Acoustic emission-based mathematical procedure for quantification of rebar corrosion in reinforced concrete

Shilpa Patil[1], Shweta Goyal[2,*] and Bilavari Karkare[1]

[1]Department of Civil Engineering,
Vishwakarma Institute of Information Technology,
Pune 411 048, India
[2]Department of Civil Engineering, Thapar University,
Patiala 147 004, India

One of the most important causes for deterioration of reinforced concrete structures is corrosion of steel rebar in concrete. Acoustic emission (AE) technique is reported as an effective non-destructive tool for qualitatively identifying the onset of rebar corrosion. The applicability of AE for quantitative assessment of rebar corrosion in concrete is investigated here. Statistical analysis of experimental results under accelerated corrosion confirmed a promising relationship between gravimetrical rebar mass loss and AE measurement. The efficacy of the developed mathematical model was further confirmed under realistic prolonged corrosion exposure. Thus, a new procedure has been developed for quantification of rebar corrosion through experimental verification.

Keywords: Acoustic emission, corrosion, mathematical modelling, non-destructive testing, reinforced concrete.

REINFORCED concrete (RC) structures have the potential to be durable and capable of withstanding a variety of adverse environmental conditions[1,2]. However, failures in the RC structures still occur due to adverse effects of external or environmental agencies. One of the main causes leading to degradation of RC structures is the corrosion of steel reinforcement[1–3]. Rebar corrosion is an electrochemical process which involves the transfer of electrically charged ions between two locations on the reinforcing bar with different potentials (anode and cathode) through the electrolyte solution provided by the pore fluid of concrete surrounding the steel[1,3].

Researchers have studied the corrosion phenomenon using various electrochemical methods (viz. half-cell potential, linear polarization resistance method, electrochemical impedance spectroscopy, etc.) which estimate corroded condition of rebar from the electrical data. The major limitation of the electrochemical methods is requirement of physical or electrical contact with the rebar for measurement, which locally damages the structures in practice.

Among the other non-destructive techniques, acoustic emission (AE) has emerged as a powerful and reliable non-destructive tool for detecting damage that occurs inside the structure and has not reached the surface yet[4]. There is a strong correlation between the AE waveforms and material deformation[5]. AE is not an electrochemical method, but by utilizing the sensitivity of the technique to the growth and initiation of micro-cracks as a consequence of corrosion reaction, the phenomenon of corrosion can be identified[6]. The researchers[1,7–9] have demonstrated that the technique can give an early warning of corrosion compared to well-established electrochemical techniques. Idrissi and Limam[10] showed a perfect correlation between the evolution of acoustic activity and corrosion current density. However, corrosion monitoring in the previous works was limited to initiation period, focusing on the onset of corrosion only.

AE technique is considered as a qualitative method to find the initiation of corrosion of steel embedded in concrete by identifying cracks developed in concrete during the progress of corrosion. However, it has not been used to quantify the rate of rebar corrosion. An attempt to quantify corrosion rate by AE activity was made by Ing *et al.*[6] by correlating absolute energy parameter obtained from AE data with gravimetrical mass loss; but they could not establish any relationship. Thus, it is necessary to develop a method to quantify the losses due to corrosion of rebar using AE technique. The present study aims to assess the rebar corrosion quantitatively using AE technique.

Different parameters of AE signals can be acquired and analysed for the AE waveforms. Some of the commonly used parameters are hit-driven data (amplitude, duration, and signal strength) or time-driven data (average signal level and absolute energy)[1]. In the present study, signal strength parameter of AE was acquired and analysed to quantify corrosion. Signal strength is defined as the measured area of the rectified AE signal, with units proportional to volt-seconds. The signal strength is often referred to as relative energy which is a measure of the amount of energy released by a specimen[11]. Research has shown that when cumulative signal strength (CSS) is plotted versus time, it will generally increase sharply at a certain time which can be correlated to damage and corrosion[1,12]. In addition, research has identified that CSS of the AE technique is a promising parameter for corrosion monitoring studies under accelerated corrosion conditions as it has a specific trend indicating active corrosion, which is similar to the curve of typical corrosion loss of steel due to sea-water immersion[13]. Patil *et al.*[13] compared CSS values with results of well-established electrochemical techniques, viz. half-cell potential and Tafel extrapolation technique and concluded that the AE technique is effective for monitoring the progress of corrosion of rebar as well as damage to concrete. In the present study, CSS parameter of AE signal is used to quantify rebar corrosion in terms of gravimetric mass loss.

