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Acoustic Emission and damage monitoring in RC beams under cyclic loading

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ABSTRACT: This paper proposes the results of Acoustic Emission (AE) measurements intended at investigating the structural response of two real-scale RC beams tested under four-point bending. Two different rebar configurations, with and without shear stirrups, were considered. Also, steel fibers are included in the concrete mixture. A loading procedure characterized by several cycles of increasing amplitude applied up to failure was implemented. Both AE and relevant mechanical parameters were continuously monitored during the whole test process. The failure behavior and the ability of various evaluation indices based on both structural and AE parameters to evaluate the damage level are presented and analyzed. AE rate exhibited good correlation with cracking initiation and evolution and, hence, they proved to be suitable for both monitoring the structural response and detecting eventual structural damage.

1 INTRODUCTION

In the field of structural engineering there is a growing interest in developing non-destructive evaluation methods capable of monitoring health condition in existing reinforced concrete (RC) members and structures. In the last decades, new damage qualification criteria based on load tests and AE monitoring have been proposed in the scientific literature (Behnia et al., 2014). However, not enough experimental data are currently available to validate those testing procedures and the related acceptance criteria for assessing RC structures. Furthermore, even less data are available for new materials, such as high performance concrete and fiber-reinforced concrete (Xargay et al., 2018). Therefore, this research aims at observing the structural response of RC beams subjected to laboratory tests during which AE are monitored. Specifically, the work is intended at investigating possible correlations between the AE indices and relevant damage levels within the member. The influence of fibers possibly spread within the concrete mixture is also investigated.

1.1 Cyclic load test

ACI 437R-03 (2003) defines a protocol of cyclic load tests (CLT) method. Specifically, it is stated that a cyclic load test should consist of at least three load steps with two repetitions each, and, hence, six loading/unloading cycles. Then, three performance indices are defined therein in terms of the three following structural response aspects: *Repeatability*, *Permanency*, and *Deviation from linearity*. Although they may be related to any mechanical response parameter, in practice deflections have been widely considered for this purpose.

Repeatability (I_R) index is a measure of the similarity of behavior of the structural member during two identical load cycles at a given load level. It is an indicator of structural performance in terms of recoverable deflection and load-deflection response in general. Permanency (I_P) is the ratio of the residual deflection to the corresponding maximum deflection achieved during the second of two identical load cycles and it is a signal that load has damaged the member and that nonlinear effects are happening. Deviation from linearity (I_{DL}) is defined as the ratio of the slopes of two secant lines intersecting the load-deflection envelope and represents the measure of the nonlinear behavior of a member being tested at a certain point "i" related to an initial reference condition. Their mathematical definitions and suggested acceptance threshold values are reported hereafter:

$$\text{Repeatability} = \frac{\text{Maximum deflection cycle B} - \text{Residual deflection after cycle B}}{\text{Maximumdeflection cycle A} - \text{Residual deflection after cycle A}} > 0.95 \quad (1)$$

$$\text{Permanency} = \frac{\text{Residual deflection after cycle B}}{\text{Maximum deflection cycle B}} < 0.10 \quad (2)$$

$$\text{Deviation from linearity}_i = 1 - \frac{\tan(\alpha_i)}{\tan(\alpha_{ref})} < 0.25 \quad (3)$$

1.2 Overview about Acoustic Emission monitoring

Acoustic Emissions (AEs) are generated by transient elastic waves in the ultrasonic frequency range that are generated due to rapid strain energy release from inside a material (ASTM E1316, 2004). An outstanding non-destructive technique (NDT) can be based on the detection and analysis of AEs, which makes possible to monitor structural elements in a passive and non-invasive manner. In the last decades, AE monitoring has been studied and implemented in both laboratory tests and field applications intended at scrutinizing the structural health status of RC elements (Ohtsu et al., 2002; Colombo et al., 2005; Lui and Ziehl, 2009). Consequently, some indices have been proposed as parameter-based AE signal analysis, conceptually linked to the occurrence of the characteristic phenomena generally referred to as Kaiser and Felicity effects (Vidya Sagar et al., 2015).

