RELIABILITY OF GLASS FIBRE-EPOXY ADHESIVE JOINTS UNDER REPEATED LOADING CYCLES THROUGH ACOUSTIC EMISSION AND ACOUSTO-ULTRASONIC TECHNIQUE

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Abstract

Sending ultrasonic signals across the joint area and listening then to received acoustic emission signals constitutes the so-called acousto-ultrasonic technique, widely applied to quality discrimination in joint structures. Here three different types of E glass-epoxy adhesive joints, produced by a handmade procedure, are in a certain measure discerned.

Furthermore, the influence on mechanical properties of the repeated application of shear stresses up to 30-50-70 % of ultimate load on adhesive joints obtained by simple overlapping was investigated. At this subject acoustic emission (AE) can supply a useful tool for reliability assessment, by measuring irreversible damage via the Felicity ratio (i.e., the ratio between the load for acoustic emission onset during the repeated test and the load in the first test). Of course signal characteristics, as showed from the different Felicity ratios, are widely modified from the different level of stress reached in the test: an analysis of amplitude distributions is proposed.

Keywords: E-glass-epoxy, shear stress, damage, acousto-ultrasonics, neural network, acoustic emission, Felicity ratio

1. Introduction

Different techniques, able to optimise the repeatability of components' characteristics in composite industry, are available to enhance automation in each phase of production process. In spite of this, some operations, among which the lay-up itself, are often hand-made, even in components for special applications. Hence comes the need for an efficacious assessment of joint mechanical characteristics, able to grant in a reliable way that an acceptable quality is reached. To attain this goal a completely passive non-destructive philosophy could be suitable, in order either to monitor the presence of internal defects in joined area or to appraise the capability of the joint to support a given solicitation without a serious damage. In this field, techniques based on ultrasonics are particularly able to recognise and measure defects and to complete data acquired through mechanical tests.

Frequent defects into bonded joints can be ascribed, according to Adams and Cawley (1988) to the presence of voids and porosity, consequent to air trapping or extraneous substances or anyhow pollutant situations, that sometimes care in preparation and respect of standards are not sufficient to avoid. Anyway, the creation of a bonded joint involves questions, widely reflected in commonly used guidelines, dealing with many different aspects of the fabrication technology. We can mention incorrect storage and manipulation of adhesive film and/or adherents, as well as chemical inconsistency or poor mixing, excluding problems of an unsuitable cure cycle, since that cycle is automatically performed and controlled.

Acoustic emission was extensively used to measure that bonded joints are respondent to the desired performances; in Muravin & al.(1991) energy and frequency spectra have been employed in a persuasive statistical and probabilistic analysis, concerning steel plates bonded with a modified epoxy adhesive. In composite adherents instead signal attenuation enhances level of uncertainties, since damage phenomena in basic material are not easily discernible from what happens into joint area due to stress application. In spite of this, some studies have been carried out; in Osaka and Fukuda (1988) different types of roving and mat GFRP underwent to monotone and cyclic solicitations with different levels of stress. The analysis was in that case led by amplitude distributions and counts rate observation, both found useful for quality discrimination. A sensible factor in AE analysis on composites is Felicity ratio, whose significance depends indeed from the capability to assess with a reasonable accuracy the new onset of stress wave signals during the immediate repetition of the loading. In other words, criteria are needed to reveal AE effective beginning, because for the intimate visco-elastic nature of adhesive joint it is often difficult to observe the real absence of mechanical stress wave through load application. Youssef & al.

(1990) for example proposed three different criteria were: reaching the first 50 events, reaching a given total AE duration (here 1 ms) or finally reaching 50 energy units. Moreover the disappearing of Felicity effect in delayed test repetition can be useful to assess the level of mechanical recuperation allowed to the structure and the so called "loading memory" of the joint, strongly depending from interface quality.

Acousto-ultrasonics (AU) is often more attractive than acoustic emission so to sever the criticality of artificial and/or of industrial defects in composite bonded joints, as in Caneva and Santulli (1991), to lead to signal pattern recognition aided by neural networks. In effect AU data need less interpretation and are more immediate, for the partially active nature of this NDT test; this tool of investigation was proved in addition by Whittaker & al. (1990) to fit particularly well in a combined use with acoustic emission analysis. While AE is able in fact to support efficiently mechanical tests, more often its outputs are completed in a persuasive mood from a preventive employment of acousto-ultrasonics on the joint area.

