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Fatigue damage identification by means of modal parameters

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Abstract

Object of the present paper is an experimental investigation about high cycles fatigue damage and corresponding variation of modal parameters (internal damping and resonance frequency) in steel specimens. On the basis of a modal approach, a mixed technique has been developed in order to relate fatigue damage and intrinsic properties of the material. The experimental procedure consists of the modal parameters assessment on steel specimens, once before fatigue test beginning, and thus repeated after every 10^5 cycles, both with constant and increasing loading levels. Infrared thermography has been used to emphasize the specimen thermal emission and the related damage phenomena.

Keywords: Fatigue Damage; Internal Damping; Resonance Frequancy; Modal Analysis; Infrared Thermography; Steels.

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1. Introduction

One of the main effects of the well-known fatigue damage phenomenon is the material properties deterioration.

As a first meaningful example, during the Fifties several studies were conducted about the possibility of a correlation between fatigue damage and internal damping variation, focusing above all on metals.

Some original experimental techniques and mathematical models were proposed (see a wide panorama in [1]), based on hysteresis loop measure and analysis. In particular, Professor Lazan's studies involved the measurement of both damping energy and dynamic modulus of elasticity (considerable a physical quantity related to the elastic modulus value); damping energy and dynamic modulus of elasticity were respectively related to the hysteresis loop area and the corresponding slope values. Depending on the so called stress history, in [1] and [2] he showed an increase for the first parameter, due to a bigger tendency of the material to dissipate energy under heat form, and a decrease for the second one.

More recently, several remarks on internal damping have been proposed in [3], where, on the basis of a huge number of experimental studies performed in Soviet Union, it has been assumed as microplasticizations activation indicator (a phenomenon highly related to fatigue damage [4]).

In the last two decades, at least two research groups have continued their experimental activity on damping variation during fatigue tests: in [5], after having modified the Amsler Vibrophore internal damping measurement methodology, a theoretical relationship between thermal increase in fatigued specimens and internal damping

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augmentation (above all, close to yield stress) was found and experimentally validated; in [6], modal analysis experimental tests are conducted on metals, elaborating both internal damping and resonance frequency results on metallic beams. The base of the modal analysis technique to assess internal damping is described in [7], where, by the way, it is applied on high damping alloys characterization and not on fatigue behavior study.

In conclusion, in these papers material behavior is mainly justified referring more to dislocation motions and microplasticizations activation than microcracks initiation and/or propagation.

A second remarkable example of material parameters sensitive to damage comes from resonance frequency analysis of the specimen. A wide number of papers (some examples in [8]) have been written about this subject: they treat concrete or steel rectangular beams, whose resonance frequency is measured before and after the realization of an artificial crack. Thus, several analysis were drawn on the effect of its position and dept on the acquired results. In general, the aim is not the fatigue behavior analysis, but the use of resonance frequency measurements as non destructive techniques to monitor cracks in civil structures.

So, in conclusion, it may be stated that, even if a lot of efforts has been done, a clear and comprehensive panorama about the phenomena related to modal parameters variation requires further work.

Object of this paper is to present the first results of a mixed methodology consisting in fatigue cycles and modal parameters monitoring, on the basis of previous experiences ([9], [10], [11]) completed by uncertainty measurement calculation, according to [12].

In particular, the aim of this research activity is to understand if modal parameters may be considered as fatigue damage indicators and to relate them to heat production and transmission phenomena.

2. Experimental setup and processing technique

According to the literature ([3], [7]), the experimental setup (widely discussed in [9], [10] and [11]) used in this work in order to estimate the modal parameters is based on modal analysis.

The specimen is clamped in cantilever (free – clamped) boundary condition, using a parallel bench vise (whose features in terms of modal behavior are described in [9] and [10]) for machine tool as constraint, whose gripping force is repeatable thanks to the use of calibrated weights.

The input is given by an operator thanks to an instrumented hammer, that hit the frontal section of the specimen near the grip (40 mm from specimen edge). The output is measured by an accelerometer, mounted in the center of the frontal section. From the FRF (Frequency Response Function), expressed as Accelerance, Receptance is calculated, and modal parameters (modal damping and resonance frequency) are extracted for the second mode (according to [7]), using the Rational Fraction Polynomial Method [10].

