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# Damage Evolution Analysis in a “Spaghetti” Bridge model using the Acoustic Emission Technique

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**Abstract:** This paper applies the Acoustic Emission (AE) Technique to analyze the damage process in a one-meter span bridge model built from spaghetti sticks during a loading test. The AE signals are analyzed in terms of four coefficients that are evaluated as predictors of structure failure, with frequency variation appearing as the strongest indicator of instability. The AE data are also compared to theoretical predictions given by the Bundle Model, confirming that underlying general patterns in damage processes are highly influenced by the geometric distribution of the structure and the loading pattern that is applied to it.

**Keywords:** Quasi-brittle Materials; Damage Process; Acoustic Emission.

## 1. Introduction

Damage process in structures or materials undergoing unstable collapse is a widely studied topic because it occurs in many different situations, including catastrophic events with heavy human and economic tolls. This process is particularly important in the case of heterogeneous materials such as rocks, concrete ceramics, and other composites, either natural or artificial. According to [1], the main phenomena characterizing damage processes in these materials are: (i) significant size-effects in the strength and failure strain, (ii) transitions from uniform damage distribution to a clear discontinuity process, known as cracks localization, and (iii) the associative effect among clusters of micro-cracks, which can either intensify or inhibit damage propagation throughout the structure during the process.

Model parameters describing damage evolution can be represented by continuous regularization functions, which filter a series of discontinuities distributed throughout space and time, thus providing valuable information regarding the ongoing damage process, indicating how and when a significant loss of material resistance can occur. In its turn, collapse study by means of apparently simple theoretical models allows one to avoid the specifics of each structure and to perceive tendencies that are common to several systems, regardless of building materials, boundary conditions and problem scale. Some such models are discussed in [2]. Aided by these models, one can describe laws that apply to processes ranging from the rupture of biological materials of microscopic dimensions [3], to seismological events throughout hundreds of kilometers [4,5].

Besides pure Mechanics, similar patterns can be found in other realms of Physics, most notably the method of renormalization groups proposed by [6], which allows to cope with instability problems such as disruption of solids and phase changes. These ideas also apply to other instability problems, like those found in time series of economic indexes [7], the degradation of social systems [8], and the collapse of ancient civilizations

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## Nomenclature

$\epsilon$	Exponential coefficient of the cumulative number of events ( $N$ ) vs. energy signal magnitude	$E_s$	Signal Energy
$A$	Amplitude signal	$f_s$	Characteristic Signal frequency
$a(t)$	Amplitude of the record register by the device during the time	$N$	Cumulative number of events
$A_p$	Maximum Amplitude of the signal	$R_A$	Rise Angle
$A_{th}$	Thresold	$R_T$	Rise Time
$b$	Exponential coefficient of the cumulative number of events ( $N$ ) vs. signal magnitudes ( $A$ )	$t$	Time
$c$	Exponential coefficient of the accumulated number of events ( $N$ ) vs. characteristic signal frequency $f_s$	$t_f$	Final time
		$t_i$	Initial time
		$t_p$	Instant of the signal maximum amplitude
		$u$	Displacement

35 [9]. In all these cases, studying the evolution of local instabilities throughout space and  
36 time is a fundamental step in predicting global instability.

37 In Mechanics, a suitable way to register local instabilities is the Acoustic Emission  
38 (AE) technique. Whether caused by a chemical reaction (metal corrosion), the spasmodic  
39 growth of vegetal, or an impact from an external source, among many other examples,  
40 when a local instability occurs, it is said to generate an event in a specific structure  
41 location, called *source*. This event causes the propagation of mechanical waves that  
42 are perceived by sensors on the structure's surface. By placing various sensors on  
43 suitable locations of the structure, space and time distribution of these events can be  
44 determined, and the parameters calculated from such measurements are a sensitive  
45 means for tracking changes within the studied structure.

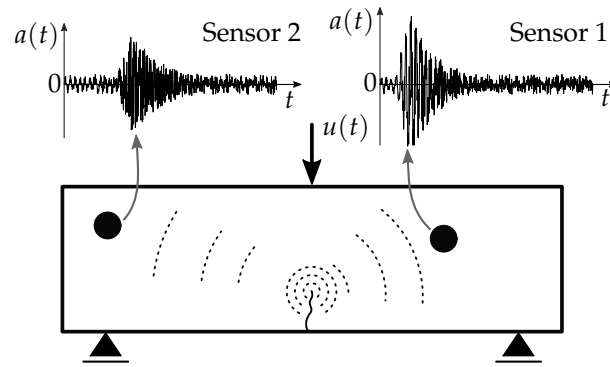
46 Here, we apply the AE technique to track a small-scale bridge built from spaghetti  
47 sticks. As the bridge is subjected to increasing load, two sensors acquire the AE signals.  
48 Measurement results are compared to theoretical predictions according to the Bundle  
49 Model [10], which is widely used in this field [11]. This comparison's primary goal is  
50 to highlight the possibility of an underlying universal pattern for structures in collapse,  
51 which is often masked by specifics in geometry and boundary conditions imposed  
52 on each structure. The use of a spaghetti bridge as the basic structure for the study  
53 facilitates the execution of typical material tests – e.g., three-point bending and uniaxial  
54 compression in a cylinder – on an easy to build, inexpensive specimen. [12] have  
55 also explored this possibility, applying artificial intelligence methods to determine the  
56 collapse load on a similar bridge.

## 57 2. Theoretical Foundations

58 This work is based upon two basic tools: the Acoustic Emission technique, and the  
59 Bundle Model. The basic principles of each tool will be presented in this section.

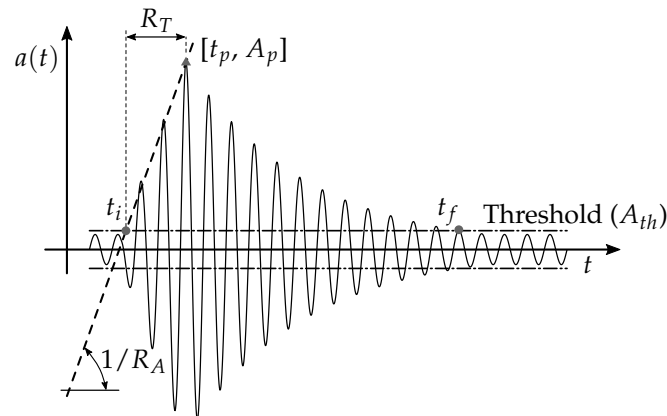
### 60 2.1. Acoustic Emission Technique

61 When a mechanical system is excited by an external source or undergoes changes in  
62 its internal structure, it presents local instabilities (*events*) that propagate as mechanical  
63 waves. These Acoustic Emission (AE) signals are usually accelerations with frequencies  
64 ranging from  $10^4$  to  $10^7$  Hz [13]. These signals are detected by accelerometers mounted  
65 on the structure's surface, as depicted in Figure 1, where the excitation is usually a force  
66 or prescribed displacement in time.



