Article:

Chang, W-S. orcid.org/0000-0002-2218-001X (2015) Repair and reinforcement of timber columns and shear walls – A review. Construction and Building Materials, 97. pp. 14-24. ISSN 0950-0618

https://doi.org/10.1016/j.conbuildmat.2015.07.002

Repair and reinforcement of timber columns and shear walls – A review

Dr. Wen-Shao Chang[1]*

Department of Architecture and Civil Engineering, University of Bath, UK

* Corresponding author, wsc22@bath.ac.uk

1. Introduction

Although it was found that most of the research foci were on reinforcement of timber connections and flexural members, columns and shear walls play a crucial role in the prevention of structural collapse. Recent trends to build taller timber structures, a demand for structures with larger span, and re-use of existing structures for different purposes have made reinforcement of timber columns and shear walls increasingly important. In addition, repair of damaged timber columns and shear walls so as to prevent further damage to the structures and elongate the life span of existing structures is also important. This paper provides an overview of techniques available to repair and strengthen timber columns and shear walls in both research and practice.

2. The need to reinforce/repair timber columns and walls

A column is a member in a structure that takes vertical load and sometimes bending moment transferred from a beam via connections. It is crucial to the stability of a structure. A timber shear wall is an important structural element that provides lateral stability to the structure and resists horizontal forces, such as earthquake and wind. They provide substantial in-plane stiffness and only limited out-of-plane stiffness. The reasons to reinforce timber shear walls are: (a) to enhance stiffness and strength; (b) to improve ductility; and (c) to increase energy dissipation capacity. Note that in this paper only shear walls made of timber will be discussed. For example, in some half-timber framed structures, stones, bricks (Figure 1) and wattle and daub (Figure 2) are often used as in-fill elements and therefore are outside the scope of this paper.

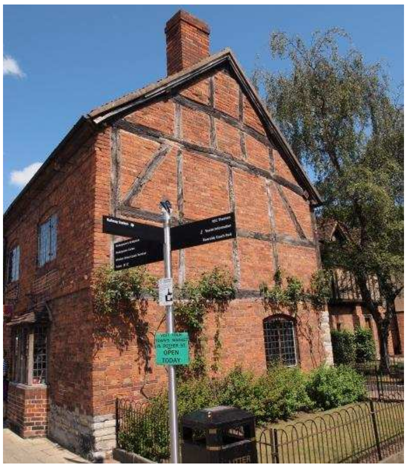

Figure 1 Half-timber frame with brick infill

Figure 2 Half-timber frame with wattle and daub infill

There are a number of situations where a column and a shear wall in a building need to be repaired or reinforced. These include biodeterioration, mechanical failure, cracks, and the need for higher strength.

2.1 Biodeterioration

Columns, when touching the ground without any measure to isolate them from damp, are prone to elevated moisture content levels which will lead to bio-deterioration due to insects (such as termites) and fungal attacks. This is a common form of decay that can be found where the column touches the ground (Figure 3). Although it is advisable when designing a timber column to select the timber carefully as the most common form of deterioration is from attack of the sapwood by insects while the heartwood remains untouched [1], the rise of moisture content in a column will lead to fungal defects and attract termites to attack the member. The termite prefers a dark and wet environment so often attacks the internal part which leaves the outside unseen, as shown in Figure 4. This failure mode in a column not only reduces the mechanical properties of timber but also reduces the effective section area. When a round column is attacked by termites and the effective section reduced by 50% from inside, the critical strength for buckling reduces by 25% and compression strength by 50%. This means that the failure mode of the column can change due to termite attack; furthermore the risk of termite attack to column members is higher due to the fact that it is difficult to observe visually. Another common form of biodeterioration, in particular to timber marine piles, is due to marine organisms. Fungi and marine borers cause significant damage to timber piles and lead to a decay in strength [2].

Figure 3 Bio-deterioration in a column that has contact with the ground

Figure 4 Timber strut attacked by termites

2.2 Mechanical failure

Compared with beam members, creep is less onerous in a column member. A column normally takes only vertical load; in some circumstances it will take combined compression and bending. The former will lead to buckling or crushing failure of the column, whilst the latter will result in partial yielding or split along the grain, as shown in Figure 5. Slender compression members are susceptible to buckling. When a compression member has (a) insufficient section size; (b) vertical cracks so the effective section is reduced; or (c) low material strength, it is prone to buckle. The buckling of a compression member is a failure that often occurs without warning. Crushing failure in a structure is less likely to happen, particularly in an engineered structure. However, as discussed previously, when a column is under high compression stress combined with termite attack from inside, there is a possibility that the column will fail by crushing due to insufficient section. It is therefore important to consider whether compression members within a structure are highly stressed, and if any action needs to be taken to ensure the prevention of the column from buckling and crushing.

2.3 Cracks and rupture

Cracks occurring in timber members often result from the differences between the drying speed in interior layers and outer ones. The drying stresses will build up if the outer layers are dried to a level that is much lower than the fibre saturation point while the interior is still saturated [3]. Rupture in timber occurs and, in consequence, cracks occur if the drying stress exceeds the strength perpendicular to the grain, as shown in Figure 6.

