

Concrete Shell Structures—Practice and Commentary

Reported by Joint ACI-ASCE Committee 334

Anton Tedesko
Chairman

Eric C. Molke
Vice Chairman

Alfred L. Parme
Secretary

Frank Baron
David P. Billington
Richard R. Bradshaw
Felix Candela

John V. Christiansen
Willhelm Flügge
Richard M. Gensert
Otto Gruenwald

Milo S. Ketchum, Jr.
James A. McCarthy
Stefan J. Medwadowski
Mario G. Salvadori

John B. Skilling
Bruno Thurlimann
Robert Zaborowski

Committee members voting on the 1992 revisions:

Phillip L. Gould
Chairman

Stuart E. Swartz
Secretary

Jack Christiansen
John F. Abel
David P. Billington
Arthur J. Boyt, Jr.
Eli W. Cohen
Morris N. Fialkow

Ajaya K. Gupta
Robert B. Haber
Kye J. Han
Harry G. Harris
Mark A. Ketchum
Milo S. Ketchum

Stefan J. Medwadowski
Luis F. Meyer
Eldon F. Mockry
John K. Parsons
William C. Schnobrich
Alexander Scordelis

David B. South
Anton Tedesko
Bing-Yuan Ting
Daniel F. Tully
Arnold Wilson

A report on the practical aspects of shell design including recommendations and a commentary 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: aggregate size; buckling; construction; design: double-curvature shell; edge beam; folded plate; formwork; model; prestressing; reinforcement; shell; single-curvature shell; splice; stiffening member; supporting member; thickness; thin shell.

ACI Committee Reports, Guides, Manuals, and Commentaries are intended for guidance in planning, designing, executing, and inspecting construction. This document is intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. The American Concrete Institute disclaims any and all responsibility for the stated principles. The Institute shall not be liable for any loss or damage arising therefrom.

Reference to this document shall not be made in contract documents. If items found in this document are desired by the Architect/Engineer to be a part of the contract documents, they shall be restated in mandatory language for incorporation by the Architect/Engineer.

CONTENTS

Preface, p. 334.1R-2

PART I—CRITERIA

Chapter 1—General, p. 334.1R-2

- 1.1—Definitions
- 1.2—Scope

Chapter 2—Analysis, p. 334.1R-2

- 2.1—Assumptions
- 2.2—Analysis of thin shells
- 2.3—Analysis of supporting members
- 2.4—Model analysis

Chapter 3—Stability analysis, p. 334.1R-3

- 3.1—Buckling

ACI 334.1R-92 replaces 334.1R-64 (Revised 1982)(Reapproved 1996) and became effective March 1, 1992. The 1992 revision included minor editorial corrections and the deletion of the year designation for ACI 318 to make the current code the applicable reference.

Copyright © 1992, American Concrete Institute.

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by electronic or mechanical device, printed, written, or oral, or recording for sound or visual reproduction or for use in any knowledge or retrieval system of design, unless permission in writing is obtained from the copyright proprietor.

Chapter 4—Proportioning, p. 334.1R-3

- 4.1—Allowable stresses and load factors
- 4.2—Shell thickness
- 4.3—Shell reinforcement
- 4.4—Prestressing
- 4.5—Concrete cover over reinforcement

Chapter 5—Construction, p. 334.1R-4

- 5.1—Aggregate size
- 5.2—Forms

PART II—COMMENTARY**Chapter 1—General, p. 334.1R-4****Chapter 2—Analysis of shell, p. 334.1R-4**

- 2.1—Thin shells of single curvature
- 2.2—Folded plates
- 2.3—Thin shells of double curvature

Chapter 3—Analysis of supporting members, p. 334.1R-5**Chapter 4—Prestressing, p. 334.1R-6****Chapter 5—Stability, p. 334.1R-6****Chapter 6—Proportioning, p. 334.1R-7****Chapter 7—Construction, p. 334.1R-7**

- 7.1—Forms and decentering
- 7.2—Concrete placing
- 7.3—Curing of concrete

Chapter 8—Models, p. 334.1R-7**Chapter 9—Standards and ACI documents cited in this report, p. 334.1R-8****PART III—SELECTED BIBLIOGRAPHY****PREFACE**

