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NUMERICAL PROCEDURE FOR EVALUATING THE INTERACTION BETWEEN MASONRY AND REINFORCED CONCRETE STRUCTURES

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ABSTRACT

The so-called arch effect is very important for evaluating stresses and internal forces at interfaces between structural masonry and reinforced concrete structures. The arch action induces stress concentrations in stiffer regions and relief where the stiffness is lower. This can be harmful for masonry over the supports however it may cause a significant reduction in the internal forces of concrete beams, mainly the bending moments. This paper presents a proposal for a numerical analysis procedure for the masonry/concrete interface using the finite element method. Its main feature is to be suitable for design purposes because it is simple and can be run on small computers. Despite its simplicity, the obtained results are adequate in terms of simulating the stress concentration on the masonry walls and the internal force reduction in concrete beams. Initially, some concepts of the arch effect and the theoretical basis for the proposed analysis procedure are presented. Afterwards, some details on the design of this kind of structure are discussed in order to highlight the main aspects that should be observed. Finally, results for three residential building cases are presented, emphasizing the differences obtained between the proposed procedure and the usual way of considering the structural masonry and reinforced concrete interaction.

KEYWORDS: arch effect, structural interaction, Finite Element Method, structural masonry.

INTRODUCTION

Nowadays there are a number of masonry buildings supported by reinforced concrete floors or by beam foundations over piles. The idea of interaction between the masonry walls and the Reinforced Concrete (RC) support structure is intuitive. Wood [1] described the wall/beam composite behaviour as a tied arch, where the beam is the tie and the arch is formed inside the wall. The arch becomes evident when the height of the wall is at least 60% of the beam span. Stafford Smith and Riddington [2] found that the minimum height/span ratio of the arch is 0.70. Tomazela [3] confirmed this former result based on numerical analysis of composite structures.

Arch action is very important because, according to the height/span ratio of the arch, the numerical modeling of the masonry walls, with the aim of studying the composite action, can be limited to the region between the first and second floors. Based on usual building dimensions, the distance between two consecutive floors is close to 2.80 m. Taking into account Wood's assumption for the height/span ratio, the beam should have a span of up to 4.67 m to maintain the simple hypothesis.

FINITE ELEMENT MODELING

The study of actual buildings allows for the evaluation of usual design situations which might not have been considered in theoretical work. For instance, the cases of walls supported by continuous beams or by beams that intersect other beams on the same floor. The aim of the present analysis is to verify the differences between the results related to the usual design approach that considers the wall's loads directly on the RC beams, and to the proposed one that considers the loads on the top of the first floor walls (see Figure 1). The two alternative models from this point onwards will be called *Proj1* and *Proj2*, respectively, where the word *Proj* is short for the name of the analyzed building. Linear elastic behaviour is considered throughout this work and there are no contact elements between the walls and the beams.

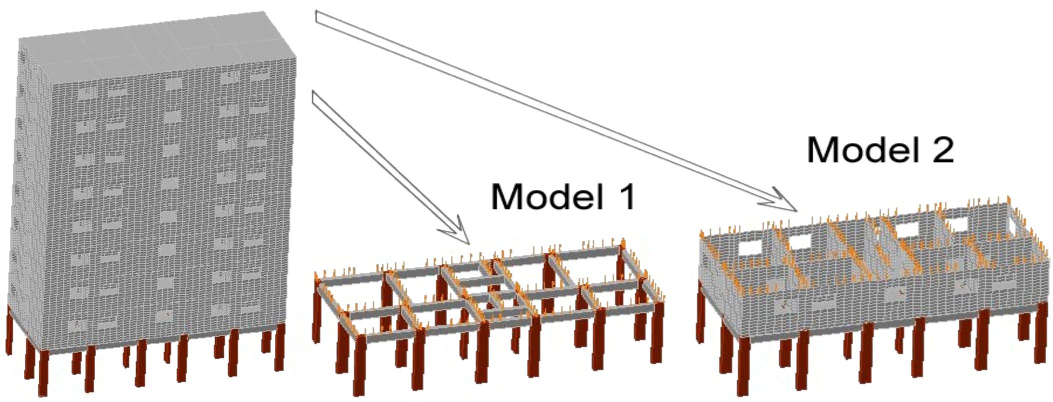

Figure 1 – Alternative Models

The RC beams and columns are simulated by BEAM Finite Elements with two end nodes and six degrees of freedom per node. The bottom ends of the columns are totally restrained. Concerning the alternative approach, the walls between the first and the second floor are simulated by MEMBRANE Finite Elements with four nodes and two degrees of freedom per node, including additional incompatible displacement modes to avoid shear locking. The computer program GMPAE, developed by Silva [4], automatically generates the FE mesh, based on the floor properties and the first course information. In both models the slabs are not simulated. The structural analysis is performed by the software LASER, developed by Ramalho [5]. Regarding the applied loads, all the vertical loads due to the entire building are considered, including dead and live loads for slabs and walls.

