AUTOMATED CONSTRUCTION USING CONTOUR CRAFTING

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Abstract

This paper presents some concepts and initial investigation of a novel construction automation approach using the Contour Crafting (CC) layered fabrication process, developed at the University of Southern California. CC uses computer control to take advantage of the superior surface forming capability of trowels, used by craftsmen and builders since ancient times, to create large intricate structures with smooth and accurate surfaces. The potential of CC became evident from the initial investigations and experiments with various materials and geometries. Using this process, a single house or a colony of houses, each with possibly a different design, may be automatically constructed in a single setup.

Introduction

Presently, the construction industry is facing various problems including high project costs, low labor efficiency, high at-site accident rates, vanishing skilled workforce, and poor control of construction projects (Warszawski, and Navon, 1998). Automation has resolved several similar problems in the manufacturing industry. The construction industry, however, largely remains manual and manpower intensive. The few attempts made towards automating certain aspects of construction have aimed only at mechanizing the same manual approach (e.g., use of a brick-laying robot) without introducing any new paradigm (Pegna, 1997). Development of new automation paradigms for whole structure construction may mitigate many of the problems that the industry is facing. In fact, new automation paradigms seem imperative for several applications, including construction of emergency homes and low income housing projects. Furthermore, the development of construction automation technologies is necessary if colonization of other planets is to become a reality in the coming century.

Conventional methods of manufacturing automation do not lend themselves to construction of large structures with internal features. This explains why the evolution of construction automation has been slow. A promising new automation approach is layered fabrication, generally known as solid free form fabrication or rapid prototyping, which uses an additive method and is capable of creating complex internal features. However, most of the current layered fabrication methods are limited by their ability to deliver a wide variety of materials applicable to construction. Additionally, they are severely constrained by the low rates of material deposition that makes them attractive only to the fabrication of small industrial parts.

Contour Crafting (CC) is a layered fabrication technology that uses computer control to exploit the superior surface-forming capability of troweling to create smooth and accurate planar and free-form surfaces (Khoshnevis et al., 2001; Khoshnevis, 1998). Using the layering approach afforded by troweling, an ancient process, a wide range of surface shapes may be created with fewer types of troweling tools than are needed for traditional plaster handwork and sculpting. Some of the important advantages of CC compared with other layered fabrication processes are better surface quality, higher fabrication speed, and a wider choice of materials.

The key feature of CC is the use of two trowels, which in effect act as two solid planar surfaces, to create surfaces on the object being fabricated that are exceptionally smooth and accurate. Artists and craftsmen have effectively used simple tools such as trowels, blades, sculpturing knives, and putty knives, shown in Figure 1, with one or two planar surfaces for forming materials in paste form since ancient times. Their versatility and effectiveness for fabricating complex free-form as well as planar surfaces is evidenced by ancient ceramic containers and sculptures with intricate or complex surface geometries as well as detailed plaster work that have shapes as complicated as flowers, on the walls of rooms.

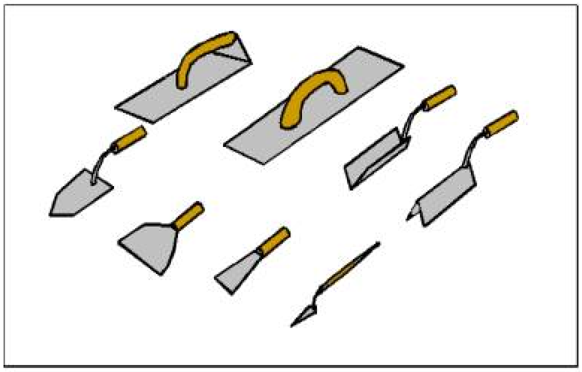

Figure 1. Simple Historical Construction Tools

In CC, computer control is used to take advantage of the superior surface forming capability of troweling to create smooth and accurate, planar and free-form surfaces (Landfoam FAQ, 2000). The layering approach enables the creation of various surface shapes using fewer different troweling tools than in traditional plaster handwork and sculpting. It is a hybrid method that combines an extrusion process for forming the object surfaces and a filling process (pouring or injection) to build the object core. As shown in Figure 2, the extrusion nozzle has a top and a side trowel. As the material is extruded, the traversal of the trowels creates smooth outer and top surfaces on the layer. The side trowel can be deflected to create non-orthogonal surfaces. The extrusion process builds only the outside edges (rims) of each layer of the object. After complete extrusion of each closed section of a given layer, if needed filler material such as concrete can be poured to fill the area defined by the extruded rims.

