Thin-shell Concrete Structures for Low Embodied and Operating Energy Plus Durability

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ABSTRACT We have designed a re-usable tooling system for building thin-shell concrete dome structures of high strength and durability with low cost and embodied energy. The proof-of-concept scale model domes shown herein are ~1 cm thick, but have survived burial under 1 m sand and repeated horizontal seismic shocks of ~2.7 g. Hundreds could be made from a single forms set, on-site, maximizing use of local materials and labor. Optimum size for human utility and this method is ~ 6-7 m diameter, 5/8 sphere volume. Only quasi-spherical structures may be made of thin-shell concrete; stress concentrations at small radius must be avoided. Primary reinforcement is non-ferrous, carbon-fiber-epoxy C-Grid": http://www.chomarat.com/en/tag/c-grid/

Keywords: Thin-shell, concrete, quasi-spherical, dome, C-Grid, seismic, low-cost

This tooling and construction system and strategy was conceived for rapid construction of durable and low-cost shelter in remote places where one must minimize import of materials, tooling, tools, and expert labor, and maximize use of indigenous materials and labor:

- Replacement of failing Alaska village housing
- Disaster relief: earthquake, flood, tsunami
- Clinic, classroom, granary, water tank, storage
- Housing, office, warehouse

The forms set, shown stacked in Figure 1 and assembled in the other figures, must be transported to the construction site(s). Imported materials would include:

- Bagged premix of Portland cement, additives for workability and strength (superplasticizer, pozzolan, silica fume), for waterproofing (Xypex, for example), and plastic reinforcing fibers.
- C-Grid carbon fiber epoxy primary reinforcement, pre-cut to size for stapling to the dome form surface, as overlapping "tiles"
- Heavy fiberglass grid for embedding in the foundation ring, for structural tie-in of the dome shell during dome mortaring
- Stainless steel staples, for tiling C-Grid
- Window and door units or materials
- #3 or #4 rebar for foundation ring core

Indigenous fresh water and sand complete the concrete mix; both must be clean, perhaps washed.

Several domes, built on the same tooling, may be built adjacent to, and interconnected with, each other, to provide more space and volume in a single building than a single dome would.

At 6 m diameter, 5/8 sphere by volume, a small "loft" could be supported by a privacy partition wall, and laterally by the dome shell, for storage and for children sleeping.

DOME FORM CONSTRUCTION

The 12 "orange peel" dome segments are fiberglass covered with 60 mil EPDM rubber sheet for staple retention, with 10 mil Teflon sheet attached with 5 mil butyl rubber adhesive. The Teflon outer surface easily detaches from the cured concrete, after the spacer shims are removed to free the individual segments. Repeated use will perforate and damage the Teflon outer surface, which can be replaced in a refurbishing operation.

DOME CONSTRUCTION METHOD

See Figures.

1. A flat, compacted ground area is prepared. The foundation ring forms are assembled, with a single continuous piece of reinforcing bar, steel or other, centered in the cross-section. The ring is poured and vibrated. The vertical heavy fiberglass tie-in mesh is installed. Cure

for 1-2 days; remove and clean the foundation forms for reuse.

2. Assemble 12 dome form “orange peel” segments with inter-segment 3/8” thick shims. Attach circular top form and skylight Sonotube
3. Staple C-Grid tiles to dome form with stainless steel staples.
4. Apply rich sand-only concrete mortar, by hand trowel or spray; trowel to desired finish
5. Install or drape polyethylene sheet to exterior, for curing vapor barrier. Cure for two days.
6. Inside dome, remove all segment assembly fasteners. Remove inter-segment shims. Remove dome form “orange peel” segments, through entry door.
7. Remove lower segment shims
8. Clean form to prepare for reuse. The Teflon outer surface requires little cleaning

INSULATION AND FINISH

If required, thermal insulation is closed-cell urethane (UR) foam sprayed on interior of the concrete shell. Foam interior is then covered with a protective plaster coat and optional interior paint. The closed-cell UR foam provides a continuous vapor barrier at the structure’s interior, where it is most effective.

In a full-size dome structure, plumbing, if any, should be installed only in interior partition walls, while electricity flex conduit may be glued to the concrete shell interior and buried in the sprayed interior foam insulation, if it is used.

