Seismic Performance of *Dhajji Dewari*

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SUMMARY
After the October 2005 Kashmir earthquake over 100,000 homes were reconstructed using the indigenous construction method of *dhajji dewari*. There is limited research to validate the performance of *dhajji dewari* construction. A better understanding of the structural behaviour of *dhajji dewari* buildings is needed as a first step towards providing confidence in this technology, and to identify those aspects which are critical to the reliable performance of the building system. Seismic analysis has been carried out to understand the structural behaviour of a typical *dhajji dewari* house, similar to those built after the 2005 Pakistan earthquake. This work sought to establish whether the building type could be modelled analytically, and in so doing determine how a representative house performs when subjected to large earthquake loads. Hence, to establish what the critical engineering details are to help ensure reliable seismic performance and identify measures that might enhance performance. Analytical results have been benchmarked against physical tests from the University of Peshawar.
The timber elements, masonry infill pieces, roof, mortise and tenon as well as scarf joints have been explicitly modelled. Nailed connections have been idealised as discrete elements, and parallel analyses undertaken to reflect joints with and without nails. Both 'pushover' and 'response-history' analyses of a whole house model were carried out to establish overall performance.
The analysis showed that it is possible to model the behaviour of traditional *dhajji dewari* buildings, and that this form of construction can safely withstand forces associated with earthquakes in high seismic regions when built properly. Potential weaknesses and further research areas are identified. This is an important step towards developing evidence based construction guidelines and training material for *dhajji dewari*.

Keywords: Vernacular, Assessment, Performance, Dhajji Dewari, Analysis

1. INTRODUCTION

The lead author came across *dhajji dewari* in 2005 and 2006 when on secondment to the Irish Non-Governmental Organisation (NGO) GOAL from Ove Arup & Partners to teach earthquake engineering to the affected population in Pakistani administered Kashmir.

The term *dhajji dewari* is thought to be derived from a Persian word meaning "patchwork quilt wall" and is a traditional building type found in the western Himalayas. It is a straightforward construction technology that can be easily built using local materials; timber and masonry infill with mud mortar. Typical images are shown in Figure 1.

Figure 1. Selection of typical *dhajji dewari* buildings from Pakistani administered Kashmir

University degrees in engineering rarely touch upon such forms of construction and research into *dhajji dewari* buildings is minimal. Design guides are limited and where there is guidance it is based on anecdotal findings, common sense principles and rules of thumb. Although valuable, these have not been properly validated through rigorous engineering testing and analysis. Buildings of similar construction are found in Britain, France, Germany, Central America, South America, Turkey, Portugal and Italy. They are known as "half-timber", "*colombage*", "*Fachwerk*", "*taquezal* or *bahareque*", "*hımış*" and "*Gaiola*" respectively. This form of construction is also referred to as "brick nogged timber frame construction" in India and an off-shoot of the French "*colombage*" exists in Port-au Prince's Gingerbread district, Haiti, where it was subjected to the otherwise devastating 2010 Haiti earthquake.

This research project applied state of the art engineering analysis to a typical *dhajji dewari* house, similar to those built after the 2005 Pakistan earthquake to establish whether the building type could be accurately modelled and in so doing, determine its theoretical performance when subjected to large earthquake loads. If this construction typology can be shown to possess earthquake resistance then it merits detailed engineering investigation to produce a construction guide. This would allow engineers to offer this construction type as a credible alternative to modern expensive and technologically complicated modern construction methods, such as reinforced concrete or steel framed construction.

A detailed documentation of *dhajji dewari* can be found on the World Housing Encyclopaedia (*http://www.world-housing.net/asia/india/report-146-dhajji-dewari*).

2. STRUCTURAL ANALYSIS MODEL DESCRIPTION

A *dhajji dewari* house of the type now commonly being constructed in Pakistan after the 2005 Kashmir earthquake was chosen for detailed non linear dynamic time history analysis as shown in Figure 2.

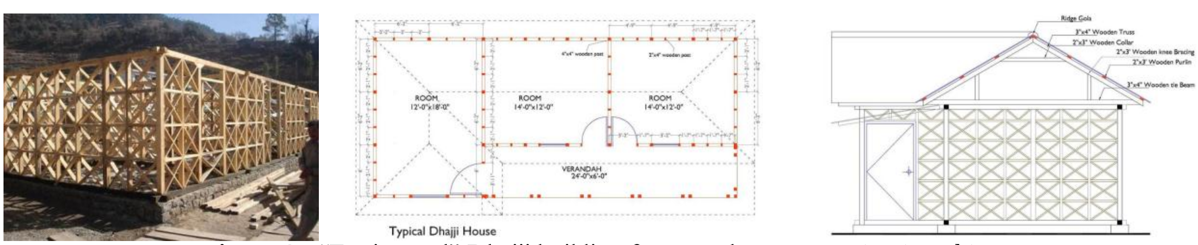


Figure 2. "Engineered" Dhajji building frame under construction in Pakistan.

