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Probabilistic Evaluation of the Separation Distance Between Adjacent Systems

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Summary

The ABS(ABSolute sum), SRSS(Square Root of Sum of Squares) and DDC (Double Difference Combination) rules for the assessment of the separation distance between adjacent structures are probabilistically evaluated through numerical simulations. Structures are modeled as SDOF systems, both linear and nonlinear. Ground acceleration histories are synthetically generated from modified Kanai-Tajimi power spectral density functions. Both wide-band and narrow-band excitations are considered. Results show that none of the rules considered in this study are satisfactory in the sense that they indicate separation distances whose probability of exceedance (i.e., the probability of pounding or collision) is not equal to the probability of exceedance of the displacement response of the individual systems. The ABS rule is consistently conservative, but its degree of conservatism is generally excessive. The SRSS and DDC rules provide conservative or unconservative results depending on the characteristics of the excitation and the relationship between the fundamental periods of the systems.

Introduction

Observations of the effects of past earthquakes indicate that pounding between adjacent structures is generally negative in the sense it leads to higher levels of damage. In some cases, pounding has been identified as the primary cause of collapse. Consequently, it has been widely recognized that pounding during earthquakes is always undesirable.

Pounding may be prevented by providing adequate separation distances between the potentially colliding structures. However, maximization of land use in metropolitan areas creates strong opposition to generous separation distances, which are then very difficult to effectively implement. The problem to be solved is then the estimation of the *minimum* separation distance necessary to preclude pounding, which is obviously equal to the relative displacement demand of the two potentially colliding structural systems.

Existing Rules for the Assessment of the Separation Distance

The International Building Code (ICB) 2000 specifies that the separation distance between adjacent buildings located on different properties (i.e., buildings separated by a property line) shall be given by:

$$S = \Delta_1 + \Delta_2 \tag{1}$$

where S is the separation distance and Δ_1, Δ_2 are the displacement responses of the buildings at the potential pounding location (i.e., at the top of the shorter building). Eq. 1 will subsequently be referred to as the ABS rule. In the case of buildings located on the same property, IBC 2000 specifies that the separation distance between adjacent buildings shall be given by:

$$S = \sqrt{\Delta_1^2 + \Delta_2^2} \tag{2}$$

Eq. 2 will subsequently be referred to as the SRSS rule.

A more rational approach is the Spectral Difference Method presented by Jeng et al., (1992), according to which the separation distance is given by:

$$S = \sqrt{\Delta_1^2 + \Delta_2^2 - 2\,\rho\,\Delta_1\,\Delta_2} \tag{3}$$

where ρ is the same correlation coefficient used by the well-known CQC modal combination rule. In a probabilistic sense, Eq. 3, which will subsequently be referred to as the Double Difference Combination (DDC) rule, is the exact solution for linear systems subjected to stationary white-noise excitations. The expression "in a probabilistic sense" means that the probability that the relative displacement response exceeds the separation distance S is the same probability of exceedance of the displacement responses Δ_1 and Δ_2. It must be noted that the DDC rule and the SRSS rule coincide when $\rho = 0$ (i.e., when the displacement responses are uncorrelated). Kasai et al., (1996) suggested that the DDC rule can still be used for nonlinear systems as long as modified natural periods T_1*, T_2* and modified damping ratios ξ_1*, ξ_2* are used when calculating the correlation coefficient ρ. In their proposed equations, T_i^* and ξ_i* (i = 1, 2) are functions of the displacement ductility μ.

Probabilistic Evaluation of Assessment Rules for the Separation Distance

Due to the intrinsic random nature of earthquakes, none of the abovementioned rules gives the separation distance needed to "avoid" pounding. Rather, there is always a finite probability that, during a given period, the relative displacement response exceeds the separation distance indicated by any of the rules mentioned above. Therefore, it is more appropriate to consider that an assessment rule is accurate when it gives a separation distance S that has the same probability of exceedance as the displacement responses of the individual systems, Δ_1 and Δ_2.

A probabilistic evaluation of the aforementioned rules for the assessment of the separation distance is then numerically performed as follows. Earthquake excitation is characterized as a random process in terms of modified Kanai-Tajimi power spectral density (PSD) functions, from which ground acceleration histories are generated using an appropriate envelope function (Figure 1). The displacement response of SDOF systems is then obtained by performing time history analysis and the relative displacement response is then given by:

$$\Delta_{rel} = \max_t \left| x_1(t) - x_2(t) \right| \tag{4}$$

where x_1(t), x_2(t) are the displacement response histories of systems 1 and 2. The relative displacement response is calculated for each of the sample acceleration histories and the

