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SEISMIC EVALUATION AND RETROFIT FOR REDUCING THE VULNERABILITY OF HOUSING IN COLOMBIA: DEVELOPMENT AND IMPLEMENTATION

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Abstract

Regions of low to high seismicity exist throughout Colombia, with major cities like Bogotá and Medellin falling within zones of intermediate seismicity according to the Colombian Earthquake Resistant Standards (Normas Sismo Resistentes or NSR). In urban centers, like Bogotá or Medellin, informal housing construction is prevalent as the population in these areas grows. According to CENAC (Centro de Estudios de la Construcción y el Desarrollo Urbano y Regional), of every 5 new homes built in Colombia today, 3 are of "informal origin", meaning they are built spontaneously without any legal procedures nor formal design. These houses are commonly built in confined masonry and, although this system is well defined in NSR-10, informal construction does not typically adhere to the standard.

As a result of the increased growth of these informal neighborhoods in Colombia, millions of people are vulnerable to death, injury or homelessness as a result of housing collapse in the design earthquake. To help address this risk, cities such as Bogotá have developed programs to support housing improvements in the most vulnerable areas. These programs allocate subsidies for home improvements to the most vulnerable households and provide them with technical assistance through the process. Build Change is working with the municipal agency, Caja de la Vivienda Popular (CVP), which is focused on providing technical assistance for subsidized home improvements, to develop an efficient approach for implementing seismic evaluation and retrofit of the large vulnerable housing stock.

With partners and local professionals, Build Change developed a manual with simplified procedures for the seismic evaluation and retrofit design of low-rise confined masonry and unreinforced masonry houses in Bogotá. These procedures are based on a similar manual developed for the Haitian context in partnership with Degenkolb Engineers, which in turn is based on the U.S. standards ASCE 31 and 41. The latter are approved references for building evaluation and rehabilitation, respectively, in accordance with the NSR-10. Adaptations were made to simplify the procedures for use in housing and for applications to confined masonry construction in Colombia, which is a building system not explicitly addressed in the U.S. standards. The procedures are outlined in this paper. This manual was reviewed and approved for use by the national *Comisión Asesora Permanente Para el Régimen de Construcciones Sismo Resistentes* in Colombia (Permanent Advisory Commission for the Regime of Seismic-Resistant Construction).

Following the approval of the manual, Build Change, the Habitat Secretary of Bogotá, and CVP initiated a pilot project to provide technical assistance to seismically retrofit approximately 50 homes in El Amparo and other neighborhoods located in the south of Bogotá, in accordance with the manual procedures. Local engineers who have received training from Build Change performed the evaluations and retrofit designs based on the manual. This paper shares the experiences of this pilot project to date, including a specific case example, and how these experiences have informed potential improvements to the manual procedures and their implementation in a retrofit program. Next steps are identified for implementing a housing retrofit program at scale.

Keywords: Seismic-resistant; retrofit; housing; reducing vulnerability.

1. Introduction

Today, Bogotá has more than 7.5 million people and is a city which is growing rapidly [1]. According to CENAC (Centro de Estudios de la Construcción y el Desarrollo Urbano y Regional), of every 5 new homes built in Colombia today, approximately 3 are of "informal origin"; they are built outside of the national code (NSR) provisions [2] or in absence of professional supervision. The informal buildings present structural deficiencies which make them particularly vulnerable to earthquakes. Therefore, more than half of the city's buildings could be at risk based on the seismic hazard, which is well known for Bogotá: an earthquake of Ms 7.4 with a return period of 500 years occurring in the frontal fault of the Western Mountains [3]. With these aspects in consideration, the potential economic, social and environmental consequences of a seismic event are quite significant for Bogotá and warrant attention.

The densification of Bogotá and other cities in Colombia is a real problem, where the lack of available open land leads people to expand their houses vertically. Most of the informal houses are growing in size incrementally by the addition of new stories above the existing building. Generally, this practice has less consequence for the vertical demands on the structure (although not negligible) than for the lateral, as the added mass will participate seismically and the original structure will likely not able to accommodate the resulting increase in lateral loads. Thus, with densification, the seismic vulnerability of the structures is increasing. It is also important to consider that within a single city block there is a variety of building heights due to incremental vertical expansion, i.e. there are 1- or 2-story buildings located beside taller, more vulnerable buildings, and the interaction between the buildings during an earthquake puts the adjacent low-rise, and inherently less vulnerable, houses at increased risk.

A large scale intervention which tackles the problem in two main areas is required in order to mitigate the high risk: (1) make the existing vulnerable buildings safer, and (2) increase the control over new informal construction to stop the growth of seismic risk.

The local government of Bogotá is taking action against this scenario through the Caja de la Vivienda Popular (CVP), a public institution responsible for social housing and neighborhood improvement in Bogotá over the last 72 years. CVP manages the subsidies allocated by the municipality to the vulnerable socioeconomic sectors of Bogotá. Build Change and CVP have set up a pilot program with the aim to provide the seismic retrofit design and construction of 50 low-rise residential buildings in Bogotá. This pilot project will be discussed throughout this paper, illustrating the basis of the applied method for evaluation and retrofit, its implementation, and a case study example.

