JAN WURM

GLASS STRUCTURES

DESIGN AND CONSTRUCTION OF SELF-SUPPORTING SKINS

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Jan Wurm works for Arup Materials and Arup Facade Engineering in London as an architect, designer, and project manager.

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FOREWORD

The use of glass as a structural component first came to prominence in the early 1990s, when the developments in engineering practice were documented by key publications: in addition to Rice and Dutton, whose book *Le Verre structurel* (Paris, 1990) set out the first engineering explanation of bolted structural glass as practiced by Rice Francis Ritchie, the glass industry began to demystify the role of glass in building through the publication of *Glass in Building* by David Button and Brian Pye (Oxford/Boston, 1993). Michael Wigginton's *Glass in Architecture* (London, 1996), finally, offered a comprehensive overview of the technology and significance of glass in contemporary architecture.

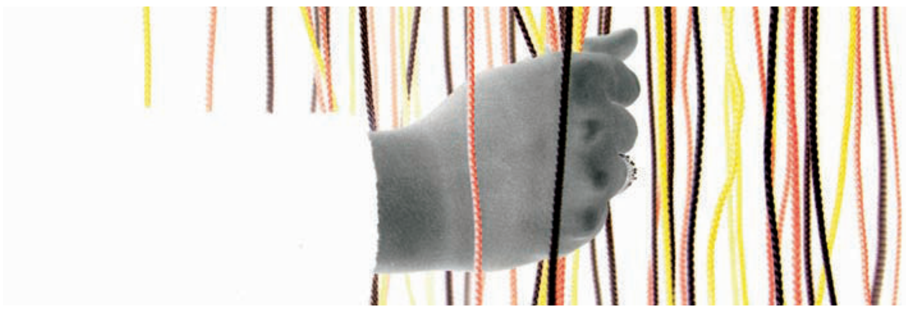
These seminal works were followed by numerous studies and publications containing detailed analyses of construction in the expanding field of structural glass construction. At the same time, a small but growing band of architects and engineers energetically developed new techniques, based on the accumulated experience, in response to the demands of their diverse projects.

When Jan Wurm joined our glass team in London he was about to present his PhD thesis, and his research struck me as clarifying a train of development beginning long before the recent period of activity and indicating numerous exciting potential routes following the present change in the direction of glass architecture. He had designed and built with his students numerous prototypes at a range of scales up to full size, exploring the process and results of using glass in many intriguing ways, freed from the obligation to succeed in meeting a client's brief. The designs were not randomly or perversely generated to challenge conventional wisdom but followed from a logical analysis of the geometry of self-supporting skins and an appreciation of the need for stability, robustness and practicality of construction.

This book presents the research projects and a selection of work in practice, and summarises the key findings of Jan's research: that glass manufacture and processing methods produce material with a set of mechanical properties and a set of physical properties within a range of forms and sizes; the combination of designed glass elements in chosen geometry delivers structural properties; and in combination the structural and physical properties can efficiently enclose unique spaces in beneficial ways.

In addition to a thorough catalogue of the current processes and the resulting properties and sizes, he systematically classifies spanning glazed enclosures and presents a geometrical typology which extends from the defining works of the early masters through contemporary projects to illustrate the potential for rational use of the inherent and modified properties of glass in the future.

Graham Dodd, Arup, London, May 2007



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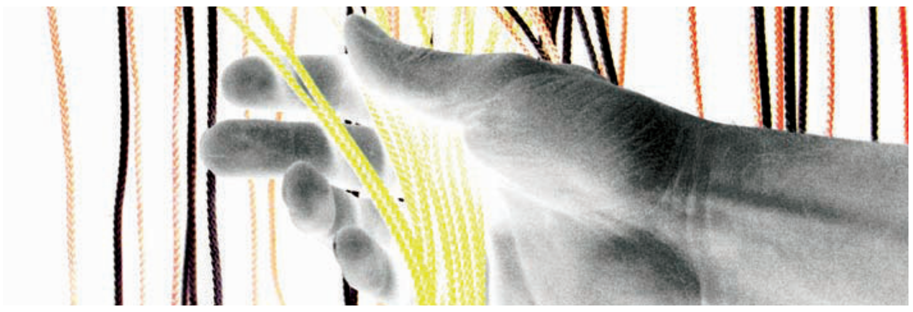

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1–3 Visualisation of changes in the professional profile of architects and engineers: the strings symbolise the decision-making processes associated with building and the colours indicate allocations to functional, structural and aesthetic questions.

1 Today, the growing complexity and technological focus in building puts the sole decision-making competency of the planner/designer as a generalist into question.

2 The inclusion of experts makes it possible to bundle decision-making within limited competencies. Integrated planning requires intense communication and coordination among the experts, to solve the building task as a synthesis of functional, structural and aesthetic challenges.

3 The development of new “creative” approaches to solutions requires that “specialised generalists” provide the overarching thematic coordination of decision-making processes. One possibility is to explore the functional, structural and aesthetic questions of the different building materials from the erspective of a “grammar of building materials”.

PREFACE AND ACKNOWLEDGMENTS

“What the structural engineer sees as a load-bearing truss is seen as a sculpture by the architect – naturally, it is both.”

– Ove Arup

Based on its geometry, its mechanical, building physical and visual qualities, every material is uniquely suited as a load-bearing component, as a building skin or design element. Within this *Grammar of Materials,* as Anette Gigon called it, no other material opens up as comprehensive a range of possibilities to the designer as flat glass, which increasingly dominates our built environment. [1]

The traditional genesis of material and architectural form, the link between constructional, functional and aesthetic aspects is today rendered more difficult in glass construction as a result of the technological complexity and the necessary specialisation of structural engineers, specialist glass designers, fire engineers, etc. In contrast to steel-, timber- and concrete construction, no specific structural forms have therefore emerged for load-bearing glass structures. [2]

This book aims to close this gap in building research by developing a methodology of design and construction for flat glass, centred on the compression-resistant flat load-bearing element – universal building skin material and a surface that is luminous in a multitude of ways – as an elemental building block for load-bearing structures across wide spans. The technical recommendations contained in the book reflect the current state of technology; it is important to stress, however, that expert planners and designers in charge of a specific project must check and, if necessary, adapt them to the established and current laws, guidelines and standards in each country. Neither the author nor the publisher can be held in any way accountable for the design, planning or execution of faulty glass structures.

I thank everyone who has guided, accompanied and supported

4 Colleagues and students who participated in the design, planning and realisation of the Tetra Glass Arch after its completion in 2000

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me through the various stages of this book. Thanks are due first and foremost to Prof. Dr. Eng. Wilfried Führer for his intensive and unfailingly positive support during my scientific training and to my guide in this field, Prof. Dr. Eng. Ulrich Knaack. I would like to thank my former colleagues Dr. Eng. Rolf Gerhardt, Dr. Eng. Katharina Leitner, Dr. Eng. Helmut Hachul, Cert. Eng. Thorsten Weimar and Cert. Eng. Jochen Dahlhausen for technical suggestions and practical assistance. I am equally grateful to Prof. Alan Brookes and Prof. Dr. Mick Eekhout for the valuable experiences during my research residency at the TU Delft in 2002 and to Prof. Dr. Phil. Andreas Beyer, Prof. Dr. rer. nat. Reinhard Conradt and Prof. Eng. Jochen Neukäter for their helpful comments.

I gratefully acknowledge the firms and my direct contacts, whose extensive sponsorships made the realisation of my research projects and the printing of this book possible. Thanks to my colleagues Graham Dodd and Bruno Miglio at Arup for providing me with the opportunity to review and revise the manuscript.

I would also like to express my gratitude to Ulrike Ruh and Odine Osswald from the publishing house for their substantial support and help in the making of this book.

Special thanks are due to my colleagues and friends at the university – Philipp Berninger, Britta Harnacke, Ron Heiringhoff, Maren Krämer, Alex Kruse, Stefan Steffesmies, Julia Wehrs and especially Ralf Herkrath – who contributed greatly to the successful completion of this work. For their personal support, as well as corrections to the content and language of this work, I extend my heartfelt thanks to my parents Charlotte and Johann Peter, and also to Anke Naujokat, Andres Tönnesmann and especially Silke Flaßnöcker and my silk baldachin. Thanks are due to all students who participated in the projects with tremendous dedication.

