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# Acoustic Emission and Digital Image Correlation Evidences of Size Effects on the Compression Failure of Concrete

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**Abstract:** Compression failure of concrete without effective confinement may show brittle failure modes, size effects being crucial for understanding catastrophic behaviours. Compression tests are performed to investigate the emitted energy during snap-back instabilities of concrete specimens having different sizes and slenderness ratios. Plain concrete specimens with sizes equal to 75, 150, and 300 mm, and slenderness ratios equal to 0.5, 1.0, and 2.0, are monitored using acoustic emission (AE) and digital image correlation (DIC) techniques. The results show the compression strength and ductility exhibit strong size and slenderness effects. As size or slenderness scale becomes larger, the failure behaviour exhibits a ductile-to-brittle transition, with the post-peak branch shifting from softening to catastrophic, showing local and global instability phenomena. In

24 particular, as the specimen slenderness increases, the final collapse shows a crushing-to-cracking  
25 failure transition, as also evidenced by the DIC technique. In brittle cases, crack propagation  
26 suddenly occurs with a catastrophic drop in load-carrying capacity, and the resulting emitted  
27 energy appears with a burst in cumulated AE curves, confirming that AE energy arises from snap-  
28 back instabilities in the structural response. This research has significant implications for the  
29 structural reliability and safety concrete structures, reducing the risk of catastrophic failure.

30

31 **Keywords:** Acoustic Emission; Digital Image Correlation; Concrete; Compression; Size effects;  
32 Ductile-to-brittle transition

33

## 34 **1. Introduction**

35 Compressive failure of brittle materials such as concrete is mainly characterised by  
36 microcrack nucleation, growth, and coalescence, over wide ranges of time and size scales  
37 (Carpinteri *et al.*, 2013). According to experimental evidence, the post-peak phase of the loading  
38 process is characterized by a strong strain localization. In the softening regime, energy dissipation  
39 occurs over a damaged surface rather than within the entire specimen volume (Carpinteri *et al.*,  
40 2007).

41 Previous research has confirmed that concrete, as a quasi-brittle material, exhibits a  
42 significant size effect on its material properties according to the change in the characteristic  
43 structural size. Specifically, small specimens demonstrate higher strength than large ones, the  
44 structural material being unchanged. Over recent decades, several size effect laws for concrete  
45 have been proposed, including Weibull's statistical theory (Weibull, 1951), boundary effect model  
46 (Duan *et al.*, 2002), Bazant's size effect law (Bazant *et al.*, 2007), and Carpinteri's multifractal

47 scaling law (MFSL) (Carpinteri *et al.*, 1995). Carpinteri's MFSL is based on the fractal theory,  
48 describing the damage of quasi-brittle materials in a non-integer dimensional space. Additionally,  
49 numerical simulations become a supplementary method for exploring the size effect of  
50 cementitious materials (Jin *et al.*, 2019; Zhang *et al.*, 2018). Various approaches, such as the  
51 cohesive model (Feng *et al.*, 2018), nonlocal continuum damage model (Marzec *et al.*, 2019) and  
52 discrete element method (Sinaie, 2017), have been used to simulate the size effect of cementitious  
53 materials (Muciaccia *et al.*, 2017; Chen *et al.*, 2018).

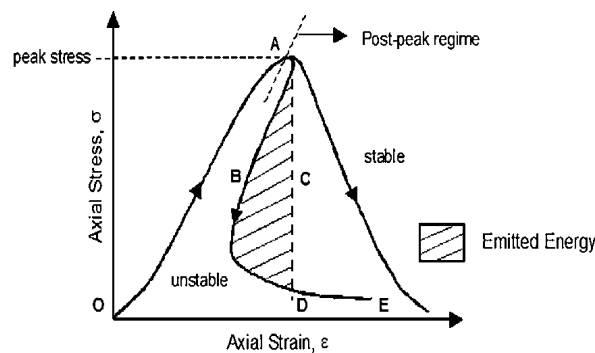
54 Based on fracture mechanics, Li *et al.* (2018) investigated the effect of shapes and sizes on  
55 compressive strength using cube and cylindrical concrete specimens of varying sizes, whereas  
56 Fladr *et al.* (2017) examined the correlation between specimen size and compressive strength of  
57 high-strength fibre-reinforced concrete. In addition, Balla *et al.* (2023) investigated the effect of  
58 specimen sizes on the compressive performance of hybrid FRP-strengthened RC square columns.  
59 Jin *et al.* (2020) assessed the compression behaviour of geometrically similar RC columns with  
60 varying specimen sizes, demonstrating that the compressive strength exhibited a significant size  
61 effect. Recently, advanced monitoring techniques, such as acoustic emission (AE) (Alam *et al.*,  
62 2015), and digital image correlation (DIC) (Keerthana *et al.*, 2020), have provided new insights  
63 into the effect of specimen sizes on the energy release rate, crack initiation, and the fracture process  
64 zone.

65 It is reported that the load-displacement curve changes significantly by varying the size scale,  
66 the structural shape remaining unchanged (Carpinteri *et al.*, 1989). The softening branch in the  
67 load-displacement curve becomes steeper when the size increases. For size scales larger than the  
68 critical one, the post-peak branch presents a positive slope. In more brittle cases, crack propagation  
69 occurs suddenly with a catastrophic drop in the load-carrying capacity. This means that both load

70 and displacement must decrease in order to have a controlled crack propagation (Carpinteri *et al.*,  
71 2018). Such a phenomenon, the so-called snap-back instability (see Fig.1), was deeply investigated  
72 concerning crack growth analysis in elastic-softening materials.

