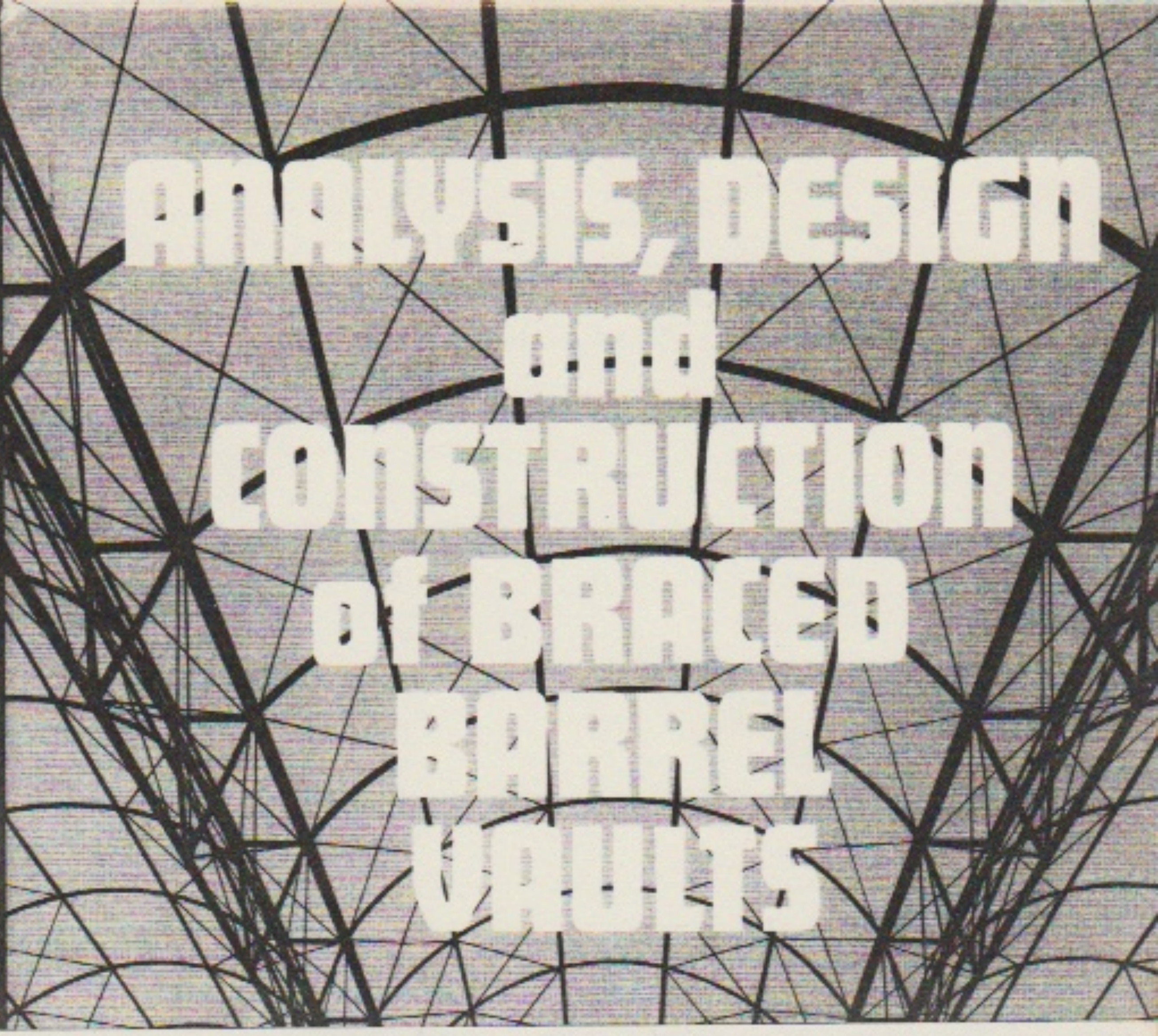

ANALYSIS, DESIGN and CONSTRUCTION of BRACED BARREL VAULTS

Design and Construction of Steel Barrel Vaults for Buildings of Medium and Large Spans

by Joseph Zeman, Prague, Czechoslovakia

Edited by

Z.S. MAKOWSKI

ELSEVIER APPLIED SCIENCE PUBLISHERS

ANALYSIS, DESIGN AND CONSTRUCTION OF BRACED BARREL VAULTS

ANALYSIS, DESIGN AND CONSTRUCTION OF BRACED BARREL VAULTS

Edited by

Z. S. MAKOWSKI

Professor of Civil Engineering,
Space Structures Research Centre,
University of Surrey, Guildford, UK

ELSEVIER APPLIED SCIENCE PUBLISHERS
LONDON and NEW YORK

ELSEVIER APPLIED SCIENCE PUBLISHERS LTD
Crown House, Linton Road, Barking, Essex IG11 8JU, England

Sole Distributor in the USA and Canada
ELSEVIER SCIENCE PUBLISHING CO., INC.
52 Vanderbilt Avenue, New York, NY 10017, USA

WITH 14 TABLES AND 395 ILLUSTRATIONS

© ELSEVIER APPLIED SCIENCE PUBLISHERS LTD 1985

British Library Cataloguing in Publication Data

Analysis, design and construction of braced barrel vaults.
1. Vaults (Architecture)—Design and construction
I. Makowski, Z. S.
624.1'775 TH2160

Library of Congress Cataloging-in-Publication Data
Main entry under title:

Analysis, design, and construction of braced barrel vaults.

Includes index.
1. Vaults (Architecture)—Design and construction—Addresses, essays, lectures. I. Makowski, Z. S.
TH2160.A53 1985 690'.145 85-15902

ISBN 0-85334-377-2

The selection and presentation of material and the opinions expressed in this publication are the sole responsibility of the authors concerned.

Special regulations for readers in the USA

This publication has been registered with the Copyright Clearance Center Inc. (CCC), Salem, Massachusetts. Information can be obtained from the CCC about conditions under which photocopies of parts of this publication may be made in the USA. All other copyright questions, including photocopying outside of the USA, should be referred to the publisher.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of the publisher.

Printed in Great Britain by Galliard (Printers) Ltd, Great Yarmouth

17

Design and Construction of Steel Barrel Vaults for Buildings of Medium and Large Spans

J. ZEMAN
Prague, Czechoslovakia

1 GENERAL ASPECTS OF DESIGN OF LARGE SPAN ROOFS IN STEEL STRUCTURES

At the design stage of large span structures, the designer has to pay special consideration not only to the structural and architectural aspects of his structure, but he has also to aim towards simple fabrication and ease of erection. The recent trends put an increasing emphasis on the optimisation of the structural material. Nowadays maximum exploitation of material combined with minimum use of energy becomes a focal point of interest. This explains the great interest in the design of structures with minimum unit weight per square area. At the same time attempts are made to simplify the fabrication with a saving in all kinds of energy during the construction.

Lamella steel vaults undoubtedly belong to the most effective systems of this kind. Their main roof shape is characterised by the form of a barrel vault. Their basic form can, of course, be adapted in various ways to different purposes and requirements of the actual structure. Some possibilities will be demonstrated in this chapter with steel barrel vaults designed by the author.

2 REVIEW OF DEVELOPMENTS

Several of the structures of this type were designed and erected some time ago and were described in earlier publications.[1,2] In this chapter the author wishes to draw attention to the fundamental principles used in his designs and refer to more recent structures. Experience shows that all the structures built so far have proved to be eminently suitable for projects involving medium and large spans, mainly because of their significant economy in material consumption, satisfying architectural appearance and also due to their effective fabrication and easy erection.

A considerable amount of practical experience has been obtained on a series of realisations over the last few years and significant progress has been achieved in improving the design and construction of such systems. Two references given at the end of this chapter contain detailed information about the previously constructed lamella barrel vaults designed by the author, and the following pages contain details of recently built barrel vaults emphasising some new aspects experienced in their design. The progress achieved shows that these structural systems can satisfy many of the requirements of modern design.

3 SOME REMARKS ON THE COMPOSITION OF THE STRUCTURAL SYSTEM

3.1 The System as a Whole

The design of main arched ribs in the diagonal form rather than the supposedly simpler system of parallel arches may seem, at first sight, to be more complicated, especially during the fabrication of structural steelwork, than the more conventional systems. However, practical experience gained during the construction of numerous structures of this type has shown that the mass production of identical or similar main lamella elements for the spatial arrangement used in this design did not present any special difficulties in the workshop. On the contrary, the prefabrication showed that it had many advantages, especially as the interconnection of assembled units lead to a very uniform stress distribution in the resulting structure (Fig. 17.1).

The resulting great rigidity of these small prefabricated units, slender in themselves, but extremely stiff when interconnected into a three-dimensional framework, can be

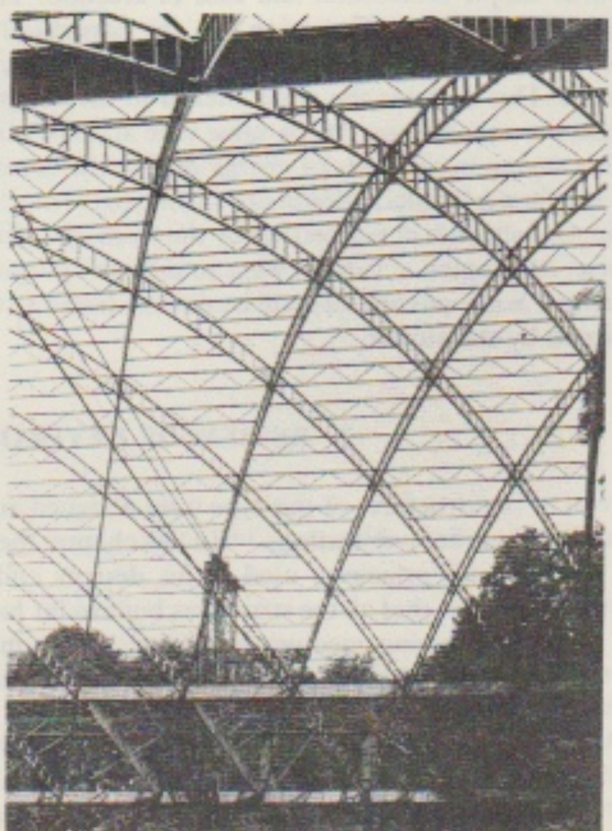

Fig. 17.1. Structural system of braced lamella barrel vault.