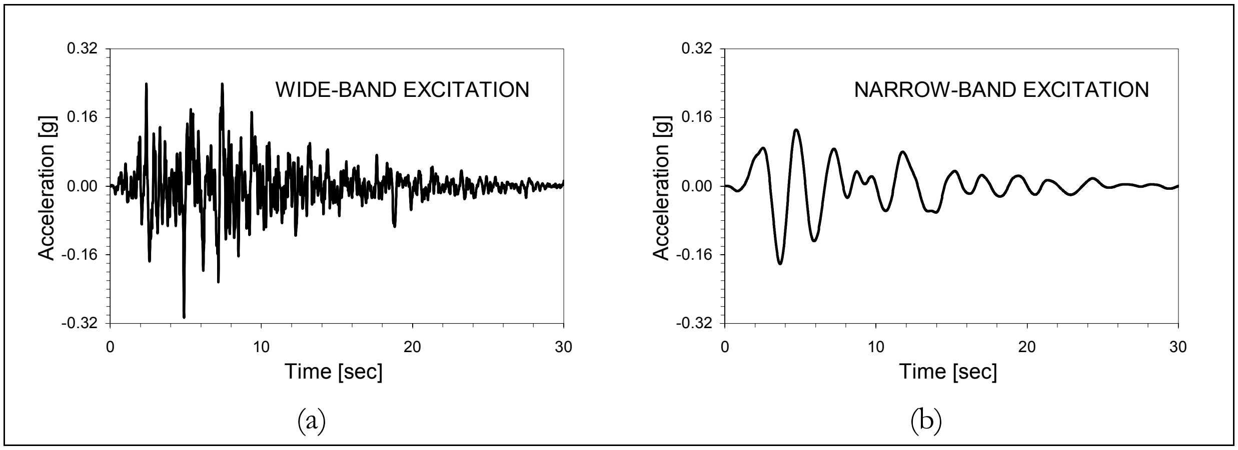

Figure 1. Sample ground acceleration histories

corresponding statistics are computed, from which the relative displacement demand for a 10% probability of exceedance is obtained. Finally, separation distances given by the assessment rules mentioned before are calculated using values of Δ_1 and Δ_2 for which the probability of exceedance is also equal to 10%.

Linear Systems

Examples of results for linear systems are shown in Figure 2. On the one hand, the analysis confirms some results already noticed by other researchers, i.e.: (1) the ABS rule always gives conservative results and its degree of conservatism is generally excessive, particularly when T_1 and T_2 are close to each other; (2) the SRSS rule gives conservative results when T_1 and T_2 are close to each other; (3) the DDC rule gives the most accurate results, particularly when T_1 and T_2 are close to each other. On the other hand, the analysis provides some new information, i.e.: (1) for wide-band excitations, the SRSS and DDC rules give unconservative results when T_1 and T_2 are not close to each other; (2) for narrow-band excitations, results given by the SRSS and DDC rules may be conservative or unconservative when T_1 and T_2 are not close to each other. Results for damping ratios greater than 5% show the same tendencies mentioned above.

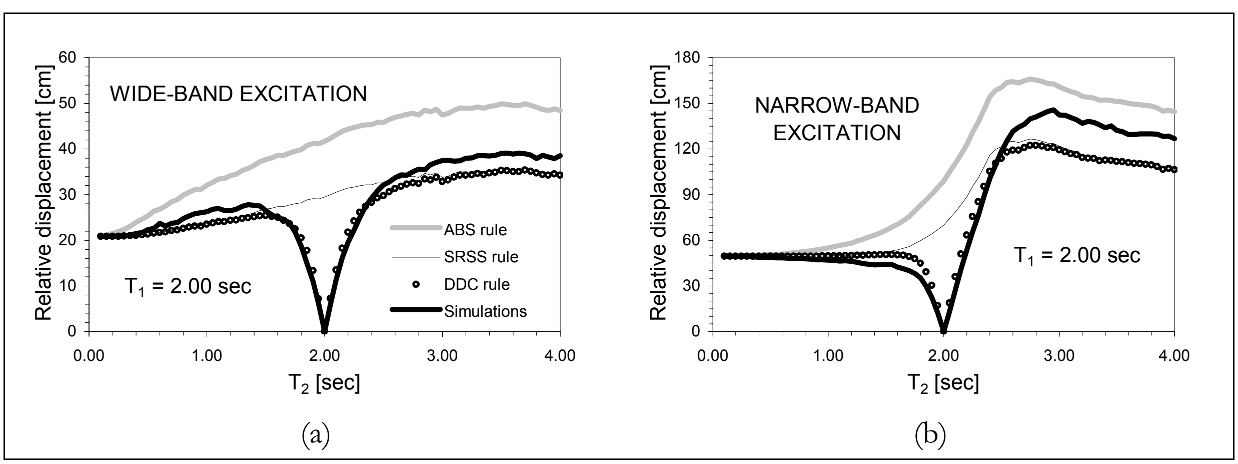

Figure 2. Relative displacement response of linear systems ($\xi_1 = \xi_2 = 0.05$)

