Earthquake Response of Domes Implemented by Hysteresis Dampers for Earthquake Isolation

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ABSTRACT

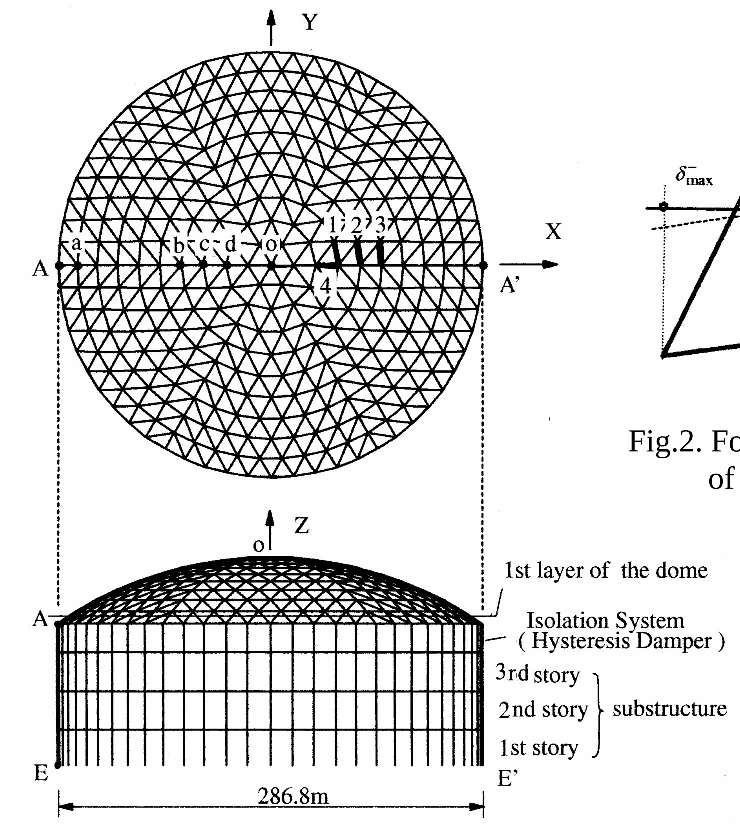
This paper presents the studies of the effect of a seismic isolation system on the responses of a space frame structure, where hysteresis dampers are installed to reduce the responses due to horizontal earthquakes. This system is applied to a latticed dome with about 300 m span, and dynamic response analysis of the systems is carried out to verify the effectiveness. From the results of the numerical studies on the dome, it is confirmed that the seismic isolation system with hysteresis dampers effectively suppresses the vertical and horizontal acceleration responses of the dome subjected to horizontal earthquakes.

1. INTRODUCTION

A space frame structure is useful to cover a large space. To ensure the safety of such a structure against strong earthquakes, it is important to investigate the dynamic response characteristics and the earthquake resistant capacities. Previous studies analyzed the elasto-plastic dynamic behavior of these structures [1-5] and proposed the design methodology considering both geometric and material nonlinearities of the structures [4,5]. Moreover, studies on the application of active and passive control systems to reduce the responses for the space frame structures have been also carried out [6,7]. Shingu and Fukushima [6] have proposed a base isolation method and a fuzzy control system of shell structures subjected to vertical earthquake.

The vertical acceleration responses and stresses due to horizontal earthquake motions are severely induced in such structures. One of the most effective ways to reduce the responses is to introduce a seismic isolation system for horizontal earthquake motions as shown in Fig.1. Another advantage of this system is to release thermal stresses in the dome when temperature changes.

The purpose of this study is to propose a seismic isolation system for a large space frame structure by using hysteresis dampers to reduce the responses due to horizontal earthquake motions.



