Les notes présentées ne sont pas nombreuses, mais cependant avec leurs contenus il me semble qu'elles réussissent à couvrir presque toute la gamme des intérêts qui peuvent se reconnaître sous le titre « structure ».

En méditant sur leurs contenus on peut ébaucher une conclusion évidente, et c'est-à-dire que la vasteté même de la matière implique des divisions précises en ceux qui s'occupent des problèmes de base, ceux qui travaillent expérimentalement et ceux qui au contraire opèrent dans le concret utilisant des techniques dont la valeur est seulement dans la rationnalité et dans l'efficacité du résultat atteint, ce qui n'est peu, même si reporté à une manque de critères généraux scientifiquement acceptés. Tout ceci porte à considérer le problème de la formation professionnelle des jeunes qui s'approchent aux thématiques structurales du problème de restauration et à reconnaître la nécessité absolue de relier la jeune association dont nous célébrons la VI° assemblée avec les autres institutions internationales qui désormais opèrent dans le domaine de l'ingénierie structurale et de la mécanique théorique et appliquée depuis plusieurs années, c'est la recommandation que tous ensemble devrions formuler à la conclusion de nos travaux.

Salvatore Di Pasquale

PRACTICAL APPLICATIONS OF SCIENTIFIC RESEARCH AND TECHNOLOGY IN THE ANALYSIS OF ARCHITECTURAL WORKS AND THEIR CONSOLIDATION

GENERAL REPORT

In the present report I wish to achieve two aims: the first is to give an account of the papers presented at this Congress Section; the second is to attempt a comprehensive survey of the current theoretical and applied researches, concerning structural restoration of buildings or ancient cities.

It is fairly advisable nowadays to spread our interest to the latter topic; in fact, this is suggested by many — at times tragic — reasons which lead the researchers to a wide range of design problems. Here, the building itself — in the accepted meaning of the word — may not to be the main object of the problem. On the other hand, a detailed and very interesting urban pattern must be taken into account, and the restoration works are to be faced with several types of structural damage, or even of seismic failures.

No doubt there is a general lack of scientific and experimental knowledge in this field, both for analytical methods and for the restoration techniques, as these are closely related to the analytical investigations of the given phenomena.

Such scientific gap, together with the absence of proper and suitable techniques, is probably due to the neglect — at least in technologically advanced countries — of the old building practice, by use of stones, bricks and other poor materials.

Perhaps, this is the reason why the masonry building techniques and theories are not included in the course of study of our universities. Since the first decades of this century, steel and reinforced concrete are the main,

the only topics to be taught, nor anything lets we hope any changes in the future.

Obviously, there are few extraordinary well-known cases of a single designer brilliantly solving all the problems related to a famous building: he straightened walls, or changed sites of temples, or built in steel or reinforced concrete parts of collapsed monuments.

Nontheless, the lack of scientific and technological knowledge remains in the common consciousness, in the mass-culture, in the technical skill needed to face many questions and wide problems, just as those of restoration after seismic collapse and damage of entire cities.

From this point of view, little or nothing has been done since today, and the studies in such field must be planned and encouraged; they must be supported by financial aids necessary to large-scale experimental works, so that comparison between theoretical hypotheses and obtained results would be possible in an actual analysis of the investigated phenomenon. In these problems — more than anywhere else — the experimental studies show their particular meanings: we refer to the recent techniques by use of epoxy resins and gluing, others using micropiles with reinforcements, others aiming to give tensile strength to masonry by suitable dislocations. All these are technical means able to stop a failure process, but they still seem to have no definite theoretical ground, nor may they be completely justified from a strictly theoretical point of view. Therefore, a detailed investigation is needed, which ought to support those " life-size experiments ", in order to set up the grounds of a masonry structural theory. We may see the origins or the attempts to define such theoretical grounds, which are however less definite than we expect — used as we are to the steel or reinforced concrete theories. Anyway, in several cases it is rather difficult — or impossible — even to define the " structural model " of a masonry work, since they nearly coincide.

Neither is it possible to apply the common simplifying schemes, reducing the structures to simple geometrical models (including conventional constraint conditions), since we must face really three-dimensional problems, where all dimensions may be compared, nor a two-dimensional model may be applied, just as in the beam or plate theory. Another very important problem is the definition of the masonry-material: it is heterogeneous, with good compressive and poor tensile strength; its weakest planes are in the joints (bad mortars), otherwise, there are intersecting strength planes and poorstrength middle zones, if the mortar are good and brick clay is less strong.

