

Numerical Modelling of Timber Braced Frame Masonry Structures (Dhajji Dewari)

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Abstract:

This paper presents numerical modeling technique for Dhajji-Dewari structures (timber-braced rubble stone masonry), and its application for the evaluation of in-plane force-deformation capacity of Dhajji wall panels of different configuration of bracings. Dhajji structures are mainly composed of vertical and horizontal timber posts and braced using diagonal bracings and horizontal studs. Wall openings are filled with random rubble masonry in weak mortar. These types of structures are known for their high lateral deformability and are mostly found in Kashmir and its surrounding areas both in Pakistan and India, locally named as “Dhajji-Dewari”. A numerical model of Dhajji wall was developed using a finite element based structural seismic analysis program SeismoStruct, based on the experimental study carried out at the Earthquake Engineering Center of UET Peshawar. In-plane force-deformation response of Dhajji wall was evaluated through static pushover analysis, and validated with the measured response. The numerical model was extended to evaluate and compare the lateral strengths of Dhajji walls of three different configurations of bracings. This can enable structural designer to select Dhajji wall with a particular bracing configuration keeping in view the required lateral strength and deformability with least possible quantity of timber for construction, which might be helpful to economize the construction of these structures.

1. Introduction

Dhajji-Dewari structure is a local name given to traditional Timber Braced Masonry Structures (TBM) found in Northern areas of Pakistan including Kashmir, in some parts of India and other nearby mountainous regions from many years (Ali *et al.*, 2012[3]; Naveed Ahmad, Ali and Umar, 2012[1]; Dar and Ahmad, 2015)[5]. The word “Dhajji” means “patchwork quilt” or “interconnected” and “dewari” means “wall” in the local Kashmiri language, therefore dhajji-dewari means an interconnected, or patchwork-quilt, wall (Ali *et al.*, 2012)[3]. Mostly these types of structures are single storey but two storey Dhajji structures can also be found in some places.

These types of structures are not just confined to this region but similar structures can also be found in Asian, Middle-East, American and European countries (N. Ahmad, Ali and Umar, 2012[1]; Ali *et al.*, 2012)[3]. Some of these structures are shown in figure 1.

In Germany, these types of structures are called as *Fachwerk* and were introduced in 7th century. *Casa baraccata* is the local name given to the half-timber framed masonry structures found in Italy. Similarly, French and German settlers brought with them the traditional *Chicago Balloon Frame* construction technique to North America. Similar structures can also be found in South America and Portugal where they are locally called as *Quincha* and *Pombalino* buildings respectively. Also, in Turkey, the upper stories of residential buildings are constructed of traditional half-timber frame, known as *Himis* (Vasconcelos *et al.*, 2013)[15]. The structural configuration of timber framed structures may vary from place to place but the main

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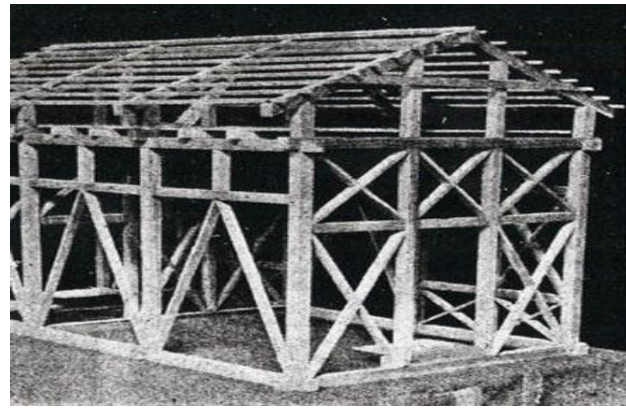
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(a)



(b)



(c)



(d)

Fig. 1: Various types of timber frame structures found across the world. (a) Balloon frame structures found in North America (Photo courtesy: National Archives Archeological Site ,College Park, Maryland) (b) Casa baraccata structures found in Italy (Photo courtesy: [www.conservationtech.com/Randolph Langenbach](http://www.conservationtech.com/Randolph%20Langenbach)) (c) Pombalino buildings found in Portugal (Photo courtesy: World Housing Encyclopedia Report 92, Cardoso, Lopes, Bento, and D'Ayala) (d) Quincha structures found in America (Photo courtesy: <http://www.mimbrea.com/author/helena-rodriguez/>)

