

Thin-Shell Concrete Architecture in the Denver, Colorado Area: An Overview and Preliminary Inventory



Naval Reserve Hangar, Buckley Air Force Base

Photograph © Scott D. Murdock, 2017

Scott D. Murdock

Extracted from a report submitted to American Public University, Department of History
May 26, 2017

Introduction

This report is intended to share the history, design characteristics, and examples of thin-shell concrete construction in the Denver, Colorado area. The inventory area includes Denver itself, as well as Aurora and Buckley Air Force Base to the east; Littleton to the south; Lakewood to the west; and Commerce City and Northglenn to the north. Photographs of extant structures are included.

Thin-Shell Theory and Design

Thin-shell concrete construction refers to the use of reinforced concrete in thin sheets, curved in ways that maximize strength, to create roofs with large clear spans with no or minimal interior support columns. Rather than a supporting framework and separate roof, the shell provides both functions, creating what is called a stressed-skin structure.¹ Thicker reinforcing ribs or edge beams add stiffness and transfer weight to columns, supporting walls, buttresses, or foundation piers. In thin-shell roofs, the ratio of shell thickness to span length can be thinner than that of an eggshell. One reference considers thin shells as those having a span length from 50 to 1,000 times the thickness of the shell.² In comparison, an ordinary eggshell has a span approximately 230 times its thickness.³

Thin-shell construction in the US began in the mid-1930s with Anton Tedesko's Hayden Planetarium followed by his Hershey Arena, and its heyday was from about 1940 until about

¹ P. C. Varghese, *Design of Reinforced Concrete Shells and Folded Plates* (Delhi: PHI Learning Private Limited, 2014), xxiii.

² A. M. Haas, *Design of Thin Concrete Shells: Volume 1 Positive Curvature Index* (New York: John Wiley and Sons, 1962), 2.

³ Michele Melaragno, *An Introduction to Shell Structures: The Art and Science of Vaulting* (New York: Van Nostrand Reinhold, 1991), 119.

1970, with the 1975 Seattle Kingdome generally considered to be the last major thin-shell building constructed in the US for many years. The decline of thin-shell construction has been attributed to a combination of technical difficulty in construction, limited adaptability of structures to changing needs, maintenance problems, public opinion of the appearance,⁴ and cost of construction.⁵ In the 21st century a new breed of thin-shell construction makes an occasional appearance, in the form of monolithic or air-inflated domes. A fabric outer cover of the dome is created and inflated on site. Reinforcing steel is erected inside the cover, and then concrete is applied (usually by spraying) to form a sturdy dome.

A close relative of thin-shell design is called folded plate. By joining plates of concrete at angles, a corrugated effect is achieved which offers a similar result as thin-shell design: a sturdy roof that spans a fairly wide area. In fact, many of the thin-shell textbooks also cover folded-plate construction as they were both modern, bold uses of concrete in construction. Also, their structural properties behave similarly to thin shells.⁶ Folded-plate construction was popular during the 1950s and 1960s, and still graces many distinctive roofs in the Denver area. However, since it is a visually distinct form, not relying on curvature for strength, folded-plate architecture is not included in this report.

⁴ Thomas E. Boothby, M. Kevin Parfitt, and Charlene K. Roise, "Case Studies in Diagnosis and Repair of Historic Thin-Shell Concrete Structures." *APT Bulletin* 36, no 2/3 (2005), 3-7.

⁵ Anton Tedesko, "Shells 1970—History and Outlook." In *Concrete Thin Shells ACI Publication SP-28*, eds S. J. Medwadowski, W. C. Schnobrich, and A. C. Scordelis. (Detroit: American Concrete Institute, 1971), 4-5.

⁶ David P. Billington, *Thin Shell Concrete Structures*, 2nd ed. (New York: McGraw-Hill Publishing Company, 1990), 291.