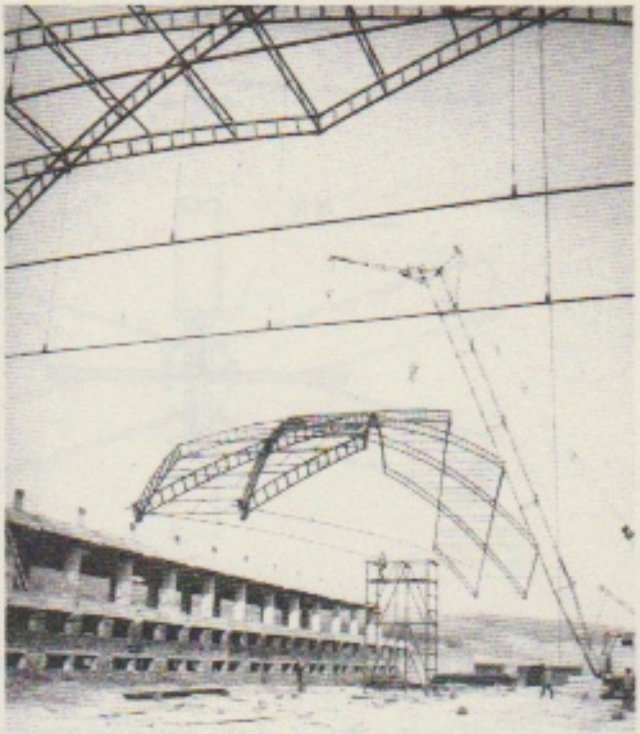

Fig. 17.2. The erection of a hall in Poprad from assembled large component parts—the span is 45 m.

appreciated during the erection. The spatial interconnection of these modular units leads to a substantial advantage expressed in reduced structural weight (Fig. 17.2).

3.2 The Jointing Details

The development of a simple joint in which six structural elements are connected together in one point represents the main reason for the success of the system (Figs. 17.3 and 17.4).

A direct contact, where the main elements run into a continuous fashion through the joint and carry their compressive forces by bearing, is fundamental in achieving simple erection and providing a satisfactory structural solution. At the same time, the connection of six components in a single joint is obtained with a minimum number of bolts. In certain cases this connection could be made by means of one bolt only.

Asymmetrical loads acting on cylindrical roofs could lead to bending moments and subsequently to tension forces occurring at the joints. In such a case the use of high-tensile bolts and the introduction of pre-stressing of the contact surfaces will take care of this situation. This is also why the thickness of the structural material in the contact areas must not be too small, in order to avoid deformations and greater elasticity of the whole connection.

It is obvious that such joints are not only suitable for easy erection, but also that they are equally simple when dismantled. Thus the whole structure could be moved to another place and re-erected there, if necessary, without undue difficulties.

3.3 The Structural Composition, Size of the Basic Module of the System and Dimensions of the Modular Units

The choice of the size of the cross and longitudinal modules of this system, as well as the size of the main basic elements, lies generally in the hands of the designer. A skilled

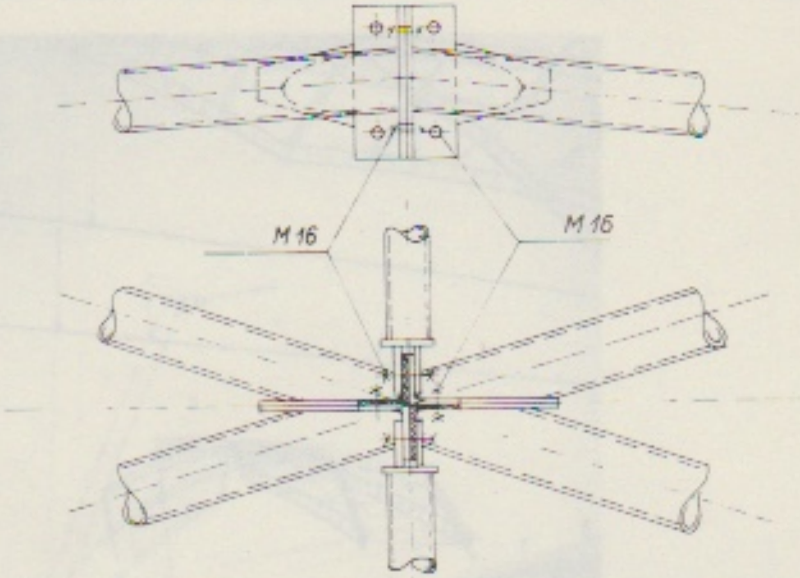

Fig. 17.3. The plan and elevation of a typical 'cross' joint for a single-layer lamella structure. 4 main elements and 2 secondary lateral units are interconnected at the joint.

designer can succeed in the choice of the optimum proportions for each relevant span (Fig. 17.5).

Generally, the longitudinal module, i.e. the cross distance of the arched ribs, depends on the distance of the supports; on the other hand the cross module is dependent on the span *and* the number of lamella subdivisions projected over the whole span. This choice will also influence the geometry of the 'cross joints'.

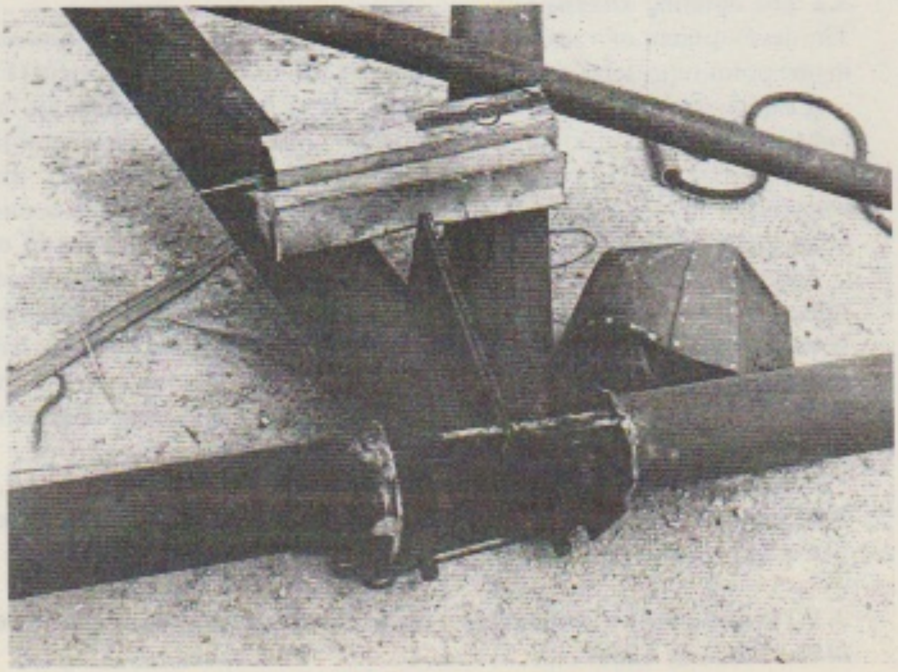

Fig. 17.4. A view of a joint during the erection.

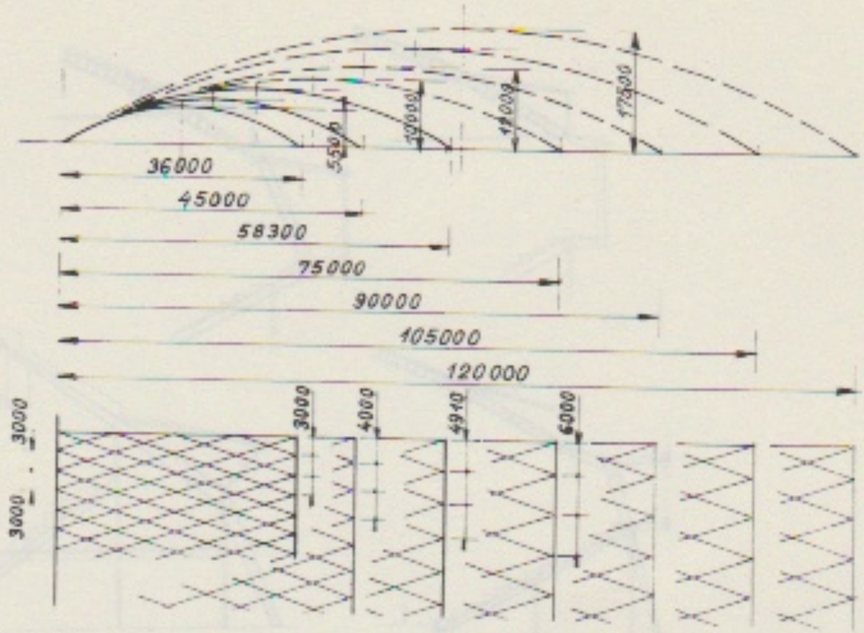

Fig. 17.5. Structural arrangements of lamella barrel vaults for different spans.

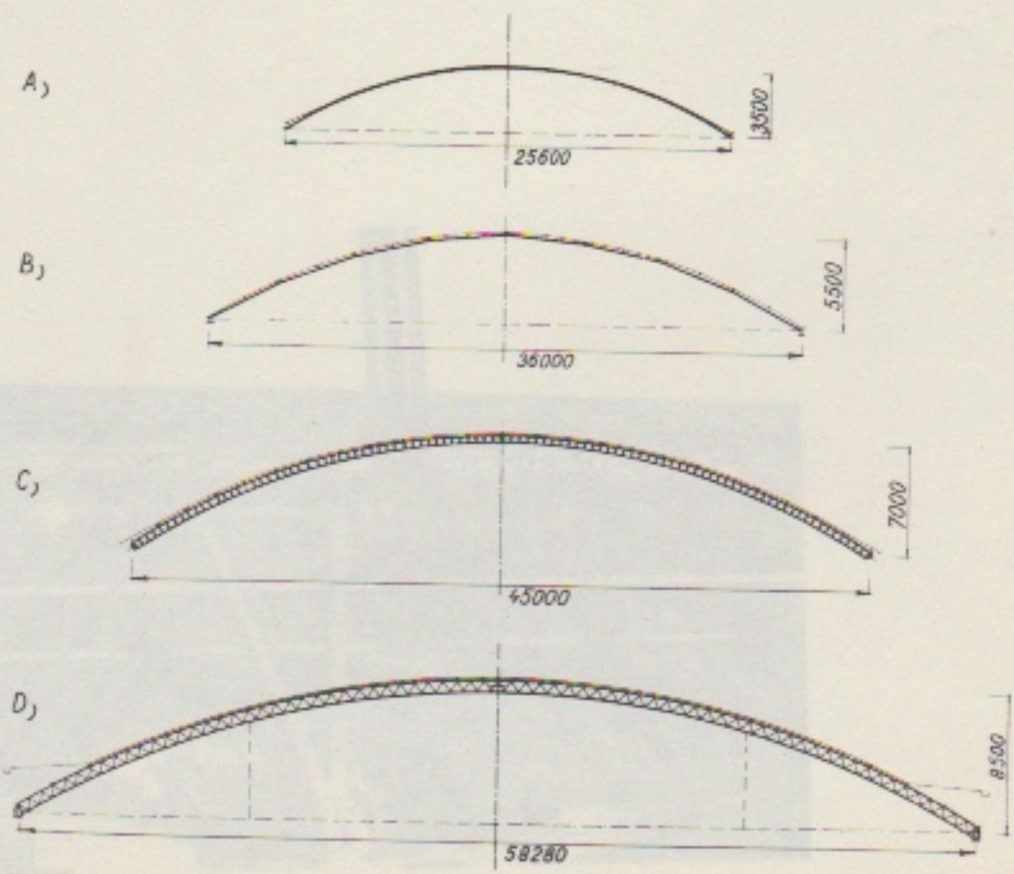

Fig. 17.6. Cross-sections for typical 'single-' and 'double-layer' lamella barrel vaults.

