DISCRIMINATION OF ACOUSTIC EMISSION HITS FROM DYNAMIC TESTS OF A REINFORCED CONCRETE SLAB

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Abstract

In the evaluation with acoustic emission (AE) of the damage and state of a concrete structure under a dynamic force, the most relevant information come from the AE hits produced by cracking processes. But, unfortunately, there are other sources of AE, which are unrelated with the damage state of the specimen, as the closing of cracks, friction between different elements, or noise from the testing equipment. The discrimination between AE hits from cracking processes and the other sources is useful in order to have an accurate evaluation. In this paper the classification of AE hits with several signal-processing techniques is investigated. Several dynamic tests were carried out with a reinforced concrete slab attached to a 3-m square MTS shaking table, and during these experiments the AE hits were recorded. The specimen represents, at the 1/3 scale, a flat slab supported on four box-type steel columns, and it was submitted to a simulation of the Campano-Lucano earthquake recorded at Calitri (Italy). After the test, the AE transients were extracted and classified according to several signal parameters. The autocorrelation, wavelet power, kurtosis, RMS in different parts of the signal and approximate entropy were calculated for each signal. A comparison and evaluation of the different classifications according to each parameter is presented.

Keywords: concrete structures, transient classification, dynamic test.

Introduction

One considerable source of damage in reinforced concrete (RC) structures when they are located in earthquake-prone areas is cyclic loading induced by ground acceleration during seismic events. These structures are commonly designed to sustain, essentially, two levels of seismic action: low-to-moderate intensity earthquakes (level I), and strong earthquakes (level II). Under level I earthquakes, the RC structure must remain basically elastic. In moderate or high seismicity regions, an RC structure can experience several tens of low-to-moderate intensity earthquakes during its lifetime. When an RC structure experiences a high number of low and moderate intensity earthquakes there is a concrete degradation of the RC structure that can even produces the slip between reinforcing steel and concrete, which is an important damage for this kind of structures [1]. As visual inspection is not possible in most cases and does not allow knowing in which state the internal part of the structure is, it would be very useful to have a non-destructive technique, which can evaluate the state of the RC structure during its lifetime. The AE technique is very suitable of this purpose because it renders the possibility of recording information of the cracking process during an earthquake, even when it is very low [2].

In order to investigate the health monitoring of an RC structure submitted to low-to-moderate intensity earthquakes using AE, a prototype structure consisting of an RC slab supported on four
box-type steel columns was placed on a shake table. This structure underwent several simulations of the Campano-Lucano earthquake recorded at Calitri (Italy) and the generated AE hits were recorded by eight AE low-frequency sensors (type VS30 set in the range 20-100 kHz) distributed near the most critical parts of the structure.

As in a dynamic test like this there are many sources of noise, a lot of precautions were taken in order to prevent spurious hits. So rubber layers and teflon films were inserted between any surfaces whose contact could generate friction noise, and four guard sensors were placed near the bottom end of the columns to prevent noise generated by the contact between the base plate of the columns and the shake table.

In spite of all the preventive measures adopted to avoid undesired noise, during the analysis of the results it was observed that the AE sensors registered spurious signals coming from friction or electromagnetic noise. As this noise could disturb the AE analysis and could also appear in a real situation when a building is monitored, it was necessary to investigate the way of filtering out the hits, which are not coming from concrete cracking processes. The investigation that has been carried out in order to classify the AE hits is presented in this paper. Different parameters calculated from the AE transients have been tested in order to know their capacity of filtering out the hits coming from friction or noise. These parameters were: the autocorrelation of the signal, its wavelet power, the kurtosis, its approximate entropy and the root mean square (RMS) of different parts of the signal.

The objective of this paper is to obtain a filter using signal parameters of the AE hits. The description of the experiment and the obtaining and analysis of the data can be found in [3]. Nevertheless, the experiment is also briefly presented here for clarity.

