Protagonism of the Infill Walls on Seismic Performance of Venezuela Buildings

A.J. Urich & J.L. Beauperthuy
B.R.S. Ingenieros, C.A., Caracas, Venezuela

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SUMMARY:
The predominant structural system used in Venezuela is the reinforced concrete frames with masonry infills. It is still common that structural engineers underestimate those masonry walls' stiffness, strength and fragility, considering them only as a permanent weight and seismic mass. However, the assessments of buildings damaged by recent earthquakes have left in evidence that masonry walls, especially infills, are the protagonists of seismic performance. Masonry walls are initially much stiffer than frames; therefore, when buildings are exposed to a seismic shake, the first pulses are resisted entirely by the infills, with minimal contribution from the main structure, which enter to play only after walls become broken; consequently, all the drift demand is concentrated in the building's stories or regions whose walls are the first to fail. The partially broken walls are used to cause a "soft story" and "short column" mechanisms that did not exist in the original configuration of the building.

Keywords: Infill walls, RC Frames, fragile failure, soft story, short column.

1. INTRODUCTION

Venezuela is located on the north edge of South America, adjacent to the Caribbean Sea. Most of the population of the country lives in zones of moderated to high seismicity due to a system of faults extended throughout the Andes Mountains and The Caribbean.

Since the decade of the fifties, the country´s expanding population has required the construction of a huge quantity of middle to high-rise buildings. For those buildings, the most popular structural system used to resist seismic loads has been the reinforced concrete (RC) moment-resisting frames. It has prevail the tradition of building the internal partitions and facade walls using masonry, which has no structural function. In residential buildings masonry walls are used or seen almost exclusively; while in office and commercial buildings they are usually alternated with other techniques that employ more flexible materials.

The actual codes governing the analysis, design and construction of structural system, consider modern criteria of ductility and energy dissipation. However, these codes barely consider the influence of rigid non-structural infill walls in the structural performance of the buildings. It is still common to find projects based on models that consider masonry walls only as a permanent load (dead gravity weight) and seismic mass. The effect of infill masonry walls on the building´s stiffness and the deformation incompatibility between those non-structural walls and the frames are usually underestimated or not even considered at all. This philosophy of analysis and design has been influenced by the other countries, where it is common to build the non-structural walls with much more flexible and lightweight materials.

Recent major earthquakes that occurred in Venezuela, since Caracas 1967 until Tucacas 2009, have shown that the real protagonists in the seismic performance of the buildings were the non structural masonry walls, either saving them from damage in those areas whose intensity did not crack the walls or allowing large structural damages in those that, like fuses, sharply degraded its strength and stiffness. This kind of performance has been observed in other countries and has been discussed by many other authors (e.g. Saatcioglu et al, 2001; Ghobarah, 2004; Pampanin, 2006) but the conclusions about this topic tend to be still controversial, and the lessons seem to be misunderstood.

This paper presents some case studies of buildings with reinforced concrete frame structure, where it has been evidenced the tendency of buildings to perform with domain of mechanisms such as soft story and short column, which are induced, not only by the original configuration of the building, but also by the modified configuration once the infill walls starts cracking. We aim to share experiences gained through the structural assessment of various Venezuelan buildings damaged by seismic loads, whose conclusions are based on the semiotic analysis of each case. This is intended to promote the study and discussion of this subject by professionals, academics and government agencies in order to contribute to standardize and disclose the state of the art in this field and to reduce the vulnerability in Venezuela and other countries with similar building practices.

2. THE ROLE OF THE NON STRUCTURAL MASONRY WALLS IN VENEZUELAN STRUCTURAL ANALYSIS AND DESIGN

Until less than a century ago, the walls made of masonry were the main system used as the structure of buildings. This have gradually evolved towards the conception of a separated structural system, while the walls began to be considered only as internal divisions and facade cladding, without structural functions. This is how, since the decade of the fifties, structures based on RC frames have become popular, allowing its wide spread use in the construction of medium to high-rise buildings.

