

SHELLS, MEMBRANES AND SPACE FRAMES

**Proceedings of the IASS Symposium on Membrane Structures
and Space Frames**

Osaka, Japan, 15-19 September, 1986

Edited by

KOICHIRO HEKI

Volume 1 SHELLS

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Department of Architecture, Faculty of Engineering, Osaka City University,
Sugimoto, Sumiyoshi-ku, Osaka, 558, Japan

Volume 1 SHELLS



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Editorial Preface

This collection of 142 papers and introduction has been prepared for the International Symposium on Membrane Structures and Space Frames to be held in Osaka, September 15-19, 1986. This symposium is organized by Professor Yoshikatsu Tsuboi, chairman, under the auspices of the International Association for Shell and Spatial Structures (IASS) and the Architectural Institute of Japan (AIJ). This symposium was planned to provide a forum on the above-mentioned themes, expanding its field to include shell structures which are basic to the IASS. These themes are closely related to two reports on Pneumatic Structures and Spatial Steel Structures which were published recently by two IASS Working Groups that were chaired by Professor Tsuboi. These are interesting fields for architects and engineers to apply to large span structures.

The contents of the proceedings are papers on the analysis, design and construction of shells, membrane and cable structures, and space frames. According to classification, the papers are arranged and printed in three volumes. The proceedings were reproduced by a photolithographic process. However, titles and addresses of papers which deviated from the publishing instructions were retyped by the editor.

In Volume 1, 44 papers are devoted to the analysis of various types of shells and related problems. Most of them are on the theoretical analysis of shells, especially on stability and dynamic problems. Coupling problems between shells and fluid and practical design and construction are also treated in some papers. Volume 2 contains 49 papers on the problems of the membrane and cable structures, such as the non-linear analysis of these structures, properties of membrane materials, loads on these soft structures, and design and realization of these structures. In Volume 3, 50 papers on space frames are included. The definition of space frames varies in various fields of engineering, but in this symposium the term "space frame" implies shell-like and plate-like spatial frames. Design philosophy, computer design, such as optimum design and formex technique, and practical design are discussed in about twenty papers. Fourteen papers are concerned with stress analysis and stability analysis of double and single layer space frames theoretically and/or experimentally. Research concerning the load carrying capacity of space frames in relation to joint rigidity is presented in some papers. A few papers on foldable structures are also included.

The papers come from various parts of the world. Their scientific content and approach varies, illustrating the need for a symposium to exchange ideas and information. New ideas, concepts, methods and results described in the papers, which were developed by continuous research referring to existing papers and review reports, will play an important role in stimulating study and practice in this field.

The editor would like to express his gratitude to each author who assisted by preparing his manuscript according to the instructions and rules. Also he wishes to express his thanks to the members of the Science Subcommittee, listed below in alphabetical order, for their devoted cooperation in reviewing the scientific contents of the manuscripts and editing, and especially to Professors Hangai, Kunieda and Ohyama, who acted as co-editors. It should be mentioned that the documents and work of the secretariat were directed by Professor Mamoru Kawaguchi, chairman of the executive committee.

Yasuhiko Hangai
Kazuo Ishii
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Motohiko Yamada

The editor is indebted to Elsevier Science Publishers for their courteous and effective production of these Proceedings.

1986

Koichiro Heki
 Editor

Developments in Civil Engineering

- Vol. 1 The Dynamics of Explosion and its Use (Henrych)
- Vol. 2 The Dynamics of Arches and Frames (Henrych)
- Vol. 3 Concrete Strength and Strains (Avram et al.)
- Vol. 4 Structural Safety and Reliability (Moan and Shinozuka, Editors)
- Vol. 5 Plastics in Material and Structural Engineering (Bares, Editor)
- Vol. 6 Autoclaved Aerated Concrete, Moisture and Properties (Wittmann, Editor)
- Vol. 7 Fracture Mechanics of Concrete (Wittmann, Editor)
- Vol. 8 Manual of Surface Drainage Engineering, Volume II (Kinori and Mevorach)
- Vol. 9 Space Structures (Avram and Anastasescu)
- Vol. 10 Analysis and Design of Space Frames by the Continuum Method (Kollár and Hegedűs)
- Vol. 11 Structural Dynamics (Vértes)
- Vol. 12 The Selection of Load-Bearing Structures for Buildings (Horváth)
- Vol. 13 Dynamic Behaviour of Concrete Structures (Tilly, Editor)
- Vol. 14 Shells, Membranes and Space Frames (Heki, Editor)

