Assessment of integrity of reinforced concrete structures using “Relaxation ratio” analysis of acoustic emissions

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Abstract

A parallel between seismic waves related to an earthquake and acoustic emissions (AE) released during fracture process in reinforced concrete (RC) beams under flexural loading was observed and Colombo et al. (2005) proposed Relaxation ratio” parameter. Relaxation ratio (RR) is the ratio between average energy released during unloading to the average energy released during loading. In this present study RC flanged beam specimens of span 2.6 m were tested under incremental cyclic loading and simultaneously the released AE was recorded. The influence of change in rate of loading on the results related to relaxation ratio analysis of RCflanged beam specimens were discussed. RR parameter is sensitive to the rate of loading applied on RC members. Also the RR results were compared with the NDIS assessment chart recommended by JSNDI. Relaxation ratio analysis is useful to assess the current state of damage in RC structures *in-situ.*
Keywords: Reinforced concrete; Acoustic emission; Damage; Structural condition monitoring

1.Introduction

In India, during the past 60-70 years several RC structures were constructed. It is essential to maintain these RC structures and keep in useful condition. Because deteriorationis a natural phenomenonand deterioration of these RC structures has started exhibiting in large number of RC structures, a systematic approach is needed in dealing with such problems.Nondestructive evaluation (NDE) of in-service RC structures is required to monitor the ongoing fracture or location of a crack[1]. This study examines the feasibility of relaxation ratio analysis of RC structures without obstructing their usage.Influence of rate of loading on RC structural members is studied to broaden the applicability to RC structures.

1.1 Relaxation ratio analysis

It is known that an earthquake is a sudden movement caused by the release of elastic energy stored in the earth’s crust and causes vibrations that propagate outward from the source as seismic waves. Analogous to this event, a similar phenomenon but on a different scale is the release of acoustic emissions (AE) during fracture process in solids under force [1].The AE released during fracture in solids is similar to the seismic waves released during an earthquake where seismic waves reach the monitoring stations placed on the surface of the earth. In both cases, there is a release of elastic energy from sources located inside a medium. Therefore,occurrence of seismic waves related to an earthquake and AE released in solids under force have similarities [2-3].

An earthquake ground motion consists of three phases, viz., main shock followed by foreshocks and aftershocks. After-shocks begin in surrounding area of main shock and thus after-shocks relax the stress concentration caused by the main shock.A parallel was drawn with sequences of seismic waves related to an earthquake (or with the three phases of earthquake ground motion) and AE released during fracture process in RC beams under incremental cyclic force and Colombo et al. (2005a, 2005b) proposed a parameter ‘relaxation ratio’ and subsequently the current status of damage in RC beam specimens (with rectangular cross section) was studied in laboratory [2-3].

$$Relaxation\ ratio\ (RR) = \frac{\text{Average energy released during unloading}}{\text{Average energy released during loading}} \quad (1)$$

Average energy released during loading is equal to the ratio between cumulative AE energy recorded during loading to the total number of hits recorded during loading. Similarly, average energy released during unloading is equal to the ratio between cumulative AE energy recorded during unloading to the total number of hits recorded during unloading. In case RR is greater than 1.0, the relaxation is dominant and is less than 1.0when loading is dominant[2-3].

