EVALUATION OF DAMAGE EVOLUTION UNDER REPEATED LOADING OF POST-TENSIONED CONCRETE BEAMS BY ACOUSTIC EMISSION

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ABSTRACT
Recent collapses of bridges have demonstrated once again the need for reliable tools for an early monitoring of damage progression. Damages due to deterioration processes, overload, bad design, poor material quality, can grow subcritically until final collapse of the structure. AE method has been successful used for more than 20 years in industry for monitoring metal equipments (pipelines, pressure vessels, gas tanks, etc.) and the technology is quite mature. The application of the AE technique in the civil engineering requires however the overtaking of several problems related to structure complexity, material non homogeneity and the high attenuation factor for high frequency acoustic waves in concrete, environmental noise. A great effort was however done in the last ten years on data handling and data interpretation.

Aim of the paper was to develop monitoring procedures based on the collection and analysis of Acoustic Emission signal to be applied on prestressed concrete structures to evaluate damage progression due to deterioration or overloading. Laboratory experimentation included the fabrication of full scale post tensioned beams 6.3 meters long with partially grouted post tensioning ducts. Voids were filled with aggressive solution in order to promote strands corrosion or stress corrosion cracking.

Beams were then tested under increasing static load up to incipient failure. Different type of analysis methods of AE signal have been adopted and compared.

INTRODUCTION

The evaluation of damage degradation of post-tensioned structures require the use of new, but not yet well established, techniques such as those based on magnetic induction, while indirect techniques such as impact echo could locate grouting defects, but do not give any information about strand conditions.

Since the difficulties in accessing to strand anchorage and the impossibilities of re-tensioning strands themselves the evaluation of mechanical characteristics and performance of such structures could be indirectly estimated, for example, on the basis of a dynamic behaviour analysis, whose main limit is however the definition of the right theoretical model. AE technique seems to be very promising in this field since it is not invasive, allows a volume evaluation and at the same time has the possibility to locate discrete defects. AE was however introduced very recently in the field of health assessment of reinforced concrete structures notwithstanding some difficulties yet to be overcome in the field of data handling and analysis. Relationship between AE signal parameters and failure processes that produce these signals have in fact to be properly defined for example by means of the development of pattern recognition techniques. With the same aim, several health indexes as well as “Load ratio”, “Calm ratio”, “Felicity ratio” or “Historical index” have been adopted (Golaski et al., 2002; NDIS 2421, 2000). More recently other indexes have been proposed. Relaxation ratio analysis was introduced by Colombo et al. (2005a; 2005b). Relaxation ratio is defined as the ratio of the average energy during unloading phase to the average energy during loading phase. Considering that AE activity during the unloading process is generally an indication of structural instability (Ohtsu et al., 2002), a relaxation ratio greater than one (relaxation dominant) implies a defective structure.

A new index called the 'RTRI ratio' (ratio of Repeated Train load at the onset of AE activity to Relative maximum load for Inspection period) was proposed by Shiotani and co-workers (Shiotani et al., 2002; Luo et al., 2004) to overcome the difficult to estimate the maximum load that has been ever experienced by existing structures. This modifies the definition of 'Load ratio' by introducing the relative maximum load instead of the previous maximum one. Values of Calm ratio and RTRI higher than 0.5 and lower than 0.8 respectively identify, following the authors, a condition of high damage degree.

Aim of this work was to evaluated the reliability of the different global AE indexes proposed in literature to quantify growing damages in post-tensioned concrete structures.

EXPERIMENTS

A post-tensioned concrete beam was tested in a four point bending test (Figures 1, 3) with increasing loads. Due to the capacity limit of the couple of the hydraulic jack used, a higher section hydraulic jack in a three bending configuration was adopted to reach higher deflections (Figure 2). The beam had a length of 6.30 m and a cross section of 0.40x0.25 m. It was reinforced with four 18 mm steel bars and post tensioned with four 4-wire strands. The tendon was completely grouted with the exception of a small portion of 25 cm in the middle of the beam which was filled with an aggressive solution (NH_4SCN based solution) in order to promote stress corrosion cracking of the strands.

