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DELAMINATION DETECTION IN COMPOSITE LAMINATES FROM VARIATIONS OF THEIR MODAL CHARACTERISTICS

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As a first step in developing a health monitoring system, the effect of delamination on the modal frequencies of laminated composite beams has been investigated. A piezoceramic patch driven with a linear rapid frequency sweep was used to induce vibrations on the structure and its response registered via piezoelectric film sensors. Modal frequencies were obtained by applying concepts of a novel method known as resonant ultrasound spectroscopy. Changes of the modal frequencies after delamination initiation, compared to those of a non-delaminated specimen, gave a good indication of the degree of damage, demonstrating the feasibility of using measured changes in the vibration characteristics to detect damage.

1. INTRODUCTION

The enormous potential that composite materials can offer to aerospace industry and many other sectors has been hindered by the lack of a reliable health monitoring system capable of detecting damage occurrence in fibre-reinforced plastics. The presence of delamination may degrade severely the stiffness and strength of composites and in some cases lead to catastrophic failure. Thus, if composite materials are to play a bigger role in industry then a reliable integrity assessment system has to be developed. The principle behind damage detection methods based on modal analysis is that damage reduces the dynamic stiffness (EI) of a structure, which results in reduction of the resonant frequencies [1]. Thus, the measurement of resonant frequencies of a structure at two or more stages of its life offers the possibility of detecting the presence of damage [2].

Over the years, several investigators using this approach have produced analytical [3–5], numerical [6–8], and experimental [9–11] results for the effect of delaminations on the vibrational response of composite laminates. All of these studies strongly indicate that changes in the modal frequencies could be used as a parameter for damage assessment. Currently, the use of changes on the modal frequencies to detect damage offers new applications where such changes can be accurately measured, such as for quality control in manufacturing. Migliori *et al.*

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[12] used a method known as *resonant ultrasound spectroscopy* (RUS) based on precise sine-sweep frequency measurements to determine out-of-roundness of ball bearings. In this approach, flaws shift and break the symmetry of the resonances of an object such that micrometric errors in sphericity of ball bearing could be detected in seconds. Whitney and Green [13] used RUS to monitor the degree of cure of a carbon epoxy composite during the cure cycle. The resonance spectrum of the panel was measured periodically and differences in amplitude, frequency, and damping were related to the degree of cure of the composite.

The aim of this work is to study the effect of delamination on the modal frequencies of currently used laminated composite beams and to examine the performance of piezoelectric materials as sensor/actuator devices. This will contribute in the development of an active damage-assessment system (array of sensors) capable of detecting damage in composites by the use of piezoelectric devices incorporated in the structure. Such a system would ideally be able to monitor continuously the integrity of structural members avoiding expensive maintenance evaluation programs.

2. VIBRATIONAL TEST METHOD

Resonant ultrasound spectroscopy is the study of spectra obtained by forced mechanical resonance of samples using swept frequency excitation [14]. It was refined at Los Alamos National Laboratories to determine the elastic constant of an object from its resonance spectrum [15]. RUS operates by placing the object to be tested on two transducers (actuator/sensor couple). The actuator is excited with a sine wave producing mechanical vibrations within the specimen at the same frequency as the actuator and the sensor detects the amplitude of the induced vibration. Also, an interesting feature of this technique is the use of mixing or heterodyning principles (the operation of multiplying a signal with an auxiliary sinusoidal signal) to achieve the narrow-band filtering of the sensor signal. This permits the optimization of the signal-to-noise ratio and at the same time the recovery of the sample resonance spectrum.

In this work, resonant frequencies were determined by correlating the maximum sensor output to the frequency scale while sweeping through the frequency range of interest, considering that the maximum amplitude of vibration occurs at resonance. Then the resonance spectrum of the sample was analyzed to infer the presence of damage by comparing it to the baseline spectrum of the undamaged structure. The number of peaks in a frequency band, their position, and their shape were used as defect detection criteria [16]. The variation of the frequency was achieved using the rapid frequency sweep technique [17]; a sine signal with a linear variation of frequency with time (chirp signal) was used, which is expressed as,

$$f(t) = A \sin(at^2 + bt), \tag{1}$$

where $\omega(t) = 2at + b$ with $a = (\omega_2 - \omega_1)/2T$ and $b = \omega_1$, T is the sweep time, and ω_1 and ω_2 are the initial and final frequencies respectively.

