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SEISMIC VULNERABILITY OF RESTRAINED AND UNRESTRAINED BLOCK-TYPE NONSTRUCTURAL COMPONENTS

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ABSTRACT

In this paper, analytical techniques are used to determine the fragility of freestanding rigid equipment under seismic excitations and to further improve their seismic mitigation measures. These measures can be carried out using some types of restraints that reduce the displacements and accelerations considerably. The results show that fragility curves for restrained blocks are sensitive mainly to the dynamic coefficient of friction and to the ratio of the vertical component of the cable forces to the weight of the block and they have direct relation to the maximum magnitudes of the pseudo-velocity spectrum curves.

Keywords: Non-structural components; fragility; sliding; SIMQKE; artificial records

1. INTRODUCTION

Non-structural components are those systems and elements housed or attached to the floors and walls of a building which are not part of the main or intended load-bearing structural system for the building, but may also be subjected to large seismic forces and depend on their own structural characteristics to resist these forces [1]. According to this definition, partitions, masonry infill panels, suspended ceilings, finishing, as well as mechanical and electrical equipments can be generally regarded as "non-structural" components.

Effects of recent earthquakes have clearly shown that the overall seismic hazard to structures cannot be efficiently reduced unless the design of non-structural components receives the same degree of consideration as primary structural members. In past earthquakes, the level of damages sustained by non-structural components was in most cases higher than that usually considered acceptable [2-4]. Many buildings that remained

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structurally sound after the earthquake lost their functionality due to damage to their non-structural components. While this is always inconvenient and undesirable for any kind of construction, it is certainly unacceptable for critical facilities, such as hospitals, that need to be functional during and after an earthquake. Examples of such damages had been seen in the 1971 San Fernando, 1994 Northridge, 1995 Kobe, and 2003 Bam earthquakes. Economic loss due to seismic non-structural damage can also be considerable. A case in point is the seismic damage sustained by buildings during the 1994 Northridge earthquake. With the loss of approximately $18.5 billion due to building damage, non-structural damage accounted for about 50% of this total [5]. The 1994 Northridge earthquake clearly demonstrated the inadequacy of previous practices that address only life safety and collapse prevention for the structure.

In the past, by limiting excessive displacements and providing simple rules for determining the maximum inertial action, the various seismic codes and guidelines had tried to decrease non-structural damages. However, and based on the inadequacy of these regulations in past earthquakes, some of the leading international building codes have adopted sweeping changes [6, 7]. One motivation for these changes is to better assure operational performance of critical non-structural systems. The new code's regulations have expanded to include new non-structural dynamic demand provisions for critical active mechanical and electrical equipments [6, 7]. Furthermore, such provisions need to be based upon recognized testing standards, such as AC156 [8]. This later standard establishes the minimum requirements for the seismic qualification shake-table testing of non-structural components and systems. To have general information on these new provisions and detailed information on the seismic qualification testing, reference is made to Gatscher and Littler [9] and Caldwell et al. [10].

In the future, the need for non-structural dynamic demand provisions will increase as more systems require active operation compliance [11]. At the moment, beside Potential problems of execution of shaking table tests for seismic qualification [12], many third-world countries lack the necessary facilities to implement the new code requirements mentioned above. To meet these requirements, the present paper suggests a numerical simulation procedure to be used to evaluate the performance of non-structural components on statistical bases. This procedure is based on generating artificial records that can be used to establish fragility curves that are necessary for identifying the performance-level for a given component.

2. NONSTRUCTURAL FRAGILITIES

This research aimed to evaluate the sliding response of free standing block-type nonstructural components in direct contact with horizontal supporting surfaces. Block-type components include all nonstructural components that their behaviors are essentially that of a rigid body, and as such can then be appropriately modeled. These components are subjected to base excitation and might be either restrained or unrestrained. The four types of response which could occur for the free standing block-type components either are at rest, or sliding, or rocking, or jumping. The combination of these motion types may also occur [13].

