NUMERICAL ANALYSIS FOR SHOCK ABSORPTION PERFORMANCE OF ACCUMULATED SEMI-ACTIVE HYDRAULIC DAMPER

MING-HSIANG SHIH[1], **CHENG-I LIN**[2] **AND WEN-PEI SUNG**[†3]

[1] *DEP.OF CONSTRUCTION ENGINEERING,NATIONAL KAOSHIANG FIRST* UNIVERSITY OF SCIENCE AND TECHNOLOGY,TAIWAN 824

[2] *DEP.OF FIRE SCIENCE,WU-FENG INSTITUTE OF TECHNOLOGY,* CHIAYI,TAIWAN 621

[3] *DEP. OF LANDSCAPE DESIGN AND MANAGEMENT,* NATIONAL CHIN-YI INSTITUTE OF TECHNOLOGY, TAIWAN 4111

[†]*E-MAIL: SUNG809@CHINYI.NCIT.EDU.TW*

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Abstract. The semi-active control does not consume a huge quantity of electricity because its controlling force comes from the oscillation of the structure system. Furthermore, it is adaptable that the control over the structure can be changed. Therefore, the optimum solutions are available to resolve the problems of the electric power system conditions and the adaptability of the controlling force, commonly found in other control methods. The damper used in this research is the Accumulated Semi-Active Hydraulic Damper, ASHD, developed on the basis of the Displacement Dependent Semi-Active Hydraulic Damper by means of installing the accumulator. The damper and the bracing series are connected together to the structure; the displacement of structure can drive the bracing series distortion to engender the action power of ASHD. When the action power passes through ASHD, the energy dissipation behaviors occur, which can form the fullest hysteresis loop. This research establishes the mathematical analysis model to analyze its energy dissipation capability based on the hysteresis loop of ASHD, obtained from the experiment. The analysis results show that no matter what energy dissipation period, ASHD perform high energy dissipation capability.

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1. Introduction

With the modernization of the cities, there appear more and more high-rise buildings. To these buildings with large flexibility, the oscillation caused by the external force must be effectively reduced so as to reach the goal of security, usage and comfort of the buildings. As a result, in terms of the structural design, not only the intensity and ductility of the building itself must be used to resist the seismic or wind force, the earthquake proof technique must be applied to prolong the structural frequency, in order to reduce the impact of the seismic or wind force. The structural control [1] [2] [3] could be applied to alleviate the oscillation of the structure so as to enhance the defense line of the building's seismic resistant capability. At present, according to the supplying fashions of its controlling force, the structural control [1] [2] [3] can be divided into the active control, the passive control and the semi-active control. Among them, the semi-active control does not require a huge quantity of electricity because its controlling force comes from the oscillation of structure system. It is so adaptable that the control over the structure can be changed. Furthermore, the active control has its problem in terms of the electric power system, and the passive control has its problem in terms of the adaptability of the controlling force, but the semi-active control can provide optimum solutions to these problems. Presently, the dampers in the field of the semi-active control include Taylor Device [4], viscous damper of Prof. Hsu [5] [6], Semi-Active Hydraulic Damper, SHD [4] [7], Electrorheological Damper [8], and Magnetorheological Damper [9], which all reach the goal of energy dissipation and vibration reduction on the basis that low volume of oil cylinder can engender great force, and its adaptable characteristics.

In order to enhance the effectiveness of the hydraulic damper, Shih and Sung put forward Displacement Dependent Semi-active Hydraulic Damper, DSHD [10], which can change the damping coefficient by means of relief valve, throttle valve, and direction control valve so that the controlling force can do negative work on the structure at every time spot. The major component of DSHD is oil cylinder device which energy dissipation characteristic is related to the structural displacement. It has a strong adaptability to the controlling force. In order to promote the energy dissipation effect of this kind of damper, this research improved DSHD by means of installing the accumulator in 2003 [11]. In addition, on the basis of the semi-active hydraulic damper, Accumulated Semi-Active Hydraulic Damper, ASHD is developed. It together with the bracing series is connected to the structure, the displacement of which can drive the bracing series distortion to engender the action power. When the action power passes through ASHD, the energy dissipation behaviors occur, which forms the fullest hysteresis loop [12]. As a result, according to the energy dissipation behaviors of ASHD, the numerical analysis model of the structural displacement function at different stages of the energy dissipation can be derived, based on Duhamel's integral and Laplace transform. The resonant oscillation engendered when the simulated external force acts on the structure can be expressed in the sine function. This research also probes into the energy dissipation behaviors of ASHD and various factors influencing the energy dissipation behaviors when the structure is resonated with the external force.

2. Analysis theory

Experiment results [12] indicate that the ASHD can change the active force direction of bracing effectively, forever making negative work to structure. So this damper performances the most full hysteresis loop that can overcome the time delay problem of semi-active control. Otherwise, accumulator, installed in ASHD, can provide the bigger initial stiffness at primary stage of response. In fact, ASHD is a shock absorption device, absorbing the mechanical energy of structure and converting into resistant force that resists the structural motion. As a result, ASHD has the best energy dissipation capability. But in each energy dissipation stage, the value of damping ratio and stiffness (c_b, k_b), provided by ASHD to structural system, will be changed. Thus, the equation of motion for structure at each energy dissipation stage is different. In this paper, it aims at equation of motion for structure after adding ASHD and inquires into the mechanical behaviors of each energy dissipation stage. In this paper, the Laplace transform and Duhamel's integral is put forward to derive the mechanical behavior of each energy dissipation stage and simulate its energy dissipation behavior for structure with ASHD, acted by external force.

