1. Introduction

In previous studies, it is shown that in near fault areas (R < 30 km) the vertical component of the earthquake appears to be significant [1, 2]. In these areas, the vertical-to-horizontal (V/H) ground motion ratio could exceed 2/3 which applies extra compression on columns and walls and affect other parts of a study such as beams, which are vulnerable to vertical loadings. For instance, the Bam earthquake of 26 December 2003 occurred in the city of Bam in the southeast of Iran [3]. That earthquake demolished the city of Bam. The greatest vertical acceleration of this earthquake was 1.1 times gravity. In this earthquake, the V/H ratio was almost 1. Another example is the Christchurch earthquake which struck on 22 February 2011 in Christchurch, New Zealand's second largest city [4]. The highest V/H ratio recorded for the Heathcote Valley Station was 1.66. These examples show that the vertical motions can play a significant role in the collapse of structures. Therefore, designing or retrofitting buildings for both horizontal and vertical components of earthquake is necessary for improving building safety and reducing the risk of death and injury in the near-fault areas. Recent papers, also, in this area suggest that this is currently a topic of interest among researchers [5-10].

In recent decades, a few studies have been conducted to investigate mechanisms for buildings to deal with vertical component of earthquakes. For instance, a research conducted by Barbieri et al [11] employed active control strategies in a two-story building on a base isolation system (which is modelled as a two-degree-of-freedom system and a changeable stiffness). The control is activated when either acceleration of excitation or velocity of the base exceeds a specific value. This study evaluated mechanism subjected to a vertical component of an earthquake. This method could decrease the top mass vibration, while some undesirable vibration can be observed at the base mass due to the actual ground motion.

Vu et al [10] proposed a vertical distributed flexibility and damping strategy (VDF) for base-isolated buildings. In this method, column bearings are installed to columns in order to reduce the vertical seismic motions in higher levels rather than in the base. There are many aspects which should be addressed about the details of this strategy in the future. For instance, details for column bearings and the resisting mechanism should be investigated as well as protecting non-structural components of isolated buildings.

Another research which was done by Furukawa et al, tested a full scale rubber base-isolated building on a shaking table in order to investigate the vertical ground motions effects [6]. In this study, the behaviour of appliances and equipment located on each floor has been addressed. It was demonstrated that a rubber base-isolation system could amplify the vertical acceleration, however, if the vertical acceleration is less than 2g, it is not detrimental. Liu et al propose an isolator including quasi-zero stiffness (QZS) and a vertical damper to reduce vertical ground motion in near fault earthquakes [8]. In concluding, some factors were identified as requiring further study as listed below.

In a very recent publication, Liu et al investigated a three-dimensional isolation of a four-storey building subjected to seismic ground motions [12]. This mechanism includes two layers which isolate a structure horizontally and vertically. As illustrated in this paper, lead-rubber bearings are used in the bottom layer to isolate the structure from horizontal ground motions, and some simple linear springs as well as viscous dampers are employed to isolate the building from vertical ones. This research compares the experimental and analytical model (in SAP2000 software) of an isolated structure with a non-isolated structure.