Foreword

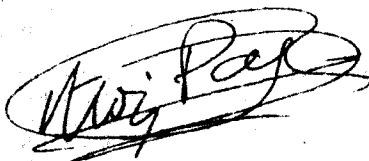
I have been involved with IASS work since the very beginning, when the International Committee for Shell Structures decided to expand its activities, becoming the International Association for Shell Structures. From the time of this transformation, spatial structures became one of the main subjects of interest at events organized or sponsored by the Association.

The first meeting of the new organization, held in Madrid in September 1959, was chaired by Professor Eduardo Torroja. I was involved in the organization of that meeting, under the direct supervision of Professor Florencio del Pozo. At the time of that first meeting, when it was decided that the Proceedings of our international meetings should be published prior to the conferences themselves, I realized that the success of this plan would require continuous and diligent work on the parts of many people and that great difficulties would have to be overcome in order to meet strict deadlines without compromising the quality of the Proceedings.

During a recent visit to Japan, I was fortunate to have had the opportunity to visit our Japanese colleagues, and to attend one of the meetings of the Organizing Committee for the Osaka International Symposium on Membrane Structures and Space Frames. Although the meeting was conducted entirely in Japanese, the contagious enthusiasm of the participants inspired me and made me excited about the upcoming conference. I could see that under the chairmanship of Professor Tsuboi, and through the continuous hard work of Professor Kawaguchi, the successful organization of the conference and production of these Proceedings was ensured.

This book is the product of that enthusiasm, but it is also the result of many dedicated hours of work on the parts of numerous people who have sacrificed part of their working hours and leisure time to achieve its production. I would like to extend my heartfelt thanks to all of these people, and to Professors Tsuboi and Kawaguchi in particular, without whom these Proceedings and this conference would have been impossible.

This is the second time that IASS has held its international meeting in Japan and I remember the productiveness of our conference in 1971 and the high quality of the Proceedings. I believe this publication is of equally high value, and it is my sincere hope that the technical and scientific benefits of the 1986 conference will equal, or even surpass, those of 1971.



R. López Palanco
President

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CONTENTS

Vol. 1

Editorial Preface	v
Foreword	vii
Organizing Committee of the Symposium	viii

INTRODUCTION

Yoshikatsu Tsuboi	1
Introduction	

SHELLS

Kohji Sumino and Yoshitaka Ozawa	9
On the Stability of Shells with Movable Edges under an External Hydropressure	
Zbigniew K. Mendera	17
Interaction of Elastic and Plastic Instability in Cylindrical Shells with Imperfections	
Kohji Sumino	25
A Consistent Theory for Thin Elastic Shell Stability	
Haruo Kunieda	33
Responses of Spherical Domes Subjected to Vertical Earthquakes	
Ipppei Kondo and Yasuo Tanaka	41
Study on the Response of Parabolic Valsereidal Shells under Earthquake Vertical Excitation	
Shiro Kato, Takashi Sohri and Akihiro Harikane	49
Earthquake Response Characteristics of a LNG Tank on a Subsoil	
Junji Tani, Hirohisa Haeji and Masakata Chiba	57
Free Vibration of Fluid-Coupled Coaxial Cylindrical Shells	
Tadahiro Fukusumi, Yoshihisa Gyoten, Koji Mizuhata and Hisashi Nozoe	65
Water Wave Responses of Cylindrical Shell Structures of Floating Type	
Youichi Minakawa	73
Lagrangian Functions of the Interactive Behavior between Potential Fluid and Elastic Containers	
in Fields of Finite Deformations	
Kiyoshi Shingu and Toshio Nishimura	81
A Study on Dynamic Response of Submerged Conical Shells	
Toshio Nishimura, Nobuyoshi Tosaka and Norio Kondo	89
Numerical Analysis for Viscous Fluid - Elastic Shell Interaction	
Hiroshi Ohmori, Hiroshi Hibino, Keiichi Katoh and Tetsuya Matsui	97
Nonlinear Sloshing of Cylindrical Liquid Storages	
Eric Savory, Norman Toy and Bahman Tahouri	105
Investigation of the Wind Flow around Domes and Barrel Vault Structures	
Li Longyuan and Lu Wende	113
Analysis of Free Vibration and Response to Turbulent Wind of Hyperbolic Cooling Towers	
by Ring-Stiffeners	
Shiro Kato and Yoshinao Chiba	121
Stochastic Stress Analysis of Cooling Tower Shells Due to Differential Settlement	
Masaru Murata, Atsushi Mutoh, Shiro Kato and Osamu Matsuoka	129
Statistical Analysis of Stresses in Rotational Thin Shells with Random Geometric Imperfections	
TaeK-Jin Kwon and Seung-Deog Kim	137
Elasto-Plastic Analysis of Spherical Shells by the Rigid Element Method	