3. TEST PROCEDURE AND SPECIMEN DESIGN

In order to study composites with self-sensing and actuating capability a cantilever-laminated beam was instrumented with two piezoelectric elements. A commercial, brass backed, piezoceramic transducer and a piezoelectric film element (AMP Inc., LDTO-028-K) were bonded near the beam's fixed end and operated as actuator and sensor respectively. National Instruments' LabVIEW® signal processing and analog to digital card (PCI-MIO-16E-1) were used in conjunction with a personal computer to implement the frequency sweep technique in an automatic framework. The actuator was fed with a 10 V chirp signal employed to drive the composite beam while the sensor response signal was conditioned by a charge amplifier (DJ Birchall Ltd., CA/04) before being digitally recorded. Figure 1 illustrates the experimental arrangement.

The specimen with no delamination was tested first in the frequency range of 100 Hz–13 kHz where several sensor maxima were identified. Then the frequency range was adjusted to 8–13kHz as the effects of delamination are expected to be more significant at relatively higher modes. As suggested by several researchers [7, 8, 18] the local response of the structure is captured by higher-frequency modes whereas lower order modes tend to be mainly affected by the global response and are less sensitive to local stiffness changes. Soon after the modal frequencies of the non-delaminated reference case were determined the delamination was induced *in situ*. A sharp and thin scalpel blade was introduced into the beam's midplane, 100 mm from the fixed end, where the tip of a small triangular piece of Teflon film had been inserted during the manufacturing of the plate. The blade was repeatedly pushed against the delamination front forcing it to grow through different stages of damage. Every time the extent of delamination was increased the software code was executed in order to monitor changes on the resonance spectrum. In this fashion, the delamination area was gradually extended from the free edge until it covered almost all of the specimen width, as schematically shown in Figure 1 and depicted

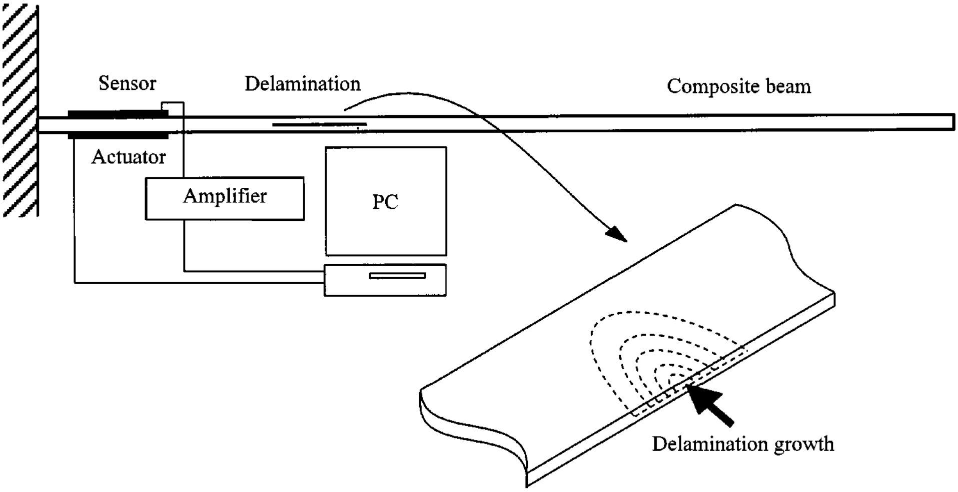

Figure 1. Experimental set up and detail of delamination growth.

