Bill Addis (Ed.)

Physical Models

Their historical and current use in civil and building engineering design

- **the book summarizes the history of model testing by design and construction engineers in a single volume for the first time**
- **model testing is alongside knowledge of materials and structural behaviour a major driver in progress in civil and building engineering**

The book traces the use of physical models by engineering designers from the eighteenth century, through their heyday in the 1950s-70s, to their current use alongside computer models. It argues that their use has been at least as important in the development of engineering as scientific theory has.

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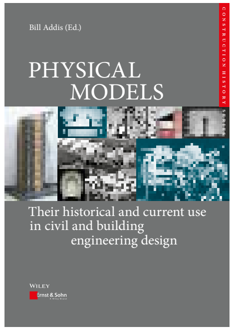

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ABOUT THE BOOK

Physical models have been, and continue to be used by engineers when faced with unprecedented challenges, when engineering science has been inadequate or even non-existent, and in any other situation when engineers have needed to raise their confidence in a design proposal to a sufficient level in order to begin construction. For this reason, models have mostly been used by designers and constructors of highly innovative projects, when previous experience has not been available.
The book covers the history of using physical models in the design and development of civil and building engineering projects including Robert Stephenson's Britannia Bridge in the 1840s, the masonry Aswan Dam in the 1890s and the Boulder Dam in the 1930s; tidal flow in estuaries and wind and seismic loads on structures from the 1890s, the acoustics of concert halls and the design of thin concrete shell roofs from the 1920s, and the dynamic behaviour of tall buildings from the 1930s, as well as and cable-net and membrane structures in the 1960s. Individual designers featured include Eduardo Torroja, Pier Luigi Nervi, Heinz Hossdorf, Heinz Isler, Frei Otto, Sergio Musmeci and Mamoru Kawaguchi.
The book concludes with overviews of the current use of physical models alongside computer models, for example in boundary layer wind tunnels, seismic engineering, hydrology, soil mechanics, and air flow in buildings.
Traditionally, progress in engineering has been attributed to the creation and use of engineering science, the understanding of materials properties and the development of new construction methods. The book argues that the use of reduced-scale models has played an equally important part in the development of civil and building engineering. However, like the history of engineering design itself, this crucial contribution has not been widely reported or celebrated.
The book includes 39 chapters written by 29 authors from ten different countries.
Bill Addis, the author of several chapters in the book, and overall Editor, has written widely on the history of building and civil engineering design. He worked for more than 15 years in the academic world, as well as over 15 years with an international firm of consulting engineers.

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Foreword of the series editors

Construction history has experienced amazing momentum over the past decades. It has become a highly vibrant, independent discipline attracting much attention through its international networks. Although research projects at national level focus on different themes, they are united through the knowledge that their diversity in terms of content and methods, and hence the associated synthesizing potential, are precisely the strengths that shape this new field of research. Construction history opens up new ways of understanding construction between engineering and architecture, between the history of building and history of art, between the history of technology and history of science.

Since Galileo's time, engineers and architects have been using physical models to build bridges between the conceptual design of engineering structures on the one hand and their detailed design on the other. As editor and one of the authors of the present volume of the *Construction History Series/Edition Bautechnikgeschichte*, Bill Addis has gathered together contributions by authors from very diverse backgrounds, different countries, to demonstrate the vital role that physical models play in the design of engineering structures. The authors' multi-method approach not only offers a fascinating and comprehensive insight into the historical development of building and civil engineering, but also enhances our perception of the changing relationship between experiment and theory in times of paradigm shifts in the aforementioned fields of historical research.

Karl-Eugen Kurrer and Werner Lorenz
Series editors

Foreword

The art of devising and capturing geometrical parameters is an essential part of architects' and engineers' daily working lives. In fact, no structures can be designed without it. The problem is that the individual components of many modern structures are subject to complicated internal stresses triggered by external loads from the wind, earthquakes and a range of other potentially complex phenomena. Building up a precise, scientifically rigorous picture of these loads and the internal stresses and deformations that arise as a result (such as the deflection of a bridge when a train travels over it) is certainly no easy task. Indeed, predicting the stresses and deformations experienced by structures and their components via purely theoretical means is, at best, only sufficient for anticipating general trends and cannot provide the precision necessary for reliable structural calculations. For this reason, both architects and engineers have long used models to help them with their plans. 'Models', in this context, are defined as physical or mathematical representations that demonstrate one or more specific properties of a structure. For example, a model of a load-bearing construction will display its structural and deformation characteristics, but not the acoustic qualities of the design in question.

Mathematical models of selected slices of reality stand out thanks to the high, comprehensive levels of precision they achieve in the predictions they produce. This is one of their great strengths. Of course, the accuracy of these predictions is dependent on the quality of each model's design. In comparison with their physical counterparts, mathematical models are also at a disadvantage when it comes to clarity and intelligibility: they typically give their results in two-dimensions and, as such, lack the potential for tactile exploration offered by three-dimensional representations. This tangibility is one of the main benefits of physical models and – alongside the consideration that they are relatively quick and easy to make – is precisely the reason why they continue to play such a central role in design processes in all branches of building and civil engineering today. Indeed, physical models are still used to grasp the key behavioural properties of a construction or engineering system at speed and to make initial optimisations before mathematical models are brought in to help generate the final result.

For hundreds of years, architects and engineers have depended on physical models for developing optimal constructions and determining the stresses and deformations experienced by entire structures and their constituent parts.

Since the late nineteenth century physical models have also played a major role in hydraulic, seismic, acoustic and wind engineering. In fact, for a long time, physical models have ranked alongside empirical knowledge as cornerstones of the construction industry, especially when new structures and novel materials were being included in designs. As a consequence, a huge range of different modelling techniques were employed from the days of the mason's lodges at Gothic building sites right up to the mid-twentieth century. In spite of their tremendous significance for the development of construction as a discipline overall, however, these creations have never been comprehensively described, classified, categorised or placed in a historical sequence. That is, at least, not until the publication of this book, which represents the very first time such a feat has ever been achieved. Even this simple fact alone is enough to make it a crucial, foundational text that will doubtless soon become an essential reference work for students and professionals in the fields of architecture, building and civil engineering alike.

Professor Werner Sobek
Institute for Lightweight Structures & Conceptual Design (ILEK)
University of Stuttgart

Preface

Both historical and current civil and building engineering are often considered in terms of the practical skills of using materials to construct artefacts, and the theoretical tools used to calculate and predict their engineering behaviour before construction begins. So often one hears talk of the theory and practice of engineering. Yet there is more to engineering than this.

Many books have dealt with the historical development of the practical aspects of construction – the history of canals, of dams, of bridges, of masonry structures, of iron construction. Many others have dealt with the history of engineering science and theory – the equations of fluid flow, the statics and equilibrium of structures, the elasticity of materials, the curious behaviour of soil, the reverberation and absorption of sound in a room.

I have long argued that there is a crucial third strand of engineering skill that is equally deserving of historical study – the skill of design. I have argued that design comprises two main activities or outcomes: to convey the designer's ideas to the people who will build an engineering artefact; and to provide the confidence that the proposed design will perform as wished by the client, and as intended by the designer [1].

Over centuries, the first outcome has been achieved by means of drawings, geometrically-faithful models at reduced scale, material data, design rules and codes of practice, and various types of performance specification specific to particular engineering disciplines.

The second outcome, providing the confidence to build, one might call it, has been achieved in simple ways such as following precedent, or learning from the experience of what was not successful. It has also been achieved in more sophisticated ways including making and testing a full-size prototype structure[1] or a reduced-scale model of an engineering construction, and the use of theories of engineering science. Today this might be described as reducing risk to an acceptable level.

The history of engineering design, then, comprises histories of the various ways that engineers have communicated their designs, and how they have provided

---

[1] In UK English it is always awkward to have to refer to a full-size, or full-scale, or actual or real structure. In American English, the word 'prototype' is used, which is much easier. However, in UK English this word means making the first few examples of a product that later goes into batch- or mass-production. In this book the UK English terms are used, despite their awkwardness.

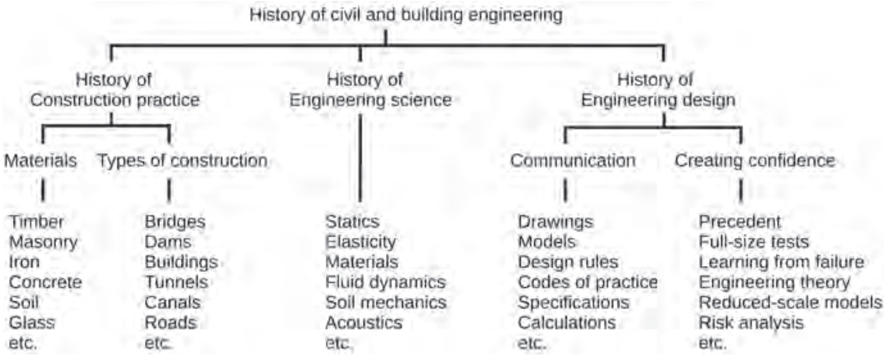

Figure 1 Diagram showing the scope of civil and building engineering history.

sufficient confidence in their designs to persuade clients to fund their projects and contractors to build them [2].

Using these ideas we can build up an overall picture of the history of civil and building engineering which also indicates where the subject of this book fits into the grand scheme (Figure 1). This diagram also provides an epistemological framework for engineering knowledge, applicable equally to the modern practice of civil and building engineering as to the history of the subject. For this reason, it also has consequences for the nature of progress in these fields. When considering the mechanism(s) by which progress is achieved, according to the idea that engineering is a matter of putting theory into practice, it is common to imply that progress occurs as a consequence of developments and progress in engineering science. However, this is patently wrong: there are no significant examples of progress in civil and building engineering construction that have arisen entirely as the result of progress in engineering science. Furthermore, there are countless examples of progress in engineering science that arose out of construction practice. Most progress has been symbiotic, with ideas and experience passing between the two with equal intensity in both directions. Reduced-scale models have often been the essential catalyst to the process, providing the only means by which the practical and theoretical worlds are brought together.

