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Characterization of fracture mechanisms, fibre bridging and correlation to AE activity

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X	R: Document, report (excluding the periodic and final reports)
	DEM: Demonstrator, pilot, prototype, plan designs
	DEC: Websites, patents filing, press & media actions, videos, etc.
	OTHER: Software, technical diagram, etc.

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Introduction

The intention with this investigation is to show that Acoustic Emission (AE) measurements recorded during laboratory crack growth experiments can be linked to characteristics of the fracture that are of interest to the DACOMAT consortium. With the implication that the results of DACOMAT interface modifications can be detected in changes to AE activity related to crack propagation and behaviour.

The objective of DACOMAT is to develop more damage tolerant and damage predictable low cost composite materials, in particular those aimed for use in large, load-carrying constructions, thus improving durability and reducing ownership costs.

Included in the overall DACOMAT concept (Work Package 5) is the implementation of Structural Health Monitoring technologies to monitor the initiation of cracks and characterise the way in which those cracks grow.

This report deliverable (D5.2) concerns the correlation between AE data and the fracture energy uptake during laboratory controlled crack growth.

Roskilde, June 2019

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Summary

An analysis of AE data recorded during static Dual Cantilever Beam (DCB) Mode I testing has been undertaken. The mechanical testing showed a variation in the nominally identical test specimen's resistance to crack propagation along the delamination interface. This variation in mechanical properties was correlated with a variation in the characteristics of the acoustic emission sensor data.

It is proposed that the success of the DACOMAT consortium in tailoring interface properties on lamina scale can be confirmed (both in laboratory tests and in structural demonstrations) using AE sensors to reveal the difference in microseismology that results when cracks are initiated and propagated along these modified interfaces.

The results of this analysis can support the development of guidelines for the utilisation of "hot-spot" structural health monitoring around critical areas where DACOMAT materials technology has been included in the design.

Further work on the correlation between fracture and microseismology in DACOMAT materials is recommended including, tests using specific DACOMAT interface modifications, demonstration in structural components, investigation into time-of-flight localisation effects, and environmental/aging effects.

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The DACOMAT project

The Philosophical Transactions of The Royal Society published a theme issue on “New perspectives in offshore wind energy” in 2015 [Failla and Arena]. One contribution proposed a design solution for wind turbine blades based on new technology in polymer composite materials engineering [McGugan *et al.*]. The approach relied on selectively activating mechanisms for obtaining high damage tolerance within the laminate material, combined with damage sensing/characterisation, and detailed material and structural models.

After reading this paper, Dr Jens Kjær Jorgensen of SINTEF began a correspondence with one of the main authors, Professor Dr Techn Bent F. Sørensen of DTU. These discussions led to SINTEF assembling the DACOMAT consortium and successfully leading an application for funding to develop and demonstrate the approach described.

The general objective of DACOMAT is to develop more damage tolerant and damage predictable low-cost composite materials, in particular those intended for use in large load carrying constructions like bridges, buildings, wind-turbine blades and off-shore structures. The developed materials and condition monitoring solutions will provide high tolerance for manufacturing imperfections and high capacity to sustain damages.

The consequence of success in the DACOMAT project will be a future where the presence of damage in an operating polymer composite structure will not cause significant uncertainty. Rather the owner will be reassured that the material used in their structure is designed to resist this particular damage propagating so long as it is operated within known “safe-flight” limits. In addition, if these limits are exceeded, either accidentally or on purpose, then the manner in which the damage will grow is entirely predictable.

Work Package 5 of the project covers Structural Health Monitoring and focusses on the sensor technologies based on Fibre Optics and Acoustic Emission. These sensors must respond to the initiation and development of cracks within the structural material.

In Deliverable 5.2 the DACOMAT project reports on investigations into whether the physical characteristics of the fracture mechanism relating to fracture resistance, such as the degree of fibre bridging in a particular fracture process zone, can be inferred from the Acoustic Emission detected during testing.

Sensors and Monitoring

Systematic observation (and measurement) during experimentation is a critical part of the scientific method. Observation is the active acquisition of information from a primary source. In living beings, observation employs the senses. In science, observation can also involve the recording of data via the use of scientific instruments. The term may also refer to any data collected during the scientific activity. Observations can be qualitative, that is, only the absence or presence of a property is noted, or quantitative if a numerical value is attached to the observed phenomenon by counting or measuring.

