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A comprehensive review on structural behavior and mechanical performance of traditional timber joints in Patan durbar square

Manish Aryal* , Sanket Koirala , and Shyam Sundar Khadka

Department of Civil Engineering, Kathmandu University, Dhulikhel, Kavre, Nepal.

Abstract

Traditional timber construction represents a critical element of Nepalese architectural heritage, integrating cultural craftsmanship with essential structural design. As Nepal lies within a highly seismically active region, the performance of timber joints, which connect primary structural members, becomes paramount, since joint failure frequently precipitates the collapse of entire buildings. This review systematically examines various traditional timber joints employed in the Patan Durbar Square area, including lap, scarf, finger, tongue-and-groove, mortise-tenon, and timber-masonry connections, synthesizing current research on their structural behavior. Non-destructive on-site observations within Patan revealed a predominant reliance on half-lap joints for beam lengthening, stop-bladed scarf joints with pegs to prevent longitudinal slippage, occasional finger joints in columns due to material constraints, and tongue-and-groove joints used where beam depths required adjustment. A critical finding from the inspection is the pronounced lack of uniformity in joint dimensions and geometries; rather than adhering to standardized engineering principles, these connections were crafted according to immediate construction needs and the available timber sizes. This inherent variability suggests that the joints were conceived primarily to facilitate construction and sustain vertical loads, not to resist the complex, multidirectional forces generated by seismic events. Consequently, while these traditional interlocking geometries perform adequately under gravity loads, they often lack the requisite stiffness, strength, and reliability to withstand strong ground shaking. Experimental data corroborate that the bending capacity of such jointed members is only a fraction (often less than 30-40%) of that of solid timber beams, rendering them particularly vulnerable in high-moment regions. A thorough understanding of these geometric irregularities and mechanical limitations is therefore indispensable for engineers and conservators aiming to preserve these heritage structures while enhancing their resilience against future earthquakes through informed, scientifically-grounded retrofitting strategies.

Keywords: Traditional timber joints; Heritage timber structure; Scarf joint; Finger joint.

1. Introduction

Nepal is located in a highly seismically active region of the Himalayas, and major earthquakes in 1934, 1988, and 2015 have highlighted the vulnerability of many traditional buildings [1]. In the historic urban centers and heritage zones of Kathmandu, Patan, and Bhaktapur, traditional Nepalese construction relied heavily on timber, which was central to both structural framing and architectural detailing [2]. Timber beams, joists, trusses, pegs, corner posts, interlocking joints, and floor systems worked together with load-bearing brick walls to create the characteristic timber masonry composite common in Newari architecture, which strengthens the overall structure [2, 3]. These features gave buildings flexibility, allowing walls and floors to move slightly, which helped them stay stable during earthquakes [3]. Buildings without this timber joinery were much more likely to suffer wall failures and collapse in the 2015 Gorkha earthquake [3]. These joinery systems are not only structural devices but also a key part of the aesthetic and cultural identity of the buildings [4].

Patan Durbar Square (See Fig. 1), a major cultural and tourist site in Lalitpur, lies southeast of Kathmandu along the Bagmati River. Known as the "city of artists" for its temples and intricate carvings, the area was historically the Malla royal palace. Lalitpur covers about 16.4 km² and relies significantly on tourism [5]. The Kathmandu Valley hosts many heritage buildings that require restoration, necessitating reliable conservation methods applicable beyond World Heritage Sites. Sal (Shorea robusta) timber is the primary structural material. Although moderately decay-resistant, its service life can be shorter than the age of existing structures, and water ingress due to roof damage often leads to significant deterioration, highlighting its vulnerability to moisture [6].

Figure 1: Patan durbar square [7].

Preserving cultural heritage is a global priority, yet in Nepal, the rehabilitation of historical monuments has often been conducted without a comprehensive damage assessment. A recent study of the Laxmi Narsingha temple addressed this by performing a de-

*Corresponding author. Email: aryalmaneesh@gmail.com

tailed seismic fragility assessment. Researchers employed two finite element models, one incorporating masonry-timber interface behavior and one without, to conduct pushover analyses and evaluate cracking patterns, failure mechanisms, and structural response. The interface model indicated higher vulnerability and a greater probability of exceeding key performance thresholds. Parametric evaluations revealed the temple's response is highly sensitive to masonry property variations, highlighting the need for refined analytical methods to accurately simulate failure in Nepalese pagoda structures [8].

Timber's contribution to the structural integrity and lifespan of traditional Nepalese buildings has been highlighted in several studies [2]. However, many of these structures are hybrid systems combining timber floors or frames with unreinforced brick masonry (URM) walls [9]. A foundational study on the seismic performance of traditional URM buildings with timber floors concluded that many are highly vulnerable to future earthquakes, with loosely connected timber floors reducing diaphragm rigidity and impairing structural action under lateral loading. The study recommended improving floor rigidity to enhance seismic performance [10]. Similarly, a recent study on dry stone/masonry buildings reinforced with timber bands showed a 45-50% increase in base-shear capacity compared to unreinforced models, highlighting timber's potential to improve lateral load resistance and energy dissipation [11, 12].