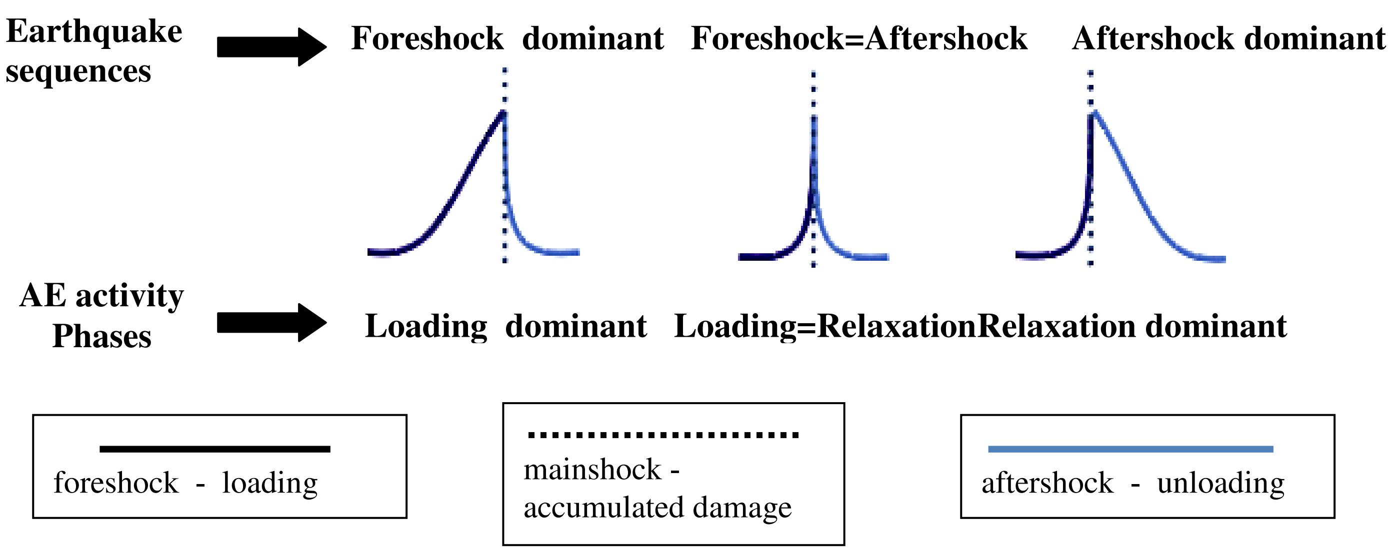

Fig.1 Schematic representation of earthquake sequences and AE activity phases [2-3].

2. Experimental program

2.1 Materials and test specimens

RC flanged beam specimens were tested and the geometry, concrete mixture and steel reinforcement details are given in Table 1 and in the same table *Ø* is nominal diameter of tensile reinforcement; *n* is number of tensile reinforcement bars; A_s is area of reinforcement; *L* is the flanged beam length; *S* is span of the flanged beam; b_w is flanged beam rib (or web) width; *D* is beam overall depth. Each specimen was loaded at mid-span and simply supported over a span *S*. Two-point loading span was 1 m with 2.6 m supporting-span. The test setup was shown in Fig.1.

Table 1. Geometric details of the RC flanged beams specimens

Specimen	Ø (mm)	*n*	A_s (mm^2)	*S* (mm)	Concrete mixture grade (N/mm^2)	*L* (mm)	W_f (mm)	*D* (mm)	b_w (mm)	d_w (mm)	Failure type	Rate of loading (kN/s)
LC2M37	20	4	1256	2600	37	3210	500	560	180	380	Flexural	4
LLR2	20	4	1256	2600	37	3210	500	560	180	380	Flexural	5
LLR1	20	4	1256	2600	37	3210	500	560	180	380	Flexural	6

2.2 Experimental arrangement

The experimental setup consisted of a servo hydraulic loading frame (1200 kN) with a data acquisition system and the AE monitoring system.The released AE signals were recorded simultaneously using a 8 channel AE monitoring system. The data acquisition records load, displacement at center of the flanged beam, strain in the steel at the center (mid-span) of the RC flanged beam and time. Resonant type AE differential sensors, preamplifiers, data acquisition system and processing instrumentation were used. The AE sensor has peak sensitivity at 75 dB with reference to 1 V/(m/s) [1 V/mbar]. The operating frequency of the sensor was 35 kHz-100 kHz. The used differential sensor had a good sensitivity and frequency response over the range of 35-100 kHz. The AE signals were amplified with a gain of 40 dB in preamplifier.

