Reinforcement of Traditional Timber Frame Walls

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Abstract Timber frame walls are common structural elements adopted in many countries for different purposes. They constitute an important cultural heritage of different parts of the world and the necessity often arises to intervene in such structures for their preservation. Different strengthening techniques have been adopted when retrofitting timber frame walls, some traditional and others more innovative. As the response of the walls, particularly to horizontal actions, is governed by their connections, retrofitting is usually concentrated at the joints, but interventions can also be carried out on timber members or on infill.
In this chapter, an overview of possible retrofitting techniques is presented, focusing on their advantages and disadvantages and their effects on the overall behaviour of the wall. The presented solutions focus mainly on experimental and in situ interventions performed for seismic purposes.

1 Introduction

Timber frame buildings constitute an important portion of many historical dwellings in the world, constituting a common vernacular architecture with varying characteristics. They became popular for their cheap and easy construction in areas where wood was abundant (North America, Scandinavia, UK), for their good seismic performance (e.g. in Portugal, Italy, Greece, Turkey, Peru), as timber frame walls act as shear walls, as well as for their low weight.

While they are recognized as an important world cultural heritage, many of these buildings have known little or no care during their life, or they have been modified without taking into account the structural response after alterations had been made and without considering concepts such as reversibility and re-treatability.

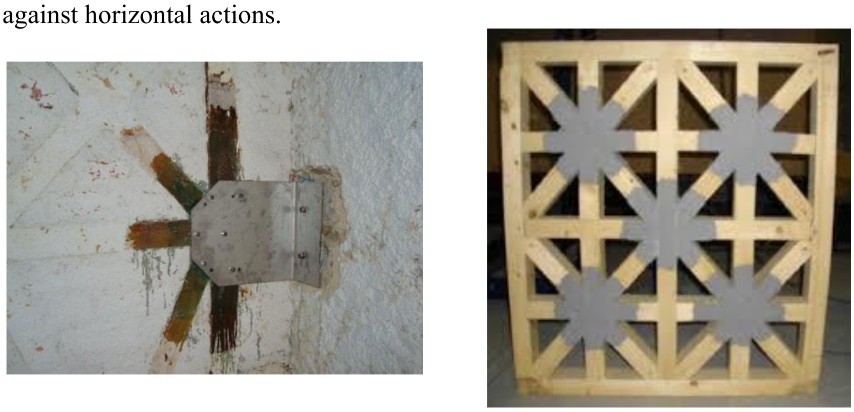
This chapter aims to present state-of-the-art traditional and modern strengthening techniques for timber frame walls and discuss their advantages, disadvantages and suitability.

Interventions in timber frame buildings can be necessitated by different problems, e.g. decay as a consequence of poor maintenance, change in use and the consequent need for additional strength, cracks or loosening of the infill materials or the timber joints, and local failures of the timber frame. Many examples [1, 2, 3] are available on restoration works done on traditional timber frame buildings, and in some cases the end result is the loss of the original structural system, as some element has been substituted by steel, concrete, or new timber.

Indeed, when intervening on traditional Portuguese half-timbered buildings (the so-called Pombalino buildings, a particular type of timber frame building with external masonry walls linked to an internal timber frame system), a common and extremely invasive practice has been the demolition of the inner part of the building, which is then substituted by reinforced concrete, keeping only the original masonry façades[4] and, therefore, actually losing the original timber frame structure.

Many examples are available on restoration works done on traditional half-timbered buildings [1, 2, 4]. Numerous Pombalino buildings in Lisbon have been retrofitted with fibre-reinforced polymer (FRP) sheets in the connections of the timber frame walls [1], or with damping systems that link the timber frame walls and the outer masonry walls through injected anchors and provide additional bracing [1] (see Fig. 1). Another practice is to project reinforced shotcrete onto the timber frame walls [5], but such a solution could effectively have an overly stiffening effect on the joints. Timber-to-timber interventions are carried out on historic buildings, for example the timber-framed churches in Poland.

In the following paragraphs, strengthening solutions will be presented based mainly on experimental results on walls and joints, focusing on strengthening against horizontal actions.



(a)

Fig. 1 Example of strengthening techniques: (a) connections between internal timber-frame walls and external masonry walls; (b) retrofitting with FRP

2 Retrofitting of traditional timber frame walls (experimental experience)

In this section, a number of retrofitting techniques that have been studied experimentally are presented. The techniques were studied specifically for protection against seismic actions. During a seismic event, the weakest point of a timber frame wall is its connections, providing that the structural timber surrounding it is sound. Consequently, strengthening interventions are usually carried out on the connections. Additional interventions include interventions on infill, e.g. using reinforced render (see Section 3), or the use of damping systems that involve the whole wall and bypass the importance of single joints. When retrofitting timber frame structures, some general principles should be taken into consideration, such as conservation plans (in particular, understanding the structural system of the building and its heritage importance), the causes of deterioration, compatibility of materials, and re-treatability if not reversibility.

