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TECHNICAL PAPER

Environmentally friendlier strengthening of masonry structure using direct greening system: an experimental study

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Abstract

The green wall benefits from existing buildings have ever more attracted the attention of the scientific community. Past studies mainly focus on the ecological and environmental advantage of existing structures, while few works address the structural benefits of the green wall. In the present study, the structural impact of the typical direct greening system referred to masonry structures is assessed. This experimental program consists of direct shear, flexural bending and in-plane test to evaluate the effect of green walls strengthening effect on the basic characteristic of masonry. For the in-plane test, wall dimensions were $900 \times 750 \times 105$ mm^3 and consisted of 10 brick rows of 4 bricks each. The horizontal load was applied by means of a hydraulic actuator. Results show that after the initial breaking point, the post-peak strength is higher for green walls strengthened panels compared with that of non-retrofitted masonry panel. Even though the green wall strengthened masonry was not showing any improvement in the initial strength, it shows the reasonable improvement in residual strength. Also, it improves the structural behavior in terms of stiffness and energy dissipation capacity. Considering the overall performance, green wall strengthening can effectively improve the residual structural performance of masonry houses. Additional structural performance, to encourage retrofitting, inexpensive and easy to implement technical solutions are desirable. A direct greening system satisfies these requirements.

Keywords Earthquake · Masonry · Seismic retrofitting · Environmental issue · Green wall

Introduction

Masonry structures have a tendency to perform badly in earthquakes due to the low strength of the masonry unit, the low-quality mortar used and the lack of adequate connections between walls. Typically, masonry houses in developing countries are built by house owners themselves or by local masons without any formal engineering supervision. The quality of masonry house construction is often low due to the lack of engineer's supervision involved [1]. Making buildings earthquake-resistant and especially unreinforced masonry structures has not always been easy for earthquake engineers. In order to reduce damage to these unreinforced masonry houses during earthquakes, it is important to strengthen the earthquake resistance of an existing masonry house. Various techniques were used to retrofit the unreinforced masonry buildings. Cost, technology, architectural impact, space reduction, the need for surface finishing, space reduction and occupant disturbance are the major drawback to dealing with the seismic retrofitting methods [2]. In addition, for old historic masonry structures, there are some additional factors to be considered: structure should be retained in their original design, character and architectural view in the process of seismic retrofitting. However, most of the traditional retrofitting methods are not satisfying these factors.

Another major problem is an environmental and sustainable issue related to these retrofitting methods. Generally, manufacturing procedure of retrofitting material used for strengthening masonry structures is not environmentally friendly. Also, at the end of retrofitted structural life, it is difficult to separate the retrofitting materials from masonry walls, when surface finishing applied to the building. Retrofitting material is almost never recycled into new products, so it may dump together with building materials into landfills. It is dangerous to the environment and soil. Table 1 summarizes the drawbacks, the material used and

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Table 1 Comparison of various retrofitting methods, drawbacks, environmental and sustainability issue

Retrofitting methods	Drawbacks	Material used	Environmental and sustainability issue
Shotcrete	Require a great deal of specialized equipment and expertise to operate	Concrete	Caustic dust can cause skin/lung problems and health hazard to workers during construction
Ferrocement	Space reduction, architectural impact and requires architectural finishing	Steel and cement	It takes high heat to manufacture steel and cement from iron and silicon
External reinforcement	Corrosion, heavy mass and requires architectural finishing	Steel	Steel is susceptible to corrosion problems and disposal at the end of the building life will be difficult
Post-tensioning	High cost, high technology, anchorage problem and corrosion potential	Steel	
Steel mesh	Lack of flexibility of steel cage makes installation around opening and the corner is difficult	Steel	
FRP	High cost and effect architecture		Creating hazardous waste when it is cut into shapes
Geo-grid and soft polymer mesh	Tough nature of geo-grid and lack of flexibility makes Industrial geo-grid application and removal is difficult	Polymer	Geo-grid and polymer manufacturing involve processing of petrochemicals. Except for manufacture from recycling, it is not sustainable
PP-band mesh	PP-band is not available as mesh, so preparation of mesh required special equipment and time	Polypropylene	
Plastic carrier bag mesh	It takes a very long time to prepare the mesh	Polyethylene	
Bamboo mesh	Mud plaster surrounding the bamboo will not provide enough protection against water intrusion and makes maintenance/inspection of bamboo difficult	Bamboo	Harvesting bamboo may not impact the environment, but the handling and processing of it certainly can. Health and safety issue related to chemical components used for handling and processing

environmental or sustainability issues of various retrofitting methods used masonry structures [3–5].

Considering these facts, new strengthening method for masonry structures by using green wall technology is proposed. In the last decade, the green rating for buildings has become common practice [6]. Recently, the rehabilitation/renovation of existing buildings to green buildings has increasingly attracted the attention of the scientific community. Past studies mainly focus on the green buildings for environmental and microclimates benefits; however, only a little study focuses on potentialities on the green wall systems to retrofit buildings [7]. In this study, the structural improvement of the typical green wall system referred to masonry structures is assessed.

Green wall system

Green wall

Green walls are vertical gardens that are attached to the exterior or interior, freestanding or attached to an existing wall. Green walls are also referred to as vertical gardens, living walls or eco-walls. According to green wall construction characteristics, classification of existing green wall systems is summarized in Fig. 1 [8].

