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## **TIMBER SEISMIC BANDS: CORRELATING THEIR CHARACTERISTICS WITH LOCAL SEISMIC ACTIVITIES AND UNDERSTANDING THEIR EFFECTS UNDER SEISMIC LOADS**

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**Keywords:** Masonry building; Timber insertions; Seismic shear band; Energy dissipation

### **Abstract**

*Masonry buildings are one of the most commonly found structures throughout the world. In seismic areas, people developed several techniques and practices to make them safer in case of earthquakes. One of the most wide-spread techniques, used for centuries in several countries of Asia, Middle East, Europe, Central and South America, is the insertion of horizontal timber seismic bands into the load-bearing masonry walls. This paper first describes the variation in the timber bands disposals and how it correlates with local seismic activities in different regions of the Alpine-Himalayan belt. This research is based on a literature review and on several on-site surveys. Then, an analysis resulting from post-earthquakes observations, some experiments and a literature review allows for a global understanding on how these timber bands may contribute to a good behaviour of masonry buildings during earthquakes: by tying the building together, by preventing the propagation of diagonal shear cracks on the in-plane walls and flexural cracks on the out-of-plane walls, by dissipating energy, etc. The third part of the paper deals with two experimental campaigns conducted to better understand the mechanical impact of the reinforcement. The first one is based on two adobe walls (with and without horizontal timber reinforcement) submitted to lateral quasi-static cyclic load. It allowed for the estimation of the lateral strength, the stiffness degradation and the dissipated energy of both reinforced and unreinforced masonry walls and for the comparison of their failure modes. The second experimental campaign focuses on the energy dissipation that occurs at the interface between the seismic band and the masonry depending on the materials used and their disposals. To this purpose, seismic bands in concrete, timber and bamboos of different configurations are submitted to lateral quasi-static cyclic loads and the energy dissipation occurring is calculated.*

## 1 INTRODUCTION

In seismic-prone areas, traditional architectures often reveal a great deal of ingenuity about the use of local resources and the development of techniques and practices that are thought to reduce the vulnerability of built structures [1] [2]. The relevance of these solutions remains marginally documented and validated by scientific communities, and the organizations involved in post-disaster reconstruction prefer not to include them in their programs. Hence, much damage is often inflicted on vernacular heritage during relief and reconstruction phases and the replacement of traditional habitat by ‘modern’ ‘imported’ solutions speeds up the disappearance of traditional skills and knowledge [3]. Moreover, in many cases, it is ineffective in terms of Disaster Risk Reduction (DRR) [1] and it deprives inhabitants of DRR solutions that are often the only one they can implement by themselves [4]. Studying existing structures and how people can repair or retrofit them make it possible to empower them and support them in doing informed choices during reconstruction processes, and finally improve their resilience in the long run. Besides, studying historic structures is necessary to avoid improper interventions that often turn disastrous when submitted to an earthquake [5].

An example of these traditional techniques developed to reduce the building vulnerability is the regular insertion of horizontal timber bands in masonry structures. Referring to the theory of local seismic cultures development [1], this study first describes the variations observed in order to understand how it correlates with local seismic activities in different regions of the Alpine-Himalayan belt. This step helps us in better understanding how these timber bands may contribute to a good behaviour of masonry buildings during earthquakes: by tying the building together, by preventing the propagation of diagonal shear cracks on the in-plane walls and flexural cracks on the out-of-plane walls, by dissipating energy, etc.