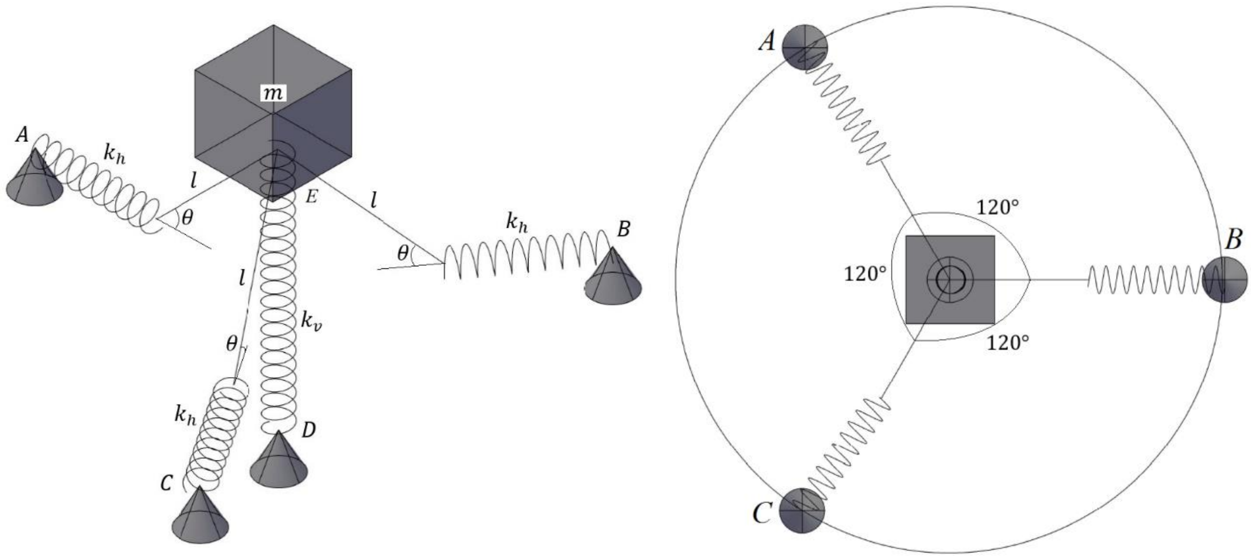
The concept of high-static-low-dynamic-stiffness (HSLDS) was proposed by Landi et al in 2016 [7]. This concept is based on high stiffness under static loading in order to limit the displacement, and low stiffness under dynamic loading to reduce the response of the system. Based on this concept, the idea of QZS has been developed [13]. This mechanism includes some springs with positive stiffness and some springs with negative stiffness. Therefore, in the equilibrium state, the total stiffness is zero. In the past decade some studies investigated different mechanisms based on this idea [14-19].

In this study, a mechanism based on HSLDS is developed for buildings to deal with damage caused by vertical component of earthquakes. HSLDS helps buildings to transfer static loadings such as dead, live, snow etc. to the ground using high stiffness, while the stiffness decreases in the event of an earthquake to reduce dynamic forces transmitted from ground to the structure. In a study by Mochida et al [9], the mechanism has been studied numerically and experimentally for static loadings. The numerical results were compared to experimental results, and it was proven that the stiffness (the slope of the load-displacement curve) decreased while the load increased.

In the present research, a two degree of freedom system is modelled in MATLAB to study the behavior of the mechanism subjected to dynamic loadings such as Bam and Christchurch earthquakes. Different factors involved in this mechanism are optimized in order to minimize the response of the system.

2. Description of the proposed model

A single degree of freedom system isolated with the proposed mechanism is modelled in MATLAB. The mechanism comprises three rigid legs with length l, one end of which is supported by a horizontal spring (stiffness:k_h) and the other end is connected to the mass (m) and is also supported with a vertical spring (stiffness: k_v). A 3D view and a top view of the model are shown in the Fig. 1 (a) and (b). The supports (points A, B, C, and D) are connected to a rigid body, which is in contact with the ground. The vertical displacements of these points are equal to that of the ground in an earthquake. It is important to note that the three horizontal springs remain horizontal all the time.



(a) (b)

Fig. 1 – (a) 3D view of the SDoF system and the isolator mechanism (b) Top view of the SDoF system and the isolator mechanism

2.1. Static behaviour

To find the static behavior and vertical displacement of the mechanism subjected to static loadings, it is necessary to find the effective static stiffness. As is presented in the Fig.2, the static load F is applied in the y direction to the top point of the mechanism, E. As a result, the internal force in the inclined bars, horizontal springs and the vertical spring are F_i, F_h, Fv, respectively. Applying the equation of equilibrium to point E in the y direction gives Eq. (1).

