The architecture of phase change at McGill

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ABSTRACT: Montreal has a history of monumental ice construction dating back to 1885 when the first large-scale ice palace was constructed for the winter carnival. At McGill University, we have experimented with large-scale ice construction since 1972. In addition to the use of traditional ice blocks, we have built composite structures using suspended nylon fabric as a substrate for depositing vaporized water in the freezing winter conditions. Our largest structure was a scale model of the Pantheon, built with snow, and spanning 34 ft. Robotic CNC and rapid prototyping (RP) methods are opening up new horizons for the water-to-ice phase change process in architecture. Since 2006, we have been working at three different scales in this field, funded by a 3 year $174 000 SSHRC grant. A small Fab@Home rapid prototyping machine has been modified to make small 3D ice objects in a -20℃ environment. One scale up, we are now working with an Adept Cobra 600 robot, producing very finely detailed 3D ice objects up to 30 cm across and 20 cm high. Both these machines are controlled by a personal computer and rely on a water delivery system with micro-valves, adapted for the purpose. The different melting temperatures of brine and pure water make it possible to use brine as scaffolding for the ice model, since the frozen brine can be melted away at a lower temperature than the ice. In 2010, we hope to scale up again, this time to the architectural scale with a new Macro robot.

Conference theme: Digital approaches to architectural design and education
Keywords: ice construction, rapid prototyping, path planning, double curvature

INTRODUCTION

> "Mon pays ce n'est pas un pays, c'est l'hiver"
> "My country is not a country, it's winter"
> Gilles Vigneault (1964)

The process of phase change has been exploited in architecture and engineering since time immemorial. The transition from liquid to solid has been the most profitable; adobe, glass and clay bricks, lime mortar and bituminous coatings come to mind as examples. In Canada, the transition from water to ice or snow has been put to work in igloos and in ice roads. In the late 19th century, many cities, including Montreal, constructed massive ice palaces in winter as centrepieces of winter festivals, using 'natural ice' harvested from lakes and rivers. One of these ice palaces is shown in Figure 1. More recently, full-scale ice hotels have become quite successful, using the skills of ice artisans at many different scales.

In recent years, robotic methods of ice fabrication have been developed at McGill University; we have mastered working with relatively small robots in freezers inside our laboratory, though the plan is to venture out into the open in the winter of 2010 with a robot that can handle 'architectural scale.'