A vast amount of studies have been dedicated to develop rational methods of analysis of block-type components in buildings in the past few decades. Earlier contributions have focused on the rocking response [14-18]. The conditions under which the response is only of sliding nature have been also investigated [13, 17, 19-22]. For unrestraint blocks, sliding response occurs only for a certain range of values of the width-to-height ratio of the block. These restrictions, however, are not applicable for restrained blocks. The equations of motion of the restrained block under sliding response have been developed by Lopez Garcia and Soong [23].

In this paper, two groups of acceleration histories have been used. The first group is based on suggested design response spectrums that includes the Iranian standard design response spectrum [24], the normalized response spectrum suggested by the 2010 edition of AC156 [8] and the design response spectrum suggested by Shakib [25]. The second group contains eight local earthquake records given in Table 1 [26]. The later records belong to soil type 2 in the IS2800 and type B in the USGS classification systems.

Table 1: Earthquake records used in this paper [26]

Earthquake	Record No.	Epicentre Distance (km)	Horizontal components		Vertical Components	
			PGA (g)	PGV (cm/sec)	PGA (g)	PGV (cm/sec)
Naghan	1-1054	5	0.808	67.359	0.580	42.614
Tabas	1-1084	54	0.790	91.697	0.683	33.615
Zarrat	16-142	27	0.317	12.964	0.109	3.843
Qasem Abad	01-1754	60	0.141	12.946	0.076	2.811
Kaboodar Ahang	01-2754	55	0.082	5.924	0.068	2.986
Zanjiran	9-1502	12	1.068	31.117	0.941	15.893
Siyahoo	01-2325	25	0.213	5.978	0.137	3.101
Sirch	01-1913	7	0.592	83.891	0.784	95.295

The method used in this paper is based on the SIMQKE software program. The acceleration histories were scaled to horizontal peak base accelerations (HPGA) ranging from 0.10 g to 1.50 g with 0.10 g increments. For each of these cases, 90 artificial records have been generated. The input data has been applied to blocks supported on surfaces with different dynamic coefficients of friction (μ_d) that range from 0.1 to 0.5. Furthermore, the effect of vertical peak base accelerations (VPGA) has been investigated by using five different vertical-to-horizontal-acceleration ratios (k) that ranges from zero to 0.67. By determining the equation of sliding motion and solving it numerically, displacement and acceleration time histories for the sliding block are obtained.

The fragility curves for nonstructural components excited by different records have been established for the sliding response. In order to form fragility functions it is first necessary to specify measures of damage. Although a variety of such measures are possible, this study has followed previous works in choosing "excessive displacement" as an indicator for the failure of an unrestrained block [13]. For restraint blocks, two limit states are considered;

breakage of the restraining cables and excessive absolute acceleration [23].

3. PERFORMANCE OF UNRESTRAINED BLOCKS

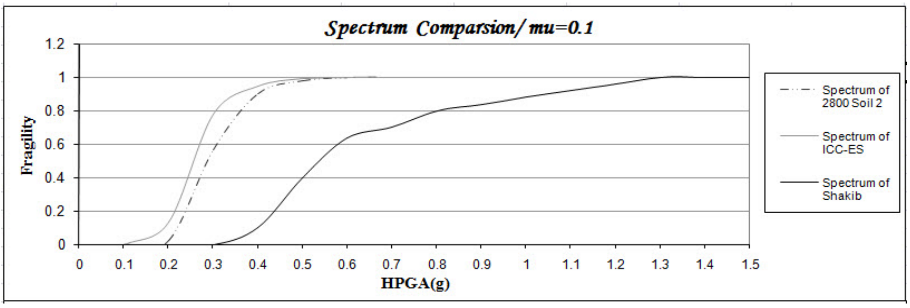
The behavior of unrestraint blocks under different seismic events has been investigated. The eight records given in Table 1, the Iranian standard design response spectrum [24], and the response spectrum suggested by AC156 [8], and the design response spectrum suggested by Shakib [25], have been applied to the unrestraint block. The block average relative peak displacements, which are obtained from the ninety peak displacements obtained from the ninety acceleration time history inputs for different coefficients of friction (μ_d) are shown in Table 2.

