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MUISNE, ECUADOR 2016: ONCE AND AGAIN RELEARNING ABOUT THE ROLE OF THE MISCALLED "NON-STRUCTURAL" MASONRY WALLS

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Abstract

A magnitude 7.8 earthquake struck Ecuador on April 16th, 2016, severely impacting the Manabí province with intensities ranging 7 to 9 (EMS). This article summarizes the results of a reconnaissance visit to the affected areas, which had the objective of evaluating the roll of masonry partition in the overall performance of buildings.

The criteria in Ecuador codes and the typical building techniques are described; some examples of the observed performance in different buildings during the earthquake are analyzed, with emphasis on reinforced concrete frames with masonry infills. The brittle behavior induced by the masonry partitions, not only in old pre-code buildings, but also in recent buildings which were supposed to be ductile frames is discussed; it is shown how some very harmful typified irregularities, as soft/weak story, captive column, torsional plan, among others, may take place not only when they are evident in the original configuration of the building, but also because a modified configuration after the masonry units start being damaged.

Keywords: Ecuador Earthquake 2016; soft story; captive column; infill RC frames

1. Introduction

The masonry walls were the main structure of buildings until less than a century ago. This has gradually evolved towards the conception of an independent structural system, while the masonry units began to be considered only for internal divisions and facade cladding, without any structural function. Throughout this progression, structures based on reinforced concrete (RC) frames have become popular since the decade of the thirties, allowing its wide spread use for medium to high-rise buildings around the world. Nowadays, in seismic prone areas is promoted to build structures with large capacity of deformation in the inelastic range (ductility) in order to allow energy dissipation, which reduces the seismic design loads. Generally, it is admitted to reach inter-story drifts as high as 20‰. In this regard, it is understood that allowing those large deformations, there will always be implicit the acceptance of damage to the structure and to the non-structural components; the philosophy of analysis and design is to control these damages in order to achieve two fundamental objectives: first, to save lives and second, to minimize economic losses.

To accomplish a ductile performance of the structure, there are a number of strict design and construction requirements; one of them, which will be the main issue in this paper, is the need to avoid the interaction of the structure with other components that may restrict its free deformation. The current codes of many Latin American countries are perhaps too timid in their regulations on this matter. The fact is that masonry is still the first option as material for partitions and facades; unfortunately, many engineers are still dragging the habit of considering them in design only as weight and mass, ignoring their influence on the stiffness and strength of the structural system.

As a pitiless inspector, the April 2016 Ecuador Earthquake (7.8 Mw) sadly reminded that masonry partitions are not only weight and mass, contrariwise, they can play a leading role in the seismic-resistant properties of buildings. In this paper, some examples from Ecuador are discussed; there are shown the most common typified irregularities that might take place in the configuration of buildings, making emphasis in how even new structures, that were supposed to be "ductile frames", behaved as old (pre '70/'80) non-ductile frames because of brittle mechanisms induced by "non-structural" masonry infills. There is also shown how harmful mechanisms as captive column, soft story or torsional plan, among others, might take place not only where they are evident in the original configuration of buildings, but also in any other place if the masonry units start being damaged. In this document, the terms wall, infill, partition or facade are used indistinct for masonry elements that were not considered by designers as part of the structural system, unless expressly specified otherwise.

2. Background

The issue of the influence of masonry partitions in the seismic performance of buildings is anything but new, there are countless researches and publications related to this topic; however, it is still a controversial subject that involves more questions than answers. Nowadays, it is widely recognized that the presence of masonry partitions has been one of the main causes of severe damages and collapses during earthquakes, in some cases, even against light to moderate shakings. In the next paragraphs, some widely referred facts about this topic are summarized, including some references where can be deepen the mentioned statements.

- *Might carry both, positive and adverse consequences*: until the late 90s, even though harmful effects had been recognized, it had been also emphasized beneficial properties, as they can take a great part of the seismic loads; a good documentary collection is presented by Al-Chaar [1]. More recent studies [e.g. 2-10] insist that, for multi-story buildings, masonry partitions might be considered beneficial only for low-intensity earthquakes, while they do not crack; because from that moment on, performance can be erratic and dominated by fragile mechanisms, even for recent structures detailed according to modern codes.

- *Modify the structural properties:* the masonry infills alter the *natural period* and *damping*; also modify the stress transfer through the structural members, changing the domain of bending in frames for compression struts through the infills, which increases the axial forces in the columns, beams and foundations [11; 12]. Even if the walls are separated from surrounding columns and roof, they also stiffen the beams that support them, concentrating stresses in a very short length of the ends of these beams, which can force the migration of rotations to the column, discarding the concept of strong column weak beam [13].

