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Freeform Rammed Earth Shell Construction

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Freeform Rammed Earth Shell Construction

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Abstract

This study focuses on applying earth as a traditional building material to explore the possibility of new architectural language that considers the physical properties and cultural significance of earth architecture by using a computational-aid form finding method. Earth construction has been used for around 9000 years all over the world with different techniques. This low-cost, low-energy processing material has been abandoned and neglected by the mainstream construction industry since industrialization. After World War Two's construction boom, innovations in new materials demonstrated the need for efficiency, standardization and mass production. Earth material has not been widely considered as a potential building material in recent urban construction. The purpose of this paper is to examine and explore the existing traditional material by applying digital form-finding methodology and fabrication techniques in order to test the new possibility of using earth material in both practical and aesthetic aspects. Instead of using rammed earth for vertical structure elements, these freeform shells can provide the entire envelope to achieve architectural and structural consistence. The proposed visitor center will be designed in the historical site of the Han Great Wall, Dunhuang, Gansu Province, China. The site was appropriately chosen for the earth wall construction technique since it was widely used in ancient times. This proposal exams the potential design methodology of shell structure to save the construction cost from economic aspect and represent the old technique with new aesthetic form and technical support.
Preface

“Human beings are at the center of concerns for sustainable development, including adequate shelter for all and sustainable human settlements” (UN Habitat Agenda, Commitments and the Global Plan of Action, 2016).

Designing a dwelling by hand with local materials from the immediate surroundings is a skill that has been practiced for thousands of years going back to ancient times. Now and in the future, it will be necessary to recover this skill to enable the world’s growing population having access to sustainable housing and better living conditions. Throughout history, master builders have discovered expressive forms through the restriction of economy, efficiency and elegance. We have much to learn from their architectural and structural principles, design and analysis methods, and their construction logic. Inspired by master builders and learning from the past, how to provide proper approaches for architectural heritage, develop innovative structural design methods for highly efficient and expressive forms, and propose the new and economical construction prototype are still needed to be explored in the future.
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Chapter 1

Revisiting the Vernacular
1.1 Importance of vernacular material

Earth is one of the oldest and most widely used materials for thousands of years (Minke, 2000). As demonstrated by the historic evidence, nearly every country in every continent has a rich heritage of earthen buildings. From the world’s highest land Tibet to the Nile shore in Egypt or the rich valleys in the south east of China, archaeologists’ findings have proven that earth as a building material inspired our ancestors and affected the way we build. According to the Auroville Earth Institute website data from introduction, ‘around 1.7 billion people of the world’s population live in earthen houses — about 50% of the population in developing countries and at least 20% of urban and suburban populations’ (Earth-Auroville, n.d.).

Regarding the rammed earth construction in the world, it has shown the possibility of achieving long lasting and marvelous architecture on all different scales. These world heritages can be found in counties such as France, Spain, Morocco, China and all over the Himalaya area. Typically in Europe, rammed earth structures existed in rural houses, chateaux and apartments. Villages in North Africa are mostly made of rammed earth. Buildings in most of the Himalayan regions like Tibet, Bhutan, Nepal and Ladakh built their communities with rammed earth structure, according to the article of “Traditional Rammed Earth” (Earth-Auroville, n.d.). Parts of the Great Wall in the North West are also constructed with local earth material. This traditional building technique is basically pouring the thoroughly mixed earth in a form of a specific thickness and then ramming it in order to increase the density (Vador, n.d., p.18). Traditional rammers are made of wood or stone. The higher density of the material will create a higher compressive strength and increase water resistance in the future.
Recent researches have proven that this traditional material is more sustainable than contemporary industrial building materials like steel, concrete and brick. In comparison with common building materials, rammed earth material has the following advantages:

1. The local earth and the ramming process give the special appearance of its look.
2. The rammed earth is very strong in compression and can be designed for multi-story structure.
3. It behaves as the heavy weight masonry with a high thermal mass which can absorb or delay the heat transfer during the day.
4. The rammed earth provides best sound insulation and excellent sound reverberation characteristics.
5. There are no flammable elements in the rammed earth wall and it is fire resistance.
6. Earth balances air humidity and indoor climate.
7. The preparation, transport and handling of earth material on site requires less energy comparing with brick or reinforced concrete.
8. The rammed earth is always reusable during its lifetime.
9. The rammed earth maintains its breathability to allow air molecules exchanging between indoor and outdoor.

(Minke, 2000, pp.14-15)

Although earth has many advantages as a sustainable material, some of its disadvantages still need to be solved in future research.

1. It is not a standardized building material. Depending on the site and its composition Loam should be tested before applying in the construction.
2. Earth mixtures shrink when it is drying. Due to the evaporation of the water used to prepare the mixture, shrinkage cracks will occur. Earth is no water-resistant. The main structure should be protected against rain and frost.

