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KnowRISK

Know your city, Reduce seISmic risK through non-structural elements

Prevention and preparedness projects in civil protection and marine pollution. Prevention Priorities

Deliverable Report

Deliverable B2 – Identification of ground motion intensity parameters that are critical for non-structural damage

Task B – RiskMAP

Deliverable/Task Leader: EERC/INGV

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Project co-funded by the European Commission – Civil Protection Financial Instrument		
Dissemination Level		
PU	Public	x
PP	Restricted to other programme participants (including the Commission Services)	
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CO	Confidential, only for members of the consortium (including the Commission Services)	

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LIST OF SYMBOLS AND ABBREVIATIONS

SISZ	South Iceland Seismic Zone
PGA	Peak Ground Acceleration
PGV	Peak Ground Velocity
FAS	Fourier Amplitude Spectrum
PFA	Peak Floor Acceleration

1. DESCRIPTION OF THE DELIVERABLE

This deliverable presents the work done and results of task B2 of the KnowRISK project. The objective of the task is to identify ground motion intensity parameters relevant for non-structural damage and their evaluation in the study areas of the project.

1.1 INTRODUCTION

Ground-motion amplitude, frequency content and duration control the damage in both structural and non-structural components of a building. The commonly used design parameters for structural components are peak ground acceleration, and pseudo-spectral acceleration. The non-structural components are affected not entirely by the ground motion but instead by a part which is filtered by the structure. In this sense, seismic loading of non-structural components becomes structure dependent. Components that are properly anchored to the structural systems are sensitive to relative displacement of structural components, which is thought to be well represented by interstory drift. On the other hand, free standing components are sensitive to floor accelerations.

The main objective of this task is to identify ground motion intensity parameters that are relevant for non-structural damage. Relevance in this sense implies accuracy and efficiency in predicting damage to non-structural damage. Although a lot of study has been carried out in terms of suitable intensity parameters for structural damage, studies in terms of non-structural damage are rare. This is due to two reasons. The first is that non-structural damage data after major earthquakes are not as readily available as structural damage data. The second reason is that a proper study of correlation between damage and excitation intensity for non-structural damage needs to rely on not only the characteristics of motion at the base of the building, but also those at different floors. In this sense, it can be expected that intensity measures for non-structural damage are structure specific. Intensity measures such as spectral acceleration, which is used for structural design, are also structure specific, but include only basic properties of the structure in the form of vibration period and damping ratio. On the other hand, suitable intensity measures for non-structural damage need to include additional parameters such as mode shapes, distribution of mass and stiffness along the height of the building, and to some extent characteristics of building contents as well. In this regard, availability of structural vibration data would facilitate efforts to identify suitable intensity parameters for non-structural damage. Such data are not as frequently recorded as ground motion data, and even when they are recorded, they are often not publicly released, as they carry important information about the buildings, which the owners might be reluctant to reveal. In addition, organizations such as insurance companies which collect post-earthquake damage data in detail are often reluctant to release such data, as they might contain personally identifiable and sensitive information about the buildings, the builders and their owners.

An alternative approach to this study would be experimental tests on full scale models. Such tests could facilitate excitation of a building and its contents to various kinds of ground motions, recording the response of both the building and the important contents, and studying the correlation between different response parameters and damage. A few studies of this type have been performed, but they are limited to some specific types of structures, and may not be generalized to a large building stock. The main obstacle with this approach is the costs and time involved in experimental tests. One such test is planned in this project as well, in task C3. Information collected from the test has been valuable in understanding some of the features of ground motion that are relevant for non-structural damage. However, more extensive tests than the ones feasible due to available resources in this project would be required for a more detailed understanding of the problem.

Efforts have been made in the literature to perform numerical modelling of movement of objects inside buildings to investigate appropriate excitation intensity measures. Some studies have conducted both numerical and experimental investigations. The results from the literature suggest that numerical modelling can be appropriate in some situations.

In this context, this task addresses the problems discussed above in two main directions. The first is related to evaluation of intensity measures that are more structure-specific than peak ground motion or response spectra based measures. This relates to the evaluation of inter-story drift spectra and floor acceleration spectra. Interstory drift spectra have been evaluated in Iceland and Italy. The second direction is through numerical modelling using the formulation of rocking of rigid blocks.

In the following, information about suitable intensity measures reported in the literature is reviewed. This is followed by a description of the progress made in this project in terms of computing some of these intensity measures. Some aspects of numerical modelling and a summary of planned work in this task are then presented.

1.2 LITERATURE SURVEY: ROCKING AND OVERTURNING PHENOMENON

In terms of free-standing building contents, the first attempt at modelling rocking and overturning during earthquakes was done by Housner (1963). Although motivated by studying the stability of inverted-pendulum like structures during earthquakes, the results presented by Housner (1963) provide a pioneering work towards development of more sophisticated models for rocking and overturning of rigid objects, which in the context of this project, applies to free-standing building contents such as furniture and other objects that are not anchored. For an object of aspect ratio (defined as the tangent of the ratio between base and height of the object), a constant base acceleration larger than, with being the acceleration due to gravity will the object if the acceleration lasts sufficiently longer. For each such acceleration, there exists a minimum duration for which it should last for overturning to occur, and the duration decreases rapidly with increase in acceleration. Housner (1963) also presents the conditions of overturning of rigid objects by a single cycle of sine wave. The overturning condition in such cases requires that the product of the amplitude and duration of the pulse is directly proportional to the slenderness ratio (or aspect ratio) of the object. This is an indication that the peak base velocity and slenderness are important intensity measures controlling the overturning of rigid blocks. For earthquake ground motions idealized as a series of velocity impulses, the amplitude of velocity impulse, the number of such impulses (or duration of excitation), and the slenderness ratio control the overturning criteria. This also suggests that base velocity and the frequency of excitation are important parameters. Housner (1963) also demonstrated that for slender objects, the pseudo-velocity spectral ordinate is a suitable intensity measure to quantify probability of overturning.

Aslam et al. (1978) performed a very detailed numerical and experimental study of rocking of rigid bodies under simultaneous action of horizontal and vertical acceleration. They discuss that the natural frequency of vibration of a rocking body is dependent on the amplitude of motion, which distinguishes rocking problem from normal elastic vibration. This makes rocking and overturning sensitive to many parameters. Under certain conditions, objects with aspect ratio as low as 2 can overturn depending on the overall size of the object and amplitude of earthquake motion. They also showed that, in general, for a given aspect ratio, larger blocks are more stable than smaller ones. They also observed that the maximum response of the blocks due to earthquake motion decreases with increasing coefficient of restitution, which is a measure of energy dissipation due to impact. In some cases, however, larger restitution coefficient, which has a direct effect on rotation amplitudes, can alter the frequency of rocking bringing it closer to resonance with some pulse of earthquake excitation, making overturning more likely. The dependency of vibration period on amplitude of motion in general implies that rocking and overturning is very sensitive to factors such as restitution coefficient, amplitude of excitation, and other small external disturbances. This study also shows that results based on single sine pulse excitation is not very reliable to estimate stability conditions of rigid blocks due to earthquake motion. Aslam et al. (1978) also distinguish between initiation of rocking and sliding motion. For rocking to initiate, the coefficient of friction between the object and the floor much be larger than the width to height ratio of the object. In addition, in lack of vertical acceleration, the horizontal acceleration must be larger than acceleration due to gravity multiplied by the width to height ratio.

