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Evolving Vernacular: Reinventing Rammed Earth in the Context of Twenty-First Century Seismic Regulation

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The vernacular architecture of the Auvergne-Rhône-Alpes region in southeast France is dominated by unstabilized rammed earth buildings. Despite a plentiful source of raw material, cultural anchorage, and low carbon footprint, the use of rammed earth in new building projects is severely constrained by contemporary building codes and norms which have been developed around industrial building products, to the detriment of natural building materials. In particular, stringent seismic regulations have rendered monolithic earth masonry difficult to justify structurally. The *Maison Pour Tous* design/build project identifies and demonstrates a replicable path for new rammed earth buildings within the existing regulatory framework. While cost remains a challenge, the successful realization of the *Maison Pour Tous* illustrates that rammed earth is no longer relegated to the region's past.

Introduction

For centuries the inhabitants of the Auvergne-Rhône-Alpes region of France have found that their soil was perfectly adapted to rammed earth construction. Their earth vernacular ultimately led to the (re)invention of contemporary concrete. Notably, in Grenoble in 1817, Louis Vicat innovated an artificial hydraulic lime cement that is considered the principal forerunner of Portland Cement in 1824.¹ Now, after more than 150 years of nearly ubiquitous concrete production, and in the face of industrial concrete's negative environmental impacts, there is a renewed appreciation for low carbon, locally sourced, simply prepared and culturally relevant building materials and techniques such as rammed earth. However, because these traditional materials and techniques have been mostly dormant since the massive reconstruction effort following the Second World War, they lack the characterization, normalization, and standardization of their contemporary counterparts. This has often limited application due to complex regulatory frameworks, particularly for public buildings or for buildings in elevated seismic risk zones. In 2017 a group of students, faculty, and researchers from the National Architecture School in Grenoble, France (ENSAG) launched a design/build rammed earth community center project, the *Maison Pour Tous* in Four, France, to chart a replicable and insurable course forward for the region's primary traditional building technology (Figure 1).

Architectural research can take many forms, from humanities-based research to those more closely allied with the hard sciences. One underappreciated yet vital form of architectural

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◁ Figure 1. South/east corner of the *Maison Pour Tous*. (Credit: Eduard Hueber / archphoto)

research can be found in the act of building, so long as the research questions are clear, the methodologies well documented, and the results are able to be validated and disseminated. The *Maison Pour Tous* project is such a case, with its clearly articulated exploration of seismic design for rammed earth buildings within the context of contemporary building codes and a contemporary culture of building.

Material Context

Ramming is an action: a construction technique. Earth is a material: a granular mixture of naturally occurring minerals. Rammed earth, in its simplest form, is building by ramming earth. The result is, by definition, a concrete: a composite of granules held together by a binder.² In contemporary concrete, sand and gravel are the fine and coarse aggregates and industrially produced Portland Cement is the binder. The dry mix, when hydrated, begins a chemical reaction producing a new solid. While this solid can be crushed or otherwise broken down, the nature of the chemical reaction is an irreversible material transformation: a construction product. According to the US EPA, 1,000 kg of CO₂ is emitted for every 1,000 kg of Portland cement manufactured for use in this product.³

Rammed earth, on the other hand, is a natural, non-industrial concrete. Sand and gravel remain the fine and coarse aggregates, but clay is the binder. The environmental imperatives of this are first that clay is naturally occurring and thus does not require any CO₂-producing transformation and second that the strength of the material is the result of a physical, not chemical, reaction. The raw material is thus infinitely reusable (not to be confused with recyclable or down-cyclable). A hybrid class of Portland Cement or lime enhanced rammed earths have been developed and are often referred to as *stabilized*. These materials, primarily used in North America and Australia, often boast high compressive strengths and enhanced erosion resistance but do not share the same level of environmental benefits, such as low-embodied energy and infinite reusability.