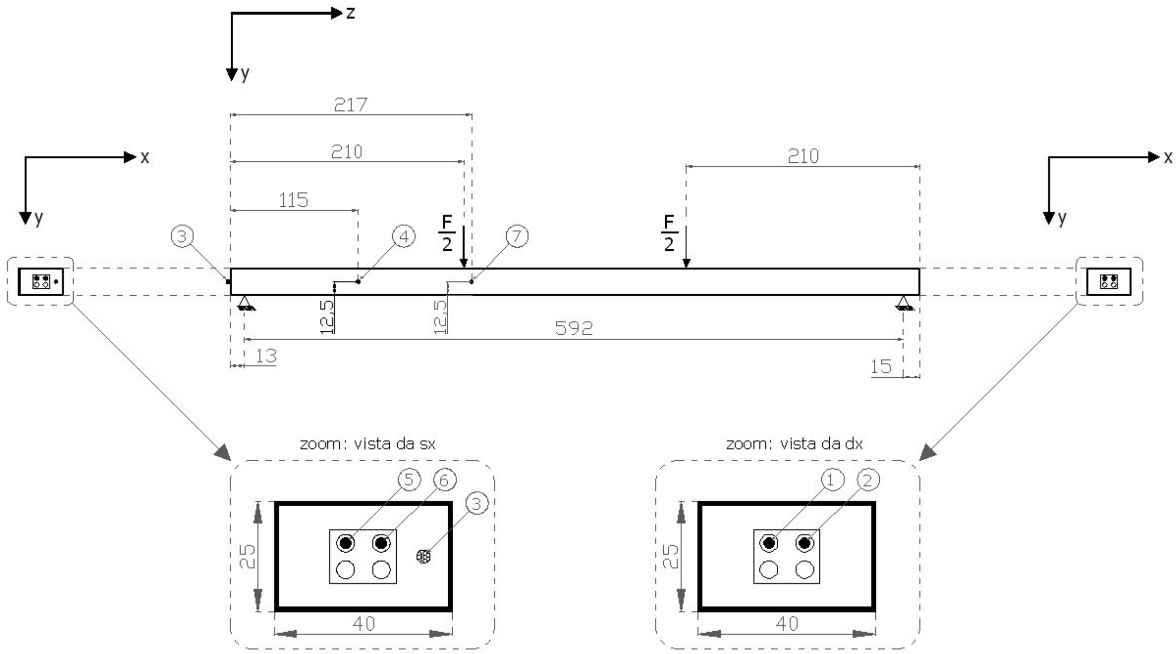

Figure 1. Side view and lateral view of the beam in the four point bending test condition. Circled numbers refer to sensor location.

AE signal were recorded by a ten-channel Vallen AMSYS-5 measurement system. The piezoelectric transducers for concrete were of type VS30-V with a flat response between 23-80 kHz. Threshold values after calibration were set at 44 dB. Some sensors were also positioned on steel wires and were of type VS150-M resonant at 150 kHz. Data from these sensors however have not been reported in this paper. Sensor location was evidenced in Figure 1 and 2. Load was applied using two (or one) hydraulic jacks and pressure was controlled with a manual oil pump (Figure 3) by step. Between each step load was kept constant for about 5 minutes. Load was calculated by the pressure at the oil pump. During loading deflection between the central point at the beam extrados and the equivalent point at the free end of the beam was measured. Three loading cycles were performed with increasing maximum load. In order to compare the four point and the three point loading condition the maximum bending moment was calculated and used instead of actual load (Figure 4).