73 The size-scale transition from ductile to brittle behaviour is governed by a non-dimensional  
74 brittleness number,  $S_E$ , which is a function of material properties and structure size. A truly brittle  
75 failure occurs only with relatively low fracture energies  $G_{IC}$ , high tensile strengths  $\sigma_u$ , or large  
76 structure size-scales  $b$ , i.e. when  $S_E = G_{IC}/\sigma_u b \rightarrow 0$ . On the other hand, if the loading process is  
77 controlled by a monotonically increasing displacement over time, the snap-back instability can be  
78 experimentally captured (Carpinteri *et al.*, 2019).

79



80

81 Fig.1. Stable and catastrophic (snap-back) response (modified from Lacidogna *et al.*, 2019)

82

83 Currently, many studies on size effects in quasi-brittle materials can be found in the scientific  
84 literature. However, concrete materials are used in a wide range of engineering applications,  
85 especially for large structures, and their size effects need to be investigated in terms of size-  
86 slenderness effect. In particular, AE techniques can provide new insights in concrete size effect on  
87 the energy release rate by means of the fractal theory, which describes the concrete damage in a  
88 non-integer dimensional space.

89 From an engineering perspective, understanding the size and slenderness effects on concrete's  
90 compressive behavior is highly relevant for large-scale structural applications. In real-world  
91 engineering projects, such as dams, high-rise buildings, and bridges, where concrete elements are  
92 subjected to significant compressive forces, size effects directly impact the performance and safety  
93 of these structures. By addressing these effects, this research provides valuable insights for  
94 structural engineers to better design concrete components with appropriate dimensions, ensuring  
95 enhanced safety and durability against catastrophic failures, particularly in large-scale structures  
96 where the traditional assumptions of small-scale testing may not apply.

97 This paper presents an experimental investigation on concrete damage using integrated AE  
98 and DIC techniques. Plain concrete specimens with different volumes are tested to investigate the  
99 size-slenderness effect. The DIC method gives a precise full-field strain measurement, while AE  
100 signals resulting from internal damage are analysed. The emitted energy is experimentally detected  
101 during snap-back instabilities of concrete specimens in compression. In more brittle cases, crack  
102 propagation suddenly occurs with a catastrophic drop in the load-carrying capacity, so the resulting  
103 emitted energy appears with a burst in cumulated AE curves. In particular, the size-slenderness  
104 effect is employed to evaluate damage domain and fractal dimension.

105

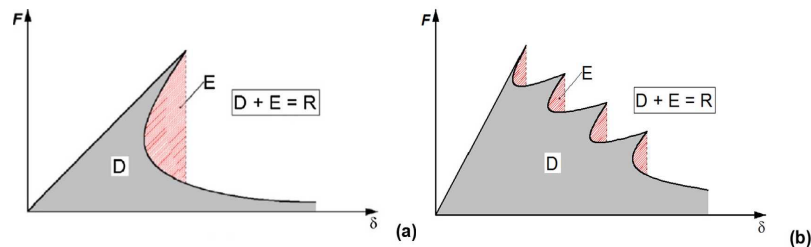
## 106 **2. Emitted energy and snap-back instability**

107 Some information on the modalities of energy release and the development of cracking  
108 patterns can be obtained on the basis of the AE monitoring technique (Aggelis *et al.*, 2011, 2013;  
109 Lacidogna *et al.*, 2020; Jiang *et al.*, 2024a). AE technique provides a non-destructive monitoring  
110 method to detect the damage evolution in materials and structures (Zhu *et al.*, 2024; Jiang *et al.*,  
111 2024b; Li *et al.*, 2020). AE waves can be measured by sensors placed on the structural element

112 surface, providing crucial information on crack initiation and propagation (Zheng *et al.*, 2022;  
113 Wang *et al.*, 2024; Han *et al.*, 2019).

114 Recently, it has been shown that the energy emission is proportional to the total number of  
115 AE signals, and it is a surface-prevailing phenomenon. This has been demonstrated by interpreting  
116 AE data with statistical and fractal concepts (Carpinteri *et al.*, 2007). Furthermore, according to  
117 the recent interpretations (Carpinteri *et al.*, 2018), the relationship between crack propagation and  
118 emitted energy, if analysed by AE, is represented by the area subtended by each snap-back branch  
119 (see Fig.2). The total energy released during the test,  $R$ , is equal to the dissipated energy,  $D$ , plus  
120 the emitted energy during the snap-back phenomena,  $E$ .

121



122

123 Fig.2. Load-displacement curves representing: (a) a catastrophic behaviour (single snap-back); (b) a global softening  
124 behaviour perturbed by multiple local instabilities (snap-back) (modified from Carpinteri *et al.*, 2018).

125

126 The mechanical behaviour of compressive specimens can be described in three stages  
127 (Carpinteri *et al.*, 2009). The first stage involves the initiation and propagation of microcracks.  
128 Approaching the compressive strength, such microcracks coalesce to form macrocracks, localizing  
129 over a preferential surface. In the second stage, the ultimate compressive strength,  $\sigma_u$ , is reached,  
130 and the inelastic deformations are localized in a crushing band. In the final stage, the material in  
131 the crushing zone is damaged. By varying the geometrical parameters of specimens, different  
132 global responses in the stress-strain diagram can be obtained (Lacidogna *et al.*, 2013).

