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MASONRY WALL-RC SLAB INTERACTION UNDER SEISMIC LOADING

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Abstract

In conventional engineering practice, masonry walls are typically analyzed independently from the rest of the structure. The gravity load is determined, and a horizontal load is applied under the assumption that RC slabs behave as rigid diaphragms, distributing horizontal forces according to the relative stiffness of the walls. The wall load-bearing capacity is then assessed in a separate model, considering the effects of bending moments, and normal and shear forces. However, spatial models that incorporate structural elements connected with masonry walls are rarely developed. This study focuses on slender masonry walls, where the height exceeds the length, a characteristic feature in traditional engineering structures. In such structures, reinforced concrete ring beams are commonly placed atop these walls, often transitioning into lintels or beams supporting the RC slab. The objective of this research is to investigate whether these elements, along with the RC slab as a whole, influence the seismic behavior of walls. Experimental studies and post-earthquake damage reports indicate that wall behavior varies significantly depending on the level of normal stress. Key influencing factors include the wall's position within the structure, load intensity, connection details, and material and geometric properties. Less-loaded walls, typically found on upper slabs, are prone to rocking failure, with or without edge crushing. Sliding failure is common under low normal forces combined with high shear stresses, whereas diagonal cracking occurs under specific stress conditions. This study develops a numerical model to explore the interaction between slender walls and RC slabs, particularly in relation to rocking and toe crushing. It aims to answer whether walls should be considered isolated or part of spatial frame systems.

Keywords: masonry walls, frame, rocking, sliding, uplifting, ring beams, stress redistribution.

1. Introduction

Although masonry structures have been used since the beginnings of civilization, a generally acceptable engineering model has not yet been developed to analyze them in practice, especially under seismic loads. There are many reasons, and they should primarily be sought in the difference in the construction traditions of different regions and the material used for masonry structures. The material characteristics of masonry walls are one of the primary unknowns. The physical properties of walls depend on the choice of binders and masonry blocks, type of loading, masonry method, quality control, geometry and many other factors. In engineering design, empirical forms are usually employed to determine the material characteristics of walls and rarely experimentally obtained data. Modulus of elasticity, compressive and shear strength of the wall, which can be determined empirically or experimentally for the proposed analysis method, are of interest for this work.

Originally, the slabs of masonry structures were made of wood as beams laid freely on the walls, followed by the use of numerous typical prefabricated beams that were subsequently monolithically connected with the structure. Today, reinforced in-situ concrete dominates in the construction of slabs. There are relatively thick plates without horizontal tie-beams in northern Europe, or thinner plates with horizontal tie-beams in the southern parts of Europe. Tie-columns are also commonly used in seismically active areas, which is not the case, for example, for German masonry tradition. For buildings where the slab is made with prefabricated single-beam elements, which are later monolithic in some way or not, the slab can usually be considered rigid in its plane. In the vertical plane, such a slab is a system of simply supported beams that transmit the gravity load to the corresponding walls. To sustain

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the seismic load, the walls can be considered as a system of cantilevers hinged at the top [1]. Distribution of the seismic force depends on material and geometric properties of individual walls and an example is shown in Fig. 1a. The presented 2D model is calculated using finite elements, and it is obtained that approximately 92% of the seismic force is resisted by the central wall (Fig. 1b). An almost identical value would be obtained if the distribution of the seismic force was basically calculated as a percentage of the individual moment of inertia of the wall in the sum of the moments of inertia of all the walls in the model.