2.1. **Mathematical analysis model.**

According to the experimental setup structure [11], ASHD is installed in test structure, shown in Figure 1. This experiment is mainly to inquire into the energy dissipation behavior of the single story structure; therefore, the mathematical equation of this experimental structure can be defined as a single-degree-of-freedom system. ASHD and structure series, so this equation of motion indicates as follows:

$$m\ddot{x} + c_b\dot{x} + k_{str}x + k_bx_b = P(t) \tag{1}$$

where:
m is the mass of structure;
$c_b$is the damping coefficient of bracing;
k_{str} is the stiffness of frame;
k_b is the stiffness of bracing;
$P(t)$ is the external force.

The contributive force of ASHD at each stage will be changed that depend on its energy dissipation behavior. In order to solve ASHD response under external force action, equation (1) can be used to get the equation of motion at different stage.

From the energy dissipation mechanism of ASHD, ASHD provides control force to diminish the reaction of structure subjected external force. The control force comes from the deformation of bracing. The accumulator can store control force and release in good time. Therefore, the contributive forces, provided by accumulator, have a direct ratio relation with bracing. In order to simplify this analysis model, the damping force provided by ASHD, is assumed to be multiplied by the relative displacement and constants of the preceding step. Then, the change of its damping force is a linear. In addition, suppose the energy dissipation modal of ASHD is supposed as the ideal status. When the motion of structure reaches a maximum displacement, the action force provided by the bracing will immediately transfer to ASHD in a twinkling. That is, the quantity of time delay is null.

2.2. **Initial stage of energy dissipation behavior.** At this stage the ASHD hydraulic device is " free shortening and making the internal force of serial bracing to equivalently change sign". The damper is not the elongation, shown in AB zone of figure 1; the deformation concentrates in the bracing, shown in BC zone of figure 1. The damping of bracing cb can be treated as the null. There is no damping force. The external force is resisted by main structure and bracing. Therefore, the Laplace Transformation and anti-Laplace Transformation are used to derive structural displacement function with Duhamel's integral, is shown as below:

$$x(t) = x(0)\cos(\omega t) + \frac{\dot{x}(0)}{\omega}\sin(\omega t) + \frac{1}{m\omega}\int_0^t \sin[\omega(t-\tau)]p(\tau)d\tau \tag{2}$$

where:

$$\omega = \sqrt{\tfrac{k_b + k_{str}}{m}}$$

2.3. **The first stage of energy dissipation behavior.** When the external force, acted on structure, exceeds the pre-pressure force of accumulator, suppose the structure keeps on deforming, the accumulator provides the constant force at this time. The AB section is allowed to be elongated, and the BC section maintains the elongation quantity at time of exceeding the pre-pressure force of accumulator. At this stage, the bracing reaches the maximum elongation quantity, the maximum internal force. Therefore, the elastic force of bracing can be ignored. Only consider the resistant force $\bar{P}$, provided by accumulator, as linear spring including force at initial stage. The resistant force at this stage, provided by ASHD, is shown as below:

$$\bar{P} = k_b \cdot x_b = P_a + k_a \cdot u_a \tag{3}$$

where :

P_a is the initial contributive force of accumulator;

k_a is a constant value, equal to the stiffness of accumulator;

u_a is the relative deformation, attains the quantity of former stage.

Substitute into equation (1) to obtain the equation of motion at this stage, yields:

$$m\ddot{x} + k_{str}x = P(t) - \bar{P} \tag{4}$$

Let $\bar{t} = t - t_1, t_1$ is initial time of this stage and initial conditions of this stage are $x(\bar{t} = 0) = x(t = t_1) = x_1, \dot{x}(\bar{t} = 0) = \dot{x}(t = t_1) = v_1$.Then, the displacement function of this stage can be acquired as follows:

$$\begin{aligned} x(\bar{t}) &= x_1 \cdot \cos(\omega\bar{t}) + \frac{v_1}{\omega} \cdot \sin(\omega\bar{t}) \\ &+ \frac{1}{m\omega} \cdot \int_0^{\bar{t}} \sin[\omega(\bar{t} - \tau)] \cdot p(\tau + t_1) \cdot d\tau - \frac{\bar{P}}{m\omega} \cdot \int_0^{\bar{t}} \sin[\omega(\bar{t} - \tau)] \cdot d\tau \end{aligned}$$

where:

$$\omega = \sqrt{\frac{k_{str}}{m}}$$

2.4. **The second stage of energy dissipation behavior.** When structure drift reaches the maximum displacement, the pressure inside the ASHD hydraulic cylinder also reaches the maximum value. The AB section changes to " free elongation" from " complete lockup" at this time. The deformation of the BC section at the first stage of energy dissipation transfers to AB section. The relative displacement of two end points of bracing is null, therefore, the equation of motion at this stage will not be considered.

