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研究課題名（和文）地震に弱い組積建物を廉価で簡単な方法で補強する設計ツールと普及のための教材の開発
研究課題名（英文）Development of a design methodology and dissemination materials for a simple and economic method for retrofitting adobe/masonry structures

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研究成果の概要：The research project intends to produce tools to promote adobe/masonry house retrofitting by PP-band meshes. The outputs of the project are a design methodology to determine the most suitable mesh arrangement and the expected seismic performance and also a set of detailing recommendations to guarantee adequate mesh installation.

交付額

（金額単位：円）

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２００８年度	1,100,000	330,000	1,430,000
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研究分野：地震工学
科研費の分科・細目：地震防災
キーワード：地震防災、耐震補強、組積建物、設計ツール、AEM、実験

１．研究開始当初の背景

Retrofitting of low earthquake-resistant masonry structures is the key issue for earthquake disaster mitigation in developing countries because it is the only way to significantly reduce casualties in future events. Among the causes of human casualties during earthquakes in the period 1900-1990, collapse of masonry buildings accounted for more than 70%. These structures included adobe houses, made with sun dried bricks, and unreinforced masonry houses, made with burnt bricks.
Because more than 60% of the world's population currently lives in an adobe/masonry house, it is expected that future earthquakes will cause great number of casualties and huge losses of existing building stock. This is an obvious threat to the sustainability of developing countries.
In order to promote structural retrofitting it is indispensable to equally consider technical feasibility, economical affordability, and social acceptability of the proposed retrofitting method. Furthermore, because self-construction is a widespread practice in those countries, the retrofitting procedure should be simple so that residents themselves can carry out the retrofitting works.
In order to reduce the number of casualties in future earthquakes, an innovative retrofitting method using inexpensive plastic packing bands (PP-bands) was proposed by the research group led by Prof. Kimiro Meguro. These plastic bands are arranged in meshes and wrapped around the adobe/masonry structure effectively increasing its ductility and hence earthquake resistant capacity.
Several experimental programs have been carried out to verify the effectiveness of PP-band meshes.

These tests confirmed the suitability of the PP-band meshes and created a database for the development of the numerical tool. Numerical simulations also confirmed the effectiveness of the retrofitting. Because PP-band original use is packing and not house retrofitting, its durability was assessed. Tests to verify its behavior under changes of temperature, effect of UV-radiation, aging, etc. demonstrated that it can be used for retrofitting structures.

２．研究の目的

The purpose of this research project is to develop tools for the promotion of the proposed retrofitting methodology. Specifically, a simple design methodology to determine the most suitable mesh arrangement and predict the expected seismic performance is to be developed. Also, detailing recommendations to fully take advantage of PP-band meshes and which can be directly used for field implementation are summarized.

３．研究の方法

In order to achieve the objectives of the research project, the following was carried out:

(1) ¼ small scale tests
The small scale tests were used to obtain information on: (a) adequate PP-band mesh detailing, (b) retrofitted material force-deformation relation, (c) expected ductility demands of the retrofitted structures, (d) structural response for the numerical simulations.

(2) Numerical simulations with Applied Element Method
These simulations, which were validated with the experimental data, were used to evaluate the structural response under different conditions so that a simplified material model was assessed.

(3) Non-linear dynamic analyses
In order to carry out these analyses, a program was developed. These analyses were used to determine the relation between ductility demand and strength reduction, which is necessary for designing a PP-band mesh retrofitted structure.

