Micro-crack classification in reinforced concrete walls by parametric analysis of acoustic emissions.

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Abstract. Fracture processes in brittle materials are governed by the generation and growth of micro-cracks. The acoustic emission technique, based on the elastic waves generated by cracks during their growth, is a way to follow the evolution of micro-cracks. Parametric analysis of emissions is based on some features that can be extracted from the waveforms and have been used on different materials to distinguish emissions originated from tensile and shear events. This classification is especially important in the study of fracturing in civil structures due to the presence of shear events that usually produce abrupt and violent collapses. This paper shows the results of parametric analysis on two types of tests performed on reinforced concrete walls. In the first test, in-plane diagonal compression is applied, looking for the generation of shear events and violent collapse. In the second one, out-of-plane force is applied to look for the generation of tensile-compression events and a non-abrupt collapse. Our results show that parametric analysis can distinguish between the two processes and suggest that it could be used as a method to predict the presence of shear events and the proximity to the violent collapse of 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 technique, which is based on the mechanical waves (acoustic emission, AE) 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].

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

Figures 1 and 2 show the two reinforced walls used for experiments 1 and 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. 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.

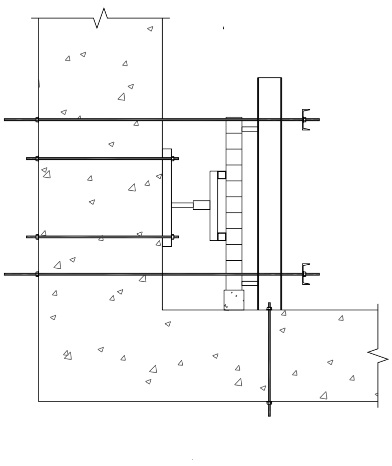

Figure 1. Schematic representation of the out-of-plane force experiment.

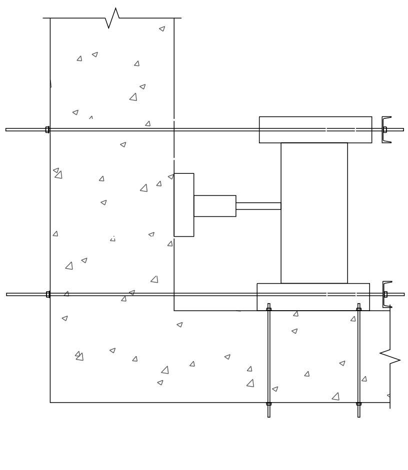

Figure 2. Schematic representation of the in-plane force experiment.

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. Figures 3 and 4 show the acoustic activity (number of emissions per second) for experiments 1 and 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 not evident. In both experiments the maximum acoustic activity occurred at the time of collapse. Similar to acoustic

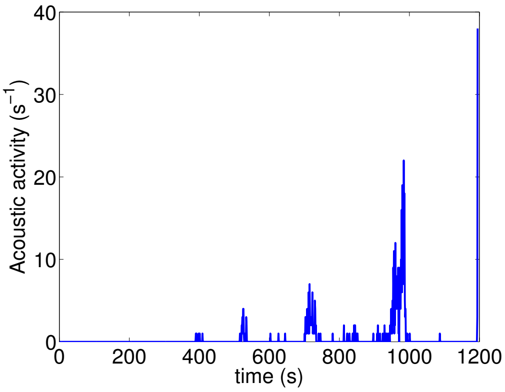

Figure 3. Acoustic activity (number of emissions per second) for experiment 1.