2.1 Mechanically fastened plates

A traditional method of strengthening timber joints is the use of metallic elements such as steel plates and bars. Steel elements can be screwed, punched or glued.

Steel plates successfully increase the load-carrying capacity of the post-beam connection and are easily implemented. They allow for a better collaboration between the horizontal and the vertical elements and they do not prevent the rotation of the connection. This is not the case when steel plates connect the main post-beam joint to the diagonal bracing. A stiffening effect occurs, thus compromising the ductility of the structure and causing brittle failure in the connections.

An increase in ductility is also observed for walls with weak infill. When using steel plates, there is a minimal loss of the original material and the intervention is potentially reversible. For cultural heritage structures, the possibility of adopting this strengthening solution could depend on its position and visibility and whether it can be hidden by finishing. Cracks may also appear on the plaster due to the presence of steel plates placed above timber. Care has to be taken when applying steel elements at minimum distances from borders, for bolts and screws, and to knots or pre-existing drying fissures, which could create a preferential failure path. In the case of non-machine-worked timber members (non-rectangular section), some difficulty could arise in applying these plates, as contact could not be guaranteed, contrary to what could obtain when using more malleable strengthening materials, like FRP sheets.

A possible problem that needs to be taken into consideration when using steel plates is the possibility of moisture ingress. To protect such interventions from weathering, stainless or galvanized steel plates should be used.

When timber frame walls are only part of the inner structure (e.g. Pombalino buildings in Portugal), steel plates used to strengthen the walls can be linked to the external masonry walls to prevent the out-of-plane failure of the latter [6]. When the walls have infill, specially crafted plates can be used in order not to cover the infill, which could push and deform the steel plates.

An experimental study carried out on traditional timber frame walls with half-lap joints [7] subjected to quasi-static in-plane cyclic loading adopted such strengthening solution. A steel plate was screwed on either side of the wall at the connection and steel bolts were used to link the two plates of each connection (Fig. 2). The walls had already been tested in the unreinforced condition and retro-fitting was applied to the damaged walls, which were appropriately repaired with either prostheses or by the substitution of the element. The results showed that an increase in strength up to 180% could be achieved; even after peak load, a good residual strength was observed for the walls (see Fig. 3). Failure occurred at the joints, but the bolts and steel plates were able to prevent the complete collapse of the connections. Additionally, both the dissipative capacity and stiffness increased after strengthening. For a timber frame walls with bracing members (St. Andrews crosses) which originally have weak connections (e.g. nailed), care should be tak-en not to over-stiffen the connections between the bracing members and main frames (see Fig. 4), as this could lead to different structural behaviour of the walls, out-of-plane failure during a seismic event, and a consequent decrease in ductility [7].

Fig. 2 Example of strengthening performed with steel plates secured with bolts.

The good seismic capacity of steel plates fastened with bolts applied to traditional timber frame walls was confirmed by Gonçalves et al. [5], with over 100% increase in strength and a great improvement in terms of energy dissipation.

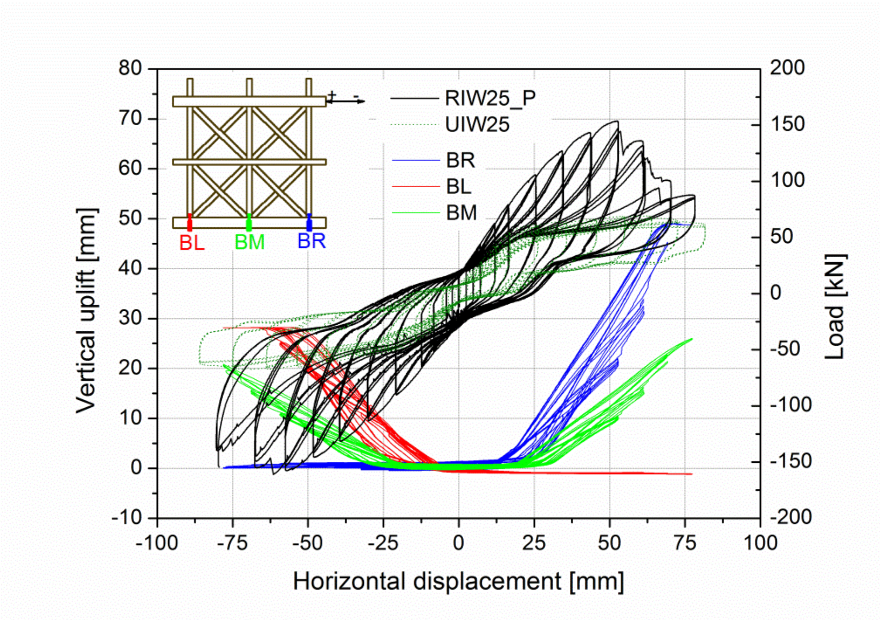
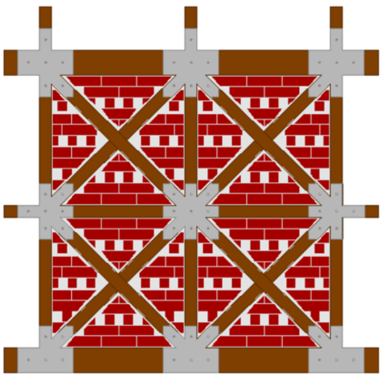
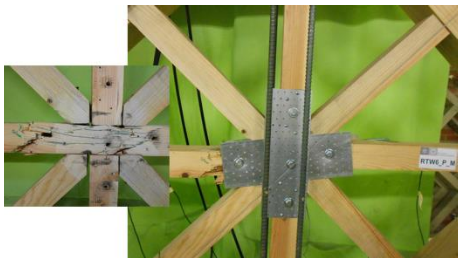