The integration of vegetation on buildings, through green walls, allows obtaining a significant improvement of the building's efficiency, environmental and ecological benefits. Several types of research show the environmental and ecological benefits of the green wall in architecture [9]. When plant attached to the wall (green direct facades), the surface is covered by vegetation and plant roots act as a structural support which is fastened to the wall itself and allows them to grow everywhere.

Ecosystem advantages of green walls

There are significant benefits of both ecological and environmental resulting from the successful use of green walls.

- Air quality improvement: It has been scientifically proven that plants can improve air quality [9, 10]. Green wall will help to improve the quality of air in any environment.
- Carbon dioxide and oxygen exchange: Plants will convert carbon dioxide, water, and energy into oxygen and glucose.

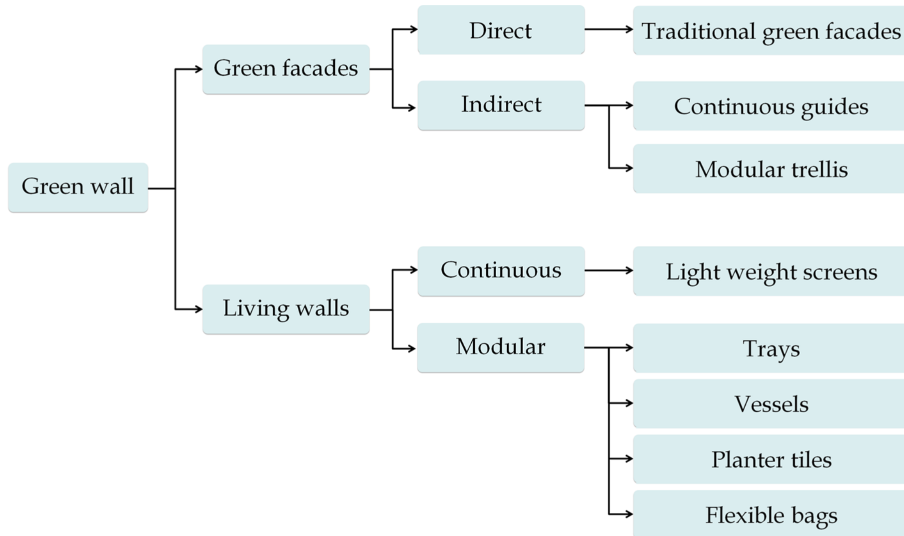

Fig. 1 Classification of green walls, according to their construction characteristics summarized by Manso and Castro-Gomes [8]

- Temperature regulation: Normally sun energy falling upon a hard surface is radiated as heat. But using a layer of vegetation to intercept the sunlight can reduce this heat [9, 11].
- Reduced energy costs: Green wall acts as a natural air conditioner, balancing humidity levels in the process to keep us comfortable. By the green wall, through an evapotranspiration process, the surrounding air is naturally cooled [12–14].
- Reduced noise levels: Plant can absorb, reflect and diffract noise, and this effect could lead to a more comfortable and pleasant environment in urban areas [15]. The efficiency appears to be dependent on the plant type, planting density and location [16].

Aim of the study

The idea of green walls has become very fashionable. Having vines mounting on brick walls can add attraction and greenery to a house. Therefore, many homeowners allow vines to grow up freely on their brick walls. Over the last decade, the green wall benefits on existing buildings have ever more attracted the attention of the scientific community. Past studies focus on the ecological and environmental advantage of existing structures; while research on the use of the green wall technique as strengthening method for masonry structure is relatively new. In the present study, the structural impact of the typical green wall system on masonry structures is assessed.

Major types of damage patterns observed during earthquakes in masonry buildings are summarized in Fig. 2. A masonry wall at any point can be under vertical compressive load, in-plane lateral load and out-of-plane load. Compressive, shear and bond strength are three major mechanical properties of masonry are responsible for these failures. Masonry has good compressive strength, but they are very low shear and tensile strength. Therefore, in this study, the effect of direct greening system strengthening on in-plane and out-of-plane strength behavior of masonry was evaluated.

Materials and methods

Material used

For the tests, brick units $215 \times 105 \times 65$ mm^3 in size were used. The mortar was a mixture of Portland cement: river sand ratio of 1:6, according to the mixing procedure for M6 mortar in EN 1996-1-1 [17] classification. A uniform mortar thickness of 10 mm was adopted for joint mortar. During construction of the model, comprehensive material tests were conducted to monitor the mechanical properties of the materials. Bricks and mortar were tested for compression and masonry prisms were tested to evaluate the masonry's strengths in compression, flexural tension and shear. Average values of the mechanical properties measured from these tests are presented in Table 2.

Reinforcement by green wall systems

Considering the socio-economic considerations of local people and workability, retrofitting masonry structures using green wall technology is proposed as an appropriate retrofitting technique.

- Masonry specimens are prepared for different testing cases as shear (prisms with three bricks and two mortar joints as shown in Fig. 3a), flexural bending (prisms with

