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An acoustic emission approach to the structural health monitoring of historical metallic tie-rods

Michele Carboni[1], Francesco Muscolino[2] and Roberto Felicetti[2]

michele.carboni@polimi.it
francesco.muscolino@polimi.it
roberto.felicetti@polimi.it
Correspondence: michele.carboni@polimi.it;

[1] Dept. Mechanical Engineering, Politecnico di Milano – Via la Masa 1, 20156 Milano, Italy
[2] Dept. Civil Engineering, Politecnico di Milano – Piazza Leonardo da Vinci 32, 20133 Milano, Italy

ABSTRACT

The application of Non-Destructive Testing and Structural Health Monitoring systems in historical buildings is of great interest due to the need to guarantee safety and conservation. The present memory focuses on the case study of the historical wrought iron tie-rods of Duomo di Milano, Italy. In recent years, two of these elements presented critical failures. Consequently, a monitoring methodology based on acoustic emission was defined. First, the fracture toughness of wrought iron was characterized by employing standard small-scale specimens taken from one of the failed tie-rods. Meanwhile, acoustic emission was acquired to define a methodology for detecting and localizing the damage events, separating those due to background noise by applying suitable pattern recognition algorithms. Subsequently, a tensile test was performed on a full-scale section of the same tie-rod. Before and after the test, phased-array ultrasonic testing and magnetic particle inspections were carried out to identify and map defects and their possible development due to load application. Finally, it was possible to conclude that magnetic inspections allow identifying the presence of surface defects effectively, phased-array testing estimates the geometry of the defect accurately, and acoustic emission is a promising technique for monitoring the structural integrity of historical metallic tie-rods.

***Keywords**: Historical metallic tie-rods, acoustic emission, ultrasonic phased-array, magnetic particles, identification and localization of fracture phenomena.*

1. Introduction

Since the 14th Century, during the construction of historical buildings, metallic tie-rods were employed to balance the horizontal thrust induced by arches and vaults or added for structural strengthening; therefore, the analysis of their state of conservation is fundamental to assess the integrity of these structural systems. The case study of this work is the Duomo di Milano (Milano, Italy), for which tie-rods were included from the beginning of the construction, and today they are still present in all five naves at the base of each pointed arch [1], as shown in Fig. 1a-b. Duomo di

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Milano tie-rods have an even more critical role than in other contemporary churches due to the Cathedral's unique structural system. Indeed, buttresses have small dimensions, so their contribution is limited, and the flying buttresses were only added in the 19th Century. Therefore, horizontal thrusts are mainly balanced by tie-rods elements [2]. In May 2009, one of the tie-rods (T01) failed (Fig. 1c), so an investigative campaign was carried out to discover its failure's causes. A few years later, a deep crack was identified on another tie-rod (T02) during a visual inspection (Fig. 1c). For this reason, a multidisciplinary study was launched to evaluate their state of conservation and the two failed components were made available to Politecnico di Milano for the experimental investigation.

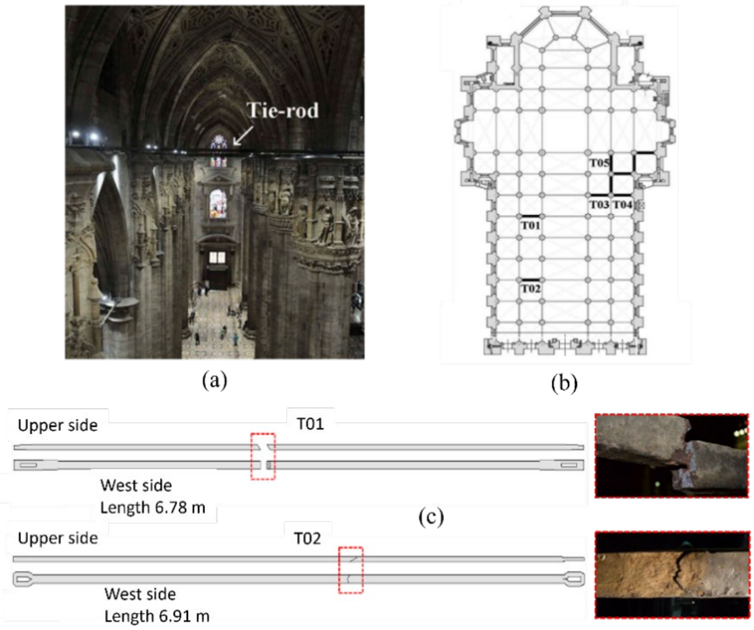

Fig. 1 Internal view (a) and plan (b) of Duomo di Milano [3]; (c) T01 and T02 failed tie-rods (left) and Tie-rods' failed region (right) [4].

