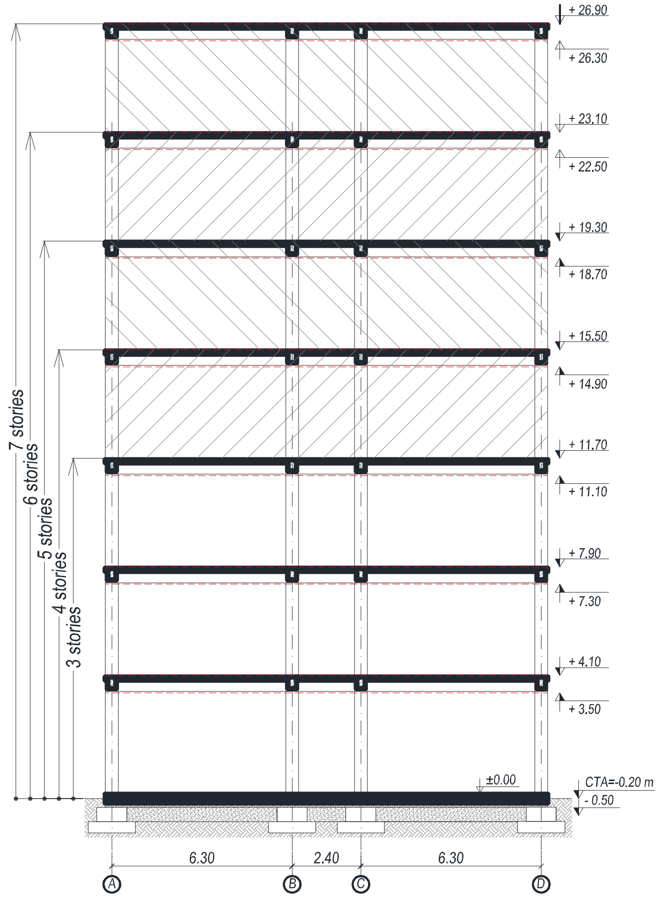

Fig. 3. Typical structural cross-section.

3. Cost comparison of the structural solutions

Total price of the studied structures have been calculated based on market prices in the place the building has been considered. Quantities of materials and the total price are presented in Table 1 to Table 5. The tables present also the differences in the quantities and corresponding prices, considering the base values the ones obtained for the reinforced concrete frame structure with masonry infill walls.

Table 1. Material quantities for 3 stories.

	Frame - quantity	Price	Masonry - quantity	Price	Difference
Concrete [m3]	162.77	€11,036.08	180.98	€12,270.44	-10.1%
Formwork [m2]	1,562.67	€19,064.57	1,306.63	€15,940.84	19.6%
Masonry [m3]	331.99	€26,692.16	394.83	€31,744.69	-15.9%
Rebar [kg]	23,481.66	€18,785.33	21,077.69	€16,862.15	11.4%
Total		€75,578.13		€76,818.13	-1.6%

Table 2. Material quantities for 4 stories.

	Frame - quantity	Price	Masonry - quantity	Price	Difference
Concrete [m3]	242.39	€16,434.04	240.18	€16,283.93	0.9%
Formwork [m2]	2,264.76	€27,630.07	1,736.71	€21,187.84	30.4%
Masonry [m3]	439.45	€35,331.94	522.84	€42,036.34	-15.9%
Rebar [kg]	30,804.44	€24,643.55	26,776.31	€21,421.05	15.0%
Total		€104,039.61		€100,929.15	3.1%

Table 3. Material quantities for 5 stories.

	Frame - quantity	Price	Masonry - quantity	Price	Difference
Concrete [m3]	311.83	€21,142.07	299.37	€20,297.29	4.2%
Formwork [m2]	2,844.91	€34,707.95	2,166.79	€26,434.84	31.3%
Masonry [m3]	546.91	€43,971.56	650.84	€52,327.21	-16.0%
Rebar [kg]	41,116.11	€32,892.89	32,474.94	€25,979.95	26.6%
Total		€132,714.48		€125,039.29	6.1%

Table 4. Material quantities for 6 stories.