**Figure 1.** Basic setup for acquiring AE signals, with two AE sensors. Although both signals refer to the same event, they differ according to their positions along the structure.

67 A typical AE signal is illustrated in Figure 2. Several parameters can be extracted  
 68 from these signals [13] but the ones of interest here are: maximum Amplitude ( $A_p$ ), signal  
 69 threshold ( $A_{th}$ ), initial time ( $t_i$ ), and final time ( $t_f$ ), where both times are functions of the  
 70 fixed threshold level. The Rise Time ( $R_T$ ) is defined as  $R_T = t_p - t_i$ , i.e., the difference  
 71 between the instant of maximum amplitude ( $t_p$ ) and the moment  $t_i$  when amplitude rise  
 72 from threshold levels was first detected. From these data, the Rise Angle ( $R_A$ ) is given  
 73 by  $R_A = R_T / A_p$ . Finally, the area under the signal is also of interest, because it bears a  
 74 direct relation with the acoustic energy emitted during the event, as explained in detail  
 75 in [14].



**Figure 2.** Typical AE signal with its parameters of interest.

76 Besides having their own meaning regarding both spatial and temporal distribu-  
 77 tions of the events in AE tests, these parameters can also be combined, generating reliable  
 78 indicators regarding the possibility of system collapse. Such indicators are:

- (a) **Relation between the number of events  $N$  and the signal amplitude  $A$ :** This relation has been long used in seismological applications, as illustrated by the classic Gutenberg & Richter law [4], which is of universal nature and does not depend on the scale of the distribution [11,15,16]:

$$N(\geq A) \propto A^{-b}, \quad (1)$$

79 where  $N$  is the cumulative number of signals and  $A$  is the signal amplitude. The  
 80 physical meaning is discussed in [17–19]. It is hypothetically related, according  
 81 to the expression  $\mathcal{D} = 2b$ , to the fractal dimension  $\mathcal{D}$  of the material domain from  
 82 which the signals generated by cracks are emitted. When the damage process  
 83 begins within a structure, signals are emitted from a micro-cracks roughly evenly  
 84 distributed in the material volume, i.e.,  $\mathcal{D} = 3$  and  $b = 1.5$ . Thus, according

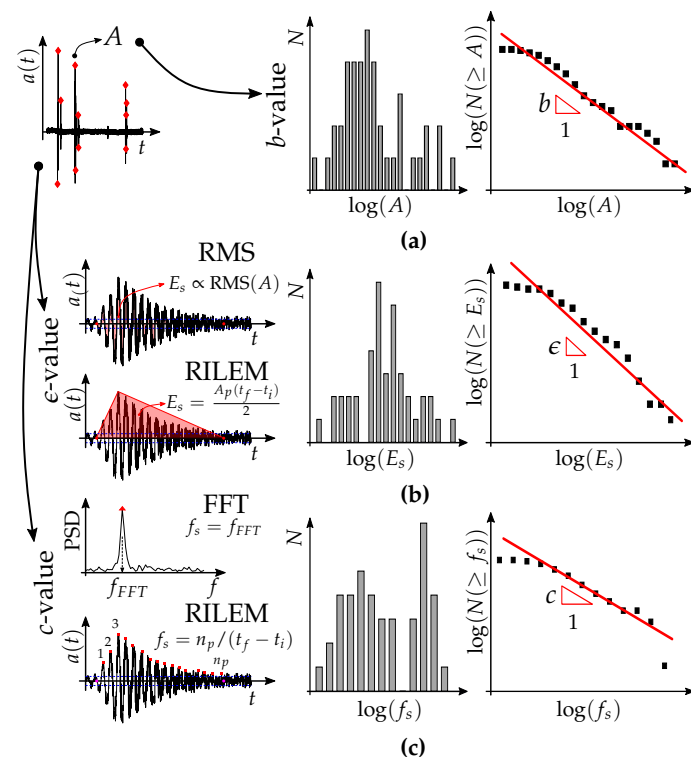
85 to Eq. 1, most events produce small-amplitude signals. As damage advances,  
 86 localization effects take place, and the signals are emitted preferentially from  
 87 micro-cracks that distribute on preferential surfaces, which results in macro-crack  
 88 nucleation. In this last phase, therefore, the values for  $\mathcal{D}$  and  $b$  become 2 and  
 89 1, respectively, and the application of Eq. 1 yields an increase in the number of  
 90 large-amplitude events. Thus, the evaluation of  $b$  and how it changes with time  
 91 allows one to keep track of damage processes.

92 The procedure for computing  $b$  is described schematically in Figure 3a. The  
 93 amplitudes due to each signals are collected and organized in a histogram. Then,  
 94 a bi-log diagram is built to illustrate the cumulative number  $N$  of signals with  
 95 amplitude  $\geq A$ . Finally,  $b$  is the angular coefficient of the fitting line. For a more  
 96 detailed discussion about this computing procedure, see [20].

(b) **Relation between  $N$  and the signal energy emission  $E_s$ :** the energy carried in the signal is also related to  $N$  in a form similar to that of the amplitude  $A$ , using  $\epsilon$  a fitting coefficient analogous to  $b$ :

$$N(\geq E_s) \propto E_s^{-\epsilon}. \quad (2)$$

97 The calculation of  $\epsilon$  is analogous to the one described for  $b$  in case (a). It is also  
 98 described in Figure 3b. Since the emitted AE signal energy is proportional to the  
 99 squared maximum amplitude ( $E_s \propto A^2$ ), it is apparent that the expected interval  
 100 for  $b$  [1.0, 1.5] translates to [0.5, 0.75] for  $\epsilon$ , as discussed in [2] and shown by  
 101 numerical simulation in [21]. As Figure 3b also indicates, one can also compute  
 102 the energy emission from the area under the signal envelope. This approach,  
 103 referred to here as the RILEM method, was proposed in [13,22]. Finally, it is also  
 104 possible to calculate energy emission from the Root Mean Square of the signal.



**Figure 3.** Precursors from AE tests, (a) obtaining  $b$  from Eq. 1; (b) calculation of  $\epsilon$  from Eq. 2; (c) determining  $c$  from Eq. 3.

