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Comparative analysis of acoustic emissions produced in abrupt and non-abrupt fracture processes in reinforced concrete walls

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Abstract. The determination of the eventual abrupt fracture of a reinforced concrete structure is of fundamental importance to estimate and mitigate the possible damages caused by its failure; of particular importance are shear-type fractures since these usually lead to sudden failure of the structure. One way to determine the presence of shear-type micro-cracks is by parametric analysis of the acoustic emissions produced by the micro-cracks during their growth. In this analysis, a direct comparisson of the waveform allows a distinction to be made between tensile-type and shear-type events. In the present study, we performed a comparative analysis of fracture processes in two reinforced concrete walls. In one of the walls an out-of-plane force was applied leading to bending and a non-abrupt failure; in the other one diagonal forces were applied leading to an abrupt shear-type fracture. Acoustic emissions were detected throughout and we found that at least one of the parameters associated with the parametric analysis allows distinguishing between abrupt and non-abrupt failures. Our results suggest that parametric analysis of acoustic emissions could be a useful tool in the prediction of abrupt failures in reinforced concrete structures.

1. Introduction

In brittle materials under gradually increasing stresses, fracture process is dominated by the generation of micro-cracks. Detection and classification of micro-cracks are especially important in civil structures due to the possibility of predicting shear fractures, which often lead to abrupt and violent collapses. Acoustic emission (AE) technique, which is based on the mechanical waves generated by the growth of the micro-crack, provides a way to follow in real time the progress of the micro-cracking process [1, 2].

However, classification of micro-cracks from AE is not straightforward. Studies similar to the inversion of the seismic moment tensor in seismology have been proposed to identify micro-crack type and location [3, 4], however, these methods are often computationally demanding and require multiple sensors. On the other hand, parametric analysis (PA) of AE offers an alternative that can be implemented more easily. PA is based on some features that can be taken directly from the AE waveform and it has been used to study micro-cracks in several types of structures [5, 6].

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In this paper we conducted a comparative study that suggests that PA is a useful tool for predicting the proximity of abrupt collapses. For this purpose, we performed two experiments on reinforced concrete walls. In the first one an out-of-plane force was applied which produced bending and a non-abrupt fracture. In the second one an in-plane and perpendicular force was applied, this process ended in an abrupt collapse. Our results show that, even in the case of one-sensor measurements, at least one of the parameters could be used as a strong indicator of the proximity of a violent and abrupt collapse. As far as we know, no such comparative study on walls has been published in the scientific literature.

2. Parametric analysis

Parametric analysis of acoustic emissions is based on the waveform detected by the sensor of the emissions. Micro-cracks produced by tensile events release most of their energy in the form of P-waves, while shear events do so through S-waves. P-waves are faster than S-waves, therefore it is expected that, for the same energy, waveforms related to tensile events reach their maximum sooner and have shorter duration than shear events. At the same time, the frequency of S-waves is shorter than that of P-waves. All these differences allow us, at least qualitatively, to differentiate the origin of AE, which is the basis of the PA. Once the threshold has been determined (see [7] for details), two time parameters are defined: duration (T) and rise time (R), which is the time it takes for the signal to reach the maximum amplitude (A). Instead of frequency, it is convenient the use of the number of counts (N) which is the times signal crosses the threshold. All these magnitudes can be merged into two parameters: average frequency $AF = N/T$ and rise ascent $RA = R/A$. Therefore, tensile events are related with higher AF and lower RA while shear events exhibit the oposite behavior [8, 9]. Thus, parametric analysis of acoustic emissions provides a classification tool that goes beyond the usual methods of AE analysis based on counting emissions in different parts of the fracturing process (Kaiser and Felicity effects) [10, 11].

3. Experimental set-up

Figure 1 and Figure 2 show the two reinforced walls used for experiment 1 and experiment 2 respectively. In Figure 1 an out-of-plane force was applied. In Figure 2 the force is perpendicular to the main plain of the wall. In both experiments walls experienced a typical cyclic loading with increasing amplitude. Both walls were connected to the same reaction wall and AE were detected with a piezoelectric sensor located on the main plane of the walls near a corner. Electric signal was pre-amplified (60 dB), frequency-filtered (100 kHz - 300 kHz) and acquired at 5.0 MHz.

