Effects of Horizontal Seismic Band on Seismic Response in Masonry Structure: Behaviour Depending upon the Material Used

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Abstract

Background (relevance and importance of the study): Masonry construction is one of the oldest building systems and practiced since the early stage of human civilization. Even though industrialized nations developed new building practices using steel and concrete materials, the majority of populations in developing countries still use unreinforced masonry building. These structures are particularly present in earthquake-prone areas. There is evidence from past events that show that masonry structures sometimes performed well and survived several earthquake events, particularly in the area where earthquake events struck regularly and enough to show how structures behave. However, an alteration from the traditional cultural building practice is observed probably due to two phenomena: the emergence of industrial materials (like reinforced concrete and steel) and the lack of proper scientific knowledge regarding such local construction cultures. Amongst traditional construction technics, one captured the attention of authorities and scientists as showing great properties: seismic bands that can be found in many parts of Nepal but also in many countries prone to earthquakes. After the 2015 Gorkha earthquake, reconstruction works started adopting the guidelines developed by DUDBC and National Building code that suggest using such seismic bands.

Research issues/objectives (or research questions): The main objective of the study is to determine the behavior and effectiveness of seismic bands in masonry structures.

Methodology: After a literature review, the development of experimental tests for determining the effect of having a seismic band in the masonry wall using timber is presented. Two specimens are then tested under quasi-static cyclic loading. The analysis of the tests is done using digital image correlation technique.

Key results: The results show a significant improvement in the response of the wall by the use of the horizontal seismic band and highlight the efficiency of digital image correlation in understanding the behavior.

Keywords: *masonry; traditional vernacular structures; seismic band*

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1. Introduction

Masonry structures constitute the oldest buildings constructed by human civilization and their technic evolved with cultural values and way of living. Such constructions are still built for residential houses in many developing countries, while in industrialized countries, those are present mainly in ancient historical buildings, churches, theatres, palace, etc with the exception to a few new masonry constructions. Most of the densely populated countries with weak financial conditions are located in the seismically active zone (Hofmann, 2015) and there is evidence showing that some traditional buildings survived several events of an earthquake while sometimes modern RC structures collapsed (Langenbach, 2002). In spite of that, traditional cultural constructions seem to be fading out and being replaced by modern construction technics. Now, some questions are emerging- is the current construction practice sustainable, did we miss to better understand and study our traditional building practice? To better understand the traditional cultural practice, several research works have been carried out.
The strength of masonry structures can be enhanced by the application of retrofitting techniques. In this paper, the main idea is to reveal the traditional practice using seismic band placed during construction of building rather than repairing it after the damage as adopted by many countries.
In the following subsections, the background about the use of the seismic band, their recommendation as per various guidelines, and codes are included. Subsection 1.2 allows one to understand the major failure modes in the case of masonry and to appreciate the advantages of having a seismic band (subsection 1.3) in the case of the masonry structure.

1.1.Seismic band

Seismic bands are a constructive device-specific to traditional masonry constructions in seismic zones. The first traces of them come from the Minoan period - age of the bronze - in Crete (Ortega, Vasconcelos, & Correia, 2015). Such a device consists of placing at a level of several horizontal joints from the ground level more or less regularly spaced pieces of wood forming a kind of ladder that is "laid" lengthwise on the masonry. Such bands may also be referred as a ring beam in (Arya, Boen, & Ishiyama, 2013; Arya et al., 2004; Blondet; M., Brzev, & Rubinos, 2011; Jithendra Bothara & Brzev, 2011; I. Standard, 2013) but that is not always the case and depends on the connection between insertions. These elements can be continuous (above the openings) and look like a horizontal beam as shown in Table 1 (at lentil, roof, plinth level) or discontinuous (at the level of the openings) as shown in Table 1 (at sill level), even punctual (at the level of the angles). These inclusions are usually made of timber or reinforced concrete in the masonry of fired or raw bricks (adobes) or in stone masonry. Sometimes, one can also find longer stones used as a band in stone masonry. Nepal National Building Code (Nepal National Building Code, NBC 203: Guidelines for Earthquake Resistant Building Construction-Low Strength Masonry, 1994) also mentioned about using bamboo as a seismic band in NBC 203. Table 1 shows the recommendation for seismic band location and material that can be used for such band by different codes and guidelines for earthquake resistant design for masonry structures. Table 2 shows the dimension for longitudinal timber member has some variation, which might be due to construction and material restriction in the region and for reinforced concrete band, all the guidelines and reference has the same recommendation for the dimension.