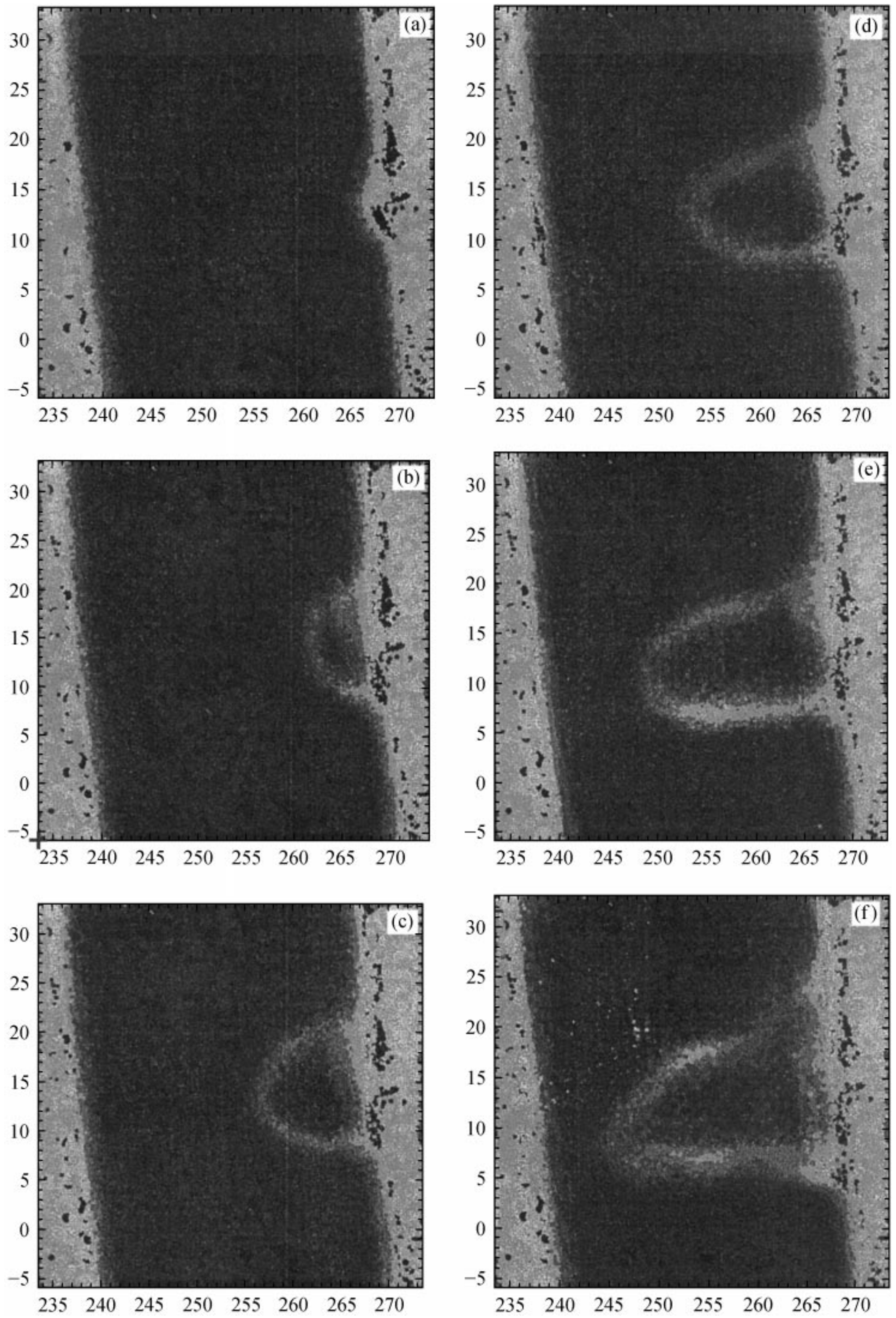

Figure 2. Ultrasonic c-scans of the gradually increasing delamination at different stages of damage (%A_{tot}). (a) $A = 0{\cdot}23\%$, (b) $A = 0{\cdot}89\%$, (c) $A = 1{\cdot}56\%$, (d) $A = 2{\cdot}01$, (e) $A = 2{\cdot}77\%$, and (f) $A = 3{\cdot}84\%$.

in Figure 2. This type of artificially induced delamination is thought to better represent damage patterns observed in fatigue loading than beams with full-width delamination and fixed lengths, as has been commonly used in previous investigations, where the delamination area covers 5–50% of the total specimen area.

