COMPARISON BETWEEN STATIC AND DYNAMIC RESULTS FOR MODE I AND MODE II FATIGUE DELAMINATION GROWTH ONSET OF UNIDIRECTIONAL COMPOSITE

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Abstract

Frequency effect on delamination fatigue crack grows behavior were investigated for carbon fiber/epoxy laminates. Classical 10Hz tests were performed on servo-hydraulic machine on double cantilever beam specimens for the mode I and three-point end notched flexure specimens for the mode II. High frequency fatigue tests were carried out with the help of a shaker at 100Hz for the mode I and 260Hz / 400Hz for the mode II. By comparing the results on T700/M21 specimens, significant effect of the frequency were found out. By increasing the resonance frequency during tests, the propagation threshold decrease for low number of cycles. Those results were discussed based on fractographic observations.

1 Introduction

Because of their lightness, stress adaptive design and strong stiffness, composite materials are more and more used in aeronautics. Aeronautical structures are submitted to vibrations during their service life due to aerodynamic turbulent flow around the structure. With the need to more and more lighten the structure, the knowledge of the effect of the solicitation frequency on the behavior of the crack propagation in a composite material seems really necessary. Other aeronautical applications, where thermal and frequency conditions are critical, are Engine fans. In this frame, studies have been conduct about load frequency effects on Ceramix Matrix Composites (CMC) with monotonic tension tests from 0.1Hz to 375Hz. The reduction of cycle to failure is linked to temperature and frequency since they promote the oxidation appearance [1-3].

Tension or compression tests were also conducted on polymers. For most of the case the frequency ranges from 0.1Hz to 10Hz. At those frequencies, there are two notable frequency effects which oppose each other: creep and hysteresis heat generation. At lower frequency, the material creep behavior is predominant and reduces the fatigue crack growth resistance. At higher frequency, the effect of heat generation can lead to the same result. Thus increasing the frequency can result in improving or degrading the fatigue resistance depending on the material [4].

Models have been developed to predict frequency influence on fatigue behavior. One way takes in consideration the creep effect by adding to the classical Paris law another one with the same form but proportional to the frequency inverse [5]. Another one based on Miner's law calculates damage generated by cycles of tensile fatigue as a summation of constant tensile test damages which are exponential functions of temperature [6]. Sun and Chan have found a model to take consideration of frequency and thermal effects on fatigue life of notched specimens [7]. Jumbo and al. extended this formula to thermoplastic material $[\pm 45]_{2s}$ [8]. Xuao et al studied the AS4/PEEK but on un-notched specimens by considering the hysteretic heating which is dominant in this type of samples. They found a variation of the Dan-Jumbo's formula where thermal effects are correlated with load frequency and stress level [9].

Fatigue crack growth (FCG) resistance tests were conducted by Merah et al on Chlorinated PolyVinyl Chloride (CPVC) to find the influence of temperature and frequency. They found that frequency sensitivity increases with increasing temperature since the crazing effect is dominant. The temperature seems to affect the Paris law multiplying factor when the exponential one is not [10]. To model their results, they use Kim-Wang's model which is a Paris's law depending on the frequency and temperature for the multiplying term and temperature only for the exponential one [11].

Studied one FCG in composite materials at high frequencies was not found in the literature. In this frame, the aim of this work is to study the frequency effect on the delamination fatigue crack grows behavior of a Carbon fiber/epoxy for mode I and mode II. The frequencies tested are 10Hz and 100Hz for mode I and 10Hz, 260Hz and 400Hz for mode II. The frequency sensitivity is investigated at room temperature for the two propagation modes with heat generation observation. The fatigue results were presented in the form of fatigue delamination growth onset and discussed based on fractographic observations.

2 Experimental procedure

2.1 Materials and specimens

Specimens used for all the tests are unidirectional composite beams composed of 20 plies of T700/M21 (Hexcel@). The beam specimens were cut out from a press manufactured plate. The curing cycle followed a standard cycle with a homogenization stage. A 25µm thickness Teflon film is inserted in the mid-plane of the laminate during the manufacturing to create an initial crack. All the specimens were pre-cracked to get at least a 2mm delamination extension before the fatigue tests.