2. Materials and methods

All the samples considered were produced by hand lay-up technique, using epoxy resin and glass-fibre reinforcing fabric. Joint area was 60x30 mm for A type, 70x30 for B type and 75x30 for C type joints. The dimensional tolerance was around ±5%, reasonable in a handmade fabrication procedure.

A-type joints have been realised by adding an additional layer of glass fibre reinforced epoxy resin between the two laminates to be coupled, before the completion of polymerisation process. B and C-type joints have instead been obtained using specific modified epoxy glue and compressing the adherents at 60 °C until the end of the cure cycle. The only difference between these two types is that in B-type surface preparation was realised through sand paper, while in C-type joints a peel-ply was used during the preparation of the adherents. Post-curing treatment was for all samples 6 hours at 40 °C. The three types of joints are represented in fig.1a, b and c.

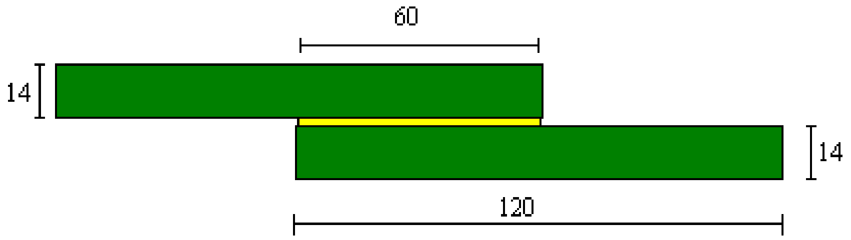

fig.1a Bonded joint type A

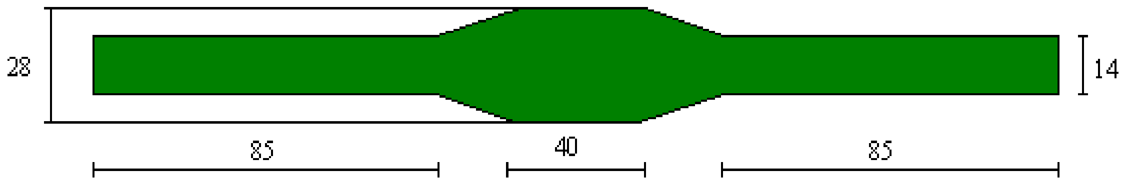

fig.1b Bonded joint type B

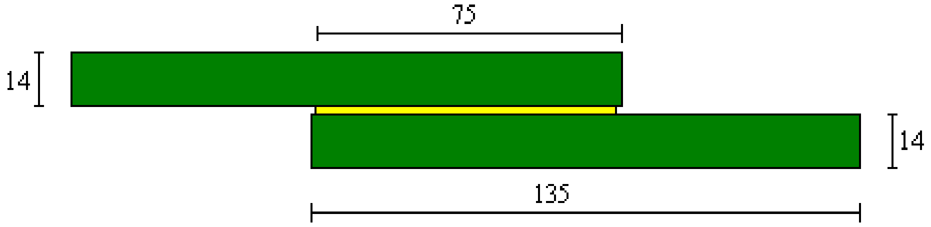

fig.1c Bonded joint type C

Acousto-ultrasonics was performed using in transmission a 2 MHz 60° oriented ultrasonic probe, connected to a GILARDONI RG20 oscilloscope and detecting acoustic emission signals through a broadband (100-1200 kHz) sensor. The ultrasonic probe and the acoustic emission sensor were placed at opposite extremities of the adhesive joint and at a mutual distance of about 70 mm; acquisition was performed for periods of 5 seconds each and repeated a minimum of 5 times per each joint. The total number of 512 points' waveform was thus more than 1000 per joint, acquired by PAC MI-TRA transient recorder. Acousto-ultrasonic data were treated with ICEPAK software so to distinguish automatically with a neural network philosophy the various situations as impressed in acoustic emission signals' patterns.

