Pounding response of buildings under earthquake motions

N. Farhadzadeh
Department of Civil and Structural Engineering, the University of Sheffield, Sheffield S1 3JD, United Kingdom
Nfarhadzadeh1@sheffield.ac.uk

Primary Supervisor: Dr Zuhal Ozdemir –Z.Ozdemir@Sheffield.ac.uk
Secondary Supervisor: Professor Andrew Tyas –A.Tyas@Sheffield.ac.uk

ABSTRACT. Simulation of structural pounding using impact element models has attracted researcher's attention for many years. This study aims at developing an impact element model which can represent the elasto-plastic pounding behavior of buildings during earthquake. This impact element model will be appropriate for modelling impact between two flat surfaces. For this purpose, Hopkinson Pressure Bar (HPB) experimental tests and non-linear finite element (FE) analysis are first conducted to investigate the contact response of different structural materials at variable loading rates. Then, existing impact element models have been applied to predict the response of experimental and numerical models. The performance of the existing impact element models particularly the linear viscoelastic model has been compared against the HPB experimental results of steel/steel impact. The results indicated that providing suitable contact parameters, the impact element models can predict the impact response of materials realistically.

KEYWORDS. Structural pounding; Hopkinson pressure bar (HPB); Contact model; Contact stiffness; Flat surface geometries; Elasto-plastic behaviour.

INTRODUCTION

Structural collision, also known as seismic pounding has been observed following many past earthquakes such as in Mexico City earthquake in 1985, Christchurch in 2011 and more recently in Gorkha earthquake in Nepal 2015. During the Mexico earthquake, 3% to 4.5% of buildings were extensively damaged/ collapsed due to pounding. One of the great buildings which collapsed due to pounding was the De Carlo Hotel which was insufficiently distanced from its neighboring building. As a result of ground excitation, buildings were induced to apply hammer like forces on one another leading to a great horizontal failure in the middle of the De Carlo Hotel building. Studies [1, 2] on seismic vulnerability of structures have recognized pounding as one of the main hazards for structures. Five different configurations of buildings have been described [1] as being the most susceptible to pounding during earthquake motions; (i) adjacent to a building with shorter stories (ii) closely spaced to a large-massed structure (iii) mid-column pounding (iv) being at the end of a raw of several adjacent structures, and (v) eccentric pounding. In addition to the five configurations, adjacent buildings with different set-backs are also known to be vulnerable to pounding.
Regular observation of structural pounding and its resultant damages/collapses have led to an extensive body of literature since 1980s. It started from analysis of structures modelled as single-degree-of-freedom systems [3, 4] and soon the investigation was taken further on to the analysis of multi-storey structures [5, 6]. Structural pounding behavior during earthquakes is mainly simulated using two approaches; (1) the Stereomechanics approach which is based on the conservation of momentum law, (2) impact element models which directly simulates the pounding forces.

Several experimental tests such as shaking table tests, pendulum tests, and dropping ball tests [7, 9] have been conducted to investigate pounding. Three-dimensional analyses of structural longitudinal, transversal and torsional pounding also exist in the literature [10-14]. Anagnostopoulos [3]; Anagnostopoulos & Spiliopulos [6] and; Muthukumar & DesRoches [7] idealized structures as lumped masses and investigated the effect of contact stiffness and energy loss on the adequacy of impact element models. Khatiwada [15] idealized two segments of a bridge as distributed mass models to observe the influence of stress propagation and the resultant deformation in the impacted bodies. Cole et al [16] studied the wave theory which is the base theory of distributed mass models as well as the disadvantages of the theory in simulating the contact stresses amplitudes and durations for different structural materials. Khatiwada [11] was the first to introduce the Sears model for simulation of structural pounding. The model is a distributed mass model which accounts for contact forces thorough the deformation caused by the propagation of contact stress waves through the impacted bodies.

