CONCEPT OF EXPERIMENTAL DETERMINATION OF BEARING AND DEFORMABILITY CAPACITY OF STRUCTURAL WALLS OF HISTORIC MONUMENTS

TARİHSEL YAPILARDA TAŞIYICI DUVARLARIN TAŞIMA VE DEFORMASYON KAPASİTELERİNİN DENEYSEL OLARAK BULUNMASI İLKESİ

Zivko Bozinovski[1] and Miodrag Velkov[2]

ABSTRACT

Historic monuments constructed of brick or stone bearing walls have survived for centuries suffering damages due to age and natural catastrophes, primarily earthquakes.

The vulnerability of these structures to seismic effects is directly associated with the strength and deformability characteristics of the structure and the built-in materials. It is therefore necessary not only to consider the seismic hazard by also analyze experimentally the bearing capacity of the materials and the structural walls.

The main concept of the considered experimental investigations incorporates definition of the strength and deformability parameters by testing of structures and some structural elements under laboratory conditions. The "in situ" realization of the experiments has shown the application of this concept in actual structures.

On the basis of the results of the ongoing experimental tests and the results of tests that have already been performed, a mathematical model has been proposed for definition of the dynamic response of masonry structures under real seismic effects. The mathematical model for definition of the dynamic response of the structure has been idealized as a typical multi-degree of freedom system consisting of masses, springs and dampers. Each mass is concentrated at the level of the floor structure and is connected by springs and dampers. Proposed for the strength - deformability of bearing walls relationship were polygonal diagrams with variable strength and stiffness after the occurrence of the first cracks.

---

1 *Assistant Professor, M., Scs., Institute of Earthquake Engineering and Engineering Seismology, University 'St. Cyril and Methodius', P.O.Box 101, 91000 Skopje, Republic of Macedonia.*

2 *Professor, Ph.D., IEEES, University 'St. Cyril and Methodius', P.O.Box 101, 91000 Skopje, Republic of Macedonia.*

INTRODUCTION

Historic monuments are structures of invaluable architectural, archaeological, cultural and historic value. Being built in seismically active areas, many of them have been and are still exposed to the permanent damaging and ruinous effect of earthquakes. Their structural system which in most cases consists of bearing walls constructed of stone or brick is highly vulnerable which has already been proved during past earthquakes.

These buildings represent massive structures with high compressive strength of the walls, insufficient tensile strength, low ductility capacity and inadequate connection of structural elements which especially refers to the connection between the bearing walls and the floor structure.

Historic monuments are mainly designed and constructed to sustain vertical-gravity loads. In most of the cases, the bearing and deformability capacity under horizontal loads is insufficient considering the nonexistence of integrity of horizontal and vertical bearing structural elements as well as the extremely low tensile and shear strength of the bearing walls.

In order to provide conditions for safety analysis (Fig. 1) of the existing buildings and proper seismic design of repair, it is necessary to have an insight into the bearing and deformability characteristics of bearing walls under vertical and horizontal loads and the behaviour of the structure during past earthquakes. Definition of the bearing and deformability capacity of bearing walls is performed analytically and experimentally, most frequently "in situ", i.e., on the walls themselves.

Presented in this report is an experimental investigation and the results of experimental investigations performed for two historical buildings situated in Ohrid and Dubrovnik. The dynamic response of a three storey masonry building has been defined by using an original mathematical model in correlation with the experimental investigations. The experimental testing was performed by using an equipment for quasi dynamic tests, while processing of the results and dynamic response were carried out and obtained by means of the VAX 11/780 computer system in IZIIS - Skopje.

