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ON THE SPECIAL EARTHQUAKE RESISTANCE OF FIVE-STORY TIMBER PAGODAS IN JAPAN

Do Kien Quoc[1], Vo Minh Thien[2], Yasuro Maki[3], Takanobu Nishiya[4]

ABSTRACT

The special ability of earthquake resistance of five-story timber pagodas in Japan remain a mystery up to now. In this paper, a typical five-story timber pagoda is considered in which its structural model includes friction bearings connecting the central pillar (*shinbashira*) and footing, the surrounding pillars and beams of roof. The unclarity in structural details and connections of the pagoda are characterized by various parameters such as the gap between the shinbashira and floors, the coefficient of friction and the weight of roof. The non-linear dynamic responses of the pagoda with the proposed model and the traditional model are then analysed together according to ground acceleration of various earthquake records. The obtained results indicate that the proposed model gives much lower response compared to that of the traditional model. This analysis helps clear understanding on the special earthquake resistance of Japanese pagodas that remained for centuries.

***Keywords:** timber pagoda, friction bearing, dynamic analysis, energy dissipation.*

1. INTRODUCTION

In a land swept by typhoons and shaken by earthquakes, the tower of Hohryuji, a typical traditional five-story timber pagoda built approximately 1300 years ago remained standing for centuries. The attractiveness of Japanese timber tower exists in their height and its perpendicular directly, representing the spiritural stretching out of their tips into the sky. There still exists over 300 timber pagodas in Japan today, and are considered as one of the typical Japanese beauty. The long existence of these pagodas in strong seismic regions is still a big question.

According to [1], [2], [3], [4], [5], the one and most important morphological factor in the construction of pagodas is very deep projecting span of eaves. By extending the beam beyond the supporting points and applying the principle of lever, it is able to support load applied on the beam outside the span. On the other hand, the central pillar (shinbashira) is often supported on the central footing stone or large beam, it plays an important role as a religious symbol. The frame of the pagoda is formed by placing lateral members (yokozai) between these surrounding pillars. The frame is carefully constructed so as to keep gaps between the central pillar and itself. The central pillar is independently placed in the center of the pagoda with no connection to other parts of the structure. It may be interesting to know that the shinbashira stands by itself without supporting any parts of the tower, it can create flexible structure resistance against earthquake. The shinbashira is strictly a Japanese invention, it is not found in pagodas elsewhere in the world. Furthermore, the secrete of enduring strength and stability lies in the tapered configuration, the variation of cross-section with height, and the weight of eaves can play an important role to protect pagodas against earthquake.

This study is a reconsideration of a former paper presented in Vietnam (2002) when the information about pagodas structure was not sufficient. Now with the structural details provided by Masaru Abe [1] and his conclusions about the proportion of body width to its total height, the ratio of the height of sohrin to its total height, the ratio of the roof width and body width and the slenderness ratio of the rafter (total cantilever span of rafter/depth of rafter)..., this study concentrates on the effect of the gap size between the central pillar and each floors, the friction connections between central pillar and footing, between the surrounding pillars and beams which the energy dissipation occurs at each level. The effects of size and weight of the eaves to the earthquake resistance of the pagodas are also considered. And to know better the behavior the pagodas, 3 records of ground acceleration as the inputs of the analysis are considered.

2. MODELLING OF FRICTION BEARINGS

According to [1], [2], [3], [4], [5] the central pillar directly supports on the stone footing, it can slide on surface of the footing and isolated pagodas against earthquake by friction forces. The friction forces between the sliding interfaces, on the other hand, plays a role of energy dissipating during the sliding motion. The motion of the friction bearings can be solved into the following modes:

- Stick mode: This occurs when the ground motion induced shear forces between the sliding interfaces of the bearing fail to overcome the maximum friction force. In such occasions, the relative velocity between the interfaces is zero.

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- Slide mode: When the ground motion induced shear force reaches the maximum friction force of sliding interfaces, the bearing takes no more shear and is then forced to slide.