Such aspects obviously contribute to get the problem more complex, so that it is not easy to face it by a general theory. This suggests to discuss particular questions, more or less resembling actual problems, leading to many

works which may be praised from a technical point of view, but have no definite theoretical ground. What happens today may also be read from the following point of view. Since there are no rigorous results, to be produced by a theory which does not yet exist, it is obvious that several restoration techniques have been shifted from steel and reinforced concrete buildings to masonry ones. Such procedures allow to quickly solve the given problem in a fairly correct way. Furthermore, I should say that this process has its reasons in the building history, since the theories (concerning and explaining structural phenomena) never went before building practice, on the contrary, this latter produced the theory itself. So, a structural restoration work (just guessed by intuition but not theoretically supported) seems to me similar to the producing the object to be restored, which cannot be explained by us following particular theoretical considerations, since such theory does not exist.

Clearly, it is not easy to outline a comprehensive view of a landscape which is not definite in its details. The following topics are particular aspects of the rather complex set of problems given by the failure phenomenon: material behaviour, restoration techniques, structures and their interaction with foundations soils, diagnosis and therapy by epoxy resins.

In what follows I shall try to give an incomplete and synthetic account on these topics and on the related studies. Finally, I shall give some concluding remarks which seem to be pertinent to the Restoration Papers.

1. *Researches on materials and masonry structures.*

Natural and artificial stones, together with the related structures, are obviously the main objet of theoretical investigations. The aim is to define physical and mechanical models, able to describe their behaviour under external forces and thermal loads.

On another side we must place the experimental researches on material samples, or on structural models, or life-size tests; by which data are obtained, necessary to control theoretical results.

Clearly, we may distinguish between materials and structures, but we must remark that the element to be assembled in the framework (brick or stone) has its own structure which determines its behaviour. Therefore, no distinction has been made here between these two topics, since methods and researches may be transferred from one particular field of investigation to another.

Stone materials, as the soils, have neglectable or no tensile strength. In masonry framework so generated, the mortar must be taken into account.

It is a different characteristic material, whose presence means uncertainties in tensile strength, while its absence leads to compression only stresses.

Apart from the analysis of the inner composition of material — which is heterogeneous and anisotropic — a theoretical investigation of masonry structures would lead to such uncertainties and random factors, so to make deceptive its results.

Problems are extremely complex and the available solutions all depend on the simplifying assumptions previously made. Therefore, the problem formulation must have its grounds on a clear mechanical model, which ought to be the more realistic as possible or must be affected by simplifying assumptions, leading to well-definite and assured solutions, such as the hypothesis — for instance — of a no-tension material.

Obviously, in such a way we cannot yet evaluate the mechanical characteristics of walls and rather well-made frames, of not ever artfully-made joints, of the filling contained between walls, and so on.

Within a theoretical foundation of a method, these problems cannot perhaps be solved. Such analytical method must be, nevertheless, the necessary guide to all operators: I believe that the recent studies on masonry structures may be considered from such point of view. A definite reference is needed in the failure diagnosis, and this is the necessary premise of structural restoration.

A correct and accepted reference cannot be but the result of a theoretical formulation, where actual material behaviours are taken into consideration, together with their type of working and assembling. This certainly requires great experience and wariness in order to assert the actual suitability of the method.

The advanced structural analysis of modern engineering mechanics has given little room to the investigation of masonry frames, so that an historical sketch of its growth may be easily outlined.

We must start from the famous paper by C. A. Coulomb, dating back to 1773, and from the subsequent applications by Mery (1840), from preceding ideas of Moseley and Navier.

But the problem of masonry structural analysis will be waiting for a hundred years before discussions will be restarted; the main topic will be — as is well-known — the masonry arch.

Only around the fifties in this century, the problem is taken up again by means of a more suitable method. Some attempts, made in the twenties to fit the elastic frame theory to the masonry arch, had no further developments. In these cases, some drawbacks were in assuming a perfectly elastic behaviour, with the only condition of being the thrust line wholly contained within the core, but the results were anyway accepted if the thrust line was contained within the arch shape.