４．研究成果

The research project output is summarized below.
(1) Design methodology
The proposed design methodology, whose scope is 1-story adobe/masonry houses with flat roofs, is shown in Figure 1 and outlined below:
1. Determine the original structure strength, V_c, and natural period, T.
2. Calculate the elastic base shear, V, according to the regional seismic code.
3. From the relation between V and V_c, estimate the strength reduction factor, R_d.
4. Choose a certain PP-band mesh density, D, and determine the ductility demand, μ_{dem}, from the μ_{dem} versus R_d graph and also the maximum displacement, $\Delta_{max}=\mu_{dem} \times$ first cracking displacement.
5. Assess Δ_{max}.
- If Δ_{max} is acceptable, proceed with out-of-plane verification.
- If Δ_{max} is unacceptable, reduce the μ_{dem}. Repeat the calculation.
6. Verify that out-of-plane deformations do not cause instability

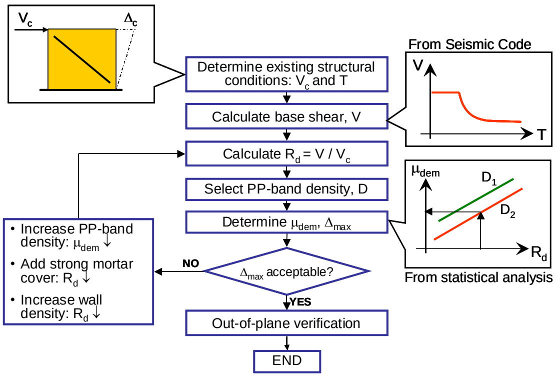


Figure 1. Flowchart of the proposed methodology

Experiments have shown that PP-band meshes do not increase the structure strength/stiffness before cracking. Therefore, it can be assumed that the retrofitted structure will have the same V_c and T as the original, unreinforced, house.

The expected R_d will be fairly high due to the relatively low resistance of the adobe/masonry houses. The higher the reduction factor, the larger the ductility demand will be as shown schematically in Figure 1. Intuitively the larger the PP-band mesh density, the less μ_{dem} for the same R_d. The nature of this relation is discussed below.

Large deformations and controlled damage are anticipated in PP-band mesh retrofitted structures. Therefore, the most important points to check in the design are maximum displacements at the corners (maximum acceptable displacement associated with in-plane actions) and the wall body (out-of-plane verification). Secondary order effects should be avoided. Excessive out-of-plane wall deformations will reduce their in-plane resistance capacity. Maximum acceptable displacements and out-of-plane verification will be discussed in subsequent sections.

If displacements due to in-plane actions are unacceptable, μ_{dem} should be reduced. This can be achieved by increasing the PP-band density. Another solution is to reduce R_d by adding a strong mortar cover or providing additional walls so that the demand on each of them is lower. In the latter case, there will be an increase in mass and as a result V needs to be recalculated. It is also possible to increase the wall density by adding more walls. However, this will change the original floor arrangement and therefore would be more expensive and probably difficult to accept by the house owner.

(2) Strength reduction versus ductility demand relation

As mentioned in the previous section, the relation between R_d and μ_{dem} for different PP-band mesh densities is needed to estimate the maximum displacement that the structure will experience. In order to develop a simple relation between these two parameters, non-linear time history analyses of several structures subjected to various strong ground motions were carried out.

Static monotonic tests have shown that the shear force – lateral deformation curve of a PP-band retrofitted walls can be roughly idealized as shown in the left curve of Figure 2. V_c and Δ_c correspond to the shear strength and cracking deformation of the original wall whereas V_r and K_r correspond to the residual strength and stiffness after the wall cracking. The first two parameters are mainly dependent on the masonry itself, V_r depends on both masonry and PP-band mesh and K_r depends mostly on PP-band. Under cyclic loading, the skeleton curve resembles the monotonic one with a gradually decreasing unloading stiffness.

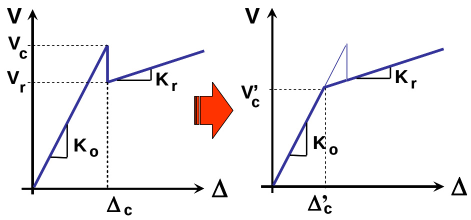


Figure 2. Idealization of shear force versus lateral deformation for a wall retrofitted with PP-band mesh

To model the retrofitted adobe/masonry structures, the skeleton curve was further idealized as shown on the right side graph of Figure 2. Additionally, the hysteresis was represented with a Modified Clough model with unloading degrading stiffness. Two additional parameters to control the later decay are necessary. In total, the model is completely defined with five parameters.