Table 1 Guidelines with the recommendation for seismic band location and material

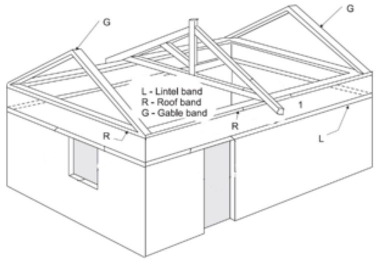
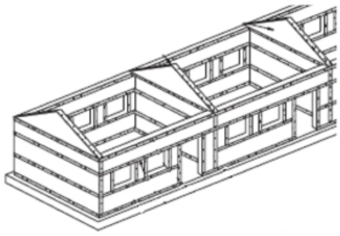
Guidelines and building codes	Seismic band material	Location
IAEE, 1980 (International Association for Earthquake Engineering) IAEE, 1986 (Guidelines for earthquake resistant non-engineered construction) IS 13828:1993 (Indian Standard) UNESCO Guideline, 2013 EQ resistant Guidelines-Afghanistan, 2003	Reinforced concrete Timber	 Lintel, Roof and Gable
NBC 203:1994 (National Building Code- Nepal) EQ resistant Guidelines-Pakistan, 2006 DUDBC 2015	Reinforced concrete Timber Bamboo	 Plinth, sill, lintel, roof and gable

Table 2 Dimension specification for timber and reinforced concrete band

Timber seismic band	Reinforced concrete seismic band
Longitudinal member Dimension: **75 mm x 38 mm** (Arya, 2003; Arya et al., 2013; B. of I. Standard, 1993; UN-Habitat, L'urgence, & NSET-Nepal, 2006) **75 mm x 45 mm** (DUDBC, 2015) **100 mm x 50 mm** (Jithendra Bothara & Brzev, 2011) Transverse member spacing =**500 mm**	**75 mm** thick with two longitudinal rebars 12 mm diameter **150 mm** thick with four longitudinal rebars at lintel level Tie spacing **150 mm c/c** using 6 or 8 mm diameter rebar (Arya, 2003; Arya et al., 2013; Jithendra Bothara & Brzev, 2011; DUDBC, 2015; Nepal National Building Code, NBC 203: Guidelines for Earthquake Resistant Building Construction-Low Strength Masonry, 1994; B. of I. Standard, 1993; UN-Habitat et al., 2006)

1.2. Failure modes

Usually, the interface is the weak bond between mortar and units in masonries. This low tensile strength creates a key reason for most of the damage (Roca, Lourenço, & Gaetani, 2019).

Damage in the structure is directly influenced by the seismic event, which has its own characteristics. Each seismic events are characterized by their horizontal and vertical component of ground motion which are influenced by the nature of fault rupture, the distance between source to site, ground condition, magnitude (Kramer, 1996). The failure pattern in the structures can vary depending on the nature of the material used, bond strength, normal axial loading due to roof and other superstructure on the wall, placement of opening, and seismic loading. Figure 1 shows the global failure mode in a masonry structure when submitted by seismic loading action. However, these entire failure modes are not necessarily occurring during any particular event. In the case of an out-of-plane wall, the failure can be due to flexural bending or corner separation or delamination of the wall while for the in-plane wall, it could be due to diagonal shear crack, shear sliding or flexural bending/rocking. If the crack formation and propagation can be limited by any means, the structural damage can be minimized and most importantly save the life of the people during a seismic disaster event. One such technique is the use of the horizontal seismic band.

