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Greek temple and timber Pagoda in Japan - comparison of the aseismic structural performances

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Abstract

Comparing the aseismic performances of two historical monuments: Greek temples such as the Parthenon in Greece and five-storied timber pagodas in Japan, which survive for centuries, we found some significant similarities in structural performances. The dynamic analyses show that both, as a piled up construction, are based on the common concept of structural design, which we may call "Flexible structural designing". Similarities in seismic behaviors between the column composed of marble drums in the Parthenon and the tall assembly of timber elements in five-storied Japanese pagodas are summarized as; 1) comparatively large damping effect at the joints with high non-linearity, 2) conspicuous improvement in shearing resistance produced by the dowels connecting the elements; and 3) generation of a restitutive force produced by the rocking movement of columns. Taking these factors into account, dynamic analyses have been carried out to examine the earthquake resistant capacity against the anticipated ground motions for a return period of 1000 years.

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 scope of the present paper is to compare the aseismic structural performances of two historical buildings : Greek temples and five-storied pagodas in Japan, the most famous exapmle of the former being the Parthenon in Greece (Photo.1) and the latter being the Gojuu-no-to in Horyu-ji in Japan (Photo.2). An effort was made to clarify and understand the inherent potentiality of the ancient buildings in their seismic performances against earthquake ground motions.

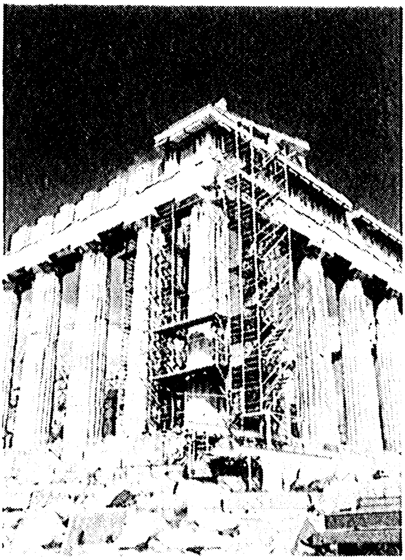

Photo.1 The Parthenon in Greece

Photo.2 The Gojyu-no-to in Horyuji in Japan

2. Structural Design Concept

Although the two kinds of buildings we are comparing are quite different in form, in material, and apparently in structure as well, the both, as a piled up construction (Figs 1 and 2), share a basic concept of the structural design in common, which we may call " Flexible structural designing". By "Flexible structural designing" we mean a structural idea to make the structure flexible with the intention to reduce the seismic forces. In Figs. 3 and 4, the predominant periods of the earthquake motions given by the acceleration response spectra is compared with the natural periods of the buildings obtained from the microtremor analysis[7,8]. The comparison clarifies that the fundamental periods of these structures, even at the lower-strain level of microtremor, are rather longer than the predominant periods of the earthquake motions. That means , with

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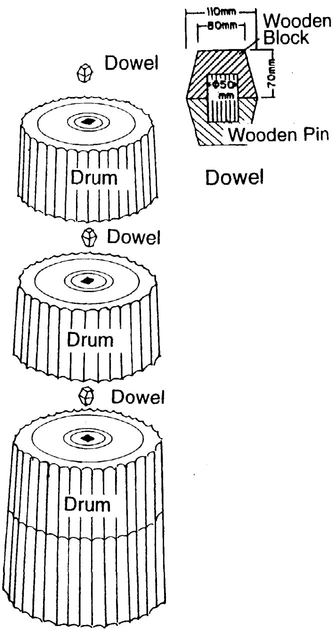


Fig.1 Piling up of marble drums in a Greek temple

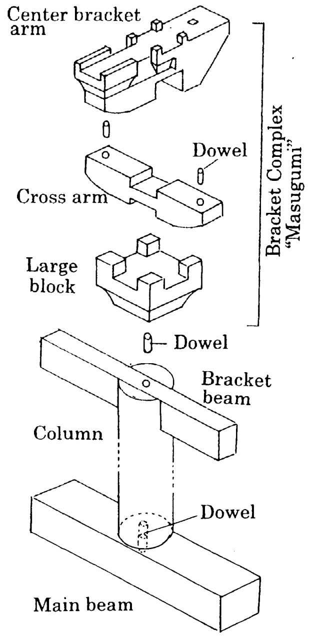


Fig.2 Piling up of timber elements of column, beam, and "Masugumi" ,in a ancient timber building