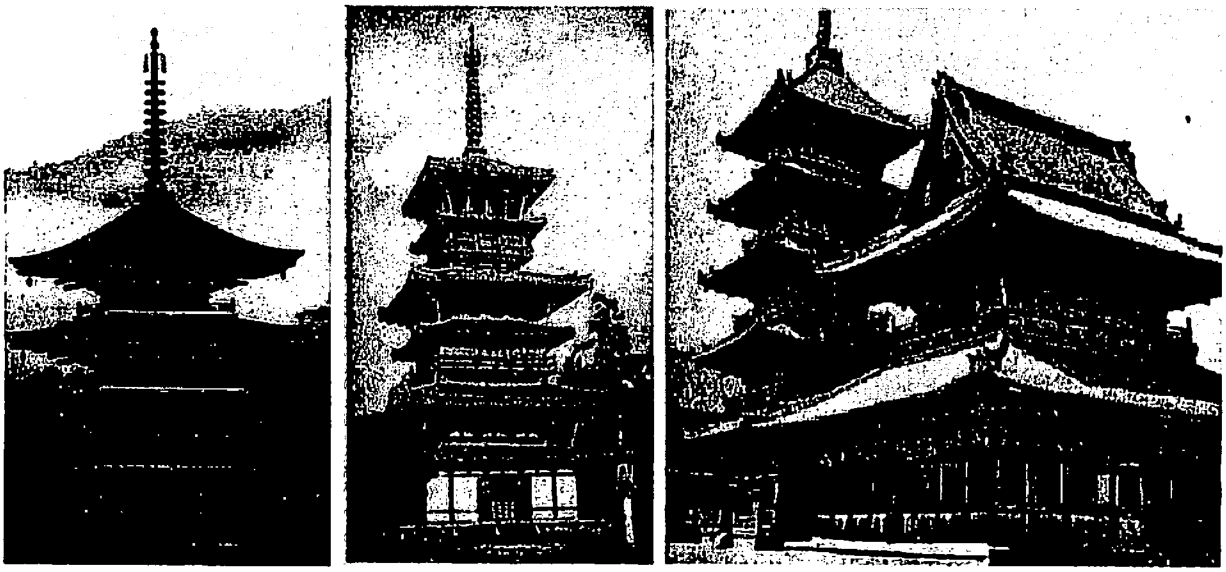

Fig.1. Images of timber pagodas in Japan

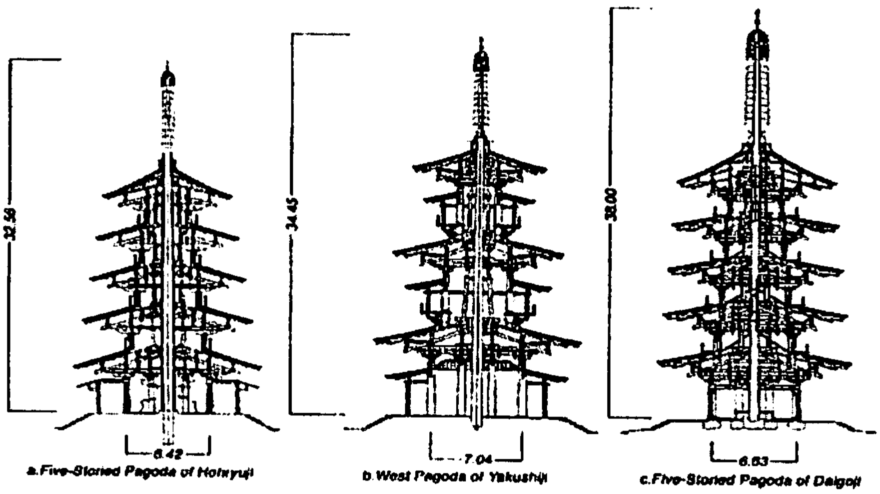

Fig. 2a. Sections of the timber pagodas

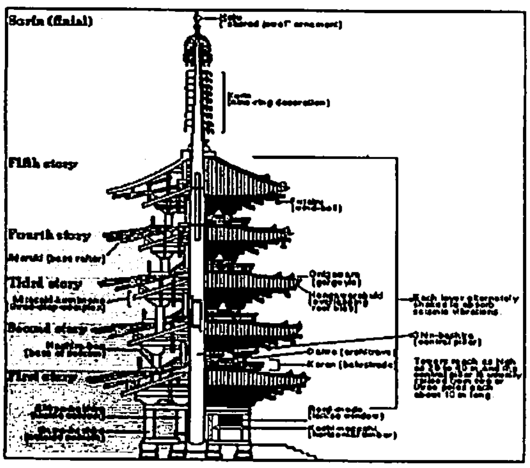

Fig. 2b. Section of timber Pagoda (UEDA Atsushi, Ed.)

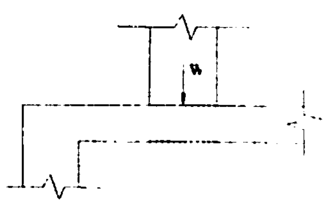

Fig. 3a. Model of column and beam

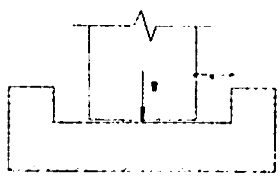

Fig. 3b. Model of shinbashira on footing

Under the assumption of small sliding displacement, the friction force acting along the sliding surfaces is governed by

$$|f| \leq \mu W \quad (1)$$

where μ is the coefficient of friction. This coefficient is a constant as considered in Coulomb's model, or dependent on sliding velocity and the bearing pressure as proposed by Mokha and Constantinou for Teflon-steel interfaces as

$$\mu = \mu_{max} - (\mu_{max} - \mu_{min})\exp(-a|\dot{u}_1 - \dot{u}_2|) \quad (2)$$

