Journal of Building Technology, 2023, Volume5, Issue1
DOI: 10.32629/jbt.v5i1.1236
ISSN Online: 2717-5103
ISSN Print: 2705-1390

Study of Variants of Housing Buildings of Masonry Reinforced at Seismic Zones

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Abstract: According to the Cuban earthquake standard NC 46:1999, the ERAD method was applied to study variants of 2- to 5-story reinforced masonry houses to be built on solid ground S2 in southeastern Cuba. The modeling was carried out with finite elements (shells) using the SAP 2000NL v19 program. The seismic load is obtained through the equivalent static method and response spectrum method. The evaluation of selected global and local control parameters is carried out by comparing their results, changing the number of floors or floor coverings and roof waterproofing, and comparing variants with different seismic hazard levels. The evaluation confirmed the conceptual design, simplified the structural design of the resulting variants, and distinguished the level of structural behavior.

Key words: reinforced masonry; housings buildings; structural behaviour; earthquake-resistant structures

1. Introduction

Housing construction has always been a decisive factor in the development of society. Cuba is currently involved in a housing construction program, where the construction technologies are still conventional or others with high energy consumption. Since ancient times, it has been feasible to use new building systems when using traditional architectural technologies, and to master the types of buildings at that time. Regardless of the type of technology, it is possible to better utilize the same technology and improve constructive systems, whether it is (the National Center for Disaster Prevention (CENAPRED) or the Japan International Cooperation Agency, 1999; ICA Foundation, A.C., 1999). This work evaluated the introduction of reinforced masonry construction technologies in building construction in earthquake prone areas of Cuba based on the experience of central and south American countries (Mexico. Federal District Government, 2004; Colombia. Ministry of Environment, Housing and Territorial Development and Standing Advisory Committee on Earthquake Resistant Building Systems, 1997; Venezuela Earthquake Research Foundation (Funvisis), 2001), and Mexico was selected as the reference country. Referring to the international reference code (European Committee for Standardization (ECS), 2005; American Concrete Institute, 2014) and professional literature (Paulay & Priestley, 1992).

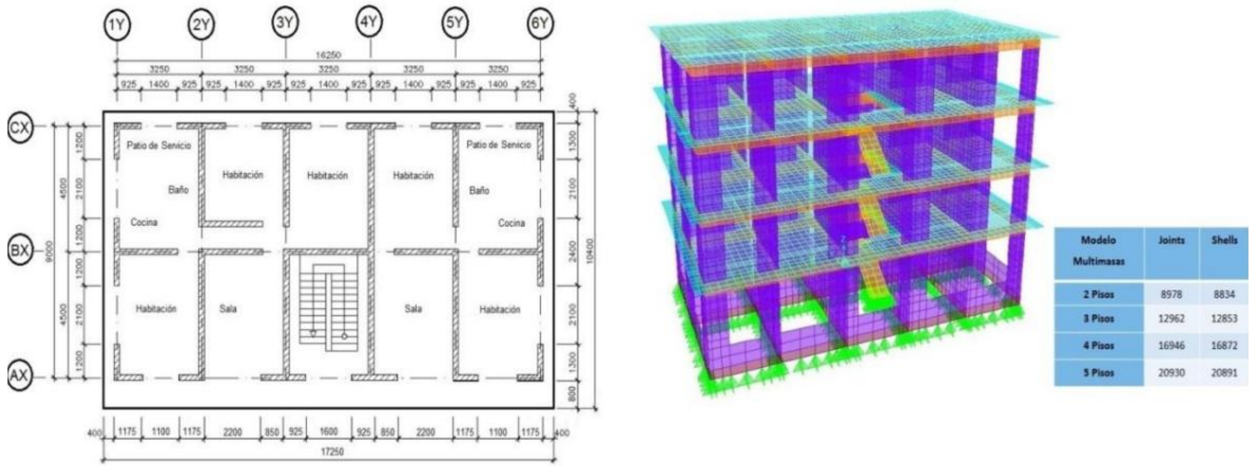
Thus, based on a single architectural project (Figure 1a) using reinforced masonry, different rational projects can be defined for each of the seismic zones of the country according to the Cuban seismic standard NC 46:1999 (Cuba. National Standardization Committee, 1999). Variants were generated for 2- to 5-story reinforced masonry residential buildings to be built in areas of moderate or severe seismic hazard in the southeastern region of Cuba (zones 2A, 2B, 3), where maximum ground acceleration values between 0.15 and 0.3 g are expected. These variants were analyzed for two solutions of floor coverings and roof waterproofing: a conventional one, called "Heavy", and another one with materials and technologies that reduce dead weight, called "Lightened" (Peña, 2011; Álvarez and Peña, 2012).

