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LOAD RESISTING BEHAVIOR OF NEPALESE REST-HOUSE

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Abstract

Traditional Nepalese rest houses, locally known as patis or sattals, are vernacular structures that have served as communal shelters and social spaces for centuries which can also be used during the earthquake. These buildings typically exhibit a hybrid structural system, with timber frames along one grid and masonry load-bearing walls along another, constructed using regionally available materials and indigenous craftsmanship. This configuration often leads to eccentricity in both mass and stiffness, significantly influencing the building's global seismic response and torsional behavior. This study investigates the load-resisting behavior of a typical Nepalese rest house, with particular emphasis on the traditional Nepali timber joints. A representative structural model was developed based on field documentation and literature, capturing key geometric and material characteristics. Numerical analysis was conducted to evaluate the structural response under gravity and lateral loads, simulating seismic actions. Special focus was given to the behavior of traditional timber joints, which are commonly constructed without nails or adhesives, relying instead on intricate interlocking geometries. A macro-modeling approach was adopted for masonry walls, while timber joints were studied at both macro and micro levels using the finite element method along with interaction properties. The results provide insights into the interaction between timber framing and masonry walls, highlighting the strengths and vulnerabilities of this traditional construction system. The findings enhance the understanding of Nepalese vernacular architecture and provide a basis for its preservation, retrofitting, and informed adaptation in contemporary practice.

Keywords: Nepalese rest house; Traditional architecture; Timber joints, Heritage structure, Seismic behaviour

1. Introduction

Traditional Nepalese rest houses, locally known as Pati, Sattal, and Mandapa, are iconic examples of vernacular architecture that embody Nepal's rich cultural and social heritage (ECS Nepal, n.d.). Typically constructed using a combination of brick masonry and timber, these structures have historically served as public resting places and communal gathering spaces. Despite their cultural significance, their structural performance has received limited attention in engineering research. Most were constructed empirically, without formal design standards, following traditional building practices passed down through generations (ECS Nepal, n.d.).

Nepal lies in one of the most seismically active regions of the world, making the study of such traditional structures especially important (EEFIT, 2019). Observations from recent earthquakes—most notably the 2015 Gorkha earthquake—revealed that many heritage and vernacular buildings suffered severe damage due to a lack of lateral load-resisting components, poor material quality, and weak interconnections between masonry and timber elements (Shrestha et al., 2017; Adhikari and Gautam, 2018). These failures emphasize the urgent need to understand the fundamental load-resisting mechanisms of Nepalese rest houses so that effective retrofitting and conservation strategies can be developed without compromising their architectural authenticity.

Comparative seismic studies on historic masonry towers in Italy have similarly demonstrated that torsional irregularities—arising from geometric asymmetries, openings, and belfries—significantly amplify structural vulnerability, as progressive damage reduces the effective

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resisting geometry and activates higher vibration modes (Casolo et al., 2013). Such findings underscore the importance of assessing torsional regularity in heritage structures, including Nepalese rest houses, to better understand their seismic performance. In this context, simplified analytical approaches become particularly valuable. The Simplified Method for Seismic Analysis (SMSA), widely used in Mexico for low-rise masonry shear-wall buildings, provides a framework for distributing lateral shear forces among walls based on their relative stiffness. SMSA has been shown to approximate the results of rigorous three-dimensional models with reasonable accuracy, especially when effective shear area factors are properly calibrated. Its appeal lies in requiring modest computational effort while still capturing essential aspects of wall behavior under seismic loading. Inspired by this precedent, the present study adopts a simplified stiffness method to evaluate the seismic response of Nepalese rest houses, comparing its predictions against more detailed three-dimensional models to assess its effectiveness.