**Experiment**

A prototype structure consisting of a RC slab supported on four box-type steel columns was designed according to Spanish codes. The prototype structure has one story 2.8 m in height and 4.8×4.8 m² in plan. It is assumed to be located in the moderate-seismicity Mediterranean area. Accordingly, from the prototype structure, the corresponding test model was derived by applying the following scaling factors for geometry, the acceleration and the stress, respectively: \( \lambda_l = 1/2 \), \( \lambda_a = 1 \) and \( \lambda_{\sigma} = 1 \). Figure 1 shows the geometry and reinforcing details of the test model. The slab measures 125 mm in depth and it is reinforced with two steel meshes, one on the top made with 6mm diameter bars spaced 100 mm, and another on the bottom consisting of 10 mm diameter bars spaced 75 mm. The slab was reinforced at the corners by shearheads consisting of steel U-shapes 60 mm in depth in order to prevent punching shear failure. The average yield stress \( f_y \) of the reinforcing steel was 467 MPa, and the average concrete strength, \( f_c = 23.5 \text{ MPa} \).

The test model was placed on the uniaxial MTS 3×3 m² shake table as indicated in Fig. 2. To satisfy the similitude requirements between the prototype and the test model, additional steel blocks were attached on the top of the RC slab (total mass \( m = 7,390 \text{ kg} \)). The shake table movements were patterned after the Calitri 1980 NS earthquake (Campano-Lucano, Italy) with the time scale compressed by a factor of \( \lambda_t = (1/2)^{0.5} = 0.707 \). Two series of seismic simulations were conducted using the Calitri 1980 NS accelerogram scaled to different amplitudes.
The Vallen Systeme ASMY-5 was used to measure AE during the tests. Eight low-frequency AE sensors (type VS30 set in the range 20-100 kHz) were placed on the test model as shown in Fig. 1b. The threshold detection of the AE sensors was set at 45 dB. To prevent undesired noise generated by the contact between the base plate of the columns and the shake table, four guard sensors were placed near the bottom end of the columns as indicated in Fig. 1a (one sensor at each column). Moreover, in order to remove or reduce the sources of spurious friction noise, rubber layers and teflon films were placed between the added steel blocks and the slab. Teflon films were also inserted between any metallic surfaces whose contact could generate spurious friction noise, such as screws, steel plates for fixing the accelerometers to the slab, cables, etc.
Noise Problem

All the preventive measures were not enough to avoid the presence of hits coming from noise sources. Three principal noise sources were indentified:

a) The friction between different elements of the experimental structure.

b) The closing of cracks

c) Electromagnetic noise

The noise source a) was reduced by the rubber layers and teflon films, but it was impossible to have it completely eliminated due to the fast movements produced during the experiment. The noise sources b) and c) could not be suppressed in any way, the first one because the same specimen has to be used during different seismic simulations, and the second one because it was produced by the shake table, at which the test model were attached.

During a cracking process a high amount of elastic energy is released fast and it propagates as elastic waves with high amplitude at its beginning and then decaying exponentially. So the temporal signal of the AE hits is non-stationary. In this article we will name them as “cracking hits”. However, in signals coming from friction or electromagnetic noise the amplitude must be approximately constant over all the duration of the hit, as the energy is released continuously during a longer period of time. So, the temporal signal of these AE hits is typically stationary. We will call them as “noisy hits”. In Fig. 3 two examples of these kinds of AE hits from our experiment are shown.

The objective of the paper is to find a way of filtering out the noisy hits. To do this, a first attempt was made noticing that hits with long duration and low amplitude were noisy hits. So the hits that do not meet the following two conditions were not taken into account:

- The duration in µs must be less than 3000 µs + 80 µs/dB*(Amplitude (in dB)-45 dB).
- The amplitude must be higher than 60 dB.

It was found, however, that this filtering was not enough as many noisy hits meet the conditions and pass the filter, so it seems that a filter based on the classical AE parameters could not work.
properly. Thus, it was necessary to find another filtering condition to eliminate the remaining noisy hits based on signal processing of the hits waveform.

Fig. 3. Examples of a cracking hit (left) and noisy hit (right).

**Filtering Parameters**

In order to build a proper filter, it is necessary to look for a signal parameter, which always takes different values for cracking and noisy hits. If this ideal parameter is found, setting the right threshold will allow us to filter out all the noisy hits. To find this ideal parameter, several signal parameters were investigated and their discrimination capacity tested. These signal parameters were:

- **The autocorrelation** [4]. As the cracking hits are non-stationary and have the maximum amplitude at the beginning of the hit, their autocorrelation must decay faster than the autocorrelation of the noisy hits, which are stationary. We measure this difference by calculating the distance between the two symmetric points of the autocorrelation whose value is 66% of the maximum value. We call this parameter “Autocorrelation Width”.