Thin-Shell Forms

The barrel shell is the simplest thin-shell concrete form. By shaping the span of the arch as a catenary, the compressive strength of the thin concrete is maximized.⁷ By placing the reinforcing ribs on the outer surface of the arch, a smooth interior roof is created. This makes it easy to remove, reposition, and reuse the concrete wooden formworks – this often gave thin shell a cost advantage over conventional construction. For purposes of study, it is convenient to consider barrel shells as single barrel or multiple barrels. Fine examples of both exist in the Denver area. Buckley Air Force Base, in Aurora, has a prototype Naval Reserve hangar engineered by Anton Tedesko (figure 1). It is similar in appearance to the larger Denver Coliseum, also a Tedesko design (figure 2). Both have a large clear span under a single barrel shell with no interior columns. The Denver Federal Center Warehouse (figure 3) and the Western Electric Warehouse (figure 4) are examples of connected multiple barrel shells that cover large areas with minimal interior columns. Local examples of this form also include the Continental Bakery (figure 5), the Rainbo Bakery (figure 6), the Ideal Cement Company Hangar (figure 7), multiple buildings at the Jewish Community Center (figure 8), and the University College Building (figure 9). Nationwide examples of this form include several by Anton Tedesko. His first large barrel vault, the Hershey Arena, still serves the public today. Tedesko also engineered two mammoth single vault aircraft hangars with 340' spans, still in use at Ellsworth Air Force

⁷ P. C. Varghese, *Design of Reinforced Concrete Shells and Folded Plates*, 14, 291.

Base, South Dakota, and at the former Loring Air Force Base, Maine.⁸ A noteworthy multiple-barrel shell warehouse is at the former Olmsted Air Force Base, Harrisburg, Pennsylvania.

A hyperbolic paraboloid (hypar) is, in very simple terms, a doubly curved surface. Think of a saddle or a Pringle® crisp; there is upward curve of the length of the crisp and a downward curve on the width. Engineers discovered that the doubly curved surface has great strength. A hypar roof can really liven up a building with its soaring lines, making it a natural for church buildings. Denver was home to the nationally touted May-D&F department store entrance canopy (demolished), a collaboration between architect I.M Pei and engineer Anton Tedesko. Other local examples of concrete hypar roofs include the Calvary Temple (figure 10) in Denver, and the more dramatic St. Stephens Lutheran Church (figure 11) in Northglenn. A nationally known example is nearby in Colorado Springs; the International Center at the Broadmoor Hotel is a larger hypar canopy, and was engineered by local engineer Milo S. Ketchum.

An interesting variation of the hypar is known as an inverted umbrella form. Combine four hypar panels so they form a canopy shape, invert so it resembles a square umbrella, and mount on a supporting column to create a roof. This form requires a rainwater drain through the center column. Inverted umbrellas may be clustered together, edge to edge, to cover a larger space with minimal interior columns and no need of load-bearing exterior walls. In the Denver area, a small office building featuring eight inverted umbrellas still stands in Littleton (figure 12). Nationally, an amazing example of inverted umbrellas covers the grandstand at the Scioto Downs racetrack in Columbus, Ohio.

⁸ Richard G. Weingardt, “Anton Tedesko: Father of Thin-Shell Concrete Construction in America.” *STRUCTURE Magazine* (April 2007): 69, accessed June 9, 2016. <http://www.structuremag.org/wp-content/uploads/2014/09/D-GreatAchievements-Weingardt-Apr07-online-version1.pdf>, 69-70.

Domes, either circular or similar rounded shapes, also have double curves lending the shape to thin-shell construction. In the Denver area, the Fan Fair shopping center (demolished) was built as a grouping of 56 transition shells (dome shapes) making a roof with a “bubble wrap” appearance. Another local variation is the original thin-shell domed Mile-Hi Church (figure 13) in Littleton. A fine example of the new style of air-inflated thin-shell construction is the large dome of Mile-Hi Church (figure 14), adjacent to the original building. A national example was Anton Tedesko’s first permanent thin-shell structure in the US, the original Hayden Planetarium in New York (demolished).

Denver Area Thin-Shell Inventory

A preliminary inventory of Denver area thin-shell concrete construction is shown in Table 1, and is intended as a starting point for further research.

