Design and Tooling for Pre-Commercialization of Energy-conserving Thin-shell Concrete Structures

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Total project cost:	EETF grant	$ 320,000
	Applicant match, cash	$ 30,000
	Applicant match, in-kind	$ 70,000
	Total	$ 420,000

Previous applications:

EETF 2011

Project Summary: Energy efficiency and conservation: this project will advance a proof-of-concept energy conserving thin-shell concrete (~1.5 – 2 cm thick) construction process to commercial readiness, from about TRL 5 to TRL 8. From the two successful prototype, scale-model structures in Figs. 1-6, built on the hand-made forms set shown in Fig 1, we will design and build tooling by which to manufacture single-side, male form sets for field production of full-size thin-shell concrete structures, ~6 m diameter, 5/8 sphere, also ~1.5 – 2 cm thick. This project satisfies the four criteria in 4.3 Prioritization. Design will be CAD, for export to tooling fab contractor; FEA of the thin shell included.

Project steps:

1. CAD four tools for production of the reusable fiberglass form set components by which the concrete shell is built on-site: a. ring foundation, outer c. side spherical segment, "orange peel"
   b. ring foundation, inner d. top spherical-section cap for "c" assembly
2. Build the four tools designed in 1; "orange peel" spherical segment, for the 12 sides, is most costly.
3. Build one set of reusable full-size fiberglass forms on the tooling built in 2; modify forms set and tooling if / as required; build a second forms set, if necessary. Consider blow molded foundation set.
4. CAD and build shim sets and other accessories for the forms sets built in 3.
5. Build two or more full-size structures, one complete with windows and interior insulation and finish.
6. Further develop the construction process, materials, and special tooling for full-size structures.
7. Test the structures built in 5 for static and dynamic (seismic) loading: strength, stiffness, and failure modes; learn added reinforcement needed at window and entry interruptions of spherical integrity.
8. Build and test additional structures with partners in Juneau and Fairbanks, for thermal performance, and for proving necessary interior air quality control. Train building crews, if market emerges.
9. Market forms sets and training for proliferation of structures, based on success in 3 - 8, above.

Technology Readiness: Figures 1-6 show two 46% scale model proof-of-concept prototype structures built in Juneau in '09–11, demonstrating how thin-shell (1 – 2 cm thick) concrete domes are practical in these aspects:

1. Forming system is quickly assembled, needs no form-release oil, accepts C-grid placement staples;
2. Chomarat C-Grid is an ideal nonferrous primary reinforcement for 1.5 cm thick concrete ; See Ref 2.
3. Form is easily removed from the cured foundation ring, then from the cured 5/8 sphere dome;
4. Concrete shell may be strong enough to meet building codes and for earth-sheltering or full burial;
5. Concrete shell may be easily insulated with interior-sprayed, closed-cell, urethane foam;
6. Insulated shell interior may be easily fireproofed and finished with ~1 cm of sprayed interior plaster;
7. Windows, heater or stove flue, plumbing vent, skylight, and entry are easily incorporated;
8. Probably compatible with magnesium-base, non-portland, cements.

We have strength-tested the instrumented, uninsulated, dome #2 measuring stiffness, rebound, and seismic endurance; video-recording the tests. We've not yet tested to failure, to determine ultimate strength:

1. Measure vertical and horizontal shell deflections as sand is piled on dome, finally fully burying it;
2. Future: During 1, measure shell strain at several or many points on shell interior, via strain gauges;
3. Horizontal axis g as repeated impulse loads, up to 2.7g so far, are applied to dome's ring foundation;
4. Since dome #2 has survived 1 - 3, perhaps subject it to repeated submerging in tide and surf; video.

This prepares us for the several steps in "synopsis", above, via well-established CAD, mechanical engineering, and manufacturing processes; no new science or materials are needed. We will advance from about TRL 5 to TRL 8, ready to manufacture and sell complete sets of forms and a few specialized tools by which, with training, quality structures will be built by replication in the field. No patentable IP will result, which is not important in our business plan; diverse concrete "art" is well known. Others have demonstrated thin-shell concrete construction for quasi-spherical buildings, supporting "technical readiness" for our system which uniquely emphasizes low capital and operating costs, low embodied energy, minimum import of materials, tooling and tools, and expert labor, for replication of several or many nearly-identical buildings on-site. Form sets and training available for sale within two years.

