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Dynamic Behaviour and Monitoring of Ancient Monuments

Comportement dynamique et surveillance des monuments

Dynamisches Verhalten und Überwachung von Denkmälern

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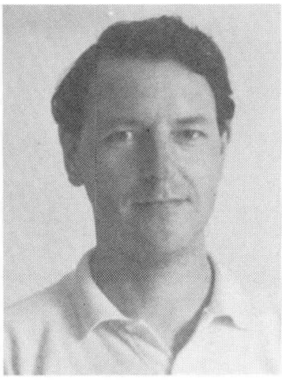

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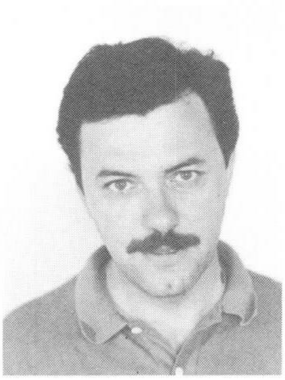

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SUMMARY
Some experiences are illustrated for the dynamic identification problem in the case of ancient monuments. The dynamic testing techniques can provide a helpful control system for the survey and monitoring of historic structures.

RESUME
On présente des expériences pour la connaissance du comportement dynamique des monuments. Les tests dynamiques peuvent constituer une technique utile pour le contrôle et la surveillance des structures des constructions historiques.

ZUSAMMENFASSUNG
Wir stellen die Erfahrungen bei dynamischen Versuchen an Denkmälern vor. Dynamische Tests können eine nützliche Technik zur Kontrolle und Überwachung der Strukturen von Historischen Bauten bilden.

1. INTRODUCTION

The development of dynamic computation techinques for the study of the dynamic behaviour of structure, together with more efficient prediction of the behaviour of structure under dynamic loads (seismic events, wind etc.) also produced a modification in the in situ techniques of structures' testing.

In fact with the comparison of the dynamic results obtained with real experiments (on the physical model) it is possible to obtain information about the structure's statical situation. With the variation of the parameters which influence the dynamic response of the mathematical model it's possible the "tuning" of the model in order to obtain as outputs the same dynamic response parameters of the actual physical one. This is the sense of the word dynamic survey as it's possible to have a structural survey of a monument through dynamic testing.

This is important expecially for those type of structures (as monumental buildings) for which statical tests are impossible or not significant and so dynamic testing techniques give important documents for the "surveying" of the monument. The dynamic survey can be put so beneath the geometric and architectural ones to furnish important elements for the exact understanding of the structural state.

This survey is useful also to give elements to judge about the safety level of the monument, for the control and monitoring of it. In fact the repetition of the dynamic survey after some events which can effect the positively (as consolidation and repairing works) or negatively (as seismic events or wind storms) can give an important identification document for the monitoring of the monumental building.

In these last years the dynamic tests in the structural field have shown important development and refinements.

Particularly they have been devoted to completely define together with eigenmodes, eigenfrequency and relative damping factors also the transfer function (or, better, the imaginary best of this function, calculated in Laplace domain) also called frequency response function.

Of course this function and all the above mentioned dynamic properties are uniquely defined for linear structures whilst for non linear structures the above mentioned properties have sense only in the neighbourhood of a certain equilibrium position.

Now usually as the monumental buildings are masonry or stone structures, the non linearity is caused by the fact that the material does non resist to tension forces and the supports are usually monolateral ones.

But of course the above mentioned non linearity shows itself only in case of large movements and high level excitations.

However the experiences in the field of dynamic tests of monuments (see references /1/-/9/) have clearly shown that it is not usually possible for this type of structures to induce high level vibrations on one hand because the structural masses are very big and on the other hand because these vibrations can be dangerous for secondary or decorative elements of the building.

For this reason it is usually possible also for stone or masonry structures, to use a linear elastic behaviour model for the interpretation of dynamic tests. So the dynamic survey through the recording of the above mentioned dynamic behaviour quantities have sense also for stone and masonry building.

Neverthless, it is sometimes preferable for slender structural such as columns or columnades, to develop a non linear analysis for the control of tests' results. In ref. 10 a method for the non linear analysis of stone blocks columns is developed in the following applied for columns and columnades in Roman Forum.

