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Research Paper

Strengthening of RC members using post-tensioned metal straps: state of the research

T. Imjai [1], U. Chaisakulkiet [2] R. Garcia [3] and K. Pilakoutas [4]

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ABSTRACT

This article reviews the state of the research on a novel and cost-effective strengthening technique for substandard reinforced concrete (RC) structures that uses Post-Tensioned Metal Straps (PTMS). The technique applies active confinement around RC structures by post-tensioning metal straps using steel strapping tools as those used in the packaging industry. The literature survey in this study indicates that some research has been carried out in strengthening normal and high-strength concrete cylinders, columns, lap-spliced elements, beams in flexure, beams and joints in shear, as well as full-scale structures tested on a shake table. Analysis and design models also exist, thus indicating that the technique is reaching maturity. Overall, the experimental results available in the literature indicate that the use of PTMS strengthening is very successful at enhancing the capacity and ductility of structures. Consequently, the PTMS provide a fast and cost-effective strengthening solution in comparison to the other traditional strengthening methods. This study contributes towards a better understanding of the potential use of the PTMS technique as strengthening/retrofit solution, as well as towards highlighting future research needs. Ongoing research work on PTMS at Rajamangala University of Technology Tawan-Ok is also summarised and commented upon.

1. Introduction

Partial and total collapses of existing buildings during strong earthquakes in developing countries (Indonesia, 2009; Haiti, 2010; Turkey, 2011; Nepal, 2015 are responsible for heavy losses and numerous casualties (Hazarika et al., 2016). Many of these collapses are attributed to collapse of numerous ductile reinforced concrete (RC) frame buildings built before the introduction of modern seismic design guidelines. Many of such collapses occurred due to structural failures of inadequately detailed critical structural elements, such as columns and beam-column joints. Therefore, the local strengthening of substandard columns and joints is necessary to reduce the seismic vulnerability of such deficient buildings.

Many repair and strengthening techniques have been successfully examined in the past. RC jacketing (**Fig. 1a**)

[1] Senior lecturer, Construction Innovation Research Unit, Dept. of Civil Engineering, Rajamangala University of Technology Tawan-Ok, Bangkok, THAILAND, thanongsak_im@rmutto.ac.th
[2] Associate professor, Dept. of Civil Engineering, Rajamangala University of Technology Rattanakosin, Bangkok, THAILAND, udomvit.k@rmutr.ac.th
[3] Postdoctoral Research Associate, Dept. of Civil and Structural Engineering, The University of Sheffield, Sheffield, UK, r.garcia@sheffield.ac.uk
[4] Professor, Dept. of Civil and Structural Engineering, The University of Sheffield, Sheffield, UK, k.pilakoutas@sheffield.ac.uk
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is considered as one of the most invasive interventions since the structural characteristics of the section are significantly modified. RC jacketing is very effective at enhancing the strength, stiffness and ductility of a member (Bett et al., 1988). However, the increase in the dimensions of the section after jacketing reduces the usable/saleable floor space. If a member's ductility needs to be enhanced, cleaner and less expensive methods such as steel jacketing (**Fig. 1b**) are usually chosen (Chai et al., 1991). However, steel jacketing requires the use of on-site welding to join the plates, as well as specialised (usually heavy) equipment and power supply. Likewise, welding depends heavily on the welders' skill and there is no generally accepted way to assess the effectiveness of welding. Full contact between the steel plates and concrete is usually necessary to ensure confinement around the RC element, and therefore the actual level of confinement is difficult to assess. Overall, concrete/shotcrete or steel jacketing are labour intensive, highly invasive, time-consuming and also can disrupt the functionality of the building.

