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Recommended procedure for conducting OPTIMAT Blades residual strength test

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Confidential

OPTIMAT BLADES

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1 INTRODUCTION

This document has been prepared within the scope of Task Group 5 of the OPTIMAT Blades project in order to realise a common methodology for performing residual strength tests. The document should be read in conjunction with the DPA for TG5 [1].

The guidelines include specifications for:

- instrumentation requirements,
- the test preparation procedure,
- the loading requirements, and
- information to be recorded.

This procedure is general in nature and to be used alongside existing standards for using specific test rigs and specific instrumentation.

2 TESTS REQUIRED

All fatigue tests will be load controlled and all static tests displacement controlled. The performance details of the tests will differ from laboratory to laboratory, depending on whether or not NDT investigations are to be performed and the nature of those investigations. However in all cases there should be a common set of tests. The main loads are given in bold in the list below and illustrated in **Figure 1**. The other loads designed to assess the specimen condition are illustrated in Figure 2:

(i) Initial "Proof" Loading

Either

a) Stiffness load, i.e. load to 2550 ue[1] and then to –2550 ue

or

b) AE: Two Acoustic Emission Loads

Calculate initial stiffness from 500 to 2500 ue. (load, displacement, strain on the 2 faces)

(ii) Constant amplitude fatigue loading

- [R-ratio (0.1/-1.0/10), Nominal lifetime (10^3,$5x10^4$,10^6,10^7), Life fraction (20%/50%/80%)]
- Constant amplitude − magnitude determined from nominal lifetime and baseline S-n curve; frequency will be specified as part of the baseline S-n curve data in order to keep temperature rise within stated limits (or should be calculated from an agreed frequency-load range curve)?
- Number of cycles = Nominal lifetime x [Life fraction (%) / 100]
- Measure load, number of cycles
- measure initial NDT parameters (if appropriate)

(iii) Final Static "Proof" Loadings

Repeat Initial "Proof" Loadings – only one AEL (if appropriate) need be applied

(iv) Residual strength test to failure

During the fatigue loading some Intermediate "Proof" Loadings could be applied, say at 20%/50% of the expected life. This is optional.

To keep the tests simple it has been decided to use a single Acoustic Emission Load (AEL) specification rather than vary it according to R ratio (i.e. the ratio of the minimum to the maximum load), load level, and the sign of the final residual strength test. The load hold period is 30 seconds.

[1] On the preliminary S-N curve for UD 0 the strain at 10^6 cycles is 3205 ue and at 10^7 cycles the strain is 2356 ue.