Many technologies exist to enhance or extend our natural senses and thus improve our understanding of mechanical processes in composite materials and structures. Any device that detects the occurrence of an event or a change in its environment is a sensor. Of particular interest to the DACOMAT consortium is the suite of sensor technologies based around Acoustic Emission and Fibre Optic sensors.

Acoustic emission (AE) refers to the elastic waves that propagate through a solid when a material undergoes an irreversible change in its internal structure. An example could be the formation of a crack during the mechanical loading of a specimen or structure. AE is typically used to detect, locate and characterise damage processes.

Using an optical fibre as an intrinsic sensor, it is possible to measure strain, temperature, pressure and other properties by modifying the fibre so that variations in intensity, phase, polarisation, wavelength or transit time of the light correlates to the measurand. Fibre Bragg Gratings (FGBs) inscribed so as to locally vary the refractive index within the core of an optical fibre can be used to measure strain at several points along the length of a fibre attached or embedded within a structure.

When we permanently mount or embed sensors like these into a structure to gather information about the performance of the material during the entire lifetime of the structure, and to remotely give warnings about an occurrence of different types of damage, then we call it structural health monitoring (SHM). Operational SHM systems can have a big influence on methods to improve the lifetime utilisation of many structural assets.

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Acoustic Emission

Acoustic emission (AE) refers to the acoustic (elastic) waves in solids that radiate outwards when a material undergoes a local, irreversible change in its internal structure due to crack formation or other forms of plastic deformation. This change could be due to aging, temperature gradients or external mechanical forces. Acoustic emission (AE) is also the term for elastic waves (or stress waves) naturally generated by any energy loss process in materials and machinery; cracking, rubbing, impact, crushing, turbulence, etc. These are all localised transient changes in stored energy with a broad spectral content.

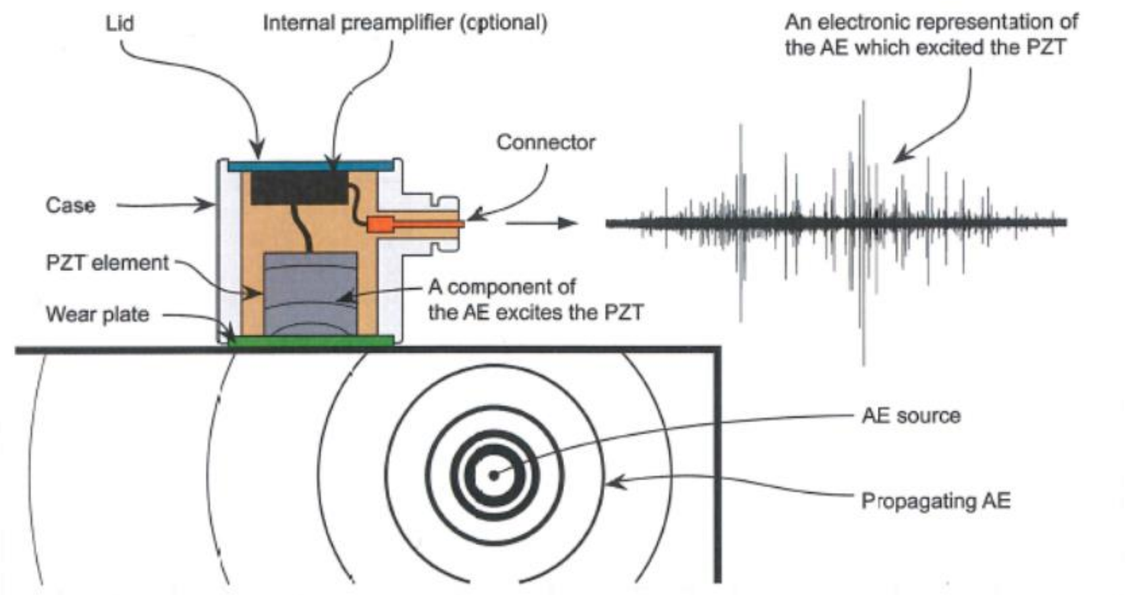

Image from Unnþórsson (2013) showing the Acoustic Emission measurement principle

When an AE generating event occurs (such as cracking at a delamination) stress wave energy propagates outwards from this initial source. Stress wave energy propagation is complex for anisotropic laminate materials like fibre reinforced polymer composites, but for standard AE monitoring it is enough to accept that the energy will spread and reach the surface of the material and travel along this surface to pass beneath the attached sensor.