This book is devoted to the use of reduced-scale models, especially in the design process for civil and building engineering projects to help raise confidence in a proposed design. While the testing of full-scale prototypes is common in other engineering disciplines, the sheer size of construction projects generally prohibits full-scale testing. Faced with this constraint, making and testing a model is an intuitive thing to do, and surely goes back thousands of years for artefacts made from the traditional materials – timber, mud and masonry. One advantage of masonry construction is that the structural behaviour of a small model can be scaled up linearly to full size, and give reliable guidance. This is why masonry construction was able to make such dramatic progress from modest houses to the temples of Ancient Greece, the vaults and domes of Ancient Rome and then to the remarkable cathedrals of the Gothic era. However, most engineering phenomena cannot be scaled up linearly, and engineering theory is needed to transpose the results of small-scale tests to full-size behaviour. There was some understanding of this even in ancient Greece, and Vitruvius mentions that some aspects of model behaviour can be scaled up linearly, while others cannot (see Appendix A1).

This book has two main aims – to fill a gap in the history of construction by demonstrating the essential contribution to engineering progress made by physical models, and to give an overview of some uses of physical models in the twenty-first century. The greater part of the book looks at the history of using physical models and within this theme, the larger part is devoted to the use of models in structural and bridge engineering and some mechanical engineering fields such as pumping water. This partition largely reflects when and how models have been used in engineering design and also the availability of historical material. The first three sections look at mechanical and structural models from ancient times to around 1980, by which time their use was in decline as computers became more powerful and widely available. The next section deals with the use of models in engineering disciplines other than structural engineering – measuring the flow and forces associated with fluid flow in hydraulic engineering and wind tunnels, the loads and dynamic response cause by seismic events, the acoustical characteristics of buildings and the behaviour of soils under load. The final section takes a look at current practice in using physical models today in several branches of civil and building engineering.

The main focus of attention in the book is on physical models used by engineers to determine quantitative data – for example predicting wind loads on a building using a model in a wind tunnel. In German the word '*Messmodell*' is a convenient term that distinguishes this type of physical model from others that are merely mechanical or 'proof of concept' models or geometrically representative. Where appropriate, this book uses the term '*measurement model*' – a direct translation of the German word – for this purpose.

Despite being a large book, it has only scratched the surface of this enormous subject. Nearly every chapter would merit the more thorough attention of several doctoral students. I have not attempted to present the first instance of each model-testing technique, nor to cover every field of civil and building engineering that has made use of models, nor to look at the use of models in experimental science with purely scientific aims, nor to present the model-testing efforts of every country. The focus of the book has been on the use of models to inform engineering design, and it uses examples wherever it has been possible to find them. While aiming to provide an overview of the whole subject, I am aware of the unintentional biases that have pervaded my own researches due to the libraries I have been able to use, the relatively few languages that I speak, and the cultural filtering of information via the non-egalitarian Internet. I have done my best to overcome these challenges.

I would like to acknowledge the assistance I have been given in compiling the book – first, and most of all, from the authors, many of whom have squeezed the work required for their chapter into very tight work schedules. I would also like to thank the authors of Chapters 3, 4, 11, 13, 16 and 19 for the help they gave me in translating their contributions from their original languages. I would like to thank colleagues and library staff in several universities and the Institution of Structural Engineers in London for the help they gave me. I give special thanks to Annette Ruehlmann in the Institution of Civil Engineers in London, who found many sources and scanned many images for me. And finally, I give my heartfelt thanks to my partner, Martine Gowie, who has been very patient while I have written and compiled the book, and who has been such a great supporter of my project, in so many ways.

Before delving further into the book, it is worth shedding any idea that the model testing discussed in the book, especially since the mid-nineteenth century, is mainly a lot of (usually) men playing with toys. Even though two articles in a 1920s popular-science journal about model tests for the Boulder Dam were informative and 'serious', their titles portrayed a rather different image – 'Toys that save millions' and 'Toy dams to save lives'! The care and accuracy with which model tests were carried out was extraordinary – often measuring strains or deflections to a hundredth of a millimetre or better. They were no more 'playing' than when brain surgeon is at work. Nevertheless, even in the 1930s, there were engineers who scorned model testing – 'a vet would hardly be entrusted to operate on an elephant if he had gained his knowledge of anatomy from a mouse'. On the other hand, another engineer noted that you can learn a lot about the behaviour of dogs by observing puppies. It is to be hoped that this book will clarify matters.

Bill Addis
May 2020

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8

Models used during the design of the Boulder Dam

Bill Addis

8.1 The US Bureau of Reclamation dams: 1925-1940

Two factors contributed to a huge transformation in the use of models in the 1920s. In 1902 the western states of the USA formed the Reclamation Service (later the Bureau of Reclamation) to prevent the terrible damage caused by regular flooding. The Bureau was given an enormous budget for research into the construction of dams, both for flood management and the generation of hydroelectric power. One major research theme, from about 1920, was to develop reinforced concrete arch dams as an alternative to conventional cantilever gravity dams. In essence, these were thin concrete shells, not too remote from the concrete shell roofs that were being developed in several European countries from around 1900.

For the first arch dams built in the early years of the twentieth century, the theoretical analysis of the dam treated the shell as a cylinder. However, this was far from ideal since, in a typical V-shaped canyon, at each higher level in the shell, the arch elements had increasingly longer spans, and there were significant discontinuities between adjacent arch elements. Despite various attempts at resolving these difficulties, it became widely agreed that the mathematical models being used were still not adequately representative of the real structure and, indeed, were becoming more and more abstract and distanced from reality [1]; a particularly harsh critic was the eminent structural engineering academic, Hardy Cross (1885-1959) [2].

8.2 Preliminary model studies

8.2.1 Stevenson Creek Experimental Dam

In 1923 a proposal was made to the Bureau's board to build an experimental arch dam to investigate thoroughly the behaviour of a concrete arch (shell) dam. Construction of the test dam at Stevenson Creek, California began in 1925 at the site of a disused miners' dam, and was completed in summer 1926. Deflections of

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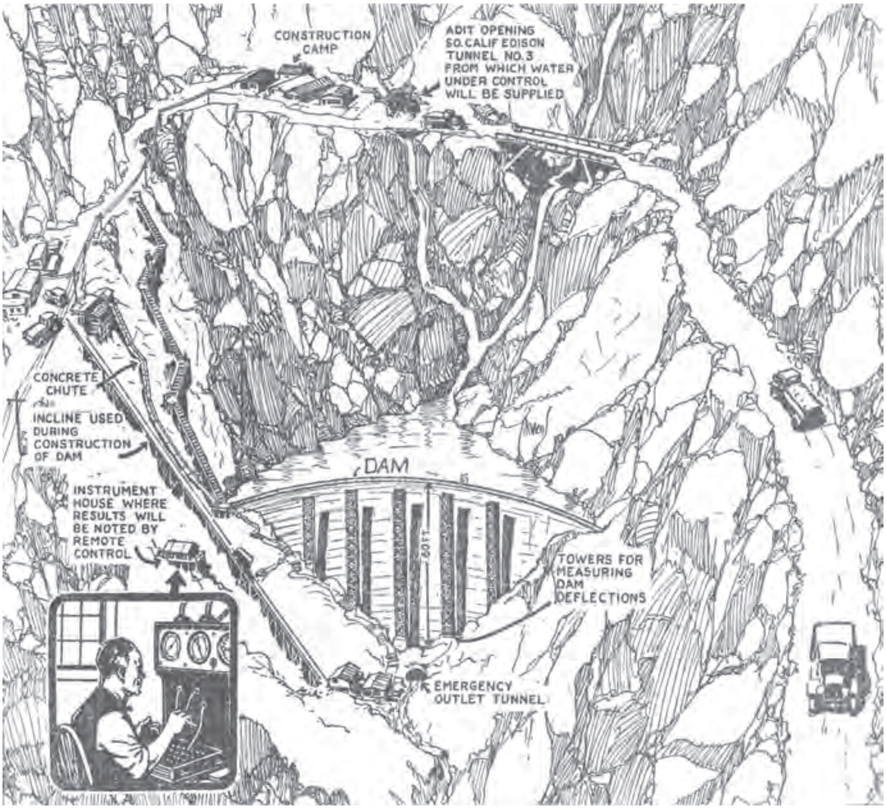

Figure 8.1 Artist's impression of the Stevenson Creek Experimental Dam, 1926. (Image: Courtesy of the Huntington Library, San Marino, CA. Southern California Edison Photographs and Negatives. No. p16003coll2_5463_full)

the thin shell were measured from the access scaffolding on the downstream face of the dam. Internal strains within the concrete were measured using electric carbon-pile telemeters, which had recently been developed by Roy Carlson (1900-1990), a physicist working on the project. These were embedded in the concrete during construction and their output was monitored remotely, via 'sensor wires', in a hut above the dam (Figure 8.1). In addition, internal temperatures of the concrete were monitored in order to be able to separate the influences of temperature-induced loads from physical loads. The dam was 18.3 m high and about 25 m long, with a constant radius of 30.5 m. Its thickness reduced from 2.3 m at the base to just 600 mm at half height, and continued with this thickness to the crest of the dam. Such a slim profile was unprecedented (Figure 8.2).

Meanwhile, measurements of stress and strain taken on other dams were not as convincing as had been hoped, as it proved difficult to interpret the data that had been collected. In December 1925 it was therefore decided that a programme of testing reduced-scale models should be carried out in parallel with the tests on the Stevenson Creek dam. The main model of the Stevenson Creek dam was made of concrete and built at 1:12 scale, 1.5 m high, 3.6 m long, and reducing

Figure 8.2 Stevenson Creek Experimental Dam in October 1926. (Image: Courtesy of the Huntington Library, San Marino, CA. Southern California Edison Photographs and Negatives. No. p16003coll2_22295_full)

from 19 cm at the base to just 5 cm thick at the top of the dam [3, 4]. One of the research team at the University of Colorado in Boulder was Dr Fredrik Vogt (1892-1970), an engineer who had previously carried out tests on model dams made of stiff rubber in his native country of Norway. His contribution to the Stevenson Dam model was aptly celebrated in the popular scientific press under the heading 'Toy dams to save lives' [5]. The concrete was made using rock aggregate from the site of the real dam, and the model was loaded using mercury in a rubber bag. Testing began in 1926 and, after a full programme of elastic tests, the main model was loaded to destruction in December 1928. Measurements taken from the model and the full-size dam were in close agreement and were used to check and improve the mathematical model used for the theoretical analysis. The model tests allowed the researchers to draw the following principal conclusions:

- A properly constructed small-scale model can be relied upon to produce strains and deformations similar to its prototype;
- Mercury is a satisfactory medium for producing model testing loads;
- The trial load method of analysis gives accurate results for a thin arch dam (The 'trial load method' involved reconciling the deflections of the shell calculated in two ways, one assuming the dam consisted of a series of vertical cantilevers, the other as a series of horizontal arches.)

