RE-CONCEIVING AFGHAN CELLULAR ARCHITECTURE FOR THE RECONSTRUCTION OF RURAL SCHOOLS

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Abstract, *Afghanistan suffers from a quarter century of war that has resulted in a devastated infrastructure and a generation of Afghans who have lived without a local school. This paper presents an architectural design investigation that seeks ways of synthesizing traditional social-cultural and formal-spatial attributes with refined material and construction capabilities becoming increasingly available worldwide. In the spirit of George Kubler's thesis of invention and variation, stabilized compressed brick construction and computer aided structural analysis are introduced as refinements within the Afghan building tradition.*

Earthen architecture underlies the embodiment of the architecture of Afghanistan. It's most elementary form can be seen in the timeless use of the archetypal square room having a static cubical nature and being multiplied in thoughtful linkages. Variations in the square cell largely come from differences in the form of the overhead enclosure. In southern and western areas of Afghanistan, mud brick is the sole vernacular building material. Therefore roofs are also of mud brick and formed of traditional vaults and domes.

Construction of earthen walls in Afghanistan have traditionally been done in three ways, pise, sun dried mud brick, and fired brick. While fired brick walls possess higher strength and durability, their use is prohibitively expensive, especially for extensive use in rural areas. *Pise* is a rural technique used predominately for courtyard and garden walls and has fallen out of favor in recent decades.[1] Sun dried mud brick has the advantage of onsite fabrication and is quick and cheap but also lacks strength and durability. This investigation advocates the integration of globally renowned methods of site-based mechanically hand-pressed stabilized mud brick. Such bricks possess a higher strength and durability than the sun dried bricks but yet are also manufactured at the site. This method is inexpensive in countries with large amounts of low salaried manual labor.

This research couples the use of the new mechanically hand pressed stabilized brick with currently available computer-aided structural design methods. Such analytic methods could be utilized at the Faculty of Engineering at Kabul University. The structural analysis is applied to a prototypical architectural design. Predicated upon the multiplication of the archetypal single cubical room, the design focuses upon small scale, single story building clusters, suitable for rural Afghan schools or other community buildings. The design proposals start with the analysis of the traditional single cell mud brick vault that is then redesigned using the new tools and compressed brick construction capabilities. The vaulting geometry is studied by structural modeling for both static and seismic stability. Construction detailing of the vault is adapted from vernacular traditions.

Predicated upon the findings of the single cell formal and structural analysis, structural and constructional parameters are then extended to consider the design of a simple cluster of vaulted cells capable of supporting a single classroom school. Natural light becomes an important issue as part of this combination of cellular vaults and must be resolved while addressing structural, constructional and drainage concerns. The single classroom cluster is then expanded into progressively larger building clusters associated with the needs of rural schools of diverse size and location.

DRAWN FROM THE EARTH: THE CUBICAL "TAQ"

The archetypal form of domes and vaulted space reach back to the dark recesses of time. The metaphysical underpinnings of these forms are derived from a desire to replicate the heavens. Constructed of the same earthen brick as the supporting walls beneath, these archetypal cellular forms are directly connected to the earth and sky surrounding them. The indigenous domed and vaulted architecture of western and northern Afghanistan is rooted to its site and unchanging in form and type. Constructed within an arid landscape having little other than earth and scant water for materials, this ubiquitous architectural form is literally drawn from the earth that surrounds it. Sun dried mud brick is the sole construction material and is formed as close to the construction site as acceptable soil and sufficient water can be found.

Vaulting of the roof is accomplished without the use of centering via the time-honored use of squinches that spring from the corners of the upper walls from which the dome or vault springs. Constructed of a single layer of bricks, the mason gradually merges these squinches with a semicircular inclined arch that is self supporting through the use of highly viscous and quick setting mortar. Since this process is done from opposite ends of the square or rectangular room, as the opposing inclined arches approach each other in the middle, an eye shaped void is created.[2] Discussions with the local mason during the completion of such a construction described this form of final enclosure as the "eye of god". He sometimes left a void at the very center of this eye that also served as an oculus within the center of the dome or vault. (FIG. 1)

REINTERPRETING THE CELLULAR FORM

A salient dimension of Middle Eastern architectural history is the ingenious artistic explorations in the manner of forming and structuring domes and vaults. The centuries long evolutionary history of working within the medium of masonry received profound culture shocks with the twentieth century introduction of steel reinforced concrete construction. The challenge of accommodating these new capabilities in a culturally coherent manner is well known and ongoing. While such difficulties are profound within those Middle Eastern countries most economically advantaged and globally connected, the austere circumstances of settings such as rural Afghanistan offer meaningful opportunities. As discussed in Benedickt's Architecture of Reality, "part of our appreciating the materiality of an object has to do with our appreciation of the natural origin of its substance and manufacturing or forming processes."[3] Compressed cement stabilized earth brick is created on or near the construction site. Using only a manually operated press, the technology of the construction process remains predicated upon manual labor, just like the traditional methods. Constructing without the use of power tools is necessary in rural areas such as Afghanistan. Designing and constructing solely of individual bricks not only allows for total manual labor but also continues to operate within some of the constraints of the traditional built form. The significant difference is in the structural and durability of the compressed stabilized brick. It is the premise of this research that these improved performance features of the compressed stabilized brick can result in improvements in the design and construction in areas such as rural Afghanistan. It is argued that such improved design is particularly important for public buildings such as schools.

The exploration for a prototypical design for rural Afghan schools began with a study of the basic programmatic needs of such schools as well as the capabilities of traditional built form. Investigations began by studying the needs of an individual classroom in terms of educational activities, space, light, furnishings, etc. A design program was developed for a one class room school building with supporting spaces as necessary for the teacher and storage. Preliminary structural investigations suggested that the compressed stabilized brick would allow for a clear span of 5 meters for the classroom. Such a span is beyond common Afghan residential construction in sun dried brick.

STRENGTH AND DURABILITY OF SUN DRIED BRICK

Sun dried mud bricks are susceptible to erosion from drainage and runoff and must be protected by a coating of mud plaster that requires periodic upkeep. However, Afghanistan's arid climate coupled with a lack of driving rains or a high ground water table protects mud construction from its worst deterioration found in other countries. Traditional walls as much as one meter in thickness support both the weight and also the thrust of the domes and vaults. Such thickness avoids concentrations of compressive loads upon the mud brick to well within structural tolerances.

The impact of severe lateral forces during an earthquake causes serious structural problems for unreinforced brick construction. The seismic performance of such construction is a function of wall thickness, internal subdivisions, roof mass, nature of the continuity with adjacent dwellings, distance to the fault and site effects.[4] Research on models of conventional mud brick houses subjected to earthquakes showed that structural failures occurred due to shear or tensile forces rather than compressive failures.[5]

COMPACTED CEMENT STABILIZED EARTH BRICK

A compressed stabilized earth building brick may be defined as one composed of a loose mixture of soil and/or fine aggregate, a stabilizer and water in a damp mix which is compressed to form a dense block before the stabilizer hardens.[6] The stabilizer most commonly used is cement at a proportion ranging from 5% to 10% that of the soil. Mechanically hand compressed and stabilized earth bricks (CSSB's) have a higher compressive strength than conventional mud bricks. The compressed bricks also have a higher density, are less absorbent to moisture and are much more impervious to erosion. This low technology is more than 60 years old. A dramatic example of such construction can be found on the campus of the University of Kansas. Broadcasting Hall was constructed in 1943 under the direction of Civil Engineering professor, W.C. McNown. using home made stabilized earth brick compressed by hand within a cast iron press made in the university foundry.[7] This building stands quietly beside buildings of conventionally fired brick and goes unnoticed as anything unusual by the campus community. This building has no protective exterior coatings and survives in outstanding condition. (FIG. 2)

Current research at the University of Warwick, U.K. is investigating the advantages of an alternative dynamic way of compacting stabilized earth brick during the manufacturing process. However, it is important to note that this research continues to verify that of the numerous types of low cost brick and block in use in developing countries, the CSSB is the best choice both economically and environmentally. This research also acknowledges the very significant contribution of the Cinva-Ram block press.[8]

Designed in 1952 by the engineer Raul Ramirez at the CINVA Center of research in Bogota, Columbia, the Cinva-Ram provides an inexpensive, easily constructed, hand operated machine for compressing earth blocks. This simple technology has been applied in many parts of the developing world because of its local applicability to those places already accustomed to earthen construction. In this sense, it is seen as a method that bridges traditional construction methods with more modern construction performance. While such construction has become increasingly popular for walls, less has been done for roofs. This is true even for those regions having traditionally built in domes and vaults. Use of the CSSB's for roofing would have a definite advantage because the cost of building with more conventional wood or concrete for the roof can increase the overall cost of the construction by as much as 50%.[9] Besides the economic advantages of the earthen roofs, such construction also has thermal advantages as well as being more readily adapted by construction trades accustomed to conventional mud brick. It is for all of these reasons that the proceeding research seeks to introduce compressed stabilized earth design in Afghanistan.

