Experimental and field performance of PP band retrofitted masonry: evaluation of seismic behavior

Jamshid Zohreh Heydariha¹, Hossein Ghaednia², Sanket Nayak³, Sreekanta Das⁴, Subhamoy Bhattacharya⁵ and Sekhar Chandra Dutta⁶,

¹**Jamshid Zohreh Heydariha**, M. Tech.

Doctoral Student, Department of Civil and Environmental Engineering
University of Windsor, Ontario N9B 3P4, Canada, E-mail: zohreh@uwindsor.ca

²**Hossein Ghaednia**, Ph. D.

Postdoctoral Fellow, Department of Civil and Environmental Engineering
University of Windsor, Ontario N9B 3P4, Canada, E-mail: ghaedni@uwindsor.ca

³**Sanket Nayak**, Ph. D., M. ASCE.

Assistant Professor, Department of Civil Engineering
Indian Institute of Technology (Indian School of Mines), Dhanbad,
Jharkhand-826 004, India, Mobile-+91-9471192395, Fax No.-+91-326-2296511
E-mail: sanketiitbbsr@gmail.com, nayak.s.civ@ismdhanbad.ac.in

⁴**Sreekanta Das**, Ph. D.

Professor, Department of Civil and Environmental Engineering
University of Windsor, Ontario N9B 3P4, Canada
Tel: (1) (519) 253 3000 Ext. 2507, E-mail: sdas@uwindsor.ca

⁵**Subhamoy Bhattacharya**, Ph. D.

Professor, Department of Civil and Environmental Engineering
University of Surrey, Guildford, Surrey GU2 7XH, UK
Tel: 01483 689534, E-mail: s.bhattacharya@surrey.ac.uk

⁶**Sekhar Chandra Dutta**, Ph. D., M. ASCE.

Professor, Department of Civil Engineering
Indian Institute of Technology (Indian School of Mines), Dhanbad,
Jharkhand-826 004, India, Mobile-+91-78944 07830, Fax No.-+91-326-2296511
E-mail: scdind2000@gmail.com, dutta.sc.civ@ismdhanbad.ac.in

Address for correspondence:

Dr. Sekhar Chandra Dutta,

Professor, Department of Civil Engineering
Indian Institute of Technology (Indian School of Mines), Dhanbad,
Jharkhand-826 004, India, Mobile-+91-78944 07830, Fax No.-+91-326-2296511
E-mail: scdind2000@gmail.com, dutta.sc.civ@ismdhanbad.ac.in

Experimental and field performance of PP band retrofitted masonry: evaluation of seismic behavior

Abstract

Unreinforced masonry (URM) buildings exhibited extreme vulnerability during past earthquakes though these are shelters of majority population in many earthquake prone developing countries. Most of the current retrofitting techniques used for such structures are either expensive or requires highly skilled labor or sophisticated equipment for implementation. On the other hand, the retrofitting technique proposed in this paper is economical and easy-to-apply. This paper aims at examining the performance of the retrofitting technique using polypropylene (PP) band. The displacement controlled lateral deformation has been investigated experimentally. The monotonic load-displacement behaviors of URM wall and the wall retrofitted with PP band are compared. It was found that URM wall retrofitted by PP band improves the ductility and energy absorption capacity by three times, and two times, respectively. Performance of a full-scale masonry building retrofitted with PP band in Nepal during last Gorkha earthquake of April 25, 2015, has also been presented in this paper. It was observed that the PP band retrofitted masonry building survived while the nearby many buildings experienced severe damage and some of them collapsed. This study demonstrates the efficacy and practicability of use of PP band for improving seismic resistance of URM structure.

Keywords: Unreinforced masonry; Retrofitting technique; PP band; Gorkha earthquake; Load-displacement behavior.