In parallel with the Vogt's model tests on the Stevenson Creek Experimental Dam, George E. Beggs (1883-1939) at Princeton University undertook his own study of the dam using a 1:40 scale celluloid model of the cross section, and employing his patented 'deformeter' to measure deflections (see Section 13.5) [6].

8.2.2 Gibson Dam

The experience gained on the Stevenson Creek Experimental Dam was carried over to the design of the arch-gravity high Gibson Dam in Montana, which is 60 m high. A 1:68 scale model was tested in 1929 [7]. It was 88 cm high, 4.1 m long at the crest with a thickness that reduced from 39 cm at the base to 6.7 cm at the top. Like the Stevenson Creek model, it was constructed in concrete and loaded using mercury in a rubber bag. The Gibson model investigations included a temperature test as well. The temperature of the model was first raised by running hot water over the faces; when a fairly uniform high temperature was obtained the model was allowed to cool, after which the temperature was further lowered by running ice water over the faces. Continuous observations of radial deflection and temperature were taken throughout the temperature cycle [8]. These model studies corresponded well with theoretical calculations and measurements of the actual dam, and gave further confidence in the trial-load theoretical calculations and the use of reduced-scale model tests for the design of large arch dams.

8.3 Boulder Dam – structural model studies

The use of model testing for the Stevenson Creek and Gibson dam served as preparation for the largest dam of all – the enormous Boulder Dam on the Arizona/Nevada border (now the Hoover Dam) (1930-1936). It is an arch gravity dam – 221 m high, 200 m thick at the base, 12 m thick and 379 m long at the crest. At its completion in 1936 it was the largest dam in the world. The hydraulic works extend about 700 metres up- and downstream from the dam. Given the unprecedented size of the project, the design engineers for both the structure of the dam and the hydraulics believed it necessary to undertake model studies to complement and check their theoretical calculations [9, 10] (Figure 8.3).

8.3.1 The 1:240 scale plaster-Celite model

The purpose of the main structural model was to confirm calculations obtained using the trial-load method of analysis which was the best available at the time [11, 12]. This would be done by measuring surface stresses on the up- and downstream faces of the dam, and measuring deflections of the faces of the dam and radial and tangential deformations of the crest, when subject to a hydrostatic loads.

The very size of the dam posed new challenges for the programme of model testing. First of all, based on the experience of the Gibson model, it was clear that a model made of concrete, even using mercury to load the model, would be too

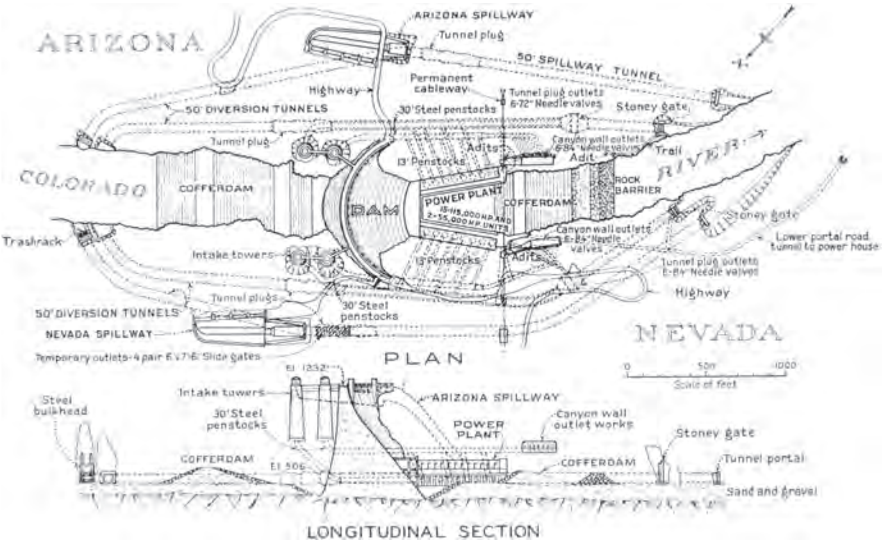

Figure 8.3 General scheme for the Boulder Dam (Source: [9] p. iv)

stiff to give deformations that could be measured to sufficient accuracy. A new model material had to be developed, with a lower modulus of elasticity but with other qualities necessary to ensure similarity with the real dam, and suitable to use for a model test. Thirteen different mixtures of materials were considered before a suitable material was found – a mixture of normal builder's plaster and a diatomaceous earth, a soft, sedimentary rock, abundant in Colorado and sold under the trade name Celite.

The model was 90 cm high, 82 cm thick at the base, reducing to 6.7 cm at the crest. The model was cast in layers 6 cm deep, which were allowed to cure for seven to ten days, and thermocouples were embedded in the model for measuring internal temperatures. The load was applied using mercury in a rubber bag that was placed in the 20 mm gap between the model dam and a fixed wooden form, that had been used for casting the model (Figure 8.4). Uniform loads could also be applied using water under mains pressure in the rubber bag. Construction of the model and test rig began in December 1930 and the first tests were undertaken on 7th July 1931.

While the model remained unchanged, different arrangements for measurement were used according to the purpose of different tests. For example, dial gauges sensitive to 0.0025 mm were used to measure the radial movement of the crest of the model dam (Figure 8.5). All rods used for mounting the gauges were made of Invar to avoid temperature effects.

After the early tests it was decided it would be important to take account of hydrostatic loads acting on the rock sides of the canyon which supported the dam. Additional loading bags for mercury were made and fitted to the model. A different arrangement of clock gauges was used to measure the tangential movement of the crest of the dam, due, in part to movement of the canyon sides (Figure 8.6).

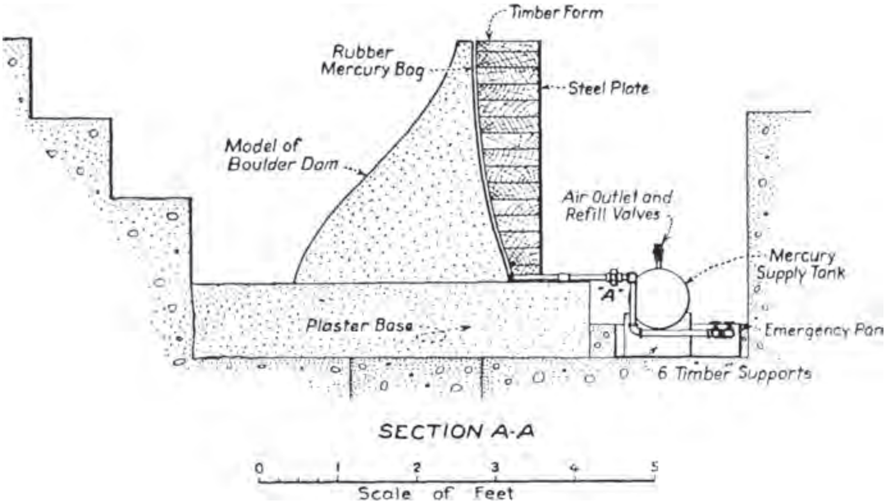

Figure 8.4 Section of the model showing the wooden form and the apparatus for introducing the mercury from below. (Source: [9] Fig.70)

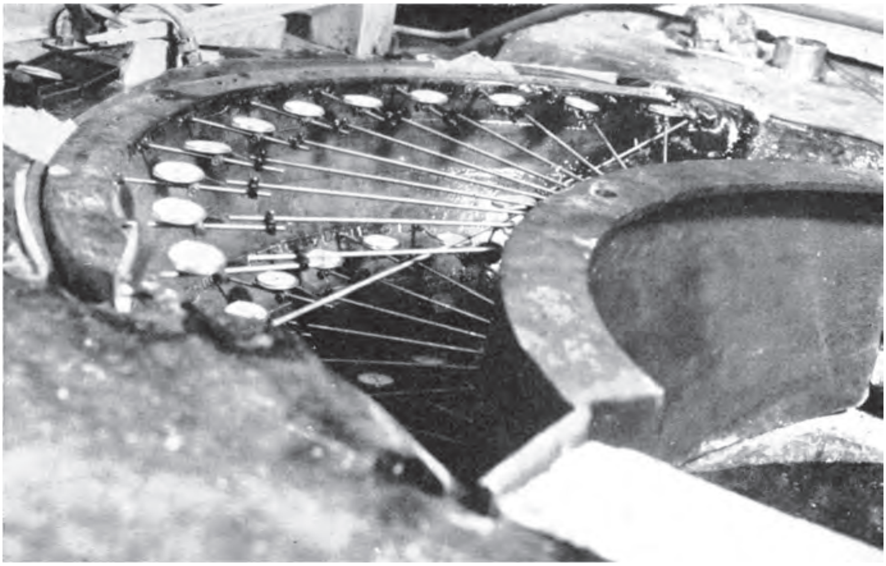

Figure 8.5 Arrangement of gauges for measurement of radial deflections of the crest on the downstream face. (Source: [9] Fig.72)

In order to measure cantilever strains on the downstream face, dial gauges were mounted between pairs of anchors (Figure 8.7). Again, tests were undertaken with and without loads applied to the canyon walls.

A further series of measurements were taken to determine the change of slope of the dam face. These were made using an optical lever system – a narrow beam of light was directed to a mirror mounted on the model, and its reflection courses. From 1936, Guido Oberti began organizing special exercises – mainly on photoelastic stress analysis – for students.

10.2.2 Models for concrete dam design in the 1930s

The construction sector that really drove the research by Danusso and his team was hydroelectric engineering. Structural modelling made it possible to optimize the sections of very complex projects, and so save on the total quantities of materials used. These savings were particularly marked on large-scale projects such as dams which used huge quantities of concrete. Moreover, the particular geometry used for dams was found to be more readily reproducible by a physical model at a reduced scale rather than by mathematical formulae.

Following the well-known model tests carried out in the USA – e.g. for the Stevenson Creek experimental dam (1925-32) and the Boulder arch-gravity dam (1930-35) [18] (see Chapter 8) –, Danusso and Oberti started a series of important experiments on dams using photoelastic stress analysis [19] (Figure 10.5).

