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RESEARCH ARTICLE

Prediction of Critical Distance Between Two MDOF Systems Subjected to Seismic Excitation in Terms of Artificial Neural Networks

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Abstract
This study focuses on preventing collisions between structures during seismic excitation based on gap size. Several approximated equations in order to estimate separation distance between buildings are collected and evaluated to measure gap size in order to avoid impact between them when large lateral displacements occurred due to earthquake. Artificial neural networks are utilized to estimate the required distance between structures. The majority of building codes suggest separation distances based on maximum lateral displacements of each building or height of buildings in order to provide safety gap size between them. Subsequently, researchers have proposed several equations to predict the critical distance. In current study, some MDOF models are equivalently modelled and optimum gap size between buildings is approximately estimated and finally a new equation for separation distance is suggested and the accuracy of formula is numerically investigated.

Keywords
critical distance, pounding, lateral displacement, seismic excitation

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1 Introduction

Commonly structural damages occur in buildings as a result of large lateral displacements that is inherently provided by earthquake ground motion. This event is caused to collision between buildings during seismic excitation. The first approach for pounding prevention is to establish a reliable estimate of the sufficient separation required for the design earthquake so that pounding between the structures will not occur. Providing a minimum gap has been the usually accepted strategy adopted by building codes around the world. The value of the separation distance between two structures that is sufficiently large to prevent pounding is known as the seismic gap or critical gap. Nevertheless, where it is possible for new buildings to be designed with sufficient gap width, the problem persists in the case of existing buildings designed under older building codes with considerably smaller gap widths than those specified in the current codes.

Although building codes pay attention to this problem, building designers are often reluctant to provide the necessary space between buildings to eliminate the problem, principally because the required space would reduce available square footage in the building being developed [1]. Various authors have studied different methods to evaluate the seismic gap that are generally less conservative than the prescriptions of the codes.

In order to decline lateral displacement, researchers have presented some studies to control displacement during earthquake. *Anagnostopolos* [2,3] also investigated effect of gap size and presented that pounding might cause severe structural damage in some cases and even collapse is possible in some extreme situations. Some parametric study results in terms of relative lateral displacement of adjacent buildings have been presented by *Hao* and *Shen* [4]. Effects of vibration frequencies, torsion stiffness and eccentricities of adjacent structures on their lateral displacements have been evaluated. *Valles* and *Reinhorm* [5] have investigated some parameters that allow some level of pounding if the effects do not jeopardize the integrity of either construction. *Pantelides* and *Ma* [6] found that by increasing damping term, the maximum lateral displacement is increased and subsequently, pounding damage is reduced. *Dogruel* [7] studied the retrofitting of one or both of two adjacent structures with passive energy dissipation devices to reduce the structural vibration and probability of pounding. A design procedure utilizing a performance function is used to obtain the damper parameters that result in the best overall system response. *Barros* and *Khatami* [8] evaluated the effect of concrete shear wall to decline lateral displacement between two buildings for avoiding collision. *Barros* and *Braz* [9] have numerically studied semi active control method and the study was experimentally implemented to compare the results of studies. *Naderpour et al* [10-12] investigated pounding hazard and suggested an equation to calculate impact velocity based on coefficient of restitution. An experimental test by using different balls was carried out by *Jankowski et al* [13,14] and shown the effect of body material to impact velocity. *Komodromos* [15], *Ye et al* [16] and *Yu* and *Gonzalez* [17], *Naderpour et al* [18] have mathematically described various equations to determine impact damping ratio.

On the other hand, some researchers have focused significantly on numerical method to provide equations based on building codes to provide separation distance between structures. *Garcia* [19-22] have focused deeply on separation distance and suggested some parameters to prevent pounding between structures. *Kasai* and *Maison* [23] proposed the spectral difference method based on random vibration theory that considers the first mode approximation for displacements of elastic multi-storey buildings. *Filatrault et al* [24] improved the equation of separation distance by using effect of damping ratio. *Penzien et al* [25] have also recommended calculating an effective period to use original period. *Rahman et al* [26] showed mitigation measure for earthquake inducted pounding effect on seismic performance.

In this paper, effect of pounding is numerically investigated and importance of separation distance is obviously shown. Using neural network and *CRVK* program, specially developed in order to solve a large number of dynamic simulations of lateral displacement, optimum gap size between two adjacent buildings is evaluated and the process to measure the separation distance is theorically suggested.

2 Building code requirements

Building codes in zones of active seismicity around the world have recognized the destructive effects that pounding may induce in constructions. The approach commonly adopted in building codes has been to avoid contact interactions between the structures by providing sufficient separation between them.

The criterion used recommended gap size are collected and listed as the below:

$$S=\delta_i+\delta_j \quad (ABS) \tag{1}$$

$$S=\sqrt{\delta_i^2+\delta_j^2} \quad (SRSS) \tag{2}$$

$$S=\beta.H_{\max} \tag{3}$$

Some of the codes recommend the Absolute sum method (*ABS*) and other codes suggested the sum of the squares of the modal response (*SRSS*) to calculate needed gap size between two adjacent buildings.

In theses equations, S is minimum separation distance, δ_i and δ_j denote maximum lateral displacement of building i and j, respectively. H is the height of taller building and coefficient of β is recommended to be 0.01. Equation (1) and (2) are widely used in sciences studies and equation (3) is commonly used by Iranian Earthquake code, which is called "Standard 2800 " [27].

The first criterion may be considered as equivalent to the absolute sum of maximum displacement of each structure, multiplied by an amplification factor. The amplification factor in most cases comes from the increase in displacements due to the non-elastic response of the structures. This criterion does not take into account that the maximum displacements in the structures, in general, will not occur at the same time. As it is highly unlikely that these two maximum displacements will both occur at the same instant and with opposite signs, a smaller gap size will usually be sufficient to avoid pounding.

3 Different method

In order to determine requirement separation distance between two buildings, various authors tested different methods to measure adequate seismic gap.

Kasai and *Maison* [23] have developed equation (2) as a reference formula and added a new term to increase the accuracy of calculated gap size. They believed that separation distance depends directly on period of buildings and gap size could be decrease as nonlinear behaviour of buildings. The relation is written as follow [23]:

$$S=\sqrt{\delta_i^2+\delta_j^2-2.\rho_{ij}.\delta_i.\delta_j} \tag{4}$$

$$\rho=\frac{8\sqrt{\zeta_i\zeta_j}(\zeta_i+\zeta_j(\frac{T_i}{T_j}))(\frac{T_i}{T_j})^{1.5}}{(1-(\frac{T_i}{T_j})^2)^2+4\zeta_i\zeta_j(1-(\frac{T_i^2}{T_j}))(\frac{T_i}{T_j})+4(\zeta_i^2+\zeta_j^2)(\frac{T_i}{T_j})^2} \tag{5}$$

Recommended separation distance is normally declined by increasing damping constant or increasing the ratio of *Ti/Tj* while for two identical buildings is reduced to zero.

A new method is proposed by *Penzien* [25] and the approaches assume that equation (5) is still valid for non-linear systems as long as T_i, ξ_i, T_j and ξ_j are replaced by "effective" properties. So, effective properties are given by:

$$T_{iNon-linear}=T_{i-Linear}\sqrt{\frac{\mu_i}{\gamma+\alpha_i(\mu_i-\gamma)}} \tag{6}$$

$$\xi_{i-Nonlinear}=\xi_{i-Linear}+\frac{2}{\pi}(\frac{(\mu_i-\gamma)(1-\alpha_i)}{\mu_i(\gamma+\alpha_i(\mu_i-\gamma))}) \tag{7}$$

Where μ_i is the displacement ductility of system "i", the factor is recommended to be $\gamma = 0.65$ and α_i is the ratio of final stiffness to the initial one. Substitution of subscript "i" by "j" gives the corresponding expressions of $T_{iNon-linear}$ and $\xi_{i-Nonlinear}$.

