Seismic structural health from drop and recovery of resonance frequencies in buildings

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Abstract

Under proper loading conditions, micro-to-nanoscale heterogeneities (i.e., the bond system) that are commonly found within the materials of a system can coalesce until causing macroscopic alterations of the system properties. The bond system is responsible for atypical and invariant-scale non-linear elastic processes in granular media, from laboratory-tested materials (mm) to the Earth's crust (km). The unusual observed behavior involves slow recovery, or relaxation, of the elastic properties after dynamic loading. Several models have been designed to explain non-linear elasticity, although their physics is still partially unknown. Here, we show that recovery processes are also observed at intermediary scales (m) in civil engineering structures, and that they might be related to structural health due to the healing of cracks. For Japanese buildings subjected to earthquakes, we observe rapid co-seismic reductions of their resonance frequency, followed by fascinating recoveries over different time-scales: over short times (i.e. seconds) for a single earthquake; over intermediate times (i.e. months) for a sequence of aftershocks; and over long times (i.e. years) for a series of earthquakes. By comparing two buildings with different damage levels after the 2011 Tohoku earthquake, we show how relaxation models can characterize the level of cracking caused by damaging events. Our results bridge the gap between the laboratory and seismological observation scales, verifying in this way the universality of recovery processes, and demonstrating their value for the detection and characterization of damage.

Introduction

Damage is understood as any change in the material of a system that negatively affects its current or future performance, meaning a loss of its optimal and original design[1]. All damage begins at the scale of the material, usually as a small defect, an anomaly or heterogeneity of variable degree. Under proper loading conditions, these micro heterogeneities, altogether called 'the bond system'[2], might coalesce until macroscopic alterations are manifested on the scale of the system[2-4]. Moreover, damage can accumulate gradually over long time periods (i.e. aging effects, cycling loadings, etc.) or can result from unexpected extreme events, such as earthquakes[5]. Structural health monitoring methods are deployed to detect damage, either based on the continuous assessment of information on system performance (in the case of long-term monitoring), or on the rapid provision of information on system capacity in the case of extreme events. One strategy to monitor structural health of civil engineering structures, consists in tracking variations in dynamic features related to structural capacity, such as stiffness or dissipation coefficients. On the other hand, elastic properties are usually tracked during dynamic excitation of granular material samples[2-4, 6-10] and also over seismological studies on fault-systems and crustal areas affected by earthquakes[11-12]. The common invariant-scale observation is a peculiar non-linear elastic response characterized by a rapid modulus perturbation that is followed by a slow relaxation accompanied by hysteresis and discrete memory[2-4]. It is believed that this relaxation (i.e. recovery, or slow dynamics) might reflect the state of the bond system. Recent studies have also analyzed non-linear elastic responses of buildings during earthquakes[13-14], detecting short- to long-term transitory variations of their resonance frequencies, in relation to the elastic features of the buildings.

Is it therefore possible to discern permanent damage from the recovery of elastic properties in buildings? Are theoretical relaxation models able to describe different levels of structural damage, could they be used as a method to monitor seismic structural degradation? How long does it take the recovery of resonance frequencies in buildings affected by earthquakes? How is the slow dynamics recovery of aftershocks following the Tohoku 2011 earthquake?

The article is organized as follows: Section 2 briefly presents the data analyzed and methodology. Section 3 shows the results of monitoring resonance frequencies in buildings during earthquakes, with focus on the long-term frequency recovery after large earthquakes. Relaxation models are then adapted to discern permanent global damage. Final remarks are presented in Section 4.