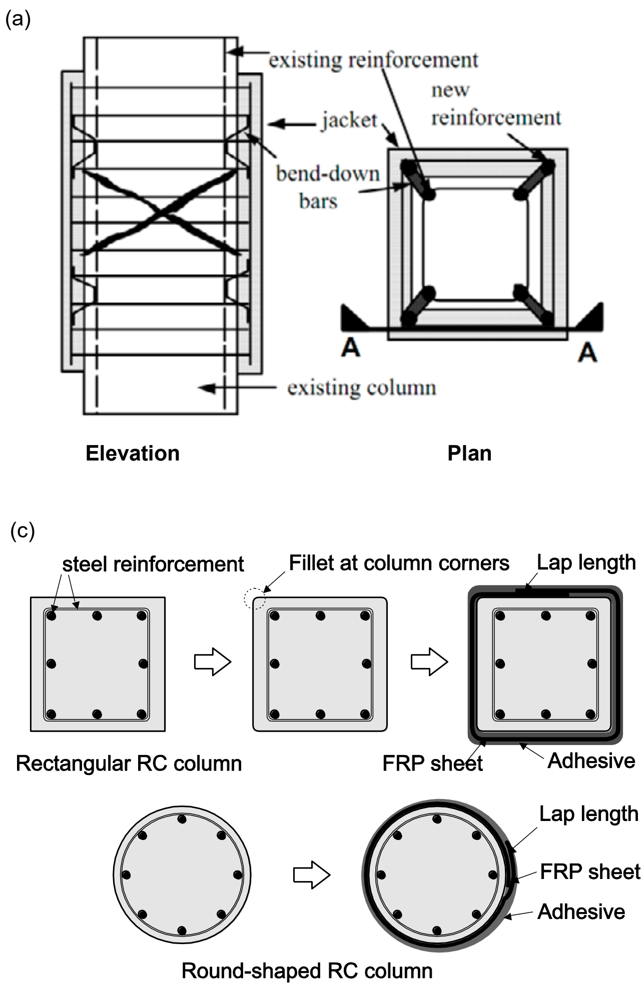

Fig. 1. Different retrofitting techniques currently available for RC strengthening systems; (a) Jacketing of a damaged column, (b) Heat tensioning of full thin steel and tie plates, (c) externally bonded FRP sheets and (d) External prestressed circular hoops (after Frangou, 1996; Frangou et al., 1995; Imjai and Garcia, 2016).

In the last two decades, externally bonded Fibre Reinforced Polymer (EBR FRP) jacketing has been extensively used for strengthening of RC structures. FRP jacketing can enhance ductility and increase the shear strength of RC columns by wrapping FRP around them, as shown in **Fig. 1c** (Imjai and Garcia, 2016). Unlike steel or concrete jacketing, FRP jacketing increases the columns stiffness only marginally (if any). FRP strengthening is usually less invasive than concrete/steel jacketing. However, the initial cost of FRP materials may discourage their use as a strengthening solution in some developing countries

While the above strengthening techniques have proven very effective at enhancing the ductility and capacity of substandard specimens, in general they only provide passive confinement. In an attempt to enhance the effectiveness of the confinement in a cost-effective manner, alternative ways to strengthen RC members using active confinement have been examined (Pilakoutas and Dritsos, 1992). For instance, externally prestressed circular hoops joined with couplers have been examined to provide active confinement to columns (Coffman et al., 1993), as shown in **Fig. 1d.** However, some concrete cover has to be removed from the columns to install the couplers (Fig. 1d), thus reducing the strength and stiffness of the column.

2. Post-tensioned metal strapping (PTMS)

Pioneering research by Frangou (1996) and Frangou et al. (1995) led to the development of a novel technique for retrofitting RC beams and columns using thin Post-Tensioned Metal Straps (PTMS). The technique uses ductile high-strength steel straps post-tensioned around RC elements using strapping tools as those used in the packaging industry (see **Fig. 2a**). Metal straps are commercially available in various thicknesses, widths and strengths. The ease of handling and strengthening objective determine the strap dimensions. Typical metal strap yield strengths vary between 300 and 1,000 MPa. Two types of tensioning machines exist i) pneumatic, in which the tension force is regulated accurately by applied air/hydraulic pressure (see Fig. 2a left), or ii) manual (Fig. 2a right), in which the tension force is controlled by the operator. A cylindrical specimen confined using an air-powered tensioning machine is shown in Fig. 2b.

To maintain the tensioning force after post-tensioning, the straps are fastened mechanically using jaws and metal seals. This provides active confinement to members, thus increasing their ductility and capacity before applying load. Compared to traditional steel/concrete and FRP jacketing, PTMS retrofitting has advantages such as ease and speed of application, low material cost and ease of quickly removing/replacing damaged straps and seals. As no adhesives or sophisticated equipment is used, PTMS retrofitting is also expected to provide cost-effective retrofitting solutions due to lower material and labour costs.

Experimental research has confirmed the effectiveness of the PTMS technique at enhancing the capacity of beams, columns beam-column joints subjected to cyclic load and a substandard full-scale RC building subjected to shake table tests. The following sections summarise the state of the research in the field of PTMS strengthening technique for RC structures. The summary also includes similar techniques (with minor variations) available in the literature.