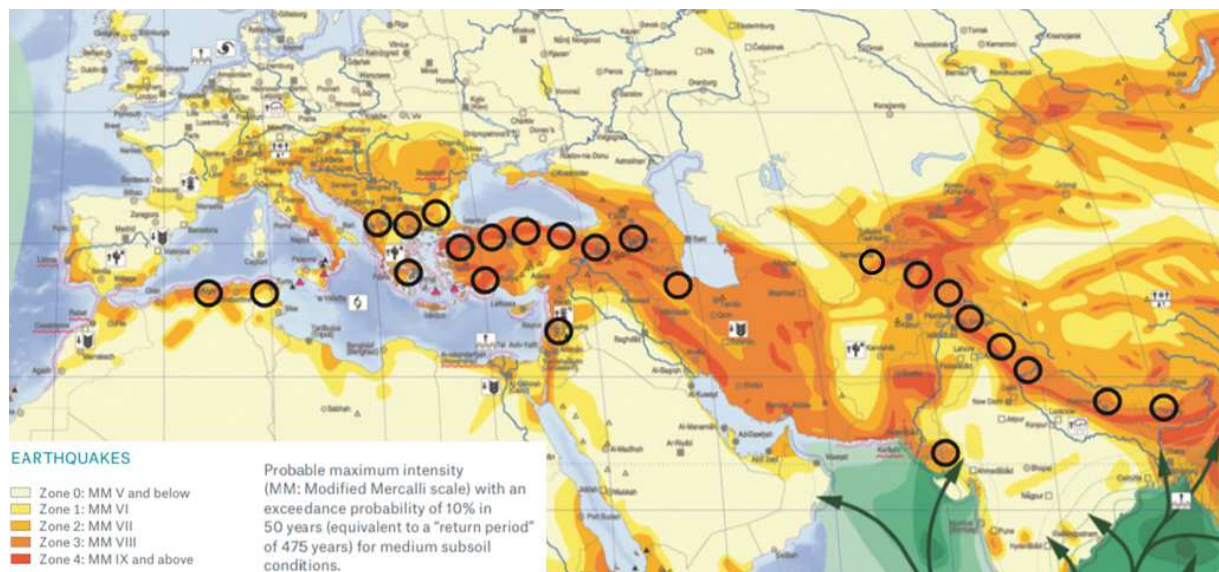
An experimental campaign was carried out by LMDC laboratory to compare the behaviour of reinforced and unreinforced masonry walls when submitted to in-plane shear loads. It allowed for the comparison of their failure modes and the energy they could dissipate and for the assessment of their lateral resistance and their stiffness evolution. Moreover, a second campaign was carried out by 3SR in order to better understand the dissipation of energy at the interface between the timber bands and the masonry and more specifically the influence of the materials used and of the design of the seismic bands on it. It was based on the reconstruction guidelines currently enforced in Nepal.

## 2 TIMBER BANDS CHARACTERISTICS IN THE ALPINE-HIMALAYAN BELT

In disaster-prone areas, inhabitants usually developed local building cultures to cope with the risks they face. In earthquake-prone areas, Ferrigni et al [1] observed different approaches of local seismic cultures depending on two parameters: the usual intensity of the local seismic activity and its frequency. Following on from this work, the study presented here focuses on a specific technical aseismic feature: the regular insertion of horizontal timber bands in masonry structure. This research focuses on the Alpine-Himalayan belt, though this practice is observed in many locations around the world [6]. It is based on a literature review and on several on-site surveys performed in Italy, Balkan countries and Turkey between 2012 and 2014 and in Nepal in 2016 and 2017.

In areas where wood is relatively scarce, a balance had to be found between the mechanical advantages of timber and the difficulty to access it. In the documented sites, the masonry itself is either in stone or in sun-dried bricks, with lime and / or mud mortar. Lower stories are in masonry with regular horizontal insertions, while upper stories are commonly (but not systematically) built with a load-bearing timber structure and masonry infills.

Continuous and numerous exchanges between populations throughout the Alpine-Himalayan belt resulted in a wide geographical dissemination of aseismic technics and practices (Figure 1). More specifically, the most famous masons and craftsmen corporations were asked to build major constructions in broad areas whose delimitations were highly connected to the prevailing political domination, from the Byzantine Empire to the Ayyubid domination, the Mongol Empire, and finally the Ottoman Empire. In some cases, local corporations were then influenced by the work of these famous corporations, thus contributing to a dissemination of aseismic features at all society levels; this dissemination was even sometimes directly supported by political authorities through legal tools or the organization of trainings [6]. But these exchanges did not prevent local variations of these technics.



**Figure 1: Map of the ladder-like timber bands technique geographic distribution and its correlation with seismic probable maximum intensities. This map results from the research carried out by M. Hofmann [6], background map by Munich Re Group.**

This study does not refer to structural systems mixing horizontal and vertical timber elements, as the authors assume that this mixing often entails major changes in the seismic behaviour of the structure. It thus focuses on horizontal timber insertions, and three main technics were documented in masonry load-bearing walls:

- A massive timber log embedded into the wall and connected to metallic anchors in façade;
- Ladder-like timber bands inserted at regular spacing;
- Several planks or logs placed next to each other on the whole wall section.