The weak point of those attempts was clearly not only in the elasticity of masonry (at least for certain values of external load), but in accepting solutions where the thrust line could be external to the cores. In such case, the solutions satisfy equilibrium but not elasto-kinematic (compliance) conditions, or they may be obtained by rigidbody statics.

A turning point in the fifties is determined by the shakedown analysis and by its several applications; limit analysis theorems — fairly apt to the computation of the maximum load in masonry arches — seem to be a logic development of old searches, dating to Villard de Honnencourt, Leonardo, L. B. Alberti, Blondel, Borra, and others, till the fundamental paper by C. A. Coulomb.

Former theoretical and experimental works on limit analysis are due to A. J. S. Pippard, E. Tronter, L. Chitty and R. J. Ashby, around 1936-38; the first application of limit analysis to masonry arches dates back to 1952, by A. Kooharian, working in the circle of D. C. Drucker and W. Prager. About these authors I shall come back dealing with the failure criterion assumed in today limit analysis of masonry, which is named by Coulomb, Prager and Drucker (the natural reference may explain as the searches find a starting point just in the results obtained by Coulomb two centuries before).

Fourteen years later J. Heyman issues an essay about statics of gothic cathedrals, followed by several papers. In those works theoretical investigations are refined, and actual applications are developped in order to give definite grounds to such methods: these are the structural restorations of the Ely Cathedral and of some Telford bridges.

We must notice that J. Heyman was the author — in 1972 — of a critical edition of the Coulomb essay. Heyman's papers are a main reference for the static analysis of masonry, as may be shown by some works by V. Franciosi and R. K. Livesley, about friction in limit analysis of masonry arches.

In such direction also the contributions of Ch. Massonet and M. Save may be included: a chapter of their treatise deals with the masonry arch. Particular attention must also be devoted to the searches of H. Joway on the limit analysis of gothic cathedrals.

The study of gothic vaults by the classical methods of the structural analysis has been attempted by aforementioned J. Heyman and by I. Segger, in a doctorate thesis at Aachen. In these works the theory of thin shells (coded around 1930 by Pücher, Finstenwalder and Flügge) has been success-

fully applied to the vaults of the most famous gothic cathedrals in north Europe: Köln, Liège, Paris, Reims.

Another main direction in researches — nearly the same years — has the object of the equilibrium problem of homogeneous and heterogeneous continua, made by unilaterally linked elements, i.e. able to give reactions whose sign is determined by the constraint type: this leads to masonry as no-tension continuum. In the basic problem a particular structural form is not defined. To the classical equations given by the elasticity theory, others are added, namely inequalities defining a feasible region, corresponding to " possible " reactions of constraints. The aim of such searches is to define behaviour models of the structure and the implementation of computational techniques.

Although the problems has been reduced to a fairly simple form, i.e. to the analysis of a model, it turns out to be rather complex, due to a non-linear formulation. In fact, not every structural element is actually engaged by the external load: that is, active constraints are not known a-priori.

Further remarks may be necessary to explain the meaning of the problem.

A masonry structure, with definite geometry, constraints and external loads, may be viewed — for instance — as an equilibrium problem of its elements (e.g. its stones), together with congruence of their strains.

Since there is simple contact of the elements (bad or no mortar), the contact surfaces — through which actions and reactions are developped — are unknown. This means that the framework, corresponding to known external loads, is not the one defined by its shape; the actual form is unknown and depends on the loads. This is the main feature of the masonry problems. The apparent structure does not coincide with the actual, resisting one.

Within the theory of structures, the masonry analysis is a problem of equilibrium in unilateral-constraint solids, or a contact problem. Once more, a first approach may be given by the elastic-plastic analysis, where the leader works by W. Prager, Koiter and J. Oden must be quoted. Obviously, the nonlinearity of the problem leads to specific algorithms and corresponding computational techniques, which cannot be cited here: nevertheless, most of them use iterative Newton-Raphson-like methods.