Confined masonry was included in the first seismic building code in Colombia, the Código Colombiano de Construcciones Sismo Resistentes issued in 1984, based on AIS 100:83, specifically for 1- to 2-story houses in response to the poor performance of unreinforced masonry houses in the Popayán earthquake in 1983 [4]. It was an effort to encourage the practice of using confined masonry that was prevalent in the 40's to 60's in Colombia, but abandoned in the 70's [5]. Although simplified provisions for new construction confined masonry houses are still included in NSR-10, Title E, many informal houses built even today do not follow the code requirements and the resulting structures in many cases can be considered essentially unreinforced masonry instead. For addressing existing buildings until now, engineers and architects in Colombia requesting permits for structural upgrades for housing have typically been using Title E, although it was developed for new construction.

Another resource available in Colombia is the *Manual de Construcción, Evaluación y Rehabilitación Sismo Resistente de Viviendas de Mampostería* [6] developed by the Asociación Colombiana de Ingeniería Sísmica, AIS, and other local entities. This manual was developed as a NSR-98, Title E [7] companion and contains very simple guidelines to retrofit existing masonry buildings that are 1 or 2 stories tall. However, it could not be used as the basis for permitting of seismic upgrades.

The seismic evaluation and retrofit methodology used in this pilot project was developed by Build Change Latin America for Colombia and is outlined in the *Manual de Evaluación y Reforzamiento Sísmico para Reducción de Vulnerabilidad en Viviendas* [8]. The Manual is based on the simplified seismic evaluation and retrofit methodology for low-rise residential masonry buildings initially developed for Haiti [9]. After the earthquake in 2010, Build Change and Degenkolb Engineers developed a simplified methodology to approach housing seismic evaluation and retrofit design for Haiti, based on U.S. standards ASCE 31 [10] and ASCE 41 [11], which are accepted by NSR-10 as an alternative method to addressing existing buildings.

The methodology was developed to address existing informal houses. These buildings typically use lower quality materials, as will be discussed in section 3.5 below, and typically have poorer construction quality control than new formal construction and therefore it would not be applicable to apply the methodology (with its assumptions based on these informal existing buildings) to a new structure that met the design and construction requirements of the NSR-10 provisions for confined masonry. For this reason, and also due to the Manual's recommendation to consider micro-zoning, whereas Title E of NSR-10 does not, applying the procedures to a Title E-compliant house may in some cases indicate that portions of the house would require retrofit.

2. Seismic Evaluation and Retrofit Procedures for Colombian Masonry Housing

2.1 Applicability and Criteria

The proposed seismic evaluation and retrofit procedures are applicable for 1- to 3-story homes (depending on the seismic hazard level and lateral system type), built with confined or unreinforced masonry bearing walls constructed of hollow clay block or solid clay brick. Suspended slabs should be constructed of solid reinforced concrete, or roofs may also be constructed of light-weight materials such as wood or light-gage framing and sheet metal roofing, in order to be considered applicable in the procedures.

The performance criteria for the procedures is structural life-safety in the design-basis earthquake. The design basis earthquake defined in NSR-10 is the earthquake with a 10% probability of exceedance in 50 years. When available, it is recommended to consider applicable micro-zoning studies in establishing the site factors. For example, considering the micro-zoning of Bogotá [12], the short-period spectral design acceleration, S_a, ranges from 0.36g to 0.73g, throughout the city.

2.2 Methodology

The procedures address both the seismic evaluation and the retrofit design of the buildings. The process starts with a site visit to document and evaluate the existing conditions of the building and site through the use of a seismic deficiency identification checklist. This is used to check that the structure and site conform to key seismic design features required for life-safety performance, such as slope stability, building configuration, system continuity, materials, wall slenderness, etc. The checklist also includes a simplified analysis of the lateral resistance of the building at each level based on the wall area percentage. The wall area percentage check requires that the horizontal cross-sectional area of the existing walls divided by the area of the building (existing wall area percentage, WAP_{ex}) be greater than a calculated minimum value (wall area percentage required, WAP_{req}) needed for adequate lateral resistance (Eqn. 1).

$$\textit{Existing Wall Area Percentage } (WAP_{ex}) \geq \textit{Required Wall Area Percentage } (WAP_{req}) \tag{1}$$

The procedures include specifics for how the required wall area percentage is derived based on site seismicity and building-specific characteristics, such as block strength, construction quality, number of stories, and type of lateral system, which were described in detail along with other aspects of the methodology by Blaisdell et al. [13].