Loading program (displacement control, with cross-head speed of 0.2 mm/min for all situations) was performed through a ZWICK 1488 Universal Testing Machine. A PAC MISTRAS system was used for AE parameters' acquisition and elaboration. With this aim a resonant (peak frequency 150 kHz) sensor, placed in the centre of the joined area, whose threshold was 40 dB and total gain 60 dB. Two guard sensors were placed on hydraulic grips' structure, so to lock out undesired noise extraneous to structural phenomena.

3. Neural network philosophy

First of all, a choice was carried out from all signals acquired; the qualitative criterion was to select from each file thirty consecutive 512 points waveforms which would clearly show a succession of precursor-body of the signal-damping without any spurious peak. From those signals, a half was each time used to train the classifier and the other half was recognised. A great attention was then dedicated towards the attainment of an appropriate neural network structure, which would optimise the pattern recognition. The result of this process is shown in fig.2.

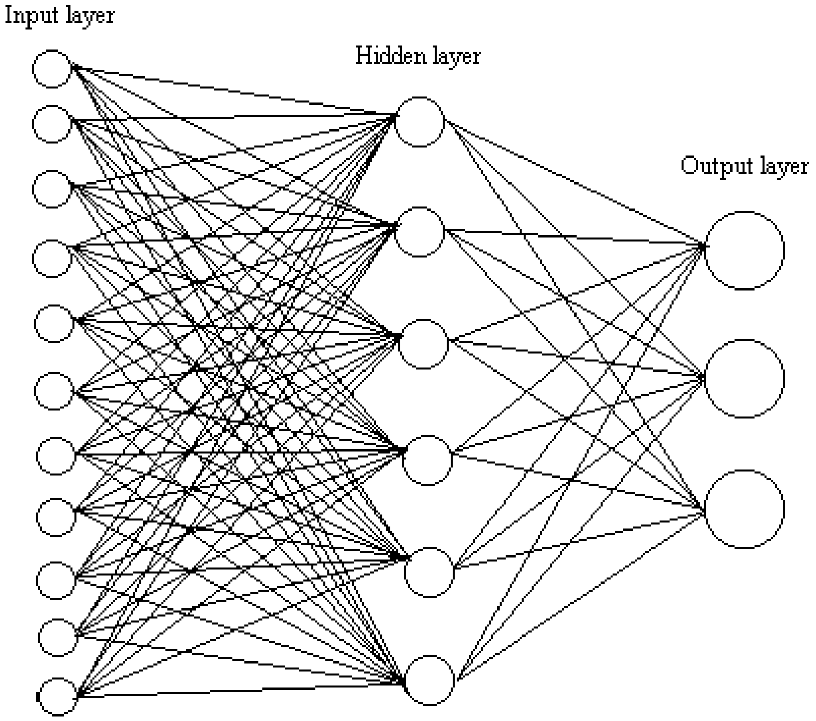

Fig.2 Neural network structure for acousto-ultrasonic data discrimination

The features that constitute the most efficient output layer of the network used for our data are all related with the area described for the signal envelope. This was found after having tested different sets of features and could be finally ascribed to the different ways of energy absorption from the ultrasonic signal through the surfaces of differently produced joints. Features used were precisely % of total area under greatest peak and % of total area under 2nd greatest peak on time, phase, power, autocorrelation and cepstral domain and % of total area under 3rd greatest peak on time domain alone, for a total of 11 features. Power and phase are obtained through forward FFT application to AE signal, representing respectively the amplitude (real) and angle (imaginary) part of the FFT. Autocorrelation instead changes the real and imaginary part of forward FFT into amplitude and angle representation. Angle is discarded and the real part of a new FFT performed on amplitude is autocorrelation. Cepstral finally, after change into amplitude and angle, take the logarithm of amplitude and report another time amplitude and angle respectively to real and imaginary, performing then an inverse FFT, whose real part is cepstral.

Error values were calculated by backward propagation i.e., processing units at each layer and adjusting their interconnecting weights, moving from the output layer nodes through the successive hidden layers, reducing thus progressively the observed error. An *RMS error* of less than 0.1 could be satisfying for the quality of the training; however, an error consequent to the individual signal pattern (pattern error) is also calculated during iteration process. The fact that, despite the low value of RMS error, the pattern error remains high could indicate problems either in the choice of the training sample or in the set-up of the neural network structure, or both. Number of training iterations is measured as *maximum counts*.