2.3 Loading procedure

ACI 437-12 proposed the cyclic load test (CLT) as a usual procedure for damage assessment of structural behavior of RC members and by following the same guidelines the loading pattern was applied on the RC flanged beam specimen (assumed as a RC girder in a bridge) as shown in Fig. 3a. The RC beam specimen is subjected to loading protocol which has two types of pattern. A series of service level load cycles are applied in between the load cycles of test trucks (TTs). These test trucks were chosen to represent the case of structural load testing in the *in-situ*. TTs were variable in loading magnitude. The smaller load repetitions are indicative of service level loads. From Fig. 3 one can observe that a series of TTs were repeated and the reason is to study the effect of loading repetitions on the AE response. The first phase of loading pattern has load intensity with relatively less peak and constitutes transport vehicle (TV) effect. The second pattern has higher peak load which constitutes elevated simulated test truck (ESTT). The two patterns together give single loading phase. Each loading phase has varying peak loads as shown in Fig. 3.

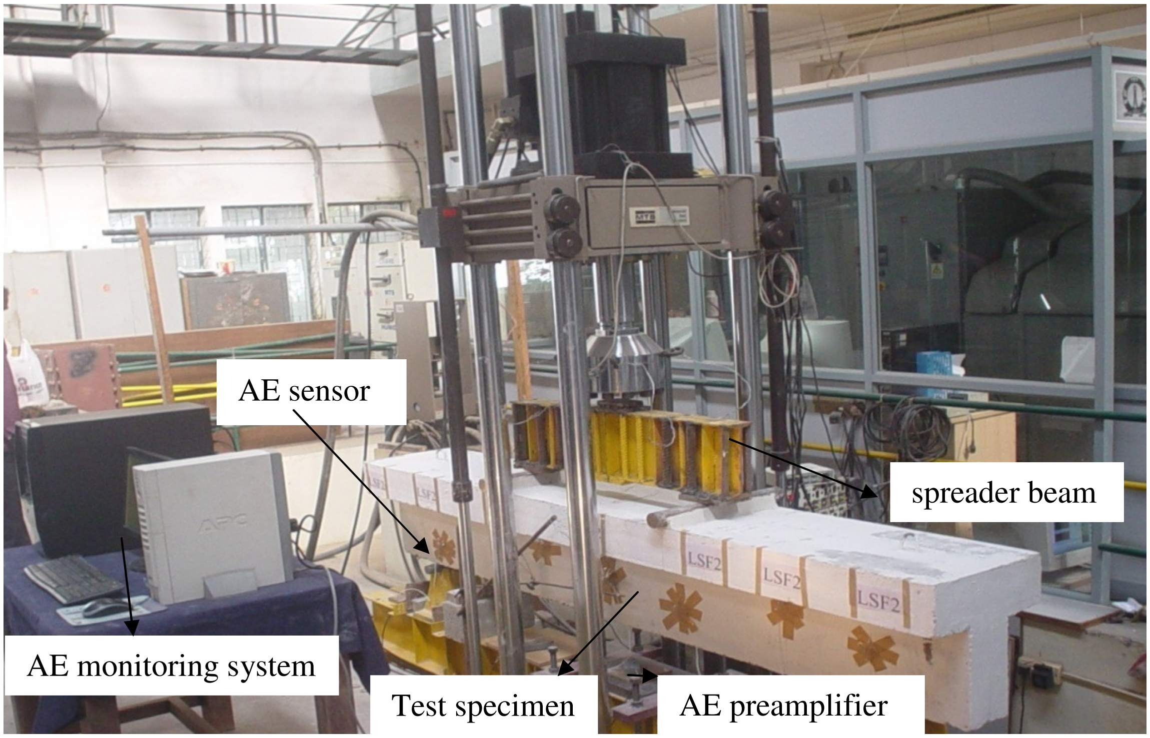

Fig. 2. RC beam test specimen instrumented with AE sensors for fracture monitoring in the test rig, Structures laboratory, Department of Civil Engineering, Indian Institute of Science, Bangalore, India