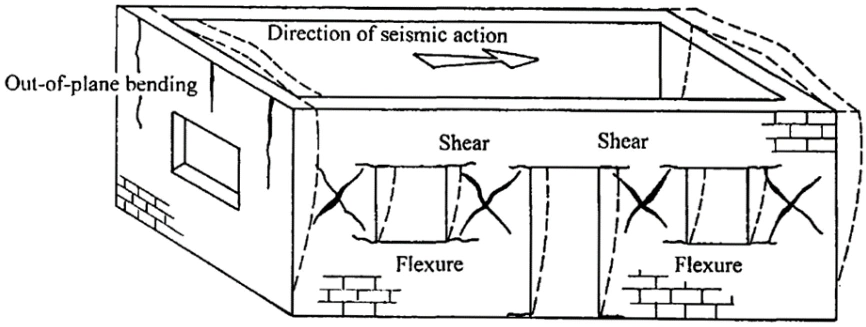


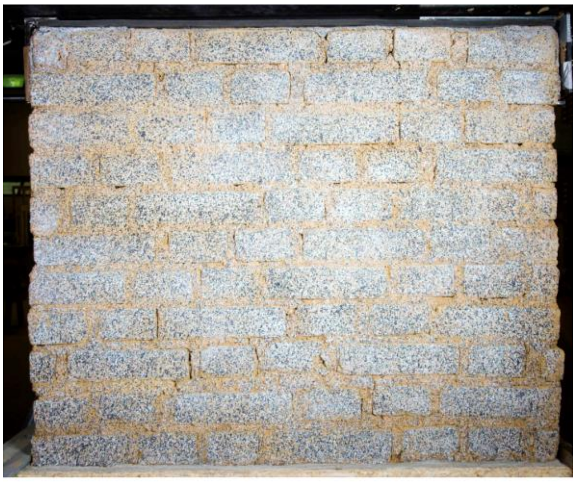
Figure 1 Various failure mode in a masonry structure (Tomaževič, 1999)

1.3. Advantages of seismic band

Several experimental campaigns were conducted by submitting a masonry structure to a seismic signal thanks to a shaking table (Jitendra Bothara & Ahmad, 2019; Mouzakis, Adami, Karapitta, & Vintzileou, 2017; Wang, Liu, Guragain, Shrestha, & Ma, 2018). They highlighted some advantages of inserting seismic bands. Their integration in masonry structures helps to improve integrity and ductility. If regularly spaced, the use of bands prevents crack propagation and is limited within the region separated by the seismic band (Aranguren, Vieux-champagne, Duriez, & Aubert, 2020)Moreover, the creation of a fused interface contributes to dissipating energy with minor damage. The dissipated energy depends on the material used and on the connection between elements (as observed with timber band) (Yadav, Sieffert, Crété, Vieux-Champagne, & Garnier, 2018). An analysis based on a stone masonry discrete element modeling of pushover test (Pulatsu, Bretas, & Lourenço, 2016) showed that when better connecting two layers of a two leaves masonry wall and reducing its effective slenderness with through-stones. With reduced slenderness, the resistance significantly increases in the out-of-plane direction. We can expect that similar effects must be revealed by the use of horizontal seismic band in the case of raw earth masonry structures, which is the objective of this study.

2. Methodology

In order to determine the influence of a horizontal seismic band in a masonry wall, a quasi-static cyclic loading test is used. The experimental setup is shown in Figure 2 where the loading actuator location is indicated. With the help of a C-shaped metallic connected to the actuator, it is possible to apply cyclic loading by changing the loading direction. Two masonry walls (dimension 0.91 m in length, 0.86m in height, and thickness of 0.32m) are built with and without a seismic band. Earth (adobe) bricks are used for the construction of the walls using mud mortar with a thickness of 20 mm. Compressive strength of brick and mortar ranges from 1.2 MPa to 1.4 MPa when tested individually, and with the compression test on the wallet, the average compressive strength about 1 MPa was obtained. These values are necessary for determining the loading conditions for the test. A speckle pattern on the wall surface, which is needed for carrying out digital image correlation (DIC), is created using black and white spray paint. DIC was quite useful in the past few decades to get information at the local level without the use of any sensor on the specimen.