Figure 1. Specimen geometry.

Double cantilever beam (DCB) specimens were used for the mode I loading. The load is applied by the means of loading blocks bonded on both sides of the specimen.

For the classical tests at 10 Hz, the specimens conform to the standards ASTM of the delamination propagation test in mode I (L=180mm, b=25mm, a_i=50mm cf. Fig 1.) [1]. For the 100Hz test, the specimens length and initial crack size have been modified to comply with the dynamical test requirements (L=80mm, b=25mm, h=2.5mm and a_i=30mm, cf. Fig. 1.).

Classical beam specimens have been used for tests under mode II loading (L=180mm, b=25mm, a_i=50mm cf. Fig 1.). Classical mode II fatigue tests have been conducted at 10Hz with a 3-ENF device (cf. Fig. 2.).

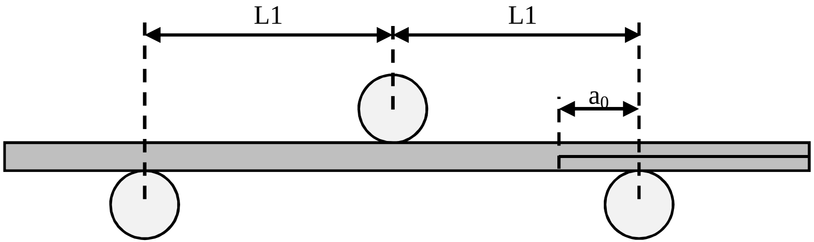

Figure 2. 3-ENF test device L1=50mm.

2.1 Fracture toughness test and fatigue test

First fracture toughness tests have been performed on a servo-hydraulic machine for the two delamination modes in order to obtain compliance laws and the values of fracture toughness G_c. The cross head speed was controlled at 0.01mm/s for both ENF and DCB tests.

The 10Hz fatigue tests were performed on a servo-hydraulic machine at a controlled displacement ratio of R=0.1. The crack propagation was followed by binocular observation for ENF test and crack gage for DCB test.

The high frequency tests (100Hz for mode I / 260Hz and 400Hz for mode II) use the resonance principle and are performed by means of a shaker.
For mode I, the specimen is loaded by the means of a device which looks like an inertial machine of tension-compression (cf. Fig. 3.). The global system dynamic representation is the one of a mass-spring system, where the specimen is represented by its opening stiffness. A spring is connected in parallel of this specimen; the compression of this spring allows to fix the initial opening of the specimen and so to define the average load during fatigue cycling.

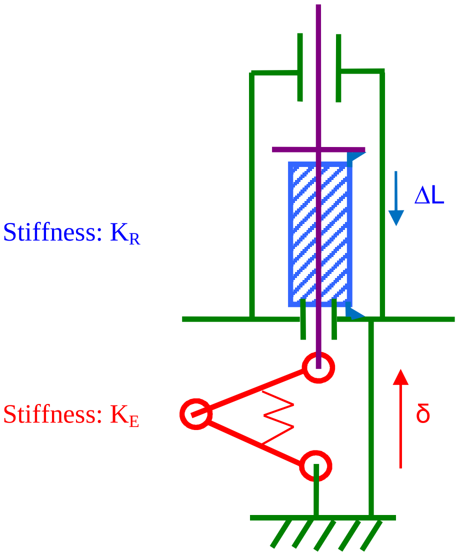

Figure 3. Kinematical scheme of the mechanical test device.

During test, the shaker generates a sinusoidal acceleration which causes the set in motion of the mobile mass M of the system and thus the specimen loading around its equilibrium position. The tests are then conducted at load control with a ratio of R=0.1. The loading frequency is chosen equal to the resonance frequency of the global system in order to take advantage of the amplification factor due to the resonance phenomenon.