Yim et al. (1980) perform extensive numerical study on rocking and overturning of rigid blocks under earthquake excitation, and their results confirm the observations of Aslam et al. (1978) and rocking amplitude and overturning are extremely sensitive to many parameters including the size of the object, its slenderness, as well as fine details of earthquake motion. In this sense, the rocking response is rather chaotic, meaning that it is very sensitive to small changes in initial conditions or external influences. They show that stability of rocking blocks does not monotonically increase with increasing size or decreasing slenderness ratio. In addition, overturning of a block by a given earthquake motion does not necessarily imply that a motion with larger amplitude will also overturn the object. They also showed that vertical acceleration significantly influences stability, although in no apparently systematic way. When the problem is looked at from a probabilistic point of view, i.e., to say that earthquake motion is considered as a random process, and rocking due to different realization of an ensemble of the random process is considered, systemic trends were observed. The probability of the rotation amplitude being larger than a given level, and consequently its overturning, was found to increase with increased intensity of motion, with increased slenderness, and with decreased size of the object.

Shenton and Jones (1990) present a detailed formulation of various modes, such as rocking, sliding, and sliding-rocking of rigid bodies subjected to base acceleration. Shenton (1996) establish the criteria for the initiation of these various modes. Sliding is initiated when horizontal inertia forces exceed the frictional force at the base of the object. Rocking is initiated when the sum of moments about one of the corners of the block due to horizontal inertia forces exceed the restoring moment provided by the weight of the object, provided that there is sufficient friction to prevent sliding. When the static frictional force is large enough to prevent sliding but too small to sustain rocking, slide-rock mode is initiated. In this task, rocking mode is emphasized, as they are more hazardous in terms of possible injuries caused to occupants. Sliding, and sliding-rocking modes are also important as they can move large objects inside a room, and potentially block exit routes. Given the complexity of the problem, the number of variables involved, and the sensitivity of the response to these variables, it was decided that initiation of rocking and overturning is given emphasis in this work.

Makris and Roussous (2000) consider the rocking of rigid blocks under near-fault ground motions which contain coherent velocity pulses. They explain the remarkable fact that the sensitivity of rocking stability and its apparently chaotic behaviour as observed both by Aslam et al. (1978) and Yim et al. (1980) is due to the effect of a succession of small random impulses. This is the case in with ground motions used by Aslam et al. (1978) and simulated motions used by Yim et al. (1980) which lack coherent pulses. Makris and Roussous (2000) focus on relatively short duration, impulsive motion, representative of strong motion in the near-fault area. Such motions are relatively well represented by simple pulses. They also correct the flaws in seminal paper of Housner (1963), which was unfortunately carried forward to publications by other authors, in the minimum acceleration required for overturning. For pulse-like ground motions, the most important parameters were identified as the slenderness ratio, the acceleration amplitude of the pulse, and the ratio between the pulse frequency and the frequency of unforced rocking of the block. The overturning of smaller blocks was found to be more sensitive to peak excitation acceleration, while that of larger blocks was found to be more sensitive to incremental velocity of excitation.

The similarities and differences of Aslam et al. (1978), Yim et al. (1980), and Makris and Roussous (2000) are very important in terms of proper modelling of building contents. This relates to the high sensitivity of rocking motion due to earthquake ground motions reported in the former two publications, but a more systematic behaviour during limited duration pulses reported by Makris and Roussous. An important implication of these results is that while the objects in the ground floor may behave chaotically during earthquakes (as they are subjected to ground acceleration, which, in general, can be considered as a realization of a random process). However, objects in higher floors may behave in a more predictable manner, as they are subjected to floor accelerations, which can be approximated by harmonic functions. This is because, the structure filters those frequencies of ground motion which are not close to one of its resonant frequencies. For short to medium height structures, fundamental mode of vibration is often dominant, and therefore, floor accelerations are more similar to harmonic motion rather than random ground motion, or a time limited pulse. Due to this phenomenon, investigation of rocking behaviour of rigid objects subjected to harmonic forces is relevant.

Ishiyama (1982) studied rocking of rigid blocks subjected to harmonic forces. The overturning criteria derived by Ishiyama (1982) is

$$h = \max\left\{\frac{bg}{A}; 0.2133g\left(\frac{b}{V}\right)^2\right\} \tag{1}$$

where, A is maximum acceleration, V is maximum velocity, g is acceleration due to gravity, b is half of the width of the object, and h is half its width. Psycharis et al (2002) derived the following condition for overturning

$$h = \left(\frac{g}{A}\right)^{1.053}\left(\frac{\omega}{p}\right)^{1.263}\left(0.2 + 1.3r - 1.21r^2\right)^{1.053} \tag{2}$$

where r is the coefficient of restitution squared, ω is the frequency of the harmonic force, and p is the frequency parameter of the block, and is a function of dimensions of the object. When the amplitude of harmonic force is variable, the overturning criteria can be obtained from Arredondo and Reinoso (2008).

1.3 LITERATURE SURVEY: ROCKING FRAGILITIES

Fragility curves for rocking can be used to estimate the vulnerability of building contents subjected to floor accelerations. There have been some studies regarding fragility of rocking or overturning rigid bodies. When excited by near-fault ground motions, the rocking response of electrical equipment studied by Dimitrakopoulos and Paraskeva (2015). Out of 6 different intensity measures considered in this study, the following two were found to be the most suitable measures.

$$IM_1 = \frac{pPGV}{g \tan\alpha} \qquad IM_2 = \frac{PGA}{g \tan\alpha} \tag{3}$$

This shows that both peak acceleration and peak velocities are important parameters. For building contents at higher floors, peak floor acceleration and peak floor velocity would be more suitable. When these two intensity measures are combined, a resulting intensity measure can be obtained as in the following equation.

$$IM = \frac{PGA}{pPGV} \tag{4}$$

It is interesting to note that the ratio between *PGA* and *PGV* is equal to the frequency of force, if the force is purely harmonic. This intensity measure is therefore the ratio between the loading frequency and the frequency parameter of the rocking object. For structural response (contents located on the higher floors), peak floor acceleration and peak floor velocity would be more suitable, and their ratio is approximately equal to the fundamental frequency of vibration of the building. It is therefore apparent that the fundamental frequency of building vibration normalized by the frequency parameter of rocking object is an important parameter governing stability of rocking objects. Dimitrakopoulos and Paraskeva (2015) found that this intensity measure combined with a suitable slenderness measure was the most suitable parameter to create bivariate fragility curves for overturning of objects.

Peak displacement demands were used by Kafle et al (2011) as an intensity measure for rocking stability. The peak corresponded to the largest spectral amplitude of 5% damped elastic response spectra. Their study found that peak displacement demand was better correlate to the likelihood of overturning than peak velocity or peak acceleration demand. They creased fragility curves based on peak displacement demand.