For the past two decades, several impact element models such as the linear or non-linear elements (Hertz model), linear or non-linear viscoelastic elements (Kelvin-Voight model) are used to assess pounding forces. The linear spring element is the simplest link element which becomes activate once the two bodies come into contact. However, this model over-estimates the pounding forces as there is no dashpot assumed in the system to account for energy loss. In contrary with linear elastic element, the linear and non-linear viscoelastic link elements include a dashpot to take into account the energy dissipation. However, one of the main disadvantages of linear viscoelastic model is the assumption of uniform energy dissipation throughout the whole time of contact. In general, these models are found to be reasonable in simulating the structural responses. However, still diverse results can be obtained when all these impact element models are applied to a single structural pounding situation which is due to the great dependency of these models on some of the contact parameters [17]. As an example, Muthukumar & DesRoches [7] has found the significant effect of the coefficient of restitution whereas Anagnostopoulos [3] found it to be insignificant.

Due to these uncertainties associated with contact parameters, simulation of structural pounding using these impact element models can sometimes be unrealistic [15]. Nevertheless, there is still a reasonable prediction of pounding forces is required to design devices such as viscous damping to restrict structural movements and minimize the possible pounding damage. However, to prevent pounding of adjacent buildings there should be at least some amount of distance between them. Therefore, the current practice codes determine a minimum distance between the two structures to prevent them from pounding which is easier rather than dealing with the post-earthquake damages. However, there still exist structures with no separation gaps; as an example in Iran, in most of the cities centers, many structures are built extremely close to each other and their structural systems do not allow connecting them together. Also in many large cities, lack of land and the cost of it as well as architectural restrictions do not allow structural engineers to leave sufficient gaps between structures. Therefore, it is essential to have precise measurements of pounding forces for the existing adjacent structures built in such earthquake prone countries.

RESEARCH AIM

The aim of this research is to develop an impact element model, which can represent elasto-plastic contact phenomenon occurring due to pounding of structures during earthquakes. The developed impact element will be appropriate for modelling impact between two flat surfaces. In addition, appropriate contact stiffness and damping parameters of the developed impact element model will be determined to model pounding phenomenon occurring between two RC buildings, two steel buildings, or one steel and one RC building. To accomplish this aim, HPB tests and non-linear FE analysis are performed to collect more data on the contact response of materials at different loading rates. A new impact element model will be developed based on HPB numerical simulation and experimental tests. The developed impact element model will be validated by finite element modelling of pounding between two single-storey buildings.

METHODOLOGY OF CURRENT RESEARCH

Preliminary numerical analysis

Preliminary numerical analysis was conducted in ANSYS-LS DYNA to simulate impact between different structural materials. The preliminary analysis provided the opportunity of understanding the stress wave propagation and the material behavior during impact. These numerical analyses were used to determine the specimen's measurements and the striker's velocities and other necessary information for setting up the Hopkinson Pressure Bar tests. Impact was modelled between two free axi-symmetric bars and a specimen which was attached to the front of the striker for steel to steel, and concrete to steel impacts. However for concrete to concrete impacts, the specimens were placed at the front of Hopkinson bar which was to prevent any damage to the Bar. The bars were modelled using shell elements with mesh size of 1 mm. HPB setup is shown in Figure 1. For modelling HPB steel/steel impact, the simplified Johnson Cook material model (MAT 15) was used and for concrete/concrete impacts, the continuous surface cap material model (MAT 159) was used in ANSYS-LSDYNA. Variable impact velocities ranging from 0.80 m/s to 26.60 m/s were determined using the numerical model of HPB. Some of the chosen velocities for concrete/concrete impact were so high that caused total failure of the concrete specimens as well as some of the concrete strikers in the experiment. The specimen's lengths were 25, 50, and 100 mm with diameter of 50 mm. The lengths of the steel and concrete strikers were 400 mm with diameter of 50 mm for all tests. However the HPB diameter was 49.2 mm. The material properties of the HPB were taken from [18] and are shown in table 1. To compare the performances of the existing impact element models, parametric study was conducted using the force-displacement response of materials during HPB experimental tests. From the obtained force-displacement data, contact stiffness and the coefficient of restitution values for each test were determined. Several impact element models such as the non-linear and linear viscoelastic, linear and non-linear elastic, non-linear Hertz-damped and linear Hunt and Crossley models were compared against the experimental test results of HPB.