Finally, measurement uncertainty range is statistically evaluated [10] on the basis of twice the standard deviation (i.e., 95% of confidence level) of twenty measurement replications for each session.

A first measurement session is firstly performed on the unfatigued specimen, in order to assess the modal parameters value before fatigue test and thus repeated at the end of each block of cycles (more details are given in Table 1).

The materials used for the experimental tests are two commercial carbon steels, C45 and C40.

Fatigue tests have been performed by means of both an Instron 8801 Servohydraulic machine (load cell 100 kN; testing frequency from 1 to 50 Hz; in this work: 20 or 30 Hz; load ratio R = 0.1) and an Amsler vibrophore 10 HFP 422 (load cell 100 kN; testing frequency from 60 to 300 Hz; in this work: about 160 Hz; load ratio: -1).

According to [9], [10] and [11], specimen geometry [10] has been chosen as a compromise between fatigue [13] and modal analysis test execution requirements (uncoupled flexural modes in two perpendicular planes).

In some cases, in order to evaluate the specimen thermal emission, fatigue tests has been monitored by the infrared thermo tracer NEC TH7102WX, supported by the Mikrospek Real Time dedicated software, having black painted the specimens surface in order to obtain a superficial emission coefficient equal to 0.9 and monitored the ambient temperature by means of a reference unstressed specimen of the same material [10].

In other cases, using the Instron machine features, also the hysteresis loops of the first 10^4 cycles have been acquired; during this measurement, the maximum allowed test frequency is of 10 Hz, which has been increased to 30 Hz to conclude the block; corresponding data have been elaborated by a dedicated Matlab® program, aiming at calculating the hysteresis loop area.

Table 1. Damping measurement – fatigue test complete execution sequence

Step	Action
1	Unworked specimen mounting on parallel bench and modal parameters measurement
2	Specimen dismounting from parallel bench and mounting on fatigue machine
3	The first block of cycles is performed and monitored with an infrared thermal camera
4	End of the block: specimen dismounting from fatigue machine, mounting back on parallel bench, modal parameters measurement
5	Steps 2 to 4 are repeated until the specimen failure. The blocks of cycles have constant stress and frequency values

3. Experimental Results and Discussion

Steels used for this work have been firstly characterized thanks to tensile tests (on at least 5 specimens) and Stair Case procedure [14], in order to evaluate ultimate strength R_m, yield stress $R_{p0.2}$ and fatigue limit σ_{D-1} in sinusoidal alternate traction – compression condition, with its scatter *s.* Such preliminary results have been reported in Table 2.

Table 2. Mechanical characteristics of studied steels

Steel	R_m [MPa]	$R_{p0.2}$ [MPa]	σ_{D-1} [MPa]	s [MPa]
C45	800	500	239	9
C40	775	612	202	7

Experimental tests performed in this work are resumed in Table 3; in particular, for each specimen, it is shown both material and identification number (*C45_1*, *C45_2*, …), the fatigue test machine and the testing frequency, the maximum stress σ_{max} , the load ratio R, the number of cycles N_b of each block, the total performed number of cycles N_f and the eventual measurement of hysteresis loops area (*HLA*); the use of infrared thermography (*IR*) is also indicated (*Yes/No*).

Specimens have been tested at different load levels (below, close to and above fatigue limit) and at different testing frequencies.

Specimens have been stressed to failure or $2*10^6$ cycles, using the same test frequency and load values for every block of cycles, with the exception of specimen *C40_1*, for which eight load steps of $2*10^4$ cycles have been executed until yield stress region (maximum stress of 250, 300, 350, 400, 420, 450, 500 and 550 MPa), and of specimen *C40_2*, stressed below the fatigue limit for only four blocks of $5*10^4$ cycles.

For sake of brevity, the results are resumed in three graphs (Figures 1, 2 and 3). The first one (Figure1) is devoted to the resonance frequency of all specimens, only reporting the mean value of each measurement session. The other ones (Figures 2 ad 3) involve the modal damping, respectively for *C45_4* and *C40_1* specimens; in particular, a comparison with hysteresis loop area and subtended area by thermal profile evolutions is reported. In these cases, to better compare data having different orders of magnitude, results have been normalized with respect to the first (Figure 2) or the last (Figure 3) value of each quantity.