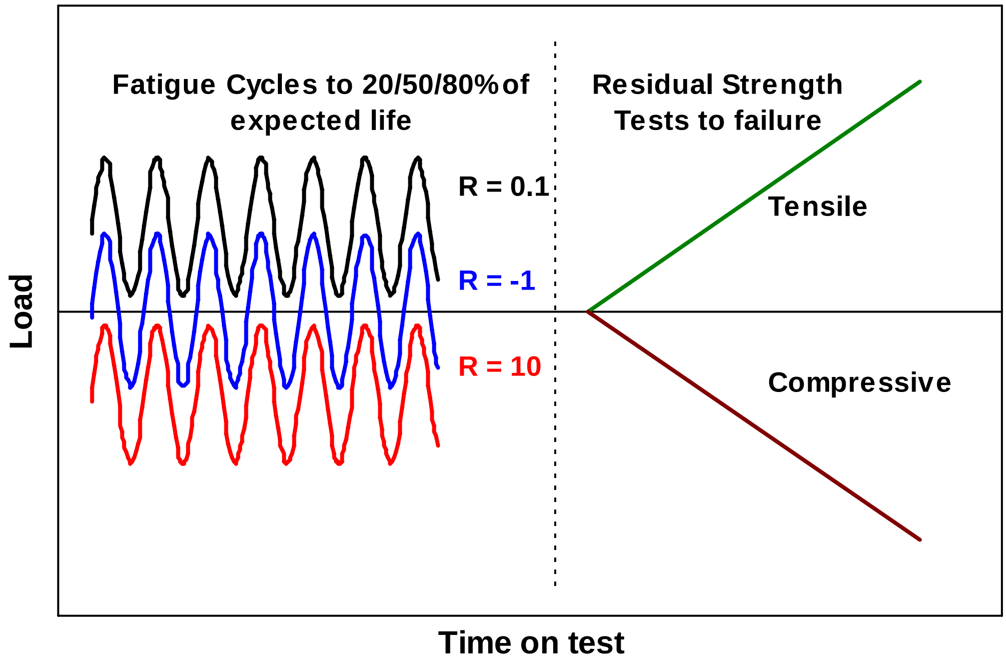

Figure 1: The main loads applied making up the 9 test combinations

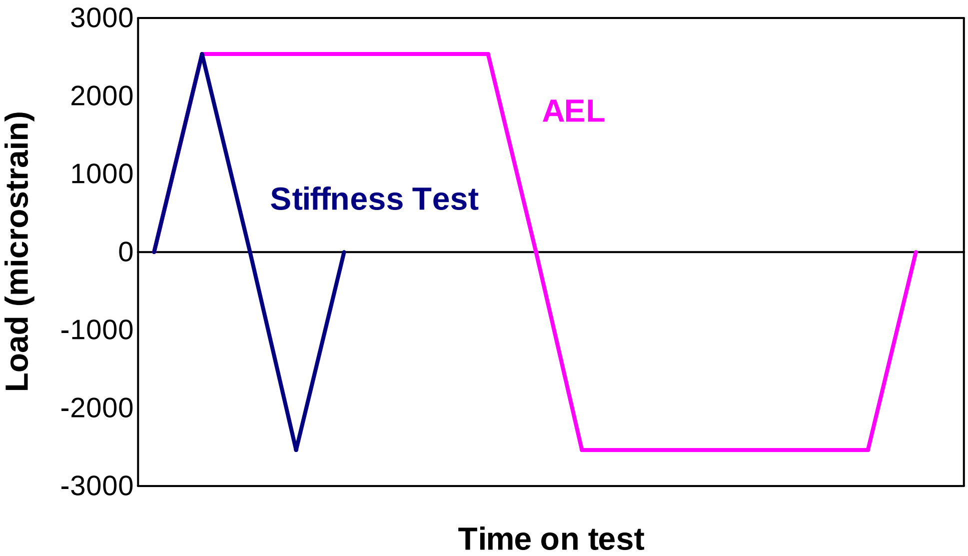

Figure 2: Acoustic Emission Load (AEL) and Stiffness Load

3 TEST EQUIPMENT

3.1 Minimum requirement:
Loading rig (minimum 100 kN capacity)

Strain gauges or extensometers – 2 off centrally mounted on opposite faces of the sample e.g. extensometer (clip strain gauges) shown in Figure 3.

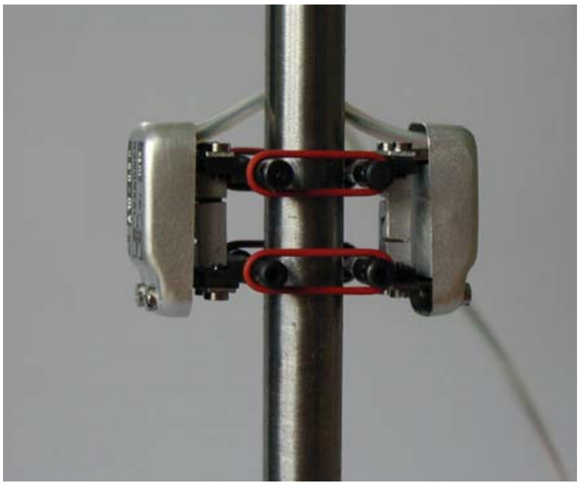

Figure 3: Indicative setup of two clip strain gauges mounted on opposite sides of a test sample

3.2 Additional options
AE System – 2 small AE sensors (separate logger fed parametrics of load and displacement)

Thermoelastic stress measurement system e.g. Deltatherm – (separately logged images)

4 TEST INFORMATION

4.1 Specimens to test

The specimens to be tested have a nominal gauge length of 35 mm and width of 24 mm with end tabs. UD (axial and transverse) and MD lay-ups are to be tested with equivalent numbers of UD layers, resulting in different specimen thickness.