Once the deficiencies are identified via the checklist and simplified analysis, a retrofit scheme can be designed in which each of the deficiencies are systematically addressed, so that when the checklist is re-applied to the building in its retrofitted state, deficiencies no longer exist. In cases where the WAP_{ex} is found insufficient, the retrofit can include increasing the effective wall area by adding new walls, infilling windows or doors to increase the area of existing walls, adding cement plaster to the surface of walls and adding a reinforced concrete overlay to existing walls. The options chosen depend on the homeowner's preferences. Alternatively, the required wall area percentage can be reduced to help the building meet the performance criteria by increasing the system ductility and converting an unreinforced masonry building to a confined masonry building through the addition of confining elements at the appropriate locations, or by removing seismic mass, such as an upper level.

3. Pilot Project in Bogotá

Caja de la Vivienda Popular and Build Change are partnered to execute and collaborate on a pilot project in Bogotá in three neighborhoods located in the south of the city. The project's main objective is to evaluate and produce retrofit designs for 50 existing houses using the manual as part of a subsidy program (see Fig. 1.), in order to not only validate that an alternative solution can be implemented in the local context, but also to find where the challenges to broad scale implementation exist and develop lessons learned in the process. Subsequently, the construction phase will be implemented by contractors hired by CVP with joint technical supervision from CVP and Build Change.

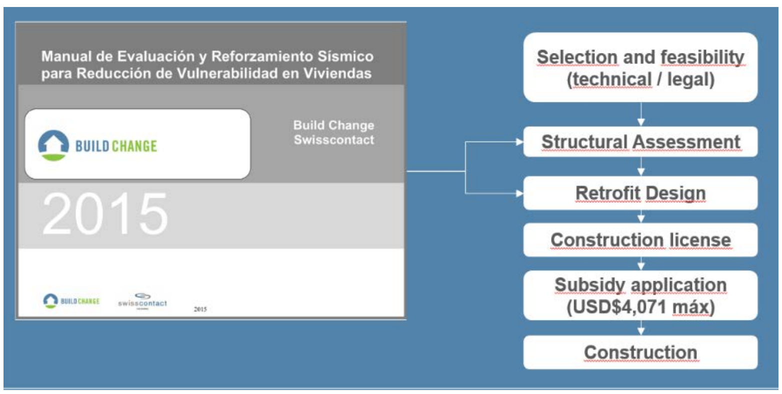

Fig. 1 – Manual application in the subsidy program

Existing houses with poor quality construction and irregular structural configurations are not uncommon in the southern areas of the city, where a lack of professional support and financial resources, combined with incremental building construction have become a base for the growing structural and architectural problems.

The municipal government of Bogotá allocates financial subsidies to help address housing problems through the Secretaría del Hábitat and CVP entities. The subsidies are aimed primarily towards alleviating poverty and increasing access to housing, and so are targeted towards homeowners in the lowest income group. Because of this, the subsidies are only available for residential buildings, up to 2 stories, and are limited to a budget of no more than 11.6 million COP (approx. USD 4,000) per house. Of this budget, typically around 30% of the funds are spent on administration and the contractor's profit for the executed works. With the remaining small budget available, it is important to optimize the intervention in order to be able to increase the safety of the house most effectively. When work beyond the budget is required, it can only be performed with contributions from the homeowners themselves. It is of note that due to the social aim of the subsidy and associated limitations, commercial or mixed use buildings, which are some of the larger, more vulnerable buildings (with open fronts) cannot be addressed within the program.

Since the Manual procedures are developed for implementation by qualified engineers, a specific training was held for CVP engineers and contractors in October 2015 by Build Change to set up a team of professionals from CVP and Build Change that would implement the pilot project together.

3.1 Evaluation of Houses

Engineers visited each of the houses that had been prequalified legally for the subsidy, and carried out structural evaluations in accordance with the Manual procedures – documenting the existing conditions and completing the deficiency identification checklist. Fig. 2 shows a typical street in one of the project neighborhoods. The engineers found nearly every type of deficiency covered by the Manual, but there were some items that were more common in the houses evaluated. The most common structural issues found in the informal houses evaluated in the southern areas of Bogotá are identified in Table 1. The evaluation not only identifies potential deficiencies in the structure, but also in some non-structural elements that could compromise occupant safety. Regarding the non-structural elements, the most common issue found was unconfined masonry parapets at the façade of the house, particularly in one-story buildings.

Fig. 2 – One and two story houses in the Usme neighborhood

Table 1 – Common Structural Issues

Site Stability	Quality of Materials	Configuration	Quality of Construction
+ Some neighborhoods are placed on hillsides with slopes over 17%	+ Low quality hollow bricks	+ Not enough shear wall area in both directions of the building to adequately withstand seismic loads + Interior walls built without foundations + Lack of vertical continuity of columns and walls + Concrete slab and walls cantilever at the front of the house	+ Insufficient confinement of shear walls (e.g. no ring beam, half sized columns, and/or lack of tie beam) + Shallow concrete cover on slabs edges and other concrete elements

3.2 Retrofit Designs

As the Manual introduces a methodology different than Title E, which many engineers working with housing are accustomed to, and as there are many variations between existing buildings, it was common that an engineer needed to work closely with a more experienced engineer during the first three or more evaluations and retrofit designs they implemented.