(c) **Relation between  $N$  and the characteristic signal frequency  $f_s$ :** this parameter was introduced by the same research team involved in this work as a reliable indicator for avalanches during a damage process [23]. This newly introduced

coefficient  $c$  is also obtained by analogous means to those given for Eqs. 1 and 2, but focusing on the frequency distribution of the AE signals, i.e.:

$$N(\geq f_s) \propto f_s^{-c} \quad (3)$$

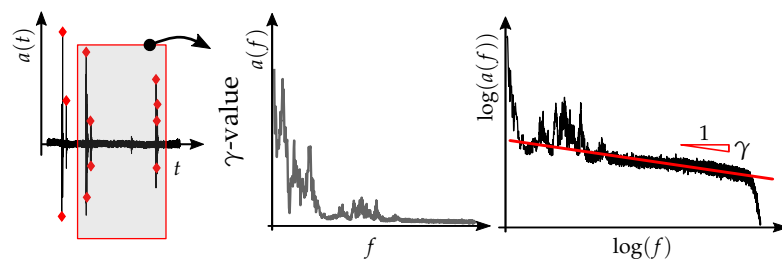
105 where  $N$  is the cumulative number of signals with frequencies greater or equal to  
 106  $f_s$ . The value of  $c$  can be calculated similarly to that used for  $b$ , as indicated in  
 107 Figure 3c: it is the slope line of the signals distribution during the damage process  
 108 as a function of the frequency that characterize the signals. As in the case of  
 109 the  $b$ -value for amplitudes, the  $c$ -value indicates changes in the damage process  
 110 and the imminence of collapse by keeping track of the acquired AE signals'  
 111 frequencies. For instance, if the number of events with lower characteristic  
 112 frequencies increases compared to the higher ones, a change in the damage  
 113 process has occurred.

114 Still regarding Figure 3c, note that there are two ways to calculate the charac-  
 115 teristic frequency  $f_s$  of the AE signal. The first is taking the ratio between the  
 116 number of cycles  $n_p$  and the signal time interval  $(t_f - t_i)$ , as proposed by the  
 117 [22] and referred to here as RILEM frequency. An alternative definition is by  
 118 determining the spectral distribution of the AE signal and taking the frequency  
 119 with the highest peak, i.e., the FFT method.

(d) **Frequency fluctuations during the damage process:** A well-known measure of  
 energy fluctuations in AE signals relies on their dependence on signal frequency  
 as described by the spectral density function (SDF), as mentioned by [24]. The  
 first observations regarding this dependence are reported by [25], who coined the  
 term  $1/f$ -noise or Flicker Noise when studying noise effects in electronic circuits.  
 According to [26], the dependence of noise energy distribution with respect to  
 frequency is given by:

$$E(f) = a 1/f^\gamma, \quad (4)$$

120 where  $E(f)$  is the energy emission,  $f$  is the signal frequency, while  $\gamma$  and  $a$  are  
 121 scalar fitting coefficients. Taking the logarithm of both sides in Eq. 4 the best  
 122 fitting line leads to a linear law, where gamma is the angular coefficient. Its  
 123 calculation is described schematically in Figure 4.



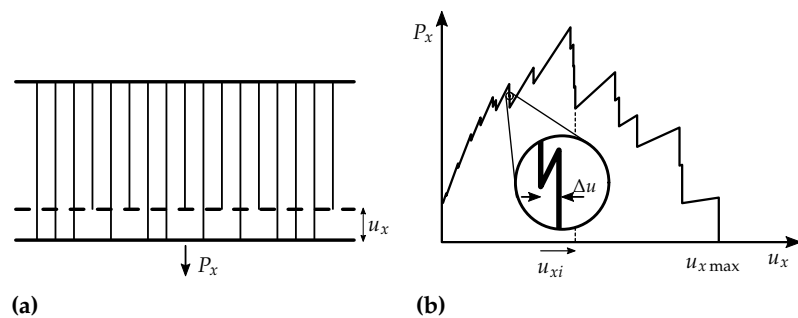
**Figure 4.** Relation between the power density spectrum and the frequency content, with calculation of the  $\gamma$  parameter.

124 As observed in [27] and many other works, this type of fluctuation is widely  
 125 observed many different scientific fields, such as geology [28], finances (Kononov-  
 126 ius and Ruseckas, 2015), bioengineering [29], and even music [30,31]. Moreover,  
 127 the distributions described in Eq. 4 is also observed to hold for frequencies rang-  
 128 ing from fractions of hertz (in seismology) to gigahertz (microelectronics), which  
 129 clearly illustrates the fractal character of this distribution and the phenomena to  
 130 which it applies [27]. In the specific case of Acoustic Emission applications, the  
 131 study of damage in historic buildings by [32] is an interesting example, where  
 132 the exponent changes in the imminence of (either local or global) instabilities  
 133 associated with structural collapse.

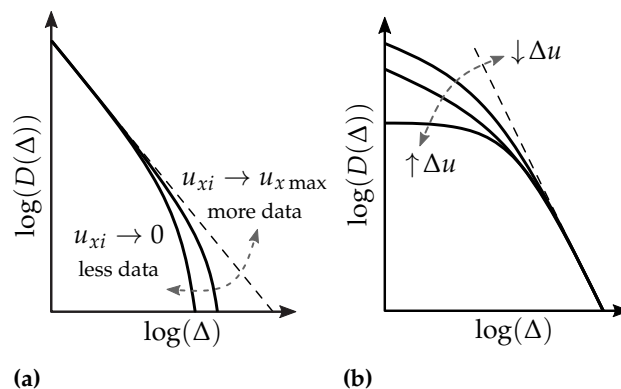
## 134 2.2. Bundle Model

135 The Bundle Model was proposed originally by [10] and exhaustively explored in  
 136 [11]. Its simplest version is the *Equal Load Shared Bundle Model* (ELS Bundle Model),  
 137 which comprises a set of parallel fibers (Figure 5a) with both ends fixed to a rigid  
 138 frame. Each fiber is assumed to have elastic behavior until reaching its respective  
 139 failure strength, which is given by a known statistical distribution. The typical load vs  
 140 prescribed displacement for this setup is presented in Figure 5b. In the classical paper  
 141 by [15], it is shown that when a continuously increasing displacement is prescribed  
 142 to the set of fibers (i.e., the set is continuously stretched by infinitesimal increments),  
 143 the distribution of number of broken bars is given by an exponential function with a  
 144 universal exponent of -2.5, regardless of the specific distribution of failure strength in  
 145 the fibers.