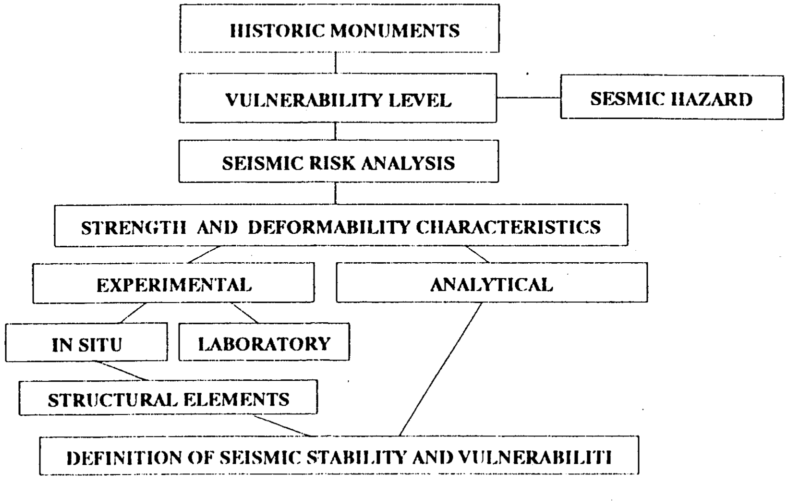

Fig. 1 Flow chart

PROJECT AND PROGRAMME OF EXPERIMENTAL INVESTIGATIONS

These investigations required that a project and a programme of the investigation process be elaborated previously. The programme of the experimental investigations defines the characteristic "representative" bearing walls for testing of the deformability and strength characteristics. The selection of walls and location for the performance of the experiment is made after detailed "in situ" inspection of the whole structure (Fig. 2).

The results obtained in this way may be considered representative for the characteristics of the materials constituting the structure.