Data and methodology

It is known that structural damage caused by earthquakes produces permanent frequency changes related to a loss of stiffness[13,15-17]; this is usually linked to the disconnection of structural and nonstructural elements, joint deformation, variations in the friction/border conditions between elements, and the opening of cracks. The recovery process observed after earthquakes would reveal the (partial or total) restoration of these effects. Here, 7 years of triggered earthquake data were analyzed in two Japanese buildings, namely the ANX and the THU. Both correspond to steel-framed reinforced concrete structures of 8 and 9 stories, respectively. Located in Tohoku, the THU building has faced considerably high loading amplitudes during its lifespan, reaching severe damage during the 2011 Mw. 9.0 event[18-19]. The ANX building, located in Tsukuba, was slightly damaged during that earthquake[20]. Besides the 2011 Tohoku event, other important earthquakes were also included in this study (i.e. the Mw 7.2 Miyagi in 2005, the Mw 6.9 Iwate event in 2008). A thorough description of the whole seismic database is available in the Ref. 21. Using the accelerograms from the sensors at the upmost floor, variations in the fundamental frequencies were monitored over time by computing the Wigner-Ville time-frequency distribution for each earthquake, as described in Ref. 13 and 14. The co-seismic frequencies shown along the article correspond to the minimum value of fundamental frequency observed along each Wigner-Ville curve. Peak Top Acceleration (PTA) is the maximum absolute value of acceleration observed at the top floor recordings, used as a proxy of the earthquake loading. To monitor the backbone recovery curves during a sequence of events, only 'small' events were considered. An event is considered 'small' if its PTA is up to 1% of the maximum PTA observed through the history of the building. Prior to Tohoku, for the THU building, 3% of PTA was used instead, which represent the lowest loading amplitudes for the period.

The log-linear recovery slopes were computed with a first-degree polynomial given by Equation (1):

y = b × log(x) + c (1)

where b is the slope, x is the time, and y is $[?]f/f_f$(Normalized frequency variation, with $[?]f/f_f = (f-f_f)/f_f$, where f_f = maximum final frequency).

Three theoretical models were used to study the long-term recovery processes. These models[22-24] are based on physical concepts and were developed based on laboratory experiments that were carried out on the recovery of broken contacts in granular materials. The ratios between final and initial relaxation times (i.e. τ_{max}/τ_{min}) were computed from the relaxation function[22]; whereas the spectral shapes were obtained from the relaxation spectrum model[23], and the spectral bandwidth was defined using the $1/[?]2$ of the maximum spectrum amplitude. The procedure to adapt these models[22,23] to our data and to compute the relaxation parameters is well described in the Ref. 14, and therefore it will not be explained here. From the long-term relaxation model proposed by the Ref. 24, the parameters a and G were obtained by non-linear regression of Equation (2):

$\frac{f}{f_f} = a \, \log_{10}\left[10^m + e^{-G}(1 - 10^m)\right] (2),$

where $a = \frac{2.3\Lambda}{2E_o}, G = \left|\frac{E_s}{\Lambda}\right|$, and m described the normalized relaxation times, $m = \log\left(\frac{t}{\tau}\right)$. The constant Λ is related to loading and E_0 and E_s represent the pre-seismic and co-seismic elastic moduli, respectively. See Ref. 24 for a detailed description.

Observations in Japanese buildings

The multi-scale feature of frequency recovery in buildings

The co-seismic opening of pre-existing cracks might cause the transient material softening at different time scales (Fig. 1). This is shown by the rapid co-seismic decrease of the building's resonance frequency that is immediately followed by its slow recovery (bottom plot of Fig. 1a). If the earthquake did not cause damage, the pre-earthquake properties of the building will be fully recovered. This reflects the coalescence over time of the granular particles within the perturbed material, towards an equilibrated arrangement[2-3] that results in the closing of cracks. During this process, several thermodynamic and mechanical factors control the number of particles in contact within the cracks over time, and consequently, the duration of the recovery[3,22].