The work presented here is part of a long-term project that aims at exploring the applicability of the AE technique

*For correspondence. (e-mail: shweta@thapar.edu)

for structural health monitoring, including identification of damage to concrete as well as quantification of corrosion of steel rebar in concrete. Identification of damage to concrete due to corrosion and progress of corrosion using the AE technique in comparison with well-established electrochemical techniques has already been published by Patil *et al.*[13]. Here, the work is further extended to establish a relationship between mass loss and CSS parameter of AE measurement due to rebar corrosion under accelerated corrosion condition. Statistical analysis tool was used to develop the mathematical model. Further, the efficacy of the developed mathematical model was checked for prolonged corrosion exposure condition. Thus, a new procedure is developed for quantification of rebar corrosion through experimental verification.

With a view to establish a generic relation between mass loss and AE measurement, the testing programme varied with the cement type (Ordinary Portland Cement (OPC) conforming to IS 12269 (ref. 14) and Portland Pozzolana Cement (PPC) conforming to IS 1489 (Part I))[15], steel type (thermo-mechanically treated steel (Tiscon TMT) and corrosion-resistant steel (Tiscon CRS)) and rebar diameter (12, 16 and 20 mm) by keeping two variables constant per set of test samples. Table 1 provides the test matrix and the corresponding test results. For all the specimens, M20 grade of concrete was prepared using the mix proportion of 1 : 2.78 : 2.73 with water-cement ratio of 0.5 according to IS 10262-2009 (ref. 16). Crushed stone of nominal size 10 mm was used as coarse aggregate and natural river sand conforming to zone-I according to IS 383-2002 (ref. 17) was used as fine aggregate. Average 7-days and 28-days compressive strength obtained for all specimens was 20 and 32 MPa respectively, according to IS 516-1959 (ref. 18).

Cylindrical specimens (60 mm diameter and 100 mm height) with concentric steel rebar of length 105 mm were used for the testing. The steel bar was drilled and threaded at one end to accommodate the threaded copper screw for electrical connections before casting. The bar was then cleaned with a wire brush to remove surface scales, if any. To protect the top (55 mm) and bottom (10 mm) portions of the rebar from corrosion, epoxy resin (Dobeckot 505C epoxy resin with Hardener EH 411) was applied. The remaining middle portion of 40 mm was subjected to accelerated corrosion (Figure 1). After allowing the epoxy to harden for 24 h, the weight of reinforcing bar was recorded to an accuracy of 0.1 g. After casting, all the specimens were cured for 7-days at a temperature of 27° ± 2°C and relative humidity of 100%. The specimens were immersed in 5% NaCl solution on the eighth day for 24 h to ensure full saturation of the test specimens. The accelerated corrosion process was initiated from the ninth day based on the earlier work done by Patil *et al.*[13].

Corrosion is generally a slow process and it takes many years for the first crack to appear on the surface of rein-

forced concrete (RC). It is normal practice to adopt the acceleration technique in the laboratory study of corrosion processes. Researchers have used various methods such as admixed chloride diffusion[3,7], alternate dry–wet test[8] or impressed current technique[4,10,19,20] to achieve the test results within a short duration. The impressed current technique is gaining popularity since the last two decades because of the advantages of achieving a high degree of corrosion within a short period of time and the ease of control on the degree of corrosion achieved[21]. In the present study, a constant voltage of 3 V was impressed between steel rebar and stainless steel (SS) mesh as described by Patil *et al.*[13]. As the voltage is impressed in steel embedded in concrete and AE sensors are mounted on the concrete surface, the applied voltage does not affect AE acquisition. Further, admixed chloride exposure was used to validate the application of the developed mathematical model. The method of alternate drying and wetting of specimen in salt water is not used as liquid absorption during wetting process and capillary action during drying process in concrete develop noise in AE data acquisition, which was observed during trial experiments on alternate dry–wet process.