**Figure 2: a) massive timber logs embedded in a partially collapsed masonry wall at Poggio Picenze (Italy); b) ladder-like timber bands inserted at regular spacing in Cumalikizik (Turkey) and c) planks insertion in a masonry wall in Kastamonu (Turkey) (Credit: Hofmann)**



And for each of these technics, variations were observed regarding the connections in-between the elements themselves, the dimensions of the timber elements and the vertical spacing between the insertions.

A focus on the North Anatolian fault – whose cultural and historical background is rather similar but recent local seismic activity (from 1800 to 2011) slightly differs – helps us understanding the correlation between the local seismic activity and these variations. The whole research leading to the results synthesized below was part of a PhD thesis [6].

Regarding the type of insertions, in more seismic prone areas, ladder-like timber bands are very commonly found, whether horizontal planks are more frequently observed in less seismic prone areas.

Timber insertions are usually located at the top of the wall, at doorsills and lintels, and, in case of lower vertical spacing, at windowsills. This vertical spacing is highly correlated with local seismic activity: for example, this vertical spacing is relatively low (40 to 70cm) in the city of Erzurum, Turkey, where ladder-like insertions are very common and the recent seismic activity high. In neighboring areas of lower recent seismic activities, this vertical spacing is up to 150cm (especially in case of planks insertions).

Moreover, connections between elements are very interesting to compare. Planks are usually connected by overlapping and basic nailing, while in case of ladder-like insertions, connections are more sophisticated: halved or chamfered joints, and in case of recent high seismic activity, dovetail joints were more likely to be observed.



**Figure 3: a) a chamfered joint in Vevçani (Macedonia) and b) a dovetail joint in Erzurum (Turkey) (Credit: Hofmann)**

Regarding their dimensions, timber planks are usually 2 to 4cm thick, but they can be as thin as 0.1cm, as observed in Safranbolu, Turkey, an area whose recent seismic activity is slightly lower. Further documenting this wide range of value would be very interesting to better understand its correlation with local seismic activity and wood availability. There are fewer variations regarding ladder-like insertions dimensions.

This research's first results support the hypothesis that technical variations are correlated to the availability of timber and the seismic activity. Next section focuses on the analysis of the mechanical effects of these horizontal insertions and their variations, in order to better understand why they are correlated to local seismic activities.

### **3 REDUCING STRUCTURES VULNERABILITY BY USING TIMBER BANDS**

Several experimental campaigns and post-earthquakes observations surveys allowed for a better understanding of timber bands roles in the reduction of structures seismic vulnerabilities [6]–[11].

Both ladder-like and planks insertions (referred respectively as techniques b and c in previous section) have several common effects providing a better behaviour to structures submitted to earthquake solicitations. They act as lintel in case of partial failure of the masonry (Figure 4a). Thanks to timber ability to resist traction, they prevent vertical and diagonal cracks from spreading (Figure 4b). Moreover, they confine the masonry elements, thus giving the wall extra resistance to out-of-plane solicitations (Figure 4c), while it is thought that they allow for movement between the wall portions and thus maintain a relative flexibility of the structure, which is of major importance to reduce the building vulnerability. Moreover, this confinement changes the structural behaviour of the wall, dividing it into several smaller portions embedded at both ends and thus changing its slenderness and resonance frequency. This confinement also increases the static compression resistance of walls [6].



**Figure 4: a) ladder-like insertions acting as lintels when partial collapse of a masonry wall occurred; b) preventing cracks propagation and c) restricting bending deflection (Credit: Hofmann)**

Besides, planks insertions increase the global compression resistance of the wall by inducing a better spreading of compression forces through the whole section of the wall [6]. Finally, they allow for the creation of a fuse interface where cracks, sliding and energy dissipation are more likely to occur. This last effect explains why some planks insertions are as thin as 0.1cm and why the wood roughness is of high impact on the insertion behaviour.