Figure 5 A column damaged due to an earthquake

Figure 6 Vertical cracks occur in a column

2.4 Need for higher strength

Recently there has been a trend all over the world to strive for higher timber constructions. Two mid-rise timber apartments were completed in London, UK prior to 2011. Another 10-storey timber apartment was completed in 2012 in Melbourne, Australia. These residential buildings are all built by using cross laminated timber (CLT), an engineered timber product with several layers of dimension lumber oriented perpendicular to one another and then glued to form structural panels. The CLT panels provide high strength and have enabled engineers to design taller timber buildings by using a shear wall system. Further tall timber buildings are at the planning stage and therefore it seems likely we will see more and more tall timber buildings in the future. To achieve taller timber buildings we need timber products with higher strength, in particular those which will be used in the lower parts of the building. Rehabilitation projects are another situation where we will need higher strength in columns and shear walls within a structure. When an existing building is redesigned for another purpose, such as an office, larger span is needed and this increases the stress level in timber columns and walls. We also need timber columns and shear walls to have higher strength in order to resist the self-weight built up when buildings are higher.

3. Repair and reinforcement of timber columns

3.1 Prosthesisation

When dealing with historic buildings, engineers and architects need to balance authenticity of the structures after renovation/repair with assurance of the strength of the structure to carry the load needed. To minimise the amount of timber being replaced, prosthesisation has become common practice when the timber members are bio-deteriorated due to termites or insects. It is a method that replaces only the decayed or failed part with a new portion.

Timber used for prosthesisation, in particular for the conservation of historic buildings, must be carefully selected so that the nature of the new timber will match that of the old. The moisture content of the timber being used should be close to that of the existing members so that moisture movement can be avoided. Figure 7 shows an example of a column being prosthesised after it was partially damaged. When a new prosthesis is adopted to replace the damaged portion in a timber member, two methods exist to connect the old and new members: (a) local and traditional carpentry as shown in Figure 8; and (b) glued-in members for the connection. For both cases, modern adhesives are often used to ensure the continuity of the new column. Although prosthesisation is common practice nowadays in historic building conservation in many countries [4], there is a lack of research work on this method.

Figure 7 A new timber component was used to partially replace a rotten column with traditional carpentry

Figure 8 Partial replacement repair in Daibei Temple (1550), China [4]

3.2 Screw reinforcement

Screws have been widely used recently to reinforce timber members; they can be used to enhance mechanical properties of cracked timber columns. When a column has cracks, the strength is reduced due to the potential of local buckling of the unsupported cracked portion, and this can be resolved by using screws to reconnect them together. Song et al. carried out a series of tests to study the effect of self-tapping screws to repair timber columns with vertical cracks and compared that with timber columns repaired by Fibre Reinforced Polymer (FRP) pads [5]. The vertical cracks were simulated by making slots in the column with a width of 6 mm and a length of 1500 mm. Vertical load was applied to the columns with pin connections at both ends. The conditions for the specimens are shown in Table 1 and the specimen design shown in Figure 9. The failure modes of each specimen are shown in Figure 10. It was observed from the tests that the maximum loading capacity of Specimen 2 (cracked and unrepaired) was more than 30% lower than that of the intact column (Specimen 1), and this shows that the vertical crack will weaken the column. The experimental results also showed that self-tapping screws will improve the strength of the cracked specimen to a level close to the intact ones. The additional work of filling the crack in a column does not affect the strength of the cracked column. The strength of the cracked column repaired by FRP pad showed similar results to those repaired by self-tapping screws.

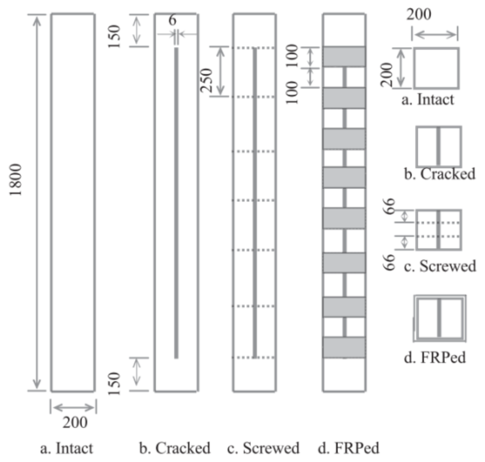

Figure 9 Specimen design of repairing cracked timber column by using screws and FRP pads [5]

Table 1 Specifications of column and experimental results by Song et al (data source: [5]).

No.	Dimensions (mm)	Slotted	Filled	Retrofit	Diameter/width[1] (mm)	Spacing (mm)	Ultimate strength (kN)
1	200 × 200 × 1800	N	–	–	–	–	846.38
2	200 × 200 × 1800	Y	N	–	–	–	570.94
3	200 × 200 × 1800	Y	N	STS	6	250	736.34
4	200 × 200 × 1800	Y	N	STS	6	250	895.03
5	200 × 200 × 1800	Y	N	STS	6	250	675.21
6	200 × 200 × 1800	Y	Y	STS	6	250	811.52
7	200 × 200 × 1800	Y	Y	FRP	100	200	835.20