Laminate UD : $[0]_4$ E-glass/epoxy

Laminate MD : $[[\pm45,0]_4; [\pm45]]$ E-glass/epoxy

The type of test and an exact loading envelope will be selected prior to each test. It is necessary to record the following data concerning the specimen.

4.2 Specimen information to be recorded

- OPTIMAT specimen name e.g. 'GEV201_D0100_0005' (which includes information on the material, production method, year of manufacture, nominal specimen geometry)

- Data to complete the optiDAT database namely

Specimen type, thickness, maximum width, minimum width, test type[2], R-value, maximum force (F_max), maximum strain (e_max), maximum stress (s_max), No. of cycles to failure (if appropriate), failure mode (if appropriate), runout (if appropriate), {target lifetime}, 'Number of fatigue cycles applied in Residual Strength Test {lifetime fraction achieved}, Residual Tensile Strength (RTS), Residual Compressive Strength (RCS), Strain at RTS (e_RTS), Strain at RTS (e_RCS), Loading rate in residual testing (LRR), Strain rate in residual test (SRR) [%/s] & [mm/min], {residual test failure mode}, {residual test failure description}, {(maximum) loading rate in fatigue test (LRF)}, (maximum) strain rate in fatigue test (SRF) [%/s] & [mm/min], wave shape, testing frequency if constant (fconstant), Initial tensile modulus (Eit), Initial compressive modulus (Eic), Final tensile modulus (Eft), Final compressive modulus (Efc)test machine, control, grip, Anti buckling guard (ABG), Temperature, Temperature control, Preconditioned, environment, RH, test description ref., No. of cycles to 10% stiffness reduction (N10sr), specimen shape, {Specimen modifications e.g. any surface preparation prior to sensor fitting}, {Other instrumentation used}, {Instrumentation topography[3]}, Remarks.

[Please note that the treatment of the data in {} within optiDAT is subject to further consideration by Rogier Nijssen[2].]

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[2] The Residual Strength Tests will have a number of different test type codes so that the common parameters can be recorded in a separate worksheet in the OptiDAT database reducing the need to add many additional columns to the main database worksheet.

[3] Specify one of a number of options e.g.

''= strain gauge or extensometer fitted both sides of sample

'1a2' = strain gauge or extensometer fitted both sides of sample with one AE sensor in position 2

5 DATA FILE NAMING

To ensure ease of data reference all data files should be named according to the OPTIMAT/FACT specimen name convention with the following *lffrrrcx.yyy* added where

l = target lifetime (10^3 = 3, $5x10^4$ = 4, 10^6=6, 10^7=7)

ff = fraction of nominal lifetime (20%=20, 50%=50, 80%=80)

rrr = R ratio (1.0 = +1.0, –1.0 = -1-0, -0.1 = -0-1)

c = sub category of test (a = Acoustic emission Examination Load (AEL), f = fatigue loading, r = residual strength test)

x = optional number where there is more than one file of the same sub category

yyy = extension appropriate to application in which data logged

e.g. 'GEV201_D0100_0005_380as2.dta'

where '_380a2.dta' would be for a test with a target lifetime of 10^3 cycles 80% of which had been applied and acoustic emission was monitored for which this was the second file and it was actually an acoustic emission data (.dta = PAC format).

6 INSTRUMENTATION LOCATION

Figure 4 shows the specimen and the nominal dimensions for the UD version. The outline of a clip strain gauge (extensometer) is shown centrally located. Also the Nano and the Pico AE of Physical Acoustic Ltd sensors shown are 8 and 5 mm in diameter respectively.

