Seismic vulnerability of building contents for a given occupancy due to multiple failure modes

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SUMMARY
A methodology is presented for assessing the seismic vulnerability of inventories of contents to multiple failure modes. An ordering method to find out probabilities of failure of a conditional mode upon the survival of the other modes is applied. The procedure considers the statistical correlation of failure modes due to contents dynamic response such as sliding and overturning, and failure modes due to nonstructural components. We applied this methodology to inventories of two types of occupancies (house and office) located at Mexico City, considering that all contents are situated on the ground level. Expected damage functions for these inventories show large differences between them, being the house inventories the less vulnerable, and the office inventory the most vulnerable, even for low intensities.

Keywords: seismic vulnerability; buildings contents; loss; occupancy; multiple failure modes

1. INTRODUCTION

Losses of building contents due to earthquakes may be significant, and even exceed the value of the building structural loss, for some occupancies such as museums, hospitals, laboratories and industrial facilities. Very few survey reports of building contents damage after an earthquake are available since structural damage is the one that gets all the attention; moreover, rescue tasks, cleaning up teams and looting may modify contents state before a survey can be conducted. In addition, access to damaged facilities may be restricted to comply with insurance policy clauses, or because of safety concerns. Due to this lack of statistical data, probabilistic models that use vulnerability functions in terms of intensity parameters must be employed (Czarnecki, 1973; Scholl, 1981; Kustu et al., 1982; ATC, 1985; Esteva et al., 1988; Ordaz et al., 2000). Porter and Kiremidjian (2001) developed a procedure to calculate building-specific vulnerability functions aimed towards optimum risk management trough assembly-based vulnerability. Chaudhuri and Shinozuka (2010) combined fragility information from hospital's structure and electromechanical systems by means of fault tree analysis relating the different component fragilities to estimate the impact of various retrofitting alternatives. Pisharady and Basu (2010) estimated the seismic fragility of selected nuclear plant components taking into account the inter-independence of failure modes for each component. Reinoso et al. (2010) estimated site specific losses for inventory of overturning objects.

The estimation of earthquake losses of an inventory of building contents must take into consideration that the losses of building contents and other nonstructural components occur simultaneously. In this work, a methodology is presented to estimate an expected damage function for building contents for a given occupancy. All significant failure modes for every content of the inventory (rocking, overturning or sliding of rigid bodies) and for the damage caused to contents by nonstructural components (HVAC, suspended ceiling systems) are taken into account. We show a typical inventory of two building occupancies (house and office) and compute the response of every object to a set of recorded strong ground motions to obtain failure probabilities in terms of peak acceleration by overturning and sliding (Hutchinson and Chaudhuri, 2006; Reinoso et al. 2010). The seismic behavior of sliding (Shenton, 1991) and rocking objects (Arredondo and Reinoso, 2008) being shaken only by one horizontal component has been considered. To obtain failure probabilities on contents caused by nonstructural components we have used available functions (Porter and Kiremidjian, 2001; Badillo et al. 2006; Chandhuri and Shinozuka, 2010). No jumping, fire or partial or total structural collapse or losses caused to building contents by other building contents are taken into account. Some nonstructural components may cause damage to the contents such as broken glasses or plaster cracking, but there is not any available empirical information, and we considered this contribution insignificant. Finally, we show as examples the seismic vulnerability of building contents for two building occupancies: house and office at Mexico City, using the city´s free-field accelerometric array, considering that all contents are located at the ground level.

2. EXPECTED LOSSES PRODUCED BY MULTIPLE FAILURE MODES IN BUILDING CONTENTS

The estimation of building contents losses during earthquakes for multiple failure modes can be derived by combining the probability of failure, $P_F(y)$, as a function of the intensity, y (p.e. peak ground acceleration), derived for individual failure modes (Pishrady and Basu, 2010). Two alternative methods can be considered for estimating this probability of failure. The first method is to assume that the failure modes are statistically independent or uncorrelated. Then, $P_F(y)$ is calculated using the product rule.

$$P_F(y) = 1 - \prod_{i,j}^{n,m} \left(1 - p_{F\,ij}(y)\right) \tag{2.1}$$

where p_{Fij} is the marginal probability of failure of the jth element in the ith failure mode, and n and m are the total number of elements and failure modes, respectively. Eqn. 2.1 implies that the probability of failure is equal to one minus the product of the probabilities of survival of each element in all failure modes. In practice, this is a conservative estimation of P_F.

