

RESPONSE SPECTRA EVALUATION INCLUDING POUNDING EFFECT

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ABSTRACT

The paper deals with evaluation of the effects, caused by pounding on the elastic response spectra. A simple tension opening gap element is added to the well known SDOF system and allows for simulation of the contact of the mass with the rigid screen, which is moving with the ground. It is found that the influence of the pounding is essential on the acceleration spectra and leads to the peak response which is considerable greater if pounding is off. The velocity and displacement response spectra are amplified due to pounding only in high periods range typical for flexible structures.

INTRODUCTION

The damage analysis after strong earthquakes shows that one of the most frequent reason for local and global damages is the effect of pounding. In the large cities where the cost of the construction area is usually high, this problem appears to be very important. In these regions the buildings are very closely spaced and the pounding phenomenon can not be avoided. The most relevant measurement towards making the structures seismic resistant is this event to be accounted for in the design process. The theory of the response spectrum method applied to peak response evaluation for SDOF and MDOF systems is discussed by Tzenov [4].

The seismic behavior of a structure can considerably be changed when pounding effects occur. Figure 1 illustrates a simple one bay three story frame, which is designed assuming that each story level displaces horizontally without interaction with other adjacent buildings. The energy is dissipated through the global mechanism, shown in Figure 1,a. However, if this building is detached from another, stiff building, using single joint, see Figure 1,b, than the collapse mechanism may totally be changed and the damage will be concentrated mainly in middle story. The energy dissipation will also be concentrated only in a single story and lateral collapse load will not be predicted correctly. Similar failure mode is shown in Figure 1,b. Such mechanisms were observed after San Salvador, Mexico and Kobe earthquakes. Now it is concluded, that the location of the structure with respect to neighboring structures should become additional design parameter. A lot of research should be done to establish the correlation between pounding and the most important dynamic parameters. Some recent results in this area are presented in [1], [2] and [3].

In the practice the pounding event appears to be a result of instantaneous contact between adjacent buildings, which are separated by a joint. Note that both buildings are deformable in horizontal direction. Because of the complexity of the problem, the problem is considered under some assumptions, such as : 1) the system is elastic and the motion causes deformations which do not exceed the elastic limits; 2) the only single degree of freedom (SDOF) system is studied as well as to answer the question is the influence of pounding essential for the response spectra or not; 3) the adjacent structure is absolutely rigid and moves horizontally in the same way as the ground, see Figure 2. The motion of the mass is influenced by the contact between both structures. Following these assumptions the problem is idealized in a large extent, but it is expected some estimates to be provided as a first iteration.

The purpose of the present paper is to evaluate the effect of pounding on the response spectra. It is shown that the pounding produces considerable increase in response spectra although only particular cases and simplified models are subject of interest. However, the importance of this event is expected to become greater when more complex structures and inelastic material behavior are suggested. The paper could be regarded only as an initial step towards evaluation the effects of pounding. It is shown that the amount of inertial (seismic) force may be increased few times due to such phenomenon, which deserves special attention and should be accounted for somehow in the design engineering practice.

COMPUTATIONAL MODEL AND RESULTS

The computational model is shown in Figure 2. The usual SDOF system used to define the response spectrum is now modified by adding gap element, relevant in simulating the instantaneous contacts between the moving mass and absolutely rigid screen. Note that due to the contacts the problem is highly nonlinear. The gap and elastic spring characteristics are illustrated in Figure 3. Following Figure 3, the equilibrium equation can be written in the form:

$$(1) \quad f_d + f_s + f_p = f_i$$

$$f_i = -m(\ddot{v} \ddot{v}_g + \dot{v}), \quad f_d = c \dot{v} \quad \text{and} \quad f_s = k_s v$$

where f_i , f_d and f_s are the inertial, damping and restoring forces respectively. The force $f_p(v)$ is the gap force, which is zero if the gap element is loaded in tension and nonzero in case of compression, see Figure 3. The governing equation (1) is then transformed as

$$(2) \quad m \ddot{v} + c \dot{v} + k_s v = v m \ddot{v}_g - f_p(v)$$

It is worth noting that the response is strongly dependent on the ground motion orientation, see Figure 2. Obviously there exists two varieties for the external action orientation and for each one separate nonlinear time history analyses should be carried out. The ground acceleration orientation is accounted for by the multiplier v , being accepted $+1$ or -1 , respectively. Thus, Eq.2 takes the form

$$(3) \quad m \ddot{v} + 2\xi \omega \dot{v} + \omega^2 v = -\ddot{x}_g$$

$$(4) \quad \text{where } \omega^2 = k_s/m \text{ and } \ddot{x}_g = v \ddot{v}_g + \frac{f_p(v)}{m}$$

It is seen from Eq.3, that the response spectra can easily be calculated based upon the well known definition if the f_p force is treated as known. Thus, the desired response spectra can be calculated in the same manner as the linear response spectra if the forces f_p are previously determined. This force is dependent on the seismic action orientation and this is illustrated in Figure 4. The evidence of this fact is clearly observed. Obviously the only compression forces in the gap element may influence the response. Thus, the gap force should be defined as a function of three parameters, $f_p = f_p(v, \xi, T)$, where ξ is the damping ratio as a fraction of the critical one, T is the undamped period. Numerical results, given below, cover only one particular case, when $v = +1$ (Vrancea, 4 of March, 1977).