A detailed LS-DYNA computer model was created as shown in **Figure 3**. The timber frame and the masonry blocks were modelled as solid elements with contact surfaces between all members to account for frictional behaviour. The light weight roof system was idealised as beam and shell elements. Nailed connections were modelled as discrete elements with non-linear material properties. The flexible mud mortar was not explicitly modelled. The masonry infill was assumed to be incompressible and the timber was modelled as an elastic material. The roof did not include horizontal diaphragm bracing as typically this is not a design feature of these buildings.

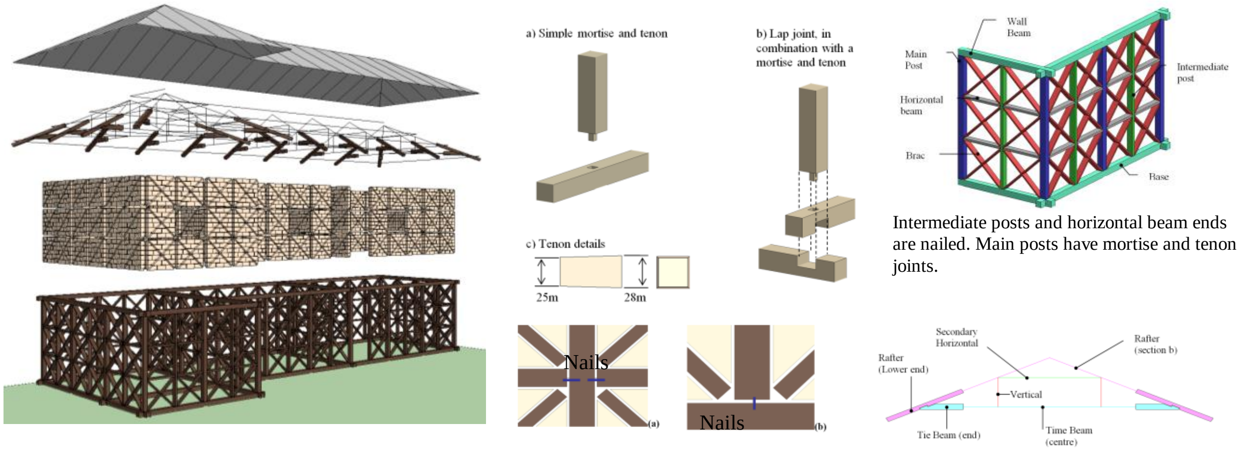


Figure 3. Exploded view of full *dhajji dewari* model and model details

The wall components the building system have been categorised to help facilitate clear communication of the various components as shown in Figure 4.

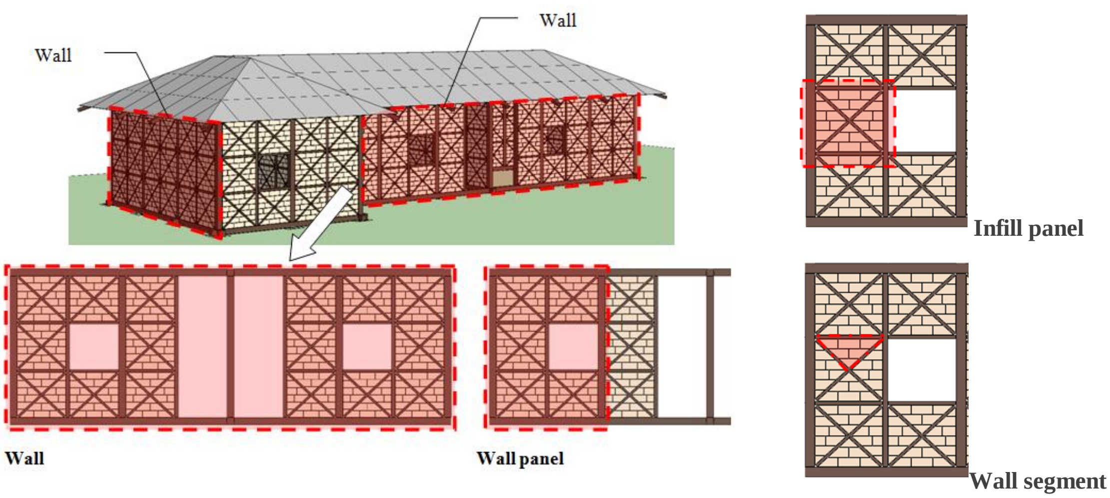


Figure 4. *Dhajji dewari* wall terminology

3. LOADING

Non linear response history analyses as well as non linear static push over analyses were performed. *RSPMatch2005* was used to generate spectrum-compatible records for the analyses. Seed records were selected using the methodology outlined in Grant *et al.* (2008), whereby records with the best initial match of the target spectrum are selected, based on certain seismological filters. Ground motions were selected from the PEER NGA database, which provides extensive meta-data for each of its records, including the usable frequency range. Two suites of ground motions were developed based on two design spectra shown in Figure 5.