More precisely, T01 was used to machine samples for material characterization [4]. Preliminary tensile tests were carried out according to the standard EN ISO 6892-1 on eight samples machined from T01. Results showed a very high standard deviation. In particular, yield stress, tensile strength, and elastic modulus were found to be equal to 142 ± 60 MPa, 199 ± 111 MPa, and 206 ± 45 GPa, respectively. These outcomes were explained by the intrinsic inhomogeneity of the material, featuring micro-voids, cracks, inclusions, and in particular, the presence of several forged welds, as discussed in the paper by M. Bellanova et al., [5]-[6]. Indeed, these elements were manufactured according to the metalworking process available at that age, which consisted in joining several wrought iron bars to manufacture a more elongated workpiece. This was carried out by hammering together the properly shaped edges of two consecutive bars at high temperatures during a traditional process named "bollitura" [3]. Consequently, the very heterogeneous metal matrix presented inclusion, porosities, and in particular macro discontinuities in the region of the manually forged weld.

Moreover, thirteen Single Edge-Notched Bend (SEB) specimens were machined from one part of T01, characterized by the presence of visible forged welds joint (point out after oxide layer removal as shown in Fig. 2.a). For this reason, six samples were machined across the weld area and the others from the base material. Fracture toughness tests were performed on SEB according to the ASTM E1820-17 standard [2-8]. The data were analyzed employing an Elasto-Plastic

Fracture Mechanics (EPFM) approach based on the J-Integral formulation to consider the material's larger plasticity scale, pointing out a J-integral value of wrought iron, including a forged-weld one order of magnitude lower than the base material, proving the need to account for the dominant defects in a practical structural safety evaluation of these historical metallic elements. Furthermore, the tests were coordinated with one exploiting SHM inspection techniques, Acoustic Emission (AE), i.e. a passive technique based on sensing the elastic energy released by a material subjected to plasticization or fracturing [7], to outline a procedure for the structural assessment of historical metallic tie-rods from a damage tolerance perspective. However, the AE data analysis was not carried out in detail, therefore is examined in this work.

On the contrary, T02 was preserved and used for non-destructive inspection. For this reason, the Guided Wave method (GW), Eddy current testing (ET), and Pulsed active thermography (TT) were studied to understand how these techniques could be adapted to perform an inspection at global, intermediate and local scales, respectively [3]. The first two techniques arrived at excellent outcomes in identifying damaged tie-rods and quickly detecting the most detrimental defects corresponding to the forged welds. However, TT was not able to precisely estimate the crack size.

For this purpose, to resolve the still open issue of evaluating the structural safety of the wrought iron tie-rod, it is necessary to assess a non-destructive technique to predict defect size and implement an advanced structural health monitoring system for real-time or on-demand damage identification. Thus, different non-destructive methods, such as ultrasonic phased array testing (PAUT), i.e. an advanced ultrasonic inspection instrument, and magnetic particle testing (MT), i.e. a non-destructive testing technique for ferromagnetic material, are investigated in this work as promising innovative methods to analyze and detect defects of this cultural material (historic tie-rods). Moreover, in-depth analysis with Acoustic Emission Testing (AE) is being examined in this work, searching for real-time monitoring of propagating cracks and the location of defects.