Finally, it has to be remarked that, in order to reach the failure or $2*10^6$ cycles, some specimens have been tested for more than one day. In theses cases, one session of twenty modal analysis acquisitions has been performed at the beginning of the new day, before the first block of cycles, aiming at verifying the eventual effect of the nightly pause; such cases correspond in the graphs to the points joined by vertical lines.

From the analysis of Figure 1, it may be observed that, in general, the resonance frequency progressively decreases during the repeated blocks with loading levels close to the fatigue limit (specimens C45 from 1 to 3). The corresponding measurement uncertainty is very low (in general less than about 1 Hz). It may be also noted that, if the fatigue test is carried on during two or more days, at the beginning of the new test day, resonance frequency systematically seems to start by a value a bit major then the last one, how if some time-dependent phenomena (as stress relaxation) have take place in the material; this will be briefly indicate in the following as *recovery*. A similar phenomenon has been reported by Lazan [2].

Table 3. Tested specimen list and main features of performed experimental tests

Specimen Name	Testing Machine	Testing Frequency [Hz]	σ_{max} [MPa]	R [-]	N_b [-]	N_f	HLA	IR
C45_1	Instron	20	400	0.1	10^5	$6.41*10^5$	No	No
C45_2	Instron	20	400	0.1	10^5	$2.00*10^6$	No	No
C45_3	Vibrophore	160	230	-1	10^5	$6.44*10^5$	No	Yes
C45_4	Instron	30	420	0.1	10^5	$2.00*10^6$	Yes	Yes
C40_1	Instron	30	Load Steps	0.1	$2*10^4$	$1.80*10^5$	Yes	Yes
C40_2	Instron	30	200	0.1	$5*10^4$	$2.00*10^5$	Yes	Yes