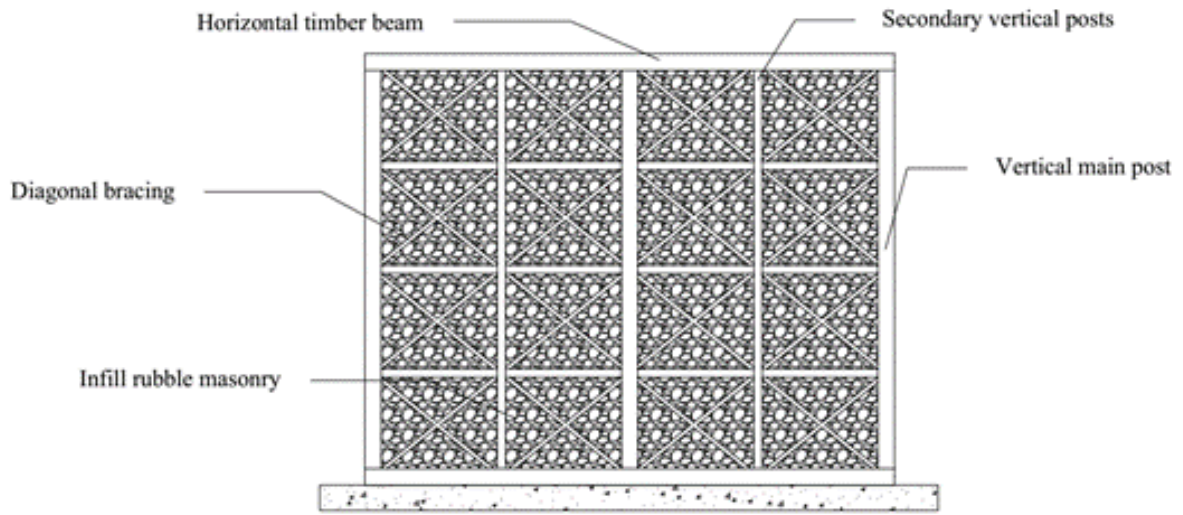
objective is same i-e to make the structure lighter and seismically more resistant.

Dhajji structures (figure 2) are mainly composed of a timber frame formed by vertical timber posts connected to horizontal timber beams (at top and bottom) and braced by horizontal and diagonal timber elements. The remaining portion is then filled with masonry in weak mortar which helps in dissipating the seismic energy. The connection between various frame elements is formed via Tenon and Mortise type of connection supplemented with mild steel nails. These structures are having high resistance towards earthquake shaking which is proved already during various small and large earthquakes (Gülhan, D., and Güney, 2000[8]; Tomaževič and Weiss, 2010[14]). The flexibility of wood material and closely spaced vertical timber posts with horizontal and diagonal bracing make the frame more resistant to breaking in the bending cycles during the earthquake (N. Ahmad, Ali and Umar, 2012[1]). This property of Dhajji system was seen in the 2005 earthquake in Pakistan, considering which Earthquake Reconstruction and Rehabilitation Authority, Pakistan (ERRA) encouraged its use for the reconstruction of houses in earthquake prone mountainous regions where this system is already known and

local persons have skills to construct these structures (Ali *et al.*, 2012[3]). Provision of proper bracing system is one of the most effective parameter in seismic performance of a structural frame (Saadati, 2014[13]). The configuration of bracings used in Dhajji structure may vary which might affect the lateral strength of the structure. In this paper lateral strength of Dhajji walls having various bracing configurations is compared in order to economize the construction of these structures and provide more lateral strength using the same amount of timber elements. For this purpose, a numerical model was prepared in a structural analysis software namely "SeismoStruct" and calibrated using the experimental results obtained from a quasistatic lateral cyclic load test performed on three full scale Dhajji walls having diagonal bracing configuration similar to as shown in figure 3, Configuration A, at Earthquake Engineering Centre (EEC), University of Engineering and Technology, Peshawar (Ali *et al.*, 2012[3]). This calibrated and validated numerical model was then used to evaluate the lateral strengths of Dhajji walls having various bracing configuration shown in figure 3 by performing static pushover analysis.



(a)



(b)

Fig. 2: (a) A typical Dhajji house in Kashmir. (b) Structural details of a typical Dhajji wall

2. Details of Experimental Program

Quasi static cyclic load testing was performed on three full scale Dhajji walls at the EEC, UET Peshawar (figure 4). Three wall specimens i-e DW1, DW2 and DW3 were tested under cyclic loading. The configuration of timber frame was same for all three specimens. The distinction was just on the basis of infill. DW1 was with hard infill with stone to mud ratio of 9:1, DW2 was with relatively softer infill with stone to mud ratio of 7:1 and DW3 was without infill. DW3 was considered in the experimental program to check the effect of infill over the lateral strength of Dhajji wall. Downward load of 2kN was applied at each main post to reproduce the effect of weight of roof truss. Moreover, different types of typical connection types used in the construction of Dhajji structures were also tested for their tension and bending capacity. Four types of connections were considered in this study which are shown in figure 5. Type 1 connection is where the main intermediate vertical post is connected to main horizontal

beam. In type 2 connection vertical main post is connected to two horizontal beams. Type 3 connection is similar to type 2 connection but having the horizontal beams projected outward 4 inches. The type 4 connection is between secondary vertical posts and main horizontal beams. Load vs deformation and moment vs rotation curves were derived which were then bilinearly idealized for defining constitutive laws for plastic hinges in numerical model. The bilinear elasto-plastic properties (both in bending and tension) for each type of connection are presented in figure 6.

