QUANTIFIABLE MEASURES OF THE STRUCTURAL DEGRADATION OF CONSTRUCTION MATERIALS

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Summary

The authors have outlined a method for analysing the fatigue degradation of mechanical structures described in terms of variations in the mobility of dynamic impedances, their real and imaginary parts and fluctuations in the strength of dynamic rigidity and the strength of the internal damping of structures expressed as a function of degradation time (the number of degrading impulse impacts). The variations are identified over the full scope of destruction ranging from nucleation to dominant fracturing. Such an identification is carried out by the method of experimental modal analysis and by energy-based methods with the use of a mechatronic accelerated testing station. The paper provides definitions of the related measurable measures of the process[6]. The point is illustrated with an overview of selected strength characteristics of modern construction steel.

Keywords: structural changes, dynamic mobility, impedance, mode, work of damping forces

MIERZALNE MIARY PROCESU DEGRADACJI STRUKTURALNEJ MATERIAŁÓW KONSTRUKCYJNYCH

Streszczenie

Przedstawiono zarys metody analizy procesu degradacji zmęczeniowej struktur mechanicznych, opisanej przez charakterystyki zmian mobilności dynamicznych, impedancji, ich części rzeczywistych i części urojonych oraz zmian mocy sił sztywności dynamicznych i mocy sił tłumienia wewnętrznego struktur w funkcji czasu procesu degradacji(liczba degradujących uderzeń impulsowych). Charakterystyki te wyznacza się w pełnym zakresie procesu niszczenia od nukleacji do dominującego pęknięcia metodą eksperymentalnej analizy modalnej i metodami energetycznymi z zastosowaniem mechatronicznego stanowiska badań przyspieszonych. Praca zawiera definicje mierzalnych miar procesu. Jako przykład zamieszczono wybrane charakterystyki właściwości wytrzymałościowych nowoczesnych stali konstrukcyjnych.

Słowa kluczowe: zmiany strukturalne, mobilność dynamiczna, impedancja, mod, praca sił tłumienia

1. INTRODUCTION

The knowledge of fatigue strength is essential in many areas of structural design, particularly where key machinery comes into the picture. Mechanical structures are damaged wherever external impact alters structural properties while the continuous accumulation of energy elevates it beyond border values causing the destruction of a pivotal structural item[19]. To reflect the nature of such processes, degradation of mechanical structures has been described in terms of energy parameters.

Degradation processes in materials and building structures have an energetic dimension [8]. Changes in the parameters of structural materials will be described by an analysis of non-stationary profiles (shown as a function of degradation time) of power spectral density of damping forces (internal friction) and, separately, power spectral density of dynamic rigidity forces as well as the work of forces causing degradation determined on that basis. The destruction of node sets in a mechanical system is described by a holistic energy model of loads[15].

2. THE CONCEPT BEHIND THE MODEL OF MECHANICAL STRUCTURE DEGRADATION

A holistic model of the load shifts which occur in the course of the degradation of a mechanical system can be described as a matrix of the spectral densities of dynamic loads [10, 3].

$$\left\{G_{N_{ik}}\left(j\omega,\Theta\right)\right\} = \mathrm{H}_{V_{ik}}\left(j\omega,\Theta\right)\cdot \mathrm{G}_{F_k F_k}\left(j\omega,\Theta\right), \quad (1)$$

where: $\mathrm{H}_{V_{ik}}$ – dynamic mobility matrix,

G$_{FF}$ – external forcing actions spectral density matrix,
k – application points of external forcing actions (components F_{kx}, F_{ky}, F_{kz})[1],
i – points of discrete stress tensor model, $i = k_1, k_2 \dots k_n, \dots r$.

