NON-LINEAR MODELLING OF EARTHQUAKE INDUCED POUNDING OF BUILDINGS

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Summary The aim of the present paper is to analyse earthquake induced pounding between two insufficiently separated buildings with different dynamic characteristics. In the analysis, elastoplastic multi-degree-of-freedom lumped mass models are used to simulate the structural behaviour and non-linear viscoelastic impact elements are applied to model collisions. The results of the study prove that pounding may have considerable influence on behaviour of the structures.

INTRODUCTION

During severe earthquakes, pounding between neighbouring, inadequately separated structures with different dynamic characteristics has been observed repeatedly [1]. It can lead to considerable damage or can be even the reason of structure's total collapse. The phenomenon of structural pounding has been intensively studied recently by applying various structural models and using different models of collisions. The fundamental study on pounding between buildings in series using a linear viscoelastic model of collisions has been conducted by Anagnostopoulos [2]. Jankowski et al. used the same model to study pounding of superstructure segments in bridges [3]. Further analyses were carried out basing on more accurate structural models (discrete multi-degree-of-freedom models [4] and using Finite Elements Method [5]), though, using linear models of collisions. On the other hand, Chau and Wei used a non-linear elastic model of collisions based on Hertz contact law to simulate pounding of structures modelled as single-degree-of-freedom oscillators [6]. In order to simulate collisions more precisely, a non-linear viscoelastic model was introduced by Jankowski [7]. The aim of the present paper is to study pounding of buildings modelled by elastoplastic multi-degree-of-freedom lumped mass systems and using a non-linear viscoelastic model of collisions.

NUMERICAL MODEL

The present paper is focused on the analysis of pounding of two adjacent, three-storey-high buildings with different dynamic characteristics. In order to simulate the response of each structure, a discrete three-degree-of-freedom model, with lumped each storey's mass on the floor level, is applied (Fig.1). The elastic-perfectly plastic approximation of storey shear force-drift relation is ensured. The dynamic equation of motion for a structural model presented in Fig.1, including pounding at each floor level, is formulated as follows:

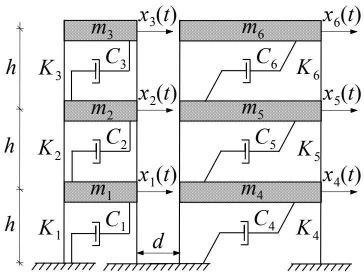

Fig.1. Model of adjacent buildings

$$\mathbf{M}\ddot{\mathbf{x}}(t)+\mathbf{C}\dot{\mathbf{x}}(t)+\mathbf{F}_S(t)+\mathbf{F}(t)=-\mathbf{M}\mathbf{1}\ddot{x}_g(t)\,; \tag{1a}$$

$$\mathbf{M}=\mathrm{diag}\left[m_1,...,m_6\right];\quad \ddot{\mathbf{x}}(t)=\left[\ddot{x}_1(t),...,\ddot{x}_6(t)\right]^{\mathrm{T}};\quad \dot{\mathbf{x}}(t)=\left[\dot{x}_1(t),...,\dot{x}_6(t)\right]^{\mathrm{T}}; \tag{1b}$$

$$\mathbf{C}=\begin{bmatrix} C_1+C_2 & -C_2 & & & & \\ -C_2 & C_2+C_3 & -C_3 & & & \\ & -C_3 & C_3 & & & \\ & & & C_4+C_5 & -C_5 & \\ & & & -C_5 & C_5+C_6 & -C_6 \\ & & & & -C_6 & C_6 \end{bmatrix};\quad \mathbf{F}_S(t)=\begin{bmatrix} F_{S1}(t)-F_{S2}(t) \\ F_{S2}(t)-F_{S3}(t) \\ F_{S3}(t) \\ F_{S4}(t)-F_{S5}(t) \\ F_{S5}(t)-F_{S6}(t) \\ F_{S6}(t) \end{bmatrix};\quad \mathbf{F}(t)=\begin{bmatrix} F_{14}(t) \\ F_{25}(t) \\ F_{36}(t) \\ -F_{14}(t) \\ -F_{25}(t) \\ -F_{36}(t) \end{bmatrix}, \tag{1c}$$

where: $\ddot{x}_i(t)$, $\dot{x}_i(t)$, $x_i(t)$ (i=1,...,6) are acceleration, velocity and displacement of a storey, respectively; $F_{Si}(t)$ is an inelastic resisting storey shear force: $F_{Si}(t)=K_i\left(x_i(t)-x_{i-1}(t)\right)$ for the elastic range till the storey yield strength F_{yi}, $F_{Si}(t)=\pm F_{yi}$ for the plastic range; K_i, C_i, are elastic stiffness and damping coefficients; $\ddot{x}_g(t)$ is an acceleration input ground motion and $F_{ij}(t)$ (i=1,2,3; j=4,5,6) stands for the pounding force between masses m_i, m_j simulated by a non-linear viscoelastic model according to the formula [7]:

$$\begin{aligned} &F_{ij}(t)=0 && \text{for } \delta_{ij}(t)\le 0 && && \text{(no contact)} \\ &F_{ij}(t)=\bar{\beta}\delta_{ij}^{\frac{3}{2}}(t)+\bar{c}(t)\dot{\delta}_{ij}(t) && \text{for } \delta_{ij}(t)>0 && \text{and } \dot{\delta}_{ij}(t)>0 && \text{(contact-approach period)}\;; \\ &F_{ij}(t)=\bar{\beta}\delta_{ij}^{\frac{3}{2}}(t) && \text{for } \delta_{ij}(t)>0 && \text{and } \dot{\delta}_{ij}(t)\le 0 && \text{(contact-restitution period)} \end{aligned} \tag{2a}$$

$$\delta_{ij}(t)=x_i(t)-x_j(t)-d;\qquad \bar{c}(t)=2\bar{\xi}\sqrt{\bar{\beta}\sqrt{\delta_{ij}(t)}\,\frac{m_i m_j}{m_i+m_j}}\,, \tag{2b}$$

where: $\bar{\beta}$ is the impact stiffness parameter depending on material properties and geometry of the colliding elements, d is the initial separation gap and $\bar{\xi}$ denotes a damping ratio which accounts for the energy dissipation during impact.