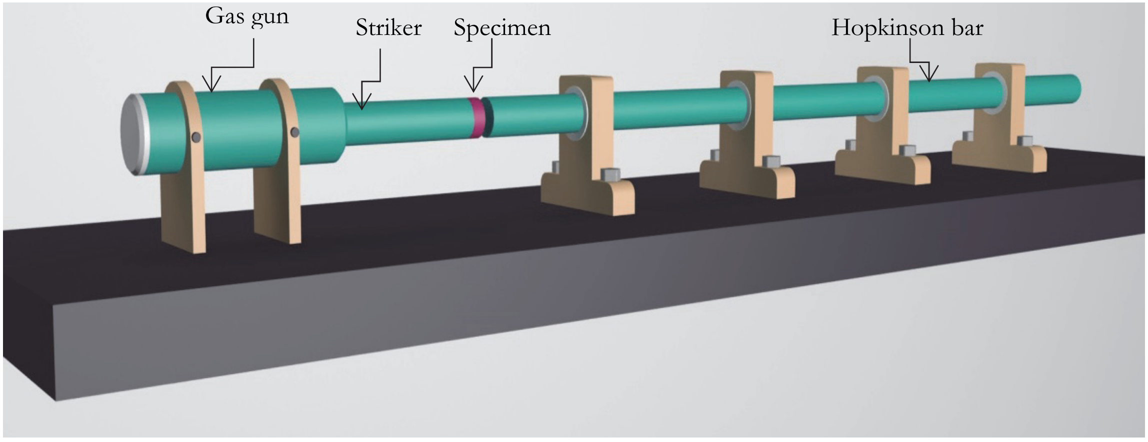

Figure 1: HPB set up.

HPB measurements and material properties	
Length and radius of HPB	5.850 m and 0.0246 m (+/- 0.00005 m)
One dimensional wave velocity (C_0)	5194 m/s (+/- 13 m/s)
Density (ρ)	7850 kg/m^3
Elastic modulus (E)	212×10^9 N/m^2 (+/- 1.5×10^9 N/m^2)
Poisson's ratio (ν)	0.29

Table 1: Properties of the Hopkinson Pressure Bar used in the experiment.

Even though all of these models were originally developed for impact between sphere/sphere and flat/sphere surfaces, they still provided reasonable results for impact of bars with flat surface geometries. The contact stiffness value for each model was modified to simulate similar forces to the HPB numerical results. The coefficients of restitution values were found to have a negligible effect on the performances of the existing impact element models. For the sake of brevity, only one of the results of the comparison between the HPB numerical simulation and the linear viscoelastic model has been provided in this paper. It should be noted that for the linear viscoelastic impact element models, displacement-time histories were obtained from the HPB numerical analysis. Providing correct contact stiffness and damping ratio/constants values as well as displacement-time histories, the impact model was quite reasonable in simulating the impact forces. Figure 2 shows the comparison of the performance of linear viscoelastic model with the HPB numerical impact model of steel to steel with an impact velocity of 5 m/s. The contact stiffness and the coefficient of restitution values for this impact were $K = 8 \times 10^9$ N/m and $e = 0.07$.

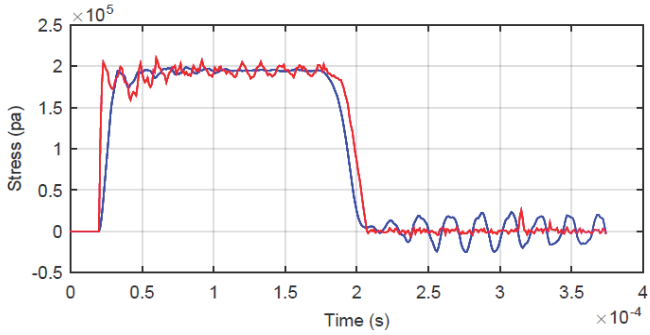

Figure 2: Comparison of linear viscoelastic model (blue line) with HPB numerical analysis result (red line) for impact of steel to steel with an impact velocity of 5 m/s; Steel specimen length and diameter 25 mm and 50 mm; Hopkinson bar length and dimeter were 5850 mm and 49.2 mm; striker length and diameter were 400 mm and 50 mm