Dynamic mobility is determined by spectral densities with account taken of frequencies of the vibrations and the impacts of the forces which degrade the structure:

$$H_{V_{ik}}(j\omega,\Theta)=\frac{G_{VF}(j\omega,\Theta)}{G_{FF}(j\omega,\Theta)}. \quad (2)$$

The dynamic resistance of a system which undergoes changes in the course of degradation is measured by mechanical impendence which in turn can be determined by the spectral densities of impact and response signals:

$$R_{V_{ik}}(j\omega,\Theta)=\frac{G_{FF}(j\omega.\Theta)}{G_{VF}(j\omega,\Theta)}. \quad (3)$$

The structure of a sample (i.e. all of its internal features) changes during the degradation of a system (a machine component or a material sample) taking place over degradation time Θ[3].

Due to its holistic nature, the modelling of the destruction of structures entails describing their behaviour in terms of physical processes whose individual components of the matrix of the distribution of dynamic loads, which are a function of dynamic time t or frequency, are determined in the function of the long time Θ they take to succumb to degradation. The real components of such a load provide a measure of the internal dissipation which causes the structural degradation of a structure[11].

The work performed by external forcing impact equals changes in rigidity and the effects of the system's damping forces which in turn are a measure of its degradation. The value of the work performed is a function of the measures of vibration damping and amplitude. Such a value reaches its peak when brought into resonance.

The degradation capacity of a structure (material sample) equals the total work of structural degradation

$$L_{degr.}=\int_{\Theta_0}^{\Theta_r}\mathrm{Re}\,N_{kk}(\Theta)d\Theta+\frac{1}{2}\int_{\Theta_0}^{\Theta_r}\mathrm{Im}\,N_{ik}(\Theta)d\Theta . \quad (4)$$

The energy capacity of construction material is defined as the work of the degradation forces which exert an impact upon the sample (item) multiplied by its capacity υ, i.e.:

$$P_m=\frac{1}{\upsilon}\left[\int_{\Theta_0}^{\Theta_r}\mathrm{Re}\,N_{kk}(\Theta)d\Theta+\frac{1}{2}\int_{\Theta_0}^{\Theta_r}\mathrm{Im}\,N_{ik}(\Theta)d\Theta\right]. \quad (5)$$

Changes in the dynamic state of a mechanical structure described by the energy characteristics of vibration loads provide a significant indication of the resulting alterations and changes occurring within its structure. By focusing on the imaginary and real components of the strengths of degradation forces seen as functions of frequency, changes (peak shifts) in such functions may be identified. Shifts in extreme values of the relevant characteristics and the occurrence of valleys (anti-resonants) in the energy characteristics of dynamic rigidities offer general insights into preliminary stresses found in the structure and suggest the degrees of degradation exerted upon a mechanical structure manifested as changes in dynamic rigidity. Changing vibration damping forces, which affect the dissipation of mechanical energy, determine the structural degradation of mechanical structures over the duration of this process. Changes in dynamic rigidities manifesting themselves with cracking reach their highest intensities predominantly in the final stages of the technical degradation of mechanical structures. An analysis of such changes allows one to define the border loads which initiate the structural degradation of mechanical structures (in the form of e.g. cracking)[2].

3. RESEARCH POSITION

The research position comprised mainly of an automated impact control unit, an electro-dynamic hammer, troughs for measuring impulse impact forces and vibration accelerations, a dual channel analyser, a computerized data transmission and retransmission system as well as a post-processor for calculating energy values and characteristics in multi-dimensional space.

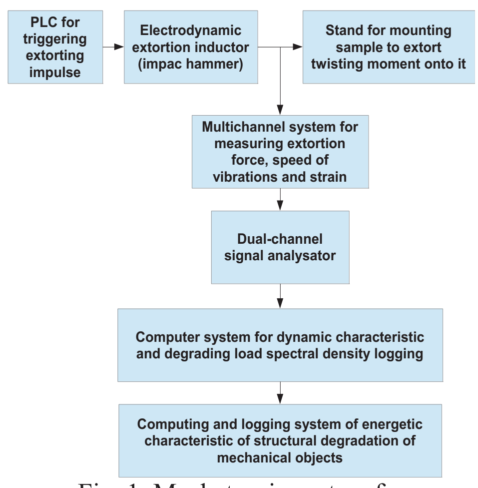


Fig. 1. Mechatronic system for determination of characteristict of structural degradation of mechanical objects[13]

