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Description of Fatigue Damage Using a Damping Monitoring Technique

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Abstract

The fatigue behavior of materials has been estimated using many different experimental techniques in order to describe damage. Fatigue damage may increase the risk of failure under cyclic load. Energy dissipation occurs in engineering metals as a function of the cyclic loading history. In order to measure energy dissipation, a damping monitoring method that estimates damping factor by vibration excitation has been used in this study. Under constant cyclic axial loads, 50% and 70% of ultimate strength, the effects of the number of fatigue cycles on the damping factor were measured for two different low carbon steels. The experimental results showed that the damping factor changes with the number of fatigue cycles.

Key words: Fatigue, Damping, Damping factor, Steel, Vibration.

Introduction

Damping is an important model parameter for the design and analysis of vibrating structures. The damping in combined and complex structures is often dominated by losses at joints etc. In addition, all engineering materials dissipate energy during cyclic deformation. Some of them, such as elastomers, plastics and rubber, dissipate much more energy per cycle of deformation than metallic materials under the same stress ratio. Because of complexity and being a part of the design process, the damping of materials and structures is usually determined experimentally.

The damping of metallic materials varies with different environmental effects, namely frequency (Carfagni and Pierini, 1999), amplitude of strain (Whaley *et al.*, 1984), and temperature (Shenglong *et al.*, 1998). In addition, damping is affected by corrosion fatigue (Eid, 1988), grain size, and porosity (Zhang *et al.*, 1993). Damping also depends on the number of fatigue cycles (Dorn, 1982). There is a functional relationship among damping, the number of cycles and applied stress (Çolakoğlu and Jerina, 2002).

The relationship between damping and the number of fatigue cycles depends on many factors, such as the mechanical properties of the material, heat treatment, and whether the material is metallic or composite. Furthermore, measurement methods and test types such as axial, bending vibration, rotating bending, and torsion tests are effective. Energy absorption has been experimentally studied by Dorn (1982) as a function of the applied stress and the number of cycles in an annealed structural steel (ASTM A 242-64 T). Energy dissipation was increased with fatigue cycles using a resonance test machine with an electromagnetic drive mechanism. In addition, absorbed energy was measured using bending rotating fatigue test for SAE 4340 steel (Feltner and Morrow, 1961). Damping was used as a parameter to determine the relationship between stress history and stress amplitude by Lazan (1968) and the phenomenon of plastic strain was analyzed in a low carbon steel. If the maximum stress amplitude is over the critical stress level, damping increases permanently with the number of fatigue cycles. However, using a 355 stainless steel/2024-T8 aluminum alloy composite, a constant damping was computed for specimens subjected to different stress amplitudes covering a range of cyclic life in axial fatigue tests (Varschavsky and Tamayo, 1969).

To describe the relationship between stress history and stress amplitude and their effects on damping, a non-destructive monitoring method (Çolakoğlu, 2001) was used in this study to measure the damping factor experimentally.

Damping

Damping is a phenomenon and a material property that can be described as mechanical energy dissipation under cyclic stress. Damping is classified in many different ways but the three major mechanisms of damping are material (internal) damping, structural damping, and fluid damping (De Silva, 1983).

Material damping results from mechanical energy dissipation during cyclic deformation within almost all engineering materials. Structural damping occurs when the mechanical energy dissipation is caused by rubbing friction resulting from relative motion between members in a structure that has common points of contacts or joints. Fluid damping can be described as if a member of the system moves in a fluid, the mechanical energy caused by drag forces is dissipated.

The relationship between stress (σ) and strain (ε) is called a hysteresis loop under cyclic loading. The energy dissipation per unit volume of the material, per stress cycle, is given by the area of the hysteresis loop. This is termed specific damping energy, D.

$$D = \oint \sigma d\varepsilon \tag{1}$$

Hysteretic damping, based on the concept of a complex modulus, is used to describe the response of a harmonic oscillator in a steady state condition. Lazan (1968) considered damping to be associated with hysteresis loop effects, so that "rate independent linear damping" would be applicable. The major difference between viscous damping and hysteric damping is that the energy dissipation depends linearly on the frequency of oscillation for a viscous system; on the other hand, it is independent of the frequency for a hysteric system (Nasif et al., 1985):