133 In particular, the softening process under displacement control is stable when the slope in the  
134 softening regime is negative (Fig.1), and a sudden drop in the load-bearing capacity occurs when  
135 the slope is infinite. The overall behaviour of specimens in compression depends on geometrical  
136 (size and slenderness) and mechanical (crushing energy and compression strength) parameters  
137 (Carpinteri *et al.*, 2013). Following previous studies (Carpinteri *et al.*, 2009), a catastrophic  
138 softening (snap-back) occurs when the global brittleness,  $B$ , is:

$$140 \quad B = \frac{S_{E,c}}{\varepsilon_c \lambda} \leq \frac{1}{2.3} \quad (1)$$

141 where  $\lambda = 1/b$  is the specimen slenderness ratio, and  $b$  is the specimen base size.  $\varepsilon_c$  is the critical  
142 compression strain, and  $S_{E,c}$  is the energy brittleness number in compression. Therefore, the  
143 stability of the compression process is governed by Eq.(1).  
144

145 In this investigation, an experimental correlation is verified between the emitted energy ( $E$ )  
146 and global or local snap-back instabilities of concrete block specimens in compression.  
147

### 148 **3. Testing plain concrete block specimens**

#### 149 **3.1 Block specimens**

150 Brittle materials usually contain pre-existing microcracks, which can control the failure  
151 mechanism and affect the structural strength (Marolt *et al.*, 2018; Morgan *et al.*, 2013). In this  
152 framework, the AE technique has been effectively applied in the analysis of fracture phenomena  
153 and fault growth (Chang *et al.*, 2004).

154 As listed in Table 1, the plain concrete used in this study is made using ordinary Portland

155 cement type 42.5, grade II fly ash, grade S95 slag powder, crushed gravel with diameter 5-25 mm,  
 156 and mechanical sand with a fineness modulus of 3.1. The composition ratio of  
 157 cement:sand:stone:water is 1:2.24:2.97:0.48. The compressive strength of concrete is equal to 33.2  
 158 MPa after curing for 28 days.

159

160

Table 1 Concrete strength and mix ratio

Concrete grade	$f_{cu}$ (MPa)	Water-binder ratio	Sand rate (%)	Fly ash (wt%)	Slag powder (wt%)	Material usage (kg/m <sup>3</sup> )					
						Cement	Fly ash	Slag powder	Sand	Stone	Water
C25	33.2	0.48	43	28	14	201	100	50	785	1044	170

161

162 In this section, the results of compression tests carried out on nine specimens (3×3) having  
 163 size of 75, 150, and 300 mm, and slenderness 0.5, 1.0, and 2.0, are presented (see Table 2 and  
 164 Fig.3). The test phases are illustrated Fig.4.

165

166

Table 2. Specimen sizes (unit: mm)

Series	Dimension (mm)	Slenderness ratio
I	75 × 75 × 37	0.5
	75 × 75 × 75	1.0
	75 × 75 × 150	2.0
II	150 × 150 × 75	0.5
	150 × 150 × 150	1.0
	150 × 150 × 300	2.0
III	300 × 300 × 150	0.5
	300 × 300 × 300	1.0
	300 × 300 × 600	2.0

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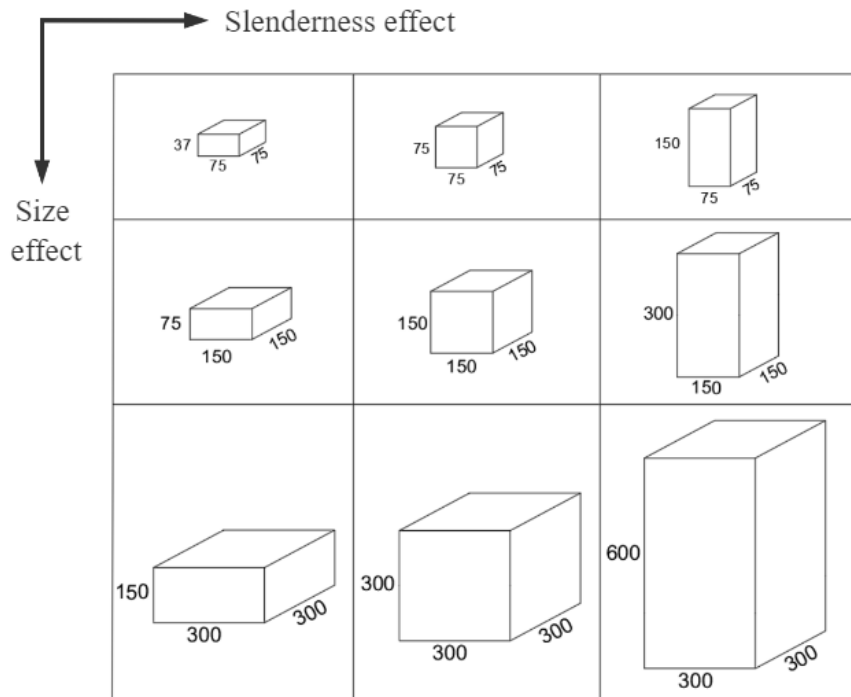


Fig.3. Size-slenderness variation

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169  
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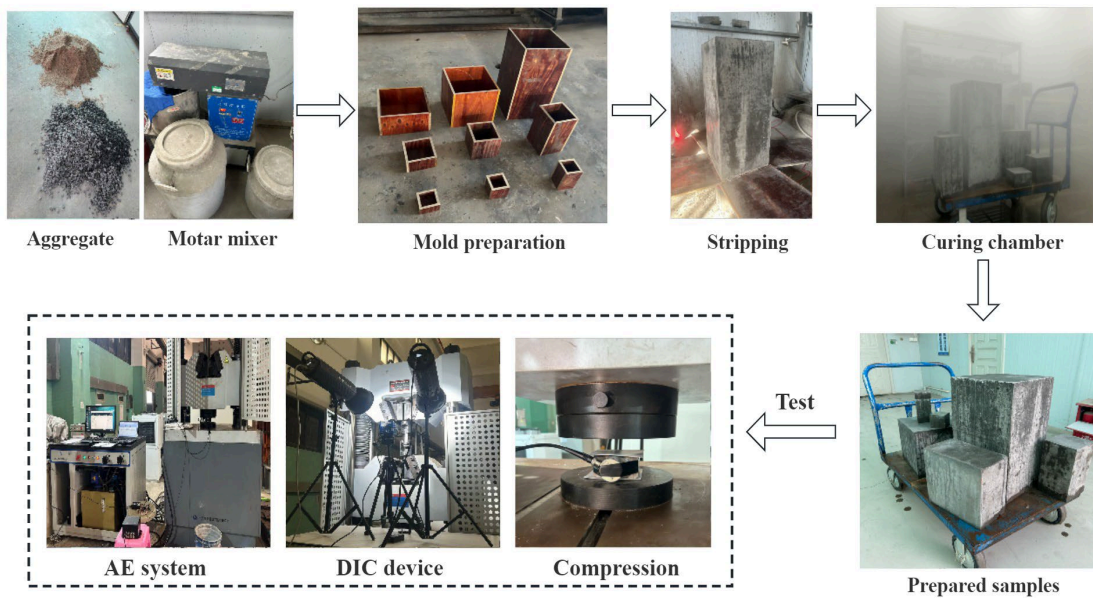