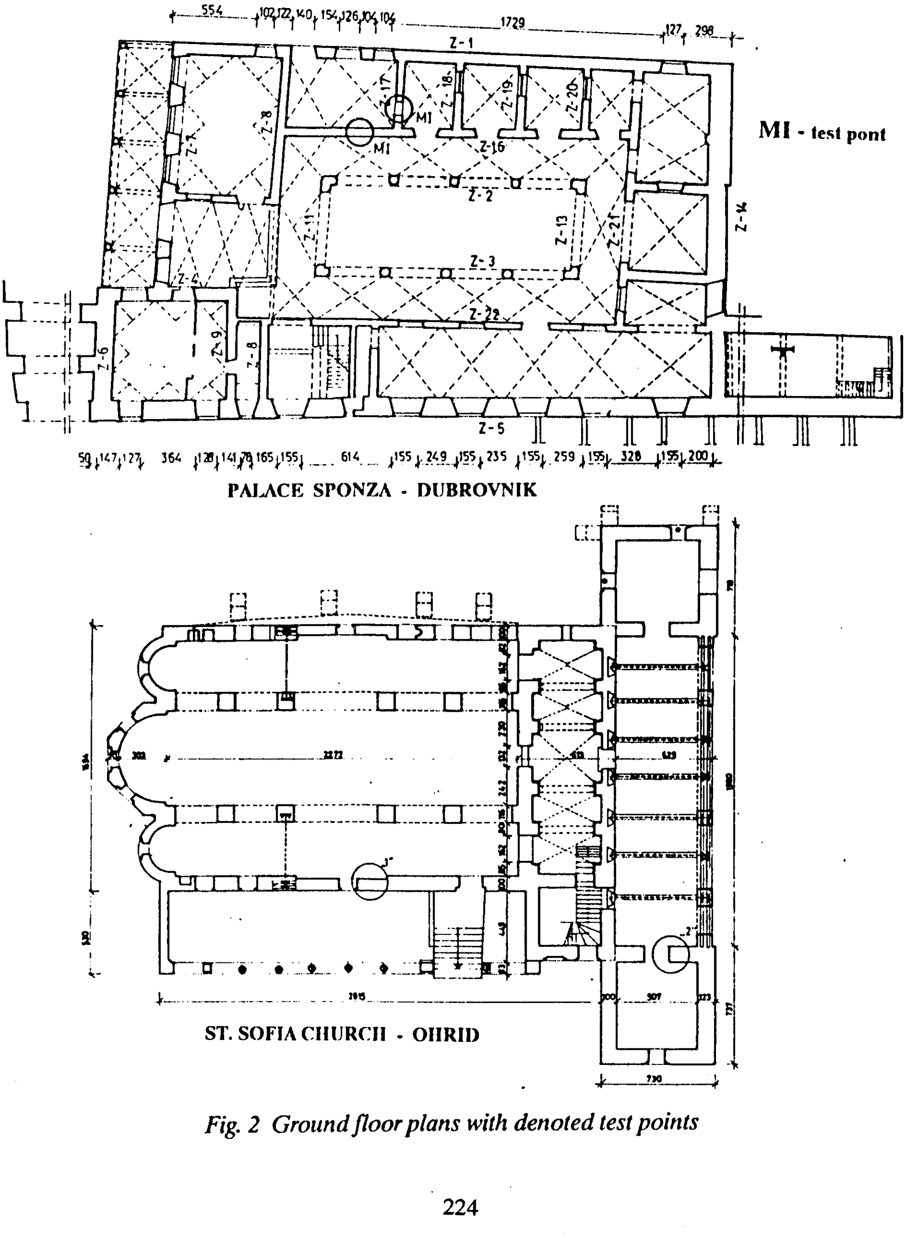

Fig. 2 Ground floor plans with denoted test points

EQUIPMENT

The equipment used for "in situ" experimental quasi-dynamic tests of walls and obtaining of the strength and deformability characteristics consists of two parts: equipment for generation of forces and measuring equipment (Fig. 3).

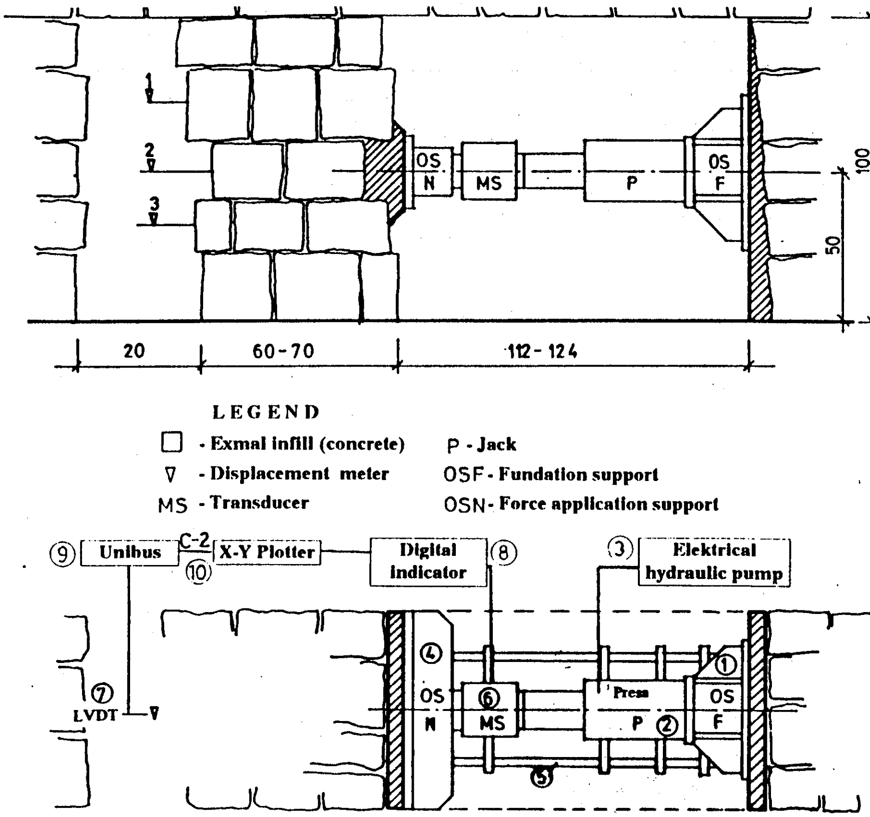

Fig. 3 Force generation equipment and measuring equipment

The force generation equipment is constructed and partially produced by IZIIS. It consists of the following elements: (1) main support; (2) hydraulic actuators with a capacity of generation of forces of 1000 and 1500 kN; (3) electromotor hydraulic pump for activation of the hydraulic actuators; (4) front support of force application; (5) base on which the stated elements are mounted. The base is a steel structure that should provide complete symmetry of the mounted elements and parallelism of areas of force application in order to provide a continuous and safe operation of the equipment.

The measuring equipment consists of: load cells (6) with a capacity of 1200 kN and 1800 kN mounted on the actuator piston, LVDT-500 Hewlett Packard displacement transducers (7), SDT 300B Kyowa digital indicator (8) (serves for power supply and amplification of signals and reading of the amount of applied force), HP 34698 multimeter, unibus (9), X-Y Plotter (10), calibrator with stable voltage and a power supply unit RTY 01-15/1.5 Iskra.