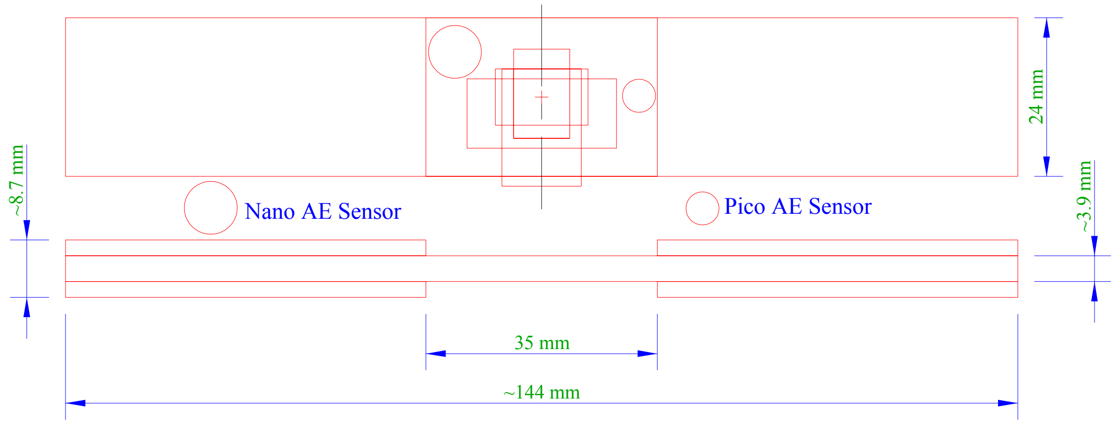

Figure 4: Position of instrumentation on specimen

Strain gauges or extensometers (clip gauges) are to be fitted so that they are centred on the specimen.

Where possible 2 AE Sensors of suitable size are to be fitted on the lengthways centre line either side of the central strain or clip gauge with a separation between their centres of 34 minus one sensor diameter in mm. For the pico this is a 29 mm separation.

7 INSTRUMENT USE

The following tests will have the following instrumentation;

7.1 Static 'Proof' Tests and Residual Strength tests
Compulsory: strain or clip gauges[4] on opposite specimen faces, load cell.

Optional: Acoustic Emission Monitoring – AE System plus additional 2 sensors on one face of the specimen

7.2 Fatigue tests
Compulsory: load cell.

Optional:

Strain or clip gauges on opposite specimen faces, load cell for the initial cycles after proof testing.

Stress monitoring - Thermoelastic stress measurement system plus single strain gauge on opposite face to camera. Can be applied to fatigue cycles only.

[4] On the residual strength tests clip gauges maybe at risk from damage which may mean strain gauges have to be fitted

8 TEST PROCEDURE

Ensure equipment to be used is appropriately serviced and calibrated

Table 1 gives the test procedure. Those tasks in the regular font are only to be done where an AE system is to be used. The Procedure in Appendix A is to be followed. Those tasks in the regular italics font are to be applied only where the Thermoelastic (TE) stress measurement system is to be used.

#	Step	Measurement		
		Strain	AE option	*TE option*
1	Attach sensors to specimen allowing for any cure time			
2	Set specimen in test rig			
3	Check sensor function	Y	Y	Y
4	Check specimen alignment			
5	Select R ratio and fatigue load			
6	Initial static "proof" load to 2550 ue OR	Y	Y	
	Apply two AELs.	O	Y	
7	Apply the full requisite number of fatigue cycles (R ratio and set load) until the given fraction of nominal lifetime	O	N (Y on 10^7 cycle specimen only)	N (Y on 10^7 cycle specimen only)
11	Final static "proof" load to 2550 ue OR	Y	Y	
	Apply one AEL			
12	Residual strength test to failure	Y	O	
13	Record results			

Table 1: Specimen Test Procedure (Y = Yes, N = No, O = optional)

9 REFERENCES

[1] Geoff Dutton, DETAILED PLAN OF ACTION WP13 AND WP14 (TG5), OB_TG5_R001, Last revised 11-12-2002

Appendix A AE TESTING PROCEDURE

A.1 Data Acquisition - System & Software

For carrying out the AE tests a dual channel AE system is preferred. The instrumentation (and software) shall be capable of detecting, processing and recording AE signals whose amplitude exceeds a pre-set (by the user) voltage amplitude threshold.