In general terms, these indices compute AE parameters obtained during the unloading and/or reloading phases of a cycle test and are related with the failure process of the RC beams. In this work, four of them are considered: Load ratio, Calm ratio, Relaxation ratio and Cumulative Signal Strength (CSS) ratio. Their definitions have been adapted as shown in Eq. (4), (5), (6) and (7). Furthermore, it can be noted that AE Signal Strength (measured area of the rectified AE signal) was used as main input parameter for calculations.

$$\text{Load Ratio} = I_L = \frac{\text{load at the onset of AE activity during reloading}}{\text{previous maximum load}} \quad (4)$$

$$\text{Calm Ratio} = I_C = \frac{\text{Cumulative Signal Strength during unloading}}{\text{Cumulative Signal Strength during the whole cycle}} \quad (5)$$

$$\text{Relaxation Ratio} = I_{RR} = \frac{\text{Average Signal Strength during unloading}}{\text{Average Signal Strength during previous loading}} \quad (6)$$

$$\text{CSS Ratio} = \mathrm{I_{CSS}} = \frac{\text{Cumulative Signal Strength during reloading}}{\text{Cumulative Signal Strength during previous reloading}} \tag{7}$$

Recently, in 2019, the standard ISO 16837 has been published specifying a test method for damage qualification of RC beams by AE, based on preceding RILEM TC 212-ACD and JSNDI NDIS 2421 recommended practices. So far, one of the major drawbacks of the proposals is that it has not been possible to determine absolute threshold values in order to establish AE based acceptance criteria, mainly due to different structure sizes and test conditions.

2 EXPERIMENTAL PROGRAM

2.1 Materials

The experimental activities presented in this work were developed at the Laboratory of Materials and Structures of the University of Buenos Aires (UBA) in collaboration with the Argentinean National Commission of Atomic Energy (CNEA). Cement from a local producer similar to CEM 42.5R, a combination of natural sand and crushed sand as fine aggregates, coarse crushed stone with maximum size of 19 mm, potable water and normal-range plasticizer were the basic constituents used for the concrete mixture. A water-to-cement ratio 0.49 was adopted. Finally, cold drawn steel wire fibers "Wirand FF3" (0.5 % in volume fraction) were added to the mix. These fibers are hooked-ended, with 0.75 mm in diameter and 50 mm in length. The main fibers mechanical properties reported by the manufacturer are: tensile strength of 1100 MPa and ultimate strain of 4%. Table 1 reports the mixture composition.

The aforementioned materials were electronically weighed and mixed in a laboratory pan mixer of 200 dm^3 capacity. Several tests on small specimens for the mechanical characterization of the concrete mixture were performed, among others, compressive strength, indirect tensile strength and bending strength. The mean compressive strength evaluated on three cylinders of 100 mm diameter and 200 mm height at 28 days was 30 MPa.

Table 1. Concrete mix proportions and mechanical characteristics

Materials (kg/m^3)	
Cement	340
Siliceous river sand	560
Fine crushed granitic aggregate	240
Coarse crushed granitic aggregate	1060
Water	166
Plasticizer	1.36
Steel fibers	40

As reinforcement of the beams, deformed steel bars of 6 mm and 12 mm diameter were employed. Their relevant mechanical properties are: nominal yield stress of 420 MPa, ultimate tensile strength of 500 MPa and rupture strain higher than 12%.

