Pounding response of structures under earthquake motions

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ABSTRACT. Pounding of structures is a common phenomenon between adjacent structures with out-of phase response which is caused by lateral seismic motions. Before the introduction of earthquake resistant design many buildings were built without any gaps between them and sometimes connected with one or two structural members. During pounding events, contact forces with high amplitude and short duration are generated which could lead to damage or total collapse of buildings. Over the past two decades, the study of building pounding and precise estimation of these contact forces has been studied by adopting several contact models. However there are still uncertainties with the adequacy of these models as different models produce different results for predicting the response of a single structure. The aim of this research is to develop/expand a contact model which can overcome the disadvantages and uncertaintaies of the existing contact models in predicting the contact forces to model seismic pounding.

KEYWORDS. Structural pounding; Hopkinson pressure bar; Contact model; Coefficient of restitution

INTRODUCTION

Pounding frequently occurs between adjacent structures with insufficient distances during earthquake where the distance between structures is not adequate to accommodate the relative movements. The relative displacements are caused by several factors such as dynamic characteristics of structure, its soil foundation and the ground motion spatial variation [1]. The most severe structural pounding reported was in the Mexico City earthquake in 1985 and Loma Prieta 1989 which resulted in the collapse of 3% to 4.5% of the buildings [2]. A survey of Loma Prieta earthquake was carried out in 1997 by Maison & Kasaei [3] who reported that mainly old adjusted structures, those structures located on soft soil and also the structures without vertical reinforcements built before 1930 were subjected to pounding.
Folz & Perion [4] investigated structural pounding caused by Saguenay earthquake in Canada. Pounding was observed in several adjacent buildings as well as the Shipshaw bridge deck against its abutments. One of the main reasons for damage/collapse of the buildings in Saguenay earthquake was pounding of structures with different heights and storey levels. The pounding forces caused by the ground motions resulted in an excessive shear forces above the buildings contact point.
The best possible way of estimating the structural responses during pounding events is through an accurate prediction of the expected force-displacement response of the adjacent buildings where the application of contact models becomes important. Over the past two decades several contact models have been adopted to estimate these forces caused by structural impact. Despite the extensive research conducted on contact behavior of structures, there is still a significant

issue with the choice of a precise contact model. In the analysis of structures even if a model adequately determines the contact forces in a single situation, defining the contact parameters can be complicated [5].

EXISTING CONTACT MODEL

Hertz contact model

All of the primary/ expanded contact models are based on Hertz law of contact which was originally proposed to estimate the contact forces resulted from an elastic impact between a sphere and a flat surface as shown in Eq. 1-3 [6].

$$F = K_{(t)} \times Z_{(t)}^{3/2} \tag{1}$$

$$K_h = \frac{4}{3}\sqrt{RE^*} \tag{2}$$

where Z, K and R are the relative displacement, contact stiffness and the diameter of the spheres.

$$\frac{1}{E^*} = \frac{1-v_1^2}{E1} + \frac{1-v_2^2}{E2} \tag{3}$$

where E, E* and v are the young modulus, effective modulus of elasticity and the Poisson ratios of the contacting bodies. The Hertz contact law is not adequate enough to estimate the contact forces for every structure as mentioned it is only limited to elastic impacts and it also does not account for energy dissipation during contact. The Hertz law of contact is the raw model of linear and non-linear elastic models which have been slightly modified. The updated Hertz law of contact, the linear viscoelastic model is a usual method of determining the pounding forces as shown in Eq. 4-6. In the linear viscoelastic model the K values are determined based on force-displacement histories obtained from experimental tests [7] and it is stated to be in the range of 1.30×10^{10} to 5.44×10^{10} for steel-steel impact and 7.90×10^{9} to 10.45×10^{9} for concrete-concrete collision.

Linear viscoelastic model

$$F(t) = K\delta(t) + C\dot{\delta}(t) \tag{4}$$

$$C = 2\zeta\sqrt{\left(K\frac{m_1 m_2}{m_1 + m_2}\right)} \tag{5}$$

where K is the element stiffness, δ is the structural member deformation, $\dot{\delta}$ is the relative velocity and C is the damping coefficient. The damping ratio (ζ) is calculated using the coefficient of restitution (e) value as shown in Eq. 6.

$$\zeta = \frac{-Ln\, e}{\sqrt{\pi^2} + \sqrt{(\ln e)^2}} \tag{6}$$

The disadvantage of this contact model is that it assumes uniform energy dissipation during the loading stage and in the restitution period of contact. Later on the linear viscoelastic model was updated [7] which could estimate the energy dissipation during just for the contact approach period. For simplicity, this model neglects the energy dissipation in the restitution period as shown in Eq. 7-9.