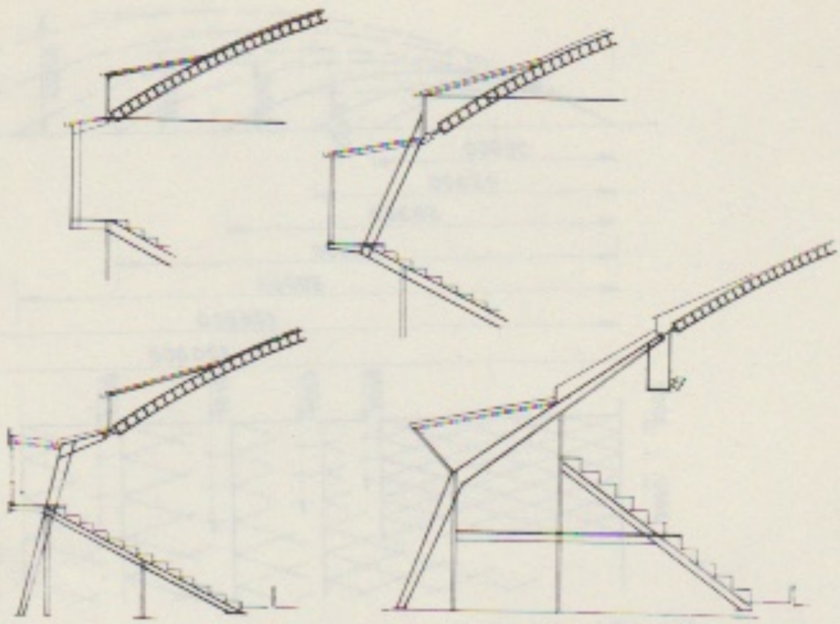

Fig. 17.7. Different solutions for the supporting structure of the lamella barrel vaults.

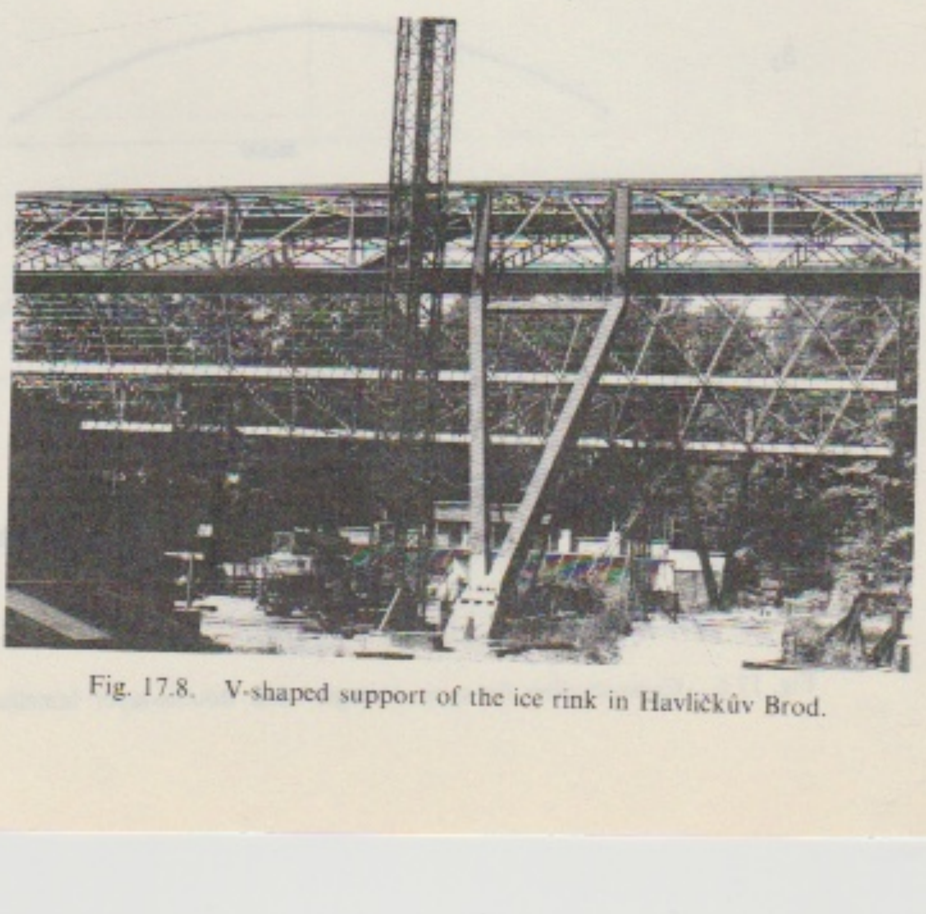

Fig. 17.8. V-shaped support of the ice rink in Havlíčkův Brod.

The magnitude of the span also affects the detailed solution of the basic lamella elements. For spans up to 36 m, it is possible to design the lamella as a simple bar and then to design the whole barrel vault as a 'single-layer' slender shell which works mainly in tension and compression without bending moments (Fig. 17.6). For spans exceeding the previously mentioned limit, the lamella vaults have to be designed as 'double-layer' lamella grids, which behave as two-hinged arches taking into account the additional stiffness due to their three-dimensional interaction.

The form of the basic elements can be either straight or curved— bow-shaped, following directly the curvature of the barrel vault. Such a continuous curvature, though it may be more appropriate for architectural reasons, brings, however, a slight complication in the fabrication, as an element with curved chords requires more time during production. However, due to the modular nature of the basic elements and the possibility of their mass production, the complication produced by the introduction of curvature affects only very slightly the final economy in fabrication.

3.4 The Supporting Systems of Barrel Vaults

The designer has some freedom in choosing the correct arrangement of the supports, not only taking into account the structural factors, but also the architectural aspects of the whole design, and hence influencing the external appearance of the building (Fig. 17.7).

It is possible, for example, to design the supports of the roof in different materials and in various ways. The structural function can be influenced by adding ties. Sometimes it is possible to obtain a special solution with the minimum number of supports, adjusting the main support system, as has been achieved in the construction of the barrel vault covering the ice rink in Havlíčkův Brod, as illustrated in Fig. 17.8 and in Fig. 17.20.

3.5 The Modification of the Overall Shape of Vaults Through the Introduction of Hipped Ends

The cylindrical form is generally of particular interest to architects, because of its characteristic contour. However, it does not always provide the best architectural solution and its use depends on circumstances and environment. In most typical cases a braced barrel vault is closed at both ends by vertical gable walls (Fig. 17.9).

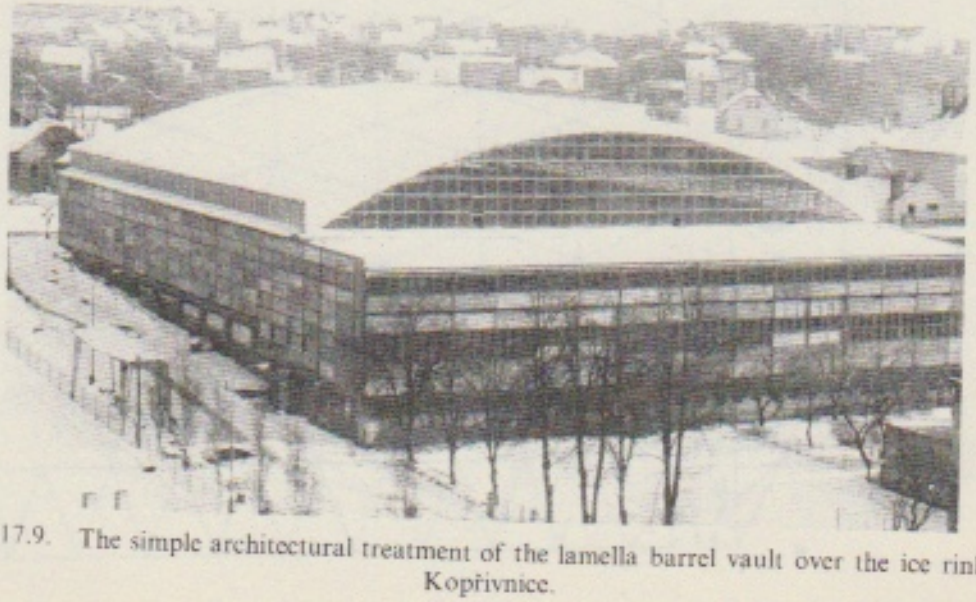

Fig. 17.9. The simple architectural treatment of the lamella barrel vault over the ice rink in Kopřivnice.

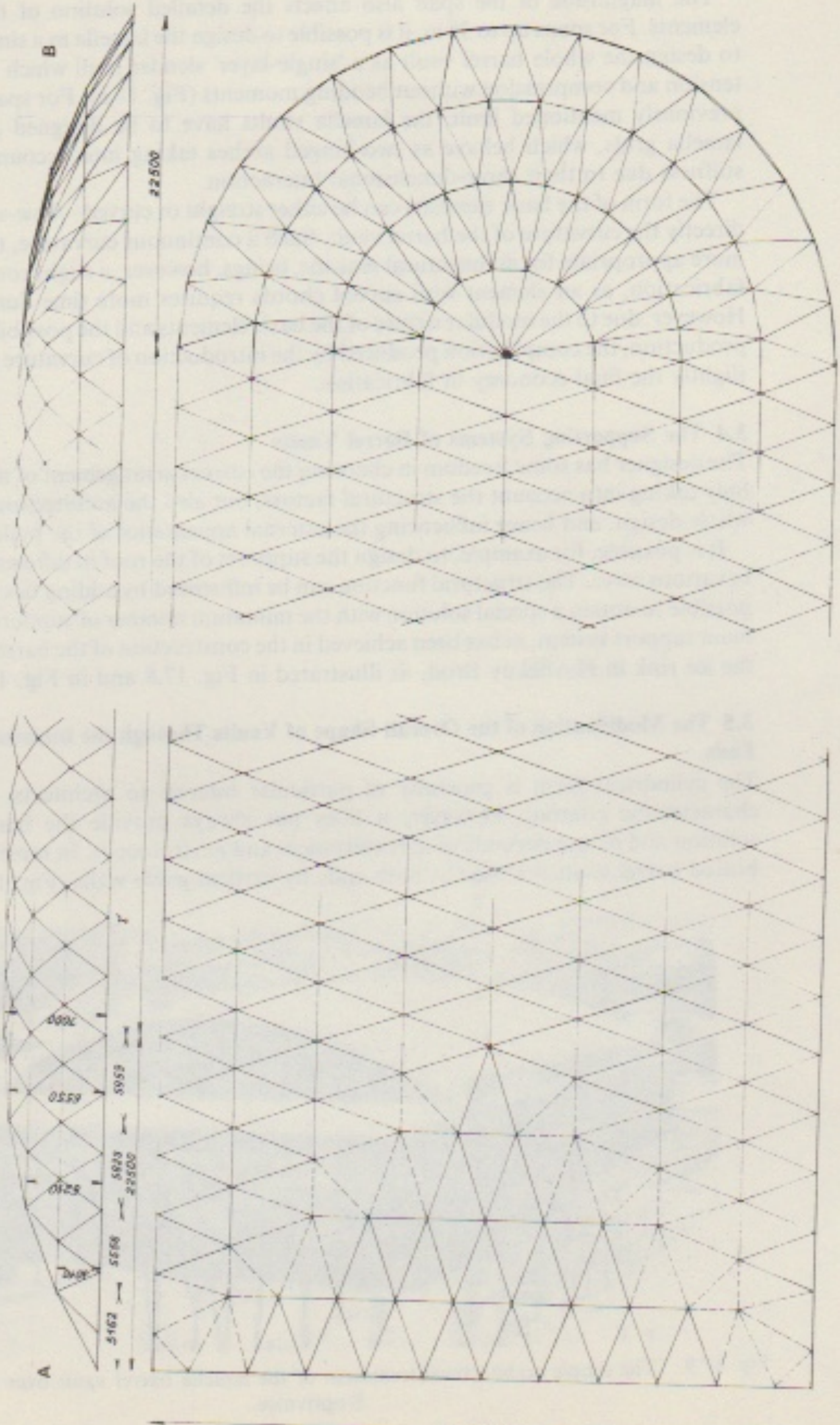

Fig. 17.10. Plans of two possible variants for the end parts in a hipped barrel vault.

