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A Literature Review on Modeling and Mitigating the Pounding Effects in Buildings

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ABSTRACT: During an earthquake event, the adjacent buildings that lack a sufficient gap from one another may experience a severe structural damage as a result of structural pounding. The effects of structural pounding specially gained more attention after the historic earthquakes of Mexico City (1985) and Loma Prieta (1989) where, a significant number of buildings were damaged due to pounding. In this paper, the analytical models that are reported in the literature to simulate the pounding forces were reviewed. These include linear elastic, linear viscoelastic, modified linear viscoelastic, Hertz non-linear elastic, Hertz-damp non-linear viscoelastic, and non-linear viscoelastic models. The accuracy of these methods has been examined and compared in this paper. Additionally, current strategies for mitigating the pounding effects in adjacent building structures are reviewed. The last component of this paper includes a case study wherein the pounding effects are mitigated via improving the effective lateral stiffness and/or effective damping ratio in the building structure of interest. Results of the case study indicate that the application of supplemental energy dissipation devices is effective in the mitigation of pounding effects in those buildings that lack any seismic gap with their neighboring structures.

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1- Introduction

The pounding of adjacent structures is deemed as one of the main reasons for structural damages observed in the past earthquakes. For instance, after the Mexico City (1985) earthquake, the 40% of damaged buildings had experienced different levels of structural pounding. In 15% of the said buildings, the pounding was found as the main reason for structural collapse [1]. In the Loma Prieta (1989) earthquake, pounding was reported as the main cause of structural damages in the 200 buildings out of more than 500 buildings that were located at a distance of nearly 90 km from the epicenter of earthquake [2].

The destructive effects of pounding are more pronounced when the vibrations of fundamental modes of the two adjacent structures are significantly out of phase [3]. Pounding of structures during an earthquake event is a complicated phenomenon which often involves plastic deformations, the formation of localized cracking and crushing at the contact surfaces, etc. The complicacy of the nature of energy transformation between the two pounding structures causes the analysis of pounding response to be quite challenging. Despite this complexity, a significant number of simplified analytical models have been developed in the literature to simulate the pounding effects of structures. This paper includes a brief review of different models that are developed to simulate the pounding effects. Additionally, a comparative study has been conducted by examining the different models. The next component of this paper includes a review on the different techniques that are available in the response mitigation of pounding structures. Among the various techniques, strengthening of structures as a feasible method of mitigating the pounding response, when no seismic gap is left between the adjacent buildings, has been numerically studied.

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2- Modeling Techniques

Two general procedures can be found in the literature to model the pounding effects in structures. These are “the classical impact theory”, and “the direct evaluation of pounding force”. Further description of these methods is provided in the following paragraphs.

The classical impact theory relies on the energy (and momentum) conservation principle. The stress/strain that is developed in the pounding structures is not determined in this method [4]. The main objective is to evaluate the effective velocity of the contact bodies after the impact is made between the two. As such, the response of structures during the impact is not addressed in this method. The classical impact theory is beneficial to study the general effects of pounding. The method is applicable for single degree of freedom (SDOF) systems of lumped mass.

In the 2nd method that is a force-based approach, the pounding force is directly calculated and then applied on the structure [4]. There are several analytical models that are constructed on the basis of the 2nd method. The principles employed in these models are typically stemmed from experimental observations. Based on these observations, the time history of pounding force is found to be affected by several factors including the mass of structures, the material and geometry of contact surfaces, and the relative velocity of structures prior to impact [4]. The pounding force is modeled using an elastic contact element (i.e., a spring) or a viscoelastic contact element (i.e., a spring and a dashpot in parallel) [5]. The elastic contact element and the viscoelastic contact element may be applied in linear models [6, 7]. The elastic contact model may also be assumed to be non-linear [8]. Likewise, the viscoelastic contact element may be employed in a non-linear fashion [9]. A comparative study conducted by Ref. [5] indicates that the non-linear viscoelastic model is superior to the other models in simulating the pounding effects. This result has been verified by the analysis runs conducted in this paper.

3- Strategies for Mitigation of Pounding Response

Current strategies for the mitigation of pounding effects between adjacent structures include: i. leaving an adequate seismic gap between the two structures [5]; ii. Connecting the two structures with structural elements [10]; iii. Using structural shields [11] or bumpers [12] to dissipate the impact at contact surfaces; iv. Strengthening the structures by improving their horizontal stiffness and/or effective damping. The pros and cons of these strategies are briefly described in the following paragraphs.

Introducing a seismic gap between adjacent structures is a mandate that is prescribed by many current seismic codes. This is an easy and very practical solution that eliminates the pounding of building structures. Although leaving a seismic gap is an effective strategy, a significant number of old buildings, constructed before the existence of this mandate, can be found that lack a suitable (if any) gap with their neighboring buildings. Furthermore, in many urban areas the shortage of lands and/or its expensive price leaves little intention for some building owners to comply with this code requirement. Therefore, in such cases structural pounding will remain as a potential threat to the constructed structures. One strategy to eliminate the pounding effects is to connect the adjacent buildings together to provide a unit structure. The connection may be provided with structural elements such as connecting beams. Additionally, a supplemental damping device such as viscous or viscoelastic devices may be employed to connect the neighboring structures. The limited gap between the adjacent structures may provide a significant practical limitation for the application of this strategy. Additionally, interaction of the connected structures may introduce higher stress demands on some of the structural elements of the buildings that must be retrofitted accordingly. Introducing structural shields or bumpers at the contact surfaces of structures are other strategies to mitigate the pounding effects. However, the applicability of these strategies may be diminished when there is no gap left between the two structures.

One of the most practical methods to mitigate the pounding effects in an existing or in a new building is to strengthen the building structure via improving its horizontal stiffness and/or effective damping. This is especially applicable when no seismic gap is provided between the building of consideration and its adjacent ones. To verify the effectiveness of this strategy, an extensive time history analysis runs have been conducted in this paper on a case structure which lacks any seismic gap with its adjacent structure. The analysis results indicate that the pounding force is decreased significantly with increasing horizontal stiffness. For instance, when the horizontal stiffness is increased by 50%, the pounding forced is decreased by 73%. An increase in the effective viscous damping will also significantly mitigate the pounding force. For example, when the effective damping ratio is increased from 5% to 25%, the pounding force is decreased by 55%. Application of supplemental dampers that add both the stiffness and damping of structure will result in significant mitigation of pounding force. By increasing the horizontal stiffness by 50%, with an effective damping ratio of 15%, the pounding force is decreased by 77%.

4- Conclusions

A review and examination of different models to simulate pounding effects in structures indicates that the non-linear viscoelastic model provides a more accurate estimation of the pounding forces. An effective strategy to mitigate the pounding effects in a structure that lacks any seismic gap with its neighboring buildings include strengthening the structure by improving its horizontal stiffness and/or effective damping ratio. Analysis runs of this paper indicate that the application of supplemental damping devices provides a practical solution for pounding response mitigation of structures during an earthquake.

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