Jan Wurm, im März 2007

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INTRODUCTION


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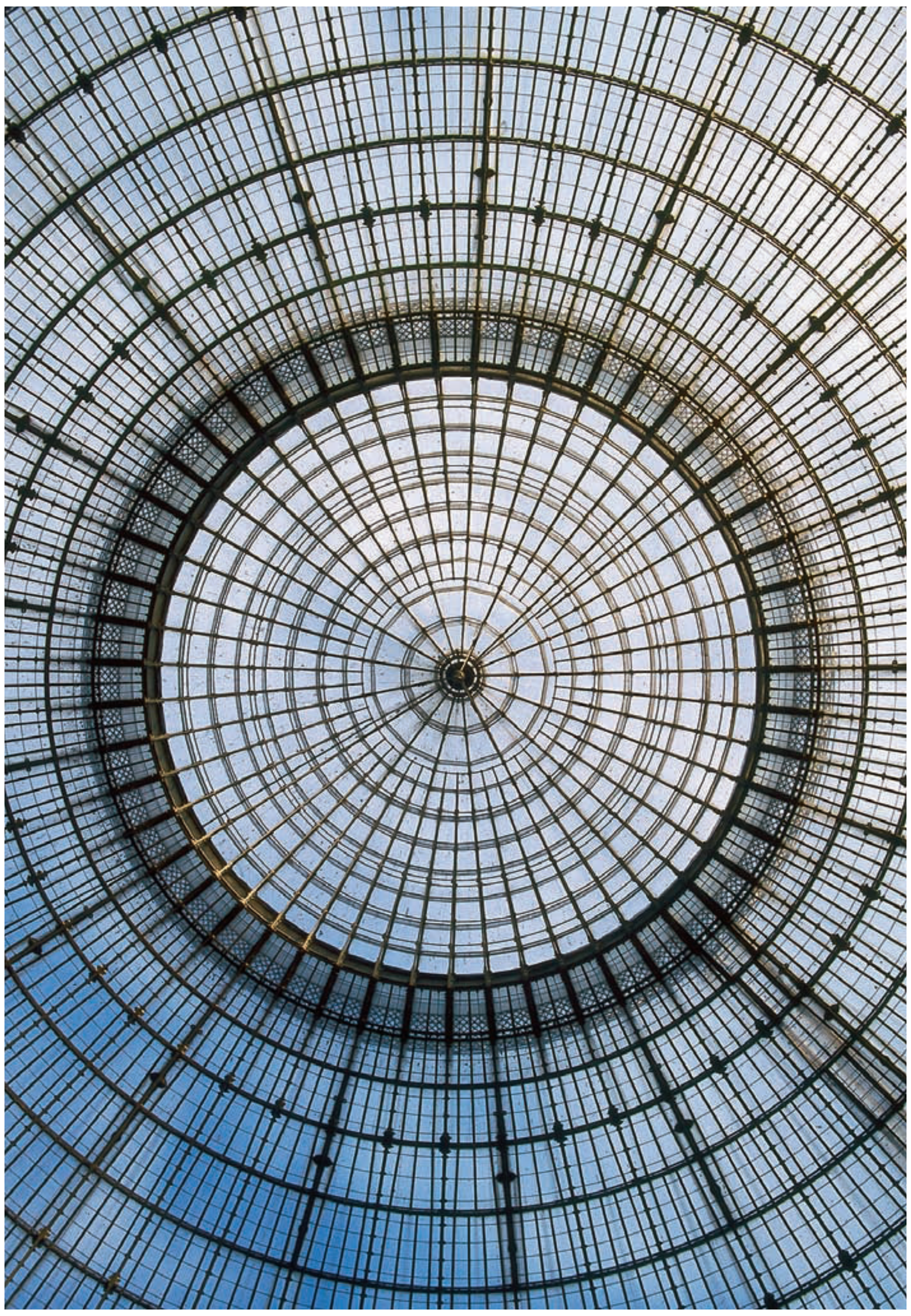
1 Glass lenses in the dome vaulted steam room of the Al Bascha hammam, 18th century, Akko, Israel

2 Palm house in Kew Gardens, London, 1845–1848, Arch.: D. Burton, Eng.: R. Turner

Flat glass has been used to enclose space for nearly two millennia and is one of the oldest manmade building materials. At the same time continual improvements to the manufacturing and refining processes make glass one of the most modern building materials today, one that shapes the appearance of contemporary architecture unlike any other. Almost any task associated with a modern building skin could be fulfilled with the help of this material. This made it possible to overcome the contradiction between the fundamental need for shelter from the elements and the simultaneous desire for openness to light, paving the way for building structures that "provide shelter without entombing [the dweller]". [1/1]

The roots of modern glass construction reach back to early 19th-century greenhouses in England. Horticulturists and landscape gardeners such as Claudius Loudon (1783–1843) and Joseph Paxton (1803–1865) pioneered a new development. While responding to the desire for cultivating exotic plants under controlled climatic conditions, they also discovered that the greenhouse proved ideal for experimenting with the new building materials of glass and iron. To best use the incident sunlight, they reduced the ratio of cast and wrought iron to glass panes and developed freestanding enclosures with domed and folded glazed roofs. The stability of these delicate structures was largely achieved by the bracing provided through small glass shingles embedded in putty. As a result of avoiding flexural tensile stress in glass, more by intuition than design, the outcome was folded plate and shell structures in which the iron skeleton formed a structural and functional unity with the glass skin. The successful synthesis of material, form, construction and purpose in these buildings where glass was employed for the first time as a load-bearing structural element created an aesthetic that has lost none of its fascination to this day. [1/2]

The significance of these 19th-century greenhouses as forerunners in the evolution of glass construction should not be underestimated. Experience in working with the new building materials was an



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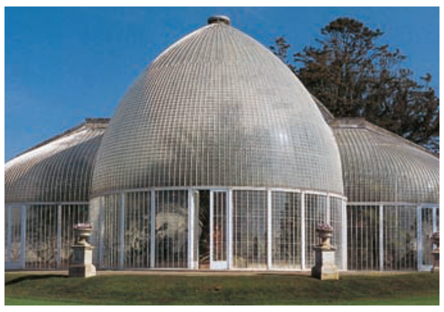

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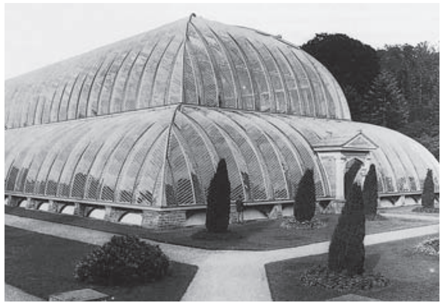

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3 Halle au Blé (now: Bourse du Commerce) Paris, 1806–1811, the world's first iron grid shell structure, Arch.: F. J. Bélanger, Eng.: F. Brunet

4 Palm house at Bicton Gardens, Arch.: D. & E. Bailey after plans by C. Loudon, circa 1843

5 Large greenhouse at Chatsworth with ridge-and-furrow glazing, 1840 (demolished in 1920), Arch.: J. Paxton

essential prerequisite for the subsequent construction of large railway terminals and atria. These glass and iron constructions were nothing short of pure feats of engineering. As the understanding of the structural characteristics deepened, the evolution of the form adhered increasingly to the emerging rules of skeleton construction. Although the separation of the skin from the load-bearing structure that was now taking place was accompanied by progress in glass technology, which subsequently led to larger sheet sizes and improved quality, by the mid-19th century glass had become a mere covering and had almost lost its constructional significance. Engineers shifted their focus to reducing the load-bearing framework that supported the glass panes.

At the beginning of the 20th century a young generation of architects recognised the visual potential of the new construction method. The openness and abundance of light in glazed halls, the aesthetics of transparent and orthogonally divided planes became the credo of a "modern" style that sought to abolish the boundary between inside and outside and abandoned traditional ideas on spatial organisation. Larger and larger window panes and glazed surfaces were more than merely a purposeful desire to improve natural daylight conditions in interior spaces: they represented a deliberate emphasis on the abstract and aesthetic qualities of the transparent material itself. Le Corbusier's call for a "struggle between the need for light and the limitations imposed by building materials and construction methods" anticipated the continual efforts of architects and engineers throughout the 20th century to reduce the facade structure to an absolute minimum. Towards the end of the 20th century the gain in transparency achieved through the "invisible" material glass became increasingly dogmatic in character as a symbol of "openness", "democracy" and "modernity", replacing the original pragmatism which had been associated with the term.

As the ratio of glazed to non-glazed surface increased, culminating in the fully glazed skin, so did the conflict between the desired trans-