where μ_{max} and μ_{min} are,respectively, the maximum and the minimum values of the coefficient of friction, and the coefficient a is to be determined from the bearing pressure, $u_1 - u_2$ is the relative displacement between the sliding interfaces. The non-sliding conditions for the bearing are

$$|f| \leq \mu W \quad \text{and} \quad \dot{u}_1 - \dot{u}_2 = 0 \quad (3)$$

And sliding occurs only if

$$f = \mu W \,\mathrm{sgn}(\dot{u}_1 - \dot{u}_2) \quad (4)$$

In (4), sgn denotes the signum function. Using the friction-pendulum isolators in SAP2000 program, this element can be used to model the gap and friction behavior between contacting surfaces. The responses of a five-story frame of timber pagoda subjected earthquakes are considered. There are great differences between the response of time history for friction bearings and those for traditional fixed-base supports and hinge supports are investigated.

3. EQUATION OF MOTION FOR NONLINEAR DYNAMIC ANALYSIS

The equation of motion of a seismic-isolated pagoda structure under earthquake load $w(t)$ can be represented as

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = BF(t) + Ew(t) \quad (5)$$

where the $u(t)$ is the displacement vector; the M, C, K are, respectively, the mass, damping and stiffness matrices; E is the location matrix of the load; B is the location matrix of the friction forces and $F(t)$ is the friction vector with its satisfying the conditions described in equation (3) or (4).

4. NUMERICAL ANALYSIS

A five-story frame of pagoda is considered in this study. According to Masaru Abe [1], the proportion of body width to its total height is between the range of 4.5 - 6.5, the ratio of the height of *sohrin* to its total height is approximately 1/3 and the ratio of the roof width and body width is about 2.2, the slenderness ratio of the rafter (total cantilever span of rafter/depth of rafter) is $\lambda < 16$.

Table I. Timber member properties

Story height	h = 4m
Total height of shinbashira	H = 30m
Body width of frame	B = 8m
The ratio of the height of sohrin to total height	1/3
Central pillar diameter	D = 0.4m
Others pillar diameter	d =0.3m
Rectangular beams and eaves	0.25x0.4m
The damping ratio	5%
Modulus elasticity of wood	$E=10^7 kN/m^2$
Coefficient of friction of wood	$\mu = 0.25$
Gap between shinbashira floors	e = 3cm
Density of wood	12kN/m3
The weight of roof	q=10 kN/m
Width of eaves	7m

4.1 Response to earthquake excitation

The response of a five-story frame of timber pagoda by using the friction bearings can reduce the shear forces resisted by the pillars that are most vulnerable during earthquake. The pillars can slide on footing surfaces, they vibrate independently during the earthquake and thus interaction between them are minimized.

Table II. Effectiveness Assessment of Seismic Isolation using Friction Bearings

Maximum response quantity*	Types of timber pagoda		
	Fixed base	Hinge supports	Friction bearings isolation
a. El Centro			
AP1 (kN)	554.6	428.5	73.75
AP2 (kN)	559	575.7	273
AP3 (kN)	599.8	448.2	73.74
MP1 (kNm)	86.09	0	0
MP2 (kNm)	232	0	0
MP3 (kNm)	86.55	0	0
VP1 (kN)	42.7	20.79	2.299
VP2 (kN)	104	42.23	2.586
VP3 (kN)	42.64	22.48	1.8
DB1 (cm)	0	0	0.1495
DB2 (cm)	0	0	0.06162
DB3 (cm)	0	0	0.09044
DS (cm)	18.75	20.42	6.176
b. Potrolia			
AP1 (kN)	812.8	653.2	88.43
AP2 (kN)	559.5	576.5	284.4
AP3 (kN)	694.2	661.5	119.4
MP1 (kNm)	102.3	0	0
MP2 (kNm)	274.6	0	0
MP3 (kNm)	89.44	0	0
VP1 (kN)	50.37	45	10.31
VP2 (kN)	122.8	104.7	12.56
VP3 (kN)	43.9	51.83	4.663
DB1 (cm)	0	0	0.9613
DB2 (cm)	0	0	0.7645
DB3 (cm)	0	0	0.79098
DS (cm)	31.49	50.65	36.66
c.Loma Prieta			
AP1 (kN)	507.1	452	71.91
AP2 (kN)	558.9	576.5	272.4

AP3 (kN)	521.4	461.6	71.3
MP1 (kNm)	57.05	0	0
MP2 (kNm)	167.6	0	0
MP3 (kNm)	65.94	0	0
VP1 (kN)	29.05	21.28	1.87
VP2 (kN)	74.8	40.59	1.4
VP3 (kN)	32.92	21.87	1.587
DB1 (cm)	0	0	0.116
DB2 (cm)	0	0	0.03065
DB3 (cm)	0	0	0.5979
DS (cm)	14.13	22.34	3.926

*AP1 = Axial of column C1, AP2 = Axial of column C2, AP3 = Axial of column C3, MP1 = Moment of column C1, MP2 = Moment of column C2, MP3 = Moment of column C3, VP1 = Shear of column C1, VP2 = Shear of column C2, VP3 = Shear of column C3, DB1 = Displacement of column C1, DB2 = Displacement of column C2, DB3 = Displacement of column C3, DS = Displacement at *sohrin*.