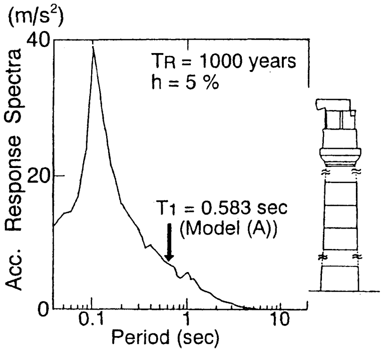


Fig.3 Acceleration response spectra of simulated earthquake motion, compared with the fundamental period of the Parthenon

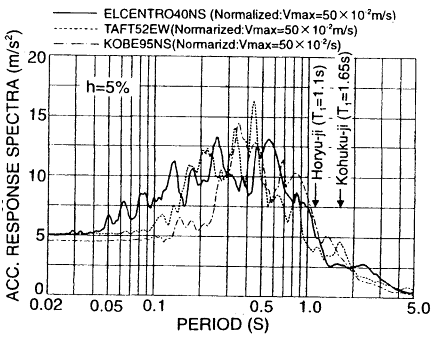


Fig.4 Acceleration of response spectra of normalized earthquake records, compared with the fundamental period of representative five-storied pagodas in Japan

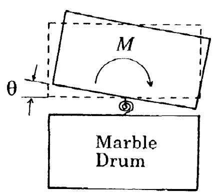


Fig.5 Rocking model of drums of a Greek temple's column

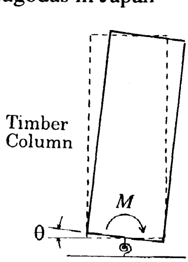


Fig.6 Rocking model of a column of a Japanese ancient timber pagoda

large non-linear response, the structural fundamental period becomes longer, and the resonance that may cause the damage will not occur. The other similarities in seismic behaviors between the column composed of marble drums in Parthenon and the tall assembly of timber elements in the five-storied pagoda are summarized as follows : 1) comparatively large damping effect at the joints with high non-linearity ; 2) conspicuous improvement in shearing resistance produced by the dowels connecting the elements ; and 3) generation of restitutive force produced by the rocking of column (Figs. 5 and 6). In the present study, the dynamic analyses focus on the mechanical properties 2) and 3).

3. Seismic Response Analysis of a Greek Temple

3.1 Analysis model

Columns of marble drums were first modeled by lumped masses systems with both translational and rotational degrees of freedom(Fig.7). In the present paper, we took the Parthnon as a typical example. The natural periods and other parameters for the analysis of the Parthenon columns were estimated by using the microtremor records of the Zeus-Olympeion Athens. The rotational spring constant at joints was assumed as[1] ;

$$K_R = \alpha \sqrt{\sigma_V} \cdot r^4 \qquad (1)$$

,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. The fundamental period of the Parthenon columns was estimated to be 0.583(s) which is longer than the predominant period of the anticipated ground motions[2] for the return period of 1000 years at the top of Acropolis hill(Fig.3). This result indicates that the Parthenon has a basic concept of "Flexible structural designing". The uniform hazard spectra at the foot of Acropolis for the return periods were evaluated probabilistically from seismological data of the region. The synthetic ground motions were simulated to fit their response spectra to the uniform hazard ones[2]. The topographical effect of the hill was also taken into account[2](Fig.8). In the process of this kind of simulation, it is important to consider the historical earthquakes, as well as, the soil conditions at the site.