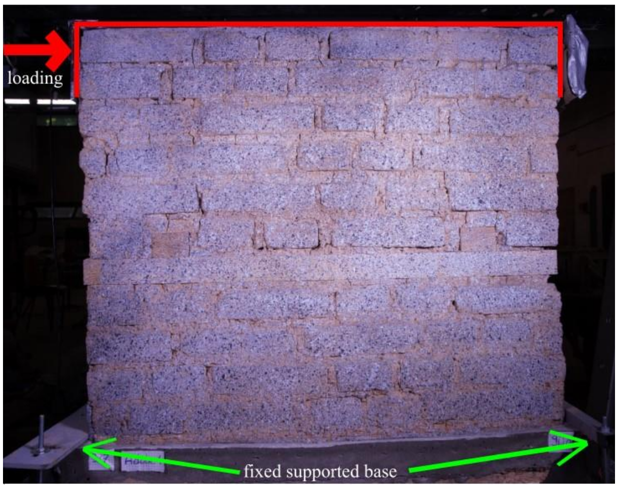


Figure 2 Masonry wall without a band (left) and with timber seismic band (right)

A dead load of 1 ton is added on the top of the wall, representative to that of a roof and any other structure supported by the wall. This dead mass is uniformly applied on the wall creating normal axial stress of 0.03 MPa. A cyclic displacement until a maximum amplitude of 80 mm is applied on the wall, as shown in Figure 3, at a variable rate of displacement (see Figure 4).

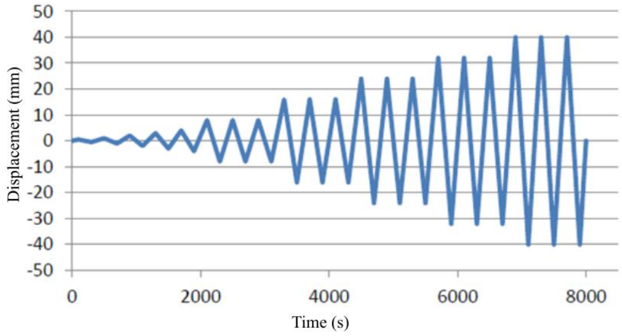


Figure 3 Displacement sequence for the quasi-static cyclic test

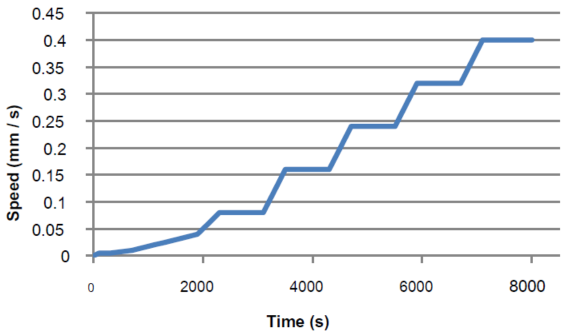


Figure 4 Displacement loading rate

3. Results

The entire experiment is recorded with a high-resolution camera with images captured at an interval of 10 seconds. These images are later analyzed using the image-correlation software

‘Tracker’ (Combe & Richefeu, 2013). Each brick is associated with a set of four points placed on its corners, forming quadrilateral, and the position each brick is tracked image by image. In the analysis, the value of the horizontal force applied on the wall at each stage is associated with the captured image. Thus, results obtained with the two walls are compared versus the applied force. Figure 5 shows the DIC output results plotted graphically using MATLAB.

