Damage analysis of stress corrosion test of pretensioning steel strands by AE monitoring

L. Calabrese, G. Campanella, P. Longo, E. Proverbio

In the present work the application of acoustic emission technique has been proposed as a tool for the evaluation of corrosion processes occurring under SCC conditions on prestressing steel strands. To simulate the possible corrosive environment under service conditions experimental tests were performed with different electrolytes and electrochemical conditions (open circuit potential, cathodic and anodic polarisation). The use of multi-variable techniques, coupled to a classic statistical approach, has permitted to discriminate separated clusters in the population of the acquired AE signals related with specific damage events. Thereby the proposed approach allowed to create corrosion maps able to classify both global and punctual degradation phenomena. In particular different areas of the maps were related to the different corrosion mechanisms experimentally observed during the SCC tests.

Keywords: Steel - Corrosion - Cold drawing - Non Destructive Testing

INTRODUCTION

Acoustic emission (AE) technique has been used since the '80s with promising results in the study of the corrosive phenomena [1]. More recently this technique has been introduced in the field of civil engineering and to evaluate the stress corrosion mechanisms typical of pre-tensioning cables used in pre-stressed concrete structures [1-5].The different analytical methods usually used to investigate damage phenomena by AE technique are based on the study of some parameters related to the properties of the gained acoustic wave. The integration of these statistics information could allow to specifically discriminate the damage phenomena that are taking place. Indeed the use of classical statistical methods to analyse AE data does not always allow a clear and global interpretation of the various corrosion mechanisms that occur during the degradation of the structures. The use of multivariate analysis, seen as a technique to support the evaluation of AE data, may allow to highlight the different corrosion processes through the identification of specific parameters related to the acquired acoustic events [3].

In the present work the application of acoustic emission technique has been proposed as a tool for the evaluation of corrosion processes on steel strands under stress corrosion cracking condition. Pieces of steel strands were immersed in different aggressive solutions and three experimental set-up were proposed (steel strand at free corrosion potential, anodically polarised, cathodically polarised). The traditional methodological approach of AE data analysis was integrated with new multivariate analysis methods. This approach was proposed with the aim to identify the different corrosion mechanisms that characterized the different tests. Finally the use of multivariate analysis technique has also enabled the creation of topological maps able to better discriminate the forms of degradation encountered during SCC testing with specific AE parameters.

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EXPERIMENTAL PART

For the stress corrosion test an eutectoid cold drawn steel was used, in the form of ½" seven wires strands. Each strands with a length of 1.20 m, was immersed in a cylindrical corrosion cell (length 32 cm and volume 0.7 l) positioned in the middle of the strand. Table 1 shows the details of the used test solutions (nominal pH 12.5) and conditions [4].

Test code	Potential	Test Solution			
		KCl [g/l]	K_2SO_4 [g/l]	KSCN [g/l]	KOH [g/l]
N12	OCP	39,08	9,11	1,70	0,80
N13	OCP	–	9,11	1,70	0,80
N14	-1300 mV	39,08	9,11	1,70	0,80
N15	-400 mV	39,08	9,11	1,70	0,80

Table 1: SCC electrochemical setup with detail of the chemical composition of the test solutions

Tabella 1: Dettaglio dei set-up di prova SCC realizzati

N12 and N13 tests have been carried out at free corrosion potential, while tests N14 and N15 have been carried out under cathodic and anodic polarisation at -1300 mV SCE and -400 mV SCE respectively. An activated titanium net was used as counter electrode and a saturated calomel electrode (SCE) as reference electrode. The tests were performed at room temperature. During the stress corrosion test the strands were subjected to a constant load corresponding to about 80% of steel nominal failure load (σ_r=1970 MPa).
AE signals were recorded by a 10-channel Vallen AMSY-5 measurement system. Two transducers (type MICRO 80, with resonance frequency of 325 KHz), were placed at the ends of each strand. The AE acquisition was carried out with a daily 24h monitoring. Before performing data analysis a de-noising procedure aimed to remove spurious events (mechanical and electrical noises) was carried out [3].