Note: [1] diameter for screws and width for FRP sheets

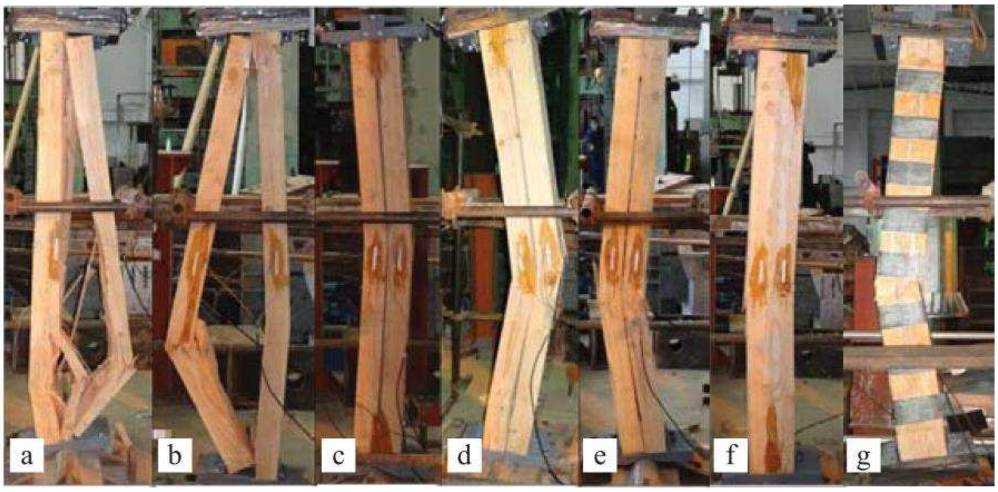

Figure 10 Failure mode of columns reinforced by different strategies tested by Song et al. [5]

This study shows self-tapping screws to be a good repair measure; in particular because it is reversible, i.e. the self-tapping screws can be removed in the future once more efficient ways of repairing timber columns have been developed. More work needs to be done on investigating factors, such as the dimensions of the cracks, the spacing of the screws and the performance under dynamic loading, before this method can be widely implemented.

3.3 Steel member reinforcement

In the early stages of reinforcement and repair of timber structures, the focus was mainly on using metallic reinforcement, such as steel bars and plates. The idea of using steel members to reinforce a timber column is to: (a) facilitate a timber column to carry or transfer load

(Figure 11); and (b) to prevent crack to split. The common forms of steel reinforcement include: (a) steel plate with nails or screws; (b) punched metal plates; and (c) steel glued-in rods. However, the focus was mainly on beam elements and connections; efforts being devoted to the reinforcement of columns were relatively scarce. Tanaka et al. compared the effect of a column reinforced by steel plate with that of one reinforced by carbon fibre sheets [6].

Figure 11 Steel members are used to connect two columns to transfer load

Buckling tests were carried out, and the parameters considered include (a) slenderness ratio of column, (b) boundary conditions for steel plates in the reinforced column, and (c) reinforcement methods (steel plates and carbon fibre sheets). The sections of the specimens of the experiments are shown in Figure 12 and the reinforcement arrangements are depicted in Figure 13.

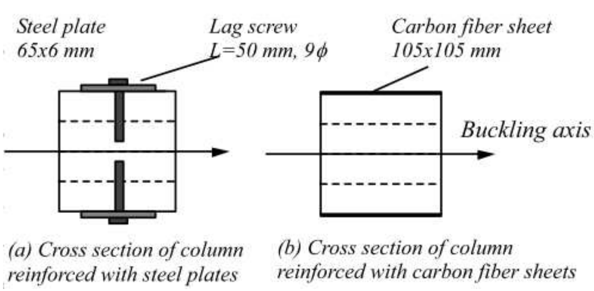

Figure 12 Section of the columns reinforced by steel plates and carbon fibre sheets [6]

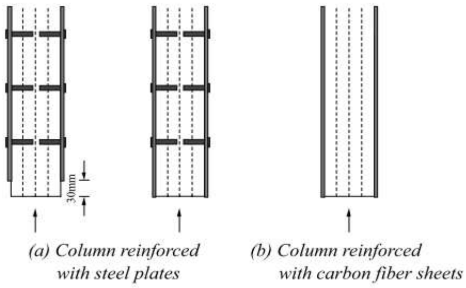

Figure 13 Different reinforcement arrangements [6]

The experimental outcomes showed that steel plates reinforced timber columns have load-carrying capacities at least 2.5 times higher than that of unreinforced timber columns, whilst columns reinforced by carbon fibre sheets exhibit 1.3 times higher load-carrying capacities than unreinforced.

3.4 Composite material reinforcement

Repair and reinforcement of damaged timber members by composite material, such as FRP and GFRP, has been developed over more than 2 decades. Composite material has a remarkable strength-to-weight ratio and leads to light weight strategies when repairing or reinforcing these damaged members. Substantial amounts of effort have been devoted to investigating increasing the strength properties of intact timber members after the application of FRP or GFRP bonded externally [7-11]. Zhang et al. carried out a series of tests on repairing cracked columns by using FRP wrapping and developed finite element models to simulate the behaviour for parametric studies [12]. The factors considered include (a) the column dimensions, (b) the crack dimensions, (c) whether the crack was filled, (d) FRP properties and (e) FRP spacing. A total of 17 specimens were tested and six different failure modes were observed. Figure 14 shows the specimens tested and factors considered. The experimental results showed that different combinations of factors, in particular the FRP spacing, will result in different failure modes. It was evidenced in the series of tests that the load-carrying capacity of a column decreases with increase in the length and width of the cracks and the influence of the crack width is more significant. It was also observed that reducing the FRP spacing will increase the recovery of load-carrying capacity of cracked timber columns.