146 As shown in Figure 6, the ELS Bundle Model also predicts two forms of distributions  
 147 that deviate from the aforementioned universal one. The first deviation takes place when  
 148 the prescribed displacement is continuously increased only to a value  $u_{xi} < u_{max}$ , i.e.,  
 149 the loading process is interrupted before the critical displacement for complete failure is  
 150 reached. In this case, since the available data does not reflect the entire failure process,  
 151 the model's predictions deviate from the universal distribution as shown in Figure 6a.  
 152 The second form occurs when the prescribed displacement occurs in discrete steps. Now  
 153 each step is large enough to cause failure of several fibers at once, causing the prediction  
 154 curve to draw away from the ideal straight line at the top left of the graph, as shown in  
 155 Figure 6b.



**Figure 5.** The Bundle Model. (a) Parallel bar model where a prescribed displacement  $u_x$  is applied and the reaction  $P_x$  is measured, (b) evolution of the load during the damage process in typical Bundle Model (Adapted from [11]).



**Figure 6.** The avalanches distribution in the Bundle Model, defining avalanche as the number of bars that break simultaneously. (a) When the prescribed displacement is continuously increased, but the test is stopped before complete failure (i.e.,  $u_{xi} < u_{x \max}$ ). (b) When  $u_x$  is applied in discrete steps with amplitude  $\delta u$ .

### 156 3. Application: The Bridge Model Analysis

157 To illustrate the effectiveness of the global parameters' evolution obtained from an  
 158 AE analysis method as predictors of structure collapse, the technique was applied to a  
 159 small-scale bridge model made from spaghetti sticks. Such bridges are built to take part  
 160 in a contest, which occurs twice a year at the Engineering School of Universidade Federal  
 161 do Rio Grande do Sul (UFRGS), since 2004. Participation in the context is mandatory  
 162 for Civil Engineering students, but it is also open to students from all other Engineering  
 163 programs. The general guidelines for the contest (geometric restrictions, mass limits,  
 164 load application, etc.) are given in [33], and the main geometric parameters are given in  
 165 Figure 7.

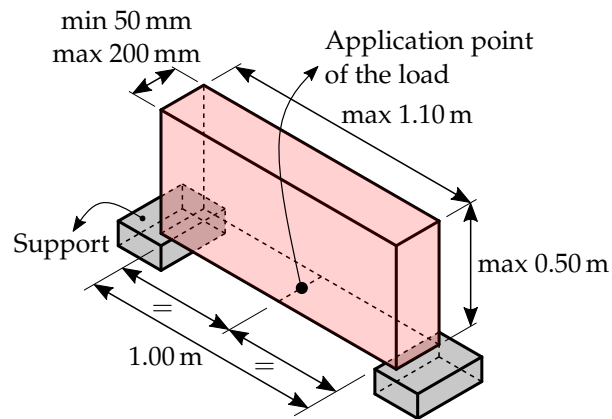


Figure 7. Geometric restrictions for the UFRGS Spaghetti Bridge contest (adapted from [33])

166 The collapse loads for all bridges evaluated in the contest are informed in Figure 8,  
 167 with four winning designs being highlighted in the same figure and depicted in Figure 9.  
 168 It is noticed that the average collapse load increases for the first six years, tending to an  
 169 approximately constant value after that. This is due to the increased tendency of most  
 170 contestants to adopt the topology depicted in Figure 9c, which is theoretically optimal  
 171 for stiffness [34].

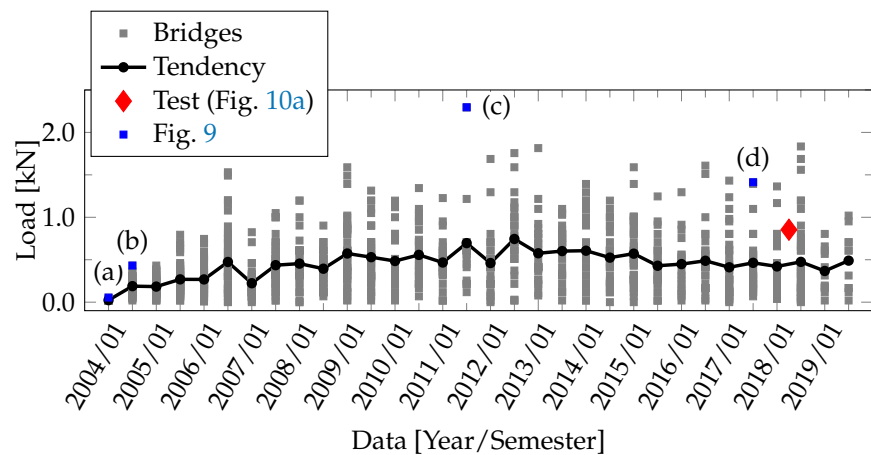
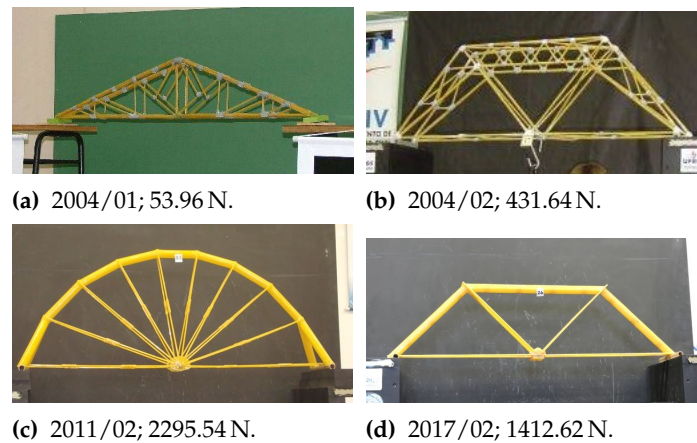


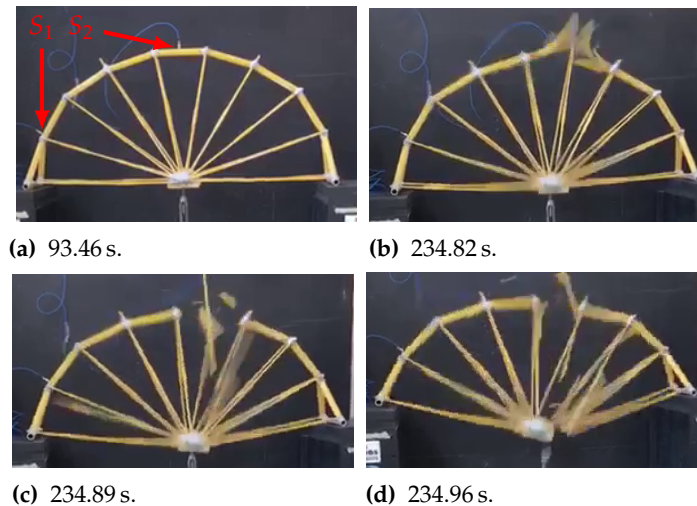
Figure 8. Evolution of collapse loads for the UFRGS Spaghetti Bridge contestants, data from [33].