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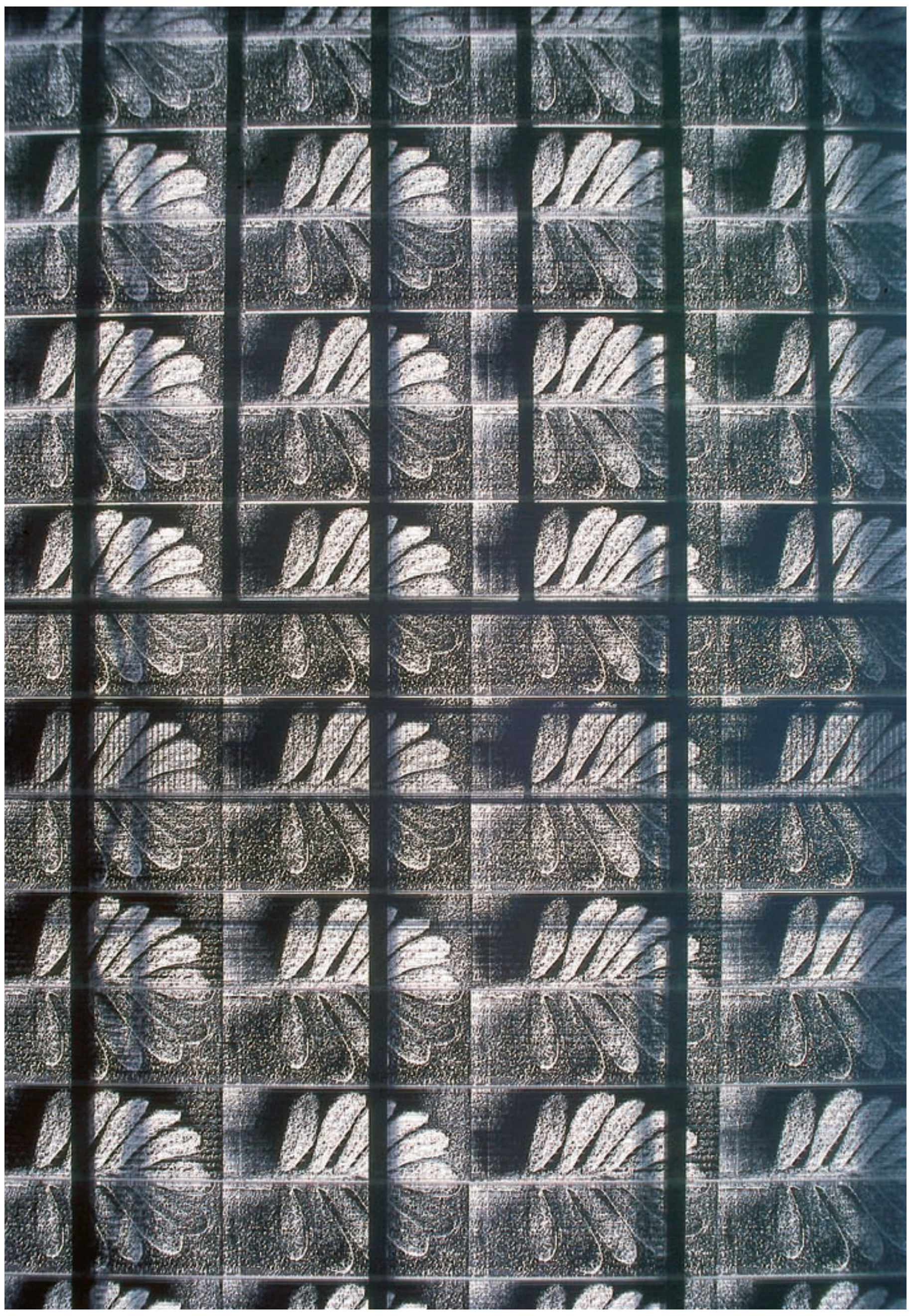
6 Glass and transparency, Reichstag dome, Berlin, 1998, Arch.: Foster and Partners, Eng.: Leonhardt, Andrä und Partner

7 Courtyard roof Sony Plaza Berlin, 1998, Arch.: H. Jahn, Eng.: Arup
The fabrics beneath the glass structure provide protection from weather, glare and noise.

parency and the physical requirements. Large glazed surfaces create additional heat losses in winter; conversely, they also generate energy gains in summer, at times even to the point of overheating. Even with the use of contemporary, highly selective coatings the energy that is transmitted into the interior in summer is often so great that the unwanted phenomenon of a "glass sauna" can only be avoided with the help of elaborate climate controls. Retrofitting and upgrading the building systems in an effort to control the internal climate is hardly a good argument for the usefulness of such glasshouses.

Today, glass has regained its significance as a building material thanks to the search for enhanced transparency. The initiative for the long-neglected research into the structural properties of glass was set in motion by steel construction institutes and companies, who also assumed responsibility for designing and executing early experimental projects. In contemporary buildings, glass is integrated into delicate load-bearing steel structures in the form of wind fins, beams, columns or props, chiefly with the goal of achieving the greatest possible dematerialisation of the skin. In this manner, constructional principles from skeleton construction are adopted for load-bearing glass structures, even though the properties of the materials differ in a fundamental manner. The "mastery" of the brittle material glass made possible by technological progress is most evident in the wide product palette for bolted point fixings for glass building components. [1/3] Glass construction is still dominated by the tectonics of steel construction to such a degree that it has yet to develop its own formal language.

The dynamic evolution of transparent skins and structures – culminating in the light-flooded spaces that dominate our public environments, the airport and railway termini, the sports and leisure arenas, the exhibition halls, shopping centres and atria in modern city centres – seems to have reached a plateau, begging the question of what the future significance of structural glass architecture might be. [1/4]



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8 Canopy structure composed of printed polycarbonate multi-skin sheets, Ricola warehouse, Mulhouse, 1993, Arch.: Herzog & de Meuron

9 Glass and translucency, Schubert Club Band Shell, Saint Paul (USA), 2002, Arch.: James Carpenter Design Associates (JCDA)

10 Dichroic coated glass panes form a three-dimensional structural system, glass sculpture "Refractive Tensegrity Rings", Munich airport, 1992, Arch.: James Carpenter Design Associates (JCDA)

It is notable that the "materiality" of the material is increasingly pushed to the foreground as a new quality. Contemporary architects gain an understanding of the material based on qualities that were already expressed in the early 20th century in the projects of the German group *The Glass Chain* and in Mies van der Rohe's early expressionist works. Architects such as Herzog & de Meuron or Bernard Tschumi understand the transparency of glass as a changeable state and emphasise the variety and sensuality of the material through deliberate mirror effects, colouring and diffused scattering of light: "One moment it is transparent; then it is reflective only to turn semi-transparent in the next minute". [**1/5**] Interpreting glass as a tangible, optically ephemeral boundary between interior and exterior inspires a new attitude towards its transparency in relationship to the physical aspects of the building skin and towards employing it as a visible "filter". The tremendous potential of structural glass to not only promote transparency but to utilise the liveliness of reflecting surfaces and the presence of a colourful absorbent building fabric is highlighted in the work of New York architect and designer James Carpenter ___Figs 9, 10. [**1/6**]

In modern glass architecture we see a growing convergence of two trends: the aforementioned aesthetics of the materiality itself and a new focus on mechanical forms, in which glass is understood as a planar structural element and no longer as a substitute for linear steel beams and columns. Load-bearing skin structures are the embodiment of unity between the building skin and the load-bearing structure. Although these structures had already been employed in 19th-century English greenhouses, it is only recently that their unique fitness for modern glass construction has been rediscovered. One of their characteristics is greater tolerance for the brittleness of glass because they allow for a far more even distribution of the flow of force than is generally achieved in skeleton structures. Curt Siegel describes load-bearing skin structures as *structural forms* that emerge as a synthesis of the possibilities inherent in the building material, the struc-

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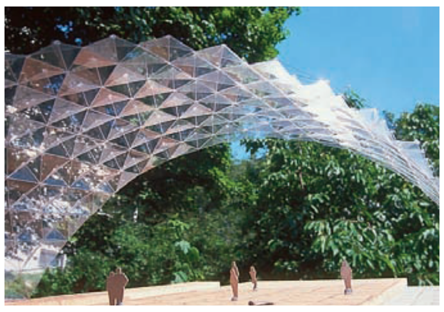

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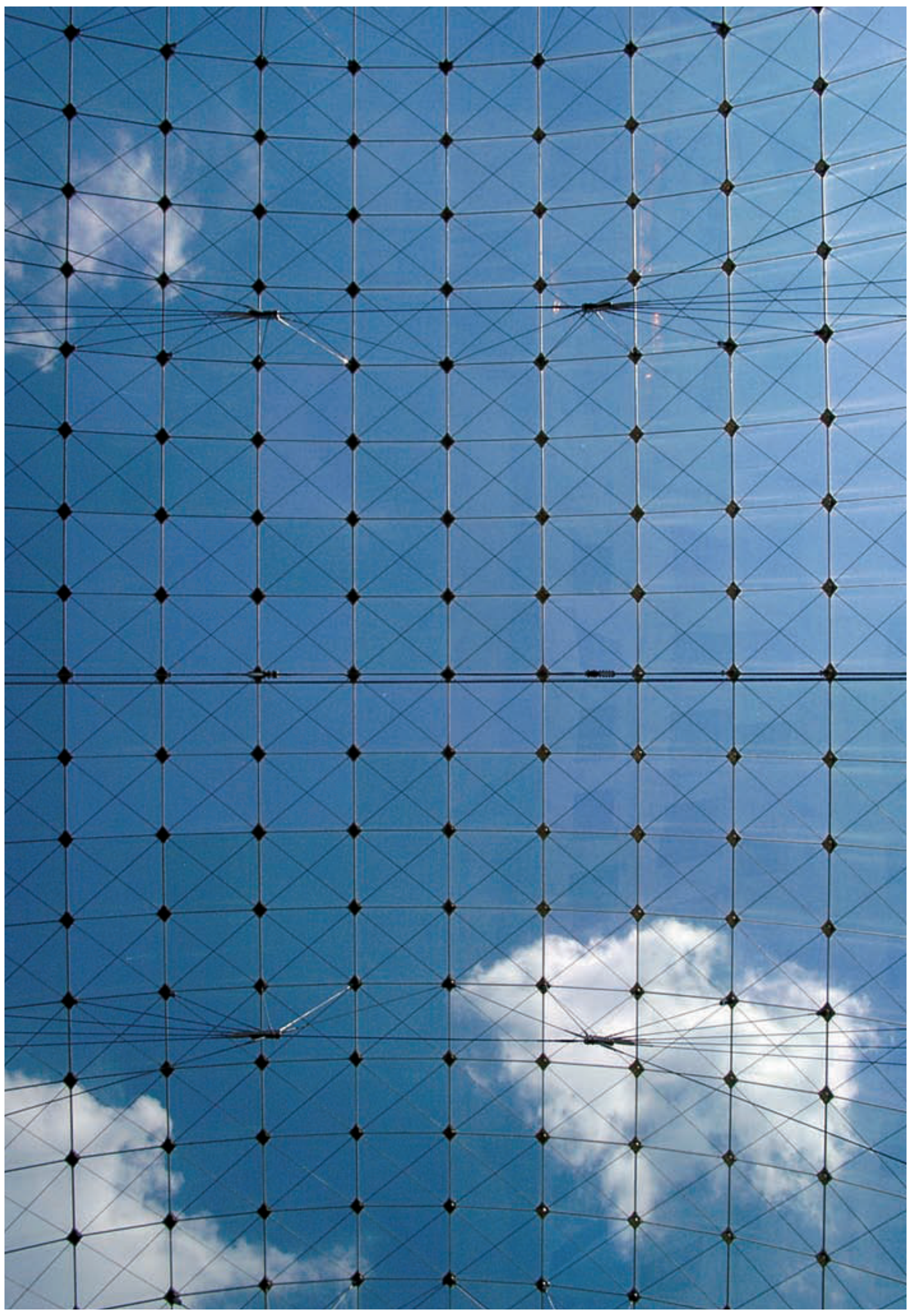