The analyses of three residential buildings are shown in the present paper, highlighting the influence of the arch-effect on the following results: internal forces in the RC structure, vertical normal stresses at the base of the walls and deflections in some of the beams.

CASE 1: LAGO AZUL BUILDING

The Lago Azul building is a seven story high masonry building. The concrete block-work walls are 0.14 m thick and 2.80 m high between two adjacent floors. Figure 2 shows a plan view of the

RC structure that supports the seven floors, superimposed by the first course of the walls, and a perspective view of the *LA2* model.

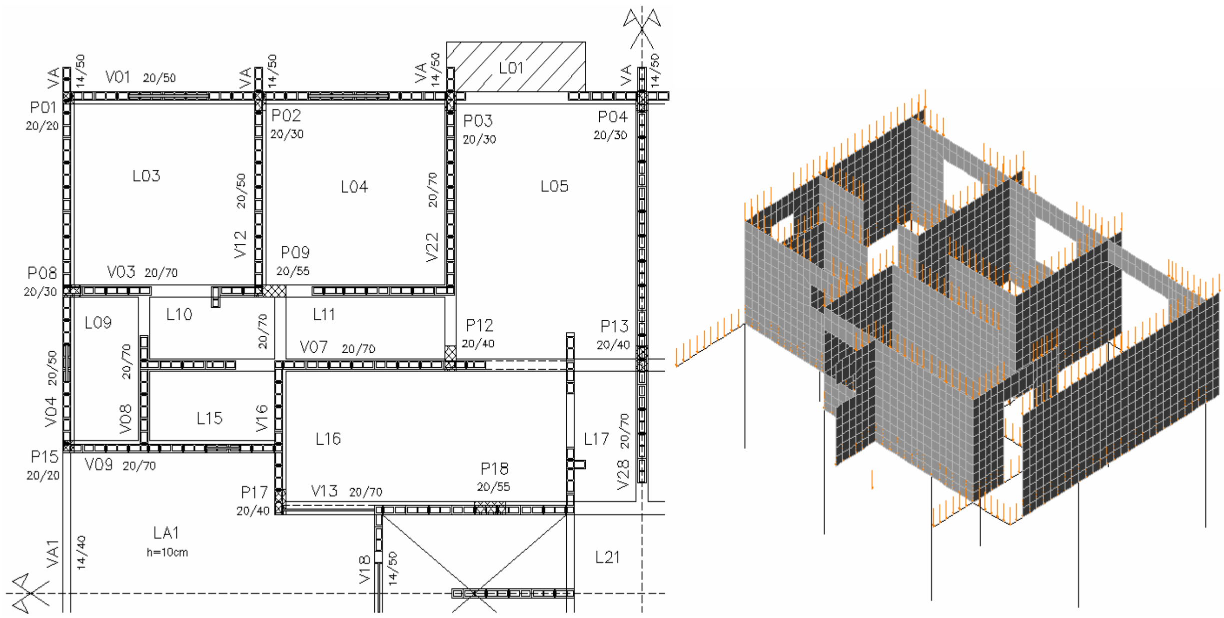

Figure 2 – Lago Azul Building

The analysis of beam V09 shown in Figure 2 illustrates how the arch-effect greatly influences the results when the wall has a length similar to the beam span. Note that the door opening near the end is small and interferes only slightly with the internal forces of the beam. Figure 3 shows the plot for the vertical deflections. Model *LA1* produces a maximum deflection that is 1/1475 of the span, while in model *LA2*, which incorporates the arch-effect; the ratio equals 1/4632.