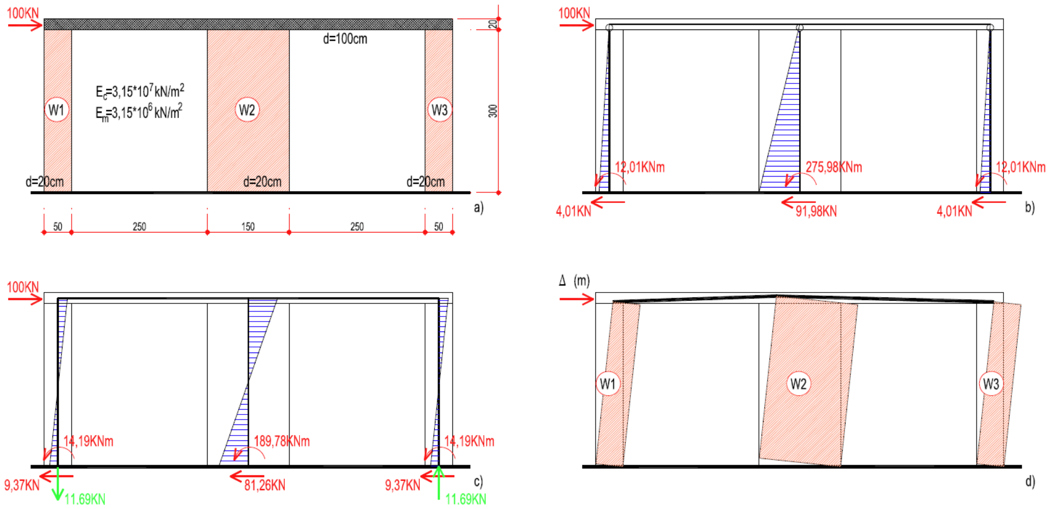

Figure 1. Structural models: a) 2D view, b) system of cantilever walls, c) frame structure, d) assumed behavior.

In the case of monolithic RC slabs, a 2D model in which the slab is modeled as a 100/20cm beam element, a different distribution of cross-sectional forces is obtained (Fig. 1.c). Such a distribution is typical for frame structures. The presented values will vary depending on the specific case, and in this case, a reduction of the transverse force in the middle wall by approx. 10% and a different distribution of bending moments in the wall plane is noticeable. For rigid RC slabs, which also have tie-beams, these framing effects come to the fore even more significantly. It is interesting to emphasize that a coupling of forces is formed in the edge walls of the frame, and that this moment partly takes over the moment from the horizontal force on the slab. This combination of forces in the left wall reduces the normal force from the gravity load, and in the right increases, which will be discussed in detail later in the text. For the example shown, this coupling takes up approx. 27% of the moment, which is not negligible.

Previous analyzes were performed for linear behavior. The assumption is that in the case of non-linear behavior of the walls, the situation will change more significantly, because after reaching the tensile strength of the coupling, the walls start to rotate more noticeably. The rotation of the wall, especially the central one from the previous example (Fig1d), acts on the slab above, attempting to lift it up, which is explored in this paper. How the wall will affect the slab depends on many factors, most of all on the type of wall failure. Below is a brief overview of wall failures types under seismic loads.

2. Masonry wall failure types

For buildings with openings (Fig. 2.b), which are the subject of research, less loaded walls located on the top slabs, will fail mainly due to the rotation of the complete wall as a rigid body (rocking). This rotation can also cause lifting of the slabs on top of the building. A similar failure occurs on the slabs below, where the compressed edge of the joint is crushed without pronounced rotation of the wall. Wall sliding occurs at relatively low intensities of normal forces and significant transverse stresses, while the characteristic diagonal failure occurs at a certain intensity of transverse and normal stresses.

The failure types of solid walls shown in Fig. 2a are also of interest for the work. In the analyzed example of the building, these walls are perpendicular to the earthquake action and in them, in addition

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to failure perpendicular to the wall plane, local tensile failure that may occur due to the interaction of walls and slab, which was already hinted at in the introduction, are also numerically registered.

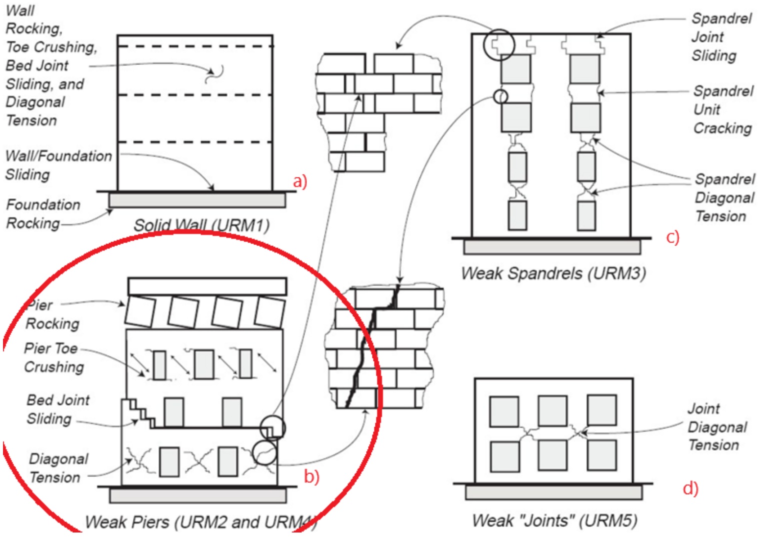
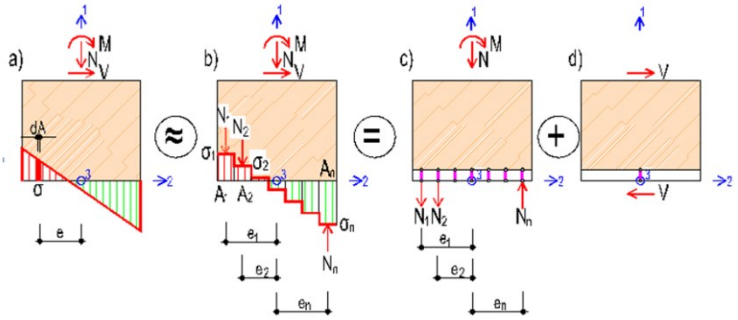


