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Brick Masonry: A Comprehensive Review of Materials, Mechanical Behaviour, Structural Performance, Analysis Methods, Strengthening and Sustainability

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ABSTRACT

Brick masonry is among the oldest and most widely used structural systems in the world and remains the backbone of low- and medium-rise construction in many countries, including India. Its use rests on available raw materials, low initial cost, thermal comfort, fire resistance and durability. However, unreinforced brick masonry is a heterogeneous, anisotropic, quasi-brittle composite whose behaviour is governed by the units, the mortar and, above all, the unit–mortar interface. It performs poorly in tension, shear and out-of-plane loading, which makes it especially vulnerable in earthquakes. This paper reviews historical development; constituent materials; bonding and construction practice; compressive, tensile and shear behaviour; in-plane and out-of-plane response, including seismic performance and infill walls; modelling strategies; durability; repair and strengthening; sustainability and alternative units; and major design codes. Key findings, comparative tables and research gaps are identified, including standardised testing of local bricks, validated models for weak mortar, performance-based design for small buildings and low-carbon masonry units.

KEYWORDS: *brick masonry, clay brick, compressive strength, masonry infill, mortar, numerical modelling, seismic performance, shear behaviour, strengthening, sustainability.*

INTRODUCTION

Masonry, an assemblage of discrete units bonded with mortar, has been used for millennia. Fired clay brick appeared in Mesopotamia and the Indus Valley more than four thousand years

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ago, and the Harappan cities were built extensively with standardised burnt bricks. Roman, Byzantine, Islamic, Mughal and European builders later developed arches, vaults and domes in brick. Brick remains a principal housing material in South Asia, and masonry forms a large share of the world's building stock.

Despite this history, masonry was treated as an empirical craft rather than an engineered material until relatively recently. Systematic study accelerated in the twentieth century through the work of Hilsdorf [1], Page [2], Hendry [3] and others, and gained momentum from computational mechanics [4] and lessons from major earthquakes. Non-engineered, poorly detailed brick buildings account for a disproportionate share of earthquake casualties, which strengthens the case for systematic assessment and effective strengthening.

This paper offers a structured, critical review of brick masonry as a material and as a structural system. It (i) summarises the properties of units and mortars; (ii) discusses behaviour under compression, tension and shear; (iii) reviews structural and seismic response; (iv) outlines numerical modelling strategies; (v) reviews durability and strengthening; (vi) discusses sustainability and alternative units; and (vii) identifies research gaps.

HISTORICAL DEVELOPMENT AND SCOPE

Early bricks were sun-dried (adobe) and later fired in clamps and kilns, which gave greater strength and lower porosity. Portland cement gradually displaced lime mortar during the nineteenth century, producing stronger but stiffer and less forgiving walls. The twentieth century brought engineered brickwork, including reinforced and post-tensioned masonry, cavity walls and hollow units, alongside standards such as CP 111, BS 5628 and Eurocode 6 [5].

This review concentrates on fired clay brick masonry, both unreinforced (URM) and confined or reinforced, used in load-bearing walls and as infill in reinforced-concrete (RC) frames. Alternative units are mentioned where relevant.

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CONSTITUENT MATERIALS

1. Clay bricks

Burnt clay bricks are made by moulding clay, usually with sand and sometimes fuel additives, then drying and firing at roughly 900–1100 °C. Their properties depend on clay mineralogy, forming method, firing temperature and kiln type. The most relevant properties are compressive strength, water absorption, initial rate of absorption (IRA), dimensional accuracy, density and soluble-salt content. Hand-moulded bricks from clamp or Bull's trench kilns vary widely, whereas wire-cut and extruded units from tunnel or Hoffmann kilns are more uniform. In India, common burnt clay bricks are specified in IS 1077 [6] and classified by minimum average compressive strength from 3.5 to 35 MPa; test methods are in IS 3495 [7]. Typical modular size is 190 × 90 × 90 mm, and water absorption is limited to about 15–20% depending on class.