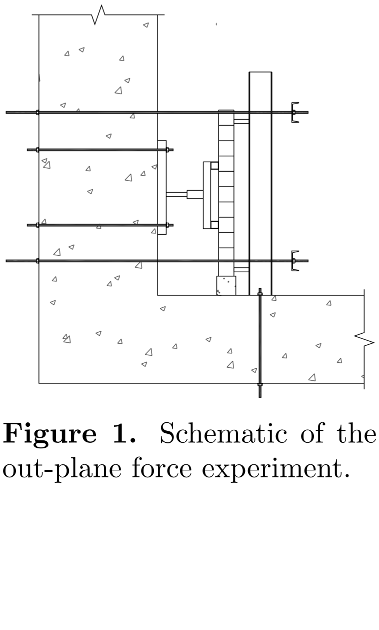

Figure 1. Schematic of the out-plane force experiment.

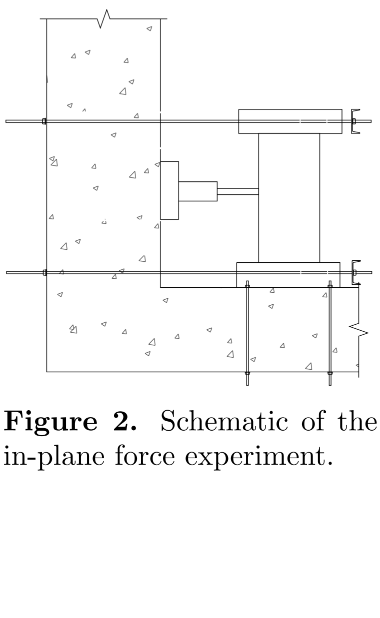

Figure 2. Schematic of the in-plane force experiment.

4. Results and discussion

Both walls were driven to collapse. Wall 1 presented a gradual deterioration due to bending evidenced by the appearance of cracks that finally led to a non-violent collapse. Wall 2 collapsed abruptly and violently due to a shear fracture that crossed the wall from side to side.

For experiment 1 the total number of emissions was 496 and for experiment 2 it was 4912, a difference of one order of magnitude. Figure 3 and Figure 4 show the acoustic activity (number of emissions per second) for experiment 1 and experiment 2. For experiment 1 and for the first cycles ($t < 800$ s) it is possible to appreciate well defined zones of very low acoustic activity, which is expected according to Kaiser effect. In experiment 2 the Kaiser effect is also evident. In both experiments the maximum acoustic activity occurred at the time of collapse. Despite some qualitative differences, Figure 3 and Figure 4 show that the final state of both acoustic activities is practically the same, which leads us to conclude that the acoustic activity does not allow us to differentiate or characterize the two experiments.

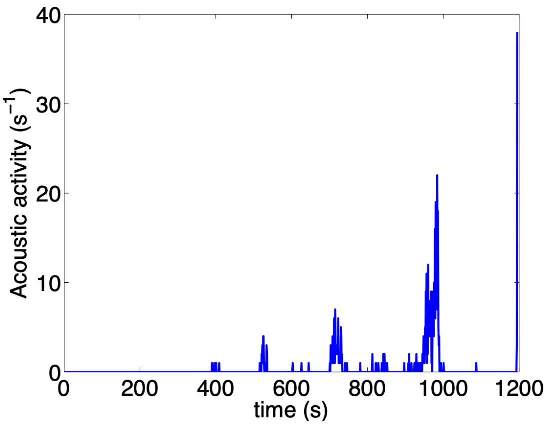

Figure 3. Acoustic activity (number of emissions per second) for experiment 1.

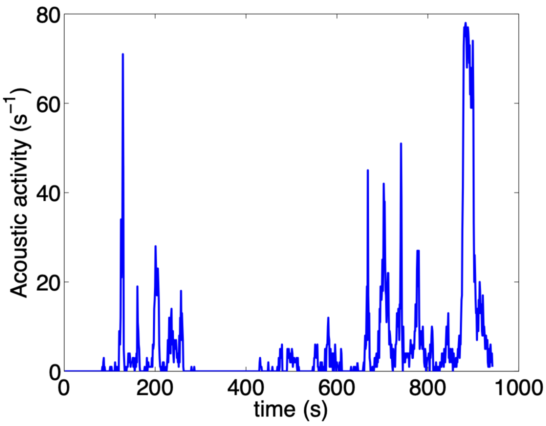

Figure 4. Acoustic activity (number of emissions per second) for experiment 2.