The rebar corrosion was monitored by AE technique and a well-established electrochemical technique, i.e. Tafel extrapolation technique. AE measurements were taken continuously till the conclusion of the test, whereas Tafel plots were obtained periodically (whenever the change in colour of NaCl solution was observed, which indicated corrosion activity). The instrumentation for AE consisted of a sensor, a preamplifier and an acquisition device (Physical Acoustic Corporation, India). A single AE sensor (30 kHz resonant-type sensor having operating range 25–530 kHz) was attached to each specimen at the top periphery of the concrete surface with the help of a highly viscous coupling agent and an electric tape. The sensor was placed away from the zone of active corrosion (which is near the central portion of the cylinder where uncoated part of rebar is located). To decide the threshold
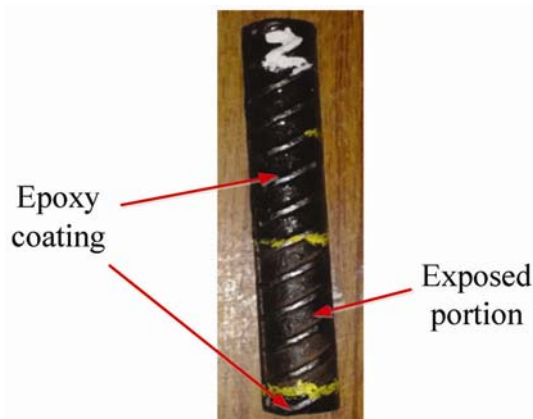

Figure 1. Preconditioned steel specimen.

and ensure that emission due to liquid absorption and related noise is not present, AE monitoring of specimens was conducted on the eighth day during saturation of specimen in NaCl solution. Based on this, the threshold applied for all AE measurements was decided as 40 dB. The potential was then applied and the specimens were continuously monitored for AE activity. Figure 2 presents a schematic diagram of the AE measurement system.

Potentiostat model 1.0 (Crest Technology) was used to obtain Tafel plots. The potentiostatic scans were carried out using steel rebar as a working electrode, stainless steel mesh as a counter electrode and saturated calomel electrode as a reference electrode with the scan rate of 0.5 mV/s in the potential range ± 1.0 V. Prior to the scans, DC supply was interrupted for half an hour. The testing was terminated when distinctly visible cracks were observed on the concrete surface. After completion of the tests, each sample was visually examined for cracks and then the cover to the rebar was carefully removed. Corrosion products from steel surface were gently removed with a wire brush. The bars were then weighed to determine the mass loss to a precision of 0.1 g.

All the specimens used for development of the mathematical model were monitored continuously for AE activity due to corrosion. Typical variation of CSS with time has already been discussed by Patil *et al.*[13]. The corrosion monitoring of specimens began on the ninth day of casting; it is known that the cement hydration process is not complete by that time. Therefore, it is necessary to discriminate between the AE signals associated with corrosion and the signals due to cement hydration which is an on-going process as concrete cures. To tackle this issue,
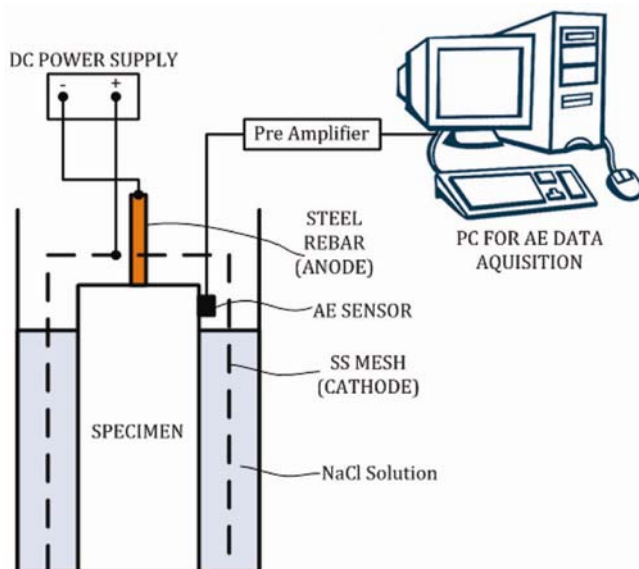
Figure 2. Schematic representation of acoustic emission (AE) measurement system.

concrete cylinder having the same dimensions but without steel reinforcement was cast and continuously monitored for AE activity. The typical variation of CSS with time for such specimens was clearly different from the AE activity recorded for specimens under active corrosion[13]. This further confirmed that CSS parameter of AE technique has the potential to detect rebar corrosion.

