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Damage warning of Fatigue Test of Cable Based on Acoustic Emission and Fractal Theory

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ABSTRACT. Damage warning timely is very important for structures which are on performance. A new damage warning method based on AE signal and fractal theory was presented. The damage index was deduced by the character of signal analysed by fractal theory. It is deduced that both the curve length and the fractal dimension (FD) of signal are related with damage development. The AE monitorning of fatigue test of GFRP cable was performed for validation. The results show that the damage acuteness index can describe damage development and warn structure failure effectively. So the fractal theory based damage warning index iseffective tool to apply in Acoustic emission (AE) test monitoring.
KEYWORDS: fractal theory; AE; Fatigue Test; damage warning

1 INTRODUCTION

Acoustic emission is a naturally occurring phenomenon of elastic waves generated when there is a rapid release of energy in a material or on its surface [1]. Acoustic emission tests monitoring is an effective non-destructive technique[2] for the detection, location and monitoring damage on steel [3-5],concrete [6] and FRP structures [7] etc.

For AE test, there are two traditional analysis methods, which are measurement parameters and Waveform analysis. Measurement parameters were usually used in AE processing technology years before. As signal processing and computer technology develop advanced, Waveform-based AE detection become practical. The technologies were developed from conventional method like spectrum analysis to intelligent methods [8, 9] including Wavelet transform [10, 11], data fusion [12] and artificial neural network [3], which makes the damage description and localization more accurately.

In the recent years fractal theory was introduced in AE signal processing. Paparo G [13] has demonstrated the correlation between the FD and the order of the space distribution of the prime AE sources. M.E. Biancolini[5] correlate the FD of AE signals with the fatigue damage of the material to anticipate the detection of crack beginning relating to the other theoretical or experimental techniques. F.E. Silva et.al [14] employed the fractal indices related to the Hurst analysis, detrended fluctuation analysis, minimal cover analysis and to the boxcounting dimension analysis to characterize the different failure modes.

In this paper, The FD based damage warning method was proposed and the AE monitorning of fatigue test of GFRP cable were also performed for validation. In the test, several AE-PZT patches bonded to the different place of the surface of the specimens to monitor the AE occurring. It is shown that the damage waning index can describe damage development and warn damage failure effectively.

2 DAMAGE WARNING METHOD

2.1 FD arithmetic and signal

FD arithmetic proposed by Higuchi [15] is suitable for analyzing an irregular time series. In this FD arithmetic, the length of time series of an AE signal, X_k^m, can be defined as follows

$$L_m(k)=\left\{\left(\sum_{n=1}^{\left[(N-m)/k\right]}\left|(X(m+nk)-X(m+(n-1)k)\right|\right).\frac{N-1}{[(N-m)/k].k}\right\}/k. \tag{1}$$

where [ ] denotes the Gauss notation, N is number of sampling points, k and m indicate the interval time and the initial time, respectively, $m=1,2...k$ within one interval. For a time interval k, k sets of new time series can generate which start at initial time m and have $(N-m)/k$ sampling points.

The average value over k sets of $L_m(k)$ is given to

$$L(k)=\frac{1}{k}\sum_{m=1}^{k}L_m(k)=\frac{1}{k}\sum_{m=1}^{k}\left\{\left(\sum_{n=1}^{\left[(N-m)/k\right]}\left|(X(m+nk)-X(m+(n-1)k)\right|\right)\frac{N-1}{[(N-m)/k].k^2}\right\}. \tag{2}$$

If the average value $L(k)$ varies directly with k^{-FD}, the signal is fractal.

$$L(k)=b\cdot k^{-FD} \tag{3}$$

where b is the curve length for time interval equaling unit and given by

$$b=L(1)=\sum_{i=1}^{N-1}\left|X(i+1)-X(i)\right| \tag{4}$$

It is seen that b shown the fluctuating amplitude of signal at time domain. It has a connection with damage amplitude.

And then, FD can be deduced as

$$FD=-[\ln(L(k))-\ln(b)]/\ln(k) \tag{5}$$

Eq. (5) indicates that FD should be the slope of the straight line.

Any signal can be denoted by the following function

$$X=\sum_{j=1}^{\infty}A_j e^{i\omega_j t}. \tag{6}$$

where A_j is the amplitude at frequency ω_j.