EXPERIMENTAL PROCESS

Generation of active force is performed by means of a hydraulic actuator which is activated by a hydraulic pump. The applied force is measured by a load cell the signal of which is read on the digital indicator. This signal is transmitted to the plotter along the Y axis. The loaded part of the wall sustains stresses suffering certain deformations which are recorded by means of displacement transducers. The transducers are placed in the wall opening that has previously been prepared for that purpose. Through the unibus, the signals of the displacement transducers are distributed along the channels and are finally read on the multimeter. The central signal is transmitted to the plotter along the X axis.

Once the applied force and displacement are obtained on the plotter, the deformability of the wall is obtained by direct plotting of force - displacement relationship diagam. The force - displacement relationship that is iterated several times in cycles provides the characteristics of strength - deformation relationship, forming a P-d diagram with a characteristic envelope (Fig. 4).

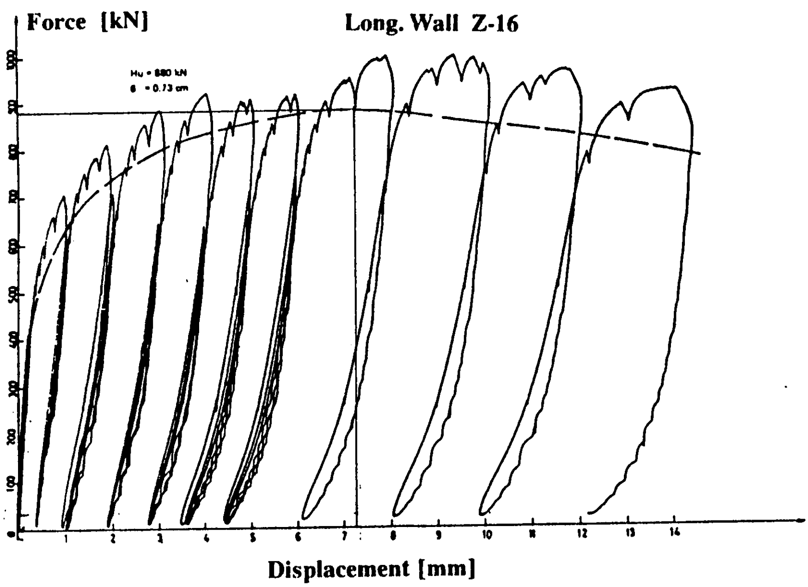

Fig. 4 Force - displacement diagram (obtained on plotter during test)

Application of transverse loads is performed in semi-cycles and after a certain loading interval, forces and deformations are read out. The experiment is conducted by loading control up to a certain deformation level. For higher deformation levels, the experiment is further conducted by controlling the deformations, i.e., the force is applied for a certain deformation increment.

Iterating the loads with the increase in defomation, the ultimate bearing capacity which drops successively with the exceedence of ultimate deformations is obtained.

RESULTS OF EXPERIMENTAL TESTS

On the basis of the recorded data, force - displacement diagrams were obtained for each testing location and each deformation transducer. Anvelopes were then drawn and ultimate main tensile stresses computed.

Figs. 5 to 7 show the results of the experimental investigations performed for the bearing walls of the church of St. Sofia (the church of the Holy Wisdonm) and the Sponza Palace.

Analyzing the experimental results, especially the nonlinear behaviour mechanism of walls up to failure, it was concluded that the behaviour mechanism depends on the following parameters: geometry of walls at plan and along height, quality of the material, the amount of axial force, etc. Accordingly, for mathematical modeling it is necessary to provide the mathematical relationships between the shape of the hysteretic diagram and the effect of stiffness deterioration and sliding on one hand and the number of cycles and amount of deformations on the other.