- *They are responsible for the most harmful typified irregularities*, such as soft or weak story, the captive column and torsional plan [2; 10; 14]. Some authors have warned that *these problems may occur in places that are not evident in the original configuration of the building*, but appear unexpectedly when the walls begin to crack [4-7; 15; 16].
- *Models:* many mathematical models have been developed to incorporate the walls in the analysis and design [e.g. 17]: simple compression struts, multiple struts, finite elements, etc. However, they have not been sufficiently calibrated yet, and their results are not always consistent, especially for middle to high rise buildings [10].
- *Criteria in codes:* most international standards prescribe limited to two options: isolate the walls so they do not interfere with the structure, or they have to be included as part of the structural system. Some codes establish penalties for irregular structures, increasing the design loads or the capacity of the structures, usually between 1.15 and 4.7 times [12]. Another aspect considered in the codes is the minimum base shear. This criterion was incorporated from the late 70s to consider changes on dynamic properties due to the masonry walls, based on natural period measurements on buildings of that time [18], an approach that is still applied. Despite the foregoing, there is still no consensus and the issue is often misunderstood and underestimated, there is still lack of clear criteria in literature and international codes about how to model and design considering the walls, or how to isolate them from the structural system [5; 19].
- *Current Trends:* As mentioned above, it is still common to use "non-structural" masonry walls in many countries. Unfortunately, there is no awareness about the excessive flexibility of the structural systems promoted by the analysis and design codes and, in general, the influence of these walls is underestimated, which is an error [8; 20; 21]. Most of developed countries began to rule out the use of masonry walls in framed structures since the late 70s and early 80s; some standards refers to this system (infill frames) as a kind of old building, and only dedicate specifications for the analysis of existing buildings, but not to promote new constructions [22]. Many authors propose two alternative building systems: reinforced or confined masonry for low-rise buildings (up to 3 or 4 stories), or reinforced concrete walls for taller buildings [23]. Recently, it has been incorporated the term "framed infills" as an option for new constructions, this new expression is used to differentiate from confined masonry and from the negative connotation of infill frames; again, they are only endorsed for low-rise buildings [10]. Moreover, in Canterbury, home of Professors Park and Paulay, the tendency is to change their design philosophy developed in the 1960s, were the ductility means damage, for alternative cost-efficient solutions of high-performance low-damage structural systems, where such equivalence ductility-damage should no longer be considered an unavoidable compromise of a ductile design, neither for structural members, nor for non structural components and content [24].

3. Building codes and typical construction techniques in Ecuador

The current building codes in Ecuador consist of various documents issued in 2014 [25-28]. Being of the most recently published in Latin America, they are consistent to the state of the art in the Earthquake Structural Engineering of the region.

The criteria of these codes are quite similar to those of many other countries. For this paper, it is important to highlight that they consider pseudo acceleration response spectra reduced by an R factor, to allow elastic models; after the analysis, the inelastic drift (Δ_M) is calculated by the formula $\Delta_{M.}$= 0,75 R $\Delta_{E.}$; where Δ_E is the elastic drift obtained by the reduced seismic loads. For ductile RC Moment resisting frames, R varies from 7 to 8 and the allowed drift is 20‰, this limit applies to all structures except for masonry buildings that is 10‰. The preceding code [29] had the same drift limits. Another subject to mention, is that irregularities are penalized affecting the capacity generally by a factor of 0,9.

The most used structural system is the reinforced concrete moment resisting frames. As in many other Latin American countries, masonry partitions and facades are used; these miscalled "nonstructural" walls used to be included in models only as weight and mass for the calculation of gravitational and seismic loads. Most of the masonry units in the studied areas are hollow concrete blocks and handcrafted clay solid bricks (Fig. 1).

Fig. 1 – Typical RC frame buildings under construction and common masonry materials

4. Building performance inferred from observed damages

There is a close relationship between lateral forces, deformation and damage: for example, ductile moment resisting frames may achieve large drifts, exceeding the d/H= 20‰ allowed in Ecuador codes; they have no damages until drifts of 2~3‰, when first cracks appear; then the elastic behavior continues until yielding of reinforcing steel, usually at drifts between 3 to 5‰; after that point, the inelastic behavior starts increasing the damages ranging from moderate to severe, until collapse mechanisms may start after having exceeded 20‰. In contrast, the masonry partitions used to show up their first cracks at drifts as low as 1‰, starting at this point a degradation progress in their strength and stiffness dominated by brittle mechanisms, achieving severe damages until complete collapse, which may possibly starts at drifts from as low as 6‰.

When structural frames and masonry walls are together, they can performance in a wide range of different manner, which will be eventually dominated by the structural frames, but in many cases will be dominated by the “non-structural” masonry walls. Using these relationships between damages and the different levels of strength-stress-deformation (drift) of materials, structural members and non-structural components, it is possible to infer how the local and overall performance of a building was after an earthquake. For building structural pathologists, this semiotic analysis of damages and other symptoms are the key to route an accurate diagnosis on the condition assessment of structures, not only after earthquakes, but also on many other kind of distresses.