**Figure 9.** A few winning designs for the UFRGS Spaghetti Bridge contest, data from [33].

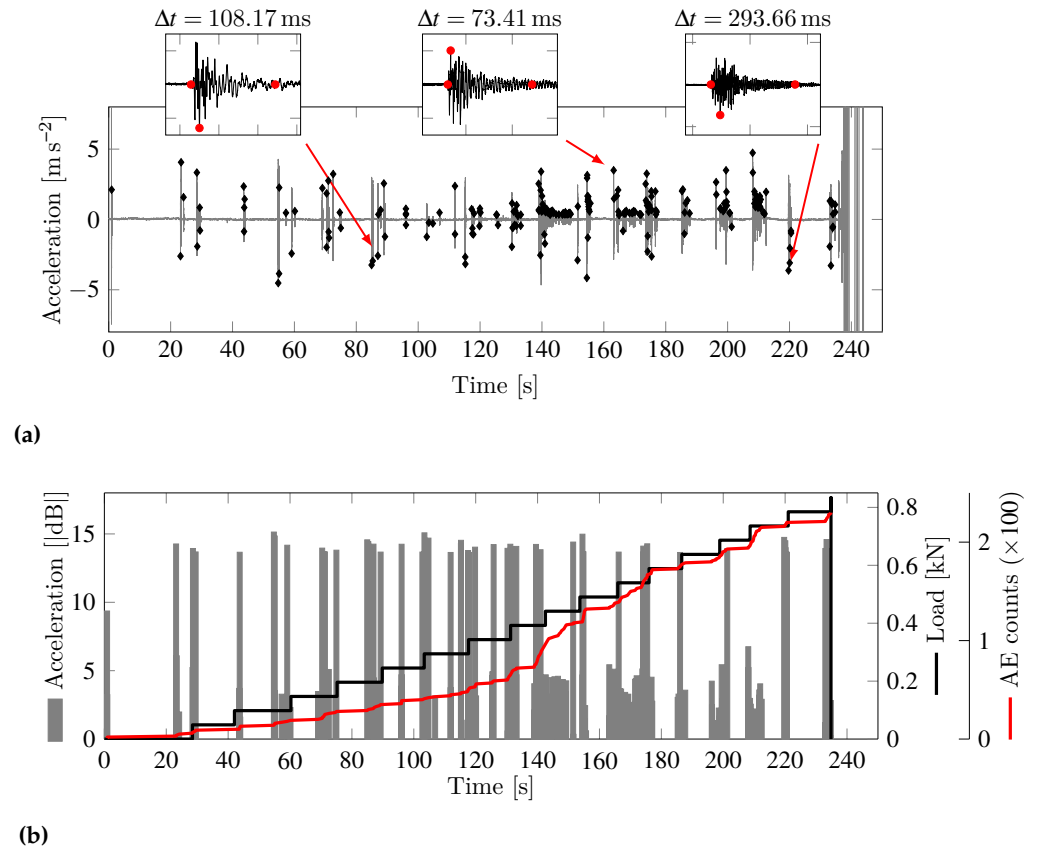
172        The spaghetti bridge used in the AE test is depicted in Figure 10, undergoing its  
 173 load test during the contest, and its corresponding collapse load is also highlighted (in  
 174 red) in Figure 8. This bridge was 1.08 m long, 0.15 m wide and 0.45 m high, with 1.40 kg  
 175 of mass. Load was increasingly applied manually to its center line, with increments in  
 176 10 s intervals until collapse occurred at  $t = 235$  s, with 784.80 N. Two accelerometers  
 177 [35] were installed on the spots marked as  $S_1$  and  $S_2$  in Figure 10a, for acquiring the  
 178 AE signals. These accelerometers are piezoelectric, with frequency measurement range  
 179 from 5 kHz to 60 kHz. Their signal was acquired through a data acquisition module  
 180 Brüel&Kjær® PULSE™ 3035, at a sampling rate of 65.54 kHz.



**Figure 10.** Damage progress over time for the studied Spaghetti Bridge.

#### 181 4. Results

182        Throughout the incremental loading test, 230 signals were detected by the AE  
 183 sensors. The overall result is in Figure 11a, which also depicts a few typical signals for  
 184 individual events. These results are also summarized in Figure 10b in terms of amplitude  
 185 peak for each signal, and their cumulative number in relation to the load.

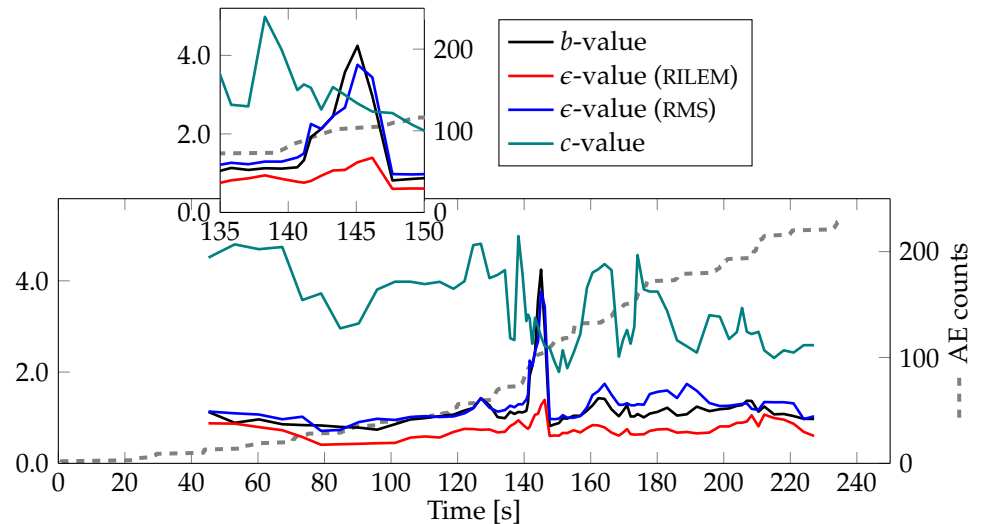


**Figure 11.** (a) AE data acquired during the loading test, with illustrating signals from individual signals. (b) Load applied to the bridge with corresponding signal counts.

186 Results show that signal occur nearly at the same time as the load is increased,  
 187 indicating that signal distribution depends explicitly on the loading pattern. Also, for  
 188  $t < 140$  s, the signal count grows at an approximately constant rate. When  $t \cong 140$  s,  
 189 there is a sharp increase in the number of signals. Finally, for  $t > 140$  s, signal numbers  
 190 grow once again at a nearly constant rate, but at a faster pace than that of the previous  
 191 one.

