VII CONGRESO NACIONAL DE INGENIERÍA SÍSMICA
BOGOTÁ, MAYO 27 A 29 DE 2015
uniandes
ais Asociación Colombiana de Ingeniería Sísmica

Adaptación de un sistema ingenieril simplificado de evaluación y diseño de reforzamiento sismo resistente para vivienda en Bogotá

Adaptation of a simplified engineered approach to housing seismic evaluation and retrofit design for use in Bogotá

M. Lisbeth Blaisdell, SE MS[1], Elizabeth Hausler Strand, PhD[2] and Juan Caballero[3]

[1]Director of Engineering, Build Change, Port-Au-Prince, Haiti; [2]CEO, Build Change, Denver, Colorado, USA; [3]Director of Programs and Partnerships for Latin America, Build Change, Bogota, Colombia

RESUMEN

Después del terremoto de magnitud 7.0 que ocurrió en Haití en el 2010, Build Change desarrolló, en colaboración con Degenkolb Engineers, una guía de evaluación y reforzamiento para pequeñas edificaciones de mampostería de Haití, basada en las provisiones y metodología de los estándares estadounidenses, ASCE 31 y ASCE 41. El ministerio Haitiano de Obras Publicas Transporte y Comunicaciones (MTPTC) adoptó esa guía; En Haití se han reforzado más de 1,300 viviendas utilizando esta guía con asistencia técnica de Build Change, y se están desarrollando actualmente tres programas de reforzamiento con tres organismos distintos.

Mientras que la exitosa implementación de la guía por Build Change y sus contrapartes en Haití ha ayudado a incrementar la existencia de viviendas seguras en ese país después del terremoto, un programa de evaluación y reforzamiento sísmico de vivienda también puede ser utilizado para reducir la vulnerabilidad en un contexto anterior a un desastre. Build Change ha trabajado con sus socios en Colombia para mostrar la utilización de una guía similar para la evaluación y el diseño de reforzamiento sismo resistente en viviendas pequeñas de mampostería en Bogotá, donde un elevado porcentaje de personas está en riesgo debido a vivienda vulnerable a sismos. Los procedimientos planteados incluyen un método de evaluación para edificaciones existentes de mampostería de baja altura que permite determinar su capacidad de resistir a sismos futuros. Se identifican las deficiencias sísmicas a través de una lista de verificación y un método simplificado de cálculo. También se han propuesto algunas técnicas especificas de reforzamiento para mitigar cada deficiencia, de manera que se pueda reforzar la estructura hasta llevarla a un nivel de desempeño de salvaguarda de vidas humanas. La ponencia describe la metodología para los procedimientos de evaluación y reforzamiento sísmico implementada en Haití, y las principales adaptaciones técnicas para ser utilizada en Bogotá, incluyendo los cálculos de esfuerzo cortante realizados como una revisión de porcentaje de área de muros. Se incluyen estudios de caso de Bogotá y de Haití.

Palabras clave: sismo resistente, reforzamiento, vivienda, reducción de riesgo.

ABSTRACT

After the 7.0 magnitude earthquake struck Haiti in 2010, Build Change developed, in collaboration with Degenkolb Engineers, seismic evaluation and retrofit guidelines for small masonry buildings in Haiti, based on the provisions and methodology of the U.S. standards, ASCE 31 and ASCE 41. The Haitian Ministry of Public Works, Transport and Communications (MTPTC) adopted these guidelines; Over 1,300 houses in Haiti have already been retrofitted using these guidelines with technical assistance from Build Change, and retrofit programs with three different organizations are currently ongoing.

While the successful implementation of the guidelines by Build Change and partners in Haiti during the reconstruction period has helped to increase the stock of safe homes there after the earthquake, a housing seismic evaluation and retrofit program can also be used to help reduce vulnerability in a pre-disaster context. Build Change has worked with partners in Colombia to demonstrate the use of similar guidelines for the seismic evaluation and retrofit design of small masonry houses in Bogota, where there is a large percentage of people at risk due to seismically vulnerable housing. The proposed procedures include an evaluation procedure for existing low-rise masonry houses in order to determine their ability to withstand future earthquakes. Seismic deficiencies are identified through use of the checklist and simplified calculation procedure. Specific retrofit techniques are included in order to mitigate each deficiency thereby retrofitting the building structure to a life-safety performance level.

The paper describes the methodology for the seismic evaluation and retrofit procedures implemented in Haiti and the primary technical adaptations for applicability in Bogota, including the lateral resistance analysis performed as a wall area percentage check. Case studies of implementation both in Haiti and Bogota are included.

Keywords: Seismic resistance, retrofitting, housing, risk reduction.

El presente artículo hace parte de las memorias del VII Congreso Nacional de Ingeniería Sísmica organizado por la Universidad de los Andes y la Asociación Colombiana de Ingeniería Sísmica. Bogotá, Mayo de 2015.