The tests were performed on a composite beam obtained from an eight-ply $[0^\circ/90^\circ/90^\circ/0^\circ]_s$ carbon/epoxy laminate of size 330 mm × 300 mm. The laminate was fabricated using T800-924C prepreg tapes. Individual test specimens of 300 mm long, 30 mm wide and 1 mm thick were cut from the laminate using a diamond-wheel saw. The actual span of the cantilever beam was 270 mm long. The elastic properties of the unidirectional ply were $E_{11} = 161$ GPa, $E_{22} = 9{\cdot}25$ GPa, $\nu_{12} = 0{\cdot}34$, $G_{12} = 6$ GPa, and density $\rho = 1536\ \mathrm{Kg\,m^{-3}}$ [19].

4. RESULTS

All of the spectra shown in Figure 3 consist of 5000 points; each point is the average of 5 sweeps at the same degree of damage. The frequency was swept from 8 to 13 kHz at a sampling frequency of 200 kHz during 1 s. In order to visualize the effect of the increasing delamination on the vibration characteristic of the specimen, the sensor response was arranged in a semi three-dimensional plot showing the signal amplitude, modal frequency, and damage area. The damage area was measured by ultrasonic c-scans, as shown on Figure 2, and is represented throughout the results as the percentage of the delaminated area with respect to the total specimen area (A_{del}/A_{tot}). Figure 3 shows eight peaks denominated modes 20–27 according to their order of appearance; all of them shift continuously to lower frequency values with increasing damage size. Additionally, mode 25 runs together or “disappear” under mode 24 as the delamination area increases. There is also a slight attenuation of the peak level and sharpness as damage grows.

Figure 4 clearly shows the reduction of modal frequencies (only four shown) as the delamination area increases. Table 1 summarizes the experimental modal frequencies for each damage size and mode number. Even though the percentile changes of the modal frequencies of the damaged specimen with respect to the baseline (F_{dam}/F_{undam}) might seem small, the absolute frequency changes are quite large and detectable, i.e., in the order of few hundred Hz. For instance, an edge delamination area as small as 0·5% A_{tot} can be reliably detected, as it induces a reduction of 10 Hz on the modal frequencies which is at least two times the value of the highest standard deviation registered in the measurements.

It is known that the stress field in a vibrating structure is non-uniform and is different for each modal frequency. The weakening effect of the delamination therefore depends on the relation between the stress field and damage location. It has been shown that the effect of delamination is less significant as the delamination moves from regions of high shear force to regions of high curvature [4, 6]. However, when dealing with higher mode numbers, the stress field is more homogeneous along the beam span and therefore the influence of delaminations on modal frequencies appears to be less sensitive to location, consequently, the frequencies