It is clear from these results that the peak displacement increases as the vertical to horizontal coefficient (k) increases, while increasing the coefficients of friction would reduce displacements. Moreover, comparing the results given by the eight seismic records, it is found that the highest results are those attributed to Sirch and Tabas Earthquakes. By investigating the properties of these two and other earthquakes, it has been found that such results have direct relation to the maximum magnitudes of the pseudo-velocity spectrum curves.

Table 2: Average displacements (cm) of 90 artificial acceleration records scaled to 1g with k=2/3 for the unrestricted blocks

μ_d	Naghan	Tabas	Zarrat	Qasem Abad	Kaboodar Ahang	Zanjiran	Siyahoo	Sirch	IS2800		ICC	Shakib, k variable
									k=0	k=2/3		
0.1	6.15	15.56	5.63	9.31	11.97	3.39	6.27	21.44	25.02	34.52	44.92	5.75
0.2	6.15	16.32	6.24	7.49	14.46	3.68	8.16	24.66	17.48	31.76	40.46	6.48
0.3	5.63	14.88	4.54	4.30	12.80	2.56	7.03	21.99	10.24	27.53	36.28	5.37
0.4	3.94	11.54	2.68	2.07	9.44	1.45	5.00	16.36	5.89	22.81	30.02	3.58
0.5	2.51	8.08	2.89	1.00	6.39	0.78	3.28	11.21	3.11	17.08	22.65	2.24

To have better understanding for these results, the fragility curves for the three response spectrum curves of the first group are presented in Figure 1. They include the Iranian standard design response spectrum with k = 0 [24], the normalized response spectrum suggested by AC156 with k= 2/3 [8] and Shakib's response spectrum [25].



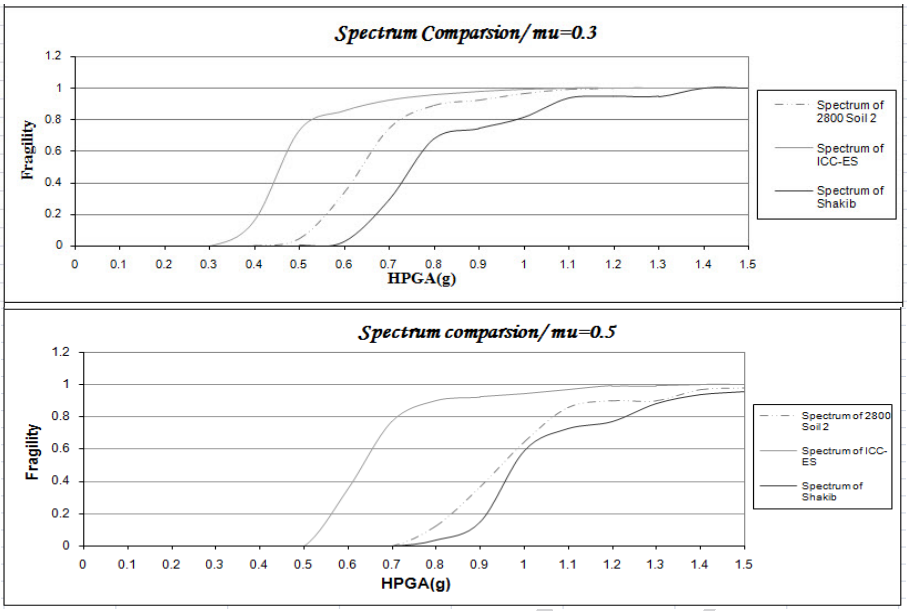


Figure 1. Fragility curves for free-standing blocks. Failure threshold = 2 cm

4. PERFORMANCE OF RESTRAINED BLOCKS

The restrained system is shown in Figure 2. It has been shown that for a given base acceleration history, the response of the restrained block depends on four parameters: the dynamic coefficient of friction (μ_d), the vertical-to-horizontal-acceleration ratio (k), the would-be natural period of the system in absence of friction (T_{eq}) and the ratio of the vertical component of the cable forces to the weight of the block (β) [23].

