CYCLIC LOAD TESTING OF FULL-SCALE ASSAM-TYPE WOODEN HOUSE FOR EVALUATION OF LATERAL CAPACITY

H. B. Kaushik[(1)], B. Chand[(2)], S. Das[(3)]

[(1)] *Professor, Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, India, Email: hemantbk@iitg.ac.in*
[(2)] *Doctoral Student, Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, India, Email: bchandbiswajit@gmail.com*
[(3)] *Assistant Professor, Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, India, Email: sandip.das@iitg.ac.in*

Abstract

Timber-frame houses are very popular in seismically active regions of different countries due to their superior performance during earthquakes. Assam-type house is one of such traditional housing typologies that has performed exceptionally well during several past earthquakes in the north-eastern Himalayan region of India. These houses are also commonly known as Ikra houses as the walls and roof of such houses are sometimes made of locally available reed named Ikra. The housing is known to have a number of seismic features that contribute to their seismic safety; these include light mass of walls and roof, good wall-frame interface connection, and unique type of flexible infill material and connections used in wooden elements at different levels. The infill walls, also known as Ikra walls, are constructed by dividing the timber frame into smaller panels and filling each panel either with woven bamboo strips or with woven river reeds. Such a construction practice makes the panels light weight due to which the house does not require extensive foundations, and therefore, can be constructed in varied local site conditions. Design or construction guidelines for such houses are practically non-existent; local people living in the earthquake-prone Himalayan region have developed these seismic features with their own experiences, and evolved a unique earthquake resistant housing typology using locally available materials. This makes Assam-type houses easy to construct, maintain, and an economical housing construction typology. However, these houses have not received due attention and their performance under seismic action has not been scientifically studied so far. In this article, a brief discussion of the construction methodology and lateral load behavior of a full-scale Assam-type house under slow-cyclic pseudo-static lateral loading is presented. A single storey full-scale house consisting of four walls with door and window openings was subjected to incremental lateral displacement cycles till failure. The experimental results showed excellent lateral load behavior of Assam-type house in terms of very high drift and ductility capacity. The house specimen underwent very high lateral displacements without significant drop in the lateral load carrying capacity. Hysteretic response of the house showed pinching behavior with more or less symmetric loops. The main timber posts showed significant bending at high lateral drift level, but they did not fail. Separation of wall-frame interface connections and failure of joints of vertical post with wall plate beam were found to be the primary reasons of failure. Most of the other joints of the house remained intact during the entire test. Results of the study can be used to scientifically convince the local people, who have started constructing reinforced concrete buildings without fully understanding their construction and design aspects, to again adopt the practice of construction of such houses. This in turn may reduce the seismic risk in the region by controlling the construction of informally constructed reinforced concrete buildings. Experimental data thus obtained can be used to develop analytical models for seismic assessment of such houses.

Keywords: Assam-type house; Timber-frame house; Seismic capacity; Slow-cyclic testing; Flexible joints

1. Introduction

Traditional wooden frame houses are found in most parts of the world. These houses are characterized by a timber frame infilled with variety of materials (masonry, rubble stone, mud, wood products, etc.). The timber framing system and the infilled materials varies in different places and known by different names, such as Edificios Pombalinos in Portugal; Casa Baraccata in Italy; Fachwerk in Germany; Ksilopikti Tichopiia in Greece; Colombage in France; Bindingverk in Scandinavia; Half-timber in the United Kingdom; Entramados in Spain; Dhajji-Dewari and *Ikra* in India; Pagoda in China; Quincha in Peru; and Baghdadi, Hımış, and Dizeme in Turkey. The performance of these houses is found to be very resilient to earthquake shakings as mentioned in various studies [1-11]. Assam-type wooden houses are one of the very few housing systems in India that have performed exceptionally well during past earthquakes compared to other popular structural systems, such as, reinforced concrete frame buildings and masonry buildings. Due to the historical high seismicity of the north-eastern Himalayan region of India, the local people have developed a unique housing system in terms of both its construction technique and the material used in the structural components. This type of construction has been in practice for many decades, and is mostly seen in the north-eastern part of India, where the local people mostly use the local resources in construction of such houses. This makes Assam-type houses easy to construct, maintain, and an economical housing construction typology. The walls of Assam-type houses are made of *Ikra* (locally available reed found in river beds) or bamboo mesh material that makes it light weight due to which it does not require extensive foundations, and therefore, can be constructed in varied geotechnical conditions. It has excellent ability to withstand seismic events which has been proven in past earthquakes [2, 12, 13]. Also, these walls have good thermal and acoustic qualities. This type of construction does not require commercially processed materials or a skilled labour force; rather unskilled local labour can conveniently construct an Assam-type house. A typical Assam-type house is shown in Fig. 1. This type of housing construction is commonly found in both rural and urban areas. The housing is known to have a number of features that influence earthquake safety of the house. These include: (a) Architectural aspects: regular plan, small openings, central location of openings, and small projections and overhangs, (b) Structural features: light mass of walls and roofs, good wall-to-frame connection, good quality and strength of materials used, and (c) Flexible connections (using bolts, nails, grooves, etc.) between various wooden elements at different levels [2, 14]. Several modifications have been observed in the construction methodology and materials used in Assam-type housing at various places to suit the local requirements. The frames and panels of the windows and doors are made of locally available wood material. The door and windows are small in size and are generally placed in the center of the walls. The main wooden posts of the house are supported on plain concrete pedestals constructed over the ground up to plinth and the connections between wooden posts with foundation are achieved through steel L-clamps. An important aspect of this housing type is its connection between various elements: main posts, intermediate horizontal and vertical studs, wall plate beams, infill wall panels, roof trusses, and roofing elements. Typical Assam-type houses may have false ceilings made of timber and bamboo mats, while in modern construction, plywood or gypsum sheets are used. Nowadays, pitched CGI (Corrugated Galvanized Iron) sheet roofing over timber trusses is the most common form of roofing used in these houses. However, in older days and in some rural areas even in the present day *Ikra* (river reed) is used as roofing.

