Earthquake resistant capacity of the Parthenon

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Objekttyp: **Article**

Zeitschrift: **IABSE reports = Rapports AIPC = IVBH Berichte**

Band (Jahr): **70 (1993)**

PDF erstellt am: **22.07.2024**

Persistenter Link: https://doi.org/10.5169/seals-53316

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Earthquake Resistant Capacity of the Parthenon

Résistance du Parthénon aux tremblements de terre

Erdbebenwiderstand des Parthenon

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SUMMARY

The anticipated ground motions required to examine the earthquake resistant capacity of the Parthenon have been generated through the probabilistic approach. Seismic response analyses of the columns have been conducted to study their feasibility to safely withstand the simulated ground motions. Static shear tests on the model marble columns have been carried out to investigate the effect of the shear keys on earthquake resistant capacity.

RÉSUMÉ

C'est à l'aide d'une approche probabilistique que les mouvements du sol permettant l'examen de la résistance du Parthénon aux tremblement de terre ont été produits. Les analyses du comportement sismique de colonnes ont été réalisées afin d'étudier leur capacité à résister au mouvement du sol simulé. Les essais au cisaillement statique dans des colonnes types de marbre, ont été exécutés afin d'étudier l'effet des clés de cisaillement sur la capacité de résistance aux tremblements de terre.

ZUSAMMENFASSUNG

Die voraussichtlichen Bodenerschütterungen, für die der Erdbebenwiderstand des Parthenon zu überprüfen war, wurden nach dem Wahrscheinlichkeitsprinzip generiert. Das seismische Antwortverhalten der Säulen wurde analysiert, um deren Widerstandskraft gegen die simulierten Bodenerschütterungen zu studieren. An marmornen Säulentrommeln wurden statische Schertests durchgeführt, um die Auswirkung der Scherenverzahnungen auf den Erdbebenwiderstand zu prüfen.

1. INTRODUCTION

The various historical monuments constructed in seismic regions have been subjected to a number of destructive or damaging earthquakes during their histories and they have survived by grace of their excellent design and construction or by chance owing to the characteristics of the earthquakes. The inherent structural complexity, variability of buildings and foundation materials, as well as, their final state of repair, make each historical monument a special case of study. In this study, our attention will be focused on Parthenon which is one of the main historical monuments in Greece. Parthenon's behavior under seismic actions for 25 centuries was completely satisfactory. However, during the various phases of the monument's history, radical alterations have occurred concerning the geometric configuration, the interconnection of structural members and the state of materials. For example, the 1981 Corinth Earthquake was reported to cause slight damage to the columns. It was considered that the wooden shear keys inserted between the drums could not withstand the seismic load due to the material weathering. The aspect mentioned above all impose the necessity to study Parthenon's earthquake resistant capacity. It was reported that Parthenon has been partially strengthened, but at that moment, earthquake resistant design has not been accomplished. The scope of this paper is to study the feasibility for the monument, in its existing state, to withstand safely the earthquake ground motions, probabilistically derived from seismological data of the region, and to conduct an experimental study for the aseismic retrofitting.

2. REFERENCE GROUND MOTIONS REQUIRED TO EXAMINE EARTHQUAKE RESISTANT CAPACITY

2.1 *General*

The input ground motions required to examine the earthquake resistant capacity of Parthenon were generated through the probabilistic approach. The procedure was explained in detail by Theofanopoulos in reference [1] and Theofanopoulos and the authors in reference [2].

2.2 *Seismic hazard analysis*

A data base of the earthquake records with magnitude greater than 5.0 which occurred in the area of Greece during the period between 1900 and 1986 was referred in this study. The region of Greece was divided into 19 seismic areas on the basis of the seismotechtonic criteria. Within each area, earthquakes were assumed to occur uniformly, randomly and independently as they were assumed to follow the Poisson process. By use of the historical earthquake records, the parameters for the seismic risk analysis, such as the annual occurrence rate of events, the b-value of Gutenberg-Richer's equation and the upper bound magnitude were estimated. Some of these parameters formulated the probability density function for each area. Furthermore, the probability density of distance between the shortest distance and the longest one from the site to the source-area was calculated for each of 19 areas. To obtain the anticipated response spectra at the site, the attenuation equation for spectral acceleration proposed by Kawashima [3] was introduced in this study,