Fig. 3 Experimental results for timber frame walls retrofitted with steel plates (RIW25_P) compared with the unreinforced results (UIW25).





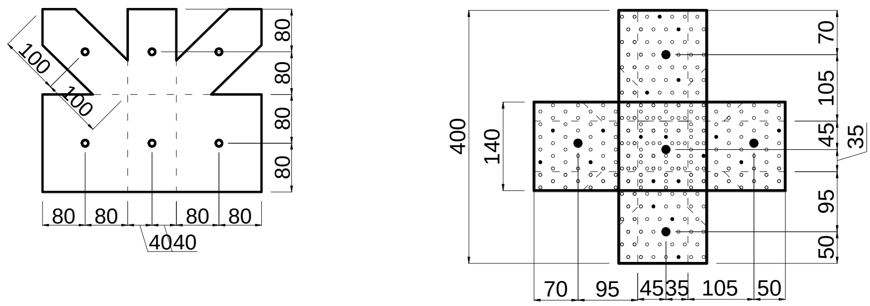


Fig. 4 Retrofitting configuration for timber frame walls: (a) with bracings connected (dimensions in cm); (b) without bracings connected (dimensions in cm).

Where necessary, steel plates could be used as strengthening for posts, offering a confining effect and preventing buckling.

2.2 Near-Surface Mounted (NSM) strengthening

A strengthening technique that has acquired popularity in recent years is the application of rods and bars (either in steel or in FRPs) using the near-surface mounted (NSM) method. This technique has proven effective for both flexural and shear reinforcement but it requires specialised workmanship. It can be used as an alternative to externally bonded reinforcement (EBR), albeit it has some advantages over EBR, namely reduced in situ installation work, easier anchorage to prevent debonding, and the possibility of achieving an invisible intervention, since a thin wood cover can be used, though it is not reversible [8]. For a detailed step-by-step illustration of how to perform this retrofitting, see [9]. A possible disadvantage of this technique is that it reduces the timber section, therefore care should be taken not to weaken the effective cross-section.

The following parameters should be taken into account when designing NSM strengthening: (1) cross-sectional dimensions of timber elements involved. Limitations on the minimum distances from the borders should be followed for the cuts; (2) presence of knots or of pre-existing drying fissures. Slots should not be made near knots, since they could weaken the surrounding zones. Important fissures near the intervention zone may need to be filled; (3) tensile strength of bars and rods. Attention should be paid to the type of element used in order to guarantee a sufficient tensile strength to the connection; (4) bond strength between bars and structural glue and between structural glue and the component material. The bond between the materials should be investigated to avoid early failure due to debonding; (5) anchorage length. Moisture ingress should not be considered a problem, as the glue isolates the reinforcement. Additionally, the strength of the glue is guaranteed even if the surrounding timber element is wet. The glues used are specifically designed for timber and are highly compatible with wood.

Eurocode 5 [10] does not provide guidelines for NSM interventions, or any other strengthening intervention, and usually the application of this retrofitting is based on experimental results from the literature (e.g. CNR DT 200 R1/2013, ACI 440.2R-08). NSM strengthening has been applied to timber only in the last two decades. Research has been performed by Jorge [9], who studied the bond behaviour between glulam and FRP and then applied FRP strips with the NSM technique to continuous double span glulam slabs for bending strengthening. From the analysis of the tests, the author suggested that an anchorage length of 15 times the diameter should be used. The same anchorage length is suggested by other authors. For FRP strips, good performances were found for bond length of 7.5 times the height of the strip [11] for concrete structures.