Various other intensity parameters have been considered in the literature, and a brief summary of these parameters is presented in Table.

Table 1. Commonly used intensity parameters for rocking response of rigid blocks

Intensity measure	Remarks	Reference
PGA		
PGV		
Arias Intensity		
IM1	$PGA / g \tan\alpha$	Dimitrakopoulos and Paraskeva (2015)
IM2	$pPGV / g \tan\alpha$	Dimitrakopoulos and Paraskeva (2015)
IM3	$\omega PGV / g \tan\alpha$	Dimitrakopoulos and Paraskeva (2015); Dimitrakopoulos et al. (2009)
IM4	$PGVt_d^{0.25}$, with t_d as significant duration	Fajfar et al. (1990)
CAV	Cumulative absolute velocity	Petrone et al. (2016)
ASI	Acceleration spectral intensity	Petrone et al. (2016)
PSA	Pseudo-spectral acceleration	
PSV	Pseudo-spectral velocity	
SD	Spectral displacement	
HI	Housner Intensity	
E-ASAR	Equipment relative average-spectral acceleration	De Biasio et al. (2015)

Di Sarno et al. (2014) present results of shaking table test on hospital building contents and estimated peak floor acceleration levels required for initiation of rocking and overturning states. Petrone et al. (2016) studied the rocking response of free standing building contents. The focus on the study was on hospital shelves, for which results from shake table tests were available to be compared with numerical models. This study found that, rocking of hospital shelves can be reasonably predicted by numerical methods such as the finite element method, or the rigid block model. They found that a combination of PGA and slenderness ratio was the most efficient intensity parameter for small blocks, while a combination of PGV, frequency parameter of the block, and slenderness ratio was found to be most efficient for larger blocks.

1.4 MAXIMUM INTERSTORY DRIFT RATIO

Non-structural components in this project include both (a) elements and parts attached to the structure, but don't carry load of the structure, and (b) contents of the building. Most of the discussion presented in the preceding sections are relevant to contents of the building such as free-standing furniture. For elements such as piping networks, non-structural walls, window panes, etc., damage is mainly related to relative deformation between adjacent floors of a building. For such cases, inter-story drift demands become relevant intensity measures. An efficient definition of inter-story drift spectra, as well as its modelling and computational steps are provided in Miranda and Akkar (2006). This model uses a combination of continuous shear and flexible beams to model buildings, which are characterized by a certain height, and a dimensionless parameter α that controls the degree of overall flexural and overall shear deformation in the structure. A value of this parameter equal to 0 represents a pure flexure mode, while a very large value (more than about 650) represents a pure shear model. Structures with lateral resisting system consisting only of structural walls may be approximated by using values of α between 0 and 2. If both moment resisting frames and structural walls are present, the values of α is typically between 1.5 and 6. For buildings with moment resisting frames only, the values of α are typically between 5 and 20.

A computer code was developed in this project to implement the model of Miranda and Akkar (2006). This allows the computation of inter-story drift spectra for different ground acceleration time series. Representative time series from the case study areas have been used with this code to produce inter-story drift spectra. Some examples of the obtained results are presented below.

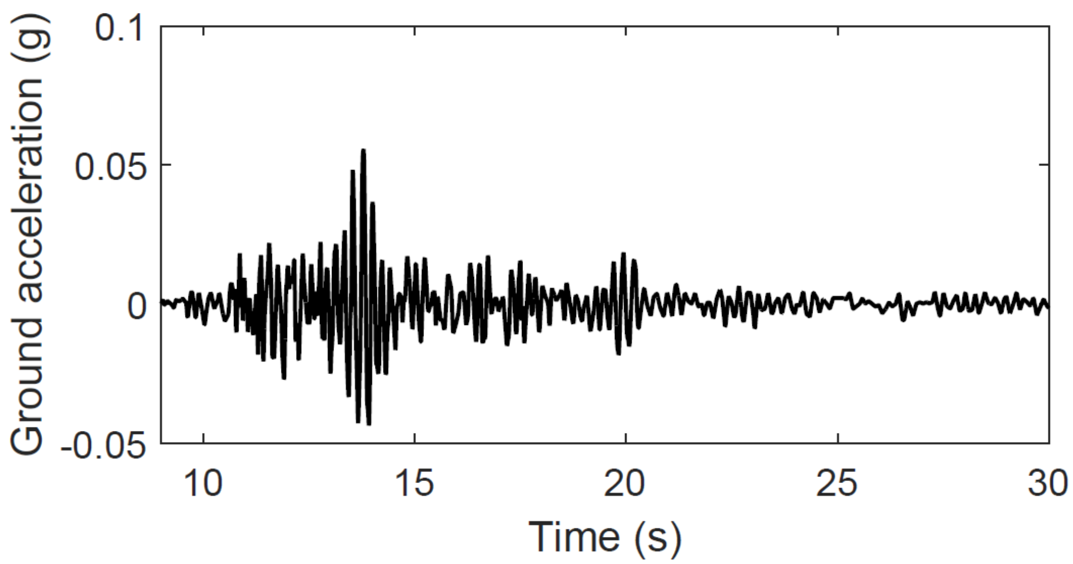
1.4.1. Study area in Iceland

The main study area in Iceland is the South Iceland Seismic Zone, of which Selfoss is the largest town. However, since Reykjavik contains most of the population of the country, drift spectra computation was performed both for Selfoss and Reykjavik by selecting some example scenarios. The hazard at these places and appropriate scenarios are explained in more detail in deliverable B1 of this project. In this section, only the main results are summarized. The following scenarios are considered.

- Reykjavik: Moment magnitude 6 event with epicentral distance of 31 km
- Selfoss: Moment magnitude 6.3 event with epicentral distance of 9 km

Recorded ground motion

The ground motion time series corresponding to these scenarios are obtained from recorded data from past earthquakes. These time series are shown in Figure 1 below. The nature of ground motion at these two scenarios is very different. The motion in Reykjavik is of low amplitude and more broad-band in nature, while the motion in Selfoss is of much larger amplitude and contains narrow-band pulses (more dominant in velocity time series) typical of near-fault ground motions.