The curve length of the signal with interval k can be deduced as

$$L(k)=\frac{1}{k}\sum_{m=1}^{k}\left\{\left(\sum_{n=1}^{\left[(N-m)/k\right]}\left|X(m+nk)-X(m+(n-1)k)\right|\right)\frac{N-1}{[(N-m)/k]\cdot k}\right\}/k$$

$$=\frac{1}{k}\sum_{m=1}^{k}\left\{\left(\sum_{n=1}^{\left[(N-m)/k\right]}\left|\left(\sum_{j=-\infty}^{\infty}A_j e^{i\omega_j t_{m+nk}}-\sum_{j=-\infty}^{\infty}A_j e^{i\omega_j t_{[m+(n-1)k]}}\right|\right)\frac{N-1}{[(N-m)/k]\cdot k}\right\}/k\cdot \tag{7}$$

$$=\sum_{j=-\infty}^{\infty}\frac{A_j}{k}\sum_{m=1}^{k}\left\{\left(\sum_{n=1}^{\left[(N-m)/k\right]}\left|\left(e^{i\omega_j t_{m+nk}}-e^{i\omega_j t_{[m+(n-1)k]}}\right|\right)\frac{N-1}{[(N-m)/k]\cdot k}\right\}/k$$

FD can be transformed to the following form

$$FD=-[\ln(L(k))-\ln(b)]/\ln(k)$$

$$=\frac{\ln\sum_{j=1}^{\infty}[A_j\sum_{i=1}^{N-1}(\left|\sin\omega_j t_{i+1}-\sin\omega_j t_i\right|)]-\ln\sum_{j=1}^{\infty}\{\frac{A_j}{k}\sum_{m=1}^{k}[\sum_{i=1}^{[(N-m)/k]}(\left|\sin\omega_j t_{m+ik}-\sin\omega_j t_{m+(i-1)k}\right|)\cdot\frac{N-1}{[(N-m)/k]\cdot k}]/k\}}{\ln(k)} \tag{8}$$

$$=\frac{\ln\sum_{j=1}^{\infty}[nA_j\sum_{i=1}^{N-1}(\left|\sin\omega_j t_{i+1}-\sin\omega_j t_i\right|)]-\ln\sum_{j=1}^{\infty}\{\frac{nA_j}{k}\sum_{m=1}^{k}[\sum_{i=1}^{[(N-m)/k]}(\left|\sin\omega_j t_{m+ik}-\sin\omega_j t_{m+(i-1)k}\right|)\cdot\frac{N-1}{[(N-m)/k]\cdot k}]/k\}}{\ln(k)}$$

It is demonstrated that the FD value is the effect of the value and the relative amplitude of ω_j. Relative more and larger frequency can obtain larger value of FD, the signal contain more higher frequency, FD value will become bigger. So the value of FD indicates relative frequency distribution of the signal. It has a connection with damage type.

2.2 FD-based damage warning index

As the structural damage develops, there will be more and more abrupt component in the signal of AE, Damage warning index can be defined as follows

$$D=\frac{\sigma_b}{\bar{b}}+\frac{\sigma_{FD}}{\overline{FD}}. \tag{9}$$

where b is the length of the signal curve of every time series. FD is the value of estimated FD of the signal curve of every time series. σ_b and $\bar{b}$ are the standard deviation and mean value of the b for every loading process, respectively. It is the same as FD.

3 VALIDATION OF EXPERIMENT

3.1 Experiment

Fatigue Test on GFRP cable was conducted to verify the applicability and efficacy of the FD-based damage index. In this chapter, experimental setup and Loading Regime are explained.

Experimental setup

The test specimen is GFRP cable as shown in Figure 1 which was composed by seven plain GFRP wires. The size of GFRP wires is 800mm long and 7mm inner diameter.

3.1.1 Test Setup and Loading Regime

Before Fatigue Test, static load test were conducted to obtain the displacement of MTS corresponding to the fatigue upper limit and low limit of the cable. The loading speed is 0.04mm/s. Then Fatigue Test of the cable were performed, the loads which were controlled by displacement until the failure of the specimen and were Sine Wave. The displacement of MTS corresponding to the fatigue upper limit and low limit of the cable employed results of the static load test. The details of the Fatigue Test are shown in Table 1.Which $\sigma_{\max}$ 、 $\sigma_{\min}$ 、 σ_f and $\bar{\sigma}$ denote fatigue upper limit, fatigue low limit, ultimate tensile stress and mean stress, respectively.