On average, to produce one single retrofit design package for submittal to the Curadurías Urbanas, (building permit offices) it took approximately one week from the start of building evaluation through a final internal technical review. The large and detailed design packages required for submittal to the Curadurías Urbanas slowed the production of design packages more so than the need to train engineers in a new methodology.

3.3 Construction Licenses: Legal Procedures

The subsidy allocation has many legal requirements related to homeowner's socioeconomic situation, the building site conditions, and type of construction. The primary requirements include those listed in Table 2.

For the pilot project, CVP checked these requirements at the beginning of the project and rechecked them before the submission of the packages in Curadurías Urbanas. During the initial screening for houses to be evaluated, 1 of 3 of the screened houses could not be part of the project because the homeowner and/or the property did not conform to all of the subsidy qualifications.

Following completion of the design package and clearance of the legal requirements, the next step was to obtain construction licenses following review by the Curadurías Urbanas for each design. The Curadurías Urbanas are private entities in charge of the design review of all construction projects in Colombia by law. During the project it was evidenced that although the Curadurías Urbanas review system works well for formal construction, it may not be as well suited for the informal housing sector because of the following: (1) social housing is not a lucrative business, so the Curadurías Urbanas are forced to attend to this type of permit at below-cost rates (2) the review system includes requirements which are appropriate for larger projects and structures, but make retrofitting as single existing informal house too expensive for the relative cost of the retrofit work to be performed. For example, the design package of a single house retrofit project typically contained more than 60 pages, including a legal framework introduction, existing building drawings, retrofit design: plans and details, soil study report, calculation of foundations, beams, columns, stairs, concrete slabs, and non-structural elements, and photos of the soil below the house and of the building.

Table 2 – Subsidy Qualification Requirements

Subject	**Requirement**
Homeowner	- One single owner - Household formed by spouses or de facto marital unions - Homeowner does not have any other government subsidy assignment - Homeowner does not have any other property
Property	- Building up to two-stories tall without concrete slab roof - Building up to 120m^2 of total area or less - Property title exists - House has water and sanitation services - No multifamily use: One single kitchen - Residential use only. No shops, garages, or stores are allowed.

In particular, a soil study is an expensive item for a social housing project, particularly when required on a house-by-house basis. The evaluation procedures in the Manual require the evaluator to examine the existing foundations for issues such as damage, settlements, and other problematic concerns that indicate in adequacy of the foundation or soils to support the structure. This approach, supplemented by a much more streamlined soil investigation methodology, would likely be sufficient to identify life safety issues for low-rise residential retrofit works, instead of having to fulfill the soil investigation requirements appropriate for larger-scale new constructions.

3.4 Cost-Efficiency

The retrofit design construction costs were analyzed for twenty of the houses included in the pilot project. These costs consider the materials, equipment, and labor needed to implement the retrofit works. The contractor’s profit and the administration costs are not included in the amounts noted. There are three types of intervention: a) retrofit only b) retrofit + architectural improvements + one story expansion for an existing one-story house, and c) retrofitting + architectural improvements + one story expansion for an existing two-story house. The results of the cost analysis are presented in Table 3. Historical and current estimated prices for new construction are presented in Table 4.

Table 3 – Estimated Average Direct Costs by Type of Intervention, 2016

Type of Intervention	**# of Houses**	**Average index cost (COP/M^2)**	**Average index cost (USD/M^2)**
a) Retrofit only.	15	\$236,154	78.6
b) Architectural, Retrofit, and 2nd level expansion.	2	\$312,845	104.1

c) Architectural, Retrofit, and 3rd level expansion.	3	\$302,532	100.6

Table 4 – Estimated Variation of Direct Costs for New Construction

Type of House	Year	Cost Index (COP/M^2)	Cost Index (USD/M^2)
SINGLE-FAMILY DWELLING - ONE STORY	2013	\$642,626	213.78
	2014	\$662,842	220.51
	2016	\$750,533	249.68

New construction costs were calculated based on data from Construdata magazine [14], and do not include the cost of demolition of the existing buildings, nor the cost for relocation of the household while the construction is being carried out. The costs of new construction are more than twice the retrofitting costs. Based on these examples, a cost-effective program should consider retrofitting as an economically competitive option for seismic risk mitigation.

The footprint of a house in the pilot project was typically 6m x 12m = $72m^2$. Assuming the existing house is a 1-story building, and applying the average index cost, the direct cost for retrofitting would be approximately 17.0 MMCOP. The current subsidy available to qualified homeowners in Bogotá, could cover approximately half of this cost, after the contractor's profit and administration is deducted: 11.6 MMCOP x 0.7 = 8.1 MMCOP. This leaves the difference, approximately 8.9 MMCOP, left for the homeowner to pay if she or he wants to complete the retrofit.