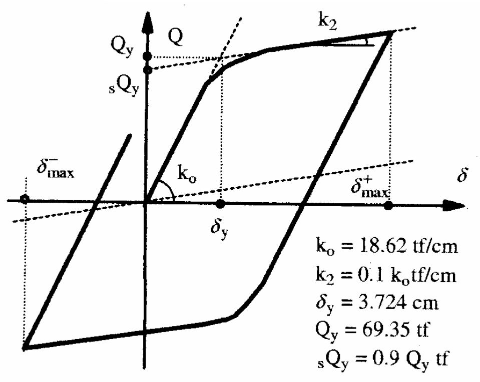


Fig.2. Force - displacement relationship of one hysteresis damper

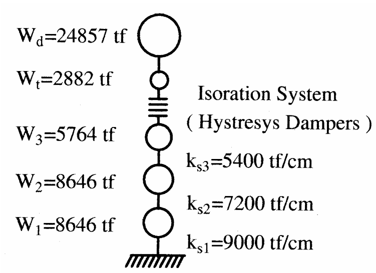


Fig.1. Numerical Model

Table 1. Member Properties

member	Young's Modules E (tf/cm^2)	Sectional Area A (cm^2)	Moment of Inertial I (cm^4)
Internals	2100	600	2.186×10^7
Tension Ring	2100	5000	2.186×10^8

2. ANALYTICAL MODELS AND NUMERICAL METHODS

2.1 Analytical models

An analytical model consists of a dome, an isolation system and a substructure as shown in Fig.1. The dome and the substructure are connected by a device to reduce their responses under earthquake motions. In this study, we assume the isolation system as hysteresis damper. The dome is a spherical cap on circular plan with 286.8 m span, 45.2 m rise and 250 m radius of curvature. Table.1 lists the material properties of constitutive members in the dome. The total weight of the dome W_d, excluding the tension ring, equals 24857 tf. The first natural period of the dome is 0.9787 sec, when the dome is assumed to have a pin – supported boundary condition.

A multiple shear spring model [8], which is here called MSS Model and shown in Fig.1, is used for numerical modeling of the hysteresis dampers for seismic isolation system to take into account their biaxial vibration characteristics. The MSS element is composed of eight uniaxial shear springs, each of which has bilinear characteristics with a hardening stiffness, $k_2 = 0.1\,k_0$. Total shear stiffness, K_0, of the isolation system, consisting of sixty hystresis dampers, is equal to $1117.2\,tf\,/\,cm$. Fig.2 illustrates the static force - displacement relationship of one hysteresis damper.

The substructure is a three-story elastic structure as shown in Fig.1. The total stiffness of the stories are k_{s1}=9000$tf\,/\,cm$, k_{s2}=7200$tf\,/\,cm$ and k_{s3}=5400$tf\,/\,cm$. The corresponding weights of these stories are W_{s1}=8646tf, W_{s2}=8646tf and W_{s3}=5764tf, respectively. Material properties of the ring girders are equal to those of the tension rings. Geometric and material nonlinearities of the dome and the substructure have not been taken into account in order to simplify the analysis of the effectiveness of the proposed seismic isolation system.

Four values of yield shear coefficient, α_y=0.1,0.15,0.2 and∞, in the isolation system, were set as the parameters to examine the effects of the isolation parameter α_y on the dynamic behavior of the dome due to horizontal earthquake motions. α_y is defined by

$$\alpha_y = \frac{Q_y}{W_t + W_d} \tag{1}$$

where Q_y is the yield shear force in the isolation system and $\mathrm{W_t}$ is the weight of the tension ring.

2.2 Numerical method

In order to characterize the fundamental vibration behavior, a dynamic eigenvalue analysis is carried out, and then the dynamic time history response analysis considering material nonlinearities of hysteresis damper is applied to the dome with a specified value for α_y under horizontal earthquake motions. An earthquake motion, El Centro (1940) NS, is used as the input excitation in the X direction for 20 seconds. Dynamic response analysis is carried out in the four cases : the maximum horizontal ground acceleration $A_{\max}$ setting to 100, 250, 500 and 700$cm/\sec^2$ to analyze the effects of the yield shear coefficient of the hysteresis dampers, α_y, on the dynamic behavior of the dome. Fig.3 shows the acceleration response spectrum of the earthquake motion, El Centro NS. T_{1p}, T_{1o} and T_1 represent the first natural periods of the dome with a pin - supported boundary condition, the structure without hystresis damper and the structure implemented by hystresis damper, respectively. As can be seen in Fig.3, the first natural period of the structure implemented by hystresis dampers increases larger than that of the structure without hystresis damper. From the results of the first natural periods and the corresponding value of acceleration response spectrum, it is expected that the proposed isolation system is effective to reduce the responses even if structure is in elastic range.