Over months after a large earthquake (Fig. 1c), we can observe slow recovery over a long-time scale (i.e., of the order of several months, to a few years), in the manner of long-term relaxation of the crustal properties of the Earth after large earthquakes[11,12]. Strong shakings can open cracks, which might gradually close due to frictional contact between the particles in the damaged zones. Equivalent shaking caused by later smaller earthquakes might contribute to the growth of these contacts, to increase the pressure and friction between the grains, and consequently to favour the recovery process. The recovery of the elastic properties, however, can also be affected by conditioning effects[4,7]. This is observed in Figure 1b, where the slow dynamics were accompanied by hysteresis and discrete memory during the aftershock sequence of the 2011 Mw 9 Tohoku earthquake. The origin of these effects is in the bond system[2-4], and particularly in the spatial arrangements of stress chains[25-27], which represent groups of multi-size contacts that relay the strongest stresses. Structural cracking generates stress-chain rearrangements that represent the mechanism for energy dissipation during each event. The energy dissipation depends on the excitation amplitude: small events generally correspond to variations of local stress chains, whereas larger events can cause changes at a global scale, which results in a new complex anisotropic network of cracks that dominates the backbone recovery (i.e., the outer loop) shown in Figure 1b. Internal recovery cycles (i.e., hysteresis) are due to local stress changes that are generated by the strongest aftershocks, without any changes to the general response of the system, and thus with maintenance of the backbone (i.e., the discrete memory). In Figure 1b, the backbone, therefore, describes the recovery of the structural state, which is controlled by the maximum co-seismic strain state of the main shock.
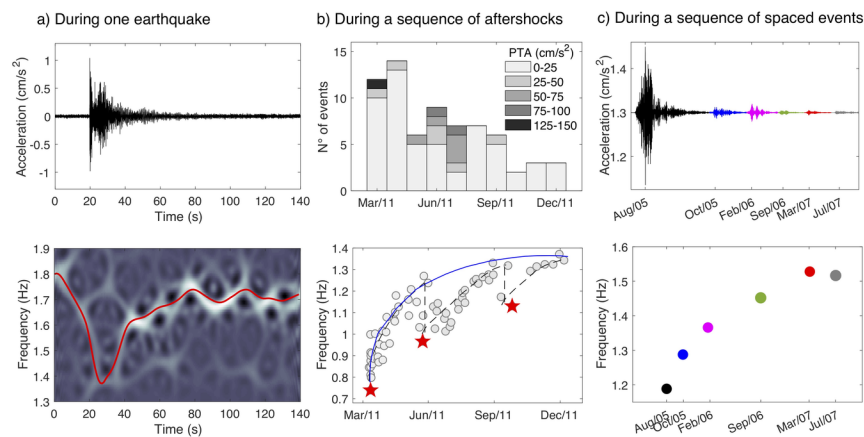
Figure 1. Different time scales of slow dynamics observed in buildings.

a, The drop and recovery of the resonance frequency (bottom panel) during a single earthquake (top panel). Red line, the co-seismic value of the resonance frequency extracted from the time–frequency distribution

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diagram. **b,** Hysteretic recovery during a sequence of aftershocks of the Tohoku earthquake (bottom panel). Each symbol indicates the co-seismic frequency computed during an earthquake, where the stars correspond to significant aftershocks. The solid blue line represents the backbone recovery. The maximum acceleration at the top of the building (PTA) for the aftershocks sequence is also shown (top panel). **c,** Long-term frequency recovery (bottom panel) during randomly spaced earthquakes (top panel). The event of Aug/2005 was a large-amplitude earthquake ($\tilde{} 330$ cm/s^2), whereas the events shown from Oct/2005 to July/2007 were of the same order of lower amplitude (i.e., the PTAs did not exceed 10% of the large-event PTA).

Backbone recovery curve and hysteresis during aftershocks

Figure 2 shows the co-seismic fundamental frequencies of the ANX and THU buildings, between August 2005 and September 2012 (Fig. 2a). We observe slow dynamics over time following three significant earthquakes (i.e., 2005 Mw 7.2 Miyagi; 2008 Mw 6.9 Iwate; 2011 Mw 9.0 Tohoku; Fig. 2, R1, R2, R3, respectively). We analyzed the time scales of the recoveries of the backbones for the weakest events, which corresponded to the weakest loading, to remove conditioning effects. Assuming a time–logarithmic function[28] (Fig. 2c), we observe that the recovery slopes increased with the loading amplitude and the damage state, as also seen previously in several laboratory-tested materials[2,4,28]. The THU building was exposed to significantly higher levels of maximum acceleration at the top of the building (PTA) and showed recovery slopes that were an order of magnitude larger than for the ANX building before 2011 (i.e., R1, R2). On the other hand, the recovery slope after the Tohoku earthquake (i.e., R3) was around 5-fold steeper for the THU building, which was severely damaged during this event[20]. Although the log–time adjustment does not have any physical basis, we assume that the rate of recovery is linked in some way to the rate of coalescence within the particles in cracked zones, so that an equilibrium state can be reached. Here, densely cracked media would show steep recovery slopes because there are more voids to be filled after strong excitation.