Figure 1. Typical resthouse (sattal/falcha) in Kirtipur showing different wall and frame layout positions at (a) Devdhoka (b) Sundarbasti (c) Kutusagal and (d) Kutujho

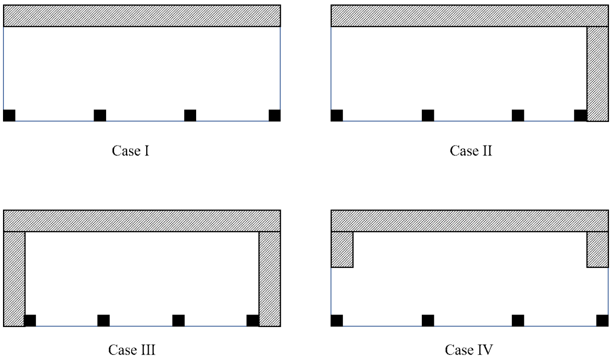


Figure 2. Different possible wall configuration of rest house

Complementary to the masonry analysis, the role of timber joinery is also critical. Experimental studies have demonstrated that traditional carpentry joints are not fully moment-resisting; for example, dovetail joints exhibit limited rotational capacity. Recent analytical work has further clarified that dovetail mortise–tenon joints provide only limited and asymmetric moment resistance, with rotational stiffness rapidly degrading after embedment yielding, while scarf joints can resist only about 40% of the shear force compared to small-scale specimen tests, effectively reducing the usable cross-section of timber members (Aira et al., 2015). These findings highlight the need to account for joint behavior when evaluating the overall stiffness and strength of hybrid masonry–timber systems.

Accordingly, this study investigates the load-resisting behavior of a representative Nepalese rest house through analytical and numerical modeling. The primary objectives are: (1) To identify the torsional regularity or irregularity of the rest house structure under lateral loading conditions and (2) To perform detailed stiffness simulations of the wall and timber frame components to evaluate their relative contribution to the overall structural response. By addressing these objectives, the study seeks to establish a deeper understanding of how traditional structural components interact to resist lateral forces, thereby providing a foundation for informed conservation, seismic strengthening, and heritage-preservation practices in Nepal (EEFIT, 2019).

2. Methodology

The methodology can be described in two parts.

Field Investigation and Analytical Assumptions

The study begins with a field investigation in Kirtipur, Kathmandu, where several existing rest houses are visually inspected to document construction techniques, materials, and structural configurations. The survey reveals that most rest houses are one- or two-storey structures, with the ground floor typically comprising a timber frame with open sides and the upper storey constructed of solid masonry walls. The masonry walls above the timber frame form a nearly rectangular plan and enclose the structure on all four sides, while the ground floor behaves as a soft storey due to the relatively flexible timber frame and open configuration. The roof system consists of timber rafters supporting planks, over which mud mortar and tiles are laid.

Field observations identify several possible ground-storey plan layouts, including parallel wall–frame systems, L-shaped configurations, and U- or C-shaped arrangements similar to the field observations (Figure 1). Based on these observations, four representative plan layouts were selected for analysis: Case I: Masonry wall and timber frame parallel in plan, Case II: L-shaped wall configuration, Case III: C-shaped wall configuration, and Case IV: Modified C-shaped configuration with the cross wall reduced to half-width in plan (Figure 2). In all cases, the upper masonry storey is idealized as a rigid body, with only its mass considered in the analysis. This simplification allows the investigation to focus on the torsional behavior of the lower, more flexible timber storey and reflects observed construction practice, where the upper storey acts as a massive, rigid block supported by a comparatively soft timber substructure.

The beam–column and base connections are characterized based on visual inspection and typical construction details observed in the Kirtipur core area. The connection between the plinth tie and column exhibits hinge-like behavior, while the beam–column joints display semi-rigid characteristics due to traditional joinery and pedestal support conditions. For analytical simplicity, the beam–column connections are modeled as rigid, and the base is assumed to be hinged.

In the analytical model, the one-storey timber frame is represented using frame elements, and the adjacent masonry walls are simulated using equivalent shell or shear elements. The total mass of the upper masonry storey is lumped at the beam level to evaluate the centers of stiffness and mass and the resulting eccentricity. Different plan configurations—parallel, L-shaped, and C-shaped—are analyzed by computing stiffness contributions from both timber frames and masonry walls, and torsional irregularity is assessed based on the eccentricity between the centers of stiffness and mass. The stiffness of the frame and wall elements is compared to determine relative load participation and to assess torsional vulnerability for each configuration.