Table 1. Preliminary Inventory of Denver-Area Thin-Shell Concrete Structures

Name	Date	Engineer	Architect
Calvary Temple	1958	unk	Ralph D. Peterson
Continental Bakery	1962	Milo S. Ketchum	unk
Denver Coliseum	1950	Anton Tedesko	Roland L. Linder
Denver Federal Center Warehouse	1964	unk	P. R. Reddy and K. R. White
Naval Reserve Hangar	1951	Anton Tedesko	unk
Fan Fair Shopping Center (lost)	1961	Milo S. Ketchum	William Muchow
Ideal Cement Company Hangar	1959	Milo S. Ketchum	Fisher, Fisher and Davis
Jewish Community Center	1962	unk	unk
Littleton Office Building	unk	unk	unk
May-D&F Canopy (lost)	1958	Anton Tedesko	I. M. Pei
Mile-Hi Church Building	1973	unk	unk
Mile-Hi Church Sanctuary	2008	unk	Fentress Architects
Rainbo Bakery	1956	Milo S. Ketchum	unk
St. Stephens Lutheran Church	1964	unk	Charles A. Haertling
University College	unk	unk	unk
Western Electric Warehouse	1948	Anton Tedesko	unk

Source: RoadsideArchitecture.com, “Colorado Mid-Century Modern Churches.” Accessed May 5, 2017. <http://www.roadarch.com/modarch/cochurch.html>; Boothby, Parfitt and Ketchum. “Milo S. Ketchum and Thin-Shell Structures in Colorado,” 40, table 1; Milo S. Ketchum. “Memoirs 5. Barrel Shells.” Accessed May 19, 2017. <http://www.ketchum.org/milo/Memoir5.html>; Roberts and Schaefer. “Denver Municipal Stadium, contract 4809.” Drawing no. A-2; Paul R. Reddy and Ken R. White, Architects-Engineers, with General Services Administration,

Public Buildings Service. “GSA Stores Depot.” Project No. 05901, drawing no. 4-2; Allison Parish, “Historic Structures Evaluation and Determination of Eligibility of the Denver Federal Center.” March 2, 2012; Roberts and Schaefer Co. with Ninth Naval District Public Works Division. “N.A.R.T. Hangar & Leantos,” job no. 5103, drawing no. 486605; Aurora, Colorado Historical Society. “Fan Fair Lost December 2013.” <http://www.ahs.co.org/endangered-places/fan-fair/>; RoadsideArchitecture.com, “Colorado Mid-Century Modern: Roof & Canopies.” Accessed May 5, 2017. <http://www.roadarch.com/modarch/coroof.html>; Wolfenbarger. *Ideal Basic Cement Company Corporate Hangar: Colorado State Register of Historic Properties Nomination Form*; RoadsideArchitecture.com, “Denver Mid-Century Modern Churches.” Accessed May 22, 2017. <http://www.roadarch.com/modarch/cochurchdenver.html>; Eric M. Hines and David P. Billington. “Anton Tedesko and the Introduction of Thin Shell Concrete Roofs in the United States,” *Journal of Structural Engineering* (November 2004) 130, no 11: 1640, table 1; Fentress Architects. “Mile Hi Church Sanctuary / Fentress Architects.” September 19, 2011. Accessed April 10, 2017. <http://www.archdaily.com/170079/mile-hi-church-sanctuary-fentress-architects>; RoadsideArchitecture.com. “Colorado Mid-Century Modern Churches (page 2).” Accessed May 5, 2017. <http://www.roadarch.com/modarch/cochurch2.html>; Eric M. Hines and David P. Billington. “Anton Tedesko and the Introduction of Thin Shell Concrete Roofs in the United States.” *Journal of Structural Engineering* (November 2004) 130, no 11: 1639-1650. Accessed July 12, 2016. <http://engineering.tufts.edu/cee/people/hines/documents/HinesBillington2004.html>.

An interesting aspect of thin-shell construction is that, because the concrete roof is such a prominent visual part of the structure, the literature tends to recognize the engineers as much or more than the architects of these buildings. The Denver area was fortunate to have several examples by Anton Tedesko, who introduced thin-shell concrete work to the US in the 1930s. Another thin-shell expert was Milo S. Ketchum Jr., a Denver engineer.⁹ Table 2 shows the wide variation in local thin-shell structures. From fanciful church buildings to massive warehouses, the Denver area had a great collection of thin-shell work.