The photoelastic study for the Santa Giustina dam, 140 m high, carried out in 1935-38, was fundamental to examining and understanding the behaviour of thick-arch dams. Tests were conducted assuming the continuous elastic arch was built not on rigid rock, as was commonly assumed, but on elastic rock, with a modulus equal to that of the concrete. Many arches were studied, with circular profiles on the up-stream and down-stream sides, both with constant and variable thicknesses and with different subtended angles. As Oberti stated: 'The analysis

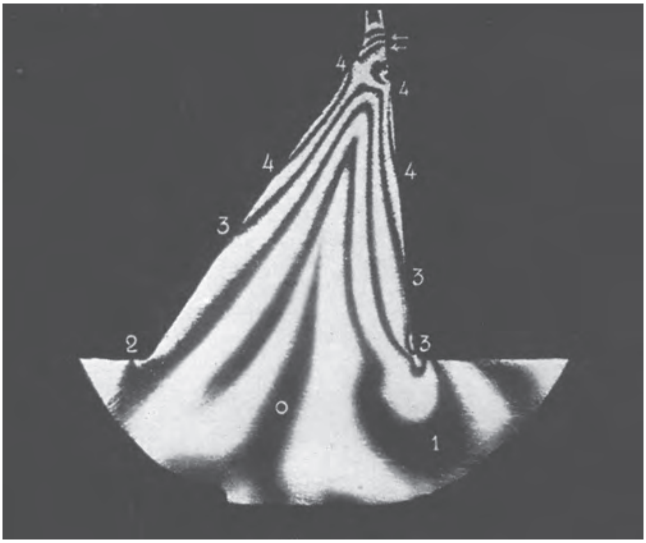

Figure 10.5 Photoelastic model analysis of a gravity dam subject to the action of ice at the *Prove Modelli e Costruzioni* Laboratory. (Source: [13])

of the results and their comparison with those of the elastic computation made it possible to clarify the statical behaviour of the structure and to reduce the initially planned volume for the lower half of the dam' [20].

Three-dimensional tests on gravity dams were carried out for the first time in 1936 for the design of the maximum-height buttress of the straight Scais dam, near Sondrio in the Italian Alps. Results were interesting for many reasons: first, to check the approximations made in the calculations which assumed a linear variation of the vertical stresses; secondly, because a new approach was achieved in the construction, which was developed in two stages by fixing the profile of the construction joint according to the isostatic lines obtained using the model [20].

Among the other tests carried out by Oberti we can mention those on a 120-metre high buttress adopted for dams at Lake Ancipa (Sicily) and Lake Bau-Muggeris (Sardinia). He used a celluloid physical model (linear scale, $\lambda = 100$) tested under hydrostatic load, imposed using mercury (13.5 times denser than water), and using a great number of electric resistance strain-gauges to determine the principal stresses and isostatic lines both on external and inner faces: 'The results, compared with those of conventional calculation, bore out a satisfactory agreement and made it possible to determine the pattern of stresses acting on the foundations' [20].

More important and extensive were the experiments carried out on three-dimensional models for arch dams. Oberti did the first investigation on the Rocchetta arch dam (70 m high), east of Genoa in 1937-38, using a 1:40 scale model made of gypsum-Celite which was tested both for elastic behaviour and for failure. Tests showed a satisfactory behaviour of the dam and – for the first time – emphasized 'how single curvature arches react to the loads acting on them, even beyond the elastic range, and made it possible to evaluate the statical resources of arch dams (even if slender and thin) and the high overall safety factor. Moreover, these results confirmed those obtained for the Stevenson Creek dam in tests confined to the elastic range, investigating high bending stresses acting on vertical elements (cantilevers). Even taking into account the balancing effect of the dead weight, the idea of designing double-curvature, rather than single-curvature, arch dams arose spontaneously' [21].

These experiments were useful for the investigations for the Osiglietta dam (1935-37) to the west of Genoa, which had to close off a 200 m wide and 75 m high gorge. Tests were planned to compare a single curvature classical type and a double-curvature type, using celluloid models and mercury to simulate the hydraulic load within the elastic range. They demonstrated that the doubly-curved dam reduced tensile stresses along the cantilevers, increasing the contribution of those elements just by reason of their arch shape. Other structural behaviour demonstrated by models led to a complete modification of the boundary conditions of the dam: rather than being encastred, it would bear upon a standard pulvino foundation embedded in the rock face, through a continuous perimeter joint [21].

10.3 The encounter between Arturo Danusso and Pier Luigi Nervi

In 1935 there took place an important encounter in the history of Italian model testing. At that time, the engineer Pier Luigi Nervi (1891-1979) – who had just become well known thanks to his design for the Berta Stadium in Florence [22, 23, 24] – was trying to define the structure of a series of reinforced-concrete aircraft and seaplane hangars, but he was not, in fact, able to determine analytically the complex interplay of forces acting on the highly statically-indeterminate structural system he had devised. Rather than calculated, the shape of the vault had been designed 'by intuition': 'I have to clarify – Nervi later admitted – that my hangars had been defined through approximate calculations derived from simplified hypotheses, on which basis it would be really imprudent to proceed with the real construction' [25]. So, he turned to Danusso and his team for help.

The complex roof – a shell composed of a double-lattice structure of reinforced-concrete ribs on a rectangular plan (110 x 36 m) – was thus reproduced at the Polytechnic of Milan as a 1:37.5 scale celluloid model (Figure 10.6). Various tests were carried out on this model to analyse its elastic behaviour under a dead load and overloads by hanging calibrated weights on the structure to simulate real loads. The dead loads acting on the structure were the self-weight of the reinforced-concrete framework and the self-weight of the roof, evaluated at 100 kg/m^2.

Loads were applied to the model using calibrated weights, hung by wires fixed to the nodes of the lattice. The lateral nodes were more heavily-loaded than the central ones owing to the slope of the vault. As live load, only wind pressure on the main doors, at an incident angle of 10° to the horizontal, was simulated. Strain-gauges on the upper and lower edges of the various beams, allowed the

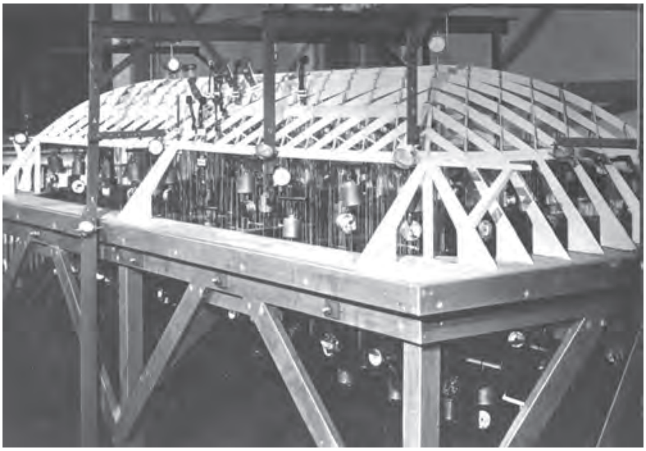

Figure 10.6 1:37.5 scale celluloid model of the reinforced-concrete hangars (first version) designed by Pier Luigi Nervi, tested at the Politecnico di Milano, 1935-36. (Image: ISMES Historical Archive)

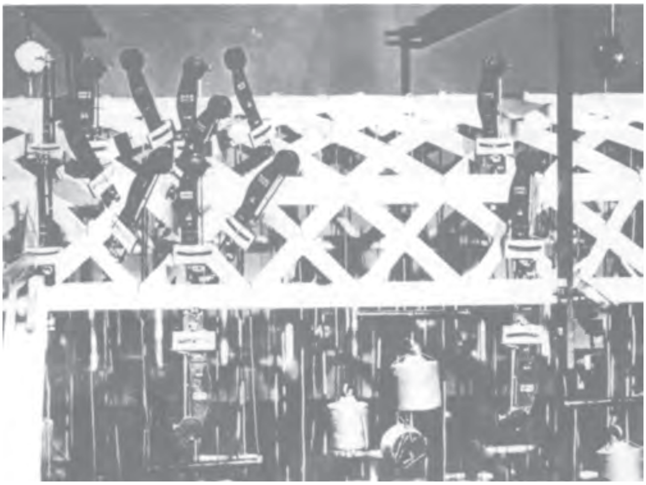

Figure 10.7 1:37.5 scale celluloid model of the reinforced-concrete hangars. Detail showing Huggenberger Tensometers (strain gauges) in place (see Section 13.4.2). (Image: ISMES Historical Archive)

axial and bending actions on the most important ribs to be studied [26, 27, 28] (Figure 10.7).

The model was tested only in the elastic range under its own self-weight and wind loads. In these experiments the model thus became the simple analogue substitute for a calculation of the system of elastic stresses, a calculation which nowadays can easily be made by means of digital numerical models. The problem of a more realistic assessment of the margin of safety thus remained open, as happens every time a structure is modelled as fully elastic.

The main reason for this choice was undoubtedly due to the large dimensions of the hangar vault, and to the unusual slenderness of the crossed ribs of which it was formed. If these extreme characteristics had been taken together it would have required excessive dimensions for models designed to simulate the real behaviour of the reinforced-concrete structure beyond the elastic range up to collapse, at the same time suffering the distortions caused by the effects of scale. Albeit within these limits, the observations drawn from the tests allowed Nervi to obtain information useful for the fine-tuning of the initial project, in particular with regard to the design of the large horizontal bracing beam, as observed so incisively by Danusso and Oberti: ‘Here, too, the calculation – like matter for Dante – may be unresponsive, deaf. Not the model, however: in fact the model was a precious counsellor of useful modifications’ [13].

It should be emphasised, however, that the bold, innovative structural design developed by Nervi, despite the minor changes prompted by the tests, was generally perfectly adequate – proof of his remarkable capacity for structural design and statical intuition, and his mastery of construction. This was a constant that characterized the results of all the experiments carried out on the works of the great architect-engineer. Experimental testing, conceived as an assessment of the

Figure 10.8 1:37.5 scale celluloid model of the reinforced-concrete hangars (second version) designed by Pier Luigi Nervi, tested at the Politecnico di Milano, 1938-39. (Image: ISMES Historical Archive)

original structural design, was, in effect, a substantial validation, providing indications for improvements in the dimensioning of single components that brought little alteration to the initial outline. The measures implemented by Nervi at the conclusion of the construction work during the decentring of the two hangars built using this structural scheme at Orvieto (1935-38) offered further confirmation of this.

A second model, at the same scale, was built and tested in 1938-39 for the six hangars to be built at Orvieto, Orbetello and Torre del Lago, conceived in this case with a symmetrical structural system and improved in accordance with the results of the tests performed on the first model (Figure 10.8). The deflections under load were determined in this second series of model tests, and later confirmed by *in-situ* measurements of the finished structure, once the thermal effects, which were not negligible, had been taken into account [29].