Summary information about the selected records, including linear scaling factor (applied before spectral matching), seismological characteristics and maximum usable period is shown in **Table 1**. More information can be found in http://peer.berkeley.edu/nga/.

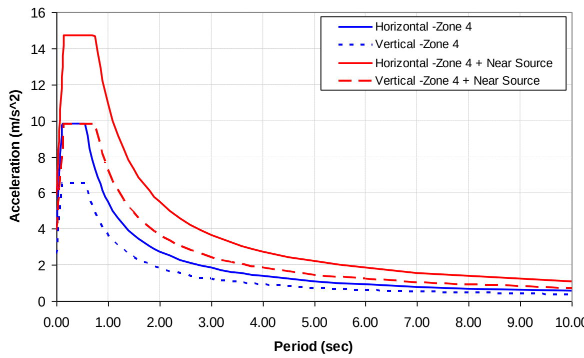


Figure 5. Target response spectra used for spectral matching of the time histories

Code: UBC97
Zone 4
Soil Type C
Moment Magnitude 7-8
Distance 0-10km
Distance 20-1000km

Figure 6. Seismic parameters

Table 1. Summary information about the time history records

Spectra	Record Number	Earthquake Name	Year	Station Name	Magnitude	Epicentral Distance (km)	Maximum usable period (s)	Scaling factor applied
1	1161	Kocaeli, Turkey	1999	Gebze	7.5	47.0	10.0	2.8
	1493	Chi-Chi, Taiwan	1999	TCU053	7.6	41.2	26.7	2.3
	1776	Hector Mine	1999	Desert Hot Springs	7.1	74.3	7.7	6.4
	2107	Denali, Alaska	2002	Carlo	7.9	67.7	19.2	5.3
2	1165	Kocaeli, Turkey	1999	Izmit	7.5	5.3	8.0	3.8
	1521	Chi-Chi, Taiwan	1999	TCU089	7.6	7.0	11.4	2.7
	1605	Duzce, Turkey	1999	Duzce	7.1	1.6	10.0	1.8
	828	Cape Mendocino	1992	Petrolia	7.0	4.5	14.3	1.4

The selected seed earthquake records were used to derive two sets of tri directional earthquake time histories. The first set was to match the UBC97 zone 4 spectra, the second set was to match UBC97 zone 4 with full near source factors.

4. FULL BUILDING RESPONSE HISTORY ANALYSIS

The building response was governed by the earthquake time histories that had been derived accounting for near source factors for which results are presented. The building was analysed twice, once with nailed connections between the primary timber members and once without nails. Graphical representation of the building performance is shown in Figure 8 and Figure 8 after the response history analyses.

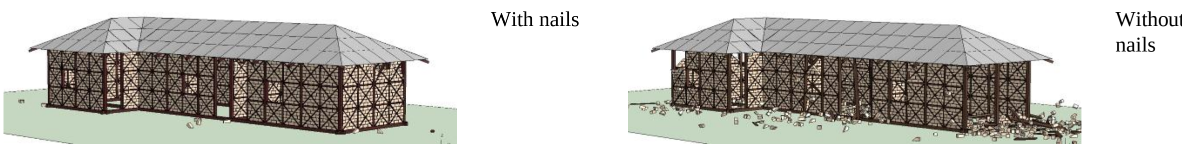


Figure 7. Final building condition after earthquake time histories

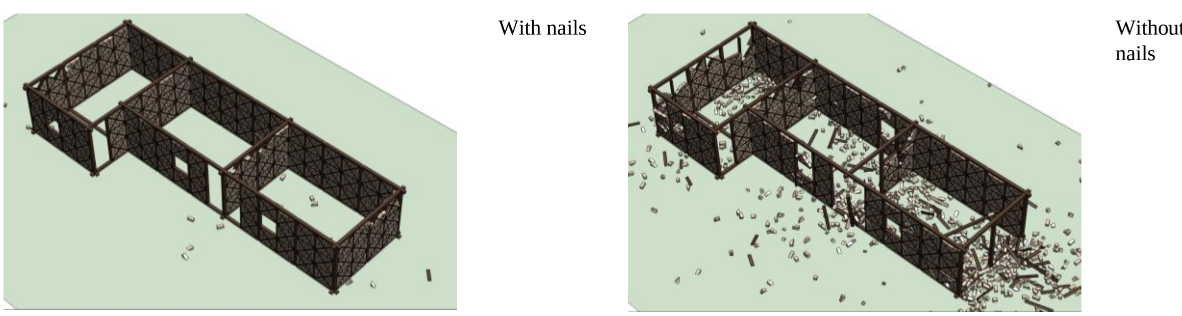


Figure 8. Final building condition after earthquake time histories (roof not shown for clarity)