Another approach is given by the complementary linear theory, i.e. by systems of variational inequalities (where signs of reactions are specified), whose energy functionals require suitable stress constraint conditions. We must remark that these formulations include the more convenient complementary energy, instead of the total potential energy, commonly used in the classical engineering mechanics. In fact, the complementary energy is expressed in terms of stresses, which are directly constrained. This approach was

indicated by A. Haar and T. V. Karman in the analysis of plastic and granular media. In this field, the recent works by Majer and his school, and by G. and M. Romano are of great interest. Much attention has been devoted also to the papers by R. Frisch-Fay on masonry column stability, and by G. Augusti on the same topic. Finally, we must quote the great theoretical and experimental work of R. L. Barnett and P. C. Hermann on prestressed beams made by disconnected elements. From my own point of view, perhaps the masonry problem may be viewed in a simpler (probably more general) form *. Born at the beginning of this century, it provides — from the point of view of G. Colonnetti — fundamental grounds to the theory of plasticity.

We cannot here review the fundamental concepts of this theory. We must only notice that dislocations are introduced in a masonry structure, in order to give stresses able to counteract non-feasible tensile ones. From this point of view, such theory is very like to the prestressing one: the only difference being in fictitious — not real — dislocations, corresponding to the fracture pattern in the masonry.

Since now I have given no remark the fact that the finite element method must be used, if three-dimensional problems are to be solved. Such method is generally used and discussed in current literature. A first approach was discussed by me in the last 1979 IASS Madrid Congress, dealing with the stability of the Cupola di Santa Maria del Fiore; that version has been implemented during seminars I was pleased to hold at the Restoration Training School of the Naples University. Together with the preceding theoretical investigations, other experimental works ought to be cited: the first ones — for instance — by R. Mark (1970) on gothic cathedral models, in which photoelasticity techniques have been used, and the more recent searches of the ISMES on the Duomo di Milano, in order to obtain an exact reference on statical restoration works.

2. Structural restoration techniques.

Trends in structural restoration techniques are more difficult to be outlined than the developments in structural analysis. Many reasons may justify such difficulties. For instance, a great deal of time must be spent in theoretical searches, while operative problems do not allow great delays to the solution of particular questions. In my own point of view — on the grounds of many available historical considerations — theoretical procedures, able to justify a given architectural operation, are always subsequent to the operation itself. Thus, for instance, no computational method for tensile structures has been implemented before they had been made. In a similar

way, only today several restoration works are required and such a great deal of interest has been devoted to these topics within the general range of structural researches. However, restoration works have ever been made all over the world (even with no Restoration Paper); several techniques have been thus developped and implemented, without fundamental — so-called scientific — research. Furthermore, we must remark the correctness of the science-engineering relationship: every technical display, able to realize particular restoration works, must be included in the science of restoration. From this point of view, this report should try to outline a very complex set of experiences and actual problems.

Obviously, the main problem is to find the causes of the failure, i.e. a correct analysis of such collapse factors should give as a consequence the knowledge of the fracture pattern; then, types and modes of operation can be chosen.

To come back to the failure causes, starting from the collapse phenomena, is a complex, often subjective procedure that cannot be discussed here in detail. Subsidence, damage of materials, traffic-induced vibrations, fatigue, microorganism aggression, design shortcomings, thermal loads, are few among many factors able to lead architectural structures to collapse.

Analysis of such factors includes many methods: several instruments and devices are required, in order to control, e.g., the monuments of ground-waters, the accelerations, the mechanical decay in materials, the thermal strains in masonry.

We must confine ourselves to the methods whose object is the structure, or its damaged parts. Almost all procedures implemented in the last years are founded on two different systems. The first provides stiffening of damaged masonry by reinforced concrete micropiles with special resin additives.

In the second, actual load-carrying frameworks are introduced in the masonry, in order to decrease external actions on the damaged parts. A further system must be added, consisting of prestressing, successfully used in 1954 by R. Morandi in the restoration of the Arena di Verona walls; this method has been also employed by J. Heyman — together with the micro-pile technique — in the Ely Cathedral restoration.

Advantages and faults of such systems, the reasons that make one more effective than the other, may lead to the main problem of restoration of monumental buildings. Such problem ought to be discussed here in detail, since the Restoration Papers give too much room to subjective and sometimes contrasting interpretations; thus, this Congress Section and the ICOMOS could contribute to the improving of the R.P. contents.