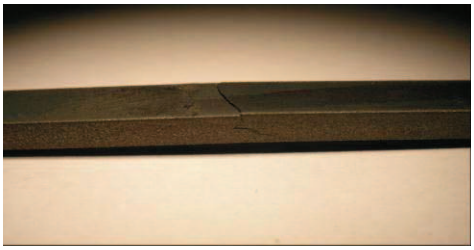


Fig. 2. Photograph of a fatigue-fractured sample of construction steel

The authors carried out a comparative study of the fatigue strength of construction steel samples and laser weld joints of samples having the same dimensions. They determined the characteristics of the structural destruction of metal sheet samples cut with a water jet along and across rolling direction. Destruction to the point of fracture formation took several to over twenty hours – duration time was longer for solid samples and shorter for welded ones (Fig. 4 and 5).

4. DEGRADATION CHARACTERISTICS AND EXAMPLES

Relevant units of dynamic mobility **H** (f, n) and their real (Re) as well as imaginary (Im) components, units of mechanical impendence **R** (f, n) as well as their real and imaginary components and units of dynamic load as well as their real and imaginary components were marked on a vertical axis representing structural degradation characteristics. The horizontal axes of three-dimensional graphs were used to represent frequencies (in Hertz) and degradation time (in minutes). The minute scaling of the time axis was subsequently replaced with number **n** of the impulses brought to bear on each tested material sample.

When reviewing such characteristics, note the logarithmic or linear scales of amplitudes of individual physical parameters. Graphs of the spectral densities of real load power components describe the structural degradation resulting from changes in the internal structures of the tested materials (damping). On the other hand, the graphs showing the spectra of spectral densities of the imaginary components of degradation load powers describe changes in sample rigidity to cracking point. Load power graphs N(t) are non-linear characteristics of sample degradation.

In analysing the graphs of spectral density spectra depicting parts of real loads and the structural degradation of individual samples, note should be taken of changes in the components of such spectra and the new induced components of the function of the number **n** of degrading impulses.

The documentation of study findings provides characteristics of various materials and samples and is helpful in drawing characteristic comparisons. A comparison has been offered of the selected characteristics of modules, real (Re) and imaginary (Im) components of dynamic mobilities, impendence modules R, their real and imaginary components and changes in the strength of dynamic rigidity and damping forces shown as a function of process degradation time (the number of degrading impulse impacts) over the full range of destruction from nucleation to dominant fracturing.