There is a distinct difference between the performance of the models with and without nails, largely resulting from out of plane failure of the short walls in the case without nails. In these locations, failure is initiated when infill at the top of the wall is dislodged. The infill is only able to fall out when the timber pieces confining the infill pulls away from the rest of the frame because of the out of plane inertia force exerted on the timber by the infill. Nailed connections help keep the timber frame together which enables greater levels of confinement to be maintained on the infill material. Hence greater overall structural stability is ensured. Close ups of the performance of the model without nails are shown in Figure 9.

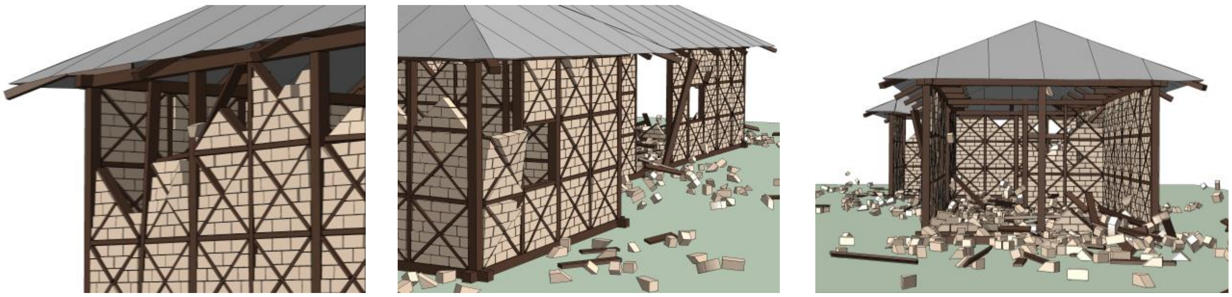
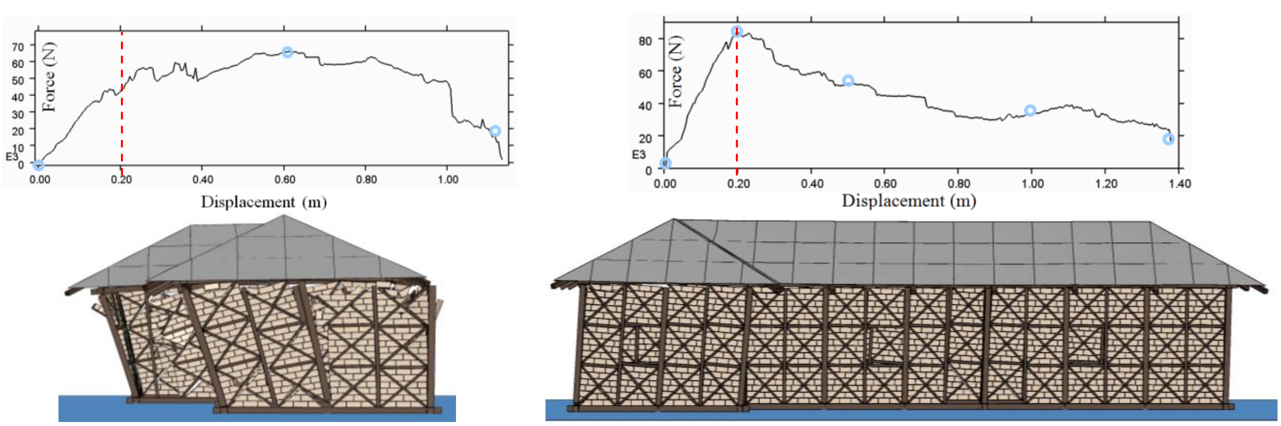


Figure 9. Close up of building behaviour without nails.

Peak forces were found to be lower in the model without nails. The structure without nails is more flexible and therefore has a longer period of vibration therefore attracting lower accelerations from the earthquake records as well as having a lower strength capacity. The model with nailed connections survives the earthquake with only minor local damage as shown in Figure 8 because it is able to maintain the infill confinement.