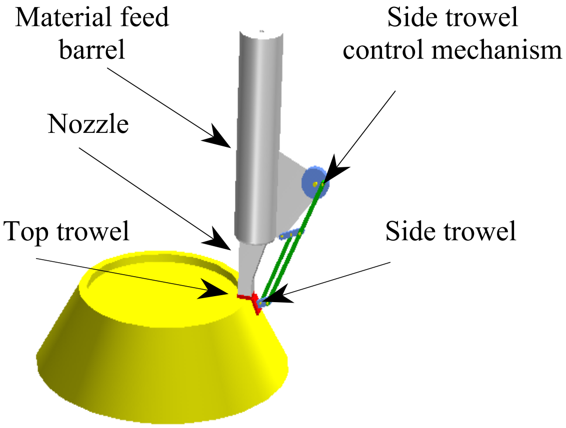

Figure 2. Contour Crafting Process

Some internal walls can be extruded within each layer to create square hatches or other types of hatches (see Figure 3). The hatching process may be required for large objects, since setting or curing can start before the filler material gets a chance to spread over the entire surface of the layer.

However, when hatching is used, each of the small hatches is filled separately, which because of their small size allows more control over the spreading and curing of the filler material. Hatching can also accelerate the forming process because it provides for concurrent extrusion and filling (i.e., as the extrusion nozzle creates new hatches, previously made hatches can be filled).

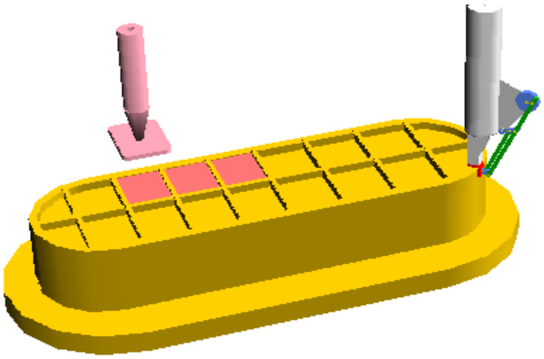

Figure 3. Creation of Internal Walls

Advantages of CC for automated construction

Among all things made by man building structures are those that are fabricated in a layered fashion. This is a clear indication that layered fabrication could be the ideal approach for automating building construction. Although several methods of layered fabrication have been developed in the last two decades (Pegna, 1997), and successful applications of these methods have been reported in a large variety of domains (including industrial tooling, medical, toy making, etc.), only Contour Crafting (CC) is uniquely applicable to construction of large structures such as houses (Khoshnevis, 2000).

The immediate impact of CC will be in the construction of emergency and low income housing structures in various regions by taking advantage of the variety of locally available resources including soil, gravel, lime stone, clay, wood chips, etc. The applicability of CC can possibly be extended to construction applications in regular residential and commercial structures that could utilize functional and exotic architectural geometries, which are difficult to realize using the current manual construction practice. Furthermore, building of structures on other planets using local materials may be achieved using the proposed technology. Such application in building construction is depicted in Figures 4 where a gantry system carrying the CC nozzle moves on two parallel lanes installed at the construction site. A single house or a colony of houses, each with possibly a different design, may be automatically constructed in a single run. Following are some interesting aspects of this automated construction process:

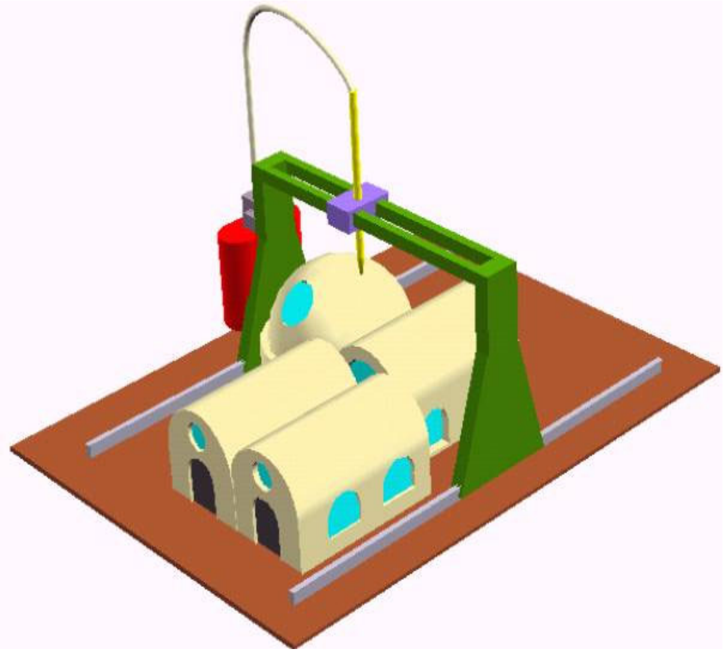

Figure 4.Residential Building Construction

- The process allows architects to design structures with functional and exotic architectural geometries that are difficult to realize using the current manual construction practice. The surfaces produced will be paint-ready, hence an automated painting system may be integrated into the CC system.
- Since deposition in CC is controlled by computer, accurate amounts of selected construction materials, such as smart concrete, may be deposited precisely in the intended locations. This way the electric resistance, for example, of a carbon filled concrete may be accurately set as dictated by the design. Elements such as strain sensors, floor and wall heaters can be built into the structure in an integrated and fully automated manner.

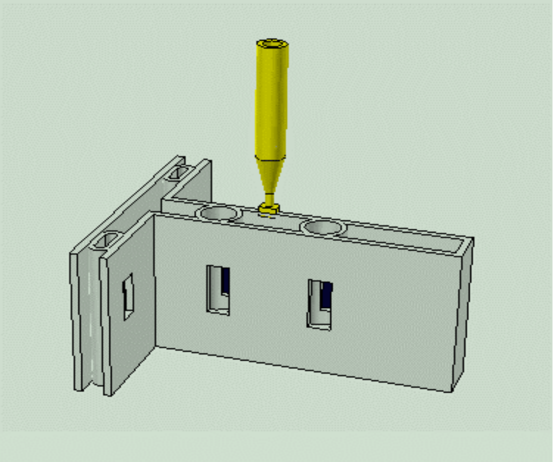

Figure 5. Complex Wall Section

- As shown in Figure 5 utility conduits may be built into the walls of a building structure precisely as dictated by the CAD data.
- The quality of surface finish in CC is controlled by the trowel surface and is independent of the size of the nozzle orifice. Consequently, various additives such as sand, gravel, reinforcement fiber, and other applicable materials available locally may be mixed and extruded through the CC nozzle.
- Multiple materials that chemically react may be fed through the CC nozzle system and mixed in the nozzle barrel immediately before deposition. The quantity of each material may be controlled by computer and correlated to various regions of the geometry of the structure being built. This will make possible the construction of structures that contain varying amounts of different compounds in different regions.
- Methods of imbedding of steel mesh and other forms of reinforcement into each layer may be devised. Note that in this configuration the CC nozzle, the inter-rim filler nozzle, and reinforcement placement mechanisms can all be on the same gantry system. The proposed system can create shapes with smooth outer surfaces and reinforced internal structure automatically and in one setup.
- The lower construction cost and time that CC offers will make frequent reconstruction of buildings a more feasible proposition. This is of special interest in commercial building sector. This possibility is especially appealing if recyclable materials are used.

<u>Experimental investigations</u>

We conducted extensive experiments which show the potential of CC for construction automation. Many of the advantages mentioned in the previous section have been validated through these investigations.

Material used for the experiments

Our examination of the properties of a few ceramic materials and compounds revealed that a type of clay procured from America Ware Co. in Los Angeles did not swell upon exiting the nozzle orifice. This probably was due to its readiness to shear and virtual absence of an elastic phase (Bardet, 1997; Craig, 1997). We qualified the Bingham characteristics of this material (Fox and McDonald, 1985; Levy and Carley, 1994). Using this material we have been able to create the several geometrical features on our CC machine.

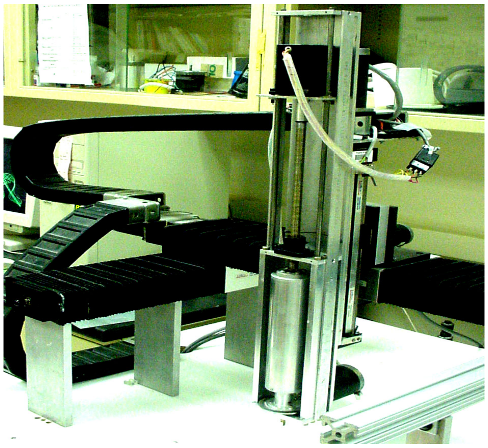

Figure 6. The CC machine for fabricating complex geometries

Description of CC machine

The machine shown in Figure 6 is modified to fabricate the complex geometrical parts for the CC process of uncured ceramic materials, which include the convex, concave, and sharp corner shapes. The machine consists of a trowel rotation system, and a vertical extrusion head capable of linear motion along three coordinate axes.