In terms of the complex modulus for a viscoelastic material in response to a harmonic oscillator, the equation of motion can be shown as (Dimarogonas, 1996)

$$m\ddot{x} + k\,(1 + i\eta)\,x = F_0 k e^{iwt} \tag{2}$$

For the steady state condition, the solution of equation (2) is the same as the solution of

$$m\ddot{x} + \frac{\eta k}{w}\dot{x} + kx = F_0 k e^{iwt} \tag{3}$$

where the equivalent viscous damping constant is $c = \eta k/w$. Viscous and hysteretic damping energies can be rewritten in terms of E and ε as

$$D_{vis} = \pi c w \varepsilon^2 \tag{4}$$

$$D_{hys} = \pi \eta E \varepsilon^2 \tag{5}$$

Experimental Procedure

The damping factor was measured experimentally using a damping monitoring technique (Çolakoğlu, 2001). First, a specimen with a small hole in one end was attached from the hole using a thin wire to measure the damping factor with free-free boundary conditions (Figure 1). Using wax, an accelerometer was placed 13 mm away from the midpoint, where deformation is maximum in bending vibration tests. A steel ball with a thin wire for handling was used to strike and induce vibrations in the specimen. The accelerometer measured the vibration and produced an electrical signal that was amplified by the amplifier and then input to the computer. An FFT transform was performed for the signal providing a measurement of the longitudinal natural frequencies of vibration modes. The computer used as an acquisition system determined the damping factor from the induced vibration by the half-power bandwidth method.

Bending vibration fatigue test was conducted to describe fatigue integrity in 1018 hot-rolled and cold-drawn carbon steels. The specimens were clamped at the midpoint to balance. The width of the clamp was 25.4 mm. An electromagnetic shaker (VTS, model VG 100-6) was used to vibrate the specimen. The maximum stresses were 50 and 70% of the ultimate strength of the specimens. The bending vibration fatigue test was stopped after a period of fatigue cycles to measure damping factors and frequencies for the first three vibration modes.

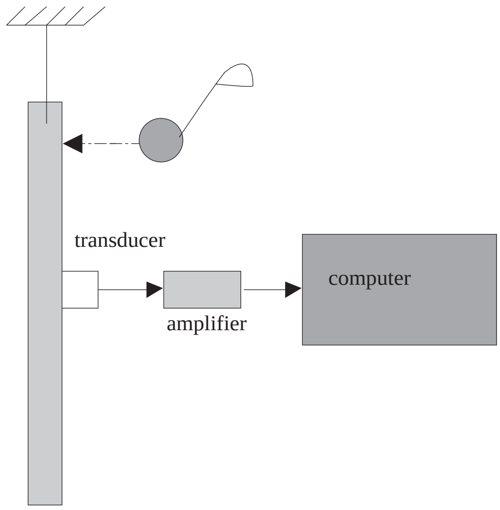

Figure 1. Diagrammatic view of monitoring method.

Experimental Study and Discussion

The damping factor was measured for the first three bending modes in 1018 hot-rolled and cold-drawn carbon steels with free-free boundary conditions. The initial average damping factor values and frequencies before fatigue are shown in Table 1. Because of work hardening, the logarithmic decrement in time response or the damping factor in frequency response is less for 1018 cold-drawn carbon steel. The beam's length was 508 mm and the cross-sectional area was 3.2×19.1 mm^2. Furthermore, the maximum stress was approximately 0.1 MPa when vibrations were induced in the specimen. The ultimate strength, elongation, and hardness (Rockwell-B) are given in Table 2 for both steels.

Using the damping monitoring method, a typical frequency response curve for a single degree of freedom system in 1018 hot-rolled carbon steel with free-free boundary conditions is shown in Figure 2. The damping factor can be estimated directly from the frequency response curve by the half-power bandwidth method. The first peak amplitude, which is the first natural frequency of several vibration modes in the specimen, is chosen for measurement of the damping factor (Figure 3).

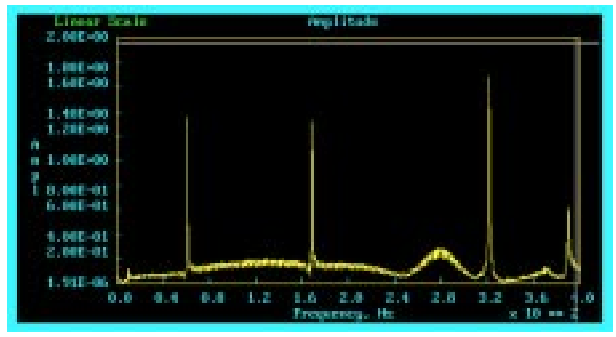

Figure 2. Frequency response for single degree of freedom system in 1018 hot-rolled carbon steel beam (L = 508 mm & t = 3.2 mm).

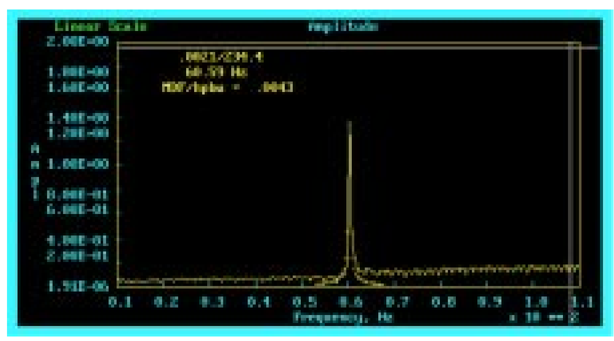

Figure 3. Measurement of the damping factor for the first vibration mode in Figure 2.