CK45 steel was used for NSM strengthening with steel flat bars, with a tensile strength between 600 and 800MPa (a value of 672.87MPa was obtained experimentally). The bars had a section of 8×20mm^2, so the ultimate tensile force that they could withstand was 108kN per bar, applied to the half-lap connections of traditional timber frame shear walls, in *Pinus pinaste*r, and tested under in-plane cyclic loads [12]. Two bars were welded together to form a cross shape and were inserted in the slots cut in the post and beam of the half-lap joint (Fig. 5). Another half-lap joint was also created between the two bars and then welded to improve the anchorage length. A structural timber glue was used, namely MAPEI Mapewood Paste 140 [13], which is compatible with both materials, has a fast drying time (7 days) and is durable.

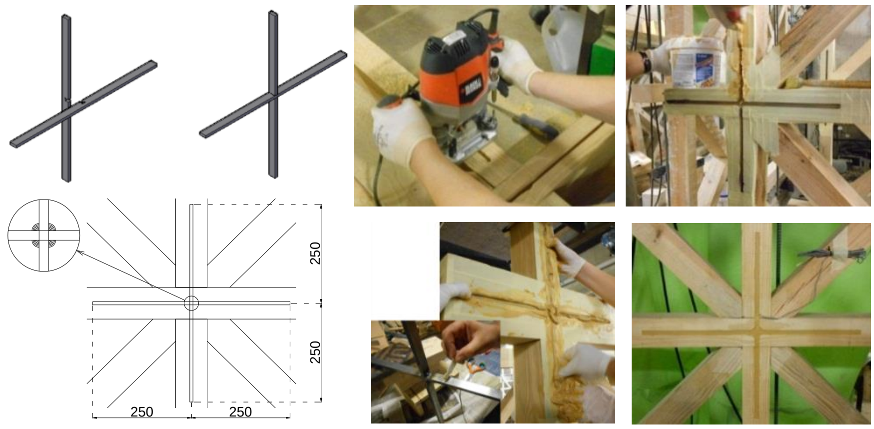
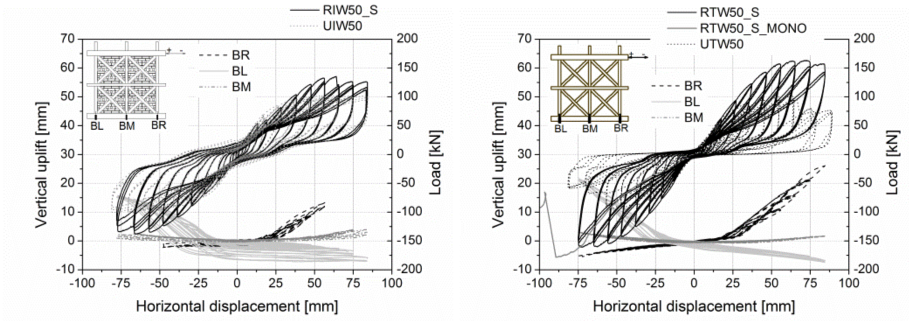


Fig. 5 Example of strengthening performed with NSM flat steel bars (dimensions in cm) [11].

An increase in strength of up to 200% was obtained, while maintaining a good deformation capacity. The retrofitting proved to be more appropriate when no or weak infill was present in the walls, as strong infill limits the deformation of timber members and makes it impossible to fully exploit the additional deformation capacity offered by NSM bars. This technique offers a very good shear response to the walls and gives additional strength to the connections, preventing early tensile/shear failure during seismic events and avoiding rocking mechanisms [12]. Stiffness increased by up to 100% and the dissipative capacity by up to 160%, particularly for walls with no or weak infill (see Fig. 6). Moreover, it was observed during the tests that NSM retrofitting hindered the opening of the connections when compared to, for example, a retrofitting performed with steel plates, indicating greater stiffening of the connections. This effect could not always be positive, so great care should be put into the selection and amount of the bar or rod used in terms of strength and deformability of the same.



(a) (b)

Fig. 6 Experimental results of: (a) infilled wall with NSM strengthening; (b) timber frame wall with no infill.

This retrofitting technique is of easier application than, for example, glued-in rods, because it guarantees easy accessibility and the cuts can be performed directly on the wall in situ when it is not necessary to substitute elements.

Apart from steel elements, NSM strengthening can be performed using fibre reinforced polymers (FRPs), either laminates or rods (see Fig. 7). It was seen, from an experimental campaign carried out on glulam slabs strengthened with NSM rods situated in the tension zone [9], how this type of strengthening could greatly improve the flexural strength of timber beams, thereby increasing their ductility. Additionally, even though it was not designed for the redistribution of any kind of moment, the technique was able to re-distribute the bending moment by approximately 25%. Other studies have confirmed the good response offered by this type of strengthening (e.g. [14,15]) when applied to timber structures. In the case of timber frame walls, if flexural strengthening of the wall beams is deemed necessary, the possible presence of infill and the possibility of its removal in order to proceed with the intervention has to be taken into account.