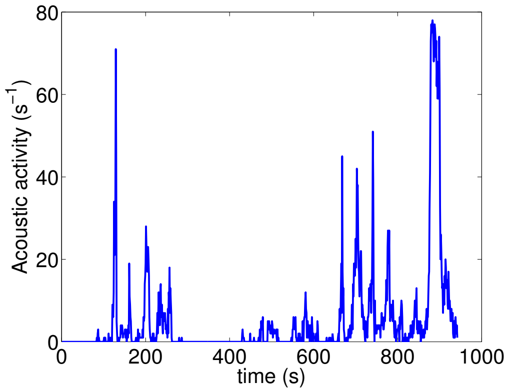

Figure 4. Acoustic activity (number of emissions per second) for experiment 2.

activity behavior is observed in the evolution of AE energy. Figures 5 and 6 show the energy, in log scale, of the emissions for experiments 1 and 2 as a function of time. As expected, most energetic events occurred at the moment of final failure. 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. Figures 7 and 8 show AF (green) and RA (red) parameters for experiments 1 and 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. 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.

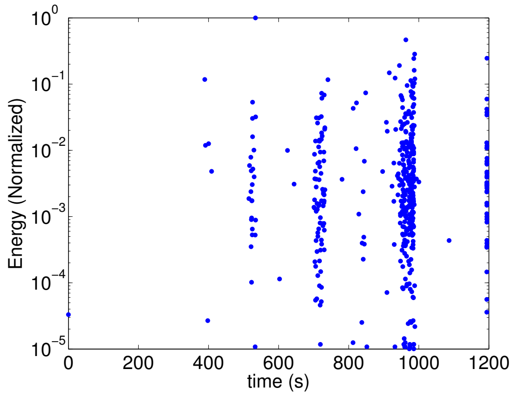

Figure 5. Energy of the emissions as a function of the running time for the experiment 1.

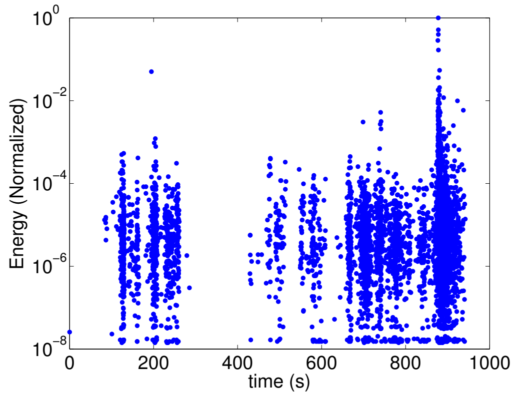

Figure 6. Energy of the emissions as a function of the running time for the experiment 2

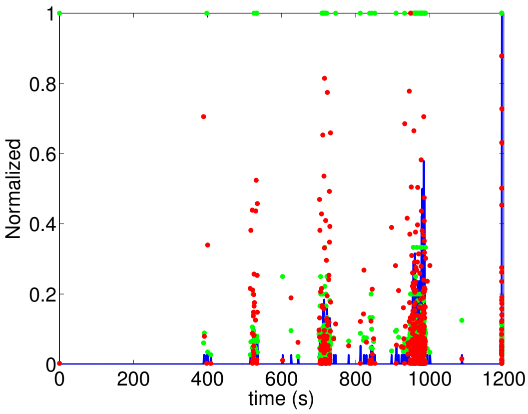

Figure 7. AF (green) and RA (red) parameters for experiment 1. Acoustic activity (blue) is plotted for comparison purposes. All values are normalized.

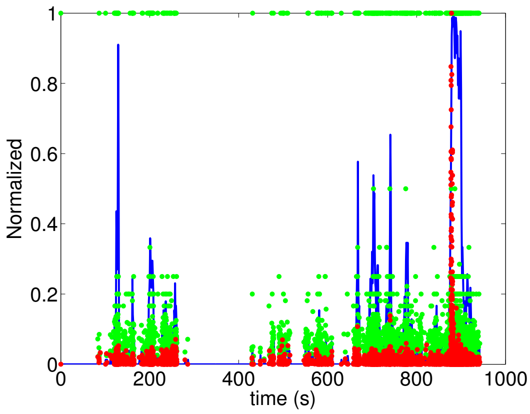

Figure 8. AF (green) and RA (red) parameters for experiment 2. Acoustic activity (blue) is plotted for comparison purposes. All values are normalized.