Technology Validation and Research Methodology: See Ref 1: AASI has successfully completed a USDOE-funded, advanced-technology project, by which we have become acquainted with the CAD and tooling techniques essential and established in the composites industry. Both the tooling and the forms sets will be built of standard-technology composites (FRP); no exotic techniques or processes, nor costly materials, are required. All project

stages will be documented. This is not primarily a data collection project, but a pre-commercialization tooling and process development investment. Process should confirm CCHRC interest in value of magnesium silicate cement, perhaps superior to "portland".

Project Schedule: 24 months: Grant Budget Form. Design and tooling construction phase reporting will be monthly, driven by milestones which represent potential go / nogo decisions: if a milestone cannot be achieved, we will recommend project termination with return of unexpended EETF funds.
Strength testing on instrumented uninsulated dome #2 will commence in Juneau after Spring '12 thaw measuring stiffness, rebound, ultimate strength, seismic endurance, during EETF abstract review.

Site Suitability: Some CAD in AK. Principal project effort will be at subcontractor(s) in the Lower 48; Alaska has no candidates for the required integrated CAD, composite tooling fabrication, and composite form set manufacture. Later, form sets could be built in AK. The first test structures will be built on the new forms and tested in the Lower 48, to:
1. Verify the tooling design and form set manufacture; modify tooling as / if needed;
2. Further develop the thin-shell concrete materials, manufacturing processes, and special tools;
3. Test the structures for static and dynamic strength and thermal performance, from which proceed the engineering calculations universally applicable for necessary building permits and perhaps code changes in Alaska and other worldwide markets. These will be temporary structures, for which no permits will be needed. The engineering analyses required for PE-stamped building permit drawings are probably beyond the scope of this project.

We will then ship the forms to Alaska to build structures at Partners for test, demonstration, and marketing purposes, but probably not permanent "installation". UAS TEC, Juneau and CCHRC, Fairbanks, are attractive. AASI will own or lease these test sites, or otherwise establish "site control".

Project Team Capabilities: See Ref 1: we are consequently acquainted with several expert composites firms in the Lower 48, capable of subcontracting the entire project except for Alaska site build and tests. We have discussed this project with one firm, who also recommended other firms.

William C. Leighty, AASI principal, and EETF project manager: BS Electrical Engineering '66, MBA '71, Stanford. Principal, Alaska Applied Sciences, Inc. Director, The Leighty Foundation. *Nota bene*: The Leighty Foundation (TLF) has no connection to this application for funding; the References are for technical insight only. AASI's role is primarily managing design and tooling fabrication subcontractors. Partners UAS and CCHRC could supply the venues for building and limited testing of the first few prototype domes in Alaska.

Market: Alaska needs low-cost, durable housing and other buildings to replace failing extant structures, to build relocated villages, provide low-cost and low-income urban housing, and to expand infrastructure. This project will pre-commercialize a construction method which features:

1. Low embodied energy, low operating energy, and low long-term maintenance; these scale-model domes required only ~1/3 m^3 of concrete. Dome #1 is insulated with ~3cm sprayed, closed-cell, urethane foam plus sprayed 1cm interior fireproofing finish plaster coat. We have measured low total thermal loss from prototype #1. This project's full-size (6m diam) dome will require ~1 m^3 concrete;
2. Lower cost-of-living in all Alaska communities, large, small, urban, remote; concrete is durable;
3. Better survival in earthquake, tsunami, hurricane, and fire than conventional construction;
4. Minimum import of tooling, tools, material, and skilled labor into remote communities;
5. Maximize use of indigenous materials (primarily sand and fresh water) and labor;
6. Flexibility in structure design: foundation, window, door, flue and vent, loft, wire and plumb;
7. Modularity: rapidly build a neighborhood; able to connect two or more domes in larger structures;
8. Ability to easily re-level the structure on heaving permafrost, using dome's structural integrity;
9. Amenable to Earth-sheltering, including complete burial except entry door, flue and vent stacks;
10. Low capital cost, rapid shell construction cycle time of ~3 days: estimated minimum cost for 6 m diameter structure, built in quantity, on-site, on grade, with no land or soft costs, at an amenable Juneau or Anchorage site, including labor at prevailing urban Alaska commercial rates:

a. Concrete shell: form set amortize, C-grid, concrete, entry framing	$ 4,000
b. Closed cell UR foam, interior spray, 4 cm thick, in dome and entry	3,000
c. Foam insulated and finished floor	2,000
d. Package windows and door	2,000
e. Minimum interior finish, loft, partition wall; no plumbing + wiring	2,000
Total	$ 13,000

This construction process is remarkably labor-efficient, based on our experience building the two prototypes in Figs 1-6, for these principal concrete shell operations:

	Person-hours
Assemble foundation ring form set; single rebar ring install	2
Remove foundation ring form set; cleanup	1
Build framed, attached entry, without exterior or interior finish	6
Assemble 13-piece dome form set, with shims	3
Install C-grid as tiles, stapled to dome form	4
Apply mortar; apply curing plastic by spray resin or poly sheet	4
Remove dome form set and shims; cleanup	3
TOTAL	23

We expect this to approximately double for the full-size structure enabled by this project.