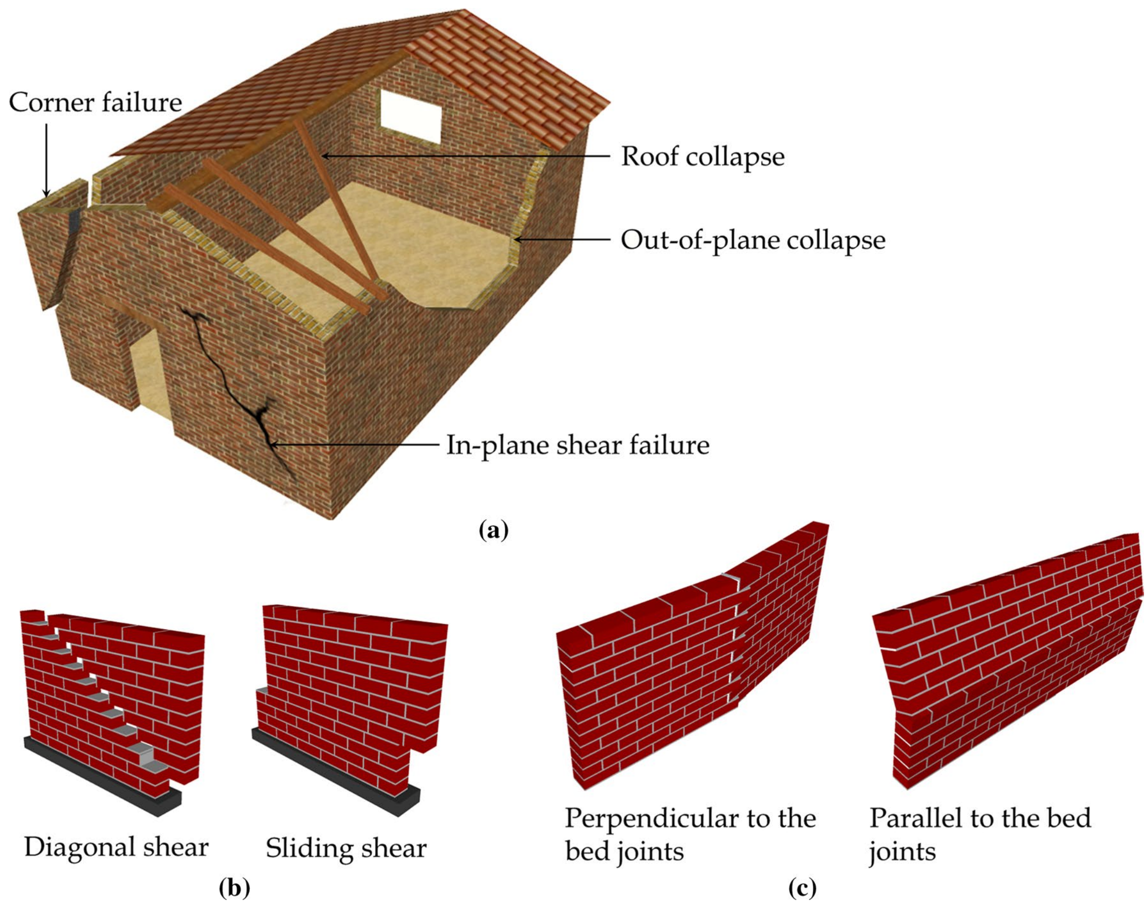

Fig. 2 Basic damage pattern of masonry structures

Table 2 Mechanical properties of brick masonry

(a)	Brick unit	
	Density	1363 kg/m^3
	Compressive strength	4.16 MPa
	Young's modulus	52.3 MPa
	Water absorption rate	8.30%
	Porosity	11.30%
(b)	Mortar	
	Density	1924 kg/m^3
	Compressive strength	5.05 MPa
	Young's modulus	360 MPa
(c)	Masonry	
	Compressive strength	1.57 MPa
	Young's modulus	126.50 MPa
	Shear strength	0.065 MPa
	Shear modulus	11.04 MPa
	Bond strength	0.135 MPa

five bricks and four mortar joints as shown in Fig. 3b), out-of-plane (wall panels consist of 5 brick rows of 3 bricks per each as shown in Fig. 3c) and in-plane (wall panels consist of 10 brick rows of 4 bricks per each as shown in Fig. 3d).

- The masonry panels are allowed some time to strengthen the mortar.
- A plant is selected where the roots are free to grow along the wall surface and which contains a large number of roots. Normally ivy and vine plants can support the green wall vegetation. Ivy plants can spread horizontally and vertically, and due to their aerial rootlets, they can climb to more heights. An endless array of plants will work in a living wall, as long as they have relatively small root systems. During this research, the action of the plant mainly regards to strengthening the masonry structures against seismic forces and hence no other special care should be taken while selecting the plant. The main factor in consideration during the selection of plant is that it should have a larger number of smaller roots within the plant as it can help to increase the tension capacity of the structure.
- The specimens were placed in outside laboratory environment. Ivy was planted in front of them and encouraged to