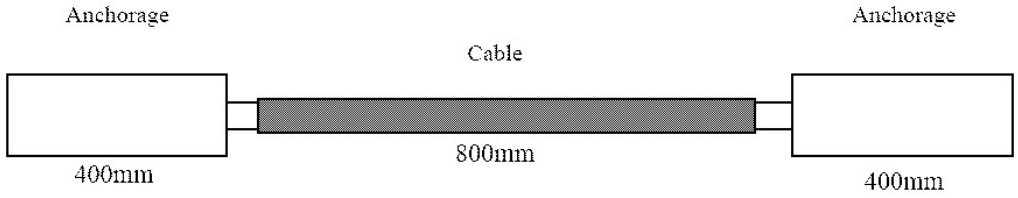


Figure 1. GFRP cable

Table 1 Outline of details of the Fatigue Test

stress	$\sigma_{\max}/\sigma_f$	$\sigma_{\min}/\sigma_f$	$\bar{\sigma}/\sigma_f$	Loading Frequency (Hz)
0.7	0.75	0.05	0.4	10

To monitor AE taking place which indicate damage development, AE-PZT sensors were boned on the surface of the specimen. The arrangement is shown as Figure 2. Sensor 3 and 4 were localized at the up and down end of the cable, and sensor 2 and 5 were putted at the surface of above and below Anchorage.

4 RESULTS

4.1 Time history result

Results of time historys of the signal when damage appear and develop slowly for different sensors (sensor 1 was broken) are shown at Figure 3. At this stage the signal contain a few peak values which demonstrate the damage developed slowly. It is also found the amplitude of different sensors are diverse whev peak value appears, the reason is that the paths of AE signal from damage to every sensor are different and the AE energy will be diffused, diffracted and dissipated as the wave spread around.

Figure 4 shows the time historys of signal when damage develops acutely. It is found of peak values appear very actively, and the amplitude are very lager then previous stage which demonstrate that the fatigue crack develop quickly.

The final failures of the cable are shown at Figure 5. It is seen that the damage at upper end is more severe than the lower end obviously. For comparable, it is also found that the most active peak values take place at sensor 4, the amplitude were also the largest among several sensors from Figure 4, which is corresponding with the actual failure cases.