Historical Context

In the Auvergne-Rhône-Alpes region, rammed earth (*pisé*) is by far the most common traditional construction material/technique, in some villages representing more than 80% of the historic building stock.⁴

The region's rammed earth is the expression of a construction culture with a long lineage that likely arrived from Morocco across Spain towards the end of the first millennium CE and which found an ideal and abundant material in the soils of the region.⁵ Beginning approximately 100,000 years ago, as the Würm glaciation began retreating into the Alps, glacial-fluvial and eolian activity deposited a homogeneous mixture of stones, gravel, sand, silt, and clay across the plain between the base of the Alps in the East and the Rhone River Valley in the West. Because this soil is naturally cohesive and deposited very close to the surface, this region was ripe for the development of an earth-architecture vernacular.⁶

An important factor in this development occurred toward the middle of the eighteenth century, with the publishing of construction treatises by scholars such as Jean-Baptiste Rondelet⁷ and a series of how-to “notebooks” on earth construction by François Cointeraux. Cointeraux offered the most consequential impact by highlighting rammed earth's economic advantages, its fire resistance, and other important characteristics—and even set up a school of “rural architecture” not far from Grenoble.⁸

Despite the ubiquity of local building cultures in earth, stone, wood, and thatch prior to the First and Second World Wars, the significant loss of craftsmen and the massive post-war reconstruction efforts largely displaced these materials and techniques with industrialized products such as steel and Portland-Cement-based concrete.

Regulatory Context

The Eurocode (as well as national supplements to the Eurocode) regulates the safety and resiliency of buildings.

The French Center for the Science and Technique of Building (CSTB) convenes industry experts to characterize, normalize, and standardize construction materials and building systems.

Despite similarities in regulation, a fundamental difference between Europe and North America is related to implementation. While code officials in North America are public employees charged with enforcement, their European counterparts—control offices—are private companies who independently certify conformity with codes and standards by authoring written opinions, primarily to insurers. While at first glance their advisory role might seem toothless, a control office's "unfavorable opinion" equates to no insurance, and no insurance equates to no financing. Even if financing is not required, an uninsured building cannot open to the public.

As with most contemporary codes and standards, the regulatory frameworks are prescriptive rather than performance-based. That is, they are in practical terms exclusive and incomplete. Materials and techniques like rammed earth fall outside the conventions of contemporary practice and are not only absent from the standards but remain so because they lack the institutional infrastructure and financial investment to gain access. This absence of approved standards renders a control office unable to render an objective "favorable opinion" on unconventional materials or practices.

In recognition of this situation, there exists in France a secondary review and approval process, an Experimental Techniques Assessment (ATEX). A "simple" ATEX-B is project specific and requires a project owner and A&E team to empirically demonstrate to a CSTB panel that the experimental method proposed performs at least as well as otherwise approved materials and techniques. As one might imagine, the testing required to gain approval adds significantly to the schedule and budget of a project and ensures that ancestral techniques remain marginal. However, the success of several ATEX-B rammed earth projects and an increasing demand has led to several architects, engineers, and researchers, including CRATERre (the ENSAG research lab dedicated to the documentation and preservation of the world's earthen architecture heritage) to collaborate on the drafting of a more broadly applicable ATEX-A. The aim of this longer, more expensive process is to characterize the performance of rammed earth generally.⁹ While this work and the CSTB approval process remain ongoing, it was far enough along and the results of independent laboratory testing were convincing enough that in 2017 a control office was willing to offer a favorable opinion of the *Maison Pour Tous* project. The control office however imposed the explicit caveat that extensive seismic force mitigation would need to be documented, approved, and implemented.