The second method takes into account dependent failure modes (Moses and Kinser, 1967). This ordering method isolates each failure mode and estimates the probability of failure precisely in a given mode as the probability of the joint event of failure in the mode of interest and survival in the modes with higher probabilities of occurrence. The method is based on the concept that the probability of failure precisely in the ith mode is equal to the probability of failure in that mode (independently of the other ones) multiplied by the probability of survival of other modes that have larger probabilities of failure. Therefore, the probability of failure of the jth element precisely in the ith mode, P_{Fij}, is estimated as the probability of failure in that mode if it survives all the previous modes; thus:

$$P_{Fij}(y) = \left[\prod_{k=1}^{i-1}\left(1 - p_{F\,kj}(y)\right)\right] p_{Fij}(y) \tag{2.2}$$

The failure modes in Eqn. 2.2 are all possible ways for which the building contents can suffer damage. Since these failure modes are mutually exclusive, the probability of failure can be expressed as

$$P_F(y) = \sum_{j=1}^{n}\sum_{i=1}^{m_j}\left[\prod_{k=1}^{i-1}\left(1 - p_{F\,kj}(y)\right)\right] p_{Fij}(y) \tag{2.3}$$

Thus, the expected losses of all contents and failure modes normalized with respect to the total initial value of the contents can be obtained as

$$\delta(y) = \sum_{j=1}^{n}\sum_{i=1}^{m_j}\left[\prod_{k=1}^{i-1}\left(1 - p_{F\,kj}(y)\right)\right] p_{Fij}(y)\delta_{Fij} \tag{2.4}$$

where δ_{Fij} is the failure cost ratio of the element *j* under the failure mode *i*.

Considering the individual contribution of each element and failure mode to the total value of all contents, we obtained the value of δ_{Fij} as the product of the expected damage of element *j* conditional to the occurrence of failure in the *i*th mode, D_{ij}, by the relative cost of the corresponding content, r_{co}, which represents the individual contribution of each element to the total value of all contents. The factor D_{ij} takes into account the fragility of each element (the susceptibility to be broken or to be damaged by overturning, by exceeding a sliding limit or by being hit by a nonstructural component).

3. FAILURE MODES IN BUILDING CONTENTS

Figure 3.1 illustrates some of all possible office contents failure modes and how the nonstructural components could further damage the contents.

