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Retrofitting of Buildings in Cyclone Prone Areas at Thanjavur District, Tamil Nadu, India

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Abstract - Cyclones pose a significant threat to rural housing in coastal regions of Tamil Nadu, particularly in the Thanjavur district. This study investigates the vulnerability of different building typologies-non-engineered, semi-engineered, and engineered structures-to cyclonic hazards through field surveys conducted in Mallipattinam and Pudhupattinam villages. The research reviews relevant literature on cyclone damage assessment, reliability-based structural design, and cost-effective retrofitting techniques, highlighting importance of both scientific and local approaches to disaster resilience. The study also examines Indian codal provisions (IS 875, IS 15498, IS 15499) for cyclone-resistant construction. Field data reveal that non-engineered houses, often built with thatch and mud without proper foundations, are highly susceptible to wind and flood damage, resulting in major structural failures. Semi-engineered buildings, while incorporating some engineered elements, still exhibit vulnerabilities due to weak connections and partial reinforcement. Engineered structures, designed and supervised according to IS codes, demonstrate greater resilience but may still suffer from issues such as wall cracking if construction quality is compromised. The analysis emphasizes the need for targeted retrofitting-such as improved roof anchorage, reinforced walls, and better drainage systems. The study concludes that multi-pronged approach involving adoption of cost-effective, locally adaptable construction techniques is essential to mitigate cyclone risks and safeguard rural livelihoods in vulnerable coastal zones.

Keywords - Cyclone, Rural housing resilience, retrofitting, IS codal provisions, structural failure mechanism.

1. INTRODUCTION

Cyclone-prone coastal regions, exemplified by the repeated impact on Pattukkottai Taluk at Thanjavur district, Tamilnadu, India. To necessitate a rigorous assessment of building vulnerability to extreme wind loads, storm surges, and flooding. This study evaluates the structural vulnerability of engineered, semi-engineered, and non-engineered housing typologies prevalent in this region. Employing a methodology integrating historical cyclone impact data, field surveys of Mallipattinam and Pudhupattinam. The research identifies failure-prone structural components, including foundations, walls, roofs, openings, and connections. The investigation analyzes structural failure mechanisms under varying wind loads to pinpoint vulnerabilities specific to each construction methodology. Furthermore, the study incorporates a cost-benefit analysis to compare the efficiency of retrofitting strategies for enhancing the disaster resilience of residential structures.

2. OBJECTIVES OF STUDY

[1] To identify failure pattern of various structural components in different types of buildings due to wind load & pressure.
[2] To find the failure mechanism of various structural components.
[3] To give retrofit measures for the existing buildings in our study area.

3. LITERATURE REVIEW

- Transforming the Existing Households as a Disaster Safehold through Cost-Efficient Architectural Execution Techniques: A Case Study of Assasuni, Shatkhira Fatama Siddique, Sheikh MD Ali Reza, Shoubhik Kumar Dey, SM Zahed Sarwar, 2024.

  Study in cyclone-prone Bangladesh found traditional homes vulnerable and proposed affordable, disaster-resistant techniques using local materials and improved joinery for resilient shelters.

- Cyclonic damage assessment of rural houses for the east coastal region of India, Pradeep K. Goyal, 2022.
  Proposes a component-based method using Damage Probability Matrices to assess cyclone damage to rural

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Indian houses, identifying weak points for targeted retrofitting to improve resilience

- Minimising damage to houses by designing for high internal pressures, Korah Parackal, Geoff Boughton, David Henderson, Debbie Falck Internal, 2022.

  Identifies internal pressurization from wind entering openings as a major cause of cyclone damage and recommends pressure-resistant designs with debris-rated shutters and impact-resistant materials.

- Vulnerability of rural houses to cyclonic wind, Pradeep K. Goyal, T.K. Datta, V.K. Vijay, 2012.

  Explored rural house vulnerability to cyclones using data analysis and probabilistic methods to develop fragility curves and predictive tools for India, noting a lack of assessments for clustered rural housing.

- Reliability-Based Structural Design, Bilal M. Ayyub and Ibrahim A. Assakkaf, 2004.

  Advocates for reliability-based structural design using probability to handle uncertainties, focusing on failure probability and simulation for safer, more resilient buildings.

4. CYCLONES

A cyclone is a large-scale rotating air mass that forms around a low-pressure center, moving counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. Cyclones are categorized into extratropical, tropical, mesocyclones, subtropical, and polar types based on their origin and characteristics.

Fig 1. Cyclone

A. Characteristics of a cyclone

[1] Cyclones are low-pressure systems rotating due to the Coriolis effect, with counterclockwise rotation in the Northern Hemisphere and clockwise in the Southern Hemisphere.