Table 1: Common unit types and their general characteristics

Unit type	Strength range	Principal advantages	Principal limitations
Hand-moulded burnt clay brick	3.5–10 MPa	Cheap, local, good thermal mass	Variable quality; high embodied energy
Machine-made / wire-cut brick	10–35 MPa	Uniform size and strength; durable	Higher cost; energy-intensive firing
Perforated / hollow brick	5–25 MPa (gross)	Lighter; better insulation	Lower shear and bearing resistance
Fly ash–lime–gypsum brick	7.5–20 MPa	Uses industrial waste; no firing	Ash quality control needed
Concrete block (solid / hollow)	3–15 MPa	Dimensionally accurate; fast to lay	Higher shrinkage and cement content
Compressed stabilised earth block	2–10 MPa	Low embodied energy; local soil	Moisture sensitive; lower strength

Note: Ranges are indicative; consult the relevant standard for specified values.

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2. Mortar

Mortar bonds the units, spreads loads across bed joints, absorbs dimensional variation and helps keep moisture out. Common binders are lime, cement and cement–lime blends. Cement–sand mortars of 1:4 to 1:6 are customary in India, with 1:6 widely used. Lime-based and cement–lime mortars suit repair and heritage work because they are less stiff and compatible with soft historic bricks.

Mortar should generally be weaker and more deformable than the unit. This promotes cracking in the joint rather than through the brick and lets the wall accommodate movement. The mismatch in Poisson's ratio between brick and mortar induces lateral tension in the brick and drives the compressive failure mechanism described by Hilsdorf [1]. Excessively strong mortar adds little wall strength but increases brittleness.

Table 2: Representative mortar mixes and typical use

Mortar type	Proportion (by volume)	Compressive strength	Typical application
Cement : sand	1:3 to 1:4	≈ 8–15 MPa	Foundations; load-bearing walls in wet zones
Cement : sand	1:5 to 1:6	≈ 3–7 MPa	General load-bearing and partition walls
Cement : lime : sand	1:1:6	≈ 2–5 MPa	Better workability; general walling
Lime : sand	1:2 to 1:3	< 2 MPa	Repair of historic masonry; low-rise heritage work

Note: Strengths depend strongly on sand grading, water–binder ratio and curing.

3.3 The unit–mortar interface

The interface is often the weakest and most variable part of masonry. Its tensile and shear (bond) strengths depend on brick suction, mortar water retentivity, laying pressure and workmanship. Highly absorbent bricks laid dry draw water from the mortar and bond poorly;

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dense, low-suction bricks may hold a water film at the interface, which also weakens bond. Pre-wetting absorbent bricks and using water-retentive mortars are the standard remedies. Bond is assessed by flexural bond, bond-wrench and couplet shear tests.

BONDING PATTERNS AND CONSTRUCTION PRACTICE

Brick arrangement governs load distribution and wall integrity; staggered vertical joints prevent continuous planes of weakness. Common bonds are summarised in Table 3.

Table 3: Common brick bonds

Bond	Description	Remarks
Stretcher	All bricks laid lengthwise; half-brick walls	Partitions and cavity-wall leaves; limited transverse tying
Header	All bricks laid with ends showing	Curved and thick walls; good transverse tying
English	Alternate courses of headers and stretchers	Strong; widely used for load-bearing walls
Flemish	Headers and stretchers alternate within each course	Attractive; slightly weaker than English bond in thick walls
Rat-trap	Bricks on edge, leaving a cavity	Economical and thermally useful; reduced strength

Good practice includes full-bed mortar joints, joint thickness of about 10 mm, limited lift heights per day, at least seven days of curing, and damp-proof courses, movement joints and adequate lintel bearing. Poor workmanship, such as unfilled head joints, thick or uneven joints and inadequate curing, repeatedly reduces strength and increases variability, and is a principal source of the gap between design assumptions and in-situ performance.

MECHANICAL BEHAVIOUR OF BRICK MASONRY

1. Compressive behaviour

Masonry compressed perpendicular to the bed joints usually fails by vertical splitting. Because mortar is softer and more laterally deformable than brick, it expands sideways and, through bond and friction, places the brick in lateral tension while the mortar itself is confined in triaxial

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compression. Hilsdorf [1] formalised this mechanism. Failure occurs when the brick's lateral tensile strength is reached, which explains why masonry can be much weaker than its units and why stronger mortar raises masonry strength only modestly.