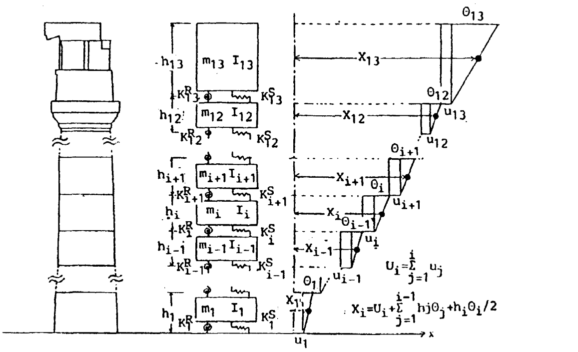
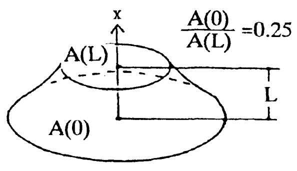


Fig.7 Dynamic analysis model of the Parthenon's column



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

Fig.8 Elastic shear beam model to calculate topographical effect of the hill

3.2 Analysis results

We applied the MDOF system shown in Fig.7 for the linear analysis of response to the anticipated ground motions. The acceleration amplification ratio of the top to the base was approximately less than 1.5 (Fig.9a). The shear coefficients was approximately lower than 0.8 (Fig.9b). The static shear friction tests[3] of one-sixth scale models of the Parthenon columns gave the following results : the friction capacity without dowel ranged from 0.6 to 0.8 ; and the dowel started work beyond this limit.

In the dynamic phase of the structure, the non-linear response analysis was conducted by using the equivalent MDOF system with the bi-linear type of load-displacement relationship shown in Fig. 10. The results indicated that the dowels undertook the overloading beyond the critical friction resistance but that the translational large displacement would occur at the columns after the dowels deteriorated due to weatheing and lost their translational resistance(Fig.11).

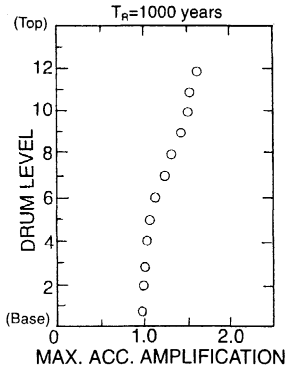


Fig.9a Acceleration response of the Parthenon's column to the ground motion anticipated for return period of 1000years

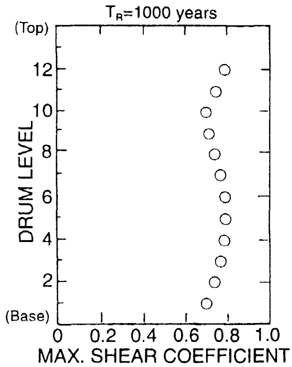


Fig.9b Shear coefficient distribution along height of the Parthenon's column due to the earthquake anticipated for return period of 1000years

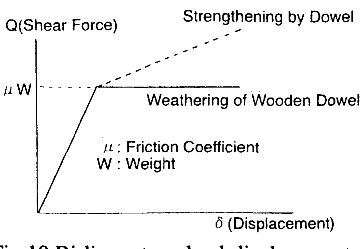


Fig.10 Bi-linear type load-displacement relationship assumed for non-linear response analysis

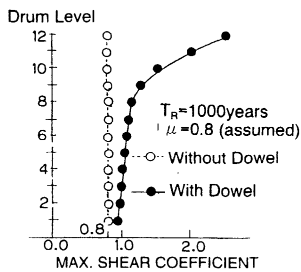


Fig.11 Shear coefficient distribution along height of the Parthenon's column, calculated from non-linear response analysis

4. Seismic Response Analysis of Timber Pagoda

4.1 Analysis model

Fig.12 provides a typical timber five-storied pagoda in Japan, designed by a modern carpenter today following the type of the Edo era (during 17th –18th Century). Shown in Fig.13, the structure is composed of the exterior square