Finite-element analyses of timber joints reveal that geometry, contact behavior, and connector arrangements significantly affect stiffness and capacity [13]. International studies confirm that even well-crafted scarf joints typically achieve only about one-third of the bending-moment capacity of solid timber, with failures often due to tension perpendicular to grain and block shear [14]. These findings underscore the critical role of joint-level behavior in the seismic performance of timber and hybrid timber-masonry structures.

Nepal presents a unique scenario with its rich tradition of masonry-timber architecture and frequent seismic events [4, 10, 15]. However, research on the actual behavior of traditional timber joints under seismic loads remains limited, creating a significant gap given that ductility, energy dissipation, and failure mechanisms of joints are key to seismic resilience [16, 17].

Several review studies emphasize that traditional timber joinery plays a decisive role in structural behavior and seismic response [18, 19, 20]. A comprehensive review of carpentry connections notes that interlocking wood-to-wood joints govern stiffness and load transfer but remain outside modern design codes due to geometric variability [18]. Other reviews highlight that joint deformation often dominates structural response under lateral loading, making accurate modeling essential for seismic assessment [19, 20]. Collectively, these studies (See Table 1) identify a persistent gap between standardized engineering approaches and the irregular, site-specific joinery found in heritage structures, reinforcing the need for joint-focused structural evaluation in conservation practice [18, 19, 20].

1.1. Motivation and aim of the study

The historic structures of Patan Durbar Square embody a rich tradition of Newari craftsmanship, with timber joinery serving as a critical yet vulnerable component of their seismic resilience. The 2015 Gorkha Earthquake starkly revealed the susceptibility of these traditional connections to failure, underscoring an urgent need to move beyond purely aesthetic conservation toward an engineering-informed understanding of joint behavior. Unlike modern standardized systems, the joints in Patan were crafted adaptively, based on available timber dimensions and immediate site needs, resulting in geometries that are highly variable and poorly represented in contemporary design codes. This variability complicates the prediction of structural performance during seismic events. Furthermore, the primary structural timber, Sal (Shorea robusta), faces degradation from moisture ingress and biological decay, threatening long-term integrity. There is a pressing need to synthesize dispersed research and on-site observations into a coherent technical foundation to guide the conservation and retrofitting of Nepal's timber heritage.

The aim of this study is therefore to conduct a structured review of the structural behavior and mechanical performance of traditional timber joints in Patan Durbar Square. This review seeks to bridge the gap between historical construction practices and modern structural engineering principles. Specifically, it aims to identify and categorize the primary joint types, examine their load-transfer mechanisms and failure modes under vertical and lateral loads, evaluate their documented seismic resilience, and highlight technical gaps in current knowledge to propose a framework for scientifically grounded, heritage-sensitive conservation strategies.

Despite existing research, significant knowledge gaps remain: insufficient experimental work on native Nepalese joints, inadequate behavioral models for semi-rigid connections, scarce data on local timber properties, and a lack of full-scale timber-masonry composite testing. Additionally, retrofit methods, including diaphragm stiffening, improved wall-floor anchorage, and reversible joint enhancement, require systematic evaluation. Literature confirms that traditional Nepalese construction heavily relies on semi-rigid, flexible timber joints, but weak connections and low diaphragm stiffness remain primary sources of seismic vulnerability [10], underscoring the need for focused study on diaphragm behavior, joint stiffness, wall-floor interaction, and advanced modeling.

Furthermore, a critical disconnect exists between laboratory analysis and on-site construction practices. While studies extensively evaluate joint performance using standardized, optimized dimensions [27, 28, 29], there is a profound lack of documentation on "on-site required dimensioning", where joint sizes are dictated by material constraints like available timber logs, irregular beam depths, and specific site geometries, rather than pre-engineered codes. Current research rarely addresses how carpenters adapt joint dimensions when available timber deviates from ideal sizes. Consequently, no engineering framework correlates these "as-built" dimensions with modern predictive failure models, leaving engineers without standardized guidance to assess the safety of irregularly dimensioned joints in heritage restoration.

1.2. Novelty of the study

The novelty of this study lies in its systematic synthesis of non-standardized carpentry practices found in Patan Durbar Square with modern structural engineering principles. While existing literature extensively documents standardized engineered timber like Glued Laminated Timber (GLT) and Cross-Laminated Timber (CLT), these studies often assume uniform material properties and geometric consistency. This review provides a novel perspective by addressing the "construction-led" design philosophy of Newari joinery, where joint dimensions were historically dictated by the unique geometry of available Sal (Shorea robusta) timber rather than pre-defined engineering codes.