In certain cases the designer can modify the support conditions and, by adjusting the shape of the ends, help the architect. The usual approach is by the introduction of inclined hipped ends as illustrated in Figs. 17.10(A) and 17.10(B). It should be noted that, although the modification of the end walls may complicate slightly the geometry, as a rule it does not complicate too much the production or the mass fabrication of the required elements. It should be added that often the introduction of hipped ends will reduce the maximum stresses in the barrel vault, leading to a more uniform stress distribution.

4 MATERIALS ECONOMY OF THE LAMELLA VAULTS

The previous notes dealt with the most characteristic features of lamella braced barrel vaults, with some remarks added on their development and practical experience gained during their construction. To end this part it would be useful and instructive to report here some data obtained through practical experience concerning the economy and steel consumption of these structural systems. The actual figures quoted later in this paper are based on structures designed and built by the author within the last few years.

In general, it can be stated on the basis of a large number of actual realisations that for lamella braced barrel vaults designed for medium and large spans, the unit steel consumption for enclosures with light roof covering is from 20 to 25 kg/m^2 of covered ground plan.

This fact illustrates clearly the extremely efficient material economy for structures of this type. At the same time, we can add the indisputable advantages of their possibilities in the mass production of modular elements, the easy handling of space saving stocks, easy transport conditions of lightweight elements and, last but not least, the exceptionally simple erection (or dismantling when necessary). All this allows us to speak of a really impressive final economy. This surely should be brought to the attention of the building industry and engineers involved in the design of similar constructional projects, especially now when the maximum economy of material and saving of energy receive the utmost priority.

5 DESCRIPTION OF SOME REALISATIONS

It is possible to divide the realised structures into two groups according to the size of their clear spans.

(i) Lamella barrel vaults constructed as a 'single-layer' system, for spans between 20 and 36 m, as a rule as cylindrical shells (Fig. 17.11).
(ii) Lamella barrel vaults as 'double-layer' systems, for greater spans, working usually as two hinged interconnected space arches (Fig. 17.12).

Details of some of the formerly constructed structures of these types have already been published. Good results and experience gained with the previous realisations evoked an interest in the further use of lamella vaults for other structures. This resulted in the construction of similar structures during recent years, often of almost identical shape, though some projects involved further development of the original ideas. Some new applications will be demonstrated in the following pages.

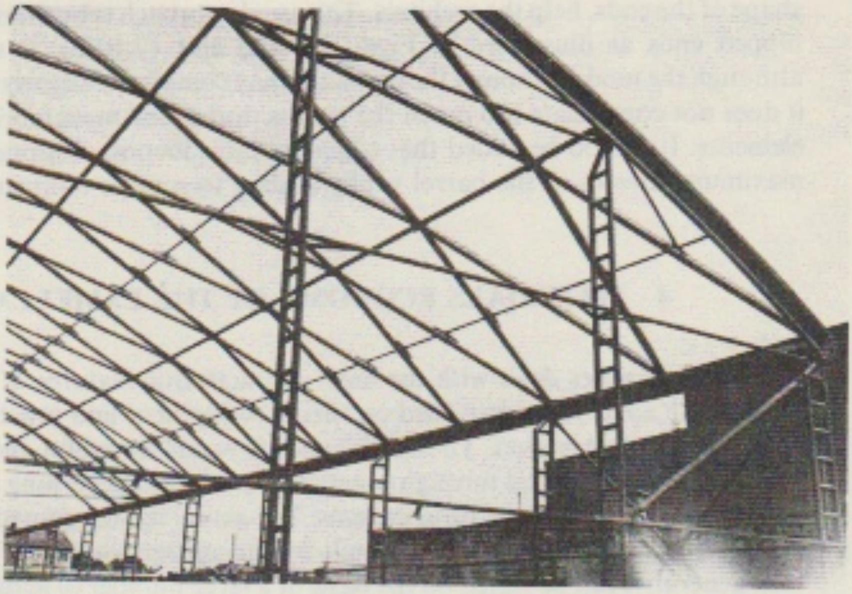

Fig. 17.11. A typical example of a slender single-layer lamella barrel vault.

5.1 Triangulated shells

A great deal of practical experience has been gained with this extremely slender type of steel shell through the erection of two halls, each with spans of 36 m, in Berlin (Fig. 17.13) and in Ostrava (Figs. 17.14(A) and (B)). The unit steel consumption is as follows:

Shell 36 m span in Ostrava, covering an area of 72 m × 36 m = 2600 m^2.
Lamella roof, 45 000 kg, 17·49 kg/m^2.
The steel in the whole structure including the supporting columns weighs 69 560 kg; hence total unit steel consumption is 26·75 kg/m^2.

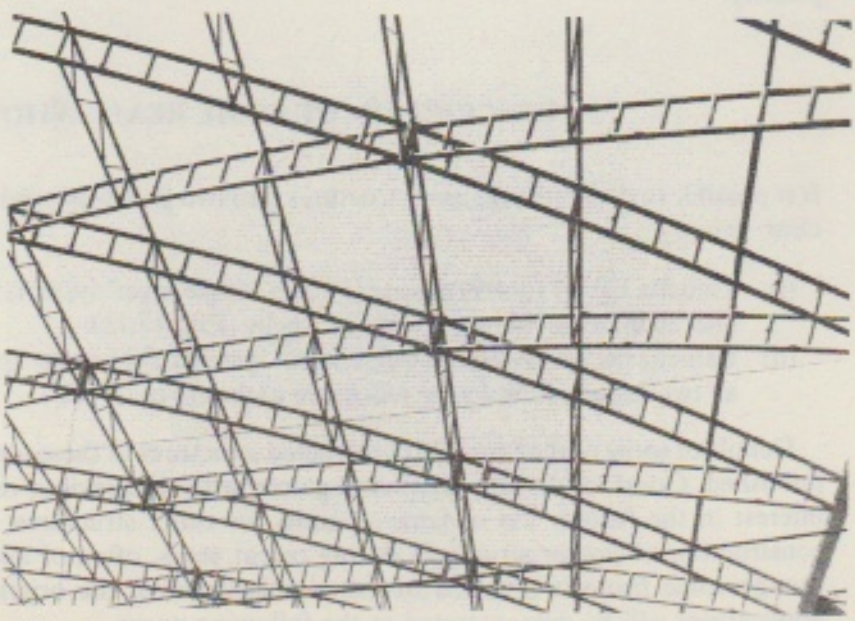

Fig. 17.12. The internal view of the interconnected mass produced modular lamella units in the structure over the ice rink Žďár nad Sázavou. An example of a double-layer system.

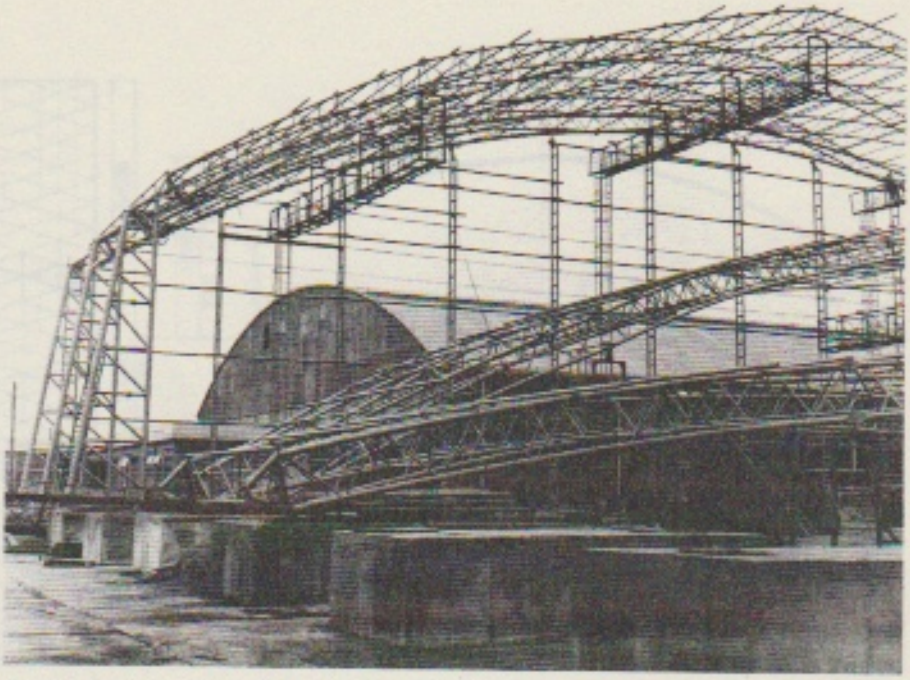

Fig. 17.13. Lamella latticed barrel vault for greater spans (the Berlin ice stadium).

Shell 36 m span in Berlin, covering an area of 127 m × 36 m = 4 560 m^2.

Roof weighs	95 960 kg	21·05 kg/m^2.
Walls	50 411 kg	11·05 kg/m^2.
	146 371 kg	

Hence total unit steel consumption is 32·10 kg/m^2.

The same type of structure has been projected for the ice rink in Popovice, near Prague, with an area of 2 500 m^2; with total steel consumption of 52 710 kg for the roof structure, the unit steel consumption would be 21·08 kg/m^2 of the ground area. Unfortunately, this object was finally realised in a slightly modified type of structural framework.

For structures of such spans the main lamella elements are very simple and slender. In the case of a cross module of 3 m, the lamella is represented by a simple circular tube having a cross-section of 128·4 mm and 5 m length.

The whole erected structure over the span of 36 m is, of course, extremely slender and elastic.