Ladder-like insertions are even more efficient as confining devices of masonry elements – providing the wood and connections are resistant enough to traction – thus increasing compression resistance [6] and restricting bending deflection (Figure 4c). However, this confinement of walls subdivisions does not prevent movements between them and thus dissipation of energy, and may be an interesting balance between a relative stiffness of walls subdivisions and a relative flexibility of the whole building. Moreover, it was noticed that two-leaf walls without proper bound stones or corner stones are more likely to be found with ladder-like insertions: this observation supports the hypothesis that ladder-like insertions improves the connection between the different vertical leaves of a masonry wall – but authors would nevertheless recommend the use of bound stones to connect properly the masonry layers. As explained in next section, ladder-like insertions improve the wall resistance to shear solicitations. Moreover, the timber elements composing these insertions usually are well connected enough to act as a belt preventing corner separation and spreading the solicitations to the building as a whole, while maintaining a relative flexibility. Finally, contrary to planks insertions, ladder-like insertions do not create water stagnation zones in the walls– accelerating wood decay and rotting – and may thus be more adapted in areas where the timber mechanical properties are affected by frequent seismic solicitations.

## 4 COMPARING REINFORCED AND UNREINFORCED MASONRY WALLS SUBMITTED TO IN-PLANE SHEAR LOADS

In order to better understand the mechanical effects of the ladder-like timber insertions and their contribution to the vulnerability reduction of the building, two walls – one reinforced with an insertion and the other not – were submitted to in-plane lateral, cyclic, quasi-static loading in order to study their structural behavior.

### 4.1 Setup

Two adobe masonry walls ( $1.3 \times 1.3 \times 0.34 \text{ m}^3$ ) were built: one was not reinforced (UM), the other one (RM) was reinforced with a ladder-like horizontal timber insertion. The longitudinal elements had dimensions of  $75 \times 45 \text{ mm}^2$ , and the transversal ones of  $50 \times 45 \text{ mm}^2$ , as recommended in the Nepalese design catalogue [12]. Longitudinal and transversal elements were connected with screws (diameter 5 mm, length 70 mm) to limit the energy dissipation in the wood-wood connections in order to ease the analysis of the global energy dissipation mechanism.

Displacements were measured through digital image correlation (DIC) thanks to a stereo-camera system, completed by three LVDT (Linear Variable Differential Transformer) sensors, and a wire sensor. To simulate permanent loads and the presence of stories in such structures, a constant vertical load of 0.2 MPa – corresponding to 10% of the compressive strength of the masonry – was applied on top of the walls. The lateral load was applied under imposed displacement, which was designed to follow recommendations of the standards ASTM E2126-05. Indeed, the control displacement curve was made of series of 3 cycles at a constant frequency (0.013 Hz), with a constant magnitude inside a series, but with increasing magnitude between two series.

### 4.2 Results

Figure 5 shows the horizontal displacement field in the reinforced and unreinforced masonry walls before failure. In the case of the unreinforced masonry adobe wall (UM) (Figure 5a), contours show a typical diagonal crack pattern. The contours of the reinforced shear wall (RM) (Figure 5b) show the apparition of a friction plane along the bed joints. Two types of failure can be observed here. The unreinforced wall experienced shear failure as shown by the presence of diagonal cracks in the joints and through some adobe units. During the first cycles of the quasi-static test, the horizontally reinforced wall showed a behavior similar to the first wall: diagonal cracks appeared at the corners of the wall. However, when the lateral force magnitude increased, a horizontal failure plane developed two beds of bricks below the timber insertion, and sliding occurred along this plane. Additionally, very few cracks appeared above the reinforcement.

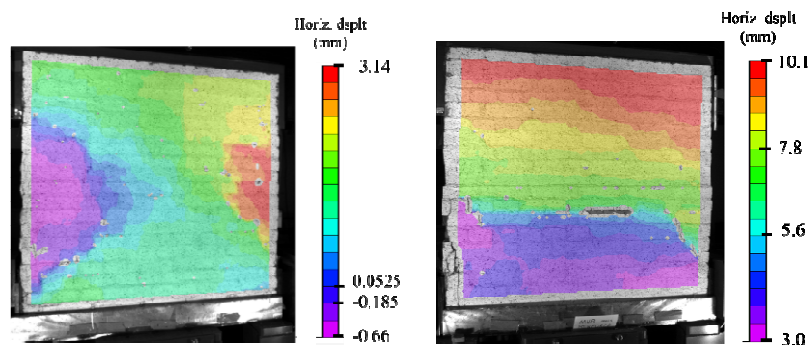
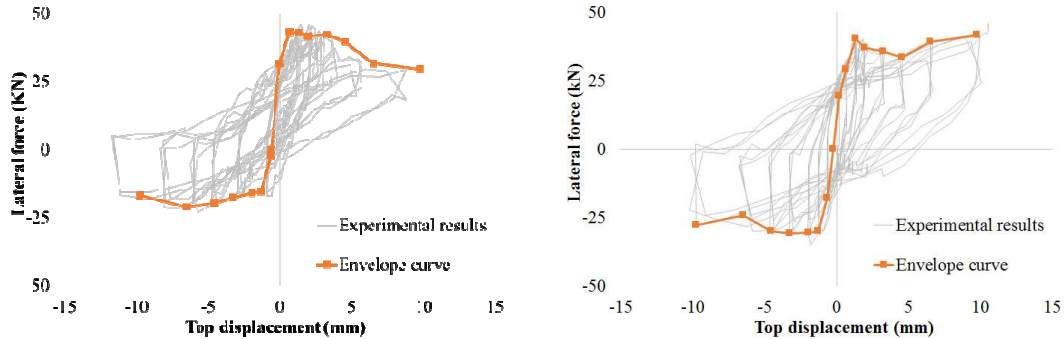