Furthermore, this work introduces a focused evaluation of timber-masonry interfaces and complex lengthening joints, such as the stop-bladed scarf joint, specifically within the high-seismic context of the Kathmandu Valley. Unlike prior research that typically investigates isolated joints in a laboratory setting, this study correlates observed on-site variations in Patan with documented failure mechanisms like splitting and embedment found in contemporary research. By identifying the technical gaps between traditional "site-fit" joinery and modern "design-led" connections, this

Table 1: Summary of review studies on timber joints and connection systems (2005-2025).

Year	Study Area	Scope / Relevance
2011 [21]	State of the art on timber-concrete composite structures: Literature review	Review of timber-concrete composite systems with focus on shear connectors and connection mechanics
2021 [20]	Designing timber connections for ductility - A review and discussion	Review of ductility, energy dissipation, and seismic performance of timber connections
2023 [18]	A state-of-the-art review of carpentry connections: From traditional designs to emerging trends in wood-wood structural joints	Comprehensive review oftraditional and modern wood-to-wood carpentry joints
2023 [22]	Design for adaptability, disassembly, and reuse - A review of reversible timber connection systems	Review of reversible and demoun timber connections, including interlocking joints
2023 [23]	Screw connection systems in timber-concrete composite structures: A literature review	Review of mechanical timber connection behavior and performance
2023 [23]	Review of timber connection design in Australia	Review of research trends and design practice for timber connections
2024 [24]	A state-of-the-art review on connection systems, rolling shear performance, and sustainability assessment of cross-laminated timber	Review of CLT connection systems and rolling shear behavior
2025 [25]	Adaptation of connection systems for integration with engineered wood products in buildings: A systematic review	Systematic review of timber connection systems and classification methods
2025 [26]	Review of long-term performance of timber-concrete composite beams	Review of long-term behavior and performance of timber connections

study offers an original framework for the development of scientifically grounded, site-specific conservation strategies for Nepalese heritage structures.

This paper helps bridge the gap between on-site non-destructive observations and published mechanical data, which creates a new "hybrid" understanding of how Patan's structures actually function.

1.3. Research data

Comprehensive research into the material and joint performance of Nepalese timber systems remains limited, but the available studies provide essential quantitative frameworks for analysis. Beyond the specific strength values and capacities documented in detailed studies, broader characterizations of timber joint behavior have been established through international research. For example, the performance of mechanical joints exhibits pronounced nonlinearity, with the ultimate load often significantly exceeding the proportional limit by substantial margins [30]. This underscores the complex load-deformation relationship inherent to timber connections.

Furthermore, the long-term integrity of these systems is governed by environmental durability, with factors such as adhesive selection proving critical to joint longevity under harsh conditions [31]. These foundational insights on nonlinearity and durability complement the quantitative data summarized in the Table 2, together forming a more complete picture necessary for the structural assessment and conservation of Nepal's timber heritage.

1.4. Methodology

This study employed a structured review methodology to investigate the structural behavior of traditional timber joints in Patan Durbar Square. The objectives were to systematically compile existing knowledge on Nepalese timber joinery, identify literature pertinent to joint-level structural performance, and synthesize the findings to highlight current research gaps and their implications for conservation and engineering practice.

The literature search encompassed major academic databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar, along with institutional repositories. To capture region-specific studies often absent from international databases, the search was extended to include theses, conference proceedings, and technical reports. Relevant Nepali sources, such as the Tribhuvan University e-Library and proceedings from Nepalese engineering institutes, were also consulted. Targeted keywords and Boolean combinations were employed, including ("Nepal" OR "Patan Durbar Square" OR "Kathmandu"), "Traditional timber joints" OR "carpentry joints", specific joint types such as "Lap Joint" OR "Interlocking Joint" OR "scarf joint" OR "mortise-tenon" OR "tongue-and-groove" OR "finger joint", "Nepalese timber architecture" OR "Newari timber structures", and performance terms like "Seismic performance" OR "energy dissipation" OR "structural behavior". These terms were strategically combined using AND/OR operators to maximize relevant results. Furthermore, due to the limited formal research on Nepalese joinery, grey literature such as post-earthquake assessment reports, heritage conservation guidelines, and engineering documentation was also systematically reviewed to ensure comprehensive coverage of the subject.

