Review of the Current State of Cob Structural Testing, Structural Design, the Drafting of Code Language, and Material Based Testing Challenges

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Abstract

Cob, also known as monolithic adobe, is an ancient, traditional building material employed primarily as a structural bearing wall system. Cob consists of clay-soil and sand, traditionally reinforced with straw, although contemporary designs can also use other types of reinforcement, such as steel. This paper will review how structural cob tests relate to current engineering design approaches for the material and the development of the proposed Cob Construction Appendix in the 2021 International Residential Code (IRC). This paper also explores the most significant finding in structural cob research to date, some inherent material testing obstacles, and recommended future testing approaches.

Report

This paper highlights the current state of research of cob construction and its relationship to the engineering and code development of the cob wall system. Likely due to the lack of proprietary commercial advantages of the material and its differences with conventional materials in strength and construction, there has been little investment in research. A list of all known small scale, partial scale and full-scale tests follow. The authors of this report have consulted or participated on a number of these tests, as indicated in the list below.

Small Scale Tests: Compression, Modulus of Rupture, and/or Modulus of Elasticity

- 1995, Saxton, U. of Plymouth Eng, *The performance of cob as a building material*
- 2006, Akinkurolere et al, U. of Technology, China, U. of Ado-Ekiti, Nigeria, *Engineering Properties of Cob as a Building Material*
- 2011, Pullen et al, U. of Oregon, *Index And Engineering Properties of OR Cob*
- 2013, Rizza & Mori-Böttger, U. of San Francisco, *Effects of Straw Length and Quantity on Mechanical Properties of Cob*.**

- 2014, Miccoli, et al, Germany, Sweden, *Mechanical behavior of earthen materials: a comparison between earth block masonry, rammed earth and cob.*
- 2014, Miccoli et al, Germany*, Bond strength of anchor pins for earthen buildings. A comparison between earth block masonry, rammed earth and cob.*
- 2017, Leza et al, Santa Clara U., *Sustainable Construction Material Research*
- 2017, Daanomah, Washington State University*, Cob Project*,
- 2018, Eberhard et al, Santa Clara U., *Cob: A Sustainable Building Material****
- 2018, Brunello et al, Santa Clara U., *Cob Property Analysis.****
- 2019, Wright & Henshaw, U. of Tulsa, *Transient Mechanical Properties of Cob*
- 2019, Sargent et al, California Polytechnic State University, Report pending ***

Partial Scale Tests: Half scale shake table test

- 2004, Ventura, U. of British Columbia, *Cob Shake Table,* video, no report
- 2008, Albert-Thenet, U. of Technology Sydney, *The Earthquake Resistance of Cob Structures.*

Full Scale Tests: In-plane reverse cyclic tests

- 2018, Eberhard et al, Santa Clara U., *Cob: A Sustainable Building Material* ***
- 2018, Brunello et al, Santa Clara U., *Cob Property Analysis.****
- 2019, Sargent et al, California Polytechnic State University, Report pending ***

Full Scale Tests: Out-of-plane tests

2019, Dente, Cob Research Institute, report pending***

** The authors of this report consulted *** The authors of this report participated

Cob is a monolithic construction material system consisting of clay-soil, sand, and a longer bio-micro-fiber reinforcement, typically straw. Contemporary designs can also use other types of reinforcement, often steel. Testing of other dominantly clay based material can be relevant to cob analysis, though will not be extensively reviewed in this report. Some examples include: Adobe codes, and research through The Getty Conservation Institute, Cob is also known as monolithic adobe, Clay documentation in Gernot Minke's [14], *Building With Earth, Design and Technology of a Sustainable Architecture [14]*, and clay plaster testing for Straw Bale Construction such as, 2003, Donahue, Lerner, *Structural Testing Of Plasters For Straw Bale Construction.*

Permitted Structures and Cob Code Development:

There is currently no adopted code in the United States that governs the structural design of cob construction. ASTM E2392-10, Earthen Wall Building Systems, has not been referenced by any International Code Council (ICC) code, though currently stands as the most recognized standard in the United States governing the structural design of cob. ASTM E2392-10 includes recommendations for R-factors, height:thickness ratios, and directs engineers to the New Zealand Earthen Building Standards NZS 4297, NZS 4298, and NZS 4299. New Zealand is a seismically active country with the most developed earthen building codes and the only recognized engineered earthen building code. Prescriptive codes for cob exist in Germany, India and other countries.

Due to the lack of a governing code in the United States, the Cob Research Institute (CRI) has submitted a proposed Cob Construction Appendix for inclusion in the 2021 International Residential Code (IRC), the prescriptive model code for residential construction in the United States. This code proposal is currently pending approval.

