

TOWARDS A SUSTAINABLE AND CONTEXT-BASED APPROACH TO ANTI-SEISMIC RETROFITTING TECHNIQUES FOR VERNACULAR ADOBE BUILDINGS IN COLOMBIA.

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ABSTRACT:

In Colombia earthen buildings, mostly adobe, makes up 80% of the national monumental heritage and historic urban centres. Moreover, vernacular earthen techniques have been largely used for dwellings in rural villages, small towns or informal settlements and represent, nowadays, a huge architectural and cultural heritage of the country. Due the brittle behaviour and low ductility of the building material, characterized by both low tensile and bending strength, earth constructions show high seismic vulnerability; nevertheless, though Colombian earthquake hazard level is considered very high, current national seismic building regulations do not include any reference to earthen architecture. Seismic failure mechanisms most frequently occurring to masonry architecture, as adobe buildings rehabilitation techniques and seismic behaviour improvement practices, have been widely published. This paper aims to investigate possible causes associated to failure mechanisms due to common adobe building practices in Colombia and intervention strategies, to be eventually implemented in order to reduce risks. The paper focuses on strategies and technologies for seismic retrofitting, while evaluating their effectiveness and feasibility through ‘sustainability’ indicators, based on literature quantitative and qualitative data, and strictly related to rural Colombian economic, social and environmental conditions, where available resources are scarce and labour often not qualified.

1. INTRODUCTION

In Colombia, traditional earthen building techniques make up 80% of the national monuments and historic urban centres and some notable examples can be found in Barichara, La Candelaria, Villa de Leyva, etc. (Ruiz et al., 2012). Most of those constructions were built during the XVI and XVIII centuries. Spanish invaders used this vernacular technology to establish cities centres and monumental architecture such as churches, abbeys or government buildings. But traditional earthen techniques - as adobe, ‘tapia’ (rammed earth) or ‘bahareque’ (wattle-and-daub) - have been also largely used for informal rural and urban dwellings, in small settlements all over the country.

Earth buildings, as load bearing masonry technologies, show quite low strength to seismic load, although Colombia is considered as a very high seismic hazard area, with spectral acceleration values up to 0.40 g. Nevertheless, actual building seismic regulation (NSR-10, 2010) do not include any reference to earthen architecture, neither for new constructions, nor for heritage renovation (Ruiz et al., 2012).

Earthen architecture structural behaviour and its main common failures under seismic action have been recently largely addressed in literature, as well as the topic of the enhancement of seismic resistance, through both building best practices and suitable retrofitting techniques.

A schematic representation of seismic failure mechanisms most likely to occur to load-bearing masonry architecture and particularly to earth buildings, have been resumed in Table 1, starting from the work of D’Ayala and Speranza (2002) and Ortega et al. (2017) respectively. Earth brittle mechanical

behaviour as building material and its low tensile and bending strength (Blondet et al., 2011; Lopez, 2018) do not allow the structure to dissipate energy, during seismic action, and this usually leads to the brittle failure of the structure. When the seismic action is quite contained, the most common failure mechanisms are those caused by bending stresses, generated by non-axial horizontal loads on the load-bearing walls. Different out-of-plane failure mechanisms types are most likely to occur, depending on wall to wall connections quality, on horizontal structures typology, ability to keep the building box-behaviour and to equally distribute loads on the masonry, as well as on the quality of the junctions of horizontal structures to the masonry (Yamin et al., 2007). Instead, due to the more intense seismic action, in-plane shear failure occurs and usually depends by openings dimension and distribution along the wall, as well as by lintels adequacy (Lourenco et al., 2018). Structural in-plane shear cracks can favour out-of-plane mechanism II, III, or V (Table 1).

Recent studies on adobe building technologies best practices, linked to structural behaviour, mainly focus on the enhancement of building well standing and load-bearing walls response under gravitational and seismic loads (Ortega et al., 2007).

The adequate ratio of load-bearing walls’ slenderness and their distribution in the building plan geometry (Rivera, 2013), the need to equally distribute loads and keep the masonry box-like behaviour (Karanikoloudis et al., 2018), avoiding the use of heavy stiff materials (Michiels, 2015), result as the most stressed topics in literature. Most of the measures presented by these studies proved quite effective for new constructions, but, for the most part, can hardly be applied to the rehabilitation of existing buildings.