1 INTRODUCTION

The dual goals of a post-disaster housing reconstruction program in which damaged or destroyed homes are rebuilt should be to (1) build new houses that are resistant to earthquakes and other disasters and satisfactory to the people, and (2) change the construction practice permanently so that houses built after the technical and financial assistance cease are also earthquake resistant. To realize these goals, important criteria relating to the technical, economic and social aspects of the project must be met [1]. These criteria are identified in Table 1. After the January 12, 2010 Mw = 7.0 earthquake struck Haiti, Build Change, a non-profit social enterprise, developed, in collaboration with Degenkolb Engineers, a San Francisco-based seismic engineering firm, seismic evaluation and retrofit guidelines for small masonry buildings in Haiti [2], based on the provisions and methodology of the U.S. standards, ASCE *31 Seismic Evaluation of Existing Buildings* [3] and *ASCE 41 Seismic Rehabilitation of Existing Buildings* [4]. Over the past five years, Build Change has implemented several housing retrofit programs throughout Port-au-Prince and the surrounding areas, demonstrating that seismic retrofitting and a homeowner-driven approach form a comprehensive solution to meeting the technical, economic and social criteria required to achieve the dual goals of both providing safe, satisfactory housing and enabling permanent change in local construction practices in the post-earthquake setting.

While post-disaster reconstruction presents one opportunity to create a large stock of safe housing and lasting change in construction practices, this opportunity is also present in the pre-disaster context. Subsidized housing improvement programs present an excellent opportunity to achieve the same goals but with the increased benefit of preventing loss of life and property prior to the disaster striking. Although the context is different, the same criteria for success concerning the technical, social and economic aspects of the project, as identified in Table 1, are applicable. It is within this framework that Build Change has developed a procedure, described in this paper, for the seismic evaluation and retrofit design of small masonry houses in Bogota, Colombia where there is a large percentage of people at risk due to seismically vulnerable informal housing, as well as the availability of government subsidies for applicable home improvements.

Tabla 1: Criteria for successful housing reconstruction programs [1]

TECHNICAL	ECONOMIC	SOCIAL
• Earthquake-resistant design • Earthquake-resistant construction • Durable • Easily expanded and maintained • Resistant to other disasters	• Competitive in cost with local, common building methods • Skills and materials widely known and locally available	• Climatically suitable • Appropriate architecture, space and features • Secure • People trust that the structure is earthquake-resistant

2 BACKGROUND

2.1 *Basis*

ASCE 31 and *ASCE 41* are performance-based standards used commonly in the United States for the seismic evaluation and seismic strengthening of buildings, respectively, which have now been combined into a single document, *ASCE 41-13* [5]. These standards were used as the basis for the development by Build Change and Degenkolb Engineers of the seismic evaluation and retrofit guidelines for masonry housing in Haiti. The most common building types used for informal housing construction in Haiti and many other countries, such as Colombia, are confined masonry and unreinforced or partially confined masonry. These standards do not explicitly address confined masonry and the specific common construction practices used in Haiti as these are not common in the U.S. Therefore, adaptation and development was required in order to make the procedure useful to the context in Haiti.

Multiple resources were referenced, including post-earthquake performance observations made by both organizations, confined masonry guidelines and codes from other countries and confined masonry testing and research performed by others previously, and the performance-based approach was adapted to confined masonry. The masonry walls were identified as the deformation-controlled elements of the system and the confining ties as the force-controlled elements. Thus the walls will exhibit some cracking and energy dissipation while maintaining confinement from the reinforced concrete ties to prevent failure and increase system ductility.

2.2 *Context*

The 2010 earthquake in Haiti killed hundreds of thousands of people, and left more than one million people homeless. The Haitian Ministry of Public Works Transportation and Communication (MTPTC) performed a post-earthquake safety assessment program, tagging homes as green (minimal or no damage), yellow (damaged with limited use) or red (damaged and unsafe) in accordance with a methodology modeled after ATC-20 *Procedures for Postearthquake Safety Evaluation of Buildings* [6]. The seismic evaluation and retrofit guidelines were developed in order to provide a technical solution that would permit a more rapid return of people to their homes. Through retrofitting damaged yellow- and red-tagged homes, the stock of socially acceptable, safe and expandable buildings could be increased in a rapid and economical way.

For the hundreds of thousands of homes damaged by the earthquake to be addressed by a retrofit program, the guidelines needed to be technically simple as it was not likely the human resources would be available to perform complex analyses for each home. ASCE-31 outlines a tiered approach to the evaluation of existing buildings, with Tier 1 using checklists and quick calculations, Tier 2 using an analysis of the structure and Tier 3 using an advanced non-linear analysis of the building to determine if the building meets life-safety performance. As the evaluator moves through the tiers, the conservatism in the evaluation reduces and the analysis becomes more detailed and the level of effort increases. The evaluator can stop the process at any tier to assess if the building meets the performance criteria and if not, to either continue to the next tier or design the rehabilitation to mitigate the deficiencies identified. Considering the resource constraints present, the guidelines developed by Build Change and Degenkolb Engineers aimed at rapid retrofit programs in Haiti utilized a Tier 1-type approach, thus accepting some conservatism as a tradeoff for reduced effort (Fig. 1).