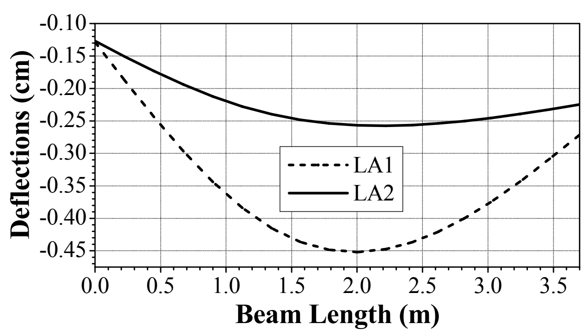

Figure 3 – Beam V09 - Deflections

In a traditional analysis, without the composite action, there is no induced axial force in the beam. However, when the model simulates the composite behaviour, axial forces appear due to the wall beam interaction. This is shown in Figure 4 for model *LA2.* The distribution of vertical normal stresses at the base of the wall is illustrated in Figure 4. Stress results are taken in the centroids of the first row of membrane elements near the beam. As expected, there are stress peaks near the supports, especially at the beginning, where there is a column. The small tension values near the middle of the span could be avoided if model *LA2* had contact elements at the interface wall/beam, in a non-linear approach. Obviously, the distribution of the same stresses is uniform for model *LA1*, with a gap under the door opening.

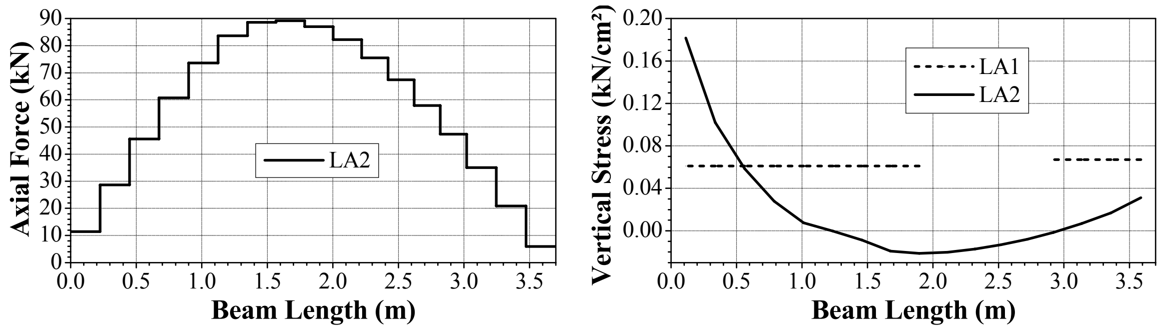

Figure 4 – Beam V09 – Axial Force and Vertical Stress

It is easy to note in Figure 5 that the reductions in internal forces are relevant not only for bending moments, but also for shear forces, which are usually considered to be less affected by the composite action. Thus, it is important to work with models that incorporate beams and walls together, in order to more accurately represent the distribution of internal forces in the structural system. Apart from better assessment of the internal forces and stresses in the whole system, it is possible to reduce the steel reinforcement required in the beams, by taking into account the arch-effect. This fact is verified by the large reductions in the internal forces of beam V09 provided by model *LA2* in comparison with model *LA1*.

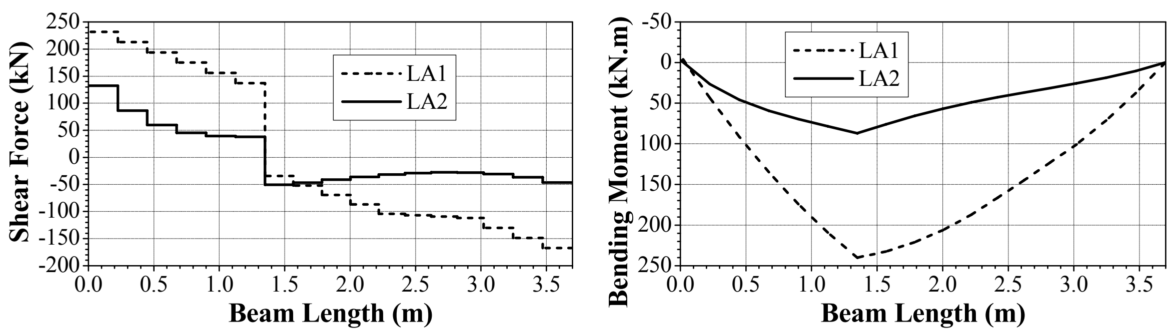

Figure 5 – Beam V09 – Shear Force and Bending Moment

The next analyzed beam is V28, which has a central span supported by two columns and an additional span that overhangs the P13 support. Figure 6 shows the deformed shape of the beam axis. In model *LA1*, the maximum vertical deflection occurs in the middle of the span between columns P13 and P04, while in model *LA2* that deflection reduces significantly, with the maximum result at the cantilever end of the beam.

Despite the predominance of tensile forces induced in the beams, there are some regions where compressive forces appear, as shown in Figure 7, over the internal support. These regions also correspond to the points of maximum compressive stresses.