Figure 2. Types of masonry wall failures - FEMA [2].

For newer buildings, the walls with openings shown in Fig. 2c are mostly executed as parapets that are built later and are therefore not of interest to the work. For the case of buildings shown in Fig.2d, beams executed as horizontal tie-beams can yield, which is discussed below.

3. Proposed model

The normal force in the wall by definition represents the integral of the normal stresses on the surface of the cross-section of the wall, while the bending moment in the plane of the wall is equal to the integral of the product of the normal stresses and the distance from the center of gravity of the section. If we divide the wall into a sufficient number of segments, it is possible to repslace the integral dependence with the discrete one and present the normal force as the sum of normal stresses in individual segments. In that case, the in-plane moments of the wall are equal to the product of the normal stresses in the segments and the distance between the centers of gravity of the segment and the wall.



$$N = \int_A \sigma \cdot dA \approx \sum_{i=1}^{n} \sigma_i \cdot A_i = \sum_{i=1}^{n} N_i$$

$$M = \int_A \sigma \cdot e \cdot dA \approx \sum_{i=1}^{n} \sigma_i \cdot A_i \cdot e_i = \sum_{i=1}^{n} N_i \cdot e_i$$

$$M_{Rd} \geq M = \sum_{i=1}^{n} N_i \cdot e_i$$

$$N_{i,Rd} = f_d \cdot A_i \geq N_i$$

$$V_{Rd} \geq V$$

Figure 3.Stress distribution a) normal stress, b) normal forces in wall segment, c) axial force in nlink elements, d) sliding.

The idea is to use universal software packages such as SAP2000nl [3] and the elements readily available in the program. The width of the segment for which we are looking for the force N_i is actually determined by the FE discretization of the wall. In the part of the wall that is connected to the rest of the structure, i.e. at the top and bottom of the wall, we introduce an artificially formed joint where parts of the wall are replaced by non-linear connecting elements in SAP2000 known as nlink elements. Direction 1 defines the axial direction of the nlink element, and direction 2 the plane of the wall. N-Δ

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dependence can be assigned to axial bonds. The load-bearing capacity of an individual connection is defined by the surface to be connected and the compressive strength of the wall while in this case, tension is neglected. The sum of all forces in the nlink elements of the joint gives the normal force in the wall, and the sum of the products of the normal forces and the eccentricity gives the bending moment in the wall where the joint is introduced. Regarding the transverse force load bearing capacity, there is only one nlink in direction 2 [4, 5]. Before the introduction of links in which nonlinearity is introduced, it is desirable to create a linear elastic model without additional connecting elements for comparison of response to gravity load.

In the first steps of the analysis, a FEM model made of finite and nlink elements is created, a gravity load is applied, and in the next steps of the analysis, the model is gradually pushed to the required tip displacement or, in the case of time history analysis, the supports of the model are excited with accelerograms. The behavior of one such simple cantilever wall model is shown in Fig.4.