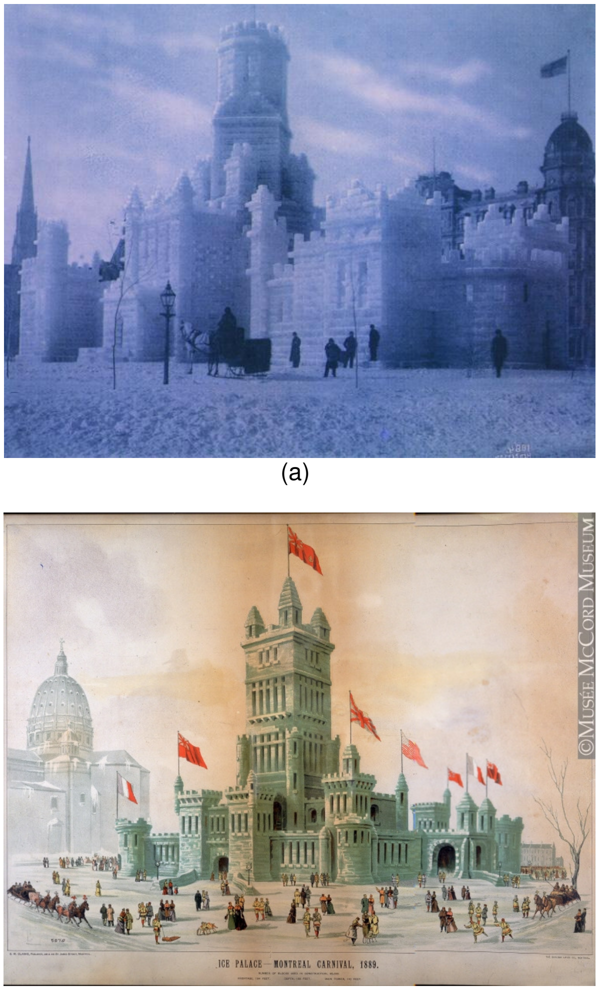
1. ICE ARCHITECTURE AT MCGILL

At McGill University, we have experimented with large-scale 'manual' ice and snow construction since 1972. Our relatively small campus lends itself very well for this kind of activity; it receives on average almost two meters of snow annually, and temperatures in the 'deep' January and February winter months rarely rise above freezing, dipping as low as -30℃. At the same time, water and power sources are readily available, and warm places to recover from the cold are close-by.

2. DOUBLE CURVATURE AS A STRUCTURAL 'LEITMOTIF'

During the 1970s and 1980s, experiments with large scale, double-curved surface structures using nylon fabric as a substrate, form-giver, and reinforcement took place at the McGill Campus. Some of the completed structures are shown in Figure 2Figure 4. Trees and buildings were used as support for steel cables, and nylon sheets were hung from the cables. Sometimes, the nylon sheets were casually stitched together, and other times they were carefully sewn. Finely vaporized water was sprayed on the structures. The spraying was mostly done at night to take advantage of colder temperatures. In order to cool the water as much as possible before it reached the ice surfaces, it was sprayed upwind into the air. That way, it drifted downwind, allowing the droplets to become under-cooled and freeze on impact, with no run-off.

A self-supporting triple hypar structure constructed in 1978 is shown in Figure 3. Pipes measuring up to 30 ft in length were used to form the edges of three hyperbolic paraboloid surfaces. The amazing property of hyperbolic surfaces is that they are elegant, smooth, and double-curved even though they can be generated by sweeping and rotating perfectly straight lines. These properties have pleased designers as varied in background as Antoni Gaudí (Lahuerta 2003) and Felix Candela (Faber 1963). Gaudí, the first architect to deliberately use hypars in his Sagrada Familia school design in Barcelona, exalted that the hyperbolic paraboloid is like the father (one set of straight edges). and the son (the other set of straight edges), forming the holy ghost (the double-curved surface). Pictures of our ice structures greatly pleased Felix Candela when they were shown to him while he visited McGill in the 1980s.



(a)

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Figure 1: Ice palaces: (a) photo (McCord Museum); (b) rendering (McCord Museum)

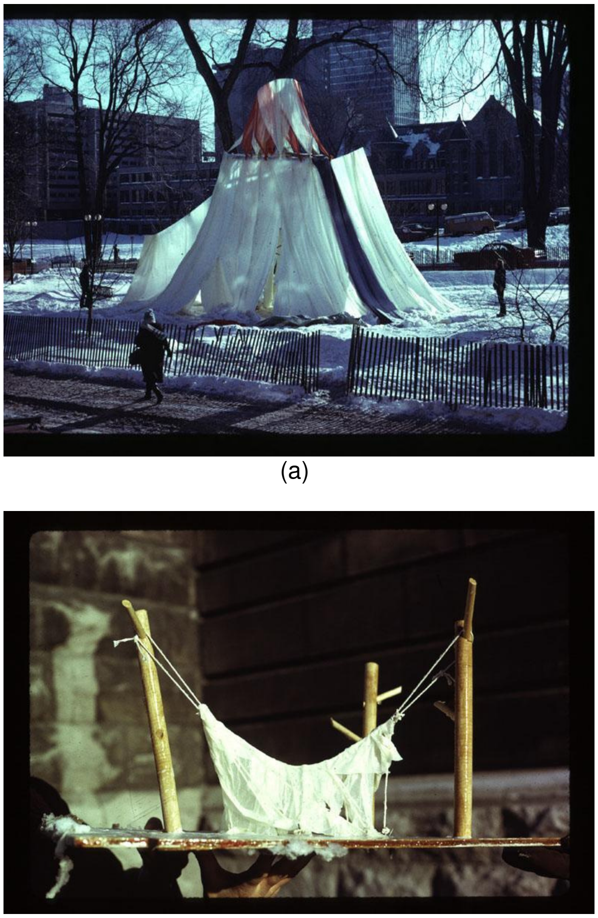

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Figure 2: (a) Double-curved nylon-reinforced ice surface structures suspended from trees; (b) Small-scale model