Table 1 presents the values of gravimetric mass loss, i_{corr} and maximum CSS obtained for each specimen at the conclusion of the test. Using these values, the effect of material variables on non-destructive data was examined and thereafter, the mathematical model to predict mass loss w.r.t. AE activity was developed. It is to be noted here that the variation in rebar diameter resulted in variation of concrete cover also, as the diameter of the concrete cylindrical specimen was kept constant. Since, this variation in concrete cover was small, i.e. 24, 22 and 20 mm for rebar diameters 12, 16 and 20 mm respectively, this effect is ignored in the present study.

To identify the significant factors affecting the measurements, analysis of variance (ANOVA) was performed as described in Kothari[22]. Under the null hypothesis that, all the data are drawn from populations with the same mean, that is the average of i_{corr} and maximum CSS values for all the three variables is the same. Table 2 reports the results of ANOVA at 99% significance level for i_{corr} and maximum CSS values.

It can be observed that the calculated *F*-values are lower than the corresponding tabulated *F*-values at 99% confidence level for all the variables with *P*-value greater than 0.01. This clearly indicates that there is not enough evidence to reject the null hypothesis. Thus, from the results of ANOVA it can be inferred that all material variables under the study, viz. cement type, steel type and rebar diameter are statistically insignificant and the difference in magnitudes of maximum CSS or i_{corr} is just a matter of chance. Based on these results, it can be concluded that, as the effect of material properties on AE measurements is not significant when the statistical tool is used, the mathematical relation can be developed using the experimental data with all these variables.

In order to establish a relation between mass loss and AE measurements, a graph of maximum CSS versus gravimetric mass loss was plotted. The nonlinear relation established between the two variables at coefficient of determination (R^2) of 0.805 (greater than 0.7) is

$$y = 10^6 e^{0.636x}, \tag{1}$$

where *y* is the maximum CSS and *x* the gravimetric mass loss.

It was observed that eq. (1) is analogous to the natural exponential growth model. To validate the coefficients of the equation and check the goodness of fit, nonlinear regression analysis was performed using the SOLVER function of Microsoft Excel. It uses an iterative nonlinear

Table 1. Test matrix and results

| Set | Material variables | | | Test duration (days) | Specimen | Gravimetric mass loss (g) | Final i_{corr} ($\mu A/cm^2$) | Maximum CSS (pV-sec) |
	Rebar diameter (mm)	Cement type	Steel type					
I	12	OPC	TMT	20	I-OT-12-1	2.61	19.88	8.04×10^6
					I-OT-12-2	3.53	26.27	7.49×10^7
					I-OT-12-3	5.68	38.95	3.48×10^7
II	16	OPC	TMT	12	I-OT-16-1	*	*	*
					I-OT-16-2	3.18	31.98	1.82×10^7
					I-OT-16-3	3.63	36.80	1.39×10^7
III	20	OPC	TMT	20	I-OT-20-1	12.38	27.72	1.18×10^{10}
					I-OT-20-2	11.78	47.64	1.37×10^{10}
					I-OT-20-3	14.98	31.69	3.90×10^9
IV	20	PPC	TMT	35	I-PT-20-1	4.78	24.21	1.29×10^7
					I-PT-20-2	8.62	25.47	2.73×10^7
					I-PT-20-3	7.59	23.98	1.17×10^8
V	20	OPC	CRS	20	I-OC-20-1	5.52	43.85	2.64×10^7
					I-OC-20-2	5.91	41.21	2.70×10^7
					I-OC-20-3	4.29	32.61	6.00×10^6

*Erroneous data. CSS, Cumulative signal strength.