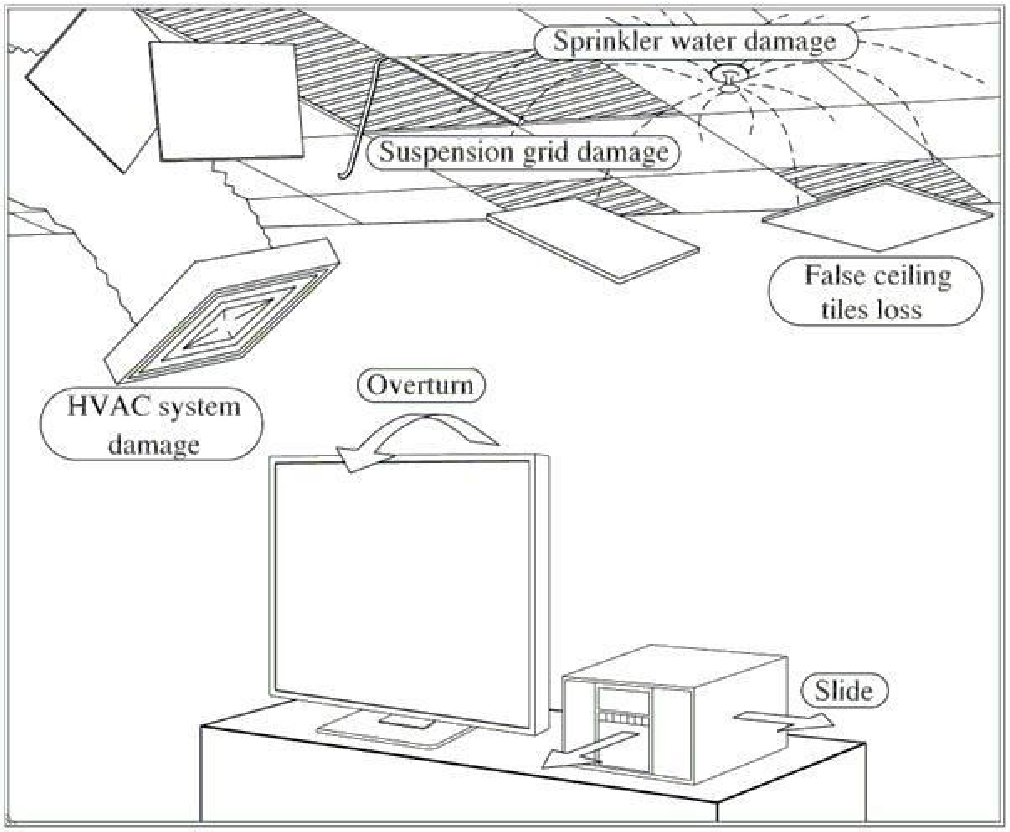

Figure 3.1. Building contents subjected to multiple failure modes; a typical office occupancy that may suffer damage due to the seismic response of individual contents (overturn and slide) and by nonstructural components (fall of suspended ceiling, sprinkler water leaks and detached HVAC systems)

3.1. Dynamic Response of Individual Contents

3.1.1. Rocking and Overturning of Rigid Bodies

The nonlinear dynamic rocking response of rigid blocks can be obtained using available models (Housner, 1963; Makris and Roussos, 1998; Shenton and Jones, 1991; Shenton, 1996; Arredondo and Reinoso, 2008) which solve the following equation that represents the nonlinear dynamic response of a rectangular block:

$$\left(I + mR^2\right)\cdot \theta'' = m \cdot R \cdot \cos(\alpha - |\theta|)\cdot y_g'' - S(\theta)\cdot mRg \cdot \sin(\alpha - |\theta|) \tag{3.1}$$

where y_g'' is the acceleration time history at the base of the block, θ the rotation, m the mass, I the moment of inertia, $R^2 = b^2 + h^2$, $\alpha = \tan^{-1}(b/h)$, g is the acceleration due to gravity and $S(\cdot)$ is the signum function. *2b* and *2h* are respectively the width and height of a rectangular block equivalent to non-symmetric geometry of the content in its most slender side. The body will start rocking when the limit of intensity $y_b = g(b/h)$ obtained from the moment equilibrium at the tip in contact with the surface is reached, ($y_g'' > y_b$), and depends only on the geometry of the content (Milne, 1885).

3.1.2. Sliding of Rigid Bodies

The nonlinear formulation for sliding (Shenton and Jones, 1991; Shenton, 1996) is given by:

$$y'' + y_g'' = -S\left(y'\right)\cdot \mu_k g \tag{3.2}$$

where y'' and y' are the acceleration and velocity time histories of the block in the center of gravity with respect to the base of the block, respectively, and μ_k is the kinetic friction coefficient,

$$S\left(y'\right) = 1, \quad y' > 0 \tag{3.3}$$

$$S\left(y'\right) = -1, \quad y' < 0 \tag{3.4}$$

The formulation considered the following conditions: (a) the slide mode starts once the mass inertial load exceeds the resistance provided by friction, (b) μ_k = 0.3 and (c) the sliding continues until the relative velocity of the body's mass equals zero, and commences again if condition (a) is satisfied

3.1.3. Probability of Failure for Individual Contents Due to Its Dynamic Response

In case of overturning, there are different methods to obtain the probability of failure for rigid unanchored objects subjected to earthquake ground motions of given intensities (Yim et al., 1980; Reinoso et al. 2010). Generally, the probability of failure for each element is obtained, using samples of time histories scaled to a specific intensity, as the ratio of the number of cases when overturning occurs to the total number of simulated responses. In case of sliding, there are also different methods to obtain the probability of failure for rigid unanchored objects subjected to earthquake ground motions of given intensities (Hutchinson and Chaudhuri, 2006). We obtained this probability as the ratio of the number of cases when a maximum sliding occurs to the total number of simulated responses. Engineering judgment must then be applied in the selection of the sliding limit for each element considered. To obtain the probability of failure two sliding limits for the objects were considered: 1) those which need a sliding limit distance up to 10 cm to fall and break from the shelf, and 2) those that only need 5 cm; details of which objects were assumed to be damage by sliding will be shown later.