The surface microaccelerations (vibrations) as the stress wave passes excites the piezocrystal inside the AE sensor. The fluctuating electric charge within the piezomaterial that results from this physical excitation is amplified and read by a fast analogue to digital signal processor inside the AE system hardware. In this way a digitised representation of the transient waveform generated as a result of the energy release within the monitored material is created.

It is possible to store all such transient waveforms from every AE test for later analysis, but as a standard composite material test can easily generate many thousands of these AE “hits” on each sensor, it is common to instead use the AE computer to extract some key characteristics from each digitised waveform and store these instead.

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Transient waveforms detected during AE testing are characterised based on a few key operator specified measurement settings like Threshold (THS), Peak Detection Time (PDT), Hit Detection Time (HDT) and Hit Lockout Time (HLT).

When the fluctuating electrical charge from the AE sensor first exceeds the Threshold voltage value (usually expressed in decibels) then the AE system registers the start of a “hit”. For the period of time specified in the PDT parameter the system checks for the peak amplitude achieved by the waveform. From this the rise time for the waveform is also calculated. If the PDT value specified is too high then false values for peak amplitude are more likely, too low and the true peak may not be identified.

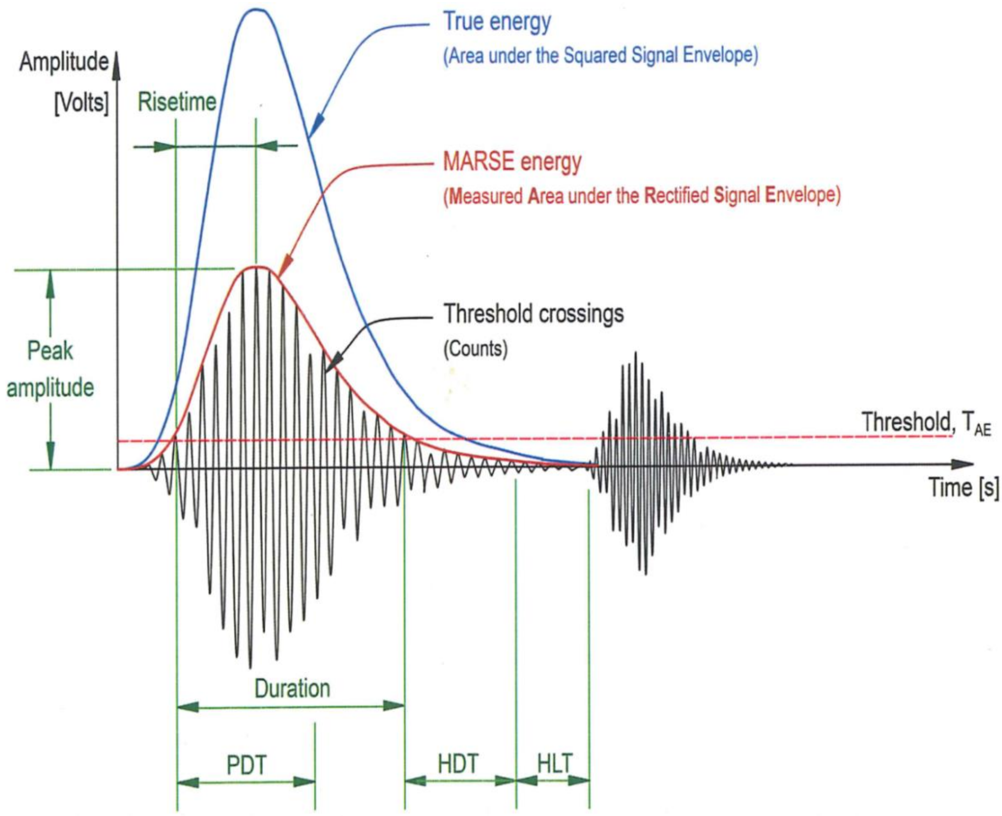

Image from Unnþórsson (2013) showing the Acoustic Emission waveform characteristics

When the fluctuating charge from the AE sensor drops below the threshold value and does not exceed it again until the time specified by the HDT then the AE system registers the last threshold crossing as the end of that particular AE hit and can calculate its duration. If the HDT parameter is set too high then the system may consider two separate hits as being one, if it is too low then it may possibly treat one hit as multiple hits.

During the Hit Lockout Time that follows the end of the HDT then any subsequent threshold crossing is not registered as the start of a new AE hit. If HLT is too high then a second AE hit occurring soon after the first may be discarded, if it is too low then the AE system may report reflections and late arriving components of a propagating wave as new AE hits.