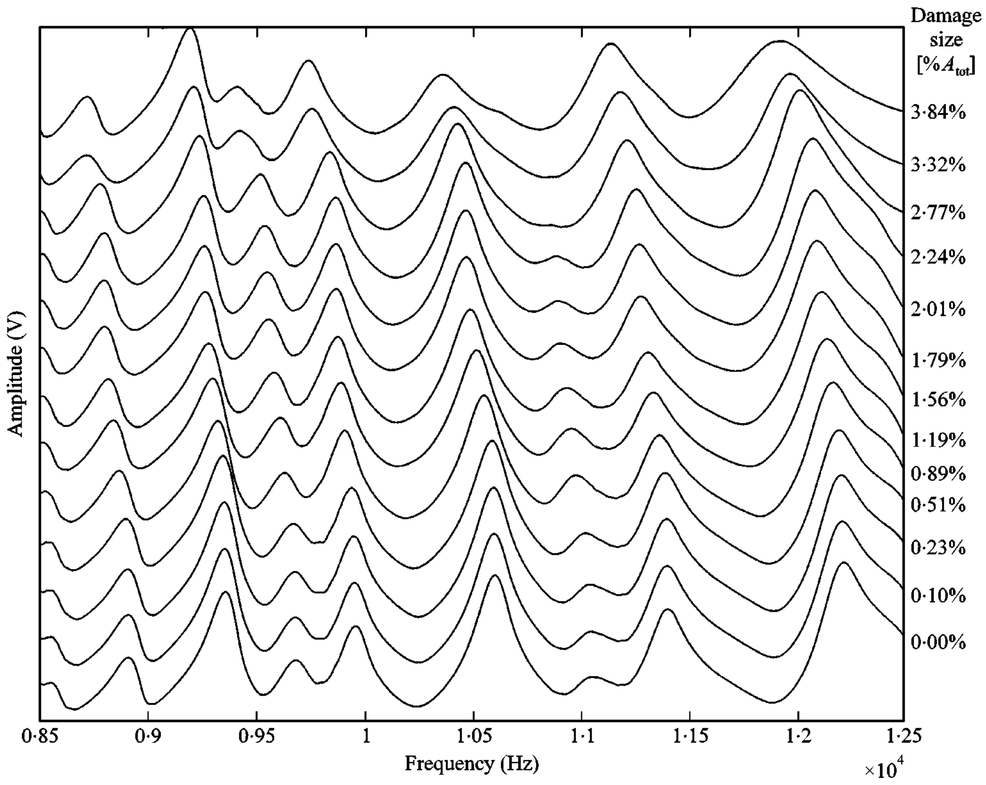

Figure 3. Damage size–frequency–amplitude record of the sensor output taken as the area of delamination increases.

tend to be equally affected irrespective of the mode number. This behaviour is illustrated in Figure 5 where frequency values are evenly affected in percentage as delamination size increases. Similar to damage, the location of the actuating and sensing devices is critical for the excitation of specific modes in the low-frequency regime, whereas is less important for higher mode numbers, i.e., frequency > 10 kHz.

5. CONCLUSION

The effect of delamination on the natural frequencies of laminated composite beams has been investigated. A piezoceramic transducer was used to induce vibrations on the structure and its response registered via a piezoelectric film sensor. Changes of the modal frequencies compared to those of a non-delaminated specimen gave good indication of the degree of damage, especially at high frequencies.

The idea of using vibration testing as a base for damage detection in composite laminates is not a new one. Nevertheless, most of the experimental work on damage detection using vibration analysis found in the literature usually explores the

Table 1

Experimental modal frequencies for different delamination sizes

amage area [% A_{tot}]	Mode no.							
	20th	21st	22nd	23rd	24th	25th	26th	27th
0·00	8913	9360	9684	9960	10 604	11 055	11 401	12 213
0·10	8911	9357	9679	9950	10 601	11 053	11 401	12 210
0·23	8913	9357	9679	9950	10 599	11 052	11 399	12 205
0·51	8903	9350	9675	9943	10 594	11 023	11 396	12 200
0·89	8875	9330	9632	9913	10 555	10 982	11 370	12 171
1·19	8847	9303	9617	9897	10 522	10 959	11 342	12 144
1·56	8827	9287	9590	9884	10 493	10 943	11 318	12 119
1·79	8810	9274	9563	9877	10 478	10 906	11 289	12 101
2·01	8808	9270	9559	9878	10 476	10 900	11 280	12 091
2·24	8812	9268	9551	9877	10 476	10 893	11 269	12 082
2·77	8788	9251	9533	9851	10 442	10 867	11 226	12 023
3·32	8730	9226	9434	9768	10 425	n.e.	11 198	11 978
3·84	8738	9206	9427	9751	10 370	n.e.	11 148	11 936

n.e.- not excited or mixed.