The purpose of this study is to analyze variants of reinforced masonry buildings based on the application of finite element models, in order to introduce them into areas with different seismic hazards in Cuba in the future.

2. Methodology

In order to achieve the proposed goal, ERAD method (Alvarez, 1994) was adopted to make the scope of this work correspond to its step 4: obtaining impact evidence of selected variable parameters on the dynamic performance of the generated building variants. To this end, the following research tasks must be addressed:

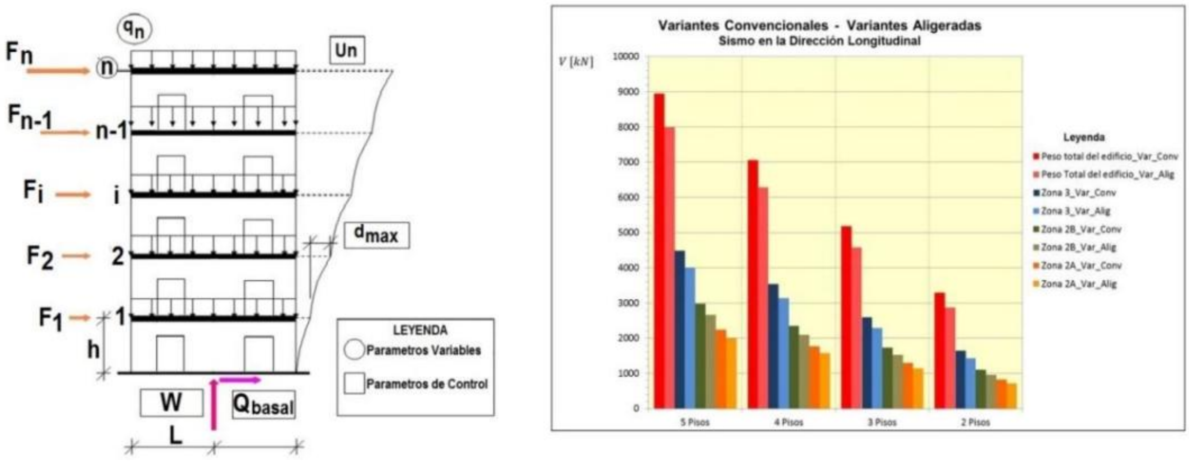
1) Structural modeling through finite elements, using SAP 2000NL version 19.
2) Evaluation of global control parameters.
3) Definition of critical zones to monitor normal and shear stresses.
4) Evaluation of local control parameters.



Modelo Multimasas	Joints	Shells
2 Pisos	8978	8834
3 Pisos	12962	12853
4 Pisos	16946	16872
5 Pisos	20930	20891

a) Architectural plan.

b) Finite element structural model.



c) Global control parameters.

d) Global control parameter evaluation. Base shear.

Figure 1. Structural modeling. Global control parameters.

3. Results

3.1 Structural modeling through finite elements, using SAP 2000NL version 19

The modeling was performed with finite element shells (Zienkiewicz, 1989 and 1991) using the SAP 2000NL v19 program (Figure 1b). The seismic requirements were obtained from the equivalent static method and response spectrum method according to the Cuban seismic standard NC 46:1999 (Cuba, National Committee for Standardization, 1999). Seismic loads are modeled as acting loads on a horizontal plane, with 100% of the seismic load acting in one main direction of the building and 30% acting in the other direction. The distribution of horizontal forces not only corresponds to the stiffness of each load-bearing wall obtained from its bending and shear deformation, but also occurs through the model used, which takes into account the bending and shear deformation of the floor slab, their fenestration, as well as the interaction between the window and the stair slabs.