Figure 1. Venezuela typical buildings

Since the construction of the first buildings with RC frame structure, the criteria of analysis and design have been evolving, in particular with regard to seismic performance. Nowadays, it is promoted to build structures with large capacity of deformation in the inelastic range (ductility), in order to allow the energy dissipation in case of seismic loads. Generally, it is admitted that the structures can reach inter-storey drifts as high as 20‰. In this regard, it has to be understood that allowing those large deformations, it will always be implicit the acceptance of major damage to the structure and to the non-structural components of the building. An adequate philosophy of analysis and design should control these damages in order to achieve two fundamental objectives: first to save lives and second, to minimize economic losses.

Figure 2 shows schematically some concepts used in the analysis and design of structures in seismic countries: the left figure shows the design spectra, which is associated with the seismic demand to be considered. It can be noticed that due to the dissipation of energy, slighter spectral accelerations (inelastic spectra) are needed for the analysis; the central figure shows how inelastic behavior is considered, the dotted line reflects the loads which would be required in case of elastic behavior, without energy dissipation, while the solid line shows the inelastic ductile behavior, allowing smaller design loads; finally, the right figures represent the philosophy of analysis and design using a model, showing how people could feel safe in a high-intensity earthquake, because even though the structure is expected to be damaged, people would stay alive. The solid lines and the red dots of the figures represent the inelastic ductile performance and therefore, the occurrence of damage to the structure.

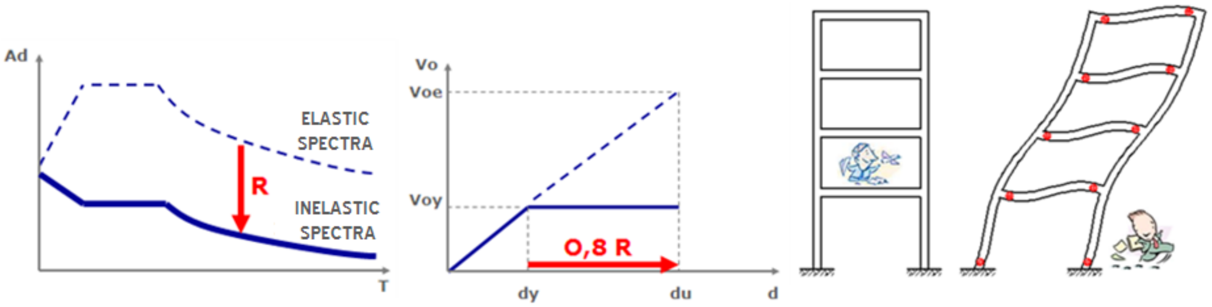

Figure 2: Schemes of some general concepts and the philosophy of structural analysis

To achieve a ductile performance the structure must accomplish a number of very strict design and detail requirements which are not pretended to be develop here. One of these requirements which will be the center of attention in this occasion is the need to avoid the interaction of the structure with other components that may restrict its free deformation. The current codes are probably too shy in their recommendations in this matter, but they are wise in their warnings.

However, in most of the projects currently developed in Venezuela, structural engineers continue dragging the habit of ignoring the stiffness and strength of the infill masonry walls in structural analysis and design. The infill walls are taken into account for their contribution as weight and mass in the calculation of the gravitational and seismic loads and they are very rarely considered as components that modify building’s strength and stiffness. Figure 3 shows the typical schemes of how the walls are usually considered in models.

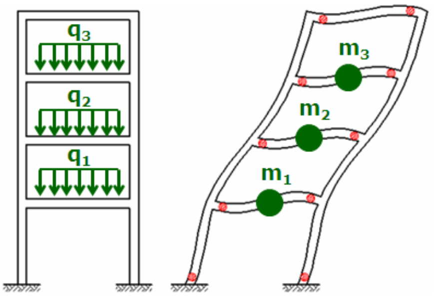

Figure 3: Diagrams of how the walls are usually considered in models

3. COMPATIBILITY OF DEFORMATIONS

The masonry walls and the RC frames perform very differently to lateral forces. The masonry walls are initially much more rigid than frames. However, their behavior is highly erratic and fragile, as they sharply decrease their stiffness and strength when cracked at relatively low deformations (drifts). Instead, the RC ductile frames are much more flexible than the masonry walls and support large inelastic deformations. This behavior is shown in Figure 4.