#### 192 4.1. Evolution of coefficients $b$ , $\epsilon$ , $c$

193 The coefficients were calculated by separating the data set into packs of 25 events,  
 194 with 5-event overlaps between successive packs. The coefficients evolution is presented  
 195 in Figure 12, accompanied by the cumulative number of signals. The figure detail  
 196 shows that the avalanche at  $t \cong 140$  s in Figure 11 matches sudden coefficient changes,  
 197 especially  $b$  and  $\epsilon$ , with higher variations of the latter when energy calculation uses RMS  
 198 values. Moreover, the sharp variation in  $c$  occurs before the avalanche, which evidences  
 199 this coefficient's usefulness as a precursor to the regime change.



**Figure 12.** Time evolution of value- $b$ , value- $\epsilon$  and value- $c$ .

#### 200 4.2. Frequency fluctuations during the damage process

201 The AE data set was divided into five intervals to evaluate frequency fluctuations,  
 202 as shown in Figure 13. For each interval, the results from computing the Power Spectral  
 203 Density were plotted in logarithmic scale, with a linear fit applied to the region where  
 204 the frequency distribution approximates a straight line in the bi-log dominium, i.e., in  
 205 the range from  $10^3$  to  $10^4$  Hz. The angular coefficient for the resulting fitting line is the  
 206 parameter  $\gamma$  used to evaluate frequency fluctuation. Frequencies below 1 kHz cannot be  
 207 reliably traced to the damage process because of interference with the structure's natural  
 208 vibration modes. The marked attenuation for frequencies above 30 kHz is due to the  
 209 anti-alias filtering embedded in the signals' electronic conditioning apparatus.

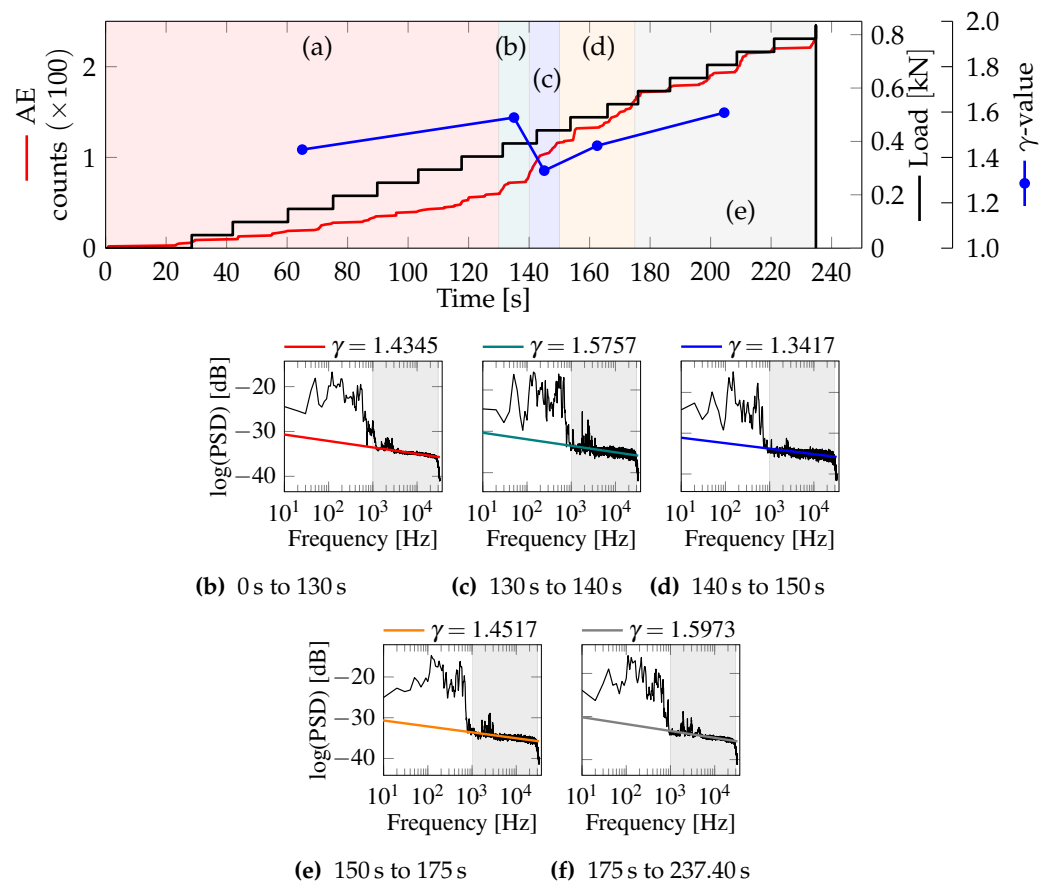
210 Still in Figure 13, the variation of  $\gamma$  is compared to load distribution and the  
 211 cumulative number of events. The decrement of  $\gamma$  (and also of  $\epsilon$ , already shown in  
 212 Figure 12) means that a wide band of frequencies is activated at each event, which agrees  
 213 with the conclusions by [6] regarding unstable physical phenomena.

#### 214 4.3. Comparison with the Bundle Model

215 Three histograms were computed to compare the AE-test results with the Bundle  
 216 Model predictions: with the first 50% of observed signals, with the first 75% of signals,  
 217 and with all signals. Corresponding results are depicted in Figure 14. This information  
 218 is complemented by Figure 15, which illustrates a typical acceleration pattern observed  
 219 throughout the tests. Due to measurement noise, a threshold  $\log(0.2) = -0.7$  is used  
 220 for computing the AE-signals. In Figure 14, this implies the nearly horizontal distri-  
 221 bution obtained for small amplitudes: as small avalanches are undistinguished from  
 222 measurement noise, the counting of AE-signals remains constant.

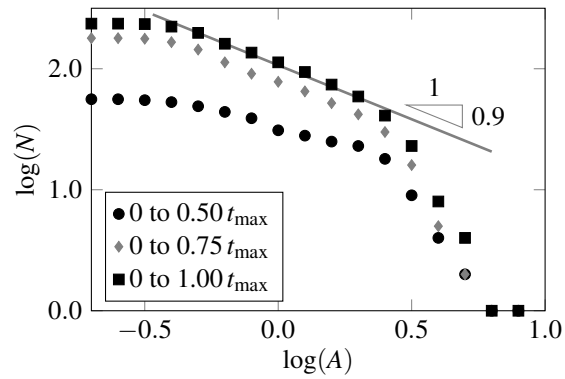
223 Comparing the results in Figure 14 to the theoretical predictions given by the Bundle  
 224 Model in Figures 6a and 6b, it is possible to observe that:

- 225 1. Experimental results agree with the general shape predicted by the model, with a  
 226 central part tending to a linear curve in the bi-log graph. This evidences that the  
 227 damage process tends to occur according to an exponential function, but its char-  
 228 acteristic exponent is different. The data are also consistent with the theoretically  
 229 expected deviations towards both magnitude extremes.
- 230 2. Reducing the sample size for drawing the distribution does not affect AE-events  
 231 distribution only at the magnitude extremes: when only the first 50% of the data  
 232 are used, the intermediate linear range reduces in amplitude, and the angular  
 233 coefficient is also affected.

