Zeitschrift: IABSE proceedings = Mémoires AIPC = IVBH Abhandlungen

Band: 9 (1985)

Heft: P-90: On the "optimum design" of large structures using physical models

Artikel: On the "optimum design" of large structures using physical models

Autor: Oberti, Guido

DOI: https://doi.org/10.5169/seals-39139

Nutzungsbedingungen

Die ETH-Bibliothek ist die Anbieterin der digitalisierten Zeitschriften auf E-Periodica. Sie besitzt keine Urheberrechte an den Zeitschriften und ist nicht verantwortlich für deren Inhalte. Die Rechte liegen in der Regel bei den Herausgebern beziehungsweise den externen Rechteinhabern. Das Veröffentlichen von Bildern in Print- und Online-Publikationen sowie auf Social Media-Kanälen oder Webseiten ist nur mit vorheriger Genehmigung der Rechteinhaber erlaubt. Mehr erfahren

Conditions d'utilisation

L'ETH Library est le fournisseur des revues numérisées. Elle ne détient aucun droit d'auteur sur les revues et n'est pas responsable de leur contenu. En règle générale, les droits sont détenus par les éditeurs ou les détenteurs de droits externes. La reproduction d'images dans des publications imprimées ou en ligne ainsi que sur des canaux de médias sociaux ou des sites web n'est autorisée qu'avec l'accord préalable des détenteurs des droits. En savoir plus

Terms of use

The ETH Library is the provider of the digitised journals. It does not own any copyrights to the journals and is not responsible for their content. The rights usually lie with the publishers or the external rights holders. Publishing images in print and online publications, as well as on social media channels or websites, is only permitted with the prior consent of the rights holders. Find out more

Download PDF: 22.08.2025

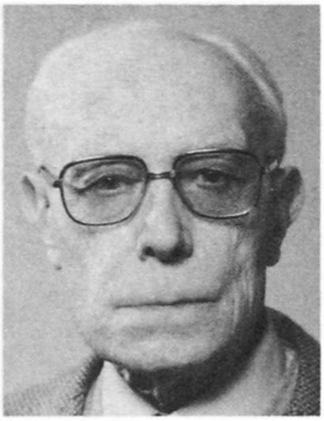
ETH-Bibliothek Zürich, E-Periodica, https://www.e-periodica.ch

On the «Optimum Design» of Large Structures Using Physical Models

Projet optimal de grandes structures à l'aide de modèles physiques

Über den «Optimalen Entwurf» von grossen Bauwerken und die Anwendung von physischen Modellen

Guido OBERTI
Em. Prof. of Structures
Polytechnic University of Milan
Milan, Italy



Guido Oberti, born in June 1907 in Milan. Doctor of Engineering and Doctor of Applied Methematics from the Milan Polytechnic University. Professor of Structures at the Polytechnic University of Turin from 1954 to the 1977. Emeritus Professor at the same University. Director of ISMES since its foundation in 1951, today President H.C. and Technical Adviser to the Institute.

SUMMARY

Any «optimizing» design of a large structure requires the interplay of art, science and experience. At present, the adoption of «computers» has caused upheaval in the use of conventional theoretical methods. Nevertheless physical models still offer interesting possibilities both in the design and in the verification of large structures, especially with difficult boundary conditions. Some examples, chosen by the author from his own experience, close the paper and show how these models help to achieve an optimum.

RÉSUMÉ

Le projet et la construction des grandes structures doivent être effectués en tenant compte de tous les facteurs de l'art, de la science et de l'expérience, afin d'atteindre la solution «optimale» pour l'ouvrage. Les techniques de vérification sont actuellement favorisées par l'emploi toujours croissant des ordinateurs, mais l'emploi des modèles physiques joue encore un rôle assez important dans les cas les plus difficiles. Quelques exemples, choisis par l'auteur, suivant sa longue expérience, concluent l'exposé, donnant une idée sur les possibilités actuelles de l'emploi de ces modèles.

ZUSAMMENFASSUNG

Ein optimaler Entwurf setzt ein Zusammenspiel von Kunst, Wissenschaft und Erfahrung voraus. Die Überprüfungsmethoden werden durch den Einsatz von Computern erleichtert, doch spielt die Anwendung von physischen Modellen in schwierigen Fällen nach wie vor eine sehr wichtige Rolle. Einige vom Autor aus seiner langjährigen Erfahrung gewählte Beispiele schliessen den Beitrag ab und zeigen den Wert dieser Modelle zur Erzielung eines optimalen Entwurfs.