INGREDIENTS AND PROCESSES OF PRODUCING CSSB'S

The creation of CSSB's involves numerous, interacting factors. These factors can first be broken into the categories of (1) ingredients and their relative proportions, (2) the methods of preparing and mixing these ingredients, (3) the process by which the stabilized mud is compacted into bricks, and (4) the treatment of the bricks prior to their use in construction. Extensive research reports and even dissertations have been devoted to only a portion of one of the above aspects.

The ingredients for CSSB are soil, cement, and water. Soil is broken into four categories of gravel, sand, silt and clay. Small gravel should be limited to small amounts because of its lack of cohesion with other materials of the mix. Sand is the best ingredient due to its high degree of internal friction and cohesion to other ingredients within the mix. Small amounts of clay and silt are useful to provide workability and plasticity of the mix. A good range for a suitable soil is 65-80 per cent sand and 35-20 per cent clay and silt.[10] For workability, clay should not be less than 10 per cent. Successful mixes are those where the soil has a texture whose particles are not less than 0.02mm nor more than 20mm.[11] Portland cement is the second ingredient of the mix. The final ingredient, water, needs to be clean and not contain salt.

Methods of preparing and mixing the ingredients begin with insuring that the soil to be used in the mix has been removed from the ground and left to dry upon a hard surface prior to mixing. Extensive research by many organizations has shown that 5 - 10 per cent by volume of the mix should be cement. Mixing begins by evenly spreading a measured amount of soil upon a hard, level surface to a thickness no more than 10 cm. The measured amount of cement is added uniformly to the layer of soil and then mixed into a uniform color.

The measured amount of water is then sprinkled upon the dry mix layer until satisfactory moisture content is achieved. The amount of water is particularly important. If the mixture contains too little water, the mix will lack workability and endanger successful chemical reactions with the cement. Excessive water can hinder resultant strength and durability of the bricks. Experience has shown 8 - 16 per cent by volume of water as a successful mixture.[12] Given this mixture of ingredients, the cement particles begin a chemical reaction with the water and form an interlocking matrix of the particles of the mix.[13] Numerous simple onsite tests have been developed to select appropriate ingredients and to do a test mixing. Once the water has been added to the mix, it is important to proceed with the compaction of the bricks within two hours and before the chemical reactions of the cement has taken place.

Through the use of a hand operated mechanical press, the mixture that fills the brick mold is compacted. According to Montgomery, "improved levels of compaction have a significant effect on the compressive strength of the sample brick and the effectiveness of the cement stabilizer"[14] Illustrations of the brick pressing process can be seen in (FIG. 3).

The final steps in the brick making process prior to use in construction involves curing and drying of the bricks. After the bricks are removed from the press, they should be laid flat upon a hard surface and kept in a humid environment for 7 days. The use of a sheet of plastic to cover the blocks may be desirable, however sprinkling them with water can also help reduce shrinkage percentage.[15] Blocks must be protected from the sun and wind during the curing and drying process to avoid loss of compressive strength. Drying will take approximately 14 days.[16] The blocks should be rotated everyday to produce uniformly dried bricks.

DETERMINING PERFORMANCE FACTORS FOR ORGANIC MATERIALS

Traditional methods of construction are fundamentally empirical and predicated upon accumulated wisdom of trial and error. In contrast, this research is predicated upon mathematical simulation that in turn requires mathematical data as to the performance of the materials and construction methods. A major challenge of this research was in seeking acceptable performance specifications for a truly loose and organic building material, mud brick.

Regardless of the considerable variability of the CSSB performance as a function of the various factors of its creation, clear evidence exists that the CSSB structurally outperforms the mud brick in nearly all cases. Perhaps the most important lesson is that the CSSB can be seen as a technology that seeks to bridge the mud brick construction and contemporary structural engineering analysis. As such, it is not surprising that CSSB data requires a wider range of possible performance specifications than what is accustomed to in industrialized materials. It should also be stated that careful analytic research of such an organic and loosely defined construction material is uncommon in advanced countries while being highly relevant for use in developing countries that are less capable of conducting independent materials testing research. There are a myriad of factors that influence the final structural capabilities of any particular block but listed below is a condensed table of the most important factors for normal mud brick compared with CSSB's.[17]

	CSSB	Mud Brick
28-day Compressive Strength	290-725 psi	≅ 290 psi
28-day Tensile Strength	145-290 psi	0-77.5 psi
28-day Bending Test	145-290 psi	≅ 77.5 psi
28-day Shear Test	145-290 psi	≅ 77.5 psi
Poisson's Ratio	0.15-0.35	≅ 0.5
Young Modulus (modulus of elasticity)	102-1020 ksi	58-116 ksi
Apparent Bulk Density	106-137 pcf	74.9-106 pcf

There is also information that indicates 1780 psi for 28-day compressive strength with sandy soil.

CONTEMPORARY STRUCTURAL ANALYSIS

The structural analysis of the proposed architectural design for rural Afghan schools utilizes a software program called RISA 3-D. Operated upon a modest sized Windows platform, RISA is an acronym for Rapid Interactive Structural Analysis and is the product of RISA Technologies of Foothill Ranch, California. This software is a general purpose three dimensional analysis and design program developed to make the definition, solution and modification of three dimensional digital models fast and easy. RISA is used extensively by structural engineers in the United States.

Application of the program follows a general three-step process. First, the digital model is constructed in accordance with the formal intentions of the architectural design. Second, the digital model is subjected to an array of likely load conditions. Third, the resultant structural response to the loads is studied according to numerous structural factors such as bending, shear, etc. The third step normally suggests modifications to the design of the digital model to improve the structural performance. Executing the second step in the process involves identifying the structural properties of the materials intended for construction. While the program comes with an extensive library of the structural properties of common building materials, analysis of the school designs necessitated research of the performance factors for CSSB's and for common sun dried brick previously discussed. RISA allows the designer to study combinations of both gravity and lateral loading conditions, including wind and seismic conditions, within the same digital model. The impacts of these loading conditions upon the digital model were studied for both sun dried brick and CSSB construction, (FIG. 4-B & C) In addition, the cross sectional profile of the structure was studied in terms of the proportioning of the domed roof and the thickness of the walls. (FIG. 4-A)

There is a direct relationship between the mass of the building and the earthquake force experienced by the building. The force of the earthquake will vary depending upon the density of the brick and the thickness of the wall sections, which determines the overall mass of the building. Given the same density of material, a thicker wall will receive a higher earthquake force than a thinner one. However, because of a higher resistance that a thicker wall provides, both of the results will be close to each other. This relationship is also similar between the traditional mud brick construction and CSSB. In the case of different types of bricks, the results will vary according to their properties. Even though the CSSB has a higher density and receives higher amounts of earthquake force, it can accommodate higher forces due to its higher stress tolerances. The analysis indicates that for maximum stresses incurred in an earthquake, the stresses in CSSB are considerably lower than the maximum allowed whereas, for mud brick, the maximum stresses experienced reach the point of possible structural failure.

DESIGN APPLICATION: A PROPOSAL FOR RURAL SCHOOLS

Masonry domes and vaults possess an underlying symmetry and balance predicated upon structural necessity and creating a singular unified space beneath. Functional and spatial needs lead to the aggregation of these singular cells into closely packed clusters of built form. The architectural design focused upon the creation of a flexible single classroom unit. The design proposal springs from developing an array of smaller spatial cells surrounding a central large cell. This clustering of surrounding cells structurally reinforces the entire cluster and results in a collection of adjoining spaces that can accommodate both the primary space of the classroom as well as secondary supporting spaces. Care was taken to introduce natural light in a manner that furnished ample luminance, enhanced the spatial volumes and also avoided creating points of structural weakness. The totality of the single classroom unit is illustrated in Fig. 6. The manner in which the design grows from a single cell to an extensive school is illustrated in Fig. 5.

Adaptability of the cellular clusters to support alternative programmatic functions is also important for the creation of larger schools or other community structures. Some examples of this formal / functional flexibility is seen in Fig. 7. In response to the harsh arid climate of western and northern Afghanistan, the particular clustering of the design promotes the creation of useful outdoor spaces. Such spaces include courtyards, arcades and gardens as seen in Fig. 8. Modular dimensions allow for a range of cellular sizes that may by close packed within a wide range of alternative compositions. A morphology of alternative cellular clustering is illustrated in Fig. 9.

CONCLUSIONS

In addition to the improved seismic performance of the CSSB construction, the CSSB's also provide superior resistance to degradation due to erosion. Traditional sun dried brick construction requires erosion protection from frequently reapplied mud plaster. Traditional flat mud roofs are particularly susceptible to degradation and also require the use of the scarce resource of wooden timbers. It is for these fundamentally pragmatic reasons that we believe the design investigation presented in this paper offers a promising incremental improvement. This paper illustrates the complexity of carefully analyzing and reconceptualizing the virtues of an archetypal traditional architectural form. The theoretical basis for this work is in the spirit of George Kubler's thesis of invention and variation.[18] Our intention is to introduce this research methodology to the reconstituted Faculty of Engineering at Kabul University. Grounding such research within the national university would promote close contact between Afghan professional architects and engineers and the local builders. It would encourage the concept of building construction as research. In this spirit, the authors have been contacting the appropriate Afghan authorities.