Table 2. ANOVA results for i_{corr} and maximum CSS values

Parameter under study	Source	Level	Degree of freedom	Sum of squares	Mean squares	F-ratio	F from Fisher's distribution (99% probability)	P-value
i_{corr}	Cement type	2	1	185.81	185.81	3.32	21.19	0.14
	Steel type	2	1	18.79	18.79	0.25	21.19	0.63
	Rebar diameter (mm)	3	2	82.06	41.03	0.50	10.92	0.62
Maximum CSS	Cement type	2	1	4.50e19	4.50e19	2.79	21.19	0.17
	Steel type	2	1	4.55e19	4.55e19	2.82	21.19	0.16
	Rebar diameter (mm)	3	2	4.55e19	2.27e19	1.09	10.92	0.39
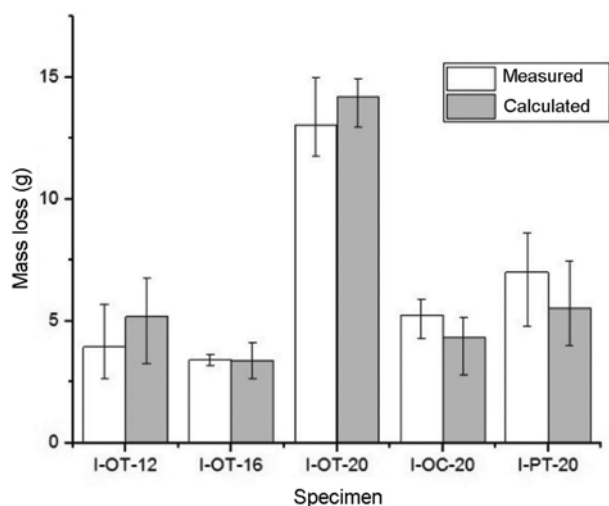
Figure 3. Comparison of measured and calculated mass loss using AE technique.

least squares fitting method which minimizes the value of the squared sum of the difference between data and fit. The refined model developed using SOLVER is

$$y = 1.05 \times 10^6 e^{0.711x}, \tag{2}$$

where y is the maximum CSS and x the gravimetric mass loss.

Hence it is concluded that mass loss can be correlated to the non-destructive AE parameter (maximum CSS) using the relationship

$$\text{Gravimetric mass loss} = (1.407 \times \ln \text{CSS}) - 5.429. \tag{3}$$

The mass loss obtained from eq. (3) was compared with the actual mass loss (Figure 3). It can be seen from the figure that the predicted (calculated) mass loss is comparable with the gravimetric (measured) mass loss. Once the mass loss is obtained, the corrosion rate can be calculated using ASTM G1-03 (ref. 23).

The mathematical model reported in eq. (3) was developed under accelerated corrosion condition using impressed current technique. To check the applicability of this model for natural corrosion exposure conditions, the faithful simulation of corrosion by subjecting the specimens for a relatively long duration is required. Hence it was decided to use admixed chloride exposure condition.

Table 3. Test matrix for admixed chloride exposure

Cement type	Steel type	Rebar diameter (mm)	Nomenclature	Repetition	Test duration (days)
OPC	TMT	12	A-OT-12	1	142
OPC	TMT	16	A-OT-16	1	142
OPC	TMT	20	A-OT-20	1	142
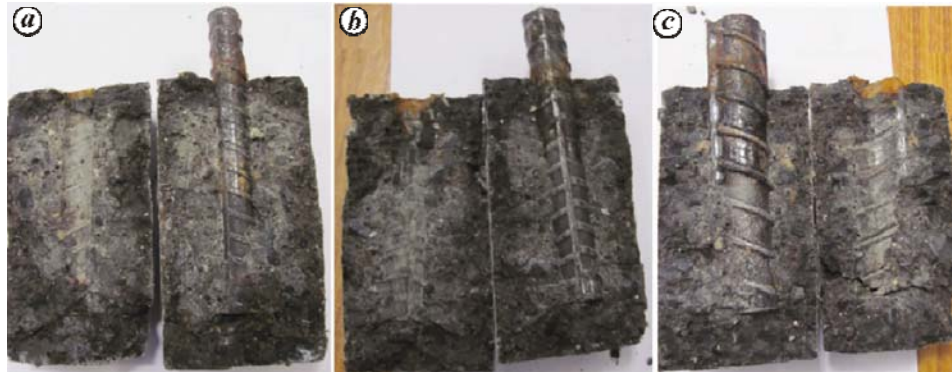
Figure 4. Condition of specimen after testing under admixed chloride exposure: *a*, A-OT-12; *b*, A-OT-16; *c*, A-OT-20.
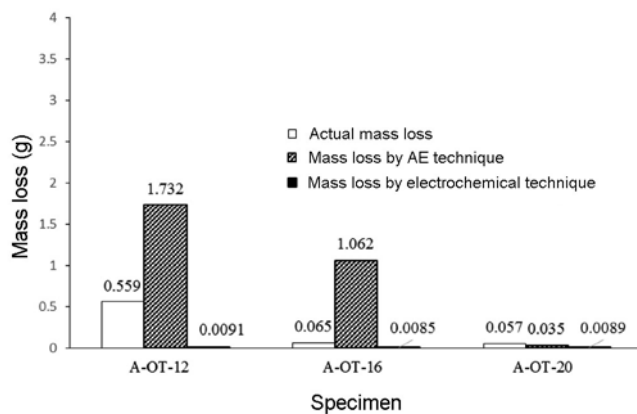
Figure 5. Comparative plot of mass loss by gravimetric, electrochemical and AE technique for admixed chloride exposure.