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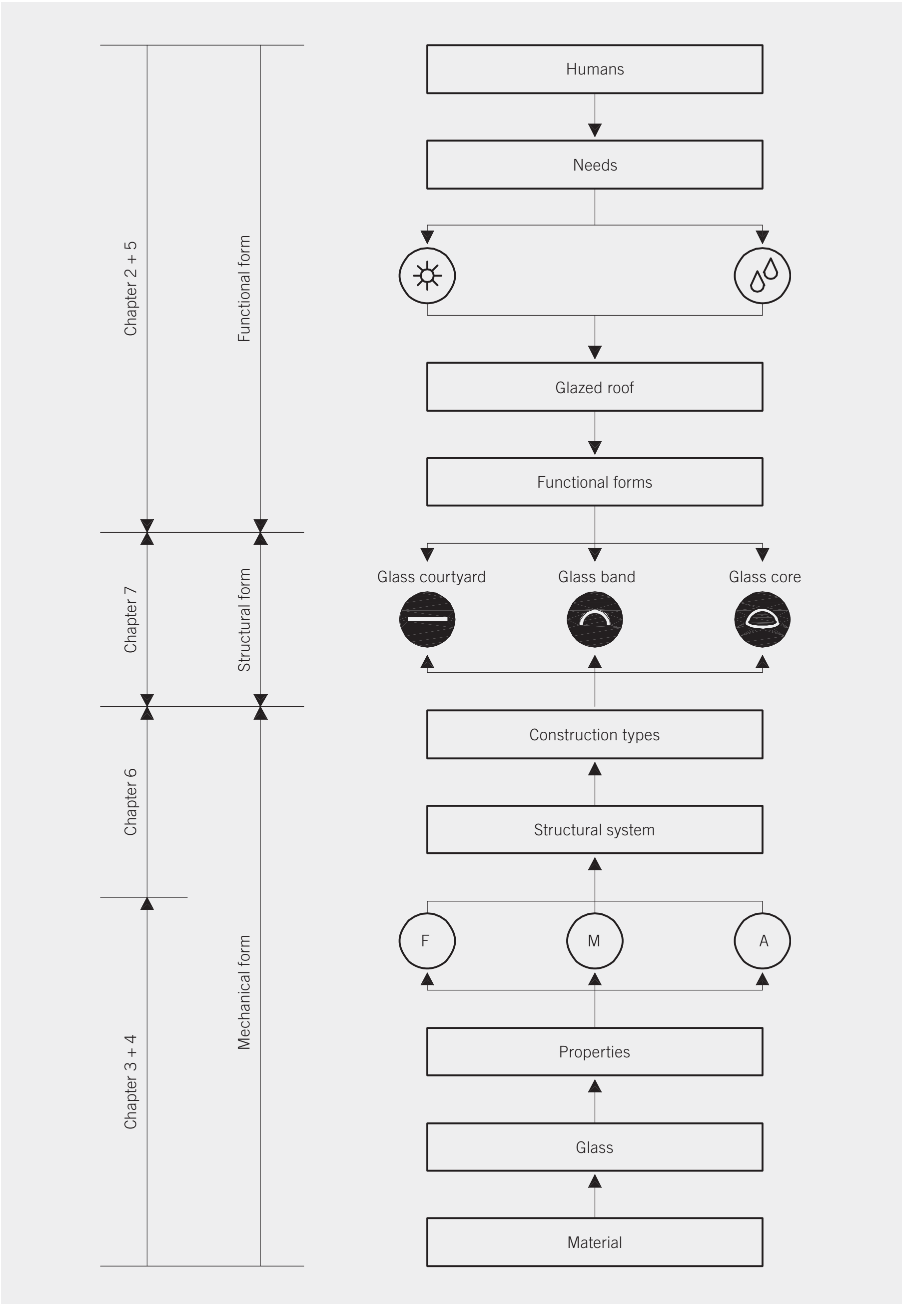
11 Glass as a load-bearing, protective and pictorial element: prototype for a space framework composed of glass, Tetra glass arch, 2000; design: Wilfried Führer and Jan Wurm, Lehrstuhl für Tragkonstruktionen, RWTH Aachen

12 Concept for a station roof; design: Christof Schlaich and James Wong, Lehrstuhl für Tragkonstruktionen, RWTH Aachen

13 Concepts for structural forms in glass construction: glass panels replace linear structural elements. Glass barrel shell with a 14 m span, Maximilianmuseum Augsburg, 2000; design and coordination: Ludwig und Weiler Ingenieure

tural and functional parameters and performance criteria of the building task, and the visual intent of the designer. [1/7, 1/8] To paraphrase Vitruvius, structural forms are the result of a creative process on the part of the architect/engineer which unifies the fundamental characteristics of utility (*utilitas*), firmness (*firmitas*) and beauty (*venustas*).[1/9]

The aim of this work, therefore, is to reveal new approaches to structural forms for contemporary glass construction of building skins and load-bearing roof structures with wide spans. At the same time, the tremendous advances in working with glass as a material are linked to the construction principles and design possibilities that are suitable for structural skins. Given the often contradictory demands arising from the functional, structural, technical and visual perspectives in engineering and designing, the geometries of the skin and the load-bearing structure have to be reconsidered for each new building task. Such a synthesis can only be successfully achieved through a direct exploration of the concrete brief in combination with an intense collaboration between architect, engineer and specialist designers. [1/10] Thus far structural forms for glass construction have only been sketched out and any attempt at formulating a specific formal vocabulary for glass structures must spring from an experimental approach. In addition to current projects by renowned architects and engineers, this work also presents case studies and prototypes, which the author developed in collaboration with students – an endeavour in which he was supported by the industry. The projects share the goal of strengthening the necessary integrated design approach to glass structures through experimental construction, planning and design. In addition to documenting the appropriate use of the building material, the systems presented in this volume also demonstrate how load-bearing components can be employed to environmental climate control. In other words, the concept of this book is to create a formal vocabulary and to recognise the aes-



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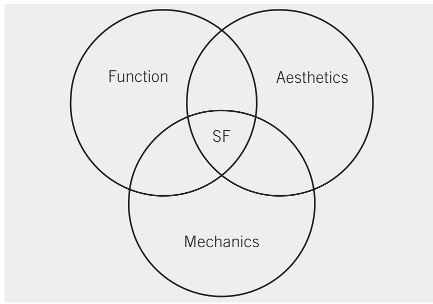

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14 Overview

15 Design workshop during the seminar entitled "Glasbau – Konzept und Konstruktion"

16 The structural form (SF) as a synthesis of mechanical, functional and aesthetic qualities

thetic quality rooted in the poetry of these load-bearing, enclosing and luminous surfaces.

To this end, Chapter 2 is devoted to an overview of the interactions between form, function and construction in roof structures. The technical foundations are systematically explored in the chapters that follow: the properties of the material including working and refining methods are explained in Chapter 3; the principles of material-appropriate jointing techniques and construction in the context of using flat glass as a spatial and structural element are introduced in Chapter 4; Chapters 5 and 6 outline the conclusions drawn from the material properties for the functional technical requirements of glass skins and for the construction principles for glass skin structures; the projects featured in Chapter 7, both realised glass buildings and experimental projects, illustrate the wide range of possible structural forms; in conclusion, Chapter 8 offers an outlook of future developments and perspectives ___Fig. 14.