3.2 Evaluation of global control parameters

The evaluation of global control parameters for monitoring the generated building variants (Figure 1c) is crucial for distinguishing these variants based on their seismic performance, which largely depends on the seismic hazard of the region in which they are located. This not only quantifies the impact of selected variable parameters on control parameters, but also simplifies the evaluation of local control parameters, confirms conceptual design, and provides important evidence to draw conclusions and recommendations on the variants to be constructed in each seismic zone.

3.2.1 Modal analysis

a) Fundamental oscillation periods

The first three coupled oscillation characteristic forms of the generated variants are very similar, corresponding to the basic translation period and torsion period in the main direction of the building. The longitudinal translation period is always relatively large and linearly decreases with the increase of the number of floors, and its function roughly corresponds to the semi empirical formula in the seismic code of masonry buildings. For variants with 4 and 5 layers, the above period is followed by a transverse translation period, while for variants with 2 and 3 layers, this period does not exceed the torsion period. The period of the main direction is given in the resonance region of the calculated spectrum of S2 soil in the Cuban earthquake standard, and the response acceleration is given. Only in the case of a two-story building can the transverse period reach a value lower than the critical period of 0.15 s of the above reaction spectrum.

b) Characteristic forms of vibration and modal participation

For all variants, the basic feature form of longitudinal translation is coupled with the basic feature form of torsion, so the modal correlation between these modes reaches a significant value. For 2-layer and 3-layer variants, the results are greater. However, the contribution of the basic torsional mode to the longitudinal reference shear is not high. For lateral seismic excitation, the maximum contribution is not determined by oscillation coupling, as the basic translation form in this direction is independent of the torsion form. Based on the contribution to baseline shear, considering the first five forms is sufficient; However, in order to achieve the cumulative amount required for modal participation, 15 different forms were considered, approaching 90%. However, for variants with fewer layers, these values are not satisfactory, but it can be proven that increasing the number of more than 15 modes does not significantly increase the baseline shear contribution in the analyzed excitation direction.

3.2.2 Equivalent static method

a) Basal shear, total building weight and seismic coefficients

The basic shear force and seismic load of the floors were calculated using the equivalent static method. Since almost all the variants for their principal directions show fundamental periods in the S2 soil resonance zone and are given low levels of ductility, the seismic demand will be conditioned by the seismic zones where they would be located. Therefore, for the most earthquake prone area in the country (Santiago City, Cuba), these variants have achieved high seismic demand (with an earthquake coefficient of 0.5); For zone 2b and zone 2a, the seismic demand is moderate (with seismic coefficients of 0.33 and 0.25, respectively). The baseline shear force in each seismic zone decreases linearly with the decrease in the number of floors, and the change is not significant due to the decrease in the total weight of the building, which is approximately 10% compared to the reduced change (Figure 1d). The baseline shear force of modal analysis in both directions of earthquake action often matches the baseline shear force of equivalent static methods that reduce the number of floors. Therefore, for the 5-story variant, the baseline shear force for modal analysis is approximately 80% of the shear force obtained by the equivalent static method, while for the 2-story variant, these values are almost equal.

b) Evaluation of total relative extreme horizontal displacement

Although the structural behavior caused by the interaction with the stair board is irregular, the variants are still classified as regular. For all variants, the relative horizontal displacement fully meets the requirements of regulation for residential buildings and ensures that there will be no significant second-order effects, as confirmed by the calculation results. They also mean that there is no damage to non structural components, let alone the structural components of the building, if they meet the strength limit state of the assumed level of danger.