Empirical relationships link prism strength to unit strength f_b and mortar strength f_m. Eurocode 6 uses the form

$$f_k = K \cdot f_b^{\alpha} \cdot f_m^{\beta} \quad (1)$$

where f_k is the characteristic masonry strength, K depends on unit group and mortar type, and α and β are 0.7 and 0.3 for general-purpose mortar. IS 1905 [8] gives tabulated basic compressive stresses as functions of brick and mortar strength, modified for area, slenderness and eccentricity. Kaushik et al. [9] tested clay-brick prisms with various brick–mortar combinations and proposed a stress–strain model with an elastic modulus of about 550 times prism strength (range roughly 300–1100 times).

The stress–strain curve is nonlinear, with a short ascending branch and a softening branch whose steepness depends on the brick–mortar pair. Strain at peak stress is typically 0.2–0.3%, and ultimate strains are low, reflecting quasi-brittle behaviour.

Table 4: Representative mechanical parameters of clay brick masonry (indicative)

Property	Typical range	Remarks
Prism compressive strength, f_m	2–15 MPa	Depends strongly on brick and mortar
Elastic modulus, E_m	300–1100 × f_m	Kaushik et al. [9]: mean ≈ 550 f_m
Flexural tensile (bond) strength	0.05–0.5 MPa	Highly variable; suction and workmanship
Initial shear strength, f_{v0}	0.1–0.4 MPa	Eurocode 6; bond-shear tests
Friction coefficient, μ	0.4–0.9	Bed-joint sliding friction
Strain at peak stress	0.2–0.3%	Low ductility in compression

Note: Values reflect general trends in the literature; use code or test values for design.

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2. Tensile and flexural behaviour

Tensile strength is low and governed mainly by unit–mortar bond rather than by either constituent. Parallel to the bed joints, failure may follow a stepped path through head and bed joints or pass through the units. Flexural strength is direction-dependent, generally lower when the failure plane follows a bed joint. This anisotropy is central to out-of-plane behaviour and to the design of two-way spanning panels.

3. Shear behaviour

Shear governs the in-plane seismic resistance of masonry walls. Three failure modes are recognised: (i) sliding along a bed joint, associated with low vertical stress and weak mortar; (ii) diagonal tension through joints and units, typical of squat walls under moderate vertical stress; and (iii) flexural rocking with toe crushing, typical of slender walls under low axial load. The Mohr–Coulomb law, with cohesion and a friction coefficient, is widely used for joint sliding. Magenes and Calvi [10] reviewed and tested the in-plane response of brick walls and showed the influence of axial load, aspect ratio and boundary conditions on failure mode, strength and drift capacity.

Drift limits are roughly 0.4–0.8% for shear-dominated failure and higher for rocking. Energy dissipation is low and strength can degrade abruptly, so confinement and good detailing are important.

4. Biaxial and combined loading

Page [2] tested half-scale brick panels under biaxial compression with bed joints at different angles and showed that strength depends on the angle between the principal stresses and the bed joints. The resulting anisotropic failure envelopes underpin the continuum and homogenised models in Section 7.

STRUCTURAL BEHAVIOUR OF BRICK MASONRY

1. Gravity load and slenderness

Wall capacity falls with increasing slenderness and eccentricity, and codes apply reduction factors based on effective height-to-thickness ratios, which depend on lateral support and end conditions. Buckling is rarely the sole limit state because even moderate eccentricity can crack bed joints and reduce the effective bearing area.

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2. Out-of-plane behaviour

Out-of-plane failure of walls and parapets is a major source of earthquake damage. The wall acts as a vertically or two-way spanning slab, and its resistance depends on flexural tensile strength, arching action, boundary restraint and vertical compression. Slender walls without effective ties to floors, roofs and cross-walls are especially vulnerable. Arching in infill confined by stiff frames can substantially raise out-of-plane capacity, but this benefit may be lost if in-plane damage occurs first.

3. Seismic performance of masonry buildings

Earthquakes including Latur (1993), Bhuj (2001), Kashmir (2005), L'Aquila (2009) and Nepal (2015) show that URM buildings can suffer severe damage. Typical damage includes diagonal cracking in piers, wall separation, out-of-plane collapse of gables and parapets, and failure of poorly anchored roofs. Tomaževič [11] treats seismic behaviour systematically, including box action, diaphragm stiffness, openings and regularity.