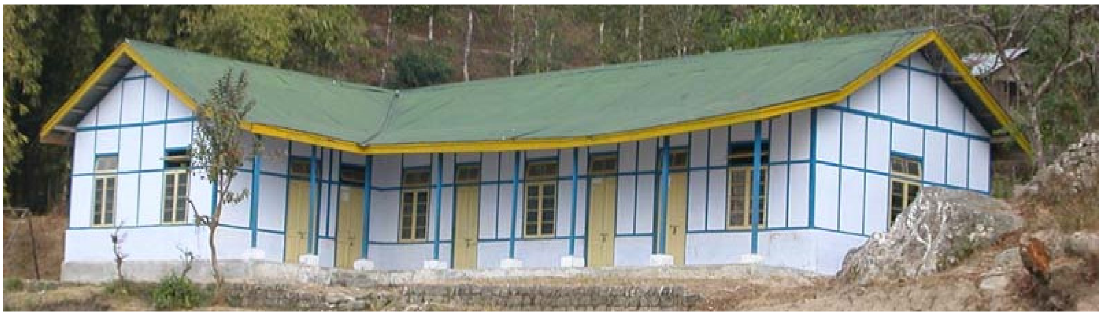


Fig. 1 – A typical Assam-type house [2]

The uniqueness of this type of house from other traditional wooden houses lies in its construction methodology, framing members, special type of connection between framing members, light-weight walls and their connections with framing members, and foundation. In spite of all these exceptionally good features, these houses have not received due attention, and only a few studies are carried out on their performance under seismic action. In the present study, a description of typical construction methodology adopted in such houses is presented, and quasi-static lateral load behaviour of a full-scale Assam-type house specimen is carried out. The full-scale specimen considered for the quasi-static cyclic test was initially considered for the shake table test. Since the house specimen did not suffer significant damage under dynamic loads, the lateral load carrying capacity was determined by conducting quasi-static cyclic test on the same house specimen after the shake table test. The results of the quasi-static cyclic test are discussed to evaluate the ultimate lateral load behavior of Assam-type houses and to understand possible reasons for such behavior of these houses built without any engineering intervention using locally available resources. The test results are also compared with those obtained for the full-scale frame specimens that were tested previously by the authors [14].

2. Description of Full-scale Test specimen

A full-scale single room house specimen of a typical Assam-type house was tested under quasi-static cyclic loading as shown in Fig. 2. The house specimen (main posts and walls) was constructed on rigid steel frame consisting of channel sections after filling concrete in the web of the channels. The main posts of the specimen were supported over the concrete using steel L-clamps, which were inserted into the concrete and welded with the channel sections. A detail description of the construction methodology of the house specimen will be discussed here. Various members and connections used in the house and their locations are shown in Fig. 3 and Fig. 4. Joints A and B (bottom of the main posts) were mutually provided such that Joint A resists the rotation of the main post along the plane of the wall (along the loading direction), while Joint B allows the rotation as shown in Fig. 4 (a and b). In this type of construction, main posts are first erected and connected to the top wall plate beam through open mortise- tenon connection reinforced with the help of steel flats and bolts to prevent the lateral sway in the joints (Fig. 4c). The main posts and top wall plate beam are then joined with horizontal and vertical framing members with the help of different connections as shown in Fig. 3. One end of the horizontal studs is connected to the main post (Joint D) using mortise and tenon joint (Fig. 4d), and the other end is connected using a shear key type of arrangement (Joint E) as shown in Fig. 4(e). The vertical studs are toothed on both the ends to facilitate insertion into the grooves (5 mm wide and 15 mm deep) cut along the length of the horizontal studs or the beams (Joint F), and nails are driven in these connections to secure the joints and to reduce the sway (Fig. 4f). The timber frame (main posts and wall plate beam) of the specimen is made of *Sal* wood (Shorea robusta) and secondary horizontal and vertical studs are made up of *Jam* wood (Syzygium cumini).

Fig. 2 – Full-scale Assam-type house specimen tested under quasi-static cyclic loading

Brick masonry of about 75 mm thickness is used as infill in the house up to sill level, and two long nails (150 mm) are driven in each main post through the mortar joints of the masonry wall to provide out of plane stability to the wall (Fig. 3). Above the sill level, the panels (*Ikra*) are meshed using locally available bamboo or river reed and plastered using cement mortar in two layers making the total thickness of *Ikra* panels to be about 45 mm. The bamboo strips (about 25 mm wide) used in *Ikra* walls are also supported vertically by inserting them into the grooves cut in the horizontal studs. The bamboo strips are also inserted into the holes made in the main posts and vertical studs to provide out of plane stability to *Ikra* walls. The masonry infill (below the sill) is also plastered with cement mortar.