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It is therefore clear that setting the correct measurement parameters for a specific AE system set up and test configuration (load type, material, damage of interest, etc.) is vital in order to get useful results. In addition, these parameters are kept the same across a test series so that the output from the series can be compared.

SSSSSSSS.mmmuuun	CH	RISE	COUN	ENER	DURATION	AMP	A-FRQ
65,3124507	1	6	20	0	74	48	270
66,1076355	1	8	53	3	134	59	395
66,9896248	1	45	7	0	92	44	76
67,4091713	1	30	26	1	129	51	201
67,6159468	1	95	74	4	234	56	316
67,616406	1	16	33	2	130	54	253
67,6164972	2	102	1	0	106	38	9
68,014025	1	62	83	9	296	61	280
68,0140847	2	46	34	2	220	49	154
68,8554357	1	8	14	0	76	48	184
70,8100043	1	22	9	0	68	44	132
70,8365203	1	18	42	2	151	54	278
71,07316	1	2	28	1	124	51	225
71,1070745	1	10	10	0	68	48	147
71,1104153	1	28	73	10	238	68	306
71,1104718	2	57	25	1	99	51	252
71,3821015	1	28	49	3	205	53	239
71,3821525	2	122	13	1	137	47	94
71,403781	1	5	2	0	12	44	166
71,6022093	1	11	21	1	104	48	201
71,6688307	1	21	21	0	67	50	313
71,7324023	1	47	43	3	165	58	260
71,732551	2	7	2	0	7	41	285
72,0293	1	11	1	0	11	42	90
72,2502037	1	69	81	9	296	67	273

An example of text data output from a test with each AE hit represented by a line of waveform parameters [time (s), channel, rise time (us), counts, energy, duration (us), Amplitude (dB), Average carrier frequency (kHz)]

When an AE source is detected by two different sensors, then the location of the event between the two detection points can be determined using time of flight calculations involving the relative position of the two sensors and the speed of stress wave energy transmission in the material.

Acoustic Emission can be thought of as microseismology. When tectonic plates in the earth's crust are pressed against each other there is a build-up in stress, when the plates shift relative to each other the stress build-up is released and generates elastic waves that travel through the earth and can be detected on the surface. Humans can feel powerful earthquakes when they occur, but most earthquakes that take place are only detected by highly sensitive accelerometers. Similarly, when AE sensors are placed on a composite test material that is under load then the microseismology occurring inside that material as a response to the load being applied can be detected. If during a test a crack appears, even a very tiny crack, then the stress wave energy released as a consequence of this will travel through the material to the surface where the AE sensor is. This sensor allows us to detect, locate and characterise different damage processes occurring in the material before it actually fails.

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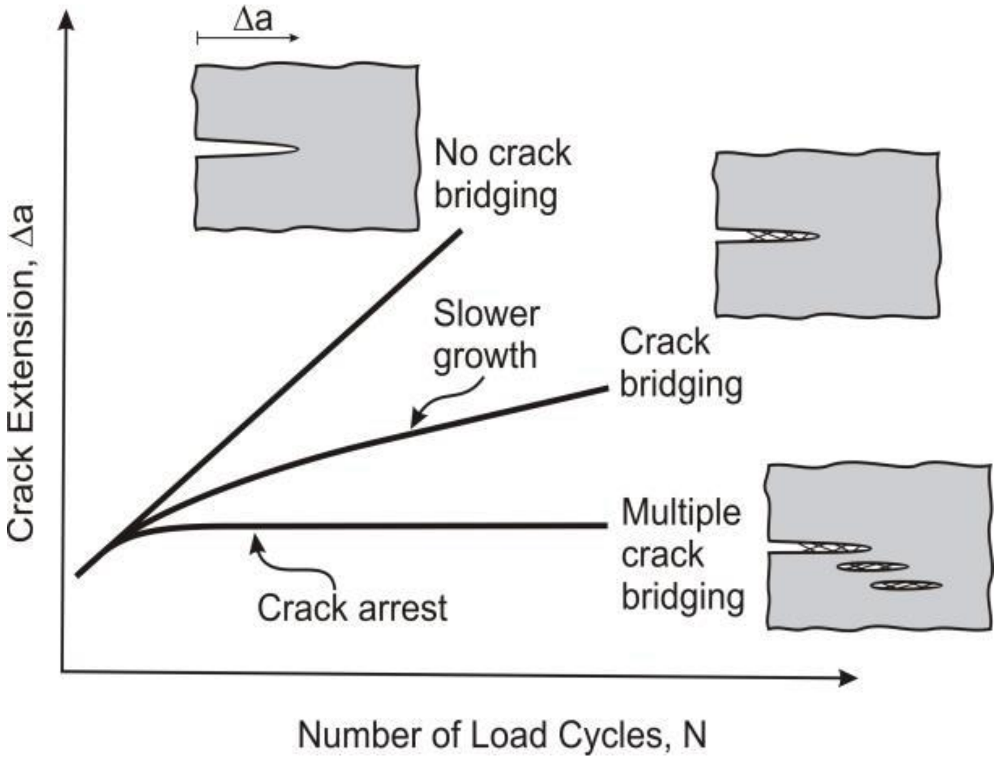
Damage tolerance in Fibre Reinforced Plastic laminates