For each input channel, the following information must be calculated and recorded for every AE hit, in real time, at a minimum resolution specified in the following table:

	AE HIT DESCRIPTOR	MINIMUM RESOLUTION
1	Channel number	-
2	Arrival Time	48 bit (250 nsec)
3	External Parameters (load, deflection, fatigue cycle)	12 bit
4	Amplitude	(up to 100dB)
5	Counts	16 bit (up to 65535 counts / hit)
6	Rise Time	16 bit (up to 65535 μsec / hit)
7	Duration	32 bit
8	Energy Counts (MARSE)	16 bit (up to 65535 energy counts / hit)
9	Counts to Peak	16 bit (up to 65535 counts / hit)
10	Average Frequency	16 bit
11	Average Signal Level	(up to 100 dB)

Table 1: AE Information to be recorded

Real-time monitoring of the cumulative values of the number of hits, events and some of the above parameters in time (e.g. Energy or Counts) is required for evaluation. The AE system must be capable of calculating and plotting on screen all of the above-mentioned quantities, in real-time. Furthermore, the AE system must perform the linear or / and zonal location techniques and plot the corresponding location graphs on screen, in real-time. Sampling of external parameters such as load, displacement etc. must also, be activated at 100 ms intervals.

MISTRAS 2001, by Physical Acoustics Corporation, can be used and settings for these systems are included below. For the sake of economy in data storing space any waveform recording can be turned off.

A.2 Sensors & Preamplifiers

Examples of the type of sensors to be used are the PAC Pico with a peak frequency of 480 kHz and the Panametrics V133. The sensitivity for both these sensors is low for the 20-200 kHz range, but sufficient enough to acquire clear signals without problems at distances not exceeding few centimetres (which is the case of OPTIMAT coupons).

Check that the preamplifiers are switched to the correct gain and that any internal filter is appropriate for the sensor used. Band Pass Filtering should be applied in accordance with the selected sensor's resonant frequency:

NOTE: Electronic filtering is proposed herein as a general precaution for noise rejection. If test conditions are assessed as being suitable, wider frequency ranges than the above can be considered.

- Co-axial, shielded, low-noise, BNC/BNC cables (RG-58, 50Ω) will be used to connect the sensors (or the external preamplifiers, if needed) to the system.
- A shielded, low noise, short (<2m) signal cable with microdot/BNC connectors shall be used to connect the sensor to an external preamplifier (if one is needed).

A.3 SENSOR MOUNTING - CHECKING

To apply the AE sensors on the surface of the specimen, proceed with the following steps:
- Connect the AE sensor to the AE system, or to the preamplifier (if needed) and then the preamplifier to the AE system.
- Smoothen and clean surface of the specimen where the sensor is to be connected.
- Apply a small amount of couplant to the sensor (silicon vacuum grease, silicon sealant – after a smear of grease to enable post test removal, or other), just enough to cover the sensor's contact surface.
- Press the sensor on the specimen's surface to ensure good contact and that only a very thin layer of couplant has remained between the sensor and the surface of the specimen.
- Use adhesive tape or other means (elastic straps, spring-loaded hold-downs, etc.) to hold the sensor firmly on the specimen's surface.
- Use adhesive tape or like to support/route the cable away from the specimen.
- After mounting each sensor, for a preliminary channel and sensor response check, break several 0.5 mm 2H leads within 2 cm of the sensor and observe the corresponding amplitudes for all breaks. All lead breaks shall be done at an angle of approximately 30° with respect to the surface, with a 2.5 mm (0.1 in.) lead extension (see ASTM E 796). For typical FRP materials, an amplitude value higher than 85 dB is, usually, anticipated, indicating good coupling. This check should be performed prior to attenuation (A.7.1) and velocity measurements (A.7.5), and the corresponding data should be kept as part of the test record. Prior to the test, however, a more thorough performance consistency check is performed (see A.7.4).