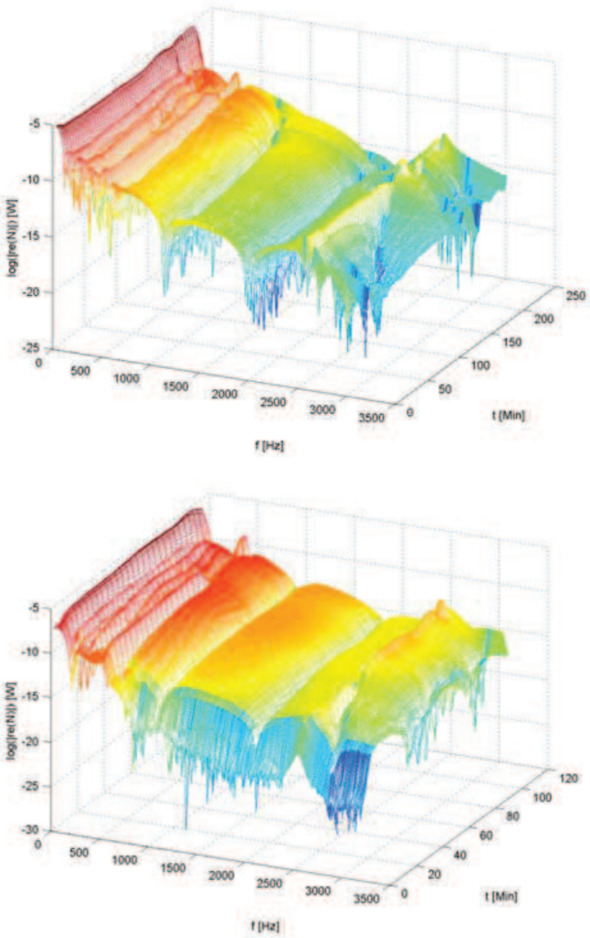


Fig. 3. Graphs representing the power of damping forces logReN(f, t) as a function of steel sample degradation time following its electrical welding (figure below)

The number of impacts and the work of structural degradation forces vary from one construction material to another. Degradation characteristics are selected from a full set of characteristics of a wide range of samples. Such characteristics include specific information on changes in the structure at hand in its degradation process until fracture. A comparison and an analysis of the characteristics shown in the figures suggests specific conclusions.

The authors compiled the selected degradation characteristics for steel samples E and F without welding and with laser welds as well as an electrically-welded sample. Variations have been found in the modes of internal structure change force powers and the steel sample and electrically-welded sample degradation time (Fig. 3).

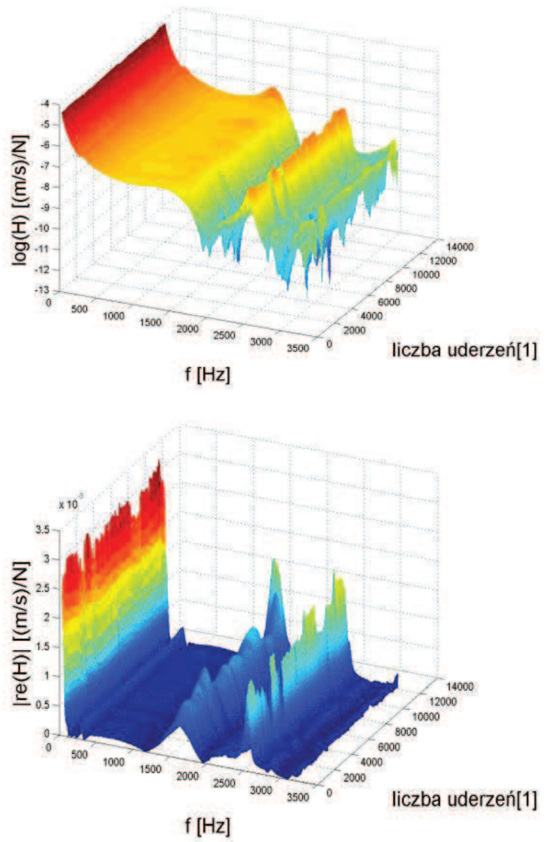
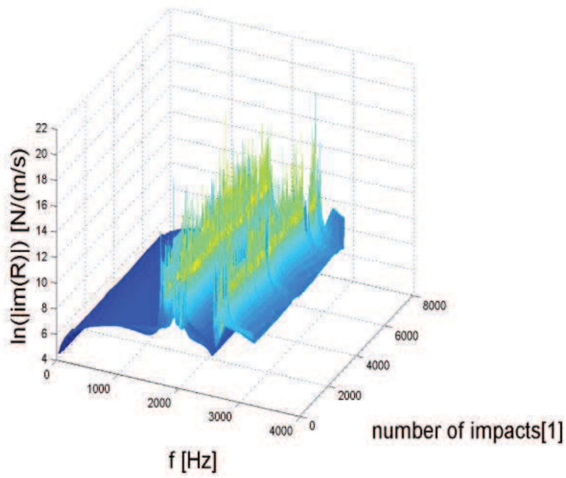


Fig. 4. Characteristics of structural degradation of welded steel sample E1

Changes in the amplitudes of dynamic mobility and impendence modes[12, 17] are essential (Fig. 3 to 5). The fact that the numbers of degrading load impulses and the changes in dynamic mobility and impendence mode amplitudes varied significantly has suggested substantial discrepancies in sample durability.