The erection of such slender elements in space appears to be one of the greatest problems. The assembly of these so extraordinarily elastic units into their final three-dimensional rigid framework requires some attention.

The actual realisation of the above-mentioned two halls proved that such erections are possible and real, although in each case the erection proceeded in a slightly different way.

During the assembly, maximum care should be exercised in order to avoid introducing residual stresses into the erected structure.

The erection procedure is important; otherwise some undesirable pre-stressing may lead to a possible reduction of the future load carrying capacity of the completed structure.

A mass production of a similar lightweight lamella shell suitable for spans of about

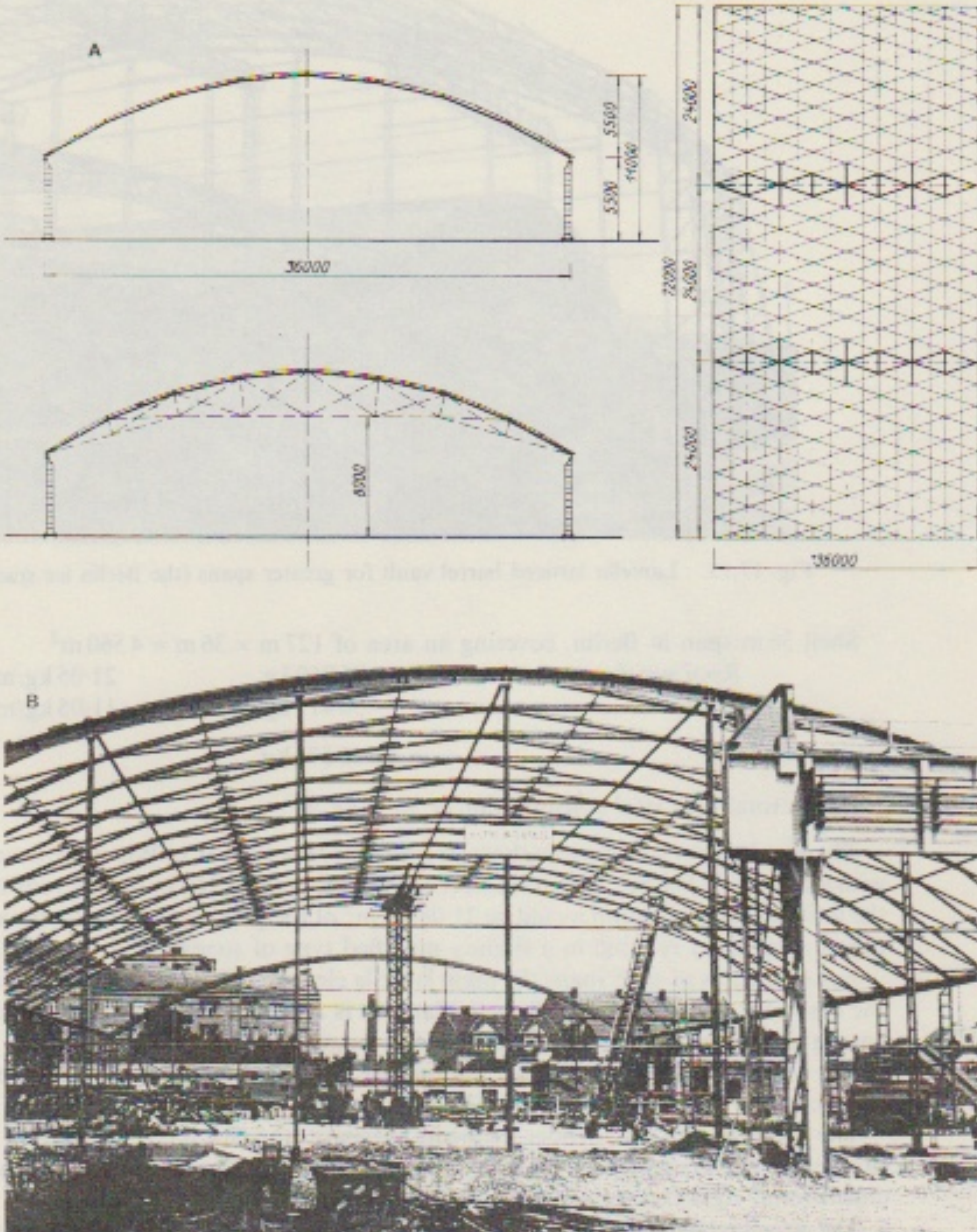

Fig. 17.14. (a) Plan and elevation of the lamella barrel vault in Ostrava. (b) View of the Ostrava barrel vault during erection.

Fig. 17.15. The experimental prototype barrel vault erected for testing in Ondara, Spain.

30 m has been carried out by the Spanish firm of Caselles from Valencia. This small manufacturing firm of steel structures, in close collaboration with the Czechoslovakian design office, decided to produce first a prototype shell having a span of 30 m and a length of 20 m in scale 1:1 and to test the structure in their workshop to the full designed load. The supervision of the test was done by a competent and authorised institute in Madrid before issuing a certificate allowing the intended mass production. The fabrication, erection and controlled load test of this experimental shell structure provided a good opportunity to obtain a detailed picture of the behaviour of such a slender structure under closely controlled conditions.

For an area of 600 m^2 covered by the shell having a span of 30 m and a length of 20 m the steel consumption was

For the roof	4300 kg	7·17 kg/m^2
For gable walls and columns	3200 kg	5·33 kg/m^2
Hence in total	7500 kg	or 12·50 kg/m^2

After the successful completion of tests on the prototype (Figs. 17.15 and 17.16), the firm Caselles in Valencia and Ondara is producing nowadays in Spain these structures in a mass series for Spanish industry and agriculture.

5.2 'Two-layer' Lamella Barrel Vaults Consisting of Latticed Elements

This form proved to be especially popular and frequently used in practice during the last few years. It has been used mostly for the roofs of sports halls and ice rinks, mainly for spans of 45 m. The first realisation of this type was over the ice rink in Kopřivnice (span 45 m with ties, covered area of the roof 2700 m^2, total area of the building 3940 m^2, steel for the roof 56 800 kg, i.e. 21·00 kg/m^2, total amount of steel including the supporting structure 109 000 kg, hence the unit steel consumption 27·65 kg/m^2) (see Fig. 17.9).

The second equally interesting application has taken place at Popgrad (main span 45 m, extended to 70·60 m by means of slender steel cantilevers, area of the main roof

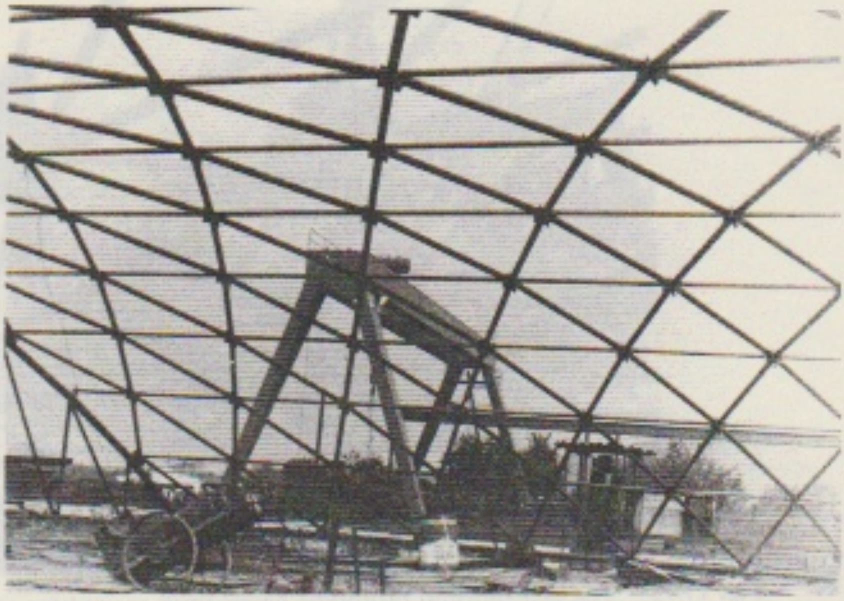

Fig. 17.16. Another view of the experimental barrel vault.

3980 m^2, total area of the whole structure 6248 m^2, steel for the roof 78 880 kg, i.e. 19·59 kg/m^2, total steel for the whole building 217 000 kg or 34·83 kg/m^2) (see Fig. 17.17).

Several other projects followed and the realisation of this type for ice stadiums in Uherský Brod, Uničov should receive special attention. There is a similar project now in preparation for Orlova.

All these structures have a special solution of their supports. The vaults are lying on the oblique cantilevers which at their upper ends are connected by means of ties, thus reducing the horizontal thrust from the vaults.

There are also barrel vaults without ties constructed recently for the halls in Kroměříž, Žďár nad Sázavou (area 3240 m^2, the weight of the steel roof structure is 75 374 kg or

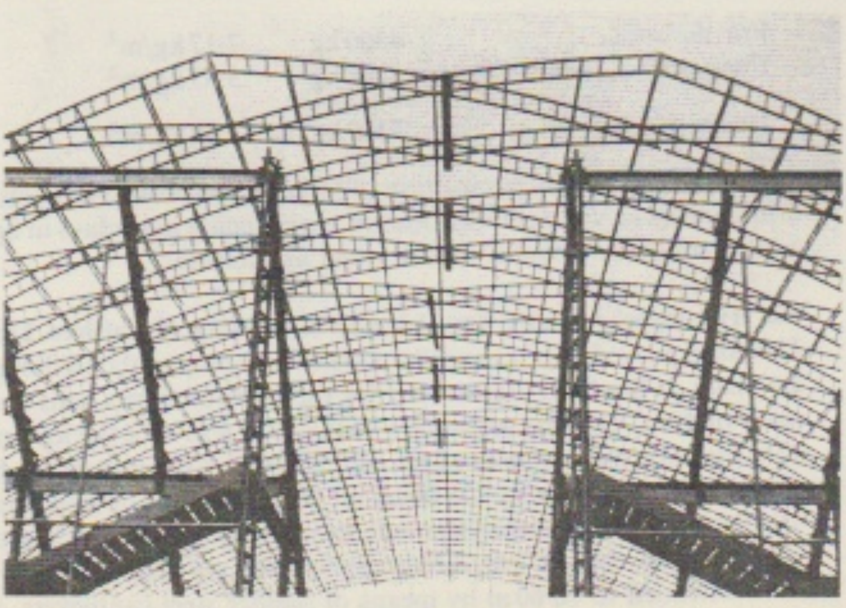

Fig. 17.17. The ice rink barrel vault at Poprad, during construction.