2.5. **The third stage of energy dissipation behavior.** When structure shift towards left and the external force, acted on structure, exceeds the pre-pressure force of accumulator, suppose the structure keeps on deforming, the accumulator provides the constant force at this time. The AB section is allowed to be elongated, and the BC section maintains the elongation quantity at time of exceeding the pre-pressure force of accumulator. At this stage, the bracing reaches the maximum elongation quantity, the maximum internal force. Therefore, the elastic force of bracing can be ignored. The damping force, provided by ASHD, is shown in section 2.3. Let $\bar{t} = t - t_3, t_3$ is the initial time of this step, the initial conditions of structure are $x(\bar{t} = 0) = x(t = t_3) = x_3, \dot{x}(\bar{t} = 0) = \dot{x}(t = t_3) = v_3$. Then, using Duhamel's integral to obtain the displacement function of this stage, yields:

$$\begin{aligned} x(\bar{t}) &= x_3 \cdot \cos(\omega\bar{t}) + \frac{v_3}{\omega} \cdot \sin(\omega\bar{t}) \\ &+ \frac{1}{m\omega} \cdot \int_0^{\bar{t}} \sin[\omega(\bar{t} - \tau)] \cdot p(\tau + t_3) \cdot d\tau - \frac{\bar{P}}{m\omega} \cdot \int_0^{\bar{t}} \sin[\omega(\bar{t} - \tau)] \cdot d\tau \end{aligned}$$

where:

$$\omega = \sqrt{\frac{k_{str}}{m}}$$

2.6. **The forth step of energy dissipation.** When the structure reaches the maximum displacement, the pressure of oil cylinder of ASHD also reaches the maximum value. The AB section changes to "free elongation" from "complete lockup" at this time. The deformation of BC section transfers to the AB section. With regard to the experimental results, consideration will not be given the time delay capacity. The relative displacement of two end points of bracing is null, therefore, the equation of motion at this stage will not be considered.

3. Numerical analysis results

For the sake of solving the energy dissipation characteristic and behaviors of ASHD installed in single degree of freedom structure, the mathematical model is established based on each energy dissipation stage with harmonic loading ($P(t) = P_0 \times \sin(w_p \cdot t)$) as input force to inquire into the benefit of every energy dissipation stage of ASHD.

3.1. **General energy dissipation behavior of ASHD.** This section studies on the energy dissipation effect of the ASHD in the initial period of structure with and without ASHD, the natural oscillation frequency of the structure is harmonic loading ($P(t) = P_0 \times \sin(\omega t)$, where ($P_0 = 1N, \omega = 10rad/sec$)) that 1.1 times of its loading frequency ($\omega = 1.1\omega_P$). The analysis results indicate that the stiffness of structure is $k_{str} = 121N/m$, bracing stiffness is $k_b = 12N/m$, the stiffness of bracing occupies one-tenth of the total stiffness of structure system and the natural vibration frequency of structure system without bracing is $\omega_n = 11rad/sec$. Comparing the time history displacement reaction of structure installation of ASHD with without installation of ASHD, the structural displacement of structure installation is much less than the structure without installation of ASHD. The structural response tends to become after several vibrations. When compares with the same structure without added ASHD under the same loading, the structural displacement of structure without ASHD is about the 0.9 m, but the energy dissipation mechanism of structure with ASHD can diminish the vibration amplitude significantly to 0.044 m. The ASHD damper shows the excellent energy dissipation capability, shown in Figure 2.

Furthermore, according to install the accumulator in ASHD, when the external force exceeds the preset initial pressure of accumulator, the contributive force of ASHD maintains constant. The accumulator utilizes to storage the action force of bracing deformation. Therefore, the hysteresis loop of the energy dissipation of ASHD device is full, as Figure 3 shown.

3.2. **The resonant oscillation behavior of the ASHD.** In this study, the bracing stiffness only expects to affect the energy dissipation of ASHD in former energy dissipation stage. Therefore, the bracing stiffness expects not predominant its energy dissipation behavior in the later stage. There are two resonant oscillation situations for external force acting. The first situation: the bracing stiffness participate the shock absorption that the natural frequency of structure is similar to harmonic loading of loading frequency to investigate this resonant oscillation behavior. The second situation: the resonant oscillation behavior of the structure with the same natural frequency of structure and loading frequency of harmonic loading. This research is based on external force $P(t) = P_0 \times \sin(\omega t)$, where $P_0 = 1N, \omega = 10rad/sec$ that means the main circular frequency of external force is 10 rad/sec, the vibration period is 0.628 seconds; the stiffness of structure is $k_{str} = 90N/m$, bracing stiffness $k_b = 10N/m$, the bracing stiffness occupies one-tenth of the total stiffness and the natural frequency of structure system is $\omega_n = 10rad/sec$ that is similar to the main circular frequency of the external force. In addition, the time duration of the external force effect is assumed at 10 seconds so as to study the reaction of the resonance structure under this external force.