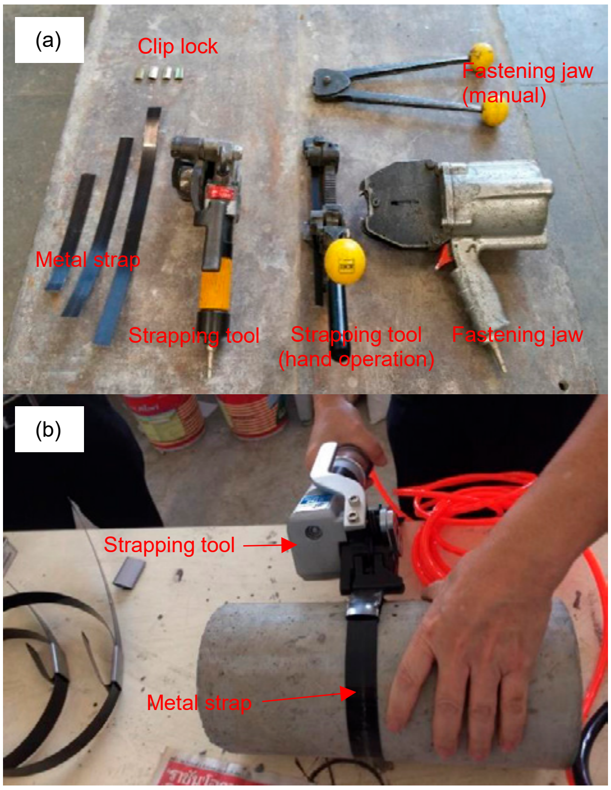

Fig. 2. (a) Post-Tensioned Metal Straps (PTMS) tool set, (b) mechanical fastening of straps around a concrete cylinder using the PTMS technique.

3. Practical PTMS strengthening for RC members

3.1 Cylinders & columns

To verify the effectiveness of the strapping technique, Frangou and Pilakoutas (1994) tested a series of small scale-scale cylindrical and prismatic specimens under axial compression. The specimens were confined externally with metal straps of 12.7 mm width and 0.5 mm thickness. Two types of steel strap were used (Bryten and Extraten) having average ultimate stresses 490 MPa and 770 MPa, respectively. Fig. 3 shows typical stress-strain results for three laterally confined cylinders and one control unconfined specimen. The clear spacing, *s'*, used between the straps for the three specimens were 0, 12.7 and 25.4 mm. It is shown that the load capacity increases by up to 80%, whereas the ultimate axial strain was up to 100% larger than that of the unconfined control specimen for a fully confined cylinder. Fig. 4 compares the normalised strength enhancement of cylinders confined with Bryten and Extraten straps for different amounts of confinement with predictions from Model Code (2010). In this figure, the normalised strength is the ratio of the maximum compressive strength of the confined cylinder

(f_{cc}) and the unconfined strength (f_{co}). It is shown that the Model Code 1990 predictions match well the experimental results.

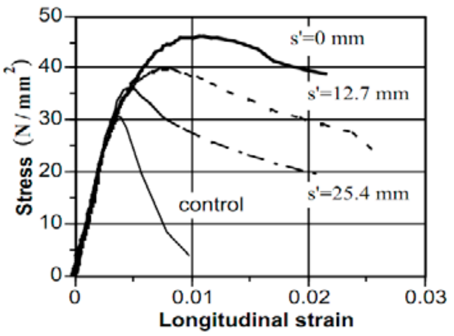

Fig. 3. Stress-strain responses for PTMS-confined cylinders and an unconfined control cylinders (after Frangou, 1996).

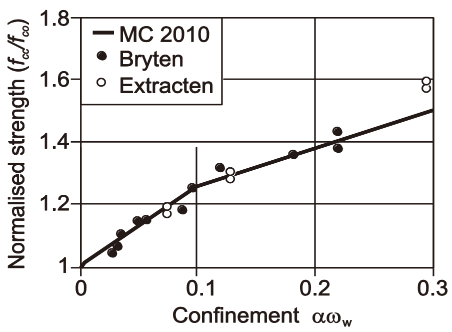

Fig. 4. Normalised strength enhancement for PTMS-confined cylinders and Model Code 2010 predictions (Frangou et al, 1996).