Since 2011, the entire Auvergne-Rhône-Alpes region has been redefined by the French National Environmental Code as either "moderate" or "medium" seismic activity risk zones. Consequently, all new construction in Four, a moderate risk zone, must meet maximum horizontal acceleration (a_{max}) of $\pm 0.3 \text{ m/s}^2$ ($\pm 0.984 \text{ ft./s}^2$). Since seismic force is a product of horizontal acceleration and mass (Force = Mass*Acceleration), massive constructions—rammed earth has an average density of $1,900 \text{ kg/m}^3$ (119 lb./ft.^3)—significantly increase the seismic

force. Despite the fact that for more than three centuries rammed earth has contributed innumerable currently standing buildings to the region's built cultural heritage, it is no longer possible to justify new load-bearing earth constructions without hybridizing the structure: rammed earth to resist gravity loads and something else to resist lateral loads imposed by seismic forces. The "something else" required to efficiently and sensibly overcome this fundamental safety (and thus insurability) question is key to the revitalization of rammed earth in the Auvergne-Rhône-Alpes region and was thus a major underpinning of the *Maison Pour Tous* project.

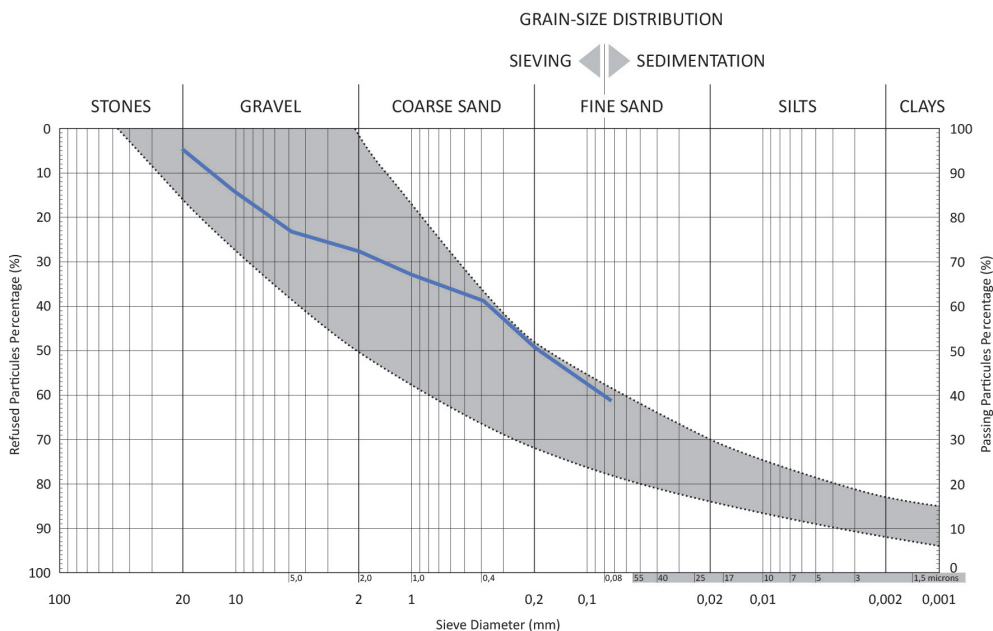
Sourcing and Field Testing

The ecological ideal in rammed earth construction is to recover material from utility trenches and foundation excavations in order to build walls. The site of the *Maison Pour Tous* was formerly a parking lot which had been filled with a lime stabilized sand-gravel mix that because of its previous chemical transformation was unsuitable for rammed earth.¹⁰ However, because glacial-fluvial soil is omnipresent in the region and because this soil horizon covers a crushed gravel horizon, quarries consider this suitable material to be waste and are generally happy to offer it for free or at very low cost. A distinct advantage to quarry-sourced raw material is that its granular composition and distribution tends to be extremely consistent.

The project team visited several quarries within a 30 km (18.6 mi.) radius of the site and carried out field tests (touch, smell, sieve, and sedimentation). Soils are granular mixtures of eroded stone that can be separated, either by sifting with different size sieves for aggregates or by sedimentation in a water suspension for fine particles. Depending on the granule size, these components have different names: in order from finest to largest following the IUSS classification system, clays are less than 0.002 mm, silts range from 0.002 to 0.02 mm, fine sands from 0.02 to 0.2 mm, coarse sands from 0.2 to 2 mm, gravel ranges 2 to 20 mm, and stones from 20 to 200 mm.