IS 4326 [12] and IS 13828 [13] set out earthquake-resistant measures for masonry in India: limited openings, horizontal bands at plinth, lintel and roof levels, vertical reinforcement at corners and jambs, regular plan and elevation, and good mortar quality. Shaking-table and quasi-static tests confirm that bands and vertical reinforcement delay collapse and increase drift capacity, though they do not eliminate damage.

4. Masonry infill in reinforced concrete frames

Brick infill is widely used in RC frames but often ignored in design. It adds considerable lateral stiffness and strength at low drift and is commonly modelled as a diagonal compression strut. Murty and Jain [14] documented its beneficial effect on seismic performance when walls are well distributed. Irregular arrangements, however, such as open ground storeys and partial-height infill causing short-column effects, can concentrate damage and cause collapse. Out-of-plane expulsion of infill is also widespread. Remedies include gaps or flexible joints, ties and mesh anchors, and explicit inclusion of infill in the structural model.

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Table 5: Typical failure modes of brick masonry and mitigation

Failure mode	Typical cause	Mitigation
Vertical splitting in compression	Lateral tension from mortar expansion	Compatible brick–mortar strengths; quality control
Sliding shear on bed joint	Low vertical stress; weak mortar	Higher bond strength; bed-joint reinforcement
Diagonal shear cracking	In-plane seismic shear on squat piers	Jacketing; reinforced plaster; FRP strips
Rocking / toe crushing	Slender piers, low axial load	Vertical reinforcement; pre-compression
Out-of-plane overturning	Poor wall–roof / wall–wall connections	Ties, bands, anchors; lower slenderness
Infill expulsion	Weak anchorage to frame	Mesh anchors; flexible joints; reinforced infill

ANALYSIS AND MODELLING APPROACHES

Modelling masonry is difficult because of heterogeneity, joint-dominated nonlinearity, anisotropy and variable input parameters. Lourenço [4] classified strategies into three levels that still underlie many current approaches.

1. Detailed micro-modelling

Units and mortar are continuum elements and the interface is a discrete element with nonlinear laws. It captures local mechanisms in most detail but demands heavy computation, so it is limited to small specimens.

2. Simplified micro-modelling

Expanded units are continuum elements, while joints are zero-thickness interfaces. Lourenço and Rots [15] proposed a multi-surface interface model with tension, shear and compression caps that reproduces softening and dilatancy. It is widely validated for shear walls.

3. Macro-modelling and homogenisation

Masonry is treated as a homogeneous anisotropic continuum using plasticity or damage models calibrated to composite test data. Lourenço, Rots and Blaauwendraad [16] presented a

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continuum model with direction-dependent yield behaviour, and homogenisation methods such as Zucchini and Lourenço's [17] derive macroscopic behaviour from a representative cell. These approaches are efficient for large structures but may miss local failure mechanisms.

4. Equivalent-frame and macro-element models

For whole-building seismic analysis, walls are idealised as piers and spandrels joined by rigid nodes, each with nonlinear force–deformation behaviour in flexure and shear. Implemented in programs such as TREMURI [18], this approach is efficient and widely used for pushover and dynamic analysis. It suits regular buildings with well-defined openings, and its accuracy depends on sound pier, spandrel and diaphragm models.

5. Limit analysis and discrete-element methods

Limit analysis, kinematic mechanism analysis and discrete-element methods suit arches, vaults and block assemblages that fail by rigid-block motion. They are useful for historic structures and out-of-plane mechanisms but do not explicitly capture deformation capacity.