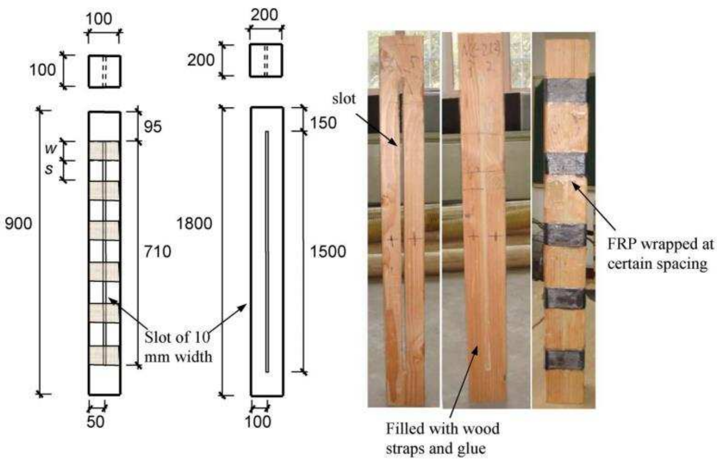

Figure 14 The specimens and different factors considered in the series of tests carried out by Zhang et al. [12]

Oprişan et al. shows different methods of using FRP composite to strengthen a timber column. They include: (a) FRP fabric with different fibre orientations; (b) FRP strips to provide confinement; (c) FRP strips to share the load; and (d) using embedded FRP rods and fabric to provide confinement [13].

A series of tests was carried out by Taheri et al. to investigate the buckling response of glulam columns reinforced with FRP sheets with different lengths and end fixity [14]. The reinforcement levels included non-reinforcement (control), fully reinforced, and partially reinforced (the FRP sheet was one-third of the length of the column and attached in the middle of the column). The boundary conditions of the column were pinned-pinned and fixed-fixed ends. It was found that columns which were fully reinforced had a higher strength compared with the other conditions. The experimenters concluded that using FRP for partially reinforcing a glulam column is more effective for the pinned-pinned case as the strength of the column reached almost half of the increase in strength of those fully reinforced, yet only used one third of reinforcing material. Most FRP composites use organic matrices in manufacturing FRP plates, but since the 90s there has been significant progress in manufacturing FRP with inorganic matrices that are non-toxic, have good fire resistance, and are not affected by UV radiation [15]. A series of tests to investigate the confinement of circular timber columns using inorganic CFRP was carried out by Najm et al. [16]. They tested 40 column specimens in axial compression, two different wrapping methods for the CFRP; spirals and full wrapping. The specimens and the carbon reinforcement used in the tests are shown in Figure 15.

The reinforced column specimens exhibited higher strength and stiffness than the unreinforced specimens. It was also observed that specimens that were fully wrapped had higher strength and stiffness compared with those that were partially reinforced (spiral reinforcement). With respect to strength increase and fibre content, it was observed that the average load-carrying capacity of the column increased with the decrease of the spacing of CFRP, i.e. increase of the amount of CFRP. The same phenomenon can be found for the axial stiffness of the column specimens. In other words, the more CFRP used, the better the mechanical properties the columns will have, as can be seen in Figure 16.

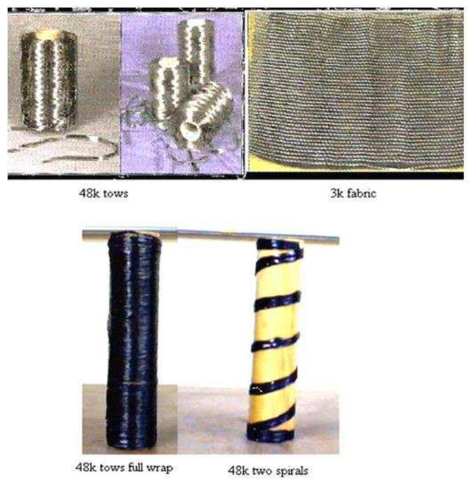

Figure 15 Column specimens and carbon reinforcement used by Najm et al. [16]

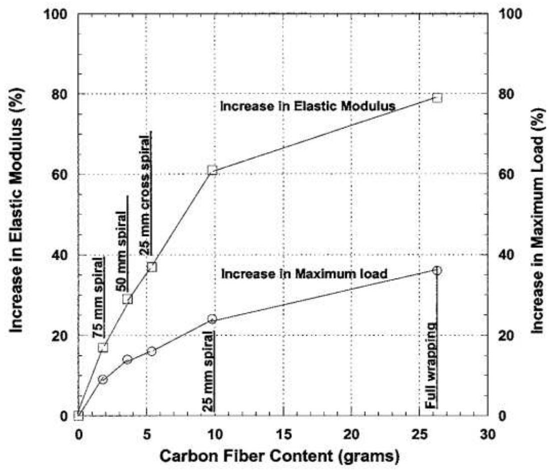

Figure 16 Ultimate strength and elastic modulus of columns versus fibre content [16]

3.5 Post-tensioned strengthening

Post-tensioned strengthening is a relatively new development in the seismic field. It can provide the column with self-centre capacity after a column has undergone large deformation. An extensive experimental campaign was carried out on beam-to-column, column-to-foundation and wall-to-foundation subassemblies for the implementation of LVL hybrid solutions [17, 18]. The design was to use external energy dissipaters together with post-tensioned effect to provide re-centring and energy dissipation capacity of a timber column. Figure 17 and Figure 18 show the specimens and experimental setup, respectively.