Fig.4. Test phases

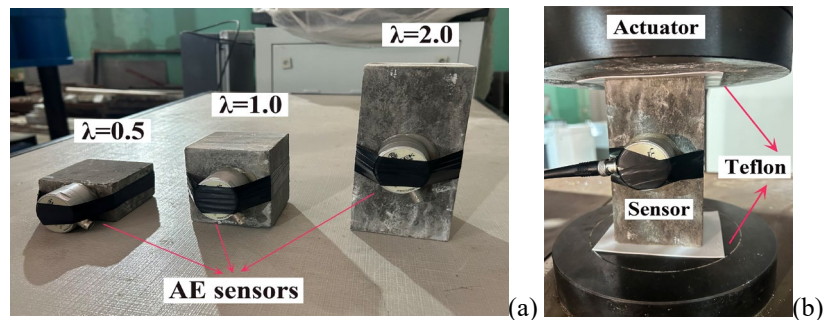
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172  
173

174 **3.2 AE monitoring setup**

175 During the experimental tests, the specimens are equipped with a thin layer of Teflon (Fig.5)  
176 in contact between the platen of the testing machine and the specimen ends, to significantly reduce  
177 the friction force and facilitate the transversal deformation. The loading process adopts a  
178 displacement-control with a constant rate equal to 0.01 mm/s.

179 Each specimen is monitored by means of the AE technique. The AE system utilized in this  
180 test is the  $\text{\AE MISSION}^{\text{\textcircled{R}}}$ , equipped with piezoelectric sensors in the range 10kHz-1MHz. Each  
181 channel has independent threshold triggers, automatically extracting AE signal parameters for  
182 continuous monitoring. The sensor is glued with silicone resin on the specimen surface, as depicted  
183 in Fig.5. The AE waves captured by the sensors were amplified with 60 dB gain before being  
184 processed, setting the acquisition threshold level up to 2 mV. In all experiments, the loading is  
185 stopped when dropping to the 20% of the peak load.

186



187

188

Fig.5. AE sensor layout (a) and compression tests (b)

189

190 **4. Experimental results**

191 **4.1 Slenderness effect**

192 The loading history and the final collapse for three specimens with size 150 mm and

193 slenderness 0.5, 1.0, and 2.0 are shown in Fig.6 and Fig.7. As expected, the more slender specimen  
194 ( $\lambda = 2.0$ ) exhibited a brittle behaviour with global snap-back instability, the post-peak branch being  
195 almost vertical compared to that of the stubby specimens ( $\lambda = 0.5$ ), which is characterized by a  
196 softening post-peak response.

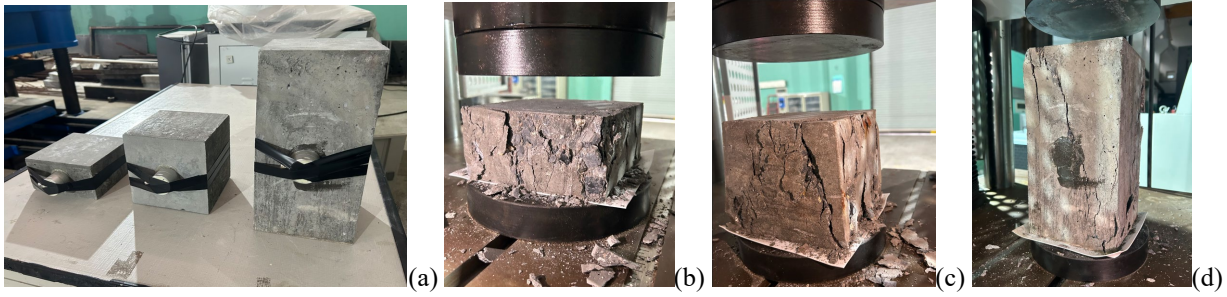
197 As regards the concrete specimen with slenderness  $\lambda = 2.0$  (Fig.6d), two severe global snap-  
198 back instabilities were detected in the post-peak branch of the loading response (see Fig.7c). A  
199 correlation emerges between the catastrophic drops (snap-back instabilities) and the AE bursts  
200 (emitted energy, E) in the cumulated AE curve. The failure mode observed during the experiment  
201 is governed by a dominant sub-vertical crack (Fig.6d).

202 The result of the concrete specimen with slenderness  $\lambda = 1.0$  is shown in Fig.7b. Its behaviour  
203 is characterized by a global snap-back instability just after the peak load. At the same time, an AE  
204 burst (emitted energy, E) is detected in the cumulated curve.