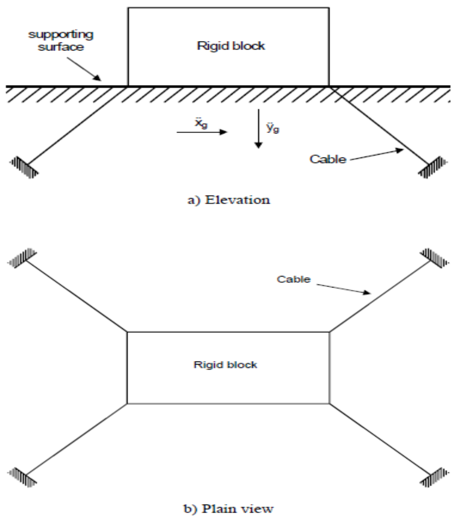


Figure 2. Rigid block attached to cables

In order to get more insight into the influence of the above mentioned parameters, many acceleration records have been applied to restraint blocks. Based on the results obtained in previous sections, the two acceleration records that yield the highest displacements are chosen to serve this purpose; namely, the Tabas and Sirch earthquake records. By taking the breakage of the restraining cables as the failure criteria for the restraint block, the maximum allowable displacement for each of the above mentioned cases depends only on β and T_{eq}. The four cases investigated in this section are given in Table 3.

Table 3: Maximum allowable displacements for restraint blocks

Case	β	Teq	The maximum allowable displacement (cm)
1st	0.7	0.05	0.0218
2nd	0.7	0.2	0.348
3rd	1.0	0.05	0.0311
4th	1.0	0.2	0.497

For the Tabas and Sirch earthquake records and for the four cases given in Table 3, the block average relative peak displacements, which are obtained from the ninety peak displacements obtained from the ninety acceleration time history inputs for different coefficients of friction (μ_d), are shown in Table 4. Compared these results with those given in Table 2, it is clear that displacements are smaller in magnitude. Furthermore, and in clear similarity to the unrestraint cases, it has been found that the probability of failure depends strongly on (μ_d). The effect of higher (β) is also noticeable in reducing displacements. On the other hand, and as shown in Table 4, the role of T_{eq} is less important.

Subjecting the block to the IS2800 design spectrum, as shown in Table 5, displacements higher than those obtained by the Tabas and Sirch earthquake records have been obtained.