AE DAMAGE ANALYSIS PROCEDURE

The statistical study of AE data acquired during SCC testing was carried out by means of univariate and multivariate technique in order to provide a detailed information on the quality of the acquired signals and their interpretation on the damaging state and its evolution in the steel strand. All the algorithms proposed for the analysis of the data has been written using Matlab 7.5 software, in particular, a three steps procedure was proposed:

Step 1: Univariate analysis

At this stage the statistical analysis was performed on 15 variables determined from the acquired AE signals.

- Common variables: Amplitude, counts, counts to peak, duration, risetime and energy. These variables are calculated directly from the acquisition equipment. Their definition is well reported in the literature [5].
- Uncommon variables: RA value, average frequency, reverberation frequency, initial frequency, reverberation time. These variables are obtained by mathematical combination of the previous ones. RA value was defined as the ratio of rise time to amplitude of the waveforms; Average frequency, the ratio between count and duration, indicates the average wave frequency over one AE hit; while initial frequency is the ratio between counts to peak and risetime; instead the reverberation frequency is defined as (duration-risetime)/(counts-counts to peak)

Test variables: Time, hour, sensor, test. These variables are strictly related to test conditions and temporal data storing.

Step 2 and 3: PCA and SOM analysis

From a mathematical point of view PCA is an orthogonal linear transformation that converts the original statistical data by projecting them to a new set of coordinates in order of decreasing their variance. PCA is widely used in statistics and neural computing with the purpose to reduce the number of significant variables and consequently reducing the dimensionality of the data set [6]. Furthermore, PCA is able to identify and classify hidden patterns in the data, favouring the understanding of the relationships between variables [7]. Self Organising Map (SOM) analysis allowed to homogenize the information previously acquired and to interpret in explicit form, by means of a topological map, the evolution of the damage of the strand during the acquisition time for the various investigated tests [8].

RESULTS AND DISCUSSION

Univariate analysis

Figure 1 shows the typical trend of the cumulative counts for all tests during time. For the N13 sample, immersed in a less severe solution, the mechanical failure of the strand occurs at highest times (nearly 300 hours). The N12 sample showed a failure time slightly lower than the N13 one. The presence of chlorides in the solution determined massive pitting corrosion on the metal surface facilitating the initiation and propagation of surface cracks.
A different behaviour was observed for the specimen subjected to polarisation. The N14 sample evidenced a significant reduction of the failure time (about 160 hours). A rapid fracture was observed for the sample under anodic regime (N15 sample). In this case, the recorded acoustic events arises solely from mechanical failure, because the test conditions were particularly critical, leading the failure of the strand in only 20 hours.
Analysing the sigmoidal trend of the curves reported in figure 1, three stages can be identified at increasing time:

I. Activation phase: At first a short stabilisation period was observed where homogenization and chemical stabilization of specimen in the corrosive solution after the filling up of the corrosion cell occurred. Afterwards on the metal surface electrochemical modification takes place that favours the localised surface dissolution. In this stage the crack initiation occurs, confirmed by a relevant increase of AE hits. At the OCP (N12 and N13 test), the AE signals medium amplitude (above 40 dB) could be related to localised attack where the thin passive layer was defected or damaged inducing the growth of localized pits [9]. The localised corrosion is however not sufficiently energetic to be clearly detected

