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Actively regulated friction slip braces

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ABSTRACT

This paper describes use of a hybrid energy dissipation device within the structural framework of buildings to regulate its energy dissipation characteristics during seismic action. The bracing system with these energy dissipation devices called Actively Regulated Friction Slip Braces, and abbreviated as ASB. These braces are designed to monitor and regulate the preload along a frictional interface during seismic action. The ASB concept is derived from friction braces implemented as passive energy dissipation devices where the preload is kept constant. The passive friction braces in this text will be referred to as CSB (Constant Strength Friction Slip Braces). The effectiveness of the ASB system will be demonstrated by the comparative response of CSB simple frame structure under impulsive and harmonic actions. Principle of operation and key design parameters of ASB are evaluated on the response of ASB simple frame.

INTRODUCTION

A recent trend in the structural research environment in dealing with seismic design is to use systems such as energy dissipation devices that defend the building against the effects of seismic actions in order to prevent or reduce the damage [Kobori]. In all applications the energy dissipater exhibits a stable nonlinear restoring force hysteresis that enhances the damping capacity of the structure.

The energy dissipation devices are in some cases designed to operate under low vibration amplitudes during the seismic action in order to delay the built of vibratory energy [Pall]. However, in most cases the energy dissipation devices are designed to supplement the ductility supply of the building and will only be operational during the large amplitude response segments to ground excitation [Filiatrault, Whittaker]. The principle is to complement the energy dissipation capacity of the building by increasing the ductility supply which will reduce the strength demand. In other words, the two groups of energy dissipater either supplement the structural stiffness or structural strength. The hybrid system we will be describing here is a unique energy dissipater that operates during all response phases and complements both structural stiffness and strength.

The purpose of this paper is to present a hybrid energy dissipation device called Actively Regulated Friction Slip Braces, ASB, to provide solutions to the problems encountered with the applications of conventional energy dissipaters. This bracing system includes an innovative device [Akbay and Aktan] which activates the energy dissipation mechanism at all stages of the building response. The energy dissipation is accomplished along a friction interface under a clamping load on the structural bracing. The slippage along the friction

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interface is observed during the inter-story response of the building. The clamping force on the friction interface is monitored and regulated during the response of the building to ground excitation.

METHOD

Overview:

The Actively Regulated Friction Slip Bracing was developed from a friction type energy dissipater that was in part developed by one of the authors. The early device allowed energy dissipation by slippage under a constant clamping force. The hybrid device (ASB) that is described here includes a mechanism that can regulate the clamping force on the friction interface upon demand. The decision on the clamping force regulation is based on a feedback response parameter.

In the following sections the friction energy dissipater with constant preload will be described first. The advantages of actively regulating the clamping force will be described following the passive device.

Friction Slip Braces:

Friction energy dissipation devices with constant clamping forces are installed on the structural bracing and designed to slip at an inter-story drift that is below the damage threshold of the building structure. The corresponding brace axial load at that drift level during slippage is designed to be lower then buckling load of the bracing. The energy dissipation is observed during the slippage along the friction interface at predefined brace axial loads. The lateral load vs. inter-story drift response of the structure appears as nondegrading elasto-plastic where, the yielding of the building is simulated by the slippage of the braces along the friction interface. The advantage of simulating structural yield before the damage threshold story drift is the increase to the ductility of the structure.

The stiffness, strength, and ductility of the building with friction bracing are uncoupled and are designed independently to provide the required balance. For example, the brace stiffness is designed by selecting a specific brace configuration and cross-sectional area. Brace strength is designed by selecting the clamping force on the friction interface. The operation of the passive energy dissipation devices are verified in scaled model of a multistory building experiments on the earthquake platform [Whittaker]. Experimental results showed significant reduction in the building response under ultimate limit state ground motion.

In multistory buildings under lateral load the slip strength of the structural bracing with friction interface also defines the yielding strength of that particular story. The clamping force on the friction interface is computed from an assumed lateral load distribution along the building height. The uncertainties in establishing the lateral load distribution will dictate whether slippage along the friction interface will initiate at a particular story. For example, soft story may form if clamping forces at all storeys except one are overestimated. In summary, the use of friction energy dissipaters in seismic defence of buildings requires a very accurate estimation of ground motion parameters. It should be also reiterated that, the friction energy dissipater is implemented to defend the building during the ultimate limit state seismic event and there is no functional expectation from these devices during the serviceability limit state lateral load demands. One may point out a practical concern on the operational reliability of these devices due to very infrequent service expectation.

As it is described in the previous paragraph, predefined level of brace axial load sets the strength of the brace which remains constant during the operation. Therefore, in this study, these brace components to implement the passive energy dissipation concept are referred as Constant Strength Friction Slip Braces, CSB.

Actively Regulated Friction Slip Braces, ASB:

Author's recent research to overcome the difficulties in the implementation of CSB in buildings led to the development of a hybrid energy dissipation device which will monitor and alter the clamping force on the friction interface thus, the energy dissipation characteristics of the structural system during the seismic action [Akbay and Aktan]. The structural bracing system having this new hybrid energy dissipation devices is called Actively regulated friction Slip Brace, and abbreviated as ASB.

Contrary to the conventional applications where the accumulated vibrational energy of the building is being dissipated near or at the ultimate level of the seismic response, the use of ASB will prevent the build-up of the vibrational energy in the early stages of seismic response. Energy dissipation is monitored and actively corrected to retain the building response below damage threshold. The ASB device can be installed to existing bracing or can be implemented with new bracing in different configurations such as chevron, X and K. The eccentric bracing could also be used so that a staggered seismic defence system is used where the yielding beams provide the last line of defence.

The prototype design of the active energy dissipation device, Fig. 1, is based on a passive device developed in part by one of the authors and reported as "Friction Slip Braces" [Whittaker]. The mounting of the device to structural bracing within a simple frame is demonstrated in Fig. 2. The main alteration in the design of the device is: its capability of controlling the pressure on the frictional interface to regulate the strength of the brace component.