To explore the conditioning effects on the recovery slope, the log–linear model was applied to the internal recovery cycles created during the aftershock sequence of the Tohoku earthquake (i.e., Fig. 2b, R3$_a$, R3$_b$, and eventually R3$_c$). The recovery slope decreased progressively as the conditioning effects were lost: from 0.069 to 0.057 for ANX, and from 0.196 to 0.128 for THU (Fig. 2c). This suggests a gradual closing mechanism of cracks that were activated by the contribution of local stress-chain adjustments to the total recovery. Furthermore, for the ANX building (which was slightly damaged during the 2011 event[20]) the recovery slopes due to the conditioning cycles were steeper than the backbone slope, whereas the opposite was seen for the THU building. This reflects the sensitivity of the structural material to the opening/ closing processes of temporary cracks while the structure is still recovering from the main shock. In a densely damaged medium, much more energy would be necessary to perturbate the bond system and generate new stress states that can change the global response, which will be limited, however, by the ultimate collapse of the building.

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### Figure 2 Long-term recovery of the fundamental frequency of the buildings (ANX, THU).

a, Co-seismic frequency computed over the years, showing slow dynamics after the important earthquakes in 2005, 2008 and 2011.**b,** Zoom-in on the recovery after the 2011 event, showing the conditioning cycles (i.e., R3$_a$, R3$_b$, R3$_c$). **a, b,** Each symbol corresponds to a single earthquake, and the colour scale is related to the PTA. The larger symbols were used to monitor the backbone curve. **c,** Log–linear recovery of the normalized frequency variation ([?]f/f$_f$ = (f-f$_f$)/f$_f$, where f$_f$ = maximum final frequency), which indicates the slopes computed from the log–linear method applied to the periods shown in **a** and**b** .

Relaxation models applied to long-term structural recovery

Firstly, from the relaxation model[24] shown in Figure 3a, the a and G parameters were computed as proxies for the elasticity. The parameter a , which is inversely proportional to the pre-seismic elastic modulus,

increased sharply during the post-Tohoku recovery. Parameter G, which is directly proportional to the co-seismic elasticity, decreased. This confirms the increase in the softening in both of these buildings. Secondly, the ratio τ_{max}/τ_{min} computed from the relaxation function in Figure 3b[22] increased from ˜6 to ˜23 in the ANX building, and from ˜9 to ˜18 for THU. This ratio denotes the different time-scale mechanisms that act in the time–logarithmic segment of the recovery and characterizes the diversity of the crack sizes[14]. From this we can infer that after the 2011 event the variety of the cracks in the ANX and THU structures was quadrupled and doubled, respectively. Additionally, the gradual reduction in τ_{max}/τ_{min} during the re-loading cycles confirms the progressive crack-closing process during the aftershocks inferred from the recovery slopes. In addition, after the Tohoku earthquake we observe clear changes in the maximum frequency variation (i.e., [?]f/f) for both models, which increased from ˜3% to ˜12% for ANX and from ˜13% to ˜33% for THU (Fig. 3a, b), which is consistent with the modulus softening and then the global change in the structural states.