[2] Strong pressure gradients within cyclones cause high wind speeds, often exceeding 252 km/h in extreme cases. The maximum winds occur around the eyewall, and the center features a calm region known as the eye.

[3] Cyclones bring primary hazards like storm surges, which cause abnormal sea-level rise, and heavy rainfall leading to inland flooding and landslides. These conditions amplify structural damage and environmental impact.

B. Codal provisions for cyclone-resistant structures

1. IS 875 (Part 3): 2015 – Code of Practice for Design Loads (Wind Loads)
2. IS 15499: 2004 - Guidelines for Survey of Housing and Building Typology in Cyclone Prone Areas
3. IS 15498: 2004 – Guidelines for Improving the Cyclone Resistance of Buildings
4. IS 456: 2000 – Code of Practice for Plain and Reinforced Concrete
5. IS 800: 2007 – General Construction in Steel

C. Classification of cyclonic disturbances

Tamil Nadu is divided into different cyclone risk zones based on wind speeds and storm surge vulnerability. These zones align with IS 875 (Part 3): 2015 – Indian Standard Code for Wind Loads and NDMA Cyclone Risk Mitigation Guidelines.

TABLE I Classification of cyclonic disturbances

SI No	Types of disturbance	Associated maximum sustained wind (1 knot - 1.85 kmph)
1	Low Pressure Area	Not exceeding 17knots (<31kmph)
2	Depression	17 to 27 knots (31-49 kmph)
3	Deep Depression	28 to33 Knots (50-61 kmph)
4	Cyclonic Storm	34 to 47 Knots (62-88 kmph)
5	Severe Cyclonic Storm	48 to 63 Knots (89-117 kmph)
6	Very Severe Cyclonic Storm	64 to90 Knots (118-167 kmph)
7	Extremely Severe Cyclonic Storm	91 to119 Knots (168-221 kmph)
8	Super Cyclonic Storm	120 Knots and above (≥222 kmph)

D. Cyclone zones in Tamilnadu

Tamil Nadu is divided into different cyclone risk zones based on wind speeds and storm surge vulnerability. These zones align with IS 875 (Part 3): 2015 – Indian Standard Code for Wind Loads and NDMA Cyclone Risk Mitigation Guidelines.

TABLE II Cyclone zones in Tamilnadu

Zone	Wind Speed (km/h)	Districts Affected
High-Risk Zone	>160 km/h	Chennai, Cuddalore, Nagapattinam, Thoothukudi, Ramanathapuram
Moderate-Risk Zone	120 - 159 km/h	Thanjavur, Pudukkottai, Kanyakumari, Karaikal,

		Tiruvarur
Low-Risk Zone	80 - 119 km/h	Madurai, Sivagangai, Tirunelveli, Virudhunagar

Fig 2 Cyclone zoning map of India

Fig 3 Cyclone zoning map of Tamilnadu

E. List of cyclones affected in Tamilnadu

The coastal regions of Tamil Nadu and Andhra Pradesh have faced frequent cyclonic events, with severe impacts recorded in multiple years. Major cyclones like Ockhi (2017), Gaja (2018), and Nisha (2008) caused significant casualties and property damage. The highest wind speed was recorded during Ockhi at 185 km/h, resulting in over 200 deaths. Cyclones often bring intense rainfall, such as Nisha's 660 mm in 24 hours and Michaung's heaviest in 47 years.

TABLE III List of cyclones affected in Tamilnadu

Cyclone Name	**Speed (kmph)**	**Location**	**Impact Summary**
Fengal (2024)	90	Tamilnadu, Sri Lanka, Andra Pradesh.	Heaviest rainfall; 37 deaths
Michaung (2023)	110	Tamil Nadu, Andhra Pradesh	Heaviest rainfall in 47 years; 17+ deaths
Mandus (2022)	95	Tamil Nadu Coast	4 deaths reported
Nivar (2020)	125	Between Pondicherry & Chennai	Heavy rainfall
Gaja (2018)	130	Tamil Nadu Coast	40+ deaths; 2.5 lakh displaced; livelihood loss
Ockhi (2017)	185	Kanyakumari, Lakshadweep	218 deaths; 600+ missing; widespread destruction
Vardah (2016)	155	Near Chennai	Severe damage; 15+ deaths; ₹1000 crore loss
Thane (2011)	135	Between Puducherry & Cuddalore	45+ deaths; major crop & property damage
Jal (2010)	110	Near Chennai	50+ deaths; 300,000 ha crops lost
Nisha (2008)	100	Tamil Nadu Coast	189 deaths; 660 mm rain in 24 hrs; 1.5 lakh houses damaged

5. CLASSIFICATION OF BUILDINGS

A. Non engineered buildings

Non-engineered construction relies on traditional methods and local materials without formal structural design or professional oversight, lacking load analysis, quality control, and adherence to safety codes. Utilizing low-strength materials and lacking crucial structural elements, these buildings exhibit high vulnerability to disasters due to inherent weaknesses and susceptibility to collapse under natural forces. Examples include mud houses, foundationless brick dwellings, and unanchored coastal homes.