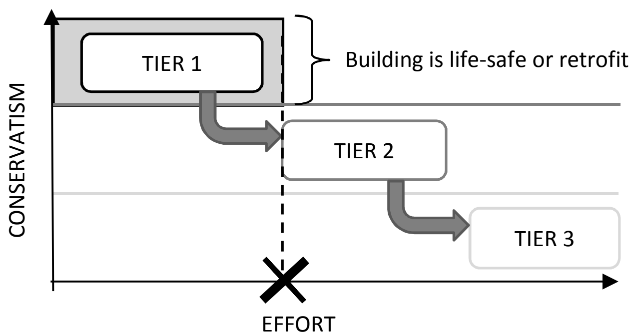

Figura 1: Technical approach of guidelines for Haiti

Figura 2: Typical masonry home in Port-au-Prince, Haiti

3 SEISMIC EVALUATION AND RETROFIT GUIDELINES FOR HAITIAN MASONRY HOUSING

3.1 *Applicability and Criteria*

The guidelines were developed to address typical low-rise (1 to 3 stories) masonry housing in Haiti. The procedures apply to confined or unreinforced concrete block masonry bearing wall buildings, with reinforced concrete slabs or wood-framed roofs (Fig. 2). The guidelines have performance criteria of providing structural life-safety in the design-basis earthquake. Seismicity levels vary throughout Haiti, with spectral short-period design accelerations ranging from 0.54g to 1.37g, and equal to 1.05g for Port-au-Prince (assuming a stiff soil site) [7]. Structural life-safety performance, as defined in ASCE 41, is the post-earthquake performance state in which *the structure has damaged components but retains a margin against onset of partial or total collapse.*

3.2 *Methodology*

The guidelines 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, which checks that the structure and site conform with 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 based on a wall area percentage check. The wall area percentage evaluation requires that the horizontal cross-sectional area of the existing walls divided by the area of the building (existing wall area percentage, PAM_{ex}) be greater than a calculated minimum value (wall area percentage required, PAM_{req}) needed for adequate lateral resistance (Eqn. 1).

$$Existing\ Wall\ Area\ Percentage\ (PAMex) \geq Required\ Wall\ Area\ Percentage\ (PAMreq) \quad (1)$$

The guidelines include specifics for how the required wall area percentage is derived based on site seismicity and building-specific characteristics, such as material quality, construction quality, number of stories, and type of lateral system. The guidelines distinguish between two lateral system types: confined masonry and unreinforced masonry.

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 PAM_{ex} was found insufficient, the retrofit can include supplementing the lateral resistance of the building through 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.

3.3 *Project Applications*

The procedures of the seismic evaluation and retrofit guidelines developed by Build Change and Degenkolb Engineers were adopted by the MTPTC in the *Guide de Renforcement Parasismique et Paracyclonic des Batiments* [7], enabling their use by qualified engineers throughout Haiti.

3.3.1 *Homeowner-driven Construction Projects*

Several home-owner driven reconstruction projects have implemented the guidelines in the last five years and at least 1,300 homes have been retrofitted. Homeowner-driven construction puts the homeowner at the center of the decision making and responsibility for the project so that they are actively participating through selecting design options, choosing a builder and then overseeing the acquisition of materials and construction works. This approach results in greater satisfaction and buy-in by the homeowner, an increased willingness to invest more in disaster preparedness, and a reduction in dependency. [8] Subsidies are disbursed to homeowners in installments so that the construction quality can be confirmed prior to the next installment being granted to engage the homeowner further as they are held accountable for the successful outcome of each phase.

Retrofitting is particularly suited to the homeowner-driven approach because the technical solutions for the retrofit can be varied to suit the needs of the homeowner. For example, in cases where larger wall spacing or more window openings are desired, reinforced overlays can be used to keep wall lengths short as they provide a more dense wall area and concentrated resistance. In cases where a homeowner would like to add a new story to the house in the future, the retrofit can be designed so that the existing home can safely resist the additional earthquake demands from the future level when it is constructed. Homeowner satisfaction is further increased because often retrofitted houses are improved, safer versions of the houses that the same families lived in before the earthquake – the ones the homeowners chose to build or buy originally (Fig. 3) [9].

Figura 3: A home in Port-au-Prince before (left) and after (right) a seismic retrofit

Additionally, the techniques used to retrofit the homes are made with locally available materials and with skills common to builders in the geographical area. The homeowner can then control all portions of the work as they are able to more easily source the materials and find a suitable builder.

3.3.2 *Cost Efficiency*

Retrofits were found to be more cost-effective than new construction, even for retrofits of red-tagged buildings. Based on the projects Build Change participated in between 2011 and 2012 (over 1000 homes), new construction was found to be on average USD 193/m^2 while retrofits of red-tagged buildings had an average cost of USD 126/m^2 and those of yellow-tagged buildings were only USD 67/m^2 [10].