The effectiveness of the PTMS technique at enhancing the axial and deformation capacity of PTMS-confined concrete cylinders was subsequently studied by Moghaddam et al. (2010). The experimental program included axial compressive tests on 72 cylindrical and prismatic specimens. Various parameters were studied, including compressive strength of concrete, mechanical volumetric ratio of confining straps, post-tensioning force in the strap, number of strap layers around the specimen and details of strap joint. Fig. 5a-b shows the normalised axial stress-strain responses for PTMS-confined cylindrical (Fig. 5a) and prismatic (Fig. 5b) specimens. In these figures, the PTMS-confined strengths (f_{cc}) are normalised to the strength of plain concrete (f_{co}). The results confirm that the use of PTMS confinement led to a significant strength increases of up to 60% and 82% for cylinder and prismatic specimens, respectively. Likewise, axial strains (which indicate deformability) exceeded 0.02 for fully PTMS-confined cylinders and prismatic specimens. Overall, the use of high confinement ratios (e.g. two layers of metal straps and no strap spacing) led to the largest capacity and deformability enhancements. It was observed that the strap ductility plays the most important role in enhancing concrete ductility. Lee at al. (2014) confirmed the effectiveness of the confining technique in cylinders subjected to cyclic load.

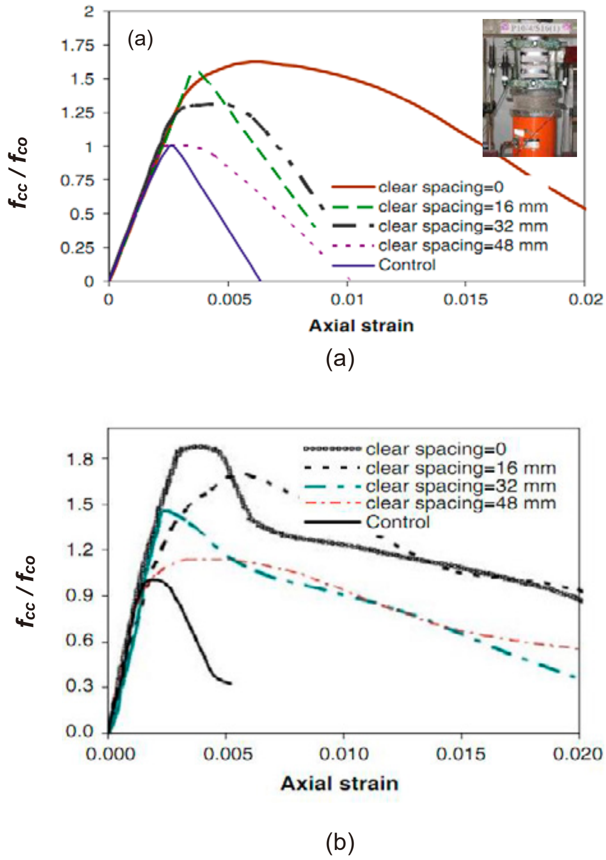

Fig. 5. Strength and deformability enhancements for PTMS-confined (a) cylinders, and (b) prismatic specimens (after [13]).

More recently, Ma et al. (2016) performed tests on nine short high-strength concrete (HSC) columns (six confined with metal straps and three unconfined columns) with a cross-section of 140×140 mm and with a 600 mm height. The columns were subjected to different magnitudes of eccentric load. Based on the test results, it was concluded that the deformability of confined HSC columns was significantly enhanced by the PTMS confinement. Moreover, failure of the columns occurred in a more ductile manner. It was also reported that the flexural capacity (from eccentric loadings) of the columns increased by up to 22% with this technique. This can be attributed to the enhancement in concrete strength provided by the confinement, which in turn enhanced the flexural strength of the PTMS-confined columns.

Holmes et al. (2015) investigated the use of a variation of the PTMS technique at improving the load capacity of concrete cylinders. The technique uses mild steel bands clamped around cylinders (**Fig. 6**). It was found that the different levels of prestressing used in the tests had minor effects on the concrete strength. However, the stress–

strain behaviour of confined concrete exhibited greater lateral stresses at peak strength. It was also concluded that concrete ductility increased by up to 53% in confined specimens.