Mode II delamination dynamical fatigue tests are based on End Load Flexure classical tests. The delaminated beam is clamped on a shaker and tested on its first flexure resonance mode frequency to take advantage of the large amplification factor. The displacement of the specimen is monitored by a Laser Doppler Vibrometer. The tests were performed under displacement control with a displacement-ratio of R=-1 at two resonance frequencies (260Hz and 400Hz) by adjusting the length of the beam (cf. Fig. 4.).

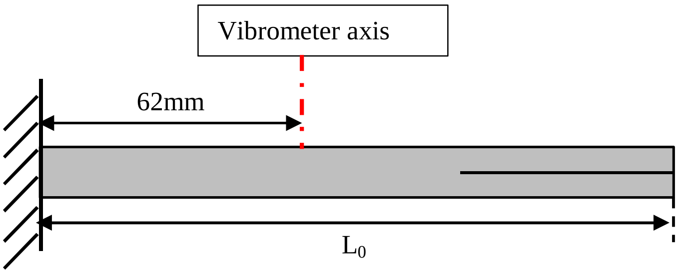

Figure 4. Length of beam tested (L_0=152mm for 260Hz, L_0=122mm for 400Hz)

The resonance frequency of the system tested is linked to the crack size by the compliance law. As the delamination propagates the resonance frequency of the system slowly decreases. As a matter of fact, this typical frequency is followed during dynamical tests by keeping constant the phase quadrature between the input acceleration and the output measure (mass acceleration for mode I and beam displacement for mode II). The test stops when the resonance frequency reaches the final desired frequency (linked to the final crack size). For the two types of test, the temperature evolution is measured with a thermal middle wavelength camera (sensitivity between 2 and 5μm)

3 Results and discussion

3.1 Mode I delamination fatigue test

The Energy Restitution Rate (ERR) in mode I used to plot the fatigue crack growth resistance curve is calculated with the compliance method:

$$G_{max} = \frac{\mathrm{n} P_{max}\delta_{max}}{2ba} \tag{1}$$

Where G_{Imax} is the maximal ERR reached during a cycle, n given by identification of the compliance law, P_{max} the maximal applied load, δ_{max} the maximal displacement, b the specimen width and a the crack length.

The Paris law is determined from the crack propagation speed and the ERR (cf. Eq.1.). It has been chosen to use dimensionless value by dividing ERR by the critical ERR (G_c).

$$\frac{\mathrm{da}}{dN} = \mathrm{k}\left(\frac{Gmax}{Gc}\right)^{n} \tag{2}$$

Where $\frac{da}{dN}$ is the propagation rate in mm/cycle.