Average acceleration method of Newmark-β scheme with β=1/4 is used for numerical integration, and the time interval for response calculation, Δt, is 0.005 sec. In this study, the mass matrix is assumed as lumped masses at each node. The Rayleigh damping matrix is used and a set of damping factors of 2% for 0.5 sec and 1.0 sec are assumed.

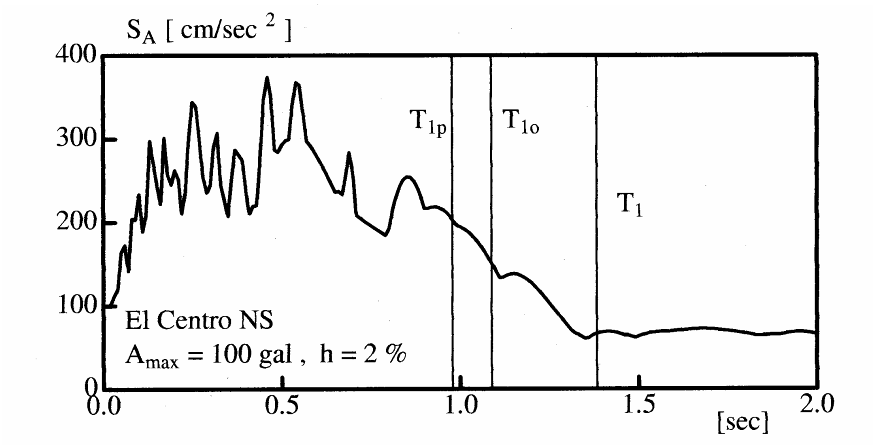


Fig.3 Acceleration Spectrum (El-Centro NS, A_{max} =100 cm/sce^2)