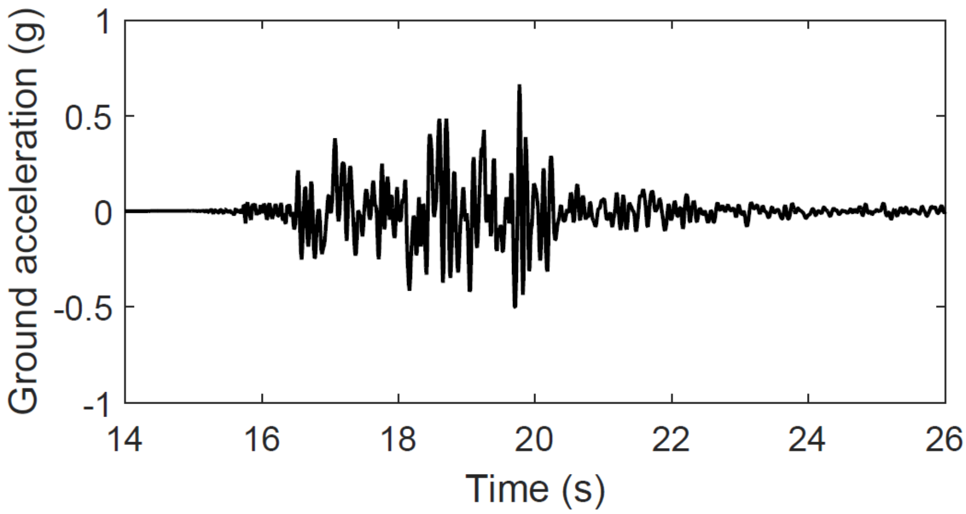
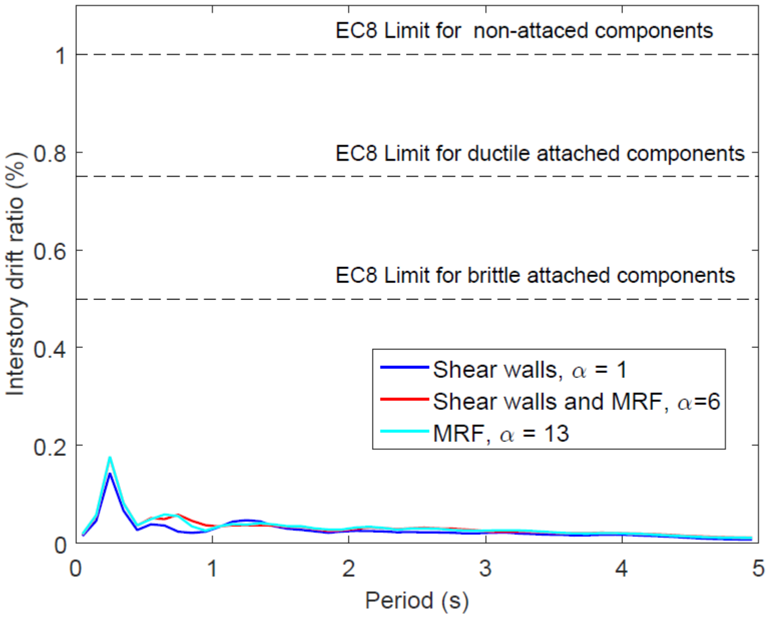


Figure 1. Ground acceleration time series used for computation of drift spectra; top: Reykjavik scenario, bottom: Selfoss scenario

The corresponding drift spectra are shown in Figure 2. On these figures the Eurocode 8 limits for different components are shown with horizontal dashed lines. For example, non-attached components have a limit of 1% interstory drift. The drift spectra are shown for three different values of the α parameter. The effect of this parameter in these scenarios seems to be not very significant. Most buildings in Iceland contain shear walls and moment resisting frames are rare. Therefore, the most relevant spectra for this case study correspond to the blue curves in Figure 1. The drift spectra in Reykjavik is much smaller than that in Selfoss, which is expected due to the much smaller amplitude of ground shaking in Reykjavik. The drift spectra in Reykjavik are lower than the EC8 limits. This, however, should not be interpreted as a general conclusion, because the results being presented here correspond to one typical scenario which contributes most to the 475-year return period hazard. Closer earthquake scenarios may produce higher drift demands on buildings in Reykjavik. The scenario in Selfoss is quite different, as it lies very close to the South Iceland Seismic Zone (SISZ, see deliverable B1). In this case, the drift spectra have a peak around a period of 0.8s, which can be attributed to the long-period velocity pulse in the ground motion used for this scenario. Buildings with fundamental period close to 0.8 exceed all levels of limiting drifts specified in EC8. This, however, is not a major concern, because many buildings in Selfoss are stiff and only 1-3 story tall, with fundamental period generally less than 0.2s. Therefore, the critical case for Selfoss seems to be brittle components attached to the structure. Also, note that these spectra don't accurately represent potential damage to free-standing contents, which is an issue that is addressed in the next section.



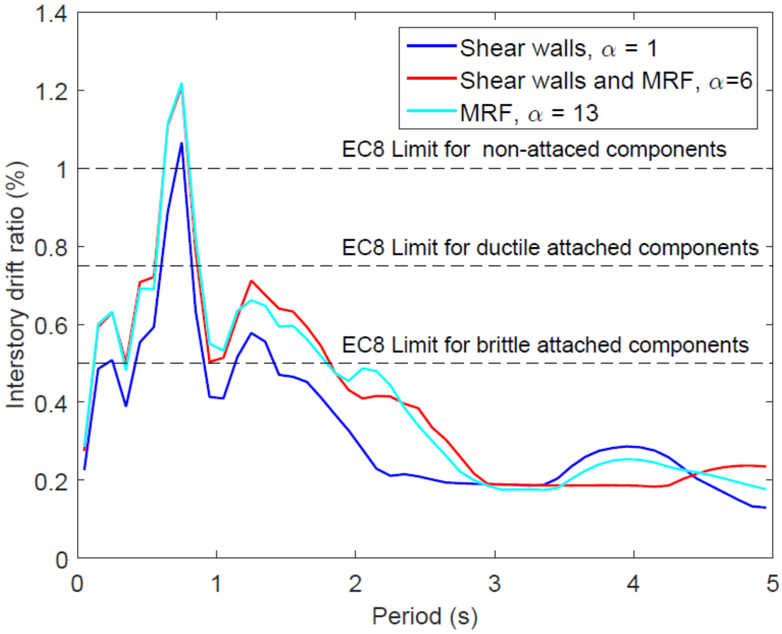


Figure 2. Drift spectra for Reykjavik (top) and Selfoss (bottom) scenarios, with 5% of critical damping.

Simulated ground motion

Scenario hazards were also estimated by using stochastic finite fault simulation procedure. The details of the simulation procedure and its verification are provided in the task B1 deliverable report. To evaluate the drift demand in Selfoss, simulated ground motion within 10km from the source were considered. This resulted in 118 simulated time series. One such time series is shown in Figure 3. The simulated time series has a PGA value comparable to the recorded motion shown in Figure 1.

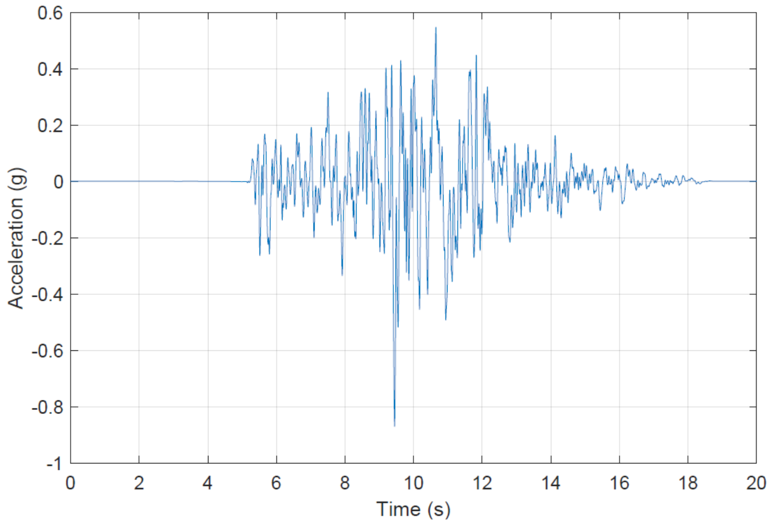


Figure 3. An example of simulated time series for hazard scenario at Selfoss (Mw~6.5 and fault distance ~5km).