Finally, *Jeng etal* [28] developed equations (6) and (7) to define a new nonlinear situation for period and damping ratio as the below:

$$T_{iNon-linear} = T_{0i}(1+0.18(\mu_i - 1)) \quad (8)$$

$$\xi_{i-Nonlinear} = \xi_{0i} + 0.16(\mu_i - 1)^{0.9} \quad (9)$$

When equation (10) is parametrically modified by equation (4), by the following expression:

$$S = \sqrt{\delta_i^2 + \delta_j^2 - 2.\rho_{ij}.\delta_i.\delta_j} > 0.25(\delta_i + \delta_j) \quad (10)$$

4 Simulation of pounding

Pounding is naturally occurred when lateral displacement of adjacent buildings exceeds from separation distance between structures due to structural behaviour or insufficient provided gap sizes due to economic problems. Consequently, buildings collide with each other and pounding is caused to damage during seismic excitation. In order to calculate impact force and energy dissipation, a new equation of motion is suggested by *Naderpour et al.* [18] which is seen as:

$$\begin{aligned} &F_{imp}(t) = k_s.\delta^n(t) + c_{imp}.\dot{\delta}(t) \quad \rightarrow \quad \delta(t) > 0, \dot{\delta}(t) > 0 \\ &F_{imp}(t) = k_s.\delta^n(t) \quad \rightarrow \quad \delta(t) > 0, \dot{\delta}(t) < 0 \\ &F_{imp}(t) = 0 \quad \rightarrow \quad \delta(t) < 0 \end{aligned} \quad (11)$$

where $n = 1.5$.

In order to determine impact force and energy dissipation, an impact between two bodies is simulated and hysteresis loop is depicted. It is assumed that dissipated energy is approximately shown by enclosed area of hysteresis curve due to impact. On the other hand, kinetic energy loss due to impact has been demonstrated by Goldsmith [29], which is seen as:

$$E = \frac{1}{2}.\frac{m_i m_j}{m_i + m_j}.(1 - CR^2).\dot{\delta}_{imp}^2 \quad (12)$$

In here, the value of CR depends on velocities before and after impact and is calculated by $0 < CR = \dfrac{\dot{\delta}_{before}}{\dot{\delta}_{after}} < 1$.

It is obviously confirmed dissipated energy during impact has to be equal by kinetic energy, calculated by equation (12). Undoubtedly, if both of energy becomes equal to each other, it shows the accuracy of the impact damping ratio.

In order to provide a new equation in terms of damping ratio, unknown parameters is considered to be c_{imp}, that depends on some seen parameters as:

$$c_{imp} \cong \{k_s, m, CR, \dot{\delta}_{imp}, \delta, \dot{\delta}, \ddot{\delta}\}$$

For this challenge, a specific link element is considered to be at the level of bodies, which included a spring and dashpot to calculate lateral displacement and energy absorption, respectively.

Damping coefficient is defined as the following expression:

$$c_{imp} = \zeta_{imp}.k_s.\delta^n(t) \quad (13)$$

Where k_s is stiffness of spring and δ_t denotes lateral displacement ($n = 1.5$). Impact damping ratio is made by different terms, which becomes:

$$\zeta_{imp} = CR_{imp}.\frac{(1-CR)}{\ddot{\delta}(t).\dot{\delta}(t).\delta(t)}.w_{CR} \quad (14)$$

In order to solve equation (14), terms need to be presented based on mentioned parameters, seen in c_{imp}. So it is estimated to be:

$$CR_{imp(i)} = \rho(i).CR^{\eta} \quad (15)$$

In equation (14), w_{CR} depends on impact velocity, which is determined as the below:

$$w_{CR(i)} = \alpha(i).\dot{\delta}_{imp}^{\beta} \quad (16)$$

In order to start the simulation of impact and solve the program to get impact damping ratio, a value of mass is given and *CRVK* program calculates lateral displacement, velocity and acceleration of spring, connected between two bodies. Stiffness of spring is determined and a *CR* is also selected. The program solves equations and calculates energy dissipation, which is equal to the area of hysteresis loop of each impact and compares with kinetic energy, calculated in equation (12). Both energies should be equal if all factors had been correctly selected.

After finishing the process, impact damping ratio is determined and numerically shown as the below:

$$\zeta_{imp} = 1.6\times10^{-2}.CR^{0.2805}.\frac{\dot{\delta}_{imp}^2}{\ddot{\delta}(t).\dot{\delta}(t).\delta(t)}(1-CR) \quad (17)$$

Finally, damping coefficient is explained by:

$$c_{imp} = 1.6\times10^{-2}.CR^{0.2805}.\frac{\dot{\delta}_{imp}^2}{\ddot{\delta}(t).\dot{\delta}(t)}(1-CR).k_s.\sqrt{\delta(t)} \quad (18)$$

5 Separation distance

As it was noted, building codes have recommended to provide require gap size between two adjacent buildings in order to avoid collision during earthquake. *ABS*, *SRSS* and *Standard 2800* [27] have suggested equations to measure separation distance based on maximum lateral displacement for first and second equation (1 and 2) and height for third equation (3), respectively. In here, by considering several dynamic multy degree of freedom systems, using *CRVK* program and neural network, optimum separation distance is calculated to cover the needed structural behavior and economical problem.

For this challenge, five scaled earthquake records are defined by different PGA, time and place of occurrence, frequencies and various earthquake characters. These records are *Parkfield* (1966), *San Fernando* (1971), *Kobe* (1995), *Loma Prieta* (1995) and *ElCentro* (1940) earthquake records. *San Fernando* has the highest acceleration among the four records discussed. This PGA amounted to 1.164g, with an epicentre distance less than 12 km. This earthquake had occurred in 1971, which vibrated this city with a magnitude of 6.61. Kobe also had a destructive earthquake in 1995. This earthquake with magnitude of 7.20 was stronger than San Fernando; in this record PGA was 0.7105g, which occurred in a distance of 18.3 km. *ElCentro* had a PGA about 0.348 and occurred in 12.2 km from epicentre by showing M_w about 6.9. *Loma Prieta* had acceleration about 0.312g and occurred at the epicentre distance of about 20 km. *Parkfield* had a destructive earthquake in 1966. This earthquake with magnitude of 6.19; in this record PGA was 0.462g, which occurred in a distance of 32 km. All mentioned records are directly normalized to investigate the effect of earthquake properties when bodies collide with each other. Scaled PGA of records are assumed to be 0.35g (See Fig.1).