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FAILURE MECHANISM	SCHEME	FAILURE MECHANISM	SCHEME
I) Bending effort perpendicular to the wall. Horizontal cracking in the base or in middle height and additional vertical cracking. Presented usually in long walls.		V) No shear transfer connections between perpendicular walls. Shear failure of masonry and vertical crack in the corner. Also caused by inappropriate junction between walls.	
II) Bending effort perpendicular to the wall with vertical cracking in centre area. 1. Diagonal cracking that constitute the fault mechanism and fissuration in the upper part of the wall. 2. Tensile failure of masonry and vertical cracks at the corners.		VI) For this fault mechanism the intermediate floor shatters the principal walls in horizontal way, producing the instability of the first floor. Fault caused by wrong connections of ground and first floor walls.	
III) Out-of-plane failure of corners caused by bending effort perpendicular to the walls with not bounded corners, or corners not well attached to the transversal walls.		VII) Fault of the roof to the interior of the house, caused by loss of the supports over the walls. A fault in the upper part of the wall provoke the roof loss its supports. Normal in buildings with heavy roofs.	
IV) Fault because of shear strength in the wall related to high horizontal loads. In many cases the cracks are related to heavy floors or roofs and are magnified in the openings of doors and windows.			

Table 1. Fault types and cracks related to seismic loads. Reproduced from Yamin et al., 2007.& Ortega et al., 2017.

In general, seismic retrofitting strategies found in literature enhance low tensile, bending and shear strengths of load-bearing adobe walls.

In this research paper, the main purpose is to analyse adobe buildings seismic retrofitting strategies most frequently proposed in literature, evaluating their sustainability and feasibility in Colombian rural context.

2. METHODOLOGY

Considering the seismic hazard assessment of Colombia and the high seismic vulnerability of large number of adobe dwellings in the country, a literature review of suitable retrofitting strategies, allowing to improve adobe buildings seismic behaviour, has been carried out. Selected strategies effectiveness and feasibility have been evaluated and compared through five indicators:

- Materials environmental impact
- Material cost and accessibility
- Integration of vernacular building practices
- Facility of implementation
- Materials durability

The rating scale used have been set considering Colombian rural context, economic, social and environmental conditions, as resources availability.

3. ANTI-SEISMIC RETROFITTING STRATEGIES FOR EARTH BUILDINGS

Literature data underline earth low tensile, bending and shear strengths, as a building material (Minke, 2006). The assessed retrofitting strategies tend to increase those strengths in axial or

non-axial wall direction, improving earth building performance under seismic loads, and have been classified as ‘Perpendicular reinforcements, Corner reinforcements and Enclosing reinforcements’.

3.1 Perpendicular reinforcements

Buttresses are frequently used perpendicular to load-bearing walls, to reduce the wall’s length left unbraced; but they find also use at the corners, as a short extension of both converging walls (Ortega et al., 2017). The material and constructive technique, used for the reinforcement, should be the same employed for the existing structure, in order to ensure the same performance of both elements under seismic loads (Lourenco et al., 2018; Karanikoloudis et al., 2018).

Perpendicular reinforcements reduce the bending moment in the middle of the walls, by transferring horizontal seismic loads diagonally to the foundations (Minke, 2001) (Figure 1). Horizontal and diagonal bending cracks and wall overturning are so avoided (Ojeda, 2002). Additionally, corner buttresses can increase walls vertical and horizontal load capacity in a 16% (Angulo et al., 2011).

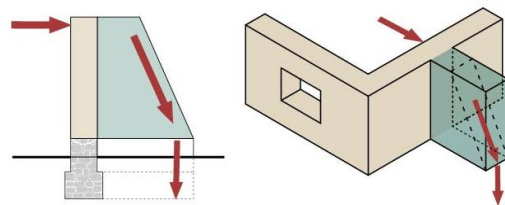


Figure 1. Buttresses seismic load transferring into foundation. Data from Minke (2001).

3.2 Corner reinforcements: braces and shape

Corners are usually considered as one of the major masonry load bearing structures weaknesses, due to bending and shear stress concentration (Ortega et al., 2017). Earth masonries are even more exposed to those stresses, even when proper overlapping and staggering is assured. Two are the main strategies suggested in literature to reinforce wall corners: reducing stress concentration by chamfering wall corners, or supply shear and bending strengths, providing corner bracings, with materials congruent with the adobe building technique.

Corner chamfering helps to reduce the shear and bending stress concentration on the junction of perpendicular walls (Figure 2) (Minke, 2001; Pennacchio, Nicchia, 2013). Even if this strategy can increase by 9% the gravitational and horizontal collapse load (Angulo et al., 2011), can only be applied during new buildings design phase, and cannot be taken into consideration for retrofit interventions.

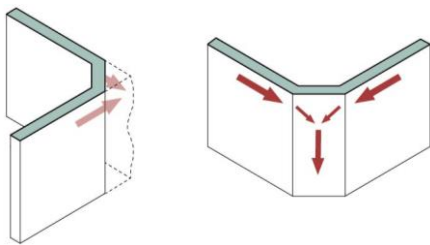


Figure 2. Rounded corners scheme. Figure from Minke, 2001.

Corner braces or corner keys reinforcements otherwise, help strengthening wall-to-wall junction as shown on Figure 3 (Angulo et al. 2011; Ortega et al., 2017).