Response spectra of 118 simulated time series for the hazard scenario in Selfoss is shown in Figure 4. The grey lines in the figure represent 5% damped response spectra of 118 simulated ground motion time series. The dashed black and the red lines represent median and 85 percentile spectra, respectively. The 85-percentile spectrum is slightly larger (at most periods) than the 475 year return period spectra. Drift spectra of simulated ground motions representing hazard scenario in Selfoss is presented in Figure 5. The grey lines represent drift spectra of 118 simulated time series. The value of α is set equal to 1 and the damping ratio is 5% of critical. The dashed black and the solid red lines represent median and 85 percentile drift spectra, respectively. There is 15 percent probability that structures with fundamental period larger than about 0.2s will be subjected to peak drift demands larger than 0.5%, at which level brittle elements attached to structures are expected to suffer considerable damage. Damage to free standing objects is expected to occur at even lower levels of drift. The results indicate that drift related damage to non-structural components in Selfoss during moderate to strong earthquakes is very likely and needs special consideration.

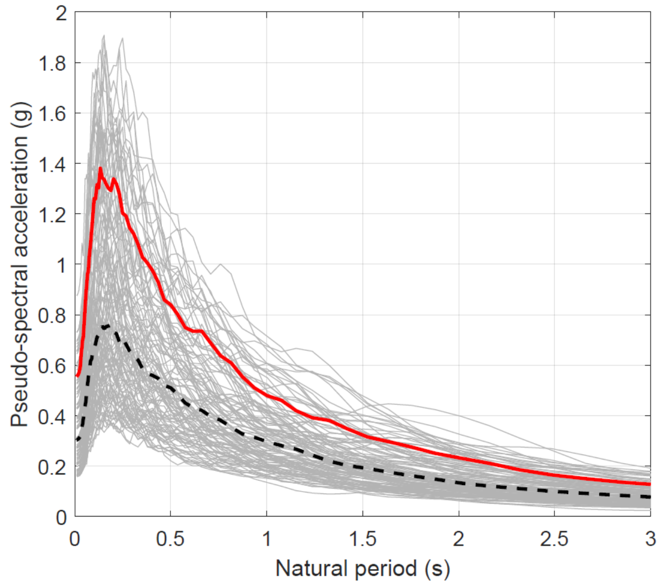


Figure 4. Response spectra of simulated ground motion for hazard scenario at Selfoss.

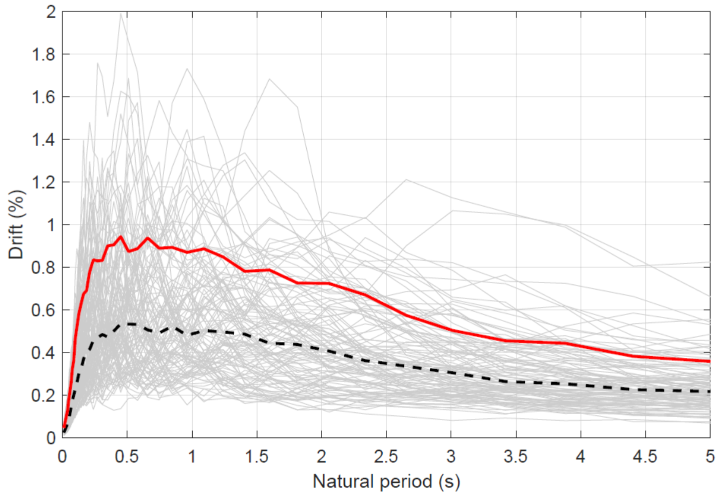


Figure 5. Drift spectra of simulated ground motions representing hazard scenario in Selfoss

1.4.2. Study area in Italy

The suitable scenarios for Zafferana area in Italy is described in detail in deliverable B1 of this project. The selected scenarios are as follows:

- Magnitude 5, epicentral distance 7km on hard rock, and soft soil
- Magnitude 3.5, epicentral distance 1km, on hard rock and soft soil

The amplification factors for soft soil (site class D) were used from Scarfi et al. (2016). The drift spectra for this case study area are constructed for standard parameters specified in Miranda and Akkar (2006). Alpha value was fixed at 650 and damping rtio is 5%. The conversion of building height to natural period was based on the equation given in EC8. The corresponding drift spectra are presented in Figure 6 below. The top panel represents hard rock site condition, and the bottom panel represents soft soil site condition. The blue and the red lines represent magnitude 3.5 and 5 earthquakes at epicentral distance of 1 and 7km, respectively.

Site effects cause significant amplifications at high frequencies for the smaller event and at lower frequencies for the larger event. For soft soil conditions, drift spectra may reach critical EC8 limits for ductile attached and non-attached components. Relevant building response in terms of drift spectra for small earthquakes is notived at short periods, the larger events affects longer periods.

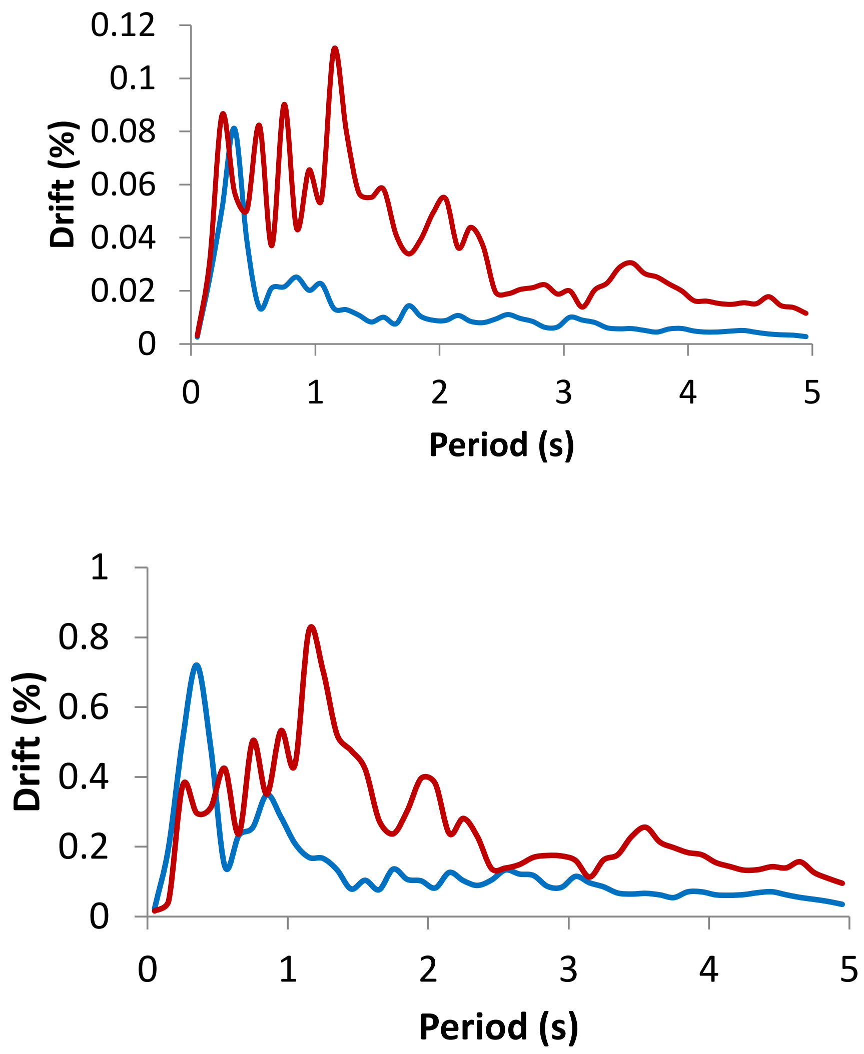


Figure 6. Maximum interstory drift spectra for two scenarios in hard rock and soft soil conditions in Zafferana.