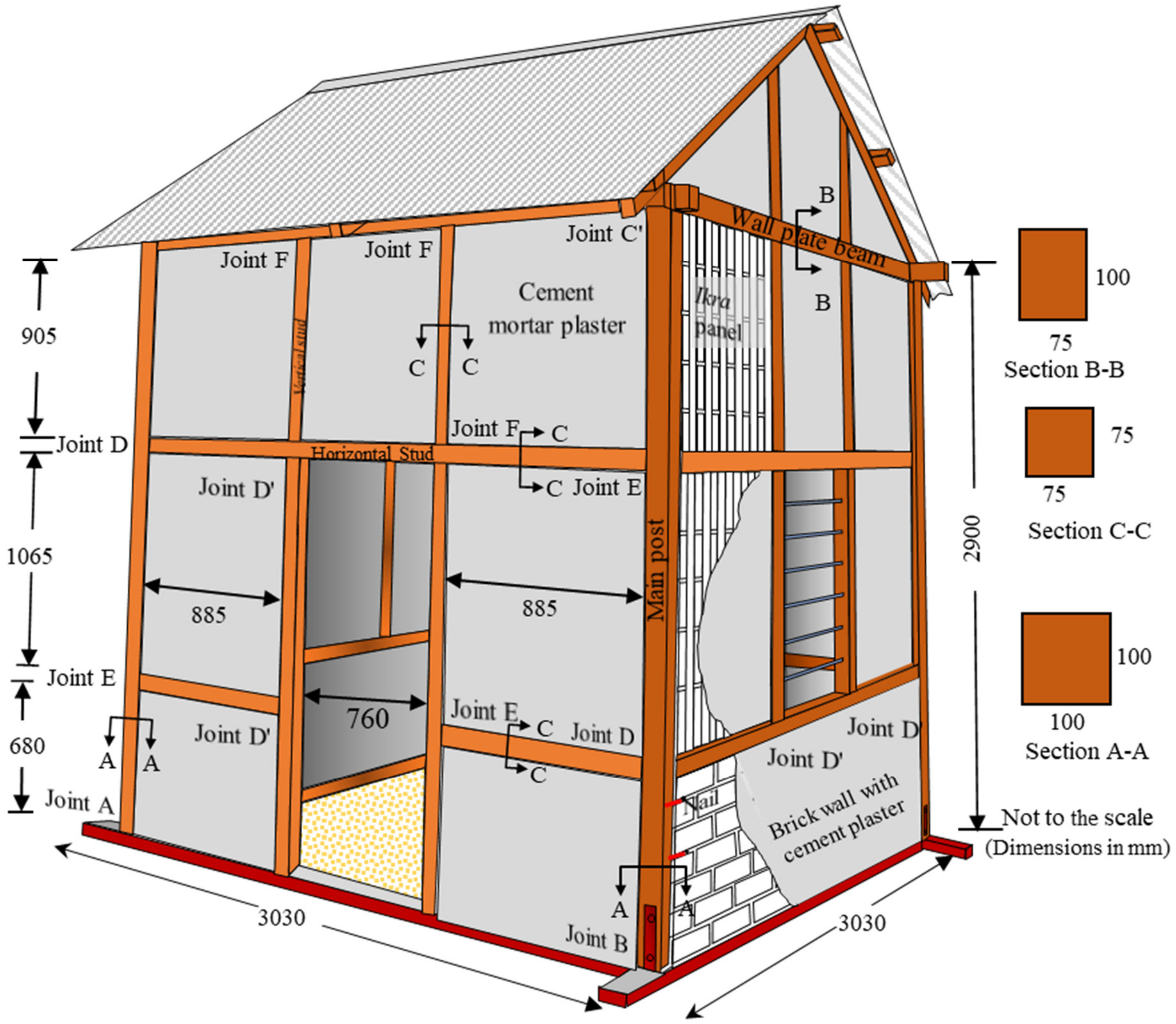


Fig. 3 – Details of various components in the construction of Assam-type house specimen

The specimen had a central window opening in one of the walls above the sill level, and a central door opening in an adjacent wall of the house specimen (Fig. 2). As per the prevalent construction practice, the connections of window panels and top connections of door posts with the frame are mortise and tenon type (Joint D'), whereas, bottom connections of doorposts are slightly inserted into the plaster of the floor without any connection. However, in the present study, the doorposts were inserted into the foundation of the specimen (concrete) in order to improve the lateral load behavior of the door posts. The house specimen was a single story, single room Assam-type house with a room size of about 2.83 m × 2.83 m and height of about 3.6 m. The main posts were made of about 100 mm square sections and the wall plate beams had section of about 75 mm × 100 mm. The intermediate stud frame sections had about 75 mm square section. The rafter sections were about 75 mm × 65 mm and purlins were about 75 mm × 50 mm in section. The roof of the specimen was comprised of three wooden trusses connected to the top wall plate beams through long nails and covered with CGI (Corrugated Galvanized Iron) sheets. The inside ceiling surface of the house specimen was covered with gypsum sheet panels fixed through nails on the grids of wooden battens.