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formed by "Gawabashira" (Outside columns, b-sec in Fig.14) and the interior square formed by "Shitenbashira"(Inside columns, a-sec in Fig.14). The central mast "Shinbashira" is suspended from the lever beams of the 4th and 5th story(Fig.14). The structural members were mainly of Japanese Hinoki cypress and Hiba arborvitae trees. Since the horizontal in-plane rigidity of the frame at each floor was sufficiently large, the timber structure was idealized as a 2-dimensional frame model composed of the outer and inner structural faces(Fig.14). The restitutive force produced by the rocking of columns[4] was illustrated in Fig.15. According to the experimental study on the column rocking (Hayashi et.al[5]), we assumed the non-linear rotational spring (Fig. 16) at the foot of column shown in Fig.14. At the joint of the penetrating beam "Nuki" and the column, the semi-rigidity model was introduced, characterized by the embedding behavior of the column into the beam (Fig.17, after Inayama,M.[6]). The bracket complex " Masugumi", the most specific element of the traditional timber structure, was modeled by a series of translational and rotational springs introduced in Fig.19. In our modeling of the translational spring, it was assumed that the wooden dowel was embedded into the wooden block(Fig.18), and that both the dowel and the block were deformed as a elastic shear body. On the other hand, the rotational spring shown in Fig.18 was modeled on the assumption that, since the lower large block was embedded into the bracket beam, the rocking of the wooden block causing the rocking movement of the bracket complex occurred.

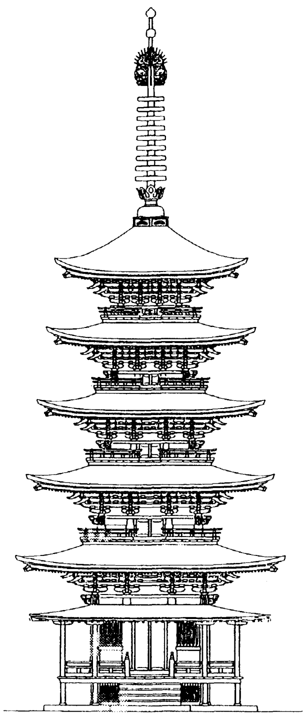


Fig.12 A typical timber five-storied pagoda

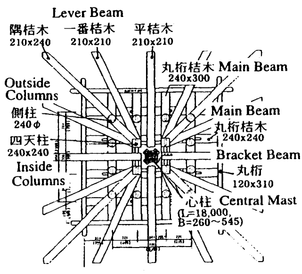


Fig.13 Plan of timber frame of a five-storied pagoda shown in Fig.12

4.2 Analysis results

As results of the eigenvalue analysis, the fundamental period was evaluated to be T_1=1.32 (s). This result suggested that it had the same aseismic properties of "Flexible structural design" as the Greek temples. The natural period (T_1) was calculated at the story drift angle of 1/200, defined as the ratio of the story drift to the height of the floor. Since the natural period depends on the response level of the structure, and since the fundamental period of Goju-no-to in Horyu-ji was reported to be 1.1 (s) obtained from the microtremor record[8] at much lower level of the displacement, the calculated period was satisfactorily adopted from an earthquake engineering point of view. The input ground motion level required to examine the earthquake resistant capacity of the five-storied pagoda was