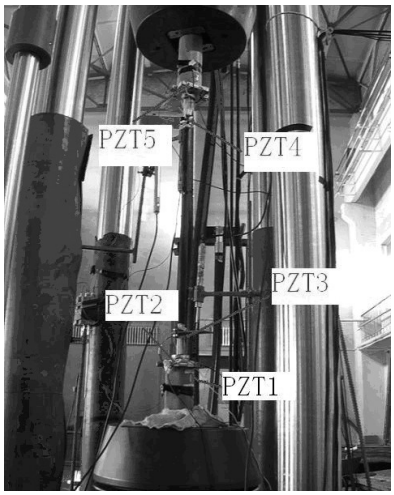
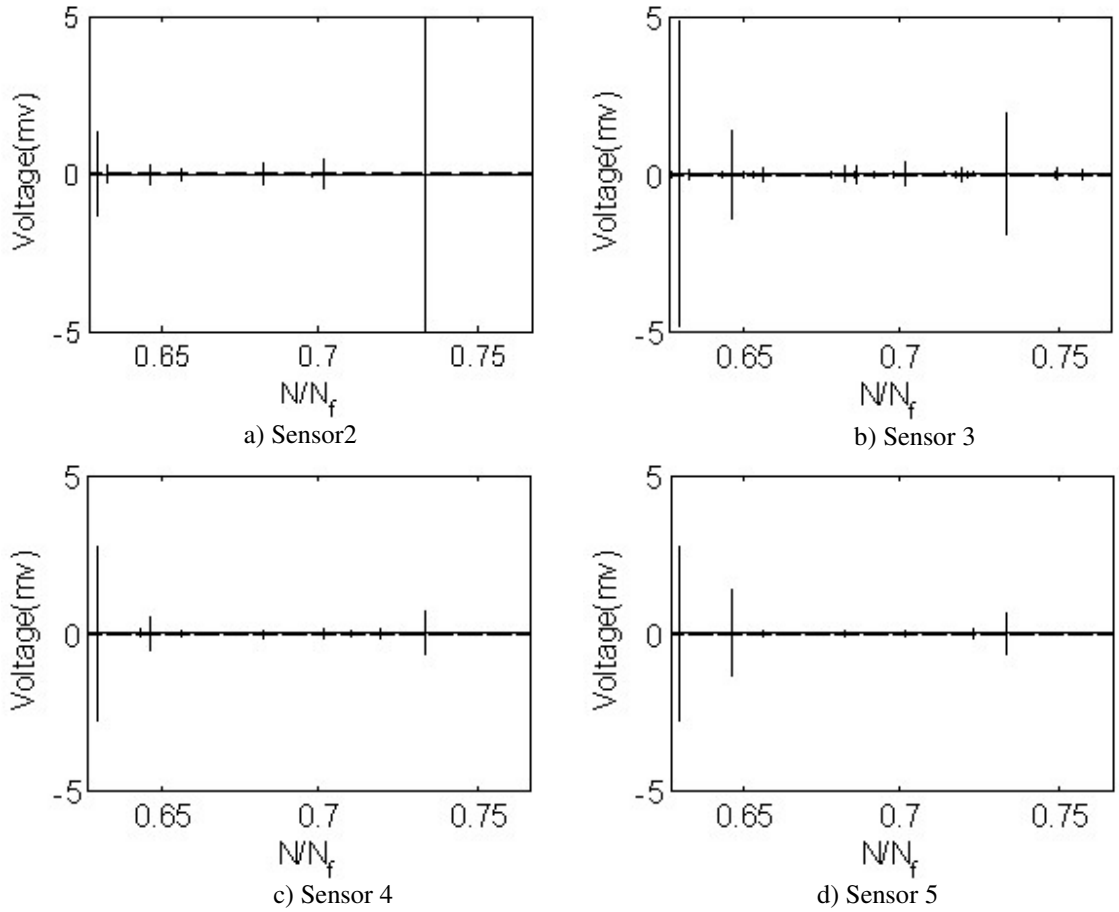


Figure 2. AE-PZT sensor localization



a) Sensor2 b) Sensor 3

c) Sensor 4 d) Sensor 5

Figure 3. Time history of stage that damage developed slowly for different sensors, where N is cycle numberand N_f is the cycle number at failure time.