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SPANS OF GLASS

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1–3 Evolution
1 Garden architecture, Wales
2 Foliage ornamentation in fan vault, cloister Gloucester, circa 1360–1370
3 Project "Ganzglastonne", 2000

4 The foliage canopy

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2.1
FROM LEAFY ARBOUR TO CLIMATE SKIN – THE SEARCH FOR PARADISE

"There is a wonderful attraction in being able to open the window and feel instead of the raw December or January air a mild balmy breath of spring. Out of doors it may be raining or snow flakes may be quietly falling from the sky, but one can indeed open the glass doors and find oneself in an earthly paradise that mocks the winter scene." Description of the winter garden of Princess Mathilde de Bonaparte, Paris 1869

The development of iron skeleton construction provided the technical and economic basis for the construction of the first glazed load-bearing roof structures in the 19th century. [**2.1/1**]

However the dematerialisation the ceiling was also influenced by cultural and religious precepts, which can be summarised as a "yearning for paradise"; although they were almost of equal significance in the evolution of glass roofs, they have received little recognition thus far. In secularised form, these precepts are an expression of humanity's dream of living in a kind of Garden of Eden in harmony with the natural environment and sheltered from all hostile influences. Long before the constructional means of at least creating a visual opening in the roof towards nature became available in the 19th century, the desired dissolution of the roof structure was suggested by symbolic and aesthetic means in sacred buildings. Although not directly related to glass construction as such, these early endeavours to create an "open-


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5 The “first house” according to Viollet-le-Duc

6 Cast iron arbour in Noyers, Burgundy, 19th century

7 “Artificial” foliage canopy: Estação Oriente, Lisbon, 1998, Arch.: Santiago Calatrava

ing towards the heavens” are still visible. Today, the development of glass roofs is largely driven by creating microclimates in the interior at a comfort level that is perceived as being natural and ideal.

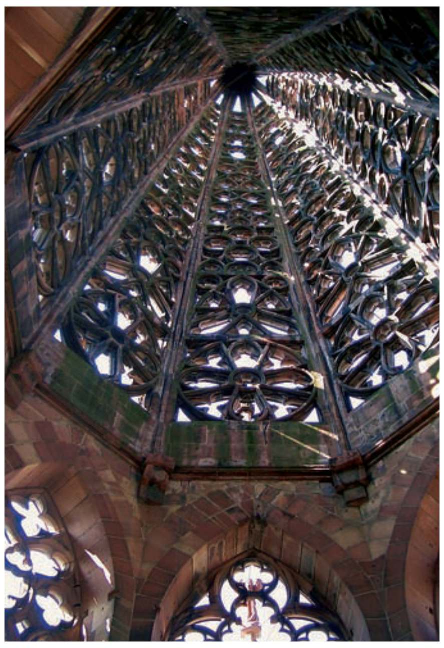
EARLY PERIOD AND CHRISTIAN SACRED ARCHITECTURE

___THE ARBOUR

The motif of a paradisiacal experience of nature is expressed in the built outdoor space of the arbour – a frame covered in climbing vines. The leafy roof of the arbour provides protection inside from rain, wind and sun, while at the same time being permeable to light; in other words, acting as a prototype for the all-encompassing glazed interior that fulfils a primordial need in humans.

Hans Teubner writes that “the arbour was nearly always linked to images of paradise […]”, for example, in the Jewish “Feast of Tabernacles” or “Succoth” which commemorates the exodus from Egypt. [**2.1/2**] The arbour is associated with the origin of architecture: Vitruvius, Laugier and Viollet-le-Duc describe the first human habitation as a rustic shelter with a roof structure composed of branches and foliage that have been tied together ___Fig. 5. These historic architectural theories are at least partly accurate. In Mesopotamia, the fertile land of two rivers between the Euphrates and the Tigris – widely regarded as the cradle of our civilisation and the locus of the Garden of Eden thanks to its favourable climate conditions – the original structures were indeed composed of “bent branches, tied together and rammed into the ground”, filled in with leaves or reeds. [**2.1/3**]

To this day, seeking shelter beneath the shade-giving leafy crown of a deciduous tree swaying gently in a breeze on a sunny day creates a more powerful sense of well-being than most interiors with abundant natural light and comfortable air-conditioning are ever able to provide.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8 View into the perforated tower spire of Freiburg cathedral, circa 1280

9 The groined vault at Amiens cathedral seen from below; the individual vault bays have the appearance of baldachins, circa 1236

10 Plastically enhanced church vault in the Mosteiro dos Jerónimos in Belim, 1502–1571

THE BALDACHIN

The Latin *tabernaculum* can be translated as arbour or as altar baldachin. In actual fact a frame that is covered with a thin silk or brocade, the baldachin was originally conceived as a ceremonial celestial symbol for earthly rulers. Later on it was used as a "portable heaven" for Christian processions, before being incorporated into altar designs as a symbol of God's protection. The depiction of the baldachin as a heavenly tent is one of the earliest explicit simulations of heaven in the history of architecture. [**2.1/4**]

The Gothic cross rib vault is an interpretation of the depiction of the baldachin. With the sequencing of vault bays in the naves of basilicas, the high clerestoried zone is experienced as a continuous lateral source of light. This lighting strategy intensifies the directional movement of the space and its function as a processional path. The image of the Garden of Eden as a common origin of both baldachin and arbour is expressed in the floral decoration on Late Gothic vaulting.

THE DOMICAL VAULT

Christian ecclesiastic architecture adopted the typology of the domed space as an image of the vault of the heavens from models dating back to antiquity. The symbolic connection between heaven and vault is enhanced by the lighting in the interior: indirect light from the apex of the dome bathes the church interior in a "heavenly glow".

The illumination of the domed space through the oculus – a circular opening in the apex of the dome – is of prime importance for the spatial effect. The central skylight is "the sole source of light, isolating the space from its natural environment and preventing other perspectives and distractions". [**2.1/5**] In the Pantheon in Rome, this opening measures 9 metres in diameter and hence roughly one fifth of the diameter of the entire cupola. In Christian centralised churches, light flows into the interior through a circle of windows in the drum, as in the Hagia Sophia (532–537), through windows in the tambour or through a lantern light in the apex of the dome, as in Florence cathedral


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11 Domed vault with ceiling frescoes in Florence cathedral, 1434–1461

12 Ceiling fresco by Correggio in Parma cathedral, 1526–1530

13 The Pantheon in Rome, AD 118–128

(1434–1461). [2.1/6] With the advent of the domed centralised building, the central skylight became first the characteristic of sacred public buildings and later of profane public structures.

The celestial symbolism was often emphasised by painting the vault cells, for example with stars on a sky-blue background, as in the early Christian baptistery San Giovanni in Fonte in Naples (approx. AD 400). During the Late Gothic, the vaulted surfaces were decorated with painted foliage. At the same time, the structural system was plastically enhanced, so that ribs and transverse arches were rendered as branches and vines: the ceiling now took on the appearance of an arbour – a direct illustration of the Garden of Eden. [2.1/7] Painting the vaulted ceilings served to enhance the dematerialisation of the ceiling construction, becoming an integral element of the architecture. In the Baroque and Mannerist periods, the symbolic meaning of ceiling frescoes began to give way increasingly to a depiction of the real world. Thus the blue sky painted in the background was both a reference to the heavens above and a realistic illustration of the physical sky behind (or above) the construction and, by this means, a deliberate expansion of the interior space. [2.1/8] In other words, painted ceilings that created the illusion of a dissolved or immaterial structure constituted the final stage in the evolution towards the fully-dissolved glazed roofs of the 19th century.

THE MODERN ERA

___THE GREENHOUSE

With the advances in technology brought about by the industrial revolution, the dream of a dematerialised roof constructed of iron and glass could finally be realised. English greenhouses featured the first glazed roofs in the history of architecture. Greenhouses became an oasis, a place promising to be the “embodiment of the dream of a happy unity of nature and man”. [2.1/9] The abundance of tropical plants, exotic scents and sounds created a dream world that gave city dwellers an