The dynamic excitation techniques of the structures can be grouped in two great families that is the natural family and the artificial one. The first is of course the easier for the operator as it is not necessary to supply and study a specific excitation technique. To this group belong wind excitatio, seismic excitation, traffic, but of course to furnish useful indications they must themselves be identified in order to permit an exact evaluation of the transfer function.

Among the artificial methods when a particolar vibration mode is to be excited, the technique of the imposed deformed shape suddenly released can be usefully employed.

The other artificial methods are based or upon the use of vibrators which can be fixed to the structure and impose forced vibrations, or on the use of vibrating tables which give impressed displacements to the footings. Of course for the monumental buildings only the first type of technique can be used. The most used instrument is certainly the mechanical vibrodine which cause harmonic excitations, variable in frequency; the electrohydraulic shakers are used to give excitations variable in time with any desired law (i.e. stochastic or not sinusoidal).

Again (ref. /11/-/25/) gas excitators and electrohydraulic ones have been used to impose impulse forces to excitate a particular eigenmode linked to the application point.

At last another type of excitation is the microseismic excitation caused by artificial explosions underground, but of course this type of test can be only rarely applied in historic centers and for monumental building.

2. EXPERIENCES

The dynamic surveying techniques have been employed for many years by the Department of Civil Engineering, sometimes in collaboration with C.R.I.S.-E.N.E.L. (and ISMES), to study some monuments in Florence and in Rome.

2.1. Columns and columnades in the Forum in Rome

In the occasion of the consolidation works of some columnades of the Roman Forum, dynamic testing has been achieved to study the structural behaviour and to determine the more appropriate consolidation works necessary for seismic protection.

Besides a computation non linear method has been developed both to obtain the "tuning" of the dynamic parameters of the tests with those of the computations, and to study and predict the responses under seismic important events which cause sections partialization with high level displacements.

Particularly the following monuments have been tested:

Castore and Polluce Temple, Vespasian Temple, Saturn Temple, Foca's Column.

The tests have been conducted exciting the monuments with impulsive load tests, and with a small vibrodine. The tests for the Foca's Columns have been repeated also after the consolidation work, "monitoring" in this way the monument. A variation in natural frequency from 0,8 Hz to 1,73 Hz has been recorded. For Castore and Polluce Temple also a finite element mathematical model has been applied.

The results have allowed to identify the most damaged structures and to turn a numerical non linear model for the study of the seismic response of monumental buildings.

In figures 1 and 2 some results of the tests are illustrated.

In figure 3 the graphs of the displacements (a) and of the rotations (b) are reported, as obtained on the numerical model with a sinusoidal motion at the base. In figure 4 two examples are reported of the experimental results in term of displacements of the top of the column of Foca before and after the consolidation works.

2.2. Colosseum

For a sector of the boundary wall of the Colosseum in Rome some dynamic tests before and after consolidation works which tends to anchor the external wall (which shows a dangerous out of vertical alignment) to the radial ones.

The tests have been conducted through impulse excitations and have been the oscillation modes of the examined wall recorded.

The results has allowed to evaluate the effectiveness of the upgrading works done, both as improvement of the anchorages between the masonry walls, and as global stiffness.

In fig. 6 the computation numerical model using finite element method of the examined sector of the monument is illustrated. With this model the tests have been interpreted. The frequency of the first mode is increased from 1.3 Hz to 1.8 Hz, as a consequence of the consolidation works.

2.3. Chains of S. Maria degli Angeli Dome in Rome

A series of tests to determine the natural frequencies of the 84 chains of the Michelangelo cloister of St. Maria degli Angeli church in Rome, has allowed to determine the existing tension in the chains and to evaluate the safety existing limits.

The tests have been repeated on some chains, after the works conducted at the upper floor in the museum and successive future controls and monitoring will be achieved during the work of positioning of further chain necessary to diminuish the chain tensions.

In figures 7 and 8 the photos of part of the chain system is illustrated, together with the deformometers applied on the chains for the dynamic tests.

2.4. Chains at St. Maria del Fiore cathedral in Florence

An investigation similar to that reported at the above paragraph has been develped on the whole chain system of the Cathedral of S. Maria del Fiore in Florence. With the tests it has been possible to evaluate the tension state of the chains and to start a study on the static behaviour of the entire building.
Besides, for a continuos in time control of the stresses, some electric extensometer which are being controlled systematically.