The trowel rotation mechanism shown in Figure 7 consists of a bevel gear, and a connector. The ratio of the bevel gear is 4 to 1, and is derived by the 5th stepper motor. The connection mechanism allows the raw material to flow continuously from the cylinder to nozzle, and can rotate the extrusion system without disturbing the material flow while fabricating complex curves.

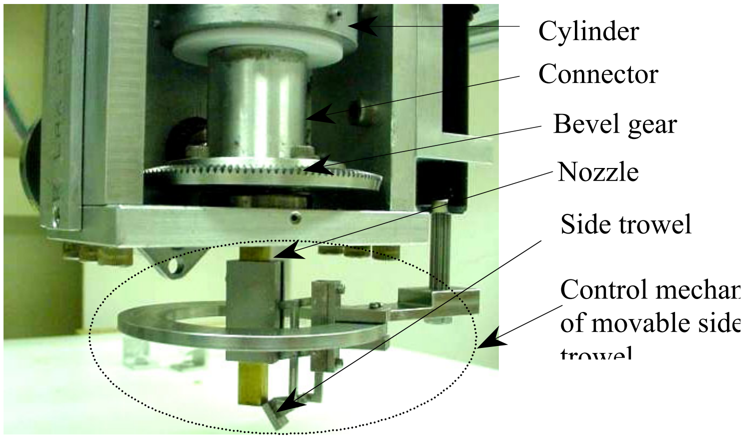

Figure 7. Trowel rotation system of the CC process

The extrusion system consists of a top and side trowel, a cylinder that contains the raw material, and a piston and a threaded feed rod that extrudes the raw material through a nozzle. The process utilizes a Programmable Multi-Axis Controller (PMAC), a high-performance servo motion controller, capable of controlling up to eight axes of motion (Delta Tau Data Systems, 1996 a, b). The eight axes can be all synchronized for completely coordinated motion; each axis can be put into its own coordinate system for eight completely independent operations; any intermediate arrangement of axes into coordinate systems is also possible. Limit switches are used to restrict motion to specified limits.

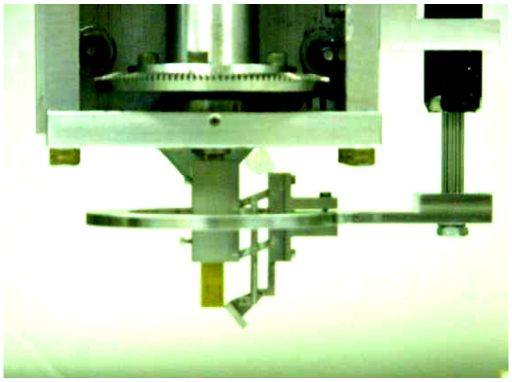

Figure 8.Side view of the movable nozzle assembly

In order to enhance the capability of CC for building certain primitive geometries and hybrid geometries made of these primitives, a nozzle with movable side trowel is designed and assembled into the existing machine as depicted in Figure 8. This nozzle assembly provides for intricate trowel motions to create various complex geometries.

Experimental results

Fabricating complex 3D shapes

Adapting the movable side trowel control mechanism shown in Figure 9 (a), our existing CC fabrication machine has been modified for fabricating a variety of 2.5D and 3D shapes that constitute the primitive construction geometries (e.g. flat floors, straight walls, pyramid, domes, etc.) and hybrid geometries made of these primitives. The primitives have been carefully chosen so that these form the basic shapes for the scaled models of adobe houses (Khalili, 2000). As shown in Figure 9 (b), typical primitives that we have considered thus far are flat floors, straight walls, pyramid, and domes. Hybrid geometries, formed as a direct combination of these primitives, will represent scaled models of adobe houses such as those adopted by CalEarth in Figure 14.