A complete signature of the recovery process is given by the relaxation spectrum[23] shown in Figure 3c. We detect mechanisms over five orders of magnitude in time, from t ˜0.1 to ˜1200 seconds; i.e., extreme values that are not revealed by the previous models. The spectrum bandwidth represents the range of the dominant relaxation times, and as the ratio τ_{max}/τ_{min}, this serves as a hint of the diversity of the crack sizes that are closed over the time of the recovery. These data suggest that a large variety of crack sizes was activated following the 2008 event (i.e., R2). The post-Tohoku spectrum does not indicate new types of cracks; nevertheless, the maximum spectrum amplitude is ˜3.5-fold that observed in the periods prior to Tohoku. This implies that the crack density increased around 3.5-fold after 2011 for both of these structures. It can also be noted that the spectra of the THU building are approximately 3-fold those of the ANX building, showing the different levels of damage between the buildings even before 2011. At the same time, conditioning effects might have been significant in the recovery process for the ANX building, which activated mechanisms with relaxation times in the order of 10^1-10^2 seconds. In contrast, during the recovery of the THU structure, the conditioning cycles just contributed to the activation of inner small mechanisms, as shown by the narrow left-shifted spectra R3$_{a,b,c}$ (Fig. 3c, right). Thus, theoretical models applied to earthquake data from real buildings fit the recovery of the fundamental frequency after earthquakes. These data indicate that non-linear elastic processes within the structural bond system might explain the transitory and permanent variations of structural dynamic responses to seismic events. In particular, the relaxation parameters reveal the internal material changes that are related to cracking and stiffness degradation; i.e., in relation to the structural health and safety of a building.
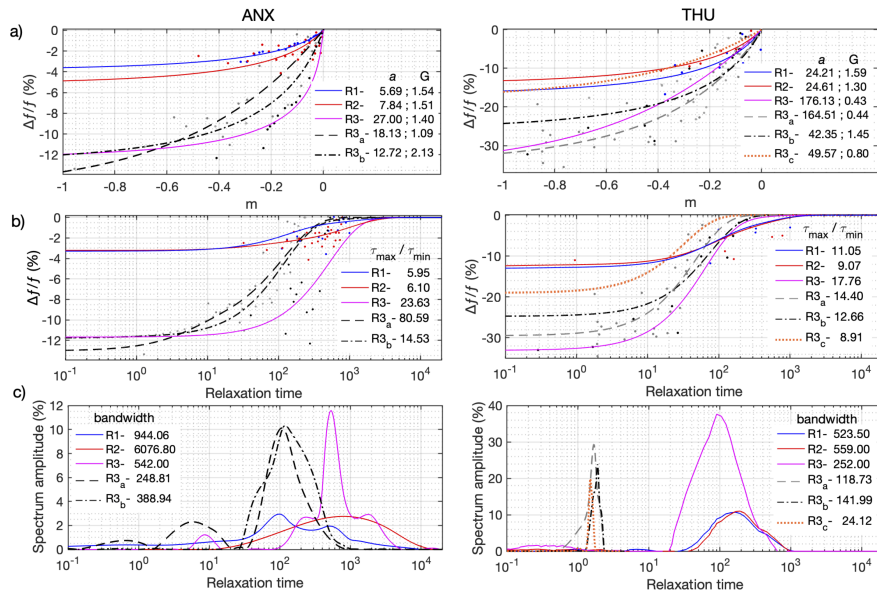
Figure 3 Relaxation models adapted to the frequency recovery of buildings for the different periods defined in Figure 2.

a , Normalized frequency variation over recovery time according to the model proposed by Ref. 24. Here, a and G are proxies for elasticity. $m = \log\left(\frac{t}{\tau}\right)$. **b,**Normalized frequency variation over the recovery time according to the relaxation function of Ref. 22. Here, $\tau_{\max}/\tau_{\min}$ is the ratio between the final and initial relaxation times computed from the model. **c,**Relaxation spectra proposed by Ref. 23.

Conclusions

By analogy with relaxation studies in granular materials, we infer that heterogeneities such as micro-scale cracking in concrete, might be responsible for detectable changes in the building properties. Hence, alterations in the bond system (i.e. driven by thermodynamic and mechanical processes) might contribute to the internal organization of particles that allows for the closing of cracks. This, however, is an ongoing research plenty of challenges to try to understand the underlying microscopic mechanisms that are responsible for the phenomena.

The procedure followed to obtain the results presented in this manuscript could be an easy way to detect variations in the structural response (i.e. damage). For example, the comparison of the

structural response in terms of relaxation parameters before and after a specific event, for a same level of deformation, could provide us with important information about the extension and density of heterogeneities (i.e. cracks). The automatized computation of relaxation parameters applied to real-time instrumented buildings, would allow us to characterize differences in the structural behavior, which is fundamental for making prompt and accurate decisions about structural health.

Acknowledgment

Conflict of Interest

The authors declare no potential conflict of interest.

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