Corner timber bracing reduce tensile cracks failures, by sharing shear stress among adjacent walls, while helping the masonry to keep its box-like behaviour, by strengthening corner junctions. Additionally, timber is able to assume the bending stress before adobes are carried to failure. Furthermore, even if the adobe masonry would crack in the corners, the braces reinforcement should keep the walls together. This type of reinforcement allows to modify the seismic response of the structure: it acquires a dissipative behaviour and therefore a greater ductility, linked to the post-peak capacity to absorb energy before breaking (Ortega et al., 2017), avoiding a sudden collapse of the corner. Angulo et al. (2011), found that, under vertical and horizontal loads, in case of corner braces fixed to the ring beam, the collapse load increase in 118% (Figure 3a), in 64% using diagonal tie braces (b), while, bracing beams parallel to the walls, showed a collapse load increase of 48% (c).

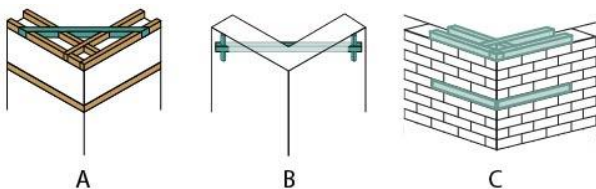


Figure 3. Corner braces options. Image redraw from Ortega et al. (2017).

3.3 Enclosing reinforcements

Enclosing reinforcements make use of tensile-strength materials to realize a further envelop all around the load-bearing masonry, helping to keep the structural integrity under tensile and

bending stress. Failure mechanisms, caused by shear stress (Table 1 IV-V) and bending cracks (Table 1 I-II-III) on the wall plane and in the corners, can be reduced making use of enclosing reinforcements. Several tests have been carried out on the topic, in Peru and Colombia (Blondet et al., 2011).

3.3.1 Plastic geogrids and synthetic ropes reinforcement: were studied for the first time in Latino America at 'Pontificia Universidad Catolica de Perú'. An interesting proposal, in this regard, is the use of a rope grid to reduce costs and make the technology accessible to poor population (Blondet et al., 2011). The behaviour of the wall compound, under horizontal non-axial loads, is schematized in Figure 4 (Invernizzi et al. 2017). Geogrid control flexural cracks caused by the maximum bending moment, thus reducing the associated failure mechanisms and, providing tensile strength to the adobe wall (Blondet et al., 2011). Considering a deflection increase of almost 750% for the geogrids reinforced walls under non-axial loads, Invernizzi et al. (2017) specified that the reinforcement is able to redistribute the stress, bracing the wall and keeping it together, as a single element. Moreover, shear capacity of geogrid reinforced elements is increased by 180% and shear deformation is 4 times larger than the unreinforced walls (Invernizzi et al. 2017). This suggests that failure mechanisms by shear cracking in walls and corners can be reduced by geogrid reinforcements.

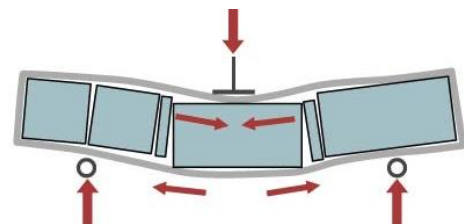


Figure 4. Adobe bricks kinematics and geogrid bending effect. Redrew from Invernizzi et al., 2017.

According to Invernizzi et al., (2017) and to 'Ministerio de Vivienda, Construcción y Saneamiento de Perú' (2017), certain aspects should be considered in geogrid reinforcement application:

- All wall surfaces, should be surrounded, by the geogrid, including openings indoor faces;
- Geogrids should be fixed by ropes passing through ring beams, basement courses and wall thickness;
- In order to control cracking and increase wall's ductility, the reinforcement should be covered with earthen plaster.

3.3.2 Timber grids: In Colombia, a wood strips grid enclosing reinforcement has been also tested. Ruiz et al. (2012) proved timber grid reinforcement to enhance adobe structures ductility and energy dissipation. Yamín et al. (2007) tested a 1:5 scale adobe house model, reinforced with timber grids, using a shake table. Results showed a load increase of 270% during earthquake shake table test; the deformation capacity during the post-peak phase was increased by 200% and the elastic range was multiplied by 4.4. During the same investigation, performed shear tests, on real scale walls, proved that the displacement under axial loads of reinforced walls increased by 400%, while shear strength was increased in 100% (Yamín et al., 2007). Additionally, the reinforcement provides tensile strength, reducing bending and tensile cracks. The reinforced walls proved to resist non-axial loads, even with an additional 32 kN load (Yamín et al., 2007).

Dowling, et al. (2005) tested an external vertical bamboo reinforcement combined with horizontal chicken wire embedded in the masonry and a ring beam. This matrix system, during a shake table test, proved to reduce bending failure mechanisms in walls and corners (Table 1 I-II-III). However, as a matrix system, its performances are not comparable to single external reinforcements; additionally, it requires quite a massive adobe removal and replacement, to be used as retrofitting strategy (Dowling, et al., 2005).