2.2 Reinforced Concrete (RC) beams

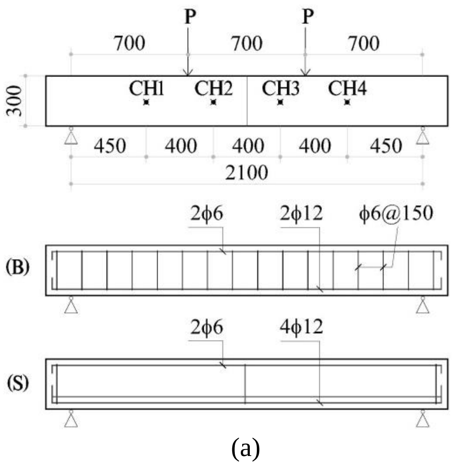
Two RC beams were cast into industrial polymer formworks, duly compacted and cured for 3 months under controlled condition before testing. The specimens dimensions were 120 x 300 mm cross-section and 2400 mm length. Each one had different reinforcing bar arrangement, expecting to obtain extreme cases of failure modes. On the one hand, the beam referred to as "B" was designed to have bending-mode failure: 2ϕ12 rebar as tension reinforcement, 2ϕ6 rebar as compression reinforcement and ϕ6 closed stirrups spaced 150 mm were used: the reinforcement ratio (ρ) was 0.63%. On the other hand, the beam namely "S", was expected to have dominant shear-mode failure: 4ϕ12 reinforcing bars as tension reinforcement, 2ϕ6 rebar as compression reinforcement and only three stirrups for constructive reasons: in this case, ρ was 1.26%.

It is worth highlighting that beam "B" was under-reinforced for bending and fully reinforced against shear failure, whereas beam "S" was over-reinforced in bending and weakly reinforced by stirrups against shear failure, so that shear should be mainly sustained by the action of steel fibers (Fig. 1a).

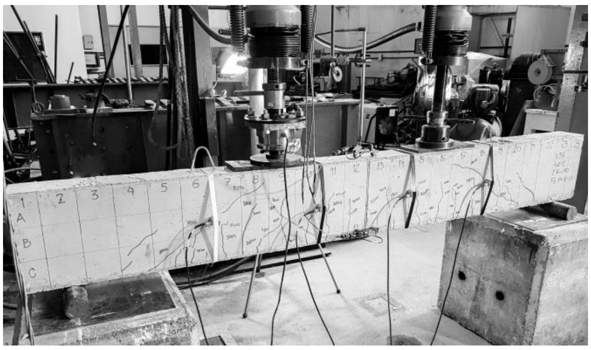
2.3 Methods

2.3.1 Test setup

The beams were tested in a Four-Point Bending Test (FPBT) configuration by two hydraulically actuated jacks with a load maximum capacity of 200 kN each one. The span was 2100 mm and loads were applied symmetrically at a distance of 400 mm from mid span. As it is widely known, this loading scheme leads to pure bending stress state in the specimen between load contact points. The tests were load controlled and the mid span section strains and deflections were monitored by means of LVDTs and cracks width were measured by using an USB microscope during load holds. A load cell was placed under one of the jacks. The test setup is shown in Fig. 1b.



(a)



(b)

Figure 1: (a) Geometry and reinforcement details: bending B and shear S beams. (b) View of the experimental test layout.

2.3.2 Loading procedure

The loading process was composed by several load steps increased every 8.8 kN. Also, each load step consisted of two loading/unloading cycles. At maximum load of all the second cycles a longer load hold was performed in order to stabilize the structural response and the measurements. Loading histories for both beams are displayed overlapped in Fig. 2. For S beam the last load step was at 61.8 kN and after it was loaded up to failure due to safety reasons.

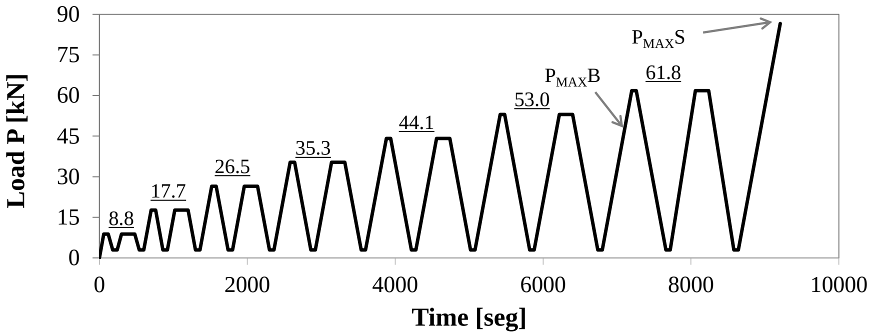


Figure 2: General loading procedure. Beam B had its maximum load at 48.5 kN. Beam S reached its failure at 86.5 kN. The values represent the load applied by each jack.