1. INTRODUCTION

This report aims at briefly presenting criteria and experimental methods concerning the construction of a large structure. In my opinion, such criteria should govern the work of the designer, in the first stage, and that of the inspector, at the final stage. I am dealing with concrete structures; however, I deem that the points made might also be extended to steel or structures of other materials.

All the above is deduced from my long professional experience both as consultant, at times also designer, and inspector of large structures.

It should be stated beforehand that any "optimizing" design comes from the combination of art, science and experience.

First of all, a construction must be a work of art: the aesthetic meaning associated with static intuition has created the most admired large structures built in the past as well as in the present time. Science, actually, may aid the designer, by providing theoretical and experimental methods that enable him to design statically correct and advanced structures, as against those of former designers. Finally, experience gained in the professional activity improves the design work, thus leading to structures which have to be regarded as "optimal" from the aesthetic, static and economic point of view.

It is also worth pointing out that methods used by the designer consider the construction as a physiologically perfect organism. Really, like a living being, any construction is born, lives, undergoing fatigue or other deteriorating phenomena, and it ends (even after centuries). Moreover, during its life the structure may run into critical events such as: removal of forms, first loading, exceptional actions (earthquakes, alluvions, wars, etc.): the far-sighted designer should bear in mind all these factors.

Design should also be "integral"; that is, it should involve not only the structure's plan and its static and dynamic behaviour (foundation included) but also the choice of materials, the construction methods, and finally, the total cost of the work. Only in this way does the "optimizing design" become rational: in the static creation, in the detailed design, and in the economical construction.

Studies and preliminary designs should be governed by as complete as possible "input" data and analysis techniques. Otherwise, the designer may later be obliged to adopt alternative plans or changes to the original ones, with unforeseen higher costs.

Finally, the "inspector" or the Board of Consultants in the case of large structures, have to be appointed at the start of construction, so that they may follow the work's progress, and support the designer and the project engineer, who may carry out acceptance tests, after the construction is completed.

2. ON THE USE OF COMPUTERS IN DESIGN

I admit that most of large structures I had to study, both at design and construction stage, as consultant or inspector, over quite a long time (about 50 years) were planned and built following theoretical and experimental methods which, although being the most refined of that time, were rather conventional, and I should say "classic".

At present, the theoretical and also the experimental trend aims at exploiting the large possibility offered by electronic devices, both through the use of digital computers (having higher and higher capabilities) and of automatic instruments.

The adoption of "computers", with their capability for high speed digital computations, has almost superseded the use of theoretical conventional methods. Sophisticated programs, suited to the computer but not to manual computation, have been developed. The engineer must learn to use them but to avoid to being ruled by them. Sometimes there is a risk of arriving at an improper use of a complex "finite element" program, because the engineer tries and solves by it every structural problem, even in cases where the use of a simple ordinary calculation may achieve a more appropriate and less costly design.

As is well known, "finite element" programs are now widely available, both in consultants' offices and at Universities. A word of caution should, however, be given. The training of finite element users is sometimes inadequate, and refined computations may lead to high costs, as well as to wrong conclusions. It is not enough to be exposed to the mathematical background during a graduate curriculum. Specialized courses, just for the engineers who intend to use them in the design and in the structural check, should be offered also by organizations with an extensive experience in practical applications. For example, in Italy a continuing education program is available at ISMES (Experimental Institute for Models and Structures), in Bergamo.

It is worth recognizing that the structural check through the rational use of mathematical and physical models may lead to additional knowledge, unthinkable twenty years ago, on the threedimensional behaviour of structures, taking also into account the nonlinear and inelastic effects. For instance it is possible to study the static or dynamic behaviour of new and existing r.c. structures and to investigate the effects of cracks, if any, of large deformations, of creep phenomena, or of ground settlements, and the redistribution of stresses, also due to local plasticity.

New criteria may arise in the design of complex or highly hyperstatic structures, supported by difficult boundary conditions and subjected to various types of normal or exceptional loads. Thus, the possibility of assessing their safety with higher reliability and of arriving therefore at a design which is more economic and safer leads, in the end, to a real "optimization" of the design.

3. INTRODUCTION OF PHYSICAL MODELS

It is worth recalling here that expecially before the advent of computers, physical models were extensively applied, in order to overcome the limits of hand computations applied to large structures (dams, bridges, sky-scrapers). In my career I have widely used physical models which, in my opinion, still remain a valid tool.