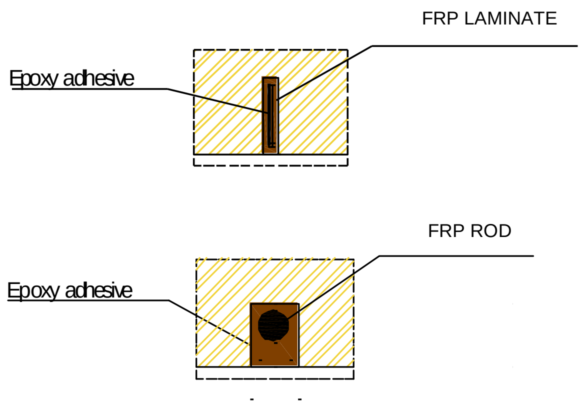


Fig. 7 Different configurations of NSM strengthening with FRPs [8].

2.3 Externally Bonded Reinforcement (EBR) using Fibre-reinforced Polymers (FRPs)

Fibre-reinforced polymer (FRP) is a composite of fibres and matrix; the fibres provide strength and stiffness and the polymer matrix protects the fibres from abrasion and transfers stresses between them. There has been an increased use of FRPs in timber technology in the last decade because they do not corrode, have a high strength to weight ratio, are non-conductive and non-metallic, and have low maintenance requirements. Different products are available (plates, rods and sheets) and different fibres can be used [16]. However, some drawback exists in terms of durability and long-term performance.

FRPs are frequently used in practice to strengthen existing timber structures. FRP sheets are glued on wall connections or members to improve their strength, usually based on empirical knowledge, as no standardisation on FRPs exists for timber, only for concrete. National guidelines are available, e.g. CNR-DT 201/2005, concerning the strengthening of timber structures with FRPs. Experimental investigations help to better understand the most appropriate solutions for FRP strengthening.

Cruz et al. [17] performed diagonal tests on reduced scale wallets strengthened with glass fibre-reinforced polymer (GFRP) rods and glass fibre fabric (GFF) sheets. The walls were retrofitted by embedding two GFRP bars to the outer timber members and gluing GFF sheets to the timber elements of the central connections. The strengthened wall panels showed a recovery strength of up to 127% and good improvement in terms of ductility (see Fig. 8).

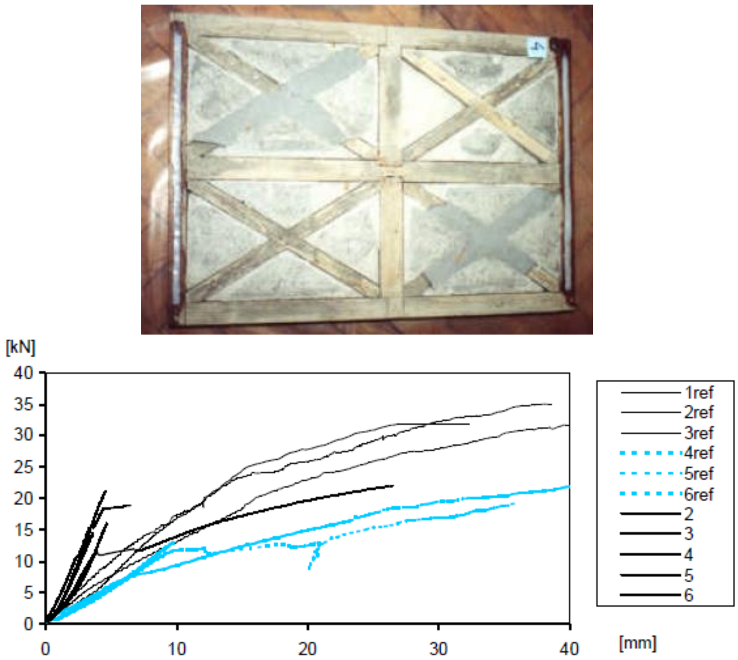


Fig. 8 Wall panels strengthened and tested with FRPs: (top) strengthened panels; (bottom) experimental results (2, 3, 4, 5, 6 – initial state of the panels; 1ref, 2ref, 3ref – panels strengthened with FRP rods and GF fabric; 4ref, 5ref, 6ref – panels strengthened with FRP rods only). [15]

More research has been carried out on modern timber frame walls, e.g. [18], but for these walls strengthening is not usually considered. An improvement in their seismic capacity is usually achieved through the adoption of different sheathing or through an alternative disposition of the frame [19]. Premrov et al. [20] studied timber frame walls coated with carbon fibre-reinforced polymers (CFRP) strengthened with fibre-plaster boards (Fig. 9). The CFRP strips were applied diagonally and different widths and number of strips were considered. Results showed that, while no increase in terms of stiffness was recorded, the strength of the walls improved.

Fig. 9 Walls strengthened with CFRP [18].