Contact of bars with spherical surface geometries

In addition to the investigation of contact between two flat surfaces, contact between bars made with spherical surface geometries was also modelled. Force-displacement curve obtained from the numerical model of HPB was compared against the force-displacement curve obtained from the Hertz model. Both force-displacement curves showed excellent agreement. The contact stiffness value calculated using the Hertz contact stiffness formula was determined to be $K = 1.72 \times 10^{10}\ \mathrm{N/m^{3/2}}$. However, this value did not provide a reasonable contact force-displacement curve because when the Hertz contact stiffness value was used the impact maximum contact force was smaller than the maximum force obtained from the numerical model. Therefore, the contact stiffness value was modified to $K = 3.17 \times 10^{12}\ \mathrm{N/m^{3/2}}$. The new K value provided a force-displacement curve which perfectly agreed with the contact force obtained from the numerical model.

HPB experimental tests and the verification of the numerical impact model of two steel bars

Six numbers of HPB experimental tests were conducted on the impact of steel/steel with specimen's length of 25 mm, concrete to steel with concrete specimen's approximate lengths of 25, 26, 51, and 52 mm, and concrete to concrete impacts with specimen's length of approximately 26 mm. The impact velocity for steel/steel impact was 19.4 m/s, for concrete to steel were 0.8, 6.5, 8.15, 18.88 m/s, and for concrete to concrete impact was 26.6 m/s. Comparison of stress-time histories obtained from the HPB experimental tests and its FE numerical model for steel to steel impact with an impact velocity of 19.4 m/s is illustrated in Figure 3. Also Figures 4 and 5 show the stress-time histories obtained from the HPB experimental test on concrete to steel, and concrete to concrete impacts.

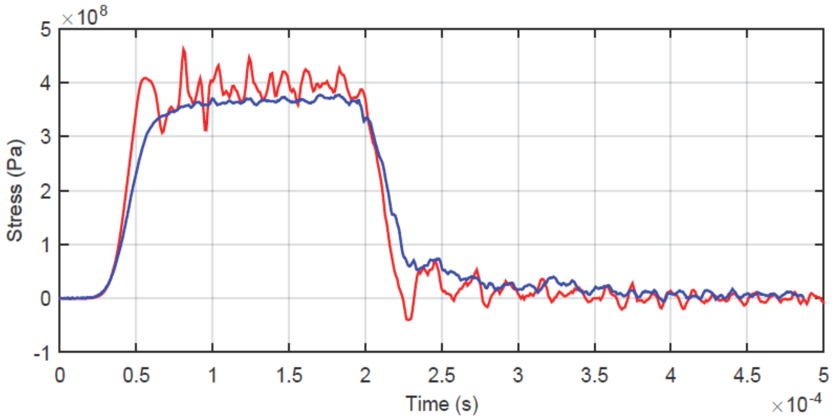

Figure 3: Comparison of the HPB numerical model (red line) with HPB experimental test (blue line) for steel to steel impact with an impact velocity of 19.20 m/s; Specimens length and diameter were 25 mm and 50 mm