Some examples from Ecuador are discussed below; more details can be revised on the complete recognition report [30]. The figures show representative pictures of buildings and the probable sequence of interstory and global drift for each performance described. The examples included in this document emphasizes on recent buildings that were supposed to be ductile moment resisting frames, but behaved quite different than expected.

4.1 Ductile bare reinforced concrete frame

It's really hard to find totally bare frames in Ecuador, only a few buildings under construction in which the internal partitions have not yet built. In these cases, cracks in beams due to typical flexural plastic hinges were observed, as expected in ductile structures (Fig. 2) The damage shown in the picture is moderate, indicating that the building experienced probable drifts in the order of d/H= 6 a 10‰, at low-to moderate deformation after the yield strength of the steel but still far from the permissible drift of 20‰.

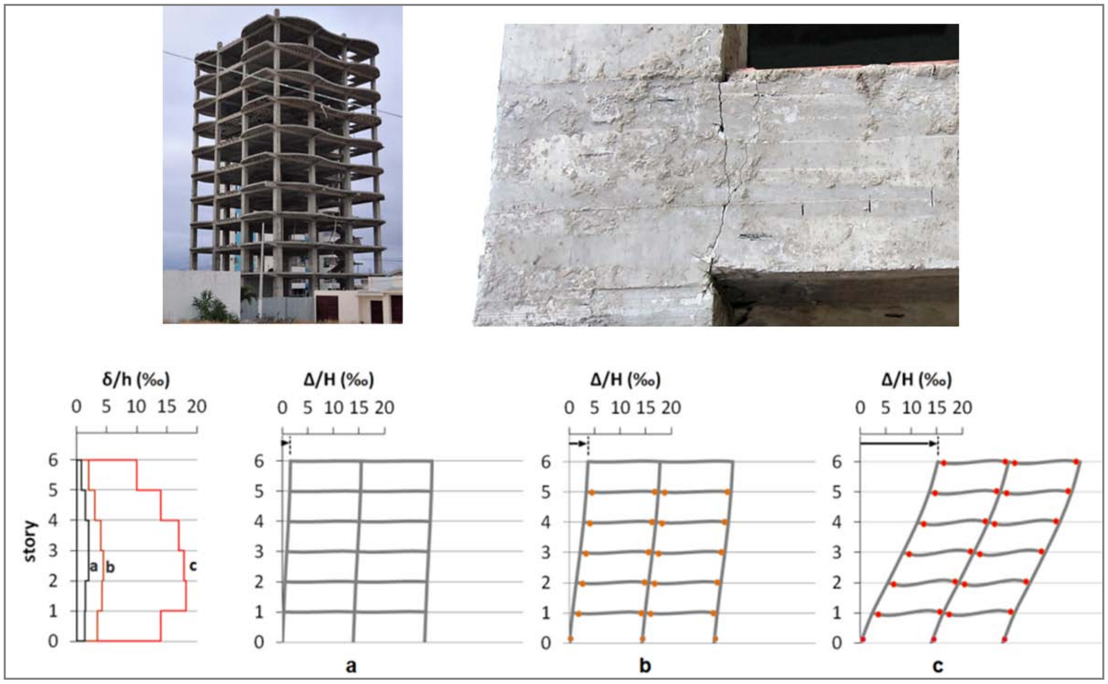

Fig. 2 – Performance of bare reinforced concrete frames

4.2 Captive Column

It is probably the biggest problem in earthquakes worldwide. The classic mechanism by the presence of walls that restrict only a portion of the column, leaving another free portion was observed; but the emphasis in this paper is in the many cases of captive columns in places where their occurrence was not predictable in the original configuration of the building, since the wall covered the entire height (Fig. 3). In these cases, the walls when partially broken, which usually is at very low drift (less than 2 to 3‰), induce the same mechanism as if a window would have been in this place.