Poletti et al. [21] performed pull-out and in-plane cyclic tests on half-lap joints retrofitted with GFRP sheets. The tests chosen were meant to capture the hysteretic behaviour and dissipative capacity of the connections and to characterise their response and, therefore, their influence on the seismic response of timber frame walls, particularly in regard to their uplifting and rotation capacity, which could lead to rocking in the walls. Uni-directional sheets were applied to both sides of the connection, forming a cross on the connection on the overlapping. The results on pull-out cyclic tests showed a very high initial stiffness and the maximum capacity of the connection for a low value of vertical uplift. Failure occurred in two parts, first on one side of the connection with the debonding of the vertical sheet (detail 1 in Fig. 10) and then on the other side with failure of the fibres perpendicular to their direction (details 2 and 3 in Fig. 10). The maximum strength achieved was 15 times greater than that of the unreinforced specimen, but the residual strength was lower than that of the unreinforced specimen. Due to the geometry of the connection and the use of uni-directional sheets instead of multi-directional ones, the fibres also worked perpendicularly to the fibres, leading to their separation and eventual failure. The same problem was encountered during the in-plane cyclic tests, since the failure of the sheets occurred in a direction perpendicular to the fibres at the height where the post met the beam. Nevertheless, the load-carrying capacity increased by 50%.

When considering timber strengthening, particularly of traditional structures, the adoption of CFRP materials is often not cost-effective, since the structure will not be able to mobilise the full capacity of the materials. By using GFRP products, the structure becomes less rigid and higher strains are reached. Carbon based products are able to give better results in terms of creep and fatigue, but it has to be analysed if their additional capacity is effectively needed. Additionally, the visual impact is lower.

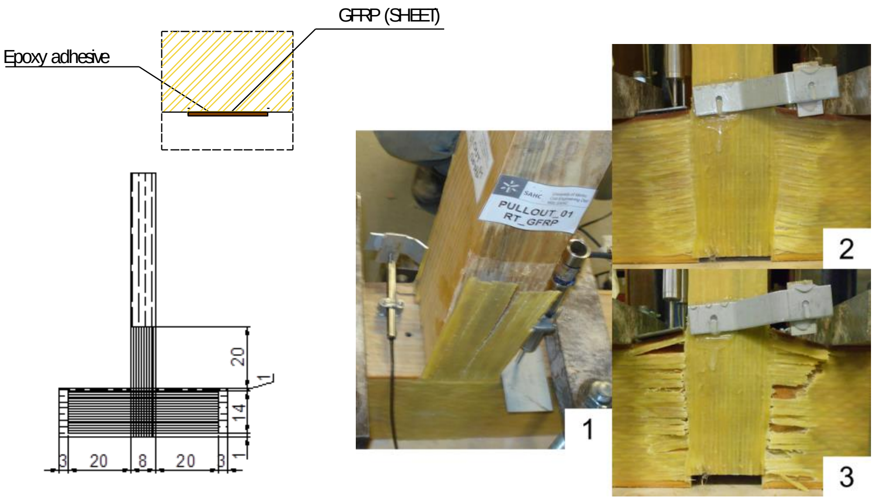
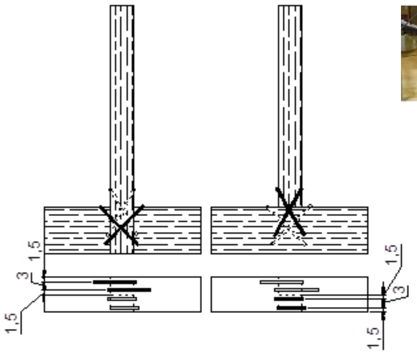


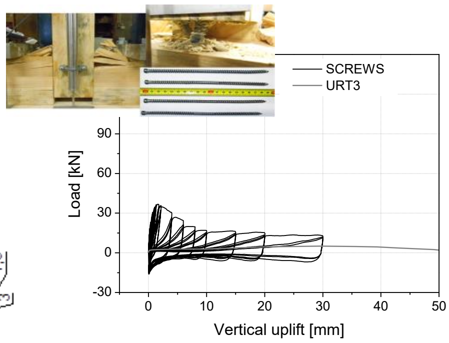
Fig. 10 Example of strengthening performed with GFRP sheets [8,19].

2.4 Self-tapping screws

One of the least invasive reinforcement techniques for timber is the use of additional screws for the connections. The screws are easily inserted, can easily reconnect a cracked element or connection and provide additional strength. Recently, the use of self-tapping screws proved particularly effective when axially loaded (e.g. [22]). Inclined arrangement of screws can transfer shear and tensile forces and strengthen bending-resistant connections. Care has to be taken to position the screws at the appropriate angles to exploit their full strength, as well as to follow the minimum distances between fasteners and the end and the edge of the timber to avoid splitting, but otherwise this constitutes an easy, cheap and reversible strengthening technique.