B. Semi-engineered buildings

Semi-engineered construction features some engineer-designed elements (slabs, foundations) but incorporates non-engineered components like unreinforced masonry walls, leading to inconsistent structural integrity. Despite using materials like RCC and bricks, partial design, variable construction quality due to limited supervision, and poor integration between engineered and non-engineered parts create vulnerabilities. These include weak connections and a lack of reinforcement in walls, resulting in compromised performance against hazards like cyclones and earthquakes. Examples include houses with RCC roofs and unreinforced walls, and buildings with partially standardized designs.

C. Engineered buildings

Engineered construction entails buildings fully designed and supervised by qualified professionals, adhering to scientific principles and standards like IS codes to ensure structural safety and durability against various loads (dead, live, wind, seismic). Utilizing tested, high-quality materials (RCC, steel, engineered wood) with standardized connections, the process involves detailed design, thorough planning, consistent site supervision, strict quality control, and comprehensive documentation. This results in structurally sound, hazard-resistant, and integrated buildings capable of withstanding lateral forces, exemplified by earthquake-resistant apartments, seismic-isolated hospitals, and cyclone shelters.

6. STUDY LOCATIONS

A. Thanjavur District

Fig 4. Thajavur map created in ARCGIS

Thanjavur is situated in the Cauvery delta, at a distance of 340km south-west of Chennai and 56km east of Tiruchirappalli. The plains adjoining the Cauvery river have been under cultivation from time immemorial, most of Thanjavur city and the surrounding areas lie in the "New Delta" a dry, barren upland tract which was brought under irrigation. To the south of Thanjavur city, is the vallam tableland, a small plateau interspersed at regular intervals by ridges of sandstone. The city has an elevation of 59m above mean sea level.

Fig 5 Pattukkottai map created in ARCGIS

B. Mallipattinam

Mallipattinam is a coastal village located in Pattukkottai taluk of Thanjavur district, Tamil Nadu. It is situated 20.5 km from Pattukkottai, and 66.5 km from Thanjavur. Adirampattinam is the nearest major town to Mallipattinam. It has area of 2.55 sq. km with sandy coast.

C. Pudhupattinam

Pudhupattinam Gram Panchayat is located in the Pattukkottai taluk of Thanjavur district, Tamil Nadu. Pudhupattinam is also coastal region near Mallipattinam with fishing and agriculture as primary occupations, and area of 1.67 sq. km with sandy coasts and estuaries.

Table IV Coastal profile of Mallipattinam & Pudhupattinam

Feature	Mallipattinam	Pudhupattinam
Latitude	10°16′50.02″N	12°30′6.83″N
Longitude	79°19′1.13″E	80°8′56.30″E
Population	7,000	5,500
Area (sq. km)	2.55	1.67
Topography	Flat, sandy, low-lying, erosion-prone	Sandy coast, estuaries & backwaters
Climate	Hot, humid	Tropical, high rainfall
Soil Type	Sandy, Alluvial Soil	Alluvial soil
Occupation	Fishing, agriculture	Fishing, small agriculture

D. Populations of Thanjavur & Tamilnadu

In Thanjavur district, the total population is 24.05 lakhs with a population density of 704 people per square kilometer. This is significantly lower than the overall population density of Tamil Nadu, which has a total population of 7.21 crores and density of 555 people per square kilometer.

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7. FIELD SURVEY – DATA COLLECTIONS

A. General details – Mallipattinam

SI. NO	**Category**	**Details**
General Information		
1	Location	Mallipattinam, Pattukkottai Taluk, Thanjavur District, Tamil Nadu
2	Cyclone, Flood & Storm Surge Prone	Yes
3	Population	5000 people (200 houses)
4	Shelter Availability	Yes, 0.8 km away (Capacity: 400–500 people)
5	Storm Water Drainage	Present but poorly maintained
Past Cyclones		
1	Cyclone Gaja (2018)	140 kmph, 50 houses damaged, 3 lives lost, 0.6m water level
2	Cyclone Vardah (2016)	65 kmph, 5 houses damaged, no lives lost, 0.45m water level