Table 1 Earthquake records that are used in the study

Erathquake	M_w	PGA	Distance(km)
ElCentro	6.9	0.348	12.2
Kobe	7.2	0.71	18.3
Parkfield	6.2	0.462	32
San Fernando	6.6	1.16	12
Loma Prieta	6.3	0.312	20

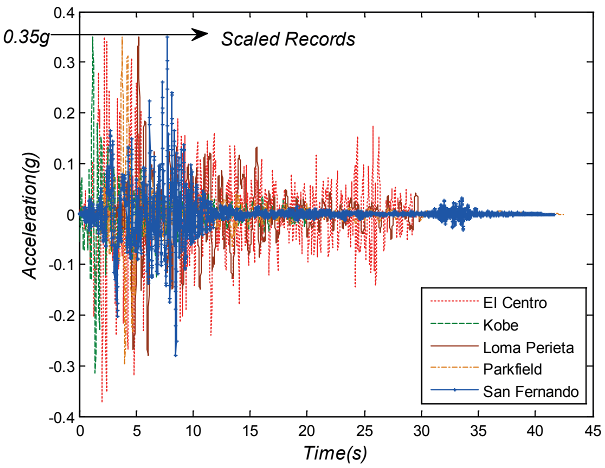


Fig. 1 Normalized acceleration records

In order to investigate the accuracy of *CRVK* program in zone of lateral displacement, the results of an experimental test is used to calibrate and confirm the program. For this work, an experimental test is considered, which was carried out by *Barros* and *Braz* [9]. A *3-DOF* system was set up with four columns at the corner having the same stiffness as shown in Figure (2). The columns are made of aluminum with an average cross section of 1.5mm by 50mm and the diaphragm floors are made of polycarbonate plates monolithically attached to the columns. The frame mass is around 19 kg and each floor has an average mass of 3.65 kg. The stiffness of the experimental frame was designed to keep the fundamental frequency near to 2 Hz. Assuming a three-story shear frame, the frame mass (M) and the stiffness matrix (K) are obtained as:

$$m = \begin{bmatrix} 3.65 & 0 & 0 \\ 0 & 3.65 & 0 \\ 0 & 0 & 3.65 \end{bmatrix} kg$$

$$k = \begin{bmatrix} 5820 & -2910 & 0 \\ -2910 & 5820 & -2910 \\ 0 & -2910 & 2910 \end{bmatrix} N/m$$

The three natural frequencies obtained with the above mass and stiffness matrices are: 2.00Hz, 5.60Hz and 8.09Hz. A damping of 0.5% along with the above mass and stiffness matrices formed the initial parameters for the modal analysis. ElCentro earthquake record was used to provide lateral loading.

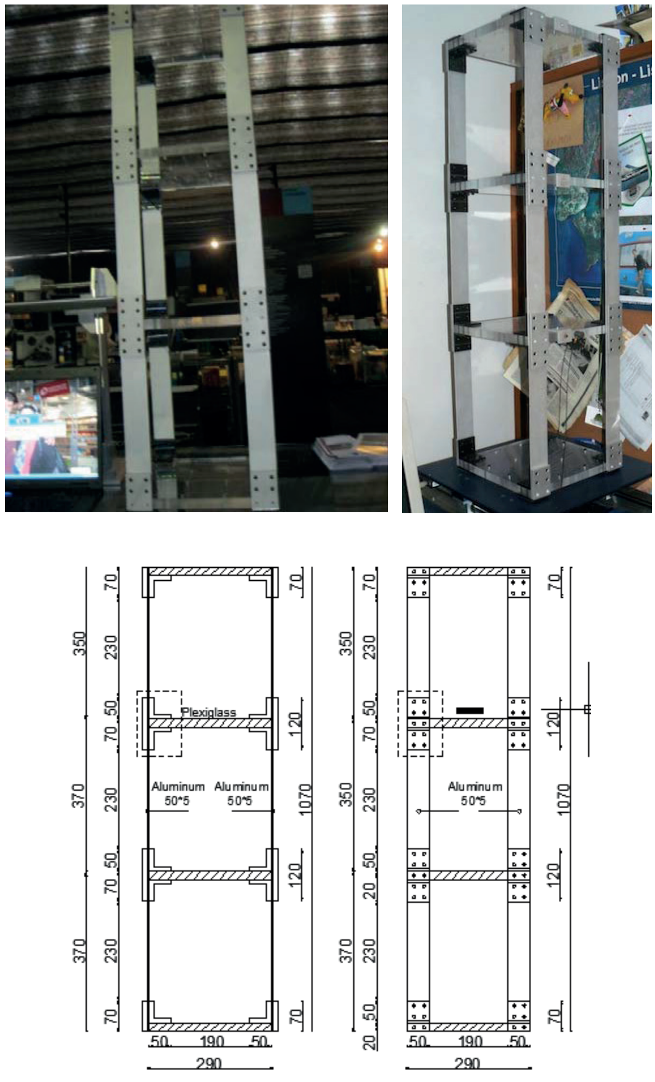


Fig. 2 3-DOF system and schematic form of model

All the information of models is defined in *CRVK* and lateral displacement of experimental and numerical analyses are compared with each other. As it is shown, the program has good accuracy in terms of lateral displacement.

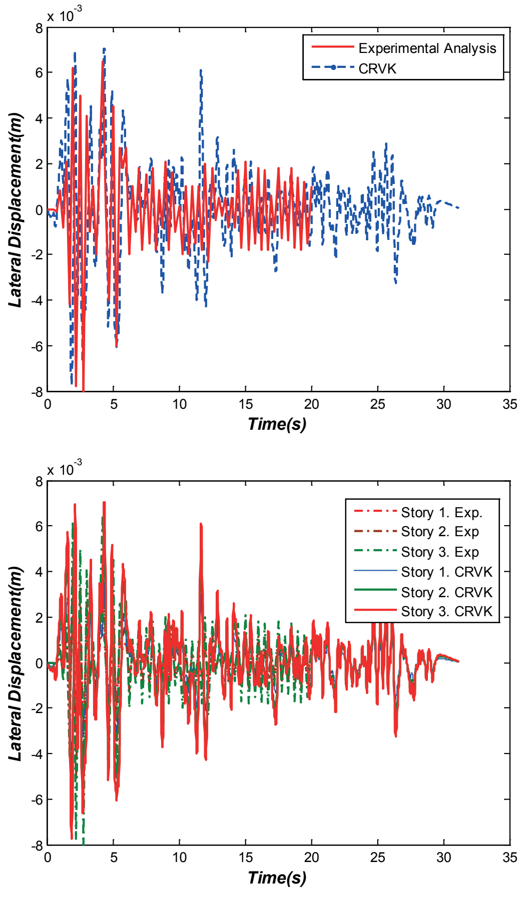


Fig. 3 Calibration of 3DOF model and *CRVK* for top level and all stories

In here, a parametric study has been conducted in order to verify the effectiveness of the separation distance and also three mentioned equations. For this parametric study, two multi degree of freedom systems are considered to be seismically fixed, assuming varous story to be located close to each other by n available seismic gap size, recommended by *Standard 2800* [27] that each story has a 3m height. Five scaled records are also used to provide lateral loading and get lateral displacement. Stiffness of each story is taken to be 1925000 *N.m* and story masses are assumed to be 5890 *kg*. Reinforced concrete buildings are generally considered to have 0.05 inherently damping.

Models are mathematically organized to have one to ten story and five earthquake records are used to provide lateral displacement. In fact, 500 models are numerically analyzed and lateral displacements of them are considered. Models are named to be *A* story and *B* story that *A* and *B* are the number of stories. Lateral displacement of top story of short building and contact level of tall building are equivalently proposed in order to investigate require separation distance between buildings. The period of models are assumed to be 0.16, 0.25, 0.35, 0.44, 0.53, 0.6, 0.67, 0.75, 0.82 and 0.9 *s* for one to ten story models, respectively.

All models are analyzed by five used earthquake records and overall peak lateral displacements of them are presented in Figure 4, which provides the maximum response at all models at the top level of dynamic systems.