OPERATIONAL FEATURES

Operation:

Basic operation scheme of the ASB is controlled by its energy dissipation device. The device is, like the one in CSB, a preloaded friction shaft and rigidly connected to the bracing. Brace is allowed to slip axially through the friction interface when the axial load exceeds the friction force developed under the regulated clamping force. Thus, when the slippage occurs, an amount of energy (equals to brace axial load times the slip displacement) is dissipated prior to any structural damage. Under increasing ground pulses, the clamping force on the friction interface is increased to give an additional strength to the brace.

The slippage along the friction interface is coerced during the early stages of the building's response by reducing the clamping force on the friction interface when the response amplitudes are small. Early initiation of energy dissipation prevents the build-up of vibrational energy and reduces the strength demand under large ground pulses during the middle portion of seismic motion.

A simple operational algorithm is incorporated in this study. The clamping force mechanism is changed at single fixed increments. The clamping force is lowered one increment if the slippage is not taking place. The clamping force is raised if the device is currently at slip state. The monitoring is performed at fixed time intervals. The design parameters of the active clamping mechanism are specified as time interval between decisions and clamping force increment. The effect of these parameters on the performance of the ASB device is studied in next section.

Design parameters:

Equation of motion for a simple frame structure modelled as a single degree-of-freedom system and subjected to a ground acceleration is written as:

$$m\ddot{x} + c\dot{x} + R(x) = -m\ddot{x}_g \qquad \cdots(1)$$

where m is the total mass of the frame; c is the coefficient of inherent viscous damping; x, $\dot{x}$, and $\ddot{x}$ are displacement, velocity and acceleration of the mass respectively; $R(x)$ is the resistance force function, and $\ddot{x}_g$ is the ground acceleration which acts at the base of the system. The resistance function $R(x)$ becomes equal: to kx when structure is linearly-elastic where k is the stiffness of the structure, and to R_y when the yield (slip) strength of the structure is reached. The R_y corresponds to the lateral load at which the slippage at the frictional interface initiates.

The operation of ASB is implemented in a discrete manner at fixed time intervals of t_s. The status of the ASB is monitored only at each t_s and decision is made on changing the clamping force. Eq. (1) is solved at fixed time increments and the ASB action is taken at fixed time intervals and the change in the strength of the brace is defined as a fraction of its maximum strength R_y. Eq. (1) is then written in the incremental form as follows:

$$m\Delta\ddot{x} + c\Delta\dot{x} + \Delta R(x) = -m\Delta\ddot{x}_g \qquad \cdots(2)$$

Two important design parameters of ASB are: a) decision time interval t_s, and b) clamping force increment. The parameter t_s is expressed in a nondimensional manner by normalizing it with the fundamental period of the frame, T, as $\frac{t_s}{T}$. The clamping force increment is the change to $\Delta R(x)$ at each $\frac{t_s}{T}$ in Eq. (2).

At each time interval t_s a decision is made on the clamping force. For example, if there the friction interface is currently not at slip state, the clamping force thus, the brace strength is reduced to a level which will invoke the energy dissipation immediately. On the other hand, if the friction interface is at slip state, the clamping force thus, the brace strength is increased one increment. For the purposes of this study the clamping force increments are retained constant. The clamping force increment size effects are studied by a parameter describing the incremental change in slip strength $\Delta R = \alpha R_y$, where α is a coefficient defining the strength increment ratio to maximum strength.

NUMERICAL EXAMPLE

General:

The effects of the two design parameters on the response of ASB is studied using a simple framed structure with one diagonal bracing scheme with a fundamental period of 0.5 seconds. In addition, response comparisons are carried out on the same frame one with an elastic bracing and another with a CSB to demonstrate the effectiveness of ASB. The elastic braced frame is assumed undamped to explicitly demonstrate the effect of ASB. Other members of the frame (the columns and the beam) are retained elastic.

The primary difficulty in the analytical simulation of ASB response is the unavailability of tools. A significant effort was made to append the ABAQUS finite element analysis program to allow the testing of active control algorithms in large non-linear structural systems [Akbay]. An element subroutine describing the ASB and clamping force regulation algorithm is developed and appended to the finite element analysis software ABAQUS [Users Manual].

The ASB operation is demonstrated on the simple frame subjected to a ground impulse. The effects of ASB parameters are evaluated using the response of the simple frame to a ground impulse as well as a simple harmonic ground acceleration.

ASB Frame under Impulsive Excitation:

The frame response is obtained under a ground acceleration impulse with an amplitude of 1 g and duration of $\frac{T}{10}$ where T is the fundamental period of the frame. The maximum slip strength of the frame is described as the base shear coefficient of 0.3. Three different values of clamping force increments of 0.04, 0.08, and 0.16 α are compared. The frame response is computed for a total time duration of $10T$.

The response of ASB building with a decision time interval ratio of $\frac{t}{T} = 0.05$ and a clamping force increment ratio of $\alpha = 0.04$ is compared with the response of the CSB and elastic frame in Fig. 3. ASB force vs. displacement hysteresis is shown in Fig. 4. Under a short duration impulse the maximum displacement during the first cycle by the ASB frame is greater than the other frames. The next response cycle however, the feature of ASB is demonstrated. The early dissipation of the energy through Coulomb damping significantly reduces the response amplitudes of the frame.

The equivalent viscous damping coefficients of the ASB frame during the first response cycle is computed and plotted in Fig. 5. Equivalent viscous damping coefficient of around 10% is computed for average values of $\frac{t}{T}$. In other words, under seismic excitations, the input energy will be dissipated immediately upon the application of the pulse and the build-up of vibration energy is prevented.

ASB Frame under Simple Harmonic Excitation:

The ASB frame response is computed under a harmonic ground acceleration with an amplitude of 0.01 g, and its frequency matching the initial frequency of the frame. The response of ASB building with a decision time interval of $\frac{t}{T} = 0.05$ and a clamping force increment ratio of $\alpha = 0.05$ is compared with CSB and elastic frame in Fig. 6. The maximum slip strength of the ASB frame and the slip strength of the CSB frame are taken equal and defined as the base shear coefficient of 0.3. It is clearly observed in Fig. 6 that the response of ASB is bounded at a limit described by its strength characteristics. The effect of early slippage is demonstrated in the ASB axial force-axial displacement relationship shown in Fig. 7. The early energy dissipation resulted in a 40% reduction of maximum displacements when compared to the CSB frame.