Figure 3. The construction sequence of rest house in Kirtipur. (a) Construction completion of plinth tie and partial completion of side wall., (b) Errection completion of post with corbel, (c) Construction competion of the floor beam and (d) construction of floor joist

The construction sequence adopted in the construction of rest house is depicted in Figure 3. It is observed that the construction technique is similar to the load bearing wall structure construction in other heritage construction. The timber joint is mostly the carpentry with minimal application of other materials like metal plates, bolts etc. In the Figure 4a and b, the connection between the plinth beam and post is shown, the connection type is a mortis and tenon joint. This joint is considered to be flexible joint which does not fully resist moment. The lower tie beam can take axial load from the post and the lateral shear force during the earthquake. The Figure 5a, shows a dove tail joint connection type at plinth level which can only take tensile load and compression load along the axis of the tie member. The Figure 5b shows the cutout prepared for beam to beam connection using scarf connection which can resist partial axial, moment and shear force. Finally, Figure 5a and b show the column to beam connection in which a pedestal is provided below the beam which is used to transfer beam load to the post gradually concentrating at the post ends at top from beam. This type of connection is a unique type which not seen in any other country so far (Figure 6a). For our present work this type of joint is considered as a rigid joint. The load resisting characteristic of different joints can be observed in literature (Sobon, 2002).

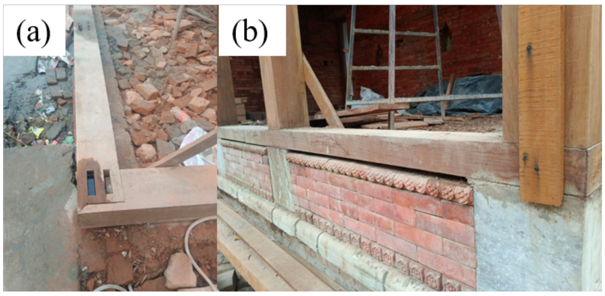


Figure 4. Timber joint (a) Groove in plinth fie for post connection (b) Plint tie beam to post connection

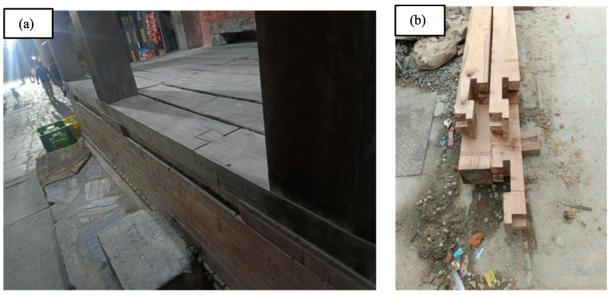


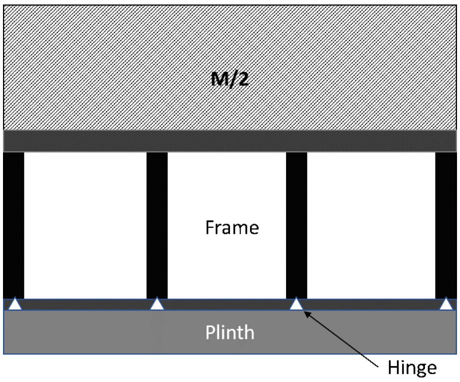
Figure 5. Timber joint (a) Dove-tail joint in plinth tie beam (b) Scarf joint preparation for floor beam

Simplified Stiffness Evaluation Approach

In order to understand the overall load-resisting behavior of the Nepalese rest house without resorting to a complete

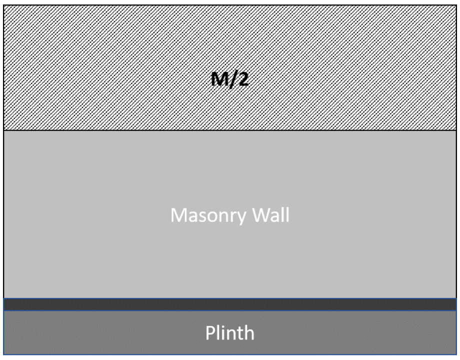
Figure 6. Timber joints (a) Beam post connection using bracket (b) Post dowel end observed in old demolished building

finite element model, the stiffness distribution of the structural system is evaluated using a simplified analytical approach. The plan dimensions are limited to a length-to-breadth (L/B) ratio not exceeding 2. The first-storey masonry walls are idealized as rigid structure, the timber frames are similarly represented as vertical bending elements connected by a stiff beam at the top, forming a system capable of resisting lateral loads through flexural action of the columns and the diaphragm stiffness of the beam. The base of the timber frame is assumed to be pinned, allowing rotation while restraining horizontal movement, whereas the beam–column connections are modeled as fixed, consistent with the semi-rigid yet continuous nature of traditional timber joinery observed in Nepalese rest houses (Figure 7 and 8).