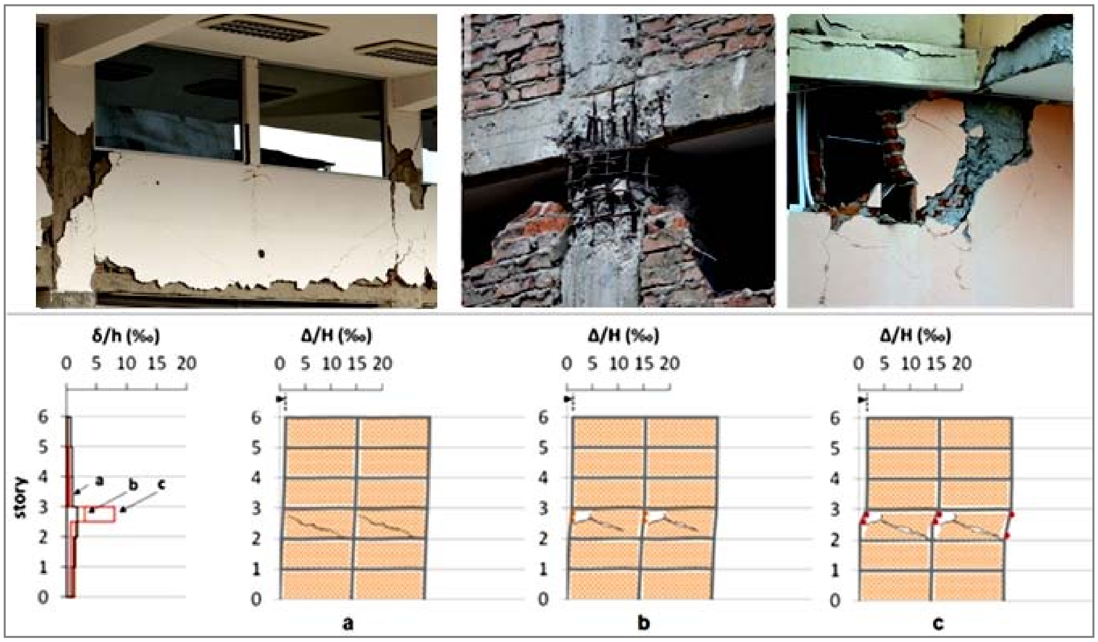

Fig. 3 – Captive column mechanisms

The classical explanation of the captive column is that the shear stress increases proportionally to the reduction of the clearance of the column, but this is not all that happens; in addition, the stiffness and the ductility are also affected, both local (structural members) and global (entire structure); even worse, all of the seismic demand is concentrated only in these columns, the shorter ones. Considering all these variables, a structure can be 20 times more vulnerable, or worse, than that with free columns. In fact, it is possible that the failure starts, not only at the large deformations imposed by earthquakes, but even at small deformations by variations in the ambient temperature. More details on these statements may be consulted in another paper by the author [31].

4.3 Direct transmission of the shearing failure from the wall to the structure

It is shown how the crack in the wall continues in columns or beams as if they were a structural unit instead of two different elements (Fig. 4). It is an extreme case of short column where the free portion tends to zero once the walls are cracked. In the case of horizontal structural members is a sort of captive beams or slabs. These problems may start at drifts as low as 1 to 2‰.

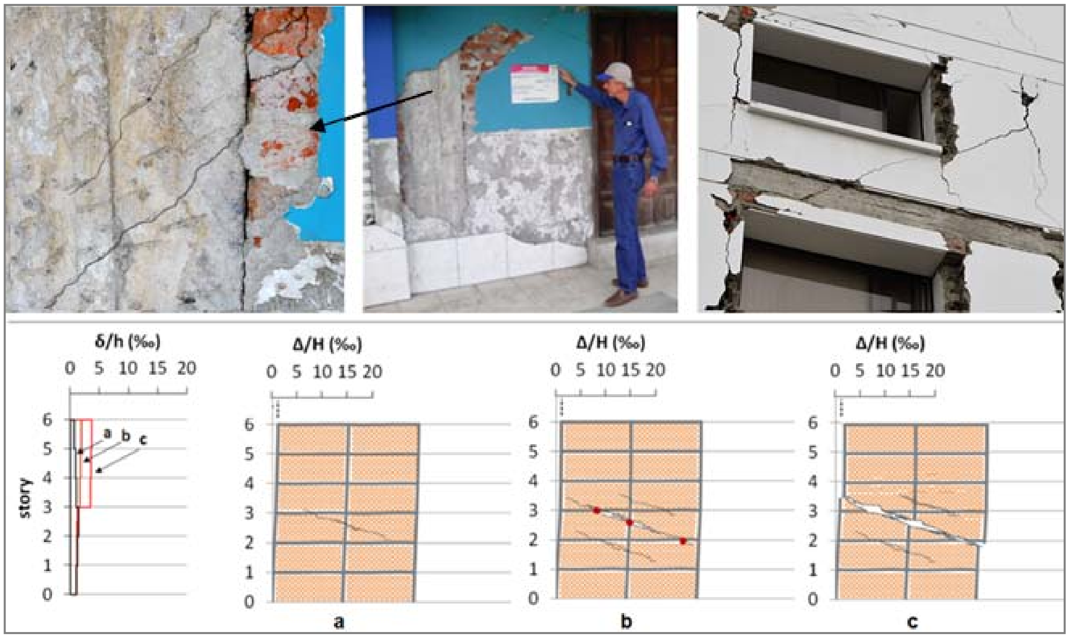

Fig. 4 – Performance when shearing failure is directly transmitted from the wall to the structure

4.4 Soft/weak story

The classic ground open story was observed; but again, the emphasis is on the large number of houses and buildings where the extreme damage in one or two stories contrasts to the sound condition of the others; this shows the formation of the mechanism even in the presence of walls in the affected stories (Fig. 5). The observed symptoms indicate a significant drift in the stories where the damage is concentrated, while the absence of cracks in the walls of other floors indicates that drifts were very low, less than 2‰.