Figure 3: Nylon-reinforced, double-curved ice structure with free edges

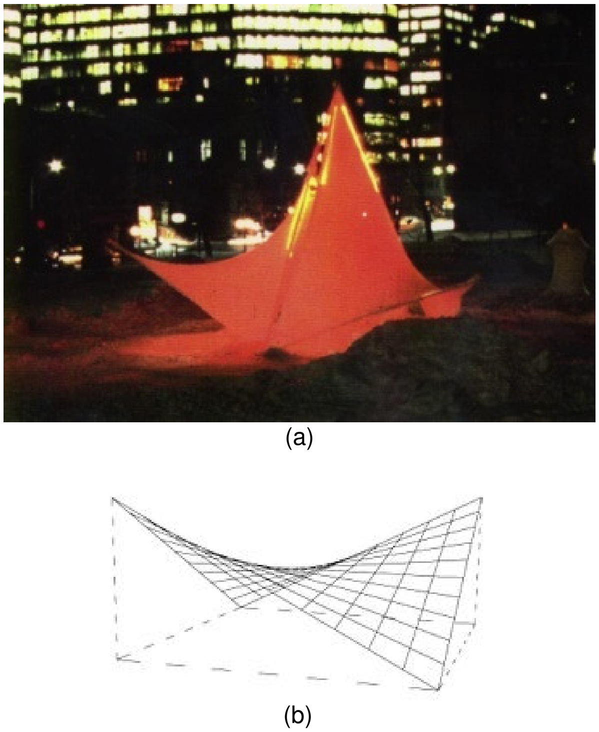

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Figure 4: (a) Nylon-reinforced hyperbolic paraboloid ice shells with rigid edges, 1978;
(b) diagram of a hyperbolic paraboloid

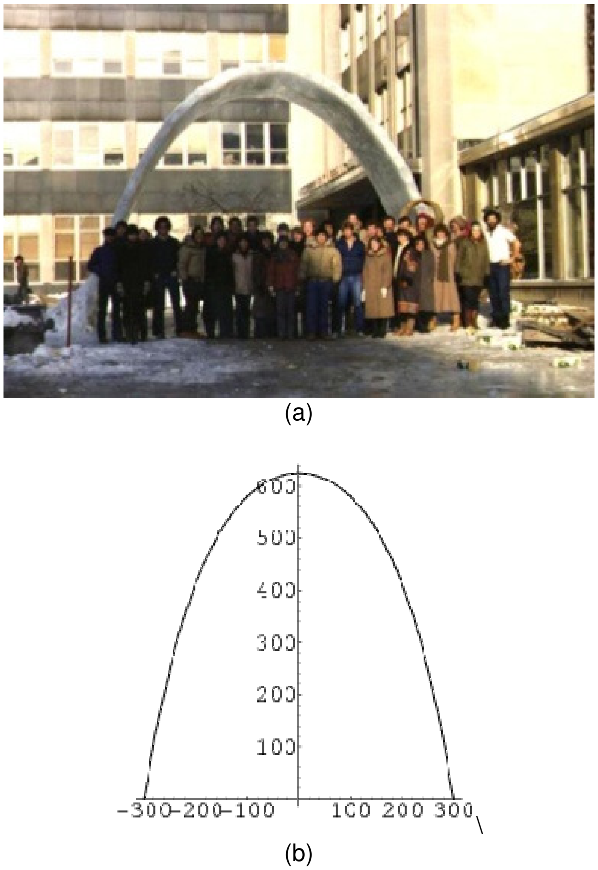
3. PURE ICE, LARGE-SCALE CATENARY ARCH

One winter, we experimented with pure ice structures, again using Gaudí's work as inspiration. Ice blocks were fabricated by letting water freeze in 2000 2-liter milk cartons. We laid these ice blocks on a plywood catenary formwork, and used snow slush as mortar to form a simple brick-like bond. The scaffolding measured 20 feet high and spanned 20 feet; the shape for the curve had been simply traced on a paper background, using a string suspended from two nails twenty feet apart and sagging 20 feet from the horizontal as our guide. The completed arch is shown in Figure 5.