$$K_{frame} = 4 * \frac{3E_f I}{h^3}$$

Figure 7. Frame stiffness along the in-plane direction



$$K_{wall} = \frac{1}{\frac{h_{eff}^3}{3E_m I_g} + \frac{h_{eff}}{A_v G_m}}$$

Figure 8. Wall stiffness along the in-plane direction

For this configuration, the lateral stiffness of an individual timber column is determined from classical beam theory as $k = 3EI/L^3$, where E denotes the elastic modulus of timber, I represents the second moment of area of the column cross-section, and L corresponds to the storey height. The masonry walls are modeled as planar shear panels, with stiffness expressed as a function of the shear modulus G, cross-sectional area, and wall height (Figure 8 and 9). Depending on the wall aspect ratio, the response is considered either shear-dominant or flexure-dominant, ensuring an appropriate estimation of the lateral resistance of each wall segment. Each wall and frame element is then assigned a representative stiffness and positioned at its centroidal location in plan. This representation enables the assembly of a plan-level stiffness model in which walls and frames act as discrete lateral springs connected through a rigid diaphragm at the floor level.

The global plan stiffness is computed by summing the stiffness contributions of all resisting elements along the principal directions. The center of stiffness (CS) is obtained as the stiffness-weighted centroid of the resisting elements, while the center of mass (CM) is defined based on the assumed uniform distribution of floor mass lumped at the beam level. The eccentricity between the CS and CM is calculated to assess potential torsional irregularity, as such eccentricity induces coupled translational and rotational responses under lateral loading. The torsional stiffness of each configuration is further evaluated by considering the rotational resistance of the equivalent spring system about its center, allowing estimation of the rotational response produced by lateral forces acting at the CM. This procedure provides a reliable measure of stiffness distribution and torsional response without the need for detailed numerical modeling, making it particularly suitable for traditional structures with complex material interfaces. Four plan configurations of the rest house are examined to evaluate the influence of wall layout on stiffness distribution. In most of the case the length of the rest house is large compared to the height of the building so, the failing mechanism is mostly due to in plane shear failure type (b) or type (a) as shown in the Figure 10.

The stiffness of the timber frame elements and masonry walls is calculated using material properties specified in Indian Standards, with a modulus of elasticity of 12,670 MPa for Sal wood (IS 883:2016) and 1,628 MPa for

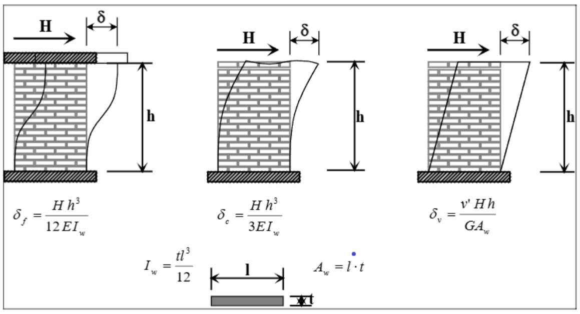


Figure 9. Force deformation cases in wall panel, left picture shows deflection of wall fixed at both ends, middle picture shows the moment deformation of free-standing wall and right picture shows the shear deformation of wall (Bosiljkov et al., 2005)

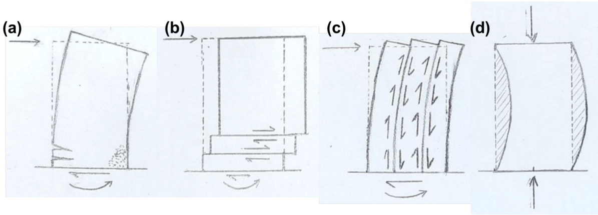


Figure 10. Failure mechanism of shear wall (a) flexural failure, (b) horizontal shear, (c) vertical shear, (d) buckling