In the case of traditional connections, and taking into consideration seismic loads, half-lap joints were strengthened by applying self-tapping screws at 30° and 60° configurations and then used to connect a post and a beam [23]. Pull-out tests were performed and results showed that this strengthening solution was able to greatly improve the strength of the connection (6 times over) and its stiffness without showing brittle failure; the solution ensured a post-peak softening behaviour and, therefore, a great capacity to dissipate energy. Failure proved to be mild, since the damage increased progressively with pulling out of the screws throughout the test, causing slight damage to the beam (see Fig. 11). After the peak load, the screws were responsible for grain disorganisation. Plastic deformations of the screws were observed at the end of the test (6mm screws were used). Though in-plane tests were not performed, it is believed that given the inclination of the screws, the solution would have been beneficial and could increase the strength and dissipative capacity of the connection, and consequently of the wall, even if not in such a dramatic way as one of the strengthening solutions mentioned above. From the pull-out tests it is clear that they would help prevent rocking behaviours in timber framed walls under seismic load.





(a) (b)

Fig. 11 Joint strengthened with self-tapping screws: (a) scheme of screw application; (b) pull-out test results and damage observed.

Trautz and Koj [24] strengthened the mitre joints of a rigid timber frame. The strengthened joints were designed for both positive and bending moments. The tests showed a significant higher load-bearing capacity compared to conventional joints with dowels or glued finger-joints.

Tannert and Lam [25] studied the effect of strengthening, by self-tapping screws, of rounded dovetail connections under vertical shear loading, considering different angles between the screw axis and the wood grain of the joist. A significant increase in the capacity and stiffness was observed.

Moisture effects have to be considered since they affect the withdrawal capacity. Metal fasteners act as constraints, and moisture variations can change the strength and stiffness properties of timber, induce cracks and affect the load-carrying capacity of the connections. In that regard, a number of studies have been carried out on the effect of moisture content variation on the withdrawal capacity of self-tapping screws (e.g. [26]).

2.5 Timber-to-timber

Though the response of timber frame walls is dominated by their connections and strengthening the connections is the most common intervention, failure can still occur in a post or beam, be it due to decay, the presence of a defect, insufficient cross-section for the current load, etc.

Various strategies can be adopted to repair posts and beams or increase their strength. The most traditional repair technique is timber-to-timber intervention [27]. Repair can refer to patching, where only the damaged part of a section is taken out and a new piece is inserted, or the substitution of a whole section; the worst-case scenario may require the replacement of a whole member (Fig. 12). Patch repairs use a combination of glues, bolts, timber dowels and screws to guarantee the continuity of the member and avoid, as much as possible, differential movements between the two parts, which could lead to water trapping. Care should also be taken in selecting the timber for repairs: same species of timber with similar grain orientation and moisture content should be adopted.

Whole section repairs may be necessary before carrying out additional strengthening. A prosthesis is created, in that case, and connected to the existing member. The connection is, once again, the most crucial point. A poorly executed prosthesis could nullify the effects of any other strengthening [23]. Traditionally, different typologies of scarf joints are adopted, with the addition of screws and bolts. More recently, glued-in rods and self-tapping screws are used to secure the prosthesis and existing member.

Other times, it may be necessary to replace the entire timber member, for example when there is extensive decay.

After post and beam repairs have been carried out, the different strengthening solutions presented in this chapter can then be applied to the posts and beams.

Fig. 12 Timber-to-timber interventions in a church in Jawor, Poland built with traditional timber frames (credits: E. Poletti).

2.5 Mixed interventions

Other types of retrofitting could be adopted for timber frame walls. Though little to no experimental studies are available on it, a strengthening method which proved effective for timber beams and slabs is the externally bonded reinforcement (EBR) with glued plates screwed to the timber element (Fig. 13) [9].

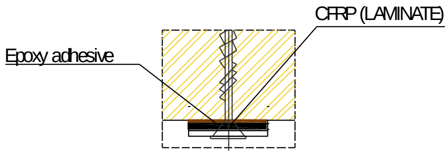


Fig. 13 Mechanically fastened externally bonded plate [8].

The intervention increased both the strength and ductility of the timber element, but only slightly reduced the timber section.

Similarly, a series of combinations of NSM and EBR techniques can be adopted for posts and beams when appropriate (e.g. NSM and FRP sheets for posts).

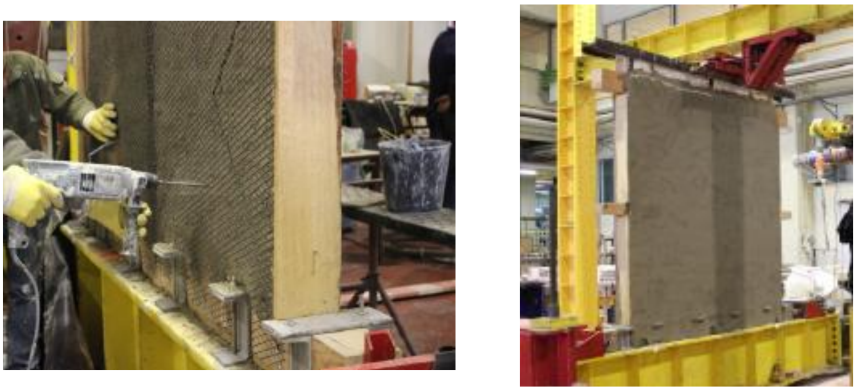
An alternative and advanced, but aesthetically invasive, solution is the use of an elasto-plastic steel damper, which consists of steel bars and rods [5] and operates along the diagonal of the timber frame wall in tension, to provide additional dissipative capacity. Results from in-plane cyclic tests showed an increase in strength and energy dissipation of over 100%.