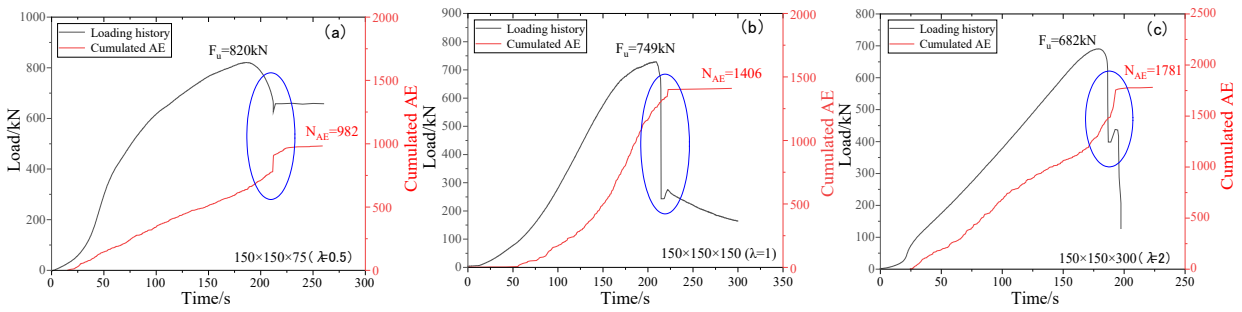
205 The loading behaviour of the specimen with slenderness  $\lambda = 0.5$  is shown in Fig.7a. It is  
206 characterized by a ductile response in the post-peak stage. The softening post-peak regime is  
207 perturbed by the loading drops (local snap-back instabilities), generating AE jumps (emitted  
208 energy, E) in the cumulated curve. The final collapse exhibits significant crushing characteristics  
209 (Fig.6b).

210 In general, as the specimen changes from stubby to slender ( $\lambda$  varying from 0.5 to 2), the final  
211 collapse shows a crushing-to-cracking failure transition, together with a transition from local-to-  
212 global snap-back instabilities, and a decrease in the compressive strength (Fig.7).

213



214  
 215 Fig.6. Final collapse for concrete specimens (a) with size of 150 mm, and slenderness (b)  $\lambda = 0.5$ , (c)  $\lambda = 1.0$ , and (d)  
 216  $\lambda = 2.0$ .



218  
 219  
 220 Fig.7. Loading history and cumulated AE curve for concrete specimens with slenderness equal to (a)  $\lambda = 0.5$ , (b)  $\lambda =$   
 221 1, and (c)  $\lambda = 2.0$ , and size of 150 mm. A correlation emerges between loading drops (snap-back instabilities) and AE  
 222 jumps (emitted energy, E).

223  
 224 **4.2 Size effect**

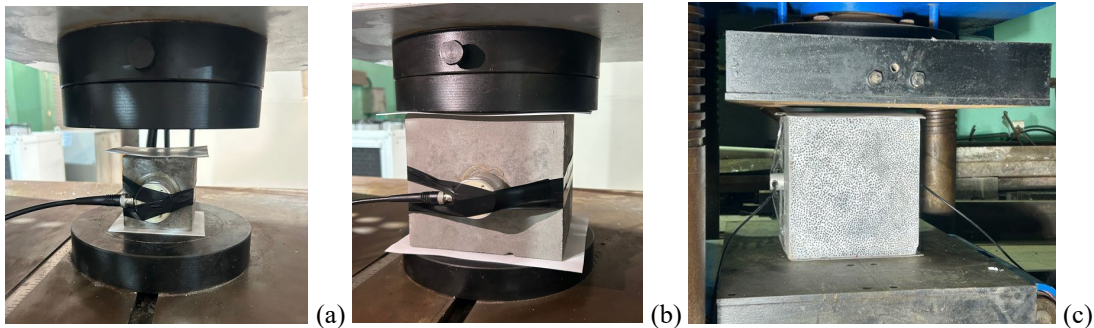
225 The loading behaviour of three specimens with the slenderness equal to 1 (Fig.8), and sizes  
 226 equal to 75 mm, 150 mm, and 300 mm are shown in Fig.9. The largest specimen (Fig.8c) exhibited  
 227 a more brittle behaviour with global snap-back instability (Fig.9c), the post-peak branch being  
 228 almost vertical compared to that of the smallest specimens, which is characterized by a softening  
 229 response. Moreover, an evident correlation emerges between the catastrophic drops in the post-  
 230 peak regime of the loading process and the AE bursts in the cumulated curve.

231 The result of the concrete specimen with size of 150 mm (Fig.8b) is shown in Fig.9b. A global  
 232 snap-back instability is detected just after the peak load, corresponding to an AE burst in the  
 233 cumulated curve.

234 The loading behaviour of the specimen with size of 75 mm (Fig.8a) is shown in Fig.9a,  
 235 showing a softening response. This post-peak regime is perturbed by small local snap-back  
 236 instabilities (Fig.9a), generating AE jumps in the cumulated curve.

237 Generally speaking, as the specimen size increases, the structural behaviour exhibits a ductile-  
 238 to-brittle transition, and the post-peak response changes from softening to snap-back, with local-  
 239 to-global snap-back transition (Fig.9).