3. Loam is not waterproof. It must have protection against rain and frost, especially in its wet area.

(Minke, 2000, p.13)

Loam is soil that consists mostly of sand, silt, and a smaller portion of clay (Kaufmann and Cutler, 2008, pp.318–319).
1.2 Modern construction problem

Kolarevic states that in history being an architect also meant being a builder. Architects were not only creating spatial effects, but also they were closely elaborating the construction of buildings. (Kolarevic, 2003). The master builders like the Greek tekton (builder) or the master masons of the Middle Ages were responsible for all aspects of buildings, including form design and production techniques regarding their construction. They had the most powerful position in this production process, stemming from their mastery of the material and its means of production. However, traditional mastery did not survive of the cultural, societal and economic changes in history (Kolarevic, n.d. p.150). The first use of perspective representation and orthographic drawings as a communication medium for building information began to separate design and construction in its early stage. In the mid-nineteenth century, drawings became contract documents, leading to a dramatic separation between construction and design in that period. The common sense of an architect (as a designer of the building) and a contractor (as an executor of the design) became clear and acceptable at this time. In Kolarevic’s opinion, the design was split from the construction conceptually and legally. Architects detached themselves from the act of the building, unintentionally give up the power they once had (Kolarevic, 2003).
Post World War Two construction innovations in new materials and new building consumption meant that the latest production methods must be developed by architecture firm in order to keep pace with new design works. These principles of efficiency, standardization and mass production have been affirmed by most firms (Tanti, 2014, p.4). This method brought a series of approaches to architecture design and construction, which led to a bigger miscommunication between the involved parties. Nowadays, because of concerns about liability, all parties disconnect from each other by legally binding documents. This structure makes the individual sharing the information accessible for shortcomings, therefore sharing drawings is not recommended in the architecture industry. The construction drawings are recreated for every stage of designing, bidding and constructing, which is extraordinarily inefficient for the working consistency (Kolarevic, 2003).

Professional practice endures from this miscommunication. The opportunity to be creative shrinks. In most cases, the only way to keep a project going is to agree with budget cuts, which ultimately detracts from the building performance and aesthetic qualities (Kolarevic, 2003).
1.3 Technology development innovated vernacular construction

Traditionally local builders considered the design and construction process through verbal communication on site to find actual problems and construction limitation immediately. In some situation, the next construction stage relies on the current construction situation (Kolarevic, 2003). Due to the lack of technology and less efficiency, this working process tends to be disappearing from the urban construction except for part of the undeveloped countries. As the previous section mentioned, design consistency needs to be addressed with technology development in the 21st century. Kolarevic’s idea of “information Master Builder” (Kolarevic, 2003) explained the importance of converting design information to building information, which provides the opportunity for “master builder” in contemporary design. Considering material properties and fabrication techniques in the earliest stage will help design to be integrated (Tanti, 2014). The 21st century’s innovation allowed the robotic arm and CNC machine to have more flexibility to manipulate traditional materials in a new way without generating a huge amount of construction waste. This customization process also opens up the possibility of manufacturing in different design scale and repetition level. This new methodology allows designers to explore the more complicated forms and construction accuracy in their final projects. Digitally generating and analyzing the design information is fundamentally redefined the relationships between conception and production (Kolarevic, 2003). In the end, the relationship between aesthetics and building performance can be thoroughly reconsidered with the help the complexity of digital information.
1.4 Materialism through the digital tool

“We are beginning to recover a certain philosophical respect for the inherent morphogenetic potential of all materials. And we may now be in a position to think about the origin of form and structure, not as something imposed from the outside on an inert matter, not as a hierarchical command from above as in an assembly line, but as something that may come from within the materials, a form that we tease out of those materials as we allow them to have their say in the structures we create” (Menges, 2012).

Digital fabrication is not just a methodology to transfer and create a digital file in a physical world. In order to understand its deeper meaning, this methodology can be seen as a scale with virtual and real in each side. Between material limitation and computational calculation, this balance point will perfectly illustrate a form emerges from the properties of the material rather than being imposed on it (DeLanda, 1998).

Digital tectonics and material computation connected the technical and philosophical works in the architecture field, in which digital model represented the act of making and material characteristics at the same time. This process effectively improves the reaction related to simulation and iteration on architecture models and design. The computational design will virtually simulate design, analyses, fabrication and assembly processes before the action to transfer the digital information in the real world. This scenario allows designers, engineers, and craftsmen to bring the issues together before the project get built on the site (Kolarevic, 2003).
This digital morphogenesis reflects the same iterative process of vernacular architecture, which is a series of improvements and adaptations throughout generations to get the best result (structural, cultural and environmental) within local conditions. Rivka Oxman states, “Vernacular architecture represents the essence of material technologies in being a pure and, generally, a direct expression of the structural and constructional potential of the material” (Oxman, 2009). It is in how the material is being processed and manipulated by traditional crafts which “elevates the material to the technologies of material systems” (Oxman, 2009). In this way, these performance iterations in vernacular architecture can be simulated in a fast digital environment instead taking generations to modify them (Tanti, 2014).
Chapter 2

Material System
2.1 The properties of earth as building material

The primary material of rammed earth building is the dirt, especially the subsoil that is located beneath the organic topsoil. ‘The physical and chemical properties of subsoil are dependent on the original parent rock geology and subsequent weathering, including hydrological and hydro-geological processes, and other changes of exposure to the atmosphere’ (Minke, 2000). Thus, the properties of subsoil are determined by the soil’s region. Figure 1 shows the stratification of an abstract soil sampling that indicates the position of the subsoil. ‘Not all soil compositions are applicable for rammed earth construction and soil must be certified prior to use by verifying its property. Additives may be needed for long-term sustainable buildings in the area where the earthen building is uncommon. Additives can improve strength and water resistance. Shrinkage is also reduced by adding additives’ (Minke, 2000).