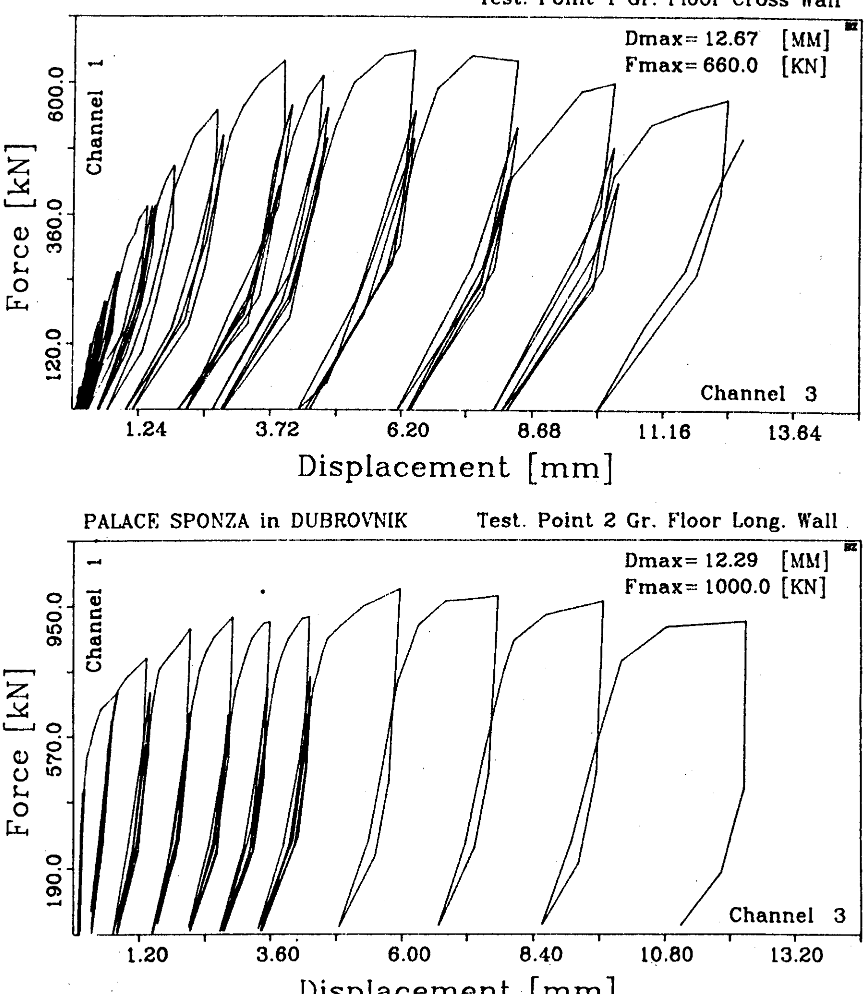

Fig. 5 P – δ diagram. Palace Sponza. Test points 1 and 2

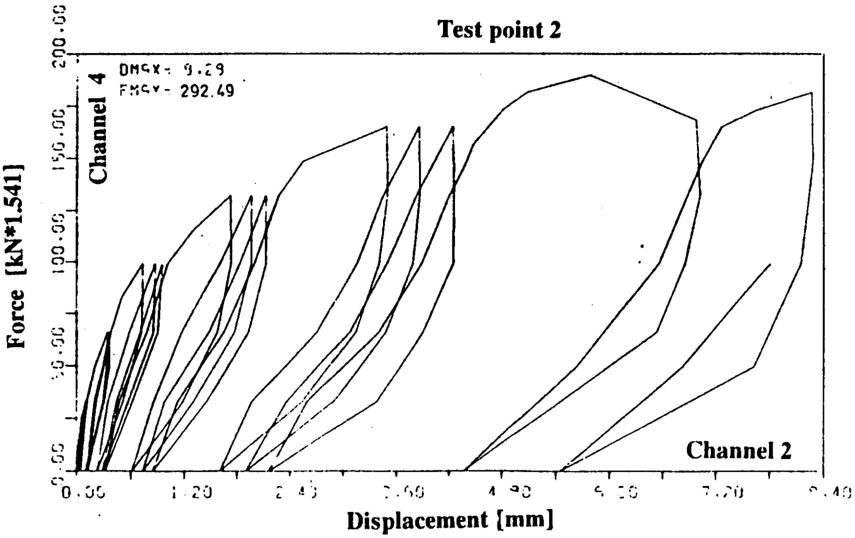

Fig. 6 P — δ diagram. St. Sofia Church. Test points 2

MATHEMATICAL MODEL

A mathematical form of the force-displacement diagram is proposed which enables cosideration of the effect of initial stiffness, the effect of stiffness deterioration depending on deformations, the effect of stiffness and deformation during repeated cyclic loads and finally, the effect of sliding for each loading cycle.