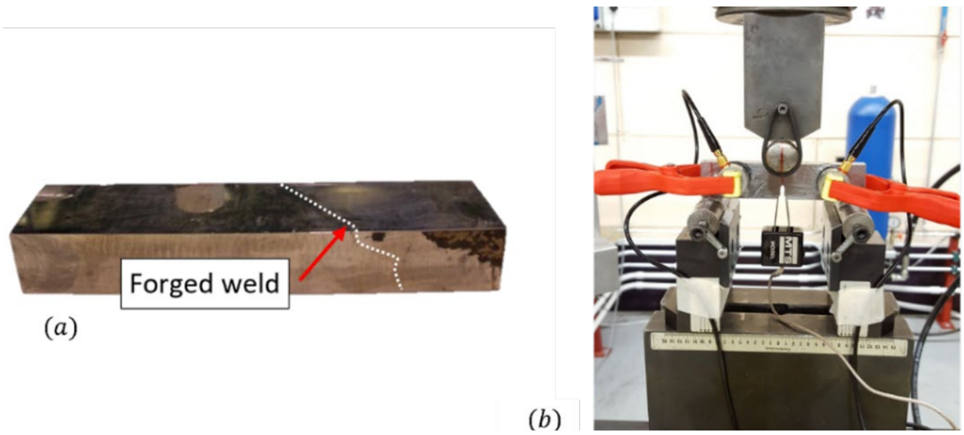

Fig. 2 (a) Part of tie-rod T01; (b) Fracture mechanics test set up [2].

2. Methodology and Material

2.1 Acoustic emission set-up

Fracture mechanics were monitored by employing two resonant acoustic emission sensors, each at one side of the SEB notch, disposed at 68 mm (Fig. 2b). It was used an AE measurement system provided by the Vallen System composed of two Vallen VS150-M piezoelectric resonant transducers (resonant working frequency of 150 kHz and a cover range of 0-600 kHz) equipped with a 34 dB Vallen AEP5 preamplifier, connected to Vallen ASMY-6 acquisition unit through low-noise cables. The data were acquired by employing the Vallen AE-Suite Software R2017.0504.1. Moreover, the OKS-1110 silicone grease was used to couple the sensors on the samples to guarantee continuity during AE signals transmission between the specimen surface and sensors [9]. In addition, grips were also applied to keep the sensors in a fixed position during tests.

2.2 Acoustic emission analysis

Acoustic Emission data can be a challenge to handle. The main problems regard the massive amount of data: the acquisition of all the waves' parameters and all the transient waveforms and the acquisitions not only of fracture mechanics events but also of background noise. For these reasons, a post-processing analysis was carried out in Matlab to manage this amount of data. Two cluster algorithms were proposed to separate fracture events from noisy ones.

The first algorithm was based on the application of an artificial neural network and pattern recognition method. The algorithm starts with identifying the main AE parameter, i.e. amplitude, counts, duration, energy, and rise-time [10]. After that, a parallel plot, i.e. a way of visualizing and analyzing high-dimensional datasets, was employed to define the correlated parameters that were used to generate the Self Organized Map (SOM), i.e. a map that applies competitive learning instead of error-correction learning [11]. Finally, the resulting map was clustered using the k-means, i.e. a partitional algorithm of statistical pattern recognition. However, the k-means mask does not allow choosing the optimal number of clusters a priori. For this reason, an algorithm proposed by D. Crivelli et al. [13] was used to evaluate the best performing clusters; then, the SOM was clusterized, and each input wave was associated with the respective group. The classification process, from searching the correlated parameter to the separation of damaging and noise signals, is summarised in Fig. 3.

The second algorithm was based on the application Discrete Wavelet Transform (DWT), i.e. signal decomposition by a sum of short-lasting functions called wavelets [14]. Looking at the spectrograms of the different AE signals was noticed that the burst signals had an energy content at the frequency range of [300:1200 kHz], much higher than the noisy ones. For this reason, it was thought to use this property to classify the different signals after choosing an appropriate threshold value.