As already mentioned, the arch-effect influence on the shear force reduction is less significant than on the bending moments (see Figure 8). The shear forces decrease along the span, keeping the maximum values practically the same near the supports. However, the reductions of the bending moments are evident, for both the positive and negative moments.

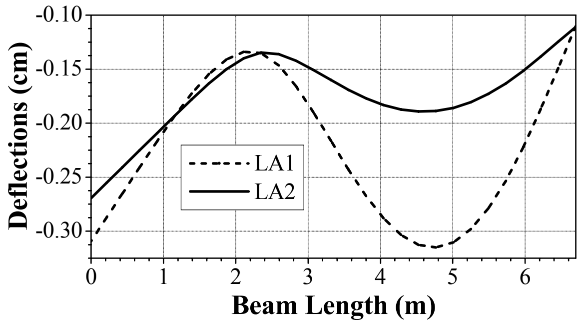

Figure 6 – Beam V28 – Deflections

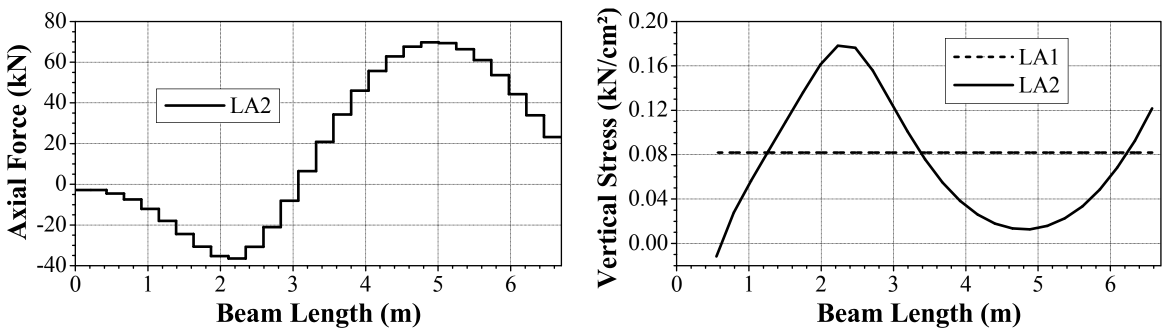

Figure 7 – Beam V28 - Axial Force and Vertical Stress

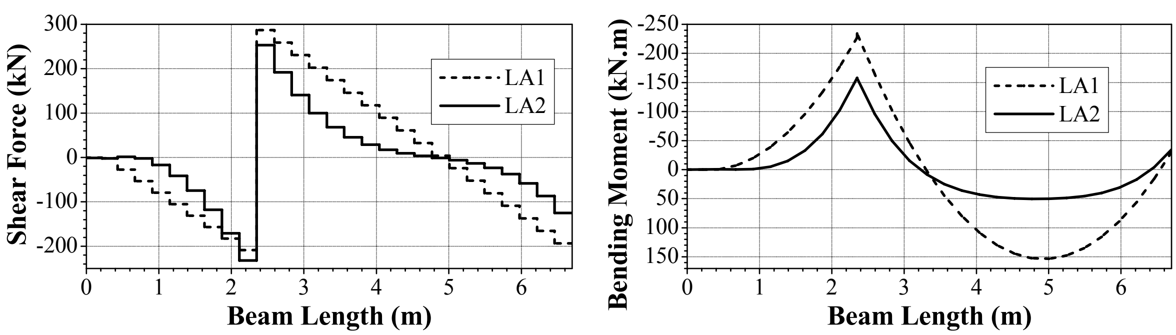

Figure 8 – Beam V28 - Shear Force and Bending Moment

CASE 2: LA DEFENSE BUILDING

The La Defense building has ten stories of RC slabs supported by masonry walls. The concrete block-work walls are 0.14 m thick and 2.72 m high between two adjacent floors. Figure 9 shows a plan view of the first course of the walls, superimposed by the RC structure that supports the upper floors, and a perspective view of the *LD2* model.