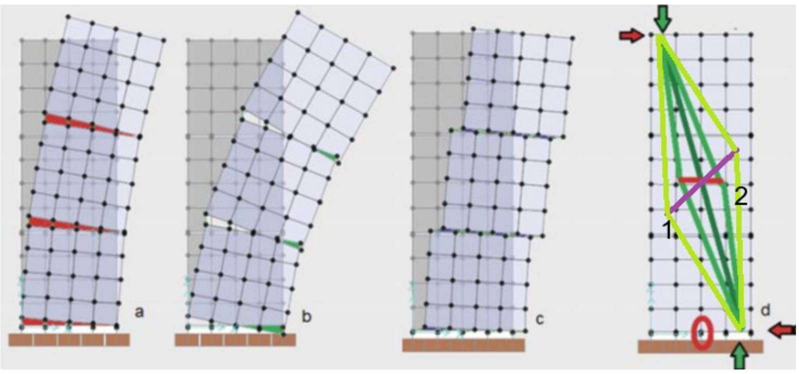

Figure 4. Wall failure: a) rocking; b) toe chrushing; c) sliding or diagonal tension; d) V_{Rd}.

Bending failure without crushing of the compressed edge is shown in Fig.4.a. The force in the far-right link does not reach the assigned compression bearing capacity. The stressed block is relatively narrow and its length is less than half the length of the associated finite element. All tensioned connections are open because no tension capacity has been assigned. The block of finite elements behaves like a rigid body and rotates around the support point. In the case of a higher normal force, the stress block is longer, which results that the last nlink element yields in compression, while the others follow the length of the stress block, so depending on the degree of stress, they can be in the linear or non-linear range. For this failure, depending on the normal force in the wall, in addition to crushing the right edge of the joint, it is possible for the left edge of the joint to open for tension. Wall sliding is shown in Fig4c. Depending on whether the relevant slip failure is V_{Rd2} or a diagonal failure V_{Rd1}, the calculated resistance is assigned to the transverse nlink element and this failure is simulated as sliding.

4. Wall -RC slab interaction

If the walls of a masonry structures are modeled as columns of a frame system, node A will move to node A' according to the pushover analysis, where it will have a horizontal, vertical and rotational component of movement (Fig.5a). If, on the other hand, the wall is modeled in the suggested way, due to the strong rotation of the wall as a rigid body, open joints are observed, left down and right up for the shown direction of pushing (Fig.5b). By opening the connection, a hinge is formed. Two opposite compressed hinges clearly indicate that a compression diagonal was formed in the model (Fig.5c). The diagonal in the wall is controlled by the width and strength of the compression block, i.e. the force N_{Rd}, and also by the shear bearing capacity of the wall V_{Rd}. By rotating the wall, the wall acts on the slab, tending to lift it up (Fig.5d), which is clearly visible from the display of model displacements. On the other hand, the slab, which is supported by other structural elements, resists this effect, which results in an increase in the normal force in the rotating wall. By increasing the normal force, its resistance to the action of the transverse force also increases. The gravity load of a structure is constant, so an increase in the normal force in a rotating wall leads to a decrease in the normal forces in other walls of that structure. The key element in this redistribution is the rigidity and load-bearing capacity of the slab.

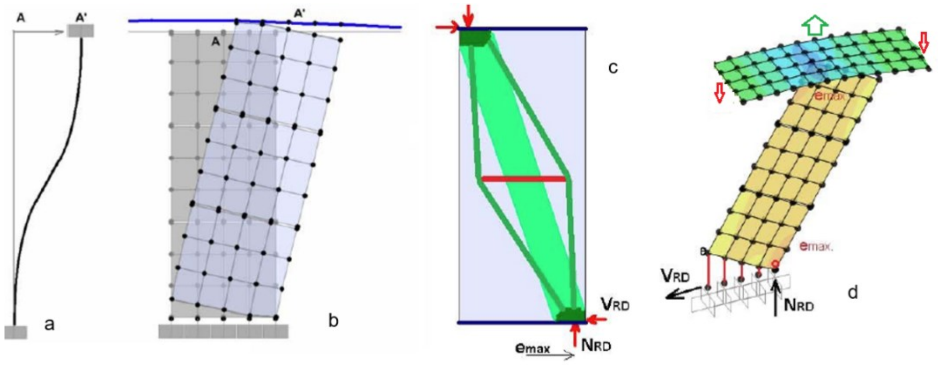

Figure 5. Columns/wall model, compressed diagonal, uplifting/increasing wall force

Refined models show more complex behavior. Fig. 6a shows the characteristic node of the model, i.e. the connection of the wall and the slab with stress components. Overturning of the wall above node shown in Fig.6c occurs when the normal force in that wall reaches the extreme eccentricity $N_{Ed,w}$. On the slab, the gravity load from that slab is entered automatically through the software and numerical model $N_{Ed,s}$. The total normal force on the wall below is the sum of those two forces, and its position is determined by the length of the stress block, which is formed using nlink elements automatically in the software. At any point in the pushover analysis, sliding may occur if the transverse force in the wall reaches the bearing capacity of the transverse connection (Fig.6d). If all the walls reach the assigned bearing capacity for the transverse force, that step is considered a collapse.