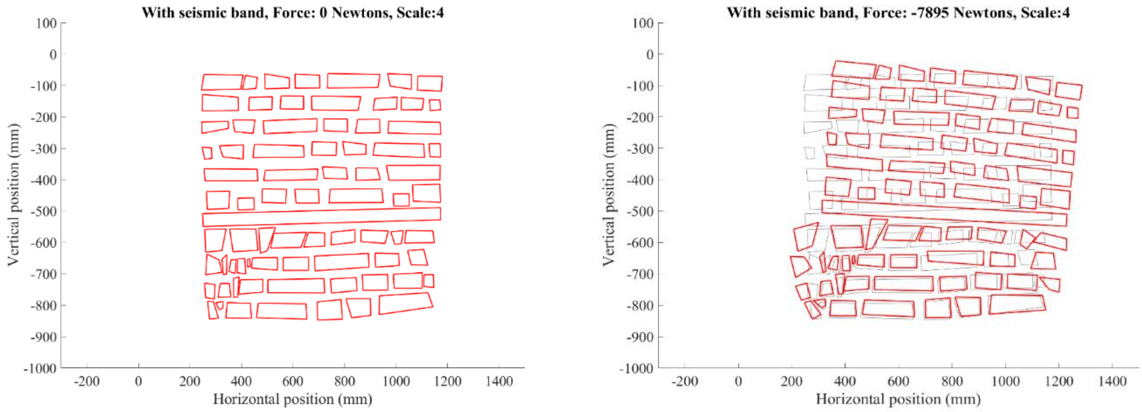


Figure 5 DIC displacement output field for masonry wall with timber band at zero force (left) and 7.89 kN force (right)

As the loading in the horizontal direction is applied, the crack opening at header joints (vertical fissures) increases to become significant. A process is established to evaluate the pattern of vertical cracks. Each crack is viewed as a quadrilateral made of four points, two from each side of adjoining bricks. Coordinates are calculated in a way so as to enlarge the cracks only when there is a difference in the values of displacement between two bricks. This displacement obtained from DIC is multiplied with the length of the head or bed joint to calculate the surface area of fissures in vertical or horizontal direction respectively. To compare the results of the two cases, it is important to consider deformation stages. For that, three cycles were chosen with constant displacement amplitudes as shown in Figure 6. The following analysis is carried out for each cycle using cracks surface area total variation in square millimeters extending upwards in the y-axis direction, dependent on the force value in the x-axis direction. The x-axis consists of the force applied by the loading actuator where the positive part indicates pulling force (when the wall is moved toward left) and negative parts indicated the pushing force (when the wall moves toward the right).

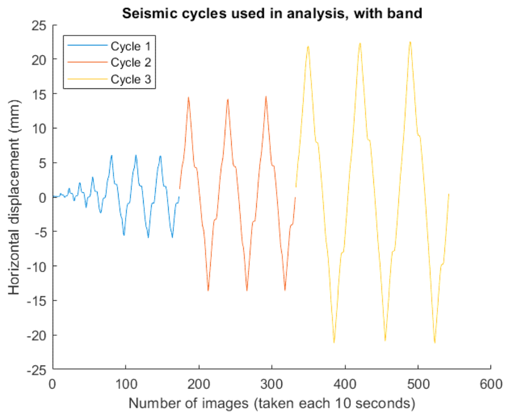


Figure 6 Classification of displacement cycle for a wall with a band

There are four main observations that can be done throughout the first loading cycle that is shown in Figure 7. Here, the cycles are classified by the peak horizontal displacement applied to the walls and each cycle indicated has three periods of oscillation. First, in the beginning, both walls have pretty similar behaviors. Crack opening increases at a very slow pace and deformation is characterized by almost perfect elasticity. Bonding between bricks is still intact so walls behave like an entire unit. Second, the wall with a horizontal band suffers 8-shaped fluctuations in the crack opening. This is due to cracks below the band that are enlarged and then closed again while slightly ripping and drifting towards permanent deformation. Third, when a force pushes the wall without a seismic band towards the right (force is negative in this case) we can see an obvious increase of the crack opening. It reveals the appearance of the first major diagonal crack in the wall without any band. We can observe sorts of steps, or a stair-like shape, while fissures jump from 100 mm^2 to around 520 mm^2. These sharp increases are the result of abrupt disconnections between certain bricks. Fourth, at the end of the first cycle, as a direct result of the newly formed crack, not much (negative) force is needed to impose displacement in the direction of the right. The now semi-detached block of bricks smoothly glides at every displacement cycle of constant amplitude.