3.3.3 Rib-lath grids reinforcements: on top of the walls, on the corners and openings, create a ‘beams and columns’ additional pattern over both faces of the wall (Ruiz et al., 2012; Yamín et al., 2003). Figure 5 resumes the reinforcement implementation process; required materials are rib-laths, wire, and lime-sand mortar. The use of rib-lath reduce bending cracks in the middle of the wall and in the corners. According to Yamín et al. (2007), the reinforced walls, tested under non-axial loads, supported 43 kN without collapsing. Under earthquake shake table test, the reinforced adobe house model showed both enhanced ductility and energy dissipation of the structure (Yamín et al., 2007). Unexpectedly, the model suffered a sudden collapse (Yamin et al., 2003).

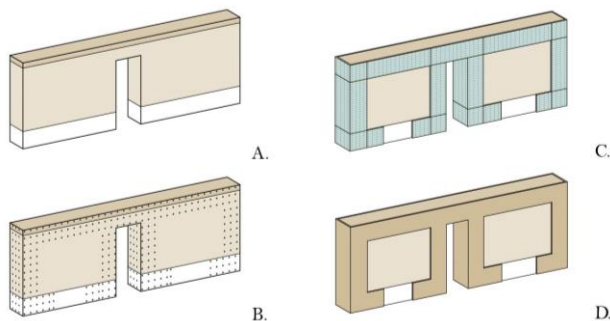


Figure 5. Rib lath reinforcement implementation. a) Adobe walls with ring beam and base course. b) Perforating wall for rib lath fixing. c) Localize rib lath d) Plastering rib lath. Redrew from Yamín et al. (2007) and Ruiz et al. (2012).

4. SEISMIC RETROFITTING STRATEGIES STRUCTURAL AND SUSTAINABLE COMPARISON

4.1 Structural efficiency data comparison

On the basis of literature quantitative and qualitative data, adobe buildings seismic retrofitting strategies, related to the enhancement of structural strengths, have been analysed. The correlation between local building practice and most frequent seismic failure mechanisms have been investigated. Table 2 show how intervention strategies, have been associated to the failure mechanisms possibly occurring, in order to reduce the risk of failure. Considering the structural framework, it is possible to state that the use of ‘geogrids and timber grids’ as anti-seismic reinforcements for adobe buildings are the most effective strategies (among the ones studied), as they present the larger increase of shear, tensile and bending strengths, energy dissipation and post-peak ductility. Additionally, they reduce shear failure in the wall plane and in the corners, and control walls’ flexural cracks.

On the other hand, ‘buttresses’ and ‘corner braces’ are both limited strategies. First one aims at controlling the bending stress on walls and corners, reducing flexural cracks on the wall plane and tensile stress in corners, while the second tends to increase ductility, bending and shear strength, reducing tensile and shear stress in the corners.

Nevertheless, a strategy combining both ‘perpendicular reinforcements and corner braces’ would reduce almost the same failure mechanisms than ‘geogrids or timber grids’ (Table 2). Unfortunately, due the lack of quantitative data, it has been not possible to compare their structural contribution to adobe structures.

‘Rib lath grids’ reduce tensile failures in the wall plane and at the corners, by increasing ductility and bending strength; nevertheless the use of this strategy has been considered too risky, due to the sudden collapse of the walls, reported by Yamín et al. (2003).

4.2 The sustainable indicators

Proposed retrofitting strategies were also analysed through five indicators, in order to verify their sustainability and feasibility into Colombian rural context (Table 4).

4.2.1 Main materials environmental impact: Reinforcement strategies have been analysed, evaluating their main material footprint. Embodied energy (EE), CO₂ released into the atmosphere, global warming potential (GWP), pollutant substances produced, waste category and last lifecycle phase management (Ashby, 2012), have been considered for the analysis (Table 3).

‘Buttresses and corner braces’ show low environmental impact, due to the low loam GWP and the possibility of disposing of the used materials into landfill dumps, at the end of the lifecycle. *Timber grids* are considered as low environmental impact technologies. Regardless of wood drying process, the EE and GWP values are however lower than those of steel or synthetic nylon. On the same way, wood show the lower CO₂ release degree, even if only slightly below the synthetic nylon values. Wood should be responsibly produced, and pollutant substances treatments avoided, in order to keep its environmental impact as lower as possible. Unfortunately, these practices are not common in Colombian rural environment, due to the lack of regulations (Ministerio de Ambiente y Desarrollo Sostenible, Colombia, ONF Andina, 2015). ‘Geogrids and rib lath grids’ reinforcements show elevated environmental impacts, due to the high GWP, EE and CO₂ release of the principal materials employed. Additionally, according to Ashby (2012), synthetic nylon is usually disposed of by incineration, or into ordinary dumps, while dangerous pollutant substances are produced, during its whole lifecycle.