Akihiko Mikame and Kazuhiro Uchida	145
A Nonlinear Constitutive Model for the Finite Element Analysis of Reinforced Concrete Shell Structures	
Zhang Lin and Xia Yiren	153
Geometrically Nonlinear Analysis for the Curved Shell Elements	
Chang-Koon Choi and Sun-Hoon Kim	161
Stress Analysis of Shells by Reduced Integrated Nonconforming Elements	
Nobuyoshi Tosaka	169
Integral Equation Method for Shallow Shell Bending Problems	
H.L. Zhao, J.R. Xie, G.Y. Xue, C.Q. Zhao, J.L. Liu and Y.X. Shen	177
Static and Dynamic Analyses and Engineering Practice of Thin-Sheet Boxed-Element Space Structures	
Nainan P. Kurjan	185
Ultimate Strength of Hyperbolic Paraboloidal Shell Footings Subjected to Vertical Loads and Moments	
Huang-Yih and Sun Bo-Hua	193
The General Solution of Conical Shells on the Elastic Foundation	
Yong-Qiu Jiang	201
Optimum Design of Fiber Reinforced Plates and Shells	
S.S. Bhevikatti and V.R. Biradi	209
Optimum Design of Cylindrical Shell Roofs	
Oscar A. Andres and Marta B. Rosales	217
Design of Tension-Free Tank Walls	
Shiro Kato, Kenichiro Hidaka and Takayoshi Aoki	225
Analytical Studies of the Historical Masonry Structure: The Florentine Dome of Santa Maria del Fiore	
Friedhelm Stangenberg	233
Material Parameters Sensitivity of Reinforced Concrete Shells	
P.K.K. Lee	241
Model Study of a 36 m Span Roof	
Kazuo Uchiyama, Yasushi Uematsu and Hiroyuki Minami	249
Experimental Study of the Asymmetric Buckling of Cylindrical Shell Roofs	
Kazuhiko Meshita, Michiya Hara and Yasuo Tanaka	257
Experimental Study on Conoidal and Cylindrical Shells with Edge Beams and Gables under Half Uniform Loading	
Hyun-Sik Choi, Tetsuyuki Tanami and Yasuhiko Hangei	265
Failure Tests of Cantilevered Cylindrical Shells under a Transverse Load	
Makoto Takayama	273
Elasto-Plastic Characteristics of Towered Type Reinforced Concrete Cylindrical Shells Subjected to Lateral Forces	
Ludevít Vágh and Miloslav Kurka	281
An Extremely Thin Wire Fabric Reinforced Concrete Element with External Reinforcement	
Herrmann Rühle	289
Development of Ferrocement-Membranes	
Tsutomu Kokawa and Kenji Murakami	297
Challenge to 20-m Span Ice Dome	
Kunio Watanabe	306
Diversified Development of PC Spatial Structure	
G.S. Ramaswamy	313
Innovative Applications of Funicular Shells	
Yang Yao, Chen Xinghui, Peng Kewei and Lin Yuankun	321
The Development and Application of V-Folded Plate Structure in China	
Mircea Mijhaltescu, Ilidko Bucur, Belint Szabo and Petru Rus	329
Some Aspects of Shell Prestressing	
Werner Sobek	337
Concrete Shells Constructed on Pneumatic Formwork	