$$F = 3\ F_i \sin\theta + F_v \quad (1)$$

Considering *x'* as the horizontal projected length of the bar (*lcosθ*) and x'_0 as an initial value for *x'* (before applying the load F), the internal force in the horizontal springs can be calculated by applying the equation of equilibrium at joints A, B or C in the horizontal direction giving

$$F_h = F_i \cos\theta = k_h\,(x' - x'_0) \tag{2}$$

From Eq. (1) and Eq. (2)

$$F = 3k_h\,(x' - x'_0)\tan\theta + F_v \tag{3}$$

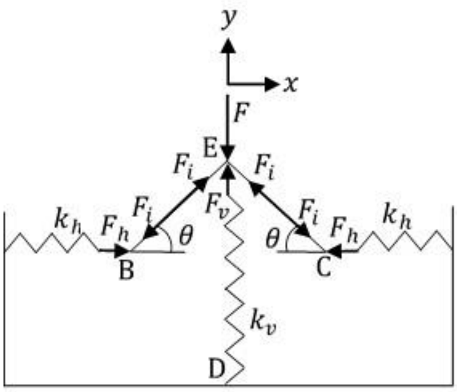


Fig. 2 – 2D view of the SDoF system and the isolator mechanism subjected to a static load F.

Taking *y'=l sinθ* as the vertical length of the bar, then *tanθ=y'/x'*. Therefore

$$F = 3k_h\,(x' - x'_0)\frac{y'}{x'} + F_v = 3k_h\,y' - 3k_h\,x'_0\frac{y'}{x'} + F_v \tag{4}$$

From the geometry

$$y'^2 + x'^2 = l^2 \tag{5}$$

In order to find the relation between *x'* and *y'*, the derivative of the Eq. (5) is taken to give

$$2y'\,dy' + 2x'\,dx' = 0 \quad \rightarrow \quad \frac{dx'}{dy'} = -\frac{y'}{x'} \tag{6}$$

The vertical effective stiffness of the system is defined based on the derivation of the force F with respect to the vertical displacement. Therefore, the relation between stiffness and force (positive displacement is considered upward) is

$$k_e = -\frac{dF}{dy'} \tag{7}$$

From (4) and (7)

$$k_e = -3k_h + 3k_h\,x'_0\frac{d}{dy'}\left(\frac{y'}{x'}\right) + \frac{d}{dy'}k_v\,y' \tag{8}$$

Finally the static effective stiffness for the mechanism is given by

$$k_e = 3k_h\left(\frac{\cos\theta_0}{\cos^3\theta} - 1\right) + k_v \tag{9}$$

2.2. Dynamic behaviour

Since the dynamic stiffness is a function of θ, the dynamic force is defined and used in the analysis instead of the dynamic stiffness. Here, y and y_G represent the displacement of the point E and the ground displacement respectively. Therefore, y' is equal to $l\sin\theta_0-(y_G-y)$ and x' is equal to $\sqrt{l^2-(l\sin\theta_0-(y_G-y))^2}$ (based on Eq. (5)). Here θ_0 is an initial angle before applying loads to the mechanism.

Finally, by using Eq. (3) the dynamic force transmitted from the ground through the mechanism is given by

$$F_{dyn}=3k_h\left(\sqrt{l^2-(l\sin\theta_0-(y_G-y))^2}-l\cos\theta_0\right)\times\frac{l\sin\theta_0-(y_G-y)}{\sqrt{l^2-(l\sin\theta_0-(y_G-y))^2}}+k_v(y_G-y) \quad (10)$$

3. Case study

In this study, the mechanism is designed to support a static load of 50 kN (the private communication, Alan Park [20]) subjected to a vertical excitation. As a part of design process, the stiffness of the horizontal and vertical springs, the initial value θ_0, and the length of the bars need to be calculated. Since the space beneath buildings is limited, the length 20 cm is considered for the bars. In this case, a space of at least 40 cm is reserved for this isolation to make sure that it would work properly. Different values of k_v and k_h are considered in order to find the best combination to minimize maximum acceleration reduction. The lowest stiffness of springs, which would result in the minimum force transmission, is assumed as the optional combination. Table 1 and 2 show the various stiffness for vertical and horizontal springs respectively.