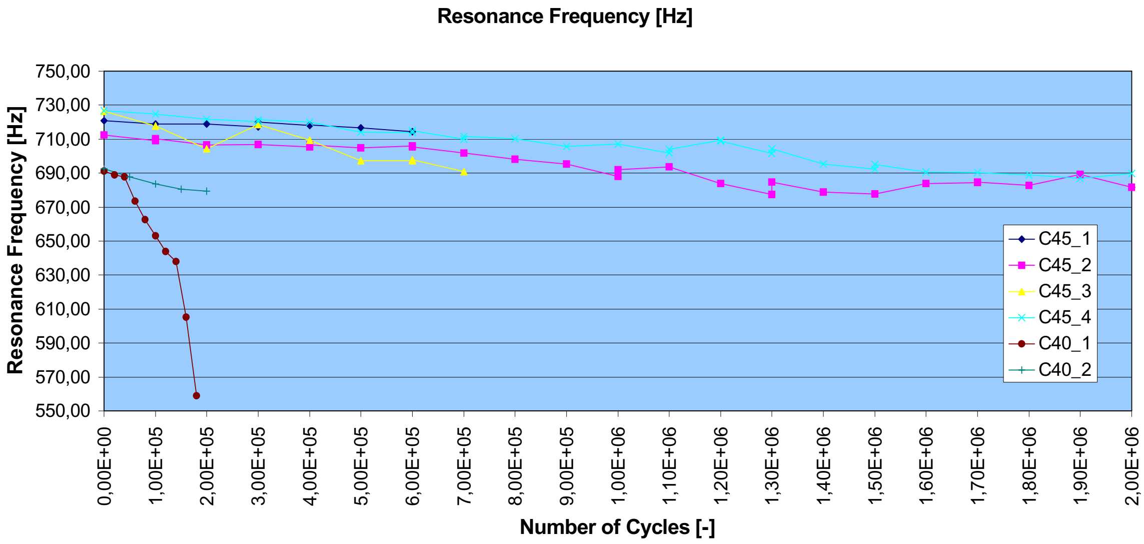

Figure 1. Resonance frequency variation during fatigue tests

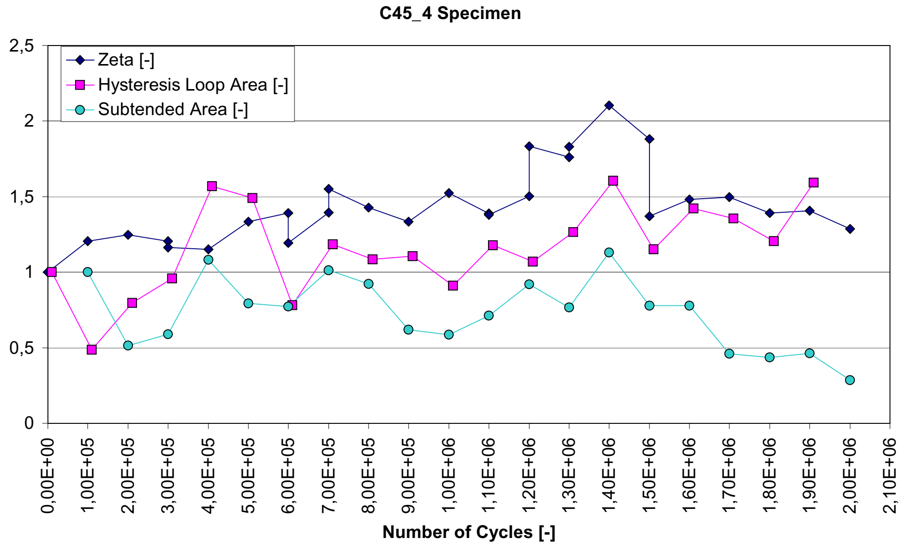

Figure 2. C45_4 specimen: normalised variation during test of modal damping, hysteresis loop area and subtended area by thermal profile

For modal damping, on the contrary, for the unfailed specimen *C45_2*, no remarkable variation is detected, while, when specimens fail, a weak increasing trend is observed. The corresponding measurement uncertainty has an order of magnitude of about 10^{-4}. Even if for sake of brevity the corresponding results are not here shown, for *C45_3* specimen, whose test frequency was higher, the total increase is major. This could be a test frequency consequence.

For stresses above fatigue limit (*C45_4*), the resonance frequency continues to decrease. This effect may be justified by the stress level value. The so called *recovery* effect is still present. Modal damping (starting from a value of 0.00098) shows an increase still weak, more evident until $1.5*10^5$ cycles (Figure 2) and then it may be noted both decreasing and stabilization. This particular behavior is confirmed by the hysteresis loop area and subtended area by thermal profile (here treated as a parameter proportional to dissipated energy, according to [10]) trends; moreover, for the corresponding number of cycles, resonance frequency also seems almost constant. So, in conclusion, all this may be interpreted as softening manifestation in the first part of the test, followed by an hardening effect in the last half a million of cycles. A test conducted using penetrant liquid emphasized the absence of cracks on specimen surface.

Further, as title of example, one specimen (*C40_2*) has been subjected to few loads lower than fatigue limit, in anelastic region. In this case, a weak decreasing trend is observed for resonance frequency, while, taking into account the measurement uncertainty, modal damping is practically constant.

Finally, on the specimen *C40_1*, eight load steps have been executed until yield stress region (maximum stress of 250, 300, 350, 400, 420, 450, 500, 550 MPa): resonance frequency decrease becomes more relevant with load increase; similarly, an increase is detected for modal damping, even if globally modest also close yield stress. Also in this case, a comparison among modal damping, hysteresis loop area and subtended area by thermal profiles is proposed (Figure 3): these parameters, normalized with respect to their final value, show a similar behavior. Further, in Figure 4(a), the corresponding thermal profiles (from whose integration subtended area is calculated) are reported, while, in Figure 4(b), modal damping value is plotted as a function of the correspondent above quoted subtended area (until $2*10^4$ cycles). It may be observed that thermal profiles reported in Figure 4(a) show two different levels for the stabilization zone referring to the same temperature signal: this effect is due to a variation in the loading frequency. The first part of each curve corresponds to a 10 Hz frequency and refers to the acquisition of the hysteresis loops. The second one corresponds to a 30 Hz test frequency.