Arnde M. Wolde-Tinsae 345
 Prebuckled Sandwich Domes and Super Domes
 Authors Index 353

Vol. 2

MEMBRANE AND CABLE STRUCTURES

Lajos Kollár and Tibor Óvári 1
 Static Problems of Fabric Tanks of Equal Strength
 Toshio Nishimura, Nobuyoshi Tosaka and Toshio Honma 9
 Membrane Structure Analysis Using the Finite Element Technique
 A.S. Day 17
 Stress Strain Equations for Non-Linear Behaviour of Coated Woven Fabrics
 Kazuo Ishii 25
 Stress Concentrations for Fabric Membrane Structures – A Problem for the Structural Design of
 Membrane Structures
 L.G. Mukhadze, G.M. Japeridze, M.L. Sekhniashvili and N.P. Chkusseli 33
 Search Method of Computation of Different Type Membranes
 Ikuya Toda, Toshihiro Suzuki, Makoto Kikushima and Yoshihito Saitoh 41
 The Influence of Directional Property of the Membrane Materials on the Membrane Analysis
 Oren Vilnay 47
 The Response of Determinate Cable Nets
 Hisashi Tanaka and Yasuhiko Hangei 55
 Rigid Body Displacement and Stabilization Conditions of Unstable Truss Structures
 Bogdan Huslar and Romuald Switka 60
 Creep and Relaxation in Net Structures
 Stefan Jendo 70
 Multicriteria Optimization of Cable Systems
 Ihsan Mungan 75
 Comparison between the Structural Behaviors of Prestensioned Cable Net and Reinforced
 Concrete Cooling Towers
 Shi-Zhao Shen, Chong-Bao Xu and Hua Guo 80
 Theoretical and Experimental Study of Prestressed Double-Layer Cable System used in a
 New Ice-Rink
 Jiro Kunita, Hajime Nakajima and Takashi Kunugi 90
 An Interactive Shape Finding Analysis for Cable and Membrane Structures
 Massimo Majowiecki 100
 Recent Developments of Design and Construction of Membrane Structures in Italy
 John F. Abel, Robert B. Haber, David C. Salmon and Martin L. Brown 110
 Development of Computer-Aided Design of Cable-Reinforced Membrane Structures in the U.S.A.
 David G. Phelan and Robert B. Haber 114
 An Integrated Design Method for Cable-Reinforced Membrane Structures
 Kyoichi Kudoh 120
 An Analysis of Cutting Pattern and the Fabrication of Membrane Panels for the Membrane
 Structure
 Marijke Mollaert, Willy De Wilde and Franky Van Damme 130
 Modular Design of Tension Structures