Subsoil structure consists of four main particle types. According to the size, they are classified to gravel, sand, silt and clay (Figure 2). Each particle category plays a functional role in the structural integrity of rammed earth. Gravel is the skeleton that provides basic structural stability. It also improves weathering resistance of exposed surfaces with sand. Binding agents that hold the material together are the clay and silt. They are created during chemical weathering. Similarly, they have very different properties from the other particle types. They swell when wet and shrink as they dry. Swelling and shrinkage occur due to the water contain in their wet and dry process. The clay’s properties are the most important aspect in rammed earth structure and they provide the essential for use as an applicable building material (Minke, 2000).
‘Soil density is defined by a number of air voids between particles in the soil’ (Minke, 2000). Less air in the soil means better soil density. For rammed earth structure, high density is achieved by the dismissing air voids through compaction helps increase the soil density. Higher density represents to better strength and durability performance response to higher density. Finally, the soil density is determined by moisture content, composition, grading and compaction (Minke, 2000). Soils with inappropriate grading can be improved by adding particles that are lacking in the original soil composition (Minke, 2000). (Figure 3)

‘Simple field tests for acceptable soil composition are illustrated in the detail by Gernot Minke in his book Earth Construction Handbook. These tests include smell, nibble, wash, cutting, sedimentation, ball dropping, consistency, cohesion or ribbon, and acid’ (Minke, 2000).

Sedimentation test: The mixture is blended with the amount of water in a glass jar. The largest particles first sink at the bottom due to the gravity effect. From this stratification, the estimated proportion of components can be clearly seen in the jar (Minke, 2000). (Figure 4)

Ball dropping test: ‘The tested mixture has to be as dry as possible and wet enough to be formed into a ball of 4 cm diameter. Dropping from a height of 1.5m to a flat surface’ (Minke, 2000). (Figure 5)

Ribbon test: Loam sample should contain certain moisture to be rolled into a thread of 3 mm diameter without any cracks. From this, a ribbon of approximately 6 mm thickness and 20 mm wide is formed and held in the palm. The ribbon is then slid along the palm to overhang as much as possible until it breaks (Minke, 2000). (Figure 6)
2.2 Traditional construction process

**Soil identification** — Same as other construction material, best performance should be insured by test the soil composition according to the requirement. In the previous chapter, the best soil for the rammed earth should be sandy or gravelly rather than clayey. So the clay content should be calculated and tested seriously during the earth selection. Local builder's skill and experience has led them to choose and identify the earth accurately (Earth-Auroville, n.d.).

**Mixing** — In order to ensure the homogeneity of the soil used in rammed earth construction, adequate mixing is essential. Meanwhile, mixing in rammed earth construction is an important process as it ensures the even distribution of moisture content within the soil matrix. The dry compounds can be mixed thoroughly before the water was added. The traditional mixing process will be a labor intense work. Sometimes, loan mill or wheel cart powered by animals are used in order to improve efficiency (Minke, 2000). (Figure 7)

**Formwork** — Traditional formwork, the boards on both sides hold earth in between, and are kept together by spacers. The openings on the finished wall are filled after removing of formwork due to the spacers' support. The formwork will then be disassembled, moved forward and reassembled in the direction of the construction (Minke, 2000). (Figure 8)
Tool — In former time, the earth was rammed manually by using rams with a conical, wedge-shaped or flat base. This extremely nerve racking buildings process is always done by a number of local builders ramming the wall together. In the Tibetan area, the traditional ramming process is made by following the rhythm of songs in order to achieve the same pace and compression force during the ramming process (Minke, 2000). (Figure 9)

The horizontal technique is widely used by many countries. Strips of walls were built horizontally and with different height from 30 to 90 cm. The wooden panel on each side is tightened with ropes through champs and keys in order to provide stability for ramming (Earth-Auroville, n.d.).
2.3 Modern improvements

In the modern construction site, the mixing process is always done by machine instead of human labor. (Figure 10) Indoor mixing can provide accurate moisture content during the process. Small scale projects will use a garden cultivator to mix the soil. Forced mixers are often applied to the modern rammed earth construction as well (Earth-Auroville, n.d.).

Refined formwork systems (Figure 11) and electrical or pneumatic ramming (Figure 12) reduces the labor input significantly and makes the rammed earth technique relevant in some industrialized style as well. Modern rammed earth formwork is designed modular, light weight, easy to be cleaned and transport in order to increase the quality and efficiency. Modern formwork is stable and well-built to provide resistance to pressure and vibration resulting from ramming. Electric and pneumatic rams are used to increase the productivity during the construction process (Earth-Auroville, n.d.).
Chapter 3
Computational Aid Form Finding
3.1 Thrust Network Analysis

How is a shell defined? Chris Williams describes it as a structure defined by a curved surface with large dimensions in two directions and small in the third (Williams, 2014) From Rippmann extra description: “a shell is characterized by its relative rigidity, distinguishing its form from a tensioned structure, such as a membrane or a cable net” (Rippmann, 2016).

Dr. Rippmann categorized the shell based on its generated method in three types (Rippmann, 2016, p.42):

Freeform or free-curved shells are created without taking into account structural considerations. They are designed by a sculptural making process (Figure 13).

Mathematical or geometrical shells are described through the use of analytical functions. Most shell geometries in the 1950s and 1960s are described by mathematical functions for fabrication purposes and to facilitate further analytical calculations. Typical shell shapes represented by quadratic surfaces, such as hyperboloids, ellipsoids and hyperbolic or elliptic paraboloids fall into this category (Figure 14).