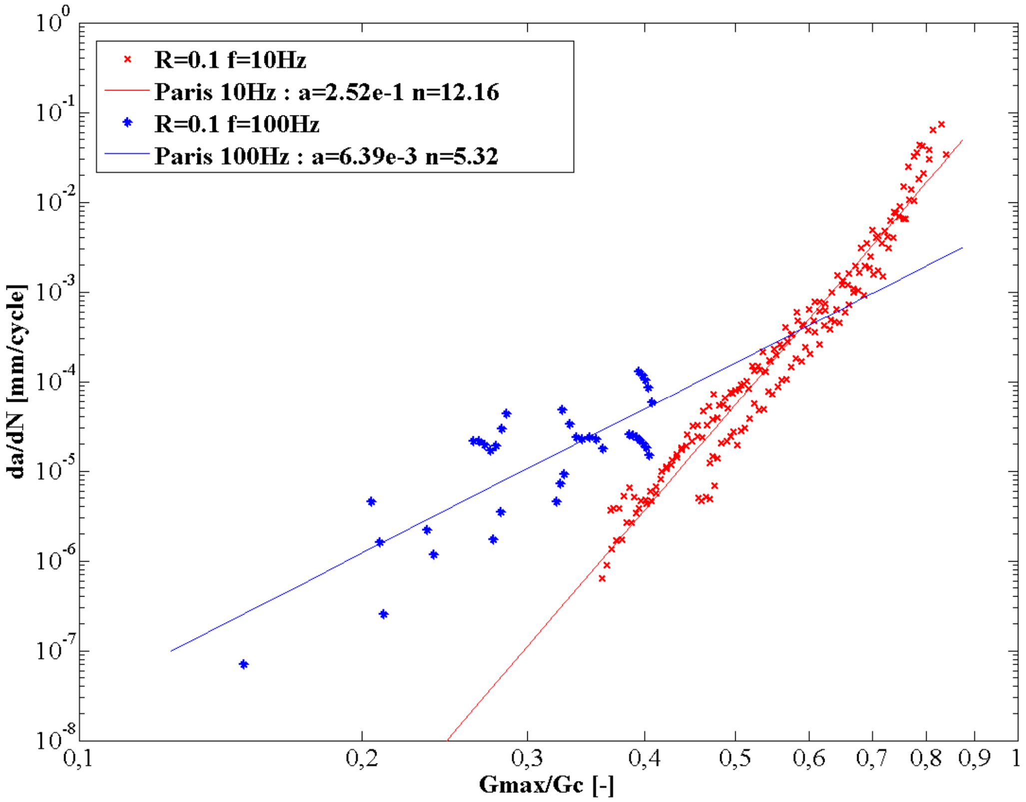

Figure 5. Normalized Paris Law in mode I for the frequencies: 10Hz, 100Hz.

The Paris curve slope at 100Hz is twice the one at 10Hz. When the loading frequency increases for the low ERR values (under 60% of G_{Ic}), the propagation rate increases : the ERR which corresponds to a propagation rate of 1.10^{-6}mm/cycle at 10Hz matches with 3.10^{-5} mm/cycle at 100Hz (cf. Fig. 5). The two Paris law intersect around a propagation rate of 7.10^{-4} mm/cycle.

During tests heat generation was measured by thermic camera and the observed crack tip relative rise in temperature was around 1°C. Moreover, the behavior difference between the two frequencies cannot be explained by a temperature increase since it should have led to increase the resistance to crack propagation. No difference of fracture surface has been seen between the two types of specimen. On the other hand, when loading at 100Hz the strain rate applied to the material is greater than for 10Hz. This strain rate rise can explain the decrease in fatigue crack growth resistance [12].

3.2 Mode II delamination fatigue test

The Energy Restitution Rate in mode II is calculated with the compliance method:

$$G_{IImax} = \frac{3\mathrm{ma}^2 P_{max}^2}{2b} \tag{3}$$

Where m was identified from the compliance law.

In order to compare classical (R=0.1) and dynamical (R=-1) results, the number of cycles for dynamical tests have been multiplied by 2. This way to compare results at R=-1 and R=0 for mode II fatigue test has already been used [13].