5. FULL BUILDING STATIC PUSH OVER ANALYSIS

Two quasi-static nonlinear pushover tests have been conducted in the long and short directions for the entire building with nails. In each case, the pushover was carried out by pushing one end of the top ring beam at a constant rate horizontally and at the same time recording the foundation forces to generate characteristic force-displacement curves for the building as shown in **Figure 10**. The buildings were displaced by over 1.0m over the building height at a constant rate until they collapsed, seen by the drop off in the lateral resistance of the building, as shown in **Figure 10**. The imposed lateral drift level is very high and is more than would be expected from the largest earthquake specified in the Uniform Building Code 1997 (UBC97, Zone 4 peak ground displacement at a building period of 1 second is approximately 200mm).



Lateral drift of 0.6m

Lateral drift of 0.2m

Figure 10. Force deflection curves and images of the two orthogonal building directions [with nails]

6. BENCH MARK TEST

After completion of the whole building model we became aware that physical testing of a *dhajji dewari* wall panels had been undertaken at the University of Engineering and Technology (UET) Peshawar, the results of which were kindly made available to Arup to benchmark our analytical model. The whole building model was cut down to a wall panel of similar overall dimensions as those of the model used in the UET Peshawar tests. The loading regime used by UET was reproduced and lumped mass elements were added at the top of the main vertical posts to reproduce the 200kg masses applied to the wall panel in the physical tests.

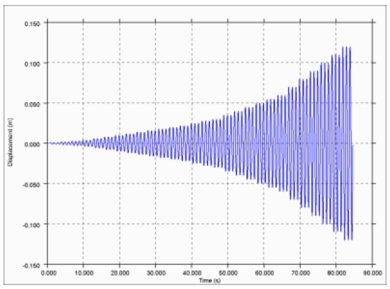


Figure 11. Cyclic push over analysis loading regime

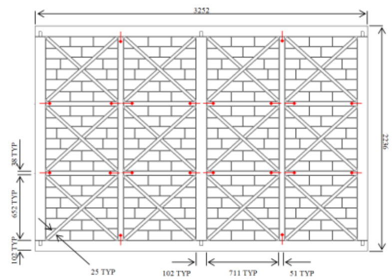


Figure 12. Wall panel push over model

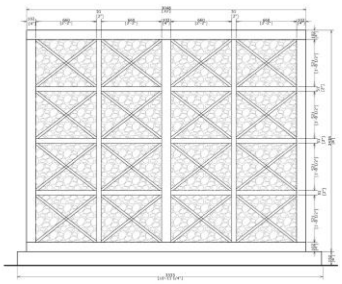


Figure 13. Physical test model by UET Peshawar . [Dr. Ali Qaiser]

The horizontal base reaction was measured at the base of the wall panel in the LS-DYNA model and was plotted against the applied displacement profile to produce hysteresis curves. These were overlaid with the physical tests results as shown in Figure 14. The comparisons showed that the LS-DYNA analysis model is able to reasonably predict the overall behaviour and deformation mechanism of the *dhajji dewari* frame made of timber, stone, mud and a few nails (See Figure 15). Given that these models were conducted without prior knowledge of each other's work the level correlation is considered good. The LS-DYNA model is not identical in terms of layout or the amount of nailing compared to the UET Peshawar test model. The UET test is initially stronger (by up to 50%) to start with. Post yielding, the UET Peshawar test results and the analytical LS-DYNA model hysteresis curves are more closely matched. The stability of the system is better defined by the post elastic behaviour where there is broad agreement. These benchmarking results provided valuable support to increase our confidence in the analysis results obtained under the whole building analysis.

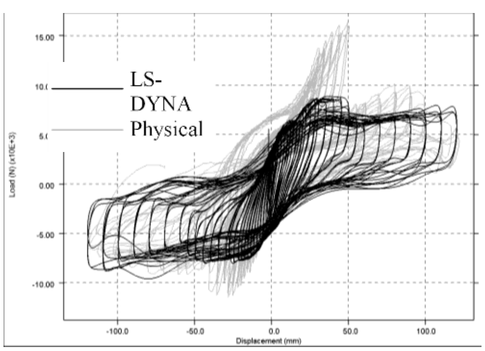


Figure 14. Hysteresis loop comparison

Figure 15. Wall panel deformation at 120mm top displacement

7. SENSITIVITY ANALYSIS

The results of the full building and benchmarking encouraged us to start undertaking sensitivity analyses. We have explored the effects of a) increased levels of overburden as shown in Figure 16, b) shortening of the diagonal braces as shown in Figure 17 and c) removal of the discrete nails from the wall panel analysis model.