The design of permitted cob structures in the State of California and the development of the structural portions of the proposed IRC appendix have been conducted by this report's authors, through their engineering firm, Verdant Structural Engineers of Berkeley, CA, and CRI, utilizing references contained in this report.

Shear wall systems in the proposed IRC Appendix: This information and the entire IRC proposal are limited to IRC Seismic Design Categories (SDC) A, B and C.

Wall Type[a]	Anchors to Foundation[b]	Anchors to Bond Beam[c]	Vertical Steel Reinforcing[b, c]	Horiz. Steel Reinforcing	Max HT (Ft)	Max Aspect Ratio (H:L)
A	none	5/8" all-thread @12", 4" from wall ends 12" embed in cob	none	none	7	1:1
B	#5 bar @ 12" 16" embedment in cob	5/8" all-thread @12", 4" from wall ends 16" embed in cob 2"x2"x1/4" washer and nut embed in cob	none	2"x2"x 14 ga WWM @ 18", 6" from foundation and bond beam	7	1:1
C	#5 bar @ 12" 16" embedment in cob	5/8" all-thread @12" 16" embedment in cob	5/8" all-thread 4" from each end of shear wall continuous from foundation to bond beam	2"x2"x 14 ga WWM @ 18", 6" from foundation and bond beam	7	2:1
D	(see vertical steel reinforcing)	(see vertical steel reinforcing)	5/8" all-thread 4" from each end of shear wall and @12", continuous from foundation to bond beam	2"x2"x 14 ga WWM @ 18", 6" from foundation and bond beam	7	2:1
E	6"x6"x10 ga WWM. 12" embed in foundation	5/8" all-thread @12", 4" from wall ends, 12" embedment in cob	6"x6"x10 ga WWM 2" from each wall face	none	7.5	1:1

a. Braced wall panel types A, B, C, and D shall be not less than16 inches thick. Brace wall panel type E shall be not less than 12 inches thick. All braced wall panels shall be not greater than 24 inches thick.

b. Not less than 8" embedment into foundation, unless otherwise stated.

c. Not less than 4" embedment into concrete bond beams. Full penetration through wood bond beam, secured with nut and washer

In-Plane Design:

The parameters used to derive allowable in-plane strengths for the proposed appendix:

Safety Factor (SF) applied to ultimate loads: Wind: 2.0; SDC A & B: 2.5; SDC C: 3.0

Wall A: All chart elements based of 2018 Testing at Santa Clara University.

- R-Factor: SDC A & B= 2.0; SDC B= 1.5

Wall B, C, & D: All chart elements based of 2018 Testing at Santa Clara University.

- R-Factor: SDC A & B= 2.0; SDC B= 1.5

Wall E: All chart elements based of 2019 Testing at California Polytechnic State U.

- R-Factor: All SDC= 3.0

Response Modification Factors:

When using static or dynamic procedures in ASCE 7 to calculate seismic demand for an unspecified earthen wall system, ASTM E2392-10 recommends the provisions for unreinforced masonry structures for all earthen wall systems. Since the publication of this standard in 2010, both the Santa Clara University and the California Polytechnic State University (Cal Poly) full scale in-plane cob wall tests, referenced above, have been conducted. The Santa Clara University test reports evaluated approximate R factors using the “Bilinear Backbone Curve” method. The Cal Poly tests evaluated approximate seismic R Factors using both the “Furthest Point” and the “Linear Regression” summaries. The use of two recognized methods in the Cal Poly reports allowed for an additional level of confidence.

All in-plane reverse cyclic tests have been conducted with the full lateral loads applied to the tops of the walls, as is typical in such tests. Cob wall buildings are heavy, mass wall systems, generally with light roofs, and are usually small, single-story structures that do not rely heavily on shear wall collector elements delivering lateral load from other areas of the structure. Due to these factors, the resultant forces for the total seismic lateral loads on walls in cob buildings subjected to earthquakes generally act close to the center of mass of the walls, well below the tops of the walls where the lateral load is applied in testing, resulting in an added factor of safety in designs derived from such testing.

All cob shear wall values are for straight walls in plan. Curved walls are common in cob construction and curved walls have structural advantages over straight walls for both in-plane and out-of-plane design. More research is needed on this topic.