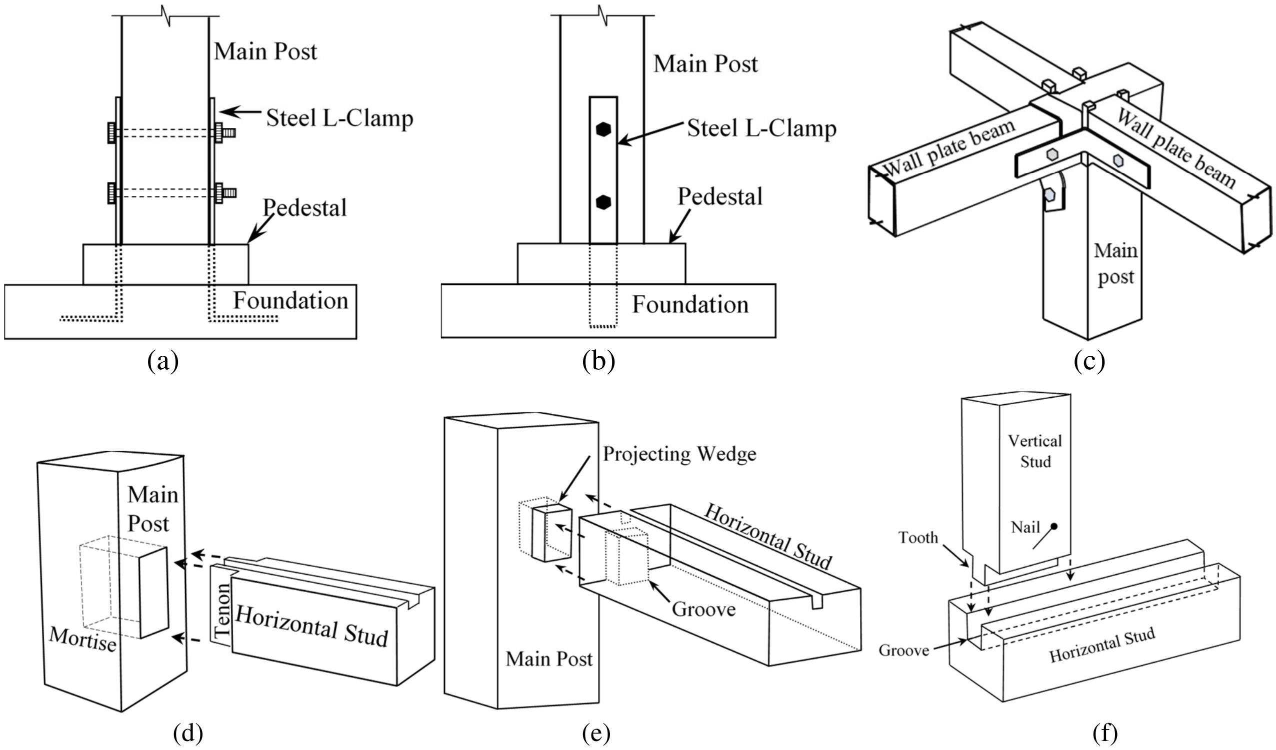


Fig. 4 – Connections used in Assam-type house specimen: (a) Joint A, (b) Joint B, (c) Joint C', (d) Joint D, (e) Joint E, and (f) Joint F

3. Test Setup and Procedure

Quasi-static cyclic testing was performed on the house specimen along the weaker direction, since the purpose of the study was to evaluate the load carrying capacity of these houses. The house specimen had a wall with central door opening and a fully infill wall in the loading direction. In the direction perpendicular to the loading (transverse direction), the specimen had a central window opening and a fully infill wall (Fig. 2). The experimental arrangement for lateral load testing of the specimen is shown in Fig. 5.

The specimen supported on grillage of channel sections was rigidly bolted to the reaction floor and the load was transferred to the specimen from the top wall plate beam level. The cyclic loading was applied to the specimen using servo-controlled hydraulic actuators of 250 kN load capacity and a stroke length of ±250 mm. Three cycles of each displacement level were applied and the response was recorded using a data acquisition system. The applied lateral displacement was increased by 2.5 mm after every displacement level up to 25 mm, and thereafter the displacement amplitude was increased by 5 mm with the frequency of each displacement cycle being 0.015 Hz ensuring the quasi-static cyclic loading (Fig. 6). The lateral response of the specimen was recorded by the load cell and displacement transducer in the hydraulic actuator in addition to LVDTs (linear varying displacement transducers) attached to the specimens (Fig. 5). Strain gauges were also fixed to the steel clamps at the bottom of the vertical posts to assess if there is any inelastic deformation of the clamps under lateral loading.

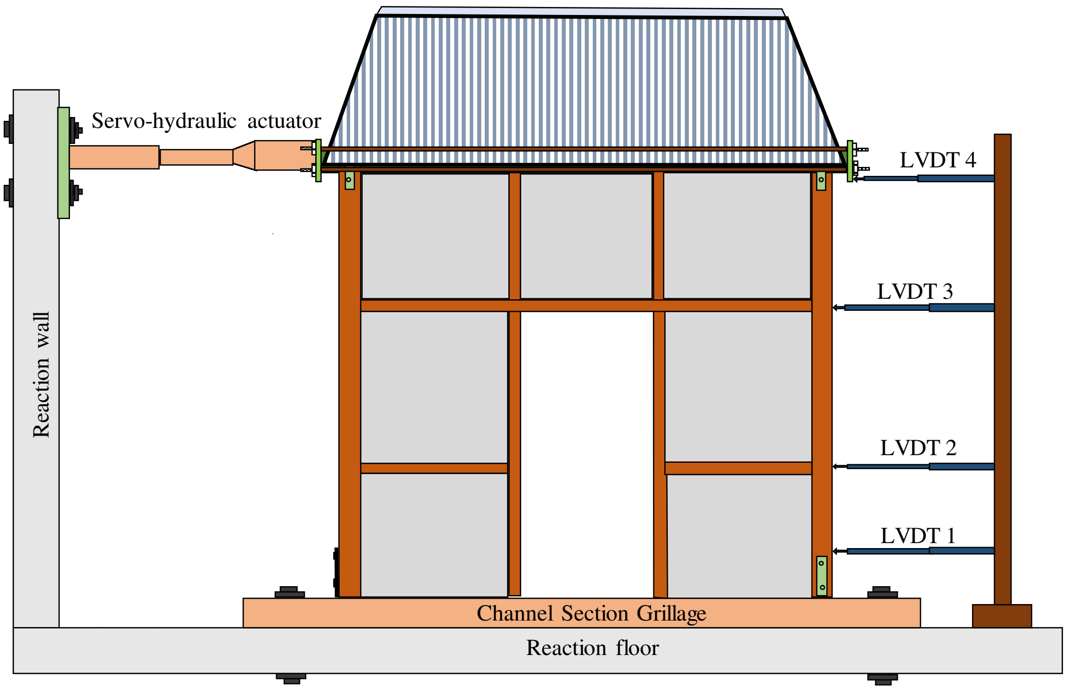


Fig. 5 – Experimental arrangement for quasi-static cyclic testing of the house specimen, and locations of LVDTs in the specimen