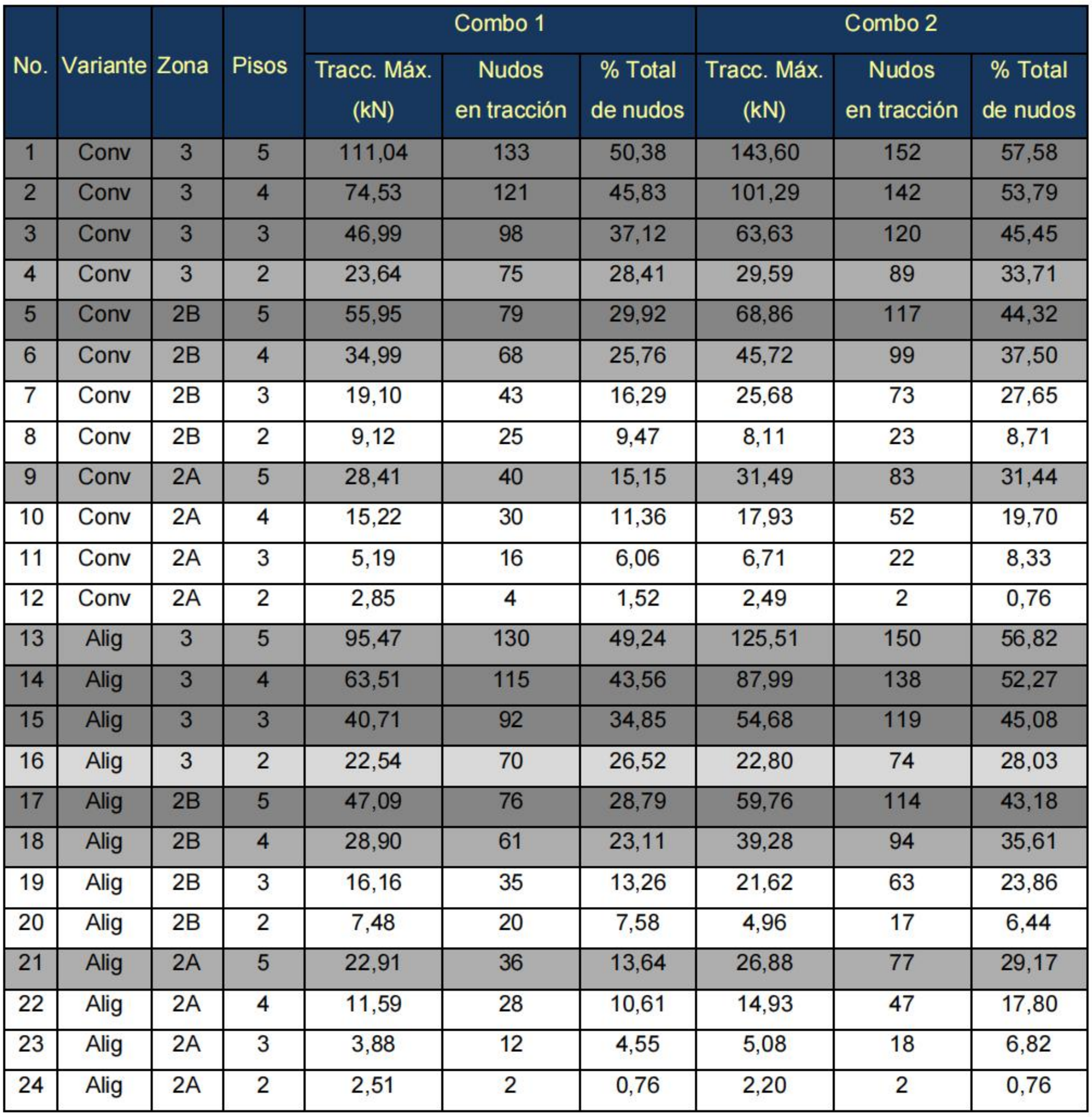
c) Reactions at the base of the structure

The above control parameters do not allow to clearly establish a criterion that differentiates these variants by their seismic behavior. The tensile reactions at the base are a control parameter that reflects the magnitude of the seismic demands and an important indicator of seismic risk, because it also implies considerable increases in soil pressures on the face opposite to where they occur.

Modal analysis shows that for all variants, tensile reactions occur, which largely depends on their location region. The stretching reaction varies greatly with the number of layers, and the change is not significant when reducing the dead load (Table 1). The propagation region of the tensile response determines three well-defined seismic performance levels, which can distinguish these variants (Table 2). A level for which the zone of propagation of tensile reactions is extensive, shown in dark gray in Table 2, covering the entire contour of the building and part of the interior foundations with high extreme values of tensile reactions (circled in Figure 2). A transition level for which the zone of propagation of the tensile reactions covers only critical areas of the building contour, with much lower values of tensile reactions (light gray color). Finally, a level for which the zone of propagation of tensile reactions is very limited or practically non-existent, with very low values of probable tensile reactions (white color).