The influence of the pounding effect is illustrated in Figure 5. The most considerable increase is found in acceleration response spectra. It is seen that the values of the response spectrum with pounding included (solid line) totally exceed the values of the spectrum with pounding excluded (dotted line). This tendency is very clearly expressed in high period range (damped case). In this region the amplification ratio is very high and reaches 7. As a rule, damping reduces the values of both 'pounded' and 'non-pounded' spectra. Finally, the response spectra are essentially dominated by the 'pounding' spectra.

Different tendency is observed in velocity spectra. The 'pounded' spectra' (damped and undamped cases) are peaked at $T=2.0$ s, whereas 'non-pounded cases' are peaked at $T=3.0$ s and more. It means that velocities are much influenced in high period range. Similar tendency is typical for the displacements spectra. The displacements before $T=2.5$ s are dominated by 'non-pounded' case, whereas greater displacements after $T=2.5-3.0$ s are provided by the 'pounded case'. Again, damping reduces the results in both 'pounded' and 'non-pounded' cases. In general, the response spectra for velocities and displacements are dominated by the 'pounded' case after $T=2.5-3.0$ s. For smaller periods pounding effect is not so unfavorable.

It can be concluded, that even in a very simple cases pounding effect may lead to considerable increase in the total acceleration values and inertial forces. It means that the pounding may offer unfavorable loading conditions for a given structures. In order to complete the search of the peak values, as a further step, the case of $v=-1$ should be added and considered.

CONCLUSIONS

The following conclusions can be derived:

- 1) Response spectra accounting for the pounding effects, can be calculated using computer software for linear response spectra. It is necessary that the gap force f_p should previously be computed or predicted. The random vibration analysis can successively be applied.
- 2) The 'pounded' response spectra are strongly dependent on seismic input orientation. This fact implies, that calculation of the response spectra require more computational efforts.
- 3) The total acceleration response spectra is considerably influenced by the effect of pounding. The 'pounded' spectra essentially dominates the 'non-pounded' ones. The differences may reach 7 times as a ratio between both spectra. In this sense pounding offers unfavorable loading conditions.
- 4) The response spectra for the velocities and displacements are dominated by the 'pounded' spectra only in high period range (T greater than 2.5 s). For smaller periods 'pounded' spectra provides smaller values.

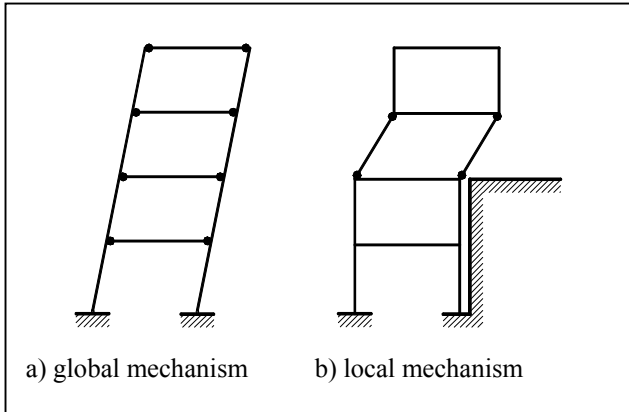


Figure 1: Two feasible mechanisms considering one bay four storey frame

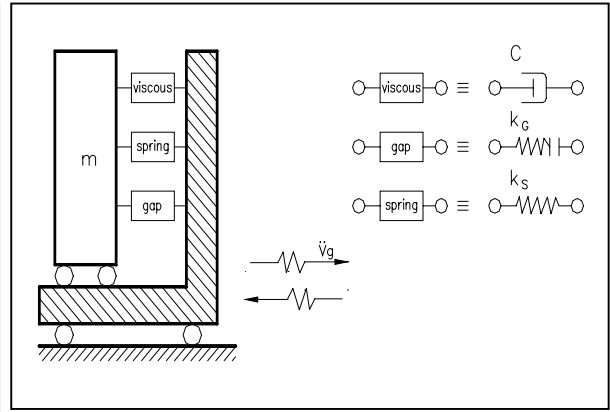


Figure 2: SDOF model, containing tension tension opening gap element to simulate the pounding