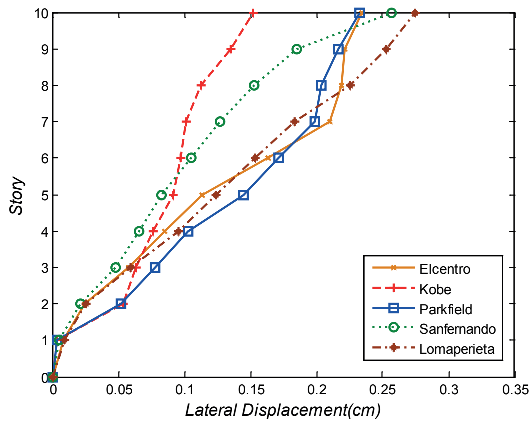
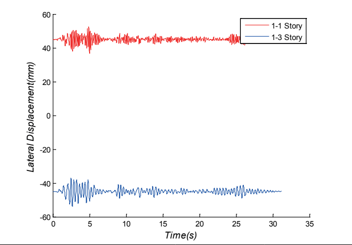
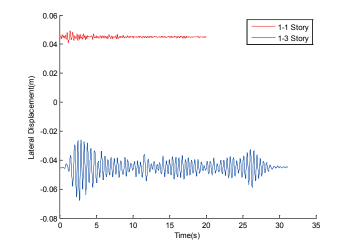
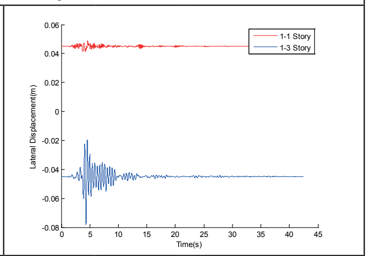
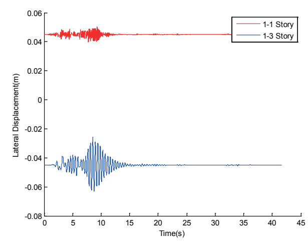
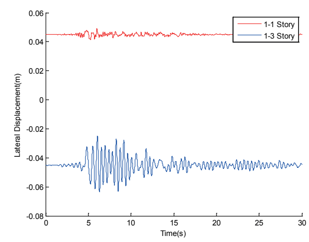


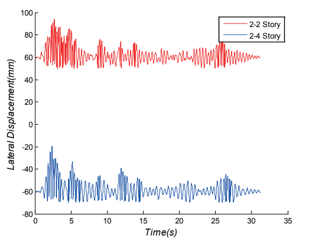
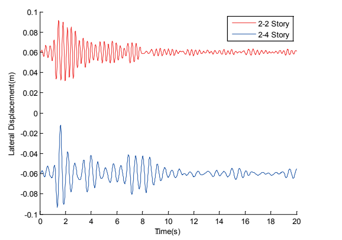
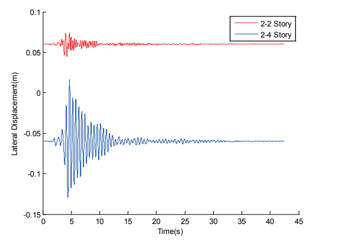
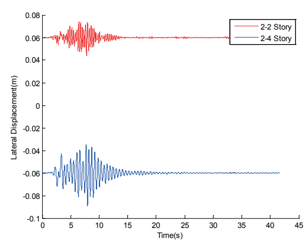
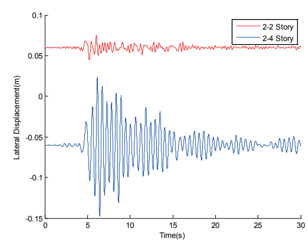
Fig. 4 Maximum lateral displacement of top story models with different records

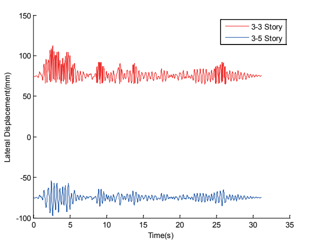
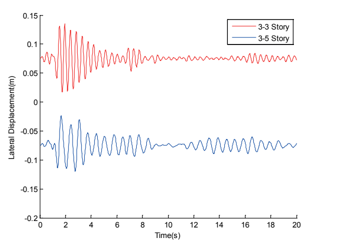
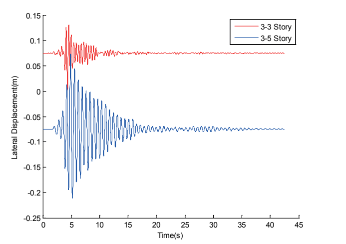
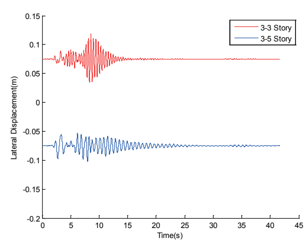
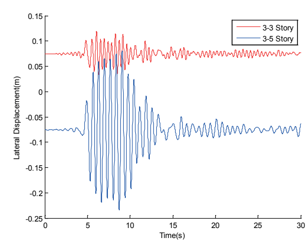
For example, maximum lateral displacement of story no. 3 of three-story building is 0.05788, 0.06313, 0.07745, 0.04802 and 0.05324 for *ElCentro*, *Kobe*, *Parkfield*, *Sanfernnado* and *Loma Prieta*, respectively.

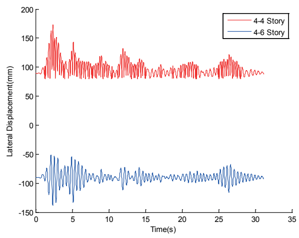
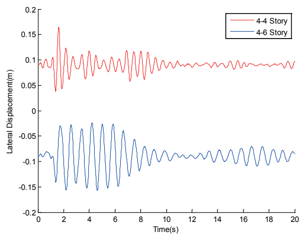
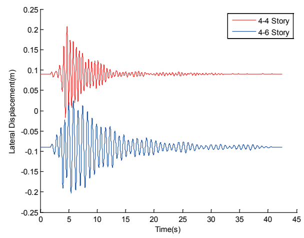
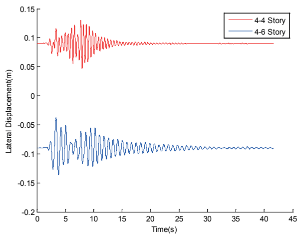
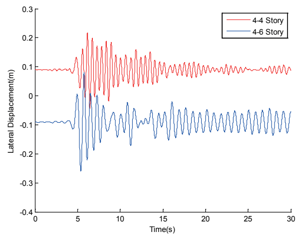
In here, all models and all records are used to analyze and investigate lateral displacement of models. After analyzing, lateral displacement of models are depicted and *CRVK* decreases gap size between models by 0.01 mm step to find nearest distance that avoid collision between models. Among 500 analyzed models, 40 depicted lateral displacements are collected and shown in Table 2. Required gap sizes for each model is automatically measured and considered to get the average of models. As records have been equivalently normalized to *0.35g,* it can be acceptable to assume that gap sizes are the average of determined separation distances. In Table 2, the average of separation distance for each model is seen by S_r .