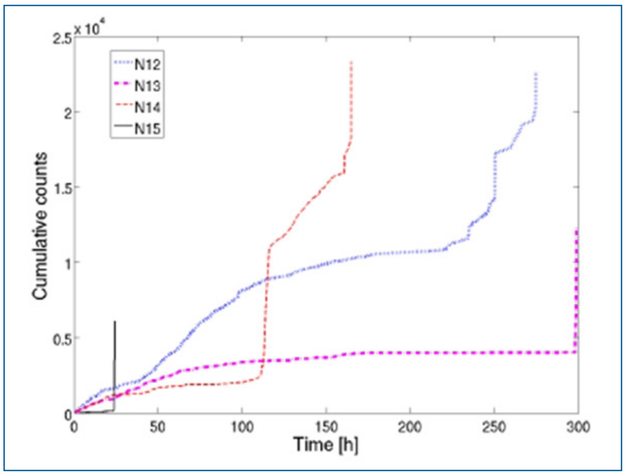

Fig. 1- Cumulative hits plot versus time

Fig. 1 - Andamento del cumulativo di eventi acustici in funzione del tempo

by AE, but it could also favour the energetically more relevant SCC [10]. This behaviour is exalted by applying an anodic polarisation on the sample [11]. Instead, when a cathodic polarisation is imposed, the presence of hydrogen favours the breakdown mechanism of a pseudo-passive layer at the metal surface of the strand and the beginning of hydrogen diffusion inside the metal, inducing a strong AE activity [12].

II. Stabilisation phase: The structure have a new quiescent phase where the increase of AE hits is very low. In this region the feed rate of the cracks becomes virtually independent from the mechanical contribution, and its advancement can be related to corrosion phenomena. In this intermediate phase the sub-critical crack propagation occurs. The reduction of AE could be related with the formation of a plastic zone at the crack tip during its propagation phase [13].

III. Failure Phase: When mechanical instability is reached, we observe energetically relevant acoustic events associable to the subsonic propagation of the crack leading to the strand failure. The intense AE activity was generated due to rapid reduction of the cross-section of the strand during its rupture. The large burst of activity characterised by very high energy and amplitude (up to 90 dB) is symptomatic of final ductile fracture of the strand [14].

It is important to highlight the differences between the various types of test relating them with the temporal evolution of the damage. Consequently the various tests have been discretised into 10 time intervals and at each time interval the centroid of the data was determined. In this way a statistical information on the evolution of individual variables over time could be evaluated, using a parameter representative of the entire population of points belonging to that segment of time.

The figure 2 shows the distribution of the centroids with respect to variable amplitude versus risetime for the four

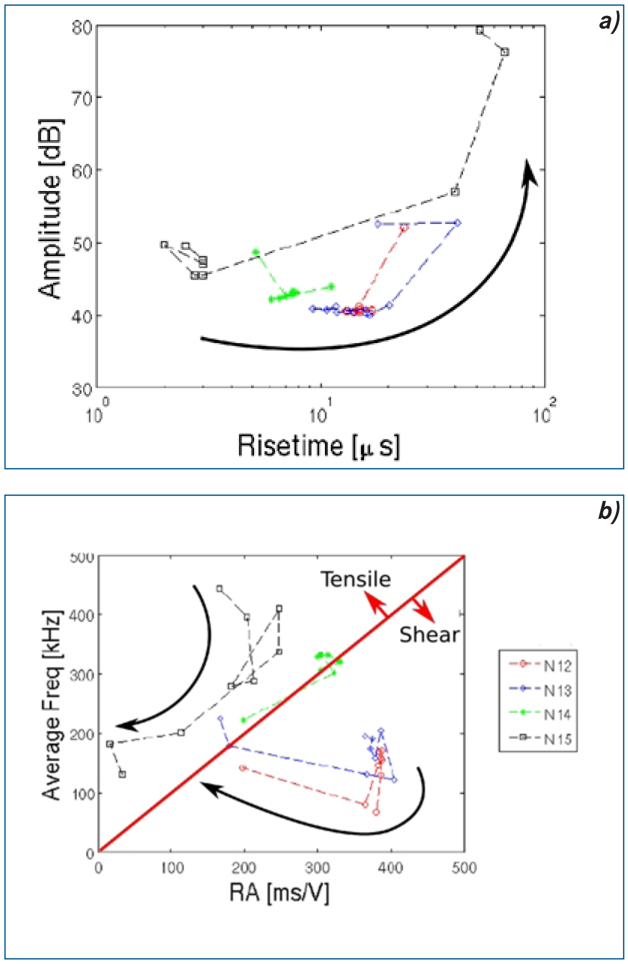

Fig. 2 - Centroid plot of Amplitude vs Risetime (a) and Average Frequencies vs RA (b) - black arrows indicate time evolution

Fig. 2 - Evoluzione nel tempo dei centroidi Ampiezza/risetime (a) e Frequenza media/RA (b) Le frecce nere indicano l'evoluzione nel tempo

categories of investigated test setup. The test N15 is characterized by low values of risetime and high values of amplitude at all time interval. The phenomenon of degradation is significant since the first immersion time. The application of an anodic polarization in fact results in a reduction of the lag time for the generation of signals AE [15].