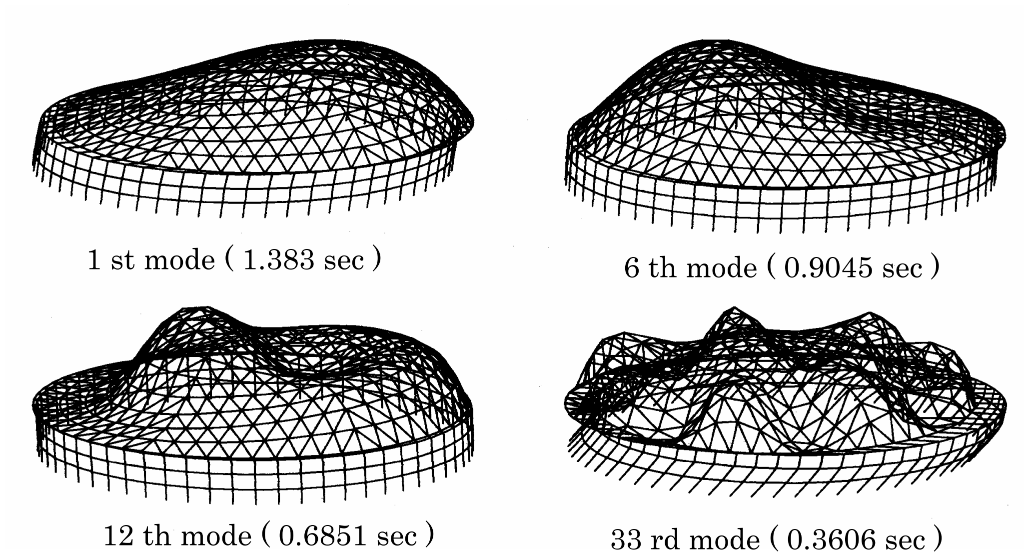


Fig.4 Vibration modes with hysteresis dampers

3. DYNAMIC BEHAVIOURS

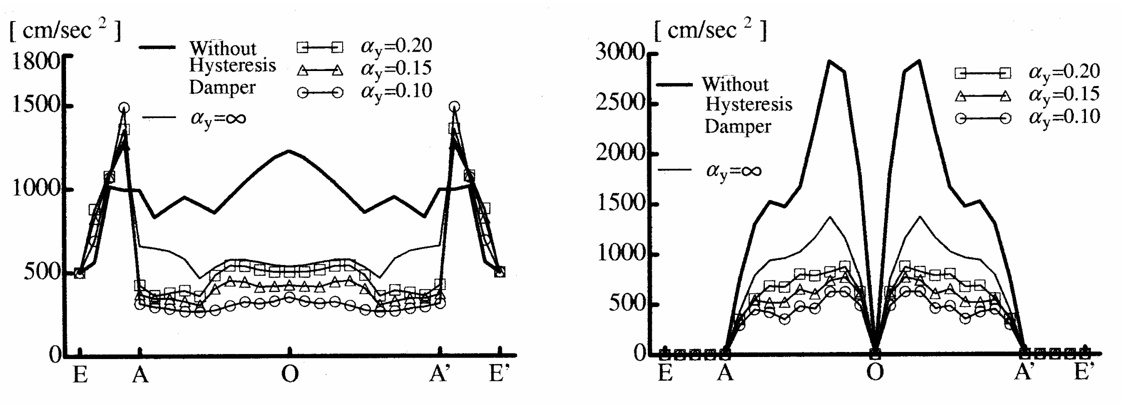
3.1 Vibration modes and natural periods

Fig.4 illustrates the vibration modes of the dome with hystersis dampers. Several modes with a significant participation factor in the X direction are selected. The first natural period of the structure with hysteresis dampers is 1.383 sec. In this mode, the modal deformation of the hysteresis damper is quite large in comparison with other modes. As can be observed from the mode shapes in Fig.4, it is expected that the vertical responses of the dome are excited by horizontal earthquake motions when hysteresis dampers are within the elastic range.

3.2 Response accelerations of the dome

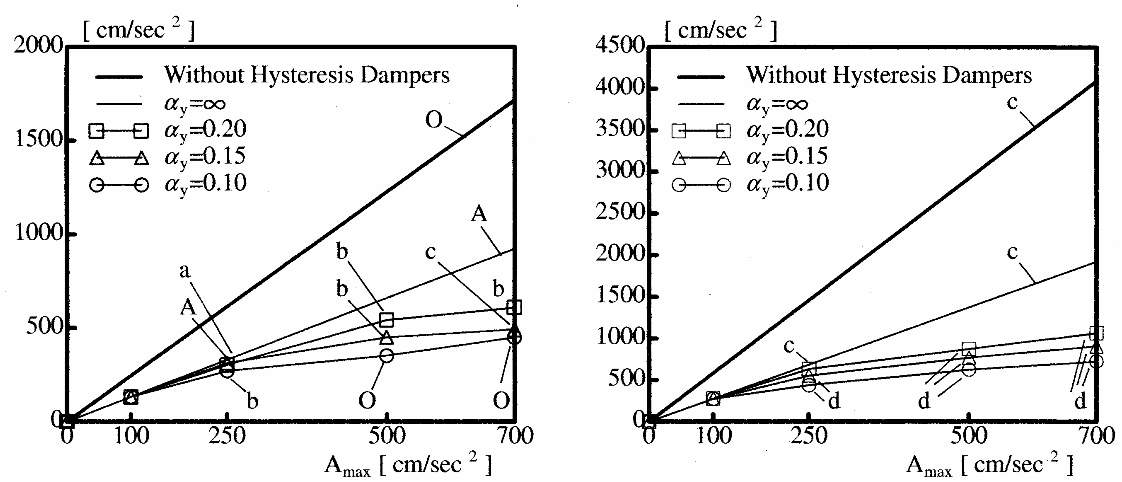
Fig.5 shows the distributions of the maximum response acceleration under the input earthquake motions of 500 cm/sce^2 . Fig.6 illustates the relationship between the maximum acceleration of the dome and the maximum ground motion A_{max}. As observed form Fig.5 and Fig.6, the maximum horizontal response acceleration of the dome is about $1400\,cm/sce^2$, the maximum vertical response acceleration is about $2900\,cm/\sec^2$ in the case of no hysteresis dampers. It is worthy mentioning that the maximum response accelerations of the vertical direction are quite larger than that of the horizontal one for the dome in the case of no histresis dampers.