3.2.1. ***The resonant oscillation behavior of ASHD in initial energy dissipation stage.*** Under the situation of resonant oscillation behavior, when the beginning of the structure starts condition as the quiescence the hour, after being subjected to the external force action, then enter the status of the resonant oscillation. By the analysis result can know, the hysteresis loop of structure keeps the stable energy dissipation of namely after the former loops, as Figure 4 show. And AHSD with the maximum hyteresis loops to absorb external force input the energy for the structure. ASHD goes to the best energy dissipation characteristic, as Figure 5 show. From here can know, the hyteresis loop that provided by the bracing is very full. It displays the energy of the structure that external force input, the bracing by means of ASHD absorbs the most parts. Comparing the displacement history of the reaction of the structure adds and does not install the ASHD, after the display setup ASHD, can limiting the displacement is within the range of certain, displaying its good displacement control. But did not install the ASHD, then make the structure reaction present the divergent trend because of the resonant oscillation, as Figure 6 show. Compare the analysis with experiment to discover, this analytical modal can reflect the energy dissipation behavior of being the ASHD into the third energy dissipation step. The bracing stiffness does not participate the holdout external force, so the structure escapes from the resonant oscillation behavior of, generating a frequency detachment effect. Therefore, the numerical analysis modal that derived in this paper, the energy dissipation behavior of ASHD under the condition of resonant oscillation can be imitated.

3.2.2. ***The resonant oscillation behavior of ASHD in later stage of energy dissipation.*** Act with the same external force in the structure, and the stiffness of the structure changes for $k_{str} = 100N/m$, bracing stiffness hold $k_b = 10N/m$, the natural oscillation frequency of the structure system is $\omega_n = \sqrt{110}rad/sec$. Because of the alteration of the bracing stiffness status, the natural oscillation frequency of the structure system changes into $\omega_n = 10rad/sec$, control the frequency homology with the lord of the external force, at this time $\omega = \omega_p$. But, because the damping force that ASHD provide has the adjustment, as Figure 7 show. Although structural displacement reaction still contain the trend of the divergence, as Figure 8. But, still can reduce the structure significantly outward the displacement of the hour of force action responds. And did not add the ASHD progress than the detection, the ASHD controls to the displacement up, have the very useful control function. ASHD here at the step still keeps the good energy dissipation characteristic, as Figure 9 show.

4. Discussion

Effect in the energy dissipation behavior of the ASHD, the most main factor is an expression of accumulator properties. Among them regard the precompression force and volumes of the accumulator as the most main the factor of controls. In regard to the viewpoint of the mechanics, the precompression is very early to start to lift a hand to and volume equal to stiffness. The following will inquire into the external force to act down, the condition of the precompression force and the volume of different accumulator descend to the influence that structure respond. This lord that inquires into case instance as the structure and external forces controls the main frequency. Also suppose the duration of the external force action as 20 seconds.

4.1. **The beginning of accumulator starts the influence of the precompression force.** In order to investigate the influence of the precompression force upon the energy dissipation of ASHD, the damping force P_a will be changed its dimension under the consideration of resonant oscillation of the structure and external force in later stage. When inquiring into this damping force distinguish to 0.2 N, 0.4 N and 0.6 N, descend the reaction of the structure in the external force action. Figure 10-12 show that are hysteresis loops of the structures added with ASHD structure inside 20 seconds.

Comparing the influence of the initial precompression force of the accumulator upon the structure displacement, as Figure 13 show. It discovers the initial precompression force P_a more big, then the ASHD it lifts a hand to enter the constant more and late. But, for the displacement control, P_a bigger, the structural displacement is smaller. The energy dissipation performance is better. The precompression of the accumulator is higher; accumulator can provide it with the biggest power more high. The ASHD can attain the same output power with fewer hysteresis loops.

But must note, the ASHD it lifts a hand to enter the constant more and late. The active force provided by the bracing deformation is bigger. So, in order to avoid the yield of bracing, add a control valve in the ASHD, makes ASHD still had the maximum to lift a hand to the upper bound.

4.2. **The influence of the accumulator volume.** The accumulator it lifts a hand to be to exceed the initial precompression force, the volume of the accumulator has something to do with the bracing deformation. This paper simulate accumulator as linear spring of the force with initial power of accumulator. For inquiring into the energy dissipation influence of the initial precompression force of accumulator upon the ASHD, the volume of the accumulator k_a dimension, distinguish to 0.3 N/m, 0.7 N/m, and 1.0 N/m a hour, is changed under the consideration of resonant oscillation of structure and external force. Taking the hysteresis loops in 20 seconds to investigate the reaction of the structure acted by external force. Also change the volume of the accumulator k_a more after the dimension, the hysteresis loop in biggest energy dissipation of the bracing under different stiffness, as Figure 14 show. The result reveals along with k_a increase, the displacement control is better, the displacement is smaller, and can provide it with the maximum to lift a hand to more high.

5. Conclusions and discussion

According to the simulated dynamic response of structure installed with ASHD, the conclusions can be drawn as follows:

(1) Installation of ASHD on the structure can significantly reduce structural dynamic response. Even under the condition that the structure is resonated with the seismic force; the energy dissipation characteristics can still be maintained. Furthermore, the displacement of the structure can be kept within a certain field.

(2) The main energy dissipation mechanism of ASHD can provide the damping force to reduce the external force on the structure and at the same time provide the controlling force with excellent adaptability, which can reduce the level of the external force according to the swing of the structural displacement.