4 SEISMIC EVALUATION AND RETROFIT PROCEDURES FOR LOW-RISE MASONRY HOUSING IN BOGOTA

Bogota is located in an area of medium seismic risk (Amenaza Sísmica Intermedia) according to *Reglamento Colombiano de Construccion Sismo Resistente, NSR-10* [11]. The city is characterized by large zones, housing millions of people in lower economic groups, which initiated as informal settlements but have been moving through the process of formalization in the recent past. In these regions, initial home construction frequently occurred without conformance to building design and construction regulations and thus homes were built without all the requirements needed to adequately resist future earthquakes, leaving a large population at risk (Fig. 4).

Figura 4: Typical Bogotá neighborhoods in the process of formalization

In response, the municipality of Bogota has allocated funds for subsidized housing improvement programs in which homeowners living in these prioritized neighborhoods can apply for grants to improve the habitability and structural safety of their homes. While disbursement of subsidies to improve habitability have been easily distributed to various localities, the structural improvement subsidies have been distributed at a slower pace due to difficulties encountered with implementing the technical solutions proposed. The cost of structural improvements has often exceeded the subsidy amount due to the extensive improvements required to convert an existing building to conform to all of the structural regulations for new buildings. The seismic evaluation and retrofit procedures proposed below are intended to provide a technical solution that permits buildings to be retrofitted to a life-safe level without requiring that all measures for new construction are met, therefore reducing the cost of designing and building the improvements.

4.1 *Applicability and Criteria*

The proposed seismic evaluation and retrofit procedures are applicable for 1- to 3-story homes (Groupo I), depending on the level of seismic risk, constructed of hollow clay block or solid clay brick confined or unreinforced masonry construction as summarized in Table 2. Suspended slabs are solid reinforced concrete, or roofs may also be constructed of light-weight materials such as wood or light-gage framing and sheet metal roofing. For existing buildings, it is proposed that the maximum height or seismic zone for the permitted systems be extended beyond that what is permitted for new construction by NSR-10 (Tabla 2).

The performance criteria for the procedures is structural life-safety in the design-basis earthquake. Considering the microzonification of Bogota [12], the short-period spectral design acceleration, S_a, ranges from 0.36g to 0.73g, throughout the city.

4.2 *Methodology*

The methodology for performing the seismic evaluations and retrofit designs for Bogota follows the same basic steps as those used in Haiti. A site visit is performed and the seismic deficiency identification checklist is completed to identify the key vulnerabilities of the building and site. Deficiencies are then systematically corrected as part of the retrofit design to convert the buildings to a conforming structure that is expected to have life-safety performance for the design earthquake. Some deficiencies are not within the scope of the simplified procedures and require a more detailed study by a qualified engineer. For example, proposed retrofit solutions for buildings on sites with liquefaction potential is beyond the scope of the procedures and could not be addressed without the detailed input of a qualified engineer.

Tabla 2: Applicable Sistemas Estructurales de Muros de Carga

Sistema de Muros de Carga			m (1)	Zonas de Amenaza Sísmica		
	Sistema resistencia sísmica (fuerzas horizontales)	**Sistema resistencia para cargas verticales**		**Alta**	**Intermedia**	**Baja**
				Altura máxima	**Altura máxima**	**Altura máxima**
1. Muros estructurales						
VULNE-RABILI-DAD	a. Muros de mampostería no reforzada o mampostería simple (MS)	El mismo	1	1 piso máximo (2)	2 pisos máximo (2)	2 pisos máximo
	b. Muros de mampostería confinada (MC)	El mismo	2	2 pisos máximo	3 pisos máximo	3 pisos máximo
REFORZA-MIENTO	c. Muros de mampostería no reforzada o con algunos confinados	El mismo	1	1 piso máximo (2)	2 pisos máximo (2)	2 pisos máximo
	d. Muros de mampostería confinada (MC) o Pórticos con Mampostería de Relleno (PMR)	Muros de mampostería confinados o pórticos con mampostería de relleno	2	2 pisos máximo	3 pisos máximo	3 pisos máximo
	e. Muros de mampostería reforzada externamente (1 cara) (2)	Muros de mampostería no reforzada y algunos reforzados externamente (2)	1	1 piso máximo	2 pisos máximo	2 pisos máximo

(1) m es el factor de reducción de la fuerza sísmica,
(2) Varía de lo permitido para edificación nueva en NSR-10

4.2.1 *Deficiency Identification Checklist*

The deficiency identification checklist includes twenty eight items divided into six major categories, identified in Table 3, each verifying that a specific aspect of the structure conforms to earthquake resistant standards based on the requirements of NSR-10 and commonly known seismic performance concerns. For example, checklist item 3.4 Altura de Pisos, requires that the story heights are no more than 3.0m for the ground floor and 2.75m for upper levels. This is ensures that the walls will have sufficient resistance to the out-of-plane earthquake demands and is consistent with the requirements of NSR-10, Section E.3.5.1 for wall slenderness (height must be less than 25 times the thickness) given the minimum wall thickness of 12cm required by the procedures [11].