$$S_A(M,\Delta,T) = a(T)10^{b(T)M}(\Delta+30)^{-1.178} \tag{1}$$

where M is the earthquake magnitude, Δ is the epicentral distance, and T is the natural period. Since it is necessary to consider the uncertainties of the normalized response spectra among the ground motions whose magnitudes and epicentral distances were the same, the coefficient of variation was assumed as 0.3 for all periods between 0.1 and 3.0seconds [4]. Through the above procedure, the probability of exceedance per year of the ground motions for all the control points were calculated. Fig.1 shows an exampled hazard curve for the natural period of 0.2 sec. Another significant task is the selection of acceptable levels of risk which should be determined on a specific project as Parthenon's retrofitting. These were directed; 1) To prevent structural and most architechtural damage due to those earthquakes reasonably anticipated to occur several times during the life of the monument (Level 1). ii) To prevent total collapse, due to the maximum credible earthquake

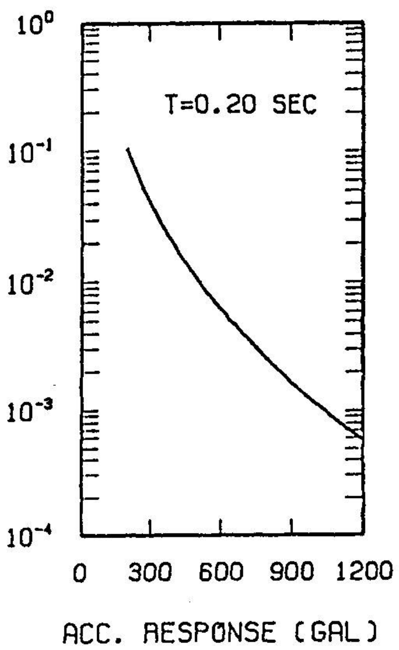
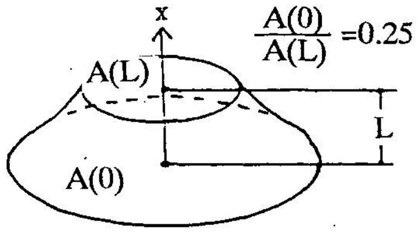


Fig.1 Seismic hazard curve for the control natural period of 0.2sec



L=70m
Vs=2000m/s
Damping ratio=0.05

Fig.3 Elastic shear beam model to calculate the topographical effect of Acropolis hill

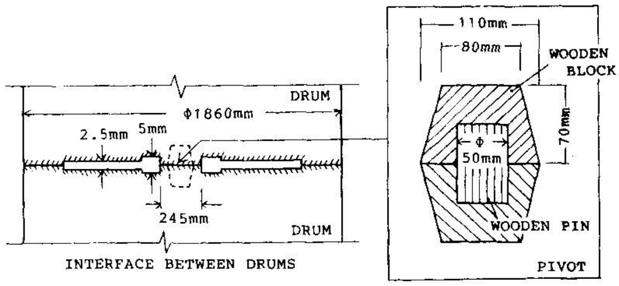


Fig.5 Drum's interface and shear key (After Penrose,C.K.(1973))

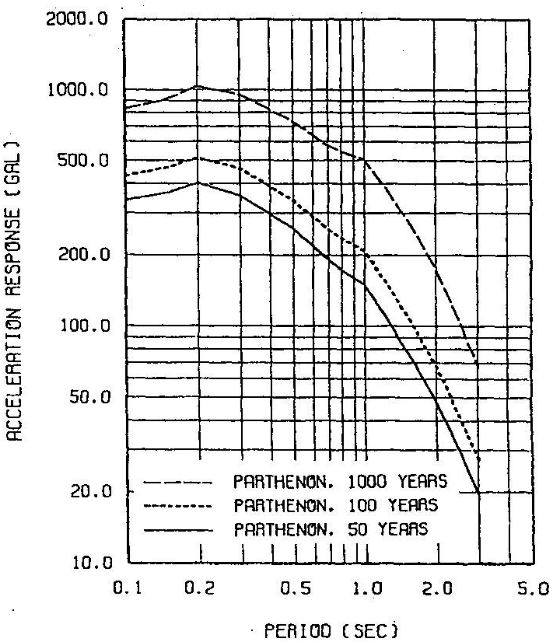


Fig.2 Uniform hazard spectra at the base of Acropolis hill for return period of 50、100、and 1000years