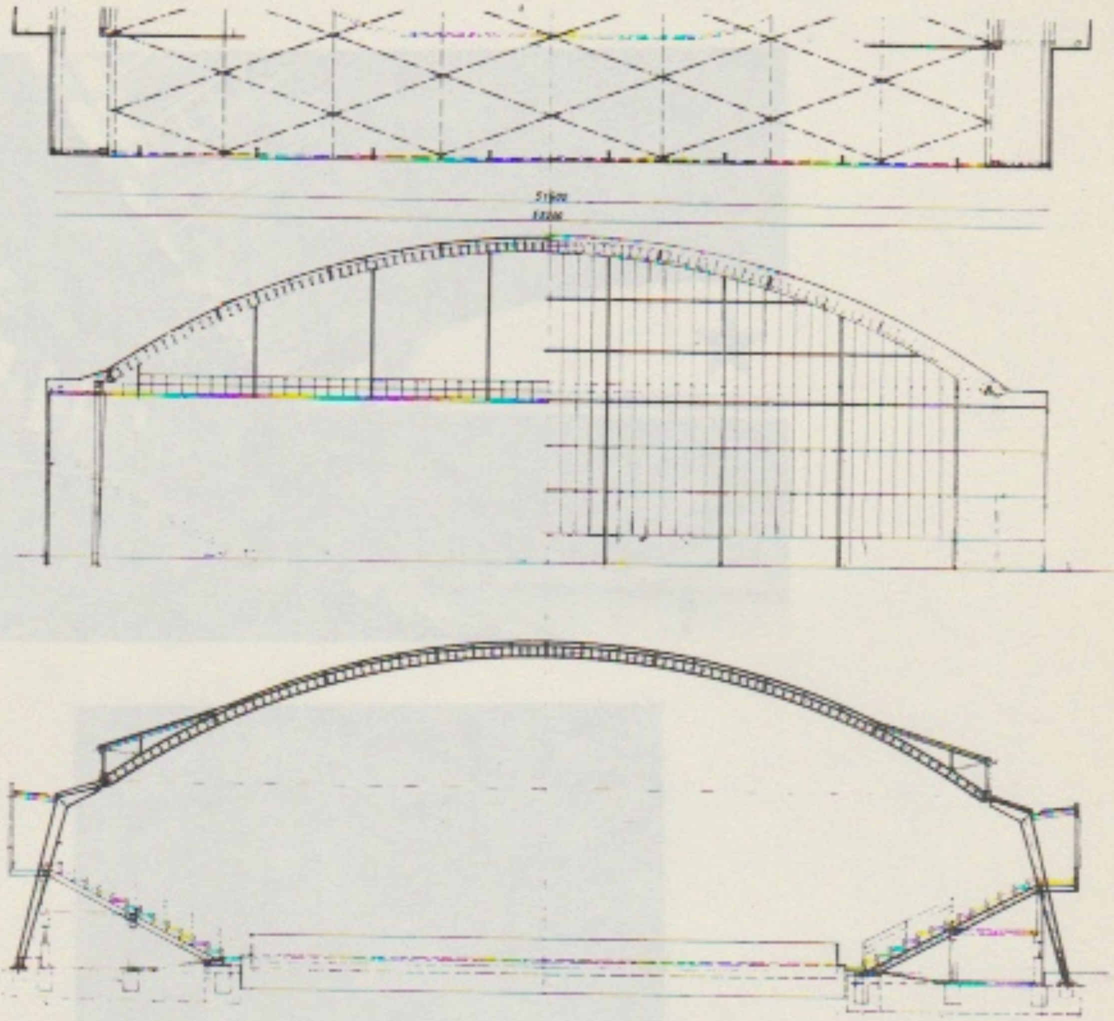

Fig. 17.18. Plan, elevation and cross-section of the double-layer lamella barrel vault in Kroměříž.

23·26 kg/m^2) (Fig. 17.18). The type of bracing used in these structures has been illustrated already in Fig. 17.12. In these cases the main structural framework is covered with a wooden roofing, which gives an extremely pleasant internal appearance of the halls. This is shown in Figs 17.19(a) and 17.19(b).

The ice stadium in Havlíčkův Brod (illustrated in Figs. 17.20 and 17.21) presents a further modification of the supporting system, different from that used in previous cases. In this structure the axis of the main vault, with a length of 56 m, is orientated in the cross direction to the ice rink area having the dimensions 60 m × 30 m. Here the vault is supported only at four points, by means of oblique stanchions in the form of a 'V'. The whole span of the main bearing vault is enlarged by means of these oblique supports to 58 m.

Supporting such a large vault at only four points, 36 m apart, required the longitudinal side parts of the main lamella vault to be reinforced. The most stressed latticed lamella units have been strengthened by means of the plate girder filler introduced between the chords. A project now receiving the attention of the author deals with the design of a lamella barrel vault having a length of 100 m, with ties arranged 5·0 m apart and resting on a

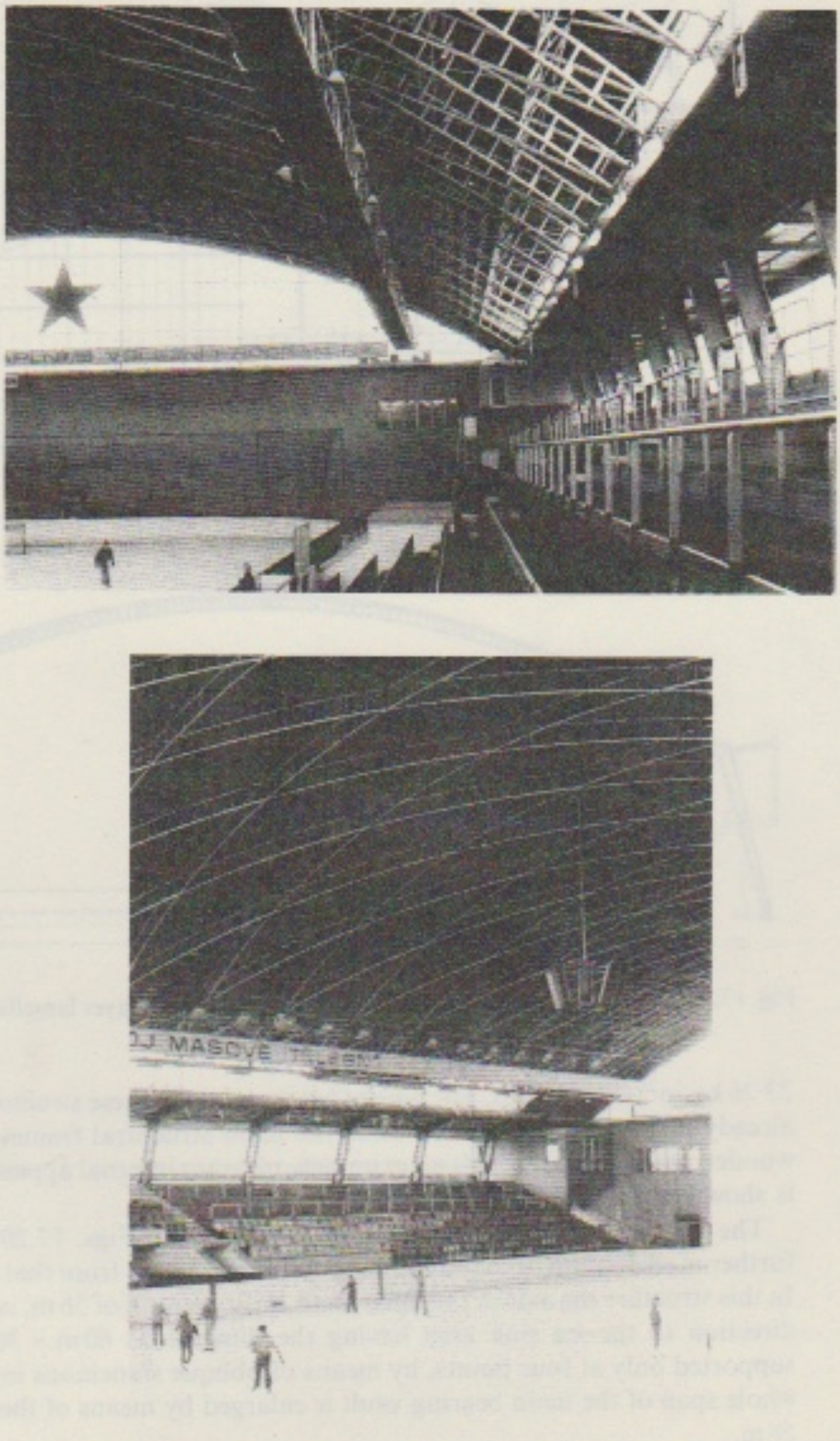

Fig. 17.19. Internal views of the ice rink in Žďár nad Sázavou.

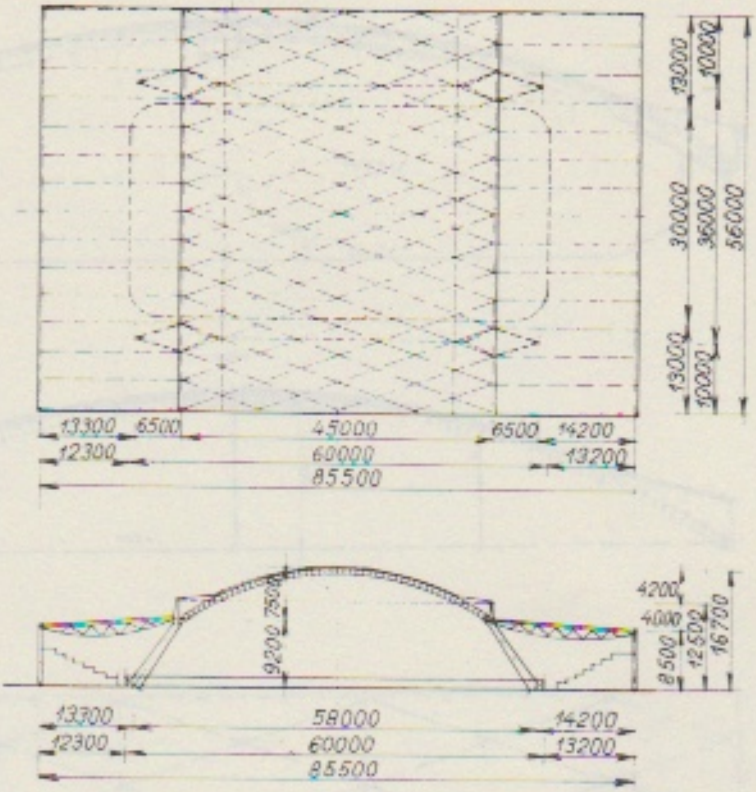

Fig. 17.20. Plan and cross-section of the barrel vault for an ice rink in Havlíčkův Brod.