Observed typical hysteresis response of tested Dhajji wall panels is shown in figure 7. It was observed that the energy was dissipated mainly at connections due to opening and closing of joints during the various loading cycles. Also, the capacity of the wall without infill was almost the same as that of with infill which is a clear indication of insignificance of infill masonry in resisting lateral load in these structures.

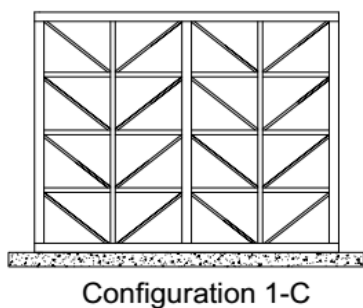
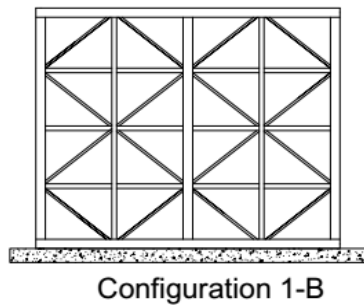
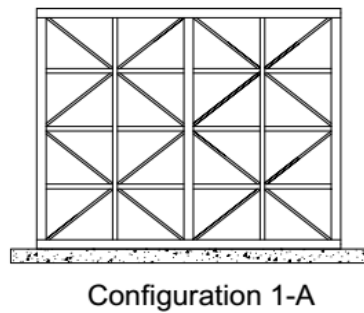
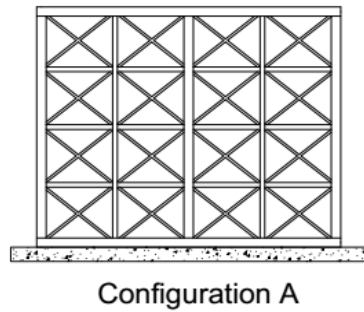


Fig. 3: Dhajji walls with various diagonal bracing patterns considered in this study.

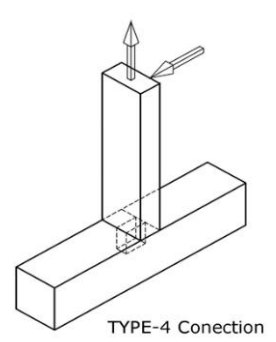
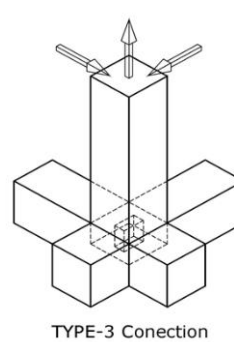
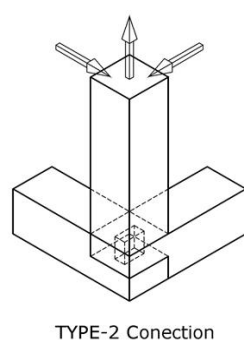
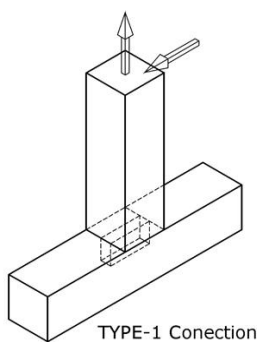


Fig. 5: Various types of connections tested in the experimental program



4: Experimental setup for testing of Dhajji wall

3. Description of Numerical Model

A nonlinear numerical model of test structure was prepared in SeismoStruct on the basis of experimental observations and static pushover analysis was performed. The modelling basic assumptions were based on the work of (N. Ahmad et al., 2012[2]; Ali et al., 2012[3]; Dutu, Sakata, Asce, Yamazaki, & Shindo, 2016[6]; Kouris & Kappos, 2012, 2014a[9]; Quinn, Dayala, & Descamps, 2016[12]). The infill masonry was ignored in the numerical model as experimental study shows that infill masonry has negligible effect on the peak strength of these structures (Araújo, Oliveira and Lourenço, 2014[4]; Ferreira *et al.*, 2014[7]; Kouris and Kappos, 2014[10]; Vieux-Champagne *et al.*, 2014[12]; Vogrinec, Premrov and Kozem Silih, 2016[17]). It might just increase the initial stiffness of the wall. The vertical timber posts and horizontal main beams (top and bottom both) were modelled as elastic bending elements while diagonal and horizontal bracing elements as truss element with a limit on their tensile and compressive strengths to replicate the pull-out behavior of the bracing elements, as observed in the experimental study. A downward force of 2 KN was applied on each main vertical post to replicate the experimental conditions. The connections between all vertical members and main horizontal members (top and bottom) were modelled using link elements and were assigned bilinearly idealized elasto-plastic properties (constitutive laws) in bending and tension (presented in figure 6) obtained from connection tests.