10.4 Model analysis and structural intuition in the work of Pier Luigi Nervi

These investigations discussed above revealed to Nervi the power of experimental model analysis and, moreover, confirmed the particular vision of engineering and structural design that he had expressed in many writings from 1931 [30, 31]. Rejecting the idea that engineering was a science, built by means of perfectly-describable phenomena and exact rules, Nervi criticized the mathematical hegemony in the curriculum of engineering schools, considering it to be the cause of the lack of creativity and, most of all, the cause of the loss of the designer's essential skill: *structural intuition*. From the moment that, in a statical problem, some data such as external forces, internal elasticity and the real materials' resistance turn out to be 'essentially unknowable', Nervi asked himself: 'what is the real value of those numbers, reached using formulae which treat accurately things which are not accurate, unless they are to give the order

26

The historical use of models in the acoustic design of buildings

Raf Orlowski

26.1 Early twentieth century

26.1.1 Model studies using the sound-pulse method

Wallace Clement Sabine (1868-1919) was the father of modern acoustics. As a young physicist working at Harvard University, he became involved in room acoustics when he was invited, in 1895, to improve the acoustics of the recently-built Fogg Lecture Hall which had very poor intelligibility. This led him to develop an experimental approach to studying reverberation, sound intensity and room acoustics. He used an organ pipe as the sound source and, working before it was possible measure sounds electrically or to record them, he relied on his ears to judge the intensity and quality of the sound [1]. In 1913, he was the first to study the reflection characteristics of auditoria by using a recently-developed technique for photographing the propagation of a sound pulse within a model of a section of a theatre [2]. The method relied on the technique of *schlieren* photography invented in 1864 by August Toepler (1836-1912) which makes visible any changes in air density [3]. A sound pulse was generated in the model and, as the sound wave and its reflections passed through the model section, they refracted the light and the image was recorded on a photographic plate [3, 4] (Figure 26.1).

Sabine tested models of the New Theatre in New York, in both elevation and plan, to verify that the sound spread uniformly through the theatre and also to demonstrate the effects of fitting a canopy in the main auditorium to try to improve its acoustics (Figure 26.2). He later collaborated with the architect C.H. Blackall while he was designing the Scollay Square Theatre in Boston, and used his sound-pulse technique to demonstrate the acoustic improvement achieved in the final design, compared to an earlier scheme.

Sabine's method was further developed, to be more practical, at the National Physical Laboratory (NPL) in Britain in around 1922 [5, 6]. A large Wimshurst machine, capable of generating a potential of 100 kV, was used to charge up a number of capacitors. Using trigger-sparks, the capacitors were discharged through two spark-gaps marked 'sound spark' and 'light spark', both within a

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Figure 26.1 Sound-pulse photographs by Sabine showing the progress of a single wave through a plan of a theatre. (Source: [4] Figures 22-24)

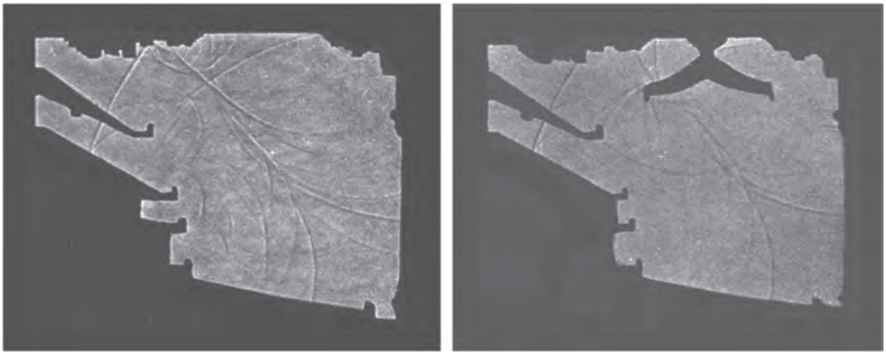


Figure 26.2 Sound-pulse photographs by Sabine showing the effect of modifying a theatre ceiling. (Source: [4] Figures 16, 19)

light-tight box. The 'sound spark' generated a sound pulse which was illuminated a fraction of a second later by light from the delayed 'light spark'. The light from the 'light spark' cast a shadow of the sound-pulse on a viewing screen or photographic plate at the end of the box. The model section of the building whose reflection characteristics were required was located so that the gap of the 'sound spark' was within the interior of the section and at right angles to its plane. The model was made of ebonite or hardwood, usually at a scale of 1 inch to 32 feet (scale factor 1:384) (Figures 26.3 and 26.4). This apparatus was capable of making photographs showing the progress of waves in a time-interval corresponding to about 125 milliseconds in a full-size building.

The sound-pulse technique was used to study the acoustics of the Royal Institution Lecture Theatre in London [5] (Figure 26.5). The photographs show that, in general, the sequence of sound reflections and their delays were favourable for good speech intelligibility, although the sound reflected from the upper part of the wall behind the speaker, which finally returned to the floor after a second reflection from the ceiling, contributed to an echo effect perceived in the front seats. It proved possible to eliminate this slight defect by mounting some sound-absorbent material on the upper part of the wall behind the lecturer.

The sound-pulse method was further developed in Switzerland in the 1930s by the Swiss engineer Franz Max Osswald (1879-1944). He was Switzerland's first

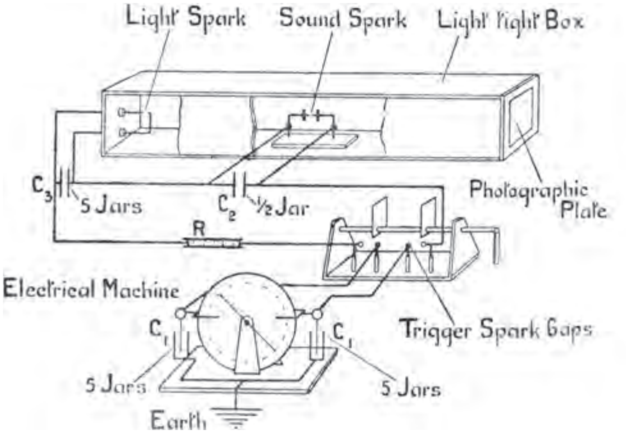


Figure 26.3 Diagram of apparatus for sound-pulse photography developed at the NPL. (Source: [5] Figure 16)

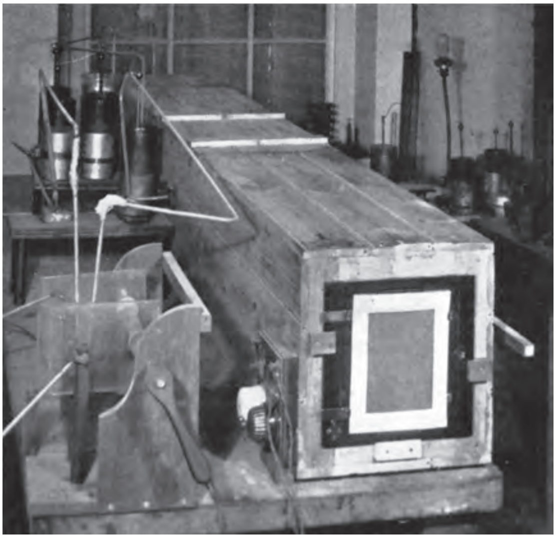


Figure 26.4 NPL apparatus for sound-pulse photography. (Image: Courtesy of National Physical Laboratory)

specialist in architectural acoustics and founder of the first applied acoustics laboratory at the ETH, in Zurich. He set up his laboratory in 1930 with an apparatus very similar in concept to that of Sabine and at the NPL (Figure 26.6a) [3, 7, 8]. Osswald undertook many studies similar in kind to those of Sabine and the quality of the photography and data that could be extracted, reflected the technical progress that Osswald had made. He undertook many studies for cinemas and concert halls, for example, investigating the effects of different profiles for the walls and ceilings [9] (Figure 26.6b). One of his first studies was for an auditorium with a movable ceiling that would enable the volume to be decreased from 8750 to 6100 m^3, and the reverberation time from 1.6, suitable for large-scale classical music, to 1.3 seconds, suitable for more intimate music and the spoken word [10] (Figure 26.7).

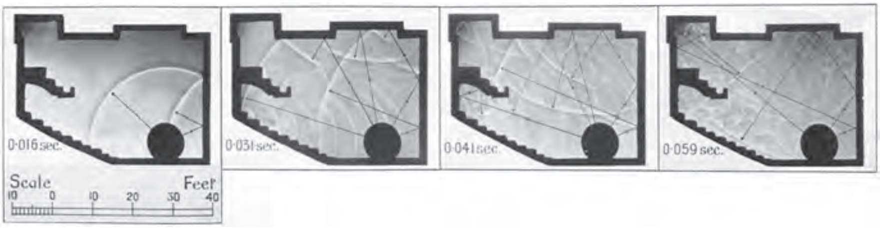
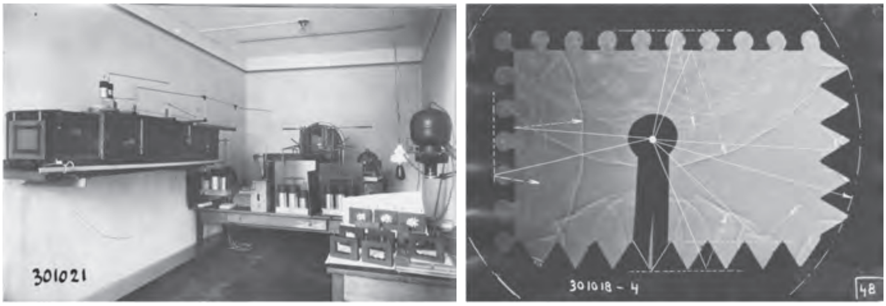


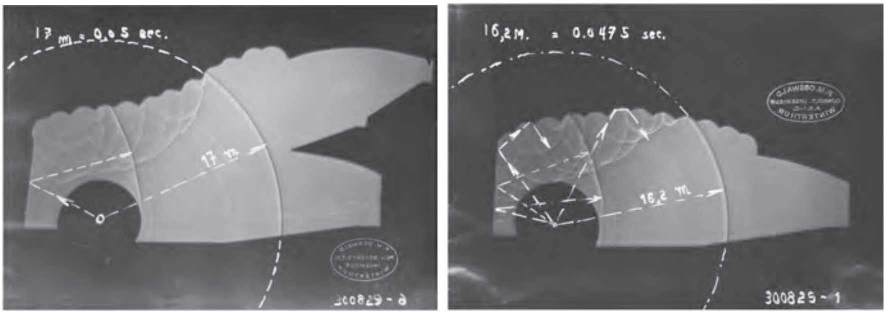
Figure 26.5 Sequence of sound-pulse photographs taken at the NPL of the Royal Institution Lecture Theatre. (Image: Courtesy of National Physical Laboratory)