Funicular or form-found shells demand a structurally-informed design process. Such forms include shapes generated through the use of hanging models and computational form finding methods to explore states of static equilibrium (Figure 15).
The first two types of shell are usually designed by architects and calculated by engineers in the following step. There is not enough consideration on the material property during the initial form design. So various forces may exist during the structural calculation such as membrane and bending forces. Comparing with funicular shells that are generated from the form-finding method, in-plane compression forces that are guaranteed without other forces existing. Following the structure principle, discrete shells can remain stable though the individual pieces’ compression connection. In order to avoid the bending moments, the geometry of a discrete shell must obey the funicular system of forces and equilibrium of the forces (Rippmann, 2016, p.42).

The exploration of funicular shapes demands the use of form-finding methods, but more importantly, it requires an understanding of the relationship between form and force in the design process. Designing buildings by means of understanding the relation between form and force are born of the need to create stable and solid structures effectively. So understanding the graphic statics as a two-dimensional design and analysis tool and three-dimensional funicular shapes is extremely important before starting the design work.

The process of form-finding is described as the “forward process in which parameters are explicitly/directly controlled to find an ‘optimal’ geometry of a structure which is in static equilibrium with a design loading” (Adriaenssens et al., 2014).
Rippmann stated specifically that the aim of shell form finding is to define the geometry only with membrane forces for the assumed, dominant load case while also meeting desired architectural, programmatic and aesthetic criteria (Rippmann, 2016, p.56).

Since the application of computational design in architecture and engineering practice, computational form-finding methods became more popular and cost efficient in both compression and tension structures. If fundamentally understand the material property before starting the form-finding process, it will be confidentially easy to achieve three criteria mentioned above.

Thrust Network Analysis (TNA) (Block, 2009) is inspired by O’Dwyer’s ‘Force Network Method for funicular analysis of vaulted masonry structures’ (O’Dwyer, 1999) and ‘Reciprocal figures which are introduced to relate the geometry of the three-dimensional equilibrium networks to their internal forces’ (Williams, 1986). TNA generates compression-only vaulted surface and networks to find possible funicular solutions under gravitational loading within a specific envelope. This methodology provided some key features to help illustrate with the clear graphical representation of forces in the system, a high level of control to explore the possibility of equilibrium solutions and fast processing time to calculate the formulation (Block, 2009, p.64).
Graphic statics use two diagrams: a form diagram, that represents the geometry of the pin-jointed figure, and a force diagram, also referred to as Cremona diagram or Maxwell-Cremona diagram, representing the equilibrium of the internal forces of and external loads on the structure. The relation between form and force diagrams is ‘called reciprocal’ (Maxwell, 1864). They follow topological, geometrical and structural properties in below:

- “The form and force diagrams are dual figures, i.e. both diagrams have the same number of edges, and each node with a valency higher than one in one diagram corresponds to space, formed by a polygon of edges, in the other, and vice versa (Figure 16 a,b);
- Each edge e in the form diagram (Figure 16a) has a corresponding edge e_, parallel to edge e, in the force diagram (Figure 16b);
- The length of edge e_ in the force diagram is, at a chosen scale, equal to the magnitude of axial force in edge e in the form diagram” (Rippmann, 2016, p.46).

From the Figure 17, edges coming together at internal nodes of the form diagram are presented by closed vector force polygons in the force diagram. It indicates that the in-plane static equilibrium of all internal nodes are guaranteed by the reciprocal relationship between both diagrams (Rippmann, 2016).
3.2 Digital design and materialization chain

Three fundamental steps – design, analysis and materialization process are stated by Rippmann and Block to clearly illustrate how to achieve this design concept.

As the image showed below (Figure 18), the first chapter of the design process consists of three interrelated steps. In order to generate an appropriate funicular form, the mandatory structure principle is required to ensure the stability of the form. RhinoVAULT (Block, 2009) allows compression force only to be generated from the defined NURB surface in the first step. According to the desired funicular form, the second step is to generate the possible tessellation pattern through the principle of force flow in the funicular form. A suitable cutting geometry is defined by considering the structural and architectural aspects and also designers’ intent for the final project. In the third step, this pattern is used to create voussoir geometry with constraining the fabrication limitation.

The second chapter is to test the digital model by using inverse equilibrium analysis (Block and Lachauer, 2011), structural models (Block et al., 2010b; Van Mele et al., 2012) and discrete-element modeling (Dejong, 2009). The form will be defined due to this analysis.

The third chapter is to fabricate the individual component using the customized machine based on material limitation and install physical pieces on site (Rippmann and Block, 2012).
3.3 Customized linking of data and applications

The digital work process for computational vault design occupies a dominant role in this entire design sequence. Customized commercial software interfaces provide a structurally organized transition between geometry representation and structural properties. Form-finding, materialization and realization must be coordinated with fluency and accurate data to create this physical free-form vault. The image below (Figure 19) illustrated by Lachauer, Rippmann and Block (2010) shows these three necessary phases in this system. Phase I shows the form-finding process of the compression-only surface according to the TNA method. Phase II depicts the generation of individual blocks from the compression-only surface. Phase III generates different data for the rapid prototyping machine in order to cut each panel efficiently and precisely. Depending on the design outcome, these three phases can go several times in this order to get the best result.