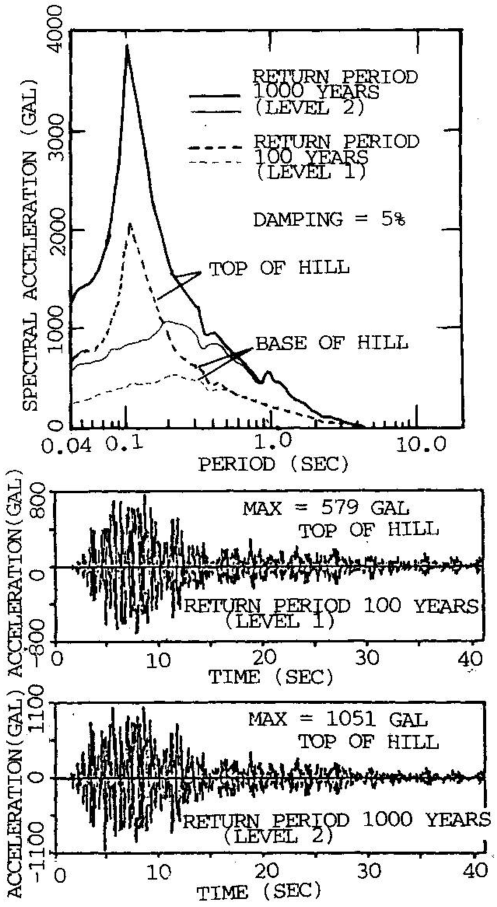


Fig.4 Synthetic earthquake ground motions for return period of 100 and 1000years, along with the target spectra

anticipated to occur (Level 2). In this study, a return period of 100 years was adopted to represent the earthquake motions of level 1 and a return period of 1000 years for the earthquake motions of level 2. The acceleration response spectra for return periods of 100 and 1000 years were obtained from the seismic hazard curves for all the control points. Fig. 2 shows the anticipated acceleration response spectra at the base of Acropolis hill for return periods of 50, 100 and 1000years.

2.3 *Simulation of synthetic earthquake ground motions*

Earthquake ground motions compatible with the anticipated response spectra for return periods of 100 and 1000 years were generated by the superposition of sinusoidal waves with a set of phase angles uniformly distributed in the interval between 0 and 2. The stationary waves were multiplied by the envelope functions proposed Theofanopoulos et al. [5]. These envelope functions correspond to earthquake magnitudes and distances, relative to active faults in the vicinity of Athens with potential to generate earthquake motions of level 1 or of level 2 , respectively.

2.4 *Topographical effect of the hill and resulted motions*

The Acropolis hill where Parthenon is located was modeled as a linearly elastic shear beam with an exponentially varying cross-section (See Fig.3). Since the height-to-width ratio of the hill is small, it may be reasonable that primary response of the hill due to earthquake motions at its base will be principally in shear. The resulted ground motions at the top of the hill for return periods of 100 and 1000 years, along with the response spectra at the base and at the top of the hill, are shown in Fig.4. Comparing the acceleration response spectra at the top of the hill with those at the base, the spectral amplitudes at the top are about 1.4 to more than 5 times greater than those at the base in the period range between 0.04 and 0.2sec. Thus, it seems feasible for the shear waves of the motion at the base, with period of about 0.1sec, to cause resonance, because the wavelength of them are compatible to the dimension of the hill. On the other hand, the maximum acceleration amplitudes of the ground motions at the base of the hill are 201gals for return period of 100years and 460gals for return period of 1000years, and consequently the amplification ratio of the maximum accelerations at the top to the base takes values of 2.3-2.9. The synthetic ground motions at the top of the hill will be used as the input motions for the seismic response analysis in the following chapter.

3. SEISMIC RESPONSE ANALYSES OF MASONRY COLUMNS

3.1 *General*

Dynamic analyses of Parthenon's columns have been conducted to study their feasibility to withstand the given ground motions safely. The analytical methods were explained in detail by the authors in reference [6] and [7].

3.2 *Structural conditions*

The column has a height of 9.6m, composed of 11 drums and a capital. The diameter of the drum ranges from 1.9m at the base to 1.5m at the top, of which average height is o.87m. The material used for the construction is white Penteric marble. Fig.5 describes the condition at the interconnection between the drums [8]. In the present state, the most of columns have beams and pediments on their capitals, while some of them have not. This structural condition was also taken into account in the linear response analysis.