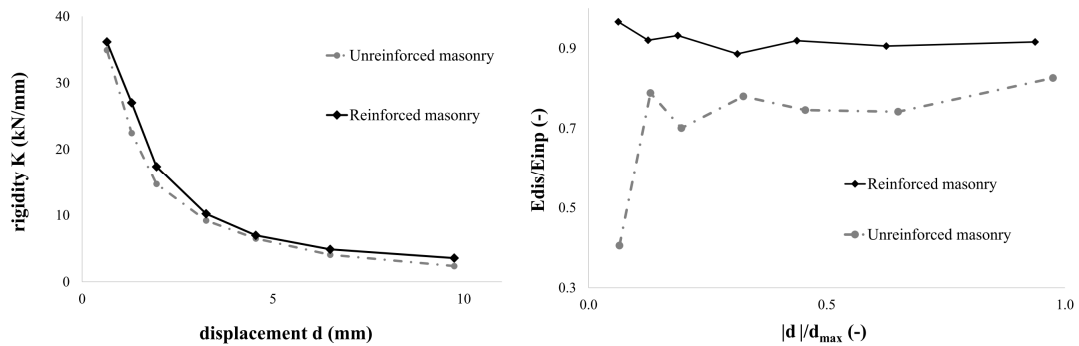
Figure 5: Horizontal displacement field obtained with DIC: from left to right; (a) UM, (b) RM.

The hysteresis curves lateral force VS displacement, corresponding to the quasi-static cyclic tests on UM and RM, are presented on Figure 6. The envelope corresponds to the points of maximal force and maximal displacement for each series of three cycles of same magnitude.



**Figure 6: Hysteresis curves lateral force VS displacement for quasi static cyclic tests on: from left to right; (a) UM (b) RM**

The stiffness degradation of the walls was evaluated by computing the slope between two points of maximal force and displacement of two loading series, which corresponds to the slope between two points of the hysteresis curves. The stiffness degradation curves (Figure 7a) illustrate similar responses for the two walls. Most of the degradation happens during the three first loading cycles, and then the stiffness stabilizes. It can be noticed that the stiffness of the reinforced shear wall degraded more progressively, which fosters the hypothesis of a more ductile behavior of reinforced masonry pointed out by the hysteresis curves.



**Figure 7: From left to right; (a) Stiffness degradation, (b) Energy dissipation.**

The hysteresis curves also reveal some information about dissipated energy in the system. The dissipated energy  $E_{dis}$  is defined as the area inside a cycle of hysteresis. The input energy  $E_{inp}$  is defined as the area under the curve, down to the x-axis. Figure 7b presents the variation of the ratio  $E_{dis} / E_{inp}$  depending on the displacement, normalized with the value of maximum displacement during the test  $d_{max}$ . The plot shows more significant energy dissipation in the case of the timber reinforced masonry wall (90%) compared to the unreinforced wall (80%). This could be explained by the friction phenomenon which is probably more important for the crack pattern depicted in Figure 5b. This dissipation of energy due to the ladder-like timber insertions is the subject of the second experimental campaign that is further explained in next section.



## 5 THE IMPACT OF USING DIFFERENT MATERIALS ON THE ENERGY DISSIPATED BY SEISMIC BANDS

Seismic bands are recommended in the design catalogue for reconstruction housing by Government of Nepal using different materials [12]. A quasi-static cyclic shear test experiment was carried out at 3SR laboratory to find the impact of those materials on the energy dissipation.

