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

1986

Koichiro Heki
Editor

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Vol. 3 Concrete Strength and Strains (Avram et al.)
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Vol. 7 Fracture Mechanics of Concrete (Wittmann, Editor)
Vol. 8 Manual of Surface Drainage Engineering, Volume II (Kinori and Mevorach)
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Vol. 14 Shells, Membranes and Space Frames (Heki, Editor)

Foreword

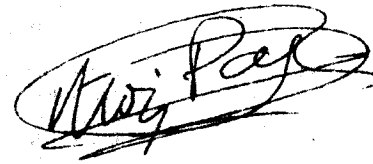
I have been involved with IASS work since the very beginning, when the International Committee for Shell Structures decided to expand its activities, becoming the International Association for Shell Structures. From the time of this transformation, spatial structures became one of the main subjects of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

$N=pR$ (a), or $N/R=p$ (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

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

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

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

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

$$1 >> \left(\frac{\partial Z}{\partial x}\right)^2, \left(\frac{\partial Z}{\partial x}\frac{\partial Z}{\partial y}\right), \left(\frac{\partial Z}{\partial y}\right)^2 \qquad (f)$$

gives

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

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 Naghdi 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,