Effect of the decision time interval t, is studied in Fig. 8. Maximum displacement amplitude of ASB, CSB and elastic frame are compared for a time duration of $10T$ in Fig. 8. The ASB response characteristics are near optimum for the range of $\frac{t}{T}$ between 0.05 and 0.25 for all α values.

Maximum response amplitudes of ASB under a varying amplitude harmonic ground motion at resonant frequency with the ASB frame is compared in Fig. 9. In this analysis, the response of the ASB building with various decision time intervals $\frac{t_d}{T}$ are compared with the responses CSB and elastic building. The slip strength of the CSB frame and maximum clamping force of the ASB frame is described as the base shear coefficient and retained constant under all excitation amplitudes. The clamping force increment of the ASB building is also retained constant. Response of ASB building is computed to be the lowest for all cases analyzed. Also, the reduction of maximum response is observed in Fig. 9 as increased apparent stiffness of the ASB frame.

CONCLUSION

The concept and development presented here is a hybrid energy dissipation device that can actively regulate its energy dissipation characteristics during seismic action. The device that is presented as a bracing system (called Actively regulated friction Slip Braces, and abbreviated as ASB) can be implemented to existing bracing or incorporated as new bracing in building structural systems.

Response of ASB building is presented under impulsive and harmonic actions. A very simple and preliminary operation algorithm is adopted for the implementation of ASB. Comparisons with other conventional frame types indicate very favorable influence of ASB to reduction of response amplitudes.

Further research will include multistory building response simulations with ASB and search for other operation algorithms to establish a design guideline for upgrading of seismic deficient buildings using ASB.

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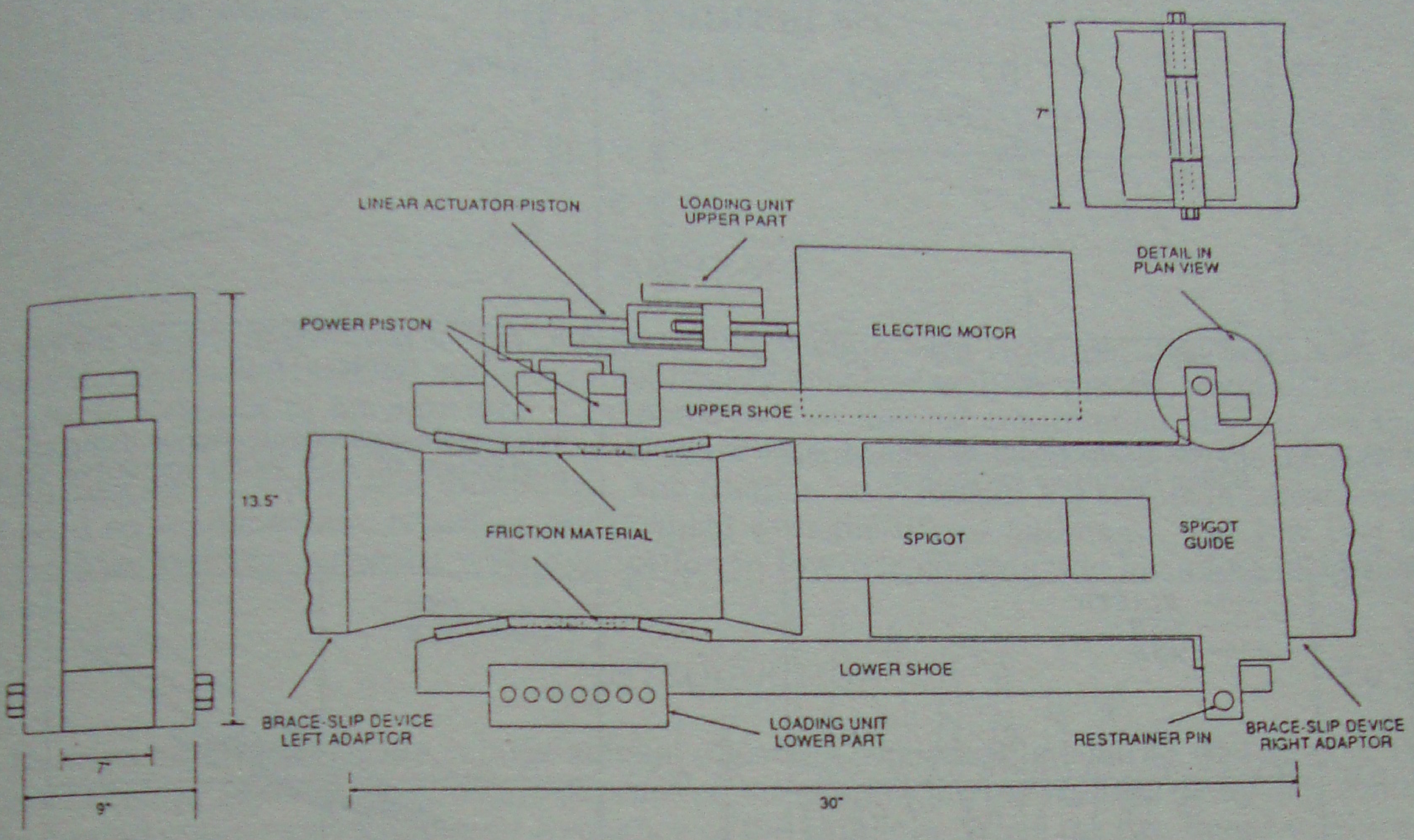

Figure 1. Prototype design of the active energy dissipation device.