Table 1 – Stiffness of the vertical spring

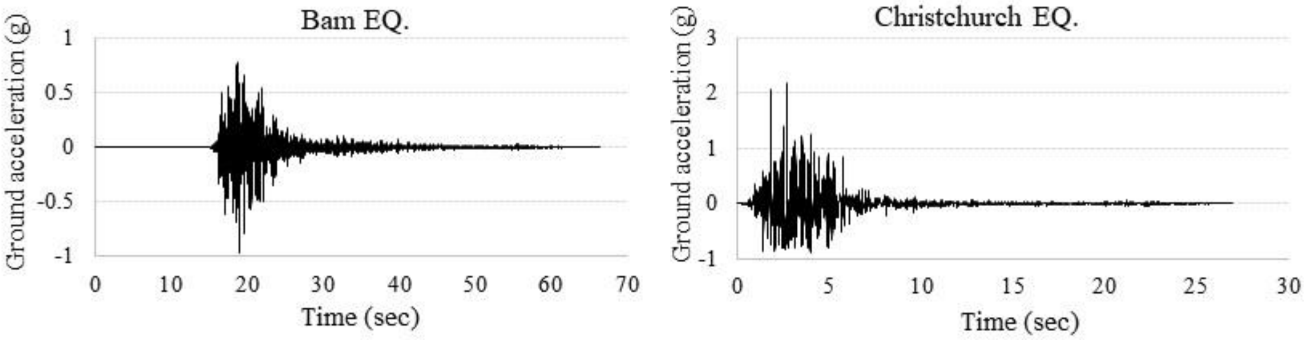
	Comb1	**Comb2**	**Comb3**	**Comb4**	**Comb5**	**Comb6**	**Comb7**	**Comb8**	**Comb9**	**Comb10**
θ_0	k_v (kN)	k_v (kN)	k_v (kN)	k_v (kN)	k_v (kN)	k_v (kN)	k_v (kN)	k_v (kN)	k_v (kN)	k_v (kN)
20°	78877	86048	93218	100389	107559	114730	121901	129071	136242	143413
25°	63834	69637	75440	81244	87047	92850	98653	104456	110259	116062
30°	53955	58860	63765	68670	73575	78480	83385	88290	93195	98100
35°	47034	51310	55585	59861	64137	68413	72689	76964	81240	85516
40°	41970	45785	49600	53416	57231	61047	64862	68677	72493	76308
45°	38152	41620	45089	48557	52025	55494	58962	62430	65899	69367
50°	35217	38418	41620	44821	48023	51224	54426	57627	60829	64030
55°	32933	35927	38921	41915	44909	47903	50897	53891	56885	59879
60°	31151	33983	36815	39647	42479	45310	48142	50974	53806	56638
65°	29766	32472	35178	37884	40591	43297	46003	48709	51415	54121

Table 2 – Stiffness of the horizontal springs

	Comb1	**Comb2**	**Comb3**	**Comb4**	**Comb5**	**Comb6**	**Comb7**	**Comb8**	**Comb9**	**Comb10**
θ_0	k_h (kN)	k_h (kN)	k_h (kN)	k_h (kN)	k_h (kN)	k_h (kN)	k_h (kN)	k_h (kN)	k_h (kN)	k_h (kN)
20°	396338	396338	396338	396338	396338	396338	396338	396338	396338	396338
25°	206460	206460	206460	206460	206460	206460	206460	206460	206460	206460
30°	122038	122038	122038	122038	122038	122038	122038	122038	122038	122038
35°	78810	78810	78810	78810	78810	78810	78810	78810	78810	78810
40°	54361	54361	54361	54361	54361	54361	54361	54361	54361	54361
45°	39472	39472	39472	39472	39472	39472	39472	39472	39472	39472
50°	29875	29875	29875	29875	29875	29875	29875	29875	29875	29875
55°	23404	23404	23404	23404	23404	23404	23404	23404	23404	23404
60°	18879	18879	18879	18879	18879	18879	18879	18879	18879	18879
65°	15622	15622	15622	15622	15622	15622	15622	15622	15622	15622

3.1. Input signals

The Bam earthquake (2003) and Christchurch earthquake (2011, Heathcote Valley Station) are used as input signals to evaluate the dynamic behavior of the system and design appropriate characteristics of the mechanism. These two earthquakes have a peak ground acceleration of 0.97g and 2.18g respectively, which are considered as severe earthquakes. The RMS of the acceleration of these earthquakes are also 0.83g for the Bam earthquake and 1.92 for the Christchurch earthquake. The ground acceleration for the vertical component of these two earthquakes are shown in Fig. 3.