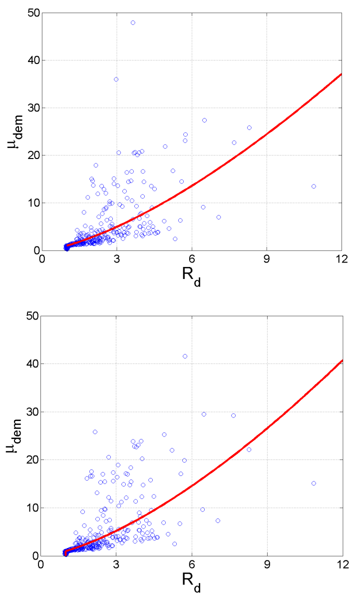
A parametric study was carried out to determine the R_d versus μ_{dem} relation. A total of 144 strong ground motion records were considered. All of them were recorded at sites with average shear wave velocities higher than 180 m/s in the upper 30 m of the soil profile. In all the cases, the peak ground acceleration (PGA) was larger than 0.1g and they were recorded on free field or the first floor of low-rise buildings.

Four structures with mechanical properties representing single story adobe/masonry houses and three different weight roofs were considered. The parameters were chosen so as to represent one of the two main walls of a 3m-high, 3m-long, 1-story adobe/brick house. In all the cases, V_r/V_o was considered equal to 0.75, a value which experiments have shown is relatively easy to achieve by tightly attaching an adequate volume of PP-band mesh.

For all the records and structures analyzed, μ_{dem} and R_d were determined and plotted as shown in Figures 3 and 4.

Table 1: Regression functions obtained for each of the group structures considered in the study

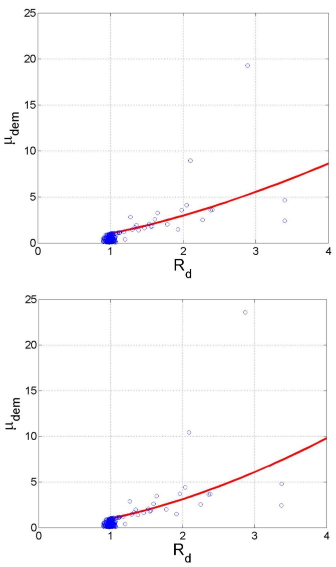
Structure type	K_r/K_o	Regression function
Adobe	0.00	$\mu_{dem} = 1.0018 \times R_d^{1.4539}$
	-0.02	$\mu_{dem} = 1.0121 \times R_d^{1.4873}$
Brick	0.00	$\mu_{dem} = 1.0247 \times R_d^{1.5359}$
	-0.02	$\mu_{dem} = 0.9905 \times R_d^{1.6512}$



(a) $K_r/K_o = 0.0$

(b) $K_r/K_o = -0.2$

Figure 3. Strength reduction versus ductility demand for adobe structures



(a) $K_r/K_o = 0.0$

(b) $K_r/K_o = -0.2$

Figure 4. Strength reduction versus ductility demand for masonry structures

Maximum R_d for adobe and masonry structures were 10.9 and 3.4, respectively. The values of μ_{dem} were 41.5 and 23.6 in the same cases. In general, the results are scattered, especially for adobe structures. For instance, for R_d equal to 3, μ_{dem} ranges from 2 to 35, if K_r/K_o=0, and from 2 to 20, if K_r/K_o= -0.2.

The large scatter does not seem to be caused by the post-peak softening behavior of the structure. Groups with different values of K_r/K_o give similar scattered results. Nor does it seem to be caused by the used strong ground motion records, which have similar characteristics. Additional evaluation of the model used is necessary to grasp the causes of the dispersed results.