Figure 17 Column to foundation specimen with post-tensioned reinforcement and external energy dissipater [18]

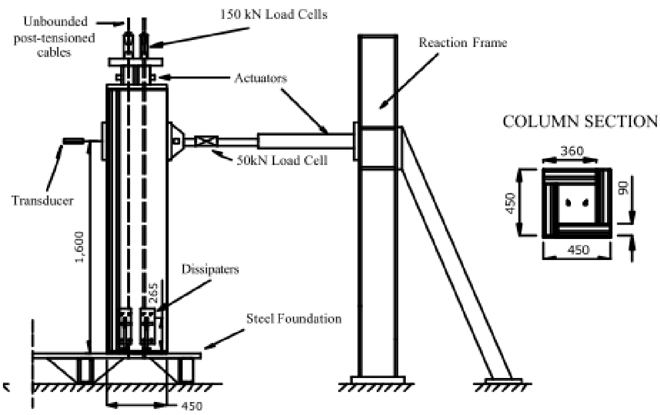

Figure 18 Experimental setup for post-tensioned strengthening of LVL column [17]

The hysteretic loop (Figure 19) shows a flag-shape, and it was observed that 4.5% of the storey drift was achieved in the tests; there was no degradation of stiffness and no structural damage after the tests. The residual deformation was still negligible as the post-tensioned mechanism helps the column to re-centre when unloading.

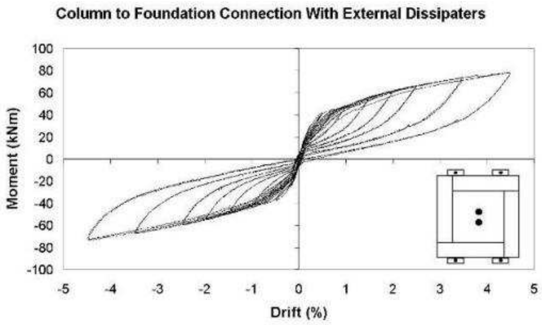

Figure 19 Hysteretic loop of a post-tensioned strengthening LVL column [17]

3.6 Enlargement of column cross section

Enlargement of the cross section of a column will help to reduce stress within the column so as to reduce the potential for buckling and material yield in compression. In some structures, such as those found in Japanese temples, large section columns will contribute to resisting lateral load by providing restoring forces [19]. Suda, Tasiro and Suzuki [20] proposed to enlarge the column base of existing structures (Figure 20) to increase the restoring force, which helps the column to return back its original position from its movement, so as to enhance the aseismic behaviour of traditional temples.

Figure 20 Enlargement of column base proposed by Suda, Tasiro and Suzuki [20]

Shaking table tests were carried out to investigate the effectiveness of the proposed reinforcement method. The reinforced column shows higher restoring force at the same deformation. A column with diameter of 300mm was used, and the column base was increased to 400 and 500mm as reinforcement. It showed, respectively, 200 and 300%

increase in restoring force when the structure has 7% inter-storey drift. This gives the whole structure better lateral force resistance.

4. Reinforcement of timber shear walls

This section solely discusses the strategy to reinforce timber shear walls; it is worth noting that repair and strengthening of timber shear walls are often achieved through an intervention on the joints and beams. There are several solutions to strengthen timber shear walls [21], such as:

- to reinforce shear walls with diagonal elements
- to reinforce the beams using wood-based materials
- to use additional sheathings
- to post-tension the walls using prestressing wire.

The first solution is the simplest method and is popular. The effectiveness of this method relies heavily on the stiffness of the fasteners connecting the boards to the frame. The second method is to attach steel diagonal elements to timber frames so as to share the force with the timber shear walls. The first two solutions are relatively straightforward and can be designed by calculation, therefore only limited research efforts have been devoted to these two methods.

The remaining solutions ensure that the reinforced timber shear walls will have higher ductility and strength. These methods have attracted more attention in research and are discussed below.

4.1 Composite material reinforcement as diagonal element

A series of research programmes have been carried out on reinforcing timber shear walls using FRP strips by experiments and numerical analyses [22, 23].A total of nine specimens were tested in three groups and the CFRP strips were glued on the fibre-plaster board (FPB) attached to the timber frames [22]. Figure 21 shows the specimen for the tests. The first group (G1) used two CFRP diagonal strips with width of 300 mm glued on to the FPB and also onto the timber frame; whereas the second group (G2) used 600 mm wide CFRP diagonal strips with the other conditions being the same as the first group. The third group (G3) has two 300 mm width CFRP strips glued on the FPB but not attached to the timber frame. The experimental results revealed that the third group had the highest elastic resistance (force forming the first crack) although it was found to increase in all the CFRP strengthened test samples. The results from this series of tests showed that the three reinforcement methods do not increase the stiffness but increase the strength. An analytical model has been further developed to approximate the behaviour of timber shear walls reinforced by CFRP strips with satisfactory agreement [23].

Figure 21 The specimen and test setup for CFRP reinforced timber shear walls [23]

4.2 Reinforcement by using wood-based materials

Timber framed structures are a common type of structure in many countries. It has been observed that the soft-storey in a timber framed structure can protect superstructure by exhibiting plastic deformation of the soft-storey [24]. Lam, Prion and He carried out tests on light-weight timber shear walls with oversized board, and found substantial increase in both stiffness and lateral load carrying capacity in shear walls built with oversize panels under monotonic loading[25]. One common way to reinforce existing timber shear walls is to add a layer of plywood or other wood-based panel [26]. The additional sheathing will facilitate taking lateral loads imposed on the existing walls. This is particularly useful to reinforce light-frame structures with soft-storey buildings. However, this is expensive and not applicable to some structures with large openings [27].

Chang, Hsu and Komatsu proposed a new solution to reinforce traditional planked timber shear walls (Figure 22) after an earthquake by inserting hardwood strips into grooves in beams that accommodate these timber planks [28]. Two different species of hardwood were used, Teak (Tectona grandis) and Padauk (Pterocarpus spp.). The results revealed that the timber shear walls reinforced by Padauk and Teak show a 100% and 60% increase in strength, respectively, compared with unreinforced and intact timber shear walls. The reinforced timber shear walls also exhibit better energy dissipation under cyclic loading.