(a) (b)

Fig. 3 – Acceleration vs. time for (a) Bam Eq., and (b) Christchurch Eq.

3.2. Criteria

The most important criterion, which should be considered in choosing the best combination for horizontal springs, vertical spring, and the initial angle, is the maximum acceleration. Since the vertical ground acceleration results in axial force fluctuations in columns [21], it could cause different types of failures due to buckling, reducing the shear capacity and uplifting. Furthermore, it is the most important factor to be addressed. In addition, the sensitivity of the mechanism to different static loads may also be an important consideration in the design process. As the stiffness of the mechanism is related to the applied loads, any changes in static loadings would result in different vertical displacements, and this situation may cause discomfort to residents and could even make them feel unsafe. The sensitivity factor (*S*) is defined by the difference between the static displacements of the system with ±10 percent changes in the static loading (Eq. (11)). While it is desirable to minimize the sensitivity, a certain amount of displacement due to change in static load is inevitable because this factor is correlated to the stiffness of the base and affects the function of the mechanism.

$$S = |\Delta_{m+10\%} - \Delta_{m-10\%}| \qquad (11)$$

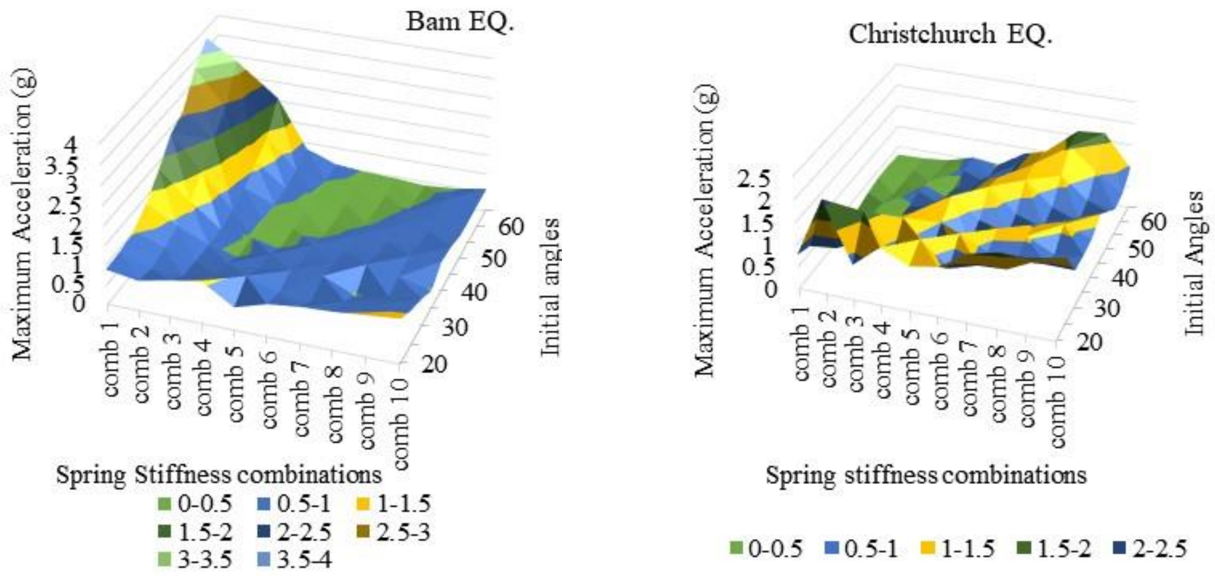
4. Results

The MATLAB simulations were performed using the differential equation solver ODE45 for the different combinations of the spring stiffness subjected to the Bam and Christchurch earthquakes and the results are presented as follows.