Figure 19 Digital Workflow: From Form Finding to Fabrication
3.4 Computational data driven paneling machine

The diagram (Figure 20) shows how the paneling tool works in order to transform digital data into real world location. In this concept, surface curvature represented by the 3-dimensional point in digital software, which is defined by X, Y, Z value. By using a customized grasshopper code and Arduino set, this digital information is transferred from computer to the machine motor. The major component of this machine is a motor-based metal stick. Each thin stick will be driven by the motor in order to deliver data to the certain position. Depending on the number of sticks, the more numbers will help to present more points on the surface, which increases the accuracy of the digital model. The ramming process should be operated through the normal face direction. This set of the machine will help to customize the earth panel without extra waste material during the fabrication. Panels are manufactured in the factory and delivery to the site for installation. This process also can ensure the consistency of environment and manufacture work.

Figure 20 Earth paneling tool
3.5 Physical material testing

The local material test is based on the previous test’s methodology and process in order to have a better understand of material property. Earth was dug out from a construction site next to Martin Luther King Dr. in Cincinnati, Ohio. In order to avoid the topsoil, most of the earth was taken from the exposure site without any organic matters. The following tests include the 2D arch form rammed in a plywood formwork, the 2-directional arch form generated from Rhinovault (Block, 2009).

Test 1 (Figure 21)

The sedimentation test in the glass bottle showed this local earth contained half clay and half gravel with less sand in it. The first test purely focuses on the raw local earth without adding any supplements in. The positive volume in the plywood mold represented a 2D arch shape. The fresh earth poured into the mold with 1.0” thick layer and reduced to roughly 0.5” after the compaction. After the ramming process and taking off the exterior mold, this piece of work was set for 3 to 4 days in order to dry the moisture in the rammed earth.

The success of the test outcome for each material can easily be seen with which of the examples are solid and strong after ramming. Due to less sandy and gravely material, the shrinkage ratio can be found in the thinnest part of the arch. The crack had happened during the curing process after ramming. Due to the high clay percentage, the edge of the rammed arch is also fragile when took the mold off.

Figure 21 2D vault work process
Test 2 (Figure 22)

The form of the 2D arch was designed in Rhinovault with the certain parameter set up. Due to component's ratio of the earth in Cincinnati. I tried to manually extract the earth mixture from local material. Adding enough water to resolve the earth and mixing the earth thoroughly by hand is the first step to extract clay from the natural earth. Then a window screen was applied on the edge of the bucket to separate the clay from gravels. After the overnight waiting, clay was poured in a baking plate for evaporating the moisture in the oven. The grounded clay mixed the sand in a proper ratio, which is about 70% of sand and 30% of clay. Then extra sands were refilled in the laser cut mold in order to provide enough strength for ramming the mixture.

The final result was unexpected after the mold was taken off. The main problem was the cracks in the material itself. Due to the window screen's size, part of the sands was still contained in the clay. So the final mixture's ratio was more than 70% of sand inside. From this test's outcome, less clay was directly related to the structure failure in this test.
Test 3 (Figure 23)
The previous tests formed the arch in the molds in order to test compressed earth integrality. This test focused on the prefabricated rammed earth component to estimate the friction and strength for the individual piece. Also, the overall stability of the arch structure consisting of earth component should be tested after assembling.

Starting with MDF boards for precise mold construction, each layer is cut by laser machine with arch shapes and thresholds for future assembling. Long metal threads hold up the entire mold layer by layer in order to create negative working form for earth compression. Side panels are held up by clamps to form the friction surface for the earth block. This 2D arch is composed of 4 pieces of rammed earth blocks that are used local earth material without any additive for reinforcement.

Figure 23 2D vault with rammed earth block
Chapter 4

Design proposal: Visitor center in China
4.1 Site Investigation

This part of the Great Wall near Dunhuang (Figure 24) was built in the Han Dynasty (206 BC – 220 AD) compared to most known Great Wall, which was rebuilt in the Ming Dynasty (1368–1644). This part of the wall was thus built over 1,000 years before many others (China Highlights, Margaux, 2015). Unlike walls that were built with masonry in Ming Dynasty, this section was constructed with local earth and plant. These two materials are rammed in layers with each other and created great strength. The Great Wall at Dunhuang is located in Dunhuang’s Gobi Desert, on the north of a desert corridor connected by tall mountains on the side. This part of the wall is located on China’s ancient Silk Road, which means that many traders and businessmen from Middle Eastern and Asian traveled through here with their camels back in time. From the historical point, the Silk Road acted as a link to connect China, Kushan, Persia and Rome from the advanced civilization aspect. Because of this connection, they shared and attracted by each other in their highly developed economics and culture. The Great wall ensured the safety and fluent transition for traders during the ancient time (Figure 26). The British archeologist M.A. Stein tried to find sites of the ancient cities in the interior of the Taklamakan Desert during his second expedition. When he came across relics of the Great Wall, he accidently found seven hundred and five bamboo slips (Figure 25) from the Han Dynasty (Editorial Committee of Chinese Civilization, 2007). Due to the historic value and relic excavation, this section of Han Great Hall is necessary to be protected and explored from its rich history.

Regarding the size of this section, ‘the Great Wall is 136 km (85 mi) long and extends from Northern Lake to the east of Maimitu near Xinjiang. On average each layer of the wall is 12–15cm (4.7”–5.9”) (Figure 27), and the remains of the wall are 0.5–2m (1.6’–6.6’) high’ (China Highlights, 2015). This section stands in the endless desert, which makes it very special comparing with surroundings.
For thousands of years, geological deformation and weathering effect vanished this historic site from people's attention. Since the city of Dunhuang is 90 km (about 60 mi) far from relic, this site is naturally located in the severe Gobi desert. There are no human activities and economic potential around here. Moreover, because of the lack of preservation knowledge from local farmers, parts of the Great Wall sections were destroyed by using the Great Wall as their daily sidewalk and construction material for their own houses. The local preservation agency and the governmental office were trying to protect the wall by applying fences due to the lack of the preservation fund. From the Figure 28, we can see fences surrounded the Great Wall in order to give a visual signal for historical site, so that the Great Wall lost its integrity considering its historical and aesthetic reasons.