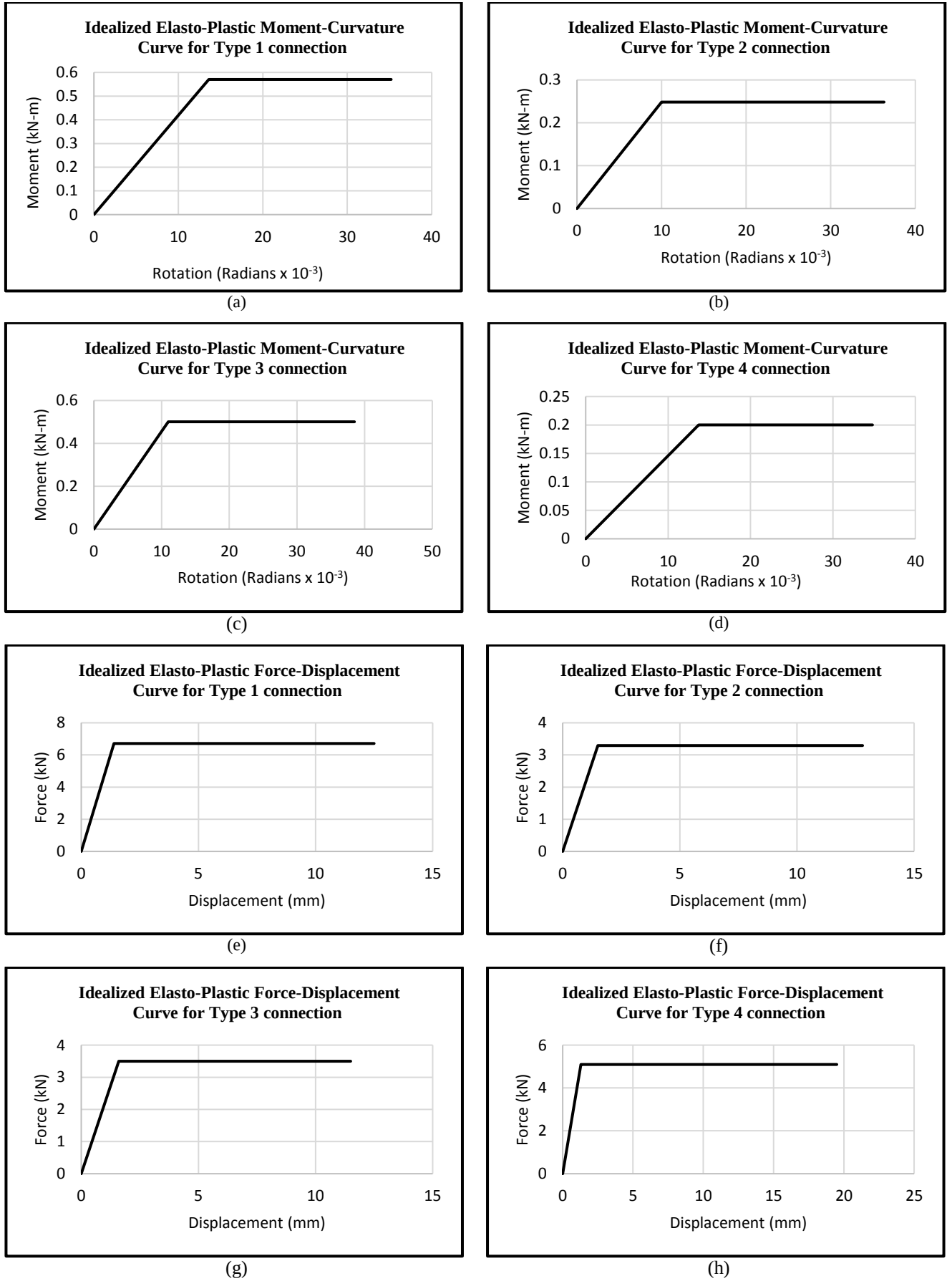


Fig. 6: Bilinearly idealized elasto-plastic curves of tested connection types used for numerical modelling. Bend test properties are presented in figures from 5(a) to 5(d) whereas tension test properties are presented in figures from 5(e) to 5(h).