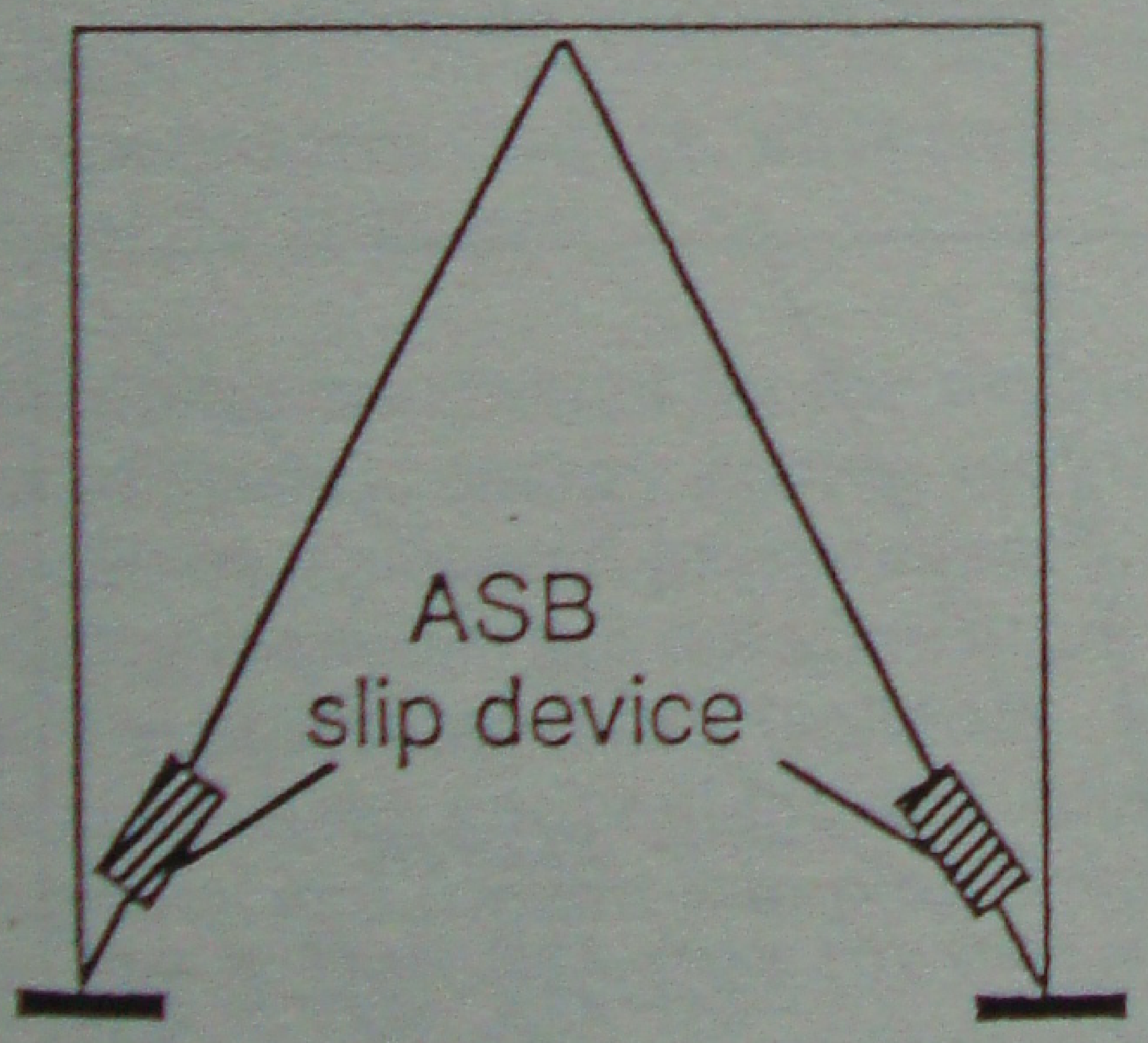

Figure 2. The mounting of the device to structural bracing.