In this exposure condition, concrete was admixed with 5% NaCl during casting of specimens. These specimens were cured for a period of 7 days and then immersed in 5% NaCl solution for a period of 142 days to further accelerate the corrosion process. The specimens were monitored continuously during this period using AE technique for corrosion activity and periodically using electrochemical technique (Tafel extrapolation technique). For all the specimens of this test, the testing was terminated when the corrosion products oozed out from the steel–concrete interface. The test duration was shorter in impressed current technique (ranged from 12 days to 35 days). Therefore, more number of samples could be cast to check the reproducibility of the data, whereas the corrosion process during admixed chloride exposure con-

dition was prolonged (142 days) and hence one specimen was cast for each rebar diameter using OPC cement and TMT steel type. Table 3 shows the typical test matrix adopted.

After testing, all the specimens were broken and gravimetrical mass loss was measured. Figure 4 shows the condition of the specimen after breaking.

The maximum CSS values recorded for the specimens of admixed chloride exposure were used further to calculate the mass loss using eq. (3). Figure 5 shows the comparative plot of gravimetric mass loss, mass loss calculated using electrochemical technique and mass loss calculated using the developed mathematical model established by AE technique.

As the corrosion under admixed chloride exposure is slow, the specimens show little mass loss (Figure 5). It is also observed that the mass loss predicted by the developed model using AE parameter is comparable to or on the conservative side of the actual mass loss. For the first two specimens, the mass loss predicted by AE technique was higher than the actual mass loss which is on the conservative side. In comparison to this, the mass loss calculated by electrochemical technique was much less than the actual mass loss values. For the third specimen, the actual mass loss was very low and comparable to the value predicted by the developed model and the electrochemical technique. Thus, it can be concluded that it is possible to predict the mass loss using the developed mathematical model by AE technique for realistic prolonged corrosion exposure conditions.

Under the conditions presented in this work, AE was found to be a reliable laboratory method to evaluate

corrosion in a variety of concentrically reinforced concrete cylindrical specimens. There is an evidence of scatter which is inherent due to heterogeneity of concrete used for various specimens which will result in variation in the extent of cracking. This will naturally affect the corrosion process and hence will be reflected in the AE measurements. Despite these limitations, interesting results have emerged in an area where very little research has been published. The following conclusions can be drawn from the present experimental work:

1. The study suggests that maximum CSS value of AE waveform is a useful parameter to study the corrosion activity quantitatively in concentrically reinforced concrete cylindrical specimens under accelerated corrosion.

2. The results of ANOVA indicate that the variables, viz. rebar diameter, cement type and steel type are statistically insignificant and the difference in magnitudes of maximum CSS is only a matter of chance.

3. The similarity in results of ANOVA obtained for magnitudes of i_{corr} and maximum CSS values by AE measurements satisfactorily validates the results of the AE technique with respect to the well-established electrochemical technique.

4. The result of nonlinear regression analysis proves significant relation between maximum CSS values and gravimetrical mass loss.

5. A nonlinear relationship between gravimetrical mass loss and maximum CSS values for all specimens, which is analogous to natural exponential growth function, demonstrates the ability of the AE technique to quantify corrosion. The proposed model predicts fairly well the corrosion activity under realistic prolonged corrosion condition.

The mathematical relation established between maximum CSS and gravimetrical mass loss as presented here is obtained through laboratory experiments under specific conditions of accelerated corrosion by impressed current technique and for specific shape and size of concentrically reinforced concrete cylindrical specimens. To obtain a generalized relation applicable for real exposure conditions, it is intended to extend the research further to apply the AE technique for corrosion monitoring of real-life structural elements, which consists of multiple rebars in concrete with variation in concrete cover and subjected to different stresses. The location of sensors in these cases will be decided based on analytical examination of the structure and on the basis of stress–strain contours (or half-cell potential contours) generated.