4.1. Acceleration Reduction

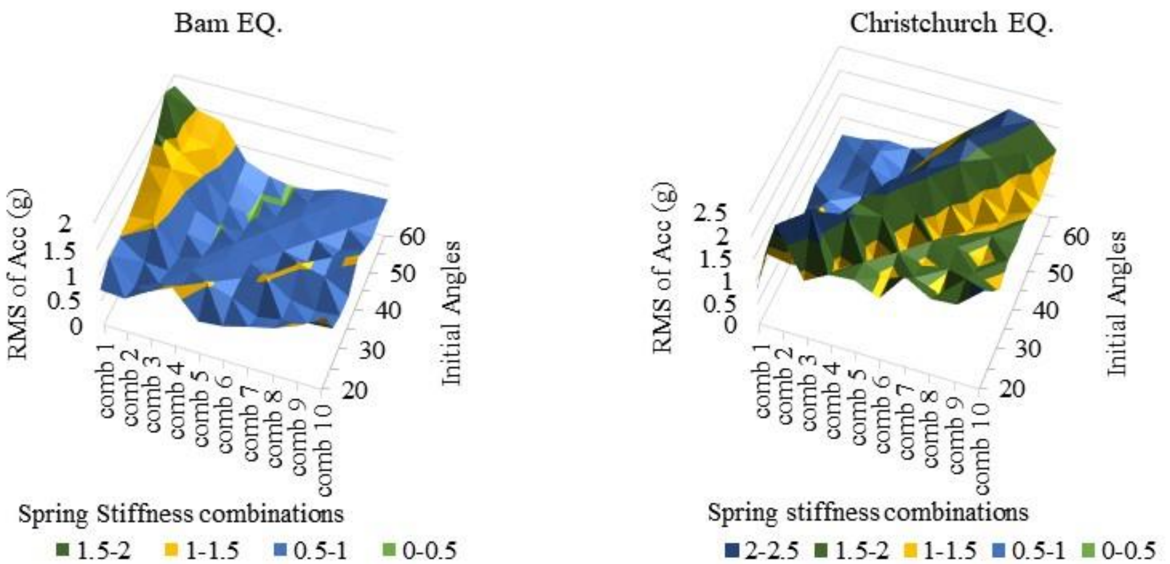
As it can be seen in Fig. 4, the peak responses of the system to the Bam earthquake are sometimes opposite to those of to the Christchurch. For instance, considering the case with an initial angle of 65° and the combination 1 for the springs, the acceleration response system subjected to the Bam earthquake is magnified to about 4 g, while it is decreased to 0.3g for Christchurch earthquake. There are only few cases which result in significant acceleration reduction for both input excitations for the same spring stiffness and initial angle θ_0. It is evident that combination 3 and initial angle of 40° reduces the peak acceleration response to 0.53g and 0.49g subjected to Bam and Christchurch earthquakes respectively. In other words, the acceleration reductions for this case would be Bam earthquake: 46% and Christchurch earthquake: 77%.

The RMS acceleration are shown in Fig. 5 for different cases subjected to the Bam and Christchurch earthquakes. The results are similar to those for maximum acceleration (see Fig. 5). For the mentioned case (combination 4 and initial angle of 40°) the reduction in the RMS acceleration are 28% and 56% for the Bam and Christchurch earthquakes respectively.



(a) (b)

Fig. 4 – Maximum acceleration of the system subjected to (a) Bam EQ., (b) Christchurch EQ



(a) (b)

Fig. 5 – RMS acceleration of the system subjected to (a) Bam EQ., (b) Christchurch EQ.

4.2. Sensitivity

Fig. 6 shows that the sensitivity of the mechanism increases when the stiffness of the springs decreases, which is to be expected. In the worst case, although the initial angle is 65° and the mechanism is geometrically stiffest, the softness of the spring increases the sensitivity and result 0.13m sensitivity. For the proposed case, the sensitivity is equal to 0.63 m.