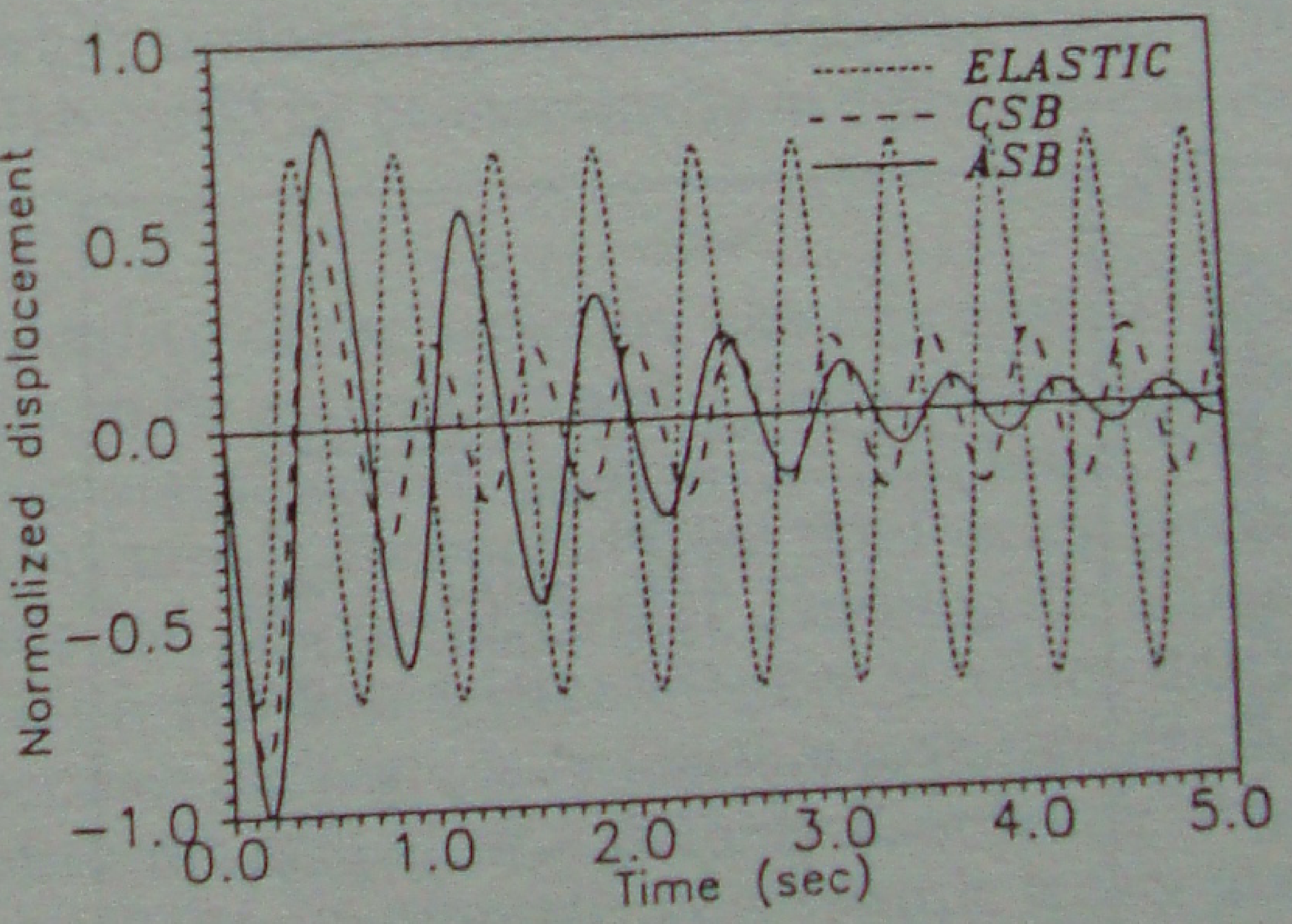

Figure 3. Displacement response under impulsive excitation.

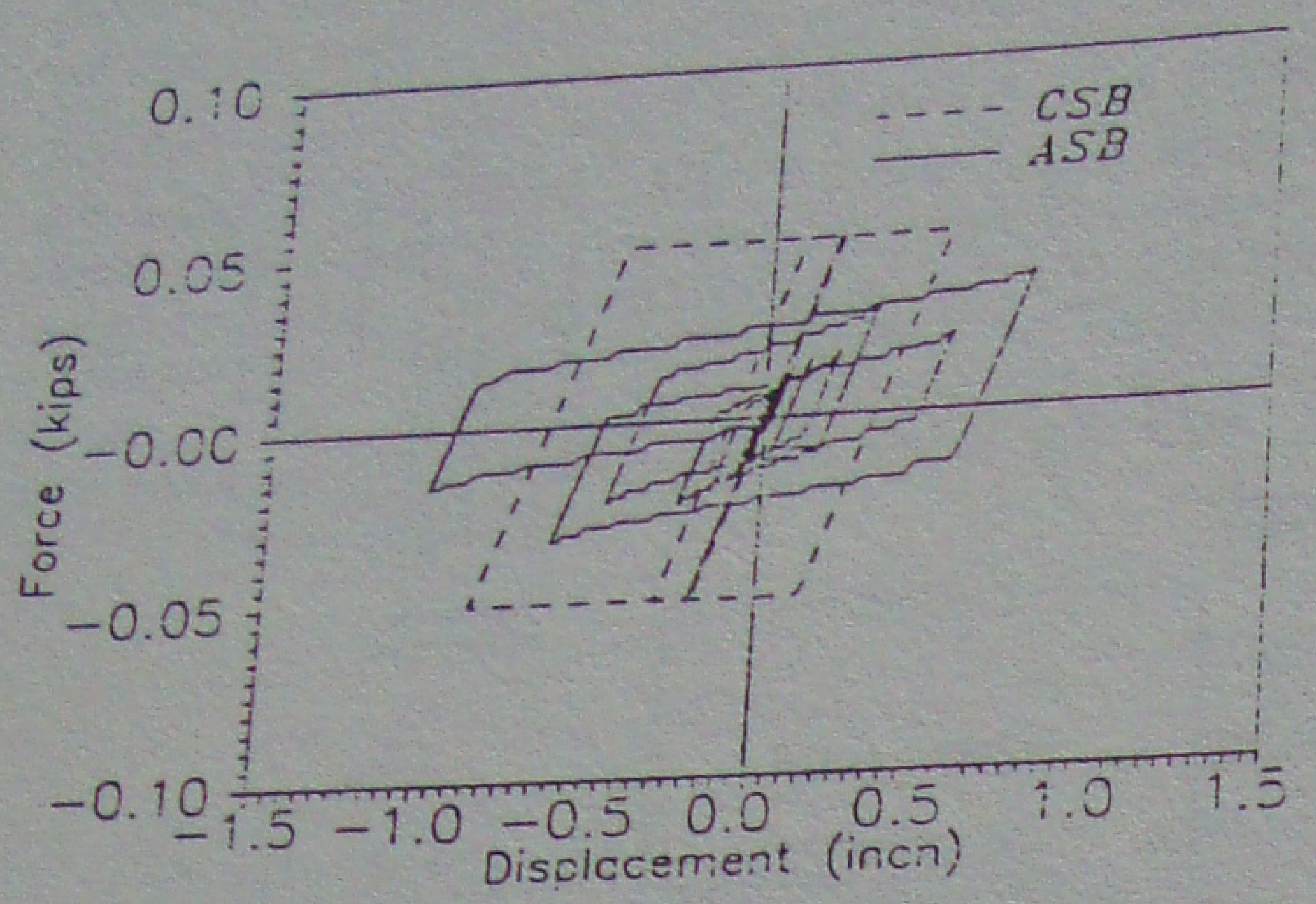

Figure 4. Force displacement relation of ASB under impulsive excitation.