While larger granules are angular solids, clays are phyllosilicates: plate shaped particles. In Greek φύλλον (pronounced *phullon*) translates to "leaf-like." When mixed with water, these microscopic particles form a colloid paste of homogeneous color, reminiscent of a type of glue. In fact, the ancient Greek root of the word colloid κόλλα (pronounced *kólla*) translates to "glue." Even when clays appear to be dry, at equilibrium moisture content, microscopic water droplets bind the platelets together through the cohesion of capillary bridges. This phenomenon can be illustrated by placing a drop of water between two smooth flat surfaces, sticking them together and then attempting to pull them apart. Like a wet-mount slide, the two plates adhere across a capillary bridge and become extremely difficult to separate. However, when fully dried by driving off the moisture with 150°C (302°F) to 200°C (392°F) heat, the platelets disperse back into individual granules (not to be confused with kiln firing at $1,200^\circ\text{C}$ (2192°F) where the platelets are permanently fused).¹¹

What all this tells us is that while fully dried clay is a dust-like powder of extremely fine flat granules, raw clay, dug from the earth at equilibrium moisture content, is a solid. Adding



◁ Figure 2. Excerpt of lab report from sieve testing indicating a passing sample after correcting for gravel composition in the 5-20mm range. (Credit: ENTPE)

moisture increases its plasticity and workability but excess hydration significantly disperses the clay particles and increases the likelihood of shrinkage cracks when returning to equilibrium. While the mass of a small piece of clay shrinks uniformly, larger pieces are likely to form cracks due to variable shrinkage. It is therefore not possible to build a monolithic rammed-earth wall solely from clay. The aggregate grains are thus the structure which resists the shrinkage of the clay during drying.

When sieved and graphed, good rammed earth soils exhibit a uniformly curved granular spectrum between 0.001 mm (clay binders) and 40mm (coarse aggregates). The results of these first field tests led to the choice of a gravel quarry in Oytier, 14.8 km (9.2 mi.) from the project site. At the time of extraction an industrial scale vibrating screen removed all material larger than 31.5 mm (1.24 in.) and ensured a homogeneous mix of the remaining granule sizes.

Refinement and Laboratory Testing

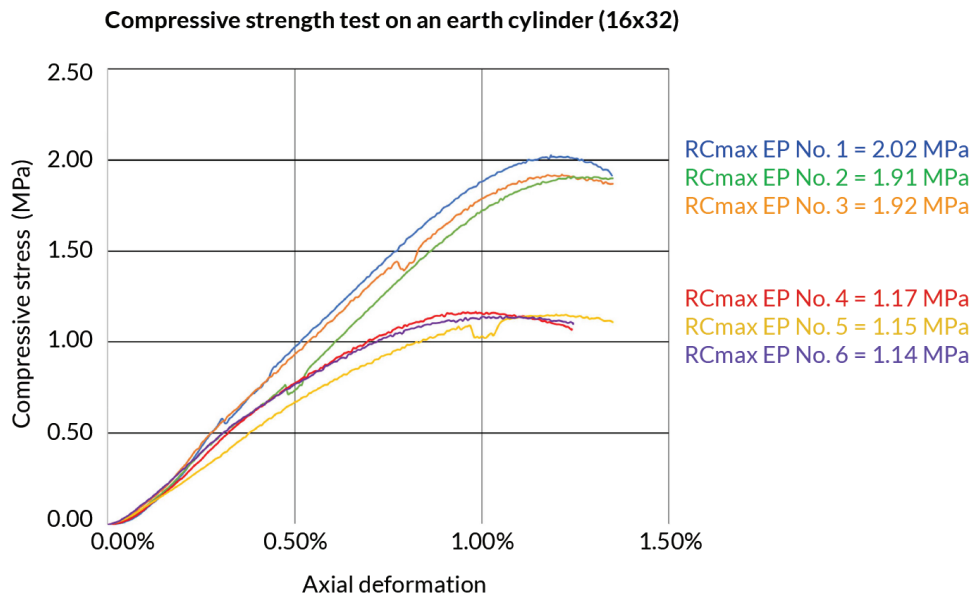
More vigilant testing followed at Les Grands Ateliers (a large-scale building experimentation complex shared by the French architecture schools). Continued sieving and graphing of the material delivered from the quarry indicated a passing but slight deficiency in gravel in the 5-20 mm range so the raw material was slightly corrected by the addition of 5% crushed gravel at 5-11 mm and 10% crushed gravel at 10-20 mm, from the same quarry. This material was added at the time of hydration (Figure 2).¹²