With the increased use of thin shells has come an increased understanding of their behavior through field observations, laboratory tests, and mathematical refinement of analytic procedures. However, because of the wide range of geometry possible with thin shells, the accumulated understanding is still limited. For some thin shell systems, such as cylindrical barrel shells, the design can be made with the same degree of accuracy as for conventional reinforced concrete construction. For other thin shell systems, such as those of double curvature, the design must be at times based on less-refined analyses in the same sense as the empirical design of flat plate floors. Therefore, it was felt desirable to divide this report into two parts.

The first part, entitled “Criteria,” covers general design recommendations. The second part, entitled “Commentary,” contains data of general interest to the designers of thin shells and reflects current practice. A “Selected Bibliography” is included as reference material on current methods of analysis.

The analysis, design, and construction of thin shell structures requires a thorough knowledge in this field. Therefore, the recommendations contained herein are not sufficient in themselves for the satisfactory execution of thin shell structures. Designers are referred to the many texts and technical papers that are readily available.

PART I—CRITERIA**CHAPTER 1—GENERAL****1.1—Definitions**

1.1.1 Thin shells—Curved or folded slabs whose thicknesses are small compared to their other dimensions. They are characterized by their three-dimensional load-carrying behavior, which is determined by their geometrical shape, their boundary conditions, and the nature of the applied load. Thin shells are usually bounded by supporting members and edge members.

1.1.2 Auxiliary members—In a broad sense, any member located along the boundary of a shell or shell segment, with a capacity to stiffen the shell and distribute or carry load in composite action with the shell. They are classified as follows in accordance with established usage, although for certain shells a member may serve in a combination of capacities:

- a) *Supporting members*—Beams, arches, trusses, diaphragms, etc., along the edges of thin shells that serve both to support and to stiffen the thin shell.
- b) *Edge members*—Beams, trusses, etc., along the edges of thin shells that do not form part of the main supporting structure, but serve to stiffen and act integrally, that is, in composite action with the thin shell to carry loads to the supporting members.
- c) *Stiffening members*—Ribs that serve only to stiffen the thin shell or to control local deformations.

1.1.3 Elastic analysis—Any structural analysis based on elastic behavior and involving assumptions that are suitable to approximations of three-dimensional elastic behavior. Analyses based on the results of elastic model tests, when conducted properly, are considered as valid elastic analyses.

1.2—Scope

1.2.1 These recommendations cover the design of thin shell concrete structures and only apply to the thin shell portions of such structures unless otherwise stated.

1.2.2 All applicable sections of the ACI Building Code (ACI 318), including the precast and prestressed concrete sections of the Code, should be followed in the design of shell structures except where they conflict with the following provisions.

CHAPTER 2—ANALYSIS**2.1—Assumptions**

2.1.1 For an elastic analysis, concrete may be assumed uncracked, homogeneous, and isotropic.

2.1.2 Poisson’s ratio may be assumed equal to zero.

2.2—Analysis of thin shells

2.2.1 Elastic behavior is the commonly accepted basis for determining stresses, displacements, and stability of thin shells.

2.2.2 The rigor and the necessary degree of accuracy required in the analysis of any specific thin shell structure depend on certain critical factors. These include: the configuration of the surface and the degree of curvature (geometry), the size of the structure, the type of boundary conditions, and the nature of the loading. Because of the complex interrelationship between these factors, specific recommendations regarding rigor and accuracy of analysis are not given.

2.2.3 Approximate methods of analysis that do not satisfy compatibility of strains or stresses in the shell may be used in cases where authoritative sources and experience have shown them to be applicable within the range employed.

2.2.4 Equilibrium checks of internal stresses and external loads are to be made to insure consistency of results.

2.2.5 An ultimate strength analysis may be used only as a check on the adequacy of the design. It is not to be used as a sole criterion for design, except where it can be proven to be applicable.

