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The applicability of acoustic emission method to modeling the endurance of metallic construction elements

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Abstract. Acoustic emission method is the most effective nondestructive inspection technique of construction elements. This paper considers the expanded applicability of acoustic emission method to modeling the damage and the remaining operational life of building structures, including the high-ductile metals. The modeling of damage accumulation was carried out to predict endurance using acoustic emission method.

1. Introduction

The current trend in the building industry establishes certain requirements for the materials used. There is a need to build more, faster and cheaper. For these purpose special materials providing better strength and endurance properties are used. Acoustic emission technology is the most practical way to determine such properties of the materials. The development of a reliable method for predicting the operational life and remaining life of the resource is the most important task in the modern construction industry.

Buildings and structures often fail when operating in severe weather conditions. Moreover, the actual operational life is often significantly shorter than the designed one. Materials used for manufacturing structures may contain defects further leading to serious breakdowns. Structural integrity can be broken suddenly - an item can break down. As a result there might be accidents and fatalities. These problems can be solved with effective quality control of components both during production and during installation of equipment and in-service, which improves not only competitiveness, but also minimizes the risk for consumers.

2. Methods

The presence of internal and external defects of various kinds causes difficulty in selecting effective nondestructive inspection technique (NDIT) of construction elements. When performing work the following NDIT are used: optical methods of nondestructive testing (including visual inspection); plastic methods of structural analysis; rebound method; method of separation with chipping and rib spalling design; ultrasonic method of determining the strength; acoustic emission method; shock pulse monitoring.

Traditionally, ultrasonic flaw detection method is used because it allows mainly detecting large defects such as discontinuities, exfoliation, debonding. It is used at the input control of semi manufacture and product. At the same time, defects are quite often generated during operation and have an extremely small size, so urgent is the development of new or adaptation of existing nondestructive inspection techniques that can detect defects of this kind (and size). A promising method for the detection of voids formed during the operation is the method of acoustic emission (AE). AE signals emitted by the material in the process of loading (destruction) may carry information about the size of cracks, their growth rate, allowing solving the problem of early detection and prediction of the destruction and the remaining useful life.

To describe the behavior of materials under load it is necessary to take into consideration the evolution of the real defects. In this regard, the development of a method of quantitative evaluation of structural changes in the solid, and the study of the general laws of the kinetics of damage accumulation become a necessary step in solving the actual problem of identifying real defects.

Most commonly known technology of NDIT is limited in application due to its material base and the physical capacity to research designs [1].

Acoustic emission is one of NDIT based on detection of elastic waves. Any defect produces its own acoustic signal that it can be registered at a great distance. Localization of the defect is made by calculating the difference between the times of a check-wave recorded by AE sensors. The main features of the acoustic control method that determine its capabilities and application area are the following: (i) the method provides detection of defects according to the degree of danger; (ii) the method has a high sensitivity to the growing defects and allows the operating conditions to determine the increment of crack to fractions of millimeters; (iii) the method has object orientation and its position does not affect the detection of defects. Currently, this method is widely used for diagnosing and heavily large high-risk facilities, as well as structures, where there is access to the control surface.

Many models were developed in order to link AE and the parameters of material destruction. Three main approaches can be distinguished. The essence of the first approach is to diagnose the stage of destruction on the Status of singular points (local extremum and fractures) of AE flow (Figure 1a). When measuring the concentration of defects during plastic deformation of materials in process of power impact a number of acts of acoustic emission N_a and residual strain ε were recorded simultaneously. After that, considering the parameters of acoustic emission depended on the residual deformation the starting point of defects development, the destructive strain component ε_d and the concentration of defects are determined [2].

A similar approach is described in [3], where the accumulation chart of acoustic pulses is associated with the time of static deformation (deformation degree) to identify the main stages of deformation (Figure 3) and to assess the long-term strength limit.