(3) With the installation of the accumulator, which can store the force engendered by bracing series distortion and at the appropriate time shift the oil flow direction of action force, ASHD can successively do negative work on the structure so as to form the fullest hysteresis loop.

(4) When hydraulic damper dissipates energy, the structure is probably resonated with the external force. But the controlling force of ASHD is so adaptable that it can limit the displacement into a certain range. However, the matters needing further attention are the yield of the bracing series and the security of the structure.

(5) The major mechanism influencing the controlling force of ASHD is the accumulator. So, when the accumulator is designed, the initial prepared pressure and the volume of the accumulator should be considered so that an optimum designing value can be achieved.

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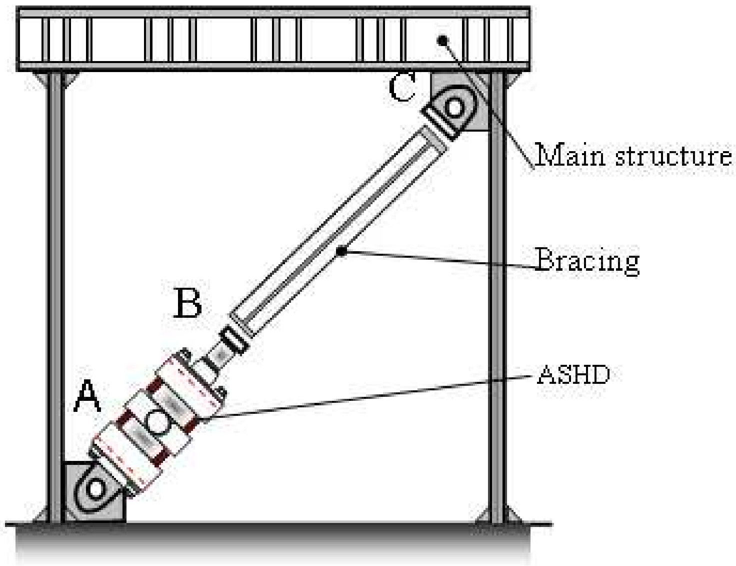

Figure 1. The installation of ASHD in main structure.

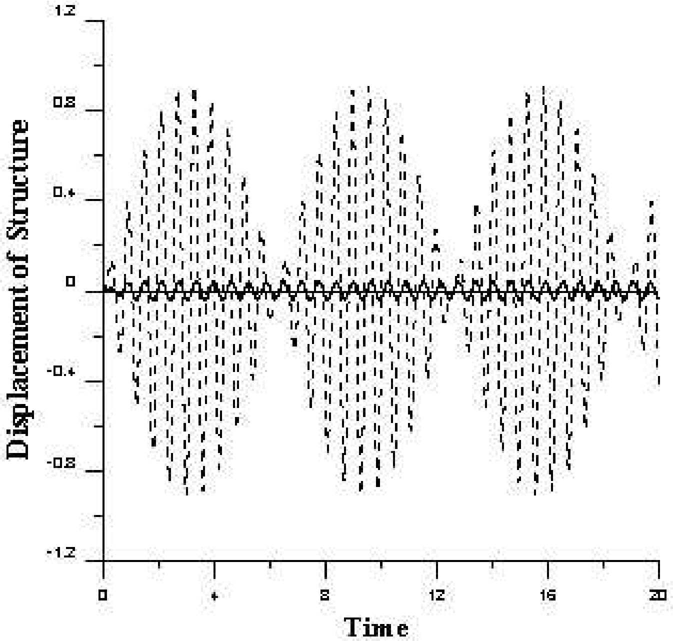

Figure 2. Time history of structural displacement for structure w/ and w/o ASHD
($k_{str} = 121N/m, k_b = 12N/m, k_a = 0.7N/m, P_a = 0.4N$)