3.2. Damage to Contents Caused by Nonstructural Components

Loss estimation of building contents must also include the damage caused by the failure of nonstructural components (architectural, mechanical, electrical and plumbing). In order to do so, it is necessary to obtain the failure probability of contents due to the damage caused by these components. There are a few probability functions available in the literature (Kennedy and Ravidra, 1984; Swan and Kassawar, 1998; Porter et al. 2007; Badillo et al. 2006) obtained after earthquake surveys and laboratory testing. Some functions are expressed through a lognormal probability distribution

$$F_{YF}(y)=\Phi\left[\frac{1}{\beta_c}\ln\left(\frac{y}{x_m}\right)\right] \tag{3.5}$$

where Φ is the standard normal (Gaussian) cumulative distribution of the logarithm of the sample of random values of Y_F (the intensity required to cause the failure of the nonstructural component); x_m is the median value of the distribution of the intensity required to produce failure in the mode considered and β_c is the log-standard deviation.

3.2.1. HVAC Systems

Most modern buildings are equipped with heat ventilation and air conditioning (HVAC) systems with lightweight but bulky components suspended from the ceiling. Often, during an earthquake, the outlet vents and ducts detach from the beams and suspension posts as shown in Figure 3.1. Chandhuri and Shinozuka (2010) observed the damage of HVAC components in 19 buildings after the 1994 Northridge earthquake. They fitted a fragility function with a lognormal distribution (x_m=0.76g and β_c=0.4). The outlet vents may not reach the floor but they eventually hit the building contents; moreover duct dislocation usually damages the suspended ceiling but empirical information is not available.

3.2.2. Suspended Ceiling System

Suspended ceiling systems referred in this paper consist on rectangular tiles mounted on a suspension grid. During an earthquake, this grid shakes and swings impacting the perimeter walls; this causes the fall of tiles and eventually the collapse of the grid. Building contents result damaged by the impact of these objects. Some buildings with occupancies such as laboratories or clothing shops are especially vulnerable, as even minimal ceiling damage could cause large losses either by hitting directly the contents or by the dust. Badillo et al. (2006) developed extensive fragility information from laboratory testing of various configurations of suspended ceilings systems. They published failure probability functions for three levels of loss of the tiles (1%, x_m=1.07g and β_c=0.115; 10%, x_m=1.42g and β_c=0.197; 33%, x_m=2.01g and β_c=0.136) and for part or total failure of the ceiling (x_m=1.67g and β_c=0.107). The fragility function of the suspension grid is statistically independent of the fragility functions of the tiles. This means that grid components could fail without the loss of tiles; however, tile failure will depend to some degree on grid failure (Badillo et al. 2006). In this work, we assumed the values of x_m and β_c for two independent failure modes: (1) when the loss of tiles is 33% and (2) for total collapse of the ceiling grid (the damage on contents could be extensive due to falling debris).

4. ILLUSTRATIVE EXAMPLE

4.1. Inventory of Building Contents for a Given Occupancy

We present as an illustrative example the inventories of building contents for two occupancies: (1) house and (2) office. Figures 4.1 to 4.2 present some selected samples of the inventories of contents that may overturn or slide (house and office). Each inventory includes dimensions of every object (where applicable, asymmetry was taken into account), replacement cost (in this case we are considering all objects as new), the amount of each type of content, an "O" if the object was calculated for overturn or an "S" for sliding, and the fragility given by D due to sliding and overturning (values of D for other failure modes are explained later). Objects that overturn or slide but rarely break are not included, but their value is taken into account to add the total value of the contents. This total value is needed to obtain the relative values of each object. The total value of contents for house and office occupancies are \$6,246 and \$48,337 USD, respectively, while the value of objects that may overturn or slide and break are \$2,496 (~40%) and \$41,892 (~87%) USD, for the same occupancies.

4.2. Strong Ground Motions

Since the rocking and sliding response of unrestrained rigid objects is nonlinear, highly sensitive to peak values, frequency content, and duration, a sample of acceleration time histories, very well characterized, is needed. In this study, 1101 recorded ground motions were used to obtain expected values of damage produced by multiple failure modes in building contents in Mexico City (therefore, the results may not be extrapolated to other regions, and other records should be employed). These records correspond to eleven subduction earthquakes in the Pacific Coast and one normal fault earthquake. All ground motions selected were recorded by the free-field accelerometric array in Mexico City Valley (Reinoso and Ordaz, 1999); therefore, all contents are situated on the ground level. These events cover a wide range of magnitudes (6<Mw<8.1) and distances to the rupture area (200<R<515km).