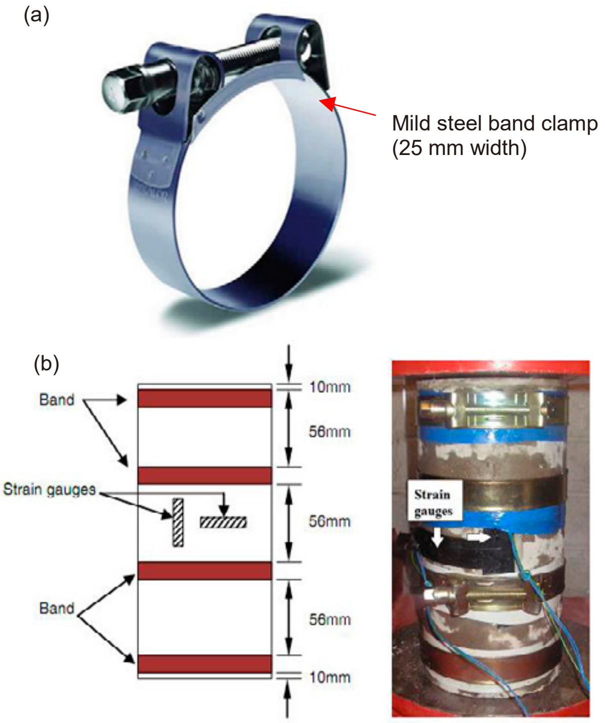

Fig. 6. Prestressing of cylindrical concrete specimens using (a) a mild steel band clamp, and (b) Location of strain gauges on a tested specimen (after Holmes et al., 2015).

3.2 Lap-splices

To study the effect of PTMS at improving the bond behavior of steel reinforcement, Samadi et al. (2012) performed cyclic tests on medium-scale RC circular columns with substandard lap splices confined with PTMS. To replicate typical substandard detailing, the longitudinal bars were lap spliced at the column base for a length of 20d_b (d_b=bar diameter), which was insufficient to develop their yield capacity. The main parameters examined were the effect of using different levels of post-tensioning force and strap layouts. Whilst the control specimens failed prematurely due to bond splitting, the use of PTMS confinement enhanced the capacity of the columns by up to 17% and led to a more ductile behaviour. However, Samadi et al. only tested lap-spliced columns with circular cross sections, whereas most columns in practice are either square or rectangular.

Research by Helal et al. (2016) examined the effectiveness of the PTMS technique at enhancing the bond behaviour of short lap spliced steel bars in rectangular reinforced concrete (RC) beams. Twelve RC beams with a short lap splice length of $10d_b$ at the mid-span zone were tested in flexure to examine the bond splitting failure. The effect of confinement (no confinement, internal steel stirrups or external PTMS), bar diameter and concrete cover were examined. The results indicated that the PTMS technique was very effective at enhancing the bond strength of the spliced bars by up to 58 % and resulted in a less brittle behaviour. Helal et al. (2016) also proposed a model to predict the bond strength enhancement in short splices due to PTMS confinement. The proposed model considers the concrete around the lap spliced bars as 'confined cylinders' of thickness c_{min} subjected to corner confining forces P_s as shown in Fig. 7a, where side cover splitting is considered. The proposed model considers the effect of the PTMS confinement through an additional confining stress σt acting over a split plane of width $c_{min}+d_b$ (see Fig. 7b). Assuming that the spliced bar slips when the pulling force in the bar exceeds the friction applied by σ_t over the split area ($c_{min}+d_b$)*l_d, the bond strength enhancement (τ_{PTMS}) due to PTMS confinement can be calculated as (Eq. 1):

$$\frac{\tau_{PTMS}}{(f_{cm})^{1/4}} = \frac{N \cdot f_p \cdot t}{456 \cdot n(c_{\min} + d_b)} \cdot \left[1 + \left(150\frac{d_b}{l_d} - 12.6\right)\frac{c_{\min}}{d_b} + \frac{2}{3}\frac{l_d}{d_b}\right]$$
(Eq. 1)

where N is the number of metal straps across the lap length l_d, f_p is the strap stress, t is the strap thickness, c_{min} is the minimum free concrete cover, and n is the total number of splices in the tension side of the cross section (which accounts for the number of developed cracks) (see Fig. 7c).

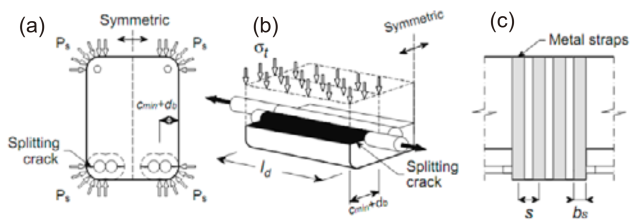

Fig. 7. Confining effect of PTMS on a lap splice experiencing splitting failure assuming $s \leq 1.30b_s$, b_s =strap width (after Helal et al., 2016).

3.3 Beam strengthening

As previously discussed in Section 3.1, the use of PTMS can significantly increase the concrete axial strain, thus indicating that PTMS can delay concrete failures in compression. This is important in strengthening of over-reinforced RC elements, where failure is typically dominated by concrete crushing. For instance, Frangou and Pilakoutas (1994) applied PTMS confinement around severely pre-damaged concrete beams that filed by concrete crushing. The results indicated the PTMS-confined beams were able to sustain load and give adequate warning prior to collapse.