3.3 *Linear response analysis*

Thirteen or twelve lumped mass systems were assumed, and rotational and translational modes at each level of drum's separation were considered. In this study, three models were assumed as follows. Model (A) represents a column with a beam and a pediment on its capital, subjected to seismic loads perpendicular to the longitudinal direction of its beam(See Fig.6). Model (B) is similar to Model (A), but it is subjected to seismic loads in the longitudinal direction of its beam.

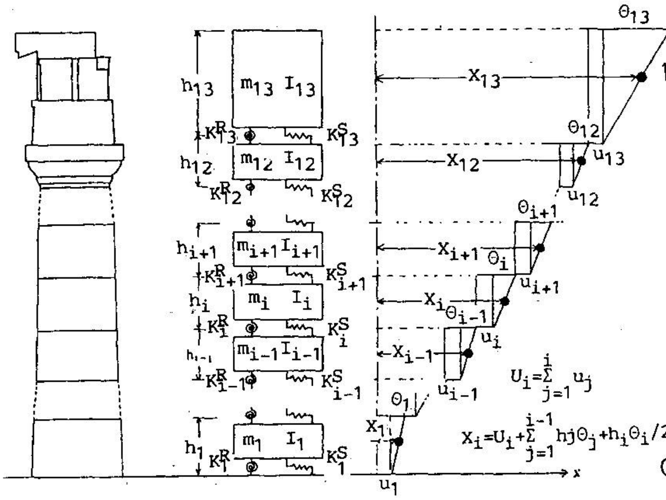


Fig.6 Model for linear response analysis of a masonry column with a beam and a pediment on its capital (Model(A))

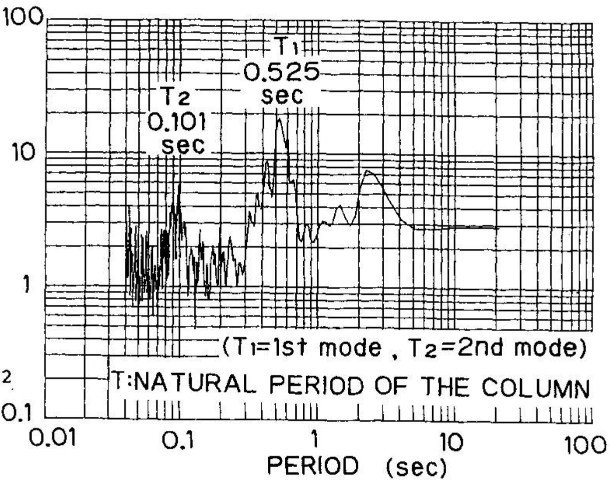


Fig.7 Fourier spectra ratio of microtremor records at Zeus-Olympeion Athens ; the ratio between the top and the base of the column

Table 1 Natural periods of Zeus-Olympeion column ; Comparison of measurements with analysis

Mode	Natural period (sec)	
	measurement	analysis
1st	0.525	0.531
2nd	0.101	0.101

Table 2 Estimated natural periods of Parthenon columns

Mode	Natural period (sec)		
	Model(A)	Model(B)	Model(C)
1st	0.583	0.275	0.236
2nd	0.086	0.037	0.046