I feel it is important to mention here too, the possibilities offered, even today, by experimental methods, both in the design and in the verification of large structures.

It is well known that the theory behind the use of models is based on the principle of similitude: prototype and model, geometrically similar, can also be physically similar when quantities of the same nature have a constant ratio at corresponding points. Such complete similitude is obtained when the non-dimensional ratios between the quantities that characterize the problem have the same numerical value both in the model and in the prototype. It is clear that the greater the number of ratios there are, the less simple the process becomes. But in our structural field the fundamental quantities are only three: the classic "length", "mass", and "time", or any three other equivalent quantities (provided they are dimensionally independent). Generally the ratios of similitude referring to length (λ), stress (ζ), and time (τ) are adopted.

The similitude of forces of inertia links the preceding ratios to the ratio (ρ) of densities, by the relationship:

$$\tau = \lambda \cdot \rho^{1/2} \cdot \zeta^{-1/2} \quad (1)$$

If the weight action has to be taken into account, the basic ratio assumed is that of the acceleration (in place of time) made equal to 1. Thus the ratio of time becomes

$$\tau = \sqrt{\lambda} \quad (2)$$

and eq. (1) yields:

$$\zeta = \rho \cdot \lambda \quad (3)$$

In static problem the variable "time" does not exist, and the basic ratios are reduced to two; however, the ratio λ, and κ, linking the two quantities normally assumed here as fundamental ("length" and "force"), to the ratio ζ of stresses, must be fixed:

$$\zeta = \kappa \cdot \lambda^{-2} \quad (4)$$

and the ratio of the other quantities having the dimensions of a stress (elastic modulus, yield limit, ultimate stress) must be equal to ζ.

Moreover, if the volume forces (e.g. the weight) are not negligible, relationship (3) is still valid and it implies the use of large scale models, the increase in the model material density or the decrease in its physical properties (elastic modulus, etc.).

When eq. (3) is satisfied during construction of the model and of its foundations, similitude is achieved also beyond the elastic limits. This has enabled us to investigate the safety of large structures (dams, bridges, sky-scrapers etc.) and to optimize their design.

4. APPLICATION OF PHYSICAL MODELS IN THE DESIGN STAGE

Tests on physical models may be classified in two main groups:
- The first group includes elastic problems.

The photoelastic and the Moiré methods were formerly applied frequently to "stress analysis". Now their use has decreased due to introduction of "finite element" methods.

Models of elastic three-dimensional structures have been largely employed as an "analog computer", and the final result can be compared with the theoretical one. The material may differ from that of the prototype.

In static tests, electrical deflectometers and strain gauges, usually applied to the surface of the model in various directions, measure displacements and strains, respectively.

In dynamic tests electromagnetic exciters and piezoelectric accelerometers are used as measuring instruments. The strains are still furnished by strain-gauges, connected to standard amplifying and recording electrical equipment.

We give as typical example: the model carried out (during 1962) for one of the reinforced concrete sky-scrapers (designed by P.L.Nervi in cooperation with the architect L. Moretti) built in Victoria Place in Montreal (Fig. 1)(°).

The model was built on a scale λ = 52.8. Given the material adopted (celluloid), the regime reproduced was purely elastic. It was laid on an elastic foundation, built of a pumice-stone and araldite block. The whole structure, model and foundation block, was then set (Fig. 2) and fixed to a large vibrating platform. The three degrees of freedom (that characterize similitude) were already saturated here, that is

$\lambda = 52.8$ $\zeta \approx 13$ $\rho = 1.88$

In function of these ratios, all other quantities involved in the problem were defined(°°).

Static and dynamic tests aimed at:

- Studying strains (and therefore stresses) in the elastic regime, particularly in connection with the effects of wind on the sky-scraper;

- determining period and deformation corresponding to the first natural "mode" of vibration;

- analysing the stresses resulting from the application to the base of the sky-scraper of periodic oscillations, with frequency equal to those of the natural "mode" of vibration referred to above.

(°) The impressive tower block, the highest building in reinforced concrete constructed at that time, approximately 145 m high and with 47 floors, has a structural plan that, at the base, is laid out on a 45 m-wide square. The large structure completed in only 13 months(in a seismic zone), has a central core made up of wind protection walls in the shape of St.Andrew's Cross, and 4 massive pillars sited at the corner of the tower block. The central core and outer pillars are linked on a level with 4th, 17th, and 31st floors by reinforced diaphragm elements which take up three floors; these elements render the whole structure almost monolithic.