More information about sensor mounting methods, couplants, and mounting fixture selection can be found in ASTM, Practice E650.

A.4 AE TEST PREPARATION - SYSTEM VERIFICATION

A.4.1 Attenuation Measurements
These cannot be performed easily on the specimen and attenuation will not be a problem. However, if a plate is available to perform attenuation measurements, the following hardware settings must be set through the systems' software:
Threshold = 40dB (unless extreme background noise, see §8.2)
PDT = 150 μsec
HDT = 400 μsec
HLT = 10000 μsec
The rest of the settings could be left equal to the default software values. The configuration (.ini file) must be saved for future reference.

In the centre region of the plate, mount and check (with 0.5mm 2H lead breaks) an AE sensor and locate points at various distances of 100 mm intervals from the center of the sensor along a line parallel to one of the principal directions of the surface fiber, and along a line perpendicular to it. At each of the marked points, break five 0.5 mm 2H leads and record average peak amplitude for all breaks, getting as far enough from the sensor, as needed in order to get a 30dB drop in amplitude from the closest lead break to the furthest lead break, in both directions. The data for all points shall be retained in file (.dta file) as part of the original experimental record. The filenames of both ".ini" and the corresponding ".dta" files must be recorded on paper.

A.4.2 Channel Response Consistency Checking

A.4.2.1 Pre-Test Sensor Check

Upon mounting the sensors, all channels must be checked for equivalent response. For that, the following hardware settings must be set through the systems' software:

Threshold = 60dB
PDT = 150 μsec
HDT = 400 μsec
HLT = 10000 μsec

The rest of the settings could be left equal to the default software values. The configuration (.ini) file must be saved for future reference.

While at data acquisition mode (line display for PAC systems), break 5 mechanical pencil leads (0.5 mm - 2H) 2cm away from each sensor. Calculate the average amplitude of these simulated AE sources for each sensor. Calculate the overall average amplitude for all the sensors. The average of amplitudes for each individual sensor must fall within ±2 dB from the overall average. If this is not true for a sensor, then the following must be checked and fixed as necessary, until a consistent amplitude average is achieved:

- coupling between sensor and surface,
- cable connections,
- preamplifier,
- sensor itself,
- AE system.

If, after checking all possible causes for sensor response inconsistency, it is impossible to achieve a consistent response from an individual sensor (e.g. due to different sensor resonant frequency, or due to sensor wear etc.), the inconsistent sensor can be used, making a relevant note on the test report. In such case, if the sensor's response is lower, adjacent sensors may be mounted closer to compensate for the reduced sensitivity.

All data recorded during this procedure must be saved and kept for future reference. The filenames of both ".ini" and the corresponding ".dta" files must be recorded on paper.

A.4.2.2 Sensor Check During the Test

If the overall test duration is long (e.g. more than one day, where the sensors are left on overnight) or if there are indications that sensors response might have changed (e.g. due to mechanical impacts on the sensors, or moving cables knocking the sensors etc.) the procedure of §7.4.1 should be repeated, at least once a day, or whenever there is suspicion that a sensor has been moved. Data should be collected for the test and a time mark placed between the sensor tests. Also the order of sensors test should remain the same to ease subsequent comparisons. Generally, it should not be expected that overall sensor sensitivity (i.e. the average lead-break Amplitude value from all sensors) will change, throughout a static test. If, however, the overall sensitivity drops by more than 2 dB during the test, compared to the initial sensitivity (average recorded in §7.4.1), one or more sensors should be remounted and the procedure of §7.4.1 should be repeated.

A.4.2.3 End of Test Sensor Check

At the end of the test, the procedure of §7.4.1 should be repeated. If the criteria of §7.4.1 and §7.4.2 are not met, a note should be made on the report. Serious sensitivity differences should, also, be taken into consideration during analysis.