Table 3: Deficiency Identification Checklist Items

CATEGORY	ITEM		CATEGORY	ITEM	
Amenazas Geológicas del Sitio	1.1	Licuefaccion	Sistema Constructivo	3.8	Voladizos
	1.2	Falla de Ladera		3.9	Danos
	1.3	Muros de Contencion del Sito	Muros (Paredes) de Mampostería	4.1	Confinamiento
Cimientos	2.1	Cimentacion de Muros (Paredes)		4.2	Vanos
	2.2	Desempeno de los cimientos		4.3	Viga de Coronación
	2.3	Volcamiento		4.4	Porcentaje de Área de Muros
	2.4	Conexión entre los elementos de la Cimentacion	Configuracion	5.1	Torsion
				5.2	Edificaciones adyacentes
	2.5	Deterioro		5.3	Discontinuidades Verticales
Sistema Constructivo	3.1	Materiales	Elementos Constructivos	6.1	Columnas de Concreto Aisladas o Disontinuas
	3.2	Ruta de Carga			
	3.3	Cantidad de Pisos		6.2	Aberturas en Losas Cerca de Muros Cortantes
	3.4	Altura de Pisos			
	3.5	Carga		6.3	Parapetos
	3.6	Sistema de Piso y Cubierta		6.4	Escaleras y Descansos
	3.7	Muros			

4.2.2. *Wall Area Percentage Check*

Checklist item 4.4 Wall Area Percentage includes a simplified analysis of the lateral resistance of the building, in which the demand (wall area percentage required, PAM_{req}) must be less than the capacity (wall area percentage provided, PAM_{ex}) (Eqn. 1). The lateral force demand is based on the equation for the pseudo lateral force, V, from ASCE 31 (Eqn. 2). For these procedures, the modification factor for inelastic displacements, C, is taken as 1.4 for a one-story shear wall structure, and the seismic weight of the building, W, is taken as the area of the building, A_b, multiplied by the number of stories, N, and an average distributed weight of 4.8kPa. The response spectral acceleration for the design basis earthquake, S_a, for the low-rise masonry shear wall buildings addressed in the procedure, is assumed to be equal to the short-period spectral design acceleration. This value is calculated in accordance with NSR-10 Equation A.2.6-3, with the site adjustment factor in accordance with microzontification requirements [11, 12]. Additionally, while the checklist requires examination confirm that an extreme torsional irregularity is not present, the lateral demands in the proposed procedures are increased by a factor of 1.5 to account for torsion in lieu of an additional detailed analysis. This results in a lateral force demand per Eqn. 3.

$$V = CSaW \qquad (2)$$

$$V_U = 1.5 \times 1.4 \times Sa \times A_b \times N \times 4.8kPa \qquad (3)$$

The resistance of the walls, which are the deformation-controlled elements, of the building in a given direction (Eqn. 4) is taken as a summation of the lateral resistance of the walls equal to the gross area of the wall, A_w, multiplied by the shear strength of the wall, v_m, and the density, or percent solid, of the wall over its thickness.

$$V_n = v_m \times A_w \times \%\, solid \qquad (4)$$

Taking typical Bloque 4 as the basis of the procedures, the hollow block compressive strength is assumed to be 2.0 MPa [13] and the percent solid is calculated from the typical horizontal cross section to be 32%. The shear strength of the masonry wall, v_m, is taken as 210kPa, which is based on calculations made in accordance with NSR-10 Sections D3.7.5 and D5.8.4.2 [11] assuming a block compressive strength of 2.0MPa and a mortar compressive strength of 5.0 MPa and is consistent with the results of diagonal shear laboratory tests [13]. These values are then inserted into the acceptance criteria for deformation controlled actions in which the demand is reduced by the force reduction factor, or m-factor, (Eqn. 5) and solved for the basic wall area percentage required, $bPAM_{,req}$ (Eqn. 6). The m-factor is taken as 2.0 and 1.0 for confined masonry and unreinforced masonry, respectively (Tabla 2).

$$V_n \geq \frac{V_U}{m} \qquad (5)$$

$$bPAM_{req} = A_w \div A_b \geq 15.1\% \times N \times S_a \div m \qquad (6)$$

The basic wall area percentage required, $bPAM_{,req}$, is then modified by a series of factors to account for building-specific characteristics to arrive at the wall area percentage required (PAM_{req}) for the specific building, story and direction under consideration (Eqn. 7). It recommended that PAM_{req} be not less than 4% for confined masonry and 8% for unreinforced masonry.

$$PAM_{req} = bPAM_{req} \times C_B \times C_Q \times C_R \times C_L \times C_W \qquad (7)$$

Where, C_B is the block strength factor, used to adjust the required wall area percentage for varying strengths of existing masonry, C_Q is the construction quality factor, used to adjust the required wall area percentage based on the quality of the existing construction, C_R is the retrofit factor, used to adjust the required wall area percentage according to if the existing building is being evaluated or the retrofit design is being evaluated, C_L is the level factor, used to adjust the required wall area percentage depending on which particular story is being analyzed in a multi-story building, and C_W is the seismic weight factor, used to adjust the wall area percentage depending on the weight of the specific building being evaluated.