When earth is over-hydrated the material becomes too plastic to compact and when the material is under-hydrated the clay particles do not adhere. In the lab, Proctor compaction testing was used to identify optimum moisture content. However, because accurately measuring moisture content demands beginning with fully dried material, optimum moisture content is impractical to quantifiably control in the field.

For this reason, the observational “Ball Test,” developed by CRAterre, is typically deployed in the field to consistently produce an optimally hydrated mix. With each batch, a ball of earth is formed in the hand and released from a height of approximately 1 m (3.3 ft.). If the ball breaks into many pieces the mixture is too dry. If the ball does not break, the mixture is too wet. At optimum moisture content the ball breaks into two or three pieces.¹³ During the mix refinement stage of the project, Proctor Test samples were regularly compared to Ball Test samples to ensure that in-the-field moisture content would be consistent with lab moisture content.

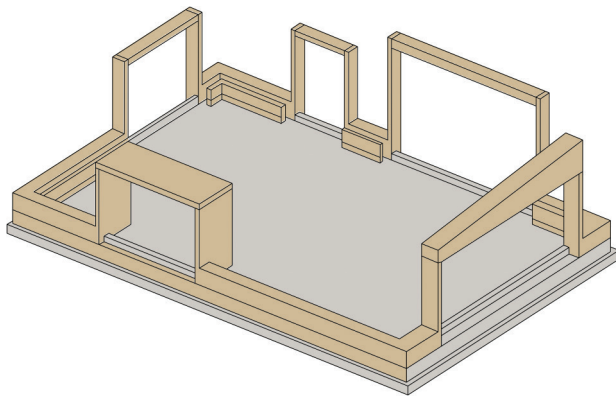
Generally, unstabilized rammed earth varies in compressive strength from 0 to 2 MPa (0 to 290 psi). In addition to a well-proportioned mix, maximum density is a key factor in achieving maximum compressive strength. Density’s variables are compaction force and lift height. In order to ensure that coarse aggregates are fully embedded in the clay matrix, lift height should not be less than twice the diameter of the largest aggregate in the mix. And since force chains in granular materials deviate from the axis of the force, lift height that exceeds five times that same diameter tends not to fully compact near the bottom of the lift.¹⁴ Because the raw material was screened at 31.5 mm (1.24 in.) in the quarry, 80 mm (3.15 in.) lifts were chosen. Use of a pneumatic backfill tamper for raming ensured maximum compaction.

A standard compression test with 160 mm x 320 mm (6.3 in. x 12.6 in.) cylinders was regularly undertaken to establish the working compressive strength of the corrected mix. These test cylinders were placed in a laboratory oven for 24 hours at 60°C (140°F) to drive off excess moisture at the core of the samples. Once the mix development samples consistently produced a result above 1.9 MPa (276 psi) of compressive strength at Les Grands Ateliers, six representative samples were transmitted to the Ecole Nationale Supérieure des Travaux Publics de l’Etat



◁ Figure 3. Compressive strength testing results of six cylindrical samples. (Credit: ENTPE)

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△ Figure 4. Axonometric illustration of reinforced concrete stem-walls and moment frames for the *Maison Pour Tous*. (Credit: Vessiere)

(ENTPE) in Lyon for independent testing in accordance with NF EN 772-1+A1 (the European norm for determining the compressive strength of masonry elements). Three samples were tested after 19 days at an ambient temperature between 20°C (68°F) and 24°C (75°F) and three were tested after 19 days at ambient temperature plus 24 hours in the laboratory oven at 60°C (140°F). The dried samples produced an average of 1.94 MPa (281 psi) of compressive strength (Figure 3).¹⁵

Structural Design

While high-quality unstabilized rammed earth can achieve a respectable 2 MPa (290 psi) compressive strength, its tensile strength, like that of unreinforced Portland-Cement-based concrete, trends around 10% of the material's compressive strength.¹⁶ This mechanical performance renders the material ineffective when designing for lateral loads like earthquake resistance, therefore requiring a second element of a hybridized structure.