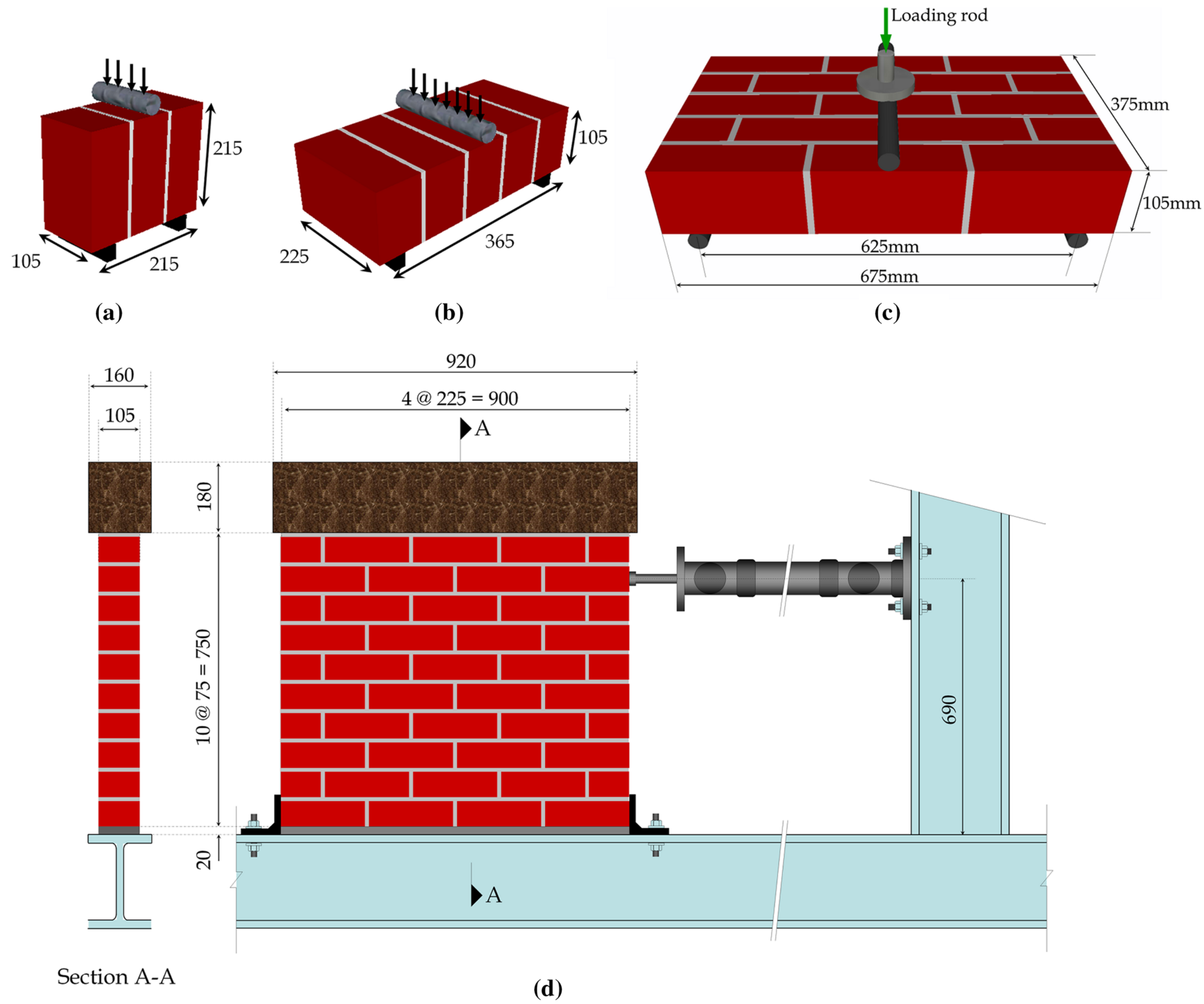

Fig. 3 Layout of specimens used and test setup for **a** direct shear, **b** flexural bending, **c** out-of-plane and **d** in-plane shear

grow over them. The specimens were built with a range of defects which we hoped would encourage ivy to take root within the wall. The defects were different forms of the hole within the mortar joints. Ivy was planted at the base of the left-hand side of each face and encouraged to grow up the walls so that on each face we would end up with one ivy covered half and one bare half.

- By the time the roots of the plant tend to spread all over the wall surface and hence it ends up forming a strong matrix and therefore it increases the tension capacity of the wall against the external forces generated by the seismic activities. Since the roots of the plant grab the wall and act as a protection layer, wall can't be easily collapsed into debris under those forces. Therefore, it plays a fundamental role in strengthening the masonry structures.

Shear and flexural bending tests on masonry prism

Basic test on masonry prisms was carried out in order to determine the direct greening system effect on shear and flexural bending behavior as shown in Fig. 3a, b, respectively. The direct shear test was conducted for three non-retrofitted and green walls strengthened masonry panels while adopting the triplet shear test. The prisms were simply supported at a 190 mm span where two steel rods were used to support the prisms at the two side bricks and the load was applied at the mid-span of the prisms under displacement control of 1 mm/min [18]. Similarly, three non-retrofitted and green walls strengthened masonry panels were tested for flexure bending. Here the three-point bending test was adopted under the displacement-controlled method [19].

Bending tests on masonry wallet

In order to investigate the green wall effect on effectiveness in walls exhibiting bending action, bending tests on masonry wallet were carried out. The dimensions of these wall panels were 675 mm × 375 mm × 110 mm and consisted of 5 brick rows of 3 bricks each. The mortar joint thickness was 10 mm. The panels were simply supported by steel rods with a 625 mm span. The specimens were tested under displacement control, and line load was applied by 20-mm-diameter steel rod at the mid-span of the masonry panel. The test setup is shown in Fig. 3c.

In-plane tests on masonry wall

The overall seismic performance of unreinforced masonry structures depends on the capacity of in-plane walls to transfer the lateral forces. Therefore, in-plane walls should have the ability to provide the post-earthquake stability in order to avoid the collapse of the entire structure. In an earthquake, the failure or deformation of in-plane walls can occur by the formation of diagonal shear cracks. Therefore, in order to evaluate the performance of the wall, in-plane tests were carried out.

During in-plane test, a horizontal force was applied parallel to the top of the wall to obtain shear failure. The tests were conducted for non-retrofitted and green walls strengthened masonry panel. Panel dimension was 900 mm × 750 mm × 110 mm. The panel was placed on a steel I-beam for testing, and while loading a concrete beam was placed on top of the upper bricklayer, in order to account for the roof weight which is transmitted to the longitudinal walls. The concrete beam was cast in the dimension of 920 × 180 × 160 mm^3. In order to prevent the wall from sliding, two welded L angle steel plate stoppers were placed on both sides of the wall toe and they were fixed using bolts to the loading frame. The loading setup is shown in Fig. 3d.