1. Di Benedetti, M., Loreto, G., Matta, F. and Nanni, A., Acoustic emission monitoring of reinforced concrete under accelerated corrosion. *J. Mater. Civ. Eng.*, 2013, **25**(8), 1022–1029.
2. Song, H. and Saraswathy, V., Corrosion monitoring of reinforced concrete structures – a review. *Int. J. Electrochem. Sci.*, 2007, **2**, 1–28.
3. Pradhan, B. and Bhattacharjee, B., Half-cell potential as an indicator of chloride-induced rebar corrosion initiation in RC. *J. Mater. Civ. Eng.*, 2009, **21**(10), 543–552.
4. Yoon, D., Weiss, W. and Shah, S. P., Assessing damage in corroded reinforced concrete using acoustic emission. *J. Eng. Mech.*, 2000, **126**(3), 273–282.
5. Vinogradova, A. and Lazareva, A., Continuous acoustic emission during intermittent plastic flow in a brass. *Scr. Mater.*, 2012, **66**, 745–748.
6. Ing, M., Austin, S. and Lyons, R., Cover zone properties influencing acoustic emission due to corrosion. *Cem. Conr. Res.*, 2005, **35**, 284–295.
7. Ohtsu, M. and Tomoda, Y., Phenomenological model of corrosion process in reinforced concrete identified by acoustic emission. *ACI Mater. J.*, 2008, **10**, 5194–5199.
8. Kawasaki, Y., Tomoda, Y. and Ohtsu, M., AE monitoring of corrosion process in cyclic wet–dry test. *Constr. Build. Mater.*, 2010, **24**(12), 2353–2357.
9. Kawasaki, Y., Wakuda, T., Kobarai, T. and Ohtsu, M., Corrosion mechanisms in reinforced concrete by acoustic emission. *Constr. Build. Mater.*, 2013, **48**, 1240–1247.
10. Idrissi, H. and Limam, A., Study and characterization by acoustic emission and electrochemical measurements of concrete deterioration caused by reinforcement steel corrosion. *NDT&E Int.*, 2003, **36**, 563–569.
11. ASTM. E1316, Standard terminology for non-destructive examinations. ASTM International, Pennsylvania, USA, 2010.
12. Noorsuhada, M. N., Azmi, I., Norazura, M. B., Shahiron, S. and Soffian, N. S., Relationship between acoustic emission signal strength and damage evaluation of reinforced concrete structure: case studies. In IEEE Symposium and Industrial Electronics and Applications, Langkawi, Malaysia, 2011, pp. 308–313.
13. Patil, S., Karkare, B. and Goyal, S., Acoustic emission vis-à-vis electrochemical techniques for corrosion monitoring of reinforced concrete element. *Constr. Build. Mater.*, 2014, **68**, 326–332.
14. IS 12269-1999. Specification for 53 grade Ordinary Portland Cement. Bureau of Indian Standards, New Delhi, 1999.
15. IS 1489 (Part I)-1991, Portland Pozzolana Cement specification, Bureau of Indian Standards, New Delhi, 1991.
16. IS 10262-2009, Concrete mix proportioning – guidelines. Bureau of Indian Standards, New Delhi, 2009.
17. IS 383-2002, Specification for coarse and fine aggregates from natural sources for concrete, Bureau of Indian Standards, New Delhi, 2002.
18. IS 516-1959, Methods tests for strength of concrete. Bureau of Indian Standards, New Delhi, 1959.
19. Gadve, S., Mukherjee, A. and Malhotra, S. N., Corrosion of steel reinforcements in FRP wrapped concrete. *Constr. Build. Mater.*, 2009, **23**, 153–161.
20. Caré, S. and Raharinaivo, A., Influence of impressed current on the initiation of damage in reinforced mortar due to corrosion of embedded steel. *Cem. Conr. Res.*, 2007, **37**, 1598–1612.
21. Yuan, Y., Ji, Y. and Shah, S. P., Comparison of two accelerated corrosion techniques for concrete structures. *ACI Struct. J.*, 2007, **104**(3), 344–347.
22. Kothari, C. R., *Research Methodology – Methods and Techniques*, New Age International Publishers, New Delhi, 2004, 2nd edn.
23. ASTM G1-03, Standard practice for preparing, cleaning, and evaluating corrosion test specimens. ASTM International, Pennsylvania, USA, 2003.