Similar to acoustic activity behavior is observed in the evolution of AE energy. Figure 5 and Figure 6 show the normalized energy, in log scale, of the emissions for experiment 1 and experiment 2 as a function of time. As in the acoustic activity, the emission energy shows bands of acoustic silence between cycles, evidence of the Kaiser effect. As expected, most energetic events occurred at the moment of final failure. Again, the energy of the emissions does not allow distinguishing between shear and tensile events and therefore cannot be used to characterize the two experiments. Neither the acoustic activity nor the energy of the emissions allow the two fracturing processes to be clearly distinguished; tensile or shearing events are obscured in this perspective.

On the other hand, parametric analysis of acoustic emissions in both experiments show clear differences. Figure 7 and Figure 8 show AF (green) and RA (red) parameters for experiment 1 and experiment 2, acoustic activity (blue) is plotted for comparison purposes and all values are normalized. For experiment 1 RA and AF took similar normalized values for all the cycles. It is especially remarkable that for the first and last cycles both parameters reached maximum values, despite the load of the last cycle being three times higher than that of the first cycle. On the contrary, experiment 2 presents a drastic change of the RA parameter at the time of collapse, while the AF parameter takes similar values during the experiment. As discussed in the section 3, the Figure shows a significant increase of the shear-type events in the last load cycle, while the tensile-type events take similar values in all cycle.

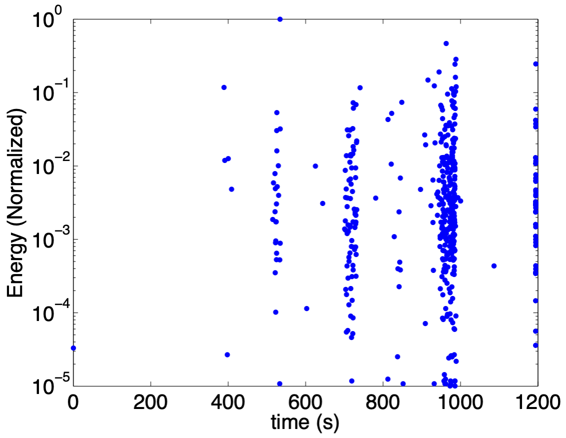

Figure 5. Energy of the emissions as a function of the running time for the experiment 1.

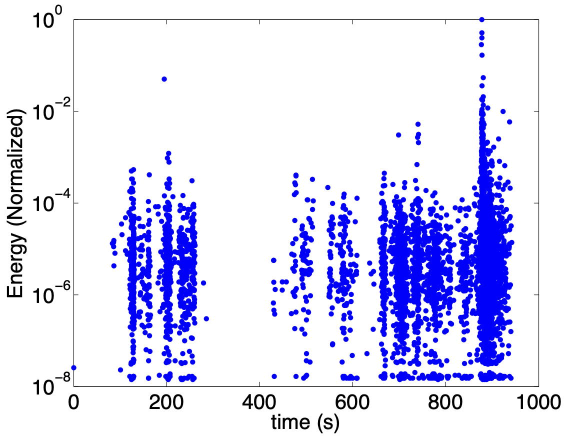

Figure 6. Energy of the emissions as a function of the running time for the experiment 2

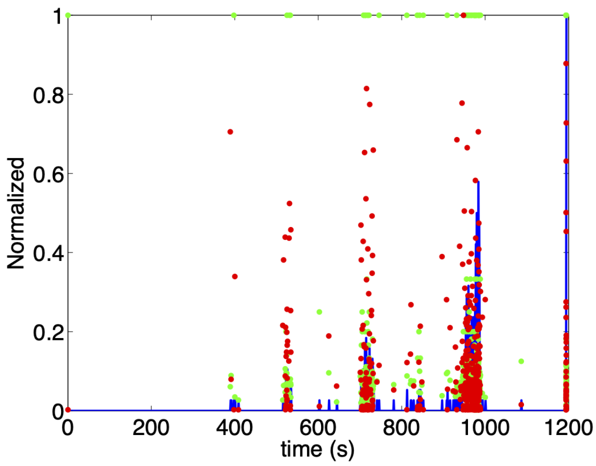

Figure 7. AF (green) and RA (red) parameters for experiment 1. Acoustic activity (blue) is plotted for comparison purposes. All values are normalized.