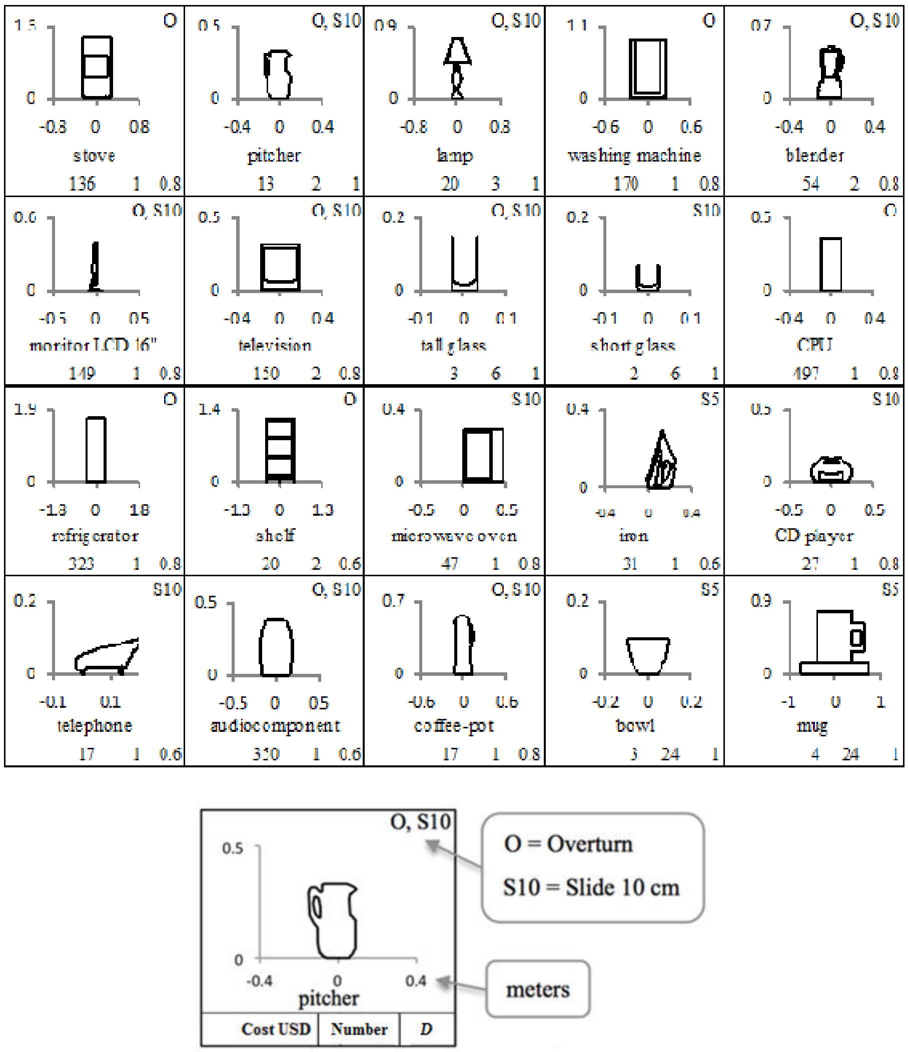

Figure 4.1. Selected inventory of contents that may rock or slide in a house or apartment; individual figures show dimension in meters

4.3. Failure Modes of Building Contents

Table 4.1 shows, for the selected two types of building occupancies, the classification of all possible failure modes. Failure modes on building contents due to its dynamic response (overturn and slide) are considered in all two cases; the sliding limit distance to failure is assumed equal to 5 cm or 10 cm depending on the object distance to the edge of the shelf (Figures 4.1 to 4.2). For house contents, we consider only the failure modes due to their dynamic response. For office contents, we also considered failure modes due to the suspended ceiling system and HVAC system.