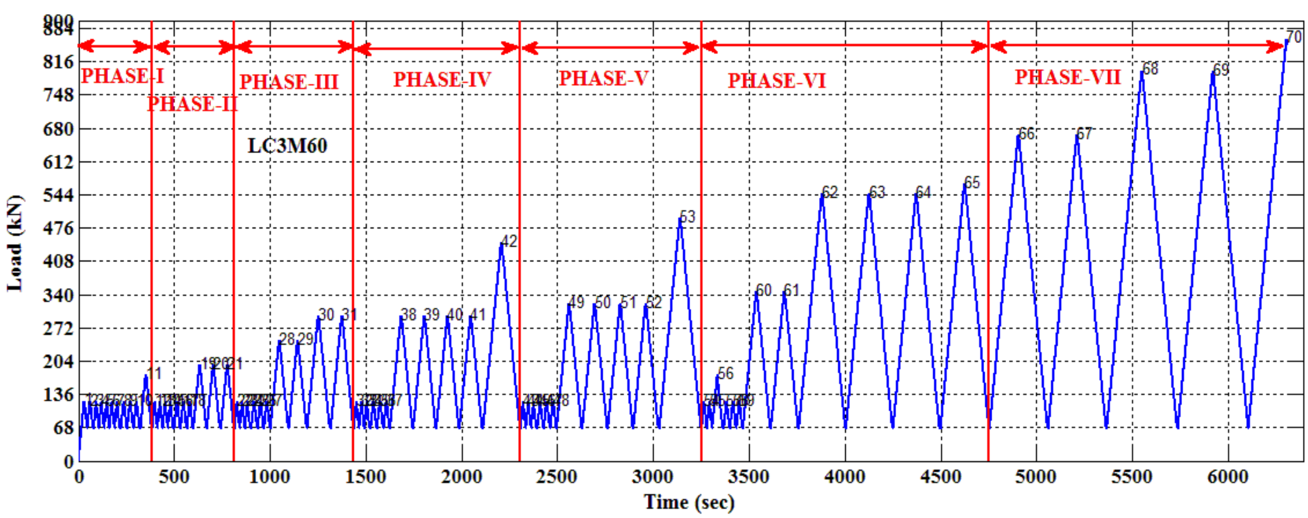

Fig. 3. Loading protocol applied to LC3M60 specimen

3. Results and discussion

Relaxation ratio values are computed based on Eq.(1) for all the test specimen.Relaxation ratio versus loading cycle number plot is divided into two phases with a dotted horizontal line at relaxation ratio equals to 1.0. The two phases are *loading dominant* when RR is less than 1.0 and *relaxation dominant* when RR is greater than 1.0. The RR value present in loading dominant area occurred when AE energy recorded during loading phase is greater than the AE energy recorded during unloading phase. Because, loading phase with higher peak loads repeated as shown in Fig.3 the relaxation ratio values does not show a clear pattern.During initial loading cycles, when the cracks were developing there was a dominance of primary AE activity (new cracks are forming during loading) and after certain loading cycles though peak loads are relatively less than the previous loading cycle the secondary AE activity (due to friction between two fractured surfaces) is prevailed in the relaxation phase. The reason could be the repetition of loading. When the new cracks are formed there is a dominance of primary AE activity and once the fracture process progresses further the secondary AE activity prevails in the relaxation dominant. 'Kaiser effect' was not observed for the loading cycle that immediately followed the loading cycles for which peak load has not exceeded the maximum of previous peak loads. A typical relaxation ratio results were shown in Fig.5.

From Fig.5a it can be observed that the loading cycles for which peak load exceeds the maximum of previous peak loading cycles relaxation ratio is much less than 1.0. The reason could be during these loading cycles, new cracks appeared in loading phase. There are more acoustic emissions recorded as compared to that in unloading phase leading to relaxation ratio being less than 1.0. But, for the loading cycles that immediately follow these cycles, there was very little AE released while in loading phase as compared to unloading case because of the absence of Kaiser effect phenomenon. While unloading, there was relatively more AE released due to friction between cracked surfaces as the existing cracks tried to close. Relaxation ratio for these cycles was more than the previous cycle. An irregular wave like trend in the plotted points was observed in relaxation ratio verses loading cycle graph as shown in Fig.5. AE activity during the unloading is generally an indication of structural deterioration.