Toshikazu Takeda, Mitsuru Kageyama and Yoshinori Homma	141
Experimental Studies on Structural Characteristics of a Cable-Reinforced Air-Supported Structure	
Yasuzo Fukao, Yoshiteru Iwasa, Yoshihiro Mataka and Akira Okada	149
Experimental Test and Stimulation Analyses of the Dynamic Behavior of Low-Profile, Cable-Reinforced, Air-Supported Structures	
R.K. Müller	157
Model tests as an Aid to Design and Construction of Membrane Structures	
Hideki Megara and Kiyoshi Okamura	161
A Study on Modeling and Structural Behavior of Membrane Structures	
Masaru Yamagishi and Choichiro Hoshi	169
Connection of Membrane Material Employing Point-Supporting System	
Nobuhiko Ishizu and Hirokazu Minami	177
A Method of Measurement of Actual Membrane Tensile Stress	
Willy De Wilde, Marijke Mollaert and Iris Tommelein	185
Some Problems Encountered in the Use of Composite Materials and Textiles in Cable Stayed Membrane Structures	
Kohichi Itoh, Kohtaro Tanaka and Yoshiaki Ohuchi	193
An Experimental Study on Tension Characteristics of Suspension Membranes	
Hirokazu Minami, Hiroshi Toyoda, Kiyotaka Kotera and Shinya Segawa	201
Some Reviews on Methods for Evaluation of Performance of Membrane Materials Being Used for Membrane Structures	
G.A. Stevens and J.J. Fendley	209
Dual-Skin Structures Using Optically-Selective Materials	
P.S. Han and M.D. Olson	217
Static Analysis of Pneumatic Structures Loaded by Wind	
Masanao Nakayama, Tosio Suzuki, Kazuo Ishii and Kazuhiko Satoh	225
Wind Tunnel Test on Spherical Pneumatic Structures	
Sumio Kawamura and Tetsuhiko Kiuchi	233
Wind Design Method of Air Supported Structures	
Yasushi Uematsu and Kazuo Uchiyama	241
Aeroelastic Behavior of an H.P.-Shaped Suspended Roof	
Eiji Kimoto and Sumio Kawamura	249
Aerodynamic Criteria of Hanging Roofs for Structural Design	
Masao Saitoh	257
Hybrid Form-Resistant Structures	
David Geiger, Andrew Stefanuk and David Chen	265
The Design and Construction of Two Cable Domes for the Korean Olympics	
Shi-Zhao Shen and You-Wen Zhang	273
Theoretical and Experimental Study of Cable-Arch System — A New Type of Mixed Structures	
Shigeru Ban, Haruji Tsubota, Kazuo Kurihara and Arata Yoshida	281
Experimental Investigation of a Tensile Fabric Structure	
Peter E. Ellen	289
Post-Tensioning of Steel Structures	
J. Ma and H.L. Zhao	297
An Investigation on the Characteristics of a Truss (Grid), Plate (Shell) and Cable-Suspended Composite Structure	
Koryo Miura, Michihiro Natori and Masamori Sakamaki	305
Technological Developments on Large Membrane Structures in Space	
Yutaka Murata	313
A Development from the Mesh Membrane Method for a Pneumatic Structure	
Kenichi Sugizaki	317
Structural Design of a Permanent Air-Supported Dome	
Akira Okada and Yasuzo Fukao	325
An Approach to Internal Pressure Control of Low-Profile Cable-Reinforced Air-Supported Structures	

Robert Krapfenbauer	333
Membrane Structures for Exhibition Buildings	
Norihiro Ikemoto, Yoshihiro Mizoguchi, Masahisa Fujikake, Osamu Kojima and Minoru Hirota . .	341
Development of a Design System for Fabric Tension Structures	
Masao Saitoh, Fumio Kuroki, Norihide Imagawa and Kohichi Itoh	349
The Analysis, Design, and Construction of a Suspension Roof for Tsukuba Expo '85	
Josef Postulka	357
Economical Ice-Halls with Hanging Roof	
Tianjian Ji	365
Design and Analysis of Orthogonal Cable-Net Roofs with Complex Shape	
O.G. Sulaberidze, Yu.K. Melashvili and Z.D. Lartsullani	373
Cable-Net Windbreaker Systems	
Authors Index	377

Vol. 3

SPACE FRAMES

Selichi Tasaka, Takashi Sohr, Hiromi Nishizono and Shiro Kato	1
Stochastic Structural Response Characteristic under Multiple Seismic Excitations	
Shiro Kato and Koichiro Ishikawa	9
Materially Non-Linear Stability of a Double-Layer Grid Due to Vertical Earthquake Motions	
Norman Toy and Timothy A. Fox	17
An Experimental Investigation of the Flow Through Structural Members	
Zhou Guo-Xing	25
Difference Operator of Grids and their Expressions with Inequable Step	
Dong Shilin and Xia Hengxi	33
The Solutions and their Comparisons of the Sandwich Plate Analogy Method in Two Kinds of Simply Supported Two-Way Orthogonal-Diagonal Lattice Grids	
A. Affen and C.R. Calladine	41
Structural Mechanics of Double-Layer Space Grids	
M. Van Laethem, E. Backx and C. Gordons	49
Stereographic Cupola	
Letteri Natesen Ramamurthy and S.S. Narayanan	57
Theoretical and Experimental Investigation of the Behaviour of Steel braced Barrel Vault under Horizontal Loading	
Koichiro Heki	65
The Continuum Analogy of Lattice Structures from the View-Point of Difference Equations	
Ariel Haneor, Robert Levy and Nancy Rizzuto	73
Investigation of Prestressing in Double-Layer Grids	
Toshiro Suzuki, Toshiyuki Ogawa and Hitoshi Ozaki	81
Large Deformation Analysis of Square-on-Square Double-Layer Grids with Member Buckling and Yielding	
Toshitsugu Saka and Koichiro Heki	89
The Load Carrying Capacity of Inclined Square Mesh Grids Constructed by a Bolted Jointing System	
R.E. McConnel, F.A. Fathelbab and D. Hetzls	97
The Buckling Behaviour of Some Single Layer, Shallow Lattice Domes	