Publications from 1994 to 2025 were considered, covering both foundational historical studies and recent research on timber mechanics, heritage structures, and modern experimental investigations. Studies were selected if they provided quantitative or qualitative data on mechanical behavior and failure modes of traditional timber joints, experimental or analytical investigations of joint performance, seismic or lateral load behavior of timber-framed or timber-masonry structures, or material properties of Nepalese timber species used in heritage structures. The search excluded non-structural or decorative carpentry studies, literature solely focused on modern engineered wood products without traditional relevance, and inaccessible non-English publications. This systematic approach facilitated the inclusion of pertinent local and international literature, establishing a comprehensive basis for synthe-

Table 2: Summary of the mechanical properties from past research

Focus Area / Research Areas	Mechanical Properties
Evaluation of mechanical and physical properties of timber available in Nepal [15]	Sal (Shorea robusta) compressive strength: 37.45 MPa (parallel), 3.2 MPa (perpendicular); tensile strength: 20 MPa.
Performance of timber joint system used in traditional monuments of Bhaktapur [32]	Plain scarf joint tensile strength: 8.40 N/mm²; tenoned scarf: 5.82 N/mm²; cross-lap joint shear: 14.99 N/mm²; column compression: 49–56 kN.
Cyclic behavior of mortise-tenon joints reinforced with metal dampers [16]	Enhanced energy dissipation and cyclic stiffness; improved rotational resistance with metal reinforcement.
Stiffness of scarf joints with dowels [33]	Dowel reinforcement increased joint stiffness by 15–25%; failure modes: embedment or block shear.
Experimental investigation of timber beams with splice and scarf joints [13]	Scarf and splice joints achieved ~30–35% of full bending capacity; stiffness reduction due to contact behaviour.
Historical scarf and splice c arpentry joints: State of the art [27]	Documented ultimate loads and bending moments of historical joints; provided performance comparison between joint types.
Lateral resistance and restoring force model of timber frames with traditional joints [34]	Mortise-tenon frames with reinforcement show 20–40% higher lateral resistance; hysteresis loops exhibit the pinch effect.
Behaviour of traditional wood joinery under monotonic and cyclic loading [19]	Joints exhibit semi-rigid response and carry up to 60–70% of member strength under cyclic loading.
Durability of structurally bonded timber joints [31]	Environmental factors (moisture, adhesive type) reduce joint performance by 10–30% over time.
Performance evaluation of traditional timber joints under cyclic loading [35]	Gap size and tightness significantly affect stiffness and energy dissipation; reinforced joints dissipate 1.5–2× more energy.

sis, comparison, and identification of research gaps.

2. Literature review

The structural behavior of traditional Nepalese buildings is fundamentally linked to their hybrid timber-masonry composition and the performance of their joinery systems. Experimental research on traditional connections such as scarf, tenon-scarf, and cross-lap joints has generated essential data on load-deformation, failure modes, and capacity, revealing a frequent lack of sufficient axial resistance, which can lead to structural vulnerabilities like floor-beam pull-out during seismic events [32]. The architecture of the Kathmandu Valley relies on this hybrid system, where timber elements form floors and roofs but typically lack the in-plane rigidity to function as effective diaphragms. This often results in flexible diaphragms and poor wall-floor anchorage, which has historically contributed to failures such as out-of-plane wall collapse during earthquakes, highlighting systemic weaknesses at timber-masonry interfaces [4, 10, 36].

The seismic vulnerability of these structures is exacerbated by the complex, semi-rigid behavior of their traditional carpentry joints. Unlike modern engineered systems, the performance of these joints is highly dependent on geometry, contact conditions, friction, and environmental factors like moisture-induced shrinkage, which can critically reduce stiffness and load-transfer efficiency [19, 28, 37, 38, 39]. The response of these buildings under lateral loads is therefore not dictated by member strength alone but is governed by joint detailing and the overall interaction between flexible diaphragms, semi-rigid connections, and masonry walls [19].

Advanced research has further reinforced the necessity of detailed joint modeling for accurate seismic assessment. Studies on various joint types, from dovetail and mortise-tenon to finger joints, confirm that their geometry and contact conditions are primary drivers of global structural behavior, influencing energy dissipation, displacement capacity, and damage distribution [40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50]. These findings affirm that a precise understanding of joint-level mechanics is indispensable for evaluating the seismic resilience of Nepal's timber heritage.

Furthermore, environmental exposure presents a significant long-term threat to structural integrity. Fluctuations in humidity and temperature cause cyclical shrinkage and swelling in timber, leading to gap formation at joint interfaces, reduced stiffness, and accelerated degradation of mechanical properties [28, 29, 37, 38, 39, 51, 52, 53]. This environmental degradation not only weakens individual connections but also alters global load paths and diaphragm action, compounding seismic vulnerability. Consequently, accurate seismic evaluation and conservation of these historic structures require modeling approaches that account for both the semi-rigid nature of traditional joints and the cumulative effects of environmental exposure [28, 37, 38].

2.1. Performance of joints

2.1.1. Lap and interlocking joints (including cross-lap joints)

The performance of lap and interlocking joints is critical to understanding the bending behavior of traditional timber flexural elements. Research indicates these connections exhibit distinct mechanical characteristics and failure mechanisms that directly influence the overall capacity and stiffness of jointed beams, providing essential insight for structural assessment and retrofitting strategies [35, 54].