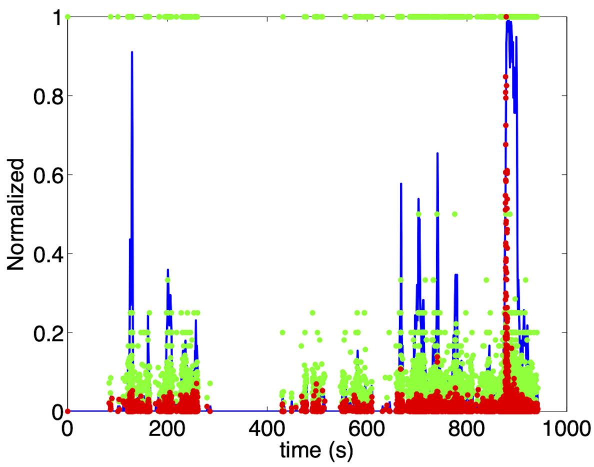

Figure 8. AF (green) and RA (red) parameters for experiment 2. Acoustic activity (blue) is plotted for comparison purposes. All values are normalized.

To make this behavior more evident, Figure 9 shows the *AF vs. RA* parametric plot for experiment 2. The blue dots are associated with the acoustic emissions generated in the cycles prior to the collapse cycle, the red dots are related to the emissions in the last cycle when the wall fails. According to parametric analysis, it is clear that collapse is dominated by the presence of shear events, which is consistent with the final state of the wall. At the same time, many of these high *RA* events correspond to the most energetic emissions which explains the explosive collapse of the wall. Although there are statistical methods to differentiate between shear and stress events in *AF vs. RA* diagrams [12, 13], this simple visual analysis allow us to observe the transition towards a high concentration of shear events in the final stage of the fracture process.

The results obtained in this comparative study can be extended to include other effects associated with this type of experiments. First, it would be interesting to locate the origin of the emissions to verify that indeed the events identified with high value of the AR parameter are associated with the main crack observed at the end of experiment 2. This could be done with multiple sensors or with a single sensor accompanied by artificial intelligence techniques [14]. Second, it is necessary to perform the experiments on a wide variety of walls to verify that the results obtained in this work represent a general behavior under the stress conditions used. Finally, it would be appropriate to use statistical techniques to clearly separate pure stress events from pure shear events [12]. This would allow a much more accurate classification and the elimination of biases originating from simple observation.

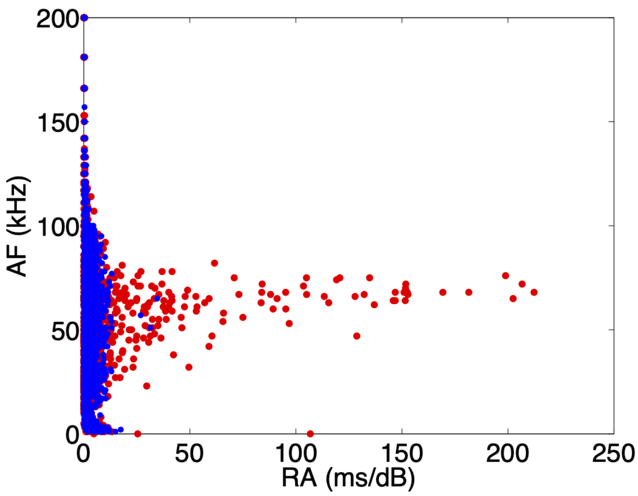

Figure 9. Parametric plot AF *vs.* RA for experiment 2. Blue dots correspond to the emissions for $t < 800$ s , and red dots for $t > 800$ s, which include collapse.

5. Conclusions

The parametric analysis of acoustic emissions allowed us to distinguish between the gradual fracture of a wall deformed and gradually fractured by bending from one where the stresses produce an abrupt and explosive collapse. For the latter, unlike acoustic activity or emission energy, which do not show significant differences between experiments, the parameter related to shear micro-cracking exhibits a drastic increase at the time of explosive collapse. This allows us to conclude that in this case the fracture occurred due to a series of highly energetic shear events, which is in agreement with what was observed in the final state of the wall. For bending, no significant variation of this parameter was observed during the experiment. These results suggest that parametric analysis could be a useful tool to detect the concentration of shear events and the proximity to abrupt collapse. However, two limitations of the present study should be pointed out. First, all measurements were performed with a single sensor, which means that magnitudes such as amplitude or energy cannot be accurately determined. We consider that this does not considerably affect the qualitative analysis performed on the parameters. Second, and perhaps more importantly, the study was performed on only two walls. Although this fulfilled the initial purpose of the study, extrapolation of these results requires further experiments on a wide variety of walls, reinforcements and composites.

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