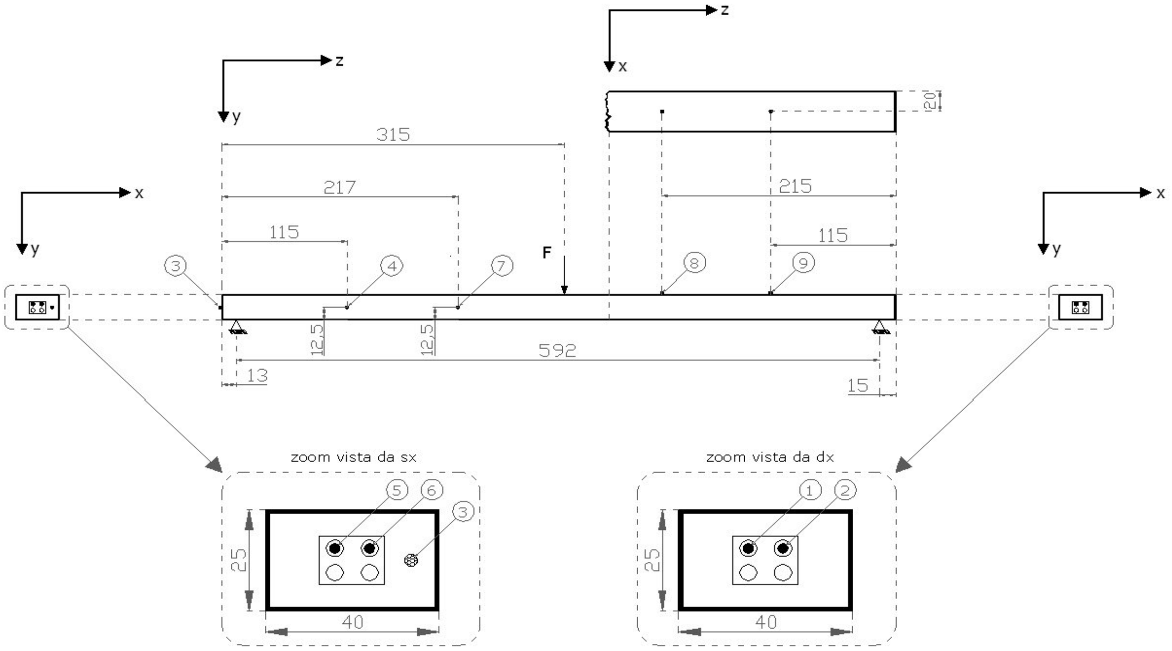

Figure 2. Side view and lateral view of the beam in the three point bending test condition. Circled numbers refer to sensor location.