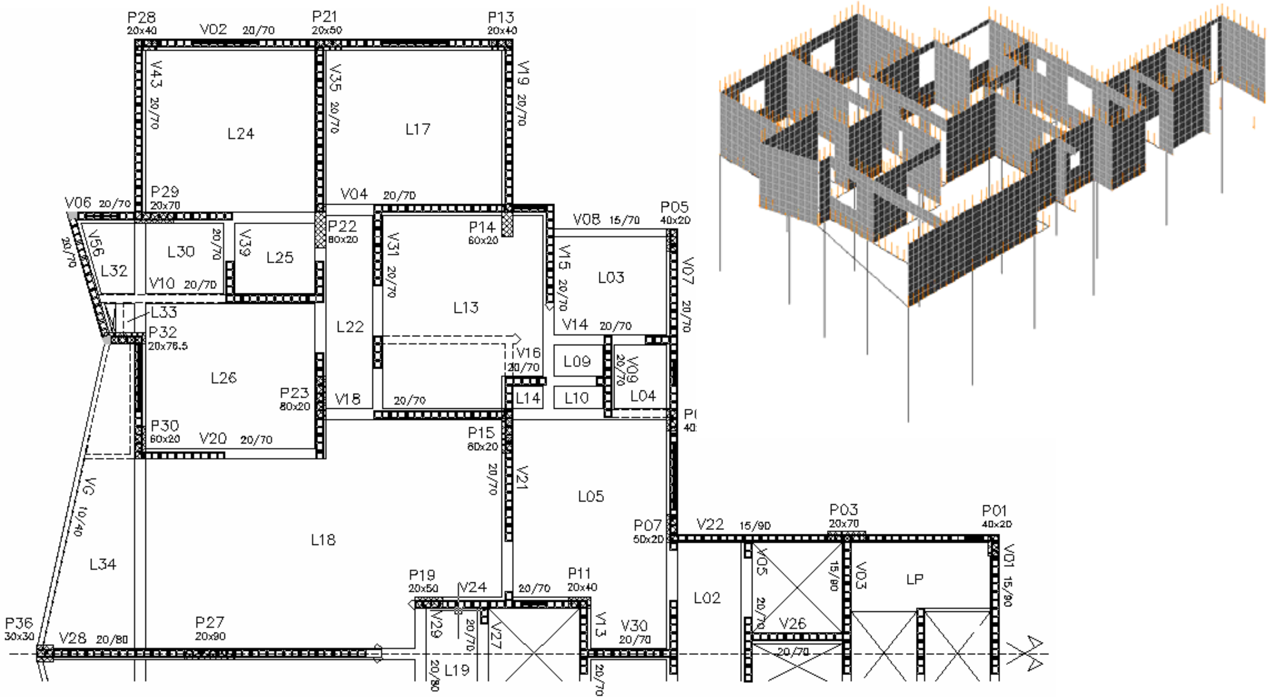

Figure 9 – La Defense Building

Beam V43 shown in Figure 9 supports a masonry wall with no openings over the first span (between columns P28 and P29). There is a small window opening in the wall over the length between P32 and the intersection of the beam with V20. The smallest vertical deflections occur between P29 and P32, a region with no wall, as shown in Figure 10. Despite being loaded only by the first floor slab, the first span between P30 and V28 has the largest deflections, as can be seen in Figure 10.

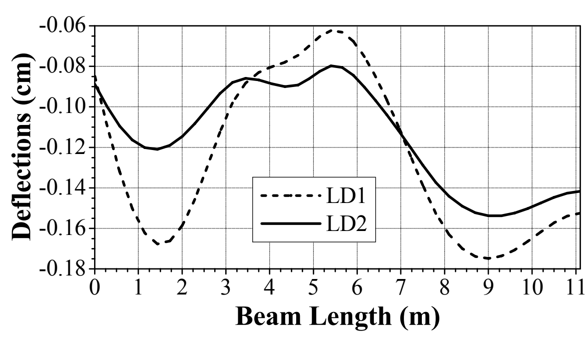

Figure 10 – Beam V43 - Deflections

The analysis of the axial force diagram (see Figure 11) shows that the tensile results are relevant only in the first span. The region between P29 and V20 is totally compressed, and the rest of the beam exhibits small tensile forces. Taking into account the arch-effect (model *LD2*), there are stress concentrations over the supports, as observed at the beginning of the vertical stress distribution (Figure 11), related to the non-perforated wall over the entire first span. Note that large differences appear between P32 and V20 because the approach proposed in this work (model *LD2*) also includes the simulation of the wall portion below the window opening by membrane elements, which creates new paths for the stresses, not represented in model *LD1*. That is also probably the reason why *LD2* results are smaller than *LD1*'s near the end of the span.