- **The wavelet power**. In previous investigations in other applications of AE, it was found that the density of wavelet power (DWP) in different frequency bands can be used to determine the source of AE hits. See [5] for more details. In this paper, the quotient of the DWP in the band [40-100] kHz divided by the DWP in the band [10-40] kHz is used as a signal parameter for the discrimination of AE hits. We call it “DWP quotient”.

- **The kurtosis**. The kurtosis [6] is a measure of the number of extreme values that are in a signal or in a distribution. A higher kurtosis implies that more of the variance is the result of extreme values, so their frequency is higher than in a signal with lower kurtosis.

- **The approximate entropy**. The approximate entropy (ApEn) is a measure of the complexity of a signal [7]. A higher value of ApEn means a higher degree of complexity. As the relevant part of the transient signal of the cracking hits is concentrated at the beginning of the hit, they are less complex and disordered than the noisy hits.
The root mean square (RMS) [6]. As the cracking hits are non-stationary, the amplitude distribution is concentrated at the beginning of the hit, and the RMS of the amplitude in the first part of the signal is higher than the RMS in the final part. The quotient of the RMS in the band [0-400 µs] divided by the RMS in the band [400-1300 µs] is used for discriminating signal parameter and we named it as “RMS rate”.

Results

All the considered parameters have very different values for pure cracking and noisy hits, as can be seen in Table 1 for the hits shown in Fig. 3, so it seems that all of them must filter the noisy hits and allow the cracking hits to pass. However, the problem is that the system under study is very complex and dispersive, so the waveform can change very much in the path from the source to the sensors. It shows that the noisy and cracking hits can have similar values of the parameters.

Table 1. Values of the filtering parameters for the hits shown in Fig. 3.

<table>
<thead>
<tr>
<th></th>
<th>Autocorrelation Width</th>
<th>DWP quotient</th>
<th>Kurtosis</th>
<th>ApEn</th>
<th>RMS rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracking</td>
<td>12</td>
<td>2.16</td>
<td>16.87</td>
<td>0.7379</td>
<td>3.5955</td>
</tr>
<tr>
<td>Noisy</td>
<td>114</td>
<td>0.056</td>
<td>2.18</td>
<td>0.8392</td>
<td>1.2001</td>
</tr>
</tbody>
</table>

For these reasons, it is necessary to test the filtering capacity of each parameter. We have visually classified a set of 200 AE hits in cracking or noisy hits and the values of the filtering parameters have been calculated. In Fig. 4 these values can be seen for the cracking and noisy hits. The ideal situation would be to have two sets or clusters of cracking and noisy hits perfectly separated, but, unfortunately, the two sets are mixed for all of the filtering parameters, although not in the same degree. In the case of the Autocorrelation Width and the Approximate Entropy the cracking and noisy hits have similar values. With the DWP quotient, the kurtosis and the RMS rate, the noisy hits have in general a lower value than the cracking hits, so the separation between the two groups and the filtering of the noisy hits is possible. Some cracking hits have a low value of these parameters and are mixed with the noisy hits, and some noisy hits have a high value of the parameters and are mixed with the cracking hits. So, any separation of the two groups of hits based on the value of the filtering parameters will have some hits wrongly classified because they have a parameter value more similar to the other group.

The automatic classifications of the hits using the filtering parameters is made by taking a threshold and place the hits with a parameter value higher than the threshold in a group and the hits with the parameter value lower in the other group. The value of the threshold is very important to achieve a correct discrimination between the cracking and noisy hits and its influence in the filtering process has to be checked in order to choose the best possible threshold for each filtering parameter. So that, a study of how adequate the filtering process is for each parameter and different thresholds has been carried out.

The results can be seen in Fig. 5, where the rate of cracking and noisy hits that passed the filter for each parameter depending on the threshold is represented. It can be seen that it is not possible to make a perfect filter, because when all the cracking hits pass the filter there is a high
Fig. 4. Values of the filtering parameters for the cracking and noisy hits: a) Autocorrelation Width. b) Kurtosis. c) Approximate Entropy. d) DWP Quotient. e) RMS Rate.