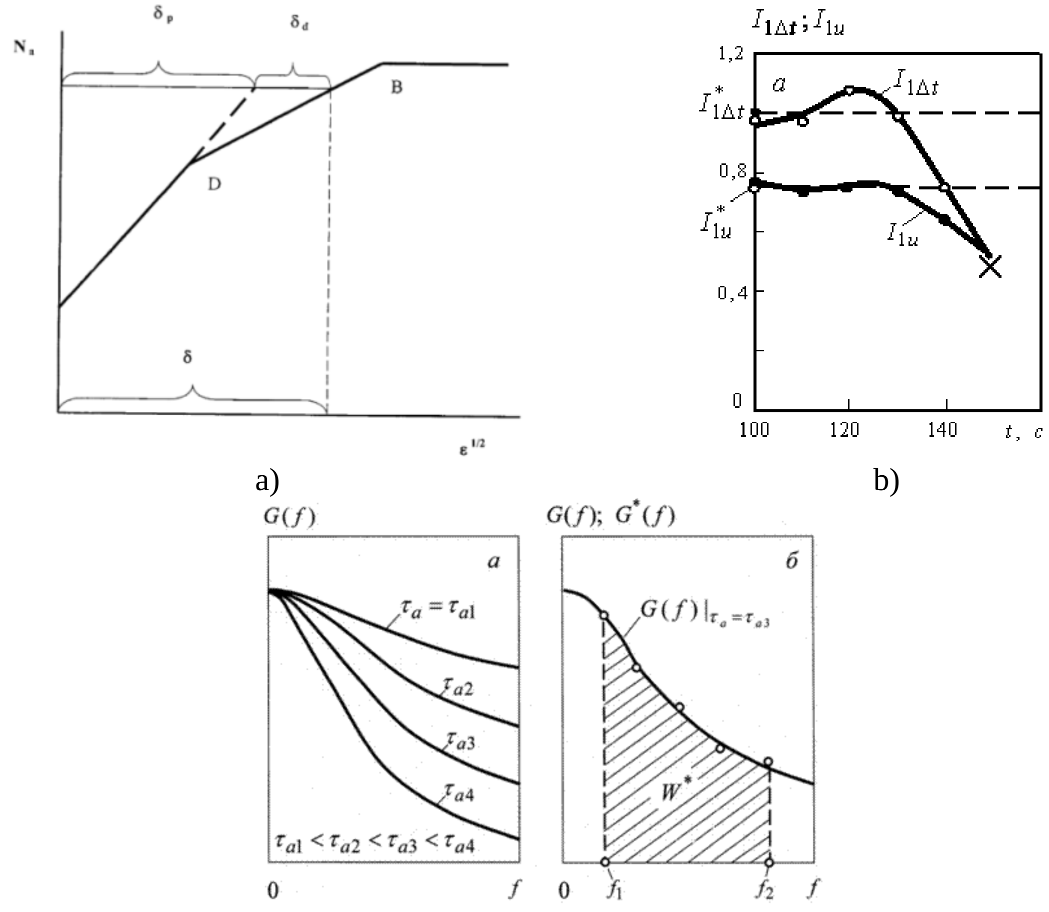
The essence of the second approach is to diagnose stages of deformation energy and time parameters of AE act [4]. The method is based on the fact that the spectrum of AE represents the spectrum of a Poisson flow of short elastic pulses. Consequently, one can estimate the total power W in the whole of the AE band of frequencies from the spectral density measured in the restricted from f_1 to f_2 band. This makes it possible to determine the total average energy per one act of AE by dividing the total power W to the value of the flow rate of AE acts. It is known that the normalized area of the spectral density $G(f)$ per unit of the Poisson flow of AE acts throughout the duration τ_a (0 ... ∞) has a band is as follows (Figure 1c)

$$G(f) = 4\tau_a \big/ (1 + 4\pi^2 f^2 \tau_a^{\,2}) . \qquad (1)$$

The average duration of the certificate AE τ_a is estimated experimentally overlaying dependence diagrams (1) to the experimental points of the spectrum of AE $G^*(f)$ (Figure 1c and d), and choosing the parameters τ_a in the formula so that the values approximating the spectrum $G(f)$ are most closely through the measured values of $G^*(f)$. Further, equating the measured power W^* and W^{**} approximating processes in the band from $f_1$to f_2, one obtain an estimated average energy of AE act E_a in the whole band. After setting the depending of the samples of the average E_a energy and the endurance of AE τ_a act degree on the deformation and damage accumulation, these parameters can identify the stage of material deformation.

The essence of the third approach is to diagnose the degradation of materials by AE invariant. Because of the random nature of the micro-flow, at some stages of deformation and fracture of solids stable (invariant) ratio can be found $I_p^* = inv$ between recorded AE parameters. Then, the appearance of deviations of recorded values I_p of these relations from their invariant values I_p^* can serve as a criterion for the transition to the next stage of deformation or fracture (Figure 1b) [5]. In addition, there is a technique [6], in which the invariant is not equal to a constant value, and a linear dependence.