The nodes and zones with extreme values of tensile reactions for the load combinations considered in the modal analysis are shown. The difference in the behavior in the main directions of the building is due to the fact that the eccentricities of the masses' centers with respect to the rotation centers of the floors are significantly higher, measured in the direction perpendicular to the longitudinal axis of the building (ey = 0.735 m). They reach very low values when measured in the direction perpendicular to the transverse axis of the building (ex = 0.065 m).

Table 1. Maximum base tensile stresses calculated by the modal analysis method



No.	Variante	Zona	Pisos	Combo 1			Combo 2		
				Tracc. Máx. (kN)	Nudos en tracción	% Total de nudos	Tracc. Máx. (kN)	Nudos en tracción	% Total de nudos
1	Conv	3	5	111,04	133	50,38	143,60	152	57,58
2	Conv	3	4	74,53	121	45,83	101,29	142	53,79
3	Conv	3	3	46,99	98	37,12	63,63	120	45,45
4	Conv	3	2	23,64	75	28,41	29,59	89	33,71
5	Conv	2B	5	55,95	79	29,92	68,86	117	44,32
6	Conv	2B	4	34,99	68	25,76	45,72	99	37,50
7	Conv	2B	3	19,10	43	16,29	25,68	73	27,65
8	Conv	2B	2	9,12	25	9,47	8,11	23	8,71
9	Conv	2A	5	28,41	40	15,15	31,49	83	31,44
10	Conv	2A	4	15,22	30	11,36	17,93	52	19,70
11	Conv	2A	3	5,19	16	6,06	6,71	22	8,33
12	Conv	2A	2	2,85	4	1,52	2,49	2	0,76
13	Alig	3	5	95,47	130	49,24	125,51	150	56,82
14	Alig	3	4	63,51	115	43,56	87,99	138	52,27
15	Alig	3	3	40,71	92	34,85	54,68	119	45,08
16	Alig	3	2	22,54	70	26,52	22,80	74	28,03
17	Alig	2B	5	47,09	76	28,79	59,76	114	43,18
18	Alig	2B	4	28,90	61	23,11	39,28	94	35,61
19	Alig	2B	3	16,16	35	13,26	21,62	63	23,86
20	Alig	2B	2	7,48	20	7,58	4,96	17	6,44
21	Alig	2A	5	22,91	36	13,64	26,88	77	29,17
22	Alig	2A	4	11,59	28	10,61	14,93	47	17,80
23	Alig	2A	3	3,88	12	4,55	5,08	18	6,82
24	Alig	2A	2	2,51	2	0,76	2,20	2	0,76

Table 2. Levels of seismic behavior according to base tensile reactions

No.	Variante	Zona	Pisos	No.	Variante	Zona	Pisos
1	Var_Conv	3	5	13	Var_Alig	3	5
2	Var_Conv	3	4	14	Var_Alig	3	4
3	Var_Conv	3	3	15	Var_Alig	3	3
4	Var_Conv	3	2	16	Var_Alig	3	2
5	Var_Conv	2B	5	17	Var_Alig	2B	5
6	Var_Conv	2B	4	18	Var_Alig	2B	4
7	Var_Conv	2B	3	19	Var_Alig	2B	3
8	Var_Conv	2B	2	20	Var_Alig	2B	2
9	Var_Conv	2A	5	21	Var_Alig	2A	5
10	Var_Conv	2A	4	22	Var_Alig	2A	4
11	Var_Conv	2A	3	23	Var_Alig	2A	3
12	Var_Conv	2A	2	24	Var_Alig	2A	2