1. STRUCTURAL ASSESSMENT

MALLIPATTINAM

North street, Mallipattinam.		
1	Type	Non-engineered (Thatched)
2	Size	5.44m × 5.06m (18.12 m²)
3	Roof	Hipped, thatched with wooden rafters
4	Walls	Thatched, poor quality, unmaintained
5	Foundation	None
6	Plinth	None, structure starts from ground level
7	Estimated Age	Less than 1 year
8	Estimated Cost	₹10,000
Structural Damage Summary		
1	Roof	Marginal damage
2	Walls & Foundation	Marginal damage
3	Columns (8 total)	5 No damage, 2 Minor damage, 1 Major damage
4	Doors, Windows, & Ventilators	No damage
5	Cracks in Walls	Not observed
6	Erosion Due to Flooding	Yes
Issues & Recommendations: The foundation lacks plinth protection and is at high flood risk, so raising the plinth or reinforcing the base with bamboo or timber is advised. Roof stability should be improved by strengthening anchorage with metal straps and better rafter connections. One severely damaged column needs immediate replacement. Storm drainage is poor and requires maintenance to prevent waterlogging. Overall, moderate retrofitting is recommended, including reinforcing the structure with treated timber and improving anchorage for better wind resistance.		

2. STRUCTURAL ASSESSMENT

MALLIPATTINAM

Umar pulavar street, Mallipattinam		
1	Type	Semi-Engineered
2	Size	12m × 8m (96m²)
3	Roof	Gable, Tiles
4	Walls	Sun-dried bricks
5	Foundation	Shallow RCC (1.2m deep)
6	Plinth	0.45m above ground level
7	Estimated Age	25 years
8	Estimated Cost	₹4,00,000
Structural Damage Summary		
1	Roof	Marginal damage
2	Walls & Foundation	Marginal damage
3	Columns	No damage
4	Doors, Windows, & Ventilators	No damage
5	Cracks in Walls	Not observed
6	Erosion Due to Flooding	Yes

Issues & Recommendations: The structure faces some minor but important issues related to flood resilience. Wall erosion due to flooding can be addressed by strengthening the lower walls with waterproof plaster or using treated bricks to prevent further damage. Roof stability should be improved by enhancing anchorage with metal straps and reinforcing the structural connections to ensure the roof remains secure during storms. Additionally, the local drainage system needs improvement to prevent waterlogging around the building. Overall, the retrofitting priority is low, as only minor improvements are needed to enhance the structure's resilience against flooding.

3 STRUCTURAL ASSESSMENT

MALLIPATTINAM

Tipu sultan street, Mallipattinam.		
1	Type	Engineered
2	Size	18.36 m × 7.5 m (137.7m²)
3	Roof	Flat RCC
4	Walls	Sun-dried Bricks
5	Foundation	Shallow Foundation
6	Plinth	0.45m above ground
7	Estimated Age	80 years
8	Estimated Cost	₹5,00,000
Structural Damage Summary		
1	Roof	Marginal Damage
2	Front & Side Walls	Marginal damage
3	Foundation	No Damage
4	Columns	18 Columns (14 No Damage, 4 Minor Damage)
5	Doors, Windows & Ventilators	No Damage
6	Cracks in Walls	Heavy—Vertical, Horizontal, Inclined cracks observed
7	Erosion Due to Flooding	Yes
Issues & Recommendations: The building addressed by strengthening the walls with higher-quality materials to ensure greater durability and safety. The roof should have its anchorage improved using metal straps to better withstand strong winds and storms. Additionally, the storm drainage system requires upgrading and regular maintenance to prevent water accumulation and related damage. Given these concerns, the retrofitting priority is high, and significant structural improvements are urgently needed to enhance the building's overall safety and resilience.		

B. General details – Pudhupattinam

SI. NO	Category	Details
General Information		
1	Location	Pudhupattinam, Pattukkottai Taluk, Thanjavur District, Tamil Nadu
2	Cyclone, Flood & Storm Surge Prone	Yes
3	Population	5000 people (200 houses)
4	Shelter Availability	Yes, 0.8 km away (Capacity: 400–500 people)
5	Storm Water Drainage	Present but poorly maintained
Past Cyclones		
1	Cyclone Gaja (2018)	140 kmph, 5 houses damaged, no lives lost, 0.6m Water level
2	Cyclone Vardah (2016)	65 kmph, No houses damaged, no lives lost, 0.45m water level

1. STRUCTURAL ASSESSMENT

PUDHUPATTINAM

Pudhupattinam.		
1	Type	Non-Engineered
2	Size	5.50m × 4.00m
3	Roof	Thatched Roof with Bamboo/Wooden Support
4	Walls	Mud/Adobe/Unreinforced Brick Masonry
5	Foundation	Stone or Mud Foundation (Shallow)
6	Plinth	0.30m above ground
7	Estimated Age	15 years
8	Estimated Cost	₹85,000
Structural Damage Summary		
1	Roof	Minor Damage
2	Front & Side Walls	Major Damage (Large Cracks)
3	Foundation	Weak