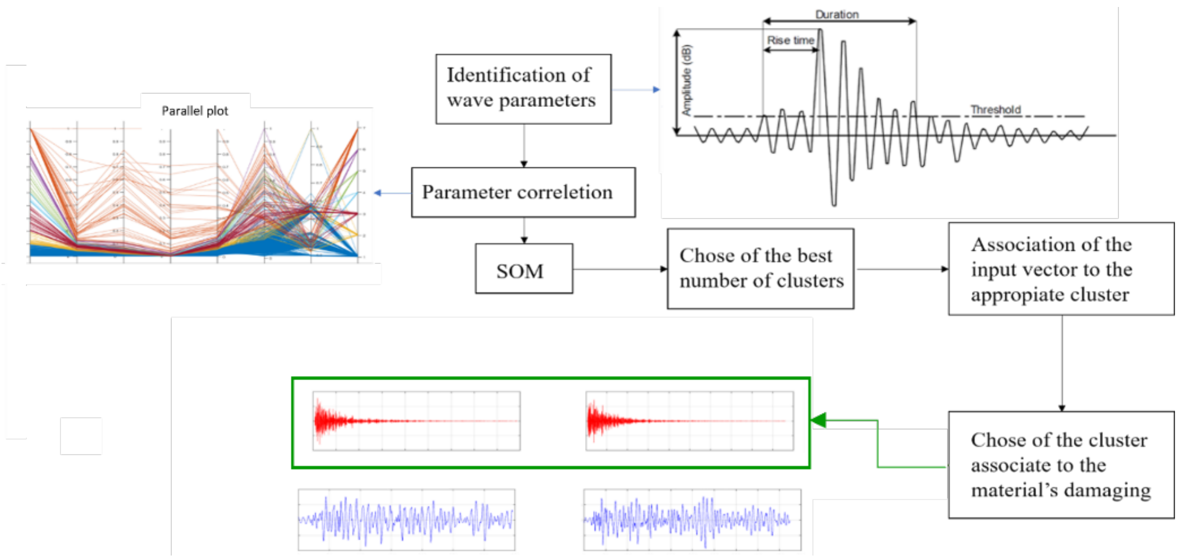

Fig. 3 Classification process.

Another essential point when dealing with acoustic emission is the localization of the events. Indeed, localization sources can give important information about the kind of events. The acquisition of Vallen offers a location algorithm based on two operations. The first regards the generation of an event build which consists of grouped hits into an event data set according to the arrival times of waves (time of flight) to the coordinated sensors. After that, according to the used number of sensors, an appropriate localization equation must be selected to localize the events.

However, this method's limitation is the computation of the arrival time. Indeed, Vallen acquired the wave when wave amplitude overcame an imposed fixed threshold to have a first noise filter, and this wave crossing time is wrongly used for the wave arrival time [9]. For this reason, to overcome the Vallen system limitation, two methods were implemented in Matlab:

- The *AIC* (Akaike Information Criterion) *picker* was based on the AIC function computation [15] of the wave inside a certain frame and computing the wave arrival time as the minimum of this function.
- The *Dynamic threshold* was based on the arrival time computation as the wave threshold crossing time, taking a threshold as a fraction of the maximum amplitude of the signal.

The localization algorithm was implemented on Matlab, and at the beginning of the code, the acoustic emission was reduced to the group associated with damage events. After that, an algorithm was developed to classify the hits in events. Then the analysis was conducted for both time picking algorithms discussed above. The velocity was computed employing the theoretical law for longitudinal and transversal elastic waves and chosen depending on the pickers' method to catch the waves' arrival time since each method can predict the longitudinal or transversal waves' arrival. Since only two sensors were employed, a mandatory linear localization [10] equation was used. Moreover, DWT was used to denoise the signals and improve the acoustic emission's source location with AIC and dynamic threshold pickers since these methods were strongly influenced by the signal-to-noise ratio in the first part of the wave.

2.3 Sample results

The data acquired during the fracture mechanics test was used to compute the fracture toughness of the samples extracted from the historical metallic tie-rod of Duomo di Milano pointing out forged weld, 'bolliture', as the weakest part of the material [2].

Concerning the acoustic emission acquisition, once defined a methodology to analyze them, the data taken from the test of thirteen samples were analyzed, conducting the study separately for samples extracted from based material and the welded regions, searching for recurrent results in the same of the two classes. However, the results were similar, so the result for only one representative sample will be presented.