Generally, infill masonry walls begin to crack at distortions on the order of 1‰ and degrade almost all its strength and stiffness before reaching distortions on the order of 6‰; Instead, the typical RC ductile frames reach close to 2‰ distortion without cracking, while significant cracks occur after the yield of the steel, typically exceeding 4‰ distortions, to finally achieve greater than 20‰ distortion without significantly degrading their strength and stiffness. Another important difference is that the masonry walls tend to develop a shear shape, while in the structural members of the frames dominate a bending behavior tending to adopt an "s" shape.

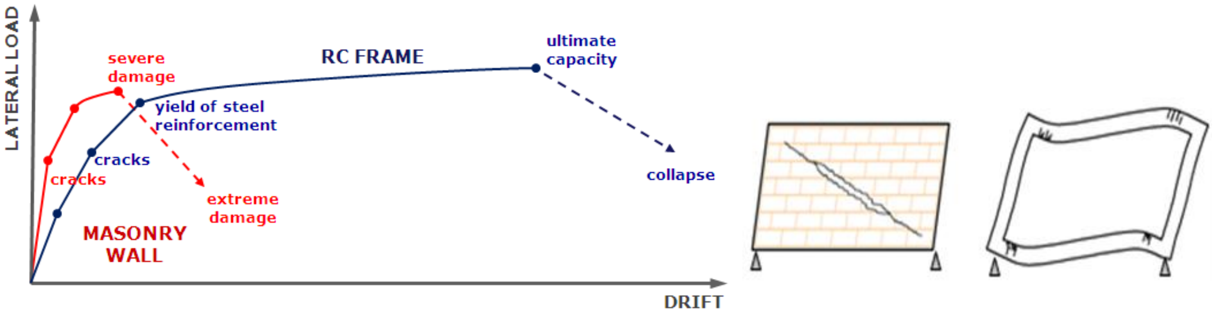

Figure 4: Typical force-displacement diagrams for masonry walls and RC ductile frames

The fact is that when both sub-systems, infill walls and RC frames are exposed together to seismic excitation, floor slab as diaphragms will force them to experience the same drift at all times, therefore, the infill walls and the frames interact and compete to dominate the structural performance. In this process, the lateral capacity will never be the algebraic sum of each subsystem´s capacity, because infill walls and frames reach their maximum strengths at different levels of distortion or drift.

The first seismic pulses are almost entirely resisted by walls with minimum contribution from the main structure, which comes to play only if the infill masonry walls are cracked and their strength and stiffness are degraded. If the strength of the infills is relatively high with regard to the frames´ structural members, then in practice, the system behaves as a masonry wall; in contrast, if the strength of the frame is the dominant, the main structure could behave as expected, but the damage in the infill walls will be major.

In most of the cases there is no absolute domain of the infill walls nor of the frames through the entire building, but in some areas or inter-stories prevail the walls and in others the frames, promoting irregularities and discontinuities in the stiffness which are highly injurious. When this occurs, the drift demand is concentrated in some stories or building regions that do not have infill walls or those whose infill walls are broken first, while the rest behaves almost as a rigid body, generating mechanisms of "soft story" and "short column", among others.

4. THE SHORT COLUMN AND SOFT STORY MECHANISMS

Some of the irregular configurations that are identified as more harmful in all the literature about buildings´ seismic design are the effect of short column and the soft story, generated by the discontinuity of rigid non-structural walls.

The short column mechanism consists of a partial constraint of a column´s body, which forces to concentrate all the deformation demand and stresses in its free portion. The most common case occurs when there are walls that do not cover all the height but they leave an empty space for a window. It is also known as captive column effect (Figure 5, left).

The soft story mechanism is when the lateral stiffness of one inter-storey is considerably lower than the adjacent ones. This configuration induces to concentrate the deformations demand and stresses in that softer inter-storey structural members. The most common case occurs when there is discontinuity in the walls, typically at many buildings´ first floor to allow parking areas (Figure 5, right).

If we look at both cases it can be identified that they are practically the same, a structural member or a structural system that is designed to distort freely in its entirety length but due to restrictions imposed by other non-structural components, is forced to concentrate all the deformation in only a portion of its total length.