Even though the results require further evaluation, a few conclusions may be drawn. For instance, it seems that the factor K_r/K_o does not affect considerably the maximum displacements experienced by the structure. Initial and residual strengths (V_o, V_r) are more important. Also, for R_d values lower than 9, μ_{dem} may be considered at most 9 for adobe structures. For masonry, a μ_{dem} of at most 5, may be expected for R_d up to 4.

A more comprehensive statistical analysis, considering more strong ground motion records and structures with larger R_d is required to reach to a final expression of μ_{dem} as a function of R_d.

(3) Maximum acceptable displacement and out-of-plane verification

A maximum acceptable displacement or drift should be defined to guaranty the structure stability. Material tests have shown that PP-band retrofitted walls under in-plane loads can tolerate very large drifts, in the order of 10% or more, without losing their in-plane resistance capacity. However, such large deformations along the plane of certain walls will cause excessive out-of-plane deformations on the walls perpendicular to them. If a structural wall is excessively damaged by out-of-plane actions, its ability to resist in-plane forces will be reduced.

There are two ways to take into account the interaction of the in-plane and out-of-plane actions on the wall in the design. One is to reduce the in-plane resistance with a penalty factor which should be a function of the maximum out-of-plane displacement. Although presently this point is under study, so far there is no model to determine what factor would be appropriate. Another way is to limit the maximum acceptable displacement to a conservative low value. Although more analyses and calculations are required to determine the most appropriate value, at this point, it is recommended to set it as a half of the wall thickness so that the resultant of vertical loads on the wall (under out-of-plane actions) always falls within the limits of the wall base.

The maximum acceptable displacement discussed in the previous paragraphs corresponds to the drift of the walls under in-plane actions or in other words, to the displacement of the walls subjected to out-of-plane actions at their side borders. If the unsupported length of the walls under out-of-plane actions is too long, the center of the walls may be subjected to considerable larger displacements perpendicular to their plane. Presently, a model to determine the displacements due to out-of-plane seismic actions for PP-band retrofitted walls is being developed.

Experiments have shown that attaching the PP-band mesh so that it is wrapped around the roof frame can greatly contribute to control out-of-plane displacements. Whenever possible, it is recommended to install the mesh in this way. Another solution to limit out-of-plane displacements in walls with large length/height ratio is to provide intermediate supports by means of pilasters well attached to the wall with PP-band meshes.

(4) Detailing recommendations

The experimental program provided useful information regarding detailing of PP-band meshes, which are required to take full advantage

of the retrofitting. These installation recommendations may be summarized as:
(a) When possible PP-band mesh ends are to be embedded into the foundation. However, they may be cut at the base when this is not possible.
(b) As much as possible, PP-band meshes should connect walls and roofs, as shown in Figure 5.

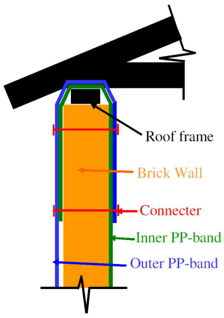


Figure 5. Wall/roof connection detail (Side view)

(c) At the wall openings, PP-band meshes are connected into two ways: 1) cutting the inner and outer mesh at the opening border, or 2) wrapping the mesh ends around the borders. The second one is more recommendable, especially for the upper border of the opening, i.e. around the lintel.
(d) The mesh overlapping length should be enough to connect at least two rows of connectors.
(e) As much as possible, meshes should be attached with connectors at band crossing points.
(f) As much as possible, meshes should be installed so that the horizontal bands are directly in contact with the walls.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計 1 件）
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①Mayorca, P. and Meguro, K., Outline of a method to design PP-band mesh retrofitting for existing low earthquake resistant masonry structures, Proc. of the 26th Annual Conference of the Japan Society of Natural Disaster Science, Japan, 2007.

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〔図書〕（計 0 件）

〔産業財産権〕

〔その他〕
ホームページ等

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