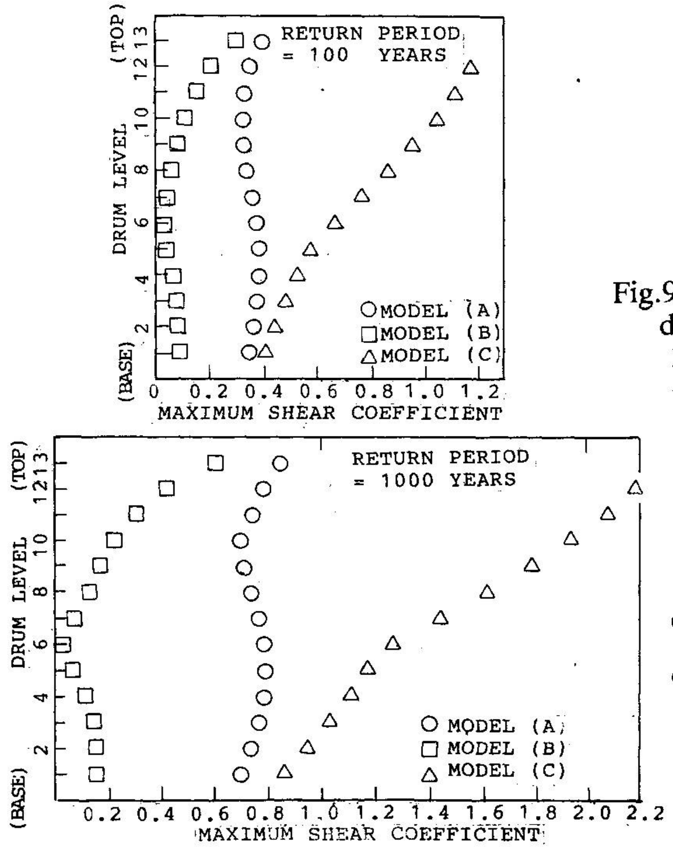


Fig.8 Results of linear response analysis ; Distribution of the maximum shear coefficients along height of columns

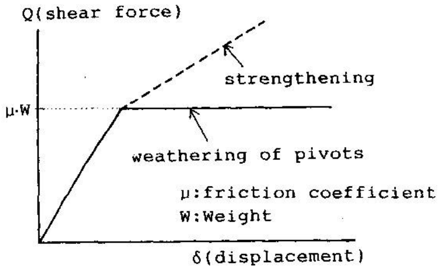


Fig.9 Assumed characteristics between load and displacement for non-linear response analysis

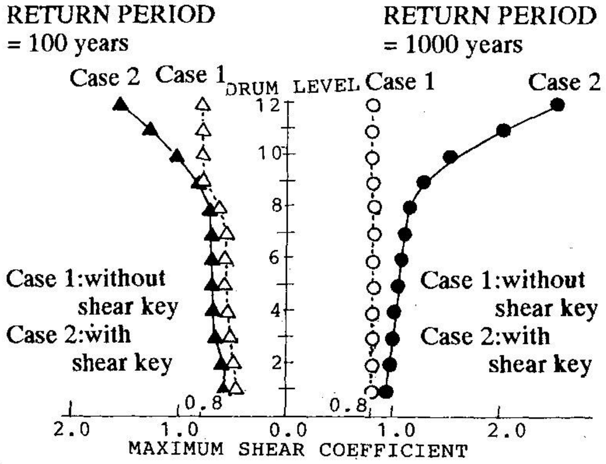


Fig.10 Results of non-linear response analysis ; Distribution of the maximum shear coefficient along height of a column without beam and pediment on its capital

Model (C) represents a column without any member on its capital. Since the dynamic characteristics of Parthenon such as natural periods of its column was not available, the natural periods, as well, as the other parameters for the analysis were estimated, considering the microtremor records at Zeus-Olympeion Athens and the difference in the dimensions between Parthenon and Olympeion. Fig.7 shows the Fourier spectral ratio of the records obtained at the top to that of the records obtained at the base of the Olympeion's column, in which the natural periods of the column for the 1st and 2nd modes are presented. For the linear analysis, the rotational spring constant K_R at each interface was assumed as the following equation.

$$K_R = \alpha\sqrt{\sigma_V}r^4 \tag{2}$$

where σ_V is the normal stress, r is the interface's radius, and α denotes the proportionality index evaluated through the eigenvalue analysis of Olympeion's column in order to obtain the natural periods equal to the estimated ones by the microtremor analysis (See Table 1). Using the estimated value of α , K_R at drum's interface of Parthenon were evaluated. Furthermore, the translational spring constant K_H was evaluated from the elastic deformation characteristics of the drum. The eigenvalue analysis using these parameters provided the natural periods of the column, as shown in Table 2. The columns have the fundamental periods longer than the predominant period of the anticipated ground motions. This results may explain that, although the recent earthquake was reported to cause the slight translational displacement at the drums' interfaces, the earthquake which hit Athens did not destroy the columns due to overturning. As results of the linear response analysis utilizing the assumed MDOF systems to the synthetic ground motions for return periods of 100 and 1000 years, the distributions of the maximum response accelerations along the height of the columns are presented in Fig.8. The shear coefficient of Model (C) attains rather high values compared to those obtained by the other models. In the case when the shear keys at the interfaces between drums of the column without any member on its capital have already weathered and they can not resist seismic loads, translational displacements may occur due to earthquake motions. This result is consistent to the fact that the differential displacements were caused by the 1981, Corinth Earthquake at the drum's interfaces of some columns.