Damage tolerance refers to the ability of a material or structure to safely sustain a given level of damage or defects whilst under an operational load. Structures made with Fibre Reinforced Plastic (FRP) laminates are damage tolerant, as long as the micromechanical mechanisms for boosting damage tolerance within a particular damage are “activated” [Goutianos and Sørensen].



Sketch from the DACOMAT project application (NMBP-06-2017) showing the effect of crack bridging and multiple cracks on crack extension as a result of the number of load cycles

This suggests that when conducting mechanical tests on laminate material crack propagation we can expect to see a variation in the values of the material properties controlling crack growth that depend on the presence (or absence) of these mechanical mechanisms within the particular crack propagation zone.

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Microseismology during crack propagation

And this variation in measured values is indeed what is found for many test series. At the DACOMAT progress meeting held in Oslo (June 2018), Reidar Joki from FiReCo presented the results of a series of Dual Cantilever Beam (DCB) specimen tests that displayed an unexplained variation in the J values, despite the fact that each specimen was fabricated and tested in an identical manner from the same source material. Furthermore the test methodology was precisely that proposed for the DACOMAT screening tests and they were all tested at the same facility on Risø, DTU Wind Energy.

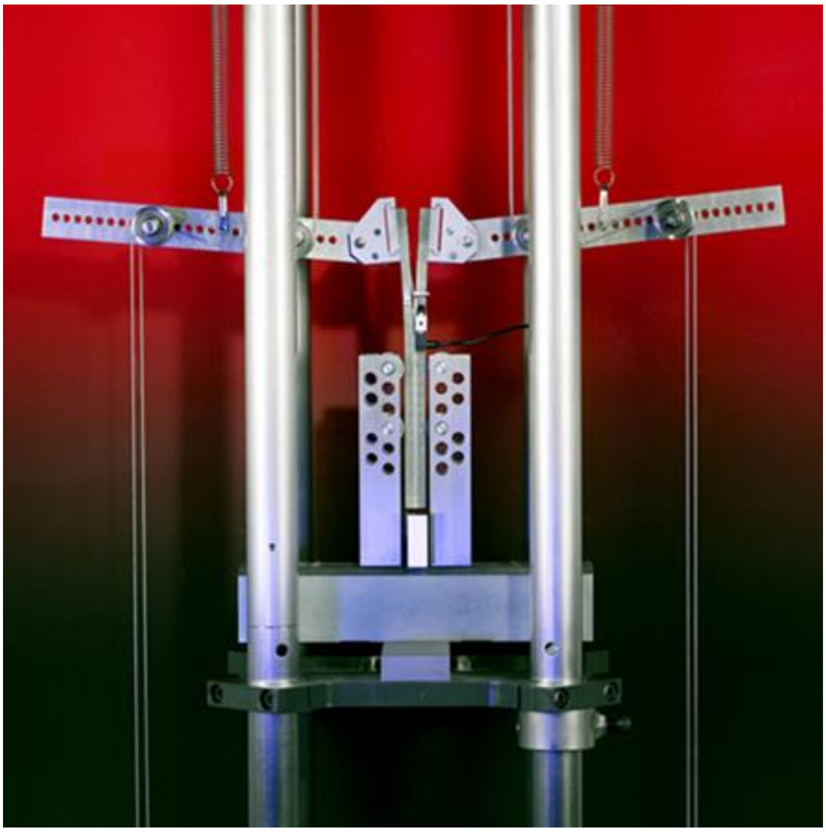

Image showing a Dual Cantilever Beam (DCB) crack opening test where the resistance to crack growth can be measured

The "A-series" test specimens CHOA01A-(01-06) was tested in Mode I, meaning there is no shear component at the crack front. When the results of the series were plotted together it was clear that a fairly significant spread in the J_R values had occurred.