Four types of shear band were prepared following the Department of Urban Development and Building Construction (DUDBC) guidelines [12], using timber, concrete and bamboo (Figure 8).

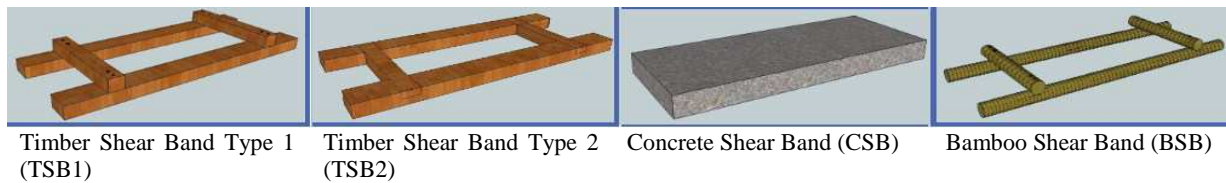


Figure 8: Different types of shear bands as recommended in DUDBC guidelines for reconstruction

Two specimens of each type of band ( $900 \times 350 \text{ mm}^2$ ) were tested using a Schenck Machine at a displacement rate of  $0.4 \text{ mm/sec}$ . The aim of these tests was to apply loading directly on the shear band and obtain the hysteresis curves allowing for an analysis of the energy dissipation at the interface of the shear bands. To set the limit of displacement for the test, the maximum limit of  $20 \text{ mm}$  for each specimen was selected except for the first TSB1 specimen that was tested up to  $10 \text{ mm}$  displacement to see the behaviour at the interface and confirm that the designed experimental set up works correctly.

The obtained data from the experiment was the displacement and the corresponding force needed to reach that displacement. A hysteresis curve is obtained by plotting the data. The area under the hysteresis curve provides the value of the energy dissipated during each cycle. The dissipated energy was measured using OriginPro 2017 software (<http://www.originlab.com/2017>), taking the average between the results obtained from the similar shear bands. Comparison of energy dissipation by various type of shear band is shown in Figure 9.

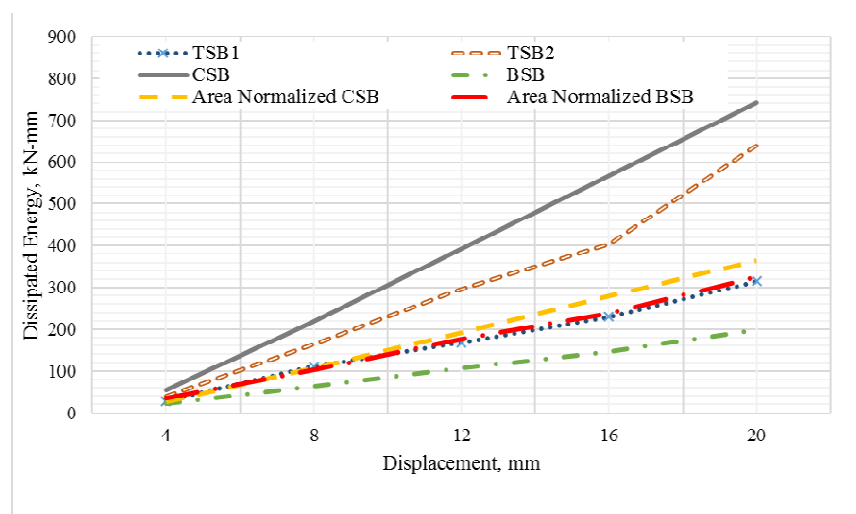


Figure 9: Comparison of energy dissipations by various types of shear band

From the comparison, we can notice that more energy is dissipated with CSB compared to other materials and least energy is dissipated by BSB. The amount of energy dissipated also differs depending on the connections between timber elements. TSB2 could dissipate more energy than TSB1. In order to observe the significance of the contact surface area, the results for the CSB and BSB were normalized taking the contact surface area of TSB1 and 2 as the reference. The energy dissipated by the normalized CSB and normalized BSB are similar to that of TSB1. The energy dissipation patterns obtained tend to follow linear form for each of the shear band materials.