Introduction

Unreinforced masonry (URM) building suffered severe damage and collapse during past earthquakes (Murty 2002; Tang et al. 2006; Murty et al. 2006; Dutta et al. 2015; Dutta et al. 2016) as compared to steel and reinforced concrete buildings. Starting from hair line crack to total collapse is the extent of failure of these URM buildings existed in seismic active zones across the globe (Bhattacharya et al. 2014). Low construction cost without requiring much technicality and pleasant aesthetics have compelled the lower economic bracket people to choose the URM buildings as their most preferred habitats. The brittle failure of these buildings against lateral loadings (such as earthquakes) leads to a wide range of human casualties and great extent of economic loss. Further, many structures of historical importance which are made of URM constructions also need to be preserved against earthquakes or wind loads. Thus, the technical community are compelled to think over this serious issue, which in turn will not only be a solution for the safe habitat for common people, but also help in preserving historical buildings and other important structures.

Various retrofitting techniques (Bhattacharya et al. 2014) are used to improve the seismic performance of unreinforced masonry. However, composite materials like fiber reinforced polymers (FRP) are often preferred due to its high strength-to-weight ratio and corrosion resistance. On the other hand, higher cost involvement, unique technical expertise required, and non-availability of the composite materials lead to the development of easily available low-cost strengthening and retrofitting techniques those do not require much technical rigor. Strengthening and retrofitting of URM wall by poly propylene (PP) band (commonly known as cartoon packaging band) was experimentally investigated in earlier studies (Mayorca and Meguro 2003; Mayorca and Meguro 2004; Meguro et al. 2005; Sathiparan et al. 2005; Mayorca et al. 2006;

Sathiparan et al. 2006; Sathiparan and Meguro 2011; Macabuag et al. 2012; Sathiparan et al. 2012; Meguro et al. 2012; Dar et al. 2014; Sathiparan and Meguro 2015; Nayak and Dutta 2016 a, b; Saleem et al. 2016). These studies reported that the post-cracking performance of the structure retrofitted with PP band improved significantly. It was also revealed that the use of PP band in retrofitting also prevent spalling of masonry resulting from tension and/or shear cracks and thus, maintains the structural integrity of wall even at larger deformations. Use of PP band for retrofitting and strengthening of various structures has a promising potential due to its high tensile strength, waterproofing property, high deformability, low-cost, easy availability, easy applicability, and ability to resist ultra violet rays when coated with mortar (Sathiparan and Meguro 2013; Sathiparan et al. 2013).

Literature review on low-cost strengthening of URM structure found that a good number of researches were carried out using PP band (Mayorca and Meguro 2003; Mayorca and Meguro 2004; Meguro et al. 2005; Sathiparan et al. 2005; Mayorca et al. 2006; Sathiparan et al. 2006; Sathiparan and Meguro 2011; Macabuag et al. 2012; Sathiparan et al. 2012; Meguro et al. 2012; Dar et al. 2014; Sathiparan and Meguro 2015; Nayak and Dutta 2016 a, b; Saleem et al. 2016). Most of these researches concentrated on improving the seismic resistance of URM structures by increasing the strength. However, study on monotonic load-displacement behavior of URM as well as PP band retrofitted masonry is nearly nonexistent. On the other hand, previous researches were carried out with model testing of structures. For experimental study of masonry structures under earthquake shaking with scaled down model is carried out by using shake table. The shake table exhibits previously collected earthquake history. The response shown under a particular ground motion may be considerably influenced by peak ground acceleration (PGA), frequency content of the motion and natural period of the structure. Thus, only reliable conclusion can be obtained by

113 studying the response under 30-40 typical ground motions and the statistical analysis of the
114 response parameters obtained from all the ground motions. This will not only require considerable
115 time but also it is not economically viable. On the other hand, statically obtained load-displacement
116 curve for unreinforced masonry and PP band reinforced masonry loaded with same strain rate helps
117 to understand the difference in behavior in terms of strength, ductility and energy absorption
118 capacity in two cases. Thus, a comparative picture of material properties and structural
119 performances in both the cases is obtained through such experiments.