If it is the case that the difference in the energy requirement for crack growth in the A-series is due solely to the presence or absence of certain mechanical mechanisms within the crack process zone, then this should be reflected in the microseismology detectable by AE sensors.

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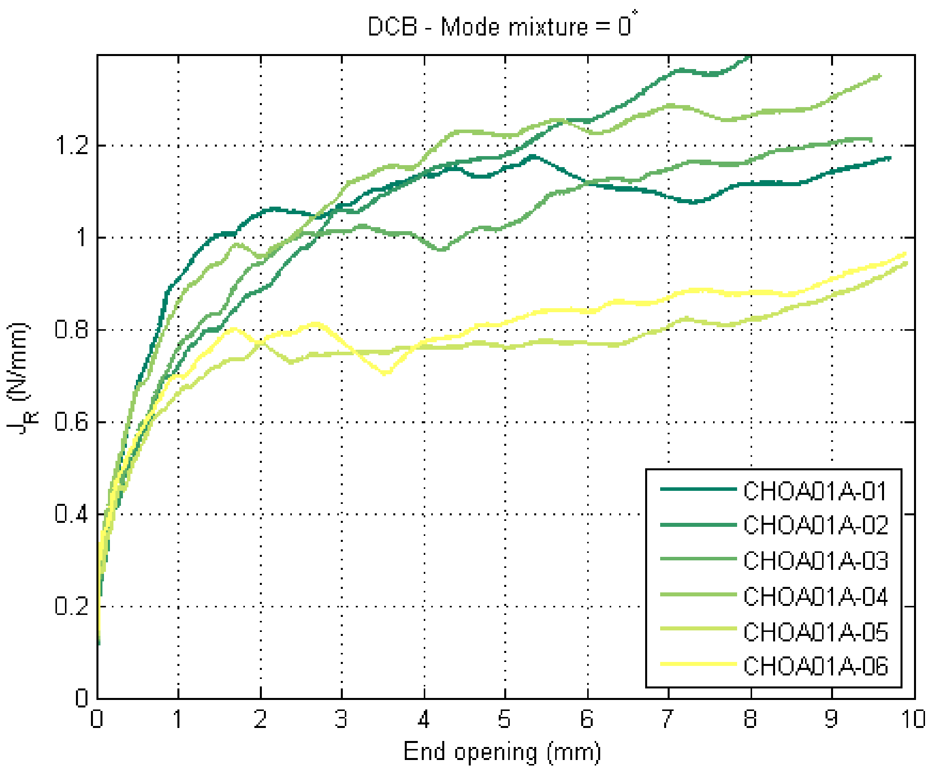


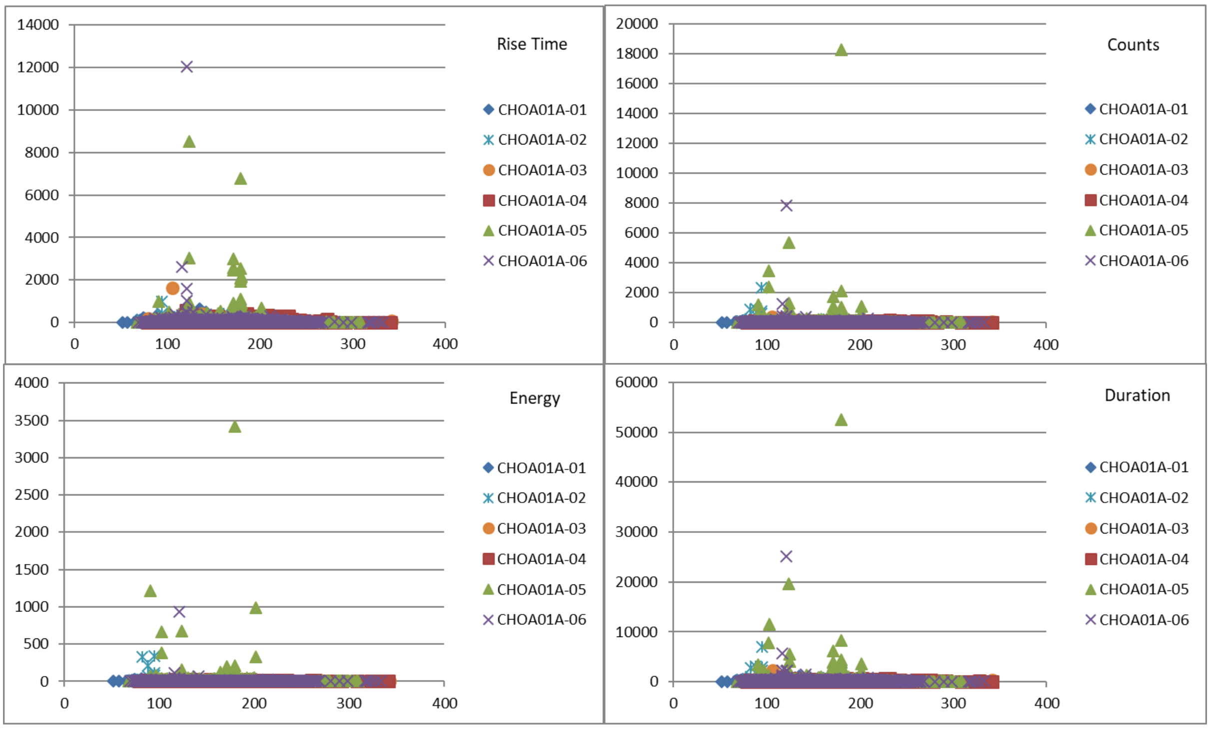
The A-series of DCB tests (0° mode mixture) showing high J_R values for specimens 01 and 04, and low J_R values for specimens 05 and 06