Presented in Fig. 7 is an oiginal mathematical model with the following basic characteristics:

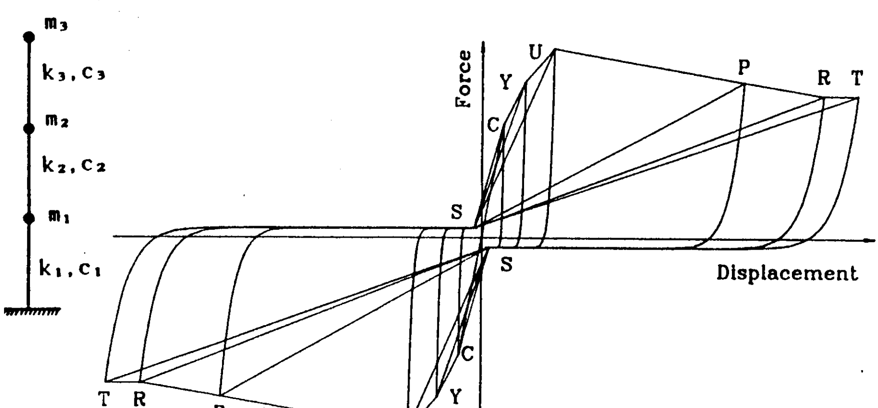

Fig. 7 Mathematical model

Stiffness from point "0" to point "C" represents an initial elastic stiffness. The effect of stiffness deterioration is considered after reaching point "C". Considered in the concrete case is the secant stiffness obtained between point "S" and the maximum required displacement. At the moment when the input load requires deformation in the reverse direction, the way back is curvilinear, i.e., in this case it is along a parabola of n-th order up to the intersection with the abscissa. At point "S", stiffness drops to zero and from this point the stiffness in the opposite direction is identical with the stiffness for the maximum displacement in the reverse direction (secant '$S - \delta_{max}$'). The stiffness deteriorates further if the deformation in the considered direction exceeds the maximum deformation in the reverse direction. This'is repeated depending on the direction and the intensity of the required deformation.

The proposed mathematical strength - deformation relationbship with a polygonal diagam gives the possibility to encompass all the phases of behaviour of the walls up to a complete failure mechanism.

Such a mathematical model provides the response of the structural model under seismic effects of different intensity and frequency content. This means that for a masonry of a certain quality it is necessary to define the characteristics of its behaviour mechanism up to failure. This is most efficiently done via "in situ" experimental testing of characteristic walls, while the strength and deformability characteristics of all the other walls can be determined analytically taking into account the specific characteristics obtained by the experimental tests. These input data are used in the proposed mathematical model and dynamic analysis is further performed under actual seismic effects.

The proposed procedure enables determination of the stability and the vulnerability level of masonry buildings under expected seismic effects as well as the characteristics of the site on which the building is constructed or is to be constructed.

Presented in Figs. 8 to 11 are the input diagram for the characteristic walls and the results of the performed dynamic analysis of a three-storey masonry building.

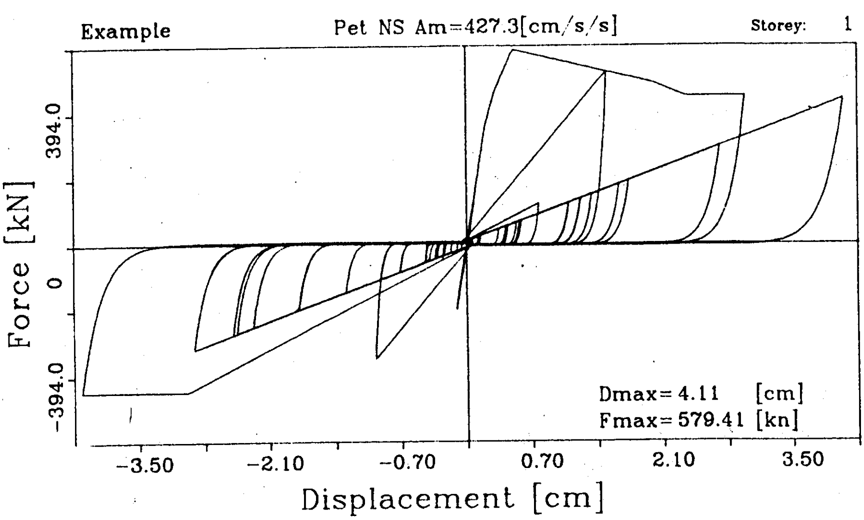

Fig. 8 Structural system respons to Petrovac earthquake N-S $a_{max} = 427.3\,[cm/s^2]$.
Force - Displacement diagram . First storey