Due to the similar location of Dunhuang, situated in the north west of Gansu Province, the Han Great Wall is surrounded by high mountains and almost not affected by the moist sea breezes. The arid continental climate is the typical condition in this region. The annual average temperature is 48.74 degree. But the temperature changes significantly during the day and night (Figure 29). The weather is torrid in the summer and severe cold in the winter. The moisture level is extremely low due to the location and frequent wind condition. The winter’s wind direction hits from the North West to the South East.
4.2 Design Methodology

Rammed earth construction is a traditional method by using the local resource to achieve building function. Han Great Wall in Dunhuang accurately responded to its local condition with ancient wisdom. The local earth was dug out and mixed with straws grew in the nearby pond. This magnificent historical structure inspired and impressed tourists who are interested in visiting here. In order to represent this traditional building technique, computational aid form-finding shell consisted of 2D-curved rammed earth panels is introduced to provide both technical and aesthetical support for the new visitor center. Material comparison in Figure 30 shows the texture style and similarity. As mentioned in Chapter 2, rammed earth material is accepted compression force only like most brick material properties. The computational form-finding process by applying the TNA method simulates compression force geometry, which can be manipulated by RhinoVAULT (Block, 2009) to achieve the desired shape for this particular building. In order to keep the original condition, local earth material helps to blend the shell with the Gobi desert’s texture. By changing the opening to the south side, the north edge of the shell naturally continued with ground texture. The last method is to keep most spaces underground to minimize the visual impact. The diagram (Figure 31) illustrates the human’s eye level, shell’s height and Great Wall’s height. Shell curvature follows the terrain’s geometry, which also improves the visual connection the natural desert sense (Figure 32).
The proposed visitor center will contain the underground museum, the information center, the multifunction auditorium, the permanent exhibition area, a cafe, a gift shop and motel rooms for visitors staying overnight. A series of trail design will be designed to help reorganize tourists’ routes and guide their tour for better experience by understanding this historic site. Archeological section cut also will represent the original structure of the Great wall. This interacting design will help visitors to understand the border of the wall and recreate the historic sense during their activities. The designed trail will help people experience a series of picturesque senses to visualize this historic miracle.

As the diagram (Figure 33) shows design inspiration from the linear wall that represents artificial matter and natural shapes of Gobi desert, the entire design language will follow the linear wall’s orientation with pattern lines parallel to the Great Wall. Common programs will be formed by six split lines that represent the natural curvature landscape. The separate shells naturally follow programs’ outlines to enclose three major areas – public, semi public and private. Interweaving shells will help to provide extra shading and tie up the different program together.
The aim of this proposal is to innovate preservation strategy with the low budget condition and the minimum impact for the overall environment. Rammed earth material is not only the local resource, which contains less embodied energy and extra contamination material, but also a good thermal mass to reduce the building’s energy assumption. So each shell will completely open to the south with the glazing system to maximize the solar gain in the winter. The arid continental climate also helps rammed earth material absorbs heat in the daytime and emit energy at night. Between shells, pedestrian path is naturally created by modified curves. The main entrance can be found easily when tourists approaching to the building. After the brief introduction for the historical site, circulation will guide tourists to the underground level experiencing multi-media explanation for the Great Wall. Videos and permanent exhibition will be displayed in this area. Natural light also hits to the underground courtyard due to the designed shell structure. After this dark experience, tourists will follow the light from the west side of museum space to the exit. Climbing to the ramp, people will be guided to the actual site by the designed trail. The trail will provide seats with rammed earth canopies for extra shading. It will also guide tourists to the archaeological section cut to get a better understand for the Great Wall construction. The trail is also designed for both side of the Great Wall in order to see the infinity walls merge to the sky in the end. Although the Silk Road location cannot be verified in this location, tourists still can experience the general surroundings back to the ancient time. From tourists’ perspective, the overall design strategy is to encourage people to deeply understand this severe site condition and its remarkable history. Merging these organic shells with the terrain will help to visually hide the visitor center in to the desert.
4.3 Construction methodology

The important challenge of construction is how to convert the digital discrete model by using the form finding method to physical parts being able to assemble. Applying TNA (Block, 2009) to find an appropriate compression-only form, this middle surface is offset on both sides in order to create a local thickness for the individual panel according to a local live load. These two offset surfaces are called intrados and extrados based on Rippmann’s the Armadillo Vault (Rippmann, et al., 2016). This unreinforced vault structure without mortar or connection between rammed earth panels also are required the specific friction on the load-transferring surface. Depending on the machine precision and production time, the intrados and extrados can be either curved or planarized. But the load-transferring surface must be accurate according to digital data. From aesthetic aspect, extrados’ curvature will represent different texture and discrete paneling style. Figure 34 shows the lifted rammed earth panel with different surface names.

Figure 34 The rammed earth panel lifted from shell
The shell structure must have supports in order to keep the horizontal thrust balance. Customized concrete foundations provide enough strength to support the shell and also distribute this heavy load evenly to the ground. These concrete holders are casted with the foundation that support shell load below the grade. They also hold the rammed earth block above the grade for extra protection from moisture and rain water. To leave these foundation parts exposed is necessary to show this important architectural and structural element.