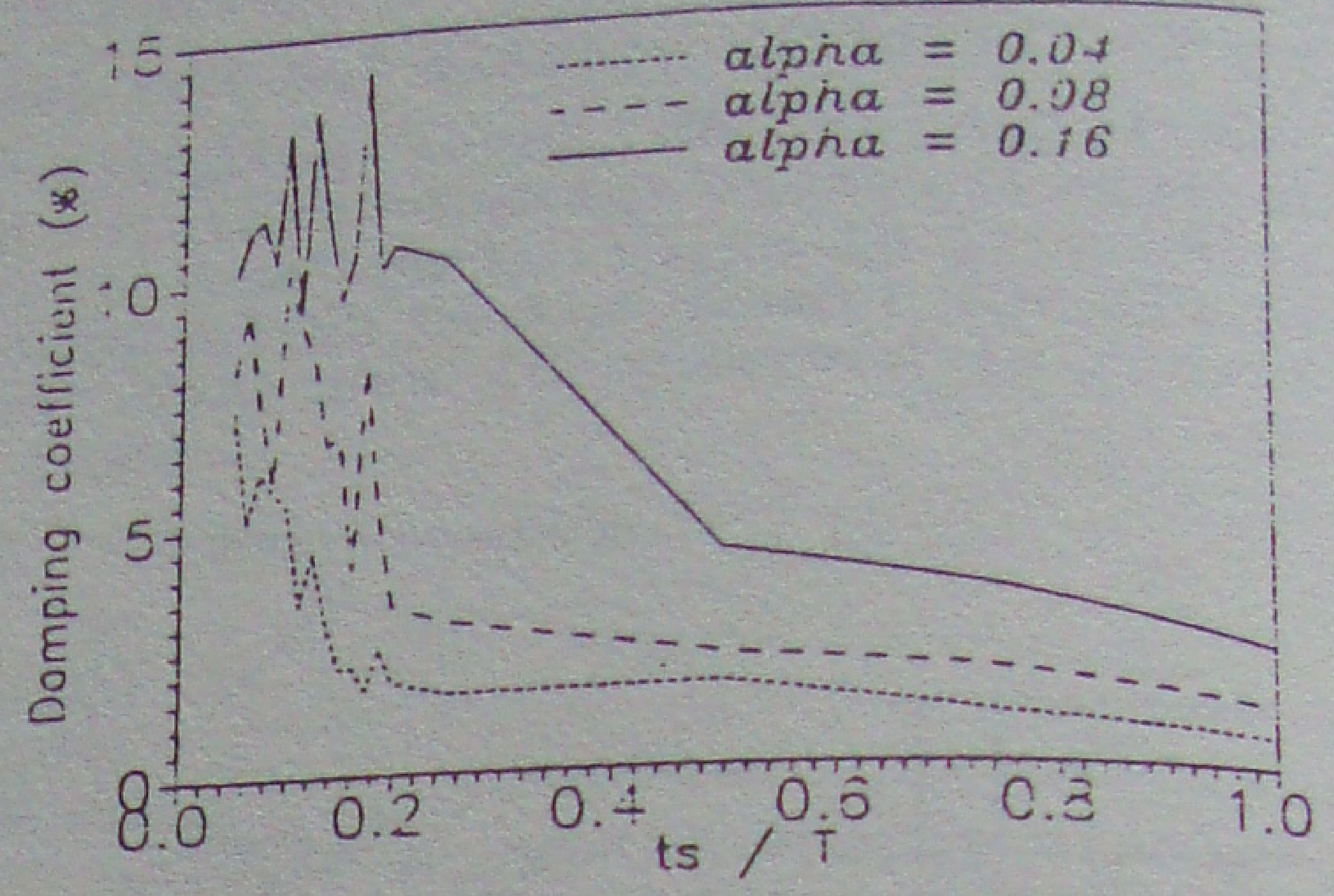

Figure 5. First cycle equivalent viscous damping coefficient of ASB under impulsive excitation.

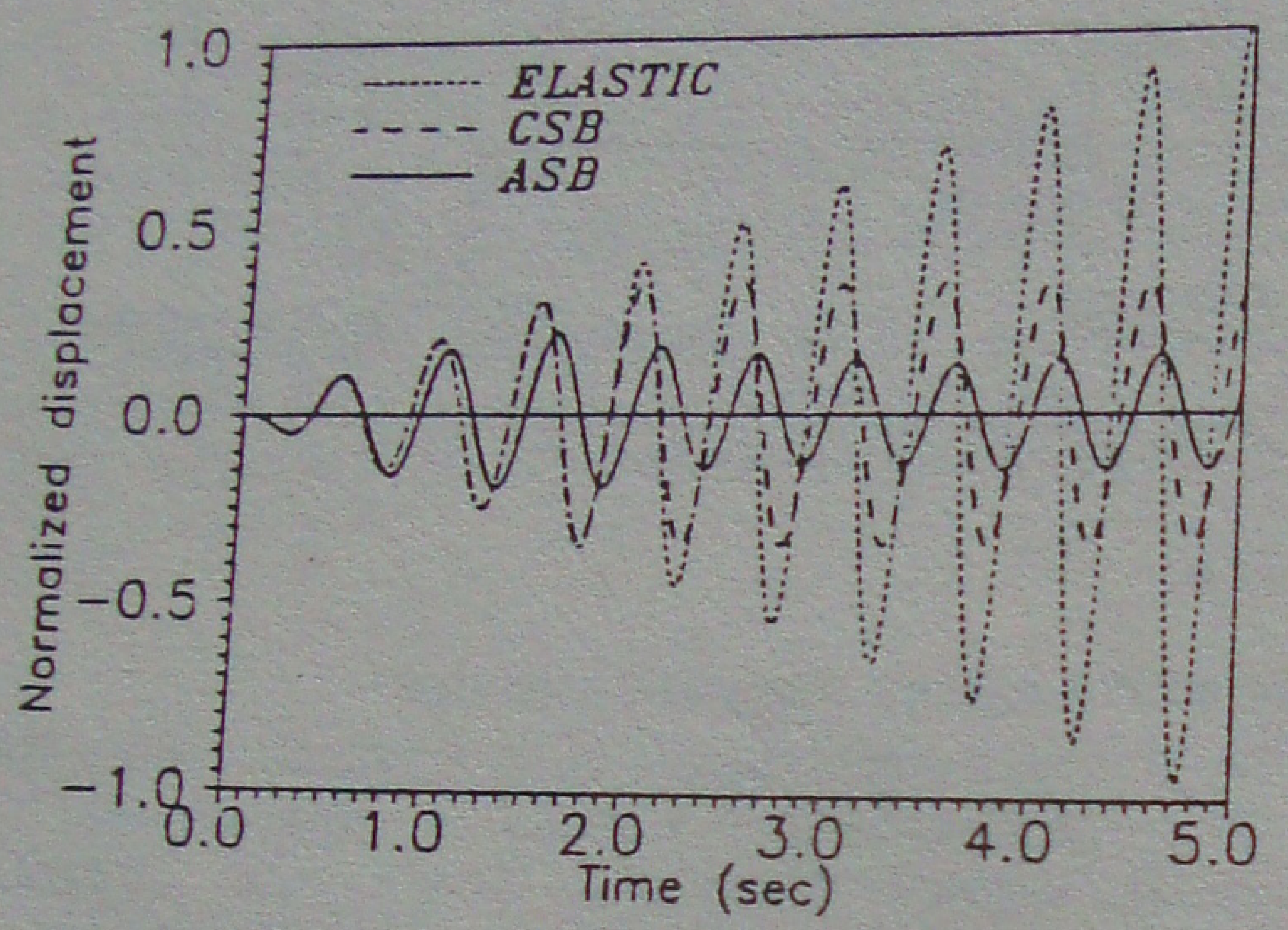

Figure 6. Displacement response under harmonic excitation.