2.1.2. Scarf joints and their variations

Scarf joints represent a principal method for beam lengthening in traditional construction. Their design, particularly when incorporating pegs or cogs, is aimed at controlling slippage and maintaining contact, with performance heavily dictated by geometric configuration rather than the quantity of connectors [27, 33, 55]. Understanding these design principles is vital for evaluating the in-situ performance of historical structures [56].

2.1.3. Finger joints

While unconventional in vertical load-bearing members, the use of finger joints in heritage structures reflects historical material constraints. The structural adequacy of these joints is contingent

Table 3: Joint performance summary

Joint Type / System	Properties/ Parameters Studied	Key Findings	Study Limitations
Lap & Interlocking Joints (Cross-lap, halved)	Bending capacity, stiffness reduction, failure modes, dowel/peg effects	Jointed beams achieve 27-42 % of solid beam bending capacity; dowels improve capacity; failures by shear, splitting [13, 27, 35, 54]	Standardized lab dimensions; softwood species; no site-specific sizing
Scarf Joints (stop-bladed, stop-splayed, pegged)	Tensile resistance, bending capacity, dowel/peg influence, contact behavior	Typically, 30-35 % of solid beam capacity; geometry more influential than number of pegs; failures by block shear and tension perpendicular to grain [13, 14, 27, 33, 55]	Focus on idealized geometry; little linkage to historic construction constraints
Finger Joints	Bending strength, compression capacity, fire/thermal behavior	Properly manufactured finger joints retain >80 % of member capacity; performance depends on workmanship and bonding [48, 55]	Modern engineered joints; adhesive-based systems unlike historic practice
Tongue-and-Groove Joints	Shear capacity, stiffness, tongue-length effect, cyclic response	Higher stiffness than lap joints; larger contact area improves load transfer; enhanced with modern fasteners [57, 58]	Studies focus on furniture or CLT panels, not heritage beams
Mortise-Tenon Joints	Moment-rotation behavior, cyclic stiffness, energy dissipation	Semi-rigid, nonlinear response; significant energy dissipation after gap closure; failures by mortise cracking or tenon pull-out [43, 44, 45, 46, 49, 50, 59]	Asian case studies; limited masonry interaction
Timber-Masonry & Diaphragm Connections	Interface friction, diaphragm stiffness, and wall-floor interaction	Flexible diaphragms and weak anchorage cause wall separation/collapse; improved anchorage enhances seismic response [9, 10, 39, 60]	Rarely include traditional joints or moisture effects

upon precise manufacturing and adhesive quality, with performance characteristics that must be carefully evaluated within a conservation context [55, 61].

2.1.4. Tongue and groove joints

Tongue-and-groove joints provide an effective means for depth adjustment and shear transfer in timber assemblies. Their mechanical advantage stems from increased bearing area, and their performance can be significantly enhanced with modern reinforcement, offering relevant insights for both historical analysis and contemporary strengthening [57, 58].

2.1.5. Mortise-tenon joints

Mortise-tenon joints are fundamental to the seismic response of traditional timber frames, acting as semi-rigid, nonlinear connections. Their behavior under cyclic loading, characterized by energy dissipation and controlled stiffness degradation, is a key factor in the global seismic performance of heritage structures [49, 59].

2.1.6. Timber to masonry interface joints

The interface between timber elements and masonry walls is a critical yet vulnerable detail in hybrid construction. The performance of this connection under lateral loads significantly influences overall stability, and retrofit strategies focused on improving anchorage are essential for enhancing seismic resilience [9, 60].

3. Case study

While studying timber structures and their joints present in Patan Durbar Square, samples were mostly from monumental buildings, including temples and museums, while commercial buildings made of timber were also observed.

3.1. Lap and interlocking joints (including cross-lap joints)

One of the most common joints between beams for lengthening or intersection is the Lapping joint. In the lengthening joint, a half lap joint is seen, whereas in the intersection at corners, a cross lapping joint is seen (See Fig. 2).

Figure 2: Temple at Swotha square with half lap joint on beam and finger joint on column

Half-lap joints were most commonly used in locations where the beam length was insufficient. Observations indicate that these