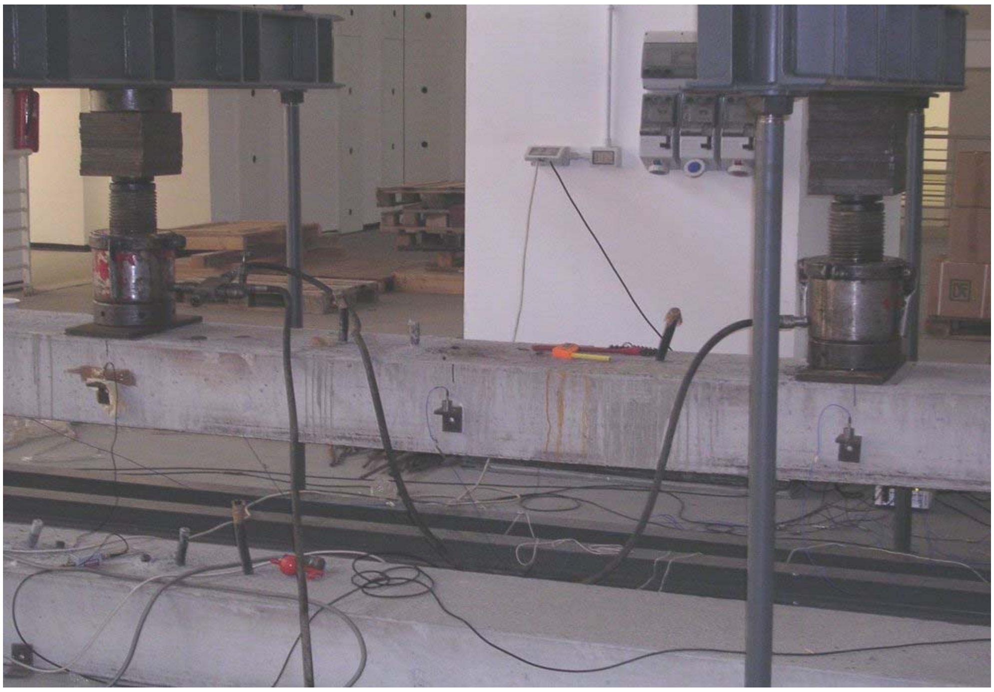

Figure 3. Four point bending test set-up

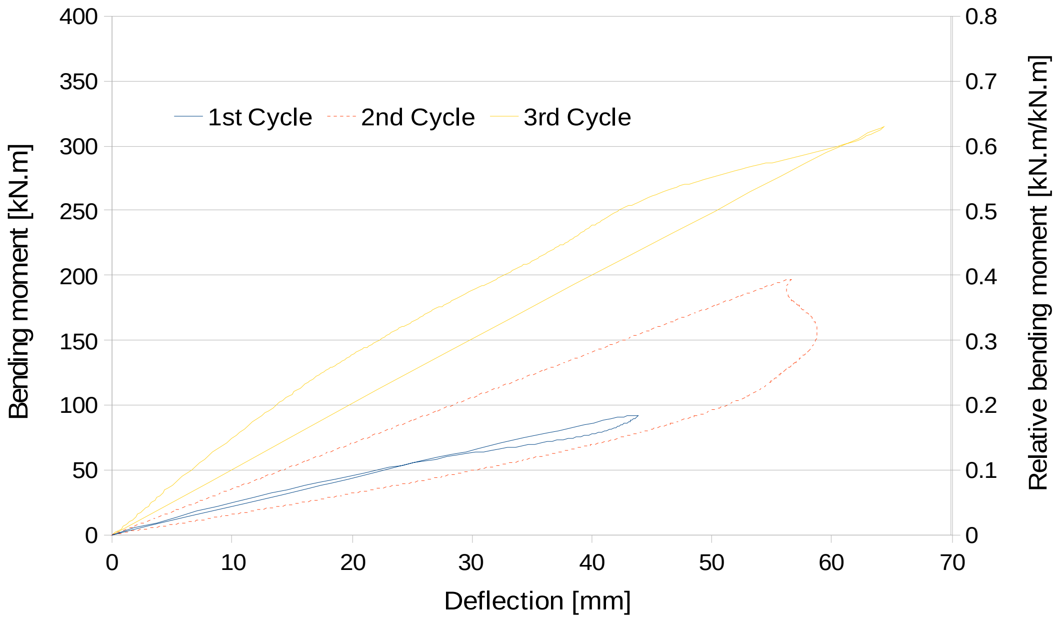

Figure 4. Bending moment vs deflection for the three loading cycles. Relative bending moment was calculated respect to the theoretical bending moment to failure

RESULTS AND DISCUSSION

AE emission during cycling or repeated loading of reinforced concrete structures could be due to different sources: crack opening and propagation or friction of existing crack surfaces which could occur during opening or closure of cracks (Luo et al., 2004). It means that in such structures damage accumulation could be related to a modification of the AE patterns. Such modification could be evidenced by the global health indexes proposed in the literature.

According to NDIS 2421 damage assessment could be evaluated by using two ratios: Load and Calm ratios. The Load ratio is the ratio of load at onset of AE activity to previous load whereas Calm ratio is the ratio of cumulative AE activity during unloading process to total AE activity during the last loading cycle. In this experimentation since maximum load was reached during a multi step ramp we defined and used "load-hold" Calm ratio in lieu of "unload" Calm ratio. For dividing the chart into zones of damage the crack mouth opening displacement (CMOD) value should be used. Since this information was not available, the limits of the chart used by Ohtsu et al.(2002) while testing reinforced concrete beam specimens were adopted, i.e. a value of 0.9 on the x-axis (Load ratio) and 0.05 in the y-axis (Calm ratio).