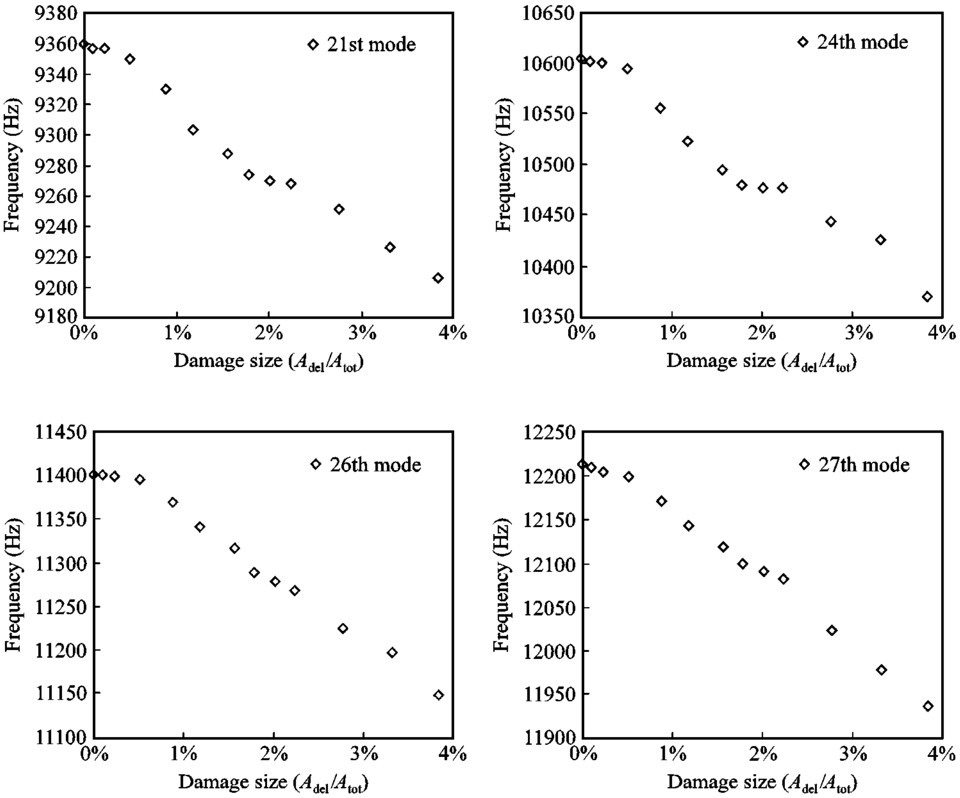

Figure 4. Effect of delamination size on the resonant frequencies as the damaged area increases.

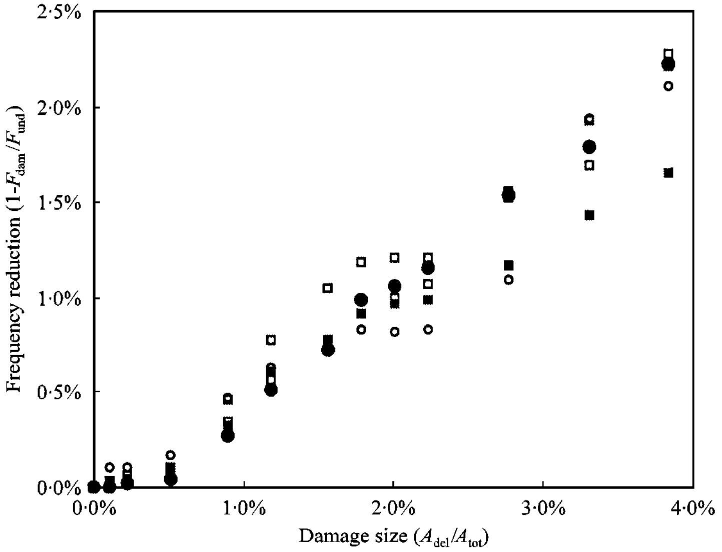

Figure 5. Normalized frequency reduction as a function of delamination size for different mode numbers: ■ 21st mode; ○ 23rd mode; □ 24th mode; ● 26th mode; □ 27th mode.

dynamic behaviour of structures on the modes of vibration associated with low natural frequencies. As shown in this work the use of vibration at higher frequencies allows the identification of delamination occurrence in the cantilever composite beam.

The time-domain inspection procedure described has demonstrated to be an effective method for modal frequency measurements. This technique uses frequency as a known parameter to which the sensor response (voltage) is related; it simplifies the signal analysis processing and eliminates problems with frequency typically encountered when dealing with frequency response function measurements. The time for each test was of the order of 1–5 s, with excellent repeatability of events. Future work will focus on detecting delamination during impact or fatigue loading. Also, in order to assess the applicability of this delamination evaluation scheme modal analysis tests will be performed on specimens with different dimensions and geometrical configurations (large plates) as well as different support conditions (simply supported, clamped edges).

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