From Fig.5, it is observed that initially the loading phase is dominant and the relaxation ratio values remains less than 1.0. During initial stages of the loading the AE energy recorded during the unloading is very limited. The release of AE energy increases in the unloading phase when the test specimen is approaching to failure. The percentage value indicated in Fig.5 refers to the load (P) at the instant RR value shifts from the loading phase to the relaxation phase to the collapse load ($P_{collapse}$). In other words, the percentage value indicating indicates load P as a percentage of collapse load. For all the specimens, load cycle 43 entered into the relaxation dominant part. The reason could be the applied loading was same for all the specimens and the specimens behaved similar till loading cycle number 43 where major cracks appeared. But, after this instant the fracture process was dependent on concrete compressive strength, loading rate, percentage of steel, shear reinforcement and geometry of the test specimen.

An increase in the rate of loading causes low recorded values for the time of collapse, displacement at collapse and maximum strain. The loading rate had influenced the AE released. In case of low rate of loading, there is a sufficient time for the damage to grow and is less scope of microcracks to develop and also less chances of spreading the micocracks fast. The recorded AE hits were less when the rate of loading is high as shown in Table 2. The first crack appeared at higher load when the rate of loading is less. Fig. 5 shows the relaxation ratio results for the RC beams tested with loading rate of 4 kN/s, 5 kN/s and 6 kN/s. Fig.6 shows the NDIS assessment chart for the specimen tested with different loading rates [4]. The AE released was affected by the rate of loading. Loading cycle 52, 43 and 35 entered into heavy damage zone for specimens tested 4 kN/s, 5 kN/s and 6 kN/s respectively. It was observed that when the loading rate is high the specimens were damaged quickly.

Table 2. Recorded downward displacement, strain in steel at mid-span and AE parameters for the RC specimens with different rate of loadings
(NOTE: Values in parenthesis is for loading cycle which crossed RR=1.0 line in relaxation ratio plot)

	LC2M37	LLR3	LLR1
Rate of loading (kN/s)	4	5	6
Total number of loading cycles applied	70	57	57
Load at collapse, $P_{collapse}$ (kN)	809	797	792
Average loading rate (kN/s)	3.66	4.43	5.20
Loading cycle entering in heavy damage zone as well as RR=1.0 line	52	43	35
Loading cycle above RR equal to1.0 line	43	43	43
Load with respect to collapse load for loading cycle entering in heavy damage zone as well as above RR=1.0 line (%)	39.92 (55.37)	55.95	37.37 (56.18)
Residual deflection for loading cycle entering in heavy damage zone as well as above RR=1.0 line (mm)	3.90 (3.40)	3.22	3.65
Strain in steel for loading cycle entering in heavy damage zone as well as above RR=1.0 line	0.00322 (0.00360)	0.00308	0.000765 (0.00085 0)
Residual deflection just before failure (mm)	5.05	6.22	5.46
Maximum strain before failure	0.00407	0.00384	0.00165
Deflection (for loading cycle entering in heavy damage zone as well as above RR=1.0 line) with respect to maximum deflection (%)	77.23 (67.33)	51.77	66.85 (70.15)
Strain (for loading cycle entering in heavy damage zone as well as above RR=1.0 line) with respect to maximum strain(%)	79.12 (88.45)	80.21	46.36 (51.51)
Deflection at collapse (mm)	16.4	15.8	16.0
Total AE energy recorded (v^2-s)	40,387,18 5	84,507,36 0	38,694,37 9
Total AE hits observed	124,9061	958,564	727,681
Duration of the experiment (minutes)	104.87	57.90	48.92

