Concrete Shell Structures—Guide

Reported by Joint ACI-ASCE Committee 334

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This guide discusses the practical aspects of shell design, including recommendations for designers of thin concrete shells. General guidance based on current practice is given on analysis, proportioning, reinforcing, and construction. A selected bibliography on analytical methods, featuring design tables and aids, is included to assist the engineer.

Keywords: buckling; design; double-curvature shell; edge beam; folded plate; formwork; model; prestressing; reinforcement; shell; single-curvature shell; splice; stiffening member; supporting member; thickness; thin shell.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

The design and construction of thin shell structures continues to evolve as building techniques and technology advances. Thin shells are appealing because of their efficient use of materials. Historically, however, shells have often required labor-intensive formwork. Innovations in forming and placing concrete have reduced labor, thus increasing the use of thin shells. Labor-reducing processes include the use of shotcrete, frequently used in concert with the use of inflatable forms. For more information on inflated forms, refer to ACI 334.3R.

While thin shells have been formed in many geometric shapes, historically the geometry has been limited to shapes that are relatively simple to design, such as domes, folded plates, and barrel roofs. Computer modeling has allowed architects and engineers to explore more complex geometries and to perform more precise calculations, leading to increased efficiency. Further, advances in concrete material technology to increase workability without losing strength have enabled more efficiency in placement of concrete. Advances in three-dimensional (3-D) printing provide an opportunity to improve the forming of complex shapes. Further into the future, there is speculation that cementitious materials will be found on the surface of Mars (McKay and Allen 1996) and perhaps other destinations in space, allowing shell structures to be built in place with available materials.

The analysis, design, and construction of thin shell structures require a thorough knowledge of shells. While finite element methods are commonly used for the analysis and design of shell structures, the following classical references are recommended to professionals interested in shells to complement the understanding gained using finite element methods: Billington (1981), Candela (1950), Flügge (1973), Timoshenko and Gere (1961), Tsui (1968), Wilson (2005), and Yitzhaki (1958).

1.2—Scope

Design recommendations in this guide are for thin shell portions of concrete structures, unless otherwise stated. ACI 318.2 and all applicable sections of ACI 318 or ACI 350 should be followed in the design of shell structures.

CHAPTER 2—DEFINITIONS

2.1—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology." Definitions provided herein complement that resource.

air form—fabric membrane that is inflated to form the shell's shape.

closed form solution—a solution calculated from a set of equations that are derived from the theory of elasticity.

member, edge—structural element along the edge of a thin shell that does not form part of the main supporting structure but serves to stiffen and act compositely with the thin shell to carry loads to the supporting member.

member, stiffening—structural element that serves to stiffen the thin shell or to control local deformations, such as ribs.

radius of curvature—the radius of an idealized arc that approximates the shell curvature. Due to varying geometry, the value may change over the surface of the shell.

thin shell—a three-dimensional spatial structure made up of one or more flat or curved slabs whose thickness is small compared to its other dimensions.

CHAPTER 3—SHELL TYPES

3.1—Examples of shell types

Concrete thin shells come in many different shapes and sizes. This section focuses on understanding the different types of shells and their uses.

The geometry and load-carrying mechanism dictate its name. For example, beam, column, slab, and wall are common names for structural elements. These names evoke a visual geometry synonymous with their shape. In many cases, there are multiple names for the same structural element. For example, the names "beam" and "girder" are often used interchangeably to describe the same structural element. This holds true for thin shells as well. For example, a barrel roof and an arched roof may be the same type of structural element. However, because thin shell geometries are less known and more complex than simple structural elements, a definition and a classification of thin shell types is necessary.

The basic definition of a thin shell is a three-dimensional (3-D) spatial structure made up of one or more flat or curved slabs whose thickness is small compared to their other dimensions. Thin shells are characterized by their 3-D load-carrying behavior, ideally by in-plane or membrane action rather than by flexure or shear.

The behavior of a shell is determined by its geometry and the way it is supported. These two characteristics in turn determine how a thin shell resists applied loading along with its self-weight. Mainly, these applied loads are vertical or normal to the surface of the shell. For typical structures, load is transferred by slab action to beams that resist such loads through flexure and shear and may carry them directly to columns. Columns convert such loads primarily to compression or sometimes to tension and on to the foundation. In contrast, thin shells enabled by curvature resist such loads by in-plane compression and tension—a so-called membrane action. This makes them remarkably efficient. At boundaries, edges, openings, and non-uniform loaded areas, loads are resisted by a combination of axial, flexure, and shear forces, then transmitted to the columns and foundation.

The thin shell definition noted previously does not give specificity to the shape or geometry of the shell. Shells are known by common names and by more scientific terms, often for the same structural element. The use of synonyms for names used to describe shells can be confusing. In this document, shells are placed into different groups based upon their geometric characteristics. In each group, common and scientific names for shell types are given. This approach to defining shells allows the reader to grasp a better understanding of the shell types and multiple names used to define each.

There are three form types of shells that can be distinguished: 1) mathematical form shells; 2) free-form shells; and 3) form-found shells. Mathematical or analytical shells can be described by an analytical formulation of the geometry. Free-form, free-curved, or sculptural shells are generated without conforming to commonly defined mathematical shell shapes. Form-found shells include natural and inverted hanging shells. Unlike the free-form and mathematical shells, their shape is not predefined but the result of a form-finding process.

3.2—Folded plates—Group 1

Definition: A folded plate is a combination of flat plates jointed together to increase the structural stiffness of the combined plates. Although folded plate structures are not curved as other shell structures, due to their similar structural behavior and geometry, they are generally included in the family of thin shells. It should be noted that the basic folded plate resists applied and self-weight loading by spanning in the short direction between folds as a one-way slab. At the folds, the reactions of the one-way slabs are resolved into the planes of the intersecting longitudinal plates. The resolved loads are then carried to the end supports as beams with a cross section with width equal to the plate thickness and depth equal to the span of the plate between folds. The membrane action that characterizes thin shells is not developed unless second-order curvature effects are considered.

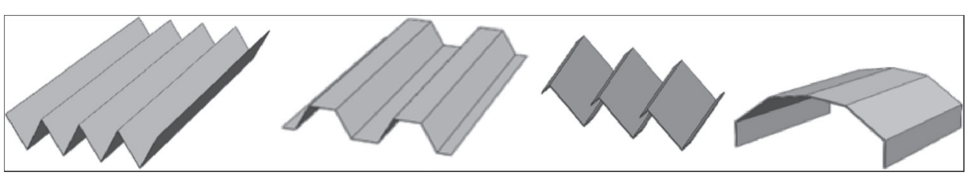
Common names: folded plate; hipped plate; corrugated plate; north light plate; butterfly plate.

Scientific names: polygonal folded plate; prismatic plate; tapered folded plate; pyramidal plate; prismoidal triangular plate; prismoidal trapezoidal plate.

Applications: roof and wall elements used in large assembly spaces such as airports, large flat storages, warehouses, schools, and manufacturing buildings.

The long span capability and efficiency of folded plates make them appealing for uses in large open spaces. Their prismatic aesthetics offer a dynamic visual appeal that is unique and beautiful. The popularity of folded plates increased after World War II with advances in precast and site casting techniques, resulting in folded plates being constructed extensively for the next 30 years.

Sample renderings and structures:



From left: V type; corrugated; northern light; and prismatic.