On the other hand, the maximum horizontal and vertical accelerations of the dome implemented by hysteresis dampers are much reduced. It is confirmed that the seismic isolation system effectively suppresses both the vertical and horizontal acceleration responses of the dome subjected to horizontal earthquakes. With a decrease in shear yielding coefficient α_y of hysteresis dampers, the vertical and horizontal response accelerations decrease. However, horizontal accelerations of substructure are contrarily increased with a decrease of α_y.



(a) Horizontal direction (b) Vertical direction

Fig.5 Distributions of the maximum response accelerations of the dome

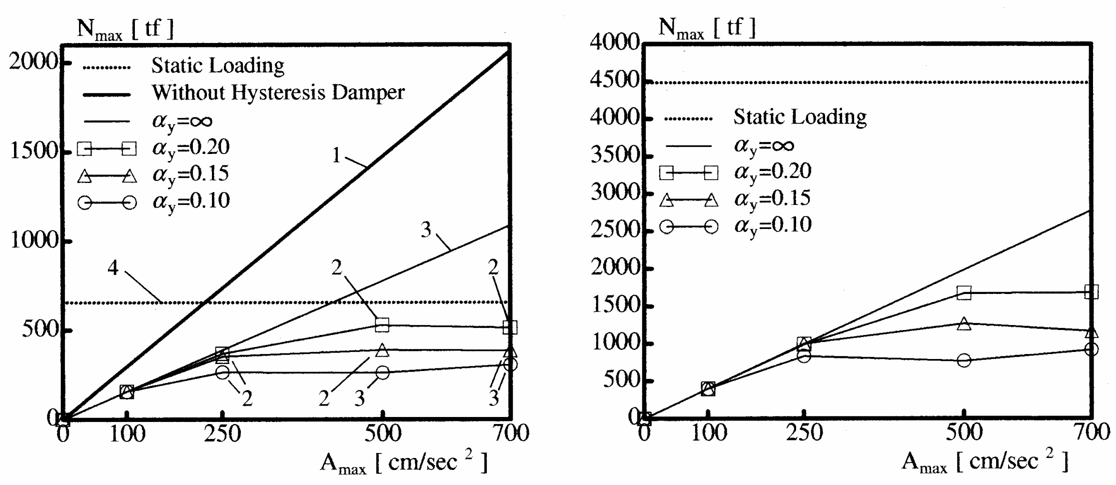


(a) Horizontal direction (b) Vertical direction

Fig.6 Relationship between the maximum accelerations of the dome and A_{max}

3.3 Axial forces of the dome

Fig 7 shows the relationship between the maximum axial forces of the dome and the applied peak acceleration A_{max}. As shown in Fig.9, the maximum axial forces of the dome are much suppressed by the hysteresis damper in a similer way to response acceleration.