3.4 *Non-linear response analysis*

A lumped mass system with only a translational degree of freedom at each drum's interface was introduced. The spring constants were determined so that the natural periods and modal shapes of the column should coincide with those of the model of the linear response analysis. To represent non-linear characteristics, bi-linear type of load-displacement relationship shown in Fig.9 was assumed. The non-linear response analysis was carried out for the Model (C) under the condition that the effect of the shear key was not taken into account due to weathering (Case 1) and that the shear keys made of titanium alloy was replaced to strengthen the columns (Case 2). The resulted distributions of the maximum shear coefficients shown in Fig.10 indicates that the shear keys can undertake the excess seismic loads, and that the overloading beyond the critical friction resistance will occur for the column without shear keys. The effect of the shear keys on the aseismic retrofitting will be investigated in the following chapter.

4. STATIC SHEAR TESTS ON MODEL MARBLE COLUMNS FOR ASEISMIC RETROFITTING

4.1 *General*

The static shear friction tests among the marble drums were conducted to understand their behavior when the drums undertake the seismic translational loads, and to investigate the effects of shear keys designed for the aseismic retrofitting. The tests were explained by the authors in reference [9].

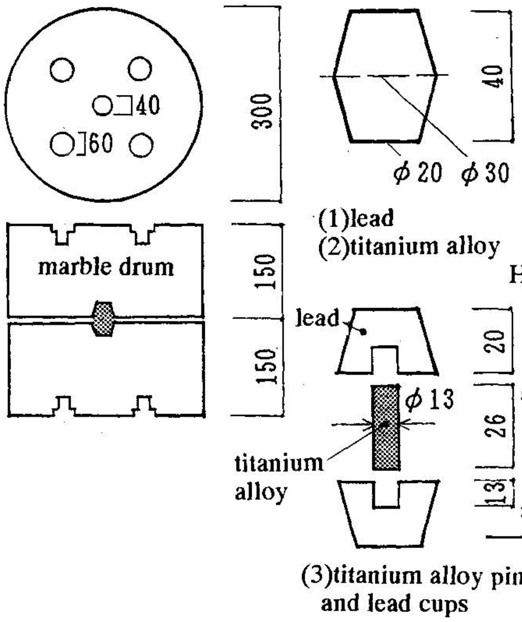


Fig.11 Model marble drums and shear keys for the static shear tests

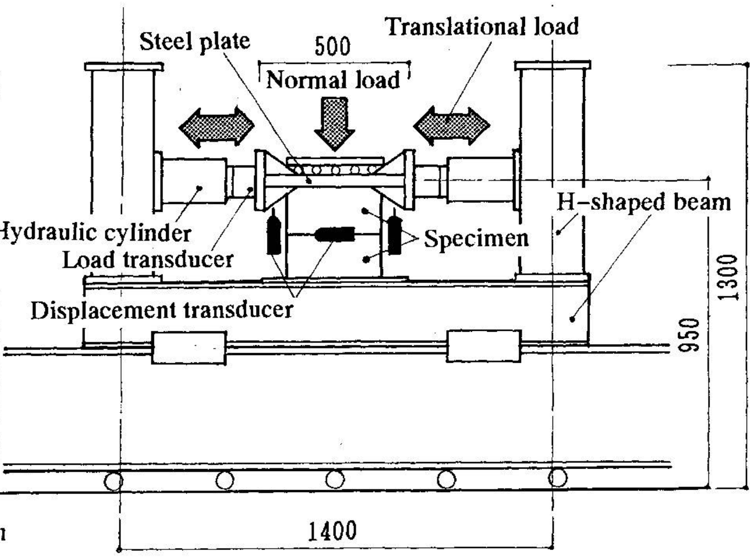


Fig.12 Apparatus for the static shear tests

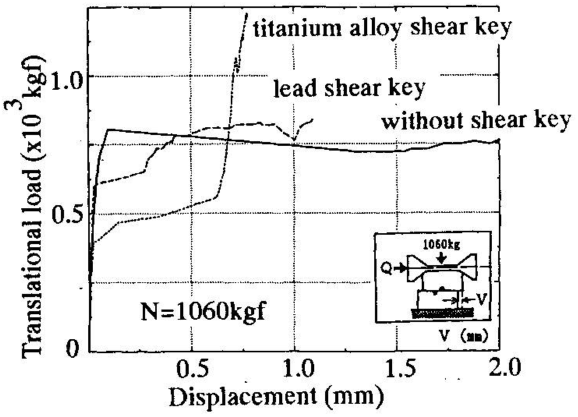


Fig.13 Load-displacement relationship of the monotonic loading tests of the drums with lead shear key, with titanium shear key, and without shear key