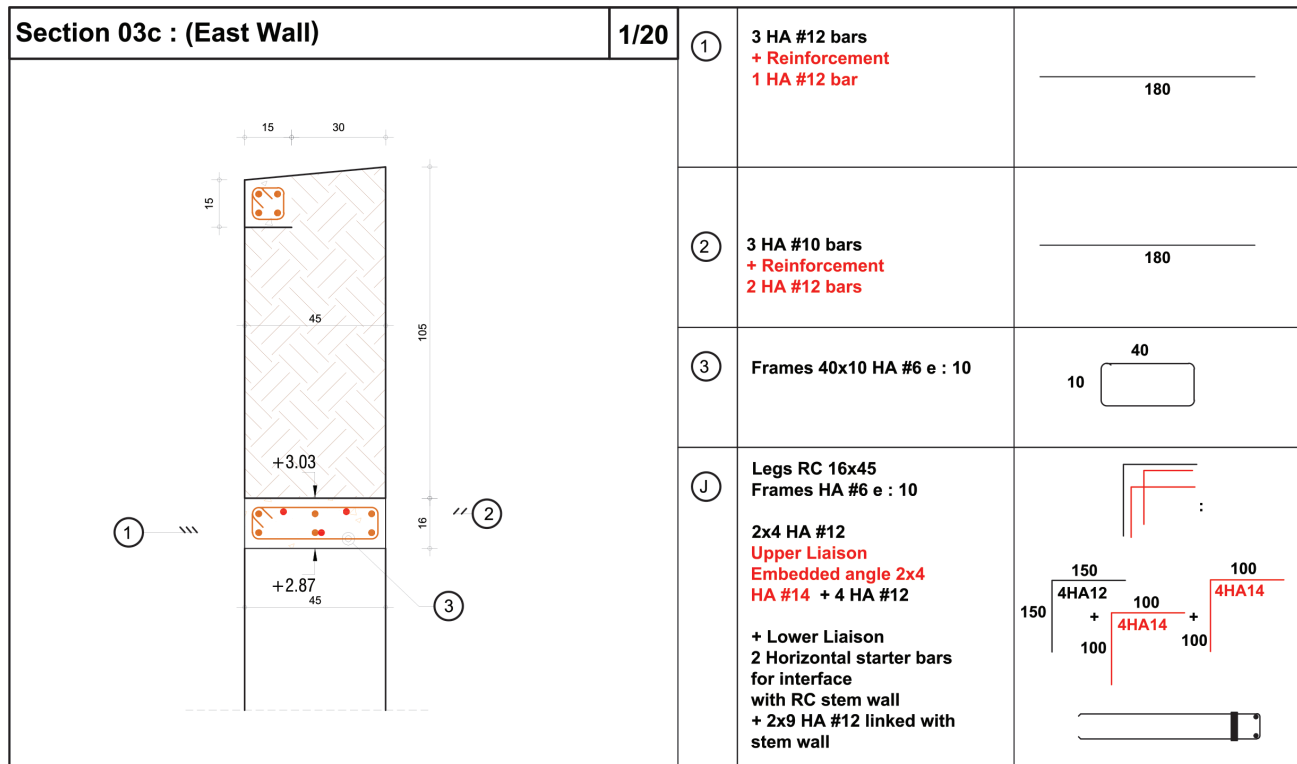
One technically feasible but impractical solution is to reinforce the rammed earth with steel bars. Like contemporary steel-reinforced concrete, arming a wall and tying a beam at its head to a foundation at its base significantly augments the assembly's performance in base shear and in tension. The problems with this solution are the corroding effect of the hygroscopic earth material on the reinforcing steel and the difficulty for a craftsman to ram with a pneumatic tamper around full-height steel bars while occupying a relatively narrow 45 to 60 cm (17.7 to 23.6 in.) wide formwork.