Results and discussion

Shear behavior

Figure 4 shows the shear strength variation with strain for the non-retrofitted and green wall strengthened prisms. In both types of prisms, the average initial shear strength was around 60 kPa. In the non-retrofitted case, the initial crack was followed by a sharp drop and there was no any residual strength remains after the propagation of the first crack. However, in the green wall strengthened prism case; due to the influence of the green wall strengthening effect, the residual strength about 15% of the initial peak strength was remaining after initial crack. Also, this strength remains for larger deformation range.

Flexural bending behavior

In the comparison of flexural strength variation with mid-span deformation as shown in Fig. 5, both non-retrofitted and green walls strengthened prisms have the initial flexural strength around 130 kPa. However, in the non-retrofitted case, the prism was broken into two pieces after initial crack and no residual strength was left after that. In the green wall strengthened prism case, strength drop was quickly regained after the initial crack due to the effect of green walls strengthening. In the end, the retrofitted prism was

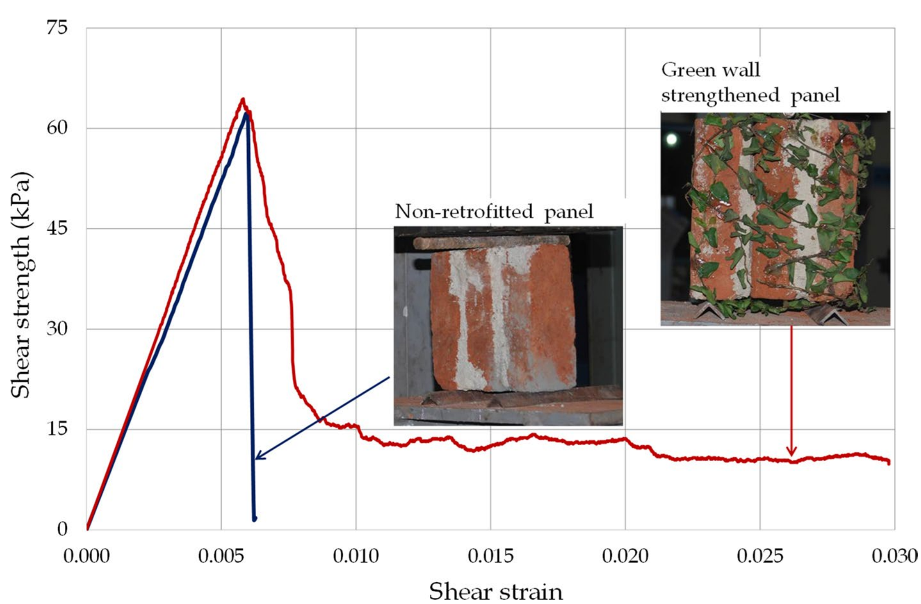

Fig. 4 Direct shear behavior of non-retrofitted and green wall strengthened prisms

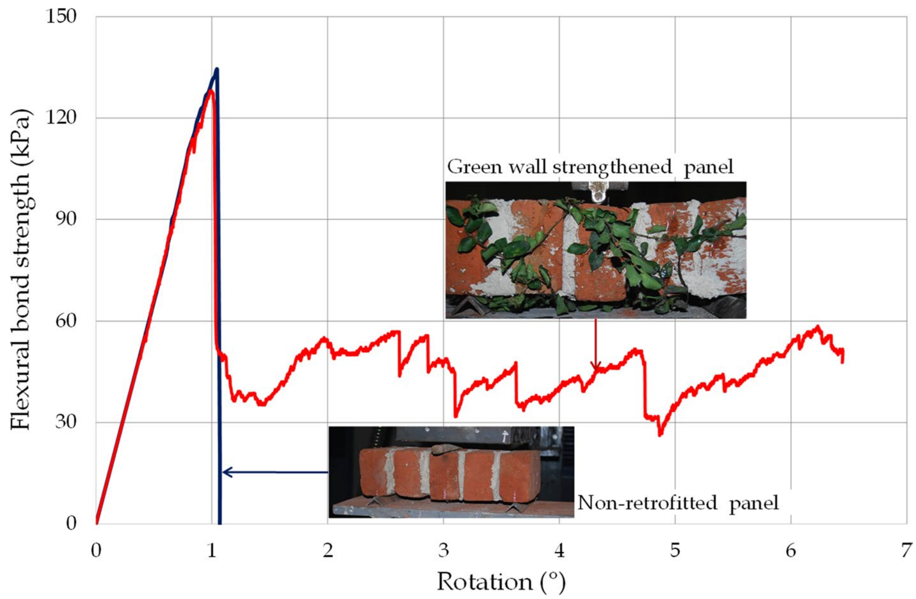

Fig. 5 Flexural bending behavior of non-retrofitted and green wall strengthened prisms (color figure online)

regained almost 35% of the initial flexural strength as the residual strength.

Out-of-plane bending behavior

In the non-retrofitted case, after initial crack, the specimen split into two pieces, and no residual strength was left. In the green wall strengthened case, on the other hand, plant influence was not observed before the initial cracking. But after cracking, strength was regained progressively due to the plant root matrix effect. Figure 6 shows the out-of-plane force variation in terms of the mid-span deformation of the non-retrofitted and green wall strengthened panels. In the non-retrofitted case, the initial strength was 0.46 MPa and there was no residual strength remaining after the first crack. In the green wall strengthened case, the initial cracking was followed by a sharp drop, but at least 20% of the peak strength remained.