Updated linear viscoelastic model

$$F(t) = K\delta(t) + C\dot{\delta}(t); \quad \dot{\delta} \geq 0 \tag{7}$$

$$F(t) = K\delta(t); \quad \dot{\delta} < 0 \tag{8}$$

$$\zeta = \frac{1}{\pi}\frac{1-e^2}{e} \tag{9}$$

There is also the non-linear viscoelastic model which is the non-linear form of the modified linear viscoelastic model but accounts for energy dissipation using different equation however this parameter is still obtained using the coefficient of restitution. The equations of this model are 10-13.

Non- linear viscoelastic model

$$F(t) = K\delta^{3/2}(t) + C\dot{\delta}(t); \quad \dot{\delta} \geq 0 \tag{10}$$

$$F(t) = K\delta^{3/2}(t); \quad \dot{\delta} < 0 \tag{11}$$

$$C = 2\zeta\sqrt{k\sqrt{\delta}\left(\frac{m_1 m_2}{m_1 + m_2}\right)} \tag{12}$$

$$\zeta = \frac{9\sqrt{5}}{2}\ \frac{1-e^2}{e\left(e\left(9\pi-16\right)+16\right)} \tag{13}$$

As it can be observed that the mentioned primary contact models estimate the energy dissipation based on an indirect parameter which is the coefficient of restitution (e). It is worth mentioning that the oldest contact model which was used to model impact forces directly from the coefficient of restitution was the stereo-mechanics model. This model is no longer recommended to be used for estimating the contact forces as it is only based on the pre-impact and post-impact velocities and does not directly consider the forces. This model is unable to account for deformation of the impacted bodies as it assumes that the impact takes a very short time [7].

Stereomechanics model

$$V'_1 = v_1 - (1+e)\ \frac{m_1 v_1 - m_2 v_2}{m_1 + m_2} \tag{14}$$

$$V'_2 = v_2 - (1+e)\ \frac{m_1 v_1 - m_2 v_2}{m_1 + m_2} \tag{15}$$

$$(1)\quad e = \frac{v'_2 - v'_1}{v_1 - v_2} \quad \text{OR} \quad (2)\ e = \frac{h_2}{h_1} \tag{16}$$

where m_1, m_2, v_1, v_2 are the masses and the velocities of the structural elements. The second part of the Eq. (16) can be obtained by dropping a ball on a plate from a certain height (h_1) over its rebound height (h_2). In this model for a fully elastic impact the restitution coefficient value is equal to 1, and for a fully plastic impact e is 0. The value of restitution coefficient is assessed to be ranging from 0.50 to 0.75 for simulation of real structural pounding [7]. In addition to the primary contact models mentioned above, two other models, the modified hertz-damped model and the Hunt-Crossley model are presented in Tab. 1 [8]. The Hunt-Crossley model is also based on the Hertz contact law.

THE CURRENT RESEARCH

The current research focuses on comparing the existing contact models using numerical and experimental data for a possible expansion of an existing contact model which can precisely determine the contact forces during structural pounding. For this purpose a series of preliminary numerical simulations was conducted using ANSYS-LSDYNA. A 2D axi-symmetric Hopkinson pressure bar test setup was modelled as shown in Fig. 1 to have a precise estimation of the experimental setup parameters such as the impact velocity, the size of the samples, etc. The model was constructed in 3 parts; hopkinson pressure bar, striker and the specimen. Convergence analysis was conducted to determine the best mesh size for the finite element analysis of the model which was found to be 1 mm. Impact was modelled between concrete- concrete, steel-concrete and steel-steel materials. In the case of concrete-concrete impact the specimen was placed at the front of the Hopkinson bar whereas for steel- steel and concrete -steel impacts the specimens were placed at the front of the striker. The arrangement of the bar and the specimen is due to the restriction with the laboratory apparatus as well as simplifying the investigation of the results as shown in Fig. 2.

Hertz-damped model	$F(t) = K\delta^{3/2} + \zeta\, \delta^{3/2}\, \dot{\delta}$, $(1+e)=\frac{k}{\zeta\dot{\delta}}\ \ln \frac{\frac{k}{\zeta\dot{\delta}0}+1}{\frac{k}{\zeta\dot{\delta}0}-e}$
Linear Hunt-Crossley model	$F(t) = K\delta + \zeta\, \delta\, \dot{\delta}$ where ζ for both Hertz-damped model and the linear Hunt-Crossley model is obtained from the implicit equation

Table 1: Contact force models.