Because the design of the *Maison Pour Tous* included at least one large opening in each of the building's four walls, the seismic design strategy was to use moment-resisting reinforced concrete frames at each opening. In addition to the lateral seismic load resistance, these elements offer the added benefit of limiting abrasive wear at the building's primary access points. From a life cycle analysis point of view, this solution segregates the gravity-load-resisting material, the unstabilized rammed earth, from the seismic-load-resisting industrial construction product, the reinforced concrete. This segregation ensures that the earth material will be fully recoverable and reusable at the end of the building's service life (Figure 4).

Because the building is a single-story, 14.5 m x 9.5 m (47.6 ft. x 31.2 ft.) rectangle, the *equivalent force method* calculation was used. The purpose of the calculation was to justify that the five reinforced concrete frames were designed to resist all lateral seismic forces.

The verification of stability and dimensioning were based on:

- Eurocode 0 and national annex for the basis of calculation of structures (NF EN 1990)
- Eurocode 1 and national annex for the calculation of actions on structures (NF EN 1991)
- Eurocode 2 and national annex for the calculation of reinforced concrete structures (NF EN 1992)



△ Figure 5. Moment frame reinforcing details for the *Maison Pour Tous* east wall. (Credit: Vessiere)

- Eurocode 5 and national annex for the design of wooden structures (NF EN 1995)
- Eurocode 6 and national annex for the design of masonry structures (NF EN 1996)
- Eurocode 8 and national annex for design under seismic loads (NF EN 1998)
- the decree n° 2010-1255 of October 22nd on the delimitation of seismicity zones on French territory—consolidated version as of May 1, 2011
- the decree of 22 October 2010 relating to the classification and earthquake-proof construction rules applicable to buildings in the so-called “normal risk” class—consolidated version as at October 31, 2012
- the guide to French recommendations EC8

In accordance with independently verified laboratory data and the above cited governing documents, the following values were assumed:

- density of reinforced concrete = 2,500 kg/m³ (156 lb./ft.³)
- density of rammed earth = 1,900 kg/m³ (119 lb./ft.³)
- G' roof = 0.5 kN/m² (10.4 psf)
- snow load for gravity = 0.77 kN/m² (16.1 psf)
- snow load for horizontal seismic thrust = N/A (altitude < 500m)
- damping of the structure by reinforced concrete: $\xi = 5\%$
- Zone 3 “moderate seismic risk”: $a_{gr} = 1.1 \text{ m/s}^2$ (3.6 ft./s.²)
- building importance category II: $\gamma_l = 1.0$

- soil class C: $S = 1.5$
- safety factor: $q = 1.5$ (least favorable)

With 140 kN (31.5 kips) of timber, 400 kN (89.9 kips) of reinforced concrete, 760 kN (170.9 kips) of rammed earth and a maximum horizontal acceleration of 2.75 m/s² (9 ft./s.²), the *Maison Pour Tous*'s reinforced concrete frames were designed to resist a horizontal seismic force ($F_{sism} = M_{sism} \cdot a_{max}$) of 375 kN (84.3 kips) or 187.5 kN (42.2 kips) in each axis. Approximately 250 kN (56.2 kips) of concrete—out of the 400 kN (89.9 kips) total or 60 kN (13.5 kips) of the seismic mass—is attributed to the foundations at the foot of the rammed earth wall and therefore produces only a negligible seismic action on the frames. It was nevertheless considered that the full seismic mass would be evenly distributed along the full height of each frame.