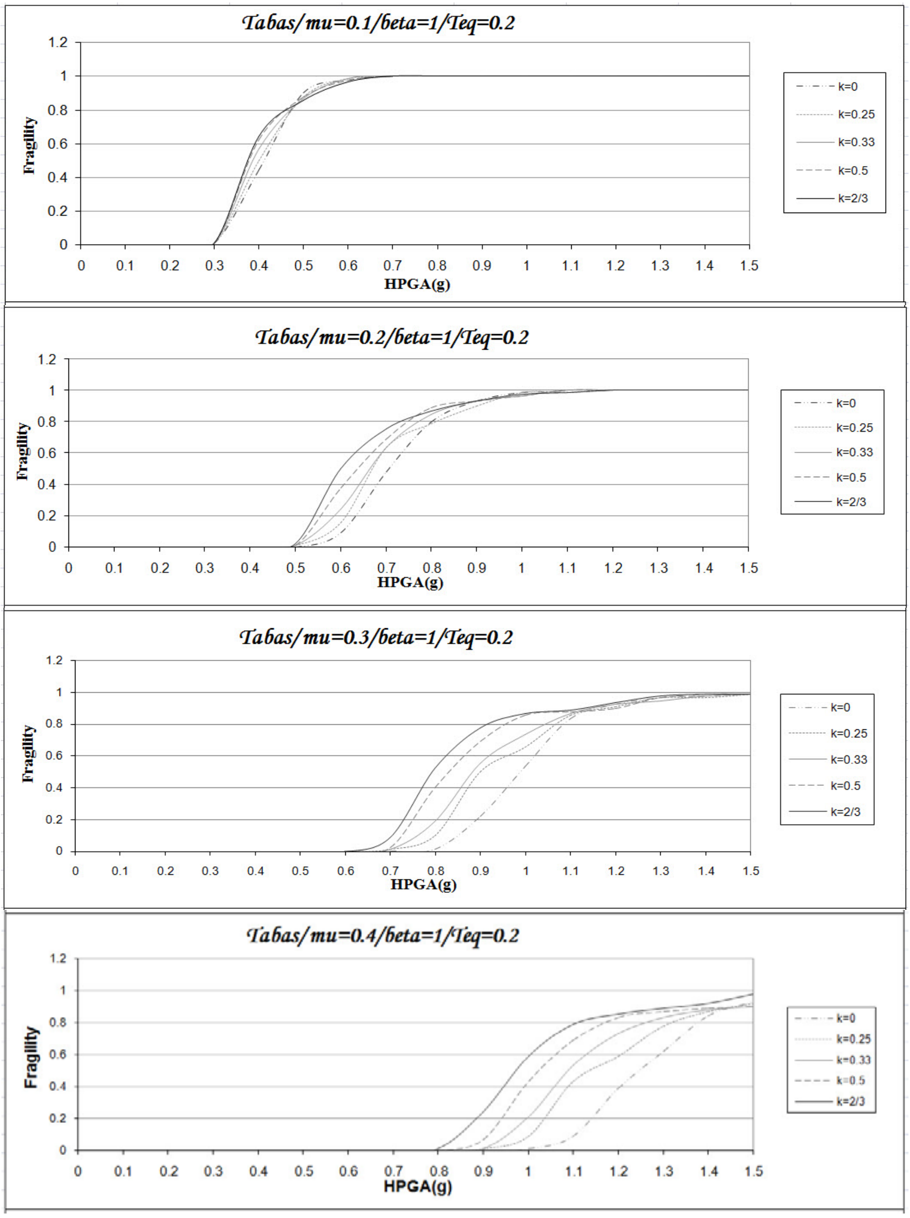
Table 4: Average displacements (cm) of 90 artificial acceleration records scaled to 1g with k=2/3 for the restraint blocks

	Tabas				Sirch			
μ_d	1st case	2nd case	3rd case	4th case	1st case	2nd case	3rd case	4th case
0.1	10.88	10.88	9.33	9.33	15.94	15.94	14.08	14.08
0.2	7.93	7.93	5.60	5.60	11.13	11.13	7.67	7.67
0.3	4.27	4.27	2.38	2.38	5.63	5.63	2.98	2.98
0.4	1.91	1.91	0.77	0.77	2.35	2.35	0.88	0.88
0.5	0.77	0.77	0.21	0.21	0.87	0.87	0.23	0.23

Table 5: Average displacements (cm) of 90 artificial acceleration records scaled to 1g with k=2/3 for the restraint blocks subjected to IS2800 design spectrum

μ_d	1st case	2nd case	3rd case	4th case
0.1	23.14	23.14	19.65	19.65
0.2	15.20	15.20	10.94	10.94
0.3	8.99	8.99	5.23	5.23
0.4	4.39	4.39	1.86	1.86
0.5	1.86	1.86	0.52	0.52

Samples of fragility curves for the Tabas and Sirch earthquakes are shown in Figures 3 and 4. As shown in these figures, fragility curves depend strongly on (μ_d) and only marginally on the other parameters. The interval within $0 < \text{fragility} < 1$ is very narrow and close to the vertical line. Moreover, fragility curves for $k = 0$ are always below those for $k \neq 0$. Furthermore, similar to the unrestraint cases, it is found that displacements have direct relation to the maximum magnitudes of the pseudo-velocity spectrum curves.