(a) Internals (b) Tension ring

Fig.7 Relationship between the maximum axial forces of the dome and A_{max}

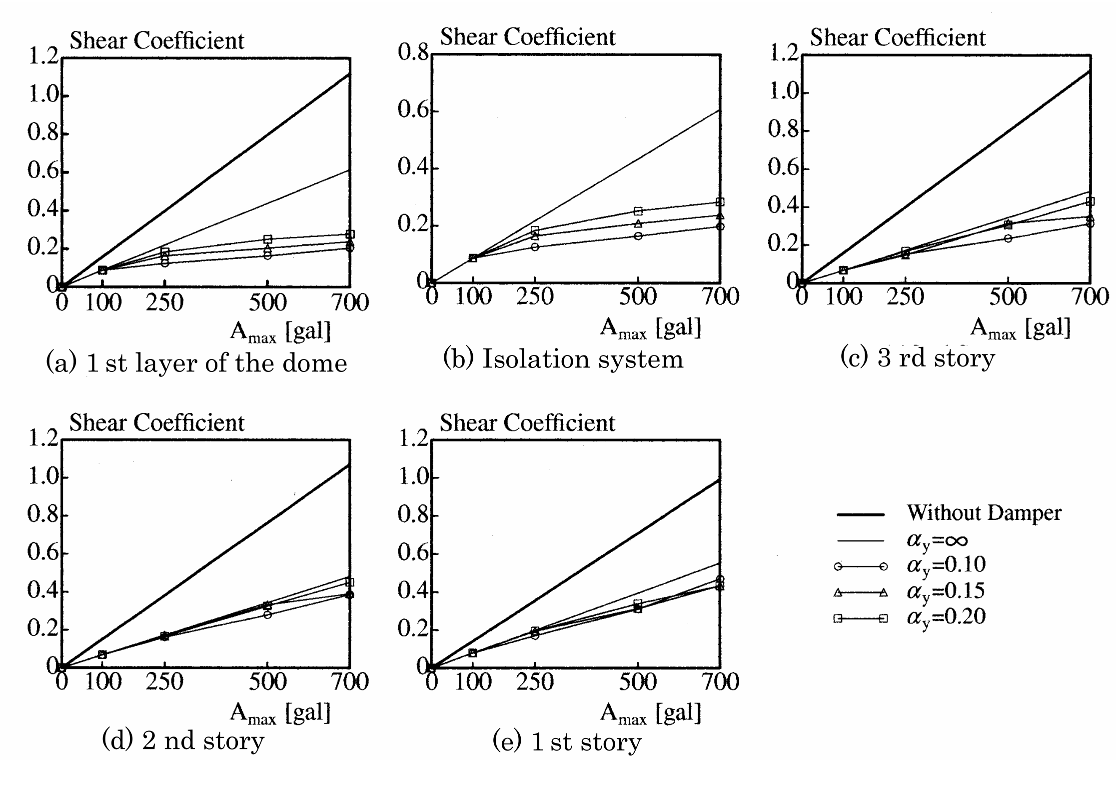


Fig.8 Relatioinship between response shear cefficients and input ground motion A_{max}

3.4 Response of shear coefficient

Fig.8 shows the response of shear coefficients which are calculated by a dynamic response analysis. The response shear coefficients of the structure with hysteresis dampers are much reduced in comparison with those of the structure without hysteresis dampers. The response shear coefficients of the dome and hysteresis dampers are decreased with a decrease in shear yielding coefficient of α_y. Because of the effect of a hardening stiffness of the hysteresis dampers, the shear coefficients of hysteresis dampers are greater than α_y when the hysteresis dampers creep over the range of elasticity. However, the reduction of the response shear coefficients of the substructure is not expected as much as expected in the response of domes.

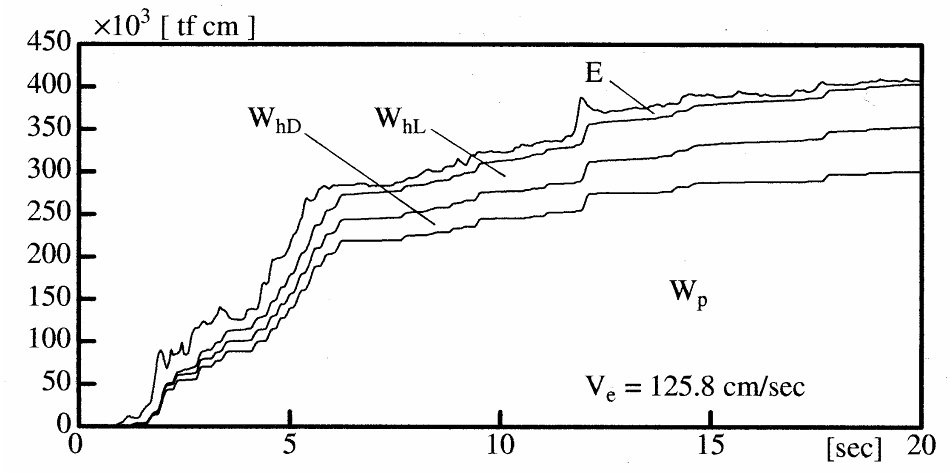


Fig.9.a Absorbed energy (A_{max} =500 cm/sec^2 , α_y =0.1)