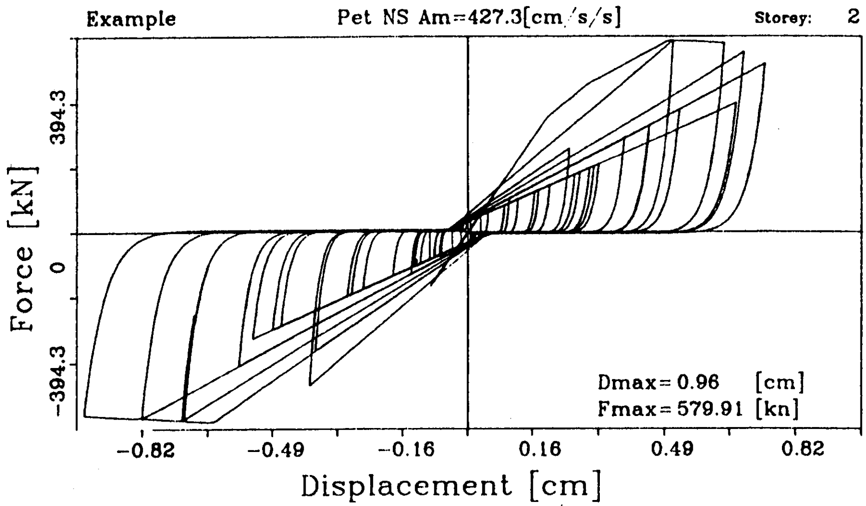

Fig. 9 Structural system respons to Petrovac earthquake N-S $a_{max} = 427.3\ [cm/s^2]$.
Force - Displacement diagram . Second storey

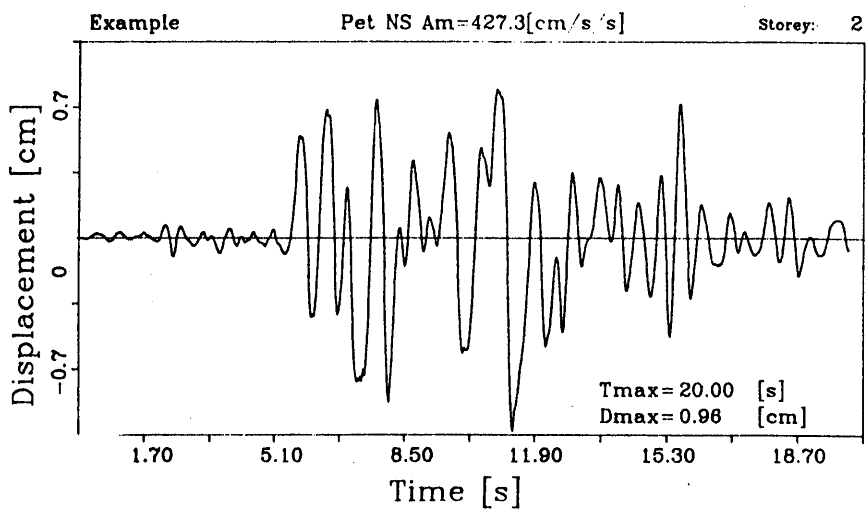

Fig. 10 Structural system respons to Petrovac earthquake N-S $a_{max} = 427.3\ [cm/s^2]$.
Displacement - time diagram . Second storey