The characteristics include four intensive modes of the real part of dynamic resistance (Fig. 4 to 6). The energy characteristics of sample degradation take the form of rigidity ImN(n) and damping force ReN(n) graphs (Fig. 6).



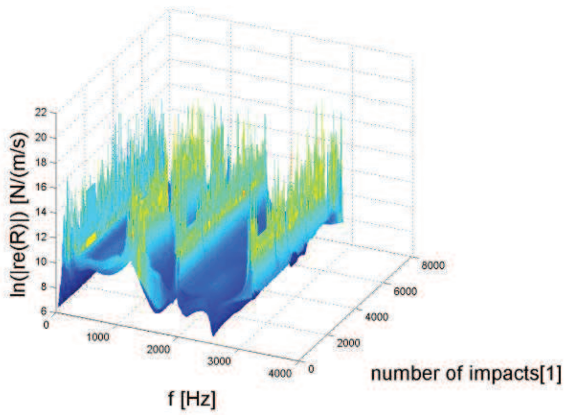


Fig. 5. Changes in mechanical impedances Im**R**(f, n) and Re**R**(f, n) during the degradation of steel sample F4

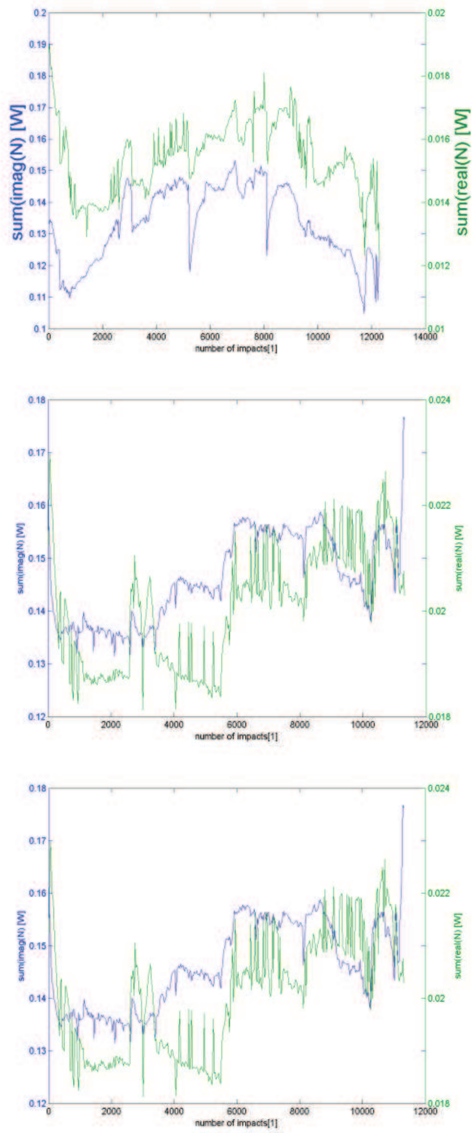
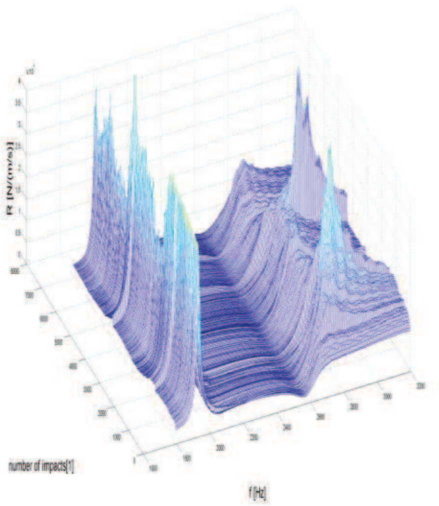