The adjustment of the interconnecting weight w_{ij} is performed between node i and j using the error value of the previous processing unit j (d_j) and the output value of the following unit i (a_i), obtaining for such an adjustment the following equation (1):

$$\Delta w_{ij} = \eta \, d_j \, a_i \qquad (1)$$

where η is the *learning rate*, a proportional constant with value <1, able to produce an acceptable learning from the network.

A better reduction of RMS error at the desired value is moreover achieved, when avoiding that back-error propagation algorithm, instead of calculating the real value of RMS error, would be trapped in a local minimum. This can be done by using small random weights, called *momentum,* able to evaluate rate changes, so that the algorithm could overstep local minima, stopping its run only at important decreases (real minima) of the RMS error curve.

Here below are reported the values finally chosen for training optimisation.

Max. count	300
RMS error	0.03
Learn rate	0.6
Momentum	0.2

4. Experimental program

a. Acousto-ultrasonic tests on 8 joints per series to discern signals from A, B and C joints.

b. Verification of shear ultimate stress (3 joints per series) for A, B and C type joints

c. Application of the sequence: *30% ultimate stress (u.s.)- zero - 50% u.s.- zero- 70% u.s. -zero* (5 joints per series) with Felicity ratio measurement

d. Shear stress application up to failure on the already tested (point c) joints to evaluate shear mechanical properties variation.

5. Results

5.1 Acousto-ultrasonics

The average results of acousto-ultrasonic data screening have showed that:
A is recognised only at 67% (the rest is evaluated as B)
B is recognised at 93% (the rest is evaluated as C)
C is recognised at 80% (the rest is evaluated 13% as B and 7% as A).
As supposed, the different physical structure of B joints presents the more easily discernible characteristics. Another observation might however concern the fact that A joints, although with a physiognomy very similar to C joints, are never confounded from neural network, with those ones.

5.2 Shear ultimate stress measure

In table 1 are reported mechanical data both for joints tested for the first time and for joints (here called *loaded*) that already underwent to the sequence (see 4 point c). The joint structure modulus was measured on the linear part of stress-strain curve, considering only the points situated from 20 to 80% of proportionality limit stress.

Table 1

Joint type	Avg.ult. shear stress (MPa)	
	Unloaded	Loaded
A	12.4	9
B	13.6	10.3
C	8.8	8.5
	Avg. joint modulus (GPa)	
	Unloaded	Loaded
A	0.518	0.872
B	0.616	0.784
C	0.683	0.652

A comment on that table could not leave out of course the evidence that joints C have, even in their first use, very poor mechanical characteristics, compared with the other joint series. This seems confirm acousto-ultrasonic data, explaining clearly why is so easy discern joints A from joints C, but not from joints B. The performance of the envisaged sequence of load applications reduces nevertheless greatly (about 30%) the ultimate shear stress of A and B joints, although it does not affect significantly the mechanical behaviour of less-resistant joints C. This means that initial performances of A and B joints could not be taken into account for a security factor coefficient, furthermore when noting that joint modulus is clearly increased from repeated loading in these two series.

5.3 Felicity ratio measurement

Some experimental criteria were used to assess the new start of acoustic emission in order to lead to Felicity ratio determination. The acoustic emission is considered to be active again during new loading whenever a counts rate (counts/second) of more than 15, including more than 10 hits is detected in a continuous period of 10 seconds. This is checked applying before acquisition a filter able to lock out from data files hits with energies <2 units and counts <5. Then, Felicity ratio F is measured by: F = (Stress for new onset of acoustic emission)/(Stress attained in the previous test)

In Table 2 are listed the results of this evaluation. Note that an unitary value is reported also for cases, when acoustic emission starts again after having reached the previous stress, since a Felicity ratio > 1 has no meaning.