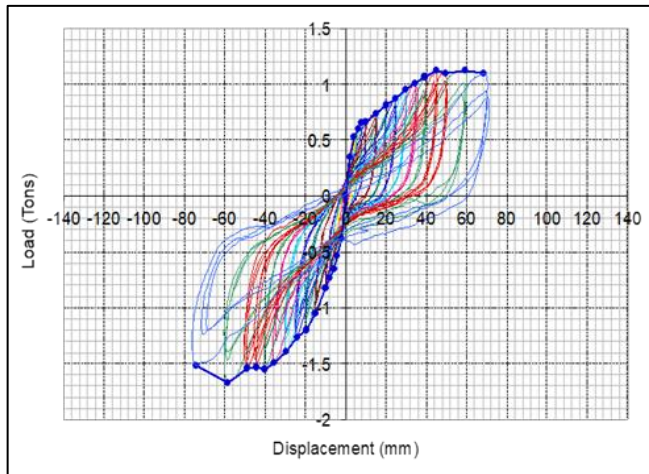


Fig. 7: Force-displacement response of timber braced frame masonry wall panels (Dhajji Dewari)

The modeling strategy for creating plastic hinges at bottom and top connections of the structure involved the definition of two nodes having same coordinates for each connection between vertical elements and horizontal timber beams. These two nodes were connected with each other using link elements having tension and bending properties according to the connection type. One of these two nodes was connected with the corresponding main or secondary vertical posts and the other was connected to the horizontal beams. The nodes which were at the bottom of the structure and connected to bottom horizontal beam were assigned with the restraints against translation and rotation to replicate the support conditions. For a better understanding a pictorial view of above discussion is presented in figure 8.

Capacity curve of the structure was obtained by performing static pushover analysis. This capacity curve was