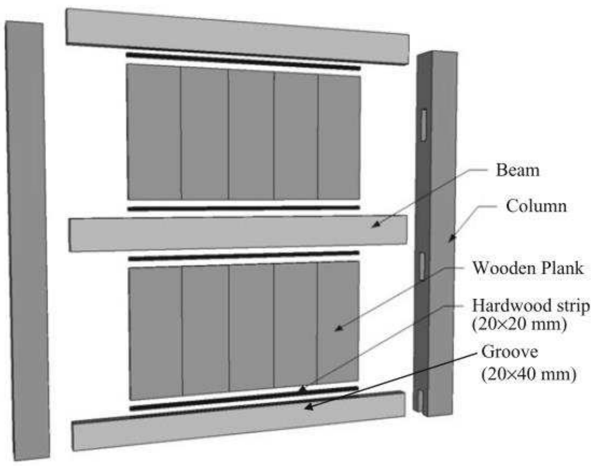

Figure 22 Schematic drawing of the reinforcement strategy [28]

4.3 Post-tensioned strengthening

Strengthening of timber shear walls by using the post-tensioned technique provides a very unique opportunity to achieve better aseismic behaviour for timber walls. In the experimental campaign described in Section 3.5 [17, 18], two different types of post-tensioned timber shear walls were tested, i.e. the single (Figure 23) and coupled timber walls (Figure 24). In the coupled wall specimens, a U-Shaped Flexural Plate (UFP) was developed and adopted to connect two smaller units of shear walls. The hysteretic loop of the coupled walls system shows a promising result as the system combines good energy dissipation capacity and recentering effect as shown in Figure 25.

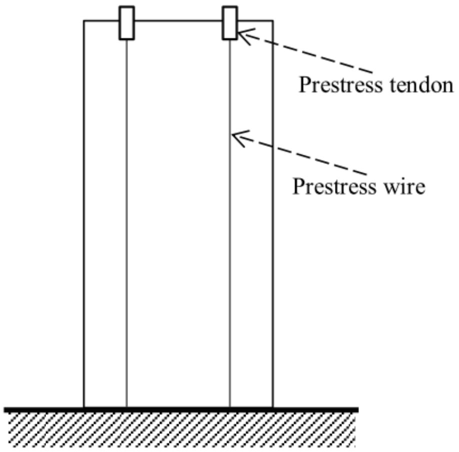

Figure 23 Schematic illustration of post-tensioned timber shear wall

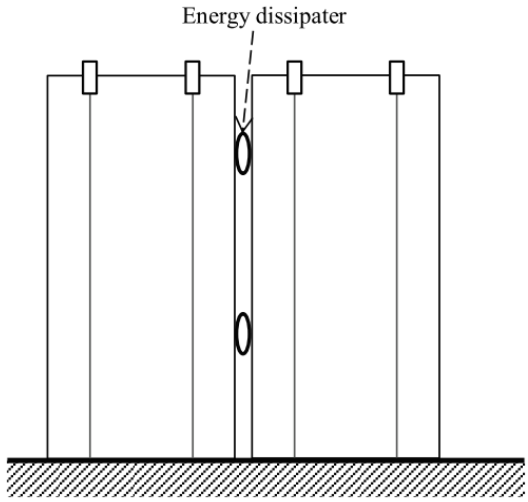

Figure 24 Schematic illustration of coupled post-tensioned timber shear walls

This technique shows good future potential for seismic-prone areas. However, to achieve a more robust system more research should be done to help engineers to deal with long-term creep in shear walls caused by post-tensioned and stress relaxation.

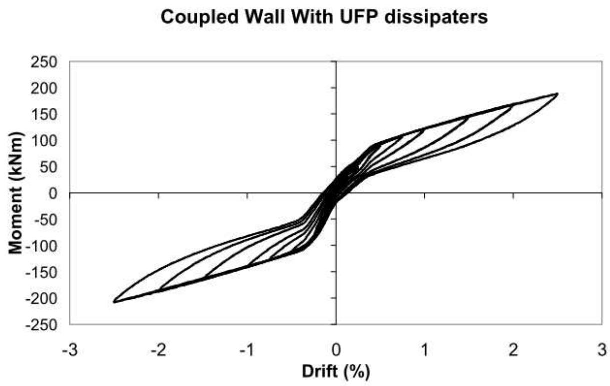

Figure 25 Hysteretic loop of coupled walls [17]

5. Discussion

The previous sections provide an overview of different methods to repair and reinforce damaged and undamaged timber columns and shear walls, tabulated in Table 2 and Table 3.