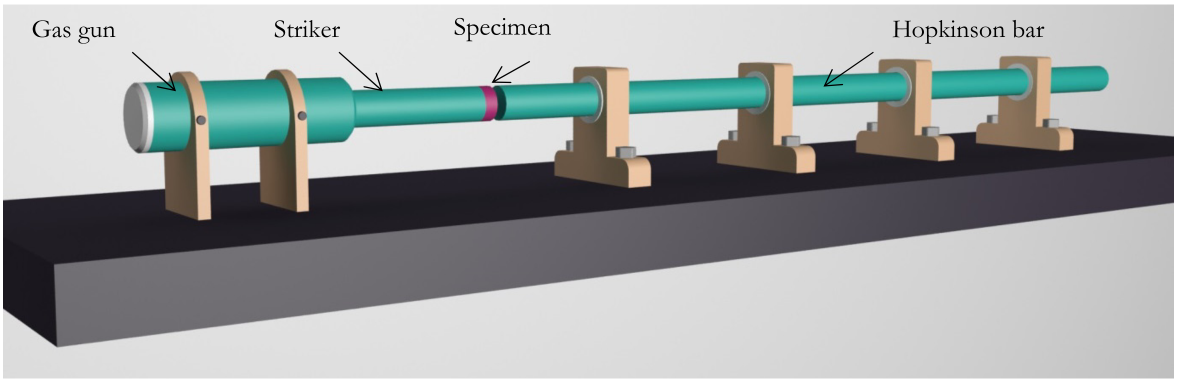

Figure 1: Hopkinson pressure bar set up.

Fig. 2 shows the contact force-time histories of steel to steel, concrete to concrete and concrete to steel impacts with the velocity of 25 m/s. The mentioned graph is one small part of the preliminary numerical simulation which was done to determine the precise laboratory setup to be conducted on the same procedure for verification of the numerical results. In LS-DYNA, for modelling steel- steel collision simplified Johnson-Cook material model was used and for concrete-concrete impact material model 72R3- damage concrete was used. All the force-time histories were obtained at the strain gauge location which is 494 mm away from the face of the Hopkinson bar.

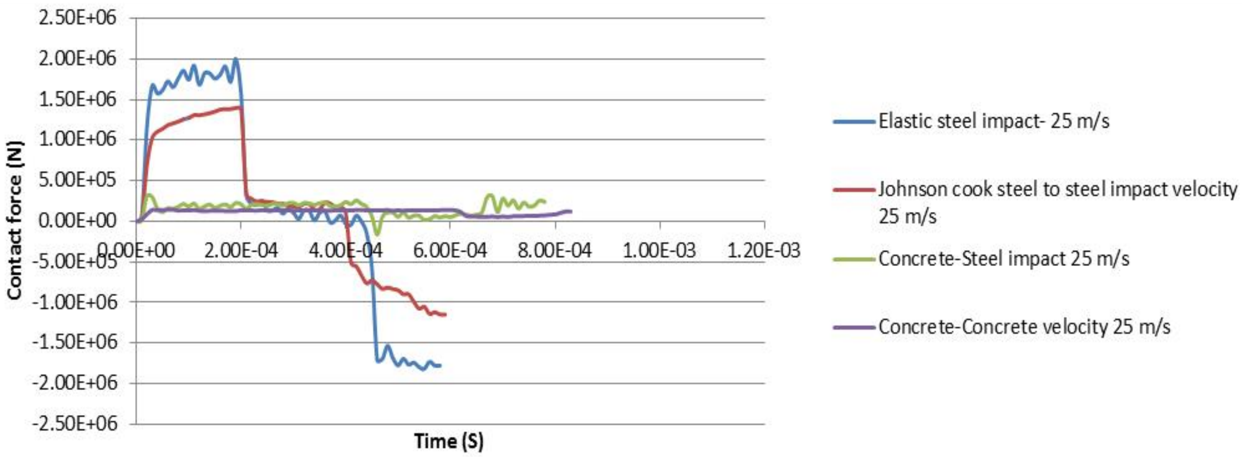

Figure 2: Force-time history of steel-steel impact with velocity of 25 m/s.

Once the experimental tests on a limited number of samples are carried out, the experimental results will be verified by the numerical models then it would be possible to model more collision numerically with more detailed data. Having the numerical and experimental results will give the possibility of comparing and applying the existing contact models to these data. Achieving precise information will make the comparison of the contact models possible therefore an existing contact model could be updated. The latter step would be to use the modified/novel contact model in pounding analysis of a

Single degree of freedom system. To accomplish the project, the novel contact model will be compared to the results obtained from the existing contact models for the same structural system.

CONCLUSION

Structural pounding is a severe event which can lead to damage/collapse of structures. In order to determine the contact forces caused by buildings' collisions several contact models have been adopted. For over two decades researchers investigated the adequacy of these contact models however there are still uncertainties with the existing contact models and their parameters as each contact model can give different result for a single case. This research aims at developing an adequate contact model which would be more reliable in estimating the structural responses than the existing ones. For this purpose an extensive preliminary numerical simulations are carried out for determining the experimental setup of the samples parameters however for the sake of brevity only the force-time history of a few impact models are presented in this paper. The variables in the numerical simulations are the structural material, the geometry and the applied velocity to the striker. Once these results are confirmed by the experimental tests, the force-displacement data will be implemented in the contact models for comparison. After verification is completed, accurate analysis will be conducted to obtain more precise data for more impact models. The accomplished numerical results will be used to compare and expand of the existing contact models. The expanded contact model will be tested against the rest of the existing contact models on pounding analysis of a single degree of freedom model.

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