The soft/weak story takes place due to an excessive flexibility or low strength in levels with fewer walls, or where they are broken first, while the rest of the building behaves in practice as a rigid body. This does not necessarily occur only at the ground floor as it is referred to in most of the literature, but it can occur at any level of the building, in some cases, mechanisms of 2 or 3 stories are presented, such as the building shown at the top right of the Fig. 5. It could be said that this is a captive building, in analogy to captive column. Previous studies [32] have estimated that the soft story can increase up to 15 times the drift demand in the affected level, compared to the bare frame.

Fig. 5 – Soft/weak story performance

The Jama School, which was under construction, is shown (Fig. 6). It consists of four identical buildings, all of two levels; one collapsed and the rest were very close to collapse. Soft/weak story on the first level appeared, even though it also had walls. Concentrated damage (plastic hinges) at the ends of the columns, both the collapsed module and the standing ones are shown; good detailed of reinforcing steel is also shown, which did not prevent plastic hinges were in columns rather than beams. Definitely, the masonry partitions in contact with the beams restricted their free deformation, turning then to the strong-stiffer members, over the columns. It is important to highlight that many of the buildings that collapsed in Ecuador behaved the same way, fortunately, it had not yet begun the class season, as the building was about to be inaugurated.

Fig. 6 – Collapse of Jama School (new building under construction)

4.5 Torsional plan

The torsional plan can be described as an unbalance on stiffness and/or mass in a building in plan, which makes some sectors to experience slightly deformations while taking a large portion of shear stresses; at the same time, other sectors develop large deformations that may lead to instability and collapse mechanisms; then, it can be noticed again the analogy to the captive column and soft/weak story, all seismic demand concentrated in a very few structural members.

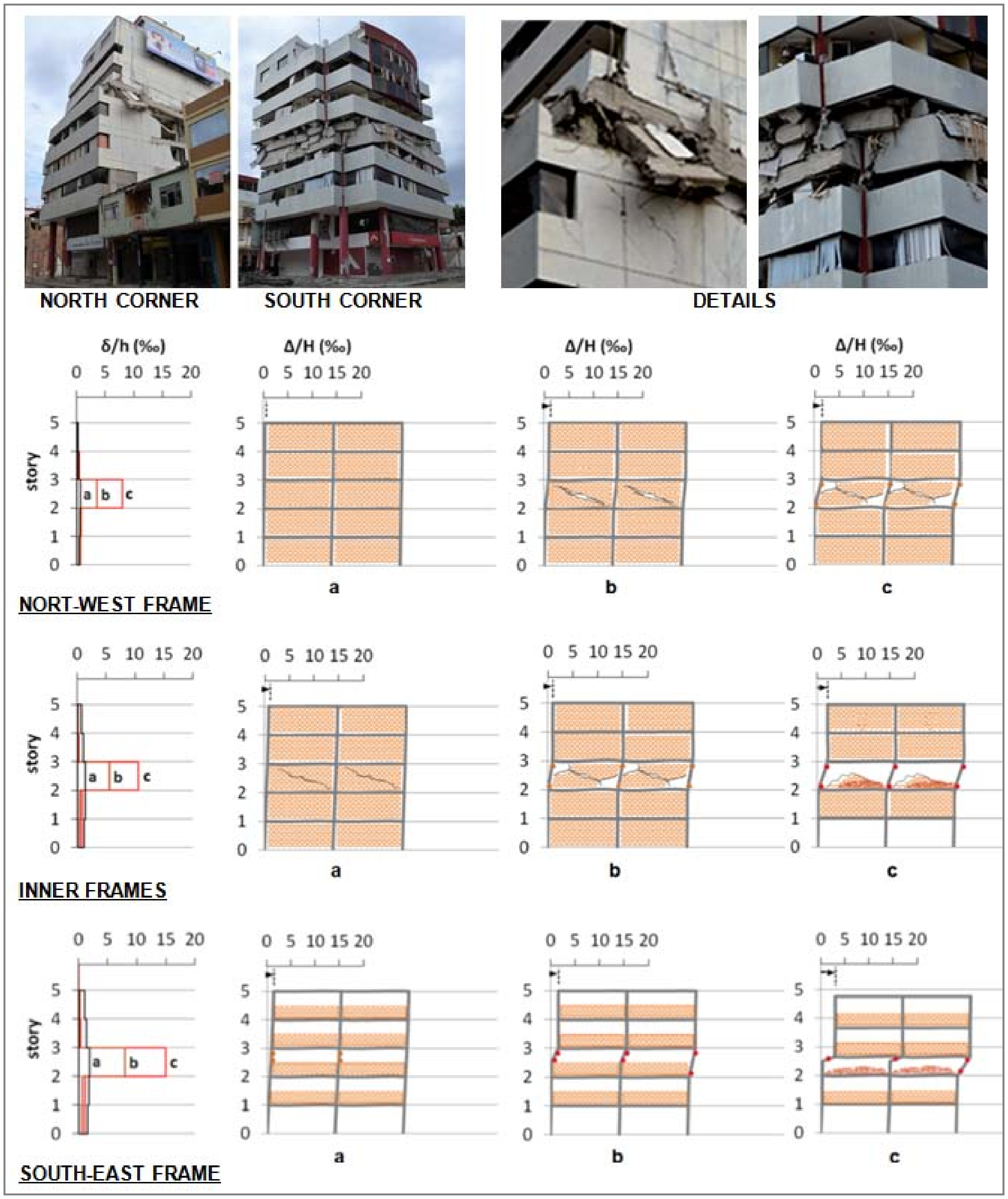

Fig. 7 – “Del Pacífico” Medical Center: torsional plan, captive column and soft story acting together