The AE data from the DCB specimen tests in the A-series shows that each crack growth provoked by the testing generated between 15 and 30 thousand acoustic emission "hits". And that almost all of these hits for each specimen across the series are very similar to one another suggesting they all belong to the same "class" of microseismological event.

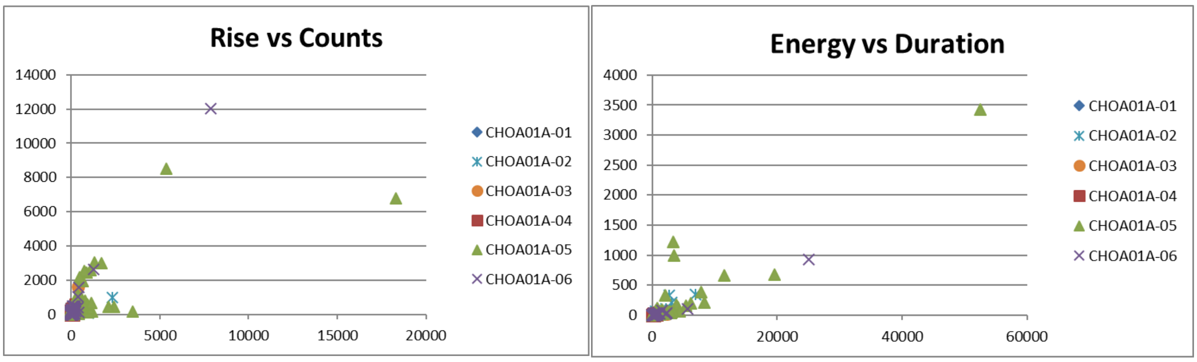
However there were some AE hits detected with a completely different waveform characteristic consisting of far longer rise times and duration/count, with a corresponding increase in the total waveform energy for a single hit. This type of AE hit was not detected in all the tests across the A-series but only in the AE output for test specimens 05 and 06, the specimens with the conspicuously lower resistance to crack growth.

Mix 0	J	AE hits	**RISE**		**COUNT**		**NRG**		**DUR**	
			av	**max**	av	**max**	av	**max**	av	**max**
CHOA01A-01	high	19997	28	**659**	20	**247**	1,0	**41**	102	**1075**
CHOA01A-02		14258	23	**972**	17	**2337**	0,7	**344**	88	**6930**
CHOA01A-03		16869	20	**1630**	15	**400**	0,5	**27**	76	**2328**
CHOA01A-04	high	23320	21	**554**	16	**261**	0,6	**30**	81	**1021**
CHOA01A-05	low	29600	28	**8522**	23	**18300**	1,6	**3421**	110	**52525**
CHOA01A-06	low	19920	21	**12027**	16	**7853**	0,6	**931**	82	**25082**

Summary table showing the AE output from the A-series
Note that the average values for the AE characteristics of RISE time, COUNTs, eNeRGy and DURation show little variation across the series. But that the maximum single hit value detected for each of characteristic is far higher in the data from specimens 05 and 06 which also returned a low J_R value