(°°) In particular:

- the ratio between stresses and that between wind pressure : $\zeta = \sim 13$;
- the ratio between times (oscillation periods, damping etc.): $\tau = \sim 20$.

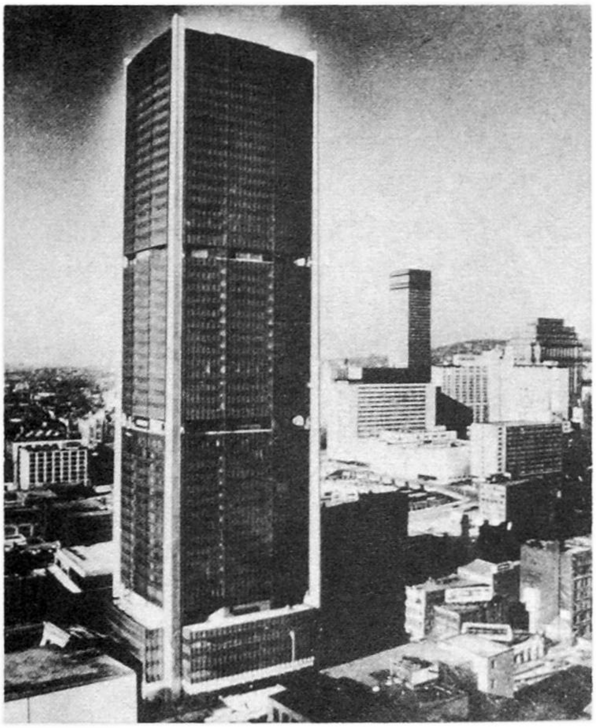


Fig. 1 Sky-scraper in r.c. in Montreal.

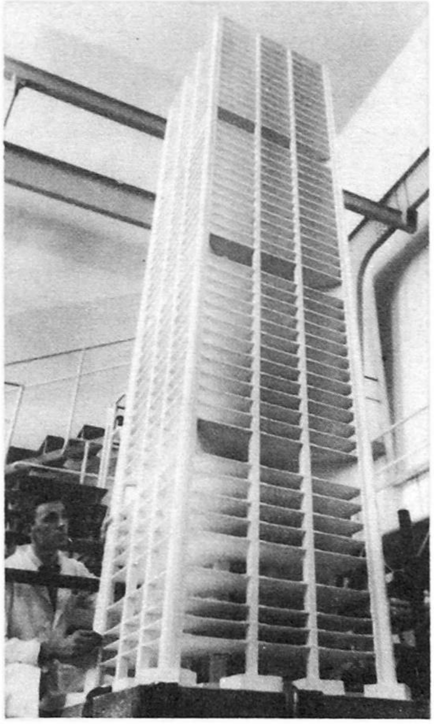


Fig. 2 The model of the sky-scraper in Montreal.

The second group includes the methods used in order to attain a real similitude with the prototype, rather than simply a check of the calculations. Tests can then be subdivided into two consecutive phases.

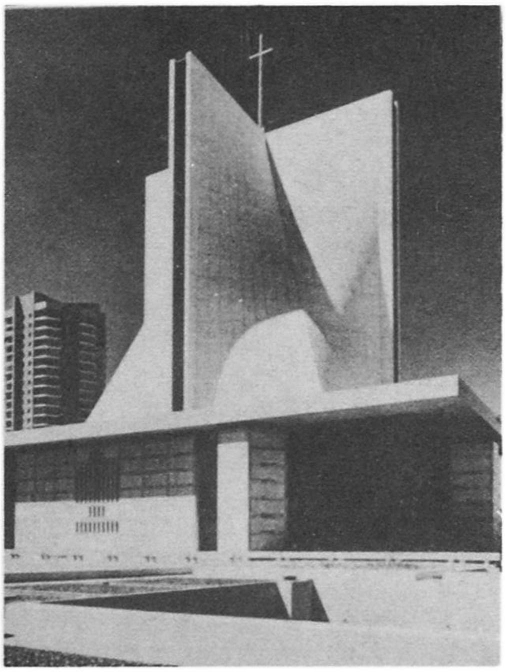
In the first phase, called "normal load phase",displacements and strains under the working loads are measured; already from the beginning various events (settlements of foundations, movement and slipping of joints, localized plasticity) can appear; it is convenient to cause them by means of load cycles repeated until the funtioning of a constant "regime" is attained.