Estimated values of C_B are presented in Table 4, continuing with the assumed compressive strength for mortar of 5.0MPa. It is recommended that existing block strength values greater than 3.0 MPa be justified by testing of block samples taken from the house under evaluation. As the existing block strength is increased, the wall area percentage required decreases.

The construction quality factor, C_Q, is equal to 1.0 for existing buildings with average construction quality. It then increases at the evaluator's discretion to a value of 1.35 for poor quality construction and to 1.75 where it is observed that the majority of the vertical masonry joints lack mortar. The value of 1.35 for poor quality was established to be consistent with the ratio of factors for average (ϕ=0.8) to poor (ϕ=0.6) quality identified in NSR-10, Section A.10 [11]. As the construction quality decreases, the wall area percentage required increases.

The retrofit factor, C_R, is taken as 0.75 for the evaluation of the existing building and as 1.0 for the evaluation of the retrofit design. The m-factors used in ASCE-31 for the evaluation of buildings are approximately 4/3 higher than those used in ASCE 41 for the rehabilitation design. To mirror this approach in simplified way, the proposed procedures use a C_R equal to 0.75 to reduce the demands when performing a seismic evaluation. When a proposed retrofit design is being evaluated, the full seismic demands are applied.

The level factor, C_L, varies based on the number of stories in the building, the story being analyzed and the roof type. It is a combination of two design parameters, the vertical distribution of seismic force based on mass and story height in accordance with Equations 4-2 and 4-3 of ASCE 31 [3], and the modification factor based on expected maximum inelastic displacements (C Factor from ASCE-31 Table 3-4 [3]). The resulting factors are presented in Table 5.

The seismic weight factor, C_W, is used to adjust the required wall area percentage when the average distributed building weight tributary to a floor is different than the 4.8kPa as assumed by the $bPAM_{req}$ calculations. Buildings with wall coverings such as plaster or reinforced concrete, or buildings with denser wall material, such as solid brick, have a higher seismic weight than 4.8kPa per floor, which corresponds to a building of typical floor plan, composed of uncovered block 4 or 5 walls. As the weight increases, the wall area percentage required increases (Eqn. 8).

$$C_W = (Peso\ sísmico\ tributario\ distribuido\ para\ un\ piso\ medianero)/4.8kPa \qquad (8)$$

Tabla 4: Factor de Resistencia del bloque, C_B

f'cu de la mampostería MPa (psi)	Factor C_B bloque 4 o 5	Factor C_B bloque solido
1.5 (218)	1.13	1.00
2.0 (290)	1.00	0.91
4.0 (580)	0.74	0.74
8.0 (1160)	0.54	0.57
12.0 (1740)	0.44	0.48
>15 (2750)	0.40	0.43

Tabla 5: Factor de Nivel, C_L

Nivel	Pisos que tiene el inmueble			Notas
	1-piso	2-pisos	3-pisos	
3	-	-	0.39	Para edificaciones con pisos y cubiertas pesadas compuestas por entrepisos y cubiertas de concreto reforzado macizas
2	-	0.57	0.65	
1	1.00	0.86	0.79	
3	-	-	0.14	Para edificaciones con entrepisos de concreto y cubierta liviana
2	-	0.19	0.46	
1	1.00	0.57	0.61	

To verify if checklist item 4.4 conforms or not during the evaluation, the PAM_{req} is calculated for each principle direction at each story of the building and compared to corresponding existing wall area percentage (PAM_{ex}) to assess is the building has sufficient lateral resistance in the existing state. The existing wall area percentage, PAM_{ex}, is calculated for a given level and direction by adding the effective areas of all the walls in the corresponding direction and level per Equation 9. Only wall lengths that are at least 1.0m long (excluding openings) are considered to contribute to the lateral resistance.

$$PAM_{ex} = \frac{t_{m1} \times l_{m1} \times CN_1 + t_{m2} \times l_{m2} \times CN_2 + ... + t_{mn} \times l_{mn} \times CN_n}{A_b} \qquad (9)$$

Where, t_{m1} = thickness of wall 1, l_{m1} = length of wall 1, C_{N1} = net area factor for wall 1, and A_b = Area of the building plan. The net area factor, C_N, (Eqn. 10) is used to account for cases when the percent solid of a wall varies from 32%, which was used as the basis for the required wall area calculations. For example a solid brick wall is 100% solid and so C_N would equal 3.13.