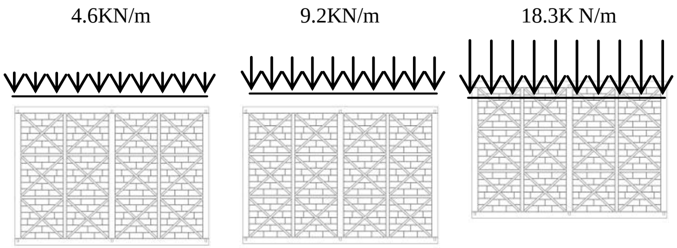


Figure 16. Three levels of overburden.
4.6 kN/m, 9.2 kN/m and 18.3kN/m

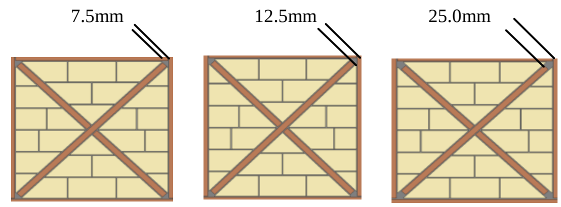


Figure 17. Shortening of the diagonal braces by 15, 25 and 50mm.

Overburden was applied as a line load acting vertically downwards on the top timber beam. The sub frame was subjected to the same cyclic displacements as before. This allows us to examine the resistance of the frames with higher levels of compression acting on them, as would be expected in a multi-storey building. In this instance the overburden acted as additional pre compression on the *dhajji dewari* walls. Increasing overburden levels were found to increase the resistance offered by the masonry due to increased friction capacity of the assembly as shown in Figure 18. Because the timber is modelled using elastic material properties, failure of the timber sections and thus loss of load carrying capacity of the sections is not explicitly captured in the current analysis model.

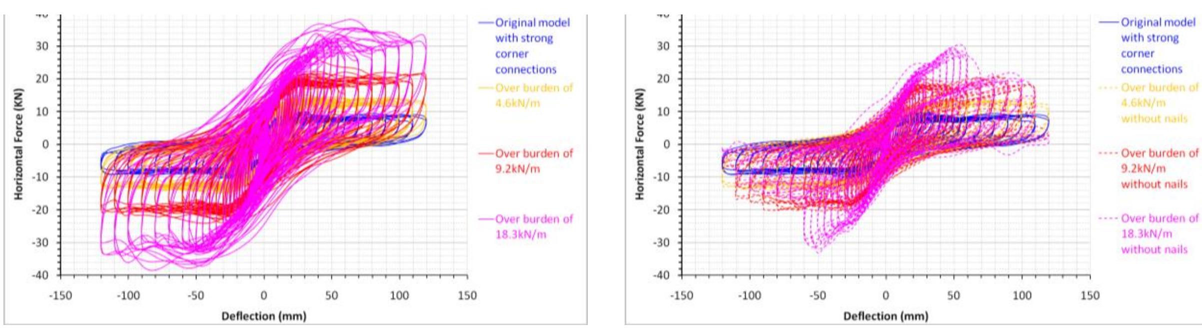


Figure 18. Hysteresis loops of varying levels of overburden with and without nails.
Note: Higher quality images can be found at www.traditional-is-modern.net/Arup/ArupDhajjiGraphics.pdf.

Superposition of the force vs. deflection curves for the three levels of brace length reduction, as shown in **Figure 19**, shows that whether or not the braces are engaged has a modest impact on the hysteretic behaviour of the structural assembly. Not having the braces fully engaged was found to reduce the amount of pinching in the hysteresis loops and thereby increase the levels of absorbed energy. The combination of shorter braces with increasing levels of overburden show reduced pinching of the hysteresis loops as illustrated in **Figure 20**. However, the maximum resisted load builds up slower compared to the case where only the overburden was increased, but at the larger overburden weights, the resistance was still increasing, rather than decreasing, when the maximum displacement of the testing was reached.