These features and economic advantages apply world-wide. Only spherical and quasi-spherical (dome, barrel-vault extended dome) structures may be built of thin-shell concrete. A robust, reusable forming system is needed to allow rapid and economical construction of thin-shell concrete envelopes in remote areas, ready for interior spray UR foam insulation and finish, as needed, as in AK. Non-ferrous primary reinforcement must be used; we have shown that Chomarat "C-grid" is ideal: Figs 4-5, and Ref 2.

See Refs 3-5. Quasi-spherical structures are available, but none of these are optimized for very low cost, on-site construction, which this pre-commercialization tooling and process development project will advance. Ref 4: Intershelter, Juneau, has demonstrated a global market for small domes, as factory-built kits transported to and assembled at a site. Concrete dome customers will include the spectrum of shelter markets for small, low-cost, permanent, very energy-efficient buildings constructed on-site, especially remote sites, in Alaska and worldwide. Multiple adjacent concrete domes may be interconnected to form larger, multi-room buildings. 6 m equatorial diameter, 5/8 sphere, is probably about the optimum technical and economic size for this construction method. Alaska potential is hundreds to thousands of structures of single and multiple integrated domes and other quasi-spherical structures -- elongation via barrel-vault midsection, for example -- proceeding from this demonstration.

Alaska synergy and economic externality benefits are:

1. Improved energy security;
2. Reduced GHG emissions;
3. Increased reliance on indigenous, firm, RE;
4. Improved prospects for AK village survival.

By signature on this application, I certify that we are complying and will comply with the amount of matching funds being offered. Signed: _____

REFERENCES

1. AASI DOE-funded R+D project final report:
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2. Chomarat C-grid:
http://www.chomarat.com/en/category/produits/produits-produits/c-grid/?from=technologie
3. Binishells: http://www.binishells.com/
4. Intershelter: http://intershelter.com/
5. Monolithic: http://www.monolithic.com/

Figure 1. Dome #1 with complete forms

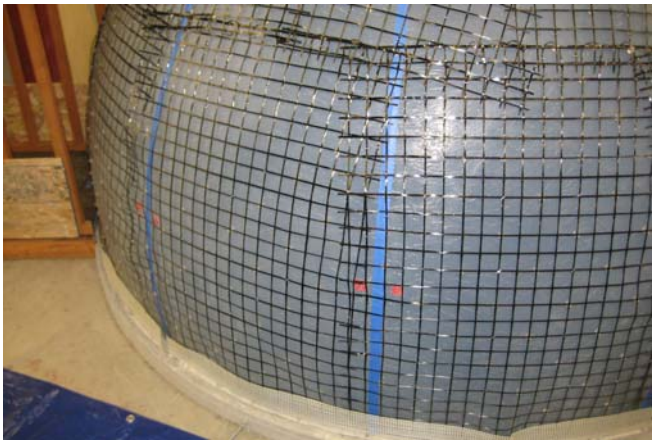

Figure 4. Dome #2: C-grid primary reinforcing

Figure 2. Dome #1: window, plumbing vent

Figure 5. Dome #2: Sprayed concrete on C-grid

Figure 3. Dome #1: note stove flue, entry door

Fig 6. Dome #2: 1 m sand on top; no damage

Figures 1-6: Approximate 46% scale models of a 6m equatorial diameter, 5/8 sphere full-size structure. This project will CAD design and build the tooling from which full-size male concrete forms sets will be manufactured for high-volume thin shell concrete dome structure on-site replication. Figure 1 shows the reusable, Teflon-coated, fiberglass forms set on which both 1 cm thick domes were built. Dome #1 concrete mortar was hand-applied; #2 sprayed. Figs 4-5: The non-ferrous primary reinforcement (carbon-epoxy fiber C-grid) is attached to the Teflon-coated form with stainless steel staples, thus preventing rust or corrosion in the 1.5cm thick concrete shell. Concrete entry roof reinforces the entry door opening. Windows may be placed anywhere, set in integral concrete shell-reinforcing “eyebrows”. Fig 6 is Dome #2 buried in sand for strength test; 1 m sand on top; no visible damage.