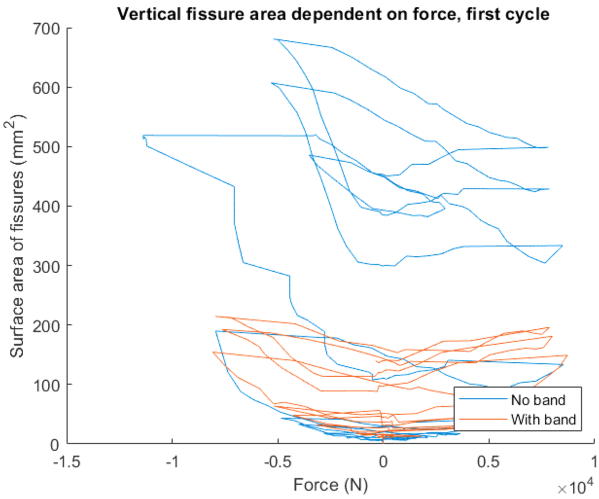


Figure 7 Vertical fissure area in relation to the applied force during the first cycle

During the second cycle (Figure 8), a more regular evolution pattern is observed. The phenomena previously described during the first cycle seems to predefine the behavior that will occur during the second cycle. The remnants of the previous loading cycle are immediately noted; the surface area is around 200 mm^2 for the wall equipped with a band and at around 680 mm^2 for the wall without any band at the beginning of the second cycle. The orange curve is way smoother and narrower than the blue one. This shows a very gradual and stable enlargement of cracks between the bricks. On the other hand, the blue curve shows a less stable pattern.

For both the wall, the surface area of cracks increases way faster at every round. Secondly, a steep decline is noticed in every direction change of the applied force. That is because separated blocks slide back to their initial positions. Being that the first crack was seen on the right side of the wall when the force is negative both increase and decrease of crack opening follow the same trend. However, when the force is positive, that is the wall is pushed on the left, the first left-side cracks appear on the wall without any band. This is why the blue curve in the top right side of the graph increases a lot more than the orange one. The maximum surface area of fissures obtained during the second cycle is approximately 800 mm^2 and 1620 mm^2 respectively for the wall with a band and without a band.

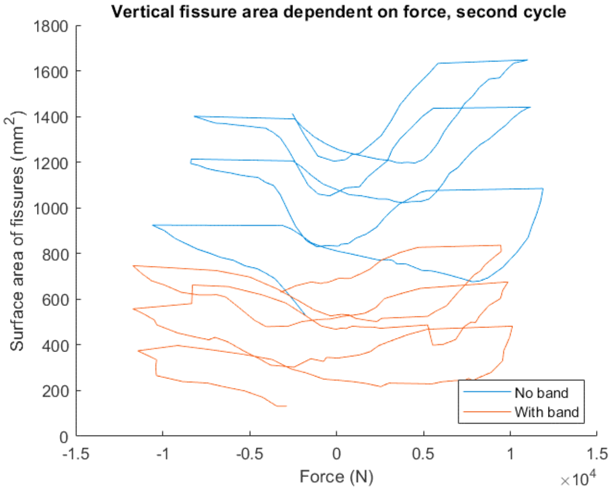


Figure 8 Vertical fissure area in relation to the applied force during the second cycle

During the third cycle (Figure 9), the behavior of the wall with the band is still the same and the orange line follows the same trend as in Figure 7 and Figure 8. This means that until the end of the third cycle of displacements elasticity is preserved in a wall with the seismic band. The same can not be said about the behavior of the wall without any band. The blue line shows that the crack surface area almost never decreases in value, which means the deformation is now permanent. Older cracks expand and new cracks in the inner parts of the wall are created every time when imposed force is at its highest. Another interesting thing to notice, in case of the wall with a band, is that while force switches directions crack surface area remains almost constant. This happens because both the upper and lower part of the wall has been disconnected at the band level, so instead of expanding, cracks simply shapeshift from rectangles into parallelograms, while covering the same surface.