An emblematic case in Ecuador in which torsional plan took place is shown Fig. 7 above, with the aggravating conjunction of the soft story and captive column. It is noted that the walls of the north facade extend to the entire height of the building, while the rest of the facades are freer; parapets are also distinguished in contact with columns in the other three facades. Then the possible sequence of collapse is described: (a) the highest density of walls in the west facade attracts the stiffness center, concentrating the maximum shear stresses to this area and increasing deformation demand toward the opposite facade, which enhance the captive column in that place; (b) the failure of the "short columns" occurs, stiffness falls in that area and the torsion is empowered, transferring greater shear stresses to the northwest side and increasing the deformation demand on internal frame members; (c) finally, the collapse of the entire affected level, *which results in soft/weak story that* *was not evident in the original configuration of the building, in this case involving two levels* (for simplicity, schemes in figure do not show all levels). By the final position of the building and other symptoms, estimated drifts outside the collapsed area were probably less than 4 to 5‰; that contrasts to the extreme displacement at collapsed levels.

4.6 Failure of foundation system

Some buildings had no damage, neither the superstructure nor the walls, except some minor cracks to masonry elements. In these cases, the building behaved as a rigid body, concentrating the deformation demand under the supposed base level, affecting foundations. The Fig. 8 shows an example were the extensive cracks on floors denotes this behavior. One of the possible reasons is the increasing reactions due to the effect of diagonal struts trough the masonry infills.

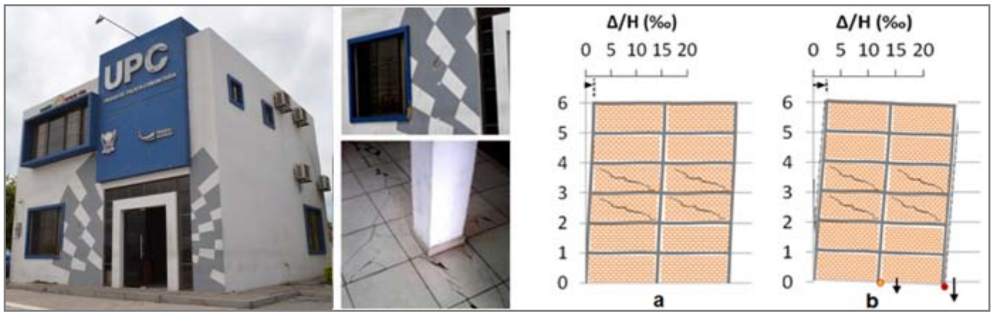

Fig. 8 – Foundations system failure

4.7 Extreme damage in masonry partitions and facades

A great destruction of masonry walls was also observed, even in buildings where no structural damage was evident (Fig. 9). It notes that the level of destruction in walls shown in the pictures can occur at much lower drifts than those accepted by current codes, even before ductile energy dissipation mechanisms in the structural members are reached.

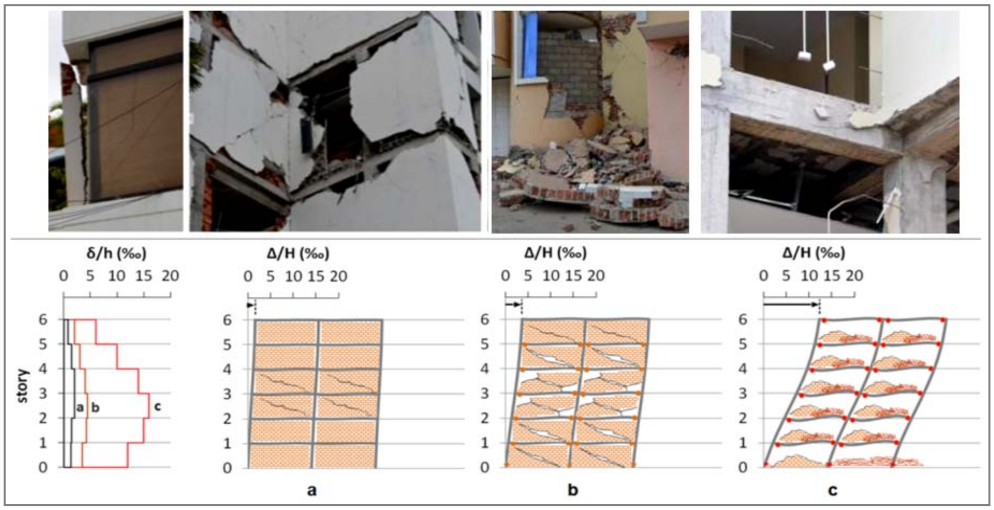

Fig. 9 – Extreme damage to partitions when performance is dominated by the frame structure