Table 2 Summary for repair and reinforcement of timber columns

			Prosthesisation	Screw reinforcement	Steel member	Composite material	Post-tensioned
Existing buildings	Cracked members	Increase strength[1]	NA[3]	X[4]	NA	X	NA
		Increase stiffness[2]	NA	X	NA	X	NA
	Bio-decay members	Increase strength	X	NA	NA	X	NA
		Increase stiffness	X	NA	NA	X	NA
	Intact members	Increase strength	NA	?[5]	O[6]	O	O
		Increase stiffness	NA	?	O	O	O
New buildings	members	Increase strength	NA	?	O	O	O
		Increase stiffness	NA	?	O	O	O
References			[4, 29]	[5]	[6]	[7-9, 12-14, 16]	[17, 18]

Remark:
[1] Strength increase compared with before intervention
[2] Stiffness increase compared with before intervention
[3] **NA** Not applicable
[4] **X**: Applicable and will not increase properties (such as stiffness and strength)
[5] **?**: Needs further research
[6] **O**: Applicable and will increase properties (such as stiffness and strength)

Table 3 Summary for repair and reinforcement of timber shear walls

			Prosthesisation	Composite material	Timber member	Post-tensioned
Existing buildings	damaged members	Increase strength[1]	X[3]	NA[4]	O[5]	NA
		Increase stiffness[2]	X	NA	O	NA
	Intact members	Increase strength	NA	O	O	NA
		Increase stiffness	NA	X	O	NA
New buildings	members	Increase strength	NA	O	O	O
		Increase stiffness	NA	X	O	O
References				[21-23]	[28]	[17, 18]

Remark:
[1] Strength increase compared with before intervention
[2] Stiffness increase compared with before intervention
[3] **X**: Applicable and will not increase properties (such as stiffness and strength)
[4] **NA**: Not applicable
[5] **O**: Applicable and will increase properties (such as stiffness and strength)

5.1 Reversibility

When dealing with architectural heritage, techniques used to repair or reinforce a structural member should be reversible whenever possible. The literature has shown there to be a lack of research into reversible repair techniques for these valuable cultural heritage buildings. Using composite materials, such as FRP and CFRP, with timber tends to be an irreversible technique due to the adhesive used. The screw repair technique proposed by Song et al. is reversible [5], but more research should be carried out to investigate other parameters such as spacing between screws, types of self-tapping screws, the effect of the size of cracks, etc.

5.2 Long term behaviour of reinforced structural members

Timber is a mechano-absorptive material and therefore creep needs to be considered when long-term loadings are imposed; it is particularly onerous when the moisture content of the timber members constantly varies between high and low levels. Post-tensioned reinforcing techniques tend to introduce high levels of stress into structural members and therefore the long term behaviour of timber columns and shear walls reinforced by this technique should be investigated. The post-tensioned system reviewed in this paper [17, 18] introduces a compressive stress on the timber column perpendicular to the grain, where beams are connected to the column. This in turn will lead to creep in the material. How this creep will affect the reinforcement will need to be addressed in the future. Another important issue to be considered is ageing and weathering of composite material used in reinforcement and strengthening. Avent tested epoxy reinforced timber connections and pointed out that the dry condition shear strength of epoxy repaired Southern pine was reduced by one-third when the repaired member was exposed to natural weathering conditions [30].

5.3 Fire performance

Timber has low thermal conductivity; it is measured at approximately 0.8 (measured in $J/h/m^2/mm/°C$) compared with 12.6 for concrete and 312 for steel [31]. Most epoxies begin to soften at 90^o-120^oC and the strength rapidly decreases. Therefore it is good practice to inject epoxy into timber to repair the interior regions and the timber will protect and slow down the strength reduction of the epoxy. In the event of fire, the composite material and epoxy are exposed to fire in those composite material reinforcement methods described previously ([5], [7], [8], [9], [22]). This will lead to the reinforcement and strengthening measurements becoming ineffective. Furthermore, when selecting the composite material and adhesives for reinforcement and repair, one should ensure that no toxic emissions occur during the fire. The strength of steel is halved when exposed to a temperature of 600^oC and therefore a similar situation can be found in steel reinforcement of timber members [5, 6]. Hence it is important to develop appropriate reinforcement and strengthening methods for timber members in the event of fire.

5.4 Effectiveness of prosthesisation

There is no evidence as to how effective the prosthesisation technique is, although this is a widely accepted practice within architectural heritage conservation programmes. Research efforts should be invested in experiments as well as in developing design guidelines for this practice, such as the buckling response of timber columns where the lower part of the portion is replaced by new timber with traditional carpentry.

6. Summary

An extensive overview has been carried out in this paper on different repair and reinforcement techniques that should be implemented on timber columns and shear walls under various circumstances. The existing research has shown that reinforcement of columns by screws and composite materials such as FRP are effective although there is a need to investigate the long term performance of these measures. Compared with timber columns, less research has been carried out to explore strategies to reinforce and repair timber shear walls. However, reinforcement and repair of timber shear walls by employing composite materials or hardwood appear to be effective, as has been demonstrated by some authors. This paper also discusses and analyses the need for future research on the repair and reinforcement of these structural elements.

Acknowledgement

This paper was first published in ‘Reinforcement of Timber Structures. A state-of-the-art report’, Ed. A. Harte, P. Dietsch, Shaker Verlag, 2015. The author appreciates permissions granted from Prof. Andy Buchanan and University of Canterbury for Figures 16-18 and 24, Profs. Suzuki and Suda for Figure 19, Profs. Weiping Zhang and Xiaobin Song at Tongji University, China, for Figures 9 and 10.