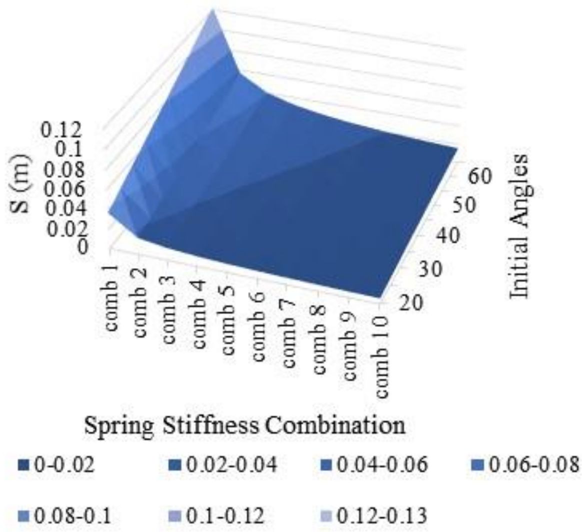
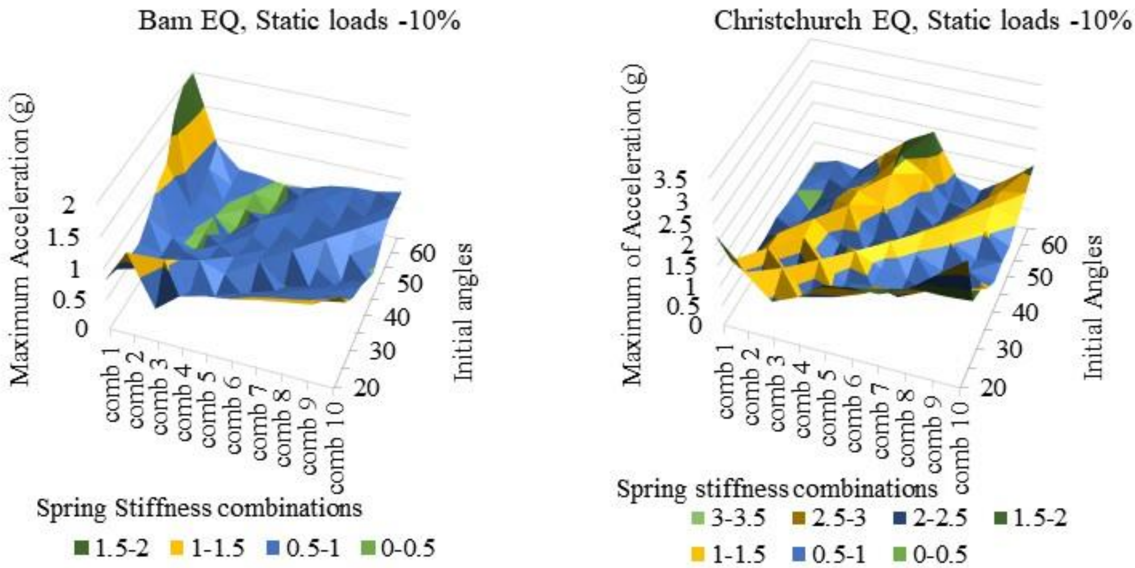