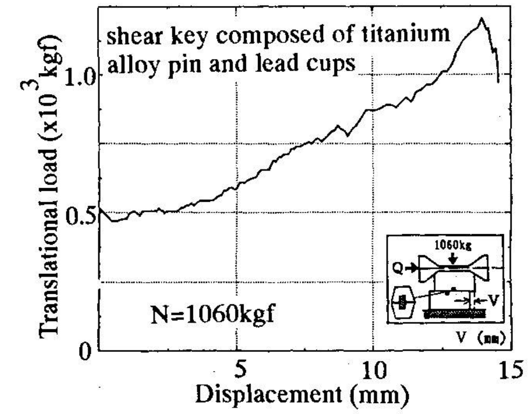


Fig.14 Load-displacement relationship of the monotonic loading tests of the drums with shear key composed of titanium pin and lead cups

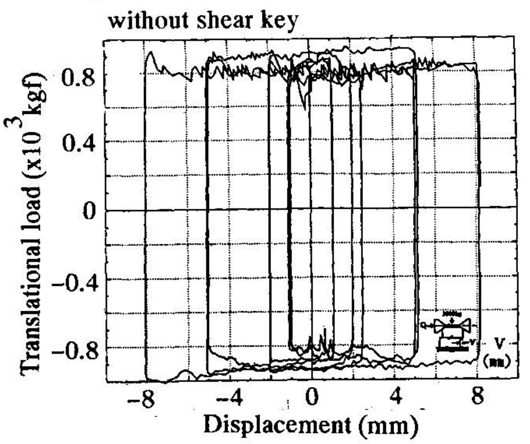


Fig.15 Behavior of interface without shear key under cyclic loading

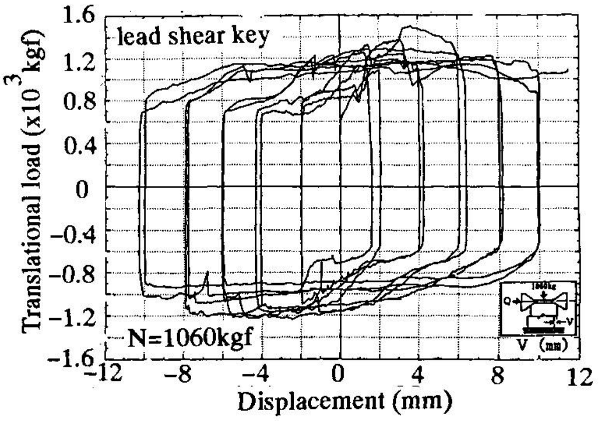


Fig.16 Behavior of interface with lead shear key under cyclic loading

4.2 *Test materials and procedure*

The cylindric marble drum, a one-sixth scale model of Parthenon column, was used, and the three types of shear keys were examined in this experimental study (See Fig.11). Fig.12 shows an apparatus for the simple static shear tests.

4.3 *Experimental results*

The load-displacement relationships of the one-way monotonic loading tests and of the cyclic loading tests are described in Fig. 13, 14 and in Fig. 15, 16, respectively. These figures demonstrate that the shear keys undertake the loads beyond the critical friction resistance (friction yielding), and that the load-displacement relationship after the friction yielding were affected by the material properties and structures of the shear keys. The experimental results indicate that the shear keys such as the one composed of titanium alloy pin and lead cups, proposed in this study, have the effect on increase of the earthquake resistant capacity.

5. CONCLUSIONS

Parthenon's behavior under seismic actions for 25 centuries has been satisfactory due to its excellent design and due to the characteristics of the earthquake ground motions. However, when the shear keys among the drums lose their function due to weathering, the seismic loads may cause damage to the columns. Replacing the old shear keys by the new ones are suggested to be adopted for the aseismic retrofitting. Future study will be needed on the overturning behavior of this structure under strong ground motions.

ACKNOWLEDGMENTS

The writers would like to express their gratitude to Dr. Theofanopoulos, N and Miss Mabuchi, Y., graduate students at University of Tokyo Metropolitan, for their technical contributions.

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