(a)

(b)

Figure 26.6 (a) Apparatus room at Osswald's applied acoustics laboratory at ETH Zurich, 1930. (b) Study of wall profiles in cinemas, 1930. (Images: Image Archive, ETH Library Zurich)



(a)

(b)

Figure 26.7 Sound-pulse study of an auditorium with variable volume, 1930. (a) Ceiling raised. (b) Ceiling lowered. (Images: Image Archive, ETH Library Zurich)

26.1.2 Model studies using the ripple-tank method

The ripple-tank method was based on the fact that ripples in a small tank of water are suitable for modelling sound waves in a space; wavelengths were typically comparable with the size of the models being tested. The method had is origin in the early nineteenth century when Thomas Young used a ripple tank to model the behaviour of light waves and to demonstrate interference. The technique was adapted by the NPL in the 1920s to provide a visual demonstration of

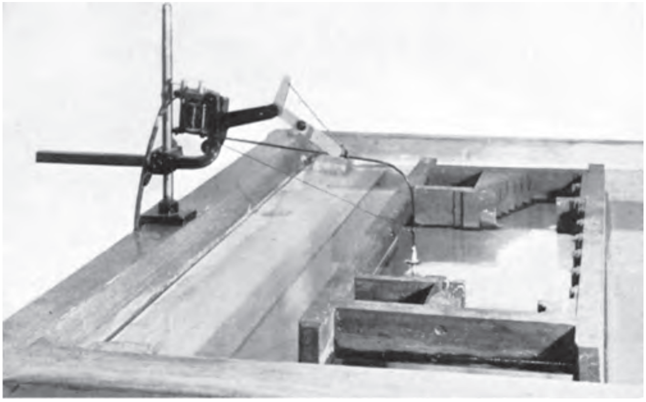


Figure 26.8 Ripple tank at the National Physical Laboratory, 1920s. (Source: [5] Figure 31)

the propagation of sound waves. A great advantage of this technique, especially compared to the sound-pulse method, was that it was easy to carry out and quick to modify the cross-section of a room to see the effect of changes on the acoustic behaviour [5] (Figure 26.8).

A typical ripple tank arrangement involved a model of a longitudinal section of a hall at a scale factor of about 1:50 placed on the glass bottom of a shallow tank of water. The reflection characteristics of the model section were observed by the behaviour of ripples produced by a plunger just dipping into the water at the location of the sound source in the hall. To help view the progress of the waves, light was shone upwards through the glass bottom of the ripple tank to cast a shadow of the waves on a screen placed above. By taking a series of photographs at intervals, the impact of the waves on selected features of the room could be shown. In one such sequence of photographs of waves in an auditorium section, the distance from crest to crest between successive ripples corresponded to sound waves of length from 0.5 metres to 1.4 metres in the full-scale building, i.e. sounds in the important frequency range 250-700 Hz (Figure 26.9). Rays showing the direction of the wave fronts were added to a diagram and the auditorium section judged to be satisfactory. With regard to possible echoes, the dimensions of the hall indicate that most sounds reach listeners after one reflection within one-fifteenth of a second of the direct sound. However, reflections from the backs of the galleries are directed upwards towards the ceiling and on reflection arrive at the floor too late to reinforce the direct sound [4].

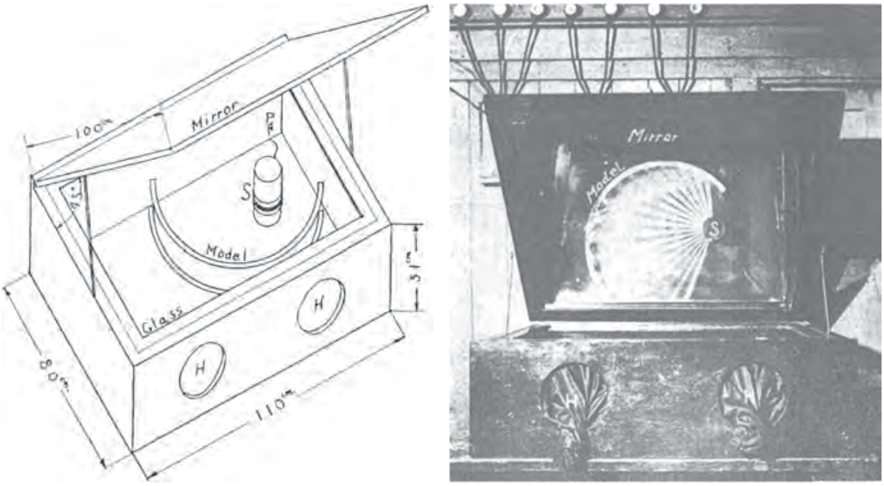
(a) (b) (c)

Figure 26.9 The progress of ripples in a sectional model of an auditorium. (a) Geometric construction. (b) Sound pulse image. (c) Ripple tank image. (Source: [5] Plate VII)

26.1.3 Three-dimensional model studies using light rays

A fundamental advantage of three-dimensional models is that they enabled complex three-dimensional sound propagation to be explored. A simple but useful way of doing this is to use light rays rather than sound sources, since light rays can be assumed to behave like sound waves at high acoustic frequencies. We find in Vitruvius the idea of imagining sound as travelling in straight lines like rays of light and this formed the basis of guidance to theatre designers from the early-nineteenth century when the first books on acoustics and theatre design were written [11]. Using a narrow light beam, the paths of individual reflections can be traced. Reflective surfaces can be modelled by mirrors and absorbent surfaces by matt black materials.

The Japanese acoustician/architect Takeo Satow (1899-1972) described in 1929 his own version of such a modelling apparatus which he had been using fruitfully for several years [12]. A polished metallic model of the cross section of an auditorium was placed in a box with a glass lid. Light rays radiated from the position of the stage and were made visible by means of smoke introduced into the box (Figures 26.10 and 26.11). A small cylindrical prism could be placed in the auditorium where a listener might be. The prism reflected light arriving from all directions perpendicularly to the incident rays so that the intensity of light (i.e. sound) arriving from different directions could be made visible (Figure 26.12). Satow considered his method particularly advantageous in allowing different auditorium sections to be made and modified easily, since it required little specialist training to use, and could also be used to convince people with little knowledge of acoustics.



(a) (b)

Figure 26.10 Takeo Satow's apparatus for creating light-ray images. (a) The wooden box showing the source of light rays, position of the model, glass top to the box and mirror used to view the rays. (b) The experimenter's view of a model under study. The holes at the front of the box provide hand access to adjust the model. (Source: [12])

31

Physical modelling of free surface water – current practice

James Sutherland

31.1 Introduction

Laboratory-based physical modelling has been the most widely-accepted method of undertaking hydraulic modelling for many years [1]. The steady rise of computing power has meant that this position is changing [2]. 2-D (depth-averaged) numerical flow models are being replaced by more detailed 3-D flow models or even computational fluid dynamics (CFD) models.

For example, back in the 1970s the modelling of tides and sediment transport in an estuary or large river would normally have been undertaken using a physical model. Today, such studies are almost always conducted using numerical models – with the exception of some very large-scale models. As another example, wave propagation studies in shallow water are now also undertaken using numerical models, where previously they were done using physical models.

However, physical modelling has been evolving alongside computational modelling. The main reason for this is that Moore's law (which states that computer power doubles about every 18 months) also applies to the equipment used to generate the input conditions to a physical model and to measure the resulting flows, sediment transport and bathymetry. The increases in computer power, the development of Ethernet technologies for transferring data and the shrinking of electronics mean that more and more detailed measurements at finer resolution and higher frequencies can be measured in physical models and in the field [3, 4]. This has allowed more detailed investigations of increasingly complex phenomena to be undertaken. This trend is expected to continue and new measuring techniques are being developed, allowing physical measurements at a greater spatial density [2, 5]. Knowledge of model scaling is also developing [1, 6, 7, 8] which improves our understanding of the applicability of model results.

As a result, there has been a trend for computer models taking over the simulation of flow and wave conditions that are linear, or close to linear, while physical models remain dominant in areas with strong non-linearity. There has also been an increase in the combined use of physical and numerical models, known as hybrid or composite modelling, to address problems in both structural design and environmental fluid mechanics [9, 10].

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Physical models can also play an important role in studies relating to climate change. Numerical models used for climate-change impact analysis cannot be validated against field measurements for conditions beyond the range of the current climate. Since we have no field data truly reflecting future conditions, a key challenge in climate-change adaptation is to rigorously test models using proxies of future conditions. Physical modelling offers the opportunity to test present-day situations and possible climate-change adaptations against a range of hydraulic boundary conditions, such as sea-water level, wave height and flow speed that exceed present-day conditions and are compatible with climate-change projections.

This chapter shows how physical models are being used today to address practical problems in the design and operation of various developments and infrastructures. The following sections describe:

- the main areas of physical testing undertaken in commercial European laboratories;
- the capabilities of some of the modern measurement techniques;
- how physical models are increasingly used with numerical models to address practical concerns.

It does not cover academic research or the more detailed, specialist equipment that is generally confined to research projects.

31.2 Physical model testing

Physical model testing plays an important part in the development and validation of the design of many coastal, maritime and freshwater hydraulic structures. Some of the most common forms of structure tested in hydraulic laboratories include breakwaters and floating structures. These may, of course, be combined in the design of a new harbour or marina, or could be entirely separate. Some examples of the different phenomena tested are given in the following sections.

31.2.1 Wave overtopping of structures

Waves passing over the top of a structure can cause damage and disruption to the structure itself and to assets being protected by that structure. Different types of activity and structure have different acceptable overtopping rates, commonly expressed as the average volume of water to pass a metre length of the structure in each second. A range of conditions is likely to be tested, from those occurring several times a year – to determine safe operational conditions – to extreme design conditions and commonly, an overload condition.