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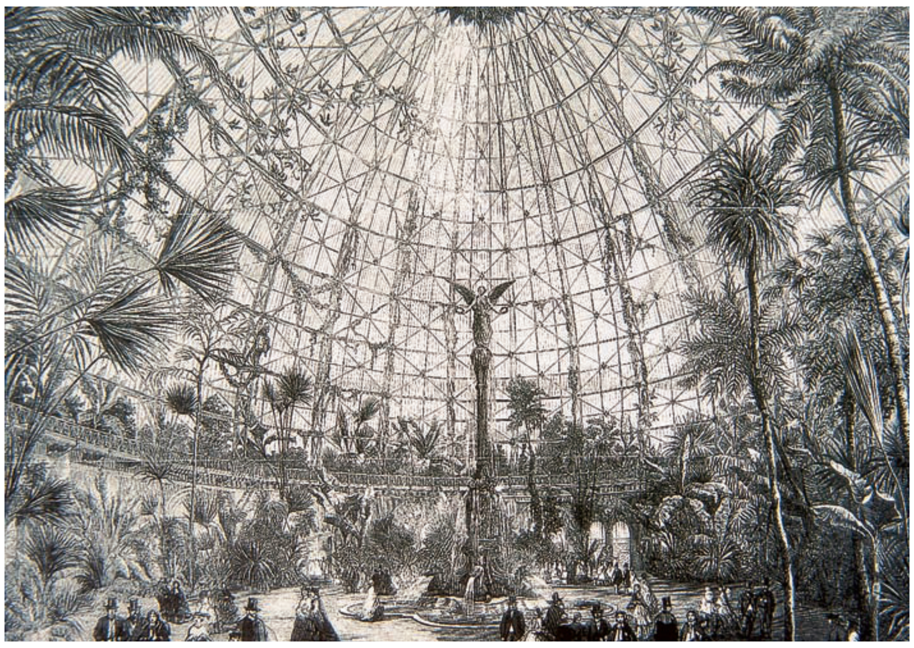
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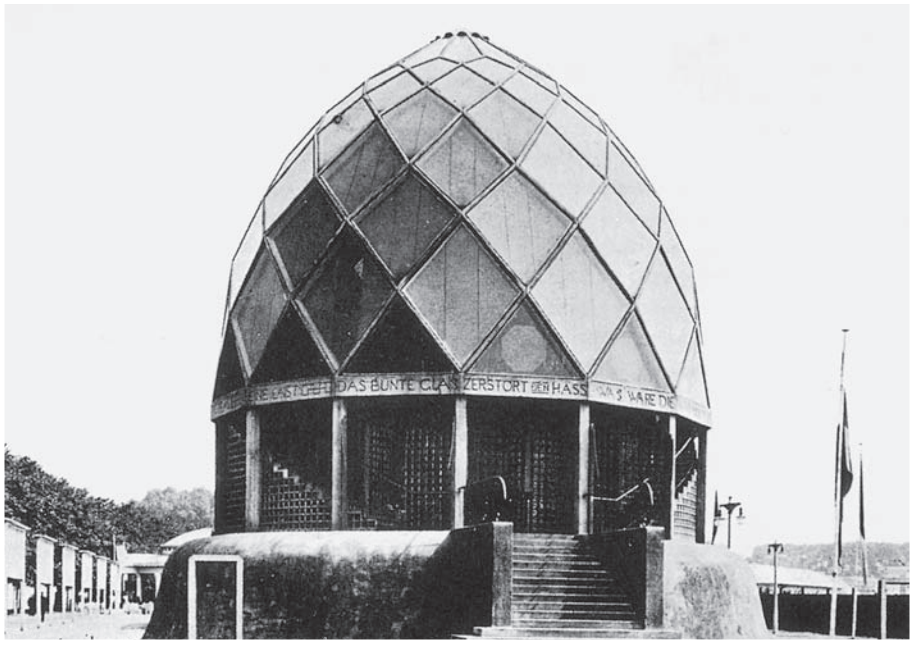
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14 Large greenhouse in the Botanical Gardens at Dahlem, 1905–1907, Arch.: Alfred Koerner

15 Interior of the People's Palace, Muswell Hill, London, 1859 (project)

16 "Coloured glass destroys hatred". Glass pavilion by Bruno Taut, Werkbund exhibition in Cologne, 1914

escape from life in the metropolis. The climate control systems, necessary for the survival of the plants, were carefully hidden from the eye of the visitor in order to preserve the illusion of a Garden of Eden in the rough climate of northern Europe. [2.1/10]

Public winter gardens and botanical buildings incorporating concert halls, restaurants and libraries elevated the individual pursuit of leisure into a bourgeois movement of recreating nature. A contemporary report describes the winter garden in Regent's Park as follows: "A veritable fairy tale land has been planted into the heart of London, a most agreeable garden that transforms all our wishes into reality." [2.1/11]

___THE "GLASS CRYSTAL"

At the beginning of the 20th century the Expressionist artists' group The Glass Chain, the most prominent members of which were Bruno Taut (1880–1938) and Paul Scheerbart (1863–1915), embraced utopian social visions associated with the use of glass as a building material. Taut designed crystalline urban domes such as the "Haus des Himmels": "The ceiling is constructed of prisms composed of colourful glass joined by electrolytic fusion; the walls are constructed of cast prisms." [2.1/12]

Scheerbart writes: "The face of the earth would be much altered if brick architecture were ousted everywhere by glass architecture. It would be as if the earth were adorned with diamond and enamel jewellery. Here on earth, we would have [environments] more precious than the gardens in the Arabian Nights. We should then have a paradise on earth." [2.1/13]

___THE CLIMATE SKIN

During the 19th century there was a universal need for living independently of weather conditions coupled with protection from the dirt and polluted atmosphere in large cities, which was architecturally ex-


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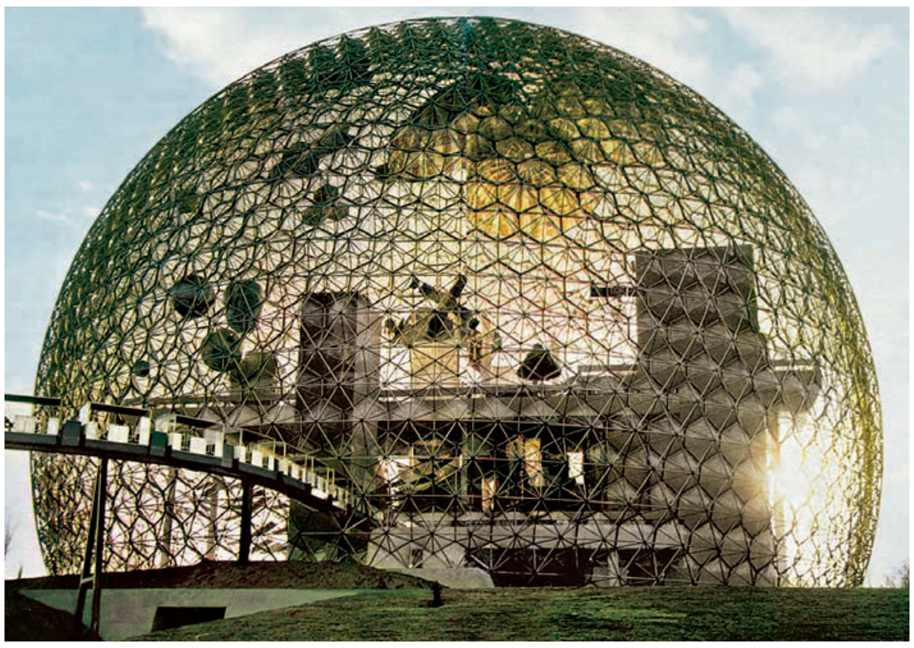
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17 Project for a geodesic dome over Manhattan, circa 1960, Arch.: Buckminster Fuller

18 Project for a pneumatically supported climate skin in the arctic, 1970, Arch.: Frei Otto in collaboration with Kenzo Tange and Ove Arup

19 USA pavilion by Buckminster Fuller at Expo '67 in Montreal

20 The large biospheres of the "Eden Project" in Cornwall, 2001, Arch.: Nicolas Grimshaw, Eng.: Arup and Anthony Hunt Associates

pressed in the idea of covering urban space in glass on a large scale. The desire for hygiene and cleanliness was combined with physical and metaphysical aspects. As early as 1808 Charles Marie Fourier (1772–1837) sought to counter the "ravages of civilisation" with his idea of the *phalanstères*, describing the ideal of a city completely covered in a glass dome that was also intended to serve as a catalyst for a new societal order. [**2.1/14**]

In 1822 J. C. Loudon developed the visionary idea of placing entire cities in "northern regions" under glass roofs for the purpose of improving living conditions. "The most economic method of creating an agreeable climate will be to cover entire cities with monumental glass roofs." [**2.1/15**]

Nearly 150 years later this vision was resurrected in Buckminster Fuller's (1895–1983) concept for a geodesic dome over Manhattan with a diameter of three kilometres and in Frei Otto's project for a climate skin in the arctic with a diameter of two kilometres. [**2.1/16**]

With a diameter of roughly 75 metres, Fuller's dome for EXPO '67 in Montreal represents a realisation of this vision on a smaller scale. Fuller writes: "From the inside there will be uninterrupted visual contact with the exterior world. The sun and moon will shine in the landscape, and the sky will be completely visible, but the unpleasant effects of climate, heat, dust, bugs, glare etc. will be modulated by the skin to provide a Garden of Eden interior." [**2.1/17**]

Today tremendous progress in building systems and glass refining processes have made it possible to regulate the flow of energy between interior and exterior in just such a manner. Glass building skins that are dynamic and self-adaptive – characterised by a harmonised energy balance sheet that is independent of non-regenerative energy resources thanks to utilising solar energy and the ability to adapt to the needs of occupants and the changing climate conditions of the environment – are associated with a yearning for a future where humankind will once again be able to live in harmony with nature.