This technique is age-old and is a wonderful example of how high mathematics has been part of construction long before math literacy was common. The general formula for a catenary, $y = k \cosh(x/k)$, was first derived in 1691.

4. ONE-FIFTH SCALE SNOW PANTHEON MODEL

For the centenary of the School of Architecture, we decided to construct a one-fifth scale model of that icon of gravity construction, the Roman Pantheon. Spanning 34 ft and reaching 34 ft in height at the top of the snow dome, this building served as the focus for the centenary celebrations.



(a)

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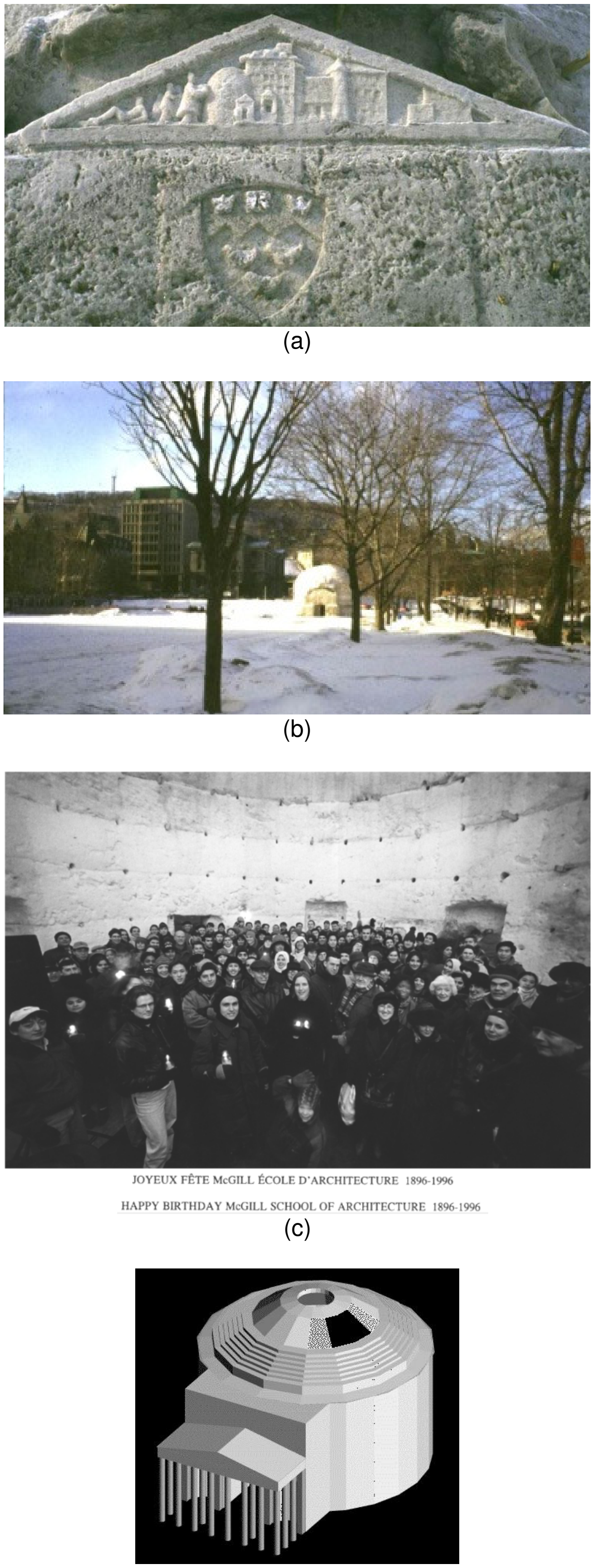
Figure 5: (a) 20 ft catenary ice arch, 1983;
(b) diagram of the catenary shape