3.5 One-Story House: Seismic Evaluation

In order to illustrate the application of the manual for seismic evaluation and retrofit of typical houses in Bogotá, one example house from the pilot project is included below. No names nor personal data are shared to protect the homeowner's privacy. The existing house is a one-story, partially-confined masonry bearing wall building, 6m x 12m in plan. Refer to Fig. 3 and Fig. 4. The example house, and the majority of informally built masonry houses in Bogotá, use lightweight hollow clay tile blocks with horizontal perforations, manufactured commercially, typically for non-structural use. These are commonly referred to as Block 4 or Block 5, with the number indicating the approximate width in inches. NSR-10 permits the use of Block 5 for confined masonry houses, provided the minimum compressive strength of the units is at least 3 MPa. The typical block used in these informal houses may have a slightly lower strength than that required for new construction, estimated at around 2.0MPa based testing performed [15]. This lower estimate is used by the Manual in accounting for the existing wall strength, although adjustments to the existing masonry strength can be made by the user for each house as needed.

Fig. 3 – Façade of 1-story example house, Usme

3.5.1 Site Hazards

The example house is located in the Usme neighborhood to the south of Bogotá. This area was mostly developed informally. The terrain in the zone is hilly and many of the houses were built on sites with high slopes where landslide risk is present. The deficiency identification checklist in the Manual checks that the house is located on a site with a slope less than 17%. If this condition is not met, it directs the user to obtain a more detailed soil stability study elaborated by a professional specialist. In the case of the Usme neighborhood, CVP had to provide such soil studies performed by consultants in several cases, focused on slope stability, bearing capacity of the soil (to confirm a minimum assumed value of 0.5 kgf/cm^2 is met) and liquefaction potential. The example house, see Fig. 3, is located on a relatively flat site and met the 17% slope requirements. Additionally, it does not have problems related to liquefaction, another deficiency checklist item.

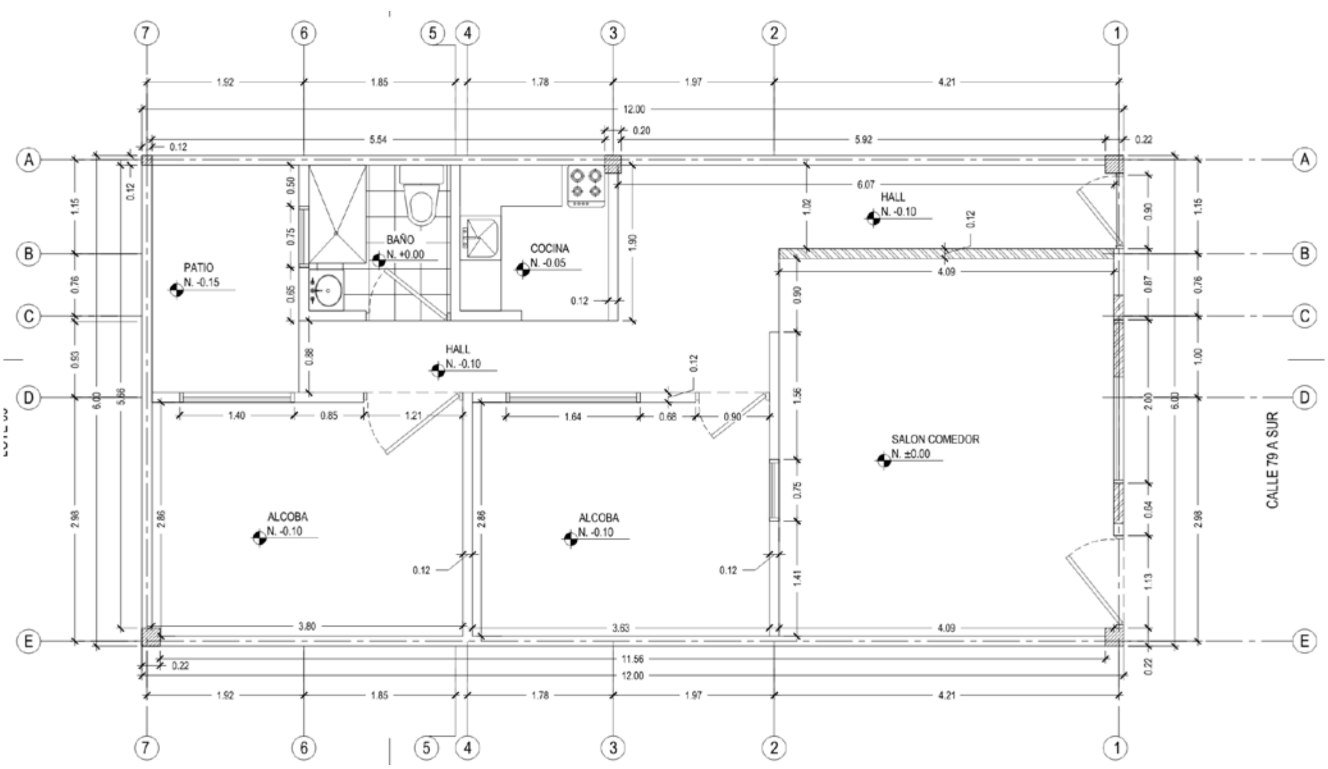

Fig. 4 – Existing wall plan configuration, Usme house.