More recently, Ma et al. (2015) examined the use of PTMS confinement on over-reinforced RC beams tested in flexure. Twelve over-reinforced HSC beams (f_c=50 or 80 MPa) were designed to fail prematurely by concrete crushing at mid-span, as shown in Fig. 8. The mid-span region of eight such beams was confined externally using metal straps and different steel strap confinement ratios. The confinement aimed at delaying concrete crushing by increasing the concrete ductile behaviour. The test results showed that the steel straps were very effective at enhancing the post-peak deformation of the confined beams by up to 126 %, and led to failures only after yielding of the tensile reinforcement occurred.

Fig. 8. Strengthening of over-reinforced HSC RC beam using PTMS to prevent concrete crushing failure (after Ma et al., 2015).

3.4 Shear

To study shear strengthening of RC beams, Imjai et al. (2016) tested a series of six beam under four-point loading. All beams were subjected to two consecutive tests, one on each span side (spans A and B). After shear failure, the specimens were repaired and strengthened using PTMS and re-tested up to failure. Specimen TB 1 was designed to fail in shear. According to CEB Model code (2010), GFRP stirrups of 3×10 mm and 164 mm spacing were provided for each side of the tested beam. The expected abrupt shear failure took place in the original specimen, as shown by the load-deflection curve TB 1A in in Fig. 9a. The repaired specimen (TB 1B) was strengthened externally by using PTMS to comply with the code of practice conditions for shear capacity, taking into account the shear capacity requirement. The results indicated that the shear capacity of TB 1B increased by 20% over the original beam. The tests also demonstrated that shear deficient members can be easily strengthened with the PTMS technique, to avoid shear failure and even achieve high levels of ductility.

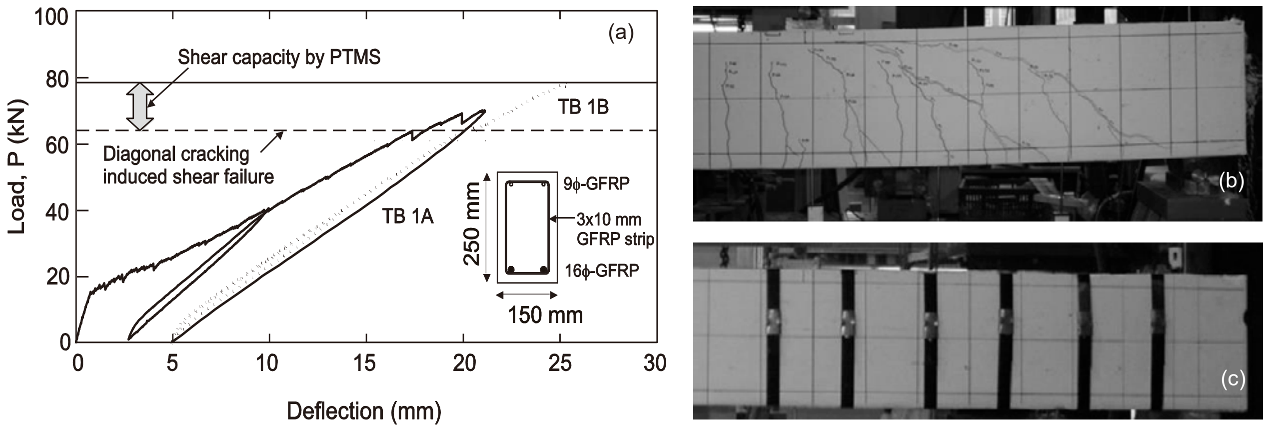

Fig. 9. (a) Load-deflection curve for specimen TB1, view of beam (b) before PTMS and (c) after PTMS strengthening.

3.5 Full-scale structures

The effectiveness of the PTMS technique at enhancing the seismic behavior of a substandard RC building was investigated through full-scale shake-table tests during the EU-funded project BANDIT (Garcia et al., 2014; Garcia at al., 2015), as shown in Fig. 10a. The bare building had inadequate reinforcement detailing in columns and joints to replicate old construction practices. The seismic excitation applied to the building ranged from PGA 0.05 g

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to 0.35 g. The 2nd floor joints of the bare building were initially damaged significantly up to a PGA level of 0.15g (see Fig. 10b), whilst the 1st floor joints experienced limited cracking (see Fig. 10c). After the initial tests, the structure was repaired and strengthened with PTMS to perform additional seismic tests. Fig. 11a shows schematically the strengthening strategy adopted for the joints. Fig. 11b shows a general view of a 1st floor joint strengthened with PTMS. The test results showed that the PTMS technique improved considerably the seismic performance of the tested building. While the bare building experienced critical damage at an earthquake of PGA=0.15g, the PTMS-strengthened building sustained a PGA=0.35g earthquake without compromising stability. It should be noted that, for the BANDIT building, the total strapping time for each joint varied from 2 to 3 hours, which demonstrates the speed of application of the proposed strengthening technique. The amount of steel straps used for the building was 220 kg, which confirms that the major costs of strengthening come from labour.