To show the effectiveness of seismic isolation, the axial, shear and moment at the column and displacement at the friction bearings location, are examized. Simulations using the recorded earthquake ground motions of El Centro (1940), Potrolia (1992) and LomaPrieta (1989) as inputs are presented.

a. El Centro earthquake (1940)

The displacements at *sohrin* due to El Centro earthquake analysed from three analytical models of the structures are expressed as Fig. 5a, 5b, 5c. Simulation results are summarized in Table II.a. The responses of the fixed-base frames and hinge supports frame are found to be very large during the time of excitation. When the friction bearings are constrained, the maximum shear forces are reduced approximately from 94% at friction bearing 1 and 97% at friction bearing 2, the axial forces are reduced from 51% at column 1 and 87% at column 3. The peak displacements at *sohrin* are reduced from 18.75 cm (fixed-base) and 20.24 cm (hinge supports) to 6.176 cm (friction bearings). The maximum displacement of central pillar (*shinbashira*) about 0.06162 cm (Fig 8a). The very small response shows that the *shinbashira* dissipates the energy of excitation by sliding to prevent the pagoda from collapsed during earthquake.

b. Potrolia earthquake (1992)

The scale of this earthquake is approximately two times of the 1940 El Centro earthquake in terms of the resulted peak structural responses of fixed-base, hinge supports while the maximum displacement at *sohrin* and shear forces can be amplified five times (friction bearings model), as presented from Table II.b and Fig. 6a, 6b, 6c. However, the maximum displacement of central pillar (*shinbashira*) about 0.7645 cm (Fig. 8b) and energy dissipated quickly by sliding. The isolation by using friction bearings at the supports show great performance in earthquake protection, as ilustrated in Table II.b for the column's base shear. The effectiveness of seismic isolation reduces base shear force from 80% at friction bearing 1 and 89% at friction bearing 3. The axial force at central pillar when using friction bearing reduces approximately 50% compare to fixed-base and hinge supports, this result can explain why the central pillar was hung during the earthquake.

c. Loma Prieta earthquake (1989)

The responses of three models are expressed as in Table II.c and Fig. 7a, 7b, 7c. The effectiveness of the isolation friction bearings and fixed-base are reduced base shear forces about 90% in average, reduced axial forces about 50%. The maximum displacement of central pillar (*shinbashira*) about 0.03065 cm (Fig 8c). The base of column rarely damage because shear force at column very small. Dynamic analysis of timber structure of pagoda indicate that the sliding friction bearing is appropriate to reality structure.

4.2 Effects of the coefficient of friction

The frames of pagoda are analysed when they are isolated for the coefficients of sliding friction from $\mu = 0.1 \div 0.6$. The maximum displacements at the bearings location have small decrease (when $\mu = 0.25 \div 0.5$) are presented in Fig. 9a, 9b, 9c. The effect of the coefficients of friction on the maximum displacements at *sohrin* and the axial force and shear force are presented in Fig. 9d, 9e, 9f due to El Centro, Potrolia and Loma Prieta earthquakes. The coefficient of friction is approximately $0.25 \div 0.35$ can be adopted, the response quantities have not changed very much, this result appropriate to the range of wood friction coefficient (the coefficient of wood on wood $\mu = 0.2 \div 0.5$).

4.3 Effects of the gaps between the central pillar and floors

Based on the conclusion of Masaru Abe, in this paper the gap between the *shinbashira* and each floors, is taken from e = 1 ÷ 15 cm (Fig. 10a, 10b, 10c). The maximum displacements at the bearings location, and at *sohrin*, the axial forces and shear forces at base columns have not changed very much in all cases. Therefore, the appropriate gap is between the range from 3 to 5cm, the hole between the shinbashira and floors prevent the pendulum movements from the main skeleton structure.

4.4 Effects of roof's weight

The unit weight of the roof considered in the analytical model is orginally 2.5 kN/m, which corresponds to light-weight. The effect of roof's weight are investigated from light-weight to heavy-weight with weight ratio (β) from 1 ÷ 6. The response quantities normalized with respect to those of the light-weight case $\beta = 1$ are presented, respectively, in Figure 11a, 11b, 11c for El Centro, Potrolia, and Loma Prieta earthquakes. The maximum displacements at the bearings location (DB1, DB2, DB3) decrease slightly, while the peak displacement at *sohrin*, axial force and shear force (AP, VP) increase with the roof's weight, only slight variations in all the cases. The inertia forces of roof structures induced during earthquakes are almost transferred to the foundation. Therefore, weight of roof has small effect to the structural response.