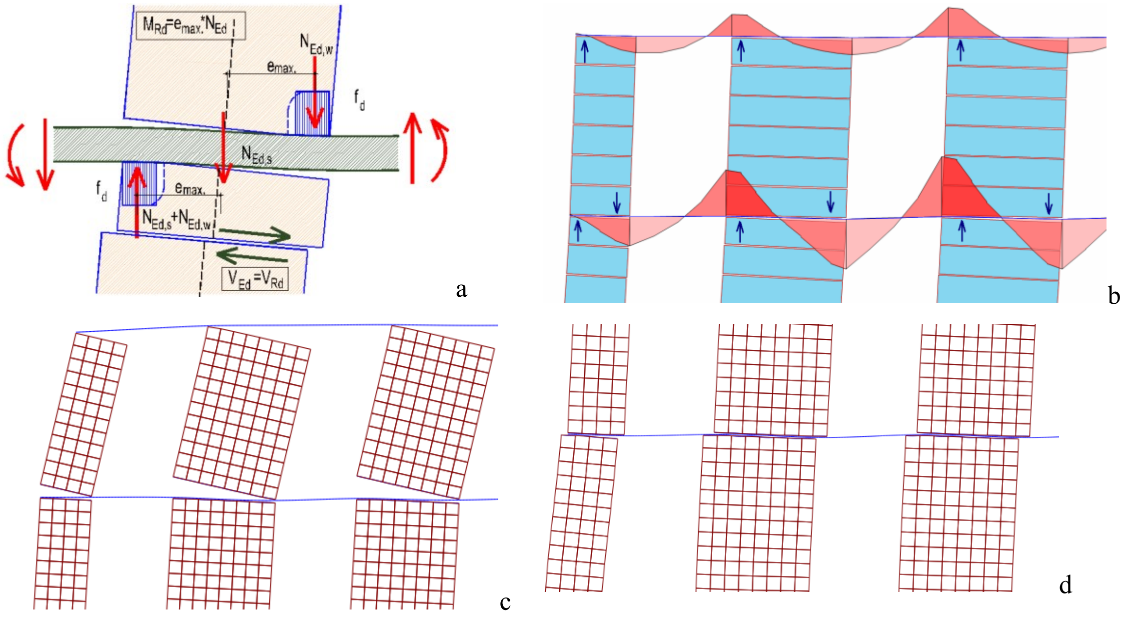

Figure 6. a) model, b) bending moment, c) rocking/crushing, d) sliding.

Figure 6b shows the diagram of the moments in the beams of the top slabs of a three-story building during the last steps of the pushover analysis. The beams of the last slab are raised, resting on the left ends of the walls when pushed from left to right, and can be imagined as a continuous beam supported on the compressed parts of the walls of the last slab. The length of the support is actually the length of the formed tension block, and the resulting force represents the gravity load from the top slab. In this case, the combination of all elements in the structure comes to full expression. This scenario is possible if and only if the beams of this slab have the capacity to act as continuous beam. Namely, in everyday

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structural planning, it is common to design these beams as simply supported beams on the clear length of the opening. By rotating the wall, the system length of the opening changes and increases to the length of the span, because the beam loses most of its support when the wall is rotated. Depending on the disposition of the slab and the associated gravity load, and the beam reinforcement layout, it is possible that minimum reinforcement in the beam enables such a scenario. It is even possible for the slabs to physically separate from the walls in a second direction locally, i.e. that tension appears in those walls.

The situation is much more complex on the slab below. At the left ends of the walls under the last slab, the supports of the imaginary continuous beam are formed, and the slab above acts as a concentrated load in the opposite corner of the wall above, as indicated. The walls under the last slab in the analyzed building models show a tendency to fail due to crushing of the compressed edge. Due to crushing, the rotation is not expressed because the wall adapts to the deformed shape of the beam. If the beams above the opening are reinforced for the gravity load only (which is usual), they are not able to resist the imposed distribution, so the behavior of the model approaches the scenario shown in Fig.2d. If, on the other hand, the building is analyzed as a frame system, these beams are usually designed as fixed. The diagram shown in Fig.6b corresponds to certain moments if we ignore the hatched part of the wall where the moment sign change occurs.