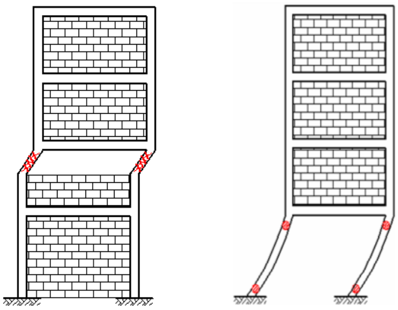

Figure 5: Short column and soft story mechanism

Figure 6 shows an example of the effect of short column, in a building located in Cumaná, about 70 km away from the epicenter of the Cariaco Earthquake, Mw=6.9, occurred in 1997. It is evident the severity of the damage and the great levels of deformation experienced by the free segment of the columns.

Figure 6: Effect of short column generated by reinforced concrete planters

Figure 7 shows a recent example of the soft story mechanism due to the absence of infill walls at the first storey that occurred in Tucacas, about 50 km from the epicenter of an earthquake of magnitude Mw = 6,2 on September 12, 2009. In this case, all the columns experienced severe damages by compression due to bending. It is important to note that no damage did occur at beams, since the presence of infill walls did not let them develop its typical bending shape, although beams where softer than columns if considered without the infill wall restrictions.

Figure 7: Typical soft story mechanism at free story

During that same earthquake, there was an extreme case, which combined both short column and soft story mechanisms. In this case, as shown in Figure 8, the building was banned immediately after the earthquake due to their precarious status.

Figure 8: Free story and short column effect

5. THE “INDUCED” SHORT COLUMN AND SOFT STORY AFTER THE INFILL MASONRY WALLS ARE DAMAGED

Previously, the short column and soft story mechanisms were commented as they are traditionally treated and widely referred to in the literature. However, these conditions are not always obvious in the original configuration of the building; even if the infill walls are continuous in all stories or throughout the whole column height, they can induce these mechanisms if they are partially broken.

Figure 9 shows a case occurred during Tucacas´ 2009 earthquake. There was no evidence to predict the short column effect prior to the earthquake. However, as shown in the figure, the “induced short column” effect was generated after the partial fail of the masonry units of the wall throw the half top of the column.

Figure 9: Short column mechanism induced after partially fails of partitions

Similarly to the example above, Figure 10 shows how an “induced soft story” mechanism that was not evident before the earthquake occurrence can also be promoted. In this case, the severely damaged walls sharply degraded its stiffness and strength inducing the same behavior that occurs when, by the original configuration, there were no walls at the first floor. The figure shows the severity of the damage of infill walls at the first storey, which corresponds to a considerable drift level, whereas the higher inter-stories have no damage, reflecting a minimum distortion.

Figure 10: Soft story mechanism induced after partitions fail

Another case of a building located in Cariaco, at a short distance from the epicenter of the 1997 earthquake (Mw=6.9) is shown in Figure 11. This building was not damaged, neither the superstructure nor the walls. In fact, the superstructure behaved as a rigid body. In this case, all the deformation demand induced by the earthquake focused under the supposed base level. This situation occurred because of the presence of very soft soils, where the upper portion of the piles acted as columns, displacing the building base level to an elevation lower than expected. Then, an "induced soft story" appeared in the upper portion of the piles, which in addition behaved as short columns.

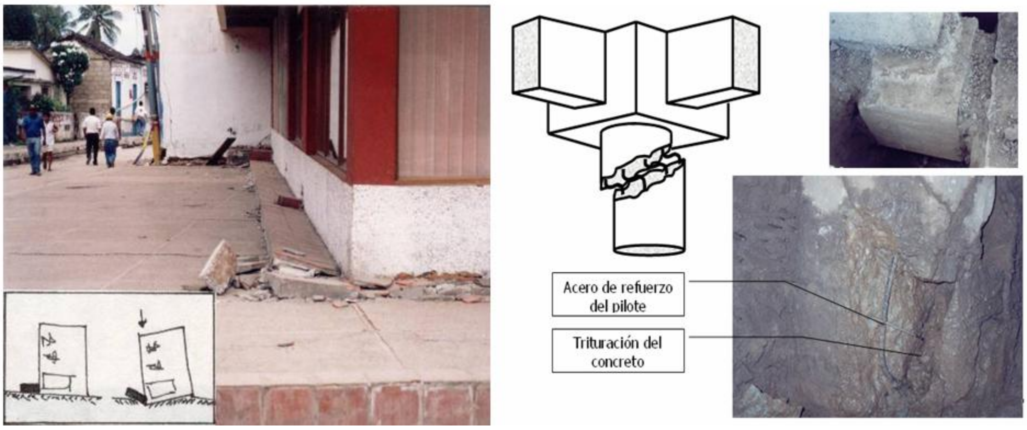

Figure 11: Failure of foundation system and drift concentration under the restrained level