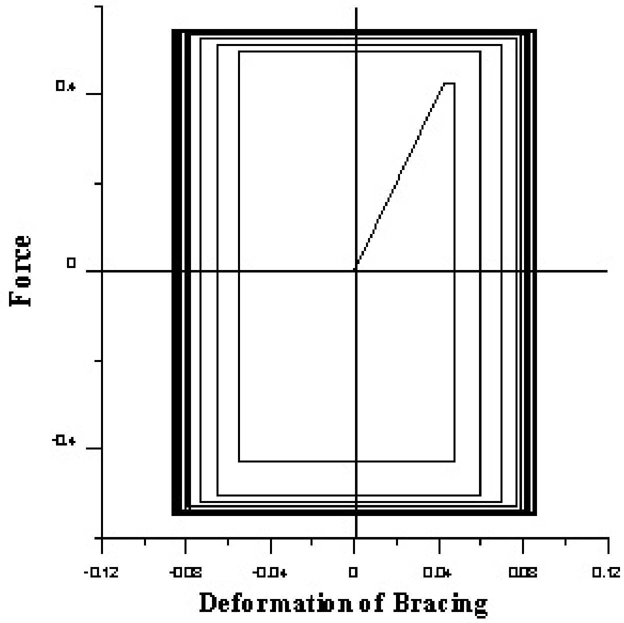

FIGURE 3. Hysteresis loop of bracing for structure w/ ASHD

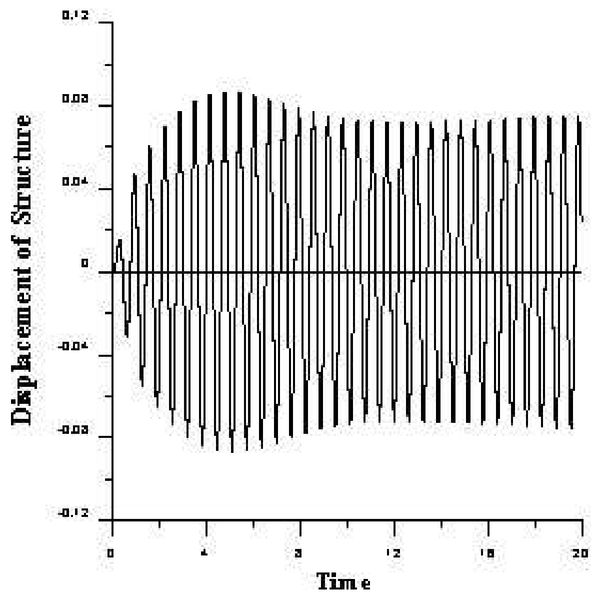

FIGURE 4. The time history of earlier stage of resonance behavior for structure w/ ASHD.

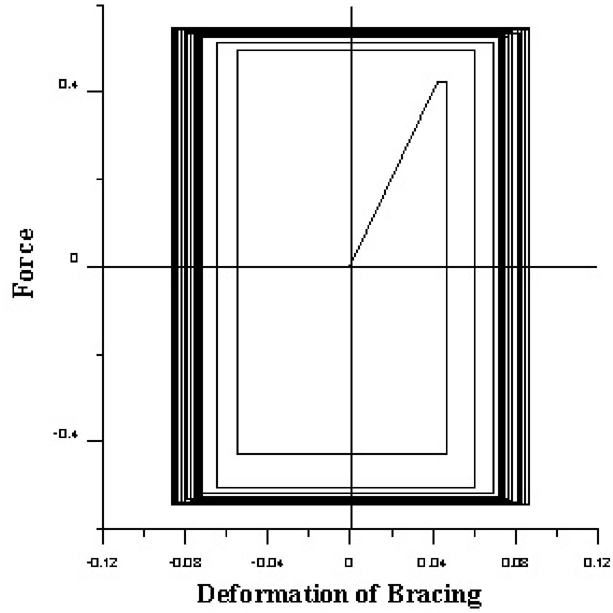

FIGURE 5. The time history of earlier stage of resonance behavior for bracing of structure w/ ASHD.

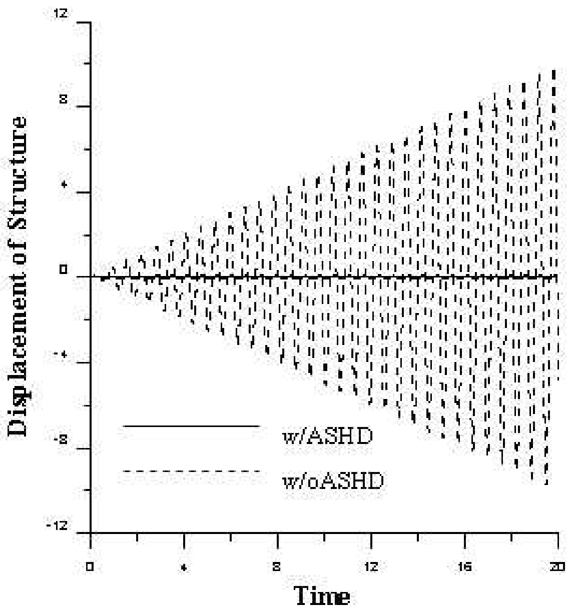

FIGURE 6. The comparison of earlier stage of structural displacement of structure w/ and w/o ASHD.

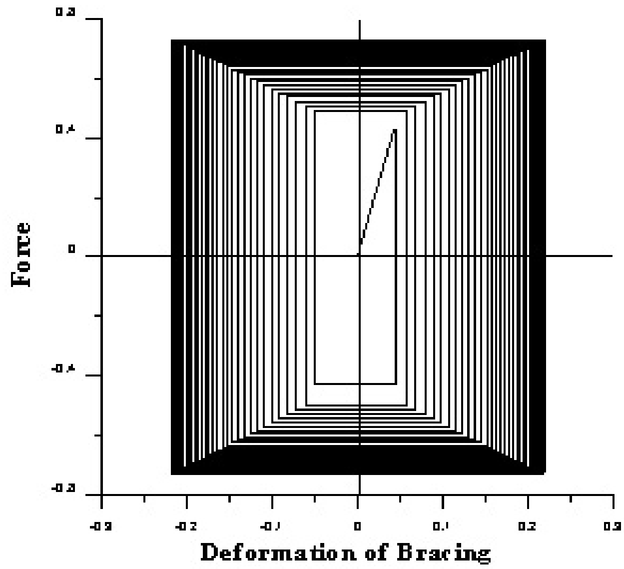

FIGURE 7. The time history of post stage of resonance behavior for bracing of structure w/ ASHD.