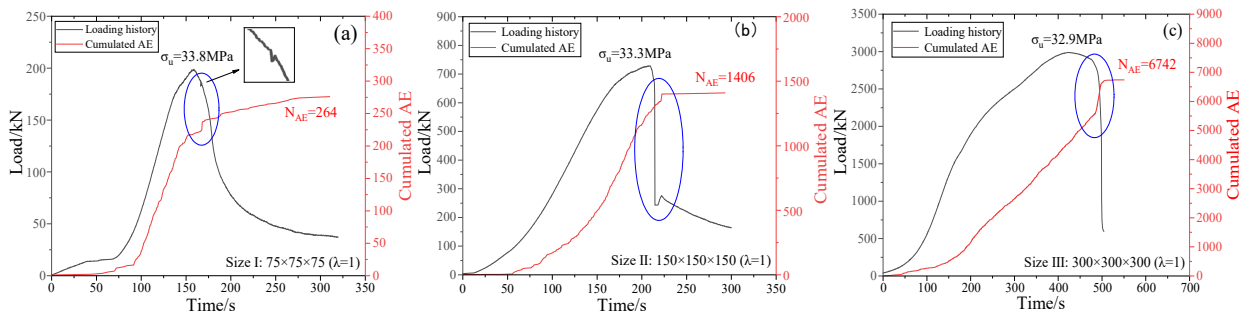
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241

242 Fig.8. Loading layouts for specimens with slenderness equal to 1 and size of (a) 75 mm, (b) 150 mm, and (c) 300 mm.

243



244

245

246 Fig.9. Loading history and cumulated AE curve for concrete specimens with slenderness equal to 1 and size of (a) 75  
 247 mm, (b) 150 mm, and (c) 300 mm. A correlation emerges between loading drops (snap-back instabilities) and AE  
 248 jumps (emitted energy, E).

249  
250

### 251 **4.3 DIC monitoring**

252 The DIC technique is a non-contact optical measurement method that tracks the motion of  
253 points on a surface by analysing the randomly distributed speckle patterns, facilitating real-time  
254 observation of surface displacement and strain (Boniface *et al.*, 2019; Zhou *et al.*, 2016; Alam *et*  
255 *al.*, 2015; Zhang *et al.*, 2023).

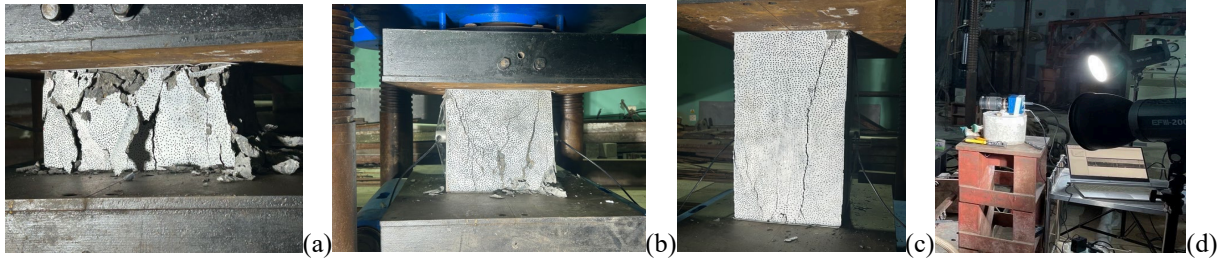
256 The final collapse for three specimens with size of 300 mm and slenderness of 0.5, 1.0, 2.0,  
257 is shown in Fig.10a-c. Before loading, a matte black paint coat is applied to the specimen surface  
258 to generate speckle patterns, with the speckle size ranging between 5 and 7 pixels. During the  
259 loading process, the DIC technique is employed for real-time recording, as illustrated in Fig.10d.  
260 Subsequently, the image analysis system is used to detect the surface displacement and calculate  
261 the full-field strain.

262 Fig.11 displays the strain cloud diagram depicting the fracture process in concrete specimens  
263 with different slenderness, obtained by DIC technique. As shown in Fig.11c, the more slender  
264 specimen ( $\lambda = 2.0$ ) exhibits a typical brittle fracture characterized by a dominant near-vertical crack  
265 occurring catastrophically (Fig.10c), together with fewer cracks with larger crack widths.  
266 Conversely, the stubby specimens ( $\lambda = 0.5$ ) show a ductile fracture characterized by several sub-  
267 vertical cracks, with a gradual increase in the number of cracks (Fig.11a). Moreover, the final  
268 collapse shows notable crushing failure (Fig.10a).

269 In summary, as the specimen shifts from stubby to slender, the structural behaviour of the  
270 concrete specimens gradually changes from ductile to brittle, with the final collapse moving from  
271 crushing to cracking.

272

273



274

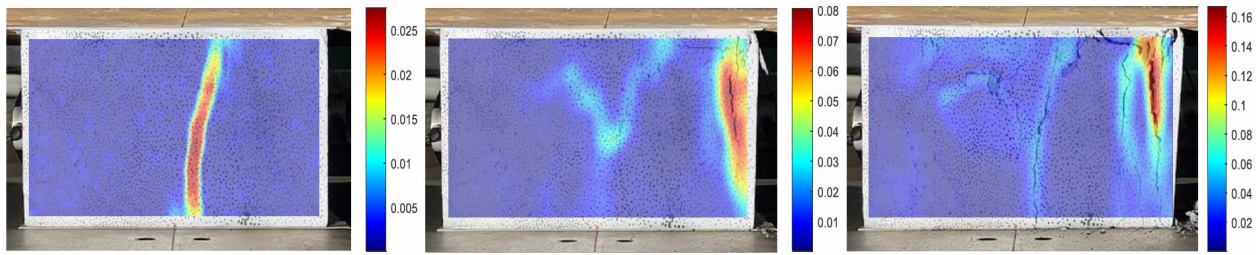
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276

Fig.10. Final collapse for concrete specimens with size of 300 mm and slenderness equal to (a)  $\lambda = 0.5$ , (b)  $\lambda = 1.0$ , and (c)  $\lambda = 2.0$ . DIC monitoring (d).