A.4.2.4 Velocity Measurements

For this task, the following hardware settings must be set through the systems' software:
Threshold = 40dB (unless extreme background noise, see §8.2)
PDT = 150 μsec
HDT = 400 μsec
HLT = 10000 μsec
The rest of the settings could be left equal to the default software values and the configuration (.ini) file must be saved for future reference.
Wave velocity measurements must be carried out in the two main directions. This can be performed by following the following steps:

- Position an AE sensor on a representative region of the specimen.
- Position one sensor 29 cm away from the first sensor in the axial direction (unless at this distance attenuation of more than 40dB occurs, in which case position the sensor closer).
- Position another sensor 50 cm away from the first sensor in the edge direction (unless at this distance attenuation of more than 40dB occurs, in which case position the sensor closer).
- Perform various lead breaks very close to the first sensor (within 2cm).
- Measure the time difference (Δt) of the arrival of the wave between the first sensor and the adjacent ones (line mode in PAC systems).
- The wave velocity in the axial direction is given by dividing the axial sensor distance (50cm) by the calculated Δt in the axial direction.
- The wave velocity in the edge direction is given by dividing the sensor distance in the edge direction (50cm) by the calculated Δt in the edge direction.

Alternatively, wave velocity can be measured using the test layout of the sensors, defined in §7.2 and § 7.3, after all sensors have been mounted and checked. In this case, various lead breaks are performed close to each sensor and the Δt, as well as the corresponding velocity values, is recorded for each adjacent sensor.

In general, the above procedure might yield different velocity values for different sensor couples, or variations in the velocity value, even within the same sensor couples. In such a case, a representative velocity value should be used for location purposes. Provided the measured velocity values exhibit a sensible range the representative velocity value should be lower than their average value. Alternatively, a Δt location formulation can be used, using a value in excess of the average Δt value for each sensor couple.

All data recorded during this procedure must be saved and kept for future reference. The filenames of both ".ini" and the corresponding ".dta" files must be recorded on paper.

A.5 PREPARATION FOR REAL TIME MONITORING

A.5.1 Data Acquisition Hardware Settings

The following hardware settings must be set (for PAC systems) during static loadings.

Threshold -
A threshold value of 35 to 50 dB, depending on extraneous noise level, type of test (loading rate, see paragraph 9.1) and attenuation characteristics of the specimen's material is acceptable for FRP applications. It is recommended (especially since location techniques are to be applied) that the threshold be common for all channels. The threshold will be set in accordance with 8.2, but the initial setting will be 40 dB.

Unless otherwise specified.
System Gain 20 dB
Peak Definition Time 150 μsec
Hit Definition Time 400 μsec
Hit Lockout Time 800 μsec
Sample Rate 4MHz (MISTRAS system only).
Parametrics Sampling Rate - In order to be able to calculate Felicity Ratio accurately, given the fact that the load increase rate shall be relatively slow, load values shall be sampled every 100 msec.
Time Driven Data Recording Rate - For better graphical representation of load when no AE hits are available, load shall be recorded at least every 1000 msec.

Upon setting the above values, the corresponding ".ini" file must be saved and retained for future reference.

A.5.2 Background Noise Check

Once the sensors are mounted on the specimen and checked (see §7.4), and the hardware settings are set as described in 8.1, a background noise check must be performed, by monitoring the system (line display for PAC systems) for at least 15 minutes.

During noise monitoring, the specimen should be mounted in the test rig and its power supply shall be on. No load shall be applied to the specimen. Hardware settings must be the ones defined in §8.1 (threshold=40 dB, unless otherwise specified). At this unloaded state, two conditions must be met:
- No AE signals should be recorded by the system
- The Average Signal Level (ASL) value should be consistent for all channels, and well below the threshold.

In case all, or most, sensors are recording the background noise, and this noise cannot be removed or minimized, the threshold should be increased for all channels by 5 dB steps, until the two conditions are met. In case individual channels record background noise, the corresponding sensors/channels must be checked.