I.M. Kani and R.E. McConnel	105
Collapse and Post-Collapse Analysis of Shallow Lattice Domes	
Motohiko Yamada, Kazuo Uchiyama, Seishi Yamada and Tomoaki Ishikawa	113
Theoretical and Experimental Study on the Buckling of Rigidly Jointed Single Layer Latticed Spherical Shells under External Pressure	
Masao Saitoh, Yasuhiko Hangai, Ikuya Toda, Takanori Yamagiwa and Takehiko Okuhara	121
Buckling Loads of Reticulated Single-Layer Domes	
Eizaburo Tachibana	129
On Application of the Quasi-Newton Method for Structural Analysis Including the Dynamic Snap-Through Problem	
Peter Disney	137
Formian: The Programming Language of Formex Algebra	
Ik Nang Anna Cheah	145
Formices and Plenices in Structural Analysis and Design	
H. Klimke and J. Kleprlik	153
Computer Aided Design of Curved Space Trusses	
Istvan Kader and Vickie L. Kraman	161
Design of Shell Structures Using 3D Structural Analysis and CAD	
Pietro Lenza	169
The Collapse of Doubly Curved Vaults	
Ali Kaveh	177
Nodal and Element Ordering for Bandwidth Optimization	
Kanagasabai Ramchandran	185
Combinatorial Approach to the Flexibility Analysis of Space Frames	
Tien T. Lan and Ruojun Qian	191
A Study on the Optimum Design of Space Trusses – Optimal Geometrical Configuration and Selection of Type	
Tsuneyoshi Nakamura and Makoto Ohsaki	199
Optimum Plastic Design of Large Regular Trusses and Control of Member Force Distributions	
Robert Levy and Ariel Hanaor	207
Optimal Design of Prestressed Trusses	
Cedric Marsh	215
Improving Space Truss Performance by Member Removal	
Jean-Marie Lagache and Joel Kasarherou	221
Theory and Practice of Michell Frames	
W. Gutkowski, J. Bauer and Z. Iwanow	229
Minimum Weight Design of Space Frames from a Catalogue	
Wolf Pearlman	237
Polyhedral Analogues of Radialia	
Michael Burt	245
Low Density Space Frames, Based on 'Regular Infinite Polyhedra'	
Jan Kolosowski	253
A Method of the Subdivision of Braced Spherical Domes with the Maximum Number of Members of Equal Length	
Michihiro Natori, Koryo Miura and Hiroshi Furuya	261
Deployable Truss Concepts in Space Technology	
Felix Escrig and Juan P. Vejarcel	269
Analysis of Expandable Space Bar Structures	
Oliver McNulty	277
Foldable Space Structures	
Joop M. Gerrits	285
Space Structures in the Netherlands	
Pieter Huybers	293
Space Structures of Timber Poles	