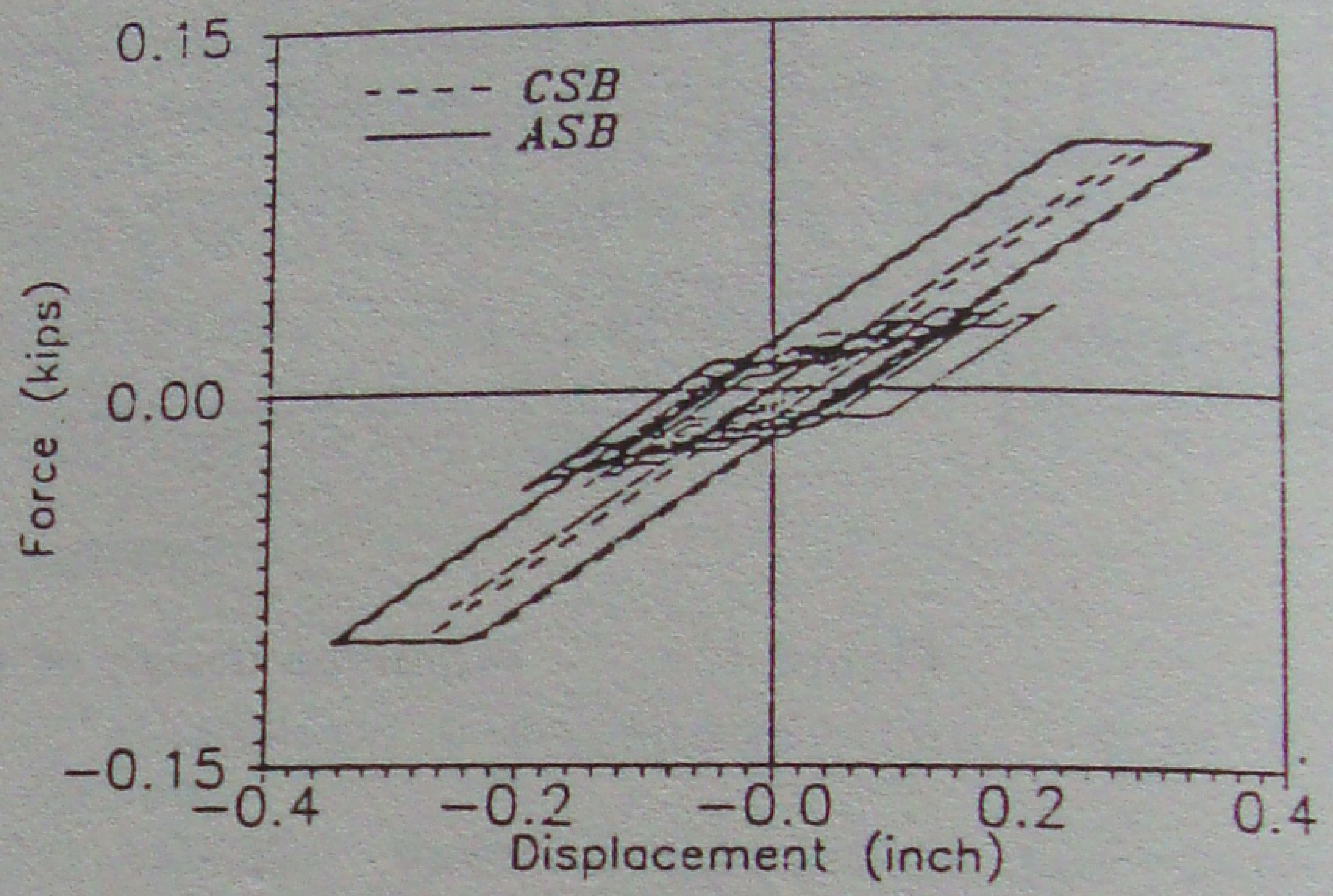

Figure 7. Force displacement relation of ASB under harmonic excitation.