In order to provide maximum resistance to possible warm spells, the time-tested *pisé* method was used during construction: forms consisted of curved, removable four-foot high plywood walls, kept apart by easy-to-remove notched wood spreaders. The building was constructed in four-foot layers, and snow from all over the campus was dumped and blown into the forms by regular grounds-maintenance equipment like front loaders and snow blowers. Minor modifications were made to the forms to tilt them for building the dome's center. This was possible because the radius of the cylindrical base of the Pantheon is the same as the radius of the dome cross-section. In fact, the interior of the Pantheon can accommodate a perfect sphere that touches the floor at the center and coincides with the surface of the dome cross-section.

During construction, the four-foot thick walls easily withstood a five-day warm spell with temperatures several degrees above freezing (complete with heavy rain!), and the 34-foot dome was successfully constructed. Unfortunately, no time was left to execute the elaborate finishing of the interior and exterior that was planned. Only a carving over the front portico gave a hint of what might have been with more time. With a 34-foot clear span, this is still the largest snow dome ever constructed. Images of the completed structure are shown in Figure 6.



(a)

(b)

(c)

(d)

Figure 6: 34-foot span Pantheon snow structure, built by adapting the time-tested *pisé* method, 1996; (a) snow carving over the front portico; (b) exterior; (c) interior, (Rick Kerrigan); (d) CAD model

5. THE USE OF ROBOTICS IN ICE CONSTRUCTION

Computer numerical control (CNC) and rapid prototyping (RP) methods are opening up new horizons for the water-to-ice phase change process in architecture. Customers can request almost any 3D form and companies like Ice Sculptures Ltd. based in Grand Rapids, MI, and Ice Culture Inc. based in Hensall, Ontario, Canada will produce it using CNC. At the University of Missouri-Rolla, Prof. Leu and his colleagues have been experimenting with rapid prototyping with ice since 1999 (Zhang 1999 and Bryant 2003).

At McGill we have been working at three different scales in this field since 2006, funded by a three year $174 000 SSHRC grant. In Barnett et al., (2009), we give a detailed technical description of our current progress at the small- and medium-scales. Here, we summarize this work.

A desktop rapid prototyping machine, the Fab@home (FAH), has been modified to make small-scale 3D ice objects in a -23ºC environment. The FAH is controlled by a PC through the USB interface, and free software will import stereo-lithography (STL) files and customizable deposition material files to generate control commands for the FAH. The FAH comes with a screw-driven syringe deposition system, which can extrude viscous, colloidal materials such as silicone, epoxy, and frosting. For water to be used with this system, contact between the water drop at the nozzle tip and the built surface is required at all times to achieve continuous deposition. In practice, when the part is only a few millimeters high, small variations in part height cause this drop to lose contact with the built surface and any further deposition occurs in large, discrete drops.

To overcome this problem, we replaced the screw-driven syringe deposition system with a pressurized reservoir supplying a micro valve/nozzle system. The micro-fluidic components were all purchased from the Lee Company, based in Westbrook, CT. Also, the FAH signal used to control the syringe was converted to a signal suitable for the valve/nozzle using a BasicStamp2 microcontroller. The fluid lines and the valve/nozzle were enclosed in pipe insulation and heated with a temperature-controlled heating rope to prevent the water in them from freezing.

At the medium-scale, we are now also working with an Adept Cobra 600 robot, producing very finely detailed 3D ice objects up to 300 mm across and 200 mm high. The Cobra is faster, more accurate and more robust than the FAH. At the same time, it was not designed for RP, so much more retrofitting is necessary.

The heating and valve/nozzle systems for the Cobra are very similar to those used for the FAH, but the signal conversion for the valve is accomplished with a function generator rather than a microcontroller, because the Cobra has different output control signals from the FAH.