Table 4.1. Classification of failure modes of building contents for two occupancies

FAILURE MODE	BUILDING OCCUPANCY	
	HOUSE	OFFICE
Overturning	√	√
Sliding	√	√
Tiles failure(suspended ceiling system)	-	√
Grid failure (suspended ceiling system)	-	√
HVAC system failure	-	√

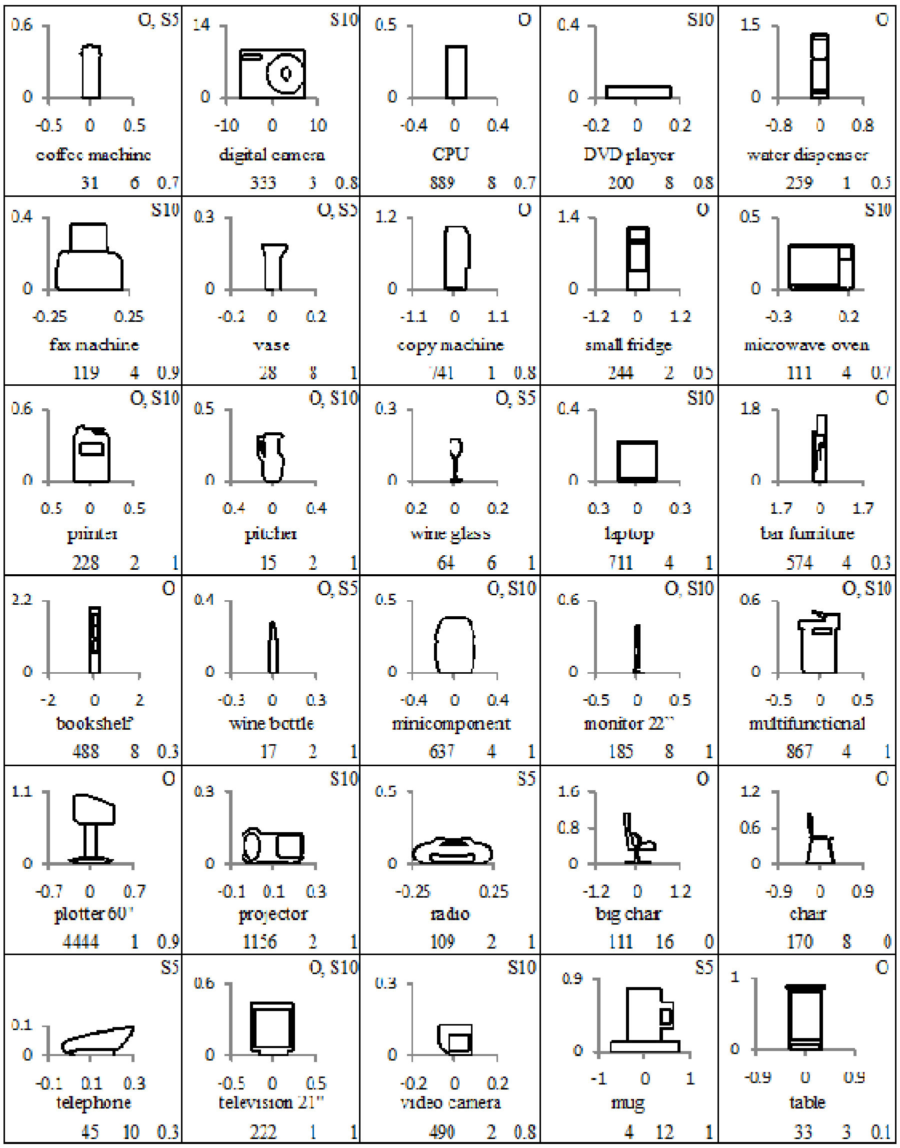

Figure 4.2. Selected inventory of contents that may rock or slide in an office; individual figures show dimension in meters

4.4. Probability of Failure, Fragility and Relative Cost for Each Failure Mode

4.4.1. Dynamic Response

Figure 4.3a compares the probabilities of failure of four selected objects (coffee maker, printer, 14" LCD monitor and 21" Television) due to its dynamic response: rocking (left) and sliding (right). It can be noted, for instance, that the 14" LCD monitor will stand still for any PGA<0.3*g*, but it will overturn with a slightly larger intensity. The printer exhibits a larger difference between the rocking ($1g$<PGA<$2g$) and overturning (PGA>$2g$) intensities. To illustrate the implication of the fragility given by the damage of the body D, Fig. 4.3b shows the failure probability of Fig. 4.3a multiplied by the expected damage of the element conditional to the occurrence of the failure in the mode considered, D. Figure 4.3c shows the failure probability multiplied by D and by the relative cost, r_{co}, of each object. It can be seen, for instance, that the coffee machine is very vulnerable but its contribution with respect to the total losses is very small; on the other hand, the 14" LCD monitor and the 21" Television contribute significantly.