A heating appliance chimney and a plumbing vent may be formed and mortared into the thin concrete shell.

The entry roof is also thin concrete, mortared into the dome shell in the continuous process of applying the high-strength concrete shell. Various “arctic entry” designs could be developed, perhaps approaching the classic “igloo” design.

The window frame must be carefully designed to eliminate stress-concentrating corners where shrinkage cracking will occur during concrete cure. Bare, custom-made, insulated glass units would be most economical. The skylight may be operable, to provide ventilation.

COST

Of course, cost will vary greatly, depending on many factors: degree of finish and size of structure, and with the costs of moving the forms set, tools, and materials to the construction site(s), and the number of domes built there. The C-Grid primary reinforcement will probably be the largest variable cost component for a simple, uninsulated dome built in a tropical climate, if no structural door and windows, nor plumbing and wiring, nor finished floor are needed.

EARTH SHELTERING

We have demonstrated that a 1 cm thick concrete dome may be completely buried, with 1 m of sand on top, without visible damage. This isotropic Earth load may strengthen the dome. However, we have not tested complete burial during multiple freeze-thaw cycles. Earth sheltering may be important to protect the interior from climatic extremes, and to provide some degree of protection from military attack: small arms fire and shrapnel.

SCALING UP FOR HUMAN USE

The optimum size for human utility and this construction method is probably ~ 6-7 m diameter, 5/8 sphere volume. The dome form segments may be difficult to manipulate, by hand, at larger size. A special curved ladder, supported at an apex pin at the top and on small rubber tires at the bottom, will be needed to apply mortar to dome upper areas.

Manufacturing complete forms sets, for the foundation ring, dome and entry, and window openings, will probably cost $300 – 500,000 for CAD design and tooling, from which the fiberglass form components could be made. We will invest in this step only when we confirm a market for the thin-shell concrete structures that could be built from such form sets. The sets could be sold or leased, including training to insure quality, safe, and economical construction in the field – including under difficult conditions. The business model should also include selling the bagged premix for the high-quality concrete mortar, and pre-cut pieces of C-Grid for tiling to the dome form.

Figure 1. Complete forms set, for foundation ring and dome. First prototype: proof-of concept one-third scale model, with skylight, window, chimney

Figure 3. First prototype, insulated, with floor. Total weight 1,050 kg.

Figure 4. Assembling the dome form to the foundation ring. A shim 3/8” thick is installed between pairs of form “orange peel” segments

Figure 2. First prototype, insulated, with insulated floor. Total weight 1,050 kg. Juneau, Alaska

Figure 5. Stapling “tiled” C-Grid to dome form

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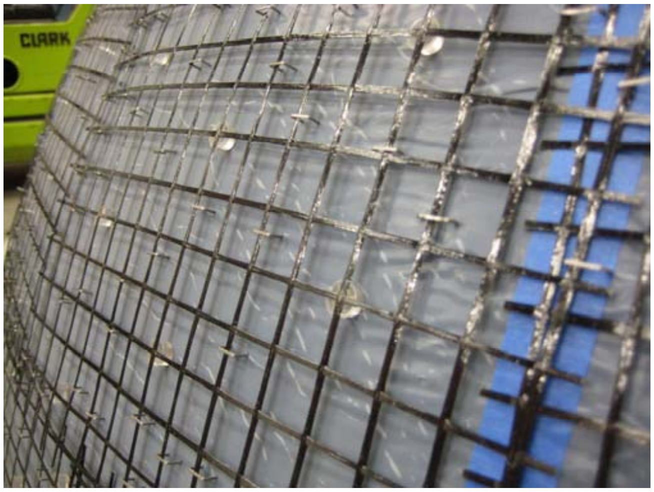

Figure 6. C-Grid attached to dome form segments with stainless steel staples. Note clear plastic “chairs” to space C-grid ~ 1 / 2 cm from Teflon surface.

Figure 7. Applying mortar ~ 1 cm thick

Figure 8. Applying mortar ~ 1 cm thick

Figure 9. Strength test: 1 m sand on top.
No visible damage. Dial indicators inside the uninsulated concrete shell showed ~ 0.010” deflection at horizontal diameter and vertical apex.

Figure 10. Seismic test: repeated ~2.7 g shocks. Wire rope wrapped around foundation ring. No visible damage.