Table 1. Measured damping factors for the first three bending modes

Materials	f_1 (Hz)	$\zeta_1(10^{-5})$	f_2 (Hz)	$\zeta_2(10^{-5})$	f_3 (Hz)	$\zeta_3(10^{-5})$
1018 HR Carbon Steel	65	440	181	146	348.5	80
1018 CD Carbon Steel	63.2	390	176.3	140	339.7	83

Table 2. Mechanical properties.

Materials	S_u (MPa)	Elongation (%)	Hardness (HRB)
1018 HR Carbon Steel	393	32	67
1018 CD Carbon Steel	859	5	95

1018 hot-rolled carbon steel

1018 hot-rolled carbon steel specimens were loaded with completely reversed cyclic stress. In these experiments, the stress was 45, 50 and 70% of the tensile strength. Damping factors and frequencies were measured for the first three vibration modes after some fatigue cycles.

The measured damping factors versus the number of fatigue cycle and the linear curve-fit of the measured results are shown in Figure 4 for the first vibration mode. The damping factor increases with fatigue cycles as expected. The increase is low up to fatigue crack initiation and a significant increase is seen in energy dissipation up to fracture after crack initiation, which occurs after 2.5×10^5 cycles for $\sigma = (0.45)S_u$, 1.4×10^5 cycles for $\sigma = (0.5)S_u$, and 7×10^4 cycles for $\sigma = (0.7)S_u$. On the other hand, frequencies for vibration modes stay constant until crack initiation and decrease up to fracture.

To improve accuracy, the damping factor was measured at least 10 times at every point. The coefficient of variation, which is equal to standard deviation divided by mean (cov. $= \sigma/\bar{x}$), is from 0.035 to 0.083 for $\sigma = (0.45)$Su, from 0.049 to 0.108 for $\sigma = (0.5)$Su, and from 0.054 to 0.088 for $\sigma = (0.7)$Su in the first mode.

1018 cold-drawn carbon steel

The 1018 cold-drawn carbon steel used in this study is a brittle material that is elastic up to approximately (0.99)Su. Fatigue life is very short compared to 1018 hot-rolled carbon steel under the same stress ratio but energy dissipation per cycle is higher because the slopes are steeper in 1018 cold-drawn carbon-steel (Figure 5). Fatigue cracks initiate after 2.5×10^4 cycles for $\sigma = (0.5)S_u$, and 1.6×10^4 cycles for $\sigma = (0.7)S_u$.

The coefficient of variation of the damping factor is from 0.042 to 0.087 for $\sigma = (0.5)$Su, and from 0.027 to 0.095 for $\sigma = (0.7)$Su in the first mode.

Using equation (5), we need to describe η and ε for calculating damping energy. η is a function of N and is described as 2ζ. The measured ζ-N relations and linear curve-fit of the results up to crack initiation are available in Figures 4 and 5. $\zeta = \zeta_0 + \delta N$ where ζ_0 is initial damping factor (N = 0) and δ is the slope of the lines. Replacing η with ζ in the elastic region, equation (5) becomes

$$D_{hys} = \frac{2\pi}{E}(\zeta_0 + \delta N)\sigma_a^2 \qquad (6)$$

The variation in damping energies calculated by equation (6) with the number of cycles is shown in Figure 6. The percentage increases, $(D_i - D_0)/D_0$ where i = 1,2,..N, in 1018 hot-rolled carbon steel until crack initiation are almost the same. They are about 10% up to 1.4×10^5 cycles for $\sigma = (0.5)S_u$ and 7×10^4 cycles for $\sigma = (0.7)S_u$. On the other hand, damping energies increase approximately 8% for $\sigma = (0.5)S_u$ up to 2.5×10^4 cycles and 16% for $\sigma = (0.7)S_u$ up to 1.6×10^4 cycles in 1018 cold-drawn carbon steel.

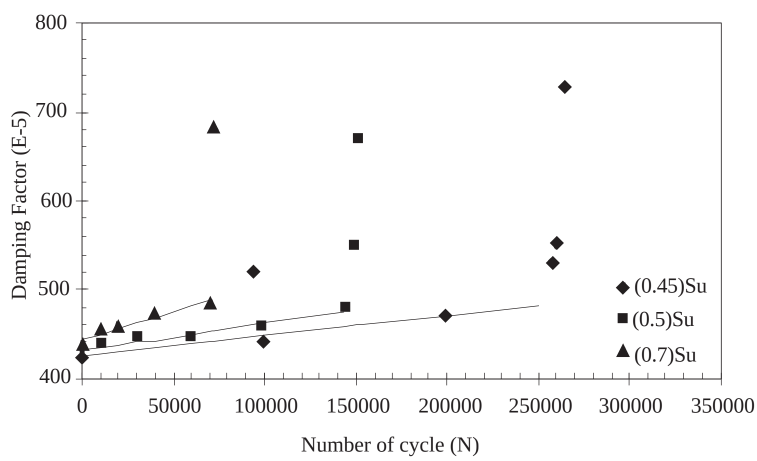

Figure 4. Measured damping factors for 1018 hot-rolled carbon-steel under bending vibration load.