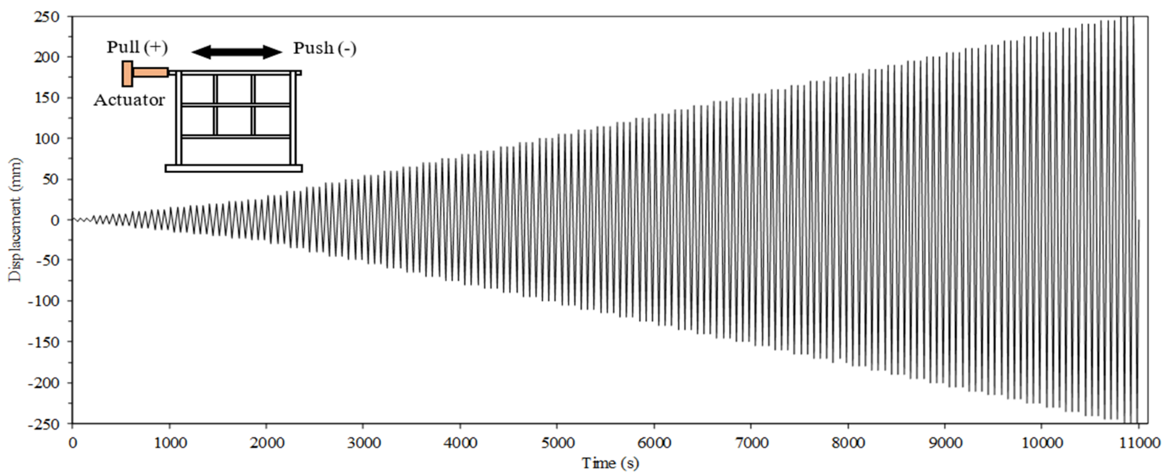


Fig. 0 – Displacement cycles applied on the specimen during the testing

4. Experimental Observation under Cyclic loading

The house specimens exhibited a large lateral deformation without much damage under the action of the applied lateral loading as one of the main post-foundation connections (Joint B) in each of the frames allowed rotation at the bottom, whereas the other (Joint A) resisted it. Even after being subjected to large deformation, Joints A and B of the main framing members remained intact during the entire cyclic testing unlike the damage observed in the main joints of other traditional houses, like *Dhajji-Dewari* or *Pombalino* construction [15-18]. This is because the main posts of the house were neither inserted into the foundation nor fixed with any wooden member. Because these connections govern the overall lateral load behavior of the house, flexible connections of the main framing members (Joints A and B) resulted in an excellent lateral load behavior. The connections of the horizontal studs with the main posts (Joints D and E) behaved quite flexibly with the loosening of the nails in the joints, allowing large deformation without noticeable damage in the joints (Figs. 7a, 7b). Similarly, at a higher lateral drift, the tooth and groove joint between the vertical and horizontal studs (Joint F) assisted in sliding of the vertical studs in the groove of the horizontal studs (Fig. 7c).

Fig. 7 – Damage observed in various components of the house during quasi-static testing: (a) Pullout of Joint D, (b) Pullout of Joint E, (c) Sliding movement of vertical stud and *Ikra* panels, (d) Tearing of top joint of doorpost, (e) Damage to top main post joint (Joint C'), (f) Hook-type steel flat in Joint C', (g) Small thickness of main post unable to prevent damage at Joint C', (h) Out-of-plane movement of transverse wall under lateral loads, and (i) Damage in the wall with door opening after 240 mm displacement

Due to the flexible connection of the *Ikra* panels with both the studs, sliding movement of the *Ikra* panels was observed in the walls of the house without any visible damage to the *Ikra* panels (Fig. 7c). However, *Ikra* panels did not slide or fall from the transverse walls of the house specimen. The sliding of *Ikra* panels caused formation of the interface crack between the panels and the surrounding studs along the periphery of the *Ikra* panels. With the increase in the applied lateral displacement, the gap between the vertical interfaces between the *Ikra* panel and the main posts increased near the corners, and on further increase in the lateral displacement, the horizontal studs were detached from the vertical main posts. Though the horizontal studs were detached, the lateral load resistance was still provided by the *Ikra* panels, masonry infill, and to a certain extent, by the interaction of the *Ikra* panels with the timber frame as ascertained from the hysteresis response. The masonry infill (below sill level) did not suffer any significant damage. Under the lateral loading, the behavior of the in-plane wall with door opening and the in-plane wall with full infill was found to be quite different. Noticeable damage was observed only in the wall with door opening, whereas no significant damage was observed in the fully infill wall. At 65 mm lateral displacement, tearing of doorpost connections by the nails present in the connection was observed (Fig. 7d), and an interface crack developed between the masonry wall and the concrete foundation in the transverse wall. At 115 mm displacement the bottom of doorpost pulled out from the concrete foundation. At 145 mm displacement, sound of wood crack was heard from the top of the main post joint, and a crack was observed in the *Ikra* panel above the door opening at 160 mm displacement.