	Frame - quantity	Price	Masonry - quantity	Price	Difference
Concrete [m3]	378.72	€25,677.20	358.56	€24,310.57	5.6%
Formwork [m2]	3,425.57	€41,791.90	2,596.87	€31,681.81	31.9%
Masonry [m3]	654.37	€52,611.51	778.84	€62,618.74	-16.0%
Rebar [kg]	48,203.00	€38,562.40	37,796.37	€30,237.10	27.5%
Total		€158,643.01		€148,848.22	6.6%

Table 5. Material quantities for 7 stories.

	Frame - quantity	Price	Masonry - quantity	Price	Difference
Concrete [m3]	444.64	€30,146.59	417.76	€28,324.13	6.4%
Formwork [m2]	4,037.64	€49,259.21	3,026.96	€36,928.91	33.4%
Masonry [m3]	761.83	€61,251.29	906.84	€72,909.94	-16.0%
Rebar [kg]	56,129.30	€44,903.44	41,912.11	€33,529.69	33.9%
Total		€185,560.53		€171,692.66	8.1%

It can be remarked that for the studied number of stories there is no remarkable change in the difference between the masonry quantity for the two structural variants (standing at 16%), but there is a steeper evolution of the concrete, formwork and rebar quantities and prices; if in case of a three stories building the reinforced concrete frame structure with masonry infill walls is slightly more cost effective, by increasing the number of stories the load bearing masonry wall structure with reinforced concrete tie-beams and pillars becomes the cost effective solution (Fig. 4).

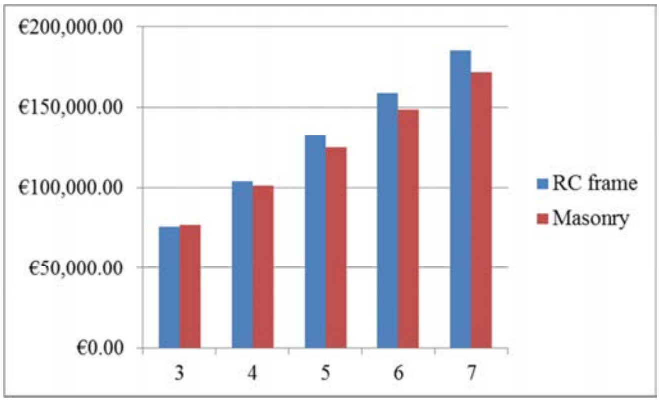

Fig. 4. Cost comparison with respect to story number.

4. Environmental impact assessment

The environmental impact analyses for the studied structural variants have been performed using Athena Impact Estimator for Buildings [17]. Using this tool the impact is assessed based on the embedded material quantity. The service and maintenance conditions have been considered unchanged for all the variants, the expected lifetime as well.

The material quantities have been taken from Table 1 to Table 5. The resulting total energy consumption for the studied structures is presented in Table 6. The comparative evolution of the total energy consumption is presented in Fig. 5., with higher energy demand for the load bearing masonry structure.

Table 6. Total energy consumption for the studied structures

Total Energy	3	4	5	6	7
RC frame [MJ]	8.46E+06	1.13E+07	1.41E+07	1.69E+07	1.96E+07
Masonry [MJ]	9.88E+06	1.31E+07	1.62E+07	1.94E+07	2.26E+07

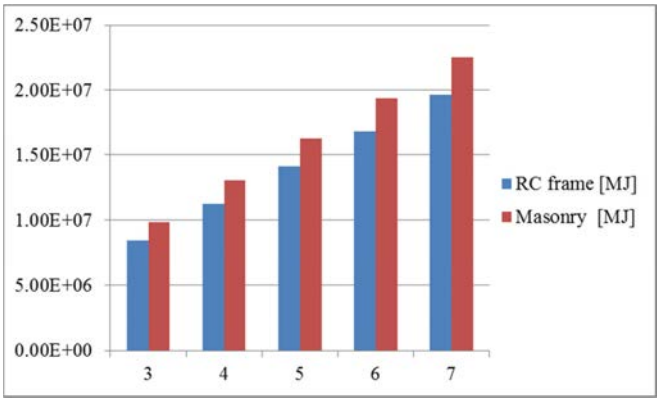

Fig. 5. Comparative evolution of the total energy consumption.

The evolution of the emissions to air (selective) for both structural solutions, for stories 3 to 7 are presented in Fig. 6. Besides the obvious linear increase of the quantities with respect to the story level the larger emission quantity resulted from the load bearing masonry wall structure can be remarked.