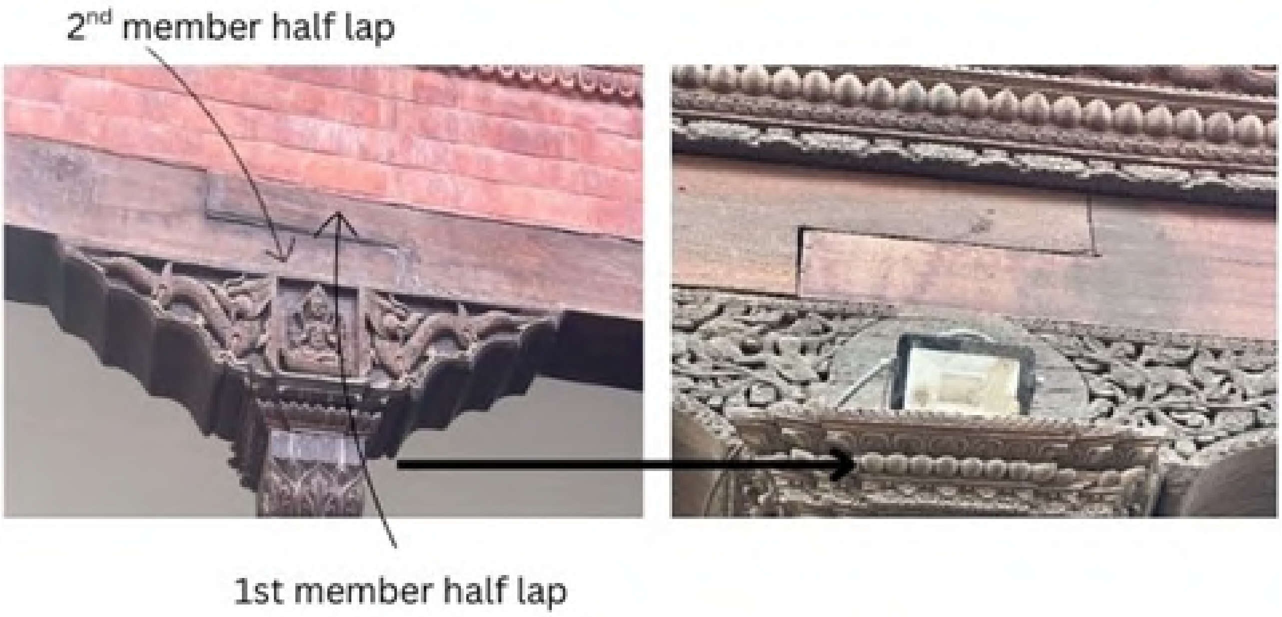

Figure 3: Half lap joint at commercial and traditional buildings of Patan

joints were generally positioned just above the columns, likely because the beams in these locations act as simply supported members and do not require highly resilient joints. The length of the half-lap joints appears to vary, ranging from less than the beam depth up to approximately three times the beam depth (See Fig. 3). The use of additional elements such as wedges, pegs, or dowels in the vertical direction could not be confirmed due to limited visibility, as no destructive inspection was performed. Lap joints are suitable for axial and shear transfer but offer low rotational stiffness.

Cross-lap joints were also frequently observed, primarily along the edges of the building, where main beams intersect and at locations where secondary beams supporting slab elements meet the main beams. In these joints, half the depth of each beam overlaps with half the depth of the adjoining beam, as the depth of the main beams is seen same in both directions. Cross-lap joints at building perimeters likely help maintain alignment of structural grids but provide limited moment resistance.

Figure 4: Mini Krishna temple with scarf joint

3.2. Scarf joints and their variations

Scarf joints, especially stop-bladed scarf joints with pegs, are the most common type of joint seen for lengthening the beam (See Fig. 4).

The joint appeared in the mini-Krishna Temple, just above the column for lengthening purposes. The key advantage of this joint type is that the peg effectively prevents slippage of the beam along its longitudinal axis. However, the presence of the cog cannot be reliably confirmed through non-destructive visual inspection. If the cog were absent, the peg would not be strictly necessary, as the joint could be assembled by sliding the beam in from the transverse direction. Based on these observations, the joint is most likely a stop-bladed scarf joint incorporating both a cog and a peg (See Fig. 5). Alternatively, the peg may have been included simply to compensate for irregularities or slight mismatches in the length of the joint. The total length of each joint appears to be approximately equal to the depth of the beam or slightly longer, with the insertion length being less than one-third of the beam depth.

Figure 5: Stop bladed scarf joint with peg

3.3. Finger joints

The column is one of the most important load-carrying members in a structure, and joints are usually avoided as much as possible. Using joints in columns can reduce their strength or create weak points, so builders generally try to use continuous members. However, in this case, a few joints can still be seen in the column, and most of them appear to be finger joints. Their presence suggests historical constraints in procuring long timber sections.

From observation, the depth of each finger appears to be roughly equal to the full width of the column, while the width of each finger is approximately one-third of the column's width (See Fig. 6). Such joints allow vertical load transfer through interlocking shear

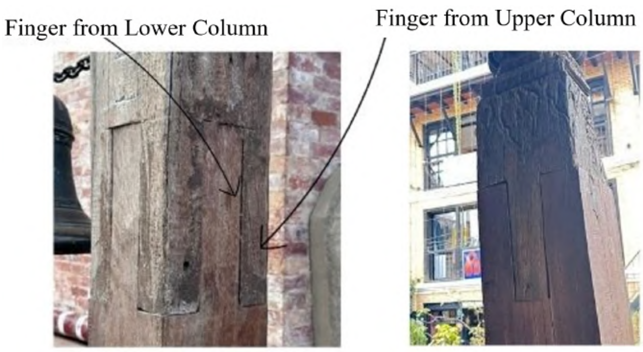

Figure 6: Various finger joints type in column.

surfaces, but they can be highly sensitive to tension-perpendicular-to-grain failures.