The advantages of the inherent conservatism in design values derived from testing procedures discussed in this section, both from the application of testing load at tops of walls instead of the center of gravity, and the testing results of straight applied to design values for curved walls, are recognized in the proposed IRC Appendix

Out-of-Plane Design:

ASTM E2392-10, "Standard Guide for Design of Earthen Wall Building Systems," recommends a height to thickness ratio of 8 for medium seismic risk and 6 for high seismic risk. CRI in conjunction with Verdant Structural Engineers, Oasis Design, Cal Poly and Quail Springs Permaculture conducted the first full scale out-of-plane cob wall tests in February and March 2019. A straw-only reinforced wall similar to Wall Type A and a steel reinforced wall containing vertical 6x6x10/10 welded wire mesh centered in the wall and embeded in the top plate and foundation were tested. A safety factor of 3 was applied to the tensile modulus-of-rupture stresses associated with ultimate failure loads, resulting in the following required height to thickness ratios (report pending):

Straw-only Wall: SDC B: 12; SDC C: 9

Steel Reinforced Wall: SDC B: 18; SDC C: 15

As a conservative measure, the proposed IRC Appendix requires height to thickness ratios of 6 for SDC A & B for all wall systems that do not contain full height vertical steel, and 8 for SDC A, B, and C for wall systems that do contain full height vertical steel bars.

Half-scale shake table tests were conducted at the University of British Columbia (UBC) and the University of Sydney Australia. No report was issued of the UBC tests, and in Sidney "the shake table was unable to produce a simulation of sufficient intensity to damage the specimens" [10]. A video of useful information on the UBC test is at: http://www.youtube.com/watch?v=ChbccUQhpJc. The shake table test portion of the video can be found between the 2:55min and 6:24min marks. There was a total of 3 tests conducted, the first (3:59min) malfunctioned due to hydraulic failure, followed by two successful tests on a new structure. The first of the two imparted a model of the 1992 Landers, CA, 7.2 magnitude earthquake (4:55min). As the test lasted 18 seconds and produced minor, centralized, visible cracks with no significant material fragmentation or damage. The second successful test was a destructive test modeled from a synthetic earthquake record (5:17min). The test documented 12s before small fragmentation occurred and 18s before large fragmentation resulted in failure. After the test, director of the UBC test facility Dr. Carlos Ventura stated, "Shaking the structure up to 2g and seeing that the structure didn't collapse completely gives us reassurance that at least there is enough left over capacity of the structure to maintain weight and not collapse on top of people." The containment qualities of the straw are evident.

Other Significant Research Findings:

- Increased benefits, such as increased strain and ductility have been exhibited in samples containing straw vs samples without straw in both the 1995 Plymouth University tests stating "The higher the straw content, the higher the strain at failure due to loading, as illustrated on Fig 2. The straw provides significant tensile strength" [1], and the 2013 University of San Francisco tests stating, "ductile behavior was clearly observed in the straw reinforced specimens". [4]
- Both full-scale in-plane reverse cyclic tests of straw-only systems similar to wall type A above, with no embedded anchorage between the wall and the foundation, exhibited rocking shear be-

havior with the USF tests stating, “The MDOF test frame induced uplift in each of the walls due to rocking shear” [11]. The wall lifted off its base on the tension side on each cycle and the material in that area remained intact. The capacity of these wall systems to remain intact can benefit performance by engaging uplift resistance of adjacent walls or buttresses. The extent of this is currently untested.

Benefits of Mesh Reinforcing Systems over Larger Diameter Bars:

The smaller diameter bars of mesh reinforcement, when acting as the foundation anchoring system similar to Wall Type E, allows for steel yielding at the wall base. The yielding of steel reinforcement prior to the failure of a compression-based system is an advantageous structural failure mechanism because it allows for warning signs to be exhibited prior to complete failure. The mesh systems also allow for more distribution to the lower strength clay material and this mechanism is similar to that of the straw fiber matrix. Larger diameter bars have exhibited tendencies to slip through the cob material at high loads, as the USF test stated, “rebar created voids in the cob” [11]. It is common for those unfamiliar with cob testing to use larger diameter bars because they are common in conventional concrete construction.

Cob does not undergo chemical curing, such as cement hydration in concrete, that significantly influences strength over time, although the reduction of moisture content of cob during drying has been shown to effect tested values. Wright & Henshaw have the most extensive documentation if this behavior in their 2019 U. of Tulsa report stating “Ultimate strength of specimens tested in compression exhibited high sensitivity to moisture contents in the low moisture region between 1% and 3% moisture.” [9] Compression tests results from all small-scale tests in this report range from 40 psi to 320 psi. None of these tested samples contained cementitious additions. Extreme drying may be a significant reason for variation in these test values.

Issues of Problematic Cob Vocabulary:

There are commonly accepted terms that, through the findings of the tests referenced in this report, have been identified as misleading. These include:

Stabilized and Unstabilized Earth: Stabilized earth refers to clay base materials with a cementitious or asphalt binder added. Unstabilized earth refers to clay based materials that do not contain such additives. Unstabilized is the only form of cob used in any of the known cob tests listed in this report. These terms unfairly suggest that unstabilized cob is unstable.