2.5. Claudio's aqueduct in Rome

Some parts still standing of the Claudio's aqueduct in Rome are in the southern suburbs of rome, just in adiacence to the railway.

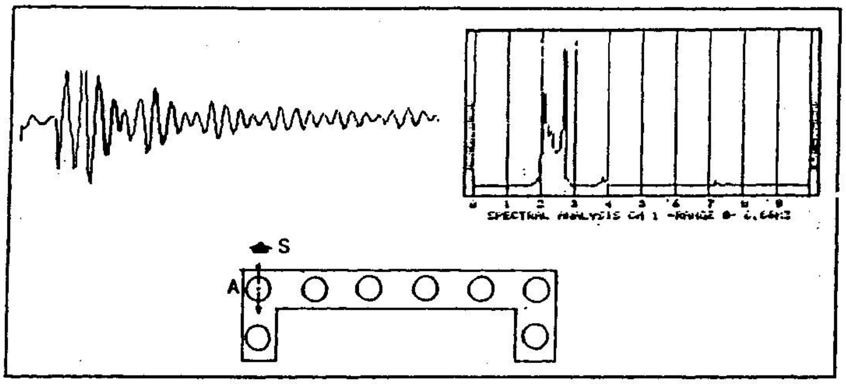
In the course of the consolidation works recently done, some dynamic tests have been developed for a survey of the structural situation of the monument and for the control of the effects of train passage, also in view of possible increase in railway traffic.

2.6. Tests on florentine monuments, in collaboration with CRIS-ENEL

In collaboration with C.R.I.S.-E.N.E.L., under the protection of Commune of Florence and the Superintendent of Monuments, some dynamic tests have been conducted and other are in programm on some monuments in Florence. In particular Brunelleschi's dome and Arnolfo's Tower have been tested. The excitation was given by natural causes (wind) for the Brunelleschi's dome, whilst for Arnolfo's Tower besides the wind action, also a vibrodine at the top of the tower was employed for excitating the structure.

The tests have been conducted by some technicals of ISMES.

The speed of some points of the structure was recorded with a laser type technology. However more details on this tests and those on Temple of Marte Ultore in Rome will be presented in the works of Chiarugi, Castodi, Giuseppetti, Fanelli, Petrini presented at this Colloquium.



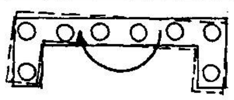
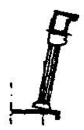
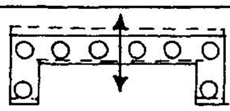
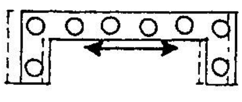
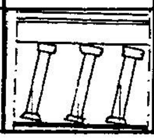
	Experimental study	Hz	Numerical models	K	Hz
TEMPLE OF SATURN		1.50		600 kg/cm^3	1.87
		1.85			
		2.10			2.05

fig. 1 Tempio di Saturno: Displacements concerning 3 eigenmodes

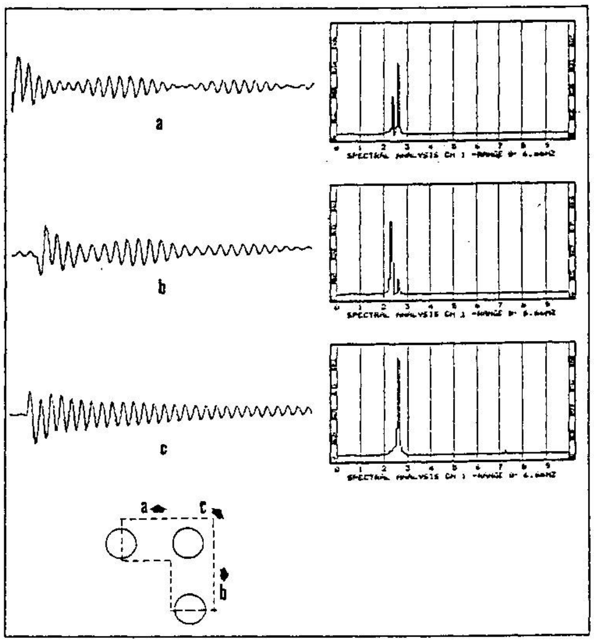
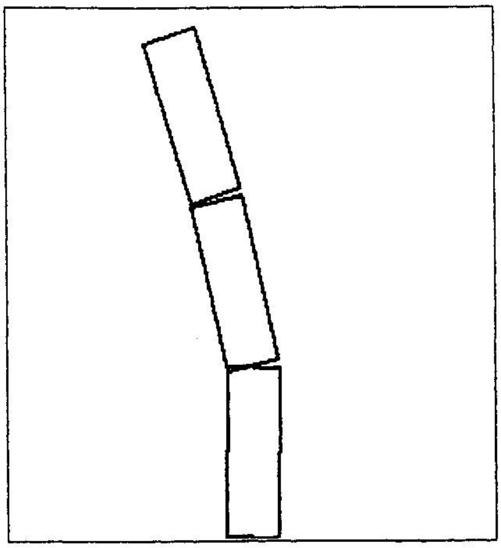