References

1. Yeomans, D.T., The repair of historic timber structures. 2003: Thomas Telford.
2. Lopez-Anido, R., A.P. Michael, B. Goodell, and T.C. Sandford, Assessment of wood pile deterioration due to marine organisms. Journal of waterway, port, coastal, and ocean engineering, 2004. **130**(2): p. 70-76.
3. Keey, R.B., T.A. Langrish, and J.C. Walker, Kiln-drying of lumber. 2000: Springer Verlag Berlin Heidelberg, New York.
4. D'Ayala, D. and H. Wang, Conservation Practice of Chinese Timber Struc*tures: 'No Originality to be Changed'or 'Conserve as Found'.* Journal of architectural conservation, 2006. **12**(2): p. 7-26.
5. Song, X., R. Jiang, W. Zhang, X. Gu, and L. Luo, Compressive behavior of longitudinally cracked wood columns retrofitted by self-tapping screws, in World Conference on Timber Engineering. 2012: Auckland, New Zealand.
6. Tanaka, H., H. Idota, and T. Ono. Evaluation of buckling strength of hibrid timber columns reinforced with steel plates and carbon fiber sheets. in 9th World Conference on Timber Engineering 2006. Oregon, United States.
7. Plevris, N. and T.C. Triantafillou, FRP-reinforced wood as structural material. Journal of Materials in Civil Engineering, 1992. **4**(3): p. 300-317.
8. Triantafillou, T.C. and N. Deskovic, Prestressed FRP sheets as external reinforcement of wood members. Journal of Structural Engineering, 1992. **118**(5): p. 1270-1284.

9. Ehsani, M. and M.L. SE, Strengthening of old wood with new technology. STRUCTURE, 2004. **19**.

10. Lopez-Anido, R., A.P. Michael, and T.C. Sandford, Experimental characterization of FRP composite-wood pile structural response by bending tests. Marine Structures, 2003. **16**(4): p. 257-274.

11. Emerson, R. In situ repair technique for decayed timber piles. in Proceedings of Building on the Future, Securing the Past Conference. 2004.

12. Zhang, W., X. Song, X. Gu, and H. Tang, Compressive behavior of longitudinally cracked timber columns retrofitted using FRP sheets. Journal of Structural Engineering, 2011. **138**(1): p. 90-98.

13. Oprişan, G., N. Ţăranu, and I.-S. Enţuc, Strengthening of the timber members using fibre reinforced polymer composites. Buletinul Institutului Politehnic DIN IAŞI, 2004. **L (LIV)**(1-4): p. 67- 75.

14. Taheri, F., M. Nagaraj, and P. Khosravi, Buckling response of glue-laminated columns reinforced with fiber-reinforced plastic sheets. Composite Structures, 2009. **88**(3): p. 481-490.

15. Davidovits, J., Geopolymers. Journal of Thermal Analysis and Calorimetry, 1991. **37**(8): p. 1633-1656.

16. Najm, H., J. Secaras, and P. Balaguru, Compression tests of circular timber column confined with carbon fibers using inorganic matrix. Journal of materials in civil engineering, 2007. **19**(2): p. 198-204.

17. Palermo, A., S. Pampanin, M. Fragiacomo, A. Buchanan, and B. Deam, Innovative seismic solutions for multi-storey LVL timber buildings, in 9th World Conference on Timber Engineering. 2006: Oregon, United States.

18. Smith, T., S. Pampanin, M. Fragiacomo, and A. Buchanan, Design and construction of prestressed timber buildings for seismic areas. NZ Timber Design Journal, 2008. **16**(3): p. 3-10.

19. Suzuki, Y. and M. Maeno, Structural mechanism of traditional wooden frames by dynamic and static tests. Structural Control and Health Monitoring, 2006. **13**(1): p. 508-522.

20. Suda, T., Y. Tasiro, and Y. Suzuki, Seismic Reinforcement by Restoring Force due to Column Rocking for Traditional Wooden Frame (in Japanese). Proceedings of disaster preventionof historic cities, 2011. **5**: p. 8.

21. Dobrila, P. and M. Premrov, Reinforcing methods for composite timber frame–fiberboard wall panels. Engineering structures, 2003. **25**(11): p. 1369-1376.

22. Premrov, M., P. Dobrila, and B. Bedenik, Analysis of timber-framed walls coated with CFRP strips strengthened fibre-plaster boards. International journal of solids and structures, 2004. **41**(24): p. 7035-7048.

23. Premrov, M. and P. Dobrila, Mathematical modelling of timber-framed walls strengthened with CFRP strips. Applied Mathematical Modelling, 2008. **32**(5): p. 725-737.

24. Chopra, A., D. Clough, and R. Clough, Earthquake resistance of buildings with a *'soft'first storey.* Earthquake Engineering & Structural Dynamics, 1972. **1**(4): p. 347-355.

25. Lam, F., H.G. Prion, and M. He, Lateral resistance of wood shear walls with large sheathing panels. Journal of Structural Engineering, 1997. **123**(12): p. 1666-1673.

26. ATC, Here Today - Here Tomorrow: The Road to Earthquake Resilience in San Francisco, Earthquake Safety for Soft-story Buildings. 2009, Community Action Plan

for Seismic Safety (CAPSS) Project, Applied Technology Council Report ATC 52-3, Redwood City, CA.

27. Iqbal, A. Seismic retrofit solutions for light timber frame buildings with soft first story. in Proceedings of the NZSEE conference. 2013.

28. Chang, W.-S., M.-F. Hsu, and K. Komatsu, A new proposal to reinforce planked timber shear walls. Journal of wood science, 2011. **57**(6): p. 493-500.

29. Pinto, L., Inventory of repair and strengthening methods timber, in Departament d'Enginyeria de la Construcció. 2008, Universitat Politècnica de Catalunya: Barcelona, Spain.

30. Avent, R.R., Decay, Weathering and Epoxy Repair of Timber. Journal of Structural Engineering-Asce, 1985. **111**(2): p. 328-342.

31. Avent, R.R. and C.A. Issa, Effect of fire on epoxy-repaired timber. Journal of structural engineering, 1984. **110**(12): p. 2858-2875.