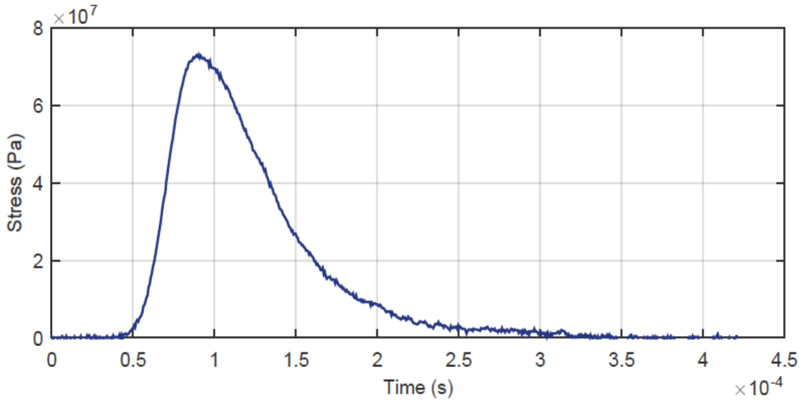

Figure 4: Stress-time history of concrete to concrete HPB experimental impact test with impact velocity of 26.6 m/s

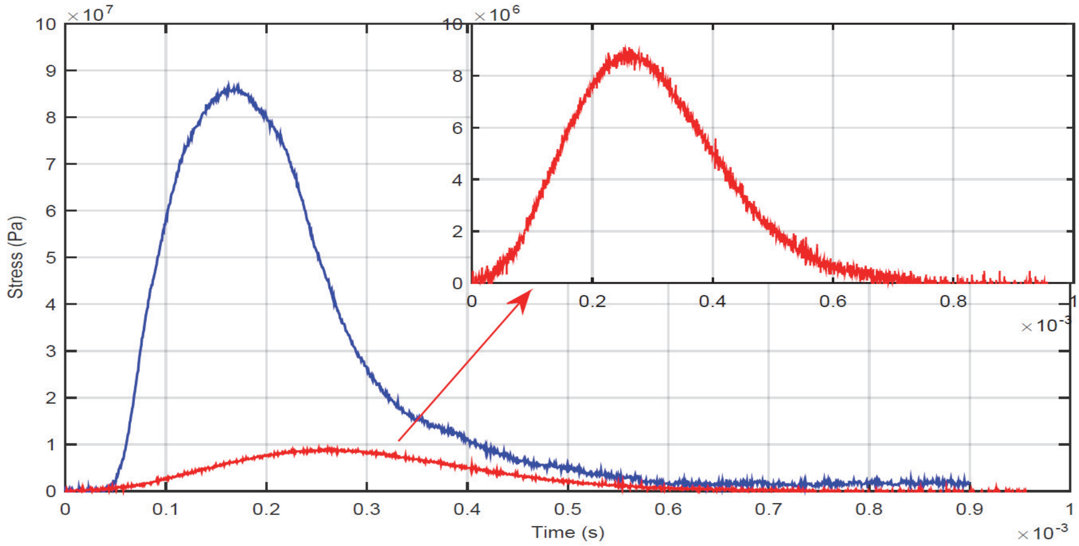

Figure 5: Comparison of stress-time histories obtained from HPB concrete to steel impact test with an impact velocity of 0.8 m/s (fully elastic- red line) with stress-time history obtained from fully crushed concrete specimen with an impact velocity of 18.88 m/s (fully plastic- blue line) - The magnified stress-time history shown in the upper right corner of the figure belongs to the elastic impact test

CONCLUSIONS

In this study HPB preliminary numerical analysis was conducted to determine HPB experimental set-ups. Impact was modelled between two steel bars, two concrete bars, and one concrete and one steel bar. Using the simplified Johnson-Cook material model, steel/steel HPB numerical model was verified against the experimental tests. Also for verification of concrete/concrete numerical model, continues surface cap model (MAT159) was used in LS-DYNA. Using the HPB experimental tests as well as the FE numerical analysis results; limited parametric study was conducted to obtain suitable contact parameters for different structural materials. With the obtained contact parameters such as the contact stiffness and the damping ratio, performance of the linear viscoelastic model was compared against the numerical results of HPB steel/steel impact. It was observed that providing correct values for contact stiffness and damping ratio/constant, as well as displacement-time histories, linear viscoelastic model is adequate enough to predict the contact forces for impact of flat surfaces even though the model was originally developed for contact of spherical/spherical and flat/spherical surfaces. However, for the development of a novel impact element model for flat surfaces, with the aid of HPB numerical analysis as well as the experimental tests, more parametric study is necessary to determine appropriate elastic and elasto-plastic contact parameters for impacts of concrete/concrete, steel/steel, and concrete/steel.