The façade is a glazing system that contains purely laminated glass with glass fins to resist lateral wind load. Each glass panel is cut by the specific shape according to the shell shape. Because of the self-support vault system, the glass panel is installed separately from the vault structure. Considering the seismic effect and building’s thermal performance, the top line of glass is sealed by mechanical connection that can provide strength for wind load and isolate seismic movement between glazing system and vault structure. This clean design hides most of the connection in the floor or inside rammed earth blocks in order to create visual connectivity and clear views.

The rammed earth block assembly is required reinforced scaffolding system to ensure the heavy block secure in its position. The additional high-quality plywood waffle structure that is fabricated by a CNC machine is installed on the top of scaffolding to provide enough support for each block accurately set in place. The last keystone piece will be installed at the end of the assembling. Actual dimension will be taken to cut the final piece block in case of correcting mistaken measurement. After all blocks are set in place, moisturized earth will be applied for both inside and outside to seal the visible gaps in between. With the earth is completely dried, seamless earth appearance will appear on the finish texture.
Figure 35 Section facing North
Chapter 5

Evaluation
5.1 Evaluation

From form find aspect:
The Thrust Network Analysis (TNA) (Block, 2009) is an innovative graphic statics method to visualize the form-finding process by computational calculation. This interacting design method massively saves time for complex form design and iteration development. Since all the data is linked to customized commercial software, efficiency and tight tolerance can be achieved through this process. Taking material properties in the initial design will also help designers to achieve architectural, structural aesthetic and constructing tectonic. So far this methodology offers wide possibilities for designers to achieve the complex form goal.

From fabrication aspect:
Since the industrial revolution impact, rammed earth material did not establish its own construction code and standard in the country. Also, this local material does not have standard material properties due to the variation of loam’s composition in the different location. So earth must be tested by expertise and special agents in order to get the best mix ratio for construction. Durability will be increased with the proper material selection and mixing method. Rammed earth construction also highly relies on experience regarding the technical and artistic concern. Prefabrication will increase the standard for individual piece’s quality due to the consistency in the indoor climate which provides consistency of the ambient condition. The machine set up for making earth panel is also considered to its accuracy and curvature limitation. But the problems of curvature tolerance and force-loading surface accuracy are still occurred during the fabrication process. Since the earth panel will be rammed in one direction, a method to avoid this visual discontinuity needs to be studied in the future. Rammed earth material is not water resistant, so innovated coating should be tested in further development. Transparent resin will be suitable coating material, but stability and the adhesive property need to be verified.
From material property:
The rammed earth material performs as the compression force only property and less heat conduction. This thermal mass material formed with TNA shell covered entire programs underground without any additional support for the interior space. This methodology maximizes the space availability and natural performance of earth in material property and aesthetic aspect. Organic vault form naturally merges into the Gobi desert with the absence of earth texture from its appearance. Due to the shortage of water resistance, exposed earth material is suitable for the arid area for its durability. Rammed earth material also can be applied for the humid climate with an overhanging roof.
Chapter 6
Conclusion
6.1 Conclusion

This paper focuses on testing the traditional rammed earth building as a structurally informed design based on the computational form-finding process to create compression only vault structure. This complex design and fabrication show that it is only possible with the aid of computational representation and calculation. From the computational form-finding to digital fabrication, these steps intertwined in order to perform the best result regarding load transfer and material property. It also requires small construction tolerances by applying digital fabrication techniques to execute the overall assembling process. In addition, the experience of rammed earth technique contributes to the accuracy and material strength in the production at later phases. Although these steps minimize the tolerance for the final assembling through digital media, manual adjustments still cannot be neglected during the process of finding voussoir geometry to optimize the pattern. The proposed rammed earth vault demonstrates the design possibilities between material limitations and fabrication constraints. This innovative trend can be further explored in arid areas that are constrained by building material and environment impact. This cost-effective structure can sufficiently provide minimal material consumption with expressive form and insulation. Due to the water-resistant issue of earth material, a particular material coating needs to be developed for future construction. Considering earth material for contemporary design can be achieved through modern technologies. The test for material can be achieved accurately, and industrialized machinery can aid with massive production. This structural-driven vault adapts to the building functional and aesthetic aspects. It also represents the materiality and purity of the space.
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Appendix

HISTORIC RAMMED EARTH ARCHITECTURE

Figure A1. Highest rammed earth building, Weilburg, Germany, 1828

The tallest house with Cob construction completed in 1828, which is still stands. All ceilings and the entire roof structure rest on the solid cob walls that are 75cm thick at the bottom and 40cm thick at the top floor.

Figure A1

Figure A2. Ksar of Aït-Ben-Haddou, Southern Morocco

The Ksar of Aït-Ben-Haddou is a striking example of southern Moroccan architecture. The ksar is a mainly collective grouping of dwellings. Inside the defensive walls which are reinforced by angle towers and pierced with a baffle gate.

Figure A2

Figure A3. The Potala Palace, Lhasa, Tibet

Enclosed within massive walls, gates and turrets built of rammed earth and stone the White and Red Palaces and ancillary buildings of the Potala Palace rise from Red Mountain in the centre of Lhasa Valley at an altitude of 3,700 metres.

Figure A3
HISTORIC RAMMED EARTH ARCHITECTURE

Figure A4. Casa Grande Ruins, Coolidge, Arizona, 1350

The adobe buildings, constructed using traditional methods, continue in use today and are now listed on the National Register of Historic Places.