4.2.2 Materials costs and accessibility: ‘Buttresses’ have a clear advantage, due to loam low-cost and high accessibility. ‘Corner braces’ reinforcement, moreover, requires a low amount of material, giving its limited extension; while wood accessibility, can be considered as a further advantage in Colombia, where national timber production present an annual growth of 3% (ONF Andina, 2018). ‘Rib lath grids’ technologies mainly require three materials, easy to be found on the local market; the reinforcement is applied only on a limited portion of the wall, reducing the materials amount needed. ‘Timber grids’ require high amounts of wood, to be applied along the whole adobe walls’ surface and high quantity of steel bolts, metal plates, wire or nails (Ruiz et al., 2012).

Nevertheless, according to literature data (Ministerio de ambiente, vivienda y desarrollo territorial, 2010; Yamin et al., 2007), required timber types can be found among local Colombian species. On the opposite, ‘geogrids’ are usually produced abroad and comes from European and US market, carrying elevated costs (Invernizzi et al., 2017).

4.2.3 Integration of vernacular building practices. Retrofit on rural minor architectural heritage, is usually carried out by local unskilled labour, still bearing vernacular knowledge. The origin of the analysed strategies assume great importance in this sense, to define their feasibility in the Colombian rural context.

Building practice related main causes	Failure Mechanism	Perpendicular reinforcement	Corner braces	Plastic Geogrid	Timber Grids	Rib lath grids
Walls without perpendicular supports	I) Bending effort perpendicular to the wall. Horizontal cracking in the base or in middle highness and additional vertical cracking.	X		X	X	X
Long walls, not bounded corners, openings next to corner	II) Bending effort perpendicular to the wall with vertical cracking in centre area. 1. Diagonal cracking constitutes the fault mechanism and fissuration in the upper part of the wall. 2. Tensile failure of masonry and vertical cracks at the corners.	X		X	X	
		X	X	X	X	X
Not bounded corners	III) Out-of-plane failure of corners caused by bending effort perpendicular to the walls or corners not well attached to the transversal ones.		X	X	X	X
Heavy roofs; large openings	IV) Fault because of shear stress in wall plane, related to high horizontal loads.			X	X	
Not bounded corners, openings next to corner	V) Shear failure of masonry and vertical crack in corner. No shear transfer connections between perpendicular walls.		X	X	X	
Wrong connections of ground and 1st floor walls	VI) Intermediate floor shatters the principal walls in horizontal way, producing first floor instability.					
Heavy roofs	VII) Roof fault into house interior, caused by loss of supports over the walls. A fault in the upper part of the wall provoke the roof loss its supports.	X	X	X	X	

Table 2. Retrofitting strategies Vs failure mechanisms.

Reinforcement	Principal material	Global Warming Potential	Waste category *	Important pollutant substances	Embodied energy [MJ/m ³]	CO ₂ emanated/ye ar [ton/yr]
Perpendicular reinforcements	Loam	20	C	none	56 – 261***	
Corner Braces Timber Grids	Wood	300-550**	A/D	(none) Borax	10,15^3	10,3^8
Rib-lath Grids	Steel (Galvanized steel mesh)	2200	D	Aliphatic & aromatic hydrocarbons; Cadmium; Chrome; Hydrogen fluoride; Zinc	10,15^5	10,4^9
Geogrids	Synthetic Nylon	1650	B/D	Phenol- amines group	10,6^4	10,05^8

* Waste categories: A) Incineration without purification - composting B) Incineration with purification C) landfill dump D) Ordinary dump E) Especial dump F) Strictly controlled dump. ** Air Vs kiln drying. ***Depending if site production and if transported soil.

Table 3. Aspects of the environmental impact considered for the principal material of each retrofitting strategy. Table data is based on Ashby (2012) & Christoforou et al., (2015).

A. Materials environmental impact:

Feasible	Low	Perpendicular R. Corner Braces Timber Grids
Impractical	High	Geogrids Rib-lath Grids

C. Traditional knowledge relevance:

Feasible	High	Perpendicular R. Corner Braces
Impractical	Low	Rib-lath Grids Timber Grid Geogrid

B. Material costs and accessibility:

Feasible	Cheap	Perpendicular R. Corner braces
Acceptable	Medium	Timber Grids Rib-lath Grids
Impractical	Expensive	Geogrids

D. Facility of implementation:

Acceptable	Medium	Perpendicular R. Corner Braces
Impractical	Hard	Geogrids Rib-lath Grid Timber Grids

E. Materials durability:

Feasible	Long	Geogrid
		Rib-lath Grid
Impractical	Short	Perpendicular R. Corner Braces
		Timber Grids

Table 4. Sustainable indicators.