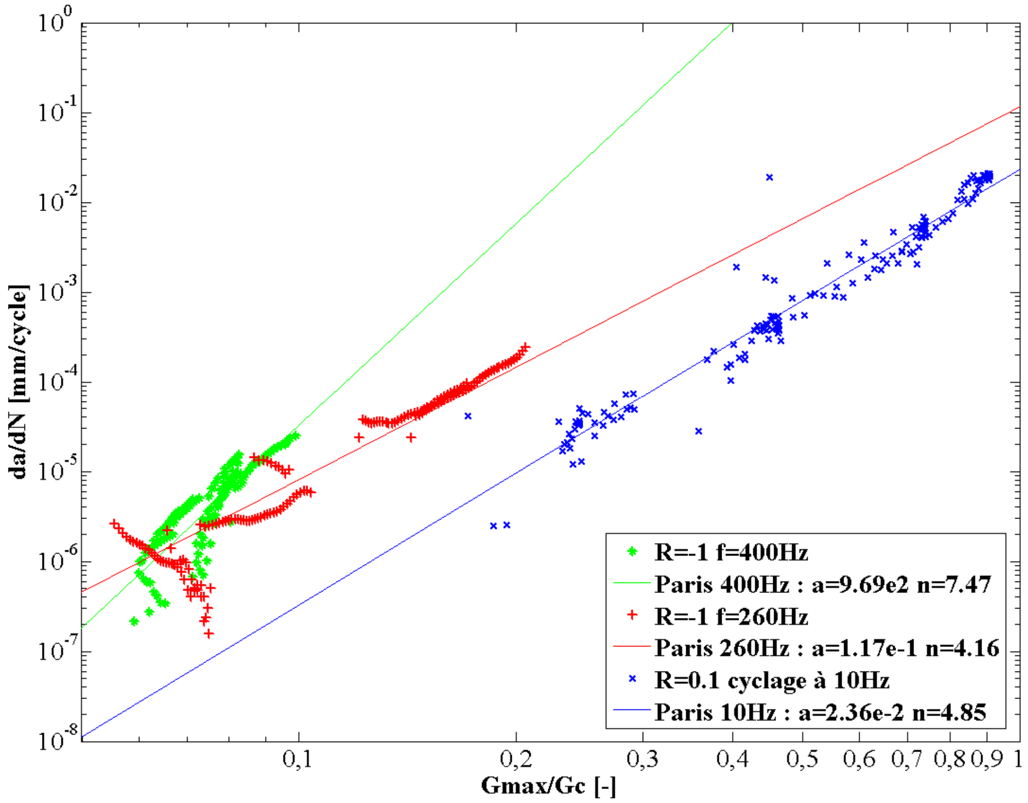

Figure 6. Normalized Paris Law in mode II for the frequencies: 10Hz, 260Hz, 400Hz.

The tests performed at 10Hz have been done by the means of the ENF test. Some authors show that the ELS and ENF tests can lead to different results in fatigue in particular for Paris curve slopes [14]. But despite the differences in loading (test type and R ratio) the frequency effect is coherent for 10Hz on one hand and for 260Hz and 400Hz on the other hand. By increasing the loading frequency, the ERR values needed to propagate the crack are smaller (cf. Fig. 6). The Paris curve slopes for 10Hz and 260Hz are nearly parallel, when the 400Hz one has a slope around two times greater. The Paris curves at 260Hz and 400Hz intersect around a propagation rate of 10^{-6} mm/cycle. This makes valuable the existence of a no-propagation threshold fatigue value which seems to be around 7% of G_{IIc}. Then both parameters of the Paris law are sensitive to the frequency.

As for the mode I tests, heat generation was observed by thermic camera and it never exceeded a temperature increase of 12°C far lower than rising temperature linked with noticeable coupling effect of temperature and frequency. Then the frequency effect seems more likely to be linked with a loading rate effect.

As the frequency increase, the fracture surface becomes planer: the resin is brittler. The micrographs show that the fracture surfaces are dominated by shear cups. The slower the frequency loading is, the deeper the cups are (cf. Fig. 7 b., d. and f.). Moreover the thermoplastic nodules are pulled out at 10Hz and are like filed down at 400Hz.

The samples tested at high frequency have a fracture with a large amount of resin unlike 10Hz loaded one (cf. Fig. 7 a., c. and e.) which show a lot of dry fibers. As the specimens are made from the same material batch, this difference can be explained by propagation in the porosity at 10Hz whereas at higher frequency the crack propagates in the inter-ply resin.