NOTES AND REFERENCES

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[2.] A. Szabo and T. Barfield, Afghanistan: An Atlas of Indigenous Domestic Architecture (University of Texas Press, 1991), pp.119-121.

[3.] M. Benedikt, For an Architecture of Reality, (Lumen Books, 1987), p. 46-52. Benedikt laments that the architecture and construction of the modern world seldom works forthrightly with primary materials that form a clear aesthetic expression of structure and form. He also argues that the most meaningful architecture is that which is open to alternative modes of accommodation, that can grow and change in response to the culture it serves. All of these qualities are being sought in the design proposal using the compressed stabilized earth block construction.

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[6.] D.E.M. Gooding and T. Thomas, The Potential of Cement-Stabilized Building Blocks as an Urban Building Material in Developing Countries, ODA Report, School of Engineering, University of Warwick (1995)

[7.] W. McNown, Soil-Cement Building Blocks and their use in the Engineering Experiment Station Laboratory Buiding at the University of Kansas (University of Kansas, 1943)

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[11] D. Montgomery, How Does Cement Stabilization Work? (Development Technology Unit, School of Engineering, University of Warwick, 1998), p.10.

[12] Soil-Cement, p.22.

[13] D. Montgomery, (1998) p.7.

[14] D. Montgomery, (2002), p.39.

[15] V. Rigassi, Compressed Earth Blocks: Manual of Production (German Appropriate Technology Exchange, 1995), p. 45

[16] Ibid.

[17] H.Houben and H. Guillaud, Earth Construction: a comprehensive guide (CRATerre: IT Publications,1994), The Modulus of Elasticity of mud brick comes from B.Jaishi,.W Ren, Z. Zong, and P. Maskey, *Dynamic and Seismic Performance of Old Multi-Tiered Temples in Nepal*. http://bridge.fzu.edu.cn/English/(2003), Data for sandy soil brick 28 day compressive strength comes from M.Catton, *Soil Cement Technology- A Resume*. Journal of the PCA Research and Development laboratories. Vol. 4 No. 1, (1962), pp.13-21.

[18] G. Kubler, *The Shape of Time; remarks on the history of things*. (New Haven: Yale University Press, 1962).

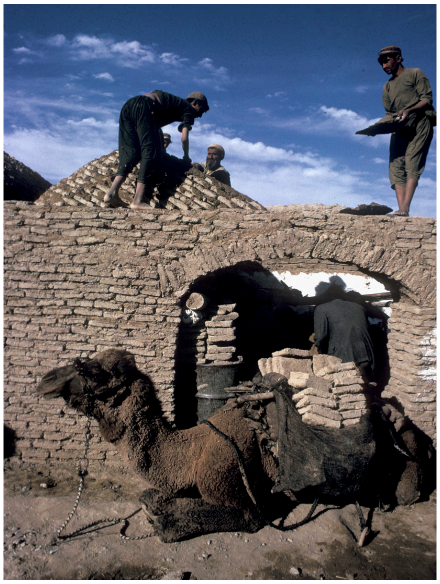


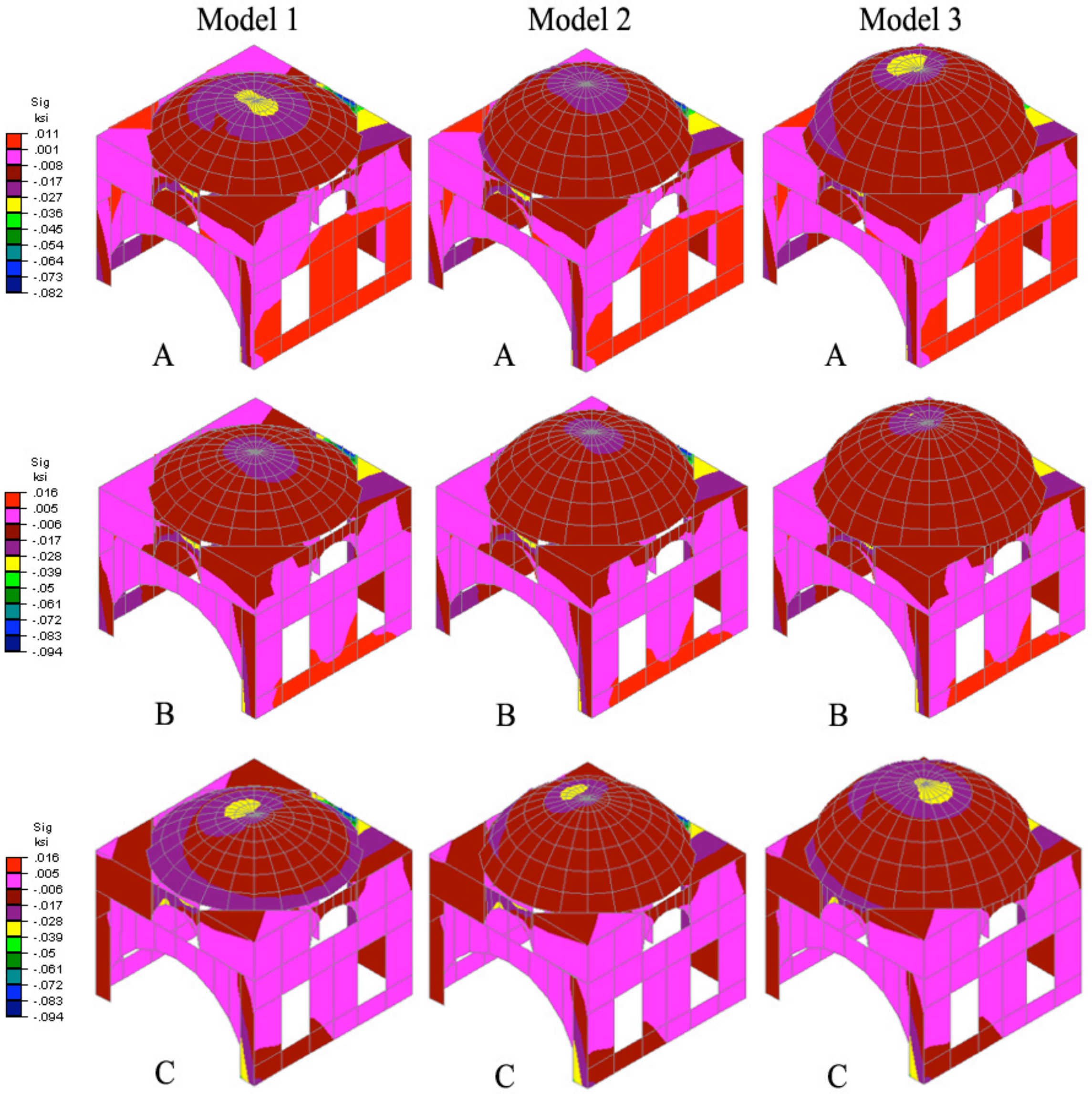
FIG. 1. Traditional mud brick construction
Farah Rud, Afghanistan,

FIG. 2. CSSB construction done in 1943
Broadcast Hall, University of Kansas

FIG. 3 Four steps in the process of creating compacted soil stabilized brick using a Cinva Ram. Architecture students at the University of Kansas under the direction of Professor Nils Gore. Photo by permission of Professor Gore.