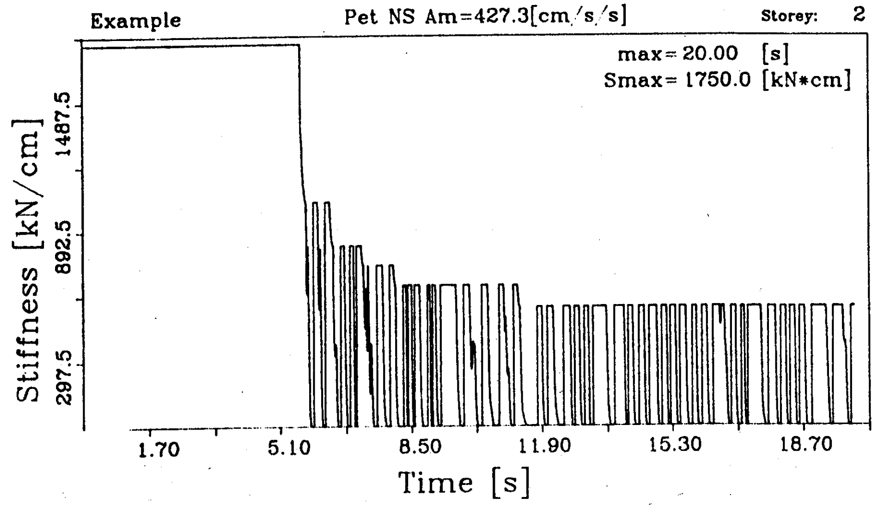

Fig. 11 Structural system respons to Petrovac earthquake N-S $a_{max} = 427.3\ [cm/s^2]$.
Stiffness - time diagram . Second storey

CONCLUSION

The in-situ experimental tests enable the obtaining of valuable data on strength, stiffness and deformability of the bearing walls of a certain masonry type. On the basis of the obtained experimental data and the proposed mathematical model for analysis of the nonlinear dynamic response it is possible to verify the stability and the vulnerability level of the existing cultural historic monuments and determine the necessity for their repair and strengthening.

REFERENCES

1. *Velkov, M., Bozinovski, Z., Jankulovski, E., Percinkov, S., Testing of the Stability of the Church of St. Sofia (Holy Wisdom) in Ohrid, Volume II, Experimental Investigations of the Strength and Deformability of Bearing Walls, (in Macedonian), Report IZIIS 87-87.*

2. *Bozinovski, Z., Velkov, M., Percinkov, S, Experimental Testing of the Bearing and Deformability Characteristics of the Bearing Stone Walls of Sponza Palace in Dubrovnik, (in Serbo-Croatian), Report IZIIS 88-29.*

3. *Bozinovski, Z., Velkov, M., Bearing Capacity and Deformability of Stone Walls of Cultural Historic Monuments, (in Serbo-Croatian), Symposium of the Yugoslav Association of Structural Engineers, Dubrovnik, 25-27 April, 1989.*

TARİHSEL YAPISAL TAŞIYICI DUVARLARIN TAŞIMA VE DEFORMASYON KAPASİTELERİNİN DENEYSEL OLARAK BULUNMASI İLKESİ

Zivko BOZINOVSKI - Miodrag VELKOV

Taşıyıcı duvarları tuğla veya taş olan tarihi anıtsal yapılar yüzyıllardan beri kendilerini, yaşlanmadan ve doğal afetlerden özellikle depremlerden kaynaklanan hasarlara rağmen korumaktadırlar.

Bu yapıların depreme karşı duyarlılıkları doğrudan doğruya, kullanılan malzemenin ve yapının mukavemet ve şekil değiştirebilme karakteristikleri ile ilgilidir. Bu nedenle sadece deprem riskini düşünmek değil, deneysel olarak malzemenin ve yapısal duvarların taşıma kapasitelerinin de bulunmasına gerek vardır.

Düşünülen deneysel araştırmanın ana amacı gerçek yapıların sınanması veya laboratuvar ortamında bazı yapı elemanlarının denenerek mukavemet ve şekil değiştirebilme özelliklerinin bağdaştırılmasıdır. Deneylerin laboratuvar dışında gerçekleştirilebilmesi, bu anlayışın gerçek yapılara da uygulanabileceğini göstermiştir.

Gerek devam etmekte olan gerekse tamamlanmış bulunan deneysel çalışmaların sonuçlarına dayanarak, gerçek deprem etkisindeki kagir yapıların dinamik davranışını yansıtmak üzere bir mekanik model önerilmektedir. Dinamik davranışını temsil etmek üzere yapının mekanik modeli sönümlü çok serbestlik dereceli bir sistem olarak tanımlanmıştır. Bu modeldeki yığılı kütleler yapının döşeme seviyesinde yer almakta, birbirlerine yaylar ve sönüm elemanlarıyla bağlı bulunmaktadırlar. Taşıyıcı duvarlar için öngörülen kuvvet - yerdeğiştirme bağıntısı, ilk çatlakların oluşmasından sonra mukavemet ve rijitliğin değişmesini ifade edebilen bir poligondur.