Nonlinear Systems

The relative displacement response for nonlinear systems is evaluated assuming that the SDOF systems considered in this study have a bilinear force-displacement relationship, where the post-yielding stiffness is equal to 0.05 times the initial (elastic) stiffness. The systems yield at a force level equal to the elastic force demand divided by a given value of *R*, the force reduction factor. In doing so, the displacement ductility demand μ is different for each of the sample acceleration histories. In accordance with the probabilistic approach explained before, the statistics of μ are calculated and then modified natural periods T_1*, T_2* and modified damping ratios ξ_1*, ξ_2* for the application of the DDC rule are obtained using values of μ_1, μ_2 that have a 10% probability of exceedance. This is a significant departure from the approach followed by Kasai et al., (1996), who derived the equations to calculate T_i* and ξ_i* (i = 1, 2) from results obtained through time-history analysis where the yielding force of the SDOF systems was adjusted for each ground motion in order to obtain predefined values of μ. The approach followed in this study, however, is more representative of an actual case scenario.

Examples of results for nonlinear systems and for the same value of *R* are shown in Figure 3, where it can be seen that: (1) the ABS rule always gives results that are even more conservative than those for the linear case; (2) for wide-band excitations, the SRSS rule gives results exhibiting the same tendencies as those for linear systems, i.e., they are conservative when T_1 and T_2 are close to each other and unconservative otherwise; (3) for narrow-band excitations, the SRSS rule always gives conservative results; (4) while results given by the DDC rule are again the most accurate, they are always unconservative for wide-band excitations and may be either conservative or unconservative for narrow-band excitations regardless of whether T_1 and T_2 are close to each other or not.

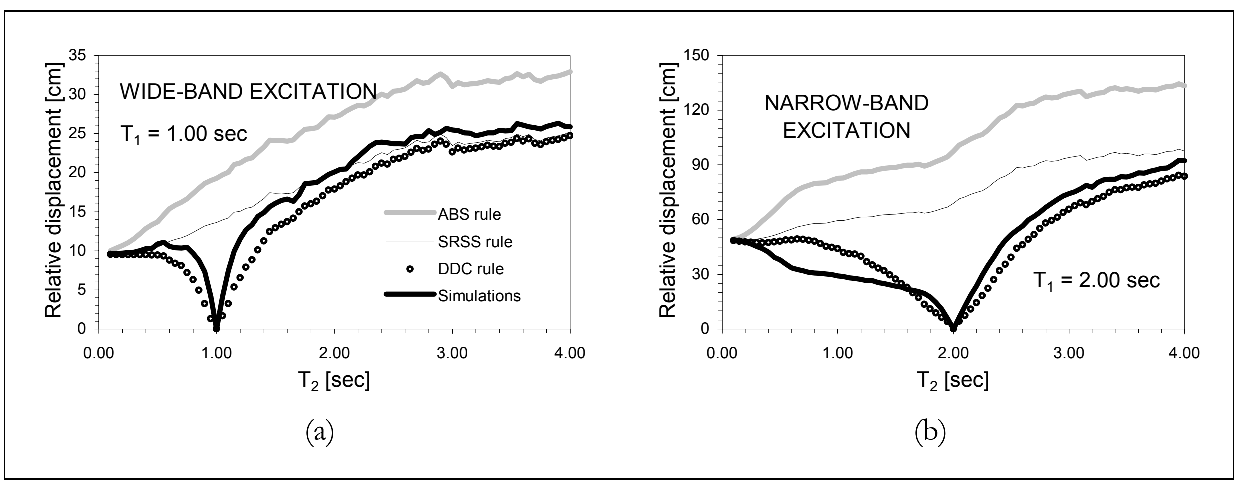

Figure 3. Relative displacement response of nonlinear systems ($R_1 = R_2 = 3$)

Results for damping ratios greater than 5% show the same tendencies mentioned above. However, in the case of narrow-band excitations, the accuracy of the DDC rules improves significantly as the damping ratio increases.

Examples of results for nonlinear systems and for different values of *R* are shown in Figure 4. This is the most general case studied and the most representative of an actual case scenario. It can be seen that results show the same tendencies as for the case where *R* is the same for both systems.