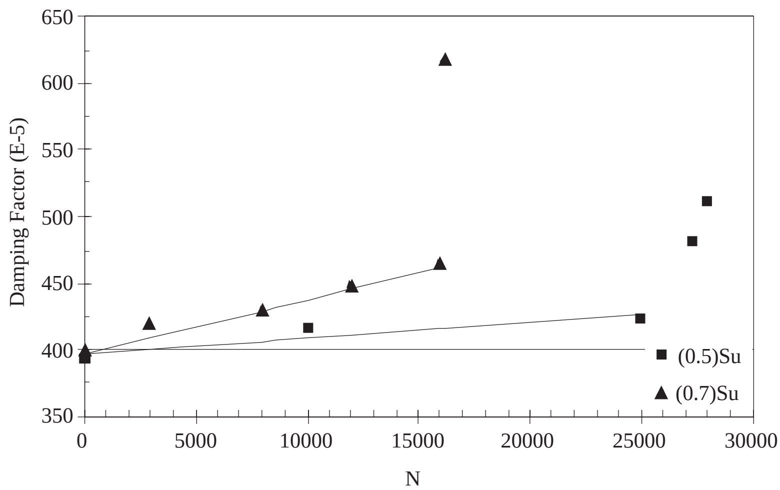

Figure 5. Measured damping factors for 1018 cold-drawn carbon-steel under bending vibration load.

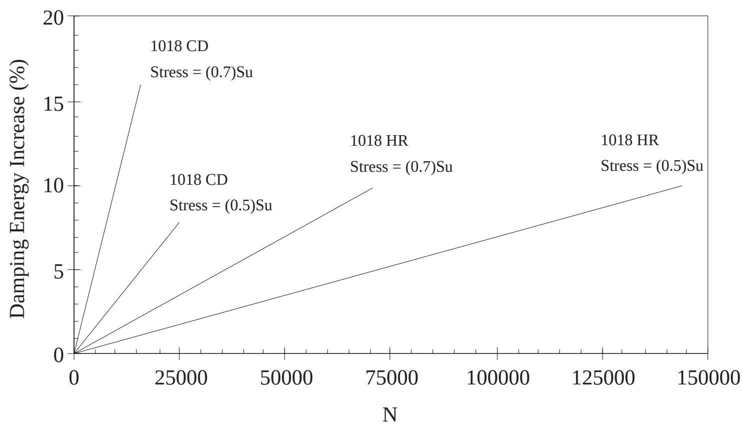

Figure 6. Variation in damping energy calculated by equation (6) with the number of cycles.

Conclusion

Using the damping monitoring method, the damping factor as a function of stress amplitude and the number of cycles was determined experimentally in two different low carbon steels. The damping factor increased with the number of fatigue cycles. Fatigue cracks initiated after 1.4×10^5 cycles for $\sigma = (0.5)S_u$, and 7×10^4 cycles for $\sigma = (0.7)S_u$ in 1018 hot-rolled carbon steel, and after 2.5×10^4 cycles for $\sigma = (0.5)S_u$, and 1.6×10^4 cycles for $\sigma = (0.7)S_u$ in 1018 cold-drawn carbon steel. Fatigue life was very short in 1018 cold-drawn carbon steel compared to 1018 hot-rolled carbon steel under the same stress ratio, but energy dissipation was high. Increases in damping energy were calculated using experimental data. The percentage increases were about 10% up to 1.4×10^5 cycles for $\sigma = (0.5)S_u$ and 7×10^4 cycles for $\sigma = (0.7)S_u$ in 1018 hot-rolled carbon steel until crack initiation. On the other hand, damping energies increased approximately 8% for $\sigma = (0.5)S_u$ up to 2.5×10^4 cycles and 16% for $\sigma = (0.7)S_u$ up to 1.6×10^4 cycles in 1018 cold-drawn carbon steel.

This application can be used in the aircraft, and automobile industries and in vibrating structures in which fatigue damage is an important factor.

Nomenclature

D	damping energy
E	Young's modulus
f	frequency (hertz)
F	force
k	spring constant
N	number of cycles

Su	ultimate tensile strength	η	loss factor
$\times$	displacement	σ	stress
w	frequency (rad/s)	σ_a	amplitude of stress
δ	slope of the curve	ζ	damping factor
ε	strain		

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