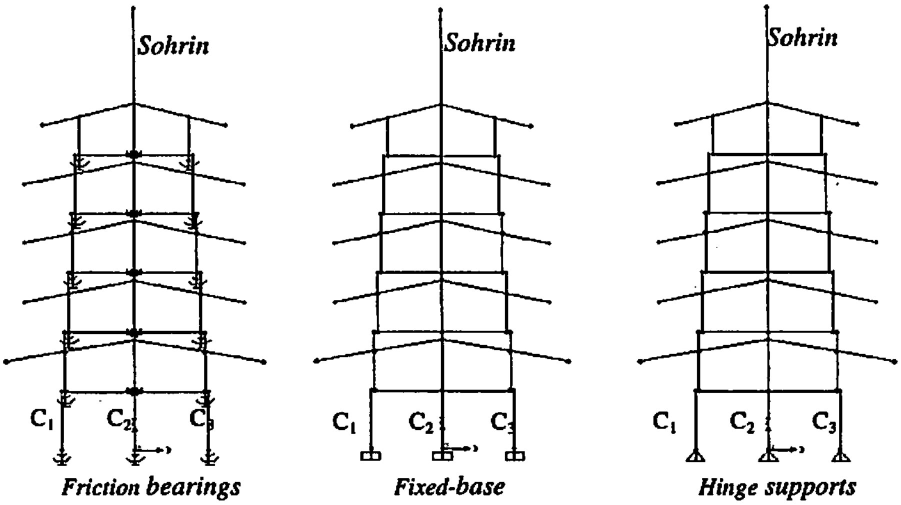

Fig. 4. Analytical models for a five-story timber pagoda

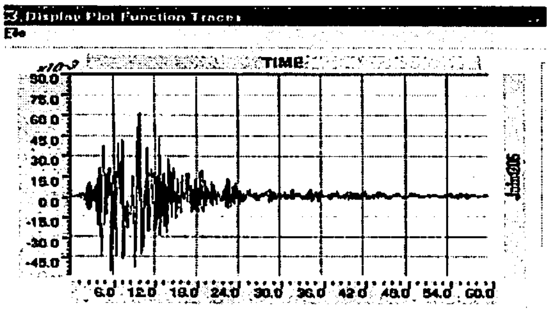

Fig. 5a. Disp. at sohrin by friction bearings model under El Centro earthquake

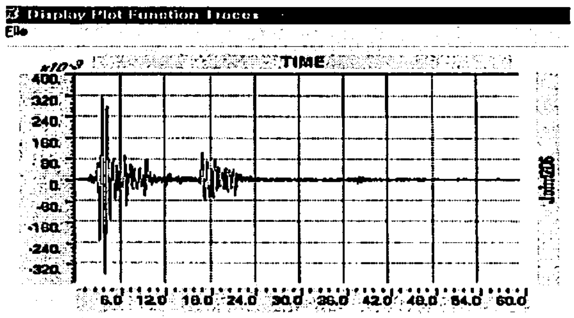

Fig. 6a. Disp. at sohrin by friction bearings model under Potrolia earthquake

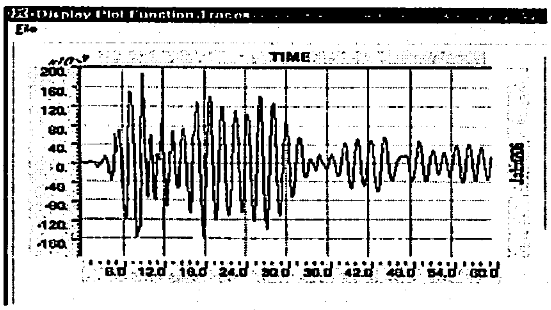

Fig. 5b. Disp. at sohrin by fixed-base model under El Centro earthquake

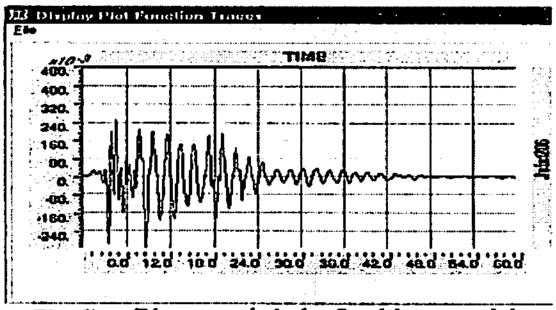

Fig. 6b. Disp. at sohrin by fixed-base model under Potrolia earthquake

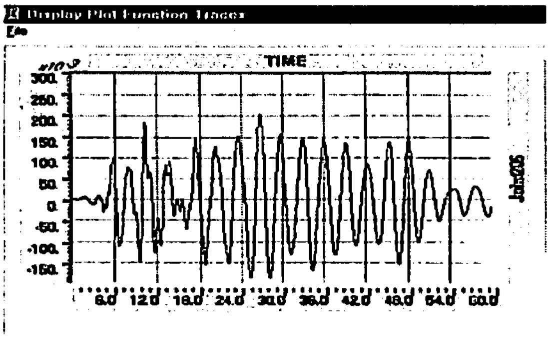

Fig. 5c. Disp. at sohrin by hinge supports model under El Centro earthquake

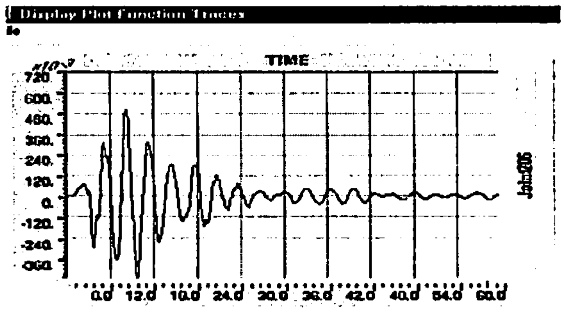

Fig. 6c. Disp. at sohrin by hinge supports model under Potrolia earthquake