RESPONSE ANALYSIS

The numerical simulations of pounding-involved response of two adjacent structures have been conducted using the model from Fig.1. In the analysis, the following basic values describing the structural properties have been used: $m_1 = m_2 = m_3 = 25 \times 10^3$ kg, $C_1 = C_2 = C_3 = 6.609 \times 10^4$ kg/s, $K_1 = K_2 = K_3 = 3.460 \times 10^6$ N/m, $F_{y1} = F_{y2} = F_{y3} = 1.369 \times 10^5$ N, $m_4 = m_5 = m_6 = 10^6$ kg, $C_4 = C_5 = C_6 = 1.058 \times 10^7$ kg/s, $K_4 = K_5 = K_6 = 2.215 \times 10^9$ N/m, $F_{y4} = F_{y5} = F_{y6} = 1.442 \times 10^7$ N, $h = 3$ m, $\bar{\beta} = 80$ kN/mm$^{3/2}$, $\bar{\xi} = 0.35$. A time-stepping integration procedure with constant time step 0.002 s has been applied to solve the equation of motion (1) numerically. In the analysis, various earthquake records have been used. In the present paper, however, the results of the study for the NS component of the El Centro earthquake (18 May 1940) are presented. An example of the displacement time histories for the case when the initial separation gap between structures, *d*, is equal to 0.02 m is shown in Fig.2(a). The corresponding pounding force history is presented in Fig.2(b). The examples of the results of the parametric study conducted for different values of gap size as well as values of mass, elastic stiffness and damping coefficients of a storey of the left-side building are shown in Fig.3-6.

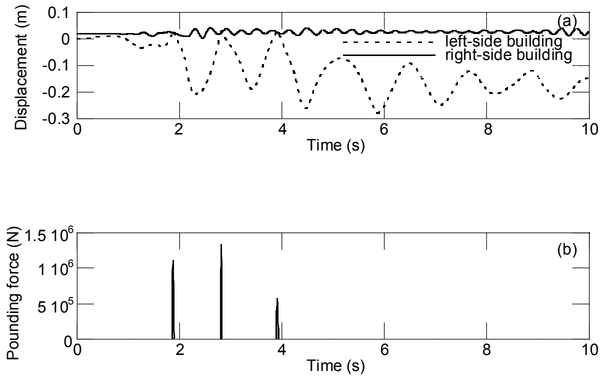

Fig.2. Time histories for 3rd stories of buildings for d = 0.02 m: (a) displacement time histories; (b) pounding force time history

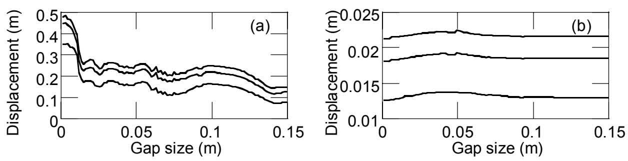

Fig.3. Max. displacement vs. gap size between buildings: (a) left-side building's stories; (b) right-side building's stories

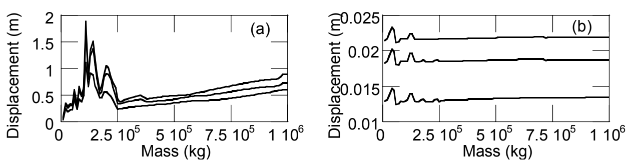

Fig.4. Max. displacement vs. storey mass m_i (i=1,2,3): (a) left-side building's stories; (b) right-side building's stories

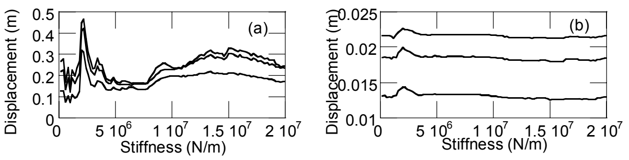

Fig.5. Max. displacement vs. storey elastic stiffness K_i (i=1,2,3): (a) left-side building's stories; (b) right-side building's stories

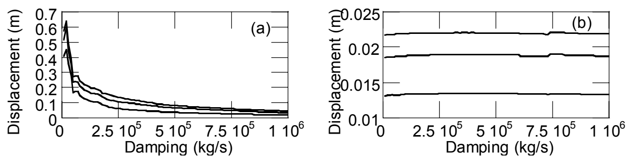

Fig.6. Max. displacement vs. storey damping C_i (i=1,2,3): (a) left-side building's stories; (b) right-side building's stories

CONCLUSIONS

In the present paper, pounding of two inadequately separated buildings with different dynamic characteristics is analysed. The results of the study indicate that pounding has a significant influence on behaviour of a more flexible and lighter structure amplifying its response, which may lead to its permanent deformation. On the other hand, the behaviour of the heavier and stiffer structure is influenced negligibly. Furthermore, the results confirm the effectiveness of the non-linear, viscoelastic model of collisions, which allows to simulate the pounding phenomenon more precisely.

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