Graphs showing the distribution of values for the AE measurements on all six A-series specimens Note that almost all the AE waveform measurements returned are confined to a low band of values with only a few high value measurements returned during the tests on specimens 5 and 6 (and to a much lesser extent on specimens 2 and 3 also)



Scatter graphs showing (Rise time vs ring-down Counts) and (Energy vs Duration) for the AE hits detected in all six A-series test specimens

Plotting the AE data in scatter graphs helps to show that the range of AE measurement values in the DCB test specimens returning a high J_R value is very compressed, whereas the test specimens with a low J value (05 and 06) have some AE activity with far greater Rise time, ring-down Counts, Energy, or Duration.

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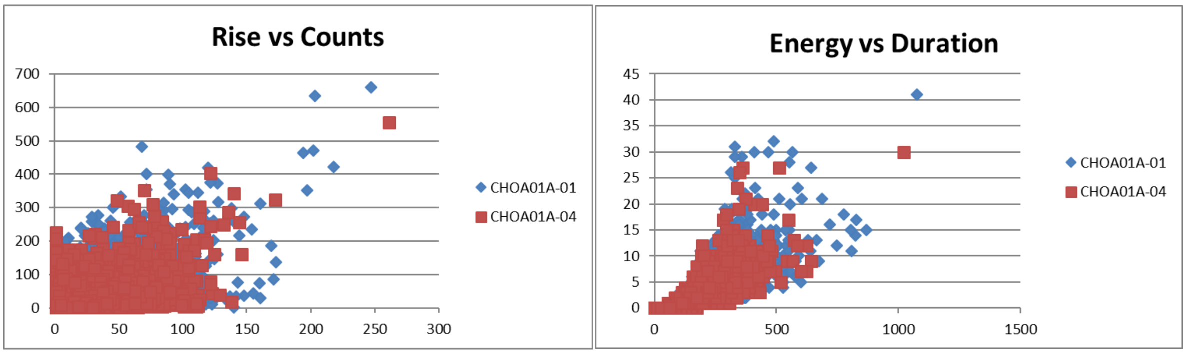

Scatter graphs showing (Rise time vs ring-down Counts) and (Energy vs Duration) for the AE hits detected in the A-series 01 and 04 specimens only

- *Compare the axis values with the scatter graphs containing all the A-series test specimens!*

When these scatter graphs are shown containing only the AE data from specimens 01 and 04 it becomes possible to see how very tightly clustered the AE output is from these specimens with high J_R values.

In fact a "zone" of AE output can be defined that generously contains all AE hits coming from specimens 01 and 04 as the test takes place. This "zone" can then be associated with AE activity coming from the DACOMAT DCB crack test specimens that have been shown to return a high J_R value.

Looking at the AE scatter graph axis for specimens 01 and 04, the limits for the "safe zone" of AE activity indicating high J_R values can be set as follows:

Rise time under 1400us
Ring-down Counts under 600
Energy under 90
Duration under 2400us

And (rather arbitrarily) we can propose that for this test setup any AE activity from test specimens that respects these limits is coming from a crack growth that shows a high J_R value. And conversely AE activity from such a test that violates one or more of these limits is likely to return a lower J_R value as the microseismology being detected is different from that found exclusively for high J_R value specimens.

Looking at the AE data returned by the low J_R value test specimens (05 and 06) it can be seen that each of these "safe zone" limits are violated several times during the crack growth, and that a single AE hit which simultaneously violates all four of these AE parameter limits occurs twice for specimen 06 and five times for specimen 05.

And whereas the AE hit characteristics for the high J_R value specimens are fully within the safe zone, the intermediate J_R value specimens (A-02 and A-03) have several hits where one or more of the waveform characteristics are out-with the safe zone.

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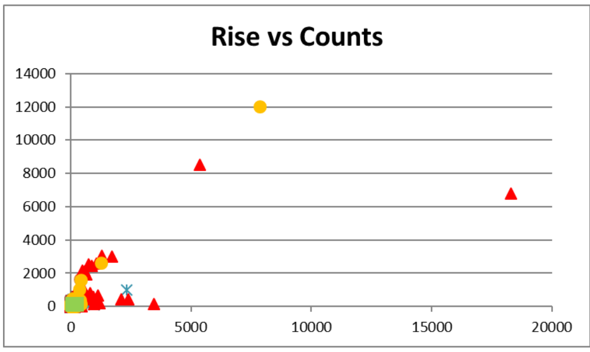