fig. 2 Tempio di Vespasiano: Displacements concerning 3 eigenmodes



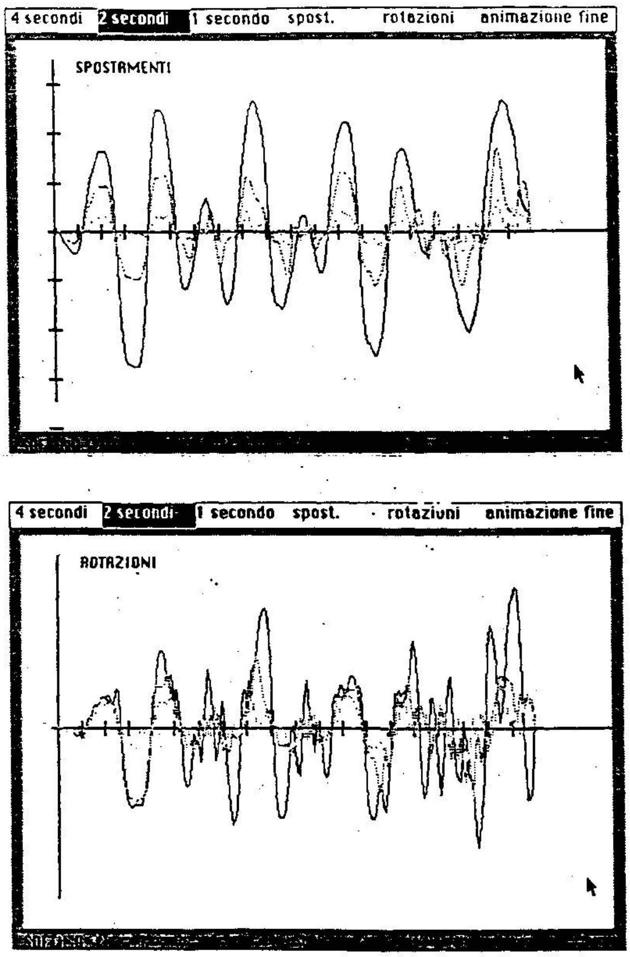


fig. 3 Colonna di Foca: Numerical non linear model and results (displacements and rotations)

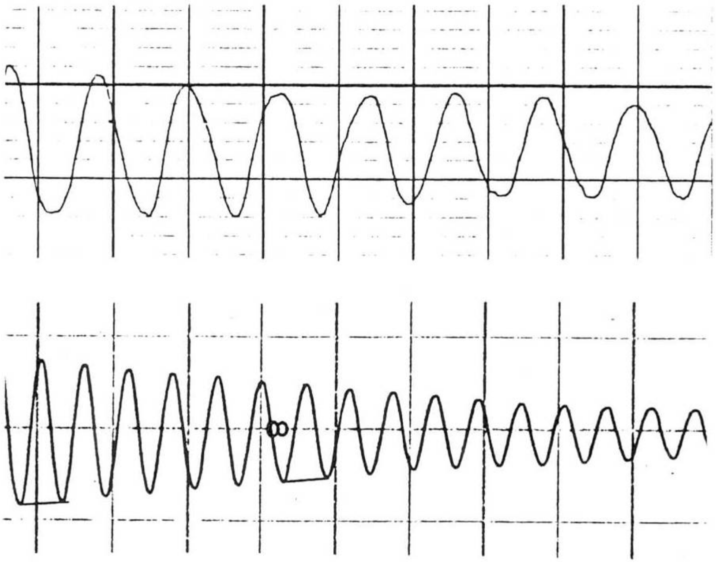


fig. 4 Colonna di Foca: Some examples of displacements effected before and after the consolidation