6. RISK OF INJURY FROM COLLAPSE OF INFILL WALLS

Figure 12 shows how the infill walls, not only modify the structural response, but often can cause by themselves serious injuries to the occupants of the building during their cracking and collapse, which could represent a mortal danger during earthquakes.

Figure 12: Risk of injury from fall of infill walls

7. THE OBSERVED PERFORMANCE SCHEMES

The performance of the buildings that has been described in the preceding paragraphs can be represented by the schemes shown in Figure 13. There are identified the following behaviors: (a) typical performance expected with free deformation of structural members; (b) soft story (ground free storey) in the building´s original configuration; (c) short column effect in the building´s original configuration; (d) induced soft story after the partial fail of the infill walls; (e) induced short column effect after the partial fail of the infill walls; (f) induced soft story below the ground level after the failure of the foundations; (g) widespread damage and collapse of infill walls subjected to large deformations.

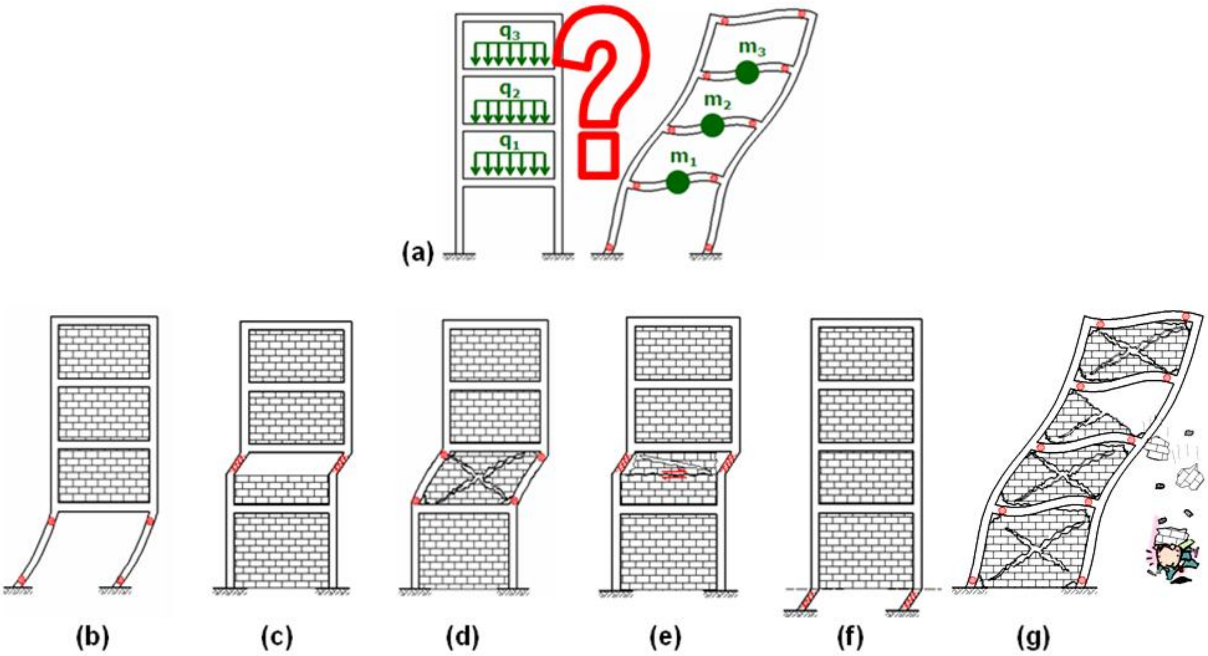

Figure 13: The observed performance schemes

8. VENEZUELAN CODES RECOMMENDATIONS RELATED TO NON-STRUCTURAL INFILL MASONRY WALLS

Even though Venezuelan standards are very timid in the regulation on the possible influence of non-structural components in the performance of the building, never cease to warn its importance. There can be cited some considerations such as: "non-structural components that may restrict the deformations of the structure… shall be approved… by the structural engineer "(Covenin 2002, 1988); "particular attention must be paid to the possible interaction of the bear structure with the partitions."(Covenin 1756, 2001); "it must be considered the effect of rigid elements, structural or not, that may affect the dynamic response"(Covenin_1753,_1987); "it must be taken into account the influence of the non-structural partition in the performance of the structure under lateral forces" (Fondonorma 1753, 2006); with regard to the soft story "in the calculation of the stiffness there will be included the contribution of the partitions"(Covenin_1756,_2001); with regard to the weak inter-storey "in the evaluation of the inter-storey strength it has to be included the contribution of the partitions"(Covenin_1756,_2001); "The contractor should not build components or non-structural elements which are not referred to in the project..."(Covenin_1756,_2001); among others.

As can be seen, the problem is not that standards underestimate the influence of the walls. It is that the users of these rules probably have not yet adapted to the criteria reflected on them. The traditional inertia coming from the old generations of structural engineers apparently is stronger than the actual codes regulations.

9. CONCLUSIONS

The assessment of various buildings conditions after some recent earthquakes in Venezuela has shown that unacceptable damages have occurred in many formal buildings of recent construction; those damages have been induced by seismic shakes far below those covered by the standards used in their projects. What could be the reasons for that? There is never a single one, but the overlap of a cluster of defects in the configuration, the design or the construction. However, the common issue has been the concentration of deformation demand in a few structural members due to the influence of non-structural masonry walls, sometimes due to the original configuration and others induced by the prematurely break of the masonry units.