M1 grade mortar and compressive strength of unit as 7.5MPa for masonry (IS 1905:1987) which align (range of E value) with the test conducted by (Vermeltfoort et al., 1993). Although traditional construction commonly uses mud mortar, and lime–surkhi mortar, field investigation confirmed use of cement mortar in the Kirtipur due to earthquake vulnerability. Using these material properties as input parameters in the stiffness equations, the stiffness contributions of the timber frame and the masonry wall are evaluated. The moment of inertia of a single timber post is calculated as $3.25 \times 10^8 mm^4$ with a storey height of 2,100 mm. For the masonry wall, the moment of inertia is $6.3 \times 10^1 2mm^4$, and the shear area is $2.1 \times 10^6 mm^2$. The shear modulus of masonry is obtained as $G_m = 678.33 N/mm^2$. Based on these values, the lateral stiffness of the timber frame is calculated as 5,344.15 N/mm, while the stiffness of the masonry wall is 242,261.9 N/mm. The ratio of frame stiffness to wall stiffness is therefore only 2.20%. This analysis indicates that the timber frame contributes very little to lateral load resistance compared to the masonry wall during an earthquake. Moreover, the pronounced stiffness irregularity significantly increases the seismic vulnerability of the building. It is observed that in all cases the eccentricity is very high, approximately 50% in X-direction (Case II) and 50% to 60% (in all cases). From above we found that the building re-constructed after Gorkha earthquake is most vulnerable in terms of stiffness irregularity in plan which will induce torsion during earthquake load in the future.

Table 1. Eccentricity calculation for different layout of wall in phalcha

Story	XCM (m)	YCM (m)	XCR (m)	YCR (m)	EccX (m)	EccY (m)
Case I	3	1.49	3.00	2.98	0.00	-1.49
Case II	3	1.49	5.97	2.98	-2.97	-1.49
Case III	3	1.49	3.00	3.40	0.00	-1.91
Case IV	3	1.49	3.00	3.30	0.00	-1.81

3. Findings

The analysis indicates that eccentricity values are significantly high in all cases, with approximately 50% eccentricity observed in the X-direction for Case II and ranging between 50% and 60% across all configurations. As presented in Table 1, the calculated eccentricities between the center of mass (CM) and the center of rigidity (CR) reveal pronounced stiffness irregularities arising from different wall layouts in the rest house. These results suggest that the building reconstructed after the Gorkha earthquake remains highly vulnerable to plan stiffness irregularity, which is likely to induce substantial torsional effects during future seismic events. The comparative stiffness analysis of masonry walls and timber frames in traditional Nepalese rest houses shows that lateral load resistance is predominantly governed by the masonry walls, while the contribution of the timber frame to overall structural stiffness is minimal, accounting for only about 2–3%. This significant stiffness imbalance leads to pronounced torsional irregularity, particularly in configurations with asymmetric wall layouts. Based on the calculated CM and CR coordinates, eccentricities vary considerably among the different cases. Case I (parallel wall and frame layout) exhibits moderate torsional irregularity in the Y-direction (EccY = –1.49 m). In contrast, Case II (L-shaped wall layout) demonstrates the largest eccentricities in both the X- and Y-directions (EccX = –2.97 m, EccY = –1.49 m), indicating a highly torsionally irregular configuration. Similarly, Case III (C-shaped wall layout) and Case IV (C-shaped layout with a partial cross wall) show increased eccentricities in the Y-direction (EccY = –1.91 m and –1.81 m, respectively), reflecting asymmetric stiffness distribution and heightened torsional vulnerability.

4. Conclusion

The findings confirm that traditional Nepalese rest houses constructed using mixed masonry–timber systems are highly sensitive to plan irregularities and stiffness imbalances. Such characteristics significantly increase the potential for torsional response under seismic loading. To mitigate these effects and enhance seismic performance, improvements in diaphragm continuity, increased rigidity of timber joints, and the adoption of more symmetric wall configurations are recommended. For more accurate assessment, future studies should focus on detailed analysis of timber joints and the interaction mechanisms between masonry and timber components. Laboratory-based experimental testing and shake-table studies under dynamic loading conditions are essential to capture realistic structural behavior. Furthermore, comprehensive structural analyses supported by experimental validation are necessary to accurately evaluate the capacity and seismic demand of these structures, thereby contributing to improved seismic resilience and long-term structural stability.

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