The connection of top of the main post with the wall plate beam (Joint C') was found to have severely damaged in the in-plane wall with door opening, and out-of-plane movement of the transverse walls was observed at 165 mm displacement (Figs. 7e, 7f, and 7h). The joints were not disintegrated completely due to the presence of hook-type and L-type steel flats in Joint C' (Fig. 7g) as shown in Figs. 7e, and 7f. Three members meet at the top of the main posts. Due to which very small thickness of timber is left at the top of the main post (Fig. 7g), damaging the top of the main post joints during the lateral loading. Therefore, to improve the lateral load behavior of these houses, the size of the main post should be increased. Major damage in the joints occurred in the doorposts, which acted as intermediate vertical posts and restricted the sliding movement of the *Ikra* panels which in turn damaged the joints. Interestingly, the top joints of the main posts in the in-plane wall with full infill did not suffer any damage due to absence of any rigid connection. The doorposts started rocking with further increase in the lateral displacement. At 215 mm displacement cycle, the cement plaster got damaged near the top of the main post joint due to out-of-plane movement of the steel flats in the transverse walls. The fully infill wall, two out-of-plane walls and the ceiling did not suffer any significant damage up to 240 mm displacement level. Overall, most of the damage in the house specimen occurred only in the wall with door opening at connections of main posts as shown Fig. 7(i). The excellent lateral load performance of the framing system can be attributed to the simple and flexible connections in the frame members, light weight *Ikra* panel and its flexible connections with the surrounding framing members.

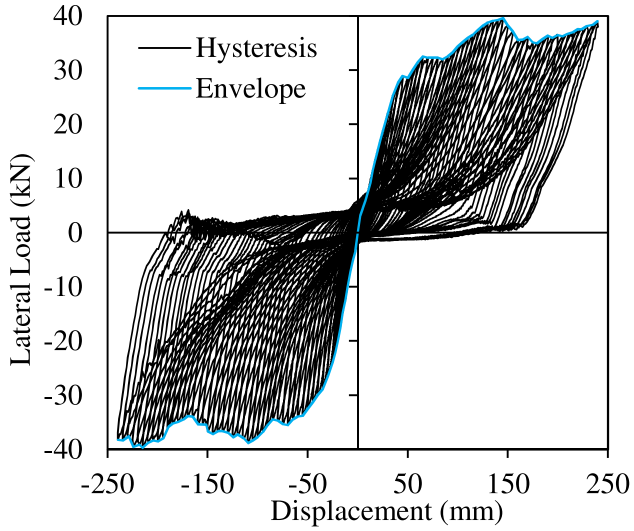
4. Influencing Parameters

The effect of various influencing parameters on the lateral load behavior of the specimen is quantified in this section by discussing the hysteresis behavior, load-deformation characteristics, energy dissipation, and stiffness degradation in the specimen.

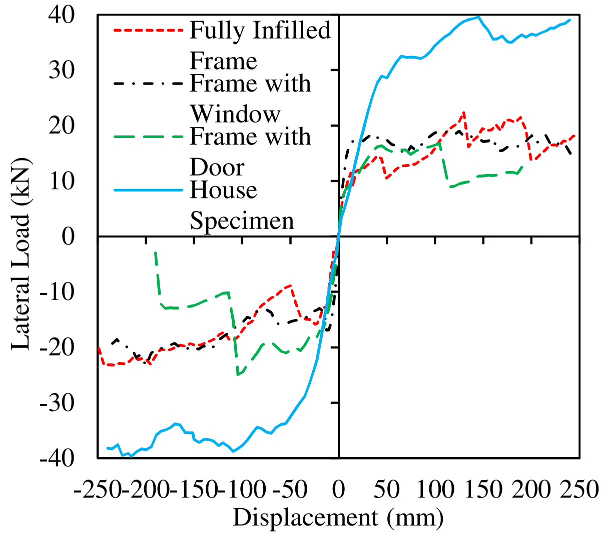
4.1 Hysteresis Response and Envelope Curves

The hysteresis response for the first cycle of every displacement level applied on the house specimen is shown in Fig. 8(a). The hysteresis behavior of the test specimen was symmetrical in push and pull directions and demonstrated extremely good ductile behavior without significant reduction in the lateral load carrying capacity even when subjected up to 240 mm displacement level. However, the hysteresis loops of the house specimen showed several kinks with increasing lateral displacement levels due to readjustment of *Ikra* panels and interface joints with the surrounding frame. The house specimen sustained the lateral load without any significant drop because of the resistance provided by the *Ikra* panels without suffering much damage, thus imparting significant strength and stiffness to the specimen under the action of lateral loading [14]. Pinching effect was observed in the hysteresis loops due to the separation of joints in the form of sliding movement of *Ikra* panel and opening and closing of horizontal stud connections with the main posts.

The envelope of the lateral load response of the house specimen was compared with the envelope response of three individual frame specimens tested earlier by the authors [14] as shown in Fig. 8(b). The individual frame specimens were frame with fully infill wall, frame with a window opening, and frame with a door opening. The frame specimens were constructed with same materials, sizes and tested under same testing conditions. The lateral load carrying capacity of house specimen was found to be nearly twice of the combined strength of the in-plane walls. The house specimen was found to have lesser initial stiffness compared to the individual frame specimens due to loosening of interface connections of infill panels (masonry wall and *Ikra* panels) with framing members during the shake table testing of the house specimen.