For frame structures where nonlinearity is analyzed, it is common for plastic hinges to appear at the ends of the beams. An analysis of this kind shows that due to the opening in tension and crushing hinges, the appearance of hinges in beams can also be expected in parts of the beam that continuously pass through the wall, and that the position of the plastic hinge in the beam is not known in advance and depends in many respects on the behavior of the wall. On the other hand, the slabs, which can take over the shown redistributions, in many ways affect the walls through a change in the intensity of the normal force in the wall, and indirectly thereby also on the bearing capacity of the wall to transverse forces, because this bearing capacity depends on the intensity of the normal force in the wall.

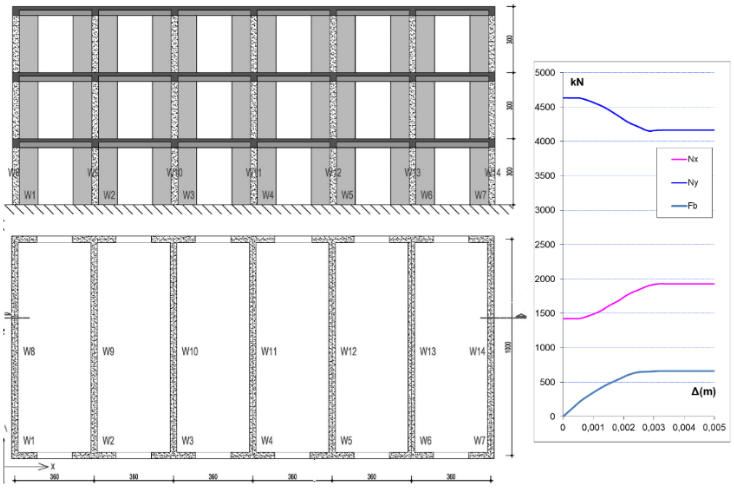

Figure 7. Building, normal forces in walls, capacity curve.

It is clear, for the building shown in the previous figure, that the main bearing walls are in the y direction. The walls in the x direction take about 23% of the total gravity load. The Nx-Δ curve shows the total normal force in all x-direction walls, and the Ny-Δ curve shows the total normal force in all y-direction walls. By following the steps of the pushover analysis, an interesting change of the normal forces in the structure is observed, which occurs due to the cooperation of all the elements of the structure. By rotating the walls in the x direction, they act on the slab tending to lift it up. The slab mainly rests on the walls of the y direction, so lifting the slab reduces the normal force in the walls of the y direction. As the total gravity load is constant for the entire pushover analysis, there is an increase in the normal force in the x direction, which in the last steps of the pushover analysis takes over by redistributing almost 32% of the gravity load. Previously, in Figure 1c, the coupling of forces that occurs during linear

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analysis of frame structures was mentioned, so in the left wall a decrease in the normal force was registered, and in the right an increase. At the beginning of the non-linear analysis, this trend exists only in the first steps for the edge walls W1 and W7, so that after the joints are opened and the wall is attached to the slab during rotation in all walls in the x direction, the normal force will increase.

The Fb-Δ curve in Figure 7 shows the building capacity curve. Independent calculations in 3MURI [6] and MINEA [7] software yielded consistent results. By using specialized software for masonry structures, these effects remain unnoticed by the user.

5. Conclusion

Masonry structures are not even a system of interconnected walls, and especially not frame systems. Their behavior is somewhere between these two models. The common design approach of analyzing buildings as a system of walls separated from the structure and connected to each other by axially rigid RC slabs gives unrealistic wall stresses because a certain frame effect certainly exists. This effect is partly investigated in the paper. To what extent it will be realized depends on many factors, the most important of which is the rigidity and load-bearing capacity of the slab.

In addition to this effect, by modeling step by step as briefly described in the paper, many other interesting features can be observed that remain hidden by using specialized software for masonry structures. The disadvantage of the approach is that it takes considerable time to analyze the specific building, so the approach can be applied mainly for research purposes. Finally, we must say that from the point of view of usability, these scenarios are questionable, and that in the case of the errection of new buildings, much more attention should be paid to proper general design than the numerical proof of load-bearing capacity.

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