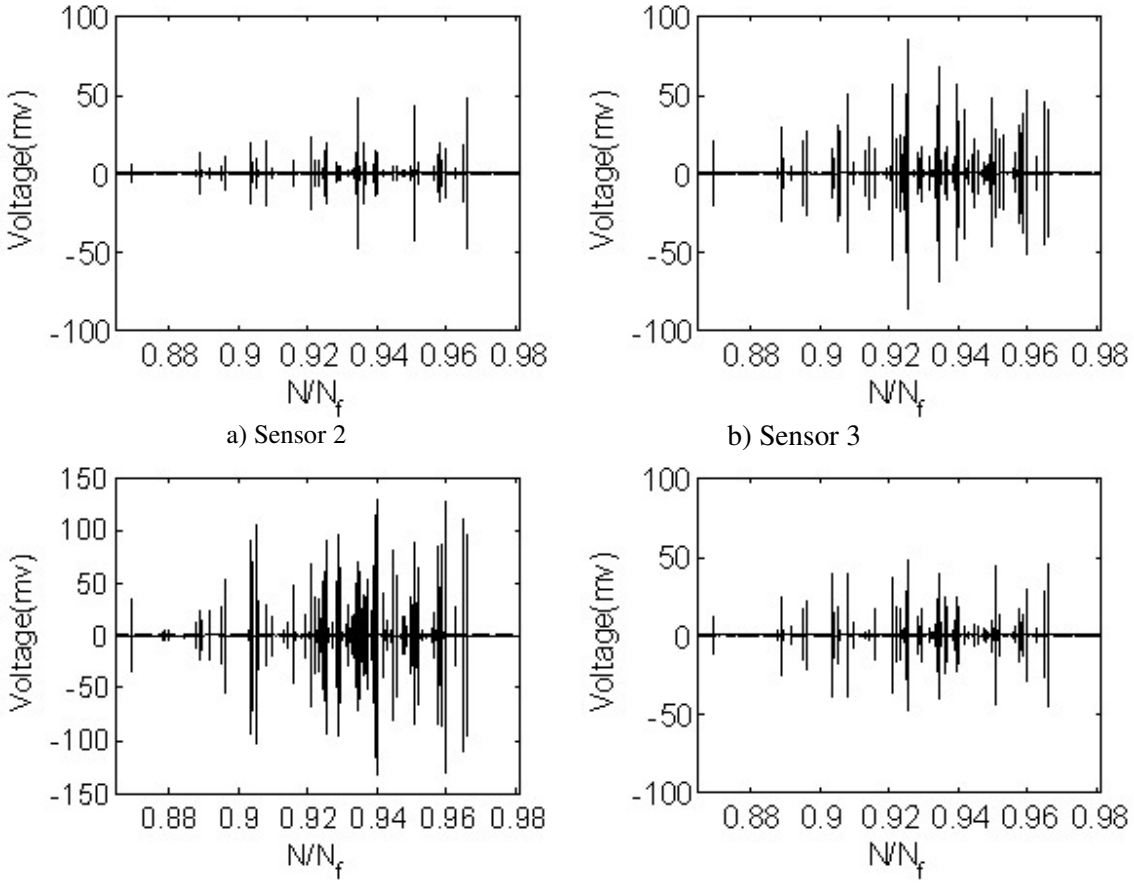


Figure 4 Time history of the stage that damage developed acutely for different sensors, where N is cycle numberand N_f is the cycle number at failure time.

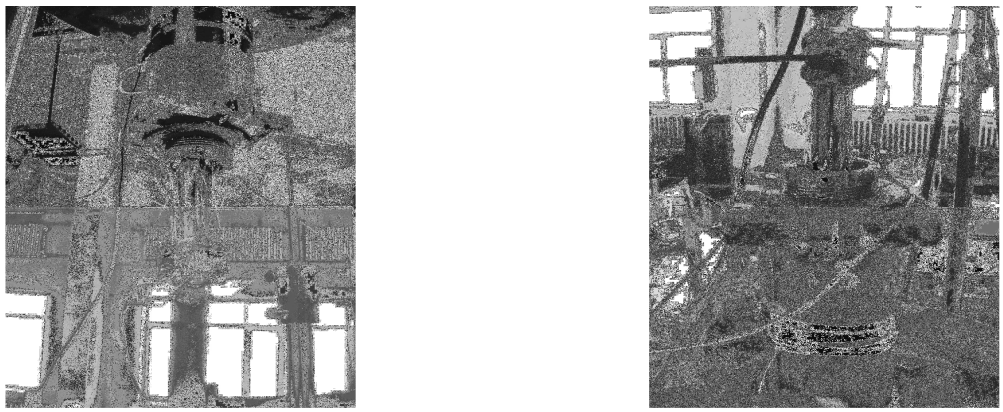


Figure 5 Failure of the cable at (a) the upper end and (b) the lower end

4.2 Damage development assessing and warning through FD-based damage warning index

Results of the damage warning index which employed time series of 1/9 of the whole time series to calculate were shown in Figure 6. It is easy to divide the time series of every sensor into three stages, which are damage appearing, damage developing slowly and damage developing acutely until failure.

At the first stage, the values of the index of damage warning are very small, which indicate damage appear but were very mild. At the second stage, the values of the index of damage warning are still small but larger than the first stage as damage began to develop. When arriving at the third stage, it is seen that the values of the index have a trend of increaseing suddenly, which indicate the fatigue cracks began to develop acutely and the structure will fail soon. So the acute increase of the index can be seen as the indicator of damage warning.

It is also found that sensor 4 has the largest amplitude of the damage warning index, which is corresponding with the failure case that the failure at the upper end is more severe than the lower end. And the amplitudes of the damage warning index for different sensors vary with the lengthes of path from failure place to sensors. So the diversity of damage warning index for different sensors also can localize damage.