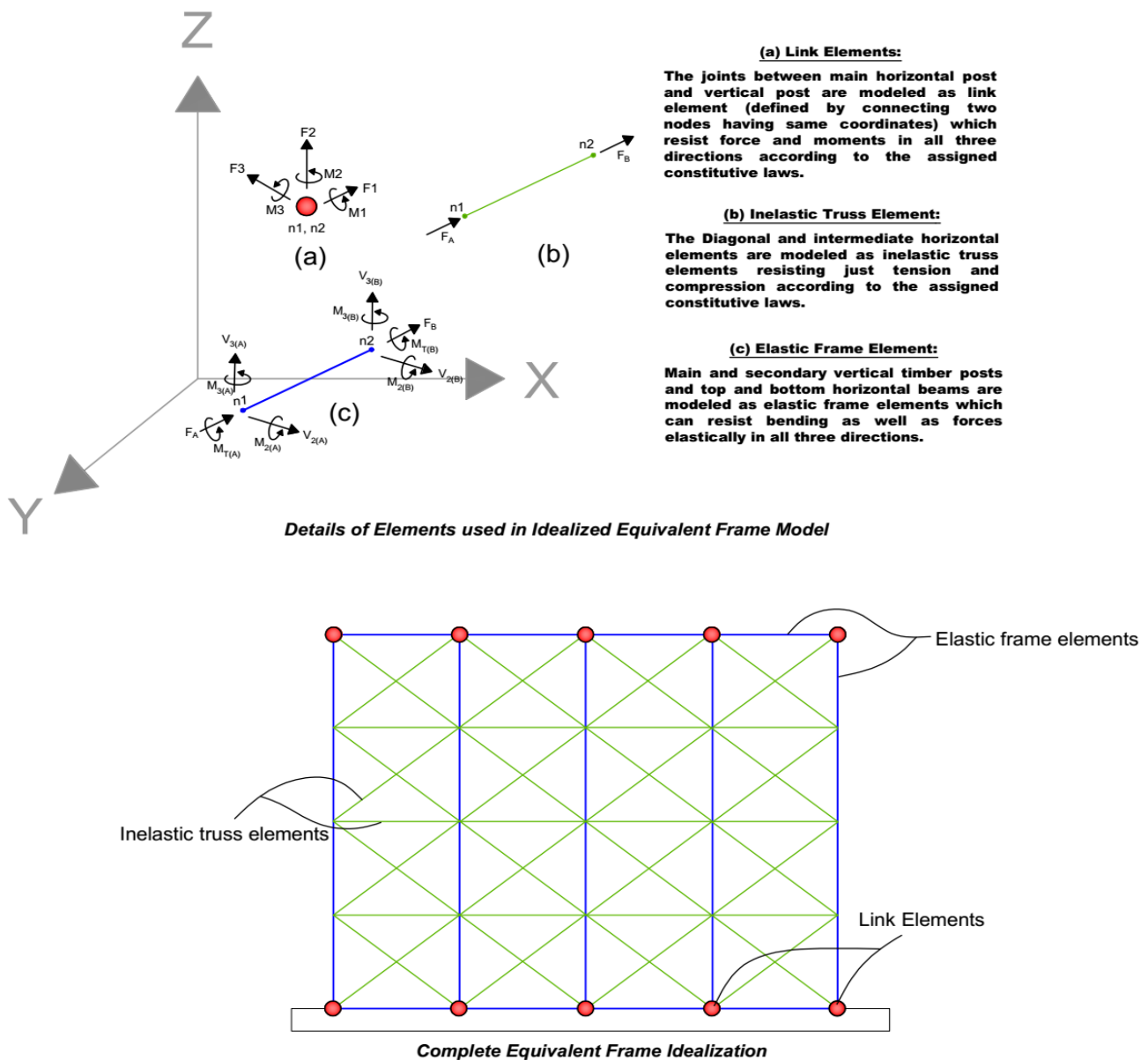


Fig. 8: Details of the element types selected for numerical model

plotted with experimental results for validation (shown in figure 9). It can be observed from figure 9 that the capacity curve from the numerical model is in good agreement with the results of experimental study. Using the validated numerical model of test structure, various Dhajji walls having different configurations of bracings were evaluated for their in-plane strength. Three Dhajji walls having different configurations of bracing i-e configuration 1-A, 1-B and 1-C, as shown in figure 3, were considered for the lateral strength comparison. The number of diagonal bracings were kept same i-e 16 while their arrangements were changed to study the effect of configuration of bracing

on in-plane strength of Dhajji wall. Capacity curves of these walls were also compared with the capacity curve obtained from numerical model of experimentally tested wall (figure 10) to study the effect of number of bracings over in-plane strength. Failure pattern of bracings was also derived for each wall type considered in this study and is shown in figure 11.

4. Observed Behavior of Studied Models

It can be observed from figure 10 that the stiffness of the walls was significantly reduced by the reduction of diagonal