Data during noise monitoring period must be saved and kept for future reference. The filenames of both ".ini" and the corresponding ".dta" files must be recorded on paper.

A.5.3 Pencil Breaks for Zonal and Linear Location Verification

A.5.3.1 General Location Checks

To verify location techniques it is useful to perform lead breaks at various positions on the specimen, using the hardware settings defined in §8.1 and §8.2. Prior to loading the specimen, break three leads at each at 1/4, 1/2 and 3/4 of the axial sensor distance.

Record the sequence of these lead breaks and, if possible, mark the corresponding positions on specimen itself. It is very useful to insert a "time mark" after each set of lead breaks (by pressing ALT + T in PAC systems), so that, during the analysis, each position can be distinguished from the others. The ".dta" filename containing the data obtained in this procedure must be recorded on paper.

Location verification can be performed during loading of the specimen, in-between the various loading stages. Strong location indications obtained during the loading of the specimen, should be, initially, searched for within or very close to the grid element upon which the simulated AE sources prior to the test yielded the same locations as the real-time source.

A.5.3.2 Specific Location Checks During Test

If the test supervisor thinks there are reasons to verify location during the test then specific locations checks in that area should be conducted. Such reason could include areas where high levels of emission are located but there is no visual evidence of damage occurring or, vice versa, areas where visible damage does not appear to have been located correctly

A.6 AE MONITORING DURING AE EXAMINATION LOADING (AEL)

A.6.1 Loading envelope

The loading envelope of an AE examination loading (AEL) is a trapezium-shaped load envelope (load, then load-hold, then unload) including a 10 minute load-hold period, performed before and after any loading as a means to evaluate the damage imposed on the by the load, or performed at any time during the life of the specimen as a means to evaluate its condition and its capability to withstand a particular load level for long term operation.

At previously unloaded (new) specimens, it is necessary to perform and repeat the AEL test before any other loading is applied to the specimen, since a high level of emission can always be expected when a structure is first loaded to a given level. Leave 10 minutes between the tests.

The AEL maximum test load value should be 0/5/10% higher than the fatigue load.

a. Gradual load increase up to 100% of the AEL
b. Load hold for 10 minutes
c. Unload completely
d. If previous load the first load applied to the specimen then repeat a-c after 10 minutes

A.6.2 General guidelines for loading

- The load increase rate to the AEL should not exceed 30% of AEL per minute and should, preferably be higher than 10% of the AEL per minute.
- The unload rate should not exceed 40% of AEL per minute and should, preferably be higher than 20% of the AEL per minute.
- A load-control loading device is preferred rather than displacement-control.

A.6.3 Real-time monitoring

During acquisition, the following graphs must be frequently checked:

a. Cumulative Hits vs. time,
b. Cumulative Hits vs. load
c. Energy rate vs. time,
d. Cumulative Energy vs. load
e. Amplitude vs. time (point plot),
f. Load vs. time,
g. Hits vs. channel,
h. ASL vs. channel,
i. Counts vs. amplitude.

It is beyond the scopes of this procedure to analyze each case of graph observations. Generally, exponential increases of a - d and extreme channel deviations in g might signify critical damage growth.

During data acquisition anything unusual concerning the test (audible noises, accidental touching of the structure, sudden bursts of AE, etc.) must be recorded. Visual inspection should be performed at least after each AEL test (see §9.2.3), or whenever there is any other indication of serious damage (strong audible noise, etc.). In case of sharply located AE sources during the test, visual inspection can be performed starting from, but not restricted to, the positions defined at the end of §8.3.

If the AST function is available, AST for sensor performance check can be performed at the operator's discretion (when there are indications that sensor sensitivity has decreased) or after each AEL test.

A.7 TASKS AFTER ACQUISITION

1. Record time of test termination and any relevant information.
2. Switch off the loading device and verify channel's response according to 7.4. Again, save and keep the data file.
3. Back-up all data (*.dta) files and all configuration files (*.ini).
4. Make a visual inspection of the specimen and note any visible damage.