Table 6: Comparison of modelling strategies for brick masonry

Strategy	Level of detail	Advantages	Limitations
Detailed micro-model	Units, mortar, interface separately	Highest accuracy for local behaviour	Very costly; many parameters
Simplified micro-model	Expanded units + interface	Good crack patterns; moderate cost	Needs interface calibration
Macro / homogenised	Single anisotropic continuum	Efficient for large structures	Limited local sensitivity
Equivalent frame	Piers, spandrels, nodes	Fast; building-level pushover	Best for regular layouts
Limit analysis / DEM	Rigid blocks or mechanisms	Arches and local collapse	No explicit deformation capacity

DURABILITY, DETERIORATION AND DEFECTS

Brick masonry is generally durable, but moisture, salts, freeze–thaw cycles and chemical attack can cause deterioration. The principal mechanisms are:

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- Moisture ingress and rising damp, causing staining, salt transport and loss of mortar cohesion; mitigated by damp-proof courses, drainage and breathable finishes.
- Efflorescence and salt crystallisation, which spall brick faces; low-salt bricks and clean sand reduce the risk.
- Freeze–thaw damage in cold climates, where saturated, highly porous bricks suffer surface scaling.
- Sulphate attack, in which sulphates react with cement hydration products, causing expansion and cracking.
- Movement cracking from thermal, moisture and settlement effects, and from differential movement between masonry and RC; control joints and sound junction details are essential.
- Corrosion of embedded steel (ties, lintels, bed-joint reinforcement), requiring adequate cover and protection.

Condition assessment combines visual surveys with non-destructive and minor-destructive tests, such as flat-jack, sonic and ultrasonic testing, ground-penetrating radar, infrared thermography and core sampling. Binda et al. [19] described integrated diagnostic procedures for historic masonry.

REPAIR AND STRENGTHENING TECHNIQUES

Strengthening aims to improve in-plane shear and flexural capacity, out-of-plane resistance, connections and ductility while limiting loss of heritage value and cost. ElGawady et al. [20] reviewed conventional retrofitting techniques. The principal methods follow.

1. Repointing, grouting and injection

Repointing with compatible mortar restores integrity and weather resistance. Lime- or cement-based grout can fill voids and cracks and restore continuity in rubble or multi-leaf walls. Compatibility of stiffness, permeability and salt content is critical, particularly in historic masonry.

2. Reinforced plaster and ferrocement overlays

Cement mortar applied over steel mesh on one or both faces, anchored through the wall, increases shear and flexural capacity and improves post-peak behaviour. It is economical and suits developing-country conditions, though it adds mass and alters appearance.

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3. RC and shotcrete jacketing

RC or shotcrete jackets give large gains in strength and confinement but add stiffness and weight, may alter load paths and need good bond to the substrate.

4. Fibre-reinforced polymer and other composites

Externally bonded carbon, glass or aramid FRP strips or sheets can raise in-plane shear and out-of-plane flexural strength with little added weight. Valluzzi et al. [21] reported significant gains in FRP-strengthened panels, although failure was often governed by debonding or substrate failure. Fabric-reinforced cementitious matrix (FRCM) and textile-reinforced mortar (TRM) systems address limitations of organic resins, such as poor fire resistance, vapour impermeability and substrate incompatibility, and are increasingly adopted.

5. Confinement, bands and tying

Steel or RC bands, tie rods and anchors enhance box action, restrain out-of-plane movement and connect walls to diaphragms. IS 13828 describes horizontal and vertical reinforcement for new low-strength masonry and bands for existing buildings. Post-tensioning with bonded or unbonded tendons also provides pre-compression and improves rocking behaviour.

Table 7: Overview of strengthening techniques

Technique	Primary benefit	Advantages	Drawbacks
Grout injection / repointing	Restores continuity	Low intrusion and cost	Limited strength gain
Reinforced plaster / ferrocement	Shear and flexure	Cheap, simple, common	Adds mass; alters appearance
RC / shotcrete jacket	Large capacity increase	Strong, robust	Heavy; foundation checks
FRP / FRCM / TRM	Shear, out-of-plane	Light, quick	Debonding; cost
Bands, ties, anchors	Box action, connections	Prevents collapse	Does not raise wall strength
Post-tensioning	Pre-compression	Improves rocking, cracking	Needs skilled design

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SUSTAINABILITY AND ALTERNATIVE MASONRY UNITS

Fired clay brick has a considerable environmental footprint: kilns burn large quantities of fuel, emit carbon dioxide and particulates. Venkatarama Reddy and Jagadish [22] showed that fired-brick walls can have far higher embodied energy than stabilised-earth-block walls, depending on kiln type and fuel. Improved kilns (vertical-shaft, zig-zag, tunnel) and better fuel use can markedly reduce emissions.