In the first stage of time test the AE are characterised by amplitude values of about 40-50 dB and by very low risetime (below 10 μs). These AE events could be related with the activation and propagation of the cracks due to SCC [16].

The specimen N14 is characterized by intermediate values of amplitude and risetime. The degradation phenomenon is relevant and homogeneously distributed along the entire period of the test but it is characterized by a lower intensity than N15 test conditions. In this case, due to cathodic polarisation of the sample, the crack propagation can be attributed to the diffusion of atomic hydrogen in the bulk of the metal. The brittle crack propagation is discontinuous

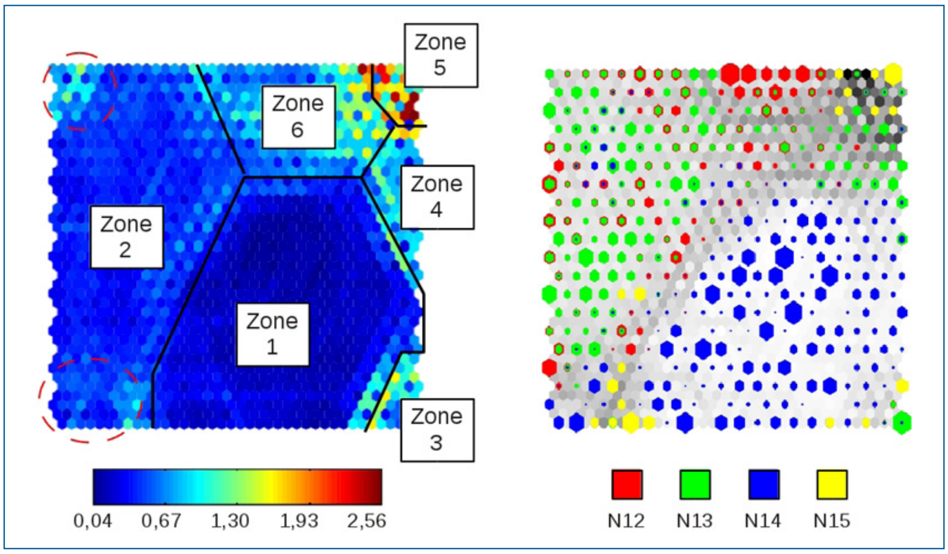

Fig. 3 - a) U-matrix resulting form the application of the Kohonen self-organizing map algorithm; b) Hits U-matrix for the variable "test condition"

Fig. 3 - a) Mappa U-matrix ottenuta mediante tecnica SOM, b) distribuzione degli hits della variabile "prova" all'interno della mappa U-matrix

and characterized by medium-energy acoustic events [17]. When the strand failure occurred the risetime, despite other test conditions, decrease significantly, probably due to the hydrogen embrittlement of the steel strand.
Much more complex are the considerations that can be drawn analysing the trends of N12 and N13 samples. Both samples show a progressive increase of the risetime and amplitude variables with increasing time of test. The values of amplitude detected are still lower than those found in the other test conditions. In particular sample N12 has amplitude and duration values slightly higher than the N13 samples, indicating the increased incidence of the sodium chloride into the solution on the growth and advancement phenomena of cracks.
The ratio between risetime versus amplitude (defined as RA value) can be considered as a parameter to deduce the wave shape. It is well known that the shape of the waveforms is indicative parameter on the fracture type, becoming an useful information for the classification of cracks in the damage analysis in different conditions [18], i.e. low RA values are related to tensile crack propagation while high RA values to shear crack propagation. Analysing the evolution of risetime and amplitude variable it is possible to scheme the crack mode evolution during test. In the first stage of the test the crack propagate by mode I, considering that tensile events are characterized by higher average frequency content. Afterwards a transition from tensile to shear propagation of the crack occurred. Finally, when the cross section of the strand is critically reduced, the cracks propagate catastrophically by tensile mode (in fact an increase of the average frequency was observed – figure 2b).