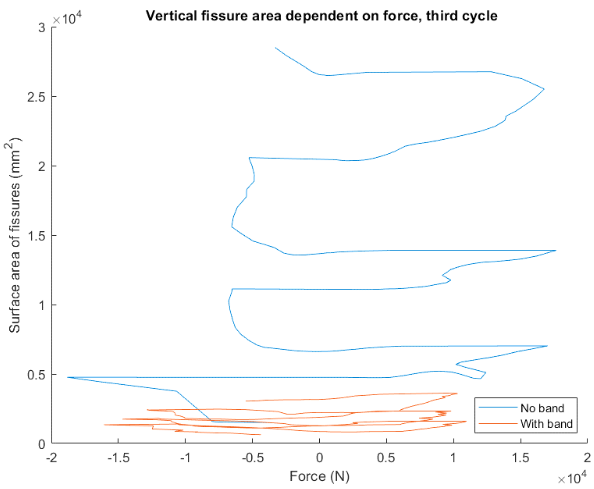


Figure 9 Vertical fissure area in relation to the applied force during the third cycle

4. Discussion

The presented experiment and its analysis have shown that the vertical crack opening is up to 2-7 times higher in a wall without a seismic band as compared to a wall equipped with one depending upon the magnitude of displacement cycle. The higher crack area indicates more damage to the masonry structural integrity. From this, one could conclude that the wall without the band tends to have several major cracks, which might increase the cost for retrofitting, if possible in the structure after a seismic event. However, when the fissure surface area is small (as seen with the wall with a seismic band), the structural integrity and safety for the occupant are maintained and such structures can be easily retrofitted at a reasonable cost. The horizontal cracks have also been studied but results are not conclusive, partly due to the fact that the opening of horizontal cracks is low due to the axial loading caused by the dead mass on the top of the wall. This phenomenon is also observed in the real structure where the gravitational load acting on the wall is high and the seismic signal has significant horizontal components. Many building codes considered only the horizontal component of the earthquake for designing but the ground motion components depend upon moment magnitude of an earthquake, source-to-site distance, ground category, nature of fault rupture. In a study by (Michele, Cristina, & Enrico, 2019), where several seismic event data were analyzed, found that the vertical ground motion component is significant for high or medium-high moment magnitude earthquake and low source-to-site distance. In the same study, it is also indicated from a structural model analysis that the dynamic amplification of the structural demand is increased for tensile axial force when impacted by the seismic signal containing significant vertical ground motion component. During this study, we studied the influence of the horizontal loading applied quasi-statically on the wall with and without a seismic band. But, further studies have to be carried out in order to determine how the presence of such a band influences the behavior of the structure in case of significant vertical ground motion and several levels of placement of such band.

It would be interesting to extend the study to other types of interface material such as reinforced concrete and bamboo as per different guidelines and from the preliminary study (Yadav et al., 2018), it is observed that sliding and energy dissipation depends on the material and its surface roughness and connection type. Therefore, it is important to carry out a similar test with other materials to verify the benefits of having such a band. From this study, we observed the crack propagation and damage in the case of a wall with timber seismic band was limited in the bottom portion (see Figure 5) but what will happen when there are several such sections separated with multiple layers of the band needs to be investigated. Moreover, structural behavior varies during quasi-static and dynamic loading. In the real scenario, the earthquake loading is dynamic where the damping and inertial force play a key role. Therefore, it is also necessary to investigate the performance of the seismic band when impacted by dynamic loading using shaking table tests and carry out numerical modeling for parametrical analysis.

5. Conclusions

The use of digital image correlation technique allows for a continuous record of cracks formation all along the displacement cycle. This is a significant advantage when analyzing crack openings in masonry structures. The use of horizontal seismic band in masonry structures permits to withstand similar force while limiting the crack propagation, making such structures more ductile and safer. The placement of horizontal seismic band at regular intervals creates section along with the height of the wall and any cracks originate in a particular section are limited within that region. Once the crack reaches the interface with the band, it propagates horizontally leading to a sliding mechanism between the interface of the band and the adjacent masonry layer, which helps in energy dissipation.

A global understanding of all the different impacts of integrating these horizontal seismic bands needs further research. Several works related to the different assumed impacts and direction of solicitations are on progress and aims at feeding each other. These horizontal timber bands were documented in many seismic areas, with local variations. Linking the observed impacts with these local specificities is another challenge. But better understanding them will further help to elaborate technical recommendations adapted to local conditions and better communicating on the stakes related to different details to allow for an informed choice and adaptation.

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