Table2 Avg. Felicity Ratio

Previously attained stress	A joints	B joints	C joints
30% u.s.	1	0.96	0.93
50% u.s.	0.90	0.87	1
70% u.s.	0.71	0.68	0.59

For a deeper analysis on these results, we can report that the measurement of a Felicity ratio of not less than 0.9 or better 0.95 is considered a symptom of not important quality degradation due to loading. One can therefore note than after application of a stress equal to 70% of ultimate stress, the Felicity ratio is much lower than the already mentioned value. Quality degradation is therefore already considerable, even in C joints, when the absolute values for ultimate stress are, as previously showed, are not comparable with those of the other joints, at least for untested specimens: this fact limits of course the significance of higher Felicity ratios in this series, at 30 and 50% u.s.

5.4 Acoustic emission amplitude distributions

The following figures represent hits distributions following amplitude and precisely in fig.3 are reported typical examples of A joints, in fig.4 B joints and in fig.5 C joints. The plots numbered with a are referred to a 30% u.s application and those numbered with b, c and d show respectively a 50% u.s., a 70 u.s. and a loading up to failure. In A joints (figs.3) generally the 30% u.s. plot is not so significant, no plastic deformation seems present in the joint area, as showed from the corresponding unitary value of Felicity ratio (Table 2). The other situations show instead about the same amount of acoustic emission, with many amplitudes higher than 70 dB: this curve has a maximum at 62-64 dB.