Among the three approaches of using the parameters of acoustic emission for assessing the material damage the first approach was chosen. The objectivity of selection is formulated by the following factors: (i) considering the number of acoustic emission events it is easy to monitor the degree of damage to the material, using the relation $N_{\text{a}} = f(\varepsilon_r^{1/2})$; (ii) AE spectral composition suffers the greatest distortions in the distribution and reception of signals, so the second approach is expanded by further relations for the restoration of the spectral composition which affects the efficiency of the data obtained; (iii) the third approach allows having an opportunity to define the beginning of the destruction of the material, but it is impossible to determine the extent of damage.



a) Peculiar relation $N_{\text{a}} = f(\varepsilon_r^{1/2})$ and scheme of determination of the point of destruction D and destructive components of residual strain; b) Graphs of invariant relations in the process of loading the sample steel 95X18. The cross shows the moment of destruction; c) spectrum of the Poisson process, depending on the duration of its events; d) the approximation of the spectrum of AE

Figure 1. Correlations between the parameters of acoustic emission and of materials fracture.

3. Damage modeling and lifetime prediction of the elements of metal structures

3.1. Account of damage to the constitutive relations

Currently the accounting for practical calculations of the damage accumulation in the constitutive relations (2) is implemented through the ratio (3):

$$\sigma = E\varepsilon, \quad (2)$$
$$\sigma = (1 - \omega)\bar{\sigma}, \quad (3)$$

where σ – current stress tensor, *E*– matrix of material constants, ε – strain tensor, ω - a measure of the damage (varies from 0 to 1, 1 - corresponds to the destruction), $\bar{\sigma}$ – stress tensor calculated for these loading conditions in the absence of damage. The selection of this ratio is primarily dictated by the ease of determining the model parameters, and secondly, an acceptable accuracy [7].

3.2. Determining the type of damage functions

To determine the state of the material at the moment and predict the remaining life the function of material damage ω is introduced as follows (0 – no damage, 1 – the destruction of the material):

$$\omega = \frac{N_A^*}{N_A}, \qquad 0 \le \omega < 1, \quad (4)$$

where N_A –number of acoustic pulses at the test loading (loading with a given amplitude loads or strains), N_A^* –number of acoustic pulses corresponding to the material destruction.

AE method is widely used for the diagnosis of steel and concrete structures as shown in the studies [1]. The results of this work demonstrated that the method of predicting the remaining life of the resource and using AE is applicable not only for classical structural materials (steel and concrete), but also for soft metals and their alloys (for example, tin-lead solder and aluminum alloys).

For AE method testing and determining the form of damage to the material features they carried out a series of experiments on the detection of acoustic signals by setting AE Micro2 digital AE system during the deformation of the material samples for diagrams accumulation of acoustic signals from developing the defects during deformation, determination of the accuracy of the method, parameters of the model of damage accumulation and the inception of the defects in the process of mechanical action. Based on the analysis results of the experiments they plotted the diagram of accumulation of acoustic pulses occurring during the development of defects in the sample depending on the strain of the alloy (for example, solder alloy-61) (Figure 2a). Further data are given for the retention of the acoustic signals during deformation of structural steel and aluminum alloy (Figures 2b and 3) [8].

Presented in Figures 2a and 3 experimental curve for samples of solder with a measure of in accuracy less than 3% can be approximated by the ratio (5):

$$N(x) = A1 * \left(\mathrm{th}\left(A2(x - x0)\right) + 1\right), \quad x = \varepsilon^{1/2}, \quad (5)$$

where *N* – the number of pulses of acoustic signals ,ε – strain, *A1*, *A2*, *x0* –model parameters, th – hyperbolic tangent function.