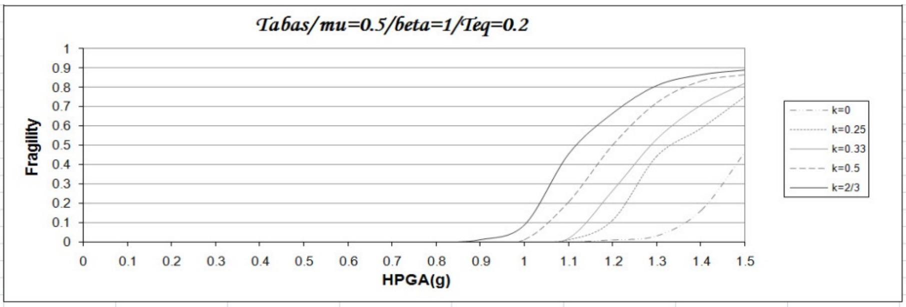
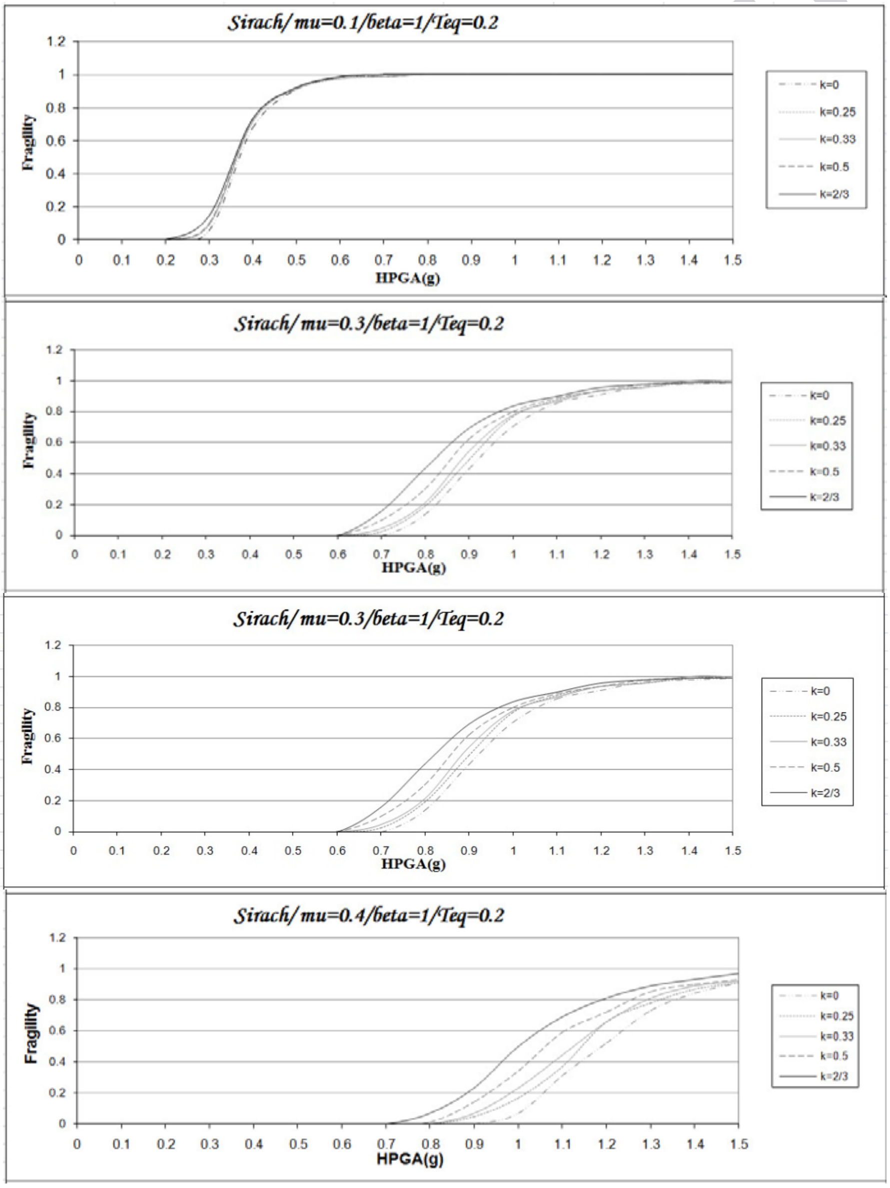