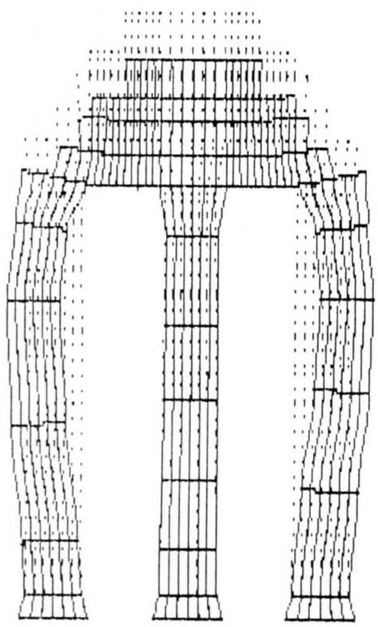


fig. 5 Tempio di Castore e Polluce: photo of the monument and of the Finite Elements model.

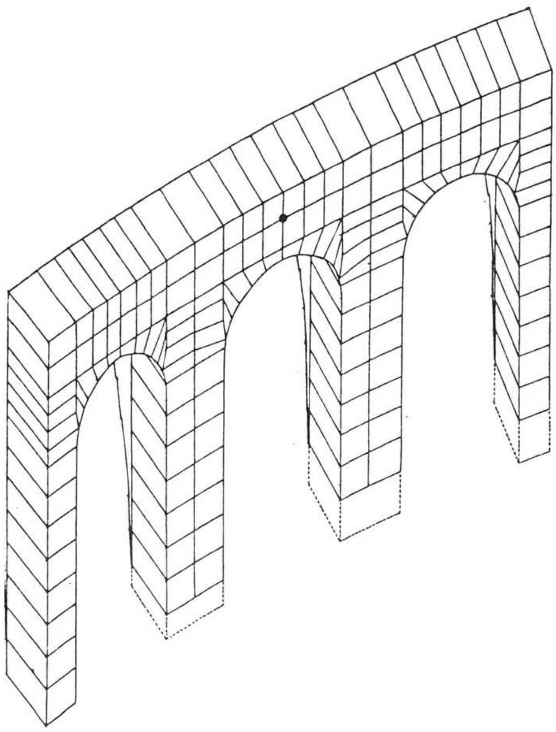


fig. 6 Colosseo: Finite Elements model of the research area.

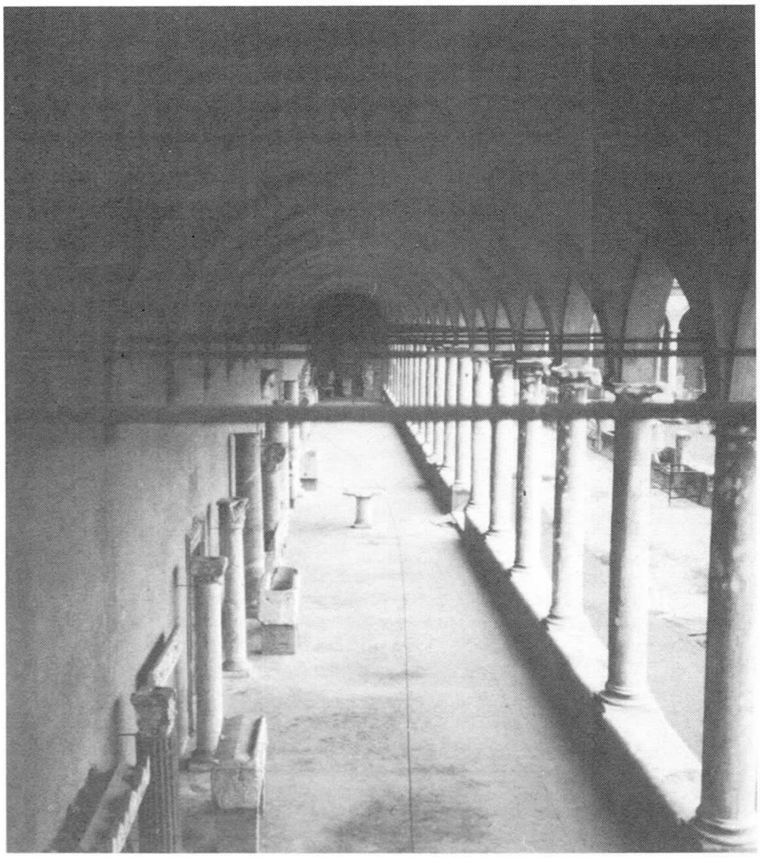


fig. 7 Photo of catenary system in Michelangelo cloister in the church of S. Maria degli Angeli in Rome.