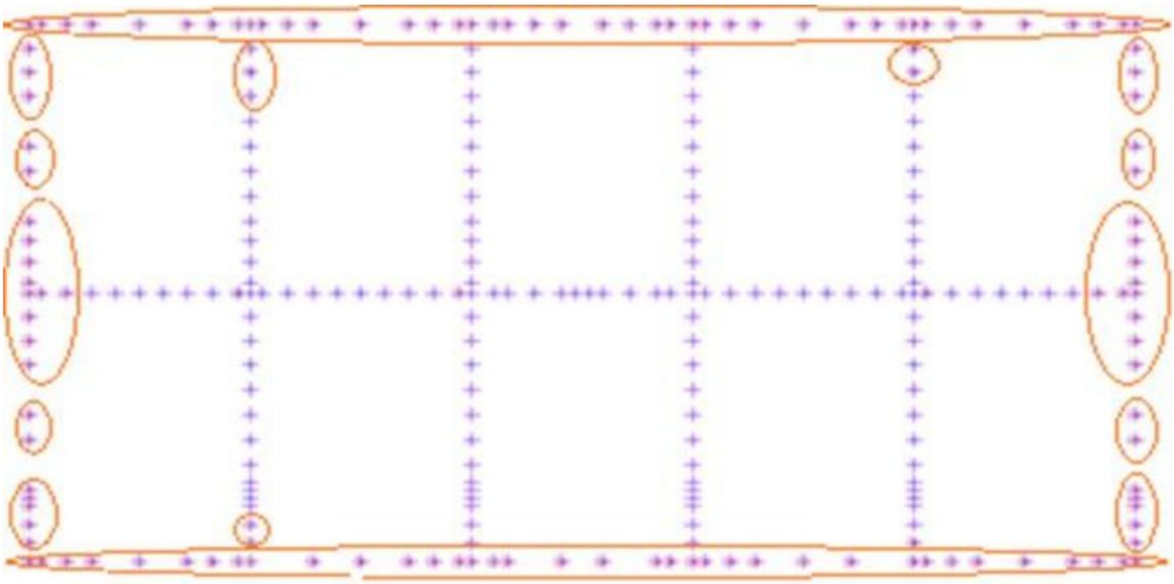


Figure 2. Tensile reactions at the soil base. Level of behavior corresponding to an extensive zone of propagation of tensile reactions. Conventional 5-story variant in zone 3. Combo 1 (100% Csx + 30% Csy). Modal analysis method.

3.3 Definition of critical zones to monitor normal and shear stresses

The study of the maximum seismic hazard zone for a 5-story building (Armero and Aliaga, 2007; Álvarez and Pérez, 2008) made it possible to specify critical zones, namely vertical compression and tensile normal stress, located on the contour lines of doors and windows, at the starting point of masonry components at the intersection of reinforced concrete frame beams, and at the junction of foundation bases and walls. For the frame beams, the horizontal normal stresses and tangential stresses are high in areas that vertically connect the walls (joints), especially in the facade element (Ax element), where the stress concentration in these joints is higher, since the frame beam vertically connects the narrowest walls of the building.

In the case of facade elements, high horizontal normal stress values also occur in the area of enclosed beams, which connect narrow brick walls horizontally, and the wide span between brick walls is related to it. When two very wide masonry components are horizontally connected, the closed beam exhibits maximum tangential stress in the area above the narrow blades, just like the internal transverse component.