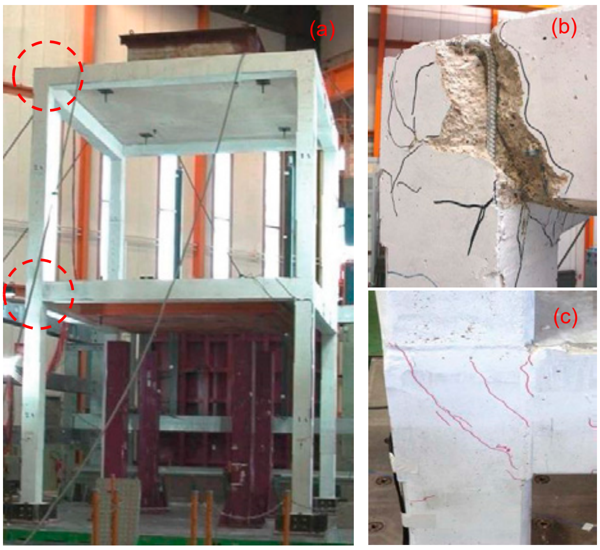

Fig. 10. (a) General view of BANDIT building on the shaking table, (b) damage of beam-column joint at the 2nd floor, (c) cracking of beam-column joint at 1st floor.

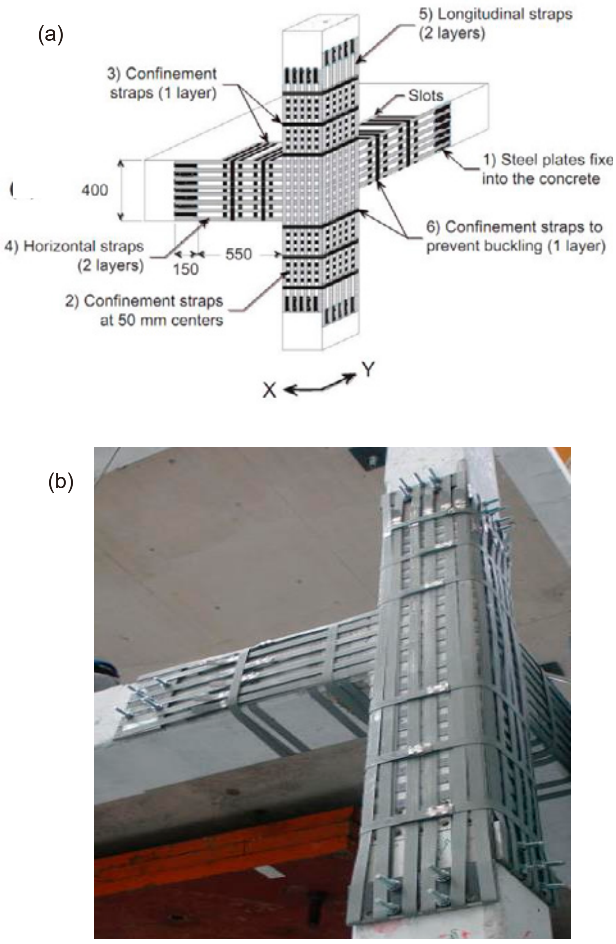

Fig. 11. (a) PTMS strengthening strategy for beam column joint at 1st floor, (b) final view of PTMS-strengthened joint.

4. Ongoing research at Rajamangala University of Technology Tawan-Ok

In the Rajamangala University of Technology Tawan-Ok (RMUTTO), Imjai at al. (2016) carried out a series of tests to verify the effectiveness and applicability of the PTMS technique at different scale levels. Two types of specimens were considered in the testing programme 1) small scale cylinders subjected to axial compressive load, and 2) large scale beams tested in bending. Laboratory work for the cylinders is underway (see strapping procedure in Figs. 12a-b) to investigate the effectiveness and performance of PTMS and to examine the confinement models proposed in Model Code (2010). Fig. 12 shows a final view of a PTMS-confined cylinder.