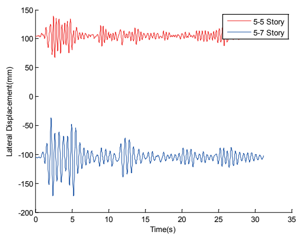
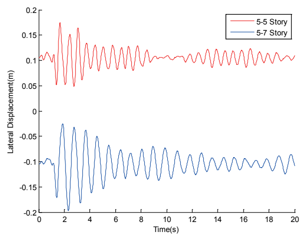
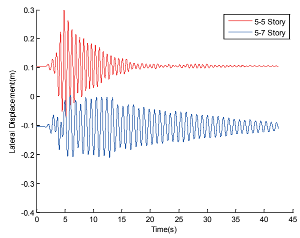
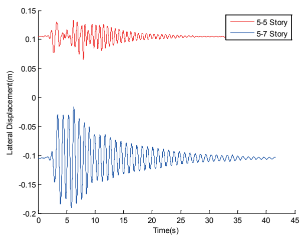
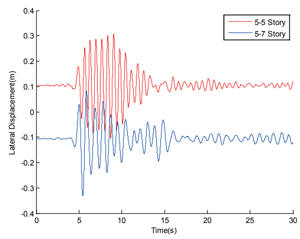
Table 2 The results of analyses for different models

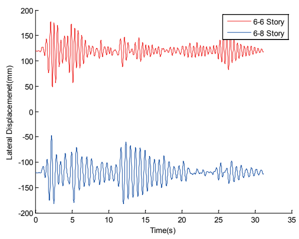
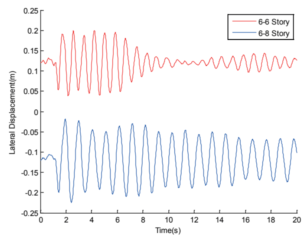
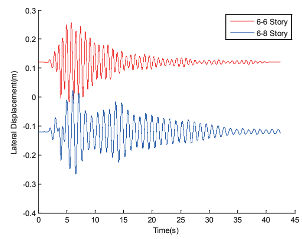
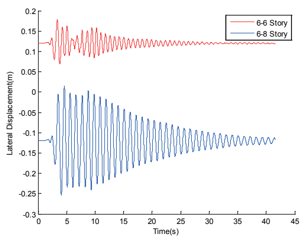
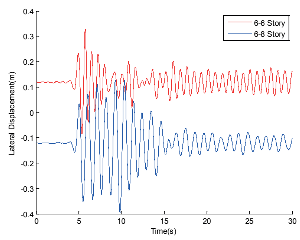
<table>
<tr><th>Model</th><th colspan="3">Gap Size = 9 cm</th><th colspan="3">S_r = 2.8 cm</th></tr>
<tr><td rowspan="4">1–3</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>ElCentro</td><td>Sr = 3.1 cm</td><td>Kobe</td><td>Sr = 2.8 cm</td><td>Parkfield</td><td>Sr = 3 cm</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="2">San Fernando</td><td>Sr = 2.4 cm</td><td colspan="2">Loma Prieta</td><td>Sr = 2.7 cm</td></tr>
</table>

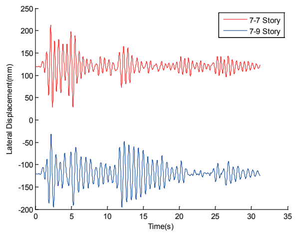
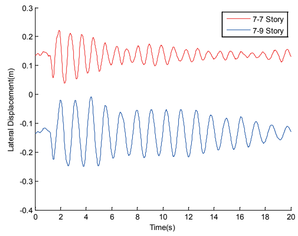
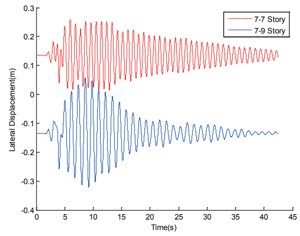
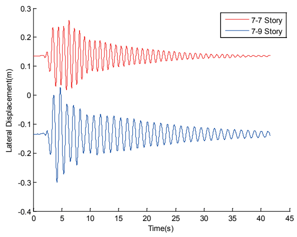
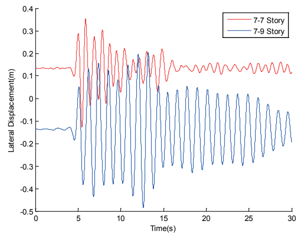
<table>
<tr><th>Model</th><th colspan="3">Gap Size = 12 cm</th><th colspan="3">S_r = 6.8 cm</th></tr>
<tr><td rowspan="4">2–4</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>ElCentro</td><td>Sr = 4.2 cm</td><td>Kobe</td><td>Sr = 7.3 cm</td><td>Parkfield</td><td>Sr = 8.2 cm</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="2">San Fernando</td><td>Sr = 4.1 cm</td><td colspan="2">Loma Prieta</td><td>Sr = 10.2 cm</td></tr>
</table>

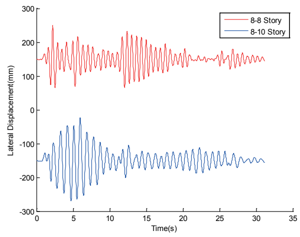
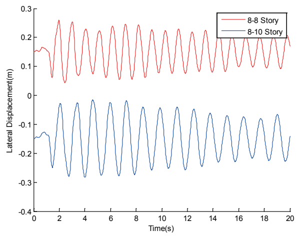
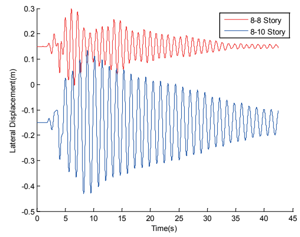
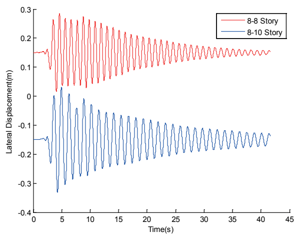
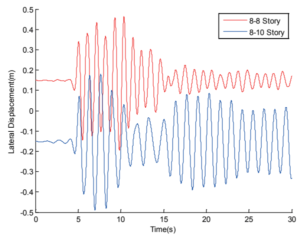
<table>
<tr><th>Model</th><th colspan="3">Gap Size = 15 cm</th><th colspan="3">S_r = 12.22 cm</th></tr>
<tr><td rowspan="4">3–5</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>ElCentro</td><td>Sr = 5.6 cm</td><td>Kobe</td><td>Sr = 10.3 cm</td><td>Parkfield</td><td>Sr = 17.5 cm</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="2">San Fernando</td><td>Sr = 6.5 cm</td><td colspan="2">Loma Prieta</td><td>Sr = 21.2 cm</td></tr>
</table>

Model	Gap Size = 18 cm			S_r = 14.98 cm		
4–6						
	ElCentro	*Sr* = 13.1 cm	Kobe	*Sr* = 11.5 cm	Parkfield	*Sr* = 20 cm
						
	San Fernando	*Sr* = 7.2 cm	Loma Prieta	*Sr* = 23 cm		

Model	Gap Size = 21 cm			S_r = 18.32 cm		
5–7						
	ElCentro	*Sr* = 10.1 cm	Kobe	*Sr* = 13.4 cm	Parkfield	*Sr* = 24 cm
						
	San Fernando	*Sr* = 13.1 cm	Loma Prieta	*Sr* = 31 cm		

Model	Gap Size =24 cm			S_r = 21.48 cm		
6–8						
	ElCentro	*Sr* = 10.4 cm	Kobe	*Sr* = 17.5 cm	Parkfield	*Sr* = 26 cm
						
	San Fernando	*Sr* = 16.5 cm	Loma Prieta	*Sr* = 37 cm		

Model	Gap Size = 27 cm				S_r = 25.2 cm	
7–9						
	ElCentro	*Sr* = 8.3 cm	Kobe	*Sr* = 20.5 cm	Parkfield	*Sr* = 28 cm
						
	San Fernando	*Sr* = 25.2 cm		Loma Prieta	*Sr* = 44 cm	

Model	Gap Size = 30 cm				S_r = 29.2 cm	
8–10						
	ElCentro	*Sr* = 16.1 cm	Kobe	*Sr* = 22.5 cm	Parkfield	*Sr* = 31 cm
						
	San Fernando	*Sr* = 28.2 cm		Loma Prieta	*Sr* = 48.2 cm	

Based on the observation of Table 2 for models, all the information of analysis are plotted and subsequently, recommended seismic gap size by Iranian code (*Standard 2800* [27]) is added to the figures for comparison and evaluation of estimated and recommended separation distance.