Figure A5. Kag Chode Thupten Samphel Ling, Kagbeni old town, Nepal

Kag Chode Thupten Samphel Ling is the monastery in Kagbeni and was established by a great scholar of Tibet in 1429, and the monastery contains a number of rare statues and artifacts. This monastery is constructed with rammed earth wall and timber beams.

Figure A6. Fujian Tulou, China

The Fujian Tulou are the most representative and best preserved examples of the tulou of the mountainous regions of south-eastern China. The large, technically sophisticated and dramatic earthen defensive buildings, built between the 13th and 20th centuries.
HISTORIC RAMMED EARTH ARCHITECTURE

Figure A7. Old City of Bam, Iran

Located in southeastern Iran, 200 kilometers south of Kerman, the ancient city of Arg-e-Bam is made entirely of mud bricks, clay, straw and the trunks of palm trees. The city was originally founded during the Sassanian period (224-637 AD) and while some of the surviving structures date from before the 12th century, most of what remains was built during the Safavid period (1502-1722).

Figure A8. Western Section of the Great Wall

Most western section of the Great Wall and its Pass are partially rammed earth wall with the upper level portion of mud brick.

Figure A9. The Great Mosque at Djenné, Mali

The walls of the Great Mosque are made of sun-baked earth bricks (called ferey), and sand and earth based mortar, and are coated with a plaster which gives the building its smooth, sculpted look.
MODERN RAMMED EARTH ARCHITECTURE

Figure A10. SWOON, by Tres birds workshop, Boulder Colorado

This Earth-inspired project is energized using 100% renewable resources, demonstrating fossil-free potential of the built environment. The structure was built using 200 tons of rammed Earth, a composite of regional dirt and pigments, compressed into 30” thick walls.

Figure A11. Ricola Herb Centre by Architects Herzog & de Mueron Laufen (Basel), Switzerland

A herb processing plant with pre-fabricated rammed earth walls in the countryside surrounding Laufen.

Figure A12. Glendale Childcare Center by Marmol Radziner, Glendale, California

The design incorporates recycled and green materials throughout the complex. The center features rammed earth walls, which not only have the potential to last indefinitely, but regulate heat flow, allowing for minimal environmental impact.
MODERN RAMMED EARTH ARCHITECTURE

Figure A13. Lacey Residence by Jones Studio
Paradise Valley, AZ
The Lacey Residence, by Jones Studio, is a 4,000 sq ft private residence located in Paradise Valley, AZ. Constructed with rammed earth material, which matched the site context.

Figure A14. Reconciliation Chapel, Rudolf Reitermann and Peter Sassenroth, Berlin, Germany
The completed chapel is enveloped by a wall made of rammed earth, composed out of clay and smaller pieces of bricks of the exploded church.

Figure A15. The Hinterland House by Morris Partnership, Rural Australia
The Hinterland House is a rammed earth house designed to be in harmony with the Australian bush. No fences, screens or garden areas were incorporated to insure as little disturbance as possible to surrounding inhabitants.
MODERN RAMMED EARTH ARCHITECTURE

Figure A16. Kindergarten, Sorsum, Germany by Gernot Minke and Kassel, 1996
This Kindergarten has a central dome that is built from mud Brick for multi-purpose use. The thickness is about 30 cm. The central dome’s free span is 10 m.

Figure A17. METI school, Bangladesh by Anna Heringer, Eike Roswag Bangladesh

The entire building is made of abobe wall in by local labor for the ground level. The second level formed with bamboo structure with light weight and sunlight.

Figure A18. House Rauch by Martin Rauch Schlins, Austria

Through this process the technique of solid rammed earth walls results in the wish to build a house exclusively with ecological materials.
Appendix


Figure 2: “Aït Benhaddou”, accessed on December, 28, 2016, https://en.wikipedia.org/wiki/A%C3%AFt_Benhaddou

Figure 3: “Historic Ensemble of the Potala Palace, Lhasa”, accessed on December, 28, 2016, http://whc.unesco.org/en/list/707

Figure 4: “Casa Grande Ruins”, accessed on December, 28, 2016, https://www.nps.gov/cagr/index.htm

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Figure 10: “SWOON”, accessed on December, 28, 2016, http://tresbirds.com/SWOON

Figure 11: “Ricola Kräuterzentrum / Herzog & de Meuron”, accessed on December, 28, 2016, http://www.archdaily.com/634724/ricola-krauterzentrum-herzog-and-de-meuron

Figure 12: “Glendale Childcare Center”, accessed on December, 28, 2016, http://eartharchitecture.org/?p=715

Figure 13: “Lacey Residence”, accessed on December, 28, 2016, http://eartharchitecture.org/?p=708

Figure 14: “Sassenroth & Reitermann: Chapel of Reconciliation, Berlin”, accessed on December, 28, 2016, http://eartharchitecture.org/?s=Reconciliation+Chapel

Figure 15: “The Hinterland House”, accessed on December, 28, 2016, http://eartharchitecture.org/?p=670

Figure 16: “Dwelling in Beja”, accessed on December, 28, 2016, http://eartharchitecture.org/?p=663

Figure 17: “Handmade School”, accessed on December, 28, 2016, http://eartharchitecture.org/?p=478

Figure 18: “Martin Rauch Builds His Own Home”, accessed on December, 28, 2016, http://eartharchitecture.org/?p=522