FIG. 4-B   TRADITIONAL MUD BRICK

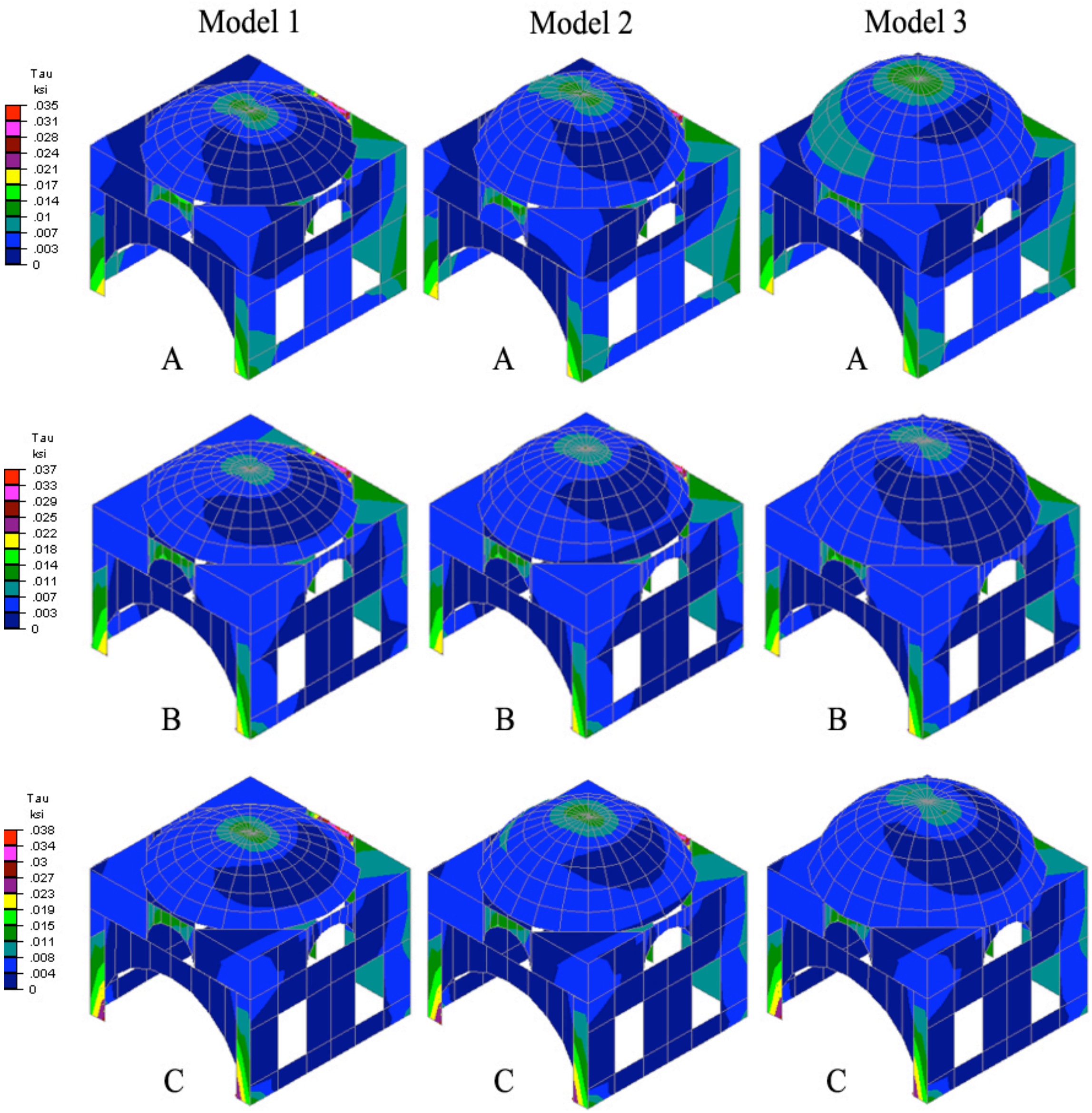
Sigma (Tensile & Compression) Stresses created by a severe earthquake in region four



All Domes are 10 cm ~ 4 inch in thickness
A: 60 cm~24 inch wall, B: 40 cm ~ 16 inch wall, C: 20 cm ~ 8 inch wall

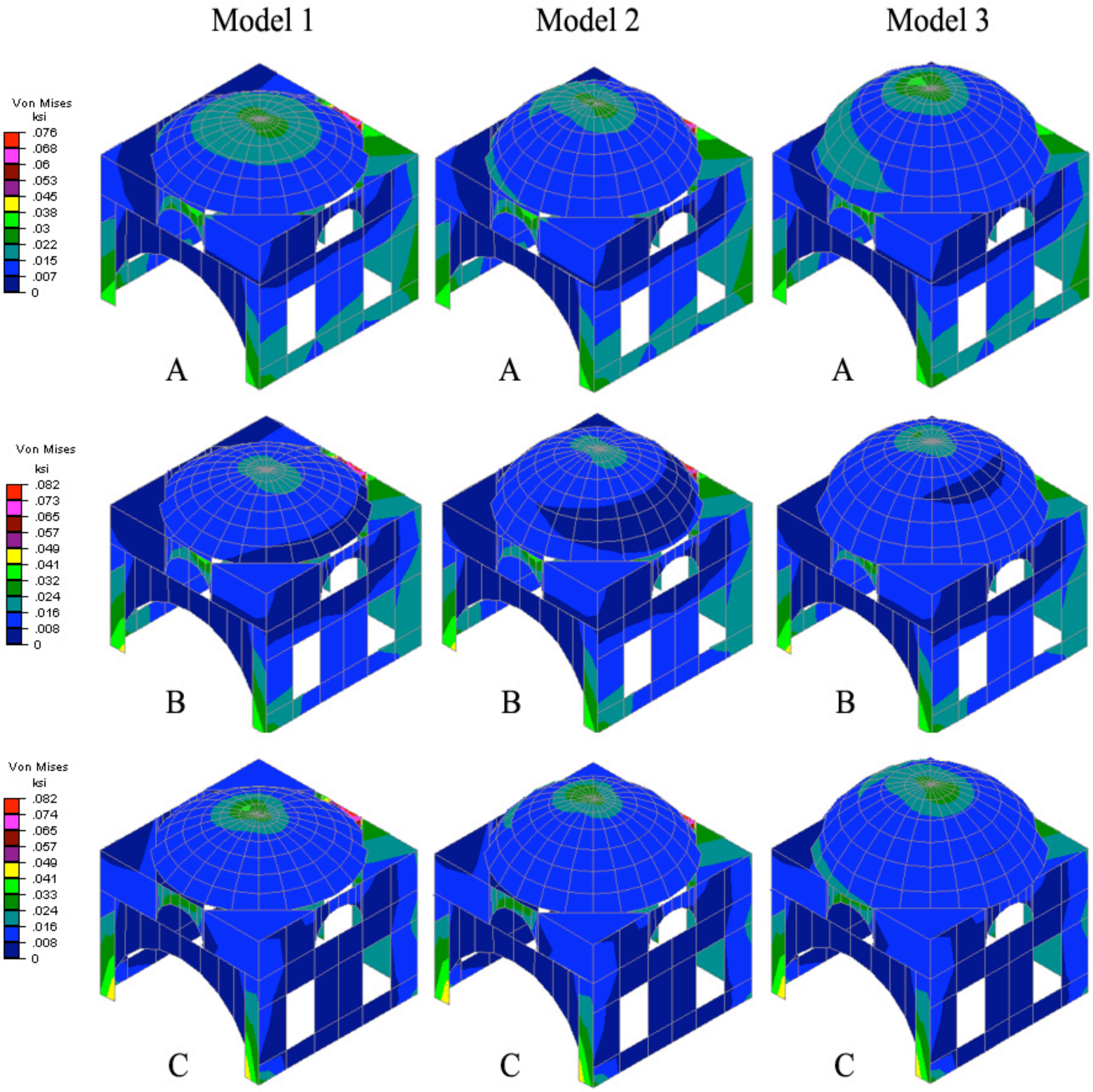
The simulations above show no indication of failure in terms of tensile and compressive stresses. The three vertical stress scales show a close relationship of stresses because of the proportional decrease of earthquake forces caused by the decreasing of the wall thickness. Overall bigger tensile stresses occur on the shallow dome.

Tau (Shear) Stresses created by a severe earthquake in region four



The simulations above show no failure in terms of shear stresses. Highest numbers are half the allowable stresses. The roof domes have little difference in comparison to each other.

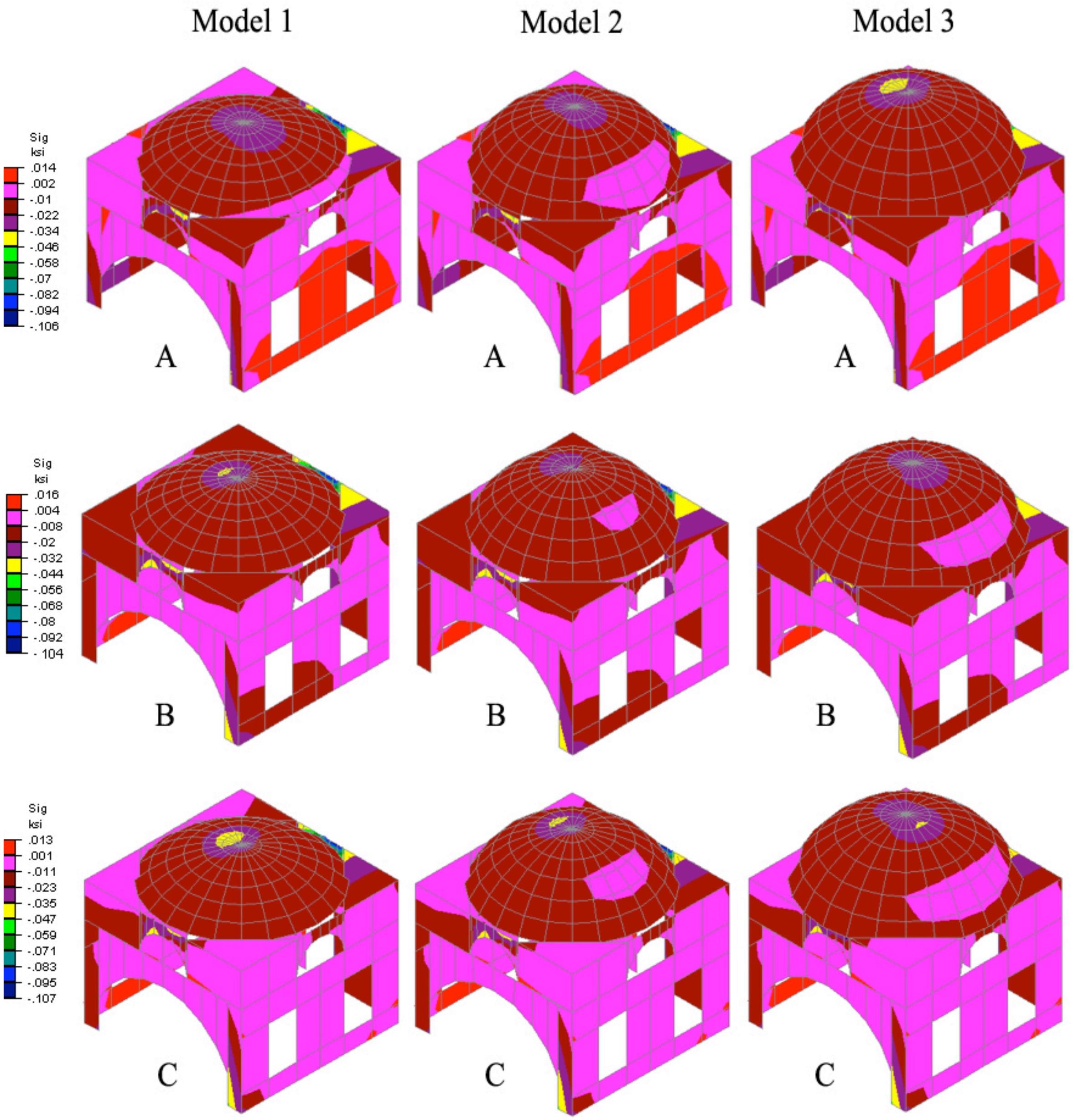
Von Mises (Maximum) Stresses created by a severe earthquake in region four