Frame number 2 (the north elevation), which is 2.3 m (7.55 ft.) tall, was thus designed with 187.5 kN (42.15 kips) shared by two legs, or a uniformly distributed load of 41 kN/m (2.8 k./ft.). Reinforcing steel linking the base of each leg to its adjacent 40 cm (15.75 in.) tall concrete stem wall allowed for the design to consider a partial embedment, yielding a maximum moment of 80 kN-m (59 kip-ft.) at the top of the frame. The frame was thus designed as a 45 cm x 16 cm (17.7 in. x 6.3 in.) rectangular concrete section – 45 cm (17.7 in.) to align with the thickness of the adjacent rammed earth work—and required a 12 cm² (1.86 in.²) section of reinforcement, or eight right angle bars 14 mm (0.55 in.) in diameter each (Figures 5 and 6).¹⁷

In order to account for the variable moisture content of the clay-bound rammed earth material and thus the permanent differential in expansion and contraction relative to



△ Figure 6. North/west corner stem wall and moment frames. (Credit: designbuildLAB)



△ Figure 7. Lifting prefabricated rammed-earth wall panels into place. (Credit: Lauriane Lespinasse)



△ Figure 8. Filling joints between prefabricated rammed-earth wall panels. (Credit: designbuildLAB)



△ Figure 9. Concrete moment frame and chamfered control joints at west rammed-earth wall. (Credit: Eduard Hueber / archphoto)

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the Portland-Cement-based steel reinforced concrete, and because the seismic force is simply buttressed by moment frames in both axes, the rammed earth remains dependent on but separate from the reinforced concrete. Full depth cold joints ensure independent movement while chamfered edges between the earth and the concrete anticipate and compensate for variable movement.

Mock-up and Realization

A full-scale mock-up wall section was realized in order to transition from the abstraction of the studio and lab to the reality of the construction site. The mock-up enabled the validation of design assumptions such as concrete frame proportions and rammed earth lift thickness, the refinement of details such as locations of butt joints and chamfer joints, and the optimization of construction site organization and task division.

To achieve the prescribed 8 cm (3.15 in.) lift heights, 15 cm (5.9 in.) of loose earth mix was evenly spread in the formwork. The height of these lifts as well as the overall wall height were

relentlessly controlled. For example, the north wall is exactly 352 cm (138.6 in.) high and therefore is composed of exactly 44, 8 cm (3.15 in.) lifts. This meticulousness ensured that the quality of the rammed earth wall was as close as possible to the quality produced and tested in small batches in the lab.

Conclusion

Today, despite its cultural and environmental sustainability, and despite advances in code compliance and normalization, rammed earth (as with other low-yield, labor-intensive building technologies) often costs significantly more than industrialized alternatives. By means of comparison, the average cost (labor and materials) in 2018 of a reinforced concrete wall in France was between 200 and 250€/m² while comparable rammed-earth construction cost four times more.¹⁸

Prior to the industrial revolution, two-thirds of total construction costs were allocated to material and one-third were allocated to labor. Since then, the ratio has inverted; contemporary mass-produced construction products are relatively

inexpensive as compared to labor costs. Thus, the savings realized by using an essentially free material like earth are inconsequential compared to the savings which can be realized by minimizing labor costs. This question of labor is further complicated by the region's weather—rainy autumns and freezing winters—which limits on-site earth construction to the spring and summer months.

The obvious response to both issues is indoor prefabrication, which limits mobilizations, maximizes efficiencies, and maintains independence from weather. The *Maison Pour Tous* took a modest, first step toward prefabrication by producing the non-loadbearing interior layer of its insulated rammed earth sandwich wall off-site and then assembling the units under the shelter of the building's finished roof (Figures 7 and 8). While this first step facilitated the rehearsing of logistical challenges like staging, drying, transportation, and final assembly, the seismic challenge limited prefabrication to non-bearing components of the building. Understanding and normalizing the behaviors of an assembly of independently rammed prefabricated earth blocks in a seismic risk zone remains key to opening the mass implementation of contemporary rammed earth in the Auvergne-Rhône-Alpes region (Figure 9).

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Notes

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