In the second phase, the applied loads are gradually increased up to collapse. In this way the ultimate load carrying capacity of the structure is evaluated. The tests can also concern various types of loadings; then the study is completed by determining the "minimum" overall safety factor of the structure, and, if necessary, of structure and foundations as a whole.

These structural models, employed for testing beyond the elastic range, are usually made of the same material as the prototype. This is possible, for steel and reinforced or prestressed concrete structures, using suitably large models (scale 1:3 - 1:20).

But for some structures, such as concrete dams, economy makes it necessary to adopt small-scale models (1:50 - 1:150) and materials (micro concrete etc.) whose mechanical properties are "reduced" in relation to those of the prototype, in accordance with the similitude laws.

A typical example is offered by the studies carried out on the St. Mary's Cathedral (San Francisco - USA). On behalf of the Archbishop of San Francisco, at the request of P.L. Nervi, tests were performed on various models in the period 1964-66 (Fig. 3)(°).



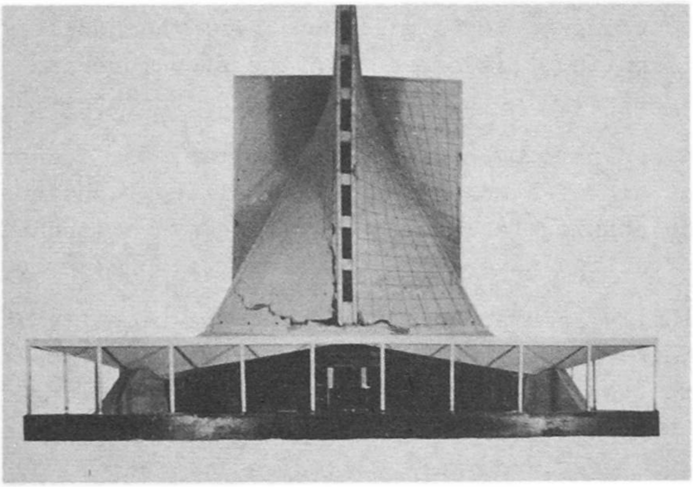


Fig. 3 St.Mary's Cathedral San Francisco-USA

Fig. 4 The model of St.Mary's Cathedral San Francisco - USA

At a preliminary stage a first elastic model, scale 1:100, served to carry out some aerodynamic tests, aimed at establishing the pressure exerted by the wind.

A second model, scale 1:40, was then constructed, with a special mixture of epoxy resin, in order to make both preliminary static and dynamic tests still in the elastic range, using a shaking table. The behaviour of the structure against the highest earthquakes foreseen in the St. Francisco area was checked.

Finally, a large model (scale 1:15) was built in reinforced micro-concrete. It incorporated various modifications introduced into the design as a result of previous tests. This model was used to carry out exhaustive static tests, gradually carried towards collapse, in such a way as to allow for evaluating the high safety factor of the imposing structure against the wind action (Fig. 4).

Special mention should be made of earthquake simulation in dynamic tests beyond the elastic range.

The tests are developed in three successive stages:
- at the beginning they are carried out by applying a sinusoidal motion in order to evaluate natural frequencies;

(°) The imposing building, supported by massive r.c. pillars, had a plan that, at the base, was laid out on a 62 m-wide square, which was subsequently increased to 75 m; the height from ground level was about 60 m, with a central hyperbolic paraboloid structure 40 m wide and 44 m high. This was accomplished by the raising of the axes of the springer square until it assumed the shape, at the top of the structure, of a cross. The roofing is made up of a mesh structure, in prefabricated r.c. elements.

- the second stage consists in generating a series of time histories, corresponding to the assigned "spectrum", applied to the base of the model set on a large shaking table;

- in the third stage only one of the time histories, that corresponding to the highest response, is applied, and its intensity is increased step-wise until failure is attained.

Indeed, in the case of failure models, it is difficult to reproduce exactly according to the similitude laws: the applied loads, the materials, the discontinuities present in the structure and also in the rock foundation (faults), especially in the case of large structures (dams).

In order to overcome these limitations, research is currently in progress with the aim of a more accurate modelling technique. The goal is that of abandoning the shaking table as an exciting system and of simulating the quake as a travelling wave at the base of the model produced by explosive devices.