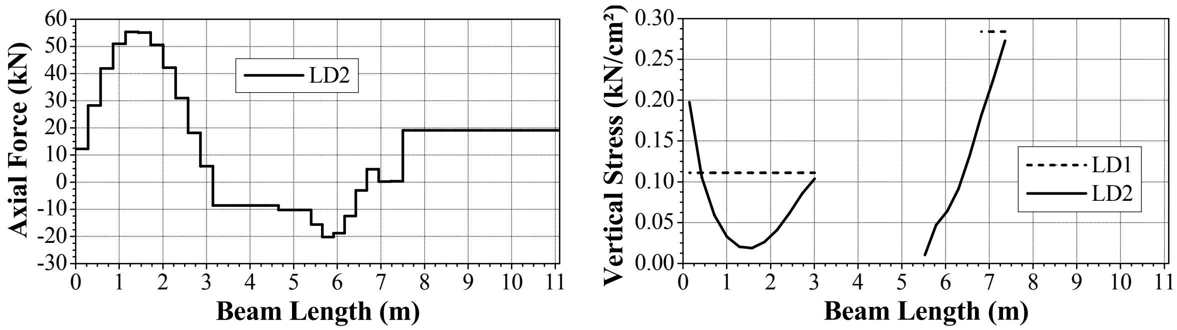

Figure 11 – Beam V43 - Axial Force and Vertical Stress

Figure 12 shows the shear force and bending moment diagrams of the same beam. The arch-effect has a larger influence on the span between columns P28 and P29. The shear force diagram is smoother for model *LD2*. Despite the lack of large reductions in the other spans, the decrease in the peak value over P30 is evident. The largest reduction of the bending moment also happens in the first span. The influence of the composite action is not as large for negative moments as it is for positive bending regions, as observed in the diagrams. Note that the results over column P32 are very close in the two alternative models. This analysis confirms that the consideration of the arch-effect is more relevant for positive bending moments.

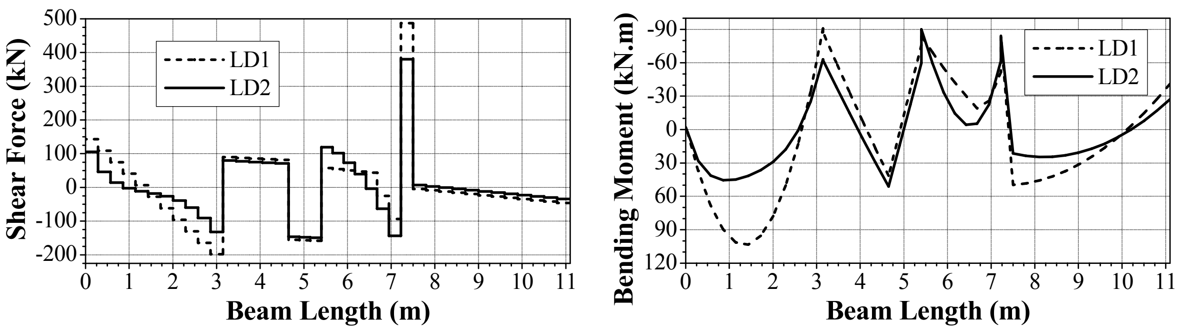

Figure 12 – Beam V43 - Shear Force and Bending Moment

CASE 3: CASA PARA TODOS BUILDING

The residential building Casa Para Todos is a fifteen story high masonry building. The concrete block-work walls are 0.14 m thick and 2.52 m high between two adjacent floors. Figure 13 shows a plan view of the RC structure that supports the fifteen floors, superimposed by the first course of the walls, and a perspective view of the *CT2* model.