2.3.3 AE system setup

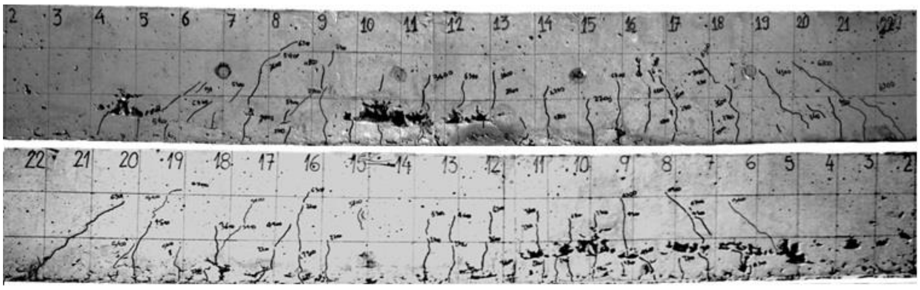
AE signals were recorded by two PAC PCI-2 AE acquisition boards. Four sensors model R15-I with 150 kHz resonant peak frequency were mounted on the beam surface. They were symmetrically distributed at mid height of the samples and horizontally spaced 400 mm, as revealed in Fig. 1. The type of sensors was chosen due to the specimen´s dimensions and those sensors supplies good sensitivity with reduced background noise. Solid vaseline was utilized as a coupling layer between the sensors and the concrete surface; the sensors were secured to the specimen by means of plastic tape. Thin rubber sheets were placed at the support in order to avoid possible friction noise. Coupling and attenuation of signals were checked with artificial sources by breaking pencil leads at the surface before starting the mechanical tests. A measurement threshold of 40 dB, a band-pass filter of 20-400 kHz and sampling frequency of 2 MHz were established. AE raw data were pre-filtered by magnitude of AE parameters in order to remove hits without physical meaning.

3 RESULTS AND DISCUSSION

Fig. 3 shows the final view of the tested beams. The addition of fibers did not significantly modify the expected behavior of B beam. On the other hand, the fibers clearly affected the mechanical behavior of S beam acting as shear reinforcement. Moreover, latter reached a yielding stage with several cracks and developed almost its full flexural capacity. The final failure of S beam was due to inclined shear cracks in shear span (Fig. 3b). As expected, unreinforced B beam presented less and more spaced cracks than S beam. For each load level, crack widths were wider for B specimen than S because of the higher reinforcement ratio.

Table 2 summarizes the structural measurements and AE ratios obtained for both beams. P_{max} was the maximum load reached during the test and P/P_{max} ratio denotes a damage parameter. Since the samples were initially uncracked and became cracked after a load level of 10 kN, their flexural stiffness strongly changed generating a pronounced non-linearity that was not necessarily related to degradation in strength. Consequently, a post-cracking reference linearity at 17.7 kN was adopted. Calm ratios defined by eq. (4) were obtained as minimum values of all AE channels for the second cycle of each load set and Relaxation ratio (6) was calculated averaged over the duration of each loading branch.

(a)



(b)

Figure 3: Cracking patterns and failure modes: (a) B and (b) S beams. Front and back beam's faces are shown.

Table 2. Structural and AE analysis results.