In-plane shear behavior

As observed during the experimental program initially in the non-retrofitted panel, the first crack appeared at the base of the panel near the second layer. Afterward, the panel was split into two pieces subjected to sliding without propagating further cracks. In the green wall strengthened panel, after

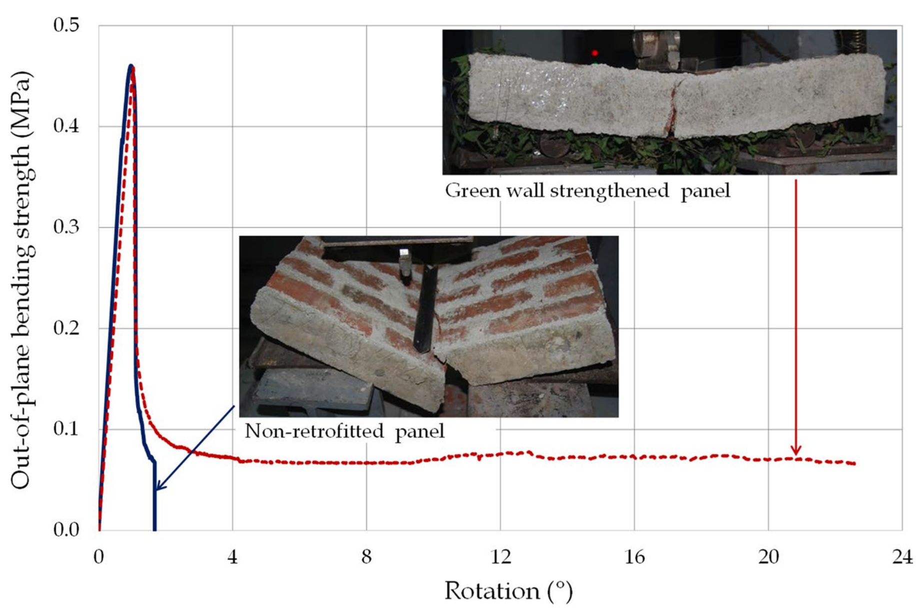

Fig. 6 Out-of-plane bending behavior of non-retrofitted and green wall strengthened panels (color figure online)

having the initial crack in the upper two layers, there is a diagonal crack observed when loading was increased.

Figure 7 shows the force–deformation relationship for non-retrofitted and green walls strengthened panels under in-plane load. It shows that after the breaking point, the post-peak residual strength and stiffness were higher for green walls strengthened panel compared with the non-retrofitted panel. The reason for residual strength of the non-retrofitted panel is fraction force due to pre-stress loading by the concrete beam. However, additional residual strength observed in the green wall strengthen panel due plant root matrix effect. So, this result shows that the direct greening system effectively improves the residual strength of the masonry panels.

In order to compare the behavior of retrofitted masonry walls in a common base, the behavior of each panel was idealized as shown in Fig. 8. Initial strength (V_0) and initial stiffness (K_0) mainly depend on the masonry properties of bricks, mortar and workmanship. Maximum residual strength after the initial crack (V_r) and residual stiffness (K_r) mainly depend on the plant tensile strength and density of the plant attachment. The comparison of basic parameters for each mesh-type panel is shown in Table 3.

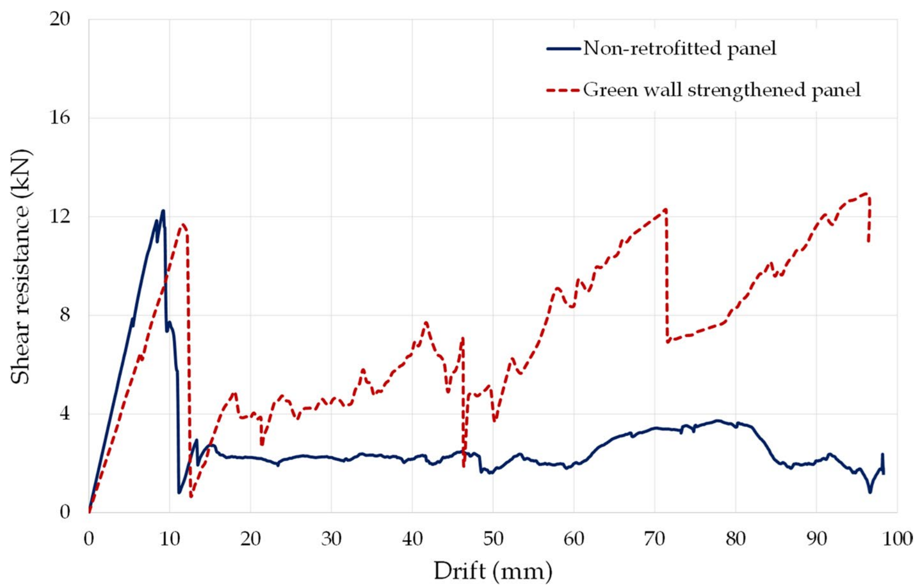

Fig. 7 Shear resistance versus deformation for non-retrofitted and green wall strengthened wall panels