3.4. Tongue and groove joints

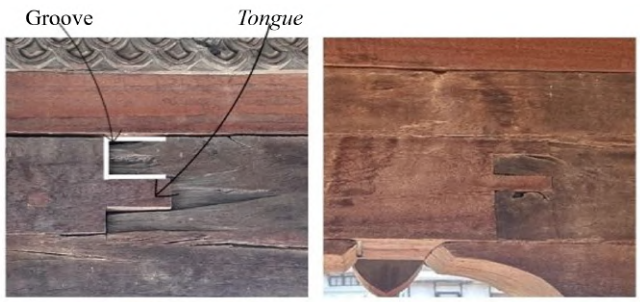

Figure 7: Tongue and groove joint

These beam joints were most commonly observed at locations where a reduction in beam depth occurred, and the remaining depth was compensated for by an additional inserted element (See Fig. 7). Although such joints appeared in multiple beams throughout the structure, their dimensions and proportions were not consistent enough to allow for systematic classification. Variations in depth, overlap, and detailing suggest that these joints were likely crafted to suit local construction needs or material availability rather than following a standardized pattern.

3.5. Mortise tenon joints

The joint is most common between the floors of load load-bearing structure, working as a band as well as a beam where the secondary beams of the floor are resting (See Fig. 8).

Although the joint appeared to be a simple butt joint, the presence of a mortise-tenon was revealed during movement of the joint during an earthquake. Tenon dimensions could not be measured, but movement patterns indicate that the joint provides partial rotational restraint. The existence of a wedge in the vertical direction could not be confirmed, and the length of the tenon could not be measured due to limited accessibility. These joints were commonly seen in the beam above the masonry of the building, and were rarely seen in the temples or monuments (See Fig. 9).

Figure 8: Mortise tenon joint appeared on the historic building of Patan durbar square

Figure 9: Mortise tenon joint

3.6. Timber to masonry interface joints

This joint type is found most commonly where the beams are resting on the masonry directly, but are not present when the beams are resting on a column, so mostly common on load-bearing structures (See Fig. 10).

A wedge was employed by inserting it into a hole made in the beam at the surface of the wall. This arrangement effectively prevents the beam from moving along its longitudinal axis, ensuring stability and restricting undesired slippage. In traditional Nepalese buildings, the performance of timber-to-masonry joints depends on the flexibility of timber connections and the limited tensile and shear strength of masonry (See Fig. 11).

4. Discussion

Limited field observations at Patan Durbar Square were conducted non-invasively through visual inspection, photography, and condition notes, without dismantling the structures. Consequently, certain joint details were inferred from accessible sides, introducing some assumptions. Despite these limitations, the study highlights the diversity of traditional timber joints in Nepalese vernacular architecture and provides valuable insights into their structural behavior and failure mechanisms. Observed joints reflect adaptation to local construction constraints, available timber lengths, and expected load paths, aligning with trends documented in experimental literature on historical timber joints.

4.1. Strength and stiffness characteristics

Half-lap and cross-lap joints were commonly used for beam lengthening or intersections. Experimental studies show that unreinforced lap joints achieve only 27-42% of the bending capacity of continuous beams, failing due to joint loosening, fibre delamination, tension cracking near fasteners, and interface compression

Figure 10: Timber to masonry interface joint

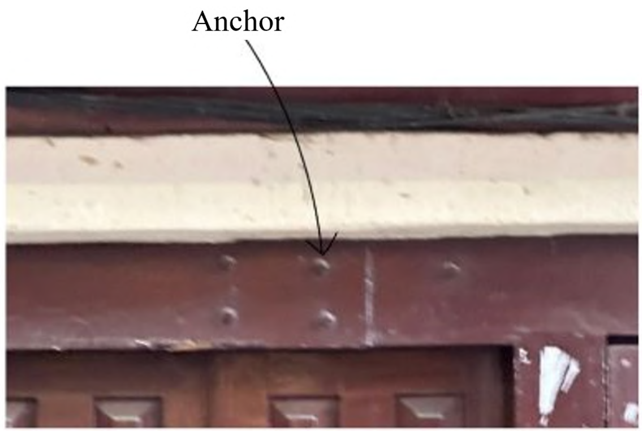

Figure 11: Modern joint with anchor dowel

cracks [54]. Introduction of wooden dowels or bolts improves performance to 65-75% of the continuous beam capacity [35]. These findings indicate that while historical lap joints in Patan provided adequate axial and shear transfer, reinforcement, whether historical or modern, enhances flexural capacity and reduces stress concentrations.