Alternatives under study include fly ash bricks, cement-stabilised earth blocks, autoclaved aerated concrete, bricks incorporating rice husk ash, plastic waste, foundry sand or sludge, and geopolymer units. These can cut waste disposal and sometimes avoid firing, but their durability, long-term strength, moisture movement and seismic behaviour must be proved on masonry assemblages, not units alone. Life-cycle assessment should also count operational energy, since the thermal mass of brick walls can reduce heating and cooling demand and partly offset embodied energy.

DESIGN CODES AND STANDARDS

National standards differ in philosophy (working-stress versus limit-state) and in their provisions for units, mortar and detailing. Major standards for brick masonry are listed in Table 8.

Table 8: Selected standards relevant to brick masonry

Standard	Region	Scope
IS 1077	India	Common burnt clay building bricks – specification
IS 3495 (Parts 1–4)	India	Methods of tests of burnt clay building bricks
IS 1905	India	Structural use of unreinforced masonry
IS 2212 [23]	India	Brickwork – code of practice
IS 4326 / IS 13828	India	Earthquake-resistant construction; low-strength masonry
IS 1893 (Part 1) [24]	India	Criteria for earthquake-resistant design
EN 1996-1-1 (Eurocode 6)	Europe	Design of reinforced and unreinforced masonry
EN 1998-1 (Eurocode 8)	Europe	Seismic design, including masonry

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ASTM C62, C270, C1314	USA	Brick, mortar and prism strength test
TMS 402/602	USA	Masonry design code and specification

Note: Check the current edition of each standard.

Codes differ significantly in strength estimation, safety factors and seismic detailing, and comparative studies report substantial variability in predicted capacity. Harmonised testing and calibration against local materials remain needed.

CRITICAL DISCUSSION AND RESEARCH GAPS

The fundamentals of masonry mechanics are broadly agreed, but several issues remain open:

- **Variability and quality control.** Local bricks and mortar show large scatter, and formulas calibrated on laboratory samples may overestimate real wall performance. Regional databases and simple field tests are needed.
- **Weak mortar and low-strength masonry.** Much existing stock uses soft bricks and weak mortar, for which models are less well calibrated.
- **Interface characterisation.** Cyclic bond behaviour and its dependence on suction, moisture and age is poorly quantified, so reliable model parameters are often unavailable.
- **Infill–frame interaction.** Design-oriented models are needed for combined in-plane and out-of-plane infill behaviour and the effect of openings.
- **Performance-based design and fragility.** Drift limits and fragility curves for different masonry types need larger experimental and post-earthquake databases.
- **Retrofit of non-engineered stock.** Affordable, locally implementable retrofit and community uptake deserve more attention than high-technology solutions.
- **Low-carbon masonry.** Durability, hygrothermal and seismic performance of alternative units must be proved at assemblage and building scale.
- **Digital methods.** Machine learning, image-based damage detection and digital twins are promising but need validation against reliable experimental data.

CONCLUSIONS

Brick masonry remains a versatile, economical and durable construction system and will stay important for the foreseeable future. The principal conclusions are:

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- Behaviour is governed by the interaction of unit, mortar and interface. Compressive failure is controlled by lateral tension in the brick, so raising mortar strength beyond a suitable level helps little, whereas tensile and shear behaviour are controlled by bond.
- URM has low tensile strength, limited ductility and strong directionality, making it vulnerable to seismic and out-of-plane actions. Failure modes are well characterised, but capacity prediction remains uncertain.
- Box action, connections, regularity and workmanship often matter more to seismic performance than higher material strength.
- Modelling options range from detailed micro-models to equivalent frames; the choice should reflect the analysis objective, data quality and required accuracy.
- Repair and strengthening choices depend on the structure, heritage value, budget and local skills; compatibility between old and new materials is paramount.
- Environmental concerns justify efficient kilns, alternative units and life-cycle-based design, provided performance and durability are demonstrated.

Future work should reduce uncertainty through better material characterisation, turn advanced numerical research into practical design tools, and develop low-cost retrofit and low-carbon alternatives for the large masonry stock of developing regions.

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