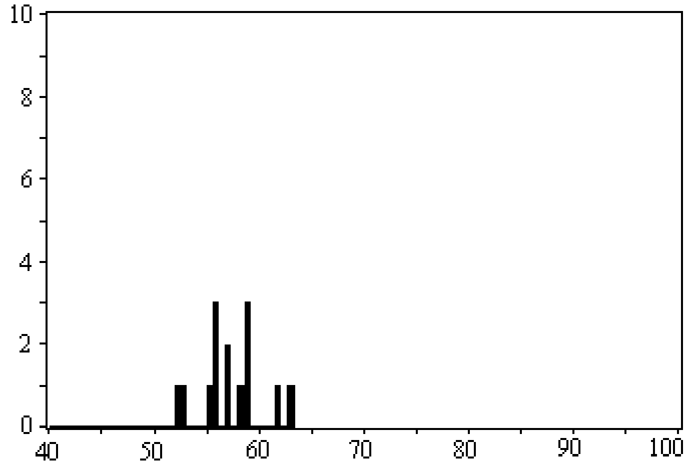

Fig. 3a Amplitude distribution for loading at 30% u.s. on joint type A

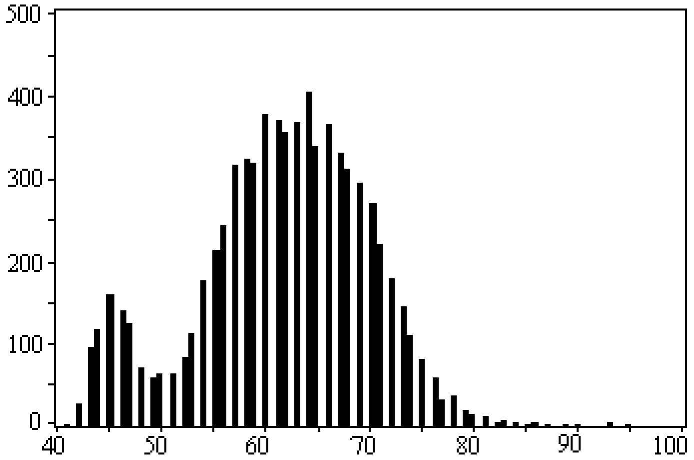

Fig. 3b Amplitude distribution for loading at 50% u.s. on joint type A

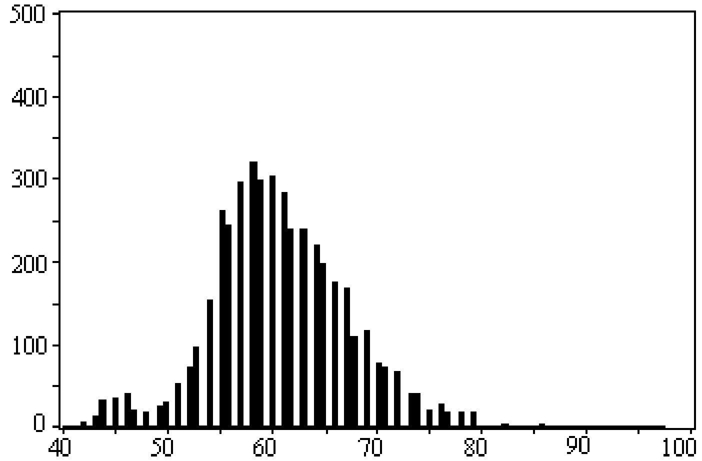

fig.3c Amplitude distribution for loading at 70% u.s. on joint type A

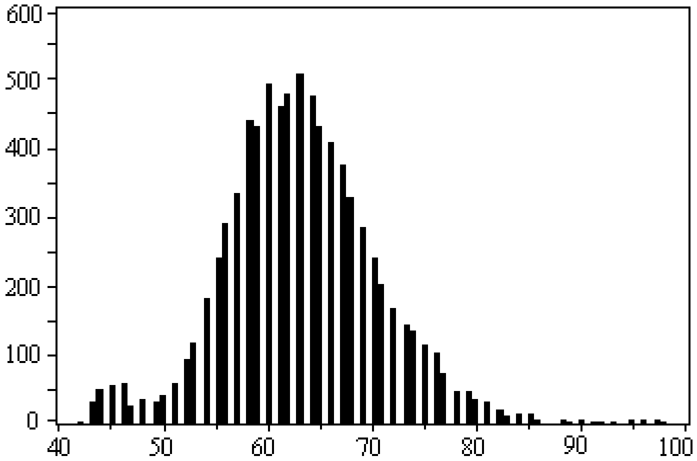

fig.3d Amplitude distribution for loading up to failure on joint type A

In B joints the 30% plot presents characteristics not much different from the corresponding plot for A joints, but the following curves do not present many high amplitude events (>70dB), even at failure: in general amplitudes are lower (distribution curve maximum at 56-58 dB) and the whole number of hits reduced. The structure seems more compact and reliable than in A series, moreover the basic material is less damaged from loading.