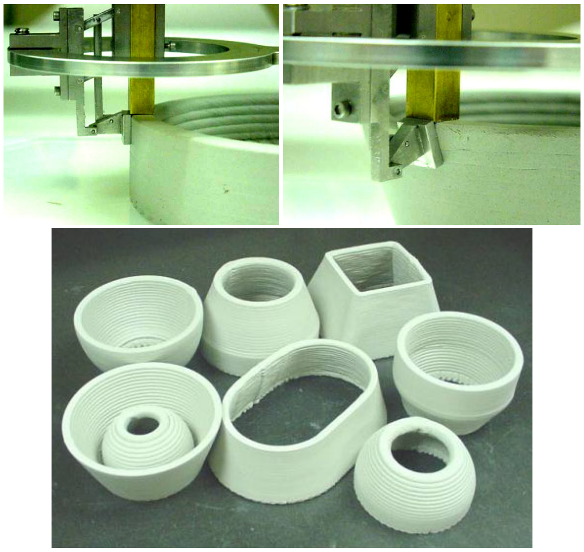

Figure 9. CC process with the movable side trowel: and various primitive parts

Roofs, overhangs, and support structures

Through extensive experimental investigations for the support material, Wax and sand were used as the support materials in order to construct overhang features such as roofs as shown in Figure 10. Note that although this approach is feasible for small parts it may not be so for housing structures. We consider using other means of building overhangs that are more suitable for constructing such structures (one such approach is depicted in Figure 16 for roofing adobe houses).

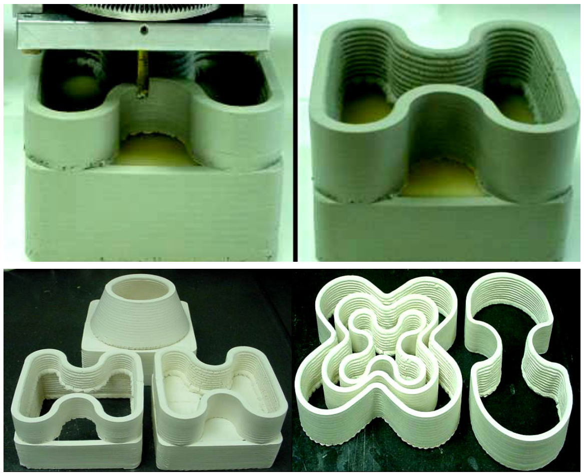

Figure 10. Fabrication of roofs, overhangs, and support structures

Depositions with hollow cavities

In order to investigate co-extrusion of multiple materials using a combination of nozzles, extensive experimentation and a series of design enhancements have been conducted. As shown in Figure 11, we have developed the capability to build layers with hollow depositions using CC. Mandrel of various shapes may be used for creating hollows of various shapes.

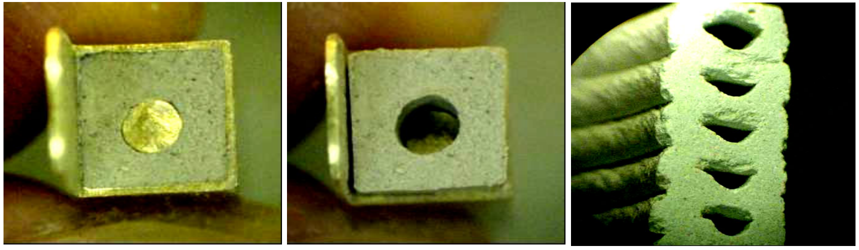

Figure 11. Laying hollow sections through CC: (a) the ceramic material in the nozzle before extrusion, (b) hollow circle formed as the extrudate emerges from the orifice, and (c) cross section of the fabricated part revealing the hollow sections

With these cavities by forcing the material through a nozzle with a central mandrel, various materials may be co-extruded if the mandrel itself is hollow and works as a nozzle to deliver a second material. This feature will provide the capability to lay base material as well as certain reinforcements simultaneously. These hollow cavities also result in lighter structures.

Furthermore, for constructing walled structures, we will first construct rims using the nozzle system, and will fill the intervening space between wall-rims using a bulk-filling mechanism, a schematic of which is shown in Figure 3.

Reinforcements and impregnation

Towards improving the strength of large housing structures built through CC, we have investigated the use of a variety of reinforcements. For example, Figure 12 shows pictures from our experiments with coil reinforcement. Owing to the high extrusion pressures prevailing in CC compared to other layered free-form fabrication techniques (Zak *et al.,* 1999), the extrudate thoroughly adheres itself around the coils without causing any internal discontinuities. Similar results have been observed from our experiments with sand impregnation.