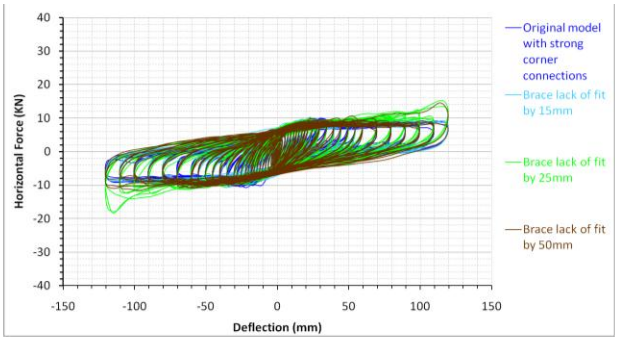


Figure 19. Hysteresis loops of brace shortening

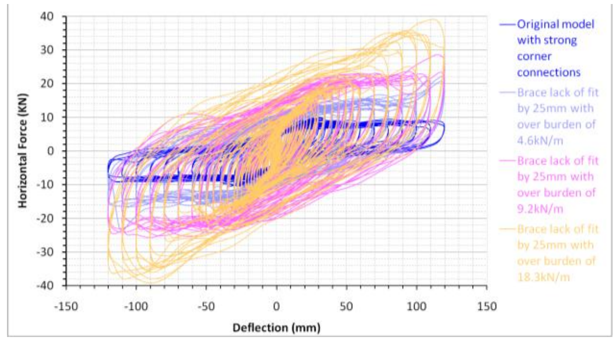


Figure 20. Hysteresis loops of increased overburden and brace shortening

Figure 21, Figure 22 and Table 2, which should be read together, show how the energy absorbed by the wall panel was affected by the various sensitivity runs. Comparison of the work done within the hysteresis loops shows that for overburden levels of 4.6kN/m and 9.2kN/m greater amounts of energy are absorbed when the braces are not as tightly engaged (83% vs. 49% and 168% vs. 116% - normalised against the model with no overburden). However, this pattern is not repeated for the highest considered overburden level (178% vs. 199%). The 25mm brace shortening increased the absorbed energy by 20% and an overburden of 4.6KN/m increase the absorbed energy by 49% compared to the original model. When combined these two features increased the energy absorption capacity of the system by 83% which is modestly more than the sum of the individual runs. At an overburden level of 9.2KN/m the absorbed energy increased it by 116% compared to the original model. When the 25mm brace shortening and 9.2KN/m of overburden were combined, the absorbed energy of the system increased by 168%. This is considerably more that the linear sum of the two and suggests that allowing the frame to move in a stable manner benefits the energy absorption of the system at this level of overburden. At a level of 18.3KN/m the 25mm brace shortening increased the energy absorption capacity of the assembly by 20% and the increase in overburden by 199% when assessed in isolation. When combined these two features increased the energy absorption capacity of the system by 178%. This is less than the linear sum of the two and suggests that at this level of overburden the system has struggled to maintain the same level of stable hysteretic behaviour. Further work is necessary to confirm the observed behaviour and ideally it will result in an optimum configuration of brace length (or no braces as the case may be) and the best amount of pre compression to the timber and masonry assembly.

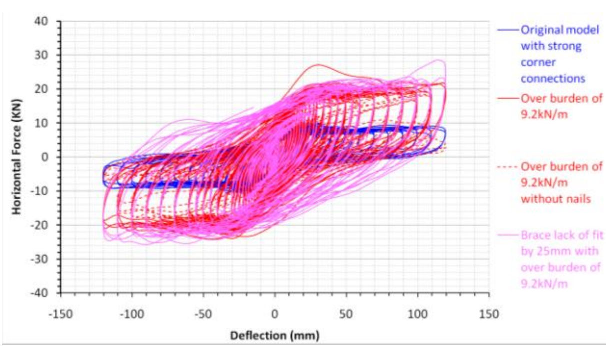


Figure 21. Hysteresis loop comparisons at 9.2KN/m

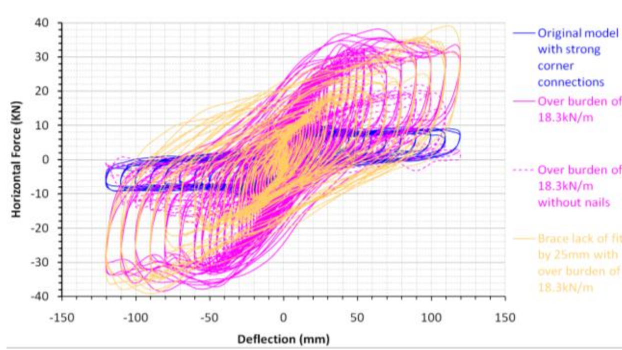


Figure 22. Hysteresis loop comparisons at 18.3KN/m

Table 2. Energy absorption comparison with varying levels of overburden					
Model description	Work Done (Joules)	Normalised work done	Model description	Work Done (Joules)	Normalised work done
Original model	5.07 x 10^4	1.00	Brace lack of fit by 15mm	5.54E+04	1.09
Overburden of 4.6kN/m	7.56 x 10^4	1.49	Brace lack of fit by 25mm	6.09E+04	1.20
Overburden of 9.2kN/m	1.09 x 10^5	2.16	Brace lack of fit by 50mm	6.13E+04	1.21
Overburden of 18.3kN/m	1.51 x 10^5	2.99	Brace lack of fit by 25mm with overburden of 4.6kN/m	9.29E+04	1.83
Overburden of 4.6kN/m without nails.	7.22 x 10^4	1.42	Brace lack of fit by 25mm with overburden of 9.2kN/m	1.36E+05	2.68
Overburden of 9.2kN/m without nails.	8.03 x 10^4	1.58	Brace lack of fit by 25mm with overburden of 18.3kN/m	1.41E+05	2.78
Overburden of 18.3kN/m without nails.	8.27 x 10^4	1.63			