The simulations above show that the stresses are slightly over the allowable stresses that are given early page. A simulation with an 80 cm wall gave a better performance for the principal stresses. Under the condition of the maximum (principal) stresses the conclusion can be made is for the resistance of the maximum stresses traditional mud brick construction requires thicker wall sections than 60 cm-24 inch.

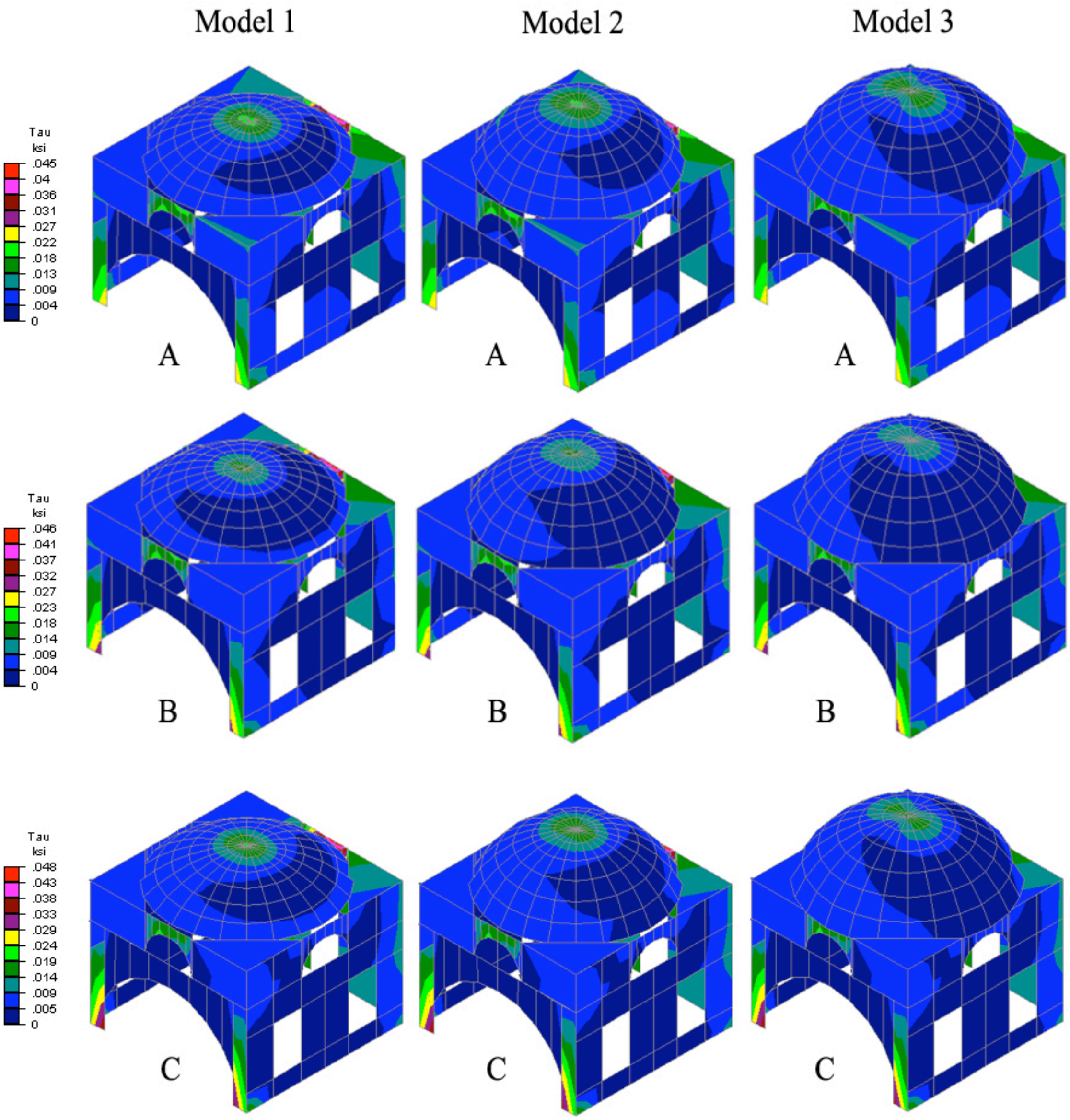
FIG. 4-C   COMPRESSED SOIL CEMENT BLOCK

Sigma (Tensile and Compression) Stresses created by a severe earthquake in region four



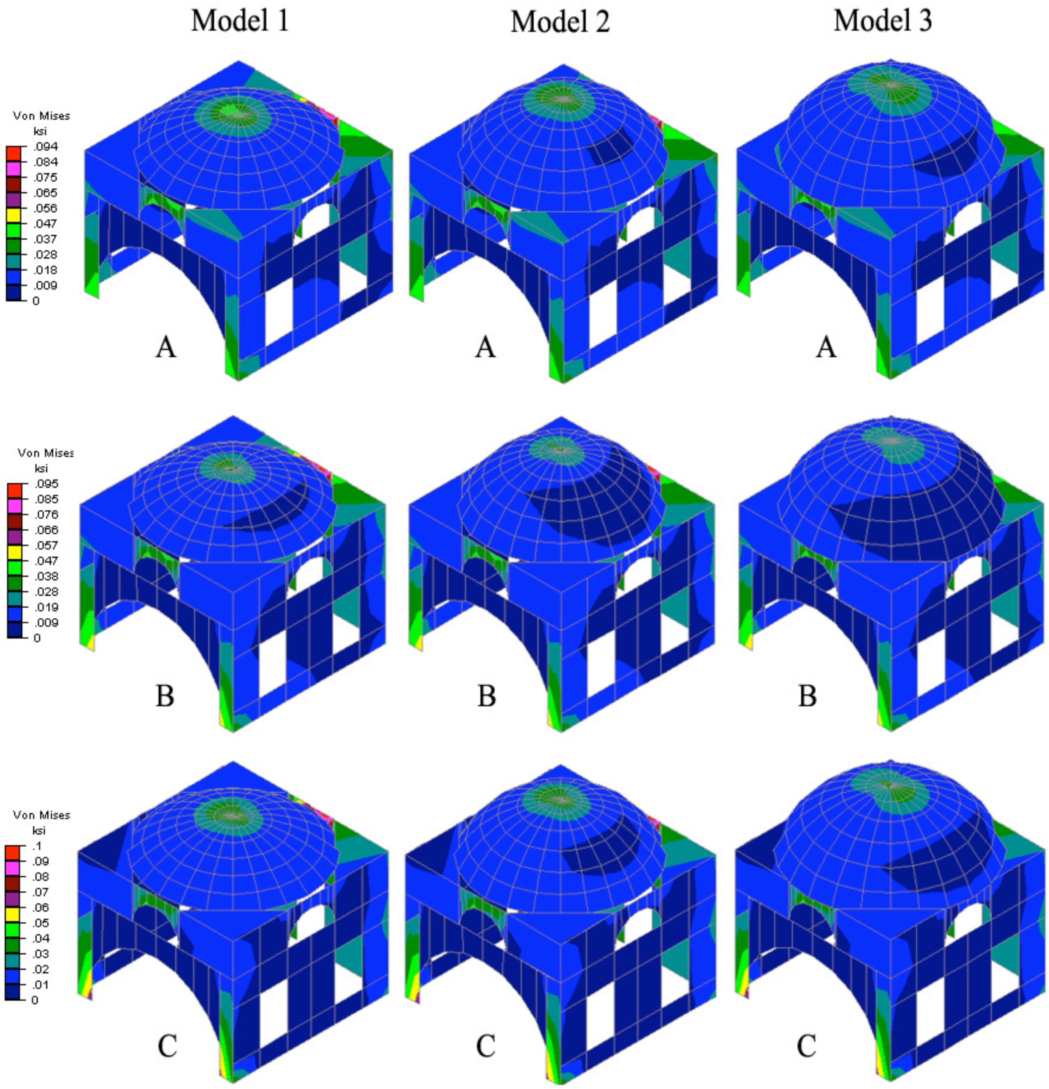
The stresses above are much lower than the allowable stresses and they are slightly over the values of the traditional bricks. This shows much better performance against traditional brick due to the comparison of the results and the allowable stresses. The shallow roof gets a larger stress than the other roofs.