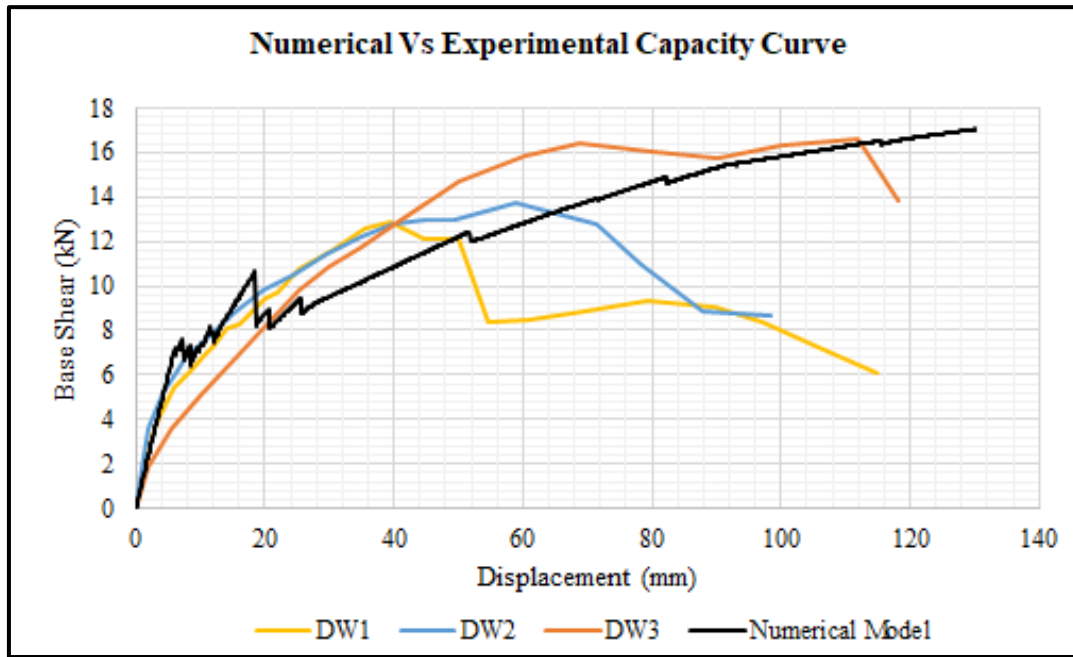


Fig. 9: Comparison of experimental and numerical capacity curves

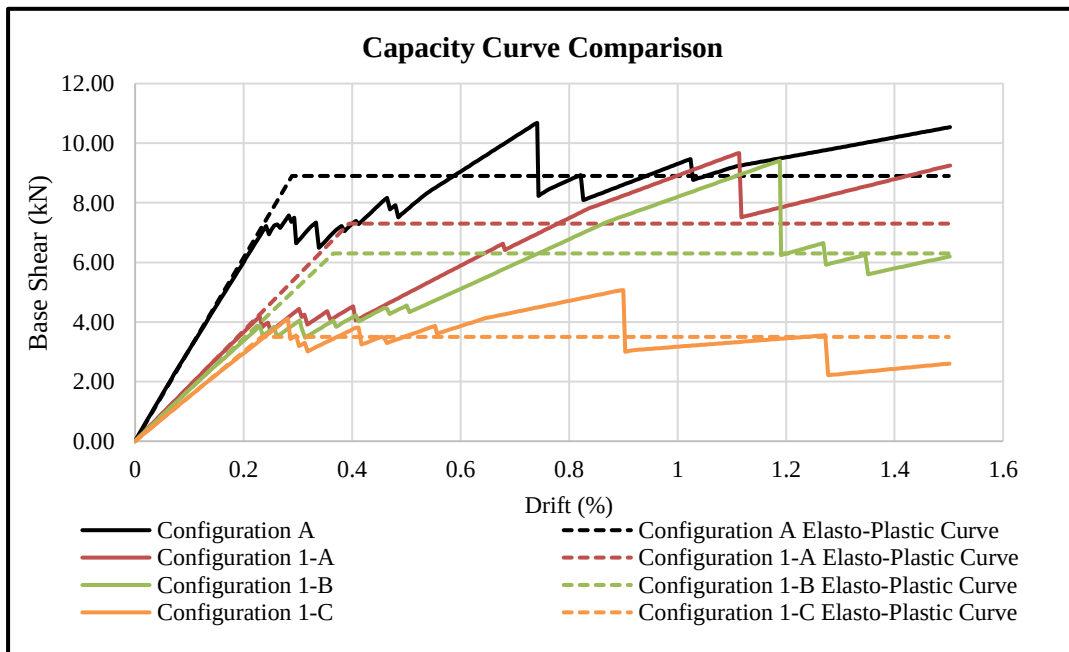


Fig. 10: Comparison of capacity curves of Dhajji walls with different bracing patterns