120 As well, the performance of PP band retrofitted full-scale masonry house subjected to
121 earthquake loading is rarely available in the literature. Hence, the current research was designed
122 and undertaken to determine the seismic performance of URM wall and URM building retrofitted
123 with PP band. The study presented in this paper has two components. The first component of the
124 study addressed monotonic load-displacement behavior of URM wall specimens with and without
125 being retrofitted with PP band. This was accomplished through full-scale tests on URM wall
126 specimens. The tests were conducted in the structural engineering laboratory of the University of
127 Windsor, Canada. The second facet of the study presents the performance of PP band retrofitted
128 full-scale masonry house which suffered recent Gorkha (Nepal) earthquake in April 25, 2015. This
129 paper presents outcomes of both components and evaluates the performance of URM masonry
130 structure retrofitted using PP band. In fact, monotonic load-displacement curve reflects the
131 behavior of masonry in terms of load-displacement interaction. Further, the demonstration on full-
132 scale masonry house depicted in this paper is crucial for giving confidence of the local people.
133 Present study is a very humble effort in this direction. In fact, such a study is particularly relevant
134 in the context of presently available literature (Nayak and Dutta 2016 a, b). However, the past two
135 studies (Nayak and Dutta 2016 a, b) were focused on improvement of dynamic behavior of

masonry structures, while the present study provides monotonic load-displacement relationship and provides an understanding of fundamental of mechanics and material behavior.

Experimental Method and Results

This study was completed using full-scale tests on two masonry wall specimens. The test setup and test specimen are shown in Fig. 1. Two specimens were built and tested under monotonically increasing displacement controlled load until failure occurred. The objective was to determine the effectiveness of retrofit technique of URM wall using PP band. Hence, specimen 1 was unreinforced masonry (URM) wall or control specimen and the specimen 2 was retrofitted using external PP band. The PP band used in this study is 12.7 mm wide and 0.67 mm thick and the breaking strength is 1.23 kN. The boundary condition for both wall specimens were fixed at the base and free at the top. Each wall was 2000 mm (10 courses) high, 1600 mm (four block lengths) long, and 200 mm (one block width) thick. Both wall specimens were cured in room condition. Hollow concrete blocks used in these wall specimens have compressive strength of 18.6 MPa and Type S mortar (CSA S304, 2014) of thickness 10 mm was used in these wall specimens has compressive strength of 17.6 MPa.

The load-displacement behavior for both wall specimens are shown in Fig. 2. Such load-displacement behaviors for masonry is extremely rare in the literature, though these curves are important for understanding the structural behavior, failure mechanism, and ductility in seismic action. In Fig. 2, the curve indicated by A, B, C, D, E, and F and solid line is for the specimen 1 (URM wall specimen) whereas, the curve shown by A', B', C', D', E', and F' with broken line is for specimen 2 (retrofitted specimen). The load data were collected using the load cell connected to the loading jack. The displacement data were collected using four linear variable displacement

transducers (LVDT) located at four different heights (shown as LVDT 1 through LVDT 4 in Fig. 1). LVDT 1 and LVDT 4 were located at 300 mm and 1500 mm above the top of the foundation, respectively. The displacement reported in Fig. 2 was acquired through LVDT 4 which was located at 1500 mm above the top of the foundation. Digital image correlation (DIC) technique was used to monitor crack initiation, crack growth, and strain distributions.

Specimen 1

The DIC data showed that there were no strain concentrations in X direction (e_{xx}) and in Y direction (e_{yy}) anywhere in the wall specimen at load of 3.5 kN and displacement of 0.3 mm (Fig. 2) and hence, DIC did not detect any cracks in the wall specimen at this stage. However, fine horizontal crack was captured by the DIC at a load of 3.7 kN and displacement of 0.4 mm (at Point A in Fig. 2). It is worth noting that this crack was not noticeable by visual inspection. At this stage, the strain value in that area was found out to be in the range of 0.2% and 0.25%.

With further loading, crack opened up very fast and the wall specimen reduced its stiffness (line AB in Fig. 2) and this resulted in increase in the displacement at a faster rate. The DIC data found that the maximum crack width at points A and B are 0.152 mm and 1.4 mm, respectively. The displacement values at these two points measured by LVDT 4 are 0.4 mm and 1.15 mm, respectively. Nonetheless, the load carrying capacity increased from 3.70 kN at point A to 5.75 kN at point B.

The loading continued and the load carrying capacity suddenly dropped by 0.97 kN (point C in Fig. 2) while the displacement increased to 1.77 mm. This happened because of the formation of the vertical cracks near the toe of the wall (Fig. 3). At this stage, wall specimen was not able to maintain the load capacity. This is because at point C, the wall began to over-turn about the toe

and hence, the load carrying capacity slowly reduced until point D. Soon after (point E) the toe of the wall crushed and the specimen looked unstable. Hence, the wall specimen was unloaded and the test was discontinued.