An example of a wave-overtopping test carried out in a wave flume, with random waves approaching straight onto the structure is shown in Figure 31.1. This type of test is known as a two-dimensional (2-D) test. Three-dimensional (3-D) tests can also be undertaken in wave basins. Often a 2-D test at a larger scale (such as 1:20) is carried out in a flume, while a 3-D test at a scale of 1:40 to 1:60 is carried

Figure 31.1 A 1:30 scale model test showing wave overtopping of a seawall. (Image: © HR Wallingford)

out in a wave basin. Modern wave paddles, driven by electric motors, can be used to generate different standard wave spectra, such Pierson-Moskowitz or JONSWAP spectra, or specialised spectra, such as combinations of swell (long-period waves generated a long distance away) and wind-sea (with shorter period waves, generated more locally). In the case of three-dimensional tests, the wave conditions can be long-crested (coming from a single direction) or short-crested (coming from a range of directions). Wave conditions can even be varied along the face of a wave-maker to represent spatial variations in incident wave conditions.

31.2.2 Breakwater stability

Another common type of hydraulic test is used to study the stability of a breakwater. These can be constructed from scaled rock or scaled concrete armour units, commonly hired from the patent holder. Rock sizes are scaled to take account of variations in the density of water and rock armour, while filter-layer scaling has to take account of permeability as well. An example of a model breakwater is shown in Figure 31.2. Templates are normally used to achieve the correct cross-section of every layer, while concrete armour units often have to be placed in a specialised way to create the correct packing density.

The movement of armour can be measured using a range of methods. Traditionally, the elevation across a number of sections through a model has been measured using a point gauge. Increasingly, terrestrial laser scanners or other optical techniques, such as photogrammetry or structure-from-motion, have been used to create a three-dimensional digital elevation model (DEM) of the entire structure (Figure 31.3). It is possible to get much more detailed assessments of damage suffered using a DEM than using a few profiles.

31.2.3 Loads on structures

Loads on structures can be measured using a whole-body force table or pressure sensors (Figure 31.4). Whole body force tables can be used to measure forces and

Figure 31.2 Waves breaking on a physical 1:48 scale model of a breakwater. (Image: © HR Wallingford)

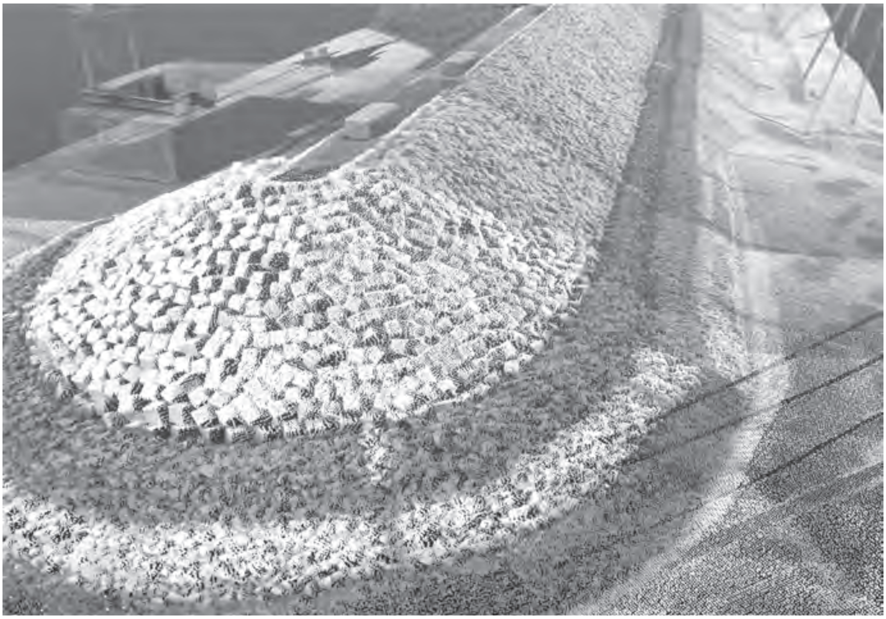


Figure 31.3 Laser scan of a 1:50 scale model breakwater used to reveal damage suffered during a test. (Image: © HR Wallingford)

dismantled and some of the components were salvaged for making new models. However, an equally serious threat to the survival of models is when an institution closes or refocuses its interest towards new activities; entire collections of models have been lost in this way. Nevertheless, some models have survived and it is to be hoped that these models continue to survive and, when necessary, are conserved, and also that models that are at present simply 'lying around' somewhere may be recognised for their value and saved, either in the original institution or in a museum. The projects mentioned in this section represent a few examples known to various chapter authors of this book.

39.3.1 Models for designing concrete shells

Dyckerhoff & Widmann was one of the firms whose own testing laboratories finally closed in the 1960s, no doubt with the loss of many models. Franz Dischinger (1887-1953) had been a pioneer of model testing from the 1920s (see Chapter 9). One experimental model shell does remain, known for the iconic photograph of it supporting 39 employees, including Dischinger himself (see Figure 9.5). The Biebrich shell is now relocated in the factory grounds of Dyckerhoff GmbH in Wiesbaden-Amöneburg [47].

Only one model remains from the *Institut für Modellstatik* at the University of Stuttgart – the 1:27 scale model in Perspex of the hyperbolic-paraboloid roof of the Alster swimming baths in Hamburg. It is now mounted in the entrance hall of the Department of Civil Engineering at the university, standing nearly two metres high (see Section 14.2.2). Fortunately its destruction was prevented in 2009, but now its condition is deteriorating as some of the glued joints have become brittle and parts have suffered damage from impact. Until now, its large size has prevented it from becoming part of a collection [48].

A few models remain from ISMES in Bergamo, though none of the iconic structures by Nervi. A 1:100 scale wind tunnel model of the Norfolk Scope Arena, Virginia (Arena built 1965-1971), produced at ISMES and tested at the *Politecnico di Torino* 1964, still exists, and has been conserved by *Centro Museo e Documentazione Storica* at the *Politecnico di Torino* (CEMED) in Turin [49] (see Figure 15.19a). Two models used during the design of St. Mary's Cathedral, San Francisco by Nervi still exist. One is a 1:100 scale wind-tunnel model, produced at ISMES in 1964 and tested at the *Politecnico di Torino*, and now preserved at CEMED (see Figure 15.16). The other is a 1:36.89 scale model of St. Mary's Cathedral made of resin that was used for static and dynamic tests at ISMES in 1965, and is now located at the *Dipartimento architettura rilievo disegno urbanistica storia* (DARDUS) at the *Università Politecnica delle Marche*, in Ancona, Italy (Figure 39.5). The same department owns another model from ISMES, a 1:50 scale model used for static and dynamic tests in 1960 during the design by Nervi of the Leverone Field House in Hannover (Figure 39.6).

The contents of Heinz Isler's test laboratory were donated after he died to the *Institut für Geschichte und Theorie der Architektur* (Institute for the History and Theory of Architecture) at ETH in Zurich [50]. This archive consists of over 500

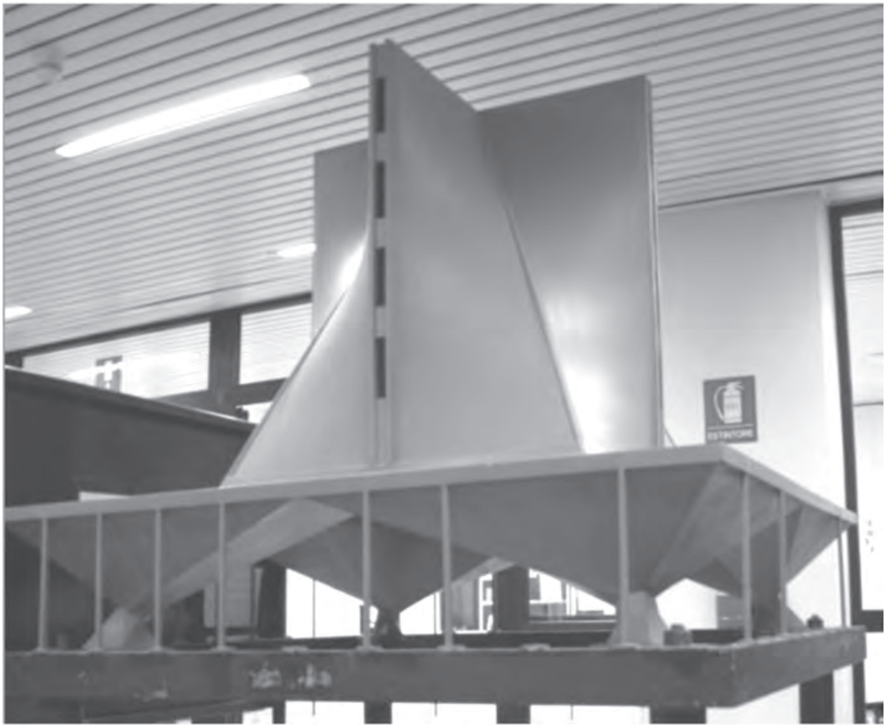
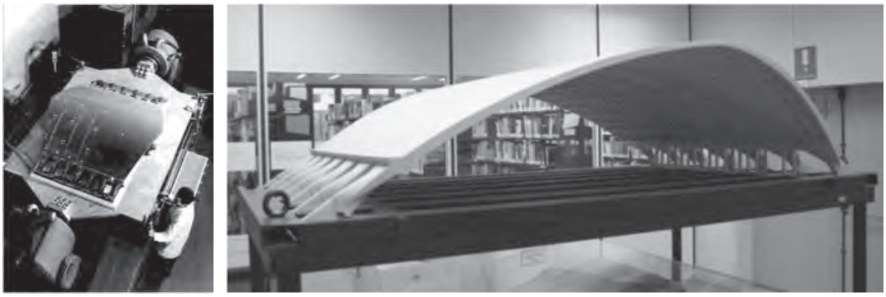


Figure 39.5 A surviving model of St. Mary's Cathedral, San Francisco designed by Nervi, 1964-1965. 1:36.89 scale model made from resin for elastic and dynamic tests. (Image: Gabriele Neri)



(a) (b)

Figure 39.6 Model for the Leverone Field House, Hannover. (a) Model under test in 1971. (Image ISMES). (b) Model now located at the *Dipartimento architettura rilievo disegno urbanistica storia at Università Politecnica delle Marche*, in Ancona. (Image: Gabriele Neri)

models of various sizes and types, of which thirty-seven are measurement models and seven or eight of these are still mounted in their original test apparatus (Figure 39.7).

Sadly no original physical models remain of the many structures designed by Eduardo Torroja (see Chapters 11 & 16) or Heinz Hossdorf (see Chapter 18).