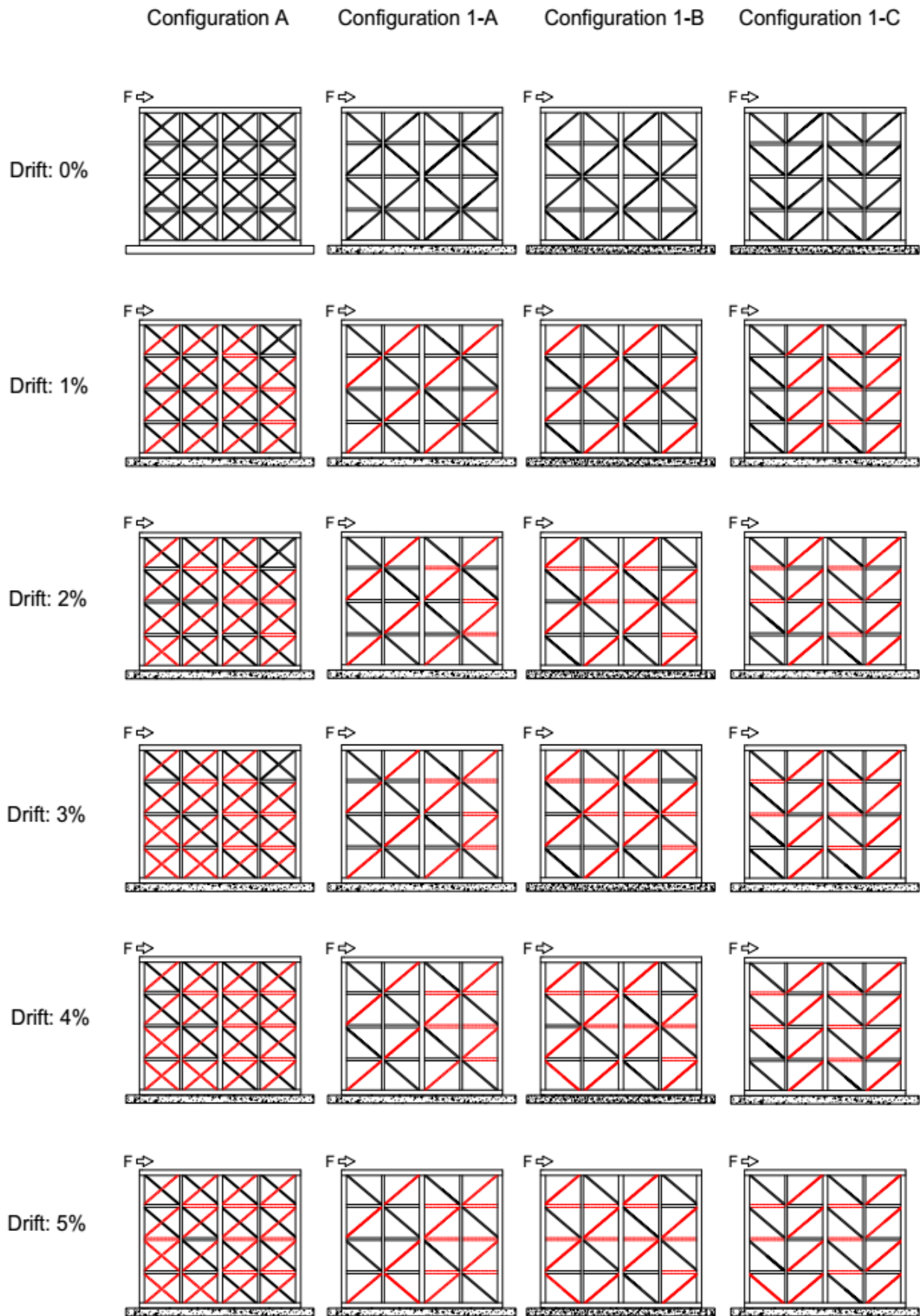


Fig. 11: Bracing element failure pattern at various drift levels (failed bracing elements are shown in Red)

bracing elements but it was not much affected by the type of configuration of bracings. It can also be observed from figure 10 that by reducing the diagonal bracing elements to half i-e from configuration “A” (number of bracings: 32) to configuration “1-A” (number of bracings: 16), the yield strength was reduced by just 18% which shows that 50% of bracing elements can be saved at the cost of just 18 % lost in in-plane strength by shifting from configuration “A” to “1-A”. Among the three proposed walls with different configurations of bracings, maximum in-plane strength was provided by the wall with configuration “1-A” whereas least strength was provided by the wall with configuration “1-C” although the number of bracing was same i-e 16 in all of them. Observing the bracing failure pattern at various drift levels, presented in figure 11, it can be concluded that those bracing elements which were under tension during a particular loading cycle were damaged at very initial levels of lateral drifts. In this particular case all of the diagonal bracings in all of the considered walls, which were under tension were failed (shown in red color) at 1% of lateral drift, after which the horizontal elements failed. Some of the bracing elements which were under compression got failed at the end of the loading cycle.

5. Conclusion

Experimental observations have demonstrated large deformability of Dhajji Dewari wall panels under lateral load, the load path is primarily characterized by the timber frame and braces truss system, nonlinear hysteretic response is governed by the opening and closing actions of connections. Masonry infill doesn't largely affect the lateral stiffness and strength of wall but contribute significantly to energy dissipation. The connection tension capacity is dependent on the bearing capacity of timber, this controls the stability of lateral force-deformation response of walls under lateral load.

The proposed numerical modelling of timber braced masonry comprising elastic modelling of main frame elements provisions with nonlinear lumped plasticity hinges at connections, inelastic modelling of timber braces using truss elements with limit of tension capacity simulating the pullout of braces. The bending capacity of connections of main frame is of less significance.

It can be concluded that the type of configuration of diagonal bracing elements do not affect the over all in-plane stiffness of Dhajji wall significantly but the yield strength of Dhajji wall is seriously affected by the type of configurations of diagonal bracings. The in-plane strength of a Dhajji wall will be maximum with a bracing configuration in which there is a complete diagonal load path i-e from one top corner to opposite bottom corner as observed in the studied walls with configuration “A” and “1-A”. If no such load path exists, the lateral strength of Dhajji wall will be significantly reduced as observed in the case of Dhajji wall with configuration “1-C”.

As this research is about the evaluation of in-plane strength of isolated Dhajji wall and not a complete Dhajji structure, however the lateral strength of a complete Dhajji structure can be also estimated using the same approach and by simple addition of in-plane strength of Dhajji walls which are parallel to the direction of loading. The resistance to the lateral load offered by the out of plane walls is negligible as compared to the resistance from in-plane walls and can be ignored for simplicity of the analysis.

Although this numerical model is based on a particular type of connections i-e tenon and mortise, but still can be used to model a Dhajji structure having any other type of connection by just obtaining the connection behavior in tension and bending from experimental testing of that connection type rather than the testing of whole Dhajji wall.

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