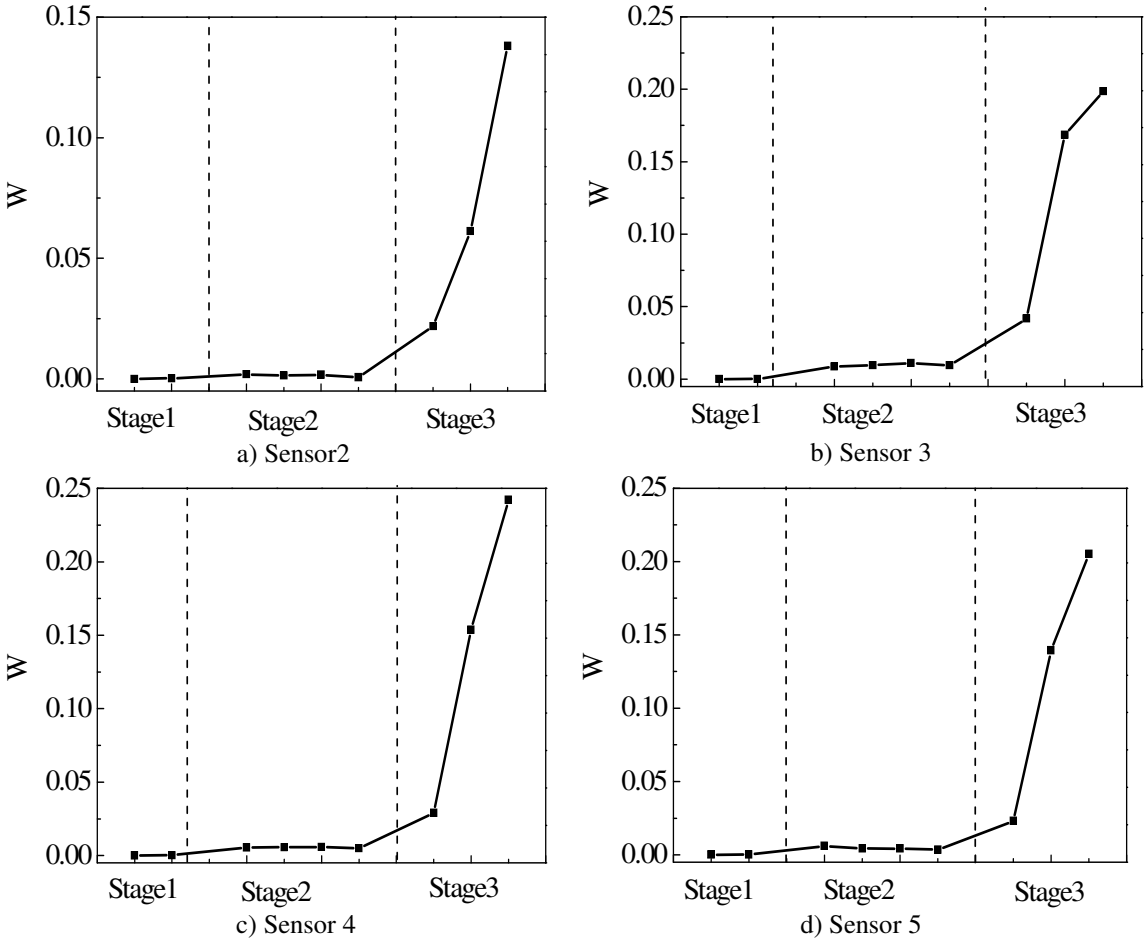


Fig 6 Results of Damage assessing index employing different values of weight coefficient for the specimen.

5 CONCLUSION

A fractal theory-based damage warning index was proposed in this paper. It was deduced that not only FD value but also the curve length for time interval of signal equaling unit are related with damage development.

The AE monitoring of fatigue test of GFRP cable was also performed for validation. There are several AE-PZT patches bonded to the different place of the surface of the specimen to monitor the AE occurring of the structure.

From the analysis results of the experiments, it is demonstrated that AE signals of the experiment are fractal and the damage warning index can assess damage occurrence and development accurately. It is demonstrated that the whole time series of fatigue test can be divided into three parts through the values of the warning index. At the third stage the value of the index has acute increase which indicates the structure burst into damage acutely and will fail soon. The tread can be seen as indicator of warning of structure failure. The method is an effective tool for structural failure warning, and it can also be used as damage localization.

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