Finally, geomechanical models were recently introduced to analyse structures with their foundations (dams, sky-scrapers, viaducts, highway tunnels). This relatively new type of model is based on the following concepts:

- they are basically failure models. Inelastic settlements gradually modify the structure state as the loading increases; therefore, only displacements are measured;

- they do not reproduce the foundations as a whole, but merely a "scheme" identified by geologists. This "scheme" must be clear, unsophisticated, easy to reproduce and suitable for any verification adopted in "situ". The purpose is one or more checks - those of greatest interest - to complete (or replace) the results of mathemathical models;

- they adopt a conservative "scheme"; therefore caution must be taken for the reproduction of the given physical parameters. Then the safety ratio obtained is a minimum value.

Following the experience acquired in this area two subspecies of model may be identified:

- one consists in modelling the structure in a conventional form, where (in certain cases) some damage is also reproduced:

- the other is that (true geomechanical model) where the structure is considered only as a device for load transmission to the foundation and where the stability check is mainly directed toward the foundation rocks and/or soils.

In this case, no artificial installation can be applied to reproduce the various loads (see wire-loading, etc.), special materials are used with strongly reduced mechanical properties, in agreement with the geomechanical scale ratio.

As a typical example I recall here a recent large model (scale 1:130) of ITAIPU buttress dam in concrete (Brazil-Paraguay), the world's largest actually constructed (Fig. 5).

The central section of the dam consists of over 180 m-high hollow r.c. buttresses, founded on stratified basaltic rock, which has extensively been reproduced in the model, built in 1978 and tested in 1979 (Fig. 6).

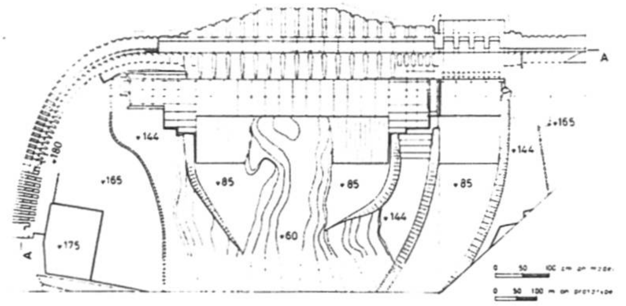


Fig. 5 Plan of the geomechanical model. Itaipu dam

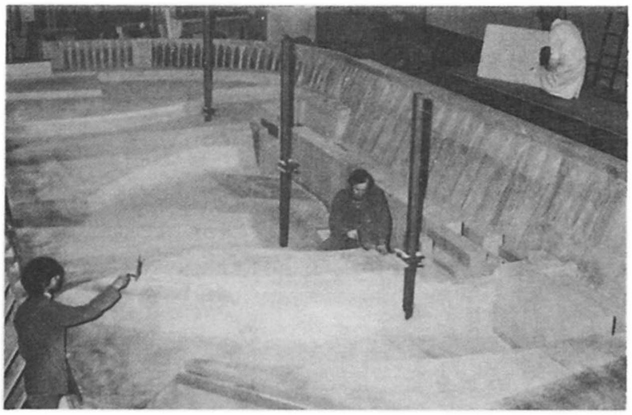


Fig. 6 The model of Itaipu. General view

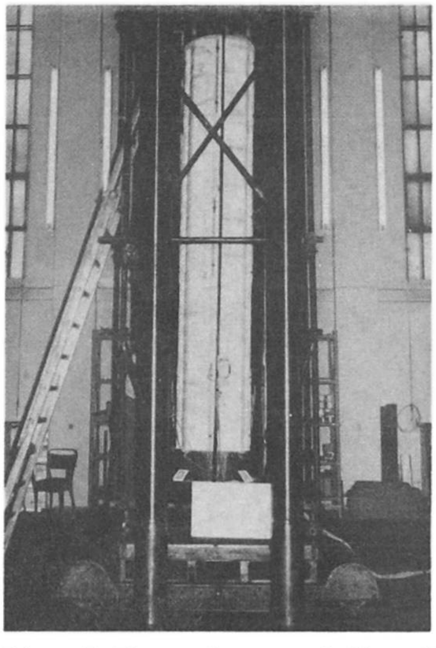


Fig. 7 The columns of the Dome tiburium under the press

5. USE OF PHYSICAL MODELS FOR THE ANALYSIS OF EXISTING LARGE STRUCTURES

Physical models are also valid when the stability and safety factor of existing large structures are to be checked. Particularly when these structures are to be controlled, and when static or dynamic (seismic) conditions were not entirely foreseen in the original design.