8. RESULTS SUMMARY

This work has demonstrated that it is possible to model the behaviour of traditional *dhajji dewari* buildings. Qualitatively the analytical model has reproduced the deformation mechanisms seen in physical tests of a similar wall and has produced quantitative results which are consistent with the physical specimens (given the differences in geometry and connections). The following points summarise the key findings from the research and analysis conducted to date:

1. *Dhajji dewari* can safely resist earthquakes in high seismic regions of the world when built properly and maintained adequately. This makes *dhajji dewari* a valid form of construction in seismic areas.
2. The timber framing provides stable confinement to the infill masonry as long as it remains together. Therefore it is critical that the timber connections are detailed to have sufficient strength and ductility. Strategic use of nails and /or metal straps improves the building performance.
3. Seismic energy is dissipated through friction between the masonry panels and the timber frame and within the yielding of the connections.
4. Increased levels of overburden acting on the masonry increases the energy absorption capacity of the assembly, which provides evidence that the use of the system for two or even more storey structures may be satisfactory. This is consistent with some observations of resilience of multi-storey buildings in Turkey, India and Haiti after recent earthquakes. Further research is merited to establish design criteria for multi storey *dhajji dewari* buildings.
5. Shortening the braces so that they are disengaged from the timber frame leads to nominally improved seismic energy absorption of the system. No adverse effects were observed from shortening the braces. Consequently brace removal may offer acceptable performance with simpler construction (as the bricks do not have to be cut or placed at angles) and reduced timber volume, which is helpful to preserve natural resources.

Broadly, *dhajji dewari* is similar conceptually to ‘confined masonry’ construction which has concrete ring beams and columns confining the unreinforced masonry infill. The main difference is that in a ‘confined masonry’ system the sand cement mortar used to bond the masonry pieces together is brittle and stiff while traditional *dhajji dewari* has mud mortar which is very weak which allows it to start yielding even under relatively small lateral loads. Also, in *dhajji dewari* construction the masonry panel sizes are typically much smaller than in typical confined masonry construction, which can be advantageous. The energy in the *dhajji dewari* system is dissipated mainly in friction between the infill and the frame, and in the mortar joints of the infill itself, and not through the non-linear material deformations of the frame members as would be the case in modern steel or reinforced concrete construction. Therefore if key connections can be prevented from falling apart, then the integrity of the timber frame is secured and the infill dissipates the seismic energy through friction which is mobilised as the masonry pieces slide across each other and against the framing members.

The analysis showed the merit of holding the system together. Further studies are warranted to establish optimum joint configurations and arrangements of the components for *dhajji dewari* building. Whilst nails are prone to rusting, the value of good carpentry connections should not be over looked to make its rightful contribution to good seismic behaviour.

It is possible to imagine that after an earthquake that there will only be limited and repairable damage to a *dhajji dewari* building due to the unique energy absorbing properties of the system. This is a significant benefit over many modern engineering concepts as are now used for structures of similar size and use, particularly in rapidly developing cities, as well as rural areas. As can be seen not only in Pakistan, but also in Turkey, and now also in Haiti, this system, whether it is called *dhajji, hımış,* or *colombage*, is suited as a housing type that may be safer, as well as relatively easy to build and repair.

9. CONCLUSION

If we are to create communities that are both sustainable and resilient, it is necessary to adopt construction technologies that make best use of available resources and are safe. *Dhajji dewari* offers hope to this cause by using durable renewable or recycled materials that are likely to be locally available. This research shows that it is a form of construction that can offer significant seismic resistance. If damaged *dhajji dewari* can be repaired relatively easily because the materials are readily available.

This research is an important step in understanding the behaviour of *dhajji dewari* structures and generating wider acceptance of this building system amongst the general public, donors and government. Having created a validated analytical model, further analyses can be undertaken to test the performance of many critical elements of the house. Further investment and research is needed, ultimately leading to:

1. An evidence based earthquake engineering building standard and construction guidelines for new *dhajji dewari* buildings
2. An evidence based earthquake engineering building standard and construction guidelines for repairing and retro-fitting existing *dhajji dewari* buildings.
3. Training materials aimed at self-builders, contractors, university students, architects and engineers and governments in a number of different regions in the world

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