The tool path generation for the Cobra is one of the major retrofitting challenges we are facing. We have developed a path-planning algorithm in Matlab to import STL files and generate tool paths for the Cobra in a similar manner to that used in the FAH software. However, we have also tried to improve upon the techniques by making the paths generated smoother and automatically generating support structures when necessary. Elsewhere, we provide a detailed description of the path-planning algorithm (Ossino 2009).

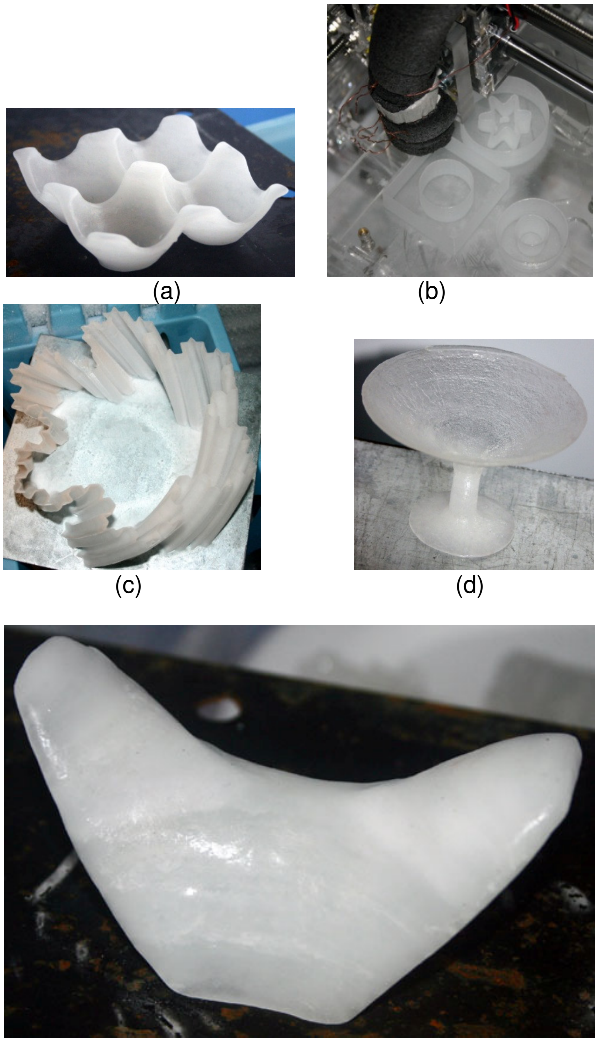
A support structure is needed to produce slanted or overhanging parts. We have elected to use a solution of potassium chloride in water (KCl brine), to build the support material. Both water and KCl brine freeze in our deposition environment of -23 ºC. When a part is completed, it is placed in a -4 ºC environment and the frozen KCl brine is melted away, leaving the finished ice part.

Figure 7 shows several ice parts we have built with our RP systems. For these parts, build times range from five to twenty hours. The deposited water path for the parts shown ranges from 0.1 to 0.5 mm in height and 0.8 to 1.5 mm in width. If the deposition rate is too high, the water will flow over the build surface, and previously frozen layers can be melted, significantly reducing build quality. The maximum rate of change of part height achieved is 20 mm/h.

In the winter of 2010, we plan to scale up again, this time to the architectural scale. We will use a larger robot having a reach of 20 ft, with a slush/snow delivery system, now in development. This system will be designed for outdoor deployment, using the natural freezing winter environment as its workspace. The varying outdoor temperatures, humidity and wind speeds will require the ability to continuously adapt the rate of flow and the speed of deposition to optimize the ice building process.

There are many architectural applications of the techniques we have developed. Small-scale ice models are very economical ways of producing intricate 3D models of architectural objects, be they scale models of buildings, site models, or building details. Rubber casts can be made from ice originals to produce high-quality copies at will.