‘Buttresses’ and ‘corner braces’ reinforcements are part of Colombian traditional building knowledge and have been used since colonial times (Table 4c). On the other hand, even considering that geogrids, timber and rib-lath grids, are the evolution of traditional reinforcements, described by Ortega et al. (2017), such strategies have been hybridized with contemporary technology, thus their application techniques requires professional skills, hardly widespread in local common rural building knowledge.

4.2.4 Facility of implementation: Quite a complex process is required to realize ‘enclosing reinforcements’, such as ‘geogrids’, ‘timber grids’ and ‘rib-lath grids’, often including high skilled labour involvement. Walls are entirely enveloped by fixing the main reinforcement elements, through ropes, bolts or wire, passing through the wall section (‘adobes’), ring beams (wood) and base courses (stones and cement mortar). Additionally, in certain cases, e.g. ‘geogrids reinforcements’, specific ties are required (Blondet, 2010), meaning that high specialized labour, hard to be found on Colombian market, must be employed from abroad. ‘Corner braces’ requires simple common junctions’ techniques, often replacing adobes with wooden elements inside the masonry, hardly involving the perforation of the entire wall section. ‘Buttresses’ technique is based on adobe building practice, so we can expect the local rural population and labour should have needed knowledge and skills. Nevertheless, T-shape or corner junctions, among added ‘buttresses’ and the existing masonry, should provide adobe overlapping and staggering, in order to assure correct and effective transfer of loads and seismic stresses. Practices needed to achieve a proper result could require certain degree of labour professional skills, as technical knowledge and supervising abilities.

4.2.5 Materials durability: Industrialized materials such as synthetic nylon or galvanized steel, employed in ‘geogrids’ or ‘rib-lath grids’ technologies, have shown good resistance against environmental or chemical agents. Galvanized steel proved satisfactory resistance to corrosion in a soil environment and has already been used for earth retaining walls technologies. ‘Geogrids’ durability has been tested after 10, 20 or even 30 years use (Fannin et al., 2013), without reporting any considerable degradation, when properly employed. Moreover, in order to fulfil their purpose, both ‘geogrids’ and ‘rib lath grids’, should be protected with earthen or sand - lime plasters, periodically maintained. Wooden reinforcements can guarantee high durability if wood biological equilibrium is assured. Wood shows high compatibility with earthen materials and high durability if protected by weathering, even if fully embedded in soil, when preserving its possibility to exchange water vapour. Finally, ‘buttresses’ durability is comparable to the entire adobe building nominal design life.

5. CONCLUSIONS.

The assessed feasibility of analysed retrofit strategies, in Colombian rural context, has been resumed in Table 5. Reinforcement behaviour, resulting by analysed indicators and produced structural enhancement, have been reported.

The lack of equivalent quantitative data do not allow to define and compare the efficiency of all reinforcements studied; anyway certain observation of some interest are possible.

The use of synthetic geogrids could generate an important enhancement of building structural strength, interesting all the main seismic failure mechanisms reported in Table 1; nevertheless, its feasibility on rural Colombian context appears quite low, due both to the high skilled labour and knowledge required both to the high cost and high environmental impact, that geogrids lifecycle carries. It could anyhow represent a feasible reinforcement strategy in case of retrofit of plastered monumental buildings, due to its high performance in addressing the whole frame of failure mechanisms and tensional efforts, possibly occurring during an earthquake.

The analysis of tensional stresses, addressed by each retrofitting strategy, have shown how, combining ‘corner braces’ reinforcements and ‘perpendicular reinforcement’ strategies, gives the opportunity to increase structural ductility, reducing the risk of a large number of failure mechanisms occurrence. Nevertheless, quantitative data based on scientific experimentation, assessing combined strategies efficiency, would be needed to further support this hypothesis. Additionally, the aforementioned reinforcements carry low costs, materials accessibility, quite low environmental impact, low skilled labour needed for implementation and are highly related to adobe traditions in Colombia. On the other hand, despite ‘corner braces’ and ‘buttresses’ show higher main materials vulnerability, if compared to ‘geogrids’ or ‘rib lath grids’, precaution and repairs needed are considered acceptable as part of usual adobe buildings maintenance.

‘Timber grids’ reinforcements have shown elevated structural strength enhancement, been able to reduce as the same failure mechanisms occurrence as ‘plastic geogrids’.

Its contribution to the enhancement of the building structural strength is supported by laboratory investigations quantitative data (see Table 5), while the use of Colombian species, for needed timber components, lowers the environmental impact of the intervention. Anyway, it requires professional supervision during the implementation process, in order to assure its correct structural behaviour. Moreover, it can be considered quite an expensive technique, distant from traditional adobe building heritage and knowledge, thus hard to set up by low skilled population of Colombia rural villages.