J.C. Chilton, C. Daffern, M.L. Kubik and R.E. McConnel	301
The 'CUBIC' Space Frame — Its Construction and Methods of Analysis Using a Micro-Computer	
Avanesov Sergei Ivanovich	309
The Development, Researches and Introduction of New Structural Approach to Space Bar Metal Blocks of Covering	
Katsuhiko Imai and Yuichi Fukuda	317
Proposing a Sliding Technique for the Economical Construction of Medium-Sized Space Frames	
David Wickersheimer	325
The Unintentional Misuse of Horizontal Space Grid Roofs	
Hao Yunsheng	333
A New Type of Space Grid Shell	
Jan Filipkowski	341
Construction of Space Frame Roof over Open-Air Ice Rink at Bydgoszcz, Poland	
Gengo Matsui, Tokio Komatsu, Hiroyuki Seki, Mamoru Iwata and Hiroyuki Shinmura	349
Study of Steel Parallel Lamella Dome	
Hiroshi Kitamura, Mikihiro Satake, Mizuo Yamada and Tokuyuki Tahara	357
Utilization of Prestressed Concrete and Lifting for Construction of a Shell Dome	
Hiroshi Terunuma, Katsuhiro Tanaka, Isao Kubodera and Toshiyuki Kawazoe	365
Non-Snow-Dropping Long-Spanned Roof Structure Facilities for Sports	
Kunio Ukai, Takeshi Yamaguchi, Naoki Uchida and Tsukasa Aoyagi	373
Structural Design of Osakajo Hall	
Shulchi Kitamura and Yasuo Tanaka	381
The Practical Design of the Single Layered Steel Space Frame Roof of a Gymnasium	
Arni Fullerton	387
Meta Structures and Urban Places: Townships Central Areas and Arcades	
Authors Index	393

INTRODUCTION.

YOSHIKATSU TSUBOI

The first IASS meeting in Japan, THE PACIFIC SYMPOSIUM PART 2 in TOKYO and KYOTO, was held in 1971, twelve years after the establishment of the IASS. At that time it was presided over by Professor Haas of the Netherlands, who had succeeded Professor Eduardo Torroja, the founder and the first president of the IASS.

The present symposium, the second in Japan, is now being held 15 years after the first IASS meeting in Japan, and it is an honor to have Professor López Palanco among us as the fourth president.

The fact that several papers to be presented in this symposium are on studies of membrane structures reminds the author of the IASS symposium in Kielce held in 1973 where Professor Rühle advised him to take the role of chairman of the Working Group for Pneumatic Structures. The author is grateful to all the IASS members who have been involved in making up the Recommendations of Air-Supported Structures which have been successfully published last year as a special issue of the IASS bulletin.

It goes without saying that membrane stresses are the vital essence of shell structures, and the IASS was founded with the belief that this state of stresses would ensure the development of reinforced concrete thin shell structures. The membrane stresses can be (A) TENSION or (B) COMPRESSION, and the choice among (A), (B), or their mixtures depends largely on the materials and forms of structures.

The basic idea of shell structures begins with

$$N=pR \quad (a), \text{ or } N/R=p \quad (b)$$

This has been known as the arch theory since olden times, and differs very much from the statics of linear members such as beams, trusses and rigid frames. For two-way arches, the above relation becomes

$$N_1/R_1=p_1, \quad N_2/R_2=p_2, \quad N_1/R_1 + N_2/R_2 = p_1 + p_2 = p,$$

which corresponds to the bending theory of plates of Sophie Germaine who constituted this idea and who lived in the era of Napoleon I. On the other hand, the basic equation for the membrane stresses of shells

$$N_{11}/R_{11} + 2 N_{12}/R_{12} + N_{22}/R_{22} = p \quad (c)$$

corresponds to the modern bending theory of plates which was established by Lagrange (or Kirchhoff) upon modification of S. Germaine's equation.

Equation (c) in a generalized form is

$$N^{\alpha\beta} b_{\alpha\beta} + p = 0, \quad \alpha, \beta = 1, 2 \quad (d)$$

where

$N^{\alpha\beta}$: stress tensor (contravariant)

$b_{\alpha\beta}$: second fundamental metric tensor (covariant),

which can be applied to all sorts of surfaces in all curvilinear coordinates. Equation (d) contains in its expression all kinds of surfaces imaginable, whether they are reinforced concrete shells or tensile membranes. Artists and architects may develop their images around the values of $b_{\alpha\beta}$ which make, as Eero Saarinen said, some of their creations beautiful and some others ugly.