Large-scale automated ice construction will be used to build ice buildings, particularly for the ice hotel and winter fair industry. The possibility of including robot-built intricate detailing (say a Moorish vault pattern in a domed roof) opens up a definite market in the winter recreational industry. It also allows students to produce full-scale models of their designs (in particular thin shell designs) and judge the spatial and structural qualities of their structures. The structural strength and weakness of a thin shell structure like a dome can be readily observed by the formation of cracks. The weaknesses of the ice structure can then be remedied and tested for new cracks after more water has been deposited to thicken the ice at the weak spots. A simple iterative process of testing and reinforcing can thus take place; students will be an integral part of the process, and they will benefit as they have in the past when they helped build our large hand-made structures.


(a) (b)

(c) (d)

(e)

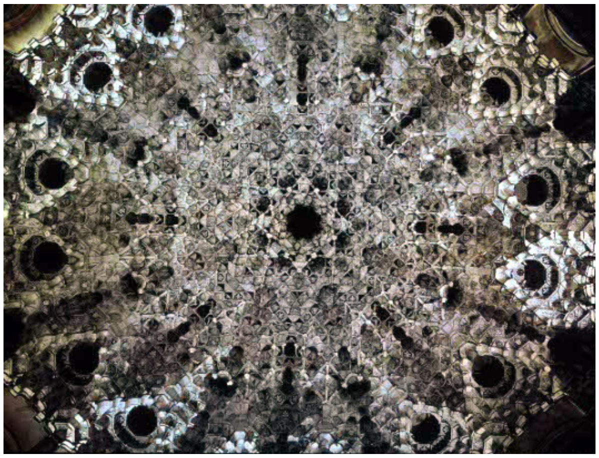
Figure 7: (a) Ice egg carton built with the FAH; (b) the FAH at work in the freezer; (c) “twisted” Koch snowflake built with the Cobra; (d) martini glass built with the FAH; (e) Hyperbolic paraboloid ice “saddle” built with the FAH

6. THE FUTURE

After scaling up to a larger robotic system, and with the experience we have behind us, there is no reason we could not build vaults as detailed as the Muslim examples shown in Figure 8.

CONCLUSION

The long history of ice and snow construction has been part of the larger history of the use of phase change in architecture and engineering. The recent introduction of robotics into this practice has opened up a large field of possibilities. At McGill, we have concentrated on additive processes like rapid prototyping, partly because subtractive methods like CNC are already well developed, and partly because we will be able to build certain parts using RP that would be very difficult or impossible to build using CNC. We plan to attack the architectural scale with a large robot in the winter of 2010. We will build on the techniques we have developed during our large-scale manual projects, some of which are now commonly used in the construction of ice hotels.



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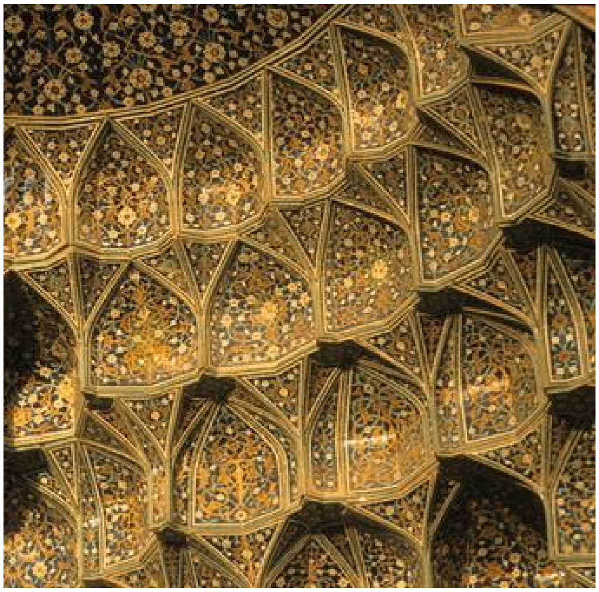

(b)

Figure 8: Muslim vaults: (a) Alhambra, Granada; b) Great Mosque Isfahan

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