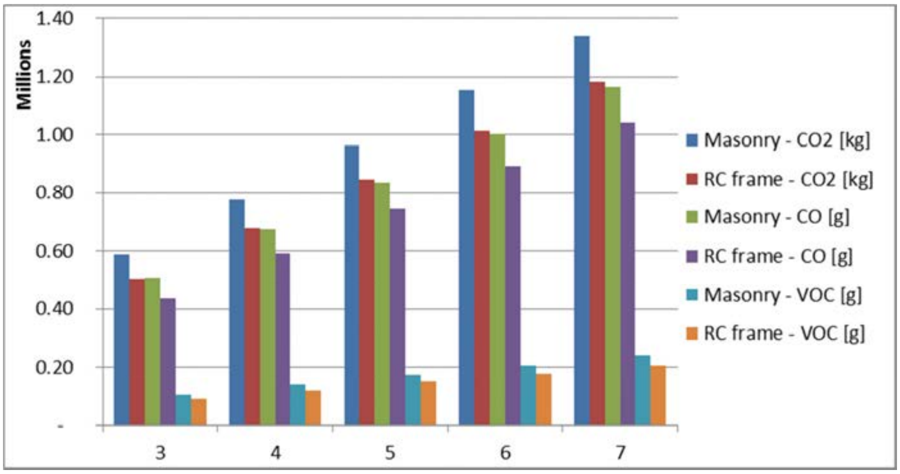

Fig. 6. Comparative evolution of the emissions to air.

The solid waste emission resulted from the studied structural solutions during their lifetime is shown in Fig. 7. In similar way the larger quantities are characteristic to the load bearing masonry wall structure, with larger overall material quantities.

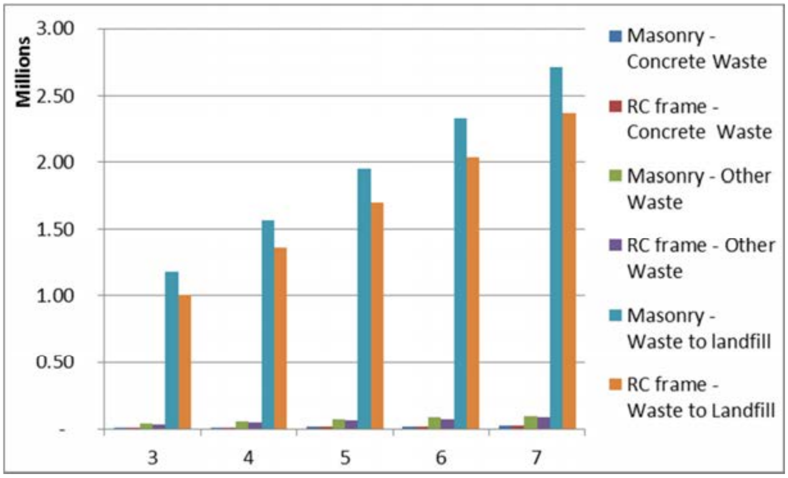

Fig. 7. Comparative evolution of the land emissions [kg].

5. Conclusions

The cost comparison emphasizes a nearly linear increase of the prices with the stories for both structural variants. For three stories the reinforced concrete frame structure with masonry infill walls seems to be the more cost efficient solution, but increasing the level number the cost of this solution increases more steeper than the cost of the load bearing masonry walls with reinforced concrete tie-beams and pillars. As consequence from economic point of view the load bearing masonry structure confirms its efficiency for the four to seven level buildings, where it is used in traditionally.

From environmental impact point of view the cost effective load bearing masonry structure seems to be the more harmful solutions, regardless of the analyzed criteria: energy consumption, carbon dioxide, carbon monoxide, volatile organic compounds, concrete solid waste, blast furnace dust or solid waste to landfill. The results are explained only by the overall larger quantities embedded in the case of the load bearing masonry wall structure, especially of the masonry itself. As consequence the study led to the typical dilemma of sustainability: which of the pillar of the sustainability to be considered in case of a similar building. Of course, other criteria might be also considered when establishing the sustainable structural solution, although the obvious choice does not seem to become simple.

It has to be mentioned that the results of the study are characteristic for the specific location of the building. The obtained values might vary for other local conditions. Even if the presented study emphasizes the differences between different structural solutions, results can be perceived through the comparison of different structural solutions.

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