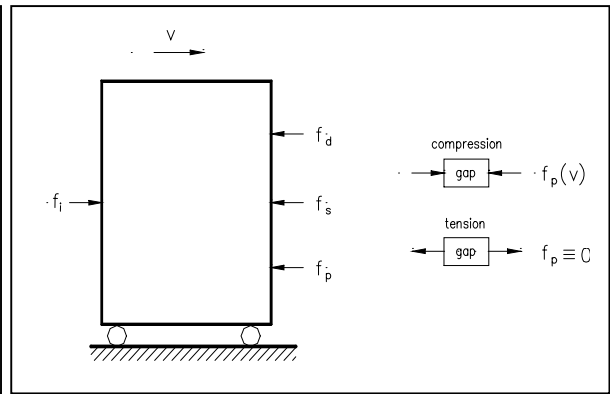
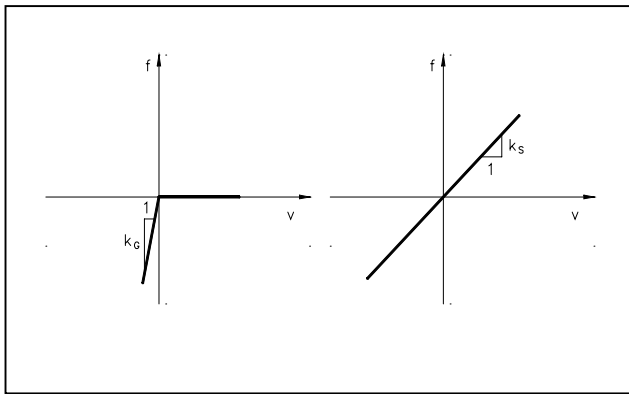


Figure 3: Element characteristics and forces, acting on the moving mass

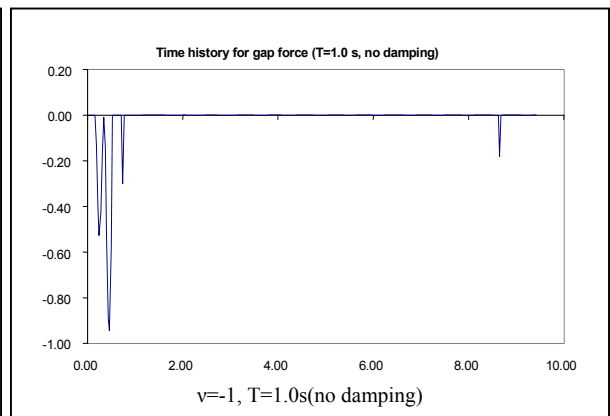
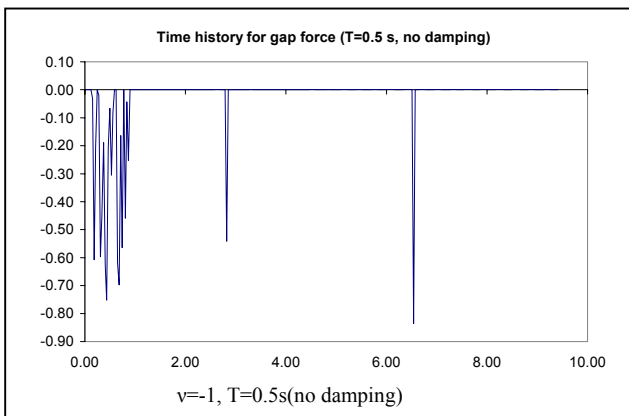
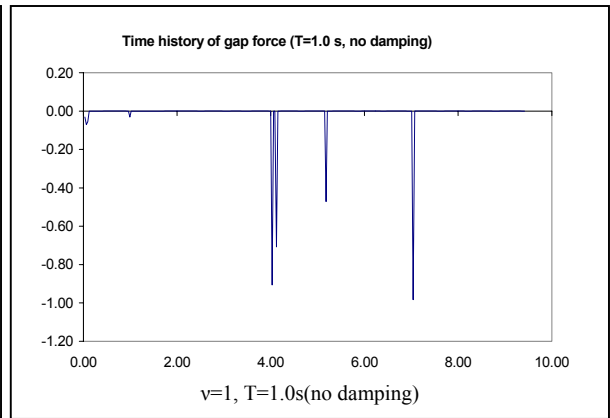
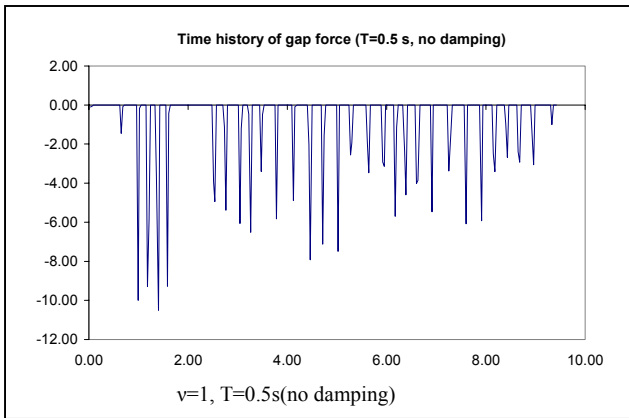