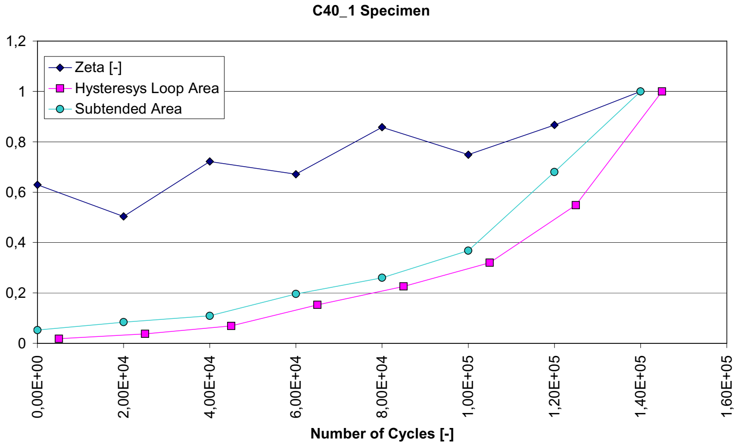

Figure 3. C40_1 specimen: normalised variation during test of modal damping, hysteresis loop area and subtended area by thermal profile

4. Conclusion

On the basis of the experimental tests here presented and discussed, some conclusions may be drawn.

The more evident observed trend is the resonance frequency decrease (some dozens of Hz) with the number of cycles progression. The frequency drop is smaller and requires in general some hundreds of thousands of cycles to become relevant if stress levels are below and close to fatigue limit, or testing frequency is low, otherwise it occurs after the first block of cycles. Further, a peculiar observed phenomenon is the pause effect, consisting in a slight augmentation of the resonance frequency measured at the beginning of the new test day to respect to the last one. This effect, already observed by Lazan, has been here called *recovery*. In conclusion, it could seem that frequency value represents both internal friction or anelastic phenomena, which are the recovered part after a pause, and microplasticity activation, dislocations motion and microcracks initiation/propagation, which properly are fatigue damage manifestations. Thus, the use of resonance frequency as damage indicator could be reasonable.

About modal damping, on the contrary, if stress level and testing frequency are adequate, a tendency to an increase has been observed, but weak. Nevertheless, this trend has been confirmed by measurements on material parameters traditionally related to damping, such hysteresis loop area and thermal emission in terms of subtended area. Further, penetrant liquid showed the cracks absence on the unfailed specimens surface. As a consequence of that, it may be supposed that damage phenomenon involve only the microplasticizations activation (not surface cracks) and so this fact could justify the modest value of the detected increase in damping parameters.

Summarizing, it may be concluded that the analyzed parameters meaningfully represent the damage progression in fatigue tests, even if differently emphasized. In particular, modal frequency variation is the most clear. On the other hand, damping parameters are less evident, even if the modest order of magnitude has to be taken into account. To this point, it may be observed that they show a similar behavior, but the modal damping one is less regular than the others. Above all the subtended area provides good results, independently on the surface temperature oscillations necessary involved by the test conditions.

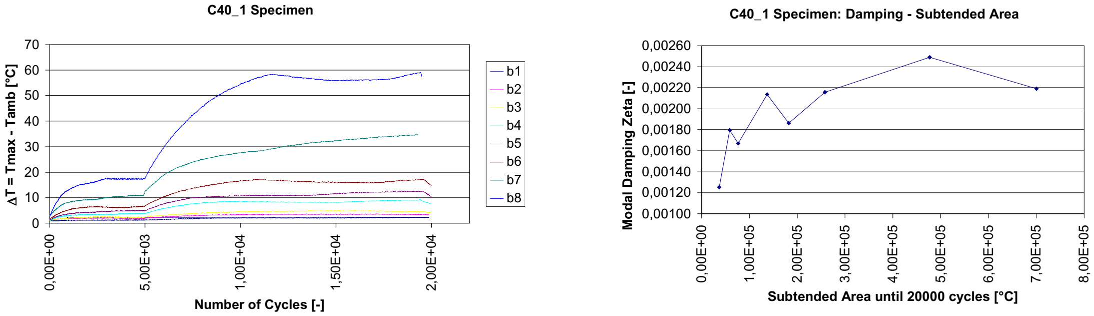

Figure 4. Thermographic acquisition for specimen C40_1 (a) and modal damping – subtended area diagram (b)

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