This type of behavior was observed even in Guayaquil, 250 km from the epicenter, where seismic loads were probably less than 10% related to actual design loads. One aspect that caught wide attention was that on July 18th, just finishing the reconnaissance visit and three months after the earthquake, unfortunately one person died due to the collapse of a wall in a house located in downtown Guayaquil. According to a press release [1], the neighbors indicated that the wall had been weakened after the earthquake, and the collapse occurred in coincidence with ground vibration due to the passage of a heavy vehicle.

4.8 Contrast with *no damage* buildings

Next to collapsed buildings, were also many others that didn’t have any damage, neither the structure, nor the partitions. Such is the case of the house shown in Fig. 10, located in San Vicente. This house was built over 100 years ago, as indicated by its owners [34] who invited us to get in, very proud of the green label displaying its facade. It was also informed that the house has performed the same way on several earthquakes before. It has two stories with a very flexible wood structure, the partitions are of masonry at the first floor and wood and cane, much more flexible and lighter, on the upper level. This shows the benefits of masonry for low-light buildings.

Fig. 10 – Ancient building of wood and masonry with no damage

4.9 Probable force-displacement curves

The preceding segments showed a wide range of possible performances that may occur, even for modern buildings, when the influence of masonry partitions is underestimated: (1) typical performance expected with free deformation of structural members; (2) widespread damage and collapse of infill walls subjected to large deformations, regardless the apparently good performance of the structural members (3) brittle mechanisms that might be induced by an inadequate configuration of partitions into the building, but they can also take place anywhere in a modified configuration of the building after the partial fail of masonry infills.

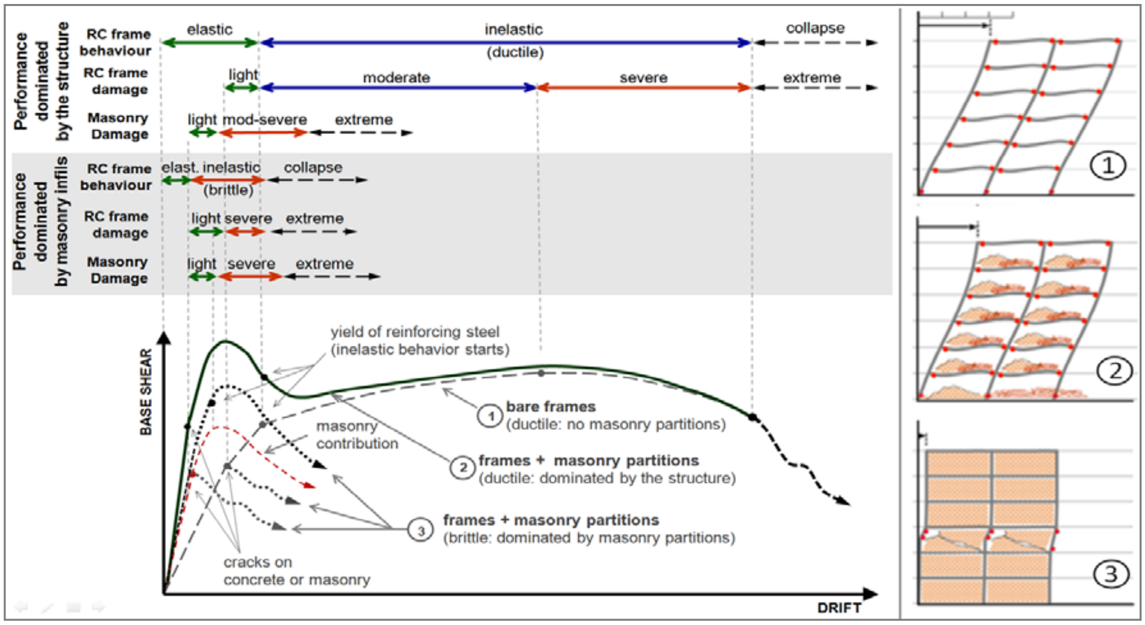

Fig. 11 force-displacement curves inferred from damages

The force-displacement curves inferred from the described symptoms are summarized in Fig. 11 above; more details are presented in a complete recognition report [30]. It shows the huge influence that masonry partitions may have on the overall capacity of the buildings, affecting the stiffness, so the natural period, the deformation capacity, the ductility, the stress distribution between structural members and those that were not supposed to be structural, etc. the figure also shows the relationship between different deformation states to damage levels in both, structural members and masonry partitions.