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4	Columns	Lack of columns
5	Doors, Windows & Ventilators	Severe Damage (Frame Misalignment, Broken Hinges)
6	Cracks in Walls	Major—Wide Vertical & Diagonal Cracks Due to Weak Construction
7	Erosion Due to Flooding	Significant Erosion Around Foundation
Issues & Recommendations: The building has major damage to front and side walls, a weak shallow foundation with soil erosion and uneven settlement, and significant erosion around the foundation due to flooding. The roof, openings, and wall cracks show minor damage, and the structure lacks columns for support. To improve stability, strengthen walls with cement plaster and bracing, reinforce the foundation with stone or concrete, and improve drainage to prevent further erosion. Raising the plinth and adding vertical supports are also recommended to enhance flood resistance and structural integrity.		

2. STRUCTURAL ASSESSMENT

PUDHUPATTINAM

Pudhupattinam		
1	Type	Semi-Engineered
2	Size	10m × 6.30m
3	Roof	Asbestos sheet
4	Walls	Brick Masonry
5	Foundation	Random Rubble Masonry
6	Plinth	0.50m above ground
7	Estimated Age	18 years
8	Estimated Cost	₹1,40,000
Structural Damage Summary		
1	Roof	Moderate Damage
2	Front & Side Walls	Moderate Damage
3	Foundation	No damage
4	Columns	Slight Deformation
5	Doors, Windows & Ventilators	Moderate Damage
6	Cracks in Walls	Minor—Hairline Cracks
7	Erosion Due to Flooding	Some Soil Erosion

Issues & Recommendations: The building requires timely repairs to ensure long-term stability. Walls should be strengthened with cement reinforcement and bracing, broken roof tiles replaced, and a water-resistant coating applied. Foundation settlement needs monitoring and reinforcement, while drainage channels should be improved to prevent water pooling. The retrofitting priority is medium.

3. STRUCTURAL ASSESSMENT

PUDHUPATTINAM

Pudhuppattinam		
1	Type	Engineered
2	Size	16m × 12.5m
3	Roof	RCC Slab with Proper Waterproofing
4	Walls	Reinforced Brick Masonry with Cement Plaster
5	Foundation	Reinforced Concrete Footing
6	Plinth	0.80m above ground
7	Estimated Age	10 years
8	Estimated Cost	₹12,50,000
Structural Damage Summary		
1	Roof	No Damage
2	Front & Side Walls	No Major Cracks
3	Foundation	Stable
4	Columns	Stable
5	Doors, Windows & Ventilators	Minor Wear
6	Cracks in Walls	Minor cracks
7	Erosion Due to Flooding	No Significant Erosion Observed
Issues & Recommendations: To maintain its stability, regular inspection and maintenance are recommended. The foundation currently shows no immediate concerns, but it should be monitored for any signs of settlement. Efficient storm drainage can be maintained by regularly clearing drainage channels to prevent blockages. Overall, the building is well-built and only requires routine upkeep to preserve its integrity.		

8. FAILURE COMPONENTS IN BUILDINGS

A. Failure mechanism of beams

Beams fail by bending (flexural failure) or shear (shear failure) as per IS codes. Twisting (torsional failure) and cracking are other failure types.

- Shear Failure: Happens when shear stress exceeds the beam's capacity, causing diagonal cracking or shearing off.
- Cracks in Beams: Visible separation in concrete due to excessive tensile stress, shrinkage, temperature changes, or shear forces, indicating the material's tensile capacity has been exceeded.
- Corrosion in a Beam: Rusting of steel rebar in reinforced concrete due to moisture and oxygen, weakening the structure.

B. Failure mechanism of columns

Columns mainly fail by buckling or crushing (material strength exceeded). Shear (from sideways loads) and twisting (torsional) failures can also occur, depending on the column's shape, material, and how it's loaded.

- Buckling: Long columns under compression lose stability and deflect sideways before reaching full compressive strength; influenced by length, dimensions, and material.
- Crushing: Short columns fail when compressive load exceeds material capacity, causing localized fracturing or yielding of concrete.
- Shear Failure: Transverse loads on a column cause diagonal cracks and potential failure along its length.
- Torsional Failure: Twisting forces on a column lead to cracks and potential failure around its perimeter.

C. Failure mechanism of slabs

Slab failures include bending (flexural), localized shear damage, and punching shear (around supports, critical in flat slabs).

- Flexural Failure: Load exceeds bending capacity, causing cracks and eventual failure (ductile with steel yielding or brittle sudden failure).
- Shear Failure: Slab's resistance to sliding forces is exceeded, leading to localized cracks or delamination in high shear areas.
- Punching Shear Failure: Localized failure around columns or supports under concentrated loads, especially dangerous in flat slabs, potentially causing rapid collapse.
- Longitudinal Shear Failure: Connection between steel deck and concrete slab fails, causing layer separation.