Data calculated from the different sensors during the three loading cycles are reported in Figure 5. It is possible to see that all points fall in the so called intermediate damage area (x>0.9, y>0.05) even if values from 1st cycle are more widely spread over the area whilst data from 3rd cycle are grouped near low calm ratio values.

The use of the new index called the 'RTRI ratio' slightly modify the result of previous chart better differentiating the three loading cycles (Figure 6). To calculate the RTRI values the ratio of the maximum bending moment with a certain load to maximum bending moment experienced during the whole experimentation was calculated. By considering the critical limits defined by Luo (Luo et al., 2004), i.e. values > 0.5 and < 0.8 for Calm ratio and RTRI respectively, it is possible to observe that all of the points relative to the first cycle loading fall in the area of high degree of damage, while for cycle two and in more extent for cycle three some points fall in the area of middle or low (lower right corner) damage degree. It seems therefore that the most of the damage was generated during the first loading cycle.

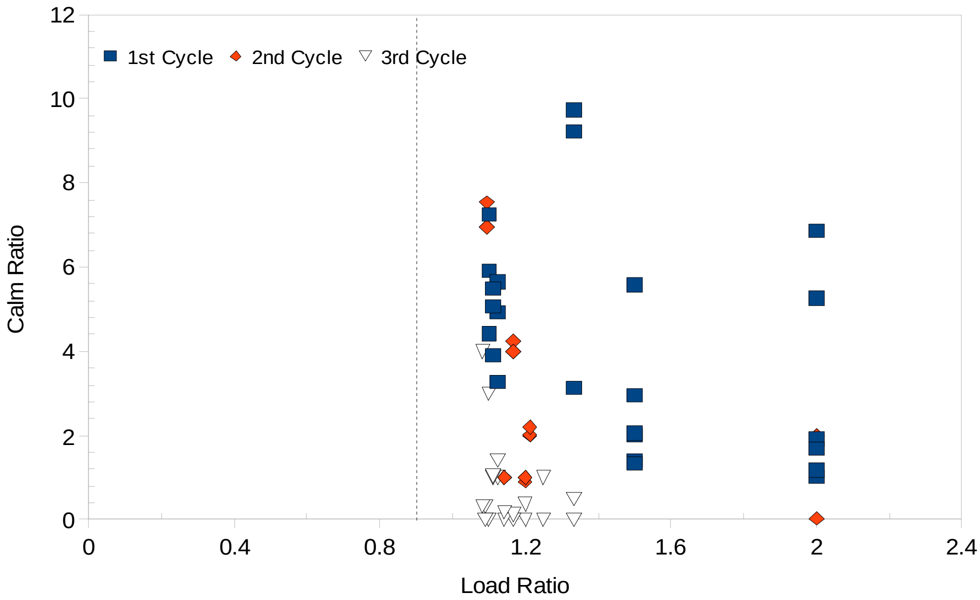

Figure 5. Calm ration vs Load ratio during loading cycles

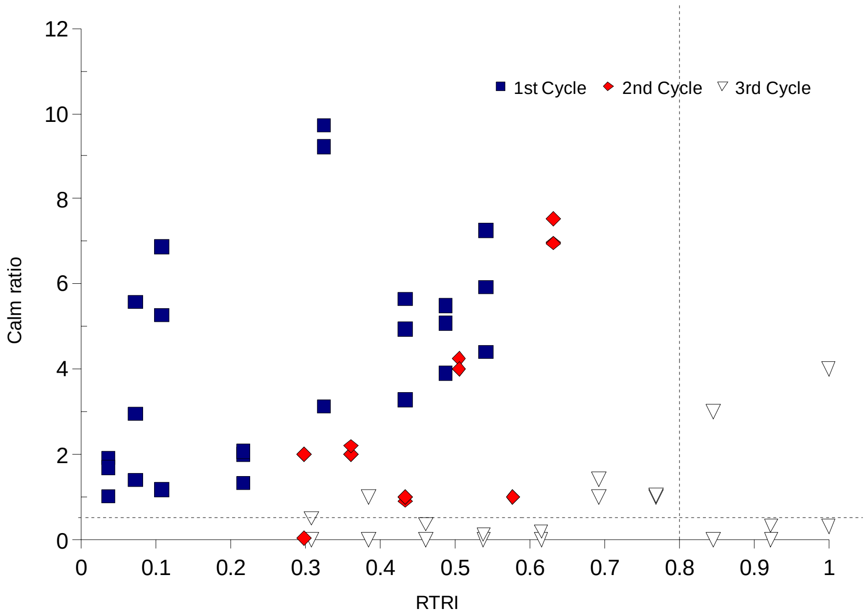

Figure 6. Calm ratio vs. RTRI ratio during loading cycles

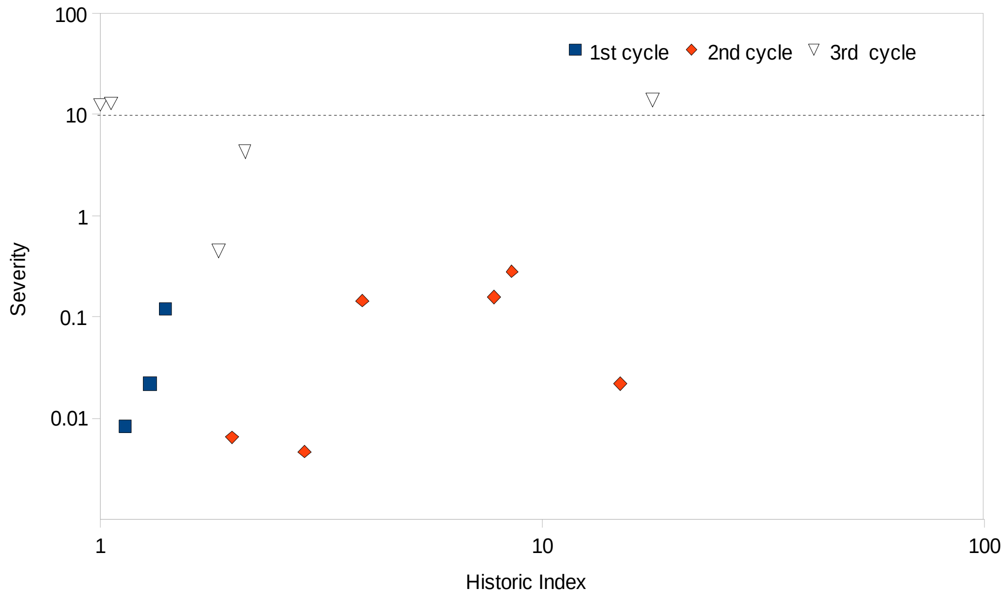

Figure 7. Mean Severity vs. Historic Index during loading cycles

The chart Severity Index - Historic Index (Figure 7) could be used with the same purpose of the Calm ratio - Load ratio chart. The historic index is an analytical quantity that traces the change of slope of the cumulative signal strength parameter measured during a test. Severity values were obtained by averaging the strongest signal strength values and helps to normalize the AE data collected making them independent of the location of the AE source, values are here reported as Volt.sec units.