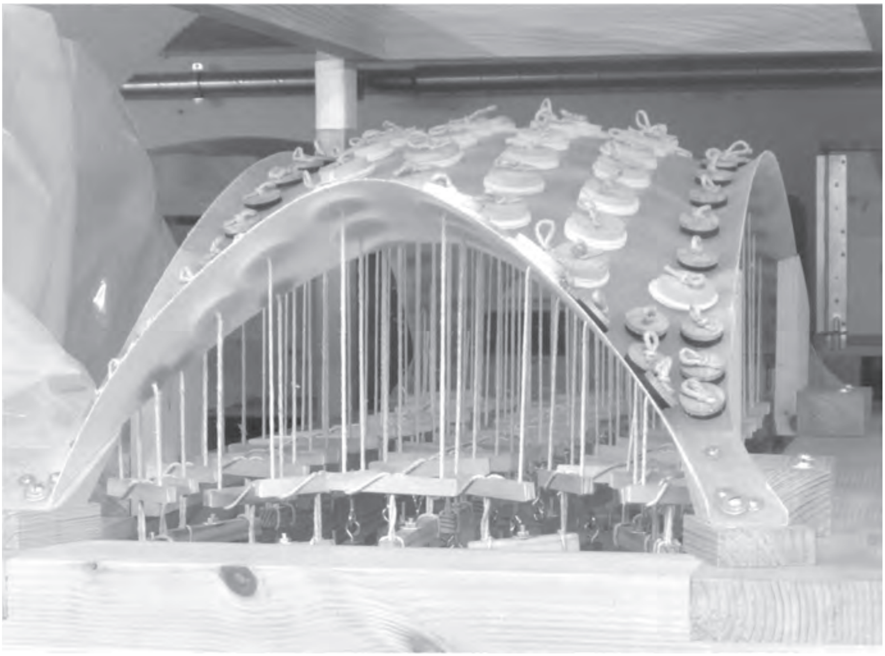


Figure 39.7 Model of one of Heinz Isler's characteristic shell roofs in its original testing apparatus. Now located in the Isler Archive at the ETH, Zurich. (Image: Bill Addis)

39.3.2 Frei Otto models

Frei Otto retired in 1990, and in 2011 the Southwest German Architecture and Engineering Archive acquired most of the models built in Otto's office in Warmbronn and exhibited them in 2017 at the *Zentrum für Kunst und Medien* (ZKM, Centre for Art and Media) [51]. The inventory embraces over 400 models, and is thus among the most comprehensive collections of models from twentieth-century Germany that exists. Among these are many form-finding models but scarcely any measurement models. A small measurement model of Otto's IL pavilion at Stuttgart, donated by Bertold Burkhardt to the *Deutsches Architekturmuseum,* (DAM), Frankfurt on the occasion of the exhibition *Das Architekturmodell: Werkzeug, Fetisch, Kleine Utopie,* bears witness to the first experiments with tensile structures and their design methods (Figure 39.8). The IL Pavilion effectively served as a large-scale experiment for Otto's much larger German Pavilion at the Montreal Expo in 1967. As the 1:75 measurement model of the Montreal Pavilion no longer exists, the small model of the IL Pavilion is the only representative of the unique experiments using models for the design of the German Pavilion [52]. The model now complements the DAM's collection of approximately twenty of Frei Otto's form-finding models. The founding director of the *Deutsches Architekturmuseum*, Heinrich Klotz (1935-1999), first presented Frei Otto's designs and models at the DAM exhibition *Vision der Moderne* in 1986 [53].

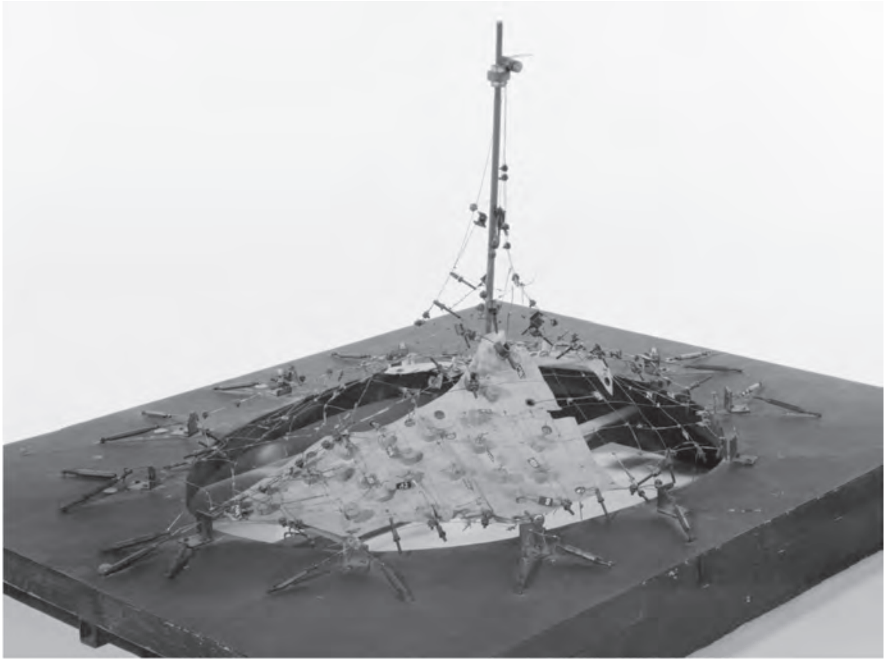


Figure 39.8 Measurement model of Frei Otto's IL Pavilion at the University of Stuttgart. (Image: Architekturmuseum München)

In Otto's original IL Pavilion, which now houses the *Institut für Leichtbau Entwerfen und Konstruieren* (ILEK), there are still several form-finding models for the Munich Olympic Stadium roof and a measurement model that was used to define the low point of the cablenet roof over the Olympic swimming pool at a scale of 1:25 [54]. This model is still located on its original marble slab which serves as a rigid base. However, despite having a cover, the model is slightly damaged and is in need of conservation. The IL Pavilion also still houses the unique apparatus constructed to measure and photograph soap-film models (see Figure 19.3). This apparatus is still cared for and is surely a candidate for perseveration in a museum.

Fortunately, there also remains the large measurement model (about 2 x 1.5 m) that was used by Otto in developing his design for the large sports hall for the Munich Olympic Games in 1972 (Figure 39.9). It is on public display in the Information Centre at the Olympia Park in Munich.

39.3.3 Miscellaneous structural models

For the design of the suspension bridge across the Lillebælt strait in Denmark in 1964, the firm C. Ostenfeld & W. Jønson Consulting Engineers (now COWI) commissioned tests to be undertaken on a 6-m long model. Fortunately, the model was rescued from destruction by Professor Guido Morgenthal at the Bauhaus University in Weimar, where it is now on display [55, 56] (Figure 39.10).

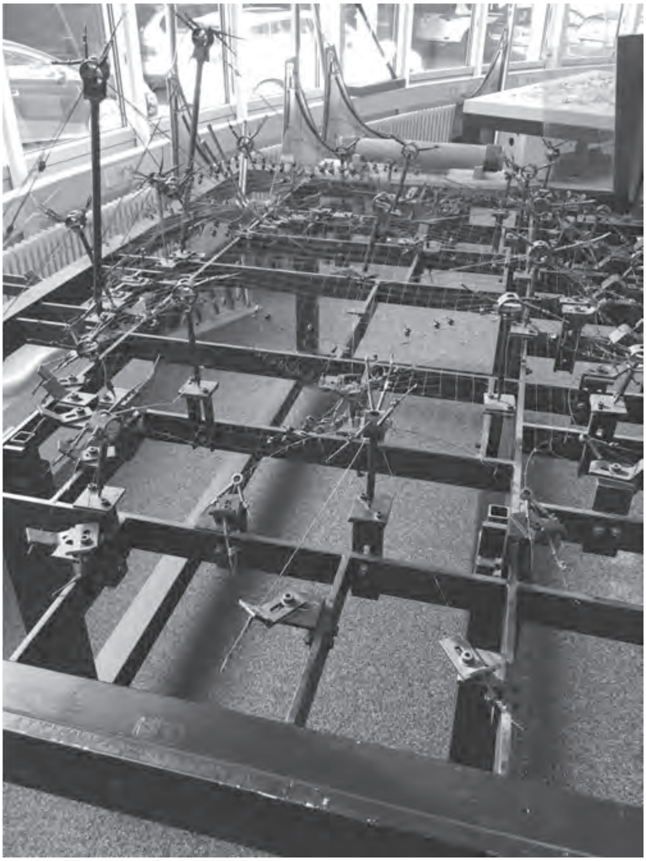


Figure 39.9 1:125 scale measurement model for the Olympic Sports Hall at the Munich Olympics, 1972. Now located in the Information Centre at the Olympia Park in Munich. (Image: Christiane Weber)

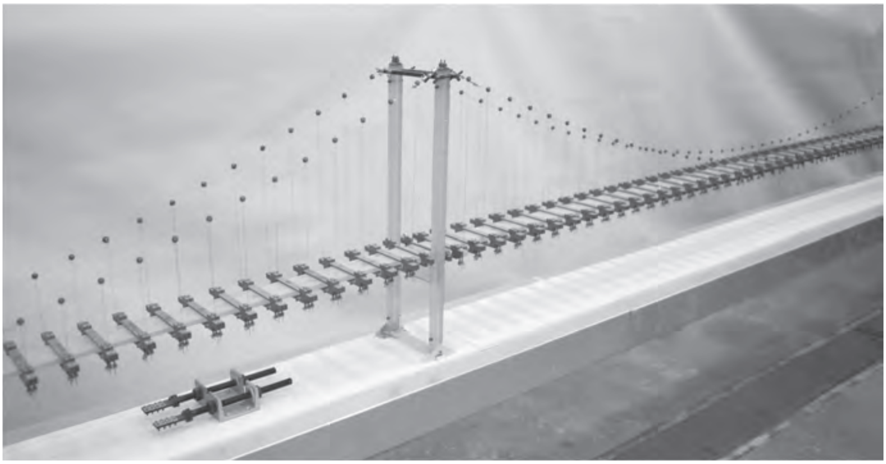


Figure 39.10 Measurement model of the suspension bridge across the Lillebælt designed by C. Ostenfeld & W. Jønson Consulting Engineers. Probably dating from 1964, it is displayed today at the Bauhaus University, Weimar. (Image: Guido Morgenthal)