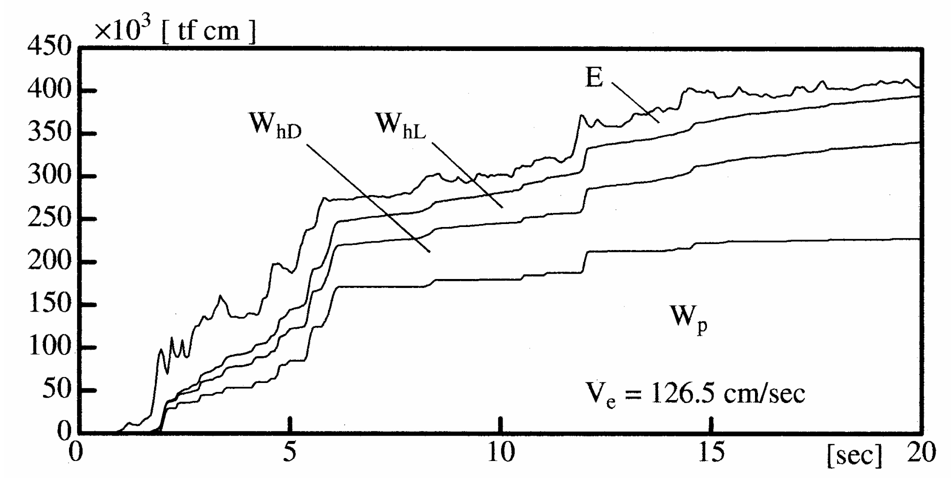


Fig.9.b Absorbed energy (A_{max} =500 cm/sec^2 , α_y =0.2)

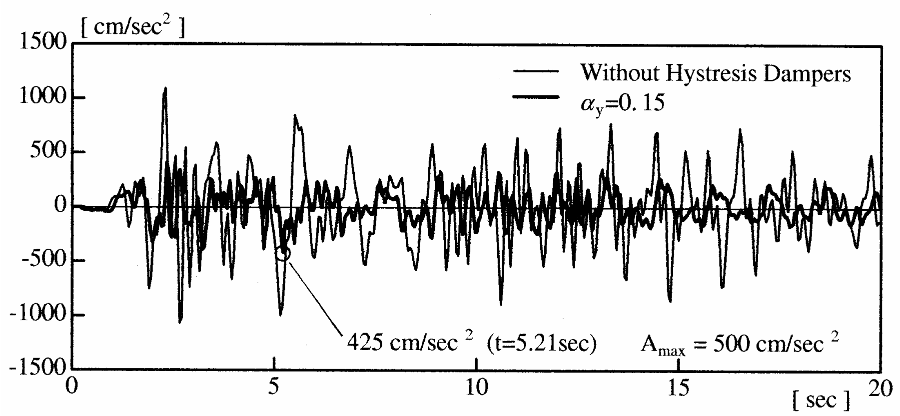
3.5 Absorbed energy of the hystesis dampers

Figs. 9.a and b show the time histories of the absorbed energy when the input ground acceleration A_{max} is $500\,cm/sec^2$. Where E represents vibration energy, W_{hD} and W_{hL} are damping dissipation energy of the dome and the substructure respectively. W_p shows the total plastic energy dissipation due to hysteresis dampers. As can be seen in Figs.10.a and b, with a decrease in shear yielding coefficient α_y, total plastic energy dissipation of hysteresis dampers is increased. However, total input energy E is considered about constant in spite of the variation of α_y.

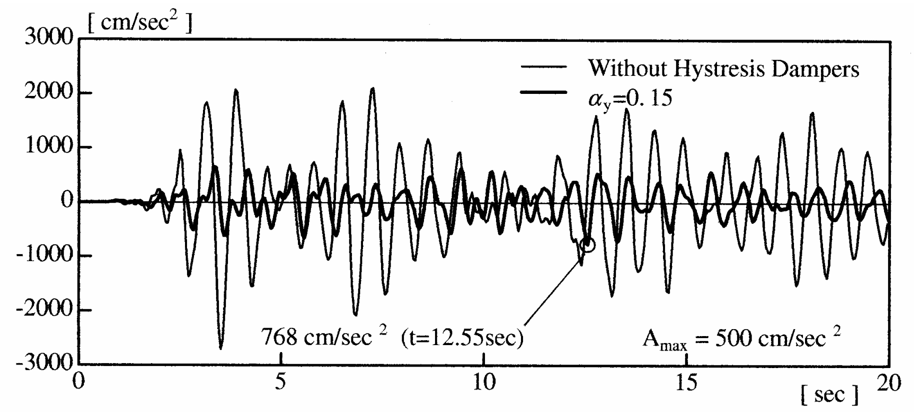
3.6 Time histories of response acceleration

Fig.10.a shows the time histories for the horizontal acceleration at the center of the dome, node (o), obtained for the peak accelerations A_{max} =$500\,cm/sec^2$. The time histories for vertical acceleration at node (d) of the dome is given in Fig.10.b.

