THE STRUCTURE AND STRENGTH OF THIN SHELL DOMES

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ABSTRACT: Dome structures have been in use since ancient times and have survived the test of time. Existing temples particularly in India have been in use since ancient times. With the advent of technology and computerization, dome structures have received impetus and greater utilization particularly in industrial dry bulk storage as well as multipurpose Public buildings used as gymnasias and Hurricane shelters in the USA.

The US Federal Emergency Management Agency FEMA has rated adequately designed and constructed domes structures as able to sustain Category 4 Hurricanes and can survive projectile impact from hurricane borne objects such as telephone poles and other large objects. This attests to the structural strength and durability of thin shell concrete domes.

This paper discusses the source of the inherent structural strength of Domes as well as the revolutionary construction procedure that has made dome structures more accessible to various industries and the public due to the cheap construction process.

1. INTRODUCTION

Monolithic RC thin shell Dome Silos present a Paradigm Shift in the way Dry bulk Materials are stored specifically using conventional Warehouse sheds, Steel Silos and Concrete Silos.

The obvious advantage is in the inherent strength of thin shell domes combined with an ingenious construction methodology using Exterior Balloon forms which also serve as the Waterproofing and Heat reflective cover, allowing a very rapid construction when compared to conventional Silos or Warehouses.

This paper is concerned with technical aspects of Dome structural performance and other engineering advantages which makes dome silos a superior structural alternative particularly for storage of dry bulk materials.

2. WHAT IS A THIN SHELL MONOLITHIC DOME?

A monolithic Dome (from the Greek word Mono and lithic, meaning “one stone”) is a structure cast in a one piece form. The form may be permanent or temporary and may or may not remain part of the finished structure.

The dome is a 360 Degree Revolution of an arch structure, which carries its load in predominantly in compression.

The inherent strength of thin shell Monolithic Reinforced Concrete Domes is in their Natural shape which allows them to
span large spaces effectively without the need for intermediate supports.

Unlike voussoir arches, which need a rigid form to support it during construction, the monolithic dome does not need any real support as it progresses during construction for as long as the concrete can carry its self weight. Therefore, construction is relatively fast without requiring any heavy shoring or scaffoldings.

The Monolithic thin shell walls Sustain most of the lateral stresses of the stored material in Compression where reinforced concrete is most efficient, and are easily supported against tension near the bottom with Tension hoops also made of reinforced concrete.

The overall inherent strength allows the use of relatively thin Reinforced Concrete walls, the shell to carry the loads.

Because of their inherent strength, domes are often prescribed in the US and elsewhere as public Shelters from hurricane and tornados.

3. THE STRUCTURAL MECHANICS OF DOME

Domes derive their strength from its geometry and shape. Being an arch that is revolved to 360 Degrees around its axis, it inherits the load carrying capacity of the arch all around. The dominant forces are for the most part compressive from the top to its midheight, beyond which a transition with tension forces occur gradually until the base where large tensile forces predominate. Because of this, concrete is very ideal as it is strong in compression. The tensile forces at the bottom are still resisted by reinforced concrete in the form of tension rings or tension belts.

The typical stress distribution is shown in the figure below where the dome is subjected to internal forces due to the stored materials inside.

Fig. 1.0 Stress Distribution in a Thin Shell Dome shown below

The stress diagrams below show the stress Trajectories in a freebody diagram of the dome which indicate generally compression forces on the legs and tensile forces at the base which keep it stable.

A Finite element analysis result of a thin wall dome is also shown below which shows the dominant stresses in more vivid detail:

Shown below is the typical stress diagram for a spherical shell or a dome, loaded internally with a granular medium. It is very important to note that up to a sector of the dome about 51 Degrees 49 Minutes, the

\[1\] From an Internet Download
stresses in the shell are exclusively compressive, then transitions into increasing tensile stresses beyond this sector and down to its base. The tensile forces are resisted by tension hoops or belts which can also be made of reinforced concrete. Thus, concrete is the preferred material in the construction of domes.

3.1 Practical Examples of the Strength of Real Domes

3.1.1 The Chicken Egg as an example of the inherent Strength of Domes

The best example of the inherent strength derived from the shape of the dome is the chicken egg, which cannot be broken or crushed without a significant effort using two hands. In fact based on a test of the chicken egg in a compression machine, the minimum force required to crush the chicken egg is about 55 lbs. along its long axis and slightly higher when the egg is laid on its side (Flatter dome). This is shown in the presentation accompanying this paper.

Given the Average Breaking Strength of 55 Lbs. or 25 kgs.

Applying some arithmetic and basic egg Dimensions taken from the internet, an average chicken egg has the following dimensions:

- Average Short Circumference 13.5 cm (large Egg)
- Average Shell Thickness 0.4 mm .04 cm
- Compressive Stress sustained along the Short Circumference
  \[ \text{f} = \frac{25 \text{ kgs}}{(13.5 \text{ cm} \times 0.04 \text{ cm})} = 46.3 \text{kgs/sq cm or 15.7 PSI} ! \]

The average compressive strength almost equals that of the compressive strength of a soft rock such as Guadalupe tuff when in fact only a 0.4 mm shell thickness is resisting the load.