Among the models which yielded highly significant results, for evaluating the safety factor of a unit structure, we mention here, as an example (Fig. 7), the failure tests, on 1:4 scale models, carried out to investigate the safety of the main columns carrying the tiburium of the "Duomo", i.e. Milan Cathedral (Figs. 8,9). The structure appeared in a critical static situation, with many fractures on the exterior face, mainly due to differential settlements of the soil. The two different materials used for construction of the models (Candoglia marble and Serizzo granite) and the geometry of the component blocks were identical with those of the prototype. By means of these structural models several types of reinforcements for the columns were tested and, step by step, a final "optimizing" solution was achieved.

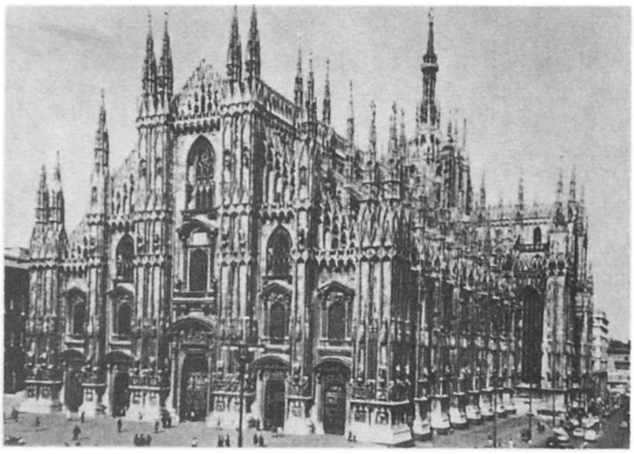


Fig. 8 The Cathedral of Milan

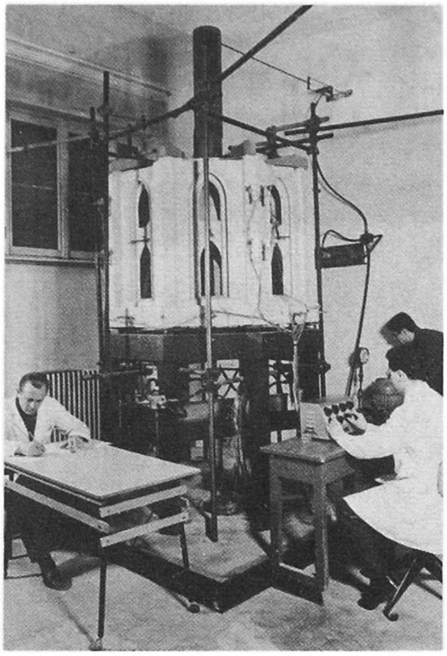


Fig. 9 Tiburium of the Milan Cathedral

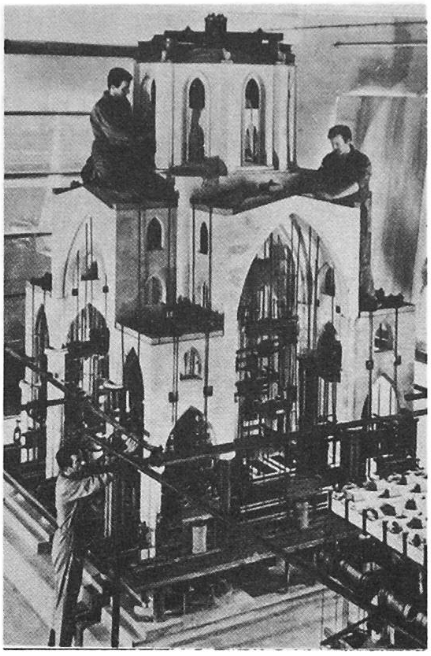


Fig. 10 The model of the Cathedral

Moreover, the general stress conditions in the masonry dome, bearing the main spire of the Cathedral, were also examined on a large 1:15 scale elastic model (Fig. 10) under various alternative scenarios of differential settlements of the foundation.

6. CONCLUSIONS

I hope to have given an idea on the actual possibilities of physical modelling of large structures (especially in plain reinforced and prestressed concrete) and of their rock foundations. Nowadays both static and dynamic behaviour, also beyond the elastic limit, can be investigated with the aim of achieving an "optimum" design.