DIC data for the bottom part of the wall specimen is presented and discussed in this paper. As shown in Fig. 2, load continued to drop as crack width increased further. At the end of the test and as shown in Fig. 4, the displacement at the height of LVDT 2 was about 1.6 mm. At this stage, the width of the crack was about 8.5 mm.

This wall specimen, after unloading, separated into two parts, above and below the horizontal crack line and the top part fell on the strong floor of the structural testing lab. Thus, the wall specimen lost its structural integrity (Fig. 5a).

Specimen 2

The load- displacement behavior of specimen 2 is also shown in Fig. 2. Unlike specimen 1, this specimen did not have any change in the stiffness between points A' and B' (see line A'-B'). The DIC data showed no sign of strain concentrations. Hence, it is concluded that the PP band retrofit delayed the initiation of the horizontal crack. The DIC data revealed that the first crack occurred at Point B' and at the load of 5.9 kN and displacement of 0.64 mm. The crack continued to grow in length and width and this has resulted in small drop of 0.4 kN (see point C'). However, this drop (0.4 kN) is significantly less than the drop that the specimen 1 experienced (0.97 kN). Hence, it is obvious that the PP band started sharing the load at this stage.

With further loading beyond point C', the load capacity began to increase until point D' when the load capacity reached 7.0 kN and the displacement was recorded at 12.6 mm. Both the maximum load and the maximum displacement values are much higher than the specimen 1

showing that the PP band not only increased the ductility of the wall, but also resulted in increase in the load carrying capacity. Comparing the load-displacement behaviors of specimens 1 and 2, it is found that the load and displacement capacities of the retrofitted specimen (specimen 2) increased by 22% and 125%, respectively.

As the loading continued beyond point D', the toe of the wall crushed as well and the load capacity dropped to 6.4 kN when the displacement reached 12.9 mm. At this stage, the test was discontinued and the specimen was unloaded. Unlike specimen 1, this wall specimen maintained the structural integrity after complete unloading (see Fig. 5b). Further, the horizontal crack in specimen 2 occurred in the first course and just above the foundation. However, the crack occurred in specimen 2 in between 3rd and 4th courses.

Seismic Performance

Load-displacement behavior of both wall specimens are shown and compared in Fig. 2. The figure shows that the unreinforced masonry wall (specimen 1) exhibited a maximum load of about 5.75 kN and a maximum displacement of 5.74 mm and the specimen separated in two parts along the bed joint between the 3rd and 4th courses. However, the retrofitted wall specimen (specimen 2) exhibited maximum load carrying capacity of 7 kN and the test was discontinued when the displacement reached 12.9 mm. Thus, the test data shows that the ductility capacities for the URM and retrofitted wall specimens are about 2.4 and 7, respectively. Ductility capacity is calculated by taking the ratio of maximum displacement and displacement where yielding like behavior (point B for specimen 1 and point B' for specimen 2) took place. Hence, the increase in ductility capacity in the retrofitted wall specimen was almost three times if compared to the URM wall specimen. Fig. 2 also shows that the energy absorption capacity is also increased due to the retrofit by PP band. The energy absorption capacity of the retrofitted wall specimen (specimen 2) is more than

two times than that of the unreinforced wall specimen (specimen 1). This has occurred due to the formation of the vertical cracks near the toe of the wall (Fig. 5b). At this stage (point C'), the wall began to over-turn about the toe and hence, the PP band experienced tension. This has resulted in moderate increase in load carrying capacity and substantial increase in the ductility of specimen 2 (point D').

The energy absorption capacity is the area bound by the load-displacement curve. In fact, unreinforced masonry is made of brick/masonry block layers and mortar layers placed alternately one after another. Both of these layers with their brittle nature make any unreinforced masonry wall to behave as brittle element. PP band have sufficient tension carrying capacity. Tightly vertically tied PP bands increase the internal friction. Further, it also resists the tension at one side of the wall caused from the tendency of in-plane overturning. Horizontally tied PP bands tend to prevent the slipping between any two horizontal layers. Thus, the ultimate displacement increases and more energy is needed to be absorbed before failure. In fact, such a cage made of PP bands provides a confinement effect for increasing overall load displacement behavior as observed here. Hence, it can be inferred that severe earthquake may be survived by using masonry with PP band retrofit through absorption of more energy in the post-cracking (inelastic) range. Even if complete survival may not be possible, at least the large energy absorbing capacity may delay the collapse time allowing the users to safely evacuate.