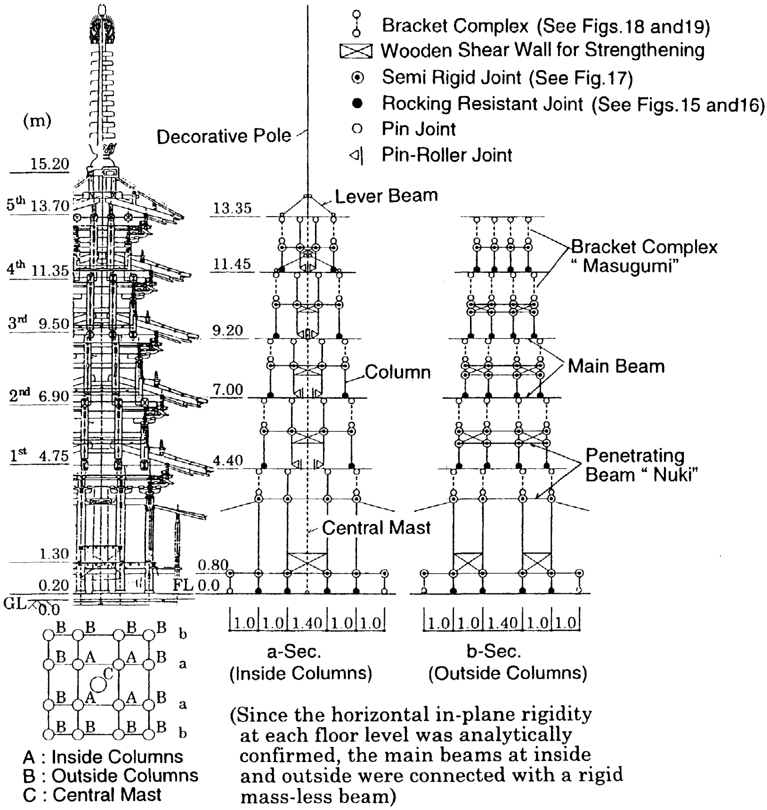


Fig.14 Two-dimensional frame model of a five-storied timber pagoda

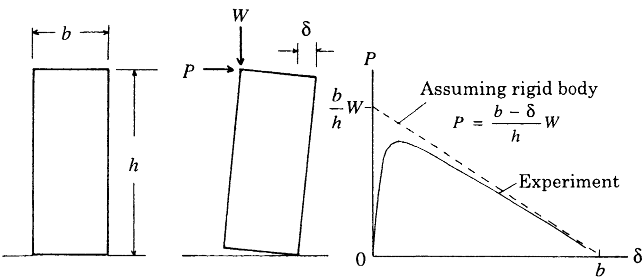


Fig.15 Restitutive force produced by rocking of column

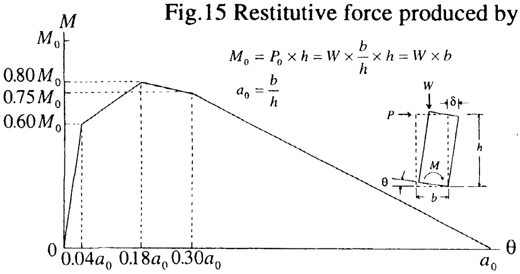
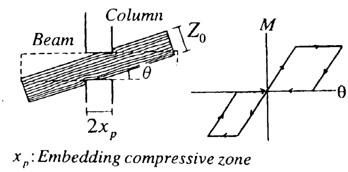


Fig.16 Non-linear rotational spring model of restitutive force shown in Fig.15



(*atfer Inayama* 1995)

Fig.17 Semi-rigidity model at joint of penetrating beam "Nuki" and column

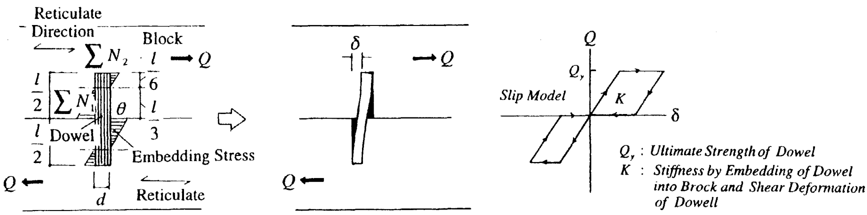


Fig.18 Modeling of combination of dowel and block of bracket complex "Masugumi"

$$\delta = s + h \cdot \theta$$

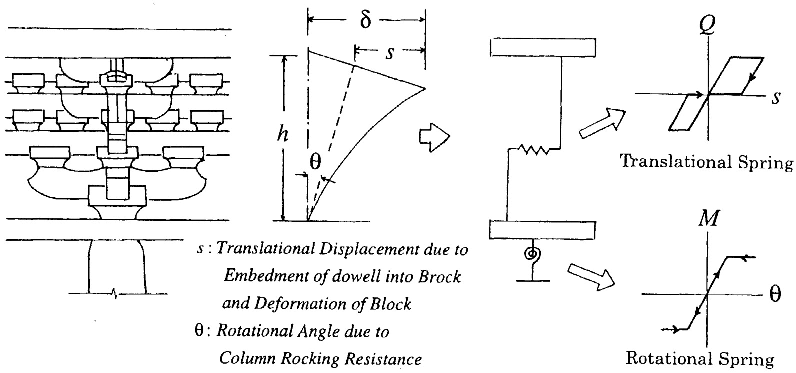


Fig.19 Spring model of bracket complex "Masugumi"

