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Seismic pounding behavior of multi-story buildings in series considering the effect of infill panels

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ABSTRACT

The aim of the present paper is to study the influence of the infill panels on the seismic pounding response of adjacent structures in series. The contribution of the masonry infill has been simulated using equivalent diagonal compression struts. Steel frames have been assumed to have elastic-plastic behavior with 1% linear strain hardening. The dynamic contact analysis has been utilized where contact surface model (target and contactor) has been applied without any connectors between the adjacent buildings. Nonlinear finite element analyses have been conducted on different configurations of infill distribution throughout the structures. The results of the analysis reveal that the existence of infill panels can substantially change the seismic behavior of the structures and may have a serious influence on their behavior during exposure to mutual pounding under seismic excitation. Moreover, the distribution of infill throughout the structure can significantly affect its behavior during earthquakes.

1. Introduction

The studies on destruction during past earthquakes show that adjacent buildings with minor seismic gaps may interact resulting in enormous damage up to completely structural collapse [1]. However, collisions between adjacent structures in series have received limited attention from researchers (see, for example, [2–5]). Moreover, it is usual during the design of different concrete or steel structures to consider the masonry infill panels as architectural partitions only. Meanwhile, ignoring the interaction between the infill panels and the surrounding frame during earthquakes may affect the behavior of colliding structures. Consequently, some specifications and codes highlight the importance of considering the effect of infill panels. For example, FEMA 356 [6] states that masonry infill panels shall be considered as primary elements of a lateral force-resisting system.

Different researches to study the effect of infill panels on the behavior of structures during earthquakes were carried out using macro models to represent the infill panels [7,8]. Sanij and Alaghebandian [9] discussed the seismic response of masonry infilled frame using three macro models to simulate the nonlinear behavior of the masonry infill walls. Nonlinear pushover analysis was performed on 2D reinforced concrete plane frames. The results indicate that masonry infill may change the distribution of plastic hinges and, in some cases, may change the seismic performance levels. Moreover, existence of masonry infill decreases the structural drifts and soft story can be developed as a result of masonry collapsing (especially at lower stories). Numerical analysis considering the structural pounding between two adjacent multi story RC structures with unequal total heights considering the influence of the infills was conducted by Favvata et al. [10]. The masonry infill panel was simulated using the equivalent diagonal strut model where the effective width of the strut was determined according to FEMA 273 (1997) and FEMA 306 (1999). The study concluded that infill panels influence the seismic response of the colliding column by increasing the demands for shear and ductility, as compared to the bare frames. Favvata et al. [11] studied the influence of the inelastic behavior of the external beam-column joint as well as the effect of the infill panel on pounding between unequal height structures. They concluded that the existence of the masonry was not sufficient to enhance the shear and ductility excessive demand of the impacted column. Karayannis et al. [12] investigated the effect of the behavior of the external beam-column joints on the collapse mechanism of multi-story structure with different cases (bare, infilled and pilotis) using both nonlinear static and dynamic seismic analysis. They concluded that the degradation of the external joints may highly influence the total response of pilotis frames. Favvata and Karayannis [13] examined

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the influence of the inter-story pounding during earthquakes on RC multistory structures considering different cases of infill panels. The results revealed substantial changes in the local response of masonry due to pounding. Karayannis and Favvata [14] carried out an investigation on fifty two pounding cases between multistory structures and a rigid barrier to study the influence of inter-story pounding. The effect of the seismic gap on pounding-involved response was also investigated. The results showed that for the zero gap distance the ductility demands of the impacted column is critical and higher than the available ductility values. Demir and Sivri [15] conducted a numerical analysis to study the effect of masonry infills on the earthquake response of RC structures with different configurations. The results showed that the existence of masonry infill modifies the general seismic performance of framed building significantly. Moreover, it enhances the stability and integrity of the frames. Dorji and Thambiratnam [16] proposed a technique for modeling the interface between infill and frame and studied the seismic response of infilled frames. The study indicated that the influence of infill thickness on the global responses (natural periods, roof displacement and inter-story drift ratios) can be insignificant.

The effect of infill panels on the seismic response of RC frames was analytically investigated and experimentally verified by Karayannis et al. [17]. A single-bay, single-story RC frame with and without infills exposed laterally to a cyclic loading was tested. In the analytical analysis, the behavior of the infill panels was simulated using the equivalent diagonal strut model. The results emphasized the significance of the effect of infill panels on the seismic behavior of the RC frames. Moreover, it was observed that the failure mechanism of the masonry is a diagonal crack. The authors concluded that, for such failure mode, the simulation of the masonry by equivalent strut is accepted.