1.5 ROCKING OF FREE-STANDING OBJECTS

Free standing objects such as furniture and equipment are vulnerable to sliding and overturning motion during earthquakes. Such objects can be classified as building contents, and are non-structural elements of a building. Sliding of heavy objects can cause damage and block emergency exits. Overturning of heavy objects is more serious as it can cause (i) damage to itself (ii) damage to structural and architectural components (iii) injury to occupants. During past earthquakes in Iceland, economic loss due to toppling of furniture and other objects and their impact on walls and floors contributed a large portion of non-structural damage (Bessason and Bjarnason, 2016).

Overturning vulnerability of free-standing objects was studied in this project through experimental tests and numerical modelling. Experimental tests were carried out on the shaking table at LNEC. Details of numerical modelling and its results are presented in this report.

1.5.1. One-sided rocking of rigid blocks

Unlike free-standing blocks which can rock about both edges at their base, there are some situations where the rocking occurs about only one edge. One such scenario is when one of the corners at the base is anchored to the floor. Hogan (1992), building on previous work of Shaw and Rand (1989), investigated the stability of one-sided rocking where one corner was permanently anchored to the floor. This model is equivalent to an inverted pendulum hitting a rigid sidewall and only considers positive rotations. In Hogan's model, both viscous damping and a coefficient of restitution provide energy dissipation.

Very few studies have addressed one-sided rocking problem. Historically, rocking of rigid blocks was studied in order to infer intensity of large earthquakes based on performance of free-standing blocks such as monuments and tombstones. A problem similar to the one studied by Hogan (1992) is the rocking of household objects, such as slender furniture placed against walls, during earthquakes. Other examples of such problems are medicine cabinets, data storage disk cabinets, etc., placed against walls. Unlike in the case of two-sided rocking, where the change of centre of rotation results in energy loss, modelled as restitution coefficient, one-sided rocking occurs about a single axis. The main source of energy dissipation in this case is due to impact of the rocking block against the wall. When the impact is not completely elastic and/or the wall is not perfectly rigid, some loss of energy at impact is expected. The loss of energy at impact is most likely related to impact velocity. Full-scale tests on rocking of furniture were performed on the shaking table operated by LNEC, Portugal. This report presents numerical modelling of the same furniture, and presents some results of simulation.

1.5.2. Problem formulation and solution

The main subject of interest in this study is the common bookshelf, this household item usually holds numerous valuables that are costly to replace as well as pose a risk to the inhabitants of the living space. The goal is to estimate the risk of overturning given a specific type of shaking, namely far-field and near-field ground motions. In recent earthquakes in South Iceland no serious harm was inflicted to the people in the area, however, considerable damage occurred due to sliding and overturning of objects such as cabinets, bookshelves, dressers, electric appliances and even store shelves.

The numerical model used here is the same as the inverted pendulum, except for a rigid barrier on one side of the block, ensuring that the rocking is strictly one-sided (Hogan, 1992). The object being studied is the IKEA BRIMNESS bookshelf (see Table 2 for details), which was also tested on the shake table operated by LNEC.

Table 2. Geometry of BRIMNES bookshelf

Dimension	Length (cm)
Height	190
Width	60
Depth	35

The geometry of the block is as shown in Figure 7. It is considered to oscillate about the centre of rotation O. It is assumed that friction is sufficiently large enough to prevent sliding motion. The height to the centre of gravity is h and half the width of the block is b. The distance from the centre of rotation to the centre of gravity is $R = \sqrt{h^2 + b^2}$, and the angle of slenderness is $\alpha = \arctan(b / h)$.

The second moment of inertia of the block $I_O = (4/3)mR^2$ where m is the total mass of the block, which is assumed to be uniformly distributed and therefore with a centre of gravity at the geometric centre of the block. This model can then be simulated as a SDOF system where the only degree of freedom is the rotation. There are two forces/moments acting on the model, a restoring force, which is a gravity force acting at the centre of gravity, and a horizontal overturning force. The overturning force in this case is caused by the base motion due to earthquake excitation. The equation of motion for this type of rocking is described by the following equation:

$$I_O \ddot{\theta} + mgR\sin(\alpha - \theta) = -m\ddot{u}_g R\cos(\alpha - \theta), \quad \theta > 0 \qquad (5)$$

where $\ddot{u}_g$ is the ground acceleration, g is acceleration due to gravity, and m is the total mass of the block. If the rocking were to be in the opposite direction, the following equation would represent that case:

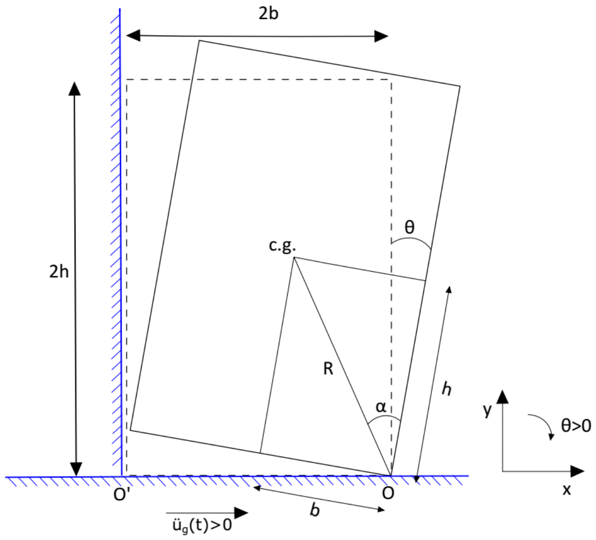


Figure 7 Schematic of a rocking block block standing adjacent to a rigid wall.

$$I_O\ddot{\theta} + mgR\sin(-\alpha-\theta) = -m\ddot{u}_g R\cos(-\alpha-\theta), \quad \theta < 0 \tag{6}$$

Combining Eq. 1 & Eq. 2 yields

$$\ddot{\theta}(t) = -p^2\left\{\sin(\alpha\,\mathrm{sgn}\left[\theta(t)\right] - \theta(t)) + \frac{\ddot{u}_g}{g}\cos(\alpha\,\mathrm{sgn}\left[\theta(t)\right] - \theta(t))\right\} \tag{7}$$

Where p is the frequency parameter (for all rectangular blocks) and is defined as:

$$p = \sqrt{\frac{3g}{4R}} \tag{8}$$

It is clear from this equation that only the length of the inverted pendulum plays a part here, whereas the slenderness α controls the force directions as well as point of impact. The excitation is modelled as a damped sinewave where the amplitude and frequency can be varied and the damping ratio is taken to be 5% of critical.

$$\ddot{u}_g(t) = a_p \sin(\omega_p t + \psi)\mathrm{e}^{-\xi(\omega_p t + \psi)} \tag{9}$$

where a_p is the wave amplitude, circular forcing frequency is ω_p, and damping ratio is ξ. The phase of the sine wave is fixed as

$$\psi = \sin^{-1}(\alpha g / a_p) \tag{10}$$

to ensure initiation of rocking (Housner, 1963).