The following problem, for instance, has not yet been sufficiently investi-

gated: must the structural restoration provide substitution of damaged parts or must it only integrate those parts which can no more perform their static functions? From this point of view we ought to discuss the complex problem of safeguarding the historic-environmental assets, located in regions threatened by the seismic risk. Furthermore, the buildings already affected by seismic damages, but not completely collapsed, need suitable structural repairs and restoration. No doubt that a structural subsystem should be provided in this cases, able to resist against horizontal actions. The following statements are also obvious: seismic loads must be carried to the ground, so that the whole foundation-soil system must be examined in detail and suitably stiffened.

On the other hand, the know-how of such operations, their modes and details are seldom certain.

Also, there are many doubts about the limits of such operations, in order to avoid deep changes or alteration of a monument or of the related historical urban environment.

So, many doubts arose when great european war-wasted towns were to be rebuilt, just as Coventry or Warsaw.

Perhaps, this is the true character of the Restoration, which is a learning in progress, the result of continuously evolving scientific and technical experiences, but also open to the contemporary artistic trends.

Obviously, it is not easy to state the limits enclosing and defining the true meaning of a restoration work.

As a reference, let us consider the example of a collapsed wall and the possibilities given by today restoration techniques. Not to speak about traditional, craft modes of operation, by which damaged parts are substituted by new ones, let us try to outline the more recent techniques, which may be summarized in four different types: micropiles, synthetic resin absorbing, fit-in of a steel or reinforced concrete load-carrying frame, prestressing.

By micropiles the load-carrying capacity of masonry is integrated by a stiffening mesh, whose elements are differently inclined, with variable diameters (some centimeters). The aim is to obtain a structural skeleton, widespread through to whole masonry.

By absorbing — in vacuo, according to very recent esperimental studies — the aim is to achieve structural connection of fractured parts, processing the whole masonry or the more damaged parts (corresponding to the fracture lines). Particular adhesives or — more generally — gluing patented matters are used, able to obtain also a good tensile strength in the masonry.

By fit-in of a real load-carrying frame, the static performance of masonry is quite annihilated.

Prestressing cables may also be included: thus, post-traction in masonry is achieved. Cable diameters are few millimeters (widespread cables) or few centimeters (if concentrated): their effects may include stiffening against horizontal loads, together with increased stability.

An examination of these four possible solutions can show the differences in the obtained results. We shall briefly discuss "formal" results, as we must think all the different methods are fit for the statical purpose, neither are the costs important, since they are often competitive.

Everyone may imagine these formal results, by simply considering the afore-introduced instance, i.e. the damaged wall, within the context of a monument. There are — in fact — some clear differences, corresponding to the several possibilities of understanding Restoration in its meaning. This leads to different questions, while the answers are always the best fit to the aim: they are often the most inexpensive solutions. So, we must also discuss the relationship between the costs of the structural restoration works and the obtained results.

In the recent engineering practice the use has been stated to evaluate the nominal life of a building and its economical duration. Different parameters should be used — with respect to recent buildings — to evaluate the ratio safety-duration or the reliability of a restored building. As E. Giangreco has keenly noted, the absence of a repetition character in restoration works a great incidence on the costs and, sometimes, can affect the use and the formal results of the more suitable techniques.

* * *

The afore-discussed four techniques are the object of three papers presented at this Congress Section.

In his note, Arq. J. O. Lajous explains particular restoration techniques by injections in earthquake-damaged structures. The aim is to restore the framework in its original structural behaviour. A system of "control-piles" is also described. In order to consolidate the foundation soil, such piles are used with variable load-carrying capacities (by means of suitable devices); furthermore, differential settlements may be controlled, so to reset the previous levels.

In the last section of the paper, a preventive technique is described, whose objects are tall buildings (mostly bell towers) in seismic zones: post-stressed (tension) cables are suitably included in the masonry and fixed at the ends to reinforced concrete frames, which give the towers a great bending-load-carrying capacity, just as seismic design requires.

I should notice and I would recommend to the Congress discussion the following author's worried remark: " The structural restoration by means of reinforced concrete frames — designed to achieve tensile strength — seems to be quite unsuitable; so, only partial restoration works ought to be carried out, in order to preserve the original static design of the monument ". I have already mentioned such problem and I believe it must be furtherly discussed. A chance is given by the paper by Prof. A. De Naeyer, describing, with many details and chronichler taste, the restoration of the great columns of the Antwerp cathedral.