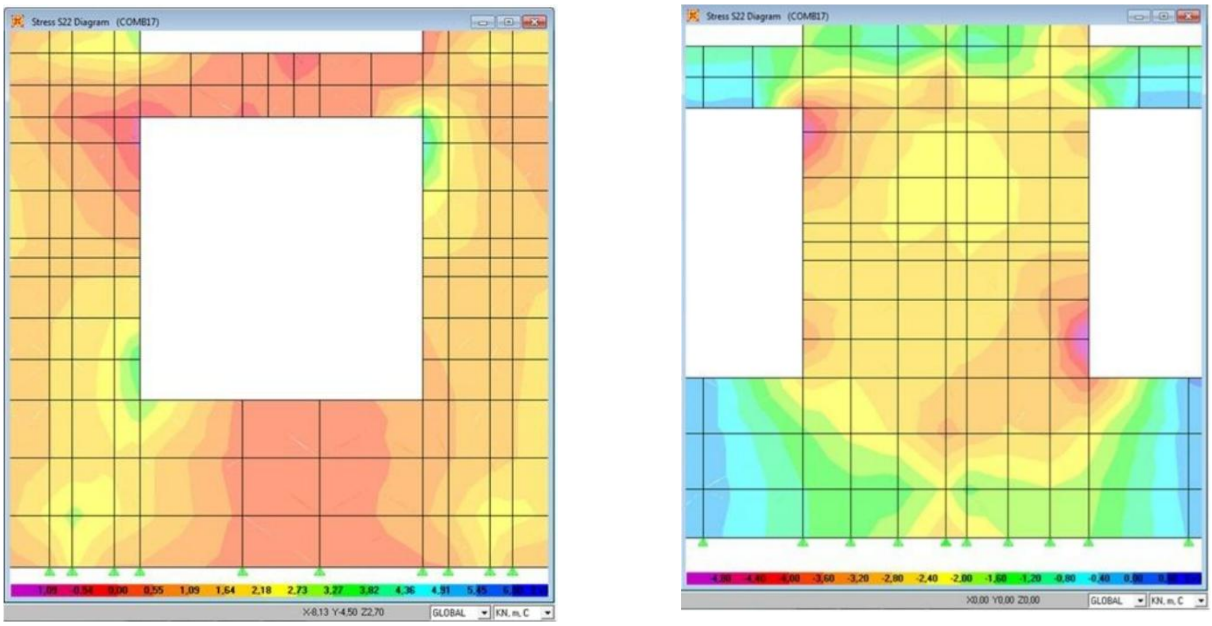
The significant values of vertical normal stress and shear stress also appear at the connections between orthogonally arranged masonry components near the building contour. Other important areas of concentration of normal stresses (horizontal and vertical) and shear stresses are located at the connection of the reinforced concrete beam for the stairway landing with the reinforced masonry wall (element Bx). It is found that the above critical zones are maintained in all floors, but stresses in the upper layer decrease considerably. Therefore, the vertical normal stress of the last two layers of brick walls is actually compressive. Only in the facade elements do the vertical normal tensile and compressive stresses reach significant values, mainly at the corners of the spans. Before the closed beam of the penultimate level, the shear stress remains significant. The definition of key areas controlled by elements allows grouping to control the tension in other variant key areas.

3.4 Evaluation of local control parameters

The evaluation of local control parameters requires the level of tension, areas that reach critical values, and the boundaries of these areas. It helps to validate conceptual design, simplify structural design of variants, and differentiate structural performance levels, thus drawing conclusions and recommendations for variants to be constructed in each seismic zone. The extreme normal and shear stresses in the critical region of vertical stiffeners under horizontal loads are defined as local control parameters.

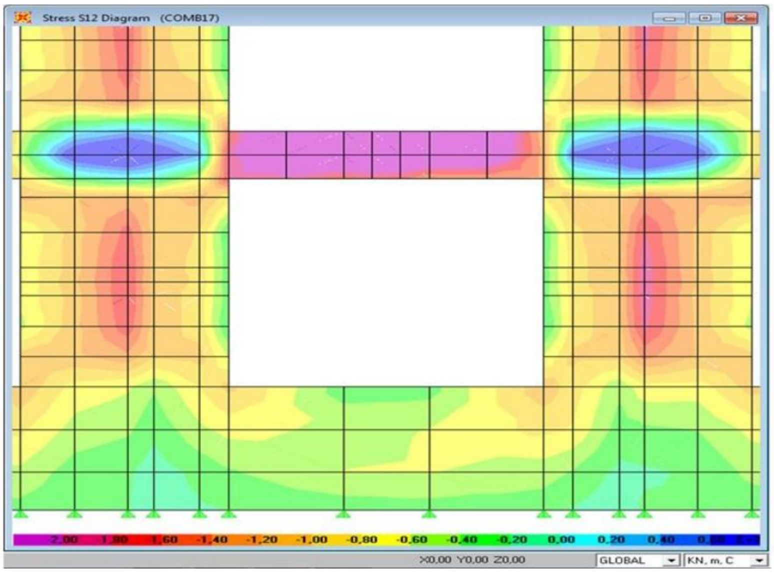
a) Testimony for evaluating local control parameters

A comparison of the maximum vertical normal stress of the first floor masonry indicates that, except for the very point area of the blade angle of the internal transverse component, the compressive stress is usually greater than the tensile stress. The values in the same order as above are recorded in the external lateral elements and the internal blade angles of the vertical facade elements near the building corners (Figure 3a and 3b). The shear stress analysis shows that the absolute maximum value occurs in the wide inner wall of the longitudinal facade element (Figure 3c).



a) The center span of the Ax element. Vertical normal tensile stress.
Combination 17: Maximum stress envelope.

b) The center wide wall of element 1y. Vertical normal compressive stress.
Combination 17: Minimum voltage envelope.



c) The central wall of the Ax component. Shear stress. Combination 17: Minimum stress envelope.