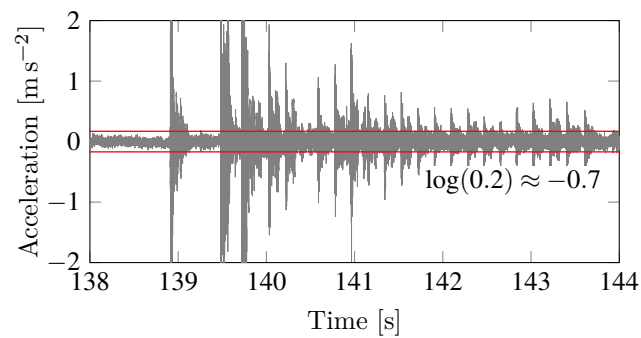


**Figure 13.** Evolution of  $\gamma$  throughout the AE test.

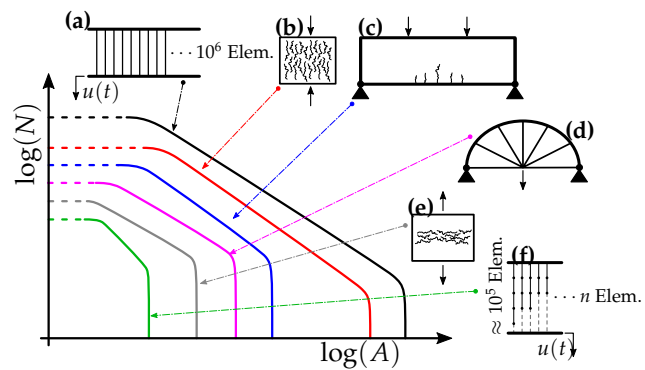
- 234 3. The results presented here suggest that the damage process occurs according to a  
 235 general pattern similar to the one predicted by the Bundle Model. However, this  
 236 tendency suffers in varying degrees from the effects of measurement noise, the  
 237 structure's external geometry, the boundary conditions applied to it, and the inter-  
 238 nal organization of the system's elements. The influence exerted by these factors  
 239 is illustrated schematically in Figure 16. The two extreme cases correspond to the  
 240 predictions given by the Bundle Model when all fibers are aligned in parallel (a) or  
 241 almost entirely in series (f), whereas cases (b)-(e) represent several combinations  
 242 of geometry and externally applied loads, which appear as intermediate arrange-  
 243 ments within the context of the model. Thus, the spaghetti bridge configuration  
 244 studied here is closer to the quasi-serial Bundle Model (case (f)), which is more  
 245 prone to localization effects than the other cases. Finally, due to the need to apply  
 246 a threshold value for negating measurement noise effects, all profiles tend to a  
 247 "plateau" for small-amplitude events.



**Figure 14.**  $N(A)$  –histograms from the AE– test results, taking into account, 50%, 75% and 100% of observed events.



**Figure 15.** Acceleration pattern typically acquired during the tests, with the amplitude threshold that defined actual AE-signals.



**Figure 16.** Frequency distribution of some measure of avalanches magnitudes in different structural typologies.

248

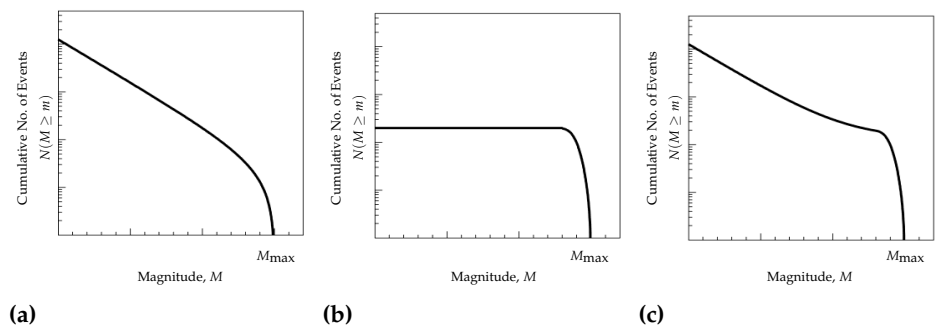
The following three examples reinforce the hypothesis presented in item (3):

249

- (a) In seismology, [36] state that seismic events may result in any intermediate form between the extreme-case histograms illustrated in Figures. 17a and 17b, depending on several characteristics of the region where the event occurs.