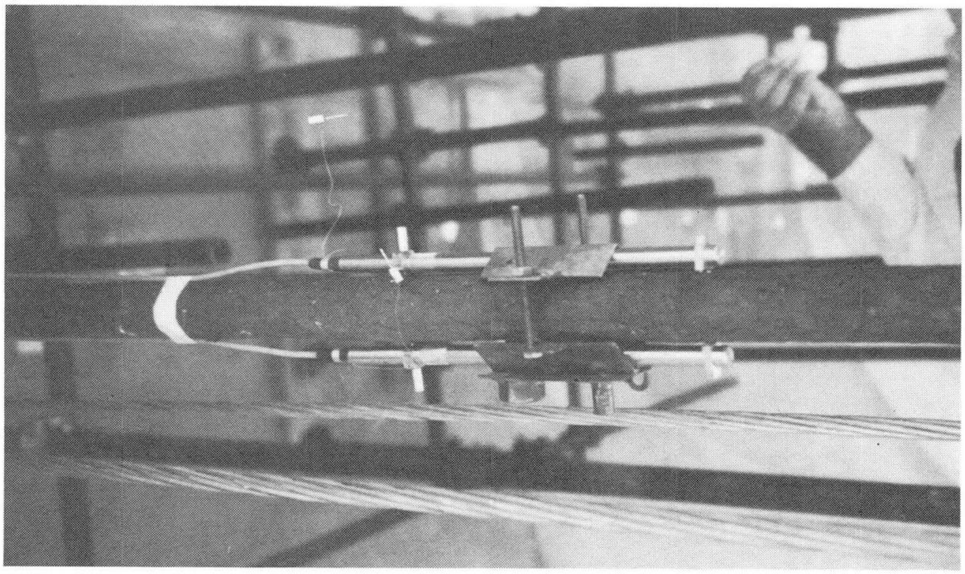


fig. 8 Photo of deformometers applied on a chain for dynamic tests.

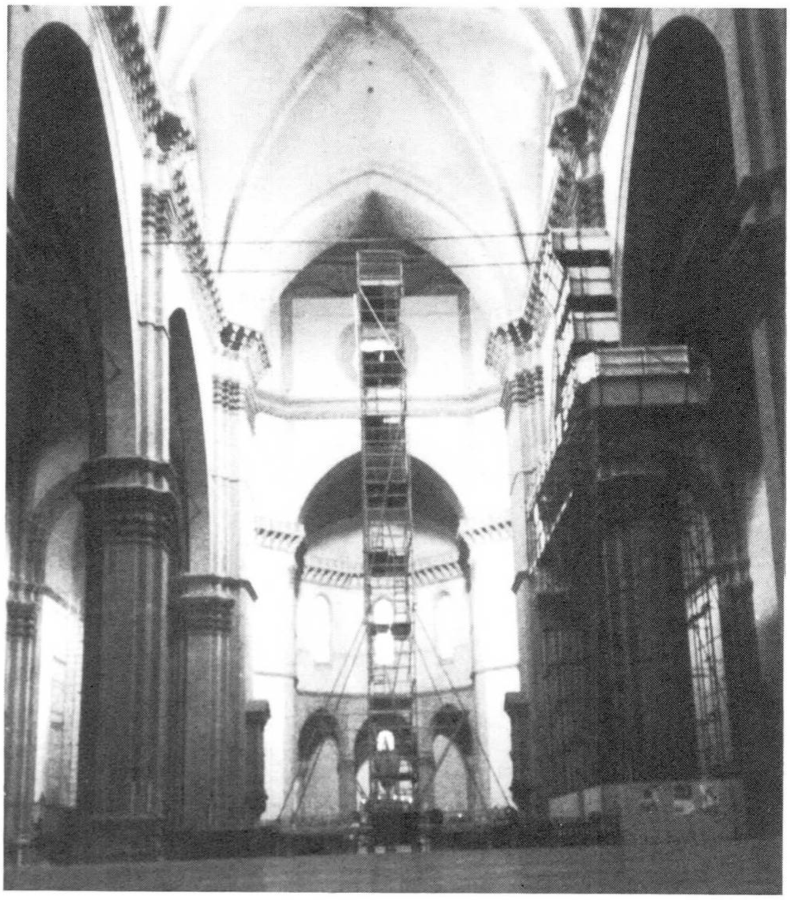
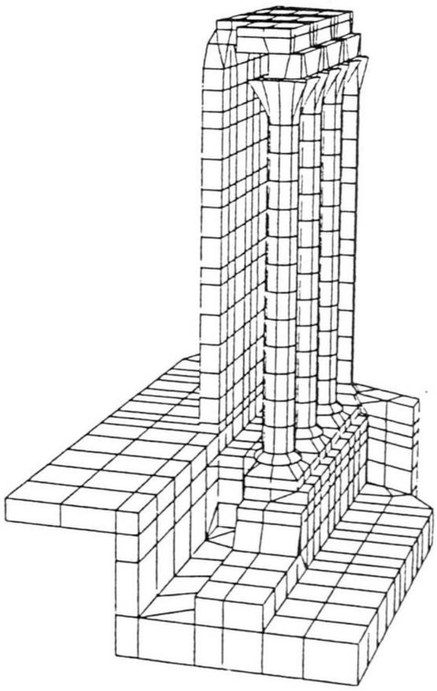