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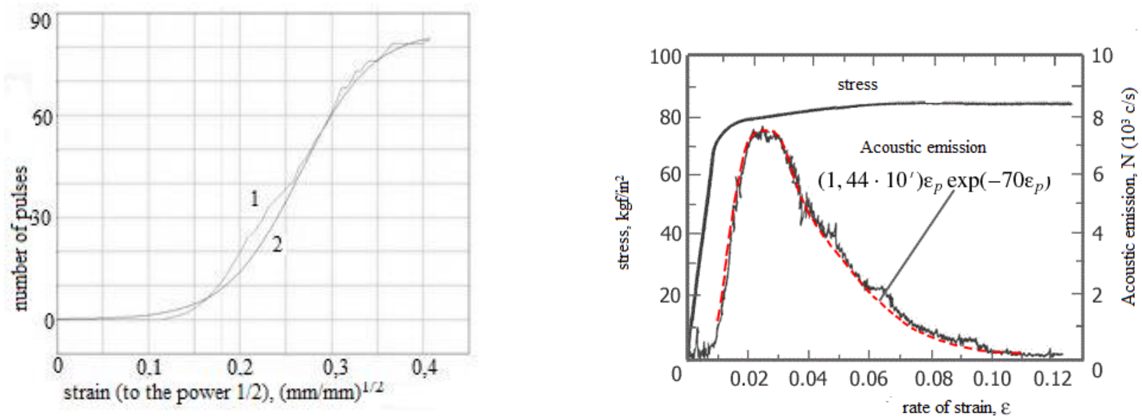

a) b)

1 - Experimental data, 2 - approximate curve.

Figure 2. a) Accumulation of AE pulses depending on the strain $\varepsilon^{1/2}$ samples of the solder; b) depending on the count rate of AE N and stressσ on the strain ε tensile specimens of aluminum alloy 7075-T6.

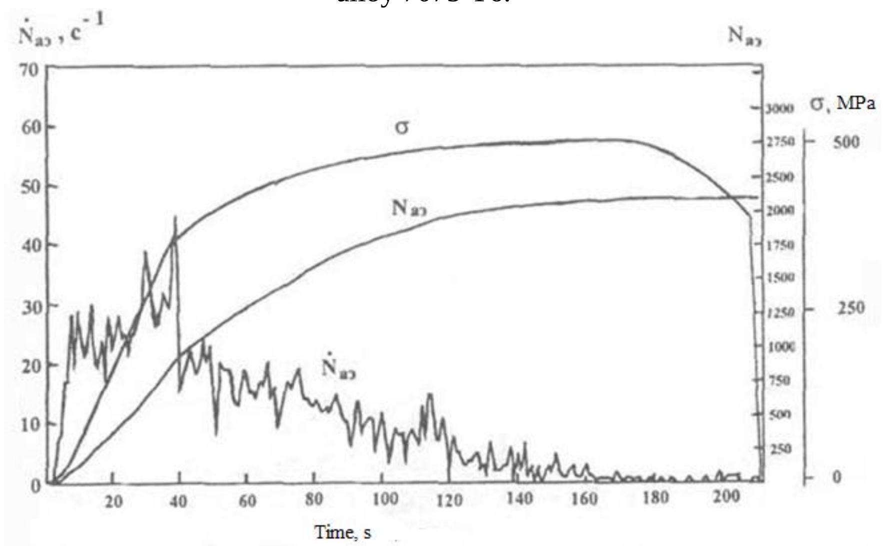

Figure 3. Flow signal intensity changes $\dot{N}_{аэ}$ and the total number of AE pulses $N_{аэ}$ depending on the time of strain (rate of strain) with static tensile specimen of steel 19G in original structural condition.

Thus, the use of acoustic emission technology allows obtaining correct results in a growth of the defect detection (such as a specific event, and the number of pulses dependent on the time) until the sample decomposition. Based on the results the damage function parameters are determined, which enables to reliably determine the remaining life of operation of the object and the relationship between stress and strain based on the accumulated damage.

The proposed method of predicting the remaining life of the operation and life of the object of the study is as follows: the finished product attached to it with AE sensors is subjected to loading test, during which the acoustic data are noted. Correlating the registered number of acoustic pulses at the test loading is determined by the point on the chart depending on the amount of acoustic pulses of strain and, consequently, to determine the current strain diagram corresponding strain of the material. A measure of accuracy in the determination of this point consists of the loading device measure of inaccuracy, a measure of inaccuracy of detection of acoustic signals and the approximation measure of inaccuracy. Thus, the total measure of inaccuracy to predict the damage degree, as a consequence, the prediction measure of inaccuracy of the remaining resource life does not exceed 9% [7].

3. Conclusion

Existing methods for assessing the endurance and the remaining operational life include insufficient mathematical modeling techniques and accurate assessment of accumulated damage during the operation and impact of this damage on the strength of quality.

Modern NDT method – the method of acoustic emission – was proposed for detailed assessment and lifetime prediction. The proposed methodology of fracture prediction using acoustic emission allows evaluating resource use of products with high accuracy, as well as to determine the place of destruction.

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