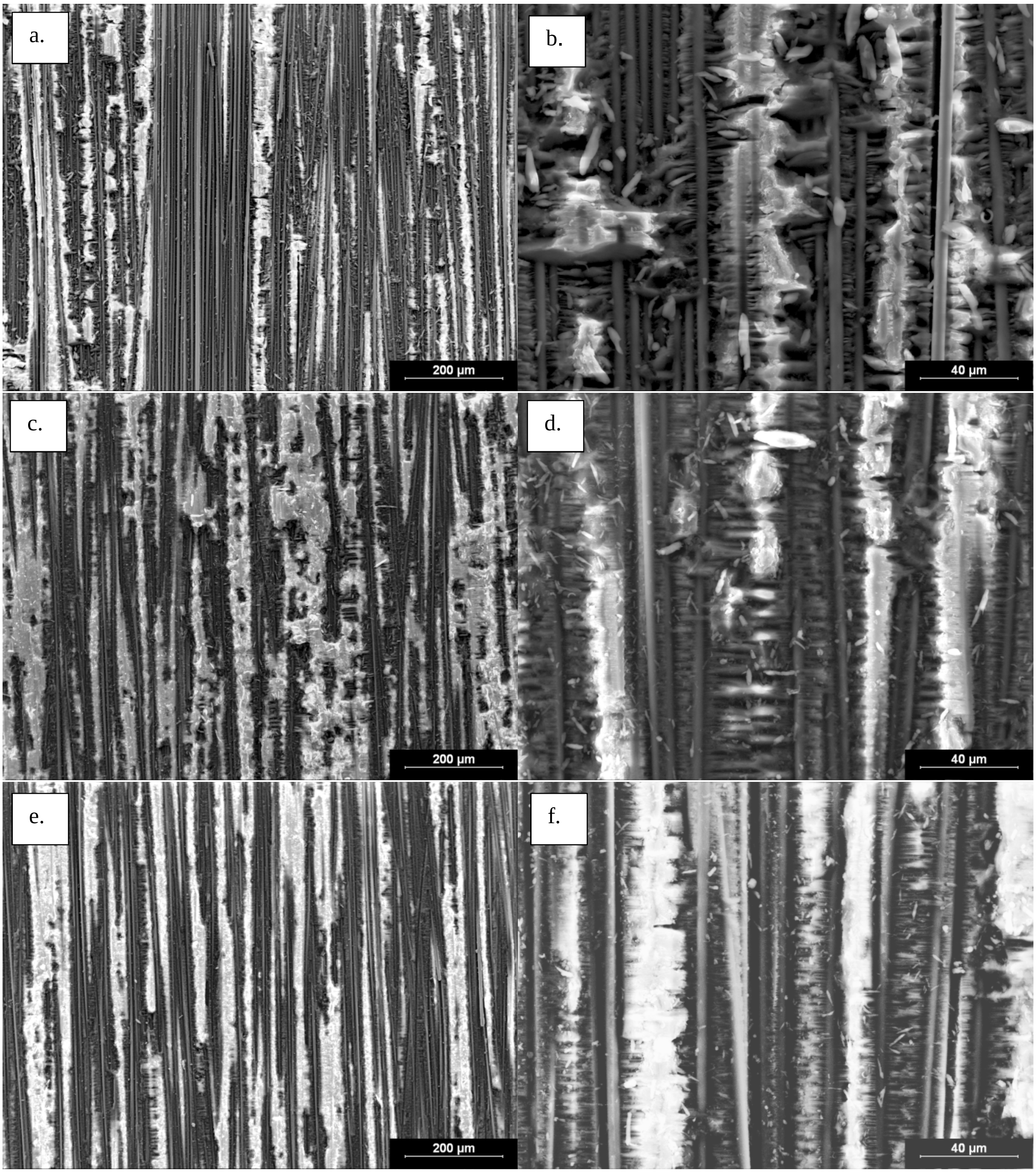

Figure 7. Fracture surfaces for 10Hz (a,b), 260Hz (c,d) and 400Hz (e,f).

4 Conclusion

Mode I and mode II fatigue tests have been conducted at different frequencies to investigate the influence of the loading frequency on the fatigue propagation rate. Results have been expressed in the form of Paris law.

For the mode I, increasing the loading frequency for low ERR value increases the propagation rate. Fracture surfaces didn’t show any obvious differences which can explain it.

For mode II, the higher the frequency is, the faster the crack propagates. This result can be explained by the resin behavior, which becomes brittler when the frequency increases. A no-propagation threshold fatigue value has been found for mode II to be around 7% of the critical static value of ERR.

For both mode increasing the loading frequency lead to an earlier failure. Then, the frequency effect has to be taken in consideration for structural design since it changes sensitively the fatigue material behavior.

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