3.5.2 Foundations

The house was found to conform to the checklist items for foundation type, foundation performance, overturning, foundation deterioration and connectivity.

3.5.3 Building System

Based on the checklist, several deficiencies were identified in the construction system of the example house. For load path, the checklist sets a maximum distance between adjacent parallel walls at 4 meters in order to control out-of-plane wall failure of the perpendicular walls, as well as ensure sufficient lateral resistance. This house had several walls that spanned further than 4 meters, without intermediate support, and was therefore found to be non-conforming. Additionally, the weight of the building, considering the existing plaster wall finished exceeded the base value, which would trigger an increase in the wall area percentage required in the following checklist section.

The house was found to conform to the checklist requirements for materials, number of levels, story height, roof system, wall condition and thickness, cantilever upper levels, and damages.

3.5.4 Masonry Walls

The example house did not confirm to any of the checks regarding the masonry wall construction. The lack of a reinforced concrete beam at the top of the wall (See Fig. 5) was identified as a deficiency itself and also implied a deficiency for the vertical confinement of the wall. Masonry walls are required to be vertically confined by a flush reinforced concrete top beam or slab (with no gap between the masonry and concrete elements). A beam at the top of the wall is required for light-weight roof conditions in order to brace the top of the wall and distribute the out-of-plane load to the adjacent perpendicular walls (the light-weight roofs do not act as an effective diaphragm for this). In buildings with slab roofs, the slab acts as the diaphragm for this out-of-plane support.

There was also a lack of adequate reinforced lintel beams above openings.

The final checklist item for masonry walls is a check on the lateral system capacity. The evaluator has to sum the wall area at a given direction in each level of the structure and verify that there is more shear wall area than that required at each level. For the example building, the Existing Wall Area Percentage (WAP_{ex}), considering it as a confined masonry system and including only the wall segments which are confined at each end, is 3.3% for the longitudinal direction 1.8% for the transverse direction. Both values fell below the minimum required wall area percentage for this house, which was WAP_{req}=5.1%. Therefore, it was found that the wall area percentage (lateral strength) for the building was non-conforming.

Fig. 5 – Masonry wall without top beam

3.5.5 Configuration

The configuration of the example house met the checklist requirements for adjacent buildings and, as a one-story structure, was not applicable for the checklist item regarding vertical continuity. However, the example house did not meet the required check for torsion: that all exterior walls have shear walls on grid, or within a quarter of the building length from the exterior. The front wall of the house did not have a length of continuous masonry wall long enough to qualify as a lateral force-resisting wall and the next interior transverse shear wall was not within the quarter-length requirement. Refer to the existing plan in Fig. 4.

3.5.6 Structural Components

As a one-story existing building with a light-weight roof, several of the checklist items for structural components did not apply: columns supporting discontinuous walls above, stairs and slab openings. Additionally, there were no isolated, gravity load-supporting columns present, so the corresponding check to avoid a short column condition did not apply. The final component check, regarding parapet height is also not applicable as the example building did not have a parapet.

3.6 One-Story House: Retrofit Design

Following the Manual, the designer has to modify the existing structure to address all the *non-conform* checklist items identified during the evaluation. Deficiencies often have more than one way to be addressed, and the designer should aim to find the most efficient solution based on the budget, builder skill, and homeowner preferences. At the end of the process it is important to apply the deficiency identification checklist again to the retrofit design in order to confirm there are no longer any existing or new *non-conform* items.

In order to increase the ductility and strength of the structure, the retrofit design for the example house includes adding confining elements, such as vertical ties and top beams, to many of the existing walls where they were not previously present. A summary of the deficiencies and the solutions applied in the retrofit design is shown in Table 5 and the resulting retrofit floor plan is presented in Fig. 7. As it is shown in Fig. 6, every new vertical tie is connected to the existing foundation, providing an anchor for tension in the confining tie under lateral loading in the wall panel.