First, it was searched for the correlated AE parameter needed to apply the first mentioned clustering algorithm. The resulting parallel plot presented a clear correlation between Amplitude, Variance*, Energy, Duration, and Count. After that, these parameters were used for the clustering process using four optimum groups. Therefore, the AE history was compared to cluster one, as shown in Fig. 4a-b, where the AE Amplitude, Load history and cumulative energy of the test were plotted as a time function. Looking at the first two graphs, the amount of data was strongly reduced after the cluster, although keeping the signal's damage events presented during the test loading. Moreover, the analysis just performed was performed using the classification method based on DWT arriving at a similar result shown in Fig. 4c.

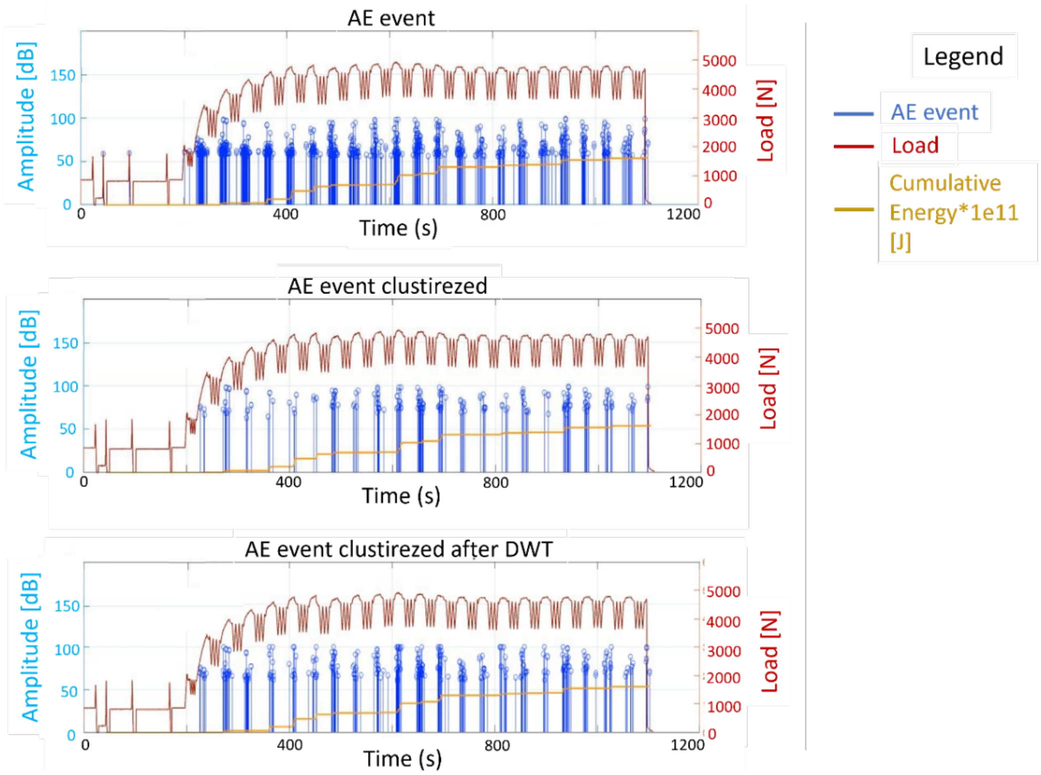

Fig. 4 Comparison between (a) all AE events history; (b) the clustered AE events employing the first cluster algorithm; (c) the clustered AE events using the DWT energy principle.