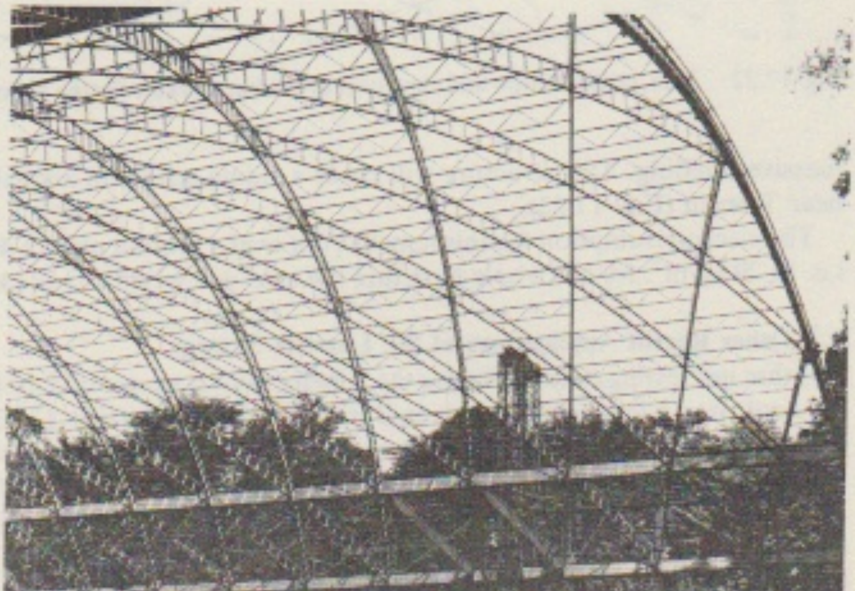

Fig. 17.21. The erection of the barrel vault in Havlíčkův Brod.

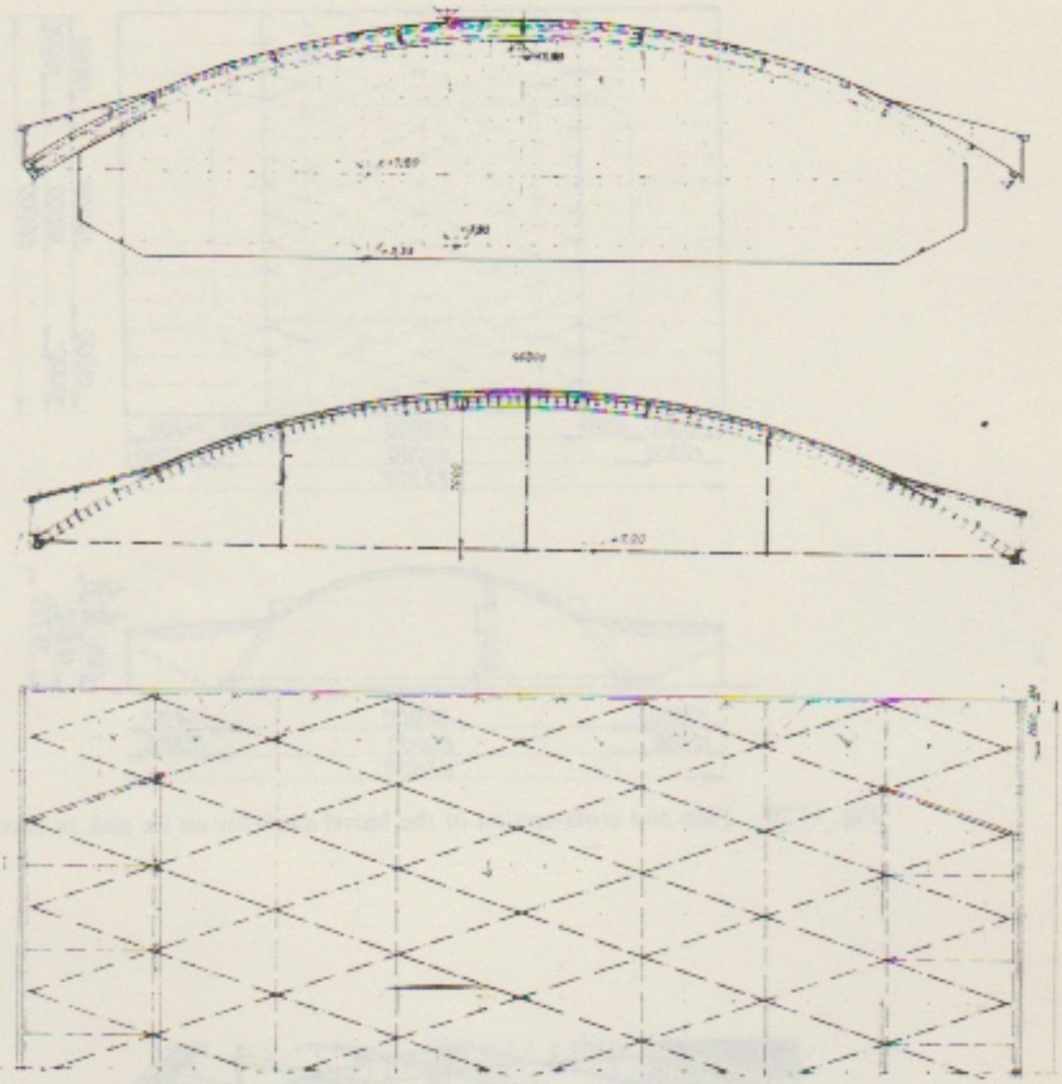

Fig. 17.22. Plan, cross-section and elevation of the barrel vault for the riding school in Motěšice.

massive building. This structure will cover a riding school in a small village, Motěšice, near Trenčin (Fig. 17.22).

The steel consumption for this lamella roof over a ground plan of 4650 m^2 is 84 978 kg, i.e. 18·29 kg/m^2, for the whole structure the steel will weigh 133 721 kg, i.e. 28·78 kg/m^2.

5.3 Other Recent Applications of the Lamella System

Another interesting example where the lamella vault system could usefully be applied was the roof over a large span sports hall in Valencia, Spain (Fig. 17.23).

In this case, the lightweight steel lamella barrel vault has a span of 43·20 m and covers, like a great hat, the central part of the roof over a large sports hall.

The remaining surrounding periphery of the whole structure of oval shape is formed by the massive concrete cantilevers covering the tribunes for spectators. The central part of this structure is in steel, and has a total length of 79·45 m with its ends spatially formed in the shape of two hemi-domes.

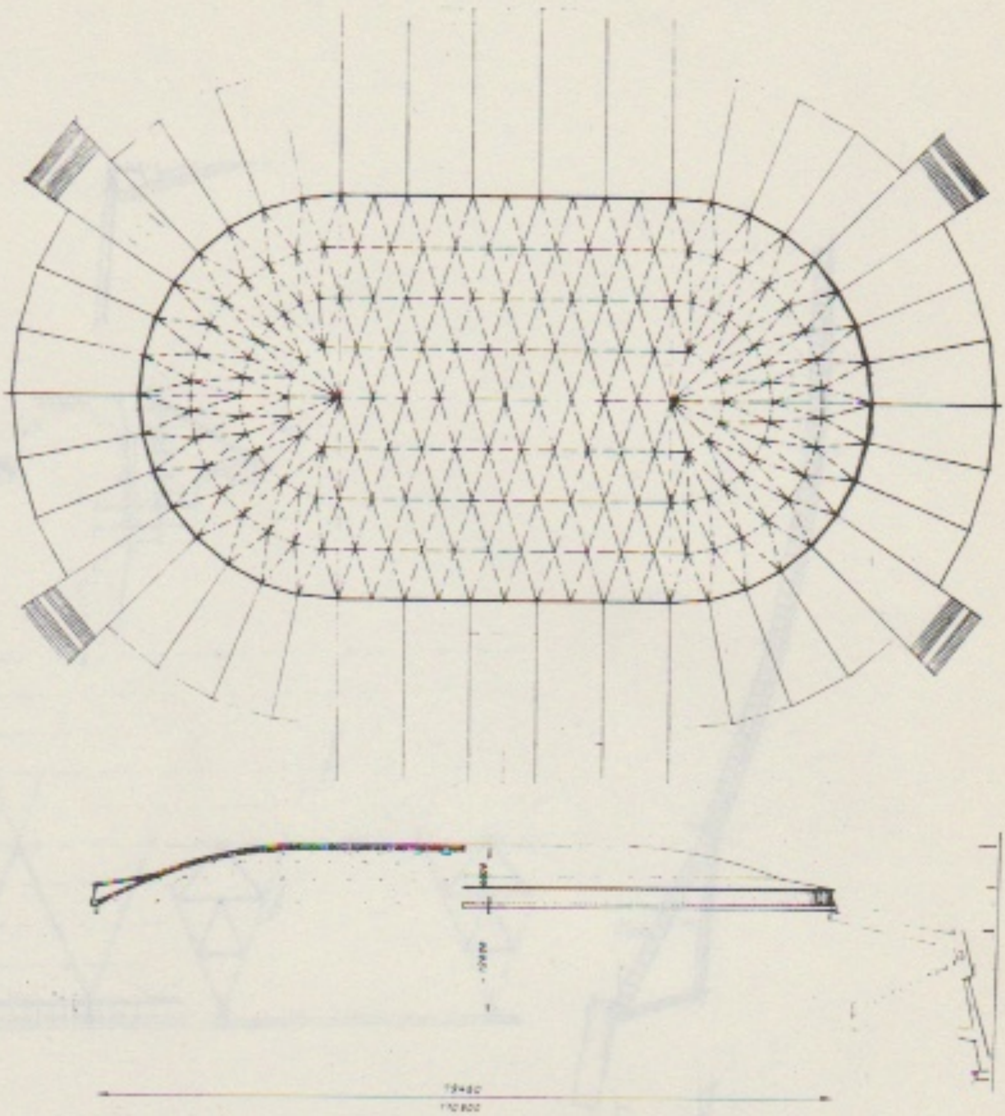

Fig. 17.23. Plan of the barrel vault erected over the sports hall in Valencia, Spain.

The lamella steel space structure lies along its whole periphery on massive concrete framed cantilevers, spaced 7·25 m apart. Figure 17.24 provides details of the supports used for this structure.

Over its supports the lamella roof is glazed by a horizontal strip of windows that follows the inner oval ground form plan of the surrounding massive concrete roof parts. This shape forced the design of the barrel vault to close both its ends by semi-domical structures. These two parts consist of lamella units, similar to those used for the central cylindrical part of the lamella vault, though their dimensions vary, whereas the main structure is formed by members of identical length.

It is possible to provide many other examples. Some of them are under active considerations for even bigger spans than those already achieved in practical applications (Figs. 17.25 and 17.26). These studies and projects of application of lamella-type roofs are for large span structures, such as sports halls, football stadiums, halls over gymnasia, cycling and speed-skating.