Different approaches were also used in the numerical simulations concerning structural pounding during earthquakes. An interesting study on collisions between buildings in series, modeled as single-degree-of-freedom systems, was conducted by Anagnostopoulos [2]. Such simplified numerical structural models were also used in other investigations focused on earthquake-induced interactions (see, for example, [18,19]). More detailed studies were conducted on discrete multi-degree-of-freedom structural lumped mass models. For example, a study considering the effect of reciprocal collisions between different buildings of different height (5 and 10 stories) during earthquakes was conducted by Anagnostopoulos and Spiliopoulos [20]. Buildings were modeled as shear beam lumped mass, multi-degree-of-freedom systems. The research concluded that collisions may both increase or decrease the response of the structure, relying on its mass and period comparing to the mass and period of the surrounding buildings, and on whether pounding occurs at single or double sides. Moreover, when the two interacting buildings have similar masses, pounding can amplify the response of the stiffer structure. Other researchers also utilized discrete multi-degree-of-freedom structural models, with the mass of each story lumped at the floor level (see, for example, [21–23]). More researches were conducted utilizing more precise structural models. The influence of impact between two adjacent 8- and 13-story steel moment resisting frames was studied by Abdel Raheem [24]. Collisions were modeled with a contact force based approach using linear and nonlinear springs. Papadrakakis et al. [25] employed finite element models of colliding structures, where the floors were modeled using single four-node plane stress elements while the walls were modeled by four linear beam-column elements. The detailed nonlinear finite element analysis of pounding between two adjacent structures was also conducted (see, for example, [26]).

On the contrary to numerical analyses, experimental studies on seismic pounding between structures are very limited. Some of the studies were focused only on verification of the parameters for impact force models (see, for example, [27]). On the other hand, most of the experimental studies concerning structural collisions were carried out on two adjacent structures only. For example, Chau et al. [28] conducted an experimental investigation using a shaking table to study the influence of pounding between two equal-height steel structures with different damping ratios and natural periods. The structures were exposed to the 1940 El Centro earthquake as well as some sinusoidal motions with various magnitudes and frequencies. The results indicated that, pounding occur in periodic or chaotic way, depending nonlinearly on the changes in parameters of the two adjacent structures and on the ground motion characteristics. The study also stated that collisions may increase the stiffer structure response and decrease the response of a more flexible structure. An experimental study was also conducted on pounding between two small structures with different masses, natural properties, and gap sizes [29]. The study concluded that collisions may considerably increase the response in some cases but may also decrease vibrations in other ones. More recently, an experimental study on pounding between three structures was carried out by the authors and the results are described in [3–5]. Three structures in one row with two configurations were experimentally tested using a shaking table to study the behavior of structures in series when subjected to different ground motions. The research results indicated that collisions may significantly affect the structural behavior. The rigid towers were observed to act as stoppers for the flexible ones and hence they were more influenced by pounding. Moreover, increasing or decreasing the in-between gap resulted in the increase or decrease in the response under different ground motions without specific trend. Furthermore, the optimal gap size was found to be either the distance large enough to prevent pounding or the zero gap distance.

The aim of the present paper is to study the influence of masonry infill panels on the earthquake-induced pounding-involved response of adjacent buildings in series. Three different structural models were utilized in the investigation (see Fig. 1). The examined towers were selected to simulate actual existing adjacent buildings. However, the examined towers were simplified to a single-bay multi-degree-of-freedom system with adjusted masses and stiffness, so as to simulate the natural frequencies of the existing buildings. Moreover, the modified (examined) buildings were designed according to AISC [30].

2. Finite element analysis

Each simplified building consists of four steel beams and four steel columns with moment of inertia equal to 392.9 cm^4 for each member supporting a concrete slab of 15 cm thickness with weight of 0.35 t/m^2 in each story. The concrete slabs extend outside the steel frames by 1.0 cm to ensure that collisions occur between them. The external buildings have three stories with a total height of 9.0 m, while the middle building has two stories with a total height of 6.0 m. The left and middle building have 3.0 × 3.0 m span, while the right one is 4.0 × 3.0 m. The gap between the three structures is 30 mm and the damping ratio is assumed to be 5% for all cases. Two arrangements of infill panels have been investigated. The first one (case 1) is the case of completely infilled frames, whereas the second one (case 2) represents the case of open first story frames (see Fig. 1).

The natural frequencies and mode shapes of vibration were obtained using the eigenvalue solution utilizing ADINA software [31]. The consistent mass matrix was used in the formulation. The natural frequencies of the buildings are presented in Table 1 and the first mode shapes are shown in Fig. 2.