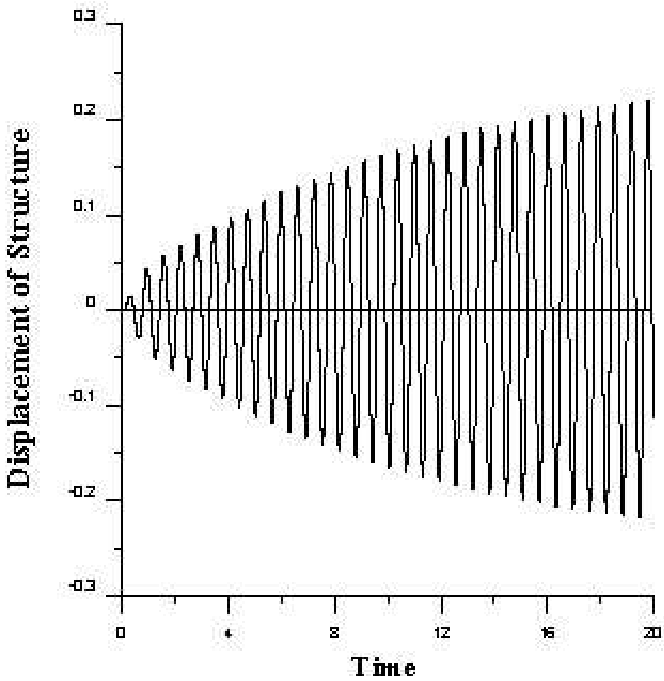

FIGURE 8. The time history of post stage of resonance behavior for structural displacement of structure w/ ASHD.

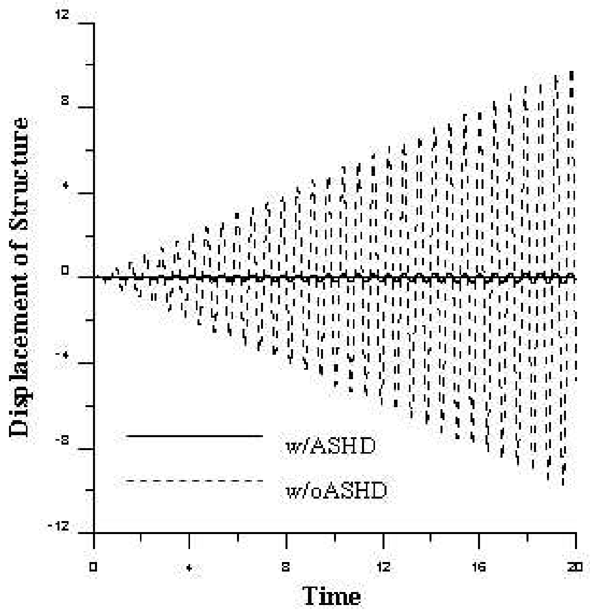

FIGURE 9. The comparison of post stage of structural displacement of structure w/ and w/o ASHD.

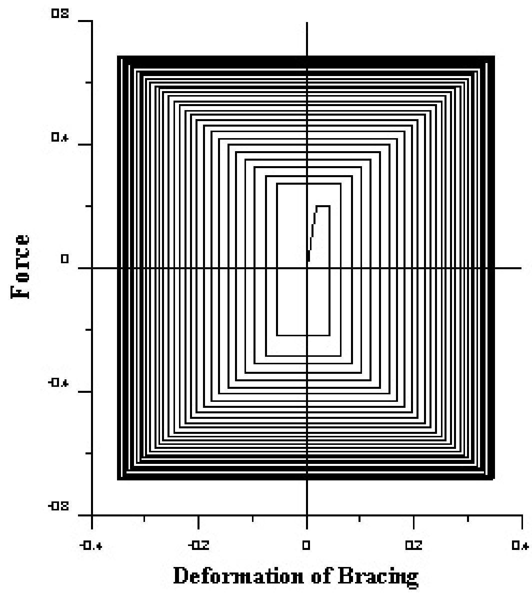

FIGURE 10. The hysteresis loop of bracing for structure w/ ASHD.
$(k_{str} = 100N/m, k_b = 10N/m, k_a = 0.7N/m, P_a = 0.2N)$

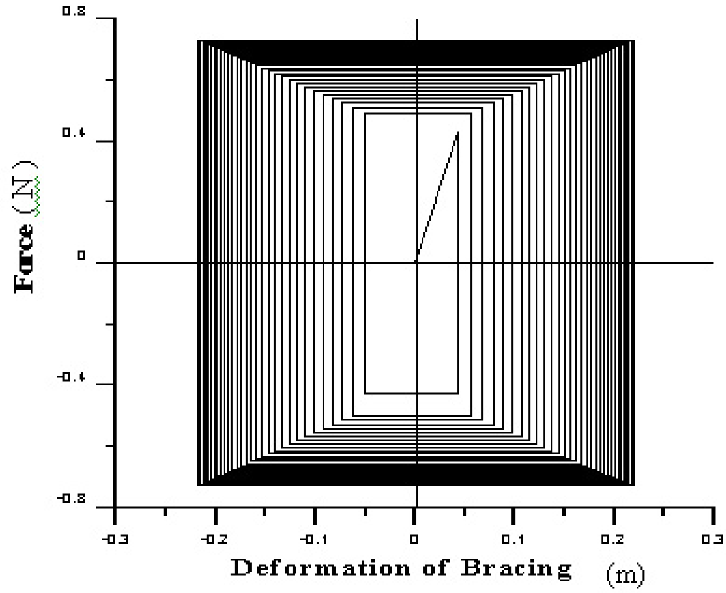

FIGURE 11. The hysteresis loop of bracing for structure w/ ASHD
($k_{str} = 100N/m, k_b = 10N/m, k_a = 0.7N/m, P_a = 0.4N$)