(a)

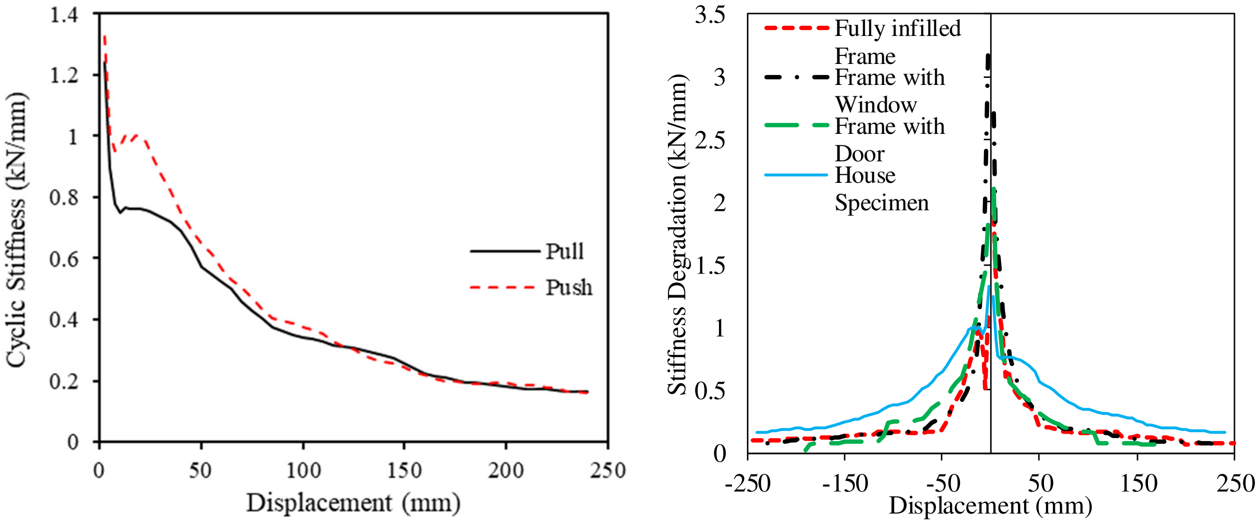


(b)

Fig. 8 – (a) Hysteresis response of the full-scale house specimen, and (b) Comparison of envelope curves of full-scale house specimen with individual frame specimens

4.2 Stiffness Degradation

Fig. 9(a) shows a comparison of the cyclic stiffness of the full-scale house specimen in pull and push directions calculated as the maximum lateral load divided by the corresponding displacement observed in various cycles of loading. It is observed that the difference in stiffness in the push and pull direction of house specimen was comparatively more in initial displacement levels and the difference reduced with increase in displacement level and became equal at about 120 mm displacement. The difference is attributed to the separation of the horizontal studs from the main posts in the push direction. Fig. 9(b) compares the stiffness degradation observed in the full-scale house specimen with that observed in the individual frame specimens. It is noticed that the cyclic stiffness degradation in case of frame specimen was similar in both push and pull directions, and as already discussed the stiffness of the individual frame specimens was found to be higher than the house specimen in initial displacement levels. This was due to the initial damage incurred in the house specimen during shake table testing, which was carried out on the same house specimen before conducting quasi-static testing. As expected, the cyclic stiffness became higher in case of the house specimen in both pull and push directions than the individual frame specimens after 25 mm displacement level, i.e., after the house specimen was subjected to the lateral displacement level (during quasi-static testing) that was higher than the relative displacement achieved during the shake table testing.



(a) (b)

Fig. 9 – Comparison of stiffness degradation observed in the full-scale house specimen: (a) in pull and pull directions, and (b) with frame specimens

4.3 Energy Dissipation

The cumulative energy dissipation (CED) was calculated by adding the area enclosed by the three hysteresis loops at every displacement level. The comparison of energy dissipated by the house specimen with individual frame specimens is shown in Fig. 10. Because of the reasons already discussed, the energy dissipated by the house specimen was found to be less than the frame specimens in initial displacement cycles, and after about 25 mm displacement cycle the energy dissipation of house specimen became highest among all the specimens. The energy dissipation was largely attributed to the sliding of the *Ikra* panels, and the interaction of different connections with the framing members.

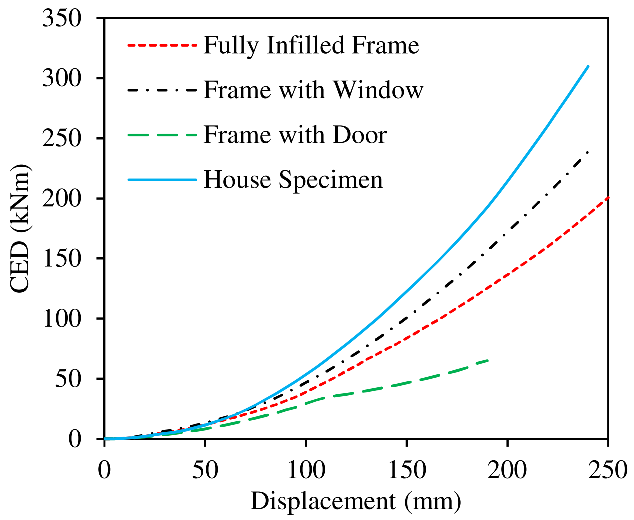


Fig. 10 – Comparison of cumulative energy dissipation of Frame specimens with full-scale house specimen