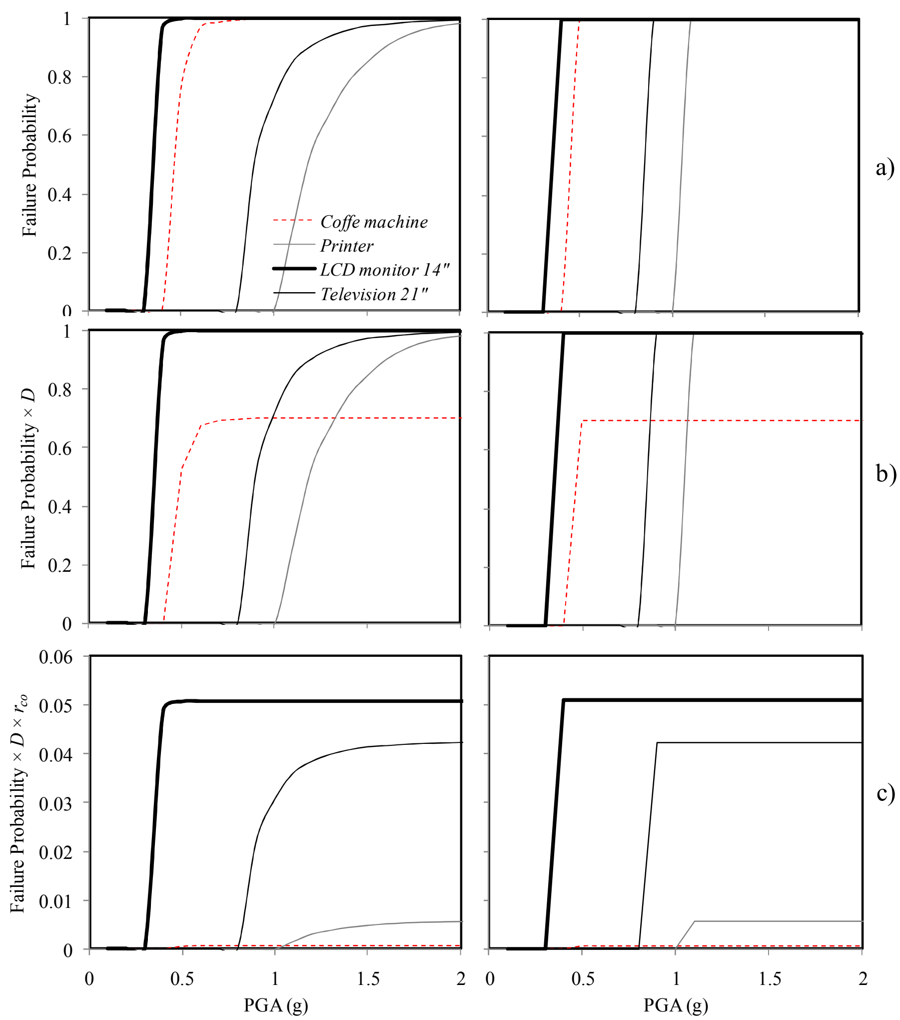

Figure 4.3. Four selected contents of the inventory of a typical office (coffee machine, printer, 14" LCD monitor and 21" Television), for two failure modes: rocking (left) and sliding (right): (a) Failure probabilities, (b) failure probabilities multiplied by the expected damage, D and (c) failure probability multiplied by D and by the relative initial cost, r_{co}

4.4.2. Nonstructural Components

Figure 4.4a shows failure probabilities of three nonstructural components: tiles (Badillo et al. 2006), grid (Badillo et al. 2006) and HVAC (Chandhuri and Shinozuka, 2010). HVAC systems (discontinuous line) exhibit larger failure probability for smaller intensities (PGA >$0.2g$); therefore, this component could cause large contents loss. Figure 4.4b shows failure probability functions multiplied by D due to nonstructural components. The values of D of 0.3, 0.5 and 0.8 are assumed when the damage to contents is caused by loss of tiles (loss of 33% of the total ceiling area), ceiling grid and HVAC system, respectively.