REFERENCES

[1] Jeng, V., and Tzeng, W., Assessment of seismic pounding hazard for Taipei City, Engineering Structures, 22(5) (2000) 459-471.

[2] Bothara, J.K., Jury, R.D., Wheeler, K. & Stevens, C., Seismic Assessment of Buildings in Wellington: Experiences and Challenges.In Proceedings of the 14th World Conference on Earthquake Engineering, October 12-17, (2008). Beijing, China.

[3] Anagnostopoulos, S. A., Pounding of buildings in series during earthquakes, Earthquake Engineering and Structural Dynamics, 16(3) (1988) 443-456.

[4] Athanassiadou, C. J., Penelis, G. G. and Kappos, A. J., Seismic response of adjacent buildings with similar or different dynamic characteristics, Earthquake Spectra, 10(2) (1994) 293-317.

[5] Papadrakakis M., Mouzakis H., Earthquake simulator testing of pounding between adjacent buildings. Earthquake engineering and structural dynamics. 24 (1995) 811-834.

[6] Anagnostopoulos, S. A. and Spiliopoulos, K. V., An investigation of earthquake induced pounding between adjacent buildings, Earthquake Engineering and Structural Dynamics, 21(4) (1992) 289-302.

[7] Muthukumar, S., DesRoches. R. A., Hertz contact model with non-linear damping for pounding simulation. *Earthquake engineering and structural dynamics*. 35(1) (2006) 811-828.

[8] Van Mier, J.G.M., Pruijssers, A.F., Reinhardt, H.W., Monnier, T., Load-time response of colliding concrete bodies. Journal of structural engineering.1 (1997) 354-374.

[9] Zhu P, Abe M, Fujino Y., Modelling three-dimensional non-linear seismic performance of elevated bridges with emphasis on pounding of girders. Earthquake Engineering and Structural Dynamics; 31 (2002) 1891–1913.

[10] Mouzakis, H. P. and Papadrakakis, M., Three dimensional nonlinear building pounding with friction during earthquakes, Journal of earthquake engineering, 8(1), (2004) 107-132.

[11] Jankowski, R., Earthquake induced pounding between equal height buildings with substantially different dynamic properties, Engineering Structures, 30(10) (2008) 2818-2829.

[12] Jankowski, R., Non-linear FEM analysis of earthquake-induced pounding between the main building and the stairway tower of the Olive View Hospital, Engineering Structures, 31(1) (2009) 1851-1864.

[13] Jankowski, R., Non-linear FEM analysis of pounding-involved response of buildings under non-uniform earthquake excitation, Engineering Structures, 37(0) (2012) 99- 105.

[14] Rajaram, C., Ramancharla., Three dimensional analysis of pounding between adjacent buildings. Journal of Structural Engineering.41(2) (2014) 161-171.

[15] Khatiwada, S., A distributed mass model with end-compliance effects for simulation of building pounding. University of Auckland, New Zealand (2014).

[16] Cole, G.L., Dhakal, R.P, Carr, A.J., Bull, D.K. In: The effect of diaphragm wave propagation on the analysis of pounding structures. In: M. Papadrakakis, N. D. Lagaros, and M. Fragiadakis: ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, 2009 Greece. Rhodes Ireland.

[17] Khatiwada, S., Chouw, N, Larkin, T., In: Simulation of structural pounding with the Sears impact model. In: M. Papadrakakis, N. D. Lagaros, V.Plevris: 4th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering; Jun/12-14/2013; Greece. Kos Ireland.

[18] Tyas, A., Watson, A.J., Experimental evidence of Pochammer-Chree strain variations in elastic cylinders. Experimental Mechanics. University of Sheffield. (2000) 331- 337.