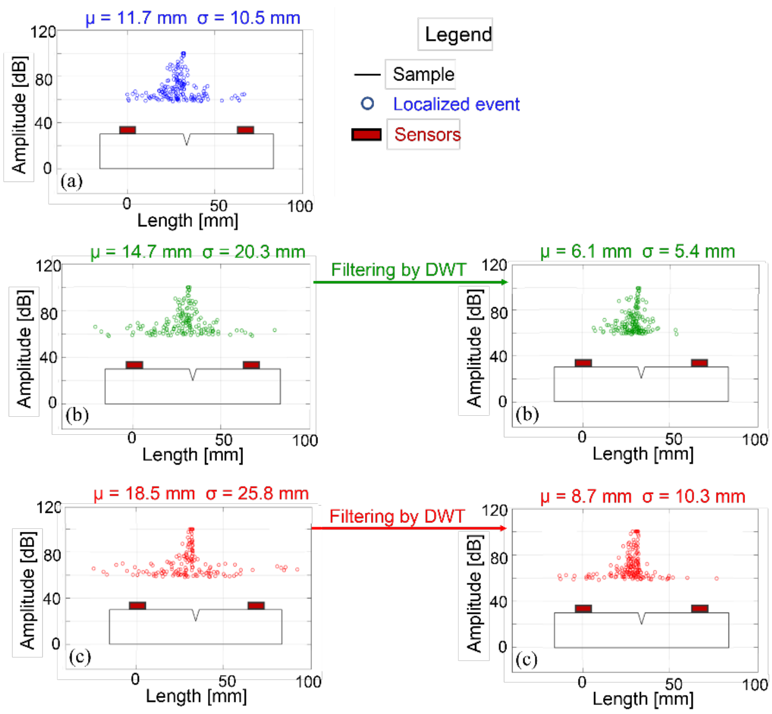

Fig. 5 Localization's results: using the arrival time of Vallen System; b) using the AIC function picker and AIC picker after DWT; c) using the Dynamic Threshold picker and Dynamic Threshold picker after DWT.

Once the data was reduced to fracture mechanics events, the localization algorithm was applied using the discussed methodology. For the different picking algorithms, it was computed the mean of the error μ and the standard deviation of the error σ. The localization result and error computation are visualized in Fig. 5. From these results, the localization algorithms showed good precision regarding fracture events localization; indeed, looking at the figures, the source location is concentrated near the sample notch. Moreover, of the different pickers' results, the AIC function after DWT was the most accurate arrival time computation, reducing the localization error of the Vallen system by almost 50 per cent.

3. Experimental work on a chunk of T01 tie-rod

Once assessing a methodology to analyze the AE of these components, it was decided to investigate the AE technique on an undamaged chunk of T01 tie-rod, with the idea of applying a tensile test in order to have a distribution of stresses similar to the one acting at the Cathedral.

First, a visual inspection was performed on the tie-rod chunk, identifying a welded part in the component, the so-called "bollitura". After that, various manufacturing processes were done to allow a non-destructive inspection with magnetic and phased array testing and reduce the tie-rod dimension to the maximum permissible, considering the testing machine load capacity. MT was performed on each tie-rod welding's side. The results almost confirmed the observations already made with the visual inspection, except for a considerable indication outside the welding region, circled in red in Fig.6a, suggesting that the defect was more extended than observed. Moreover, PAUT was employed in all the MT indication areas to precisely measure the defect. A grid was drawn on the inspection area with a cell dimension equivalent to one-half of the probe dimension to scan all the areas and be able in the post-processing to superimpose the images and display all sections' scans. The results revealed delamination from one edge of the bollitura to the MT indication's end, as shown in Fig.6b.

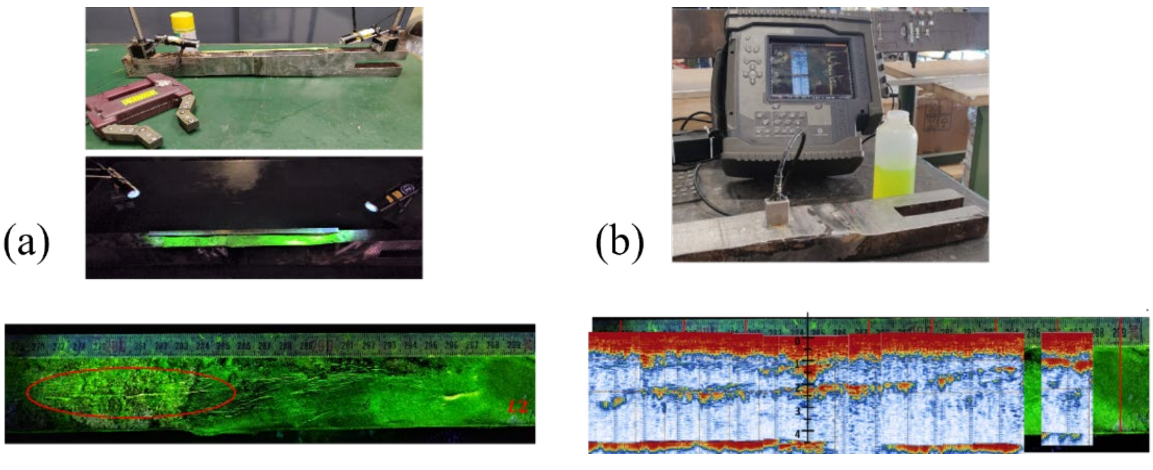

Fig. 6 (a) MT set up and results; (b) PAUT set up and result.