In the seismic office design, a static analysis of the structure subjected to several seismic loads is often performed to ensure the safety of the structures against strong earthquake motion. The static seismic loads will be calculated by an absolute acceleration distribution when an absolute acceleration at a certain node of the dome takes maximum.



(a) Horizontal acceleration at the center of the dome



(b) Vertical acceleration at node (d)

Fig.10 Time hisotry for the nodal response acceleration of the dome

Fig.11.a shows the horizontal and vertical absolute acceleration contours of the dome under A_{max} =500 cm/sec^2, when the horizontal acceleration of the center of the dome, node (o), takes maximum at t=5.2sec. Fig.11.b illustrates the horizontal and vertical absolute acceleration contours of the dome under A_{max} =500 cm/sec^2 when the vertical acceleration of the node (d) takes maximum at t=12.55sec.

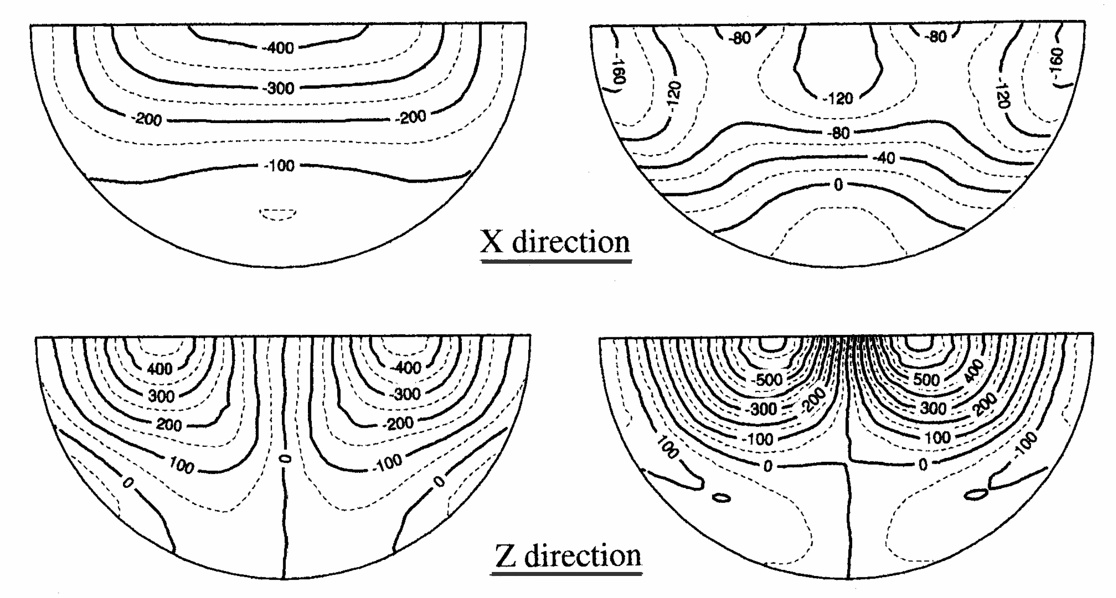


Fig. 11.a Absolute Acceleration Distribution (t=5.2sec, A_{max} =500 cm/sec^2)

Fig. 11.b Absolute Acceleration Distribution (t=12.55.sec, A_{max} =500 cm/sec^2)

5. CONCLUSION

The paper investigated the effect of a seismic isolation system on the responses of space frame structures where hysteresis dampers are installed to reduce the responses due to horizontal earthquake motions. It is confirmed that the seismic isolation system effectively suppresses both the vertical and horizontal acceleration responses subjected to horizontal earthquakes, leading to great reduction in axial forces and shear coefficients of the dome.

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