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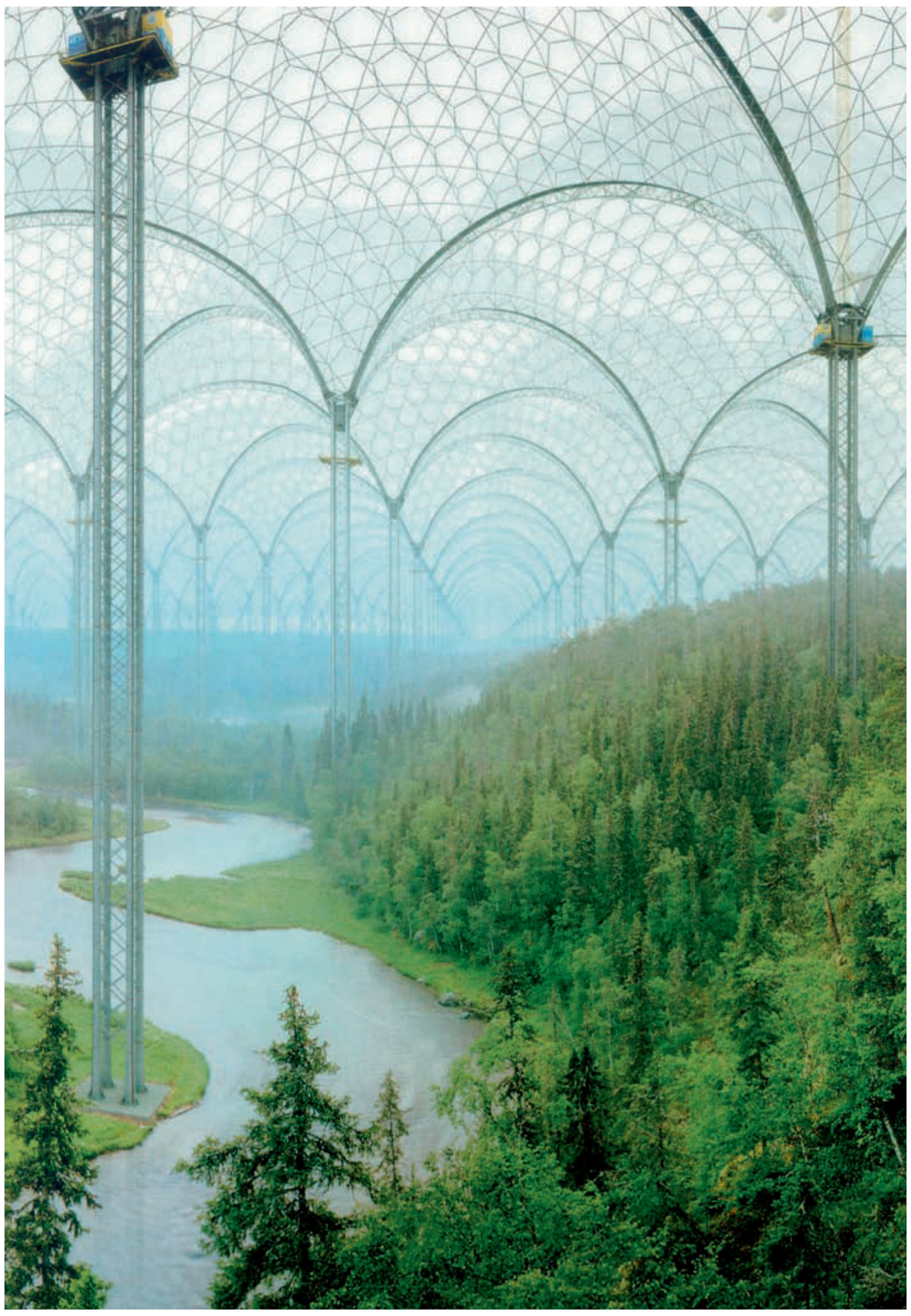

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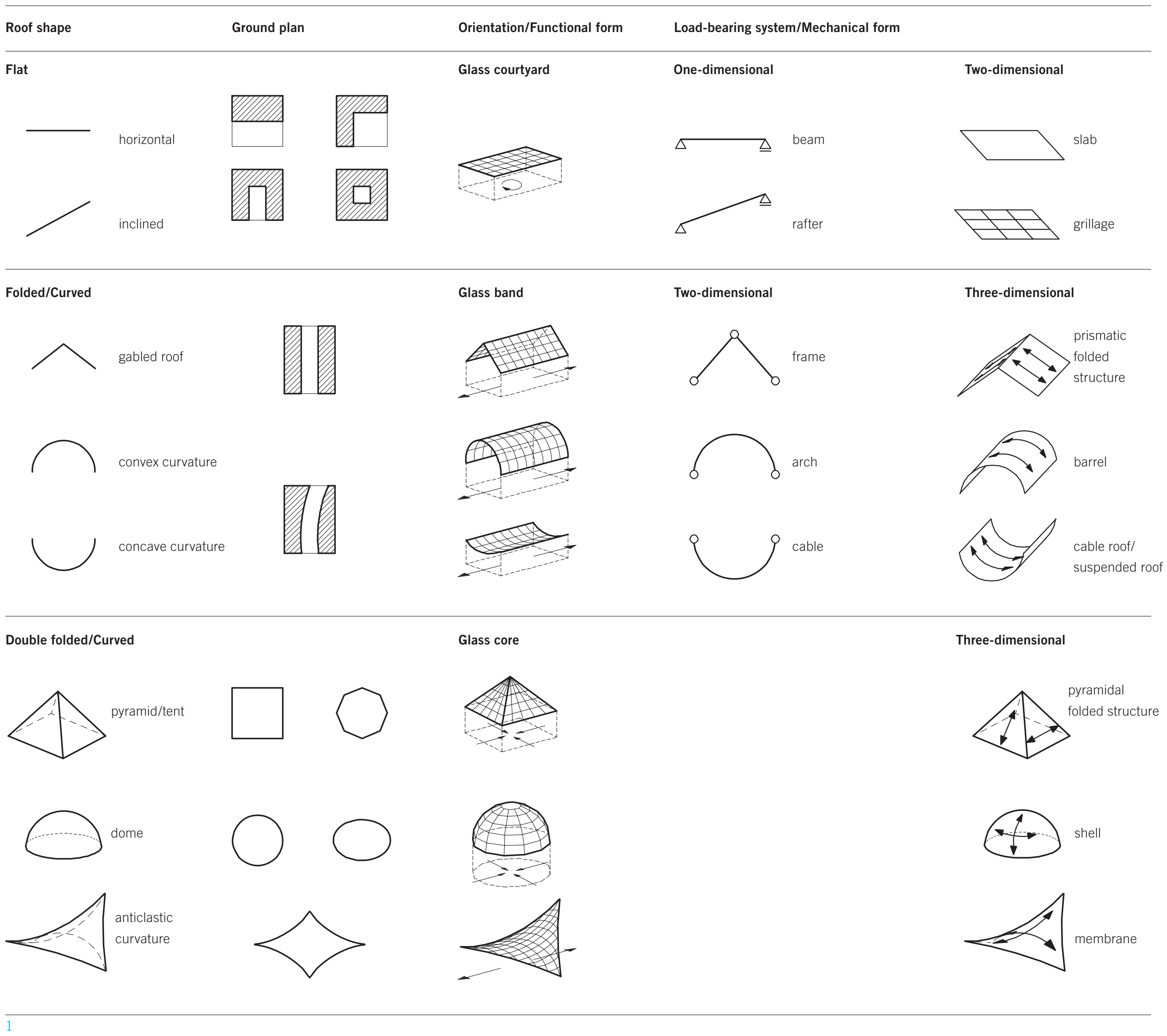
21 The foliage canopy made of glass: Art Academy on Berliner Platz, Berlin, 2002, Arch.: Behnisch Architekten

22 "Tropical Island" in Berlin Brand, 2004

23 Staged nature, photo montage by Taiteilija Ilkka Halso, Orimattila

Thus many contemporary projects display the yearning for paradise that has been associated with the glasshouse since the 19th century as a synthesis between humans and nature. Lounging beneath the colourful glazed roof of the thermal baths at Bad Colberg or taking a break in the atrium of Berlin's Academy of Art is designed to induce in the visitor a feeling of "dwelling beneath a canopy of leaves". [**2.1/18, 2.1/19**]

Modern examples of *leisure paradise* environments such as the "Tropical Island" near Berlin, which accommodates a tropical rainforest with lagoons, auditoria and bars, aim to present visitors with quasi-pristine nature in an over-the-top fun and entertainment package – a combination that is "purchased" at the cost of an excessive investment into building services and energy supply for air conditioning and control technology.