Table 2. Comparisons of Denver-Area Thin-Shell Concrete Structures

Name	Description
Calvary Temple	Hyperbolic paraboloid, single surface
Continental Bakery	Multiple barrels, undulating
Denver Coliseum	Single barrel, 254' span
Denver Federal Center Warehouse	Multiple barrels
Naval Reserve Hangar	Single barrel, 136' span ^a
Fan Fair Shopping Center	Domes, 36 arranged in 4 rows of 9
Ideal Cement Company Hangar	Single barrel, diamond section, 112' span
Jewish Community Center	Undulating barrels on multiple buildings
Littleton Office Building	Hyperbolic paraboloid inverted umbrellas, eight
May-D&F Canopy	Hyperbolic paraboloid, 112' by 132'

⁹ Thomas E. Boothby, M. Kevin Parfitt and Mark Ketchum, “Milo S. Ketchum and Thin-Shell Structures in Colorado.” *APT Bulletin* 43, no. 1 (2012): 41, accessed June 7, 2016. <http://www.jstor.org/stable/41548693>, 39.

Mile-Hi Church Building	Scalloped domes
Mile-Hi Church Sanctuary	Dome, 232' span
Rainbo Bakery	Barrels, three
St. Stephens Lutheran Church	Hyperbolic paraboloid, four surfaces
University College	Barrels, some structural some decorative
Wells Fargo Bank	Barrels, three
Western Electric Warehouse	Multiple shallow circular barrels, 50' span

Source: Eric M. Hines and David P. Billington. "Anton Tedesko and the Introduction of Thin Shell Concrete Roofs in the United States," *Journal of Structural Engineering* (November 2004) 130, no 11: 1640, table 1; Boothby, Parfitt and Ketchum. "Milo S. Ketchum and Thin-Shell Structures in Colorado," 40, table 1; Karen J. Weitze. *Cold War Infrastructure for Strategic Air Command: The Bomber Mission* (Langley Air Force Base, VA: United States Air Force, Air Combat Command, 1999, 32; Roberts and Schaefer Co. with Ninth Naval District Public Works Division. "N.A.R.T. Hangar & Leantos," job no. 5103, drawing no. 486605; Tedesko, *Thin-shell arch selected*, 47; Wolfenbarger. *Ideal Basic Cement Company Corporate Hangar: Colorado State Register of Historic properties Nomination Form*; Fentress Architects. "Mile Hi Church Sanctuary / Fentress Architects." September 19, 2011. Accessed April 10, 2017. <http://www.archdaily.com/170079/mile-hi-church-sanctuary-fentress-architects>; Aurora, Colorado Historical Society. "Fan Fair Lost December 2013." <http://www.ahs.co.org/endangered-places/fan-fair/>
^a Buttresses angle inward toward the arch, allowing useable hangar width of 150 feet.

Around the country, hundreds of thin-shell buildings were constructed. Table 3 lists selected examples that offer good comparisons for the Denver area buildings.

Table 3. National Comparison Structures

Name	Description
International Center, Colorado Springs	Hyperbolic paraboloid, Milo S. Ketchum
Ellsworth Air Force Base Hangar, SD	Single barrel, 340' span, Anton Tedesko
Hayden Planetarium (original), NY	Dome, 81' diameter, Anton Tedesko
Hershey Arena, PA	Single barrel, 245' span, Anton Tedesko
Loring Air Force Base Hangar, ME	Single barrel, 340' span, Anton Tedesko
Olmsted Air Force Base Warehouse, PA	Multiple barrels, Anton Tedesko
Scioto Downs Grandstand, OH	Hyperbolic paraboloid inverted umbrellas, Gensert, Williams and Associates

Source: Eric M. Hines and David P. Billington. "Anton Tedesko and the Introduction of Thin Shell Concrete Roofs in the United States," *Journal of Structural Engineering* (November 2004) 130, no 11: 1640, table 1; Boothby, Parfitt and Ketchum. "Milo S. Ketchum and Thin-Shell Structures in Colorado," 40, table 1; Karen J. Weitze. *Cold War Infrastructure for Strategic Air Command: The Bomber Mission* (Langley Air Force Base, VA: United States Air Force, Air Combat Command, 1999, 32; Concrete Construction. "Largest Inverted Umbrella Roof" http://www.concreteconstruction.net/products/general-construction-equipment/largest-inverted-umbrella-roof_o (March 1, 1960)