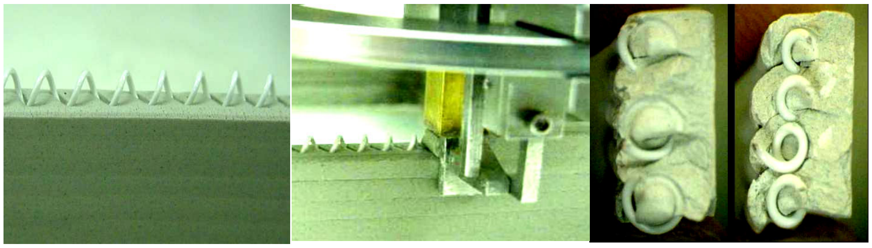

Figure 12. Reinforcement process of CC: (a) metal coil placed on a top layer, (b) a fresh layer of extrudate covers the coil, and (c) cross sections of the fabricated part with the reinforcement coil showing a reasonable adhesion between layers

As shown in Figure 13, two simple modular components may be delivered by an automated feeding system that deposits and assembles them between the two rims of each layer built by CC. Concrete may then be poured between the rims of each layer to contain the steel mesh. The mesh can follow the geometry of the structure. Note that in this configuration the CC nozzle, the steel feeder, and the concrete filler feeder are all on the same gantry system. Thus the use of reinforcements seems promising in our CC process.

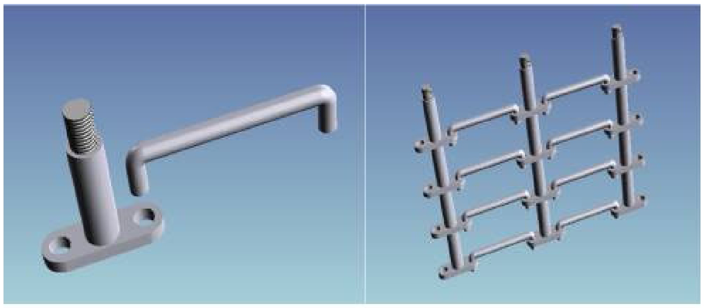

Figure 13. Steel reinforcement modules and mesh

Summary and future work

Preliminary investigation of CC process indicates that the process is feasible and has significant potential in construction automation. The potential of CC became evident from the presented experimental investigations. Experiments with ceramics material show the versatility of the process relative to the use of a variety of fabrication materials. The process seems especially suited for automated construction of emergency structures as well as large scale construction of houses with exotic features such as adobe houses.

In order to facilitate accurate deposition of material and efficient fabrication of the proposed housing structures, we are currently developing a computer control software by modifying our current control software for fabricating both primitive as well as hybrid geometries. The new software will allow for experimenting with various types of trowel motions and material flow patterns. In devising our construction control software we will benefit from the ancient body of knowledge that is currently being harnessed by CalEarth for building supportless closed structures. An example of a clever and ancient manual method of constructing such supportless structures is shown in Figure 14. Here the vault is constructed by first laying side squinches, and the dome structure is built layer-by-layer. Figure 15 shows a vault structure made of clay bricks using this traditional manual procedure. Our corresponding deposition pattern, inspired by these ancient methods, could be such as the one schematically illustrated in Figure 16.

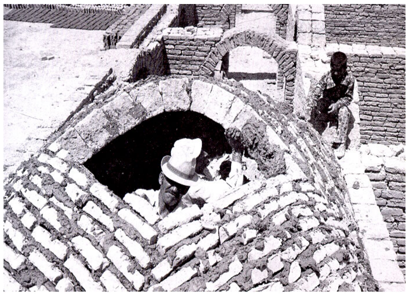

Figure 14. Manual construction of adobe form structures using clay bricks (Source: Khalili, 2000)

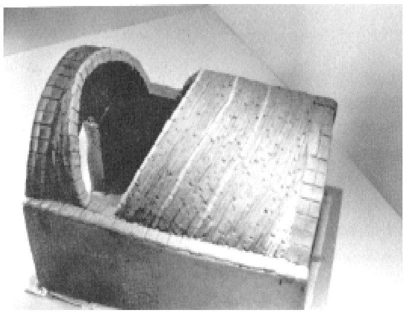

Figure 15. A vault structure made of clay bricks (Source: Khalili, 2000)

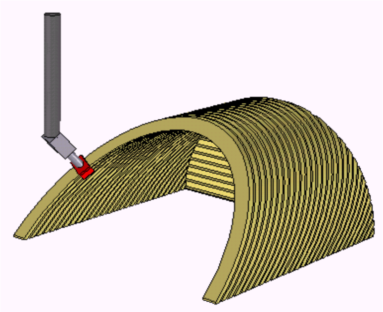

Figure 16. Our approach to fabricate supportless structures

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