Further, a closer look at the load-displacement curves (Fig. 2) clearly shows that during post-cracking (inelastic) displacement the unreinforced wall (specimen 1) exhibited gradual reduction in its strength, while the PP band retrofitted wall specimen (specimen 2) maintained a positive gradient. In fact, the gradual strength deterioration exhibited by unreinforced wall (specimen1) may be due to continuous damage and crack propagation. Finally, this wall specimen

could not maintain its structural configuration and separated into two parts. On the other hand, PP band provided a better overall confining effect to the entire wall specimen (specimen 2) since this specimen maintained its structural integrity even after completion of the test.

Performance of PP Band Reinforced Full Scale House during Gorkha (Nepal) Earthquake of April 25, 2015

The increased ductility and energy absorbing capacity is demonstrated on-site by a full scale building constructed using PP band. Fig. 6 shows the PP band retrofitted building constructed near a traditional nonretrofitted building at Nepal. Fig. 7 illustrates the different stages of reinforcing masonry house with PP band to provide a pictorial description of application of the same.

Damage of the reinforced (using PP band) masonry house during Gorkha (Nepal) earthquake of April 25, 2015, of magnitude 7.8, is presented in Fig. 8. Mortar cover of the PP band spalled out but no major damage occurred, while many neighbouring URM buildings collapsed. In fact, the other building shown in the figure is also damaged. Hence, two inclined bracing members are installed to prevent it from collapsing (Fig. 6a). This clearly indicates the effectiveness of PP band even in real life application through exhibition of better performance during earthquake.

Another common nature of failure of masonry building consists of separation of corner junctions leading to out-of-plane collapse of the wall in the orthogonal direction of shaking. This on-site case study showed that the initiation of such a failure can be avoided by peripheral PP bands (Fig. 9). The figure shows that the joint separation started but the out-of-plane collapse did not occur because of binding effect of peripheral PP band having high tensile strength.

Summary and Conclusions

Previous studies (Mayorca and Meguro 2003; Mayorca and Meguro 2004; Meguro et al. 2005; Sathiparan et al. 2005; Mayorca et al. 2006; Sathiparan et al. 2006; Sathiparan and Meguro 2011; Macabuag et al. 2012; Sathiparan et al. 2012; Meguro et al. 2012; Dar et al. 2014; Sathiparan and Meguro 2015; Nayak and Dutta 2016 a, b; Saleem et al. 2016) have shown that masonry structure when reinforced with PP band has exhibited greater resistance to earthquake. However, quantification of the improvement of the material behavior through experiments is hardly documented in the literature. Example of on-site (field) application and evidence of better performance on-site during real life application are extremely terse. The present study made an effort to throw light on above two aspects.

First component of this study compares the load-displacement behaviors of unreinforced masonry and PP band retrofitted masonry walls. The test data were obtained through displacement controlled lateral loading as depicted in the paper. The comparison of load-displacement behaviors revealed that retrofitting of URM wall using PP band enhances the ductility capacity and energy absorption capacity to almost 3 and 2 times, respectively, in comparison to unreinforced masonry wall. This is due to increase in maximum load carrying capacity of retrofitting of URM wall using PP band by 22%. After the initiation of vertical crack, in order to prevent the specimen from over-turning about its toe, PP band experienced tension which result in more ductile behaviour. The ductility of URM wall wrapped with PP bands is increased by 125%. This improvement is considerable which enables the structure to avoid collapse at least in moderate earthquake ground shaking and may possibly reduce the damage in severe earthquakes.

The other valuable part of the paper is the observed performance of PP band retrofitted building during real earthquake. The study presents an on-site (field) demonstration on the performance of

a masonry building retrofitted with PP band. It shows that a PP band reinforced masonry house survived during last Gorkha (Nepal) earthquake of April 25, 2015, of magnitude 7.8, while many neighboring URM houses collapsed. This endorses the on-site performance of this low-cost and easy-to-apply retrofit technique during a real earthquake and adds confidence to adopt this technique in the real construction. This endeavor as a whole can be a starting point for this retrofit technique scientifically acceptable and practically applicable.