Fig. 6. Changes in the characteristics of rigidity forces Im**N**(n) and damping force powers Re**N**(n) causing the degradation of samples E8, F8, E3 (welded)

A symptom of structure degradation are changes in its dynamic properties manifesting themselves with variations in dynamic mobilities and mechanical impedances presented as a function of the number of degrading energy doses applied to the structure. Changes (declines and increases) in the frequency **f** of dynamic characteristic modes indicate alterations in the internal structure (damping) and the dynamic rigidities of structures (Fig. 7 through 8). A case in point is an increase in mode frequency, which is symptomatic of the strengthening of material structure.



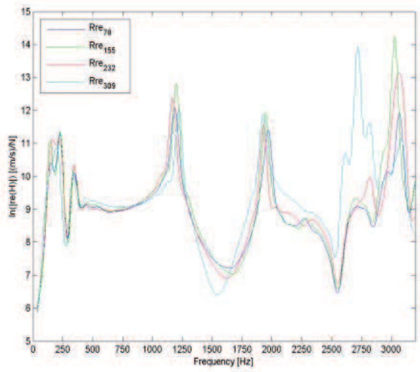


Fig. 7. Changes in impedance (dynamic resistance) Re**R**(f)(E8)]

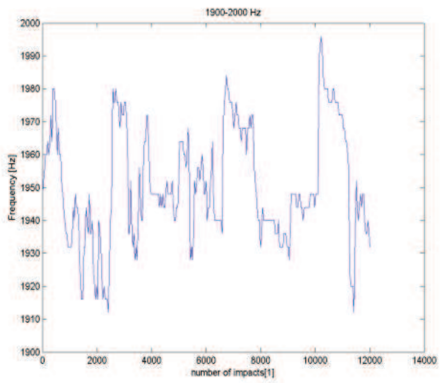


Fig. 8. Periodic changes in **frequency f** of impendence mode Re**R**(n)(E8)

The cumulative effects of loads which degrade a mechanical structure[9] are reflected in the curve of successive incremental growth in the work of structure degrading forces:

$$\Delta\ L\ (\mathrm{k}) = \sum_k \left[L_k(dL) \right], \qquad (6)$$

where: k=0, 1, 2,…n – successive region of degrading impacts,

$L_k(dL)$ - work of degrading force performed after **k** impacts,

dL – unit dose of the work of structure degrading forces.

The shape of curve $N_d(\Theta)$ indicates a trend in material sample degradation (Fig. 9).