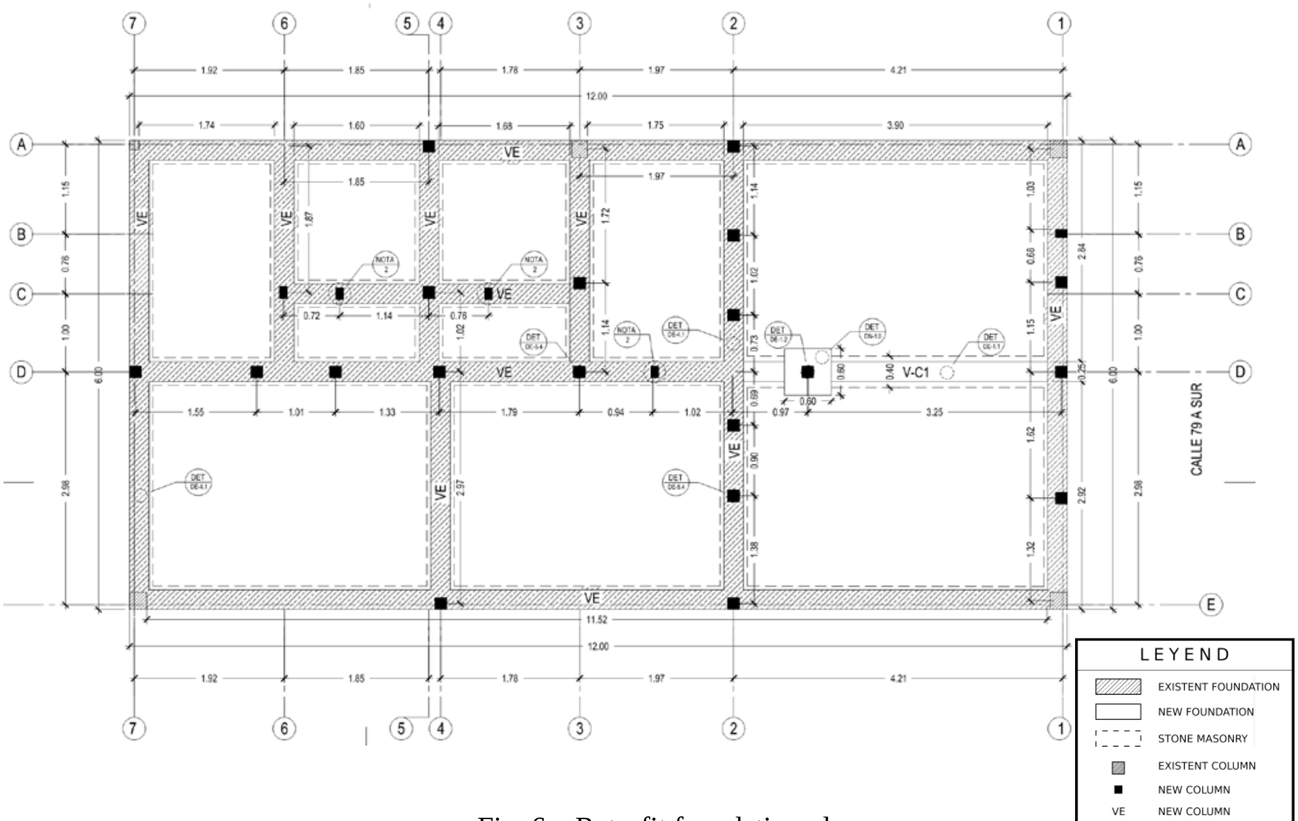

Fig. 6 – Retrofit foundation plan

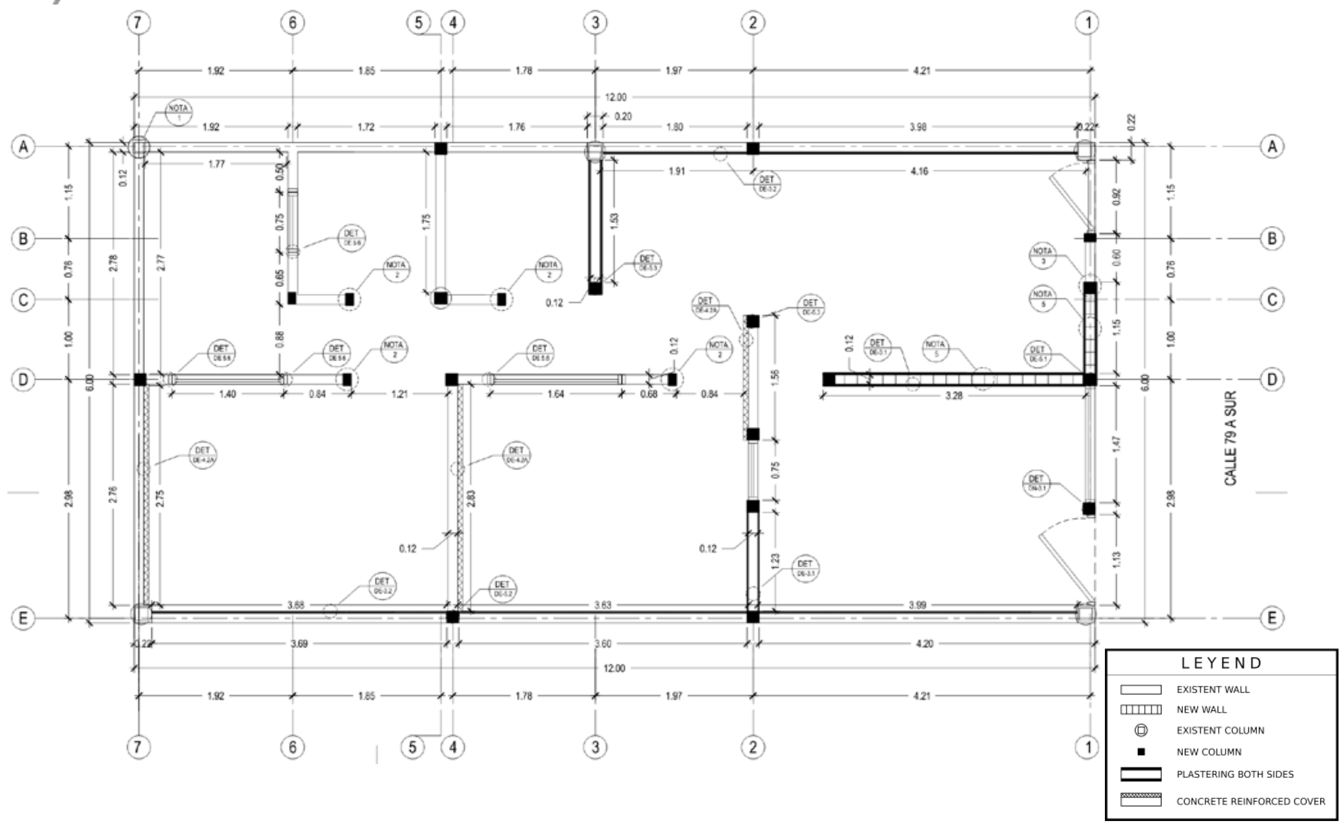

Fig. 7 – Retrofit wall plan

Table 5 – Identified Deficiencies and Retrofit Solutions

Deficiency	**Retrofit solution taken**
Spacing between parallel walls greater than 4.0m	New walls were added to the structure to reduce spans below 4m.
Seismically heavier structure compared to the standard (plastered walls)	The additional weight was incorporated into the design by taking a proper weight factor in determining the required WAP.
The masonry is not tight to the confining elements.	New concrete columns were added and they will be poured against the indented wall edges, and a new top beam was added.
Windows and doors do not have reinforcement on their edges or lintels.	New concrete elements were added: at the windows vertical ties were added to each side, vertical tie columns were added at each side of the door openings, and the openings were extended to the top beam above.
Absence of continuous top beam on all walls.	Top beams were added on every wall which are continuous and interconnected.
Wall area percentage is insufficient in both directions.	Different retrofitting technics were considered, such as the addition of new walls, new confining elements for existing walls, new structural plaster, and reinforced concrete overlays. See Table 6.
Torsional problem due to insufficient lateral resistance at the front of the building.	A confined masonry shear wall was added to the front wall.

Table 6 – Wall Area Percentage Summary

	Existing Building	Retrofit Design

Direction of analysis	Existing Wall Area Percentage	Required Wall Area Percentage (Evaluation)	Required Wall Area Percentage (Retrofit)	Retrofitted Wall Area Percentage (effective)	Utilization Factor
	WAP_{ex}	WAP_{req}	WAP_{req}	WAP_{eff}	WAP_{req}/WAP_{eff}
Transversal	1.8%	5.1%	7.0%	7.3%	0.97
Longitudinal	3.3%	5.1%	7.0%	7.3%	0.96

4. Conclusions

During the process Build Change identified several critical aspects which could help similar projects have success:

4.1 Technical