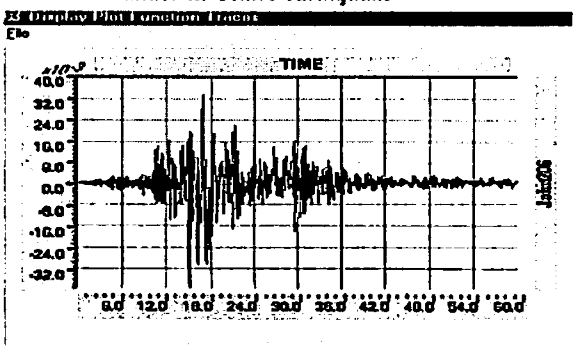

Fig. 7a. Disp. at sohrin by friction bearings model under Loma Prieta earthquake

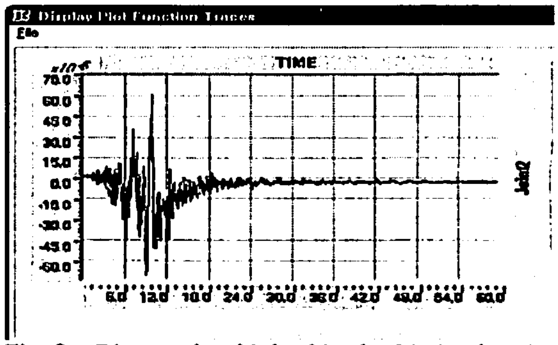

Fig. 8a. Disp. at the shinbashira by friction bearings model under El Centro earthquake

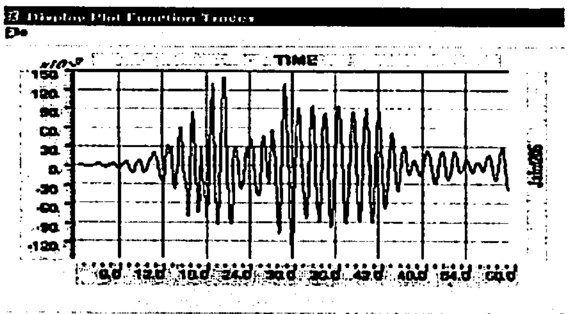

Fig. 7b. Disp. at sohrin by fixed-base model under Loma Prieta earthquake

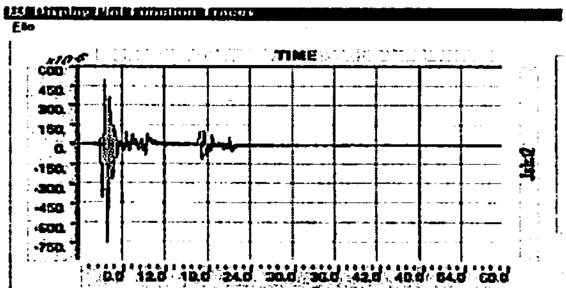

Fig. 8b. Disp. at the shinbashira by friction bearings model under Potrolia earthquake

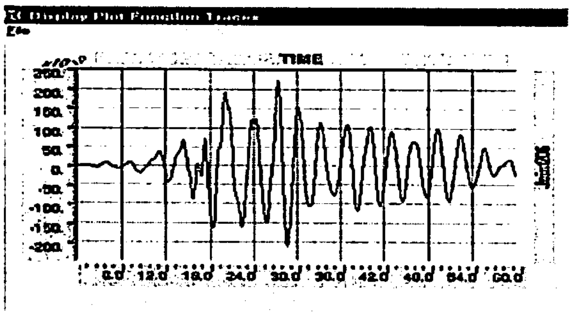

Fig. 7c. Disp. at sohrin by hinge support model under Loma Prieta earthquake

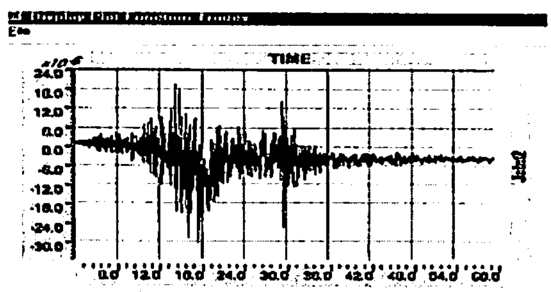

Fig. 8c. Disp. at the shinbashira by friction bearings model under Loma Prieta earthquake