Figure 3. Fragility curves for restrained blocks subjected to Tabas earthquake record for β=1.0 and T_{eq}=0.20 with different values for μ and *k*.



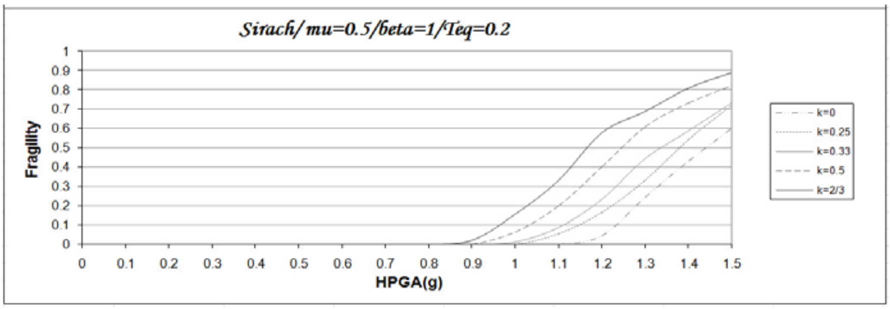


Figure 4. Fragility curves for restrained blocks subjected to Sirch earthquake record for β=1.0 and T_{eq}=0.20 with different values for μ and k.

5. SUMMARY AND CONCLUTIONS

In this paper, the performance of a rigid block resting on a rigid supporting base subjected to horizontal and vertical base excitations, has been studied. The results of unrestraint blocks indicate that the coefficient of dynamic friction (μd) is one of the most important coefficient influencing displacements and accelerations. Furthermore, it is clear from these results that displacements increase as the vertical and horizontal peak accelerations increase.

The results of the present investigation indicate that restraints are very effective in reducing horizontal displacements. In this study, five different parameters have been investigated. They are the coefficient of dynamic friction (μd), the HPGA, the VPGA, the would-be natural period of the system in absence of friction (Teq) and the ratio of the vertical component of the cable forces to the weight of the block (β). Investigating these results leads to the confirmation of the earlier conclusion; the coefficient of dynamic friction (μd) has a strong influence on both displacements and accelerations.

Generally, it can be concluded that restrained schemes are the obvious choice for block-type nonstructural components whose failure mode is given by excessive horizontal displacements. In the case of components whose failures modes are given by excessive displacements and excessive absolute accelerations, restraints have been also used. In these cases, the controlling failure mode is given by breakage of the restraints. Post-tension forces, which significantly influence the corresponding fragility curves, can then be conveniently selected so that the resulting probability of failure is low enough.

Within the range of data tested in this paper, it is clear that the normalized response spectrum suggested by ICC yields the highest displacements and therefore can be used as an envelope for the nonstructural components test. However, more detailed study need to be carried out to establish the performance level associated with this test. Furthermore, and in all the cases studied in this paper, it has been found that maximum magnitudes of the pseudo-velocity spectrum curves have direct relations to fragility curves. Moreover, it has been found that fragility curves for $k = 0$ are always below those for $k \neq 0$. Therefore, it is always advisable to use both HPGA and VPGA in evaluating the fragility curves.

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