The computed response of separation distance for five earthquake records based on the period of models shows that commonly recommended separation distance by *Standard 2800* [27] indicates a fluctuation response among required gap sizes during earthquake records. The majority of models have shown considerable discrepancy in zone of gap size in comparison of recommended gap size and required gap size. For instance, needed gap size between models has to be more than recommended gap size during *Loma Prieta* record, but the value of separation distance is obviously seen to be less than calculated separation distance by *Standard 2800* [27] in another records.

An artificial neural network (ANNs) is an information processing tool that is inspired by the way biological nervous systems, process the information. The key element of this tool is the novel structure of the information processing system. An ANNs is configured for a specific application, such as pattern recognition or data classification, through a learning process. Learning in biological systems involves adjustments to the synaptic connections that exist between the neurons; the same process happens in ANNs. A biological neuron has major parts which are of particular interest in understanding an artificial neuron and include: dendrites, cell body, axon, and synapse. A neuron is an electrically excitable cell that processes and transmits information by electrical and chemical signalling. Chemical signalling occurs via synapses, specialized connections with other cells. Neurons connect to each other in order to form neural networks [30].

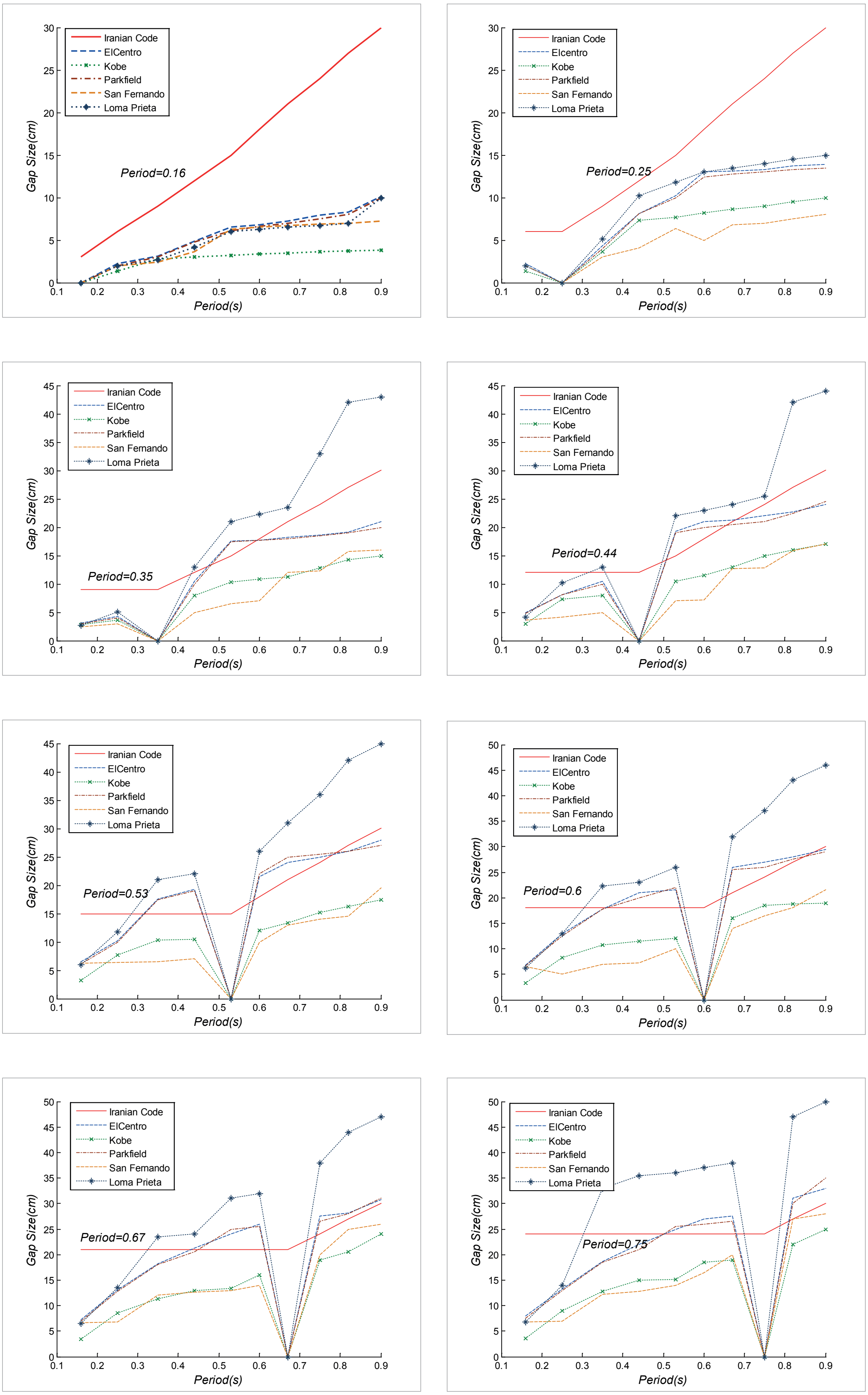


Fig. 5 Sufficient gap sizes for different models under various earthquake records

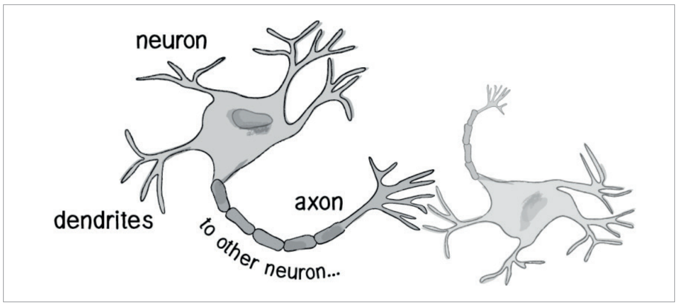


Fig. 6 Schematic of a biological neuron [30]

In order to generate a trend for calculating gap size between two buildings, neural network is used to coordinate all the information of analyses. For this challenge, seven inputs have been taken into consideration.

These inputs are period of first model, period of second model, and height of first and second model, masses of models and dominate frequency.

The target parameter was considered as the critical distance between the models (buildings).

Backpropagation is the generalization of the Widrow-Hoff learning rule to multiple-layer networks and nonlinear differentiable transfer functions. Since networks with biases, a sigmoid layer, and a linear output layer are capable of approximating any function with a finite number of discontinuities, input vectors and the corresponding target vectors are used to train a network until it can approximate a function. Standard backpropagation is a gradient descent algorithm in which the network weights are moved along the negative of the gradient of the performance function. The term backpropagation refers to the manner in which the gradient is computed for nonlinear multilayer networks. There are a number of variations on the basic algorithm that are based on other standard optimization techniques, such as conjugate gradient and Newton methods. Properly trained backpropagation networks tend to give reasonable answers when presented with inputs that they have never seen. Typically, a new input leads to an output similar to the correct output for input vectors used in training that are similar to the new input being presented. This generalization property makes it possible to train a network on a representative set of input/target pairs and get good results without training the network on all possible input/output pairs. The most common backpropagation training algorithm is Levenberg-Marquardt which was used in this investigation [30].