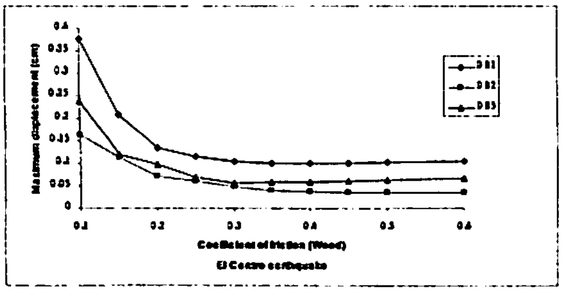

Fig. 9a. Maximum Disp. at friction bearings

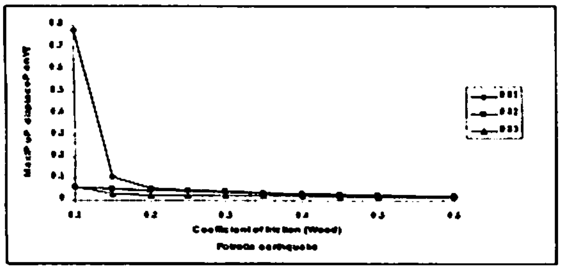

Fig. 9b. Maximum Disp. at friction bearings

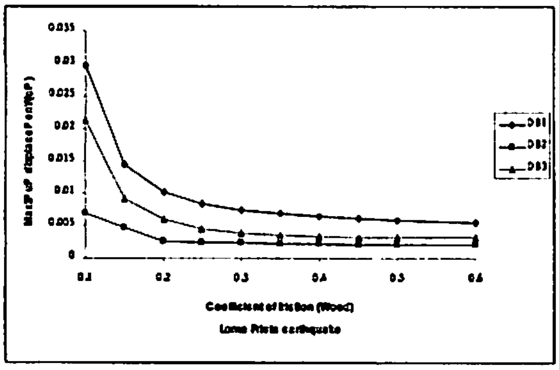

Fig. 9c. Maximum Disp. at friction bearings

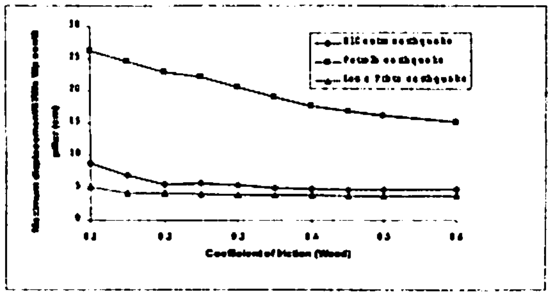

Fig. 9d. Maximum Disp. at sohrin (DS)

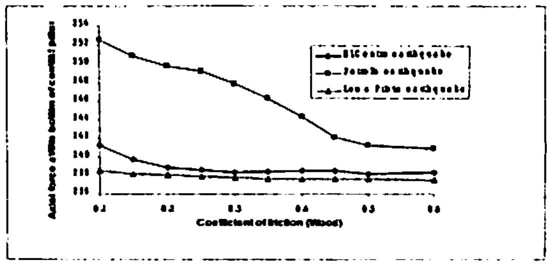

Fig. 9e Axial force at friction bearings (VP2)

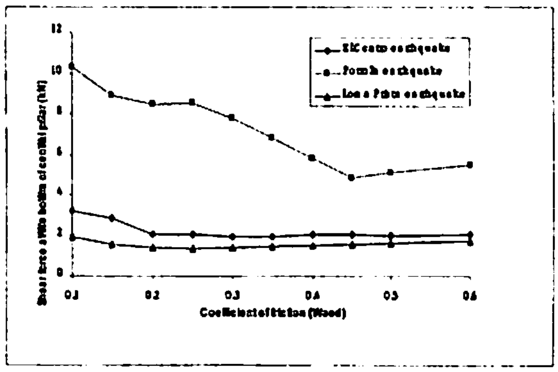

Fig. 9f. Shear force at friction bearing (AP2)