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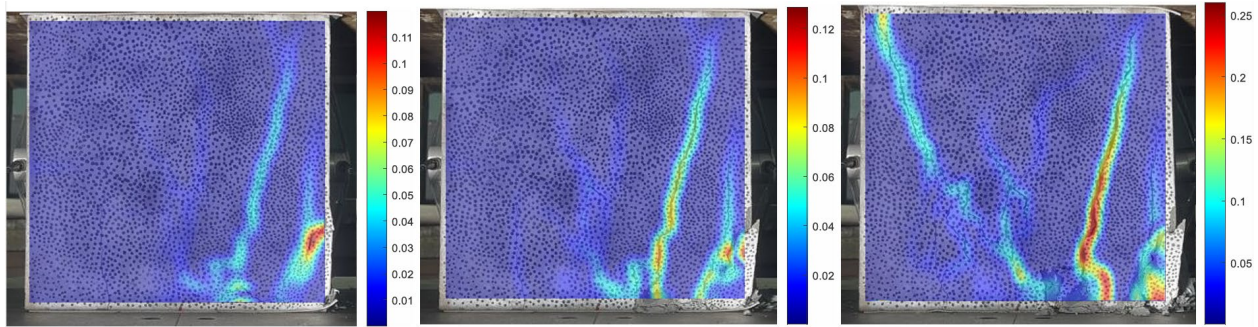
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(a)  $\lambda=0.5$

279

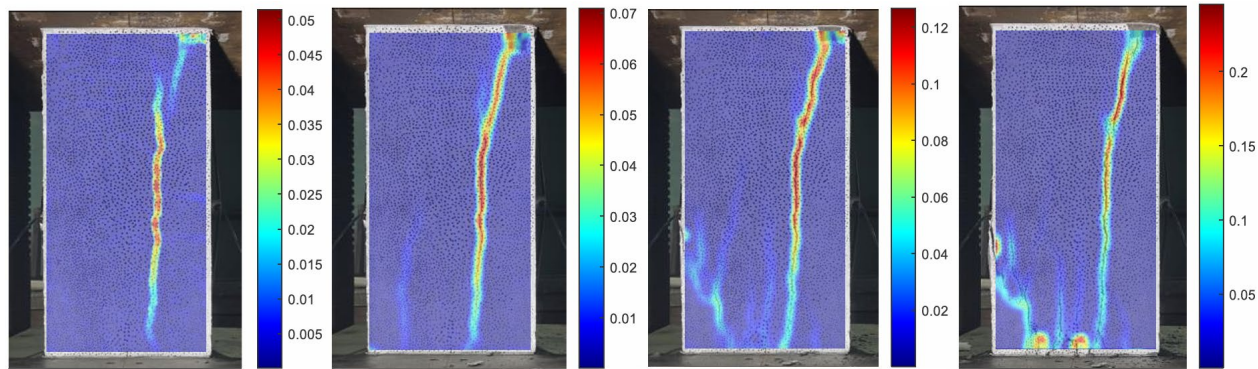
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(b)  $\lambda=1.0$

281

282



(c)  $\lambda=2.0$

283

284

Fig.11. DIC strain cloud diagram of the fracture process in concrete specimens with size equal to 300 mm and slenderness equal to (a)  $\lambda = 0.5$ , (b)  $\lambda = 1.0$ , and (c)  $\lambda = 2.0$ .

## 285 **5. Fractal domain of emitted energy**

286 Considering the fragmentation theory, the energy detected during microcrack propagation,  $E$ ,  
287 is emitted over a fractal domain comprised between a surface and a volume (Carpinteri *et al.*,  
288 2012). Therefore, the following size-scaling law is assumed for the energy emission during  
289 fragmentation:

$$290 \quad E \propto V^{D/3} \quad (2)$$

291 where the fractal exponent,  $D$ , is comprised between 2.0 and 3.0. Considering  $L$  as the  
292 characteristic dimension of the specimen, thus,  $V^{D/3} = L^{3(D/3)} = L^D$ . If  $D = 3$ , the damage will be  
293 distributed in the whole specimen volume. On the contrary, if  $D = 2$ , the damage will be organized  
294 on a preferential surface.

295 This indicates that the fractal energy density (having non-integer physical dimensions),

$$296 \quad \Gamma = \frac{E}{V^{D/3}}, \quad (3)$$

297 can be considered as the size-independent parameter (Lacidogna *et al.*, 2019).

298 Furthermore, AE can be detected during microcrack propagation. The energy emission,  $E$ , is  
299 proportional to the total number  $N_{\max}$  of AE signals (Lacidogna *et al.*, 2019). Accordingly, the  
300 total number of AE signals,  $N_{\max}$ , over a fractal domain, can be considered as the size-independent  
301 parameter:

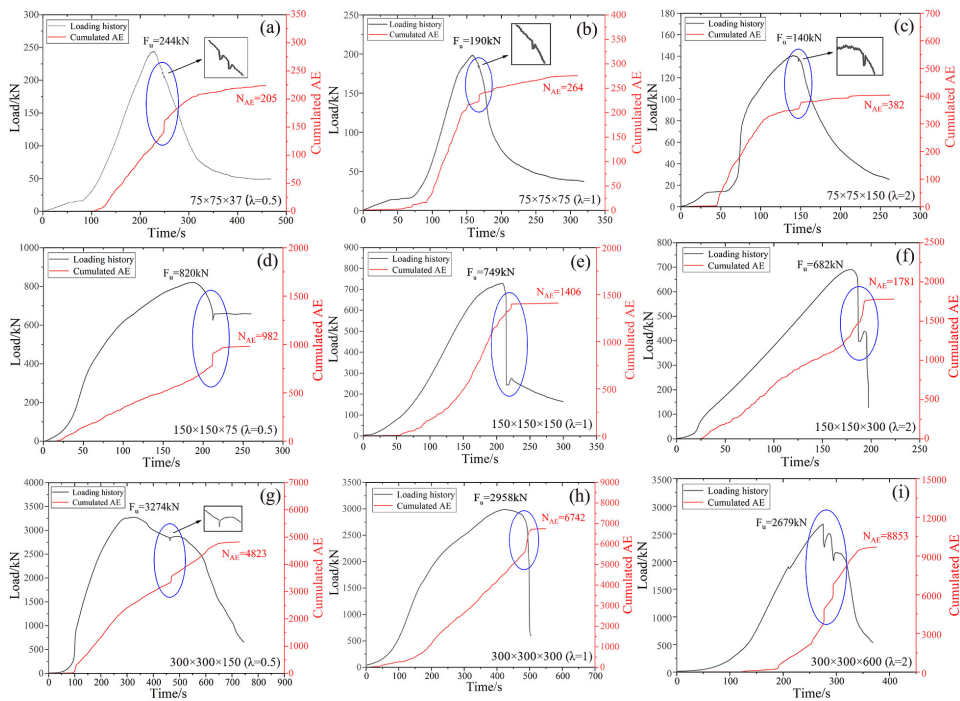
$$302 \quad \Gamma_{\text{AE}} = \frac{N_{\max}}{V^{D/3}} \quad (4)$$