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 significan 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

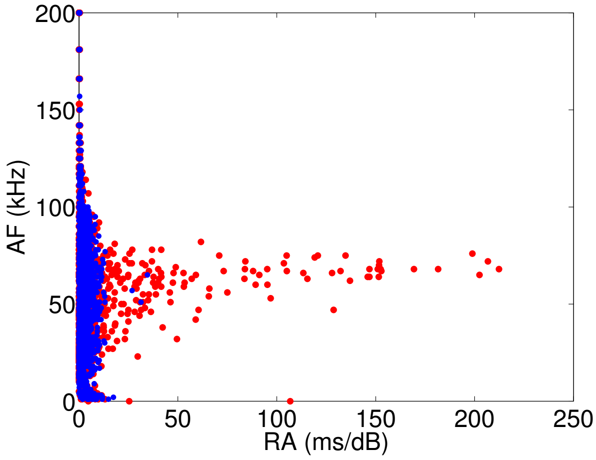

Figure 9. Parametric plot AF vs RA for experiment 2. Blue dots correspond to the emissions for $t <$ 800 s , and red dots for $t >$ 800 s, which include collapse.

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.

References

[1] Grosse C U and Ohtsu M 2008 *Acoustic Emission Testing* (Berlin: Springer-Verlag) p 11-18

[2] Nakamura H, Ohtsu M, Enoki M, Mizutani Y, Shigeishi M, Inaba H, Nakano M, Shiotani T, Yuyama S and Sugimoto S 2016 *Practical Acoustic Emission Testing* (Japan: Springer) p 5-34

[3] Graham C C, Stanchits S, Main I G and Dresen G 2010 Comparison of polarity and moment tensor inversion methods for source analysis of acoustic emission data *Int. J. Rock Mech. Min. Sci.* **47**(1) 161

[4] Panteleev I A 2020 Analysis of the Seismic Moment Tensor of Acoustic Emission: Granite Fracture Micromechanisms During Three-Point Bending *Acoust. Phys.* **66**(6) 653-665

[5] Aggelis D G 2011 Classification of cracking mode in concrete by acoustic emission parameters *Mech. Res. Commun.* **38**(3) 153-157

[6] Moradian Z, Einstein H H and Ballivy G 2016 Detection of cracking levels in brittle rocks by parametric analysis of the acoustic emission signals *Rock. Mech. Rock. Eng.* **49**(3) 785-800

[7] Clavijo J, Wang H and Sánchez S 2019 Observation of significant differences between electromagnetic and acoustic emissions during fracture processes: A study on rocks under compression loading *J. Phys. Conf. Ser.* **1386**(1) 012107

[8] JCMS-IIIB5706 2003 *Monitoring method for active cracks in concrete by acoustic emission* (Federation of Construction Materials Industries Japan)

[9] Ohno K and Ohtsu M 2010 Crack classification in concrete based on acoustic emission *Constr. Build. Mater* **24**(12) 2339-46

[10] Panesso A, Samboní C, Romero P, Castellanos S, Marulanda J, Thomson P 2019 Caracterización experimental de daño en vigas de concreto sometidas a carga cíclica usando emisión acústica *Congreso Nacional de Ingeniería Sísmica (Cali)* (9: 29-31 Mayo, 2019, Cali, Colombia) (Cali: Universidad del Valle) p 671

[11] Sagar R V, Prasad B and Singh R 2015 Kaiser effect observation in reinforced concrete structures and its use for damage assessment *Arch. Civ. Mech. Eng.* **15**(2) 548-557

[12] Farhidzadeh A, Salamone S and Singla P 2013 A probabilistic approach for damage identification and crack mode classification in reinforced concrete structures. *J. Intell. Material Syst. Struct.* **24**(14) 1722-35

[13] Prem P R and Murthy A R 2017 Acoustic emission monitoring of reinforced concrete beams subjected to four-point-bending *Appl. Acoust.* **117**(1) 28-38