probabilistically evaluated from the seismic hazard analysis[2] utilizing the data base of the earthquake records with the magnitude greater than 5.0 that occurred during the period between 1600 and 1995 in the central region of Japan(Fig.20). The seismic hazard curve of the maximum velocity amplitude, defined at the base rock, showing that the velocity level was 17.4 $\times 10^{-2}$(m/s) for the return period of 1000 years(Fig.21). Since the soil condition has a great effect on the amplification of the earthquake motions, the one-dimensional model of shear wave propagation(Fig.22) was employed through the equivalent-linear technique shown in Fig.23. As for the incident wave defined at the upper face of the base rock (GL-15m), the earthquake record of ELCENTRO40NS was used after normalizing at the prescribed velocity level. The seismic response analysis was successfully conducted for the input strong motion shown in Figs 24 and 25, with assuming the damping of Rayleigh model of 5% at 1st and 2nd modes. Fig.26 presents the results of the seismic response analysis : shear coefficient; the relative displacement; and the story drift along the height of the building. The calculated story drift angle shown in Fig.26 was not excessively beyond the deformation limit of 1/30 corresponding to structural collapses of traditional timber frames. (The criterion of 1/30 was drawn from static shear tests of traditional timber frame) This calculation indicated that the structure would be safe against the earthquake ground motions anticipated for the return period of 1000 years. The present analysis also indicated that the decorative pole at the top acted as an active mass damper during severe earthquakes. Furthermore, it suggested that collision between the central mast and the beams would not occur.

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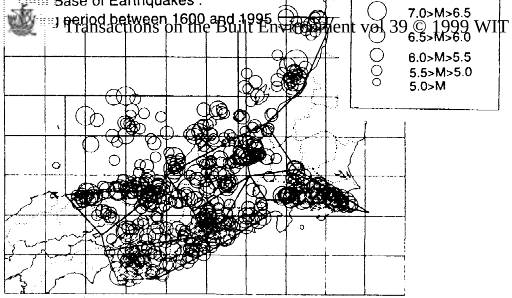


Fig.20 Earthquake epicenters for the period 1600-1995 in the central region of Japan

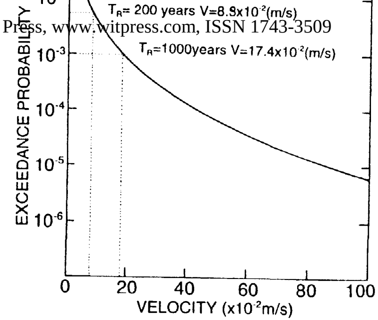


Fig.21 Seismic hazard curve of maximum velocity amplitude

Depth(m)	Soil	ρ (tf/m^3)	Vs(m/s)
GL ~ -3	Sandy Soil	1.95	140
-3 ~ -7	Sandy Soil	1.96	160
-7 ~ -9	Sandy Soil	1.89	260
-9 ~ -12	Gravelly Soil	1.71	400
-12 ~ -15	Rock	1.78	500