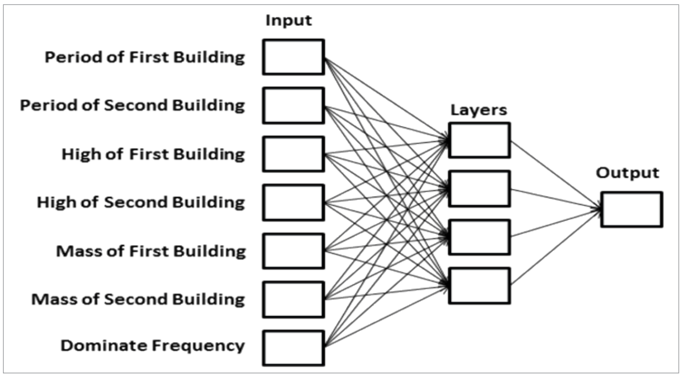
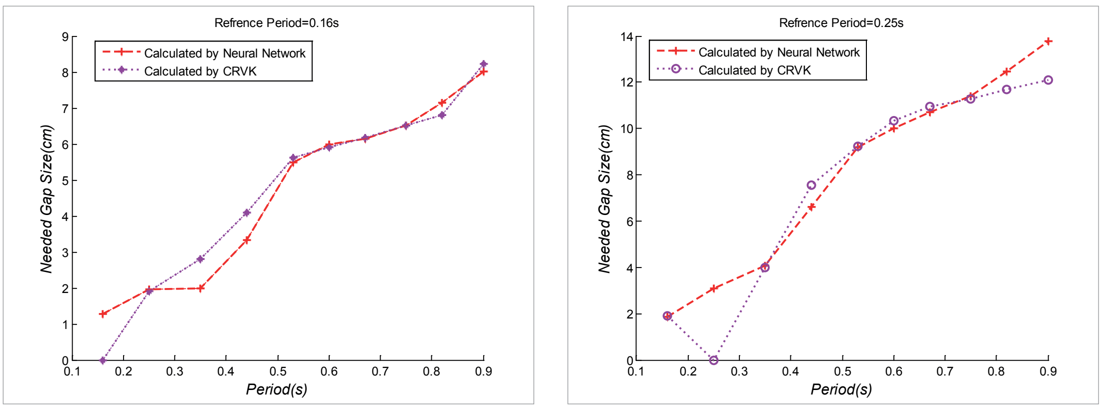


Fig. 7 Schematic of a neuron model
(output = critical distance needed between buildings)

As the first step for providing sufficient information and training, verifying and testing of neural networks, all inputs are informed and logically trained. After training, layers try to make a process, which is able to justify inputs for outputs and moreover, predict some responses with new inputs. In here, information of models is clearly defined as inputs and neural network provides some solutions to get outputs. The results of *CRVK* program and neural network are compared with each other which is shown in the Figure (8) exhibits good accuracy.



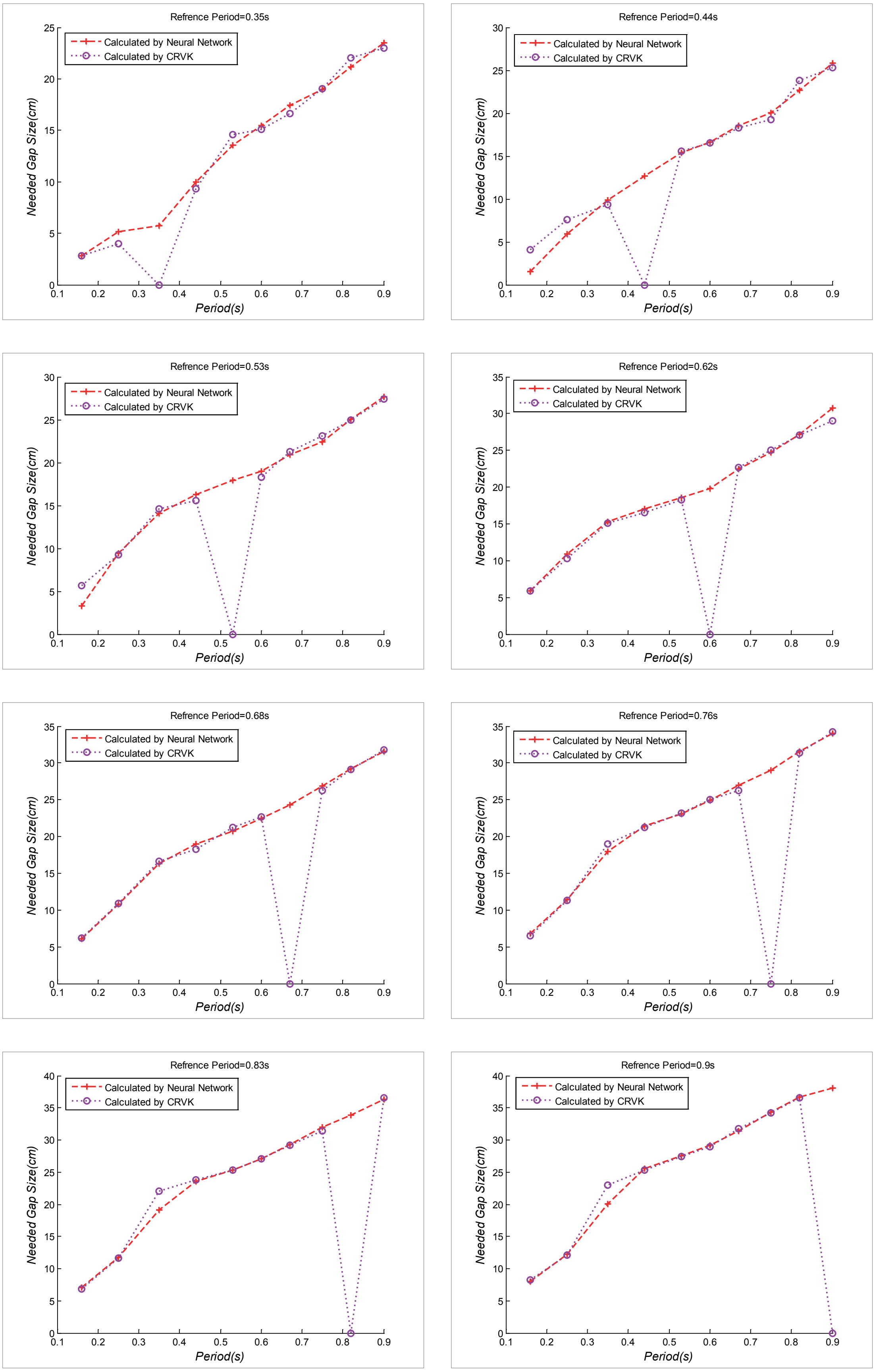


Fig. 8 Coordination of neural network and *CRVK* for gap size

Finally, the results of separation distance with *CRVK* and neural network are collected and combined with each other. A new equation by using both periods of buildings is created by coordination of the results which is a reference to estimate safety seismic gap (S_{op}) size between two buildings.

The equation is written as:

$$S_{op} = \sqrt{u_i^2 + u_j^2 - 2.SF.u_i.u_j} \tag{19}$$

where u_i and u_j are peak lateral displacements of adjacent buildings and *SF* denotes separation factor, which depends significantly of period of buildings and is obtained as:

$$SF = \left(\frac{T_j}{T_i}\right) - 10.5\left(T_j - T_i\right) \tag{20}$$

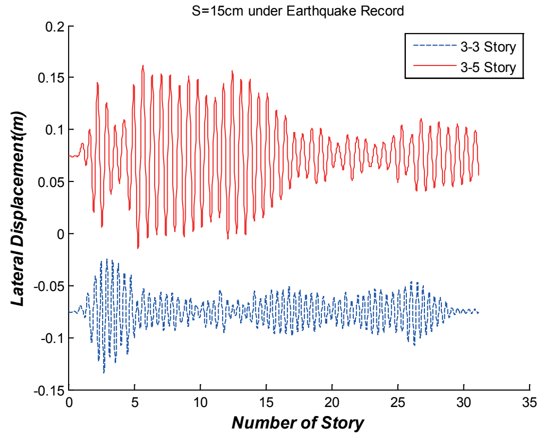
By having T_i and T_j, separation factor is numerically determined and gap size is accurately calculated to complete Equation (19).