Unreinforced Cob: All cob contains straw, testing noted above has concluded that increased ductility is exhibited by samples containing straw vs samples that do not. The 2018 edition of the International Building Code does not directly specify what the requirements for a reinforced system are as compared to an unreinforced system. It is not within the scope of this report to specify how straw fibers are preserved in the clay matrix. It is our understanding that the bio-microfiber reinforcement of the preserved straw particles are similar in nature to that of codified glass and metal micro-reinforcements. Therefore cob systems containing only straw would be better termed as “straw-only” instead of unreinforced.

Testing Complications:

Through collaborating and consulting on cob testing programs at various locations, the authors of this report have identified certain topics as complications in cob testing:

- **Partial Scale**: half-scale model tests of full-scale wall behavior is imperfect because straw size and particle size do not scale.
- **Sample Size:** Due to the length of the straw pieces in the mix, it is important to not test sample sizes that are too small, and therefore distort the results due to forced clumping of straw unlikely to occur in field practice.
- **Labor Intensive:** Cob wall construction is typically unhazardous and accessible to builders without expertise, though it can be labor intensive. Cement mixers assisted the Santa Clara University tests. No tests have been conducted using backhoe or similar large equipment assisted mixing.
- **Drying Time:** Typical cob wall construction is limited to approximately 8”-12” of wall thickness per day. When isolated test wall samples are being constructed, this can result in many days of a few hours of labor, which can complicate housing skilled practitioners near testing sites.
- **Weight:** The great weight of full-scale walls can complicate coordination with the construction area, storage area and possible relocation to the testing apparatus.
    - SCU acquired a high strength dolly to overcome this problem [11,12], while the Cal Poly testing chose to manufacture a portable testing apparatus transported to where the walls were built and stored more easily by local cob practitioners. There were design and functionality complications of the portable testing system that were ultimately resolved.

Recommended Additional Research:

- Continued full-scale testing to increase the sample-size of results, accuracy of R-factor predictions, and explore all possible reinforcing strategies.
- Anchorage testing, both wet set and post installed.
- Tests conducted on machinery assisted mix batches.
- Testing the limits of steel corrosion in clay.
- Testing various forms and lengths of bio-microfiber reinforcements
- Testing effects of perpendicular walls and buttressing on rocking shear failure
- Thermal testing of various densities and functionality and thermal testing of wall insulation techniques (non-structural).
- Fire wall testing.

References

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[2] Akinkurolere et al, *Engineering Properties of Cob as a Building Material.* University of Technology, China, and University of Ado-Ekiti, Nigeria, 2006.

[3] Pullen & Scholz. *Index And Engineering Properties of Oregon Cob.* University of Oregon, 2011.

[4] Michael Scoles Rizza and Hana Mori-Böttger. *Effects of Straw Length and Quantity on Mechanical Properties of Cob*. University of San Francisco, 2013.

[5] Lorenzo Miccoli, Fontana, and Urs Mueller. *Mechanical behavior of earthen materials: a comparison between earth block masonry, rammed earth and cob*, 2014.

[6] Lorenzo Miccoli and Patrick Fontana. *Bond strength of anchor pins for earthen buildings. A comparison between earth block masonry, rammed earth and cob*, 2014.

[7] Leza et al, *Sustainable Construction Material Research Project, Cob Flexure*. Santa Clara University, 2017.

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[11] Eberhard et al, *Cob: A Sustainable Building Material*, Santa Clara University, 2018.

[12] Brunello et al, *Cob Property Analysis*. Santa Clara University, 2018.

[14] Minke. *Building With Earth, Design and Technology of a Sustainable Architecture*, 2009.

[15] Donahue et al. *Structural Testing Of Plasters For Straw Bale Construction*, 2003.

Anthony Dente *PE, principal of Verdant Structural Engineers in Berkeley, CA has designed natural building systems under and alongside his partner, natural engineering veteran, Kevin Donahue, for over a decade. Anthony is a board member of the Cob Research Institute and has provided support for natural building testing programs striving to increase appropriate building options for future engineers.*

Kevin Donahue *SE, principal of Verdant Structural Engineers in Berkeley, CA, and predecessor firm KDSE, has been active advancing natural building engineering, contributing to "Design of Straw Bale Buildings," Bruce King 2006, coauthoring "Structural Practices: Straw Bale Construction" Structure Magazine, September/October 2012, advancing straw bale IBC and IRC code efforts, and engineering many natural building projects as a practicing engineer.*