2.3—Analysis of supporting members

2.3.1 Supporting members shall be designed in accordance with a recognized elastic analysis.

2.3.2 A portion of the thin shell shall be assumed to act with the supporting member.

2.4—Model analysis

2.4.1 Models may be used as the basis for a design and/or to check the validity of assumptions involved in a mathematical analysis. When models are used, only those portions that significantly affect the items under study need be simulated. Every attempt must be made to ensure that these tests reveal the quantitative behavior of the prototype structure.

CHAPTER 3—STABILITY ANALYSIS

3.1—Buckling

3.1.1 When investigating shells for stability, consideration shall be given to the possible reduction in the value of the buckling load caused by large deflections, creep effects, and the deviation between the actual and theoretical shell surface.

CHAPTER 4—PROPORTIONING

4.1—Allowable stresses and load factors

4.1.1 Unless otherwise stated, concrete and steel stresses and load factors will be as specified in the Building Code (ACI 318).

4.1.2 Minimum standard cylinder strength f'_c shall be 3000 psi.

4.2—Shell thickness

4.2.1 Shell thickness is not always dictated by strength requirements but often by deformation of edge members, stability, and cover over reinforcing steel.

4.2.2 Stress concentrations due to abrupt changes in section shall be considered and, where necessary, the thin shell shall be gradually thickened.

4.3—Shell reinforcement

4.3.1 The stress in the reinforcement may be assumed at the allowable value independently of the strain in the concrete.

4.3.2 Where the tensile stresses vary greatly in magnitude over the shell, as in the case of cylindrical shells, the reinforcement capable of resisting the total tension may be concentrated in the region of maximum tensile stress. Where this is done, the percentage of crack control reinforcing in any 12 in. width of shell shall be not less than 0.35% throughout the tensile zone.

4.3.3 The principal tensile stresses shall be resisted entirely by reinforcement.

4.3.4 Reinforcement to resist the principal tensile stresses, assumed to act at the middle surface of the shell, may be placed either in the general direction of the lines of principal tensile stress (also referred to as parallel to the lines of principal tensile stress), or in two or three directions. In the regions of high tension it is advisable, based on experience, to place the reinforcing in the general direction of the principal stress.

4.3.5 The reinforcement may be considered parallel to the line of principal stress when its direction does not deviate from the direction of the principal stress more than 15 degrees. Variations in the direction of the principal stress over the cross section of a shell due to moments need not be considered for the determination of the maximum deviation. In areas where the stress in the reinforcing is less than the allowable stress, a deviation greater than 15 degrees can still be considered parallel placing; a stress decrease of 5% shall be considered to compensate for each additional degree of deviation above 15 degrees. Wherever possible, such reinforcing may run along lines considered most practical for construction, such as straight lines.

4.3.6 Where placed in more than one direction, the reinforcement shall resist the components of the principal tension force in each direction.

4.3.7 In those areas where the computed principal tensile stress in the concrete exceeds 300 psi, placement of at least one layer of the reinforcing shall be parallel to the principal tensile stress, unless it can be proven that a deviation of the reinforcing from the direction parallel to the lines of principal tensile stress is permissible because of the geometrical characteristics of a particular shell and because for reasons of geometry only insignificant and local cracking could develop.

4.3.8 Where the computed principal tensile stress (psi) in the concrete exceeds the value $2\sqrt{f'_c}$ (where f'_c is also in psi), the spacing of reinforcement shall not be greater than three times the thickness of the thin shell. Otherwise the reinforcement shall be spaced at not more than five times the thickness of the thin shell, nor more than 18 in.

4.3.9 Minimum reinforcement shall be provided as required in the Building Code (ACI 318) even where not required by analysis.

4.3.10 The percentage of reinforcement in any 12 in. width of shell shall not exceed $30f'_c/f_s$. However, the maximum percentage shall not exceed 6% if $f_s = 20,000$ psi, 5% if $f_s = 25,000$ psi, or 4% if $f_s = 30,000$ psi when the latter values are acceptable. If the deviation of the reinforcing from the lines of principal stress is greater than 10 deg, the maximum percentage shall be one-half of the above values.

4.3.11 Splices in principal tensile reinforcement shall be kept to a practical minimum. Where necessary they shall be