Parameter (%)	Bending (B)					Shear (S)						
Load (kN)	8.8	18	27	35	44	8.8	18	27	35	44	53	62
P/P_{max}	18	36	55	73	91	10	20	31	41	51	61	71
Crack width (mm)	0	0.07	0.13	0.19	0.25	0	0.05	0.09	0.11	0.13	0.15	0.17
Repeatability	103	102	103	102	104	120	122	103	103	102	104	102
Permanency	3	4	2	1	1	3	9	2	1	1	1	2
Deviation from linearity	-	-	16	23	27	-	-	12	16	19	20	26
Load ratio	104	93	78	62	32	111	88	73	66	70	56	24
Calm ratio	0	5	10	17	30	0	1	1	3	7	8	11
Relaxation ratio	0	28	36	186	228	0	1	1	5	20	40	69
CSS ratio	0	10	24	26	35	4	7	18	20	32	35	38

Fig. 4 shows two correlation charts between the AE indices. Although standard ISO 16837 recommended a correlation between Load and Calm ratios, such as the one presented in Fig. 4a, the relationship of Fig. 4b is proposed as a possible alternative. For instance, CSS ratio of 0.22 and Relaxation ratio of 0.15 as boundary values for "severe damage zone" are suggested. In fact, during normal service existing RC beams used to work at 40% of its load capacity, whereas 50-55% of load level could generate some permanent damage. Cracks width of 0.10 mm corresponds to the serviceability limit for adverse exposure conditions in several recommendations, and in the experiments was achieved for B beam at 45% and for S beam at 36% of ultimate load. As it is expected, a load test should not cause significant permanent damage to the structure, therefore, the proposed limit values seem to be adequate in order to preserve the integrity and durability of the structural member. Additionally, it must be taken into account that fibers restricted cracks opening by bridging effect and, hence, wider cracks could be expected in RC beams without fibers.

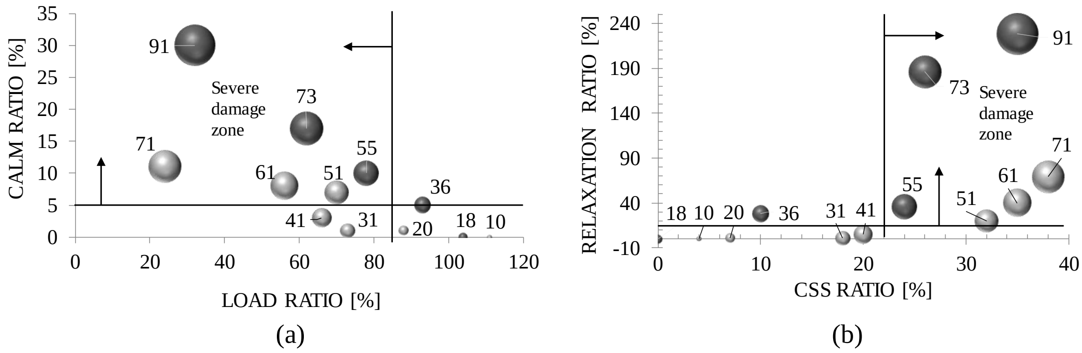


Figure 4: AE indices correlation charts for samples B (dark grey) and S (light grey) (a) Load vs. Calm ratios (b) CSS vs. Relaxation ratios. Note: diameter of spheres indicates percentage of failure load.

Further comments based on the obtained results are reported hereafter.

Repeatability and Permanency indices never overcame the thresholds reported in eqs. (1) and (2), respectively. Therefore, they proved to be insensitive to the degree of damage. Deviation from linearity index was the most sensitive among those defined by ACI 437R-03 (2003). However, in both tests, the latter exceeded its threshold for loads extremely close to physical failure (91% for B and 71% for S). More structural tests must be done in laboratory and "in situ" to verify if these tendencies prone to insecurity are repeated. If the trends are confirmed, it will be necessary to review the limit values of the analyzed criteria.