Tau (Shear) Stresses created by a severe earthquake in region four



The shear stresses are six times less than the allowable stresses while on the other hand the traditional model was two times lower than the allowable stresses. None of the models show any structural problems. The model 1 roof gets a larger stress than the other two models, but the differences are structurally insignificant.

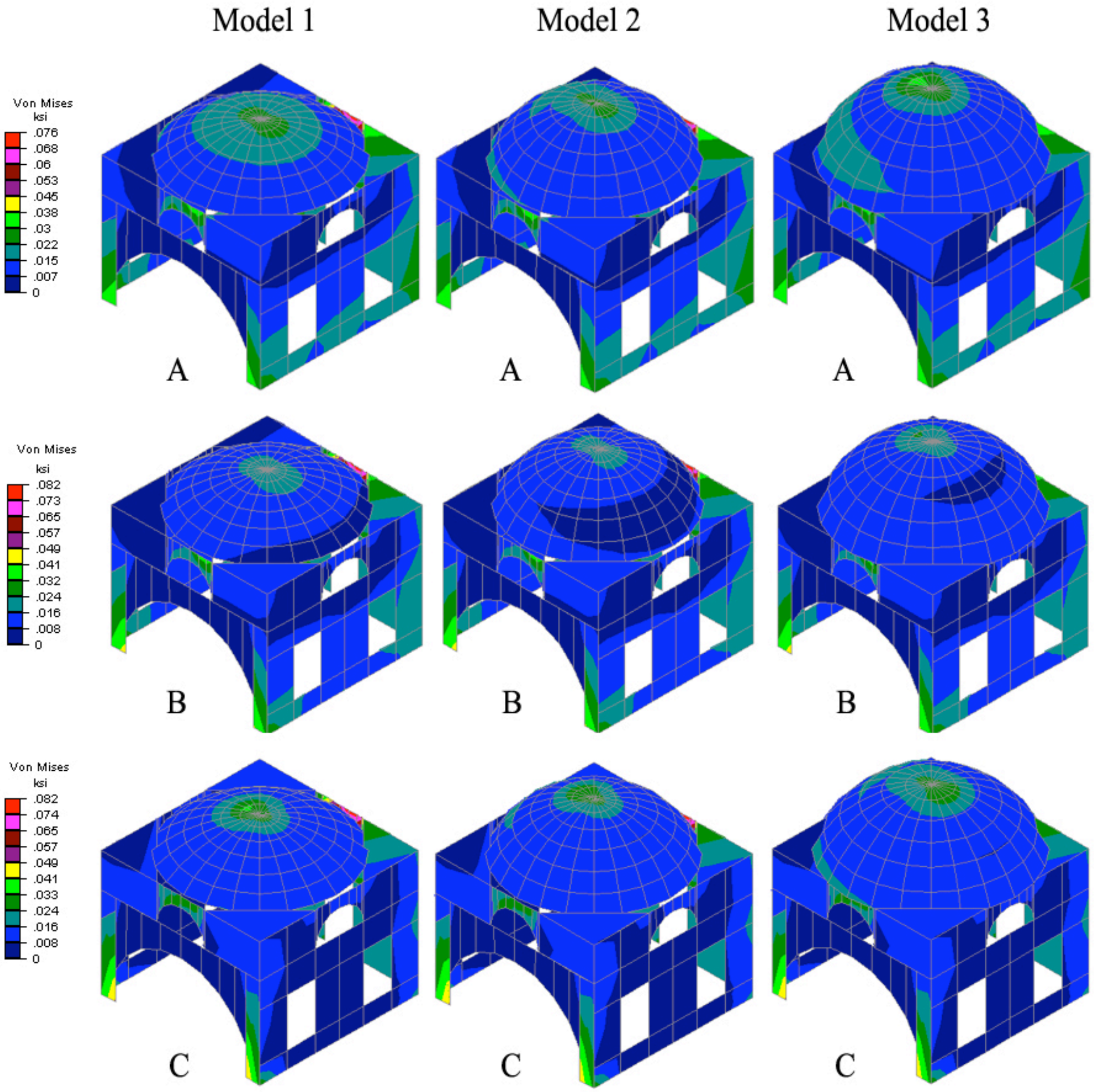
Von Mises (Maximum) Stresses created by a severe earthquake in region four



The principal stresses are again lower than the lowest maximum allowable stresses. In comparison, the principal stresses in traditional mud brick, are stressed to possible failure. All model 1 roofs show larger stresses than the other models, but the difference is insignificant.

FIG. 4-B TRADITIONAL MUD BRICK

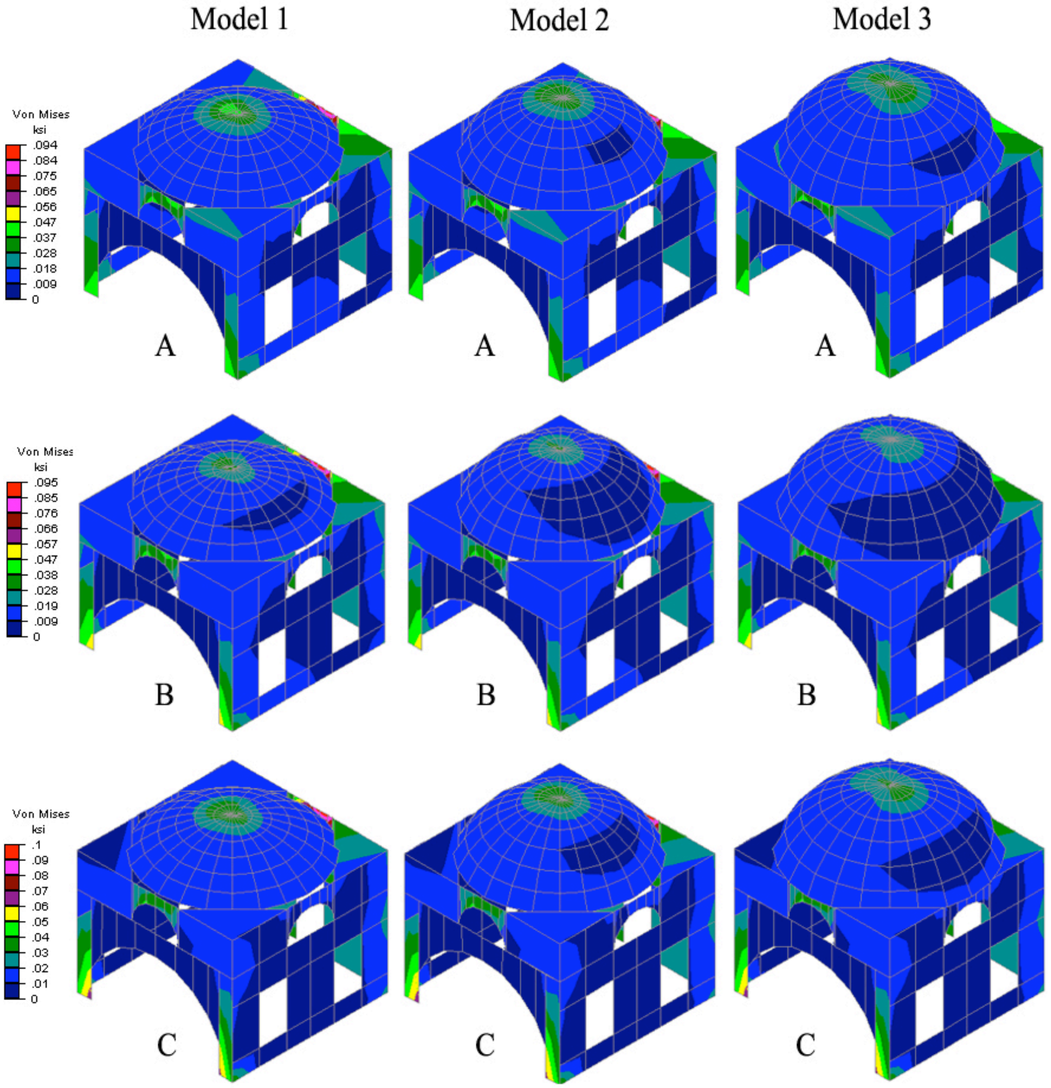
Von Mises (Maximum) Stresses created by a severe earthquake in region four



The simulations above show that the stresses are slightly over the allowable stresses for mud brick. A simulation with an 80 cm wall gave a better performance for the principal stresses. Under the condition of the maximum (principal) stresses, the resistance of the maximum stresses in traditional mud brick construction requires thicker wall sections than 60-cm/24 inches.