Tedesko learned early, at the Hershey project that thin-shell designs could not simply be handed over to just any builder. The concrete work is too particular, and unfamiliar to most builders. With the Hershey Arena, he "became the designer, organizer, decision-maker and

construction supervisor.”¹⁰ Another author described the necessary relationship, “A successful shell project is an enterprise in which the closest coordination is necessary among the three partners involved—the architect, the engineer, and the builder.”¹¹ After the American Society of Civil Engineers’ publication of Manual 31 on Shell Design in 1952,¹² many other firms tried their hand at thin-shell work.

¹⁰ Richard G. Weingardt, “Anton Tedesko: Father of Thin-Shell Concrete Construction in America,” 70.

¹¹ G. S. Ramaswamy, *Design and Construction of Concrete Shell Roofs* (New York: McGraw Hill Book Company, 1968), 7.

¹² Anton Tedesko, “Shells 1970—History and Outlook,” 3.

Photographs



Figure 1. Naval Reserve Hangar, Buckley Air Force Base. Single barrel shell.
Photograph © Scott D. Murdock, 2017.



Figure 2. Denver Coliseum, Denver. Single barrel shell.
Photograph © Scott D. Murdock, 2016.



Figure 3. Denver Federal Center Warehouse, Lakewood. Multiple barrel shells.
Photograph © Scott D. Murdock, 2017.



Figure 4. Western Electric Warehouse, Denver. Multiple barrel shells.
Photograph © Scott D. Murdock, 2016.



Figure 5. Continental Bakery, Denver. Multiple undulating barrel shells.
Photograph © Scott D. Murdock, 2017.



Figure 6. Rainbo Bakery, Commerce City. Three catenary barrel shells.
Photograph © Scott D. Murdock, 2017.



Figure 7. Ideal Cement Company Hangar, Denver. Single barrel shell, diamond shaped.
Photograph © Scott D. Murdock, 2016.



Figure 8. Jewish Community Center, Denver. Multiple buildings with undulating barrel shells.
Photograph © Scott D. Murdock, 2017.



Figure 9. University College, Denver. Multiple barrel shells.
Photograph © Scott D. Murdock, 2017.



Figure 10. Calvary Temple, Denver. Single hyperbolic paraboloid.
Photograph © Scott D. Murdock, 2017.



Figure 11. St. Stephens Lutheran Church, Northglenn. Four hyperbolic paraboloids.
Photograph © Scott D. Murdock, 2017.



Figure 12. Office Building, Littleton. Eight inverted umbrella hyperbolic paraboloids.
Photograph © Scott D. Murdock, 2017.



Figure 13. Mile-Hi Church, Lakewood. Single serrated dome.
Photograph © Scott D. Murdock, 2017.



Figure 14. Mile Hi Church, Lakewood. Large, air-inflated dome.
Photograph © Scott D. Murdock, 2017.