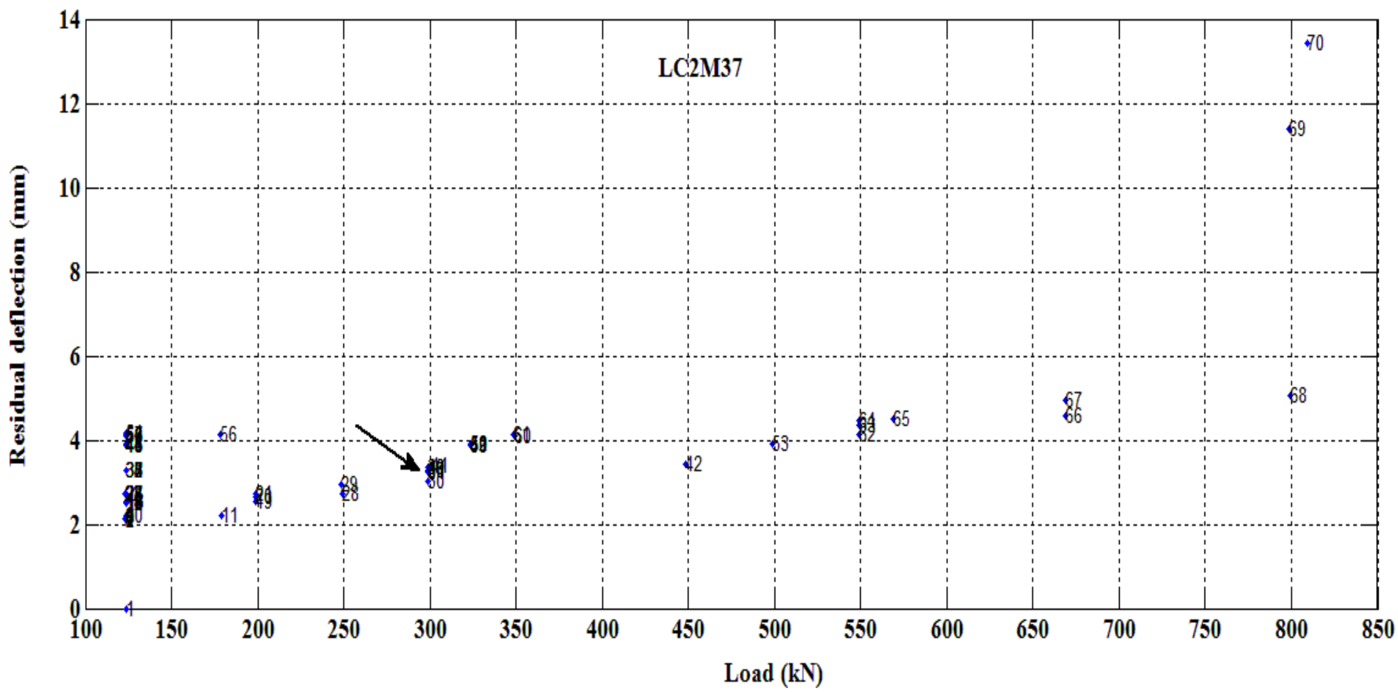

Fig.4 Residual displacement verses peak load plot (the arrow indicates the loading cycle where residual deformation is suddenly rising)

5. Conclusions

Based on the above experimental results the following major conclusions can be drawn.

1. The loading cycle which entered in the relaxation dominant region in the relaxation ratio plot is equal or close to the loading cycle which entered in the heavy damage zone in the NDIS assessment chart for most of the specimens.
2. The procedure for fixing the limits in NDIS assessment chart showed acceptable results in accordance with relaxation ratio plot. Therefore, load versus displacement plot can be used for fixing the limits if crack mouth opening displacement (CMOD) data is not available.