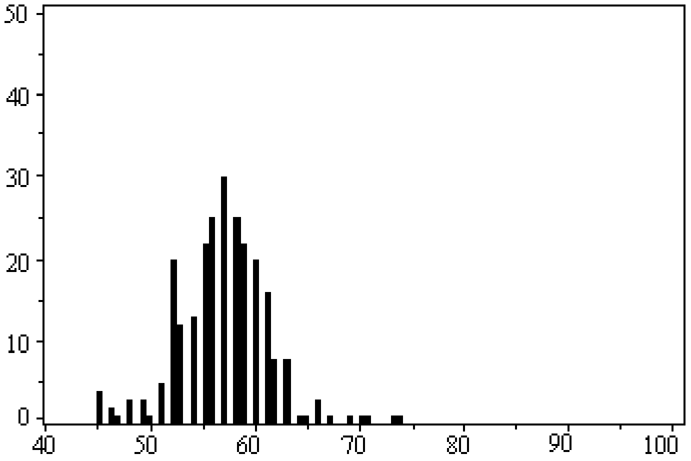

Fig. 4a Amplitude distribution for loading at 30% u.s. on joint type B

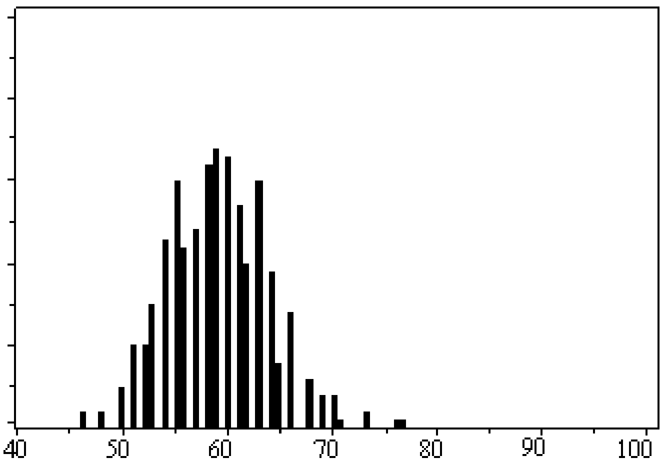

Fig. 4b Amplitude distribution for loading at 50% u.s. on joint type B

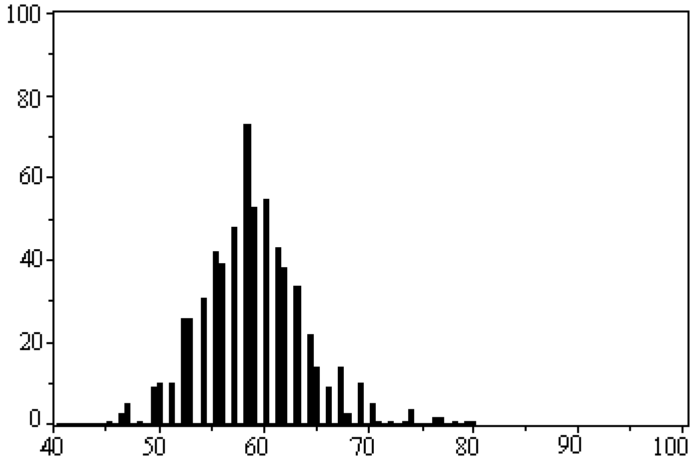

Fig. 4c Amplitude distribution for loading at 70% u.s. on joint type B

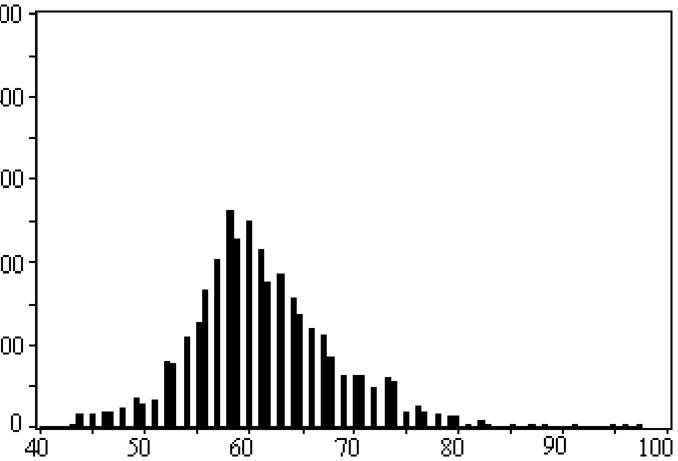

Fig. 4d Amplitude distribution for loading up to failure on joint type B

In C joints damage initiation is very precocious, since many hits are present already in 30% u.s. loading and their amplitudes more often exceed 70 or even 80 dB. Of course afterwards a reduction of hits number could be revealed from 70% plots, indicating only that a serious damage has already been produced. In any case the acoustical activity showed during failure is the highest from the three joint types and the form of the curve approaching a Gauss distribution hints probably the presence of all kinds of damage, sensibly affecting the basic material itself.