$$C_N = \frac{((solid\ area)/(net\ area))}{0.32} \qquad (10)$$

If the existing wall area percentage is found to be below that required, the building does not conform and corrective action is required for the level and direction found to be non-confirming. In this case, the effective wall area percentage (PAM_{eff}) is supplemented by the addition of structural elements. To simplify the retrofit design, the additional resistance provided by new structural elements is accounted for using adjustment factors, or K-factors, which relate the strength of the added element to the strength of the block 4 masonry walls used as the reference wall type (Eqn. 11). K-factors are proposed for new masonry, thin cement plaster overlays and thicker reinforced concrete overlays in the procedures. The effective wall area percentage, PAM_{eff}, accounting for the retrofit elements is calculated by Eqn. 12.

$$K_{element} = \frac{Shear\ resistance\ of\ added\ element}{Shear\ resistance\ of\ block\ 4\ masonry\ wall\ with\ existing\ wall\ strength} \qquad (11)$$

$$PAM_{eff} = \frac{A_m}{A_b} + \frac{0.095m \times (\sum K_m L_m + \sum K_p L_p + \sum K_c L_c)}{A_b} \qquad (12)$$

Where, A_m = sum of existing wall areas in the level and direction under consideration that will remain in the retrofitted state, A_b = the plan area of the building, K_m = adjustment factor for new masonry walls, L_m = length of new masonry walls in the level and direction under consideration, K_p = adjustment factor for cement plaster overlay, L_p = length of walls with new cement plaster overlay added in the level and direction under consideration, K_c = adjustment factor for reinforced concrete overlay and L_c = length of walls with new reinforced concrete overlay added in the level and direction under consideration.

4.3 *Example Evaluation and Retrofit in Bogota*

In 2014 Build Change worked with partners to apply the proposed procedures to a pilot project, performing several seismic evaluation and retrofit designs for existing homes in Bogota. One of the retrofit designs was built and is presented below.

4.3.1 *Building Evaluation*

The existing house was a one-story building approximately 40m^2 in plan, with walls composed of existing block 5 partially confined masonry bearing walls with a light-weight roof. The existing plan is shown in Figure 5. The primary deficiencies identified were *load path* as the maximum permitted spacing between parallel walls was exceeded, *confinement* as an upper ring beam was not present and the top of the walls were unconfined, *vanos* due to the lack of lintel beams above openings, *upper ring beam* due to the lack of an upper ring beam, and *wall area percentage* as the PAM_{ex} was found to be less than the PAM_{req} for both principal directions.

The spectral design acceleration, S_a, was 0.52g and the number of levels was taken as 2, assuming that a second level would be added in the future, resulting in a $bPAM_{req}$ of 15.7%. Due to the lack of all necessary confining elements, the building wall evaluated as an unreinforced masonry building with an m-factor equal to 1.0. C_B was taken as 1.0 for f'_{cu} = 2.0MPa; C_Q was taken as 1.0 for average quality construction; C_R was 0.75 for the evaluation; C_W was taken as 1.39 due to the presence of plaster wall coverings on most walls; the level factor, C_L, was taken as 0.86 for the ground floor of a two-story building. The resulting required wall area percentage, PAM_{req}, was 14.1%. The existing walls resulted in a PAM_{ex} equal to 6.1% in transverse direction and 3.1% in the longitudinal direction.