Acknowledgements

The authors are thankful for the partial financial support given to them by the Natural Sciences and Engineering Research Council of Canada (NSERC) located in Ottawa, ON, Canada. The authors also sincerely thank Lucian Pop and Matthew St. Louis for their help in lab work at the University of Windsor. Finally, special gratitude and thanks are due to Josh Macabuag for providing the photos of the performance of the URM in Nepal.

References

- Bhattacharya, S., Nayak, S., and Dutta, S. C. (2014). "A critical review of retrofitting methods for unreinforced masonry structures." *International Journal of Disaster Risk Reduction*, 7, 51-67.
- Dar, A. M., Umair, S. M., Numada, M., and Meguro, K. (2014). "Reduction of PP-band mesh connectivity for masonry structure retrofitting." *Journal of Japan Society of Civil Engineers, Structural Engineering & Earthquake Engineering*, 70(4), 586–595.
- Dutta, S. C., Mukhopadhyay, P. S., Saha, R., and Nayak, S. (2015). "2011 Sikkim Earthquake at Eastern Himalayas: Lessons learnt from performance of structures." *Soil Dynamics and Earthquake Engineering*, 75, 121-129.
- Dutta, S. C., Nayak, S., Acharjee, G., Panda, S. K., and Das, P. K. (2016). "Gorkha (Nepal) earthquake of April 25, 2015: Actual damage, retrofitting measures and prediction by RVS for a few typical structures." *Soil Dynamics and Earthquake Engineering*, 89, 171-184.

325 Macabuag, J., Guragain, R., and Bhattacharya, S. (2012). "Seismic retrofitting of non-engineered
326 masonry in rural Nepal." *Proceedings of the Institution of Civil Engineers-Structures and*
327 *Buildings*, 165(6), 273-286.

328 Mayorca, P., and Meguro, K. (2003). "Efficiency of polypropylene bands for the strengthening of
329 masonry structures in developing countries." *Proc. of the 5th International Summer*
330 *Symposium*, JSCE, Tokyo, Japan, 125-128.

331 Mayorca, P., and Meguro, K. (2004). "Proposal of an efficient technique for retrofitting
332 unreinforced masonry dwellings." *Proc. of the 13th World Conference on Earthquake*
333 *Engineering*, Vancouver, B. C., Canada, August 1-6, Paper No. 2431.

334 Mayorca, P., Sathiparan, N., Ramesh, G., and Meguro, K. (2006). "Comparison of the seismic
335 performance of different strength masonry structures retrofitted with PP-band meshes." *Proc.*
336 *of the 5th International Symposium on New Technologies for Urban Safety of Mega Cities in*
337 *Asia*, Thailand, 535-544.

338 Meguro, K., Mayorca, P., Sathiparan, N., Guragain, R., and Nesheli, N. (2005). "Shaking table
339 tests of 1/4 scaled masonry models retrofitted with PP-band meshes." *Proc. of the Third*
340 *International Symposium on New Technologies for Urban Safety of Mega Cities in Asia*,
341 Singapore, 9-18.

342 Meguro, K., Sathiparan, N., Sakurai, K., and Numada, M. (2012). "Shaking table test of two-story
343 masonry house model retrofitted by PP-band mesh." *Proc. of 15th World Conference on*
344 *Earthquake Engineering (15WCEE)*, Sociedade Portuguesa de Engenharia Sismica (SPES),
345 Portugal.

346 Murty, C. V. R., Arlekar, J. N., Rai, D. C., Udasi, H. B., and Nayak, D. (2002). "Masonry
347 structures." *Earthquake Spectra*, 18(S1), 187-224.

348 Murty, C. V. R., Rai, D. C., Jain, S. K., Kaushik, H. B., Mondal, G., and Dash, S. R. (2006).
349 "Performance of structures in the Andaman and Nicobar Islands (India) during the December
350 2004 great Sumatra earthquake and Indian Ocean tsunami." *Earthquake Spectra*, 22(S3), 321-
351 354.