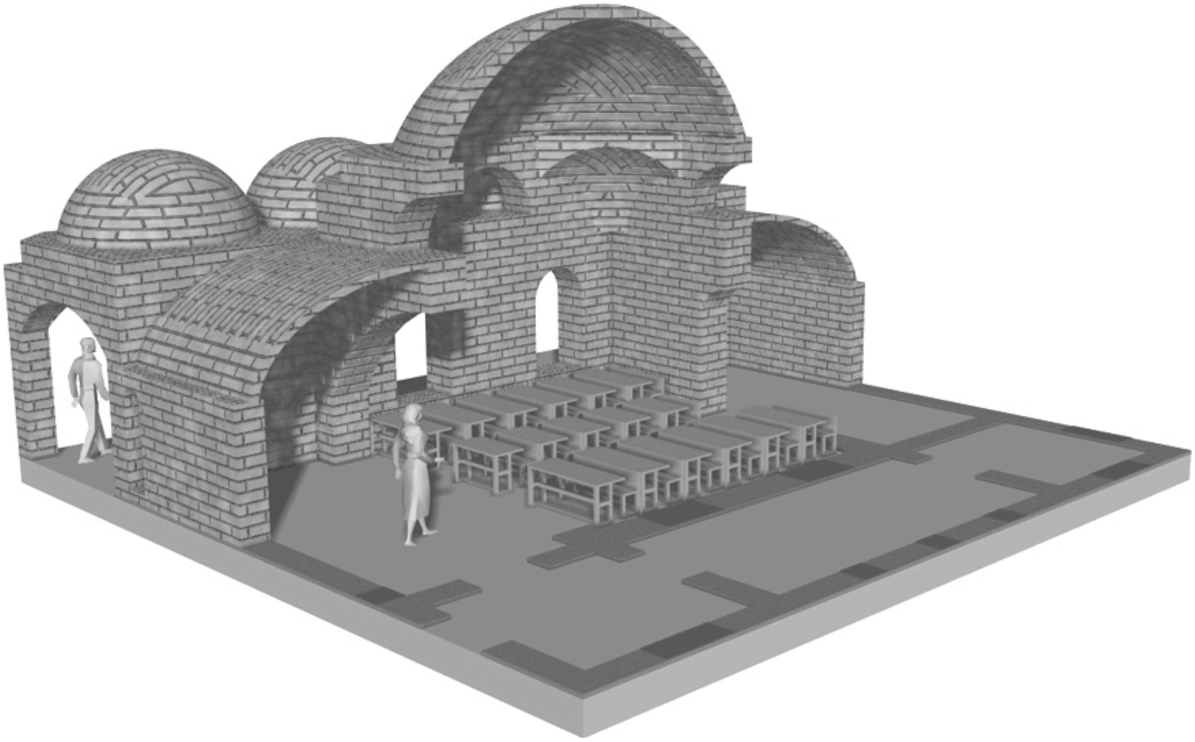
FIG. 4-C COMPRESSED SOIL CEMENT BLOCK

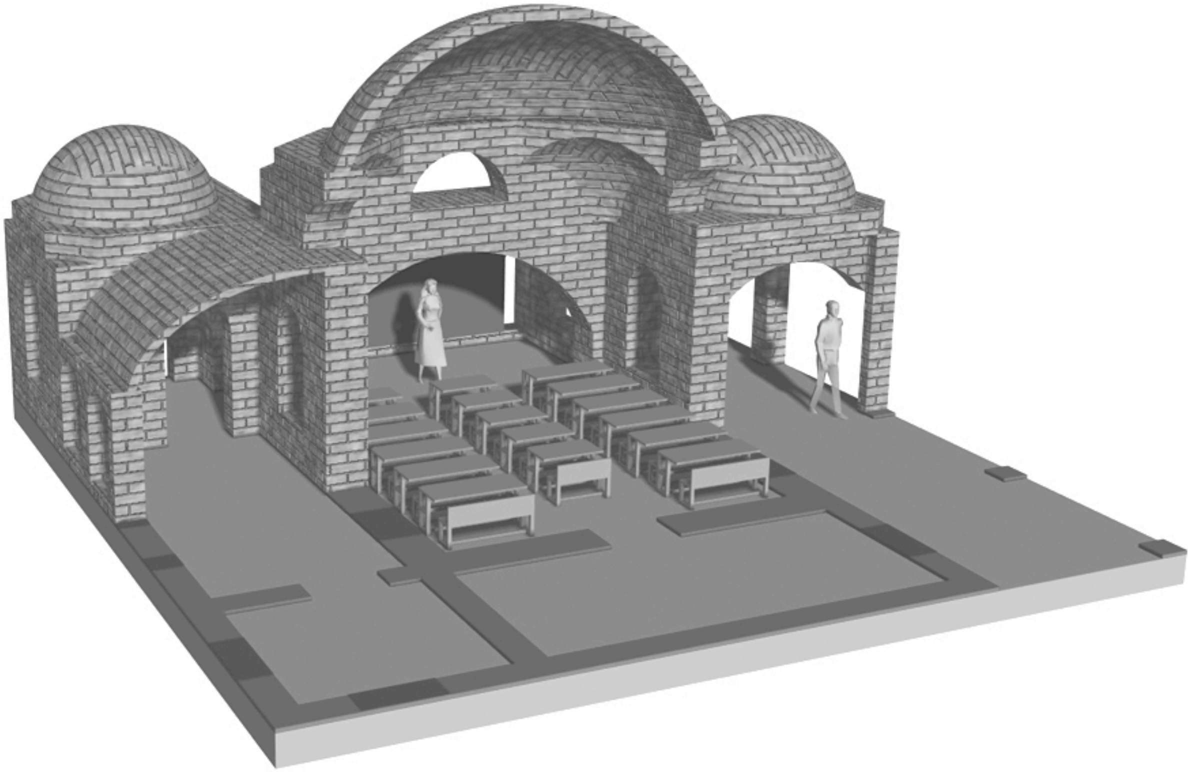
Von Mises (Maximum) Stresses created by a severe earthquake in region four



The principal stresses are lower than the lowest maximum allowable stresses. In comparison, the principal stresses in traditional mud brick, are stressed to possible failure. The shallow domes of all model 1 roofs show larger stresses than the other models, but the difference is insignificant.

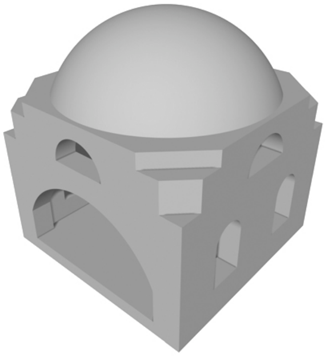
FIG. 5 SECTION PERSPECTIVES OF TYPICAL CLASSROOM