Fig. 5. Percentage of cracking and noisy hits that passed the filter depending on the threshold for each parameter.
percentage of noisy hits that pass the filter too. When all the noisy hits are eliminated, almost all of the cracking hits are eliminated too. In general, the percentage of cracking and noisy hits that passes the filter increase and decrease together with the variation of the threshold, although the behavior is different for each parameter. In the case of the Autocorrelation Width, the percentage of noisy hits that pass the filter is higher than the percentage of cracking hits for most of the values of the threshold. The other parameters have a better performance because the percentage of cracking hits is always higher than the noisy ones, but, as it have been said before, neither of them is perfect.

At this point, it is necessary to choose the parameter and threshold that we are going to use. With Fig. 5 it is possible to choose the parameter and the threshold that can be used depending of our needs. If it is necessary to have all the cracking hits and it does not matter if a certain percentage of noisy hits is not filtered, then a low threshold of the kurtosis or the DWP quotient can be used. In our case, it is desirable to have the highest percentage of cracking hits together with the lower percentage of noisy hits, so we have chosen to use the parameter and threshold with the maximum difference between the percentage of cracking and noisy hits that pass the filter. With this choice we make sure that most of the hits that pass the filter are cracking hits.

Table 2. Percentage of cracking and noisy hits that passed the filter when the best threshold is used, their difference and best threshold for each parameter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Autocorrelation Width</th>
<th>DWP quotient</th>
<th>Kurtosis</th>
<th>Approximate Entropy</th>
<th>RMS rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracking hits that pass the filter (%)</td>
<td>91.01 %</td>
<td>76.40 %</td>
<td>74.16 %</td>
<td>59.55 %</td>
<td>79.78 %</td>
</tr>
<tr>
<td>Noisy hits that pass the filter (%)</td>
<td>84.68 %</td>
<td>18.92 %</td>
<td>14.41 %</td>
<td>33.33 %</td>
<td>17.12 %</td>
</tr>
<tr>
<td>Maximum Difference:</td>
<td>6.33 %</td>
<td>57.48 %</td>
<td>59.75 %</td>
<td>26.22 %</td>
<td>62.66 %</td>
</tr>
<tr>
<td>Threshold:</td>
<td>58.1</td>
<td>0.49</td>
<td>4.5</td>
<td>0.72</td>
<td>1.69</td>
</tr>
</tbody>
</table>

In Table 2 the maximum difference between the percentage of cracking and noisy hits that pass the filter for each filtering parameter can be seen. Using this criterion, the best filtering parameters are RMS rate, Kurtosis and DWP quotient. As the maximum difference is achieved by using RMS rate, it has been used to filter the AE hits in [3]. The AE hits that have been used to obtain the filtering results are a subset of the AE hits, which have been recorded in the experiment, so it is expected that very similar percentages of cracking and noisy hits passed the filter when we applied it to the whole set of AE hits. By this reason, after the filter we must have about a 79.89 % of cracking hits and about 17.12 % of noisy hits. In the AE hits, which are visually classified we have a 55.5 % of noisy hits and a 44.5 % of cracking hits, so we have a little more noisy hits than cracking hits, but the difference is very low. It is expected to have similar rates in the whole set of recorded AE hits, so we have that after the filtering process we have 3.83 times more cracking hits than noisy hits. This means a very good improvement over the initial situation.

The quality of the filter can be checked in the analysis of the results. After the filtering process the AE hits are analyzed in [3], where it can be seen that the cumulative AE energy is related
with the hysteretic strain energy. In [3] it is shown that the results are consistent with the experiment and the hysteretic strain energy, so we concluded that the filtering process is adequate for this kind of experiment.

Conclusions

We have investigated the way of filtering noisy AE hits, which come from friction or electromagnetic noise. To do so, several signal parameters have been tested in order to find which one provides very different values for the noisy and cracking hits. It was been found that the complexity of the specimen and the dispersion properties of the material make it difficult to separate the noisy and cracking hits because sometimes parameters have similar values.

In order to find which parameter is the most appropriate the percentage of cracking and noisy hits that pass the filter for each parameter were obtained considering a wide interval of threshold values. It was found that RMS rate, Kurtosis and DWP quotient are the most effective parameters because they have the highest difference between the rate of cracking and noisy hits that pass the filter.

This filtering process makes the analysis of the AE results clearer and more precise, and allows us to carry out conclusions with more confidence as we are sure that most of the AE hits that we are analyzing came from a cracking process and not from a noise source. The results of the AE analysis are shown in [3].

References