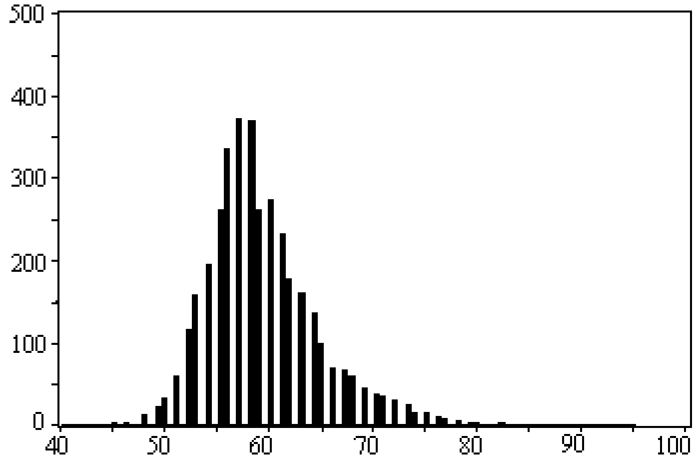

Fig. 5a Amplitude distribution for loading at 30% u.s. on joint type C

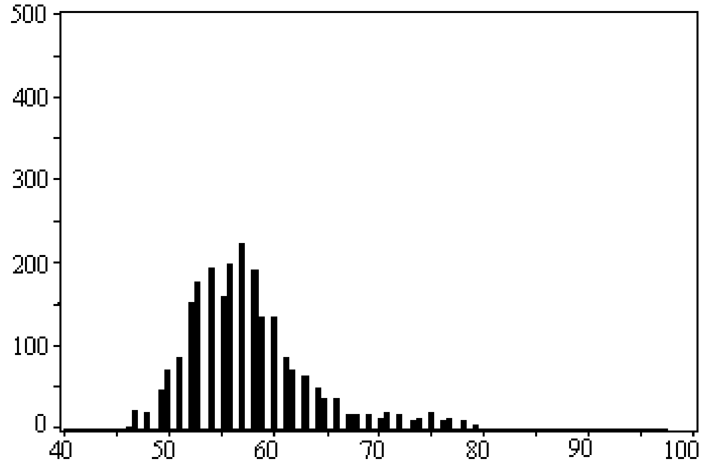

Fig. 5b Amplitude distribution for loading at 50% u.s. on joint type C

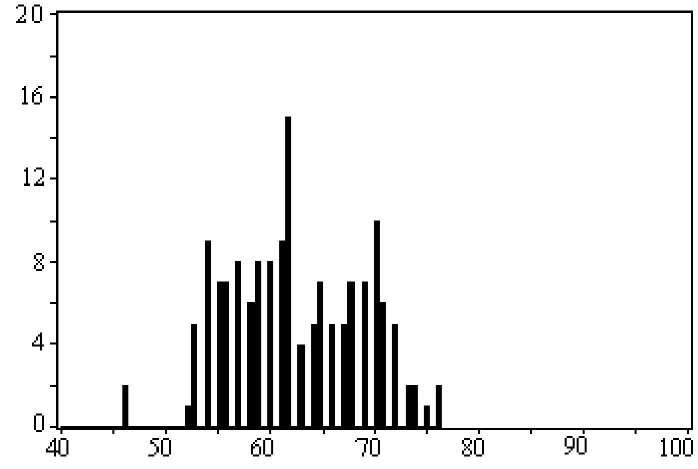

Fig. 5c Amplitude distribution for loading at 70% u.s. on joint type C

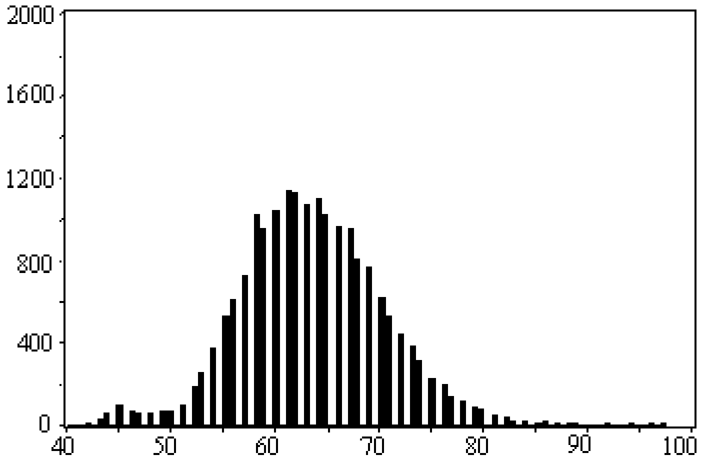

Fig. 5d Amplitude distribution for loading up to failure on joint type C

6. Conclusions

The preventive application of acousto-ultrasonics to bonded joints subjected to repeated shear stress application monitored with acoustic emission has allowed to recognise the important level of structure degradation in this situation, due to out-of-standards handmade procedures of fabrication.

Fundamental tools for this analysis have been revealed in Felicity ratio measurement and AE events' amplitude distribution that would permit to outline and possibly calculate security coefficients for the application of these joints in industrial procedures.

Another important instrument for quality prediction and discrimination would be supplied in future studies on these joints observing their viscoelastic recuperation i.e, verifying whether a delay in new stress application would influence Felicity effect.

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