The current codes warn about the vital need to consider the influence of non-structural components in the structural performance, in particular rigid masonry walls, recommending that they must be isolated or that they have to be incorporated in the analysis and design as part of the structure. Despite these warnings, there is still the tendency of dragging the inheritance of considering walls in models only for their weight and mass, underestimating their stiffness, strength and fragility, which occasionally leads to the soft story and the short column mechanisms, among others.

The reason is that there is no compatibility in the deformation between the structural frames and the Venezuelan typical infill walls, which are much more rigid than the frames they are in, but fragile and with erratic behavior. Therefore, in the buildings with structures based on RC frames, of medium height, very flexible, the first pulses of the quake are received purely by the infill walls, with minimal contribution from the frames, which begin their work only where there are no infill walls or where they are broken first, concentrating all the deformation demand in those sectors, while the rest of the building behaves, practically, such as a rigid body and does not participate in the necessary energy dissipation, throwing away the entire hypothesis considered in the seismic analysis and design of the structure.

Sometimes, at low intensity earthquakes, the infill walls have not even cracked and their presences have been favorable. It is clear that in these cases, due to the high stiffness of infill walls, buildings have experienced inter-storey drifts well below from those which can be inferred from an analysis of the structure without the constraints of the walls. However, must not be underestimated the vulnerability of these buildings to earthquakes of intensity exceeding the occurred, that to overcome the capacity of the infill walls could induce the harmful mechanisms already mentioned.

On the other hand, even if the structural frames dominate the performance over the infill walls, at the levels of drift that are being accepted today, damage to the masonry units would be of large proportions, including the detachment of fragments or an entire wall that can cause fatal injuries to people who are in the building or around it.

There is an urgent need to increase the study of seismic performance of Venezuelan typical buildings and rethink the criteria that are being used in its analysis and design. That is not only a Venezuela´s issue, but also an issue of many other countries with similar construction techniques. If there is pretended to continue using the infill masonry as building system for the non-structural walls, then the main structure will have to be much more rigid and resistant, so the expected drifts are compatible with the maximum that can be developed by the infill masonry walls. In any case, it must never be dismissed the strength, stiffness and fragility of the masonry.

To achieve better compatibility of deformation between the main structure and the non-structural masonry walls, the structural systems based on RC walls must be favored over RC Frames with infill walls, as it was showed in the performance of many buildings in Chile during the earthquake of the year 2010.

Finally, the key is facing the need of verifying the deformations compatibility of all structural members, non-structural components and materials used in the building´s construction. It must be kept in mind that earthquakes are implacable inspectors that will always reveal if this verification has been properly done.

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