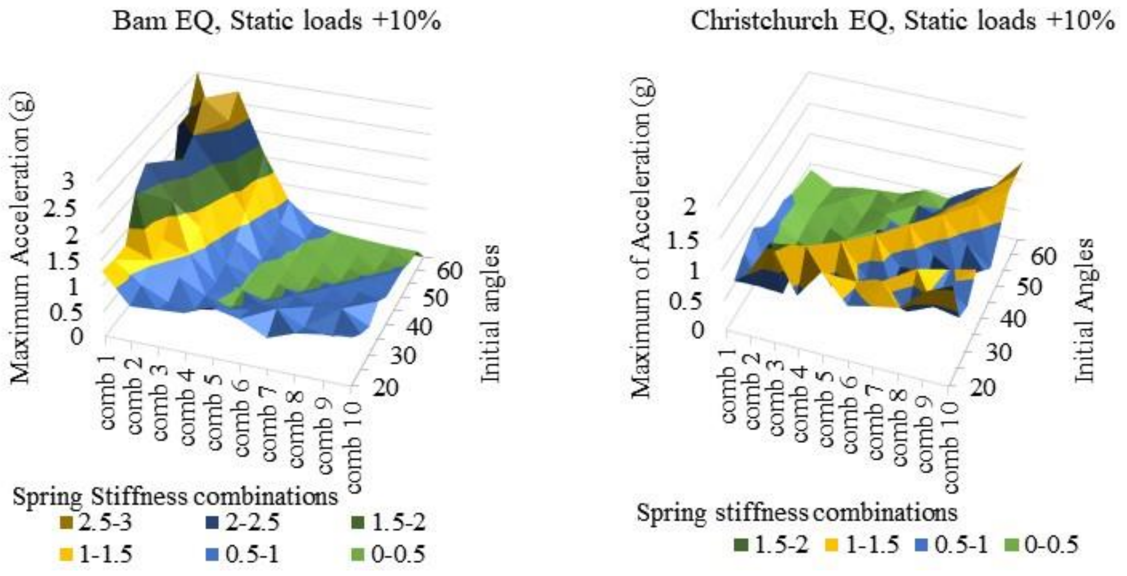
Fig. 6 – Sensitivity



(a) (b)

Fig. 7 – Maximum acceleration of the system with 10% less static subjected to (a) Bam EQ., (b) Christchurch EQ

In addition, it is important to consider the acceleration reduction for the cases with ±10 percent changes in the static loading; because in the event of an earthquake, the static loads may be different from the design case which would affect the response of the structure. Fig. 7 shows the maximum response acceleration of the system with 10 percent less static load. As can be seen, the response of the structure subjected to Bam excitation is generally lower than the case with the design load, while that for Christchurch excitation it is higher. The opposite is true for the system with 10 percent more static loading (Fig. 8). In other words, the higher loads result in more reduction in the response of the system subjected to the Christchurch earthquake, however, this causes higher acceleration response for the Bam earthquake. For the case with an initial angle of 40° and combination 4 for spring stiffness, the acceleration reduction for the case with 10% more static loads subjected to the Bam and Christchurch earthquakes is 37% and 64% respectively. Moreover, the acceleration reduction for the other case with 10% more static loads would be 33 percent (Bam excitation) and 77 percent (Christchurch excitation).



(a) (b)

Fig. 8 – Maximum acceleration of the system with 10% more static loading subjected to (a) Bam EQ., (b) Christchurch EQ.

5. Conclusions

Overall, in the near-fault areas with strong vertical ground motions, the proposed mechanism may help to decrease the response acceleration of the system considerably. This study has proposed the optimum factors for the mechanism to minimize peak and RMS acceleration. The amount of the reduction varies depending on the characteristics of the base input signal. For this purpose, the system was analyzed subjected to the Bam and Christchurch earthquake signals, which have significantly different frequency characteristics. More work may need to be done to make sure that the proposed mechanism works for a broad range of earthquakes. For the optimized case (the static loads of 50 kN and bar length of 20 cm) the best combination for the spring stiffness is: k_h = 5.44e^{+4} kN/m, k_v = 5.34e^{+4} kN/m, and the initial angle θ_0 = 40˚. This combination results in the optimum response with at least 33% acceleration reduction considering static loads variation.

However, this study only considered the effects of the vertical excitations on the mechanism. Since an earthquake consists of excitations in different directions, considering the combination of horizontal and vertical excitations may affect the function of the mechanism, which needs to be explored. In addition, this study is about a function of a single mechanism located beneath a column. In a building each column bear different static loads which cause different displacements. These differential displacements should also be explored. Moreover, in the event of earthquake, the horizontal movement of the building would affect these mechanisms. The consequential changes to the load distribution need to be considered.

6. References

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