fig. 9 Photo of the church of S. Maria del Fiore in Florence during the test effected on transversal chain.

fig. 10 Claudio's aqueduct at Quadraro.



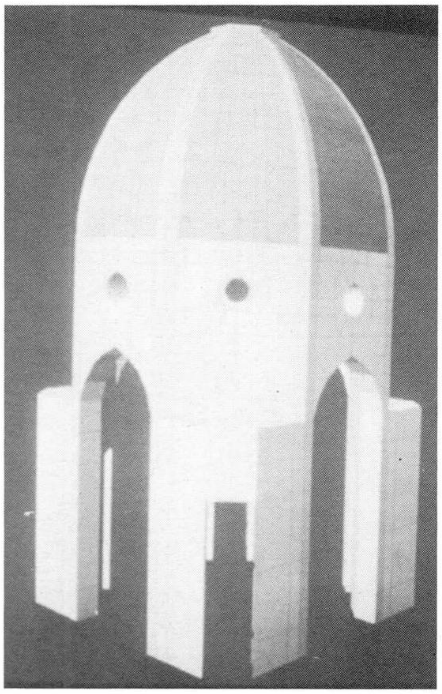


fig. 11 Tempio di Marte Ultore and Brunelleschi's Dome numerical models (CRIS-ENEL)

MONUMENT	KIND OF EXCITEMENT	SURVEY SYSTEM	SURVEY DATA	NUMERICAL MODEL
Tempio di Castore e Polluce	impulse	Acceler. Vibrom. Extensom.	eigenmodes	F.E. non linear model
Tempio di Vespasiano	impulse	Acceler. Vibrom. Extensom.	eigenmodes	non linear model
Tempio di Saturno	impulse	Acceler. Vibrom. Extensom.	eigenmodes	non linear model
Colonna di Foca	impulse vibrodina	Acceler. Vibrom. Extensom.	eigenmodes trasf.func.	non linear model
Colosseo	impulse	Acceler. Vibrom. Extensom.	eigenmodes	F. E.
Chiostro di S.M. degli Angeli	impulse	Acceler. Vibrom. Extensom.	eigenmodes	cont. model
Chiesa di S.M. del Fiore	impulse	Vibrom. Extensom.	eigenmodes	cont. model
Cupola del Brunelleschi	wind	Acceler. Vibrom.	eigenmodes trasf.func.	E.F.
Torre di Arnolfo	vibrodina	Vibrom. Laser	eigenmodes trasf.func.	-
Claudio's Aqueduct	train	Acceler. Vibrom.	frequency	-

Tab. 1 Dynamic experimental tests effected with the cooperation of the technicals of the Dipartment of Civil Engineering of Florence

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