5. Summary and Conclusion

The lateral load behavior of Assam-type house, which is a common housing typology in the north-eastern Himalayan region of India, was evaluated experimentally in the present study by carrying out quasi-static cyclic testing of a full-scale house specimen. The study showed that the ability of the Assam-type house to undergo high lateral deformation without suffering major damage is primarily due to its typical framing system, flexible joints of the framing members, and light-weight infill walls (*Ikra*). Unlike other similar housing typologies, the connections of the main posts with foundation of Assam-type houses are such that the posts are not inserted into the foundation, thereby reducing the possibility of the failure of the post-foundation connection. Further, the flexible connections between the horizontal and vertical studs make the frame even more deformable. Such types of connections between different members of the frame, and between the *Ikra* panels and the frame, are not commonly observed in other traditional housing systems. The absence of rigid joints in the entire wall-frame system is one of the primary reasons for better performance of the Assam-type house during severe past earthquakes. Further, the *Ikra* panels in the house do not damage the surrounding timber frame even at large lateral drifts because of their light weight and their unique flexible connection with the timber frame that allows sliding of the *Ikra* walls in the frame. From the comparison of experimental results, it can be concluded that there is a significant influence of connection of *Ikra* panels with the timber frame on the lateral stiffness, energy dissipation, and the overall lateral load behavior of the Assam-type house. The lateral load carrying capacity of the house specimen did not drop even after a displacement level of 240 mm. The lateral load carrying capacity of the house specimen was nearly two times the lateral strength of the individual frames of the house tested previously. Based on the test results, it was observed that the cross-section of the main timber posts of these houses must be increased for further improving the lateral load behavior of the Assam-type houses. Results of the study can be used to bring back the confidence of local people on the age-old Assam-type housing by developing guidelines for construction and design of such housing. Improperly designed and constructed reinforced concrete buildings as well as unreinforced masonry buildings have performed poorly during several past earthquakes in the region. Therefore, it is important to present before the local people the advantages of the local housing typology for reducing the seismic risk in the region. Experimental data obtained in the present study can be utilized by the scientific community for development of analytical and finite element models for seismic assessment of such houses.

6. Acknowledgements

Authors acknowledge the financial assistance provided by the Ministry of Human Resource Development (MHRD), and a research grant (DST/TSG/STS/2012/65-G) provided by Department of Science and Technology, Government of India.

7. References

[1] Rai DC, and Murty CVR (2005): Preliminary report on the 2005 North Kashmir earthquake of October 8, 2005. *National Information Centre on Earthquake Engineering*, Indian Institute of Technology Kanpur, India.

[2] Kaushik HB, and Ravindra Babu KS (2012): Assam-type House. *World Housing Encyclopedia*, Report no. 154.

[3] Kaushik HB, Dasgupta K, Sahoo DR, and Kharel G (2006): Performance of structures during the Sikkim earthquake of 14 February 2006. *Current Science*, **91** (4), 449–455.

[4] Kaushik HB, and Jain SK (2007): Impact of great December 26, 2004 Sumatra earthquake and tsunami on structures in Port Blair. *Journal of performance of constructed facilities*. **21** (2), 128–142.

[5] Dogangun A, Tuluk OI, Livaoglu R, and Acar R (2006): Traditional wooden buildings and their damages during earthquakes in Turkey. *Engineering Failure Analysis*, **13** (6), 981–996.

[6] Langenbach R (2007): From 'opus craticium' to the 'Chicago frame': Earthquake-resistant traditional construction. *International Journal of Architectural Heritage*, **1** (1), 29–59.

[7] Kouris LAS, Meireles H, Bento R, and Kappos AJ (2014): Simple and complex modelling of timber-framed masonry walls in pombalino buildings. *Bulletin of Earthquake Engineering*, **12** (4), 1777–1803.

[8] Quinn N, D'Ayala D, and Descamps T (2016): Structural characterization and numerical modelling of historic quincha walls. *International Journal of Architectural Heritage*, **10** (2–3), 300–331.

[9] Ceccotti A, Faccio P, Nart M, and Simeone P (2004): Seismic behavior of wood framed buildings in Cadore mountain Regioni–Italy. In *13th World conference on earthquake engineering*, Vancouver, Canada.

[10] Poletti E, and Vasconcelos G (2015): Seismic behaviour of traditional timber frame walls: Experimental results on unreinforced walls. *Bulletin of Earthquake Engineering*, **13** (3), 885–916.

[11] Wu Y, Song X, Gu X, and Luo L (2018): Dynamic performance of a multi-story traditional timber pagoda. *Engineering Structures*, **159**(October 2017), 277–285.

[12] Kaushik HB, and Dasgupta K (2013): Assessment of seismic vulnerability of structures in Sikkim, India, based on damage observation during two recent earthquakes. *Journal of Performance of Constructed Facilities*, **27** (6), 697–720.

[13] Jain SK (2016): Earthquake safety in India: Achievements, challenges and opportunities. *Bulletin of Earthquake Engineering*, 14, 1337–1436.

[14] Chand B, Kaushik, HB, and Das S (2019): Lateral load behavior of traditional Assam-Type wooden house. *Journal of Structural Engineering*, **145** (8), 04019072.

[15] Ali Q, Schacher T, Ashraf M, Alam B, Naeem A, Ahmad N, and Umar M (2012): In-plane behavior of the Dhajji-Dewari structural system (wooden braced frame with masonry infill). *Earthquake Spectra*, **28** (3), 835–858.

[16] Vasconcelos G, Poletti E, Salavessa E, Jesus AMP, Lourenço PB, and Pilaon P (2013): In-plane shear behavior of traditional timber walls. *Engineering Structures*, **56** (Nov), 1028–1048.

[17] Aktaş YD, Akyüz U, Türer A, Erdil B, and Güçhan NŞ (2014): Seismic resistance evaluation of traditional Ottoman timber-frame hımış houses: Frame loadings and material tests. *Earthquake Spectra*, **30** (4), 1711–1732.

[18] Vieux-Champagne F, Sieffert Y, Grange S, Polastri A, Ceccotti A, and Daudeville L. (2014): Experimental analysis of seismic resistance of timber-framed structures with stones and earth infill. *Engineering Structures*, **69** (Jun), 102–115.