Fig.22 One-dimensional soil model of shear wave propagation

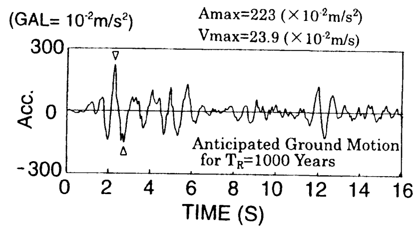
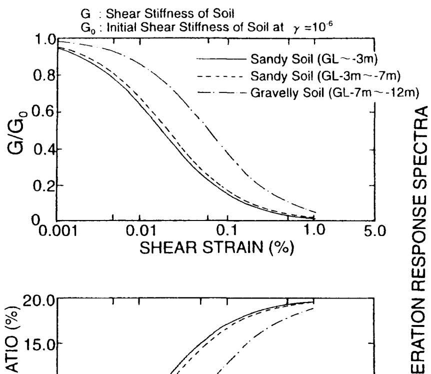
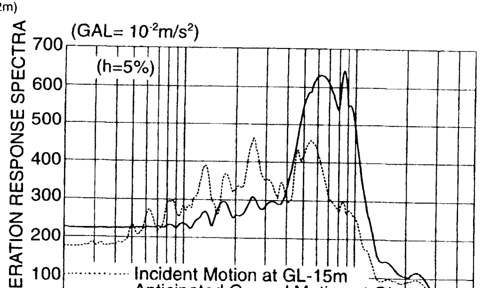


Fig.24 Anticipated ground motion for the return period of 1000 years





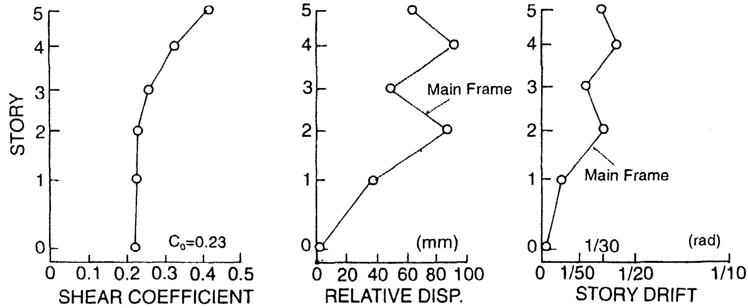


Fig.26 Calculated shear coefficient, relative displacement, and story drift of the timber frame for the anticipated earthquake motion

Concluding Remarks

What we learn from these comparative considerations is that, as far as the aseismic retrofitting measures of historical monuments concerns, the inherent structural excellence of ancient structures, especially in their dynamic phase, should be evaluated and respected both as exactly and totally as possible. In order to assess the aseismic safety of these structures, it is important to consider the historical earthquake records, as well as, the geotechnical conditions. Probabilistic approach is effective in simulating the input ground motions for earthquake response analysis. Great effort should be made to clarify and understand the inherent potentiality of the ancient buildings in their seismic performance against earthquake ground motions.

References

1. Hanazato, T.,Theofanopoulos,N. & Watabe, M., Seismic Response Analysis of Parthenon, Proc. of STREMA89, Firenze,1989
2. Theofanopoulos, N., Hanazato, T. and Watabe, M., Probabilistic Approach to Generate the Reference Motion for the Protection of Historical Monuments Against Earthqaukes, Proc. of STREMA89, Firenze,1989
3. Mabuchi,Y., Hanazato, T. Watabe, M. : Static Shear Friction Tests on the Model Marble Columns of Parthenon for the Aseismic Retrofitting, Proc. of STREMA93, Bath, 1993
4. Ban, S. : Study on statics for structures for structures of temple and shrine Part-1, Technical Papers of Annual Meeting, A.I.J.,1941 (in Japanese)
5. Hayashi,T., Karube,M.,Harada,M Takahashi,Y. and Kimura,T.: Full-size test of ancient traditional wooden frame under horizontal loading (Part 1), Technical Papers of Annual Meeting of A.I.J.,pp267-268,1998 (in Japanese)
6. Inayama,M. : Design of embedding resistant joint (Structure by penetrating tie beam), The Kentiku Gijyutu, pp106-111,1995.11 (in Japanese)
7. Kubota,H. and Yamabe, K.: A study on aseismic properties of the five-storied pagodas, Proc. of 12WCEE, pp3989-3994,1992
8. Uchida,A. Kawai,N. and Maekawa,H. : Dynamic Characteristics of Traditional Wooden Building (Part 2), Technical Papers of Annual Meeting of A.I.J.,pp171-172,1996 (in Japanese)

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