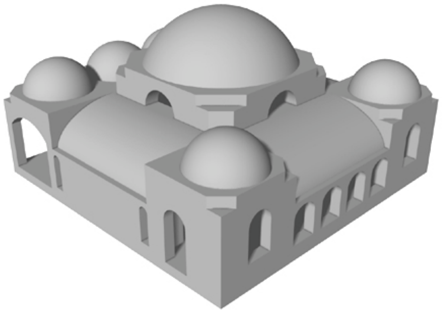


Design by Cenk Yoldas

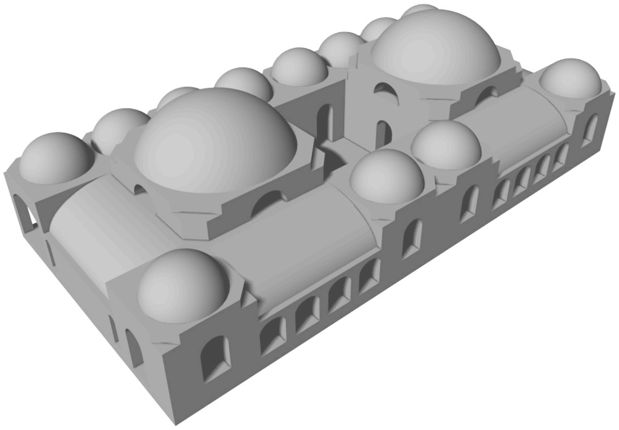
FIG. 6 CELL GROWTH



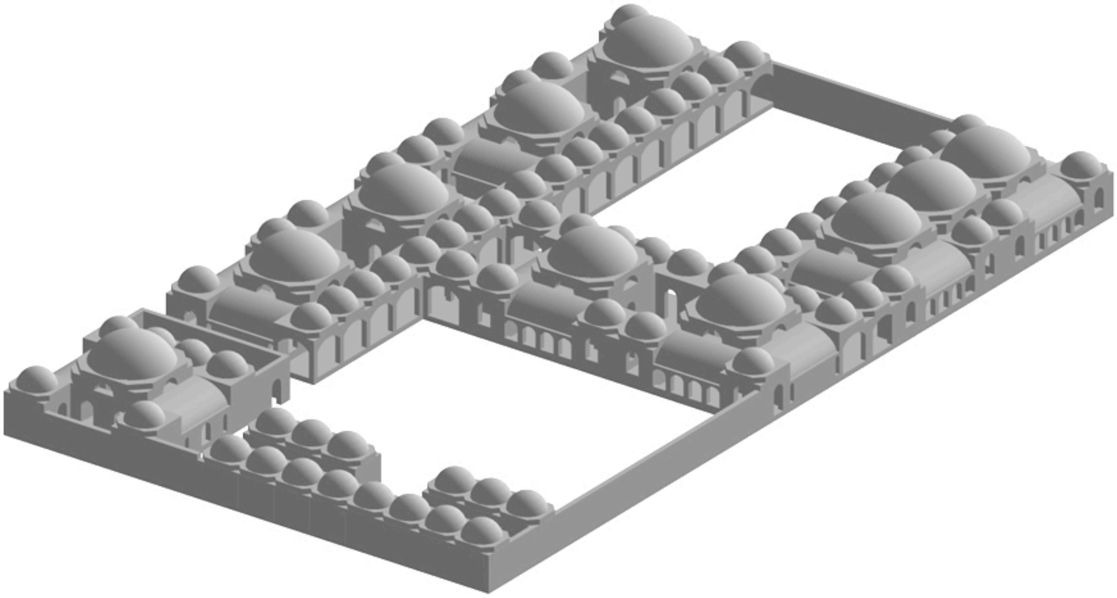
Single Cell



Single Classroom Unit



Double Classroom



Prototypical School

Design by Cenk Yoldas

FIG. 7 ALTERNATIVE PROGRAM ACCOMADATION

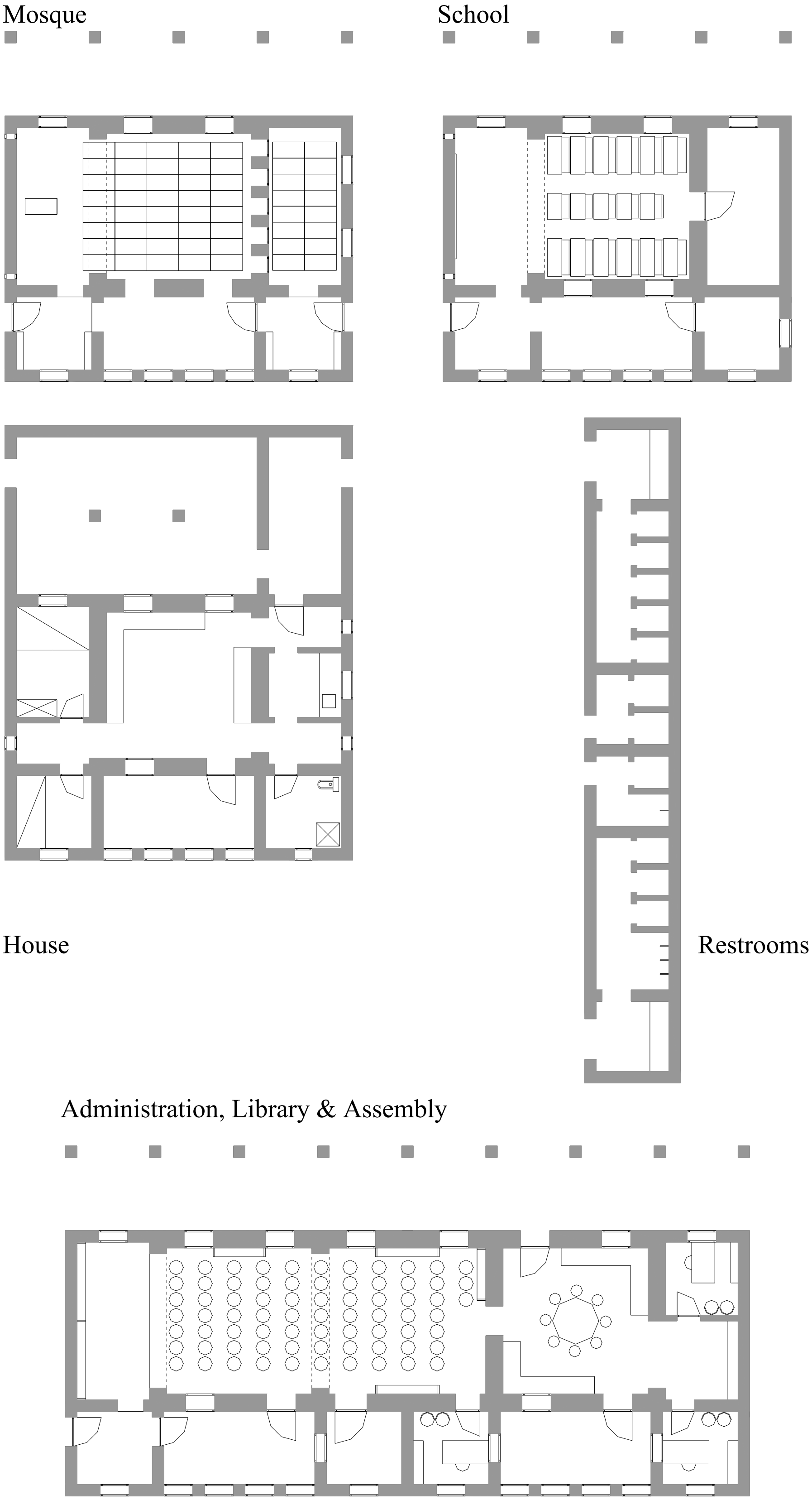
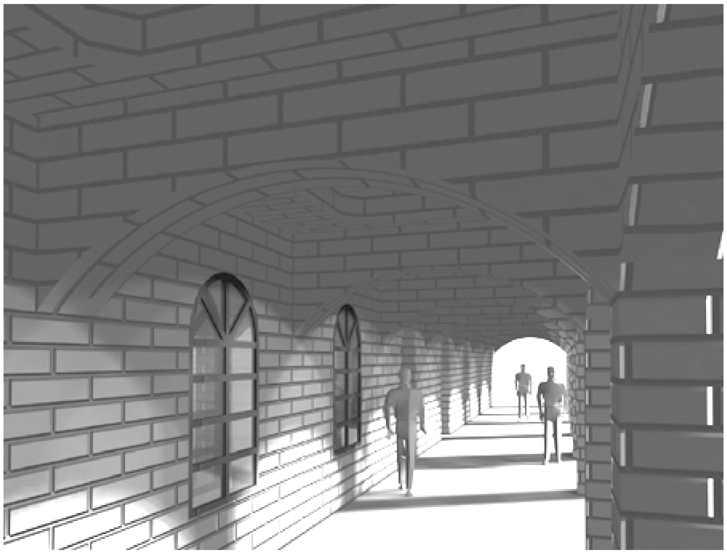
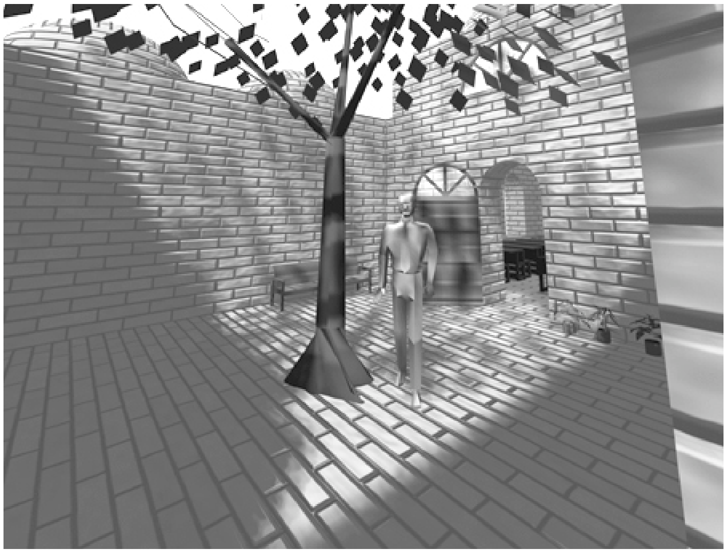


FIG. 8 ALTERNATIVE OUTSIDE SPACES



Colonnade Space: This works as a transitional space between the units. It also contributes to the passive solar design.

Garden Space: This is a place where students or other users can grow plants and vegetables.



Courtyard Space: It is a common gathering space between two-classroom units. It can serve as a playground or outdoor classroom.

Design by Cenk Yoldas

FIG. 9 A MORPHOLOGY OF ALTERNATIVE CELLULAR CLUSTERING