Load ratio showed a decreasing trend when the load level increased (damage increase). It was observed that Load ratio became below 1.0 after initial cracking occurred (cracks width ranging between 0.05-0.07 mm), which suggests that is linked with the creation of new macro-cracks. Nevertheless, its main disadvantage lies on the subjectivity of its definition (eq. (4)) that can generate significant scatter in the calculations. On the other hand, Calm ratio presented a relatively stable tendency increasing with the load level. It is clearly associated to crack opening and closing movements and cracks width. A change in trend was observed when the load reached approximately at 40 to 50% of the failure load of specimens. This range could be limited by adopting a threshold value of 0.05 as proposed by Ohtsu et al. (2002). Thus, the incorporation of fibers did not significantly change the AE characteristics of RC beams in comparison with experimental data from the literature reference. By last, Relaxation ratio gave similar results to the Calm ratio for both specimens and has the advantage that it can contemplate different duration of loading/unloading stages at the same cycle.

4 CONCLUSIONS

This work has presented some results experiments on RC beams with fibers that were loaded in cycles up to failure meanwhile recording the AE activity and key mechanical parameters as the applied load, deflection and cracks width. The analysis of the AE data was done based on four ratios proposed in the scientific literature.

The results demonstrate that fibers influence the structural behavior of the RC beam without stirrups, but the AE overall response seemed to be not significantly affected for the implemented test setup. Specifically, failure shifts from shear mode to mixed shear/bending mode due to the contribution of fibers, hence leading to similar response in terms of AE events.

CSS ratio emerges as an interesting alternative for the widely known Load ratio, as its evaluation is not subjective and is based in the same physical effect. Relaxation ratio is auspicious for “in situ” testing because in those cases is more difficult to obtain fully repeatable and controlled conditions.

Finally, AE indices Calm ratio, Relaxation ratio and CSS ratio provided the most consistent results and, therefore, are promising measure for damage detection and quantification intended to set up a stop criterion during a proof loading.

Additional work is needed to establish in which conditions the AE analysis gives repeatable and reliable results. Moreover, the boundaries of its application must to be further examined.

References

ACI 437R, 2003, Strength Evaluation of Existing Concrete Buildings, American Concrete Institute, Michigan, USA, 28 pp.

ASTM E 1316, 2004, Standard Terminology for Nondestructive Testing, *Books of Standards*, ASTM International, W. Conshohocken, Pennsylvania, USA, 40 pp.

Behnia, A., Chai, H.K. and Shiotani, T., 2014, Advanced structural health monitoring of concrete structures with the aid of acoustic emission, *Construction and Building Materials*, 65, 282-302.

Colombo, S., Forde, M.C., Main, I.G. and Shigeishi, M., 2005, Predicting the ultimate bending capacity of concrete beams from the “relaxation ratio” analysis of AE signals. *Construction and Building Materials*, 19, 746-754.

ISO 16837, 2019, Non-destructive testing - Acoustic emission testing - Test method for damage qualification of reinforced concrete beams, International Organization for Standardization, Geneva, Switzerland, 5 pp.

Liu, Z. and Ziehl, P., 2009, Evaluation of reinforced concrete beam specimens with acoustic emission and cyclic load test methods. *ACI Structural Journal*, 106(3): 288-299.

NDIS 2421, 2000, Recommended practice for in situ monitoring of concrete structures by AE, Japanese Society for Nondestructive Inspection (JSNDI), Tokyo, Japan, 6 pp.

Ohtsu, M., Uchida, M., Okamoto, T. and Yuyama, S., 2002, Damage Assessment of Reinforced Concrete Beams Qualified by Acoustic Emission. *ACI Structural Journal*, 99(4): 411-417.

RILEM TC 212-ACD, 2010, Acoustic emission and related NDE techniques for crack detection and damage evaluation in concrete. Test method for damage qualification of reinforced concrete beams by acoustic emission, *Materials and Structures*, 43, 1183-1186.

Vidya Sagar, R., Raghu Prasad, B.K. and Singh, R.K., 2015, Kaiser effect observation in reinforced concrete structures and its use for damage assessment, *Archives of Civil and Mechanical Engineering*, 548-557.

Xargay, H., Folino, P., Nuñez, N., Gómez, M., Caggiano, A., Martinelli, E., 2018, Acoustic Emission behavior of thermally damaged Self-Compacting High Strength Fiber Reinforced Concrete. *Construction and Building Materials*, 187, 519-530.