3 Interventions on infill

Infill plays an important role in half-timbered structures, as it increases both the strength and stiffness of the timber frame. When intervening on infill panels, one has to take into consideration the building's performance and the position of the half-timbered wall. An external unsheltered wall has different requirements than an internal infill wall. It is important not to trap moisture inside the wall and not to alter the connection to the timber frame.

When repairing traditional half-timbered walls, infill is usually replaced with modern bricks and cement-based mortars, which could exacerbate moisture problems by capturing and transferring moisture to the timber frame and joints.

An intervention that affects both the infill and timber frame is the application of reinforced render, which is often performed in practice [5]. It consists in applying a steel mesh covering the whole wall and then spraying it with shotcrete. Tests performed on walls on which reinforced render was applied on both sides [6] showed that this solution greatly increased the stiffness of the walls, without taking advantage of the dissipative capacity of the connections (Fig. 14).



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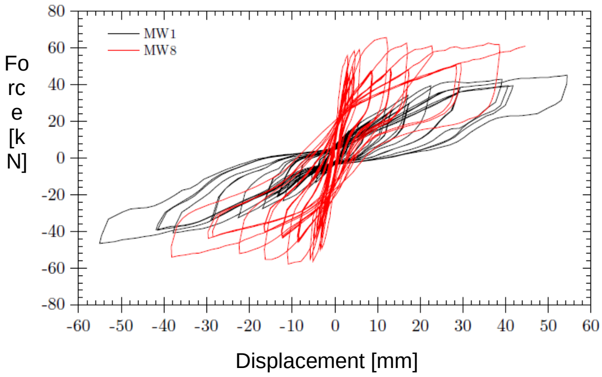

(c)(

Fig. 14 Timber frame wall with reinforced render [6]: (a) steel mesh applied; (b) final appearance after the application of shotcrete; (c) experimental results (black: unreinforced wall; red: reinforced wall)

Traditional timber walls used for partition purposes (tabique) but not structural purposes have been retrofitted using earth-based renders to enhance their thermal insulation [28].

4 Discussion

When dealing with the strengthening of timber frame walls, strengthening is usually applied to their connections, as they affect the overall response of the walls [5,7] since they represent the dissipative mechanism of the wall. All retrofitting techniques discussed in this chapter are able to increase the strength and stiffness of timber frame walls and improve their ductility. Table 1 provides an overview of the strengthening techniques with some recommendations to be considered.

While FRP and NSM retrofitting provide a great improvement to the structure, they are non-reversible, and this could be an issue when dealing with heritage buildings.

Additionally, the durability of all strengthening techniques has to be addressed, particularly for externally bonded solutions, since little information in that regard is available in the literature. Interventions on timber alter its moisture content, and this can affect the whole structure. Moreover, the durability of FRP materials and epoxy resins used in different retrofitting techniques can be affected by ageing and weathering.

The same can be said for interventions with prostheses. In this case, apart from the compatibility of materials and the durability of epoxy resins, it is also important to address the level of continuity between the original structure and the prosthesis and the possibly altered response due to the prosthesis.

Table 1 Applicability of strengthening techniques to timber frame walls.

Type of strengthening	Compatibility with timber frame walls	Comments
Steel plates	✓	
NSM	✓	Appropriate for connections. For flexural strengthening of other elements, beware of accessibility due to infill
FRP sheets	✓	Appropriate for connections. For flexural strengthening of other elements, beware of accessibility due to infill
Self-tapping screws	✓	
Timber-to-timber	✓	Care in grain direction. When prosthesis is used, is it appropriately connected?

5 Conclusions

In this chapter, an overview of different retrofitting techniques for timber frame walls has been given, based mainly on experimental results. Though the focus has been on interventions for seismic actions, these techniques can also be applied to other circumstances due to the adoption of walls such as shear walls. Little research is available on the reinforcement of traditional timber frame walls, but the results available on walls and other elements have shown possibly effective interventions.

Traditional interventions such as timber-to-timber, metal fasteners and steel elements are able to restore and improve the capacity of walls. NSM strengthening, either with steel or FRP elements, is able to greatly increase the capacity and ductility of walls and has the potential of being an invisible intervention. Externally bonded FRPs also gave good results, but their durability has to be addressed.

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