Once the primary defects were defined inside the tie-rod, different acoustic emission set-ups were studied to monitor and localize events in this region in 2D and 3D ways. For this reason, hits were generated in known position using the artificial Hsu-Nielson source and the data were analyzed in Matlab using an iterative localization algorithm for 2D and 3D localization [10]. The results pointed out that the set-up visualized in Fig. 7a was optimal and that the AIC function was the best algorithm to localize in 2D and 3D ways.

4. Tensile test results

The mentioned set-up was used for the tensile test carried out by an electro-mechanic Schenck testing machine with a maximum load cell of 1000 kN. The tie-rod was tested in displacement control, applying three times a sequence of loading and unloading to evaluate the acoustic emission in both phases. The data acquired were analyzed using the procedure and the result of SEB analysis. As presented in Fig. 7b-c, the AE history was compared to cluster one using the two-cluster methodology already discussed and also, in this case, correlating the AE Amplitude and Load history as a function of time. As seen for the SEB analyses, the amount of data was strongly reduced after the cluster; indeed, the hits were reduced from one million and a half hits to sixty thousand, although keeping the signal's damage events.

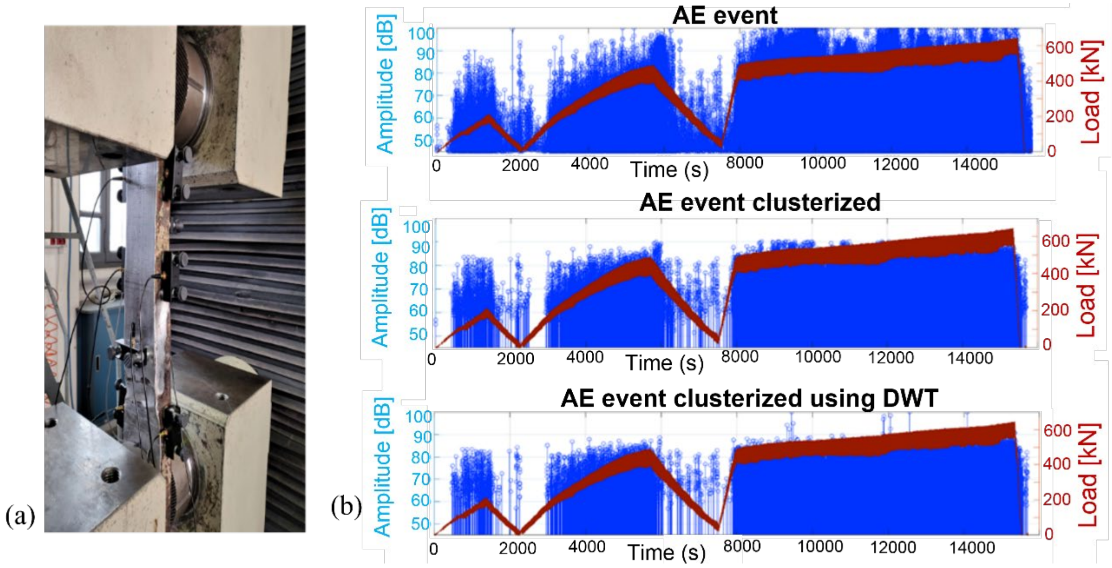

Fig. 7 (a) Tensile Test Set-up; (b) AE history, AE history of clusterized events, AE history of clusterized events after DWT.

After that, the localization algorithm was applied to the clusterized events, and in Fig. 8, 3-D localization using the AIC picker after DWT is reported. The results indicate two main localization regions coincident with the delamination edges identified with the phased array.