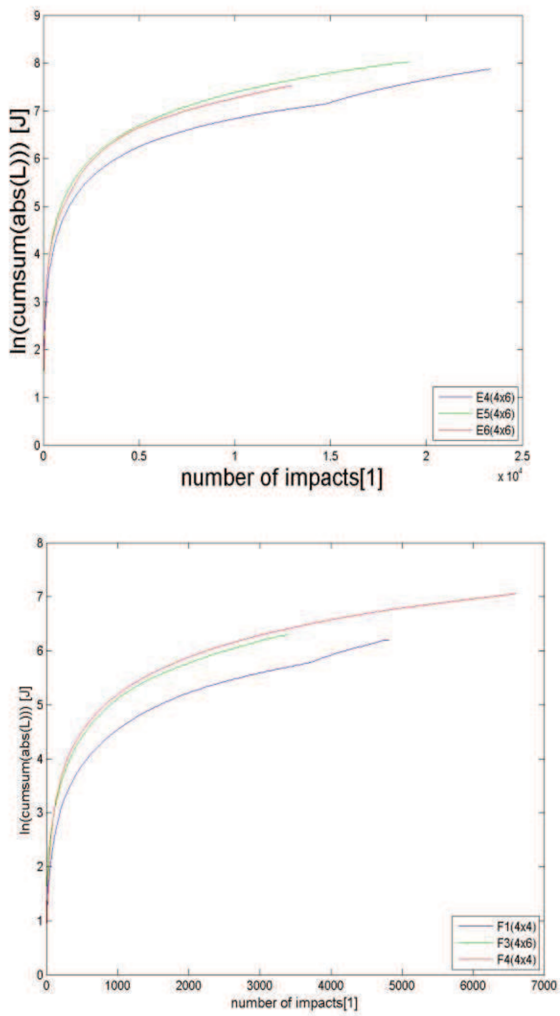


Fig 9. Comparison of graphs showing the accumulation of forces which cause the structural degradation of steel samples (,F1, F3, F4)

By integrating the energy degradation function $N(\Theta)$ (Fig. 6) while accounting for individual impulse powers, the authors determined the work of degradation forces L_d (the work of the rigidity force and the work of structural dissipation forces L_{dys}) as well as the unit work of degradation forces L_{dj} and the unit work of structural dissipation forces $L_{dysj.}$

The energy **degradation capacity** of a material sample equals the total structural degradation work. The table shows energy characteristics of the structural degradation sustained by selected construction steel samples.

Energy calculations suggest that the durability of electrical welds is a function of welding parameters. In the case of laser welding, on the other hand, the fatigue strength parameters of steel E exceed those of steel F durability.

An important measure of fatigue durability is provided by the percentage share of the work of sampling forces (which is a measure of changes in the internal structure of a material) in the total work of degradation forces. Information on the energy values of the amplitude measures of fatigue durability has found its application in construction diagnostics and specifically in the design of machinery components which are reliable in terms of their durability. For the purposes of control diagnostics, use can be made of a methodology for studying the modes of dynamic characteristics which provide a measure of changes in the properties of mechanical structures undergoing technical degradation.

Table.1. Energetic parameters of construction steels durability

Energetic measures	Type of sample						
	5(wel. par.: 221A, 80cm/min)	**9**(wel. par.: 190A, 65cm/min)	**15**(wel. par.: 202A, 65cm/min)	E1(wel. laser) (4X6)	E3(wel. laser) (4x6)	E4 (4X6)	F4 (4X4)
L [J]	420	720	683	1580	1657	2634	1158
L_{Im} [J]	416	715	678	1564	1646	2613	1155
L_{Re} [J]	57	76	71	196	190	334	97
$\frac{L_{Re}}{L}$[%]	13,5	11	10	13	11,5	11,5	8,4
$\frac{L}{S}[\frac{J}{mm^2}]$	15			66	70	110	
$\frac{F}{S}[\frac{N}{mm^2}]$	29			38	38	38	44
$\frac{L}{V}[\frac{J}{mm^3}]$							1,6

5. CONCLUSIONS

1. Structural degradation characteristics can be broken down into the phases of nucleation, steady increases in non-elastic deformations, and the brief rapid rise of non-elastic deformations.
2. Varying vibration damping, which is a factor in the diffusion of mechanical energy, is a measure of the structural degradation of a mechanical structure. Changes in dynamic rigidities, which manifest themselves with cracking, occur in the final phase of the technical degradation of a mechanical structure. An analysis of such changes facilitates the determination of border load values which trigger the structural degradation (e.g. cracking) of mechanical structure components.
3. At the peaks of their dynamic mobilities, samples which reach the final stages of degradation undergo cracking. The fact that characteristic peaks shifted and that mode frequencies in energy characteristics declined (or increased) goes to confirm that the concerned mechanical structure has degraded.
4. Similarities in spectrum shapes of real and imaginary parts, dynamic mobility modules and the spectra of loads impacting upon the mechanical systems in question, as well as changes in parameters such as a function of the number **n** of the applied impulses show that structural degradation depends on changes in dynamic properties, i.e. changes in the internal structure of materials leading to structure cracking.
5. Changes in the internal structure and structural rigidities which represent modifications of the structure's dynamic resistance, contribute to unstable changes in process characteristics.

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