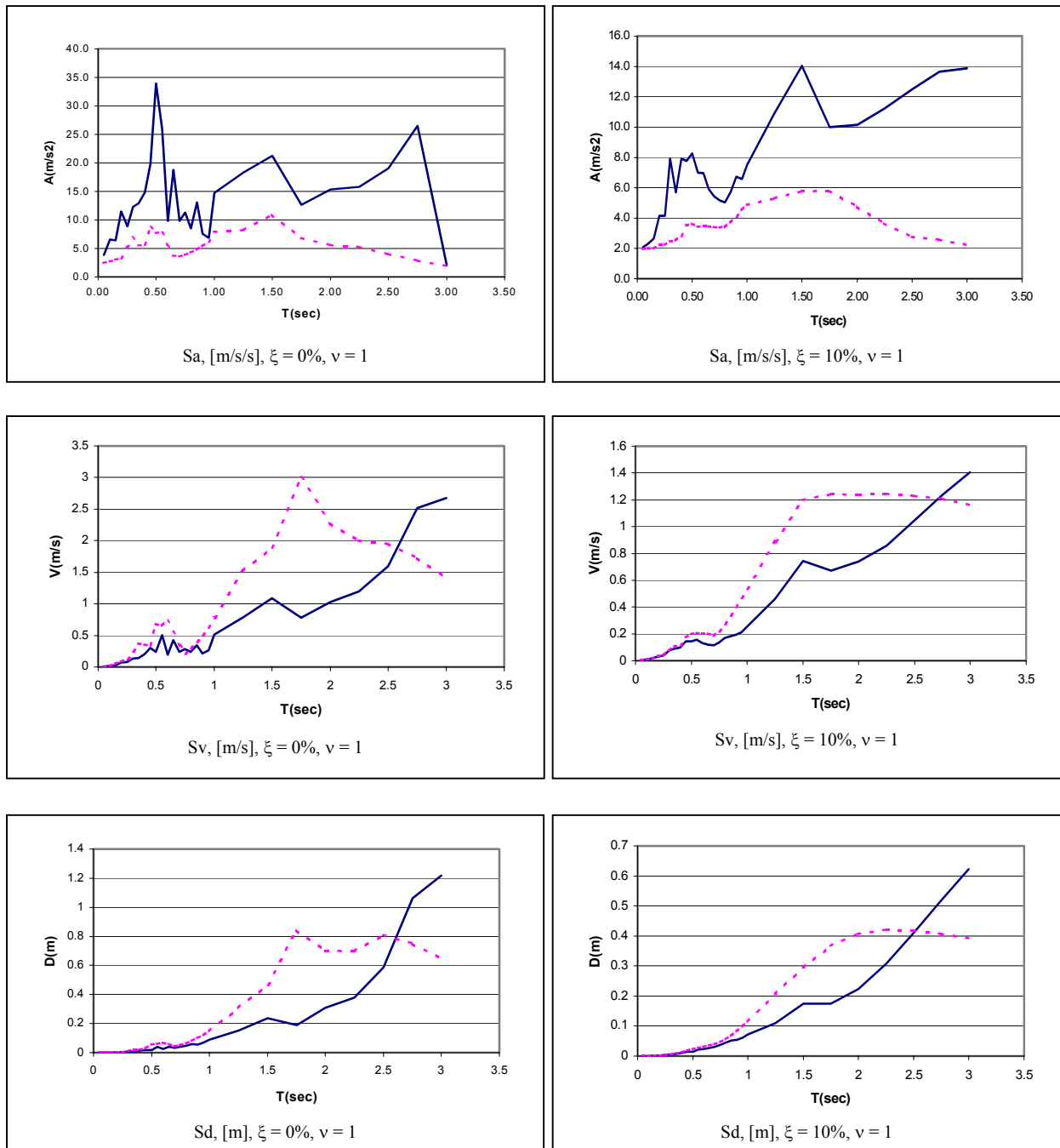
Figure 4: Gap force, considering two oscillators ($T = 0.5$ s and $T = 1.0$ s), using different orientation of the input

Figure 5: The effect of pounding on the response spectra

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