4.5. Expected Value of Damage for the Whole Inventory

Figure 4.5 shows the expected damage caused by all failure modes considered in this work obtained with Eqn. 2.4 according to the occupancy type: house (thin continuous line) and office (gray continuous line). Note that the maximum expected value, which is the limit of all losses given by the sum of D times the relative cost r_{co} considering all objects failing at the same time are 0.33 and 0.8 for house and office. Office losses are twice larger than house losses due mainly to the type of contents and HVAC related losses.

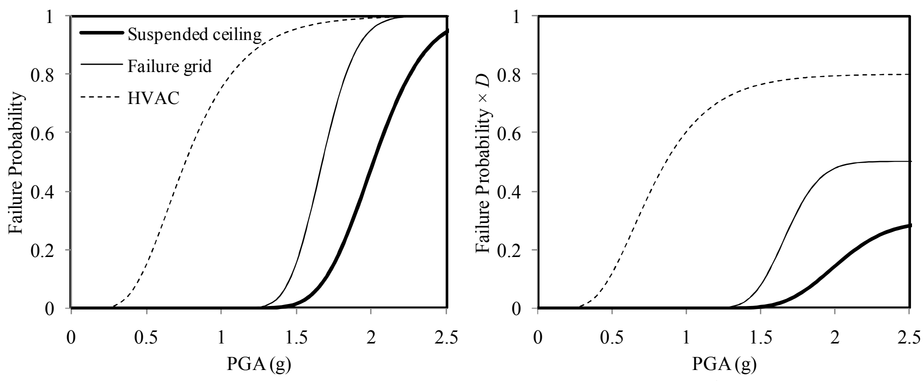

Figure 4.4. Selected failure modes caused to the contents by nonstructural components (suspended ceiling, Badillo et al. 2006; failure grid, Badillo et al. 2006; and HVAC, Chandhuri and Shinozuka, 2010): (a) Failure probability and (b) failure probability multiplied by the expected damage, D

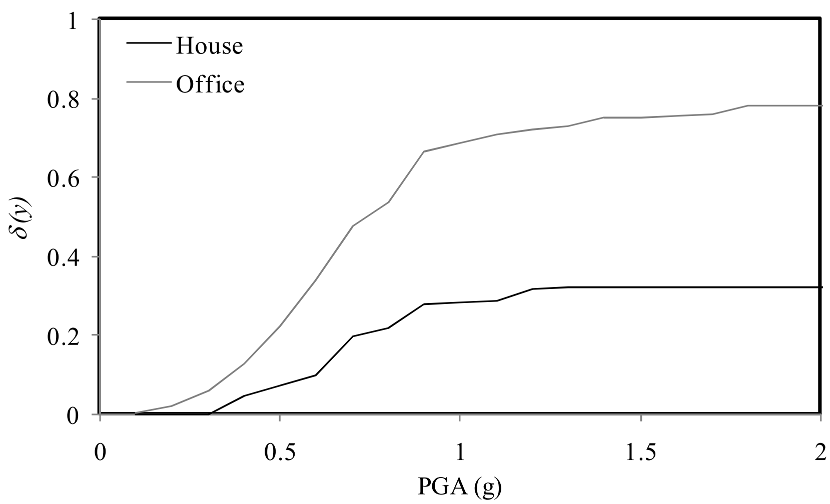

Figure 4.5. Expected damage for the whole inventory according to two occupancy types considering all possible failure modes

5. CONCLUSIONS

We presented a methodology to obtain the expected value of earthquake damage of building contents for a given occupancy for multiple failure modes. An ordering method to find out probabilities of failure of a conditional mode upon the survival of the other modes is applied. This method considers the correlation of multiple failure modes such as the dynamic response of the building contents (overturn and slide) and nonstructural components (suspended ceiling system, HVAC) that produce damage to the contents.

We applied this methodology to inventories of two types of buildings located in Mexico City given by their type of occupancy: house and office; all contents are situated at the ground level (free-field). The expected damage functions obtained show that the house occupancies are less vulnerable than the office, with losses around 33% of the total inventory value for intensities between 0.5 and 1g. For the same intensities, office losses are much larger (80%) since they depend mostly on more vulnerable contents and HVAC components inflicted damage.

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