Fig. 12. (a)-(b) Post-tensioning strapping, and (c) view of PTMS-confined cylinder.

The second group of tests comprised five RC beams 2500 mm long with a 150×200 mm cross section (Fig. 13a). Two ϕ9 mm mild-steel bars (*fy*=235 MPa) were used as flexural bottom reinforcement in all of beam specimens. Shear spans were reinforced in shear with 6 mm steel stirrups (two legs) at a spacing of 120 mm. The beams were tested in four-point bending. All of beam specimens, being technically over-reinforced, failed due to concrete crushing in a brittle explosive manner. After failure (Fig. 13b), the beams were repaired by replacing the crushed concrete, and subsequently strengthened with 0.8×25 mm metal straps and 950 MPa ultimate stress. The strengthening of the beam resulted in an increase in the load carrying capacity of the beam by up to 25%, thus enabling the beam to behave in a more ductile manner. It should be noted that future research should investigate the behavior of PTMS-strengthened elements subjected to shear. Further development of PTMS applications is underway for repairing slabs, cantilevers and other structural and non-structural components such as masonry or timber. Results from these testing programmes will be presented by the authors in forthcoming articles. These preliminary results demonstrate that it is possible to design RC members with new reinforcing materials, which do not comply with the under-reinforced category and yet give adequate warning prior to collapse.

5. Design guidelines

Based on the experimental work presented in previous sections, several models have been proposed for aid in the design of PTMS-strengthened concrete structures. Moghaddam et al. (2010a, 2010b) proposed equations to predict the constitutive behavior of PTMS-confined concrete. Ma et al. (2014) also proposed a confinement model specifically for HSC. Additional work by Ma et al. proposed numerical models for circular HSC columns confined with metal straps (Ma et al., 2015; Chau-Khun et al., 2015). Overall, the literature survey indicates that while the technique is reaching maturity, it is still necessary to develop design guidelines before the technique can be widely used in practice.

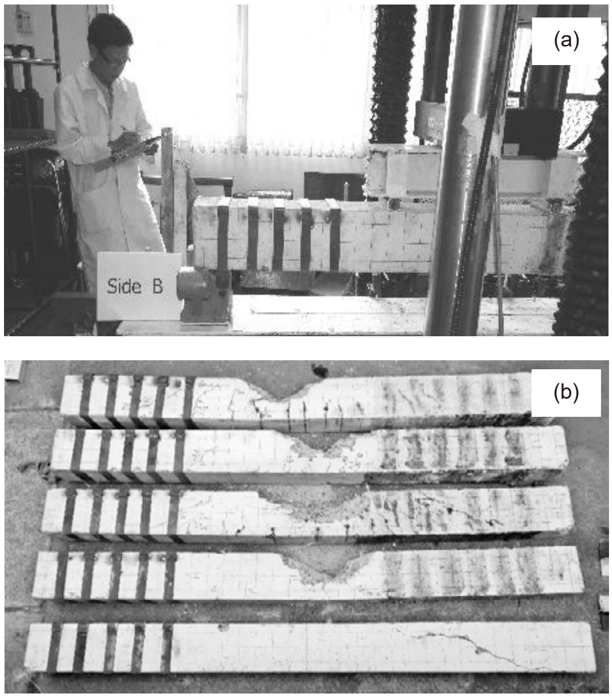

Fig. 13. (a) Shear strengthening using PTMS prior to testing, (b) failure mode of RC beams after shear strengthening (concrete crushing) – after Imjai et al., 2016).

6. Future challenges

More experiments are required at large scale, as well as on full scale buildings so as to demonstrate the effectiveness of the technique under all conditions and experimental data are required to check the behaviour of the PTMS technique under dynamic cyclic loading. Moreover, the durability of the metal strap and clip under different exposure conditions should be investigated. In addition, ways of protecting the straps and clips from accidental damage or vandalism should be also examined.

7. Concluding remarks

The Poste-Tensioned Metal Strapping (PTMS) technique has proven extremely effective in strengthening reinforced concrete (RC) elements subjected to compression, shear, flexure, as well as in bond splitting-dominated situations. The low cost of the strengthening materials used and the ease and speed of application make this technique very competitive for the repair and strengthening of RC members, particularly in substandard structures in developing countries. A very important factor contributing to the success of the strapping technique is the fact that a tensioning force can be applied at the time of strengthening. While the PTMS technique is reaching maturity, it is still necessary to develop design guidelines before the technique can be widely used in practice.

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