Both equations indicate required separation distance to avoid collision and also save the land of structures to response nonlinear behavior of buildings and prevent economical problems during seismic excitation. Needed seismic gap size is numerically estimated for various periods by equation (19) and also logically confirmed by neural network.

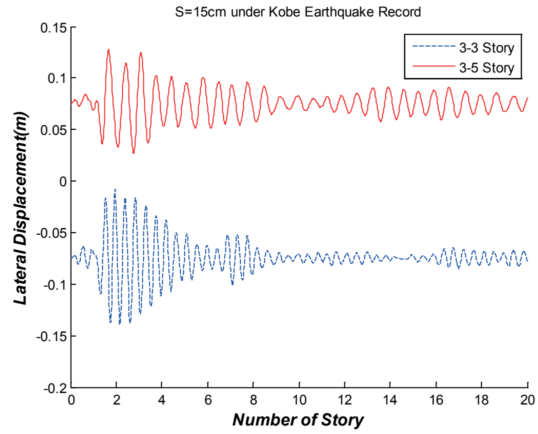
6 Numerical study

In a parametric study, a 3-story and 5-story typical buildings are considered. Based on the described assumption in this study, both buildings are assumed to be two multy degree of freedom systems with the same characteristics in zone of story stiffness, height story, masses and damping and also with three and five lumped masses by having 1500 kg, $1.7*10^6$ stiffness of each story and inherently 0.05 damping coefficient. The fundamental period of models are experimentally estimated to be 0.35s and 0.53s. A set of earthquake records are used that have been scaled to have PGA=0.35g (*ElCentro*, *Parkfield* and *Kobe*). Separation distance between models is considered to be 15 cm. Story No. 3 is considered to focus significantly on impact for investigation of force and energy absorption to evaluate optimum separation distance.

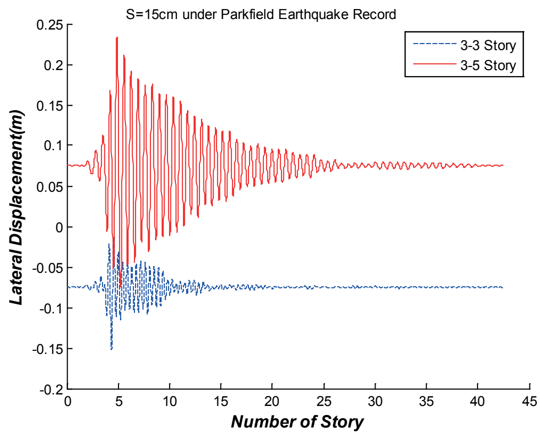
Lateral displacements of models at the third level are depicted and where pounding occurs, are obviously seen. The largest number of collisions between models takes place in *Parkfield* record, (about 45 impacts), and sudden decrease in number of collisions in *Kobe* record and *ElCentro* without any collision. The reason of displacement of models describes high value of impact forces in buildings, when lateral displacements exceed from predicted gap size and models collide with each other. This can be seen in figure (9) where the impact forces are plotted in terms of time and lateral displacement.



ElCentro



Kobe



Parkfield

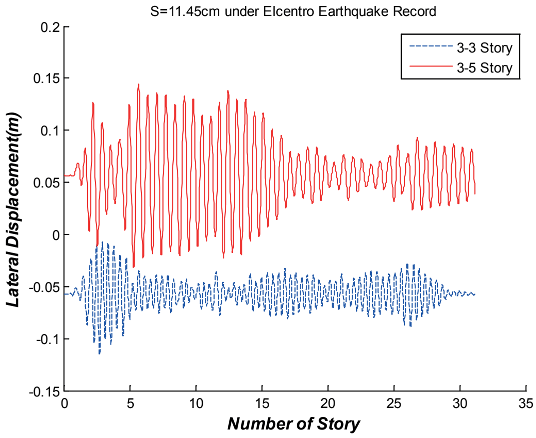
Fig. 9 Results of lateral displacements with three different earthquake records

In two first figures, separation distances are more than required and the third figure shows some collisions because of small separation distance. Therefore, considered separation distance between models does not seem to be beneficial for the seismically conditions under the specific excitation. In fact, models show various responses in different records by having the same gap sizes which depends significantly on characteristic of earthquakes.

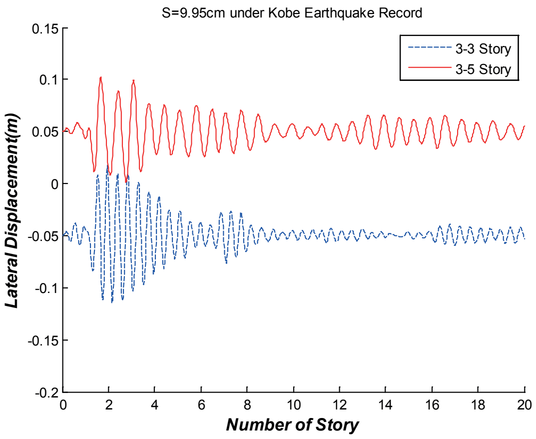
In here, three gap sizes are calculated by equation (19) based on peak lateral displacements and equation (20) in order to calculate required separation distance.

Table 3 The results of calculation of gap size (cm) by different approaches for two models with T = 0.35 and T = 0.53 sec

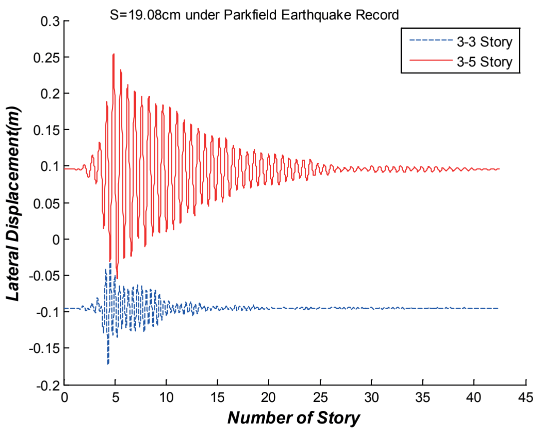
	$U_{3\text{-}3}$	$U_{3\text{-}5}$	Standard 2800 [27]	Equation (19)
ElCentro	5	8.7	15	11.45
Kobe	6.7	5.27	15	9.95
Parkfield	6.21	15.85	15	19.08



ElCentro



Kobe



Parkfield

Fig. 10 Final lateral displacement of models under different earthquakes by using suggested separation distance, equation (19)

It is obviously seen that using equation (19) can calculate the best separation distance between two adjacent buildings without collision.

7 Conclusions

In current study, different equations to calculate separation distance between adjacent buildings are collected and various solutions are numerically investigated. Building codes require separation distance based on peak lateral displacement or hight of the tallest building to calculate gap size for avoiding collision between structures. In order to investigate the effective gap size for prevention of collision between models, a nonlinear hysteresis impact model has been considered to simulate impact and equation is suggested based on cyclic process to calculate impact force and dissipated energy during seismic excitation. For this subject, a parametric study has been conducted to evaluate separation distance and justify a new space for selecting gap size with sufficient accuracy. Two MDOF systems with different hight and various periods, by having same lumped masses, are assumed to be located close to each other and three scaled earthquake records are used. Numerical study have shown that providing separation distance is very important, but it has to be considered that seismic gap size can be sufficiently calculated to avoid collision. Two mathematic program and neural network are especially used to coordinate relative responses for presenting the value of separation distance based on period of structures. Finally, sufficient gap sizes for different buildings having various periods is presented which is able to estimate seismic separation distance between structures with acceptably accuracy. The validation of gap sizes are confirmed by numerical analyses.

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