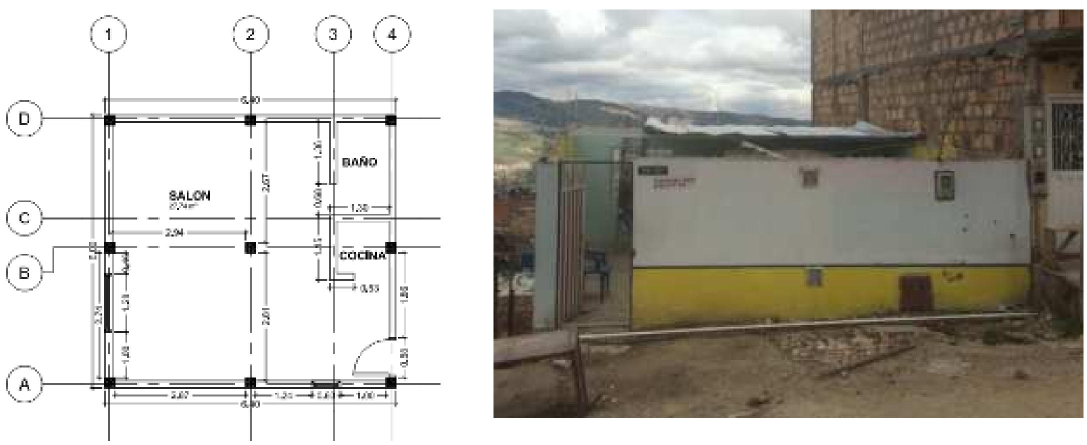

Figura 5: Floor plan (left) and photo (right) of the existing building

4.3.2 *Retrofit Design*

For the retrofit design, walls and corresponding foundations were added to the interior to reduce the spacing between parallel walls and to increase the effective wall area percentage. The walls were added according to the homeowner's spatial needs and current regulations. A continuous upper ring beam was added to the top of all walls to provide confinement to the wall as well as reinforced lintels above the window and door openings. Cement plaster overlay was added to some of the existing walls and a window at Line A was infilled to further increase the effective wall area percentage. Additionally, confining elements were added to increase the ductility of the building and reduce the required wall area percentage (Figure 6). Considering the increased m-factor of 2.0 for confined masonry, the increased C_R factor of 1.0 for retrofit design and the increased C_W factor of 1.55 for the weight added to the building by new elements, the PAM_{req} for the retrofit design was equal to 10.5%. In the retrofit condition, the PAM_{eff} was 12.5% in the transverse direction and 11.2% in the longitudinal direction, thus exceeding the amount required.

4.3.3 *Cost*

The cost of the retrofit construction, including materials and labor totaled approximately USD 5,700 or USD 143/m^2. It is of note that additional works were performed as part of the retrofit to increase the habitability of the home and so this cost includes not only the works specifically required for the seismic strengthening, but also the cost of other works required for habitability. The cost for the structural work in a new home in Bogota is estimated as USD 200/m^2.

Figure 6: Floor plan (left) and photo (right) of the completed retrofit

CONCLUSIONES

The methodology of the seismic evaluation and retrofit guidelines developed for Haiti to implement rapid retrofit programs at scale after the 2010 earthquake have been adapted to the construction practices and structural design requirements in Bogota for integration into a complete solution to the technical, social and economic criteria required for addressing the large seismically vulnerable stock of housing in the metropolitan area. The proposed procedures provide a simplified method of identifying and addressing seismic deficiencies within one- to three-story buildings of confined and unreinforced masonry construction. The proposed methods for rehabilitating the homes use local construction practices and materials to increase direct accessibility to homeowners and facilitate the implementation at scale with the homeowner driven approach.

AGRADECIMIENTOS

The authors would like to acknowledge Build Change's institutional partners in Colombia: Swiss Contact, SENA and Caja Vivienda Popular. We would also like to acknowledge José Joaquín Alvarez Enciso for his valuable input, Eduardo Castell on behalf of Asociacion Colombiana de Ingenieria Sismica and Luis Guillermo Aycardi on behalf of Fundacion Vivienda Segura for their support in the development of the procedures for Bogota.

REFERENCIAS

[1] E. Hausler, "Long-term change in construction practice through post-earthquake reconstructions," presented at the 1st International Conference on Urban Disaster Reduction, Kobe, Japan, 2005.

[2] *Seismic Evaluation and Retrofit Manual, MTPTC Training, April & May 2011*. Build Change and Degenkolb Engineers, revised September 2013.

[3] *Seismic Evaluation of Existing Buildings*, ASCE/SEI 31-03.

[4] *Seismic Rehabilitation of Existing Buildings*, ASCE/SEI 41-06.

[5] *Seismic Evaluation and Rehabilitation of Existing Buildings*, ASCE/SEI 41-13.

[6] *Procedures for Postearthquake Safety Evaluation of Buildings*, ATC-20, 1989.

[7] *Guide de Renforcement Parasismique et Paracyclonic des Batiments,* Ministere des Travaux Publics Transports et Communications, Haiti, 2013.

[8] *Building Back Housing in Post-Disaster Situations – Basic Engineering Principles for Development Professional: A Primer*. Build Change for International Resources Group (IRG), USAID, January 2012, revised January 2014, Draft.

[9] *Seismic Retrofit of Housing in Post-Disaster Situations– Basic Engineering Principles for Development Professional: A Primer*. Build Change for Parsons Engineering, USAID, January 2014, Draft.

[10] "Homeowner-Driven Housing Reconstruction and Retrofitting in Haiti: Lessons Learned, 4 Years After the Earthquake," Build Change Report, January 9, 2014.

[11] *Reglamento Colombiano de Construccion Sismo Resistente, NSR-10*, Ministerio de Ambient, Vivienda y Desarrollo Territorial y Comision Asesora Permanente Para el Regimen de Construcciones Sismo Resistentes, 2010.

[12] *Decreto 523*, Secretaría General de la Alcaldía Mayor de Bogotá D.C., 2010.

[13] Jairo Andrés Giraldo Galvis y David Mauricio Méndez Nivia, "Evaluación de Vulnerabilidad Sísmica en Viviendas de Mampostería en Estratos Uno y Dos Según Tipificación de la Estructura," Facultad de Ingeniería de la Universidad de Los Andes, Bogotá DC, Colombia, 2006.

El presente artículo hace parte de las memorias del VII Congreso Nacional de Ingeniería Sísmica organizado por la Universidad de los Andes y la Asociación Colombiana de Ingeniería Sísmica. Bogotá, Mayo de 2015.