D. Failure mechanism of walls

Wall failures happen through shear and diagonal stresses varying by wall type (concrete, masonry) and loads. Concrete walls can slide in shear, bend, or fail in diagonal tension/compression. Masonry walls can have brick failure and mortar joint failure.

- Shear Failure: Shear stress exceeds capacity, causing sliding along a plane or diagonal cracking.
- Diagonal Tension/Compression Failure: Diagonal stresses exceed strength, causing cracks and potential failure.
- Overturning: External forces cause the wall to rotate or tilt due to insufficient resisting moment.
- Sliding: Wall slides at its base due to inadequate friction or horizontal forces.
- Bearing Capacity Failure: Pressure from the wall exceeds soils capacity, leading to settlement or failure.

E. Failure mechanism of foundation

Foundations mainly fail due to shear (general, local, punching) and bearing capacity issues, influenced by soil and load. Other failures include sliding, uneven sinking, and base failure.

- General Shear Failure: Continuous failure surface in dense/stiff soils with ground heave and well-defined failure.
- Local Shear Failure: Failure surface doesn't reach the surface in compressible soils, with slight heave and significant soil compression.
- Punching Shear Failure: High soil compression with vertical shearing; no ground heave or footing tilt.
- Base Failure: Soil shear strength exceeds bearing capacity, causing foundation support failure.
- Differential Settlement: Uneven foundation sinking leads to cracks and damage in the building.

F. Failure mechanism of purlins

Purlins fail due to bending, local buckling, or shear, particularly in continuous systems. Weak bracing, connections, and supports also contribute.

- Local Buckling: Buckling of lips, flanges, or webs in the top (compression) region in continuous purlins.
- Shear Plus Bending: Failure at lap connection edges due to combined bending and shear, especially in Z-purlins.
- Pull-Through Failure: Connections to rafters/trusses fail by rupture or bearing, particularly with Z-purlins.
- Bolt Failure: Concentrated forces at bolts in lap joints cause failure and purlin cross-section distortion.
- Shear Failure: Insufficient shear capacity, especially in concrete purlins, leads to sudden failure under heavy loads.

G. Failure mechanism of rafters

Rafters fail from overload (bending, shear, or both), material decay (rot, pests), or weak connections leading to progressive failure, especially in wind.

- Bending Failure: Overloading causes excessive bending and stress, leading to cracks on the top or bottom. Common with heavy snow or defects.

- Shear Failure: Forces near supports try to cut the purlin, resulting in diagonal cracks, especially at the ends, often under concentrated loads.

- Material Degradation: Moisture, insects, or fungi weaken the purlin over time; signs include soft, crumbly wood, musty smells, or rot.
- Progressive Failure: Failure starts at a weak connection (e.g., loose nail) and spreads to other members, causing sagging or instability.

H. Failure mechanism of joists

Joists fail through cracking, sagging, or collapse due to shear, horizontal shear, tension, moisture, or installation issues. Specifically, I-joists can fail from tension, rolling shear, crushing, and lateral buckling.

- Shear Failure: Shear capacity is exceeded, causing cracks parallel to the grain. Common at timber-masonry connections, leading to sliding or buckling.
- Horizontal Shear Failure: Cracks run horizontally along the joist, indicating failure within its shear capacity.
- Tension Failure: Tensile stress exceeds strength, causing the joist to split or crack.
- Moisture and Rot: Water damage leads to wood rot, significantly weakening the joist and increasing susceptibility to other failures.

I. Failure mechanism of clamps

Clamps fail due to material fatigue, corrosion, or incorrect tightening (too loose or too tight). Manufacturing flaws and material defects can also cause failures.

- Material Fatigue: Repeated stress or vibration causes cracks to grow over time, leading to failure.
- Corrosion: Moisture or chemical exposure weakens the clamp, making it brittle and prone to breakage or leaks.
- Excessive load: Over-tightening damages the clamp through cracks, stripped threads, or buckling.

J. Failure mechanism of struts

Long struts buckle (bend sideways) under compression, not just crush. This is due to slight flaws or off-center forces. Buckling is the main failure mode for longer struts.

- Buckling: Slender struts bend sideways under compression, especially with imperfections or off-center loads.
- Inadequate Section Size: If a strut is designed with inadequate section, it will fail when subjected to the designed load.

K. Failure mechanism of thatched roof

Thatch roofs commonly fail due to leaks (at joints, poor drainage), wind damage (lifting thin/loose thatch), and structural problems.