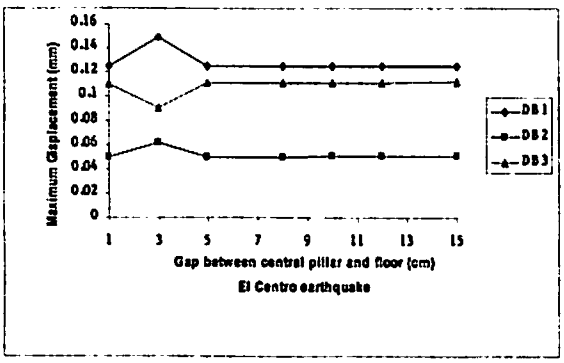

Fig. 10a. Effects of the gaps between shinbashira - floors

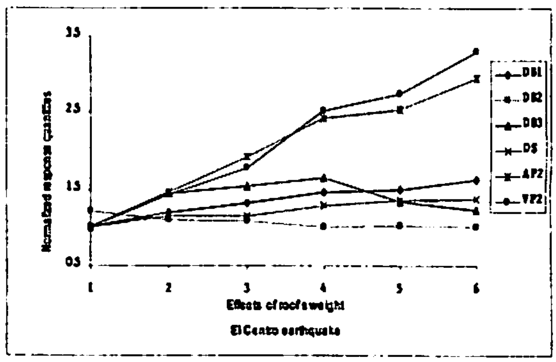

Fig. 11a. Effects of roof's weight β

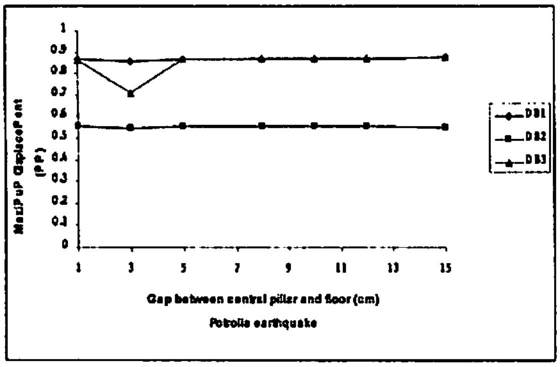

Fig.10b. Effects of the gaps between shinbashira - floors

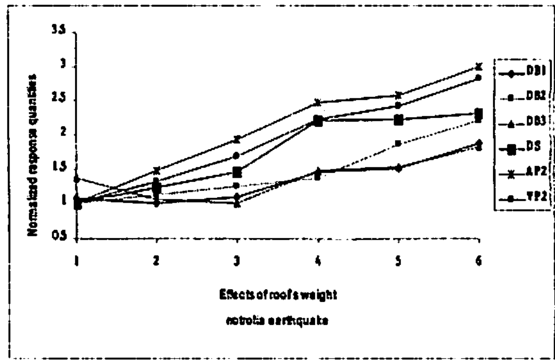

Fig. 11b. Effects of roof's weight β

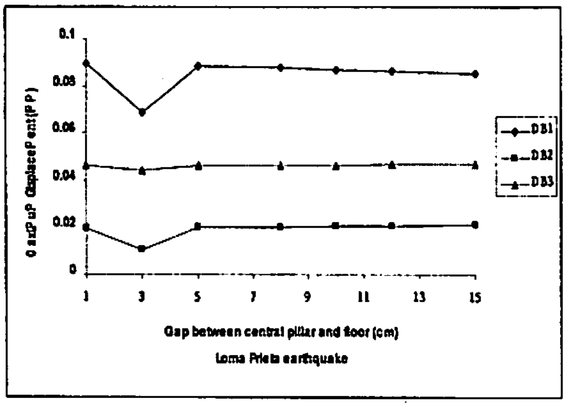

Fig.10c. Effects of the gaps between shinbashira - floors

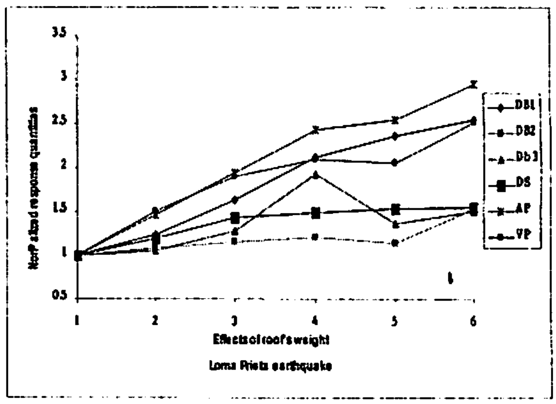

Fig. 11c. Effects of roof's weight β

5. CONCLUSIONS

The non-linear dynamic analysis of the sliding structure has been carried out, based on the reality of structure description and the concept of shear balance at sliding interfaces following a prescribed friction mechanism. The seismic isolation by friction bearings has great effectiveness in reducing the shear forces at the bearings, so the columns hardly to be damaged under earthquakes. The central pillar attached to the ground serves as a snubber, constraining each level from swinging too far in any direction. The columns and beams are not firmly connected, so each level can vibrates in a flexible manner during an earthquake, and the tapered configuration can endure strength and stability of timber pagodas. The combination of these features helps to protect the pagodas against earthquake. The basic principle of the flexible structure demonstrated by five-story pagodas in Japan may serve as an solution illustration to the vibration control which could be applied to other structures such as towers, buildings,... From the above analysis, it is hoped that the excellent solution used in the Japanese pagodas may extends to a level applicable to modern highrise structures.

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