Figure 3. Evaluation of local control parameters.

The evaluation of the maximum normal stresses in the reinforced concrete frame beams of the second floor in the span area and at the nodes showed that the vertical compressive normal stresses are in the same order as the tensile normal stresses. At the nodes, the maximum normal tensile stress reaches a value slightly higher than the compressive stress. The evaluation of the maximum horizontal normal stress in the node and in the spans of the frame beams indicates that they are similar, as the latter occurs in the connection with the node. The maximum horizontal normal stress in the nodes is significantly higher than the vertical normal stress at these nodes. The evaluation of the maximum shear stresses in the nodes and span zones of the truss girders shows that, as is the case for the horizontal normal stresses, they reach very similar values, but are recorded in different elements. The maximum shear stresses for span areas of the frame beams appear in the narrow spans of the interior cross members (short coupling beams), while the maximum shear stresses are recorded in the interior nodes of the facade element, with dimensions much smaller than the nodes of the interior cross members and connecting elements with structural behavior closer to flexible reinforced concrete portal frames.

b) Testimony obtained from comparing local control parameters evaluated for the generated variants

The evaluation of local parameters confirms the known situation of global parameter evaluation: the seismic performance of the generated variant largely depends on its location area, and the proportion of seismic acceleration values between different location areas is the same. Because in almost all the main direction variants, they all show the seismic coefficient determined by the basic period of S2 soil resonance zone. The controlled local parameter values for each floor removed from the 5-story variant should be reduced by at least 20%.

4. Discussion

1) Due to these variants showing the basic period of the S2 floor resonance zone, seismic demand will be affected by the seismic zone and will vary linearly with the number of floors.

2) The measures planned to reduce gravity loads, interlayer and deck static loads have not significantly changed earthquake demand (only about 10%).

3) As the number of floors decreases, the baseline shear force in modal analysis often matches the shear force calculated by the equivalent static method.

4) The relative horizontal displacement fully meets the requirements of Cuban housing seismic standards, ensuring that structural or non structural components are not damaged.

5) The evaluation of ground tensile response makes it possible to distinguish variants generated at three clearly defined seismic demand levels.

6) The evaluation of local parameters confirmed that the seismic performance of these variants largely depends on their location area, with a 20% reduction in local parameters for each floor removed from the 5-story variants.

7) The evaluation of local parameters characterizes the critical areas of reinforced concrete and controlled reinforced concrete components.

5. Conclusion

Research on building variants to be built on solid soil (S2) in southeastern Cuba shows that the quasi elastic behavior of so-called reinforced masonry meets high seismic requirements due to its basic oscillation period. During these periods, by maintaining the resonance zone of the S2 floor, it was determined that the seismic demand varied linearly with the number of floors. The measures planned to reduce gravity loads, interlayer and deck dead loads have not significantly changed the high seismic requirements.

These structural designs with high seismic requirements will ensure a low likelihood of structural or non structural component damage, as the relative horizontal displacement fully meets the requirements of Cuban housing seismic standards.

The tensile response on the ground is shown as a global discriminant parameter, allowing the differentiation of variants generated at three well-defined expression levels of seismic demand. Therefore, it is not recommended to build 5-story variants in the transition zone of Santiago, Cuba (zone 3B) or zone 2B, where up to 4-story variants can be built. Only in zone 2A (Bayamo City), it is recommended to build a 5-storey variant. For the city of Santiago, Cuba, reinforced masonry buildings of up to 3 stories seem to be recommended, with a more rigorous seismic-resistant design than for the variants located in other areas.

The evaluation of the local parameters made it possible to identify the critical zones of the controlled reinforced masonry and reinforced concrete elements. This will facilitate a subsequent seismic-resistant structural design differentiated from the variants studied, where the critical zones require not only a reinforcement amount corresponding to the high seismic demands, but also a construction detailing in accordance with these demands (conceptual design).

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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