A. Qualitative and quantitative adobe structures enhancement due to analysed reinforcements

Stress	Structural strength enhancement	Strength base reinforcement				
		Corner Braces	Perpendicular Reinforcement	Plastic Geogrid	Timber Grid	Rib-lath Grid
Ductility	Displacement on base under dynamic loads [%]				200	200-300
	Displacement under horizontal non-axial loads [%]			750		
	Increase post-peak phase ductility	X			X	
	Supply ductility by increasing the tensile strength of the walls			X	X	X
	Increase energy dissipation				X	X
Shear stress	Increased shear strength [%]			180	100	
	Shear deformation [%]			400	400	
	Reduce shear failure in walls plane			X	X	
	Shear stress transfer between walls	X				
	Reduce shear failure in corners	X		X	X	
Bending stress	Bending load increase [%]			300	38 kN ^c	43 kN ^c
	Reduce tensile failure in corners	X				X
	Reduce walls failure by flexural cracks		X	X	X	X
	Transfer walls bending moment diagonally to foundations		X			
	Increased collapse load (Vert. & Hor.) [%]	48-64 ^a	16 ^b			
	Load resistance in earthquake shake table [%]				270	
	Collapse				Non total	Sudden
References	Corner Braces	(Ortega et al., 2017) (Angulo et al., 2011)				
	Perpendicular R.	(Min. Vivienda, Peru, 2017) (Minke, 2001) (Ortega et al., 2017)				
	Plastic Geogrid	(Blondet, 2010) (Invernizzi et al., 2017) (Min. Vivienda, Construcción y Saneamiento, Peru, 2017)				
	Timber Grid	(Ruiz et al., 2012) (Yamin et al., 2007) (D’Ayala, Speranza, 2002)				
	Rib-lath Grid	(Yamin et al., 2007) (Ruiz et al., 2012)				

a. Corner braces located matching with ring beams presented an increase of 16%

b. Buttresses located in corners. c. Unreinforced walls failed by their own weight

B. Sustainable advantages and disadvantages

Retrofitting concept	Strategy	Advantages	Disadvantages
Strength-base reinforcement	Corner Braces	Low environmental impact; Low material costs; Vernacular knowledge – based technology, Easy installation.	Periodical material control and maintenance required.
	Perpendicular Reinforcement	Low environmental impact; Low material costs; Vernacular knowledge - based technology; Easy installation; Long Durability.	Material vulnerability
	Plastic Geogrid	Long durability (20-30 years)	Non-vernacular knowledge - based technology; Installation high qualified skills needed; High environmental impact; Expensive material costs
	Timber Grid	Low environmental impact; Medium material costs.	Non vernacular knowledge - based technology; Installation qualified skills needed; Periodical material controls and maintenance required.
	Rib-lath Grid	Long durability	High environmental impact; Expensive material costs; Non vernacular knowledge – based technology; Installation high qualified skills required

Table 5. Resume table. A) Qualitative and quantitative adobe structures enhancement due to analysed reinforcement strategies. B) Advantages and disadvantages of the reinforcement strategies, according to the sustainable indicators.

Literature data on 'Rib-lath grids' strategy reported sudden collapse during research tests (Yamín et al., 2003), while, the huge impact of the intervention, the high skilled labour needed, and the high environmental impact, make it a quite unfeasible strategy, in the analysed context.