The impact is assumed perfectly elastic meaning that there is no energy loss. This implies that at impact, the kinetic energy is conserved and the rotation is reversed. However, some dissipation can be expected. This approach differs from the freestanding case, were the kinetic energy loss is a function of the block slenderness.

$$r = \left[1 - (3/2)\sin^2\alpha\right]^2 \tag{10}$$

This equation only applies for two-sided rocking. The energy loss described by this equation is caused by the centre of rotation being shifted instantly from one corner to the next, upon impact.

1.5.3. Modelling and simulation

Since the equation of motion is a non-linear one, a numerical integration is required to solve the problem for an arbitrary excitation. An analytical solution can be used for a pulse type excitation as presented by Housner (1963), by assuming a small slenderness α. The differential equation is solved numerically in MATLAB by using the Newmark-beta algorithm (Newmark, 1971). The algorithm is set up to solve Eq. 3 and has a stopping condition which detects when the block hits the ground/wall and reverses the velocity at the next timestep. The performance and accuracy was successfully verified against the standard ODE solver available in MATLAB which uses a Runge-Kutta scheme. For the model being studied, the dynamic parameters are presented in Table 3. These are descriptive for this specific shelf adjacent to a rigid wall. It is to be noted that R < 1 and p is slightly larger than 2, and the system might therefore be sensitive to short pulses as has been demonstrated in previous studies of two-sided rocking.

When the dynamic properties have been defined, an overturning spectrum can be evaluated as a function of the excitation amplitude and angular frequency. The requirement for the block to start overturning is:

$$a / g > \alpha \tag{11}$$

Table 3. Dynamic parameters of the BRIMNES shelf

Parameter	Value
Slenderness (α)	0.1822 (-)
Radius (R)	96.6 (cm)
Frequency (p)	2.7598 (rad/s)
r	-1

The range of values used for amplitude is therefore between the initiation acceleration $g\alpha$ and extreme earthquake acceleration which in our case is chosen as $2g$. The frequency range is taken as the probable values of the natural frequency of typical building, which generally have a natural period between T_p = 0.05 - 1 second. The angular frequency is computed as $\omega_p = 2\pi / T_p$. The overturning spectra can furthermore be normalized by the slenderness and frequency parameters to obtain a more general solution. The normalized quantity is then derived as

$$\frac{a_p}{g\alpha} > 1 \tag{12}$$

When the normalized frequency ω_p / p equals 1, resonance like phenomenon occurs, making the system highly unstable.

1.5.4. Simulation results

The numerical simulation is run using the above-mentioned setup, and the resulting overturning spectra for one-sided rocking are presented in Figure 8. The yellow colour indicates simulations where the block overturns and the blue colour indicates whose scenarios where overturning does not occur. The results indicate, as expected, that overturning is more probable for higher amplitude shaking. The required amplitude for overturning seems to decrease with increase in the pulse period. At a period close to 1, an amplitude of greater than 0.3 g is required to overturn the shelf. The results indicate multiple bifurcations, typical of chaotic systems. For example, at a given period, a lower amplitude excitation might overturn the shelf, which may not be overturn by a slight higher amplitude excitation of the same frequency. As the frequency ratio increases, the bifurcation leaves get wider, indicating more orderly behaviour.

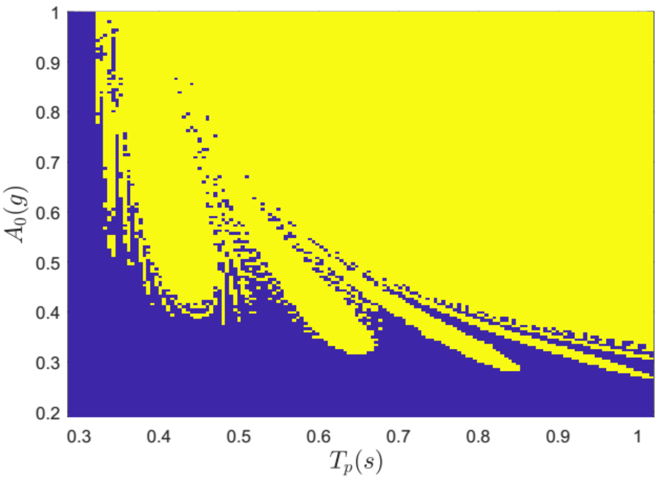


Figure 8. The overturning spectra of the Brimnes bookcase for single-sided rocking of rigid block.

The overturning spectrum for two-sided rocking of the same shelf is presented in Figure 9. A similar trend is observed, where overturning becomes more likely for higher amplitudes and higher periods. However, the two-sided rocking shelves appear to be more stable, as the overturning starts at a relatively higher amplitude as well as higher periods.

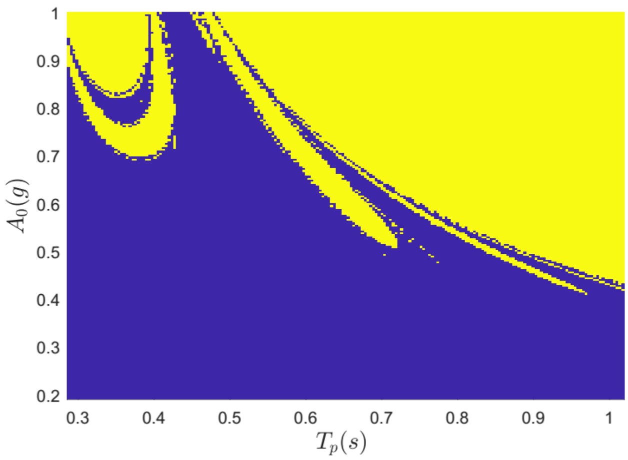


Figure 9: The overturning spectra of the Brimnes bookcase for two-sided rocking of rigid block.

This could be explained by the fact that the two-sided rocking dissipates energy due to the coefficient of restitution, which in this case is less than 1 as described by Eq. 11. Another contributing factor could be that two-sided rocking has a wider range of rotation giving the block a larger range to rock about without overturning.