The effective stiffness of each specimen was calculated considering a loop from the first compression to tension values and from tension to compression loading again. After separating the results for each of the loops, linear regression was done to obtain gradient and intercept for the best fitting curve. The gradients obtained give the effective stiffness of shear band against sliding for each specimen as given in Table 1. Likewise, the elastic limit of loading and the corresponding displacement, energy dissipated within elastic limit and maximum energy dissipated was obtained (Table 1) from the hysteresis loop as explained earlier. As observed in the tabular value, the average stiffness and the plastic energy dissipated (which could be used as information about ductility behaviour) of TSB2 and CSB are comparable, and that of BSB is the least which means a small amount of force can make large displacement with bamboo used as a shear band. These values of stiffness and energy dissipated can be used in development and validation of numerical simulation code for carrying out the parametric analysis for shear band using different materials.

S.No.	Name of specimens	Force, kN	Elastic		Energy dissipated		
			Displacement, mm	Effective Stiffness, k (N/m)	Elastic, kN-mm	Maximum, kN-mm	Plastic, kN-mm
1	TSB1_1	12.4	6.3	1.61E+06	75.32	109.5	34.18
2	TSB1_2_dry	11.45	8	1.33E+06	112.3	314.76	200.46
3	TSB2_1	10.78	8.08	1.35E+06	167.46	298.9	131.44
4	TSB2_2	14	7.87	2.61E+06	201.53	639.5	437.97
5	CSB_1	18.09	10.95	2.63E+06	406.25	877.71	471.46
6	CSB_2	13.15	7.9	1.21E+06	180.67	607.07	426.40
7	BSB_1	6.25	8.22	6.19E+05	56.28	200.7	144.42
8	BSB_2	6.23	7.9	8.90E+05	72.11	197.26	125.15

**Table 1: Effective stiffness and energy dissipated by shear band**

Significant differences were observed in the seismic performance behavior of shear bands with different materials and configurations. These performances are to be balanced with materials and skills availabilities and their sensitivities to the quality of execution, which was not assessed yet.

## 6 CONCLUSIONS AND ACKNOWLEDGEMENT

After Erzurum earthquake (1983, 2004, Turkey), Kocaeli earthquake (1999, Turkey) and Kashmir earthquake (2005, Pakistan), it was noticed that timber structures that had been properly maintained fared better than many concrete structures, and that the rather long distortion phase preceding collapse allowed for inhabitants to evacuate [7], [8], [13].

Horizontal insertions are one of these aseismic techniques that suffered more from the lack of recognition, of scientific knowledge and from political and economic contexts than from a lack of efficiency [6], but this trend seems to evolve as reconstructions in Pakistan after 2005 earthquake and in Nepal after 2015 earthquakes shows [12], [14]. But these techniques and their variations are still misunderstood.

The experimental campaign that was carried out by LMDC showed important results regarding the ladder-like timber insertions. As expected, a diagonal cracks pattern appeared in the unreinforced wall submitted to shear loads. The reinforced wall behaved similarly at the beginning of the test, but then a horizontal failure plane appeared and sliding occurred along this plane, and very few cracks appeared above the reinforcement. Moreover, the stiffness of the reinforced shear wall degraded more progressively, which fosters the hypothesis of a more ductile behavior of reinforced masonry. Finally, 12% more energy was dissipated in the case of the timber reinforced masonry wall.

This dissipation of energy due to the ladder-like timber insertions was the subject of the second experimental campaign, with a comparison between different materials and insertions designs used during the reconstruction in Nepal. Though concrete seismic band seems efficient regarding the energy dissipation, its cost is usually much higher than that of timber and local workers often lack basic skills to build it. Besides, low quality nails do not allow for satisfying connections when using hard timber and the research further argued for the use of embedded connections. However, these conclusions regarding the energy dissipation should be put in perspective with the lack of knowledge on the other functions of the shear bands, and more specifically on the impact of their rigidity.

In order to allow for a dissipative movement and increase the friction when using bamboo, it would be interesting to improve the roughness of the bamboo and increase its contact area by testing crushed and tangled bamboo bands. Moreover, it would be very interesting to study the sensitivity of the different kinds of insertions to improper execution. Observations following earthquakes in Italy, Pakistan and Turkey showed that timber structures with masonry infills had fared well, even though some of them were of low quality, which is hardly ever the case with reinforced concrete structures [6], [13]. The current development of an affordable shaking table at 3SR will allow for testing real-scale technical details and conducting more academic research.

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