REFERENCES

- Angulo-Ibáñez, Q., Mas-Tomás, A., Galvañ-Llopis, V., Sántolaria-Montesinos J., 2012. Traditional braces of earthen constructions. Valencia. *Construction and Building Materials*, Elsevier.
- Ashby, M., 2012. *Materials and the Environment: Eco-informed Material Choice*. Butterworth-Heinemann.
- Blondet, M., 2010. *Manual de construcción con adobe reforzado con geomallas, de viviendas de bajo costo saludables y seguras*. Pontificia Universidad Católica, Lima, Perú.
- Blondet, M., Vargas-Neumann, J., Tarque, N., Iwaki, C., 2011. Construcción sismorresistente en tierra: la gran experiencia contemporánea de la Pontificia Universidad Católica del Perú. *Informes de la Construcción* 63(523):41-50. doi: 10.3989/ic.10.017
- Christoforou, E., Kyli, A., Fokaidis, P., Ioannou, I., 2015. Cradle to site life cycle assessment (LCA) of adobe bricks. *Journal of Cleaner Production* 112: 443-452.
- D'Ayala, D., Speranza, E., 2002. An integrated procedure for the assessment of seismic vulnerability of historic buildings. *Proceedings of 12th European Conference on Earthquake Engineering*. Elsevier Science Ltd.
- De Filippi, F., Zanet, E., 2018. The "Cartilla de mantenimiento" as a tool for deprotection and maintenance of the earthen architectural heritage in Tunja, Colombia. *World Heritage and knowledge: representation, restoration, redesign, resilience*. pp. 757-766. Gangemi Editore, Roma.
- Dowling, D., Samali, B., Li, J., 2005. An improved means of reinforcing adobe walls-external vertical reinforcement. *SismoAdobe 2005, May 16-19, PUCP, Lima, Perú*.
- Fannin, R., Quinteros, V., Vaslestad, J., 2013. Durability of geosynthetic reinforcement: exumation of geogrid from a sloped reinforced soil wall after 25 years. *Geo Montréal*.
- Invernizzi, S., Mattone, M., Vachey, P., Gentile, M., 2017. Experimental study of earthen walls with geogrid reinforced mud plaster. *Vernacular and earthen architecture. Conservation and sustainability*. pp. 763-770. CRC-Press/Balkema, Taylor and Francis, London.
- Karanikoloudis G., Lourenço, P.B., Torrealva, D., Cancino, C., Wong, K., 2018. Mitigation of seismic vulnerability in earthen historic structures with traditional strengthening techniques. *Proceedings of 16th European conference on earthquake engineering*. Thessaloniki. .
- López, C., 2018. Desarrollo normativaes AIS 610-EP-17: Evaluación e intervención de edificaciones patrimoniales de uno y dos pisos de adobe y tapia pisada. [interv.] Santiago Torres.
- Lourenço, P.B., Ciocci, M.P., Greco, F., Karanikoloudis G., Ciancino, C., Torrealva, D., Wong, K., 2018. Traditional techniques for the rehabilitation and protection of historic earthen structures: the seismic retrofitting project. *International Journal of Architectural Heritage*, 13(1):15-32. Taylor & Francis.
- Michiels, M., 2015. Seismic Retrofitting Techniques for Historic Adobe Buildings. *International Journal of Architectural Heritage*, 9(8):1059-1068. Taylor & Francis.
- Ministerio de Ambiente y Desarrollo Sostenible, Colombia, ONF Andina, 2015. *Uso y legalidad de la madera en Colombia*. Bogotá.
http://www.minambiente.gov.co/images/BosquesBiodiversidad yServiciosEcosistemicos/pdf/Gobernanza_forestal_2/12_Uso_y_Legalidad_de_la_Madera.pdf (27 January 2020).
- Ministerio de ambiente, vivienda y desarrollo territorial, 2010. *Reglamento colombiano de construccion sismo resistente NSR-10*. Asociacion Colombiana de Ingeniería Sísmica, Bogota.
- Ministerio de Vivienda, Construcción y Saneamiento, Peru, 2017. *E.080 "Diseño y Construccion con tierra reforzada"*. Lima.
- Minke, G., 2001. *Construction manual for earthquake resistant houses built of earth*. Gate-Basin, Eschborn.
- Ojeda, M. 2002. *Análisis de la estabilidad de muros en tierra y su comportamiento ante un sismo*. Bogotá: Pontificia Universidad Javeriana.
- ONF Andina. Sesión No. 7. Comité Asesor Estratégico I Misión de Crecimiento Verde, 2018. *Presentación del estudio sobre economía forestal*. Bogotá.
<https://www.dnp.gov.co/Crecimiento-Verde/Documents/comite/Sesion%207/presentacion%20DNP%2001%2002%202018%20-%20202.pdf> (27 January 2020)
- Ortega, J., Vasconcelos, G., Rodrigues, H., Correia, M., Lourenço, P.B., 2017. Traditional earthquake resistant techniques for vernacular architecture and local seismic cultures: A literature review. *Journal of Cultural Heritage*, 27:181-196. Elsevier.
- Pennacchio, R., Nicchia, R., 2013. Promoting vernacular architecture as a central topic in academic research and education through Design – Build Studios with indigenous communities of Mexico. *Vernacular heritage and earthen architecture, contributions for sustainable development*, ed. M. Correia, G. Carlos & S. Rocha. CRC Press/Balkema, Taylor and Francis, London.
- Rivera, A., Rivera + Muñoz Sociedad de ideas mutuas., Fundación Jofré, 2013. El adobe. <http://eladobe.cl/> (27 January 2020).
- Ruiz, D.M., López, C., Rivera, J.C., 2012. Propuesta de normativa para la rehabilitación sísmica de edificaciones patrimoniales. *Apuntes*, 25(2):226-239. Bogotá.
- Yamin, L.E., Ruiz, D.M., Reyes, J.C., Phillips, C., 2007. Estudios de vulnerabilidad sísmica, rehabilitación y refuerzo de casas en adobe y tapia pisada. *Apuntes* 20:286-303. Bogotá.
- Yamin, L.E., Rodriguez, A.E., Fonseca, L.R., Reyes, J.C., Phillips, C.A., 2003. Comportamiento sísmico y alternativas de reabilitacion de edificaciones en adobe y tapia pisada con base en modelos a escala reducida, ensayos en mesa vibratoria. *Revista de Ingenieria de la Universidad de Los Andes* 18:175-1