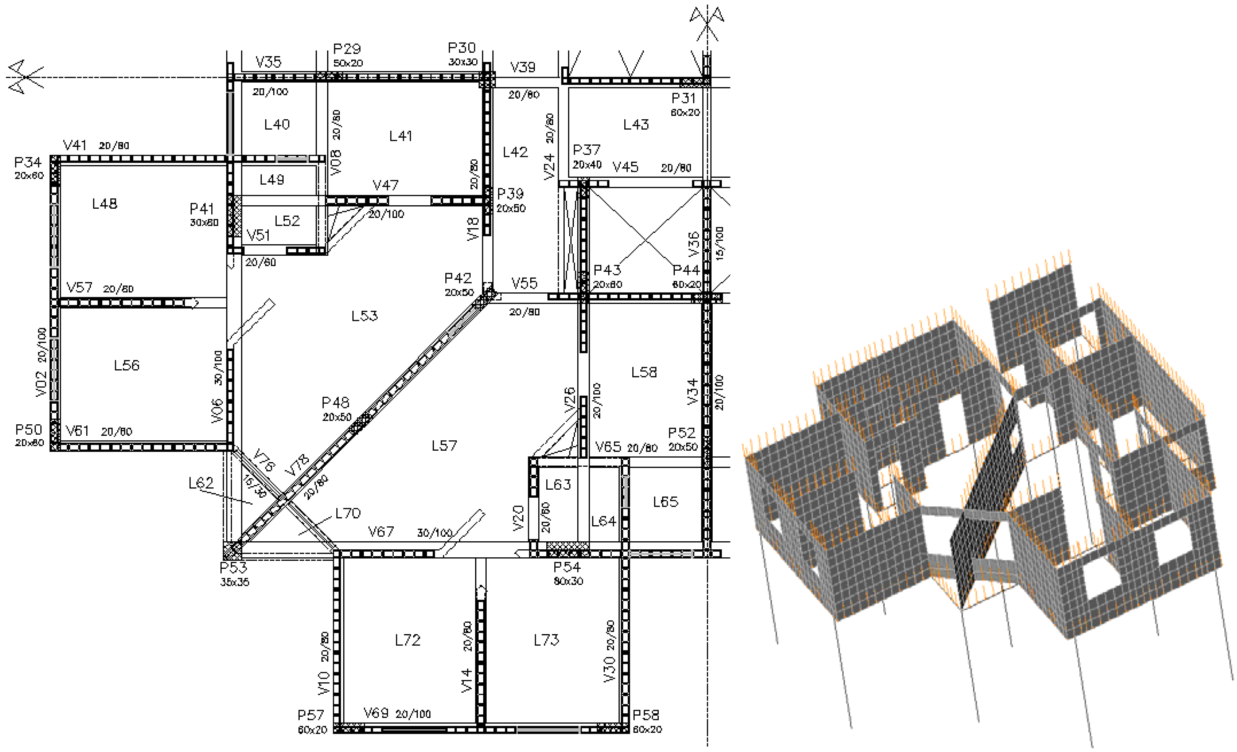

Figure 13 – Casa Para Todos Building

Beam V67 shown in Figure13 was chosen for the analysis in this third case, which includes vertical deflections and internal forces of the beam and vertical normal stresses at the base of the corresponding wall.

The influence of the arch-effect on the vertical deflections is clearly observed in Figure 14, even with the walls not spanning entirely over the beam. The largest deflections occur between columns P53 and P54, where the influence is evident. It is worth noting that the vertical deflections include the vertical translations of the top sections of the columns, as in the former buildings.

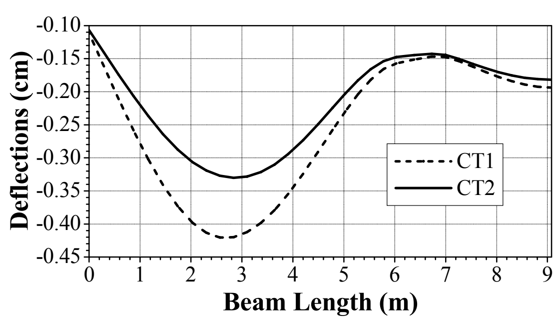

Figure 14 – Beam V67 – Deflections

Figure 15 shows the axial force diagram, where it is easy to identify the horizontal paths that correspond to lengths without walls. The largest values occur between V10 and V14. Note that the axial forces diminish over the columns. The null results near 6 m correspond to the support on P54. Note that in some cases (e.g. beam V28 of the first example) compressive forces appear at such places. Regarding the vertical normal stresses, the differences are small over P54, while the arch-effect leads to the increase of stresses at the wall between beams V10 and V14. Following the same tendency of the 2 previous buildings, the peak stresses in model *CT2*, which includes the composite action, correspond to almost double the stress produced by model *CT1*.