PCA and SOM analysis

PCA analysis results and correlation matrix of variables was used to identify uncorrelated AE variables for the SOM analysis. The Kohonen's self-organizing map algorithm was, therefore, applied to the residual variables detected by PCA. The SOM analysis was summarised in the the U-matrix map reported in figure 3a. The uniform areas of low value (blue pixels) group together elements belonging to the same cluster. In this specific case, we identified six relevant discriminated areas related with specific cluster. Furthermore additional information can be obtained by plotting the so called hits-U-matrix. This graph shows the projection of data samples into the map. The colours are related to a specific level of a variable and hexagon size is related to the numbers of AE hits related to that cluster point. In the figure 3b the map of test variable, related to the data clustering of figure 3a, is reported.
In addition, relating these results with the topological maps of the single variables the data clusters could be related with local area of specific variables, on the basis of their magnitude distribution. In particular:
Region I: This area is associated mainly with the test N14 (blue hexagon in figure 3b).
Region II: The second region is located in the left corner in the U-matrix map and is mainly dominated by N13 test.
Region III: The third region is located in the bottom right area of the U-matrix map and is not clearly related with a a specific test, although it is mainly influenced by N14 data.
Region IV: the fourth region is located on the right area of the U-matrix map and it is related mainly with N13 test.
Region V: the fifth region is located in top right zone of the U-matrix map. In the region V events with very high energy are coupled with N15 test. These events are usually related with energetically significant waves, confirming that the experimental set-up imposed in the N15 test induces the most critical conditions.
Region VI: the last area is located in the top area of the U-matrix map and is related mainly with N12 test. Interesting is the comparison between region IV and region VI. The former is related with N13 test, instead the latter is related with N12 test. By the previous univariate analysis, it was inferred the strong compatibility between these two types of test. Only some discrepancies were detected evaluating the distribution and the intensity of specific variables. This indicates that the information deduced from the univariate analysis were also appropriately interpreted by the neural network analysis. Furthermore the SOM analysis allows to

discriminate more clearly the significant acoustic events of these two tests, distinguished by relevant energy magnitude. The N12 test is identified by high duration and low reverberation frequency. At the same time the N13 test data are characterised by highest failure times (coupled with low duration and high reverberation frequency).

CONCLUSIONS

The electrochemical conditions (strand potential and the electrolyte solution) affect the evolution damage in SCC tests of pre-tensioning steel strands. The technique of acoustic emission method was proposed as a valid procedure to support the traditional statistical techniques in the corrosion phenomena interpretation. The coupling of these two methods has allowed to obtain a more accurate interpretation of the degradation phenomena that took place on the strands in the various test set-up configurations. By means of topological maps processed through the SOM has been possible to associate each individual test to a family of data marked by significant variables with specific intensity related both to test configuration and damage mode that has taken place .

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Studio dei meccanismi di SCC su trefoli in acciaio attraverso analisi SOM di segnali di emissione acustica

Parole chiave: Acciaio - Corrosione - Trafilatura - Prove non distruttive

Nel presente lavoro è stata proposta l'applicazione della tecnica dell'emissione acustica come strumento di valutazione dei processi di corrosione su trefoli di acciaio sollecitati a trazione. Per simulare le possibili condizioni di corrosione in cui si possono trovare i trefoli nelle strutture in calcestruzzo armato precompresso spezzoni di trefoli di acciaio di 1,20 metri sono stati immersi in diverse soluzioni aggressive e in diverse condizioni di prova (a potenziale di corrosione libero, polarizzato catodicamente, polarizzato anodicamente). L'utilizzo di tecniche multivariabile, accoppiate ad un approccio metodologico classico, ha consentito di suddividere in cluster la popolazione di segnali acquisiti, consentendo in tal modo di creare delle mappe di corrosione sia globali che puntuali. Nelle mappe le diverse aree sono state correlate ai differenti meccanismi di corrosione studiati.