Stop-bladed and stop-splayed scarf joints, often equipped with pegs, effectively prevent longitudinal slippage and maintain joint contact. Quantitative studies confirm that scarf joints typically retain 25-40% of the bending capacity of unjointed beams, depending on joint geometry and reinforcement [13, 14]. Stiffness degradation occurs early due to localized crushing and slip at contact surfaces, emphasizing that scarf joints act as deliberate structural weak points to maintain continuity rather than strength.

Mortise-tenon joints, frequently found above masonry, provide partial rotational restraint and exhibit semi-rigid behavior under lateral loading. Experimental studies indicate that traditional mortise-tenon joints display higher rotational stiffness at small deformations (15-35% of rigid connections) and exhibit energy dissipation under cyclic loading, with damping ratios of 10-20% [16, 19]. Such performance explains why structures employing these joints often show reduced seismic damage despite lower nominal strength.

Finger joints, observed occasionally in columns due to timber procurement constraints, and tongue-and-groove (T&G) joints, used to accommodate reduced beam depths, show adequate load-bearing and shear transfer when carefully executed [48, 57, 58, 61]. Modern reinforcement, including self-tapping screws, dowels, or bolts, can significantly enhance stiffness and load-bearing capacity without compromising historical authenticity.

4.2. Deformation capacity and energy dissipation

Cyclic loading tests underscore that mortise-tenon joints outperform scarf and finger joints in rotational capacity, often sustaining rotations of 0.04-0.06 rad before strength loss, whereas scarf joints typically fail below 0.02 rad due to grain splitting [13, 27, 59]. Half-lap and dovetail joints exhibit intermediate behavior, with dovetail joints sustaining 30-40% higher displacement than half-lap joints [57]. These deformation capacities, combined with hysteretic energy dissipation, explain the enhanced seismic resilience of timber structures with flexible traditional joints.

4.3. Environmental degradation effects

Environmental factors significantly influence joint performance. Prolonged moisture exposure reduces joint stiffness and strength by 10-30%, affecting both adhesive and bearing-dominated joints [15, 31]. Aging-related micro-cracking and repeated low-amplitude loading further reduce effective stiffness and increase slip, highlighting the importance of considering in-situ conditions for conservation assessments [30, 55].

4.4. System level implications

At the structural level, joint flexibility alters global response. Numerical studies indicate that realistic joint stiffness values, often 30-50% lower than idealized rigid assumptions, reduce seismic force demand while increasing displacement capacity [30]. Similar effects are observed in masonry buildings with timber bands and frames, where flexible timber connections reduce wall out-of-plane failure and crack widths by 20-40% [10, 11]. Collectively, these findings support the view that traditional joints act as controlled deformation zones, where limited individual strength is offset by ductility and energy dissipation across the system.

The combined observational and quantitative evidence demonstrates that different joint types serve distinct mechanical functions: scarf joints maintain continuity with limited strength, mortise-tenon joints act as ductile rotational hinges, and pegged or dowelled joints enhance stiffness while preserving deformation capacity. However, most quantitative studies are based on standardized specimens, whereas joints in Patan Durbar Square exhibit non-uniform geometries, variable timber quality, and long-term environmental exposure.

There remains a critical need for site-specific quantitative testing that incorporates degradation effects, which would refine assessments of residual strength and ductility. Such data would improve the reliability of seismic evaluation and guide conservation strategies for historic timber structures, balancing structural safety with preservation of traditional construction techniques.

5. Conclusion

Traditional timber joints are a defining element of Nepal's architectural heritage, integrating cultural craftsmanship with essential structural roles. In the seismically active Kathmandu Valley, particularly Patan Durbar Square, these connections are critical to building performance, with failure often leading to systemic collapse.

This study combined a structured literature review with non-destructive field observations to evaluate joint behavior. While limited by the non-invasive approach, the investigation clarified the diversity, detailing, and functional roles of joints such as half-lap, scarf, finger, tongue-and-groove, mortise-tenon, and timber-masonry interfaces.

Field and experimental data show that these joints were adapted to material and site constraints, providing adequate axial and shear transfer but limited moment capacity. For instance, scarf joints exhibit only about 12% of the bending strength of solid timber, highlighting seismic vulnerability. Mortise-tenon joints offered some ductility, while timber-masonry connections relied on wedges or anchors for stability.

Overall, traditional joints reflect a construction-led design rather than a standardized engineering approach. Their performance under vertical loads is often sufficient, but many remain vulnerable to high bending and seismic demands. Future conservation must prioritize detailed joint-level assessment, scientifically informed reinforcement, and further research into diaphragm action, timber-masonry interaction, and local material properties, ensuring both seismic resilience and heritage preservation.

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