3. References:

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Fig. 5. Relaxation ratio results for the RC beam specimens tested with rate of loading (a) 4 kN/s (b) 5 kN/s (c) 6 kN/s

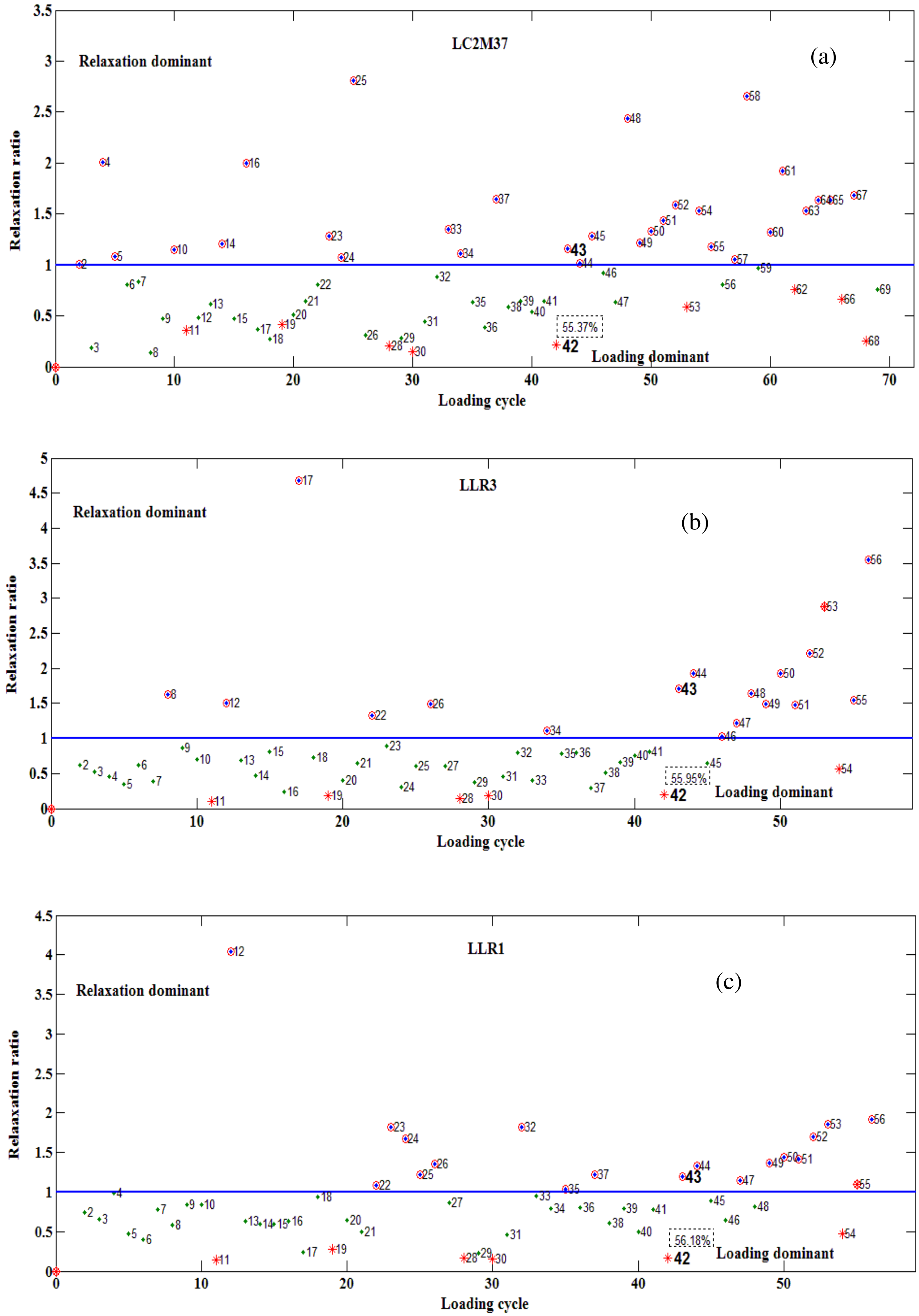

Fig. 6. Implementation of NDIS-2421 criterion to the AE data related to specimen tested with a rate of loading (a) 4 kN/s (b) 5 kN/s (c) 6 kN/s. [loading cycle 52, 43 and 35 entered into heavy damage zone for specimens tested 4 kN/s, 5 kN/s and 6 kN/s respectively].