Bibliography

- American Society of Civil Engineers. "Anton Tedesko." Accessed June 9, 2016. <http://www.asce.org/templates/person-bio-detail.aspx?id=11219>.
- Aurora, Colorado Historical Society. "Fan Fair Lost December 2013." December 17, 2013. Accessed July 16, 2016. <http://www.ahs.co.org/endangered-places/fan-fair/>.
- Billington, David P. *Thin Shell Concrete Structures*, 2nd Ed. New York: McGraw Hill Publishing Company, 1990.
- Boothby, Thomas E., M. Kevin Parfitt and Charlene K. Roise. "Case Studies in Diagnosis and Repair of Historic Thin-Shell Concrete Structures." *APT Bulletin* 36, no. 2/3 (2005): 3-11. Accessed June 7, 2016. <http://www.jstor.org/stable/40004699>.
- Boothby, Thomas E., M. Kevin Parfitt and Mark Ketchum. "Milo S. Ketchum and Thin-Shell Structures in Colorado." *APT Bulletin* 43, no. 1 (2012): 39-46. Accessed June 7, 2016. <http://www.jstor.org/stable/41548693>.
- Concrete Construction. "Largest Inverted Umbrella Roof." March 1, 1960. Accessed May 19, 2017. http://www.concreteconstruction.net/products/general-construction-equipment/largest-inverted-umbrella-roof_o
- Fentress Architects. "Mile Hi Church Sanctuary / Fentress Architects." September 19, 2011. Accessed April 10, 2017. <http://www.archdaily.com/170079/mile-hi-church-sanctuary-fentress-architects>
- Haas, A. M. *Design of Thin Concrete Shells: Volume 2 Negative Curvature Index*. New York: John Wiley and Sons, 1967.
- Hines, Eric M. and David P. Billington. "Anton Tedesko and the Introduction of Thin Shell Concrete Roofs in the United States." *Journal of Structural Engineering* (November 2004) 130, no 11: 1639-1650. Accessed July 12, 2016. <http://engineering.tufts.edu/cee/people/hines/documents/HinesBillington2004.html>.
- Ketchum, Milo. "Memoirs 5. Barrel Shells." Accessed May 19, 2017. <http://www.ketchum.org/milo/Memoir5.html>
- Medwadowski, S. J., W. C. Schnobrich, and A. C. Scordelis, eds. *Concrete Thin Shells ACI Publication SP-28*. Detroit: American Concrete Institute, 1971.
- Melaragno, Michele. *An Introduction to Shell Structures: The Art and Science of Vaulting*. New York: Van Nostrand Reinhold, 1991.
- Parish, Allison. "Historic Structure Evaluation and Determination of Eligibility of the Denver Federal Center, Lakewood, CO." Colorado Cultural Resource Survey Architectural Inventory Form. March 2, 2012.
- Ramaswamy, G. S. *Design and Construction of Concrete Shell Roofs*. New York: McGraw Hill Book Company, 1968.

Reddy, Paul R. and Ken R. White, Architects-Engineers, with General Services Administration, Public Buildings Service. "GSA Stores Depot." Project No. 05901, drawing no. 4-2.

Roadside Architecture. "Colorado Mid-Century Modern Churches." Accessed May 5, 2017. <http://www.roadarch.com/modarch/cochurch.html>

Roadside Architecture. "Colorado Mid-Century Modern Churches (page 2)." Accessed May 5, 2017. <http://www.roadarch.com/modarch/cochurch2.html>

Roadside Architecture. "Colorado Mid-Century Modern: Roof & Canopies." Accessed May 5, 2017. <http://www.roadarch.com/modarch/coroof.html>

Roadside Architecture. "Denver Mid-Century Modern Churches." Accessed May 22, 2017. <http://www.roadarch.com/modarch/cochurchdenver.html>

Roberts and Schaefer Co. "Denver Municipal Stadium, Contract 4809," drawing no. A-2, July 1, 1949, held in the offices of Denver Coliseum.

Roberts and Schaefer Co. with Ninth Naval District Public Works Division. "N.A.R.T. Hangar & Leantos," job no. 5103, drawing no. 486605, held in the 140th Civil Engineer Squadron engineering vault, Buckley Air Force Base.

Tedesko, Anton. "Thin-shell arch selected for Denver Coliseum." *Civil Engineering* 24, no. 7 (July 1954): 46-50.

Varghese, P. C. *Design of Reinforced Concrete Shells and Folded Plates*. Delhi: PHI Learning Private Limited, 2014.

Weingardt, Richard G. "Anton Tedesko: Father of Thin-Shell Concrete Construction in America." *STRUCTURE Magazine* (April 2007): 69-71. Accessed June 9, 2016. <http://www.structuremag.org/wp-content/uploads/2014/09/D-GreatAchievements-Weingardt-Apr07-online-version1.pdf>.

Weitze, Karen J. *Cold War Infrastructure for Strategic Air Command: The Bomber Mission*. Langley Air Force Base, VA: United States Air Force, Air Combat Command, 1999.

Wolfenbarger, Deon. *Ideal Basic Cement Company Corporate Hangar: Colorado State Register of Historic Properties Nomination Form*. Denver, CO: Colorado Historical Society, November 21, 2005. Accessed July 10, 2016. <http://www.historycolorado.org/sites/default/files/files/OAHP/NRSR/SDV9446.pdf>.