- Leaking: Common at ridges, valleys, corners, and flashing due to cracked capping, poor thatching, or water pooling.
- Wind Damage: Lifted or thin thatch at corners or poorly compacted areas is easily damaged by strong winds.
- Structural Failures: Broken support beams can cause the thatch to sag into the roof space.

L. Failure mechanism of timber column

Timber columns fail mainly from compressive stress and instability (buckling in slender columns). This can cause crushing or wood fiber breakdown and natural defects.

- Buckling: Thin, long columns buckle (bend sideways) under compression due to lack of support, overload, or poor design.
- Crushing: Wood deforms under perpendicular loads.
- Degradation: Rot or insects weaken wood.
- Defects: Knots cause local weakness.
- Shear: Forces at joints cause shear failure.

9. RETROFITTING MEASURES

A. Non-engineered structures

1. Addressing Roof Uplift with Ropes:

- The aerodynamics around buildings create significant suction forces on the roof, which can lead to it being lifted off.
- To counteract this, the suggestion is to tie down the thatched roof to the supporting framework or the building envelope using organic ropes.
- Due to the limited lifespan of organic ropes, it's recommended to replace them annually before the cyclone season.
- A diagonal pattern of rope placement is preferred for better resistance.

2. Limiting Roof Overhang:

- The overhang of the roof beyond the walls should ideally not exceed 450 mm.
- Larger overhangs are more susceptible to uplift forces.
- If the overhang is greater than 450 mm, it should be properly tied back to the wall framework to prevent it from being torn off.

3. Anchoring Main Posts to the Ground

- The main structural posts of the building should be firmly anchored to the ground to resist uplift forces.
- A minimum anchorage depth of 900 mm is recommended for the posts.
- Anchor bars should have a minimum length of 450 mm.

4. Using Multiple Anchor Poles:

- Each main post should be secured using four anchor poles.
- These anchor poles should be placed at least at two different levels with a vertical spacing of 500 mm and in different directions to provide better stability.

5. Protecting Mud Walls:

- A protective barrier or revetment made of stone or brick should be built around the base of the mud wall up to the maximum flood level.
- The outer surface of the mud wall should be plastered with a special waterproof clay or cement/lime mortar to enhance its resistance to erosion.

6. Implementing Triangular Roof Frames:

- For sloped roofs, triangular frames can be installed with a maximum spacing of 2.0 meters.
- The members of these triangular frames must be strong enough to support the cross runners of the roof.
- Proper connections between the elements of the triangular frame should be ensured using metal straps, bolts and nuts, and steel flats to improve the overall structural integrity.

7. Connecting Triangular Frames to Anchorage:

- The main triangular frames of the roof should be firmly connected to anchorage elements or bond beams located at the level of the eaves (the lower edge of the roof).
- These anchorage elements, in turn, should be connected to the main posts of the wall using U-bolts.

8. Anchoring Roof to Masonry Walls:

- For walls made of brickwork in random rubble masonry, a bond beam or anchorage beam provided at the top should be anchored to the foundation using mild steel rods properly encased in cement mortar.
- The total area of anchorage reinforcement provided should be at least twice that required to transmit the calculated uplift force.

9. Discrete Anchorage in Masonry:

- Discrete anchorage of the roof into brick/rubble masonry can be achieved using anchorage reinforcement.
- The effective weight of the masonry above the anchorage point should be considered as 1.5 times the uplift force at that specific anchorage location, based on a simplified load-flow pattern.

B. Semi-engineered structures

1. Restraining Tiled Roofs:

- To provide restraint against uplift for tiled roofs, concrete or masonry restraining bands should be installed at approximately 1.2m to 1.5m spacing.
- The dimensions of the restraining band are suggested to be around 100 mm x 50 mm.
- Each restraining band should contain at least one 10 mm diameter reinforcing bar.
- Hip, valley, and ridge tiles must be firmly embedded in a continuous band of cement mortar. If these tiles have nailing holes, nails inserted through them into the mortar bed can act as effective shear connectors.

2. Securing Tiled Roof by Bond Beam:

- The entire tiled roof system should be securely fixed to a bond beam (a horizontal reinforced concrete or masonry beam at the top of the walls).
- This bond beam, in turn, needs to be connected to the foundation using holding-down bolts.
- These holding-down bolts should be designed with a factor of safety of 2.0 to resist uplift forces.

3. Using U-bolts for Asbestos Sheet Cladding:

- When asbestos sheets are used for roof cladding, U-bolts are preferred over J-bolts for securing them to the supporting structure.
- The recommended number of U-bolts at various locations is indicated.