1 Classification of roof types according to shape and orientation into glass courtyard, glass band and glass core

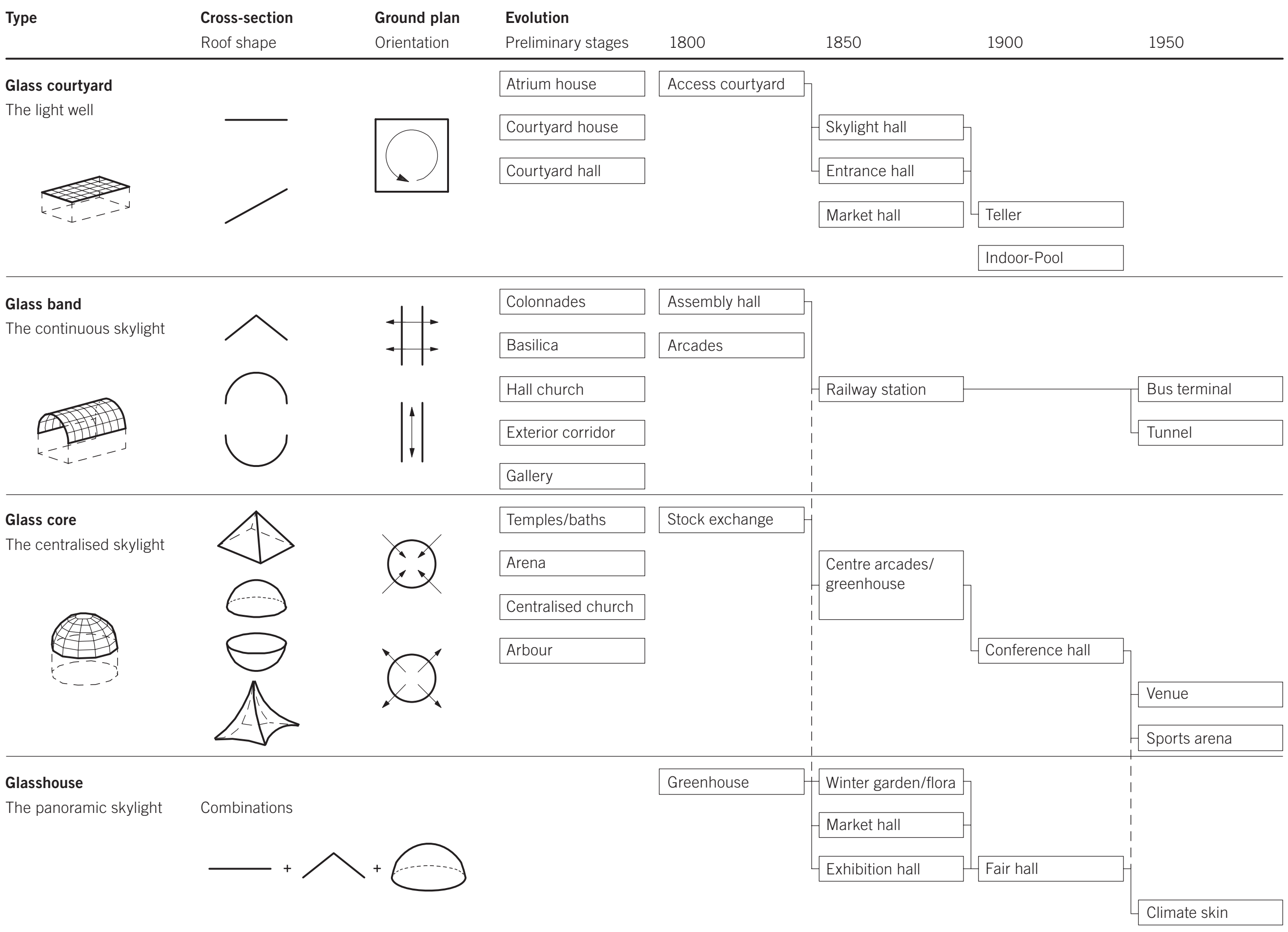
2.2 THE GLASS ROOF: FORM, FUNCTION AND CONSTRUCTION

THE FUNCTIONAL AND MECHANICAL FORM

The 19th century witnessed the advent of dematerialised structural systems composed of linear compression-resistant and tensile materials such as wood or steel. For the first time, these structures were partially or entirely clad in glass. In central and northern Europe, the separation of structure and skin that emerged during the industrial revolution was born out of the necessity to protect large spaces in railway terminals, factory and assembly halls or arcades against the elements, while at the same time supplying them with natural daylight. The evolution of the glass roof is thus closely linked to that of *low-rise construction*. The interaction between functional and mechanical aspects in defining a form is particularly evident in these large-span roof structures.

After plan and cross-section, the *functional form* of the skin is usually developed on the basis of the intended use and the functional requirements of the building task. Structural systems can only fulfil their function by transferring all dead and imposed loads acting on them to the subsoil. All load-bearing elements necessary for this load transfer to occur must be combined into a complete structure capable of carrying loads – the *mechanical form*. The properties and the availability of building materials are important aspects in the constructional and technical design of roof structures. [**2.2/1**]

In this work, glass roofs are differentiated according to functional and mechanical form based on the typology of skylight designs estab-



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2 Diagram representing the evolution of different glass roof types

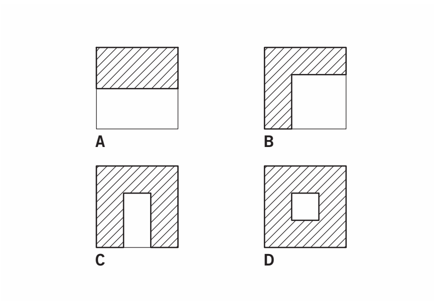
lished by J. F. Geist. The basic types of "*glass courtyard*", "*glass band*" and "*glass core*" are summarised in ___Fig. 1. The glass courtyard is defined by a planar (two-dimensional) roof, the glass band by a single folded or curved roof and the glass core by a double-folded or curved roof. Typologically, the *glasshouse* is characterised by a glass skin on all sides, the sculptural quality of which liberates it from unequivocal typological references. [**2.2/2**]

The flow of force in the structural system and the stresses exerted on the load-bearing elements are dependent on the geometry of cross-section and plan, and it is for this reason that the form and dimension of structural systems are interdependent. For large spans, a flat roof will quickly prove to be uneconomical, whereas a double-folded or curved roof can be realised with relatively little material expenditure. In this sense, glass courtyard, glass band and glass core also differ in terms of the spatial expanse and dimension of the area they cover.

___HISTORIC EVOLUTION

The historic evolution of the glass roof and its typical appearance in the glass courtyard, glass band, glass core and glasshouse is illustrated in the diagram ___Fig. 2. The overview presents the trends and evolutionary lines of cross-section (roof shape) and plan (orientation) from the first glass roof constructions circa 1800 to the present day. Solid construction typologies which are characterised by a similar spatial configuration are given as examples in the column headed "preliminary stages".

The overview provides a sketch of the evolution from the start of the industrial revolution around 1800 to today in 50-year increments. Circa 1850, the need for large skylights gave rise to plans designed for new building tasks such as museums, market halls, stock exchange buildings and libraries. Large halls were needed for the manufacture, distribution and presentation of trade goods and as convening places for a new urban public interested in recreation and the pursuit of cul-



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3 Plan types for the glass courtyard
A The annexed glass courtyard
B The corner glass courtyard
C The inserted glass courtyard
D The interior glass courtyard (atrium)

4 Teller hall of main post office in St. Petersburg

5 Semi-public circulation space Familistère de Guise, circa 1860

6 Interior of glass courtyard as constructional completion, the Schlüterhof at the Deutsches Historisches Museum in Berlin, 2003, Arch.: I. M. Pei

7 The annexed glass courtyard, shed roof Museum Meteorit, Essen, 1998, Arch.: Propeller Z

8 The annexed glass courtyard, expansion Museum Rietberg, Zurich, 2007, Arch.: ARGE Grazioli Krischanitz GmbH

tural education. Towards the end of the 19th century, new social structures translated into an increase of administrative bodies and the emergence of the modern service-oriented society. Large entertainment and sports arenas are the architectural expression of the leisure society as we know it today.

___THE FLAT OR INCLINED ROOF – THE GLASS COURTYARD

A planar roof area is horizontal or pitched, the roof profile is one-dimensional.

The top-lit courtyard screened off from the external surroundings is one of the oldest forms of spatial organisation. It serves to provide light and access to adjacent spaces and is defined by a tranquil, introverted ambience that is an invitation to linger. The interior square atrium terminating in a horizontal glass ceiling, in which none of the lateral enclosing elements are dominant, constitutes the purest form of a glass courtyard. Originally an open light well in Roman homes, the atrium is today often annexed to existing light wells and used as a lobby, exhibition space or cafeteria. With the growing dematerialisation of the wall, glass courtyards emerge in less introverted forms in which one or several directions are singled out. The opening can be additionally emphasised through a rectangular plan or the incline of the roof area. In the case of an "inserted glass courtyard", only three sides are enclosed by solid building components, and the orientation towards the open, often fully-glazed front assumes a prime importance for the organisation of the floor plan. A "corner glass courtyard" has two adjacent open sides, reinforcing the diagonal flow in the interior space. The "glass courtyard annex", finally, is open on three sides. The tranquil character of the glass courtyard can be preserved even in the case of shed and saddle-roof constructions with the help of interior dust or luminous ceilings suspended from the primary structure. A double-skin construction of this kind marks the skylight hall as a variation on the classic glass courtyard. [**2.2/3**]