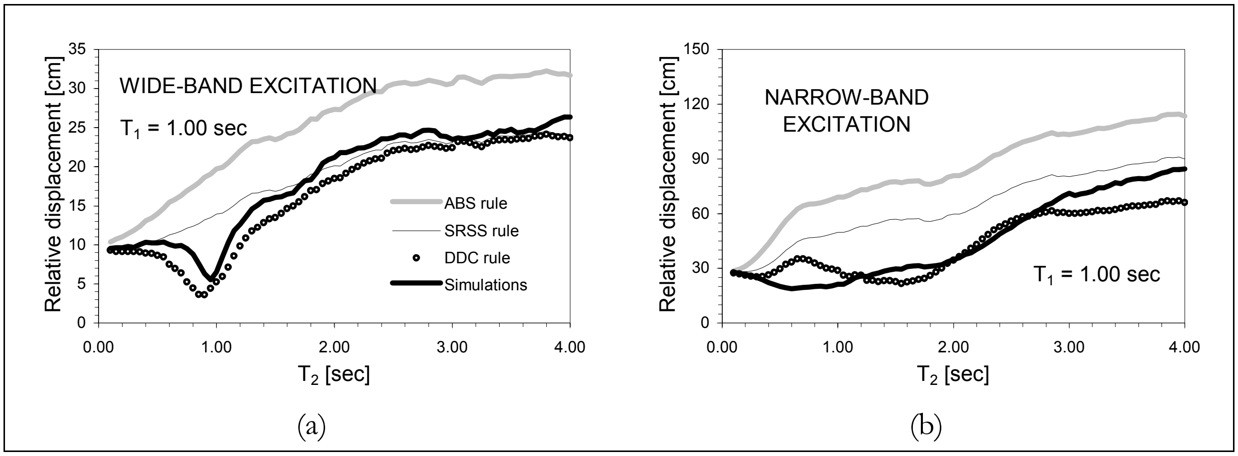

Figure 4. Relative displacement response of nonlinear systems (R_1 = 2.5, R_2 = 4.0)

Concluding Discussion

The analytical study described in this paper clearly shows that none of the existing rules is completely satisfactory in the sense that they cannot accurately predict the relative displacement demand between two adjacent systems. The SRSS and DDC rules give results that are conservative or unconservative depending on the characteristics of the excitation and the relationship between the natural periods of the systems. In other words, the actual risk of pounding or collision is unknown. On the other hand, the ABS rule gives consistently conservative results, but its implementation is difficult because of its generally excessive degree of conservatism.

It must be noted that, from a performance-based design point of view, the appropriate separation distance may or may not have the same probability of exceedance as the displacement response of the individual systems depending on the performance level (i.e., life safety, collapse prevention, etc.). Consequently, the most useful design tool is the complete relationship between the separation distance and the probability of exceedance (for a given period), so that *S* can be chosen for any desired probability of exceedance. An example can be seen in Figure 5, where *S* for a 10% probability of exceedance is also indicated. For comparison purposes, values of *S* given by the SRSS and DDC rules (using Δ_1, Δ_2 having 10% probability of exceedance) are shown as well. It can be seen that the corresponding probabilities of pounding are very different from the target 10% probability.

The probability-of-pounding vs. separation-distance relationship shown in Figure 5 was obtained through numerical simulations, which is a useful approach for research purposes but clearly not practical for real case applications. Further research is currently being carried out to find a theoretical expression for the probability-of-exceedance vs. separation-distance relationship so that the separation distance can be assessed directly based solely on the displacement response of the individual systems.

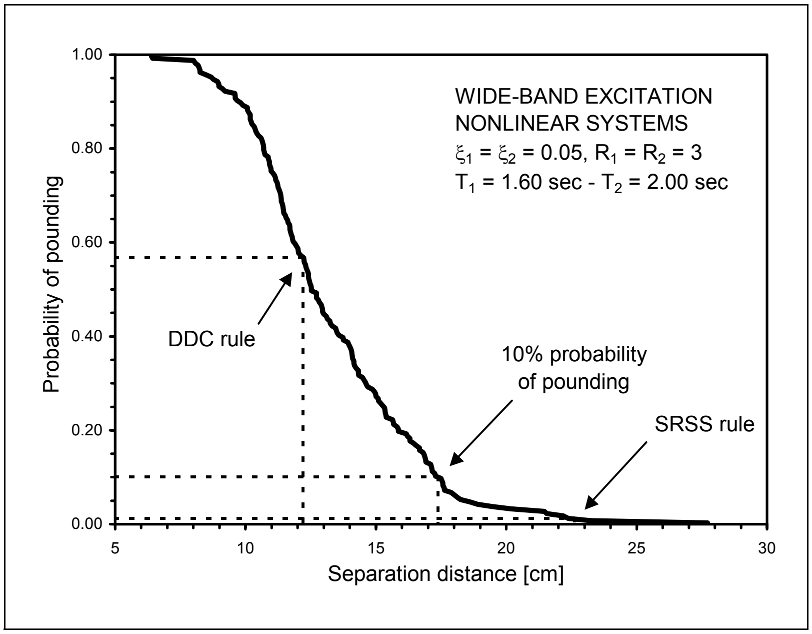

Figure 5. Probability of pounding vs. separation distance

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