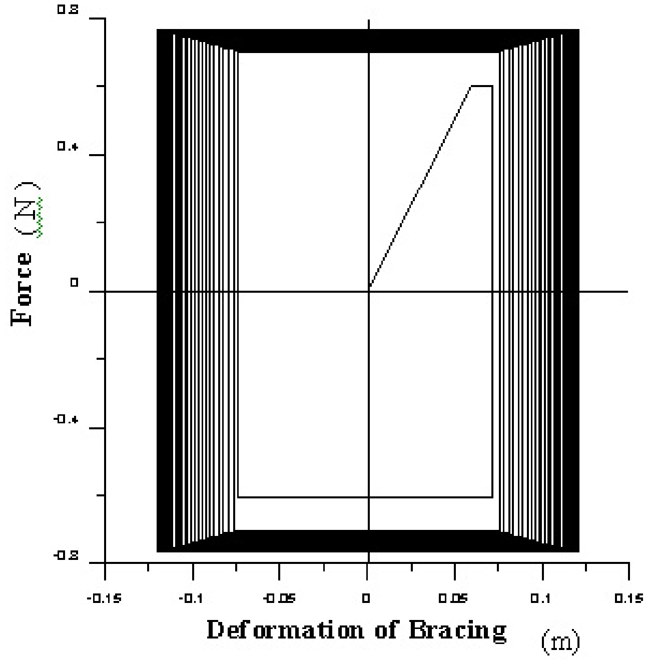

FIGURE 12. The hysteresis loop of bracing for structure w/ ASHD.
($k_{str} = 100N/m, k_b = 10N/m, k_a = 0.7N/m, P_a = 0.6N$)

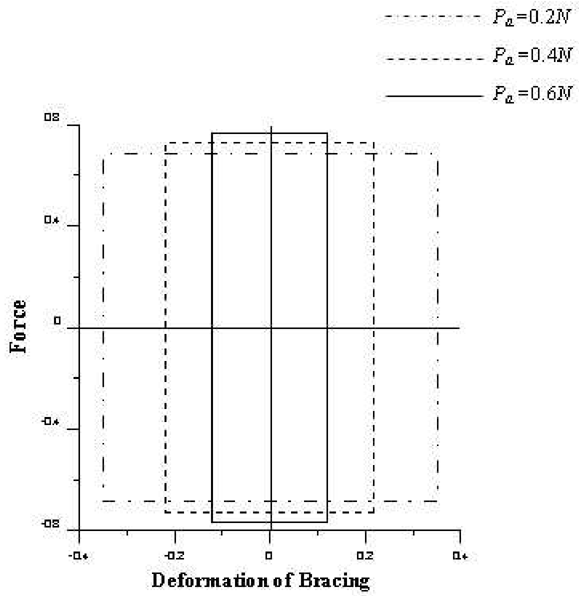

FIGURE 13. The comparison of hysteresis loop of bracing for structure w/ ASHD under various initial pre-pressured pressure.

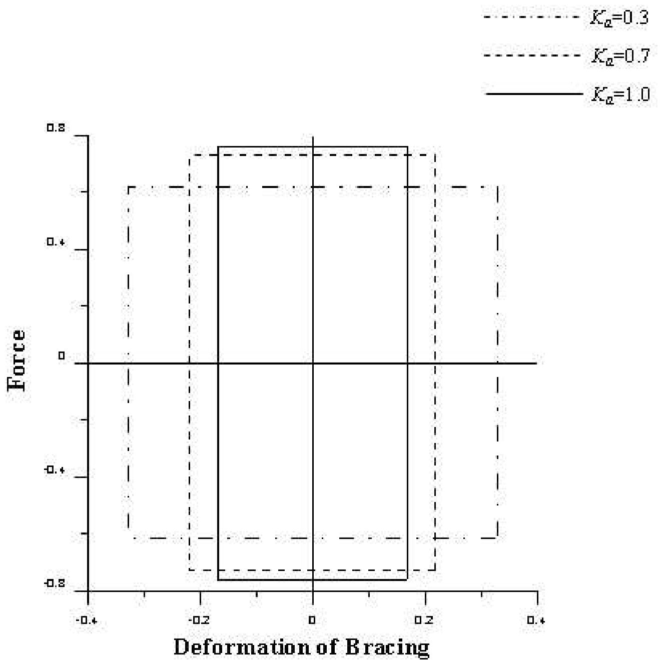

FIGURE 14. The comparison of hysteresis loop of bracing for structure w/ ASHD under various volume of accumulator.