308

309 where  $\Gamma_{AE}$  is the value of AE signals fractal density.

310 The total number of AE signals and loading history from nine specimens with different  
311 volumes is shown in Fig.12. It has been observed that compressive strength and ductility exhibit a  
312 strong size-slenderness effect by changing the specimen volume. The size-slenderness effect on  
313  $N_{max}$  is represented as a function of the specimen volume (Fig.13). The log-log diagram shows a  
314 slope close to 0.73, i.e. a fractal dimension equal to 2.19, emphasizing that the energy emission  
315 occurs in a fractal domain close to a surface. Thus, the fractal AE density is  $4 \text{ cm}^{-2.19}$ , i.e. 4 signals  
316 per unit surface.

317



318

319 Fig.12. Loading history and cumulated AE curve for different specimen volumes with slenderness equal to 0.5, 1.0,  
320 and 2.0, and sizes of 75, 150, and 300 mm.

321

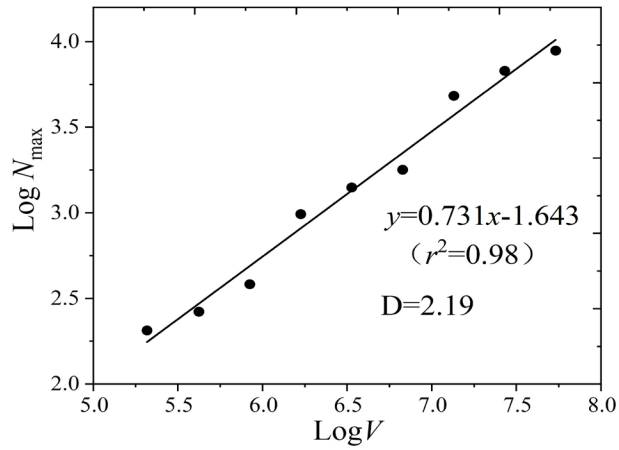


Fig.13. Fractal domain of energy emission.

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323

324

## 325 6. Conclusions

326 In this paper, the results of experimental tests carried out on plain concrete specimens are  
 327 analysed, to demonstrate that the emitted energy is generally due to snap-back instabilities.  
 328 Concrete specimens with different sizes and slenderness ratios are considered, and all the tests are  
 329 monitored using integrated AE and DIC techniques. The conclusions are as follows.

330 (1) As the size-slenderness increases, the compressive strength decreases, and the structural  
 331 behaviour exhibits a ductile-to-brittle transition, with the post-peak response changing from  
 332 softening to snap-back. In addition, as the specimens change from stubby to slender, the final  
 333 collapse shows a crushing-to-cracking failure transition, as evidenced by the DIC technique.

334 (2) For large and slender specimens (size  $\geq 150\text{mm}$  and  $\lambda \geq 1$ ), the crack propagation occurs  
 335 suddenly with a catastrophic drop in the load-carrying capacity, and the resulting emitted energy  
 336 appears with a burst in the cumulated AE curve. In contrast, for small and stubby specimens  
 337 (size=75mm or  $\lambda=0.5$ ), the softening post-peak regime is perturbed only by local snap-back  
 338 instabilities.

339 (3) The fractal domain of the emitted energy presents a dimension equal to 2.19, emphasizing  
340 that AE occur in a fractal domain close to a surface. In particular the AE density is equal to 4  
341 signals per unit surface.

342 The findings provide valuable data on the role of size and slenderness in concrete failure  
343 modes, with significant implications for engineering applications in large concrete structures.  
344 Understanding size effects and the ductile-to-brittle transition helps optimize the design of concrete  
345 components in large infrastructures, preventing catastrophic failures. This study highlights the  
346 importance of considering these factors in designing structures like skyscrapers, dams, and bridges.  
347 The integration of AE and DIC techniques offers a reliable method to assess and predict concrete  
348 failure modes, enhancing safety and serviceability in real-world applications.

349

### 350 **Credit authorship contribution statement**

351 **Zihan Jiang:** Writing – original draft, Methodology, Investigation, Data curation,  
352 Conceptualization. **Zhiwen Zhu:** Writing – review & editing, Methodology, Data curation,  
353 Conceptualization. **Federico Accornero:** Methodology, Supervision, Conceptualization, Writing-  
354 Review & Editing. **Giuseppe Lacidogna:** Writing–review & editing, Project administration,  
355 Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

356

### 357 **Declaration of competing interest**

358 The authors declare that they have no known competing financial interests or personal  
359 relationships that could have appeared to influence the work reported in this paper.

360

## 361 **Data availability statement**

362       Some or all data, models, or code that support the findings of this study are available from the  
363 corresponding author upon reasonable request.

364

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371

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