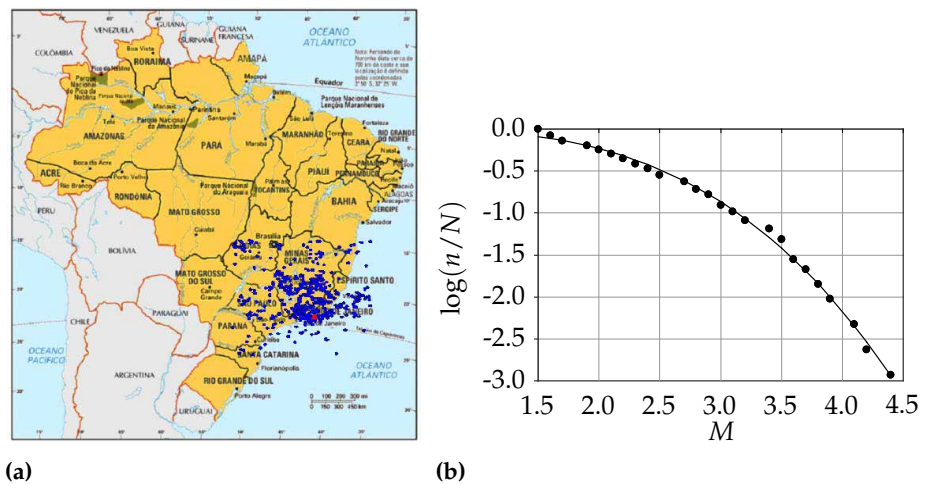
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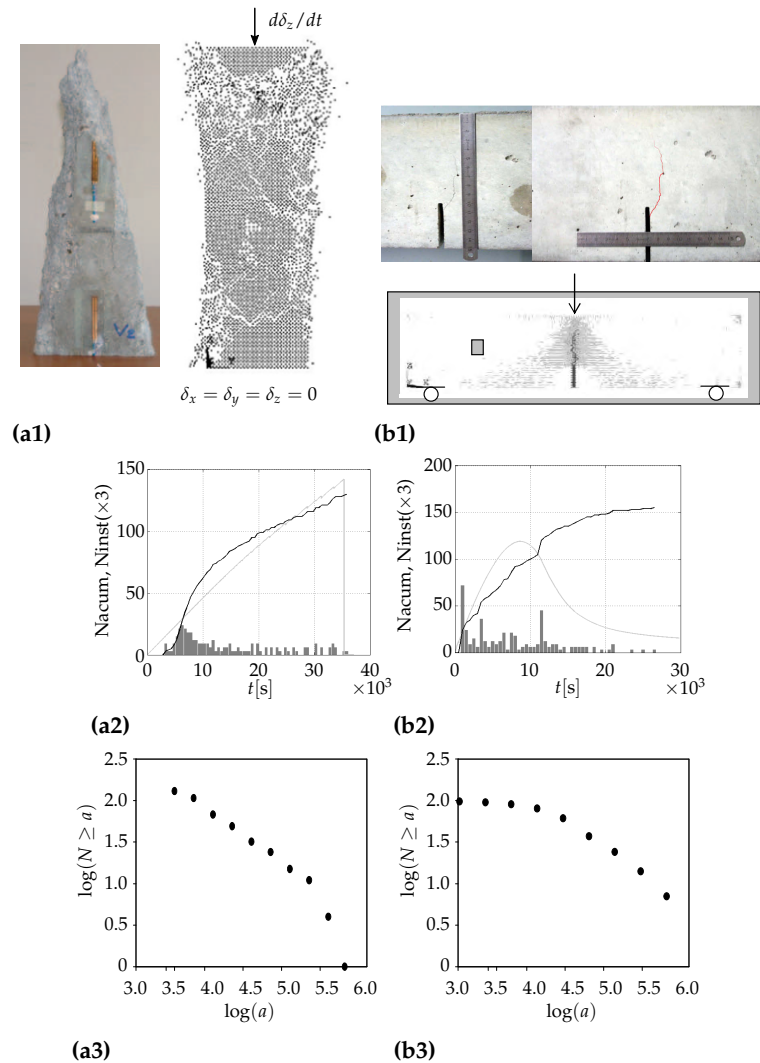
**Figure 17.** Histograms of earthquake temporal distribution, where  $M = \log(A)$ . (a) According to the universal law given by the Gutenberg-Richter model, which is similar to what is predicted by the Bundle Model. (b) Prediction for earthquakes with a definite magnitude. (c) Intermediate case. (From [36]).

- 252 (b) The behavior noted by [36] is also observed in the seismic behavior in the region  
 253 of Angra dos Reis, Brazil, as evidenced by the corresponding histogram of seismic  
 events in Figure 18.



**Figure 18.** (a) Distribution of epicenters of seismic events with  $M_w \geq 1.5$ , recorded from 1959 to 2013 within a  $1200 \text{ km}^2$  area in South-Eastern Brazilian SCR. The red point shows the site of the Angra dos Reis NPP (CNAAA). (b) Relation between  $\log(n/N)$  for the region during the same period [37].

- 254 (c) In [37], a comparative analysis is made between a prismatic specimen under  
 255 uniaxial compression and a pre-fissured beam under flexion on three points. Both  
 256 structures were made from concrete, and the comparison was carried out both  
 257 by numeric and experimental means. The results are summarized in Figure 19,  
 258 making it clear that geometry and boundary conditions significantly influence  
 259 structural behavior. For instance, the histogram for the beam tends to horizontal  
 260 for small magnitudes because new ruptures tend to occur at the extremities of the  
 261 pre-fissures, favoring localization of avalanches and connection between events.  
 262 As for the prismatic specimen, ruptures are equally likely to appear at every part  
 263 of its structure in the initial phases, with localization occurring only for advanced  
 264 stages of the damage process.  
 265



**Figure 19.** AE simulation results on concrete structures. (a) prism under uniaxial compression, (b) pre-fissured beam. (1) Results in terms of final configurations. (2) load vs time response (light-gray line), accumulated number of AE signals (dark line), and instantaneous distribution of events (histogram bars)(3) Accumulated number of signals vs their magnitudes in bilogarithmic scale [38].

## 266 5. Conclusions

267 In this work, acoustic emission (AE) data were collected from a load test applied  
 268 to a small-scale spaghetti bridge model, where the load increased until the structure  
 269 collapsed. Four different parameters ( $b$ ,  $\epsilon$ ,  $c$ , and  $\gamma$ ) were computed from the AE  
 270 data, and their usefulness in identifying damage progression was evaluated. The main  
 271 conclusions from such a procedure are:

- 272 • The evolution of the coefficients  $b$ ,  $\epsilon$  and  $c$  through time are suitable measures of  
 273 the local instability associated with changes in the AE regime, with  $c$  (related with  
 274 the event frequency distribution) being the most sensitive of the three.
- 275 • Computing  $\epsilon$  from the RMS-value of the AE signal yields improved sensitivity  
 276 compared to the traditional RILEM method.
- 277 • Analysis of frequency changes (variations in  $c$  and  $\gamma$  coefficients) are useful not only  
 278 considering the isolated AE signals but also the complete information collected by  
 279 the AE sensors. In particular, the  $\gamma$  coefficient presented a sharp reduction shortly  
 280 before the localized damage became evident during the load test, which reinforces  
 281 this coefficient's usefulness as a failure predictor.

- 282 • The minimum values for coefficients  $c$  and  $\gamma$  are consistent with the observations  
 283 by [6] on the tendency of all phenomenon scales to participate when an instability  
 284 occurs.  
 285 • Compared to the Bundle Model's theoretical predictions, experimental results  
 286 presented here highlight the influence of boundary conditions, geometry, and  
 287 internal organization on the collapse pattern of structures.

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 295 tation of data; in the writing of the manuscript, or in the decision to publish the results must be  
 296 declared in this section. If there is no role, please state "The funders had no role in the design of  
 297 the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or  
 298 in the decision to publish the results".

### 299 Abbreviations

300 The following abbreviations are used in this manuscript:

301	AE	Acoustic Emission
	CNAAB	Central Nuclear Almirante Álvaro Alberto
	FFT	Fast <i>Fourier</i> Transform
302	UFRGS	Universidade Federal do Rio Grande do Sul
	RILEM	International Union of Laboratories and Experts in Construction Materials, Systems and Structures
	RMS	Root Mean Square

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