The analysis of the criteria, leading to the restoration choices, is reported. Then, the author describes the works carried out on every stone of each column, by means of resin injections in the pier brick core. The greatest stiffness obtained may be used — as the author says — to carry random loads with increasing safety.

Even in this case, the author is worried by the generalized use of reinforced concrete or steel frames, in order to consolidate the much more stiff ancient masonry structures: " the actual trend is to call for the same safety factor as in modern structures... since neither the characteristics of ancient frameworks, nor the stress distribution are known; thus, the masonry structures are stiffened much more than necessary, what leads to costly solutions in all respects ".

The paper presented by Arch. F. Leblanc gives a clear and synthetic account of a structural restoration of brick masonry vaults, by means of high pressure epoxy resin injection. Brief historical notes on the building are followed by a detailed report of the different work-stages. The used technique is fully described, with special attention to the critical analysis of the pressure values to be recommended. Finally, a detailed account is given of materials, times, consolidated masonry quantities, with relating (fairly low) unitary costs. Therefore, it is easy to forecast an increasing use of such recent, unexpensive techniques.

The paper presented by J. L. Toupin describes several techniques for the restoration of great timber frames of French area buildings. Three methods are examined in details: dismantling and reassembly, stiffening by complementary frames, regeneration of damaged parts by resins and fiberglass. Particularly significant experiences are discussed, where such methods have been used. Perhaps, timber structures more than masonry require great competence and professional skill in restoration design, furthermore, a great deal of craftsman ability is needed in carrying out the work.

From the author's point of view, the recent techniques of fiberglass

and resins may considerably help the timber-framing jobs. Obviously, the undamaged parts of the frame must be re-used.

In the paper by Prof. B. H. Feilden and Arch. A. Alva, a general analysis of seismic behaviour of monuments is outlined.

Many data have been obtained by ICCROM in the study of Guatemala, Friuli and Montenegro earthquakes.

Complexity, generality and difficulty of treated topics do not allow to summarize here the contents. I think that the great and well known experience of Prof. Feilden may find here a further confirmation.

The paper presented by Arch. C. Alessandri, E. Baroni and B. Leggeri gives an account of experimental studies on the increase in strength of masonry materials, i.e. bricks, mortar, clay and mortar mixture. Tests have been carried out on natural-state samples, and on in-vacuo impregnated samples by synthetic resins. The results let forecast — according to the authors — interesting structural applications of such techniques to no-tension materials.

The paper by Arch. C. Blasi and M. Pecchioli concerns a photoelastic experimental analysis of stresses in elementary masonry structures, just as piers, lintels, arches. Unlike the searches of R. Mark, the models are here made by disconnected stones, in simple contact, without tensile reactions. The obtained results are very interesting, but I think some theoretical remarks are needed to the complete explanation of the results.

The last paper, by Arch. C. A. Anselmi and Ing. L. Fino, deals with stress analysis in masonry by means of a suitable mathematical model. In order to avoid some computational difficulties, the authors suggest a truss model, which just seems not very like the masonry to be investigated.

A detailed discussion would be necessary, in order to exactly evaluate the effects of the assumed hypotheses on the numerical results.

The notes presented by B. Hoberg, M. Kairamo, B. M. Johnson and J. Stewart concern topics not closely connected with structural problems: but their arguments are so interesting to require a very deep discussion.

Particularly I must underline the problem treated by B. M. Johnson about the thermal upgrading of historical building relating to their use; also I must talk about the works by J. Stewart for the connection between the materials restoration and their mechanical properties.

* * *

Not many papers have been presented at this Congress Section, yet their contents seem to cover nearly all the particular topics and interests collected within the title " structures ". Reflecting on their contents could lead to a first — obvious — conclusion: the great extent of such matters requires sharp sub-divisions into different sections. In fact, some researchers are concerned with basic problems, others with experimental analysis, others — finally — carry out works and operations where different techniques are used.

Since there is a lacking of general, scientifically assured criteria, such techniques may be judged by their results only. This leads to the problem of the teaching and training of young engineers who will approach structural restoration. Furthermore, schools are needed, where professional abilities and skill may be suitably represented.

From this point of view, this young Association — whose 6th assembly is being celebrated — ought to be connected with the other International Associations of structural engineering, applied and theoretical mechanics. This could be recommended by us all at the end of this Congress Section.