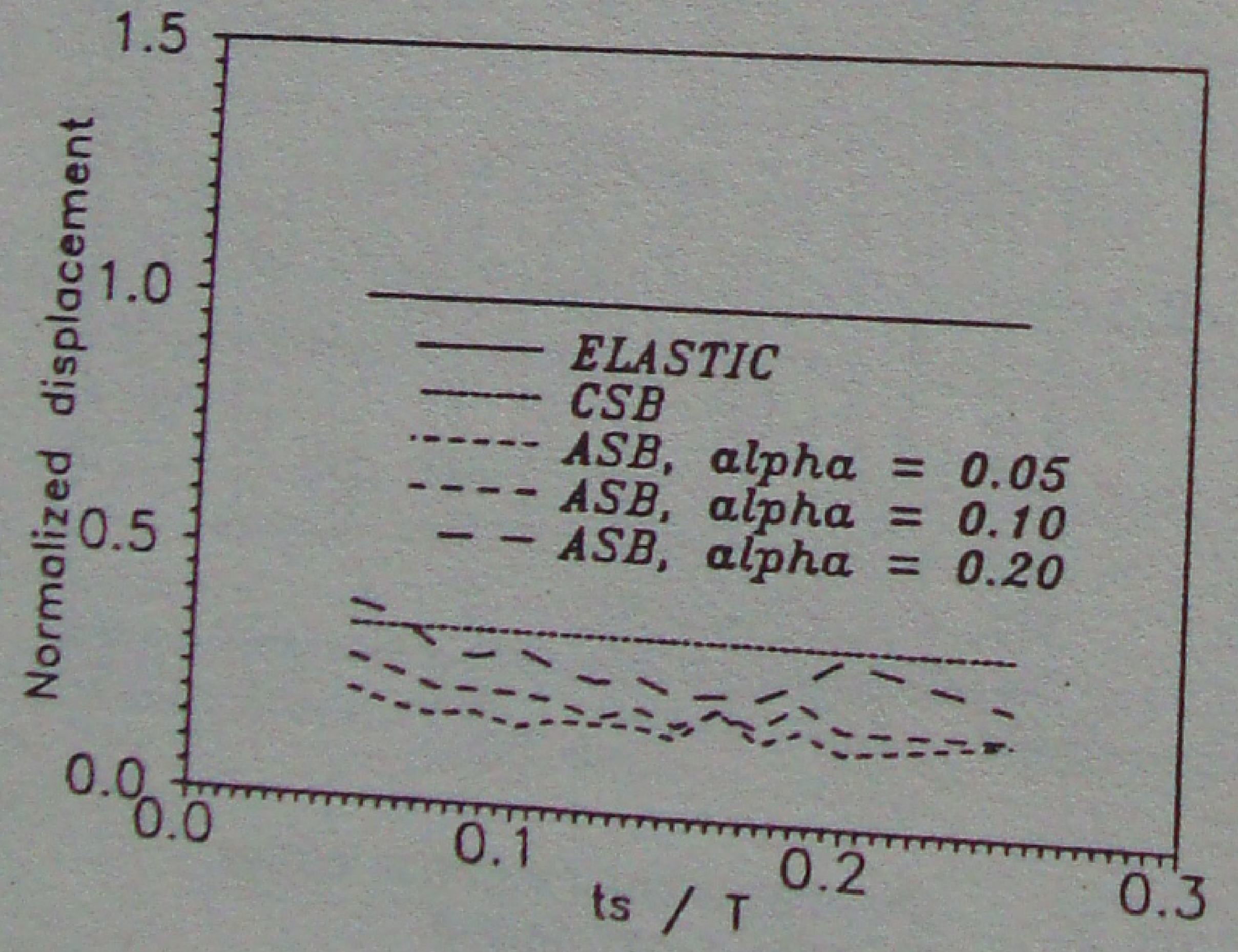

Figure 8. Effect of decision time interval.

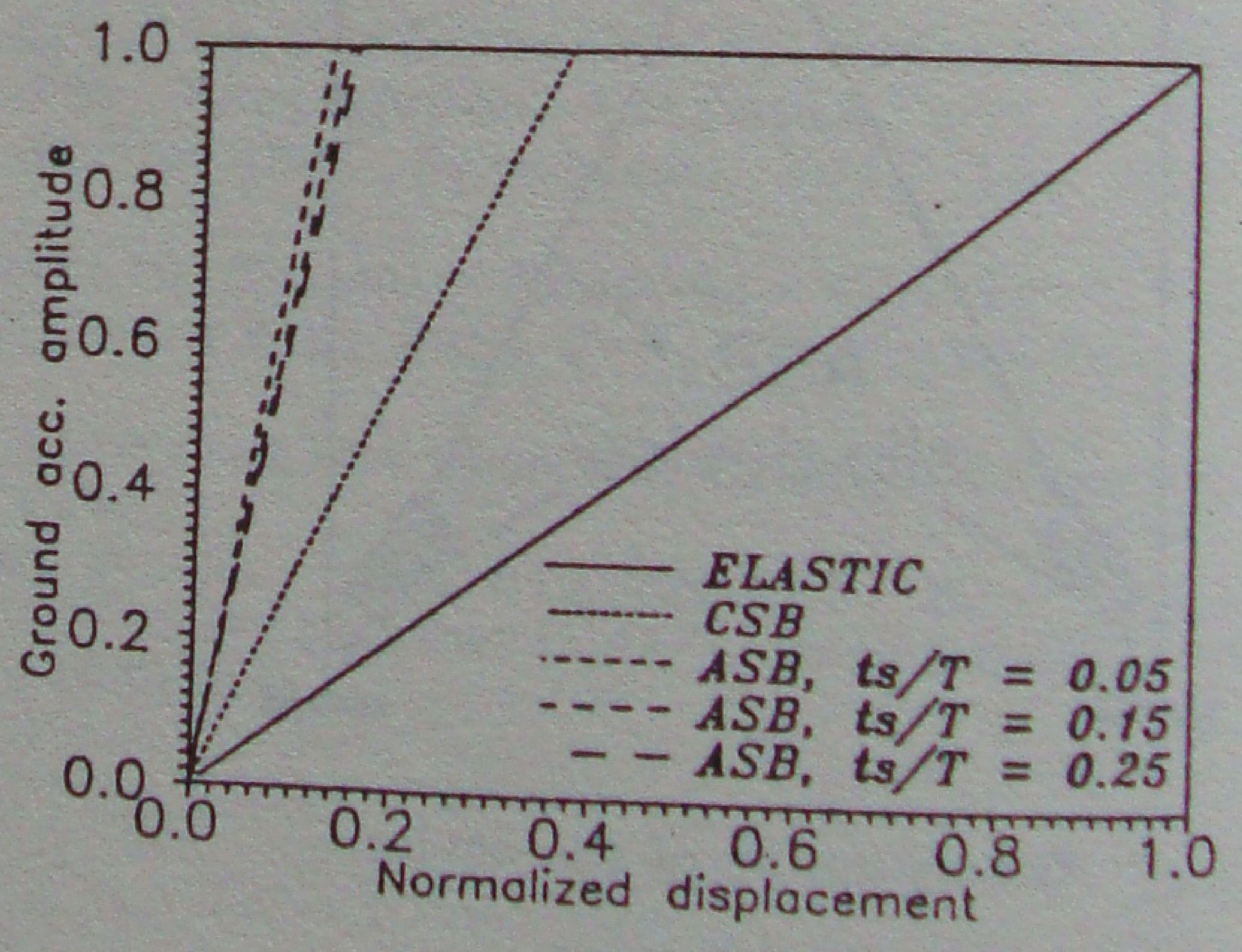

Figure 9. Max. response amplitudes under varying amplitude harmonic excitation.