352 Nayak, S., and Dutta, S. C. (2016a). "Improving seismic performance of masonry structures with
353 openings by polypropylene bands and L-shaped reinforcing bars." *Journal of Performance of*
354 *Constructed Facilities*, 30(2), 04015003.

355 Nayak, S., Dutta, S. C. (2016b). "Failure of masonry structures in earthquake: A few simple cost
356 effective techniques as possible solutions." *Engineering Structures*, 106, 53-67.

357 Saleem, M. U., Numada, M., Amin, M. N., and Meguro, K. (2016). "Seismic response of PP-band
358 and FRP retrofitted house models under shake table testing." *Construction and Building*
359 *Materials*, 111, 298-316.

360 Sathiparan, N., and Meguro, K. (2011). "Seismic behavior of low earthquake-resistant arch shaped
361 roof masonry houses retrofitted by PP-band meshes." *ASCE Practice Periodical on Structural*
362 *Design and Construction*, 17 (2), 54–64.

363 Sathiparan, N., and Meguro, K. (2013). "Shear and flexural bending strength of masonry wall
364 retrofitted using PP-band mesh." *Constructii*, 14(1), 3-12.

365 Sathiparan, N., and Meguro, K. (2015). "Strengthening of adobe houses with arch roofs using tie-
366 bars and polypropylene band mesh. *Construction and Building Materials*, 82(1), 360–375.

367 Sathiparan, N., Mayorca, P., and Meguro, K. (2012). "Shake table tests on one-quarter scale
368 models of masonry houses retrofitted with PP-band mesh." *Earthquake Spectra*, 28(1), 277–
369 299.

370 Sathiparan, N., Mayorca, P., Nesheli, K., Ramesh, G., and Meguro, K. (2005). "Experimental
371 study on in-plane and out-of-plane behavior of masonry wallettes retrofitted by PP-band
372 meshes." *Seisan Kenkyu Bimonthly Journal of Institute of Industrial Science*, University of
373 Tokyo, 57 (6), 26-29.

374 Sathiparan, N., Mayorca, P., Nesheli, K., Ramesh, G., and Meguro, K. (2006). "Experimental
375 study on unburned brick masonry wallettes retrofitted by PP-band meshes." *Seisan Kenkyu*
376 *Bimonthly Journal of Institute of Industrial Science*, University of Tokyo, 58 (3), 301-304.

377 Sathiparan, N., Sakurai, K., Numada, M., Meguro, K. (2013). "Experimental investigation on the
378 seismic performance of PP-band strengthening stone masonry houses." *Bulletin of Earthquake*
379 *Engineering*, 11(6), 2177-2196.

Tang, A., Rai, D. C., Ames, D., Murty, C. V. R., Jain, S. K., Dash, S.R., Kaushik, H.B., Mondal,
G., Muruges, G., Plant, G., and McLaughlin, J. (2006). "Lifeline systems in the Andaman and
Nicobar Islands (India) after the December 2004 great Sumatra earthquake and Indian Ocean
tsunami." *Earthquake Spectra*, 22(S3), 581-606.

Figure Captions

Fig. 1. Test set-up

Fig. 2. Load-displacement behavior

Fig. 3. Vertical crack initiation on the wall specimen 1

Fig. 4. Crack opening on the wall specimen 1 at point D

Fig. 5. After test condition of the wall specimens

Fig. 6. (a) PP band retrofitted building along with other buildings and (b) enlarge view of PP band retrofitted building

Fig. 7. Different stages of reinforcing masonry building with PP band

Fig. 8. Damage condition of various parts of the masonry building reinforced with PP band

Fig. 9. Failure of the corner junction: (a) initiation of crack at corner junction; (b) collapse avoided due to presence of PP band

Vertical crack

a) Vertical displacement on the reference line

b) Vertical displacement contour using DIC

(a) Wall specimen 1

(b) Wall specimen 2

(a)

(b)

(a) PP band wrapping near window (b) PP band wrapping near door

(c) Plastering after wrapping with PP band (d) PP band retrofitted building

(a)

(b)

(c)

(d)

Crack of corner junction

(a)

**Collapse is avoided
due to PP band**

(b)