In-plane equilibrium of shells may be expressed by

$$N^{\alpha\beta}{}_{;\alpha} + p^{\beta} = 0 \quad (e)$$

where $;$ denotes two-dimensional covariant differentiation. Solutions of Equations (d) and (e) have been formulated for some particular curvilinear coordinates in the elementary theory of shells. Among others the solutions of (d) and (e) by Hetényi, which are obtained taking advantage of Cartesian Coordinates, are surprisingly realistic.

Moreover, the theory for shallow shells for

$$1 \gg \left(\frac{\partial z}{\partial x}\right)^2, \left(\frac{\partial z}{\partial x} \frac{\partial z}{\partial y}\right), \left(\frac{\partial z}{\partial y}\right)^2 \quad (f)$$

gives

$$N_x \frac{\partial^2 z}{\partial x^2} + 2N_{xy} \frac{\partial^2 z}{\partial x \partial y} + N_y \frac{\partial^2 z}{\partial y^2} = p \quad (g)$$

instead of (d).

Condition (f) plays the role of converting curvilinear coordinates to Cartesian. This made possible establishment of the Vlasov (D.M.V.) type equations of shallow shells with bending which, well-understood by engineers as a combination of the plate theory and the two-dimensional stress state, have been adopted in a number of practical shell designs.

In local problems of a deep shell, Equation (g) is equally valid, as long as Condition (f) is satisfied in the relevant local coordinates, which enables comprehension of the behaviors of the shell in a realistic way.

Discussion of the behaviors of a shell in the general coordinates inevitably leads to tensor analysis, but the exercise of differential geometry is not the only concern. Actual stresses and curvatures are strongly desired, instead of stress tensors and second fundamental metric tensors, respectively. In this respect, most impressive was a paper by Nagdhi in which he established the basic equations of shells in general orthogonal curvilinear coordinates which, before him, had been made possible only in curvature line coordinates by researchers of vector analysis including the author. Nagdhi could thus largely extend the shell formula constituted by researchers such as Flügge. Flügge was also a pure

scholar who concluded his study of shells with the tensor theory.

The great works of Torroja in the field of civil engineering encouraged utilization of the results of developments in shell theory, especially those studied in other fields in more generalized forms. Contributions by Donnell, Reissner, Koiter and others to shell engineering are examples of this sort.

It may be said that the technical and esthetic developments of reinforced concrete shells have been achieved on the basis of progress in the shell theory and the method of its analysis. The author recollects that 1959 was the year in which the IUTAM meeting on the Theory of Shells was held in Delft with Prof. Koiter as the chairman. The author remembers Prof. Reissner who kindly spoke to supplement the author's paper, and the short-time address by D. Donnell together with the hearty hospitality extended by Prof. Koiter. If the author had not met, after this conference, Prof. Johansen of Denmark who suggested he attend a meeting to be organized by Prof. Torroja, the author might have missed an opportunity to witness the foundation of the IASS which occurred at this very meeting. In the same year the study of deep spherical shells was commenced in Japan in connection with the import of an atomic power reactor from the U.K. for the construction of Tokai No. 1 plant. A series of joint researches, including Prof. Baker of Cambridge University, Prof. Yokoo of Kyoto University and the author, on asymmetric deformation problems of pressure vessels are unforgettable memories of the author. The year 1959 thus is a reminder of the formation of the IASS and the prosperity of shell structures. A short conversation with Prof. Torroja at the Madrid horse race grandstand is a pleasant memory of the man who passed away the following year.

Haas and Paduart, who succeeded Torroja as the second and third presidents, respectively, devoted themselves to the development of reinforced concrete shell structures. To have steel space frames included among the subjects to be studied by the IASS was the opinion of both Haas and the author, and this was realized afterward.

Then, tension structures including pneumatic structures came to be studied by the IASS. These inclusions of newly developed materials and structural systems into activities of the IASS have contributed greatly to the expansion of the territory of the Association.

Within the three decades since Torroja established the IASS, shell and shell-like structures have thus been developed with a variety of applications such as reinforced concrete vaults, tension structures, membranes (as soft structures), and so on. It should be noted, however, that the *raison d'être* of all these structures in design, theory,