3.1.2 Performance and Strength of Domes

The dome, when finished, is earthquake, tornado and hurricane resistant (the US Federal Emergency Management Agency rates them as "near-absolute protection" from F5 tornadoes and Category 5 Hurricanes). Recently, a number of monolithic domes constructed using MDI techniques have survived major disasters: Several monolithic domes in Florida survived direct hits by Hurricane Katrina in 2005.
Many monolithic domes were in the path of the 2005 and 2006 wildfires in Oklahoma and Texas, and survived with only slight charring of the exterior foam insulation.

In 2003, a monolithic dome government building in Iraq, suffered a direct hit from a smart bomb. The dome survived a direct hit by a 5,000 lb (2,300 kg) smart bomb. The interior of the structure was totally destroyed, but the dome itself remained standing (see picture).

This domed government building in Baghdad, formerly a part of Saddam Hussein's regime, was hit by a 5,000 lb (2,300 kg) bomb. Apart from the hole made by the entry of the bomb, it remained structurally sound.

Over 500 Dome silos in the modern days mostly for industrial dry bulk storage have been built by Dome Technology alone worldwide over the years.

The dome was hit because it was being used as the headquarters for Iraqi intelligence among other building clusters being used for bulk storage.

**4. INNOVATIVE CONSTRUCTION USING AIR FORMS**

Although Thin shell domes have been extensively used in the past, dating back several centuries, the use of dome for bulk storage has taken off significantly in the 80’s with the introduction of the *Air Form* by Dome Technology Inc. based on the patent by Barry South.

The figure above shows a dome built several centuries ago in Dhyanalinga, India and still standing today, a testimonial to the structural strength and durability of Domes.

The figure above shows the layers of materials that make up the thin shell.

Thin shell dome construction took off with the invention of the air form which provided a convenient guide to the construction, provided an all weather construction inside the air form and provided a permanent water proofing on the outside and resist UV
generated heat, keeping the interior temperature stable and with minimum fluctuations when coupled with the urethane foam insulation.

Once the ring beam is installed, the air form which is like a hemispherical balloon is inflated.

Additional layers are added in sequence such as the urethane foam; rebar guides, rebars and then the shotcreting.

This procedure is best illustrated in print by the drawings downloaded from the internet in step by step sequence.

4.1 Step by Step Construction Sequence

The following is the illustrated sketches of the construction sequence:

4.1.1 Foundation Preparation:

Foundation — The Monolithic Dome starts as a concrete ring foundation, reinforced with steel rebar. Vertical steel bars embedded in the ring later attached to the steel reinforcing of the dome itself. Small domes may use an integrated floor/ring foundation. Otherwise, the floor is poured after completion of the dome. (David South Jr)

4.1.2 Inflation of Air Foam Balloon

Airform — An Airform – fabricated to the proper shape and size – is placed on the ring base. Using blower fans, it is inflated and the Airform creates the shape of the structure to be completed. The fans run throughout construction of the dome. (David South Jr)

4.1.3 Spraying of Insulation

Polyurethane Foam — Polyurethane foam is applied to the interior surface of the Airform.

Entrance into the air-structure is made through a double door airlock which keeps the air-pressure inside at a constant level. Approximately three inches of foam is applied. The foam is also the base for
attaching the steel reinforcing rebar. (David South Jr)

4.1.4 Rebar Installation

Steel rebar — Steel reinforcing rebar is attached to the foam using a specially engineered layout of hoop (horizontal) and vertical steel rebar. Small domes need small diameter bars with wide spacing. Large domes require larger bars with closer spacing. (David South Jr)

4.1.5 Shotcrete Placement

Shotcrete — Shotcrete – a special spray mix of concrete – is applied to the interior surface of the dome. The steel rebar is embedded in the concrete and when about three inches of shotcrete is applied, the Monolithic Dome is finished. The blower fans are shut off after the concrete is set. (David South Jr)

A video presentation accompanies this paper and can also be accessed over the web

5. DURABILITY

Dome structures have been built since ancient times and they have withstood the test of time without collapse or damage.

Domes Built to Federal Emergency Management Agency’s (FEMA) P-361 Community Safe Room guidelines which meet or exceed the International Code Council (ICC) 500 guidelines for safe shelters and the Texas Department of Public Safety (DPS) Texas Safe Shelter Initiative (TSSI).

Thin shell domes designed to the prescriptive FEMA requirements meet the "near absolute life safety protection" of a building during an extreme wind event such as a hurricane or tornado.

According to FEMA, "Near-absolute protection means that, based on our current knowledge of tornadoes and hurricanes, the occupants of a safe room built in accordance with FEMA guidance will have a very high probability of being protected from injury or death."

Since domes rarely act as a community storm shelter in relation to the time it can be used for other purposes, domes provide a free-span interior that can be built out into a variety of applications such as gymnasiums, cafeterias, libraries, churches and sanctuaries, conference centers and emergency response headquarters.

Currently, Dome structures have been rated for Category 4 Hurricanes where major damage is expected in communities.

Thus, FEMA has subsidized the construction of hurricane shelters made of thin shell domes along the coastal areas of Texas, as they can resist projectile hits such

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2) www.dometechnology.com
as from telephone poles and other hurricane borne objects flung into them. This attests to the durability and survivability of dome structures when designed and constructed properly.

6. CONCLUSION

Monolithic dome structures offer several advantages over conventional type structures particularly for use as emergency shelters and multi purpose halls. Its advantage in the storage of dry bulk materials also confer advantages in terms of larger storage capacity for a comparable footprint, fire protection, weather protection and explosion damage control.

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