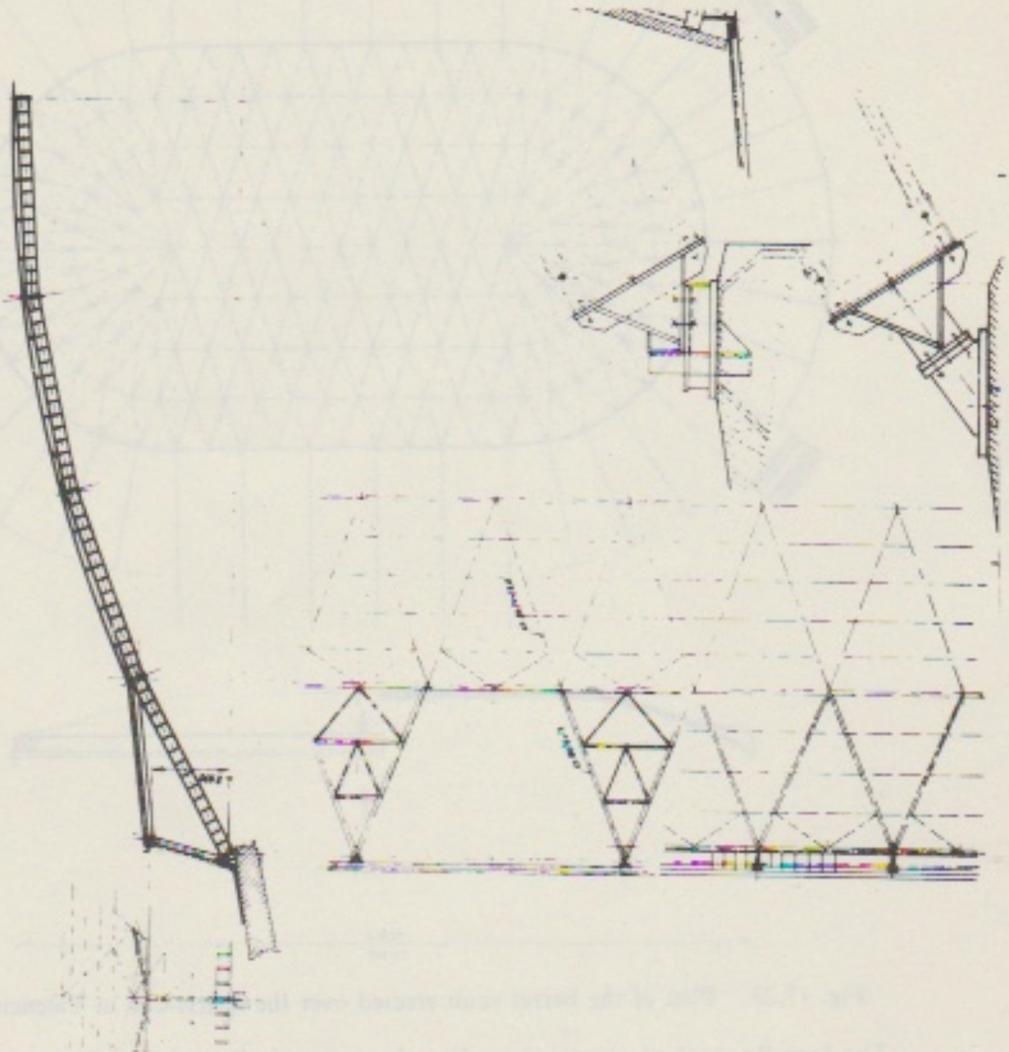

Fig. 17.24. The details of supports used for the Valencia Hall.

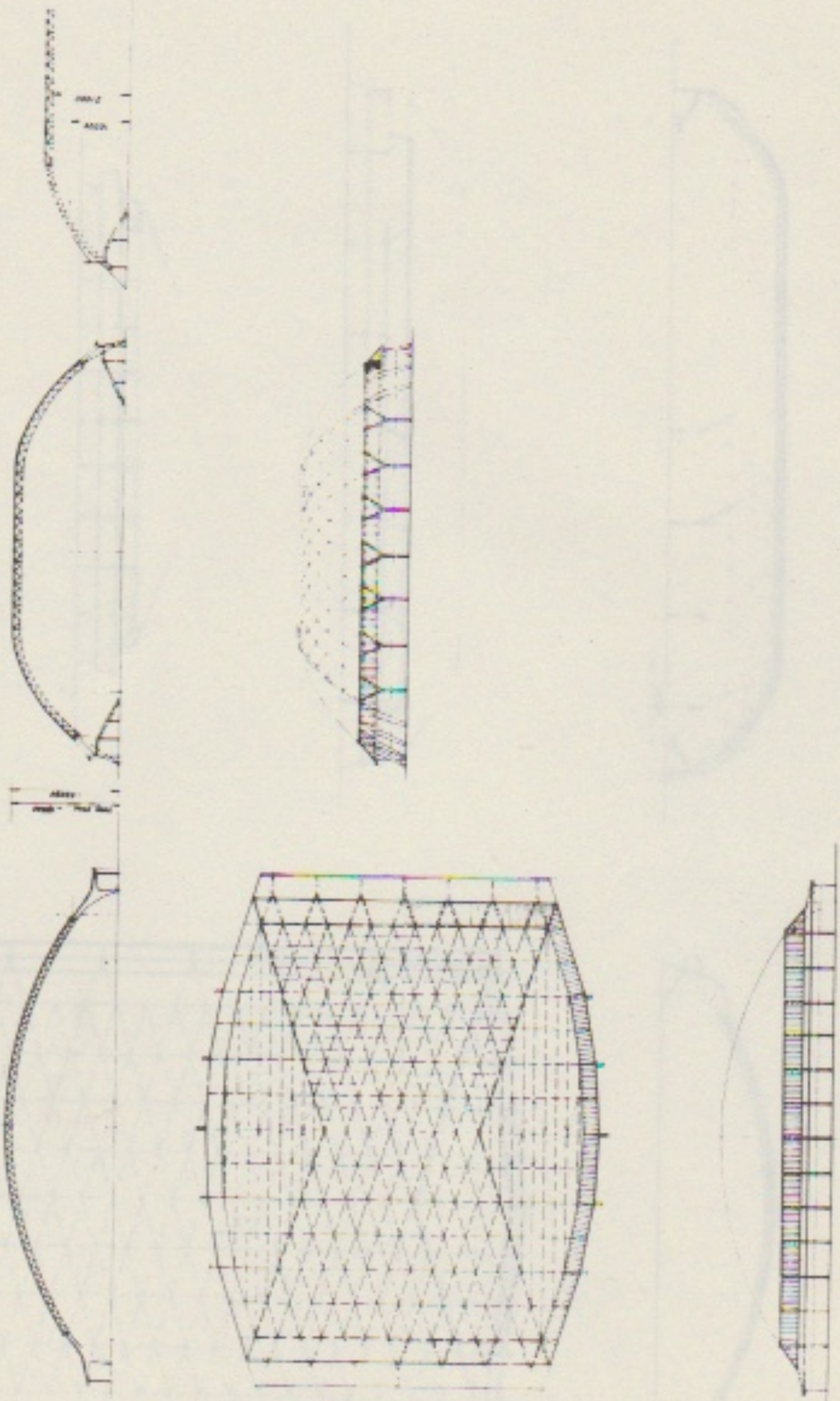

Fig. 17.25. Examples of projects now under active consideration for large span braced barrel vaults.

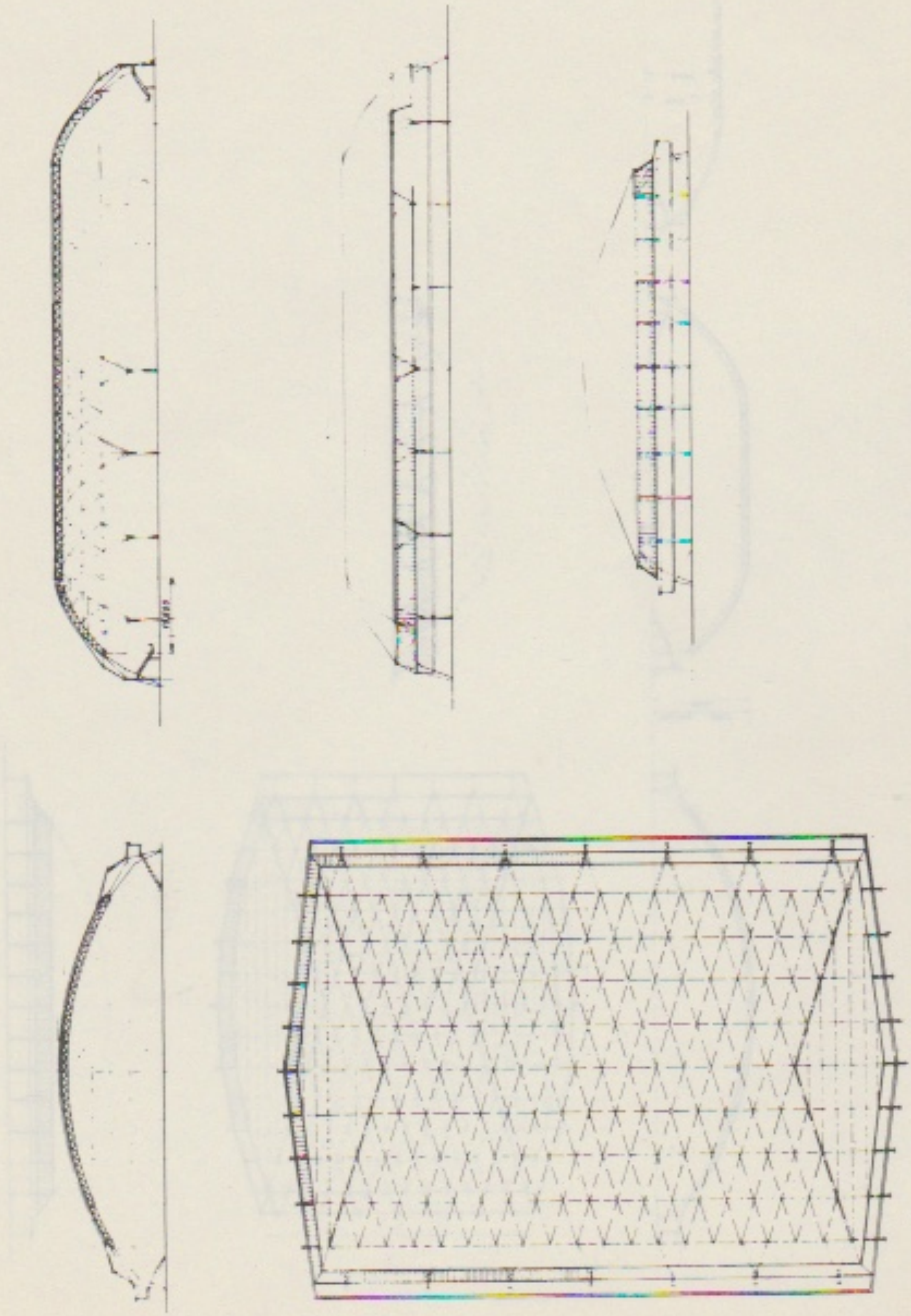

Fig. 17.26. A project for a lamella barrel vault for a sports hall of 98 m span.

The enclosed line drawings and photographs give some ideas and demonstrate the structural and architectural potential of such systems. The calculations proved that even for those large span lamella barrel vault structures the steel consumption lies between 25 and 35 kg/m^2 of the ground plan area. This, surely, can be declared to be very satisfactory.

REFERENCES

1. Zeman, J. Zwei neue Sporthallen in der CSSR. *Stahlbau*, **8**, 1973, pp. 252–254.
2. Zeman, J. A system for constructing light-weight roofs for various spans. *Acier-Stahl-Steel*, **6**, 1973, pp. 270–281.