1.5.5. Rocking response to near-fault and far-fault ground motions

When the frequency parameter is relatively high, we would expect most pieces of furniture to be PGA sensitive. This means that ground motions with high-frequency energy are more likely to overturn the block. A simulation of both cases is presented here. The Near-fault ground motion record used here was recorded on the second floor of the Selfoss Town Hall during the 29 May 2008 Ölfus Earthquake in South Iceland. The moment magnitude of the earthquake was 6.3 and the epicentral distance was approximately 5 km. The simulation shows that considerable rocking does take place, however the block does not overturn (see Figure 10).

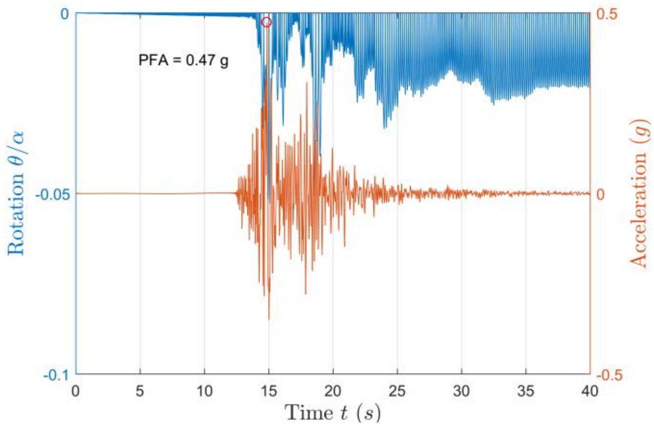


Figure 10: Numerical simulation of a one-sided rocking block excited by near-field ground motion.

For the far-field case, a record from Montenegro is used. In this case, the record from the 15 April 1979 Earthquake is used. The epicentral distance in this case is 65 km and the moment magnitude is 7. The results are presented in Figure 11. Despite the lower PFA, the far-fault motion overturns the block. Both events are strike-slip and were recorded on rock sites.

This test shows that the far-field motion overturns the block and the near-field motion does not. The interesting part is that the far-field PFA is considerably lower. We can investigate this further by comparing the Fourier Amplitude Spectra (FAS) of the records and see where the frequency parameter of the Brimnes shelf lies in the frequency spectra. The comparison is shown in Figure 12, which indicates that the far-field motion has a dominant peak in its FAS at a frequency corresponding to the frequency parameter of the Brimness shelf.

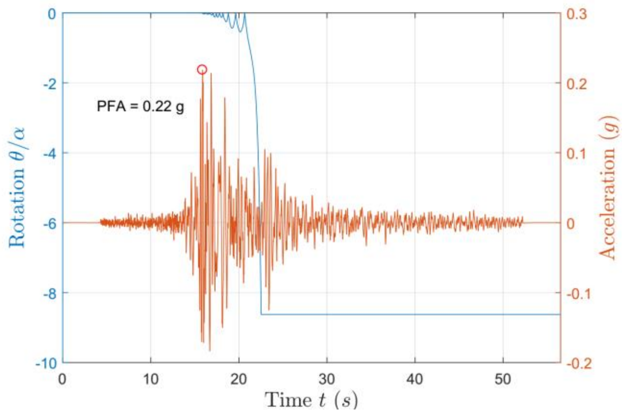


Figure 11: Numerical simulation of a one-sided rocking block excited by far-field ground motion

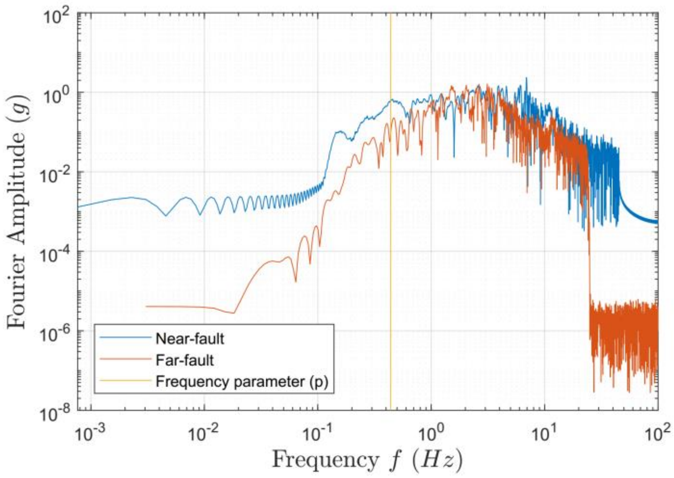


Figure 12: Fourier spectra of both records along with the Brimnes shelves frequency parameter.

From Figure 12 we see very clearly the differences in frequencies and how the far-fault record is relatively more dominant on the in the high frequency range, close to the frequency parameter. This explains, to a large extent, how the weaker motion can overturn a block that a more powerful one could not.

1.6 DISCUSSION AND CONCLUSIONS

A detailed literature survey on the intensity parameters relevant to non-structural damage is presented. Much of the knowledge in this filed comes from numerical modelling of rigid blocks. Some empirical data from past earthquakes has also contributed to a better understanding of ground motion parameters that are best correlated to non-structural damage. In this regard, two parameters stand out. Drift spectra provides information on the deformation of the structure and should be related to damage experienced by components attached to it. On the other hand, floor acceleration spectra are expected to be more relevant for free standing objects such as building contents and heavy machinery/equipment mounted on building floors. A study of drift spectra in Iceland and Italy case study areas is presented in this report. Different scenarios of far-away and near-by earthquakes are considered. In the Icelandic study area, drift spectra were computed from recorded and simulated ground motions. The results indicate that brittle components attached to structural elements could experience drift demand well more than allowable drift during expected moderate to large earthquakes in South Iceland.

The issue of overturning of building contents is studied in detail. A mathematical formulation for objects standing against walls is developed and a numerical analysis method to simulate their response to base shaking is formulated. The free one-sided rocking of a rigid block using the inverted pendulum model has been studied with respect to the harmonic characteristics of a household bookshelf. Numerical simulations using a damped free vibration were performed and the overturning spectra presented for one-sided and two-sided rocking. It is apparent from the overturning-spectra presented, that one-sided rocking is less-stable than two-sided rocking making it a more conservative estimate of hazard analysis for household items. A case study of two different earthquake records was performed. The simulations revealed that the overturning is not only controlled by the amplitude but the frequency content of the excitation is equally important. It is important to keep in mind that the inverted pendulum is a non-linear model and results comparable to those obtained here may not necessarily occur for other similar scenarios. A more extensive study including large collection of near-fault and far-fault ground motions could be conducted, and parameters such as PFA along with epicentral distance of know faults could be used to estimate the probability or risk of overturning. Moreover, the intensity of the excitation at a certain frequency range around the frequency parameter could be quantified to better evaluate how frequency content effects the overturning of the block (for both types of rocking).

Further research opportunities are in determining the damping, or coefficient of restitution, for the one-sided rocking case. Adding damping to the model could increase the stability, and given that bookcases and shelves are mostly made of the same materials experimental results from few cases should be sufficient to clarify whether it plays an important role in the simulation or not. In addition, models of reliable floor acceleration spectra would be useful in establishing vulnerability of building contents. A major obstacle in creating such models is a lack of reliable equations to estimate dynamic properties of buildings using simple equations based on geometrical and typological properties of buildings. Further research in this area can improve analytical modelling of non-structural vulnerability.

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