4. Reinforcing Hollow Concrete Block Masonry Walls:

- If hollow concrete block masonry is used for walls, designed reinforcements can be run through the hollow cores, effectively creating pilasters (vertical columns integrated into the wall) with reinforcement.
- The spacing between these reinforced pilasters should not exceed 3.0 meters.
- The reinforcements within the pilasters must be well-anchored into the foundation and integrated with the lintel band and the bond beam (at the top of the wall)

5. Anchoring Roof to Strong Brick Walls:

- If the building has strong walls made of good quality brickwork, the roof can be anchored directly to a continuous lintel band using cyclone bolts (specifically designed anchor bolts for high wind resistance).

C. Engineered structures

1. Enhancement/Shielding Factors for Building Clusters:

- When buildings of similar heights are clustered with an inter-building spacing less than twice the width of an individual building, aerodynamic interactions need to be considered.
- Corner Buildings: For corner buildings located on the periphery of such clusters, the pressure loadings due to wind should be increased by a factor of 1.50. These buildings are more exposed to direct wind forces.
- Interior Buildings: For all buildings located within the cluster (not on the periphery), a shielding factor of 0.80 can be applied to the wind pressure calculations. These buildings benefit from the windbreak effect of the surrounding structures.

2. Roof Pressure Adjustments for Industrial Sheds:

- For industrial sheds with gable roofs located at the corners of outer rows in a cluster, the roof pressures should be enhanced by a factor of 1.50. Similar to corner buildings in general clusters, they experience higher wind loads.
- For evaluating roof pressures on interior industrial buildings with gable roofs within a cluster, a shielding factor of 0.80 can be considered.

3. Allowable Stress in Steel under Wind Loading:

- In all engineered buildings where wind loading is the primary design consideration, no increase in the allowable stresses in steel beyond the limits specified in IS 800 (Indian Standard for General Construction in Steel - Code of Practice) is permitted. This ensures a conservative design approach under dominant wind forces.

4. Parapets and Roof Slab Anchorage in Masonry Buildings:

- For engineered buildings parapet wall with a minimum height of 600 mm should be provided. Parapets can help reduce wind pressures on the roof.
- Additionally, the roof slab in such buildings should be anchored to the continuous lintel beam using adequate ties to resist uplift forces.

5. Ductile Detailing in Multi-Hazard Areas:

- In regions prone to multiple hazards, particularly earthquake zones III and above, even if wind loading governs the design forces, the ductile detailing provisions outlined in IS 13920 (Indian Standard Code of Practice for Ductile Detailing of Reinforced Concrete Structures Subjected to Seismic Forces - Code of Practice) must be followed. This ensures that the structure has sufficient ductility to withstand seismic forces, even if the primary design was for wind.

6. Elevated Construction in Flood-Prone Areas:

- In areas susceptible to flooding, all public engineered buildings, including cyclone shelters, should be constructed on raised ground with appropriate peripheral retaining walls. This elevates the structure above potential flood levels, minimizing damage.

7. Shear Walls for Open Ground Storey Buildings:

- If engineered buildings are constructed with openings at the ground level (often referred to as stilt or open ground storey buildings), adequate symmetric shear walls must be provided in both principal horizontal directions of the building. This is crucial for resisting lateral forces from wind or earthquakes, especially in multi-hazard prone areas (earthquake zones III and above). The open ground storey makes the building more vulnerable to lateral instability.

8. Rounded Corners for Reduced Drag:

- Wherever functionally feasible without compromising the building's use, the corners of the buildings should be rounded off with a suitable radius of curvature. This aerodynamic shaping helps to reduce the drag forces exerted by the wind on the structure

9. Bracing in Industrial Gable Roof Buildings:

- In industrial buildings with gable roofs, plan bracing should invariably be provided at the bottom chord level of the trusses. This bracing serves two critical purposes:
    - To prevent buckling of the bottom chord members due to uplift forces caused by wind.
    - To distribute the horizontal wind loads acting on the gable end walls to the main structural system.
- Upper chord bracing is also recommended, at least near the gable end walls, for added stability.

10. CONCLUSIONS

- Rural houses in cyclone-prone Thanjavur, Tamil Nadu, especially non- and semi-engineered types, are highly vulnerable to wind and flood damage due to poor construction practices and materials.
- Structural failures are often caused by wind pressure entering through openings, weak roof anchorage, inadequate wall connections, and lack of flood-resistant features.
- Flooding and poor drainage lead to erosion and further instability, particularly in low-lying coastal areas.
- Retrofitting measures like stronger roof anchorage, reinforced walls, and improved drainage can greatly enhance housing resilience.
- New constructions must follow reliability-based design and IS codes (e.g., IS 875, IS 15498) for safety.
- Using local, cost-effective materials and better joinery can make rural homes disaster-resilient.
- Even moderate cyclones (110–140 km/h) in Thanjavur can cause severe housing damage and displacement.

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