5. Discussion

As mentioned before, the issue about the role of masonry walls in the seismic-resistant performance of buildings is anything but new, countless publications have discussed almost every topic mentioned here, this paper included a few references in section 2; the idea is not to be redundant, but to show things from another point of view, from the field of structural pathology of buildings. Leaning in the examples and figures above, some common myths can be rebutted, which will be the emphasis this time:

- *Many structures performed well, as no damage was noticed even on masonry partitions.*
  False: At the drift level that masonry has no damage (until 1~2‰) the contribution of the frame members is minimal. Until this point the columns and beams only have helped in the distribution of tensions throughout the masonry members, which are absorbing almost all the lateral loads. So, if not cracked the walls, then they as a structure performed well, while columns and beams have not worked yet.
- *Many buildings experienced only non-structural damage.*
  False: For many buildings with low to moderate damage in masonry partitions, especially for low rise buildings and old pre-code buildings, the main resisting elements were precisely the masonry walls. We must be very careful with this situation, as many walls that were degraded by the earthquake will be only made-up, while others will be replaced but perhaps with different materials; both will change the performance of the buildings against future earthquakes.
- *The structure performed well, as expected, because it didn´t collapse. Damages are acceptable.*
  False: The target building performance used to be dominated by masonry elements instead of the structural RC members. Even though collapse prevention capacity might be achieved by the main structure, the life safety level for masonry elements will be exceeded long before the structure dissipates a reasonable amount of energy by inelastic deformation. Destruction of masonry elements may be present for shakings 4 to 6 times lower than those used as design loads.
- *The irregularity factor of 0,9 cover the increase on demand, resulting in a safe structure.*
  False: If the performance is dominated by masonry elements, affecting strength, stiffness/period, ductility, etc., the overall capacity at the life safety or collapse prevention level could be less than 10, 15, 20 times of those selected for design, or even worse. An example: a structure designed for R factor of 6; a captive column half height affects 30% percent of the columns in one level; it will make them to fail in shear (brittle, no ductility, no "R") by the time the rest of the columns have not work yet (due to their relative stiffness); so the overall shear capacity will be reduced to a $V_f = (30\% / R) \times V_n = 0{,}05\ V_n$, which means that the final overall capacity (V_f) will be 20 times less than the nominal V_n expected by designers.
- *When the walls fill the entire height are always beneficial, since they take part of the seismic loads without causing harmful irregularities.*
  False: it is known that buildings may perform better because of the strength coming from masonry walls, but careful about possible benefits of the walls; usually, in the case of regular structures of 1 or 2 floors the walls are still beneficial, even if they have not been conceived as part of the structure, which highlights the value of masonry structures. For taller buildings, fragile mechanisms shown in this paper are common; the more harmful typified irregularities might take place regardless being or not in the original configuration of the building.

The fact is that whether or not considered as a structural component, the masonry walls use to be the protagonists when combined with flexible structures, because their strength and deformation properties are not compatible. So, the miscall “non-structural” masonry walls should be named “non-intentionally-structural” masonry walls, as well defined by other authors [e.g. 14].

6. Conclusion

The Muisne, Ecuador Earthquake 2016 repeated the widely referred lessons about the role of the miscalled “nonstructural” masonry walls in the seismic-resistant performance of buildings. Now questions arise: *Once again… Why? Until When?* To try to answer the “Why” it should be mentioned that the real issue is not the problem related to masonry infills; by no means, the main issue is *not to recognize the problem*, because underestimating its influence on structural performance may leads to a number of failures that they can induce. Based on the experience in Ecuador, this paper has presented an outline of certain angles of this subject, trying to explain it in a simple and didactic way to try to capture the attention of students and young professionals who, at the end, will be those who have in their hands the changes that seem to be obvious and urgent. Surely from them will be the answer to “Until When”.

It is worth repeating the need to stop persisting in refined models to include masonry partitions for promoting new-mid to high rise buildings. These models might be suitable for very low-rise buildings, in fact, many performed well in Ecuador, showing the benefits of masonry to resist earthquakes loads for those cases. On the contrary, mid to high-rise buildings showed the incompatibility between their flexible structures and their masonry infills. It is also important to mention that trying to separate a wall of such a flexible structure is an utopia. The key is to promote very stiff structures that among other benefits, takes away the problem of the better now called "non-intentionally-structural" masonry walls; in this regard, Chile [35] seems to be the best in the region.

It will be a sweeping change of paradigms for many countries, but it will be absolutely necessary. The fact is that dragging the inheritance of considering walls in models only for weight and mass, underestimating their stiffness, strength and fragility, place the structural engineering of many countries far from the current global trend of performance-based design and low-damage seismic design, which is important not only for the structure, but also for non-structural components and content. This is one of the issues to be reviewed in the codes and construction practices of many countries around the world to minimize the expected damages in future earthquakes, as a step towards having more resilient buildings and communities.

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