With the Manual approved by the Commission, Colombia has a tool to address low rise masonry buildings' seismic vulnerability. In urban areas, where densification means blocks are composed of 1- to 5-story tall buildings, the mitigation approach should be focused on the entire block as vulnerable buildings will interact with safer buildings, jeopardizing their safety. There is no simplified methodology in Colombia for existing buildings taller than 3 stories. The existing capacity of qualified builders needs to be stimulated for all types of construction, including low-income housing, equally. When the lateral systems were analyzed through the evaluation of 30 houses, all were found deficient in strength. The seismic vulnerability of this building type should be addressed soon, before the design earthquake occurs. Engineers who use the Manual need training and mentoring by more experienced engineers during their early application of the methodology.

4.2 Financial

Retrofitting cost is very competitive when compared to new construction costs in smaller homes, particularly if the additional cost of redevelopment, demolition and new construction, and the associated social problems are considered. Based on the cost analysis of 20 house retrofit designs, the subsidy covers around 50% of the cost of the required retrofit intervention for a single-story house. The homeowner has to cover the other 50% or more to complete the retrofit. For people in vulnerable sectors of society, this is a steep challenge. Other financing options need to be made available to homeowners.

4.3 Social

Perhaps the most challenging part of a prevention program is to make people aware of the risks which their houses pose to them. The last major earthquake to hit Bogotá happened in 1917, therefore people might have the notion of the potential loss due to Popayán 1983, or Armenia 1999, which happened in very different contexts than those that exist in dense, urban Bogotá. Retrofitting a house has a positive effect on the occupants and their neighbors. Homeowners are emotionally invested in the home they have built over the years. With a retrofit program, builders and homeowners would more easily understand the deficiencies in existing homes will be more able to identify the adequate means to overcome them.

5. Acknowledgements

We would like to express our gratitude to those who have participated actively in this project: CVP, Secretaría del Hábitat, engineer José Joaquín Álvarez, and architect Ricardo Ramírez.

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