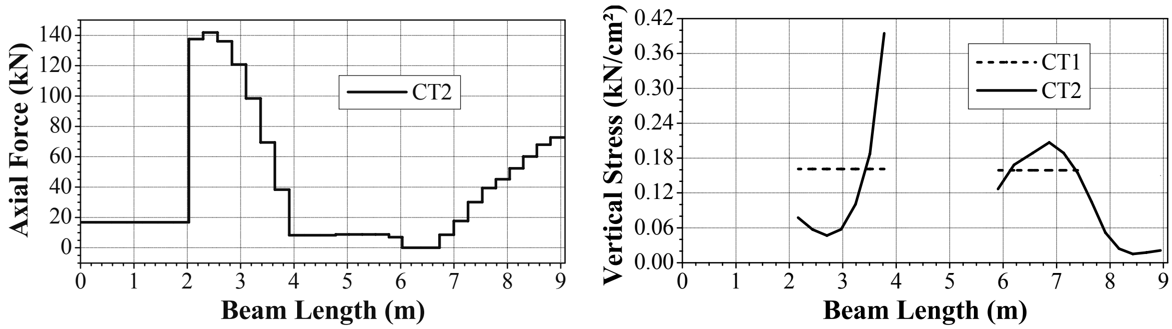

Figure 15 – Beam V67 - Axial Force and Vertical Stress

The influence of the arch-effect on the shear forces is small, as observed in Figure 16. The biggest differences appear between columns P53 and beam V14. Note that the peak values are nearly the same for both models. The differences in bending moments seem to be small because of the scale of the plot, however, considering the actual values, significant reductions corresponding to the composite action can be noticed. Once more the largest influence is in the positive bending moment regions.

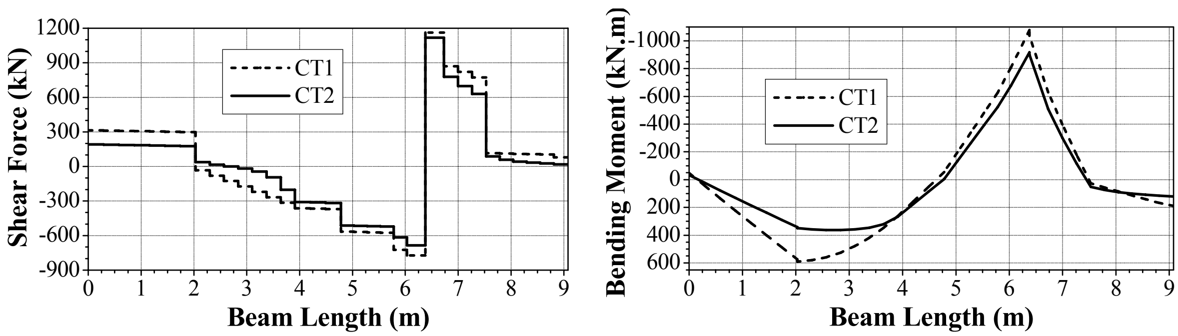

Figure 16 – Beam V67 - Shear Force and Bending Moment

CONCLUSIONS

This paper presents an approach to evaluate the influence of the arch-effect on the structural analysis of multi-story masonry buildings supported by RC beam/column structures. The proposed approach is simple and suitable for design purposes. The arch-effect is beneficial in terms of reducing the calculated deflections of the beams. The largest reductions occur in spans bounded by column supports at the ends. When the beam is supported by other beams, the analysis of the deflections has to be more meticulous, because the differences between the results obtained with the two alternative models can be very small.

Models that take into account the wall/beam composite action allow for the assessment of axial forces induced in the beams. In a wall/beam system, the beam works as a tie while the arch is formed inside the wall. In the examples presented, there is a predominance of tensile forces in the beams. However, in some parts of the beams, not loaded by walls or over column supports, there are compressive axial forces. In a traditional analysis, the loads of the walls are usually assumed as uniformly distributed on the RC structure. An approach that simulates the composite action, like the proposed one, which includes membrane elements to simulate one story high walls, allows for the assessment of stresses at the base of the walls. These stresses are relevant for designing the wall and for determining the loading on the beams. Another important feature is the possibility of representing parts of the walls below and over the openings, which becomes part of the structural system, and not only additional loads. The arch-effect reduces the normal stresses at the middle base of the walls. Nevertheless, it causes significant increases near the stiffer supports (nearly twice the results obtained with the traditional approach in the analysed beams). The proposed approach provides a simple way of evaluating these stress concentrations, which actually appear in the structural system, as many experimental studies have shown [1,6].

The influence of the arch-effect on shear forces was the hardest one to determine in the present work. The other results showed some regularity in most of the cases. To sum up, the composite action produced some reduction in shear forces in many cases, especially in parts of the beams between two supports. Over the supports the benefits of the arch-effect were nearly irrelevant in most cases. However, there was no clear tendency, since beam V09 of the Lago Azul building had significant reductions of the shear forces even over the column supports. The most significant effect of considering the composite action is the reduction in the bending moments in the beams. According to the observed reduction of the results, mainly in the positive bending moments, a large decrease in required reinforcing steel can be obtained when considering the composite behaviour. Minor reductions also appear in the negative bending moments in some cases.

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