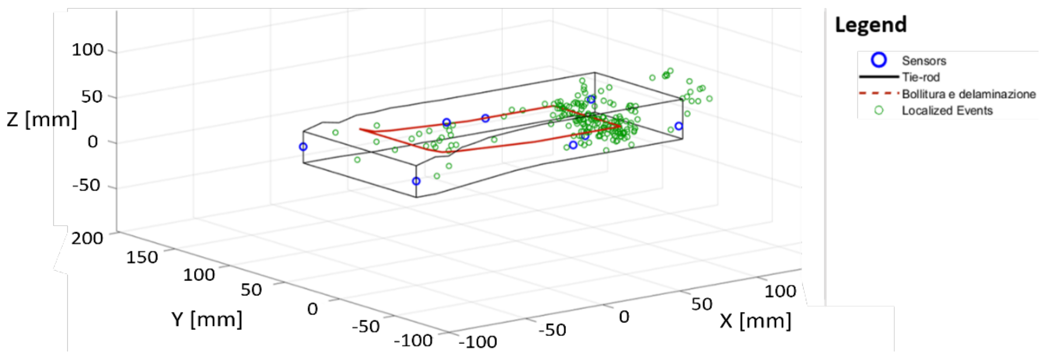

Fig. 8 3-D AE localization results using AIC function after DWT.

Another investigation campaign was then carried out, after the tensile test, using PAUT and MT to ensure that these AE localization events were associated with material damage. Therefore, MT images were compared before and after the test, noting differences in one side of the tie rod, circled in red in Fig. 9. After that, this indication was correlated to the AE localization, observing that the two regions were almost coincident. The same procedure was carried out with the PAUT, pointing out a defect propagation after the tensile test circle in black in Fig. 9.

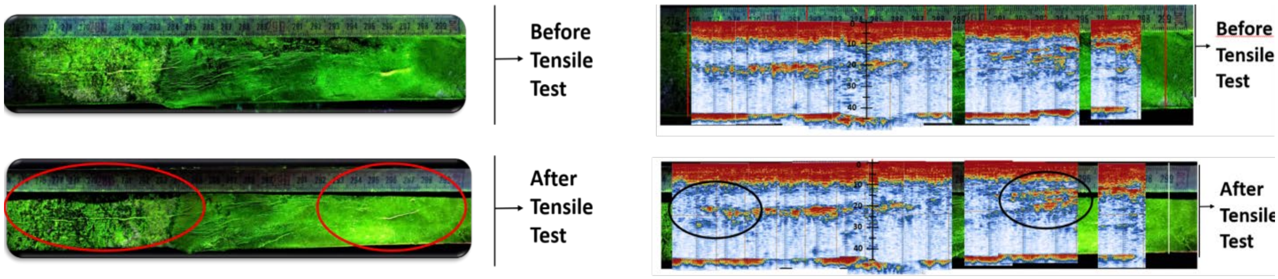

Fig. 9 MT (left) and PAUT(right) results' comparison before and after tensile test.

Conclusions

This research work addresses the still open issue of the historical wrought iron tie-rods structural safety. Two main topics are deeply studied: assessing an SHM system for the Duomo di Milano's tie-rods using AE and an investigation campaign with MT and PAUT to verify these elements' integrity state.

Initially, the SEB AE study provides a methodology able to analyze the AE of these components. In particular, optimum results in classification among the fracture and noise signals are provided using the k-SOM application and DWT. Moreover, the localization algorithm using different methods (Variable Threshold and AIC function pickers) for acquiring acoustic waves' arrival shows a good precision regarding fracture events localization. Indeed, wave decomposition by DWT methodology improved the localization of the events using the AIC and Variable Threshold pickers. Finally, this analysis concluded that using the AIC function picker after DWT provides the best result regarding 1D localization events.

The inspection on the part of the tie-rod T01 points out that MT and PAUT can detect the defects of these components. In particular, MT can identify the presence of superficial defects. Instead, PAUT can accurately define the geometry of the fault. The AE tearing test analysis compared to the second inspection with PAUT and the MT confirmed that the AE SEB analysis method is affordable and can be used to analyze this material damaging acoustic emissions.

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