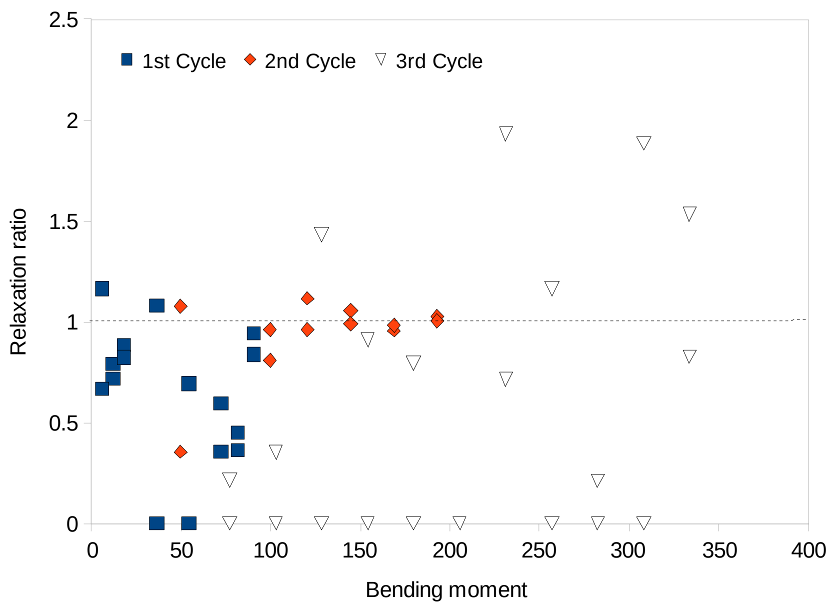

Figure 8. Relaxation ratio vs. bending moment during loading cycles

Basing on the literature (Golaski et al., 2002; Archana, 2006) the transition from no significant to minor damage should be positioned around a value of the Severity index about 10. Using such configuration Severity to Historic index chart seems less restrictive than the NDIS criterion. Only the input form AE events from the third loading cycle however are located in this minor damage zone.

Relaxation ratio is defined as the ratio of the average energy during unloading phase to the average energy during loading phase, a relaxation ratio greater than one (relaxation dominant) implies a defective structure. Once again, in this work, the unloading step was substituted by the load hold on step, and therefore Relaxation ratio values are plotted vs load (i.e. bending moment) instead of cycle number. Results are reported in Figure 8.

From this chart it is clear that by increasing damage accumulation in the beam (from loading cycle 1 to loading cycle 3) points move from a "loading dominant" to a "relaxation dominant" condition. Such result seems therefore clearly capable to identity more than the Severity-Historic index chart the critical status of the highly damaged structure.

CONCLUSIONS

AE technique was applied to identify damages in post-tensioned concrete structures. Different evaluation procedures were adopted and compared. Contrasting results were however obtained. NDIS criterion as well as Calm ratio - RTRI chart indicated the first cycle as the most critical one. First damages in effect were generated at this stage. Severity- Historic index chart as well as the Relaxation ratio methods evidenced instead a higher damage level in last loading cycle. Such contrast could however be considered only apparent when thinking that each procedure could be specific for certain damage condition. Such aspect needs however to be deeply investigated.

ACKNOWLEDGEMENT

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REFERENCES

Archana N. (2006) "Acoustic Emission Monitoring and Quantitative Evaluation of Damage in Reinforced Concrete Members and Bridges", *Master Thesis*, Louisiana State University

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

Colombo, S., Forde, M.C., Main, I.G., Halliday, J. and Shigeishi, M. (2005b), "AE energy analysis on concrete bridge beams", *Materials and Structures,* Vol. 38, No 11, 851-856.

Golaski, L., Gebski, P., and Ono, K. (2002), "Diagnostics of reinforced concrete bridges by acoustic emission", *J. Acoustic Emission*, Vol. 20, 83-98.

Luo X., Haya H., Inaba T., Shiotani T., Nakanishi Y., "Damage evaluation of railway structures by using train-induced AE", (2004), *Construction and Building Materials*, Vol. 18, 215-223.

NDIS 2421 (2000), *Recommended Practice for In-Situ Monitoring of Concrete Structures by Acoustic Emission*, Japanese Society for Non-Destructive Inspection.

Ohtsu, M., Uchida, M., Okamato, T. and Yuyama, S. (2002), "Damage assessment of reinforced concrete beams qualified by acoustic emission", *ACI Structural Journal*, Vol. 99, No. 4, 411-417.

Shiotani T, Nakanishi Y., Luo X., Haya H. and Inaba T., "Evaluation of structural integrity in railway structures using train-induced acoustic emission" *Structural Faults and Repair 2003*, Engineering Technics Press, (CD-ROM), 2003.