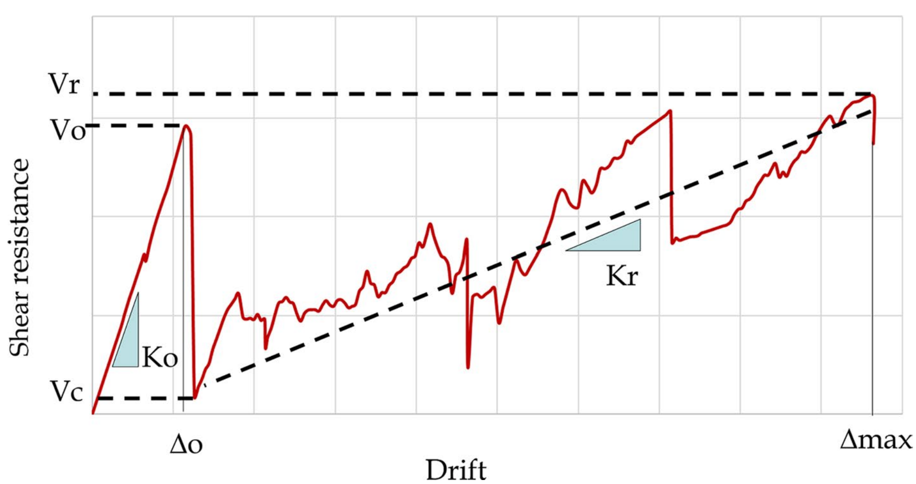

Fig. 8 Real and ideal behavior of masonry wall

Table 3 Comparison of basic parameters for in-plane test each mesh-type retrofitted panel

Retrofitting condition	V_0 (kN)	K_0 (kN/mm)	V_c (kN)	V_r (kN)	K_r (kN/mm)	Vr/V_0	K_r/K_0
Non-retrofitted	12.24	1.45	0.81	3.73	0.036	0.305	0.024
Green wall	11.66	1.00	0.69	12.93	0.141	1.109	0.141

The effective stiffness of a wall is defined by the gradation of the force–deformation graph. According to the force–deformation curves presented in Fig. 7 and results from Table 3, the green wall retrofitted panels show relatively higher residual stiffness and strength than the non-retrofitted panel.

Summary

Based on test results, Table 4 summarizes the mechanical properties comparison of non-retrofitted and green wall technology strengthened masonry under various loading conditions. Even though the green wall strengthened masonry was not showing any improvement in initial strength, it shows the reasonable improvement in residual strength.

A previous study by Sathiparan and Meguro [20] on mesh-type retrofitting found that there is a significant role of mesh density in the behavior of masonry wallets [21]. Their finding shows that the value of the residual strength and residual stiffness is depending on

- Properties of the material (tensile strength and modulus of elasticity).
- The volume of the retrofitting material used for retrofitting
- The mesh attached tightly to the wall (gap between the hole and closer mesh cross joints)

Green wall systems also expect to act as mesh-type retrofitting; therefore, its performance depends on plant types and the amount of plant root attached to walls and the attachment between root and masonry wall.

Limitation of the method and future research direction

Limitation of green wall systems

A direct green wall system for masonry structures has huge economic and environmental potential. However, there are some limitations/drawbacks to using the direct green system as well.

- The growing space for the plants may also be limited because direct green wall systems cannot provide a lot of space for the roots to expand. This disadvantage limits gardeners to grow smaller varieties of plants that are slow to grow.
- A direct green wall system can be messy too and thus requires a lot of maintenance.
- In long term, the roots of the plants may enter in the mortared surface of the walls and produce the deterioration of the joints and weaken the masonry walls.
- The moisture that remains on the wall due to the presence of the roots may be harmful from the point of view of durability and resistance.
- Hindering or limiting access for inspections and repairs of masonry.

The key to avoiding damage, while retaining a level of external vegetation, lies in planned preventive maintenance by proactive trimming or pruning or plant growth.

Further research recommendations

Based on experiences, learned from this research, following future research will give the concrete idea for suitability of the green wall retrofitting method for masonry structures.

- The present investigation evaluated the effectiveness of green wall systems in enhancing strength and deformations. However, in real application masonry walls are not only fails in in-plane, but also fail in out-of-plane, corner integration, etc. To evaluate the real behavior of green wall systems strengthened masonry walls under seismic loads, it would be better to perform the laboratory test under static out-of-plane loading on masonry wall and pushover loading on house models.
- Referring to the green wall technology strengthening of existing walls, attachment of plant roots to the wall would be an important factor which may govern the effectiveness of the masonry wall on resisting to lateral loads. Therefore, the study of the bond between plant roots and the wall would provide an improvement in load resistance and would introduce the possibility of optimizing plant option used for green wall technology.
- The method proposed for strengthening the existing masonry houses too. Therefore, it is required to perform

Table 4 Comparison of mechanical behavior of non-retrofitted and green wall technology strengthened masonry

		Direct shear	Flexural bending	Out-of-plane	In-plane
Initial strength (kPa)	NR	62.22	134.72	460.29	129.52
	GW	64.43	128.07	458.17	123.39
Average residual strength after crack (kPa)	NR	–	–	–	25.71
	GW	15.38	45.65	145.81	75.98

the test with partially damaged walls strengthened by green wall technology.

- During plant's growth, some climbing plants also require guidance to ensure that they cover the entire wall surface. It is also important to refer that some climbing plants can damage the building's surface, destroying it with their roots and entering in voids or cracks. Considering the analysis of different kinds of plants could be used as the comparison may give deeper insight.

Conclusions

In spite of being popular in building industry, unreinforced masonry walls suffer from a poor performance against seismic loading. In order to prevent human fatalities and economic losses that generate from earthquakes, retrofitting of masonry houses is an essential fundamental approach. Various techniques were used to retrofit unreinforced masonry houses. However, in addition to cost and technology, the major problem with these retrofitting methods is an environmental effect due to retrofitting. Because most of the retrofitting materials require use and processing of petrochemicals or disposal of retrofitting material at the end of the design life will be difficult and dangerous to the environment. Therefore, this research aims at investigating alternative options to strengthen unreinforced masonry walls with the direct greening system. To achieve this objective, basic prism test, in-plane and out-of-plane tests on unreinforced masonry wall and wall strengthened by the direct greening system were performed.

The tests on non-retrofitted and green wall strengthened masonry show that:

- In the comparison of shear strength, non-retrofitted masonry prism lost its entire load-bearing capacity immediately after the initial crack occurred. However, in the case of green walls strengthened prism, it could keep a residual strength about 15% of the initial peak strength.
- In the comparison of flexural bond strength, non-retrofitted prism lost its strength after the first crack, while in the green wall strengthened prism case, it quickly recovered the strength and shows the residual strength about 35% of the initial peak strength.
- In the out-of-plane tests, after initial crack, non-retrofitted specimens split into two pieces, and no residual strength was left. In the green wall strengthened case, on the other hand, plant matrix influence was not observed before the initial cracking. But after cracking, strength was regained progressively due to the plant matrix. There was residual strength around 20% of the initial peak strength was observed.
- The green wall strengthened panel shows relatively higher residual stiffness and strength than the non-retrofitted panel.

Even though these improvements not high as other retrofitting mention earlier, green wall strengthening can provide a large deformation reserve. To encourage seismic retrofitting, inexpensive and easy to implement technical solutions are desirable. Retrofitting using the direct greening system satisfies these requirements. Considering the overall performance, it can be concluded that green wall strengthening effect can effectively improve the residual structural performance of masonry houses.

Referring to the direct greening system of existing walls, attachment of plant roots to the wall would be an important factor which may govern the effectiveness of the masonry wall on resisting to lateral loads. Therefore, the study of the bond between plant roots and the wall would provide an improvement in load resistance and would introduce the possibility of optimizing plant option used for the direct greening wall system.

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References

1. Dixit AM (2004) Promoting safer building construction in Nepal. In: 13th world conference on earthquake engineering, Vancouver, Canada
2. Orhon OF (2012) Retrofit to preserve: review of seismic retrofitting methods for historical URM buildings. In: 8th international conference on structural analysis of historical constructions, Wroctow, Poland
3. Sathiparan N (2015) Mesh type seismic retrofitting for masonry structures: critical issues and possible strategies. Eur J Environ Civ Eng 19:1136–1154
4. Paudel SK (2008) Engineered bamboo as a building material. In: Xiao Y, Inoue M, Paudel SK (eds) Modern bamboo structures. CRC Press, Leiden, pp 33–40
5. Smith A, Redman TA (2009) Critical review of retrofitting methods for unreinforced masonry structures. In: EWB-UK research conference, London
6. Shafigh P, Mahmud HB, Jumaat MZ, Zargar M (2014) Agricultural wastes as aggregate in concrete mixtures—a review. Construct Build Mater 53:110–117
7. Perini K (2013) Retrofitting with vegetation recent building heritage applying a design tool—the case study of a school building. Front Archit Res 2:267–277
8. Manso M, Castro-Gomes J (2015) Green wall systems: a review of their characteristics. Renew Sustain Energy Rev 41:863–871
9. Perini K, Ottelé M, Fraaij ALA, Haas EM, Raiteri R (2011) Vertical greening systems and the effect on air flow and temperature on the building envelope. Build Environ 46:2287–2294

10. Pugh TAM, MacKenzie AR, Whyatt JD, Hewitt CN (2012) Effectiveness of green infrastructure for improvement of air quality in urban street canyons. Environ Sci Technol 46:7692–7699
11. Wong NH, Tan AYK, Chen Y, Sekar K, Tan PY, Chan D, Chiang K, Wong NC (2010) Thermal evaluation of vertical greenery systems for building walls. Build Environ 45:663–672
12. Perini K, Rosasco P (2013) Cost–benefit analysis for green façades and living wall systems. Build Environ 70:110–121
13. Wong NH, Tan AYK, Tan PY, Wong NC (2009) Energy simulation of greenery systems. Energy Build 41:1401–1408
14. Kontoleon KJ, Eumorfopoulou EA (2010) The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone. Build Environ 45:1287–1303
15. Pal AK, Kumar V, Saxena NC (2000) Noise attenuation by green belts. J Sound Vib 234:149–165
16. Rutgers R (2012) Living Façades: A study on the sustainable features of vegetated façade cladding, M.Eng. Dissertation, Delft University of Technology
17. British Standards Institution, BS EN 1996-1-1 (2005) Eurocode 6: Design of masonry structures - Part 1-1: General rules for reinforced and unreinforced masonry structures, European Committee for Standardisation, London, UK
18. British Standards Institution, BS EN 1052-3 (2002) Methods of test for masonry—part 3: determination of initial shear strength. BSI, London, UK
19. British Standards Institution, BS EN 1052-2 (1999) Methods of test for masonry—part 2: determination of flexural strength. BSI, London, UK
20. Sathiparan N, Meguro K (2013) Shear and flexural bending strength of masonry wall retrofitted using PP-band mesh. Constructii 14:3–12
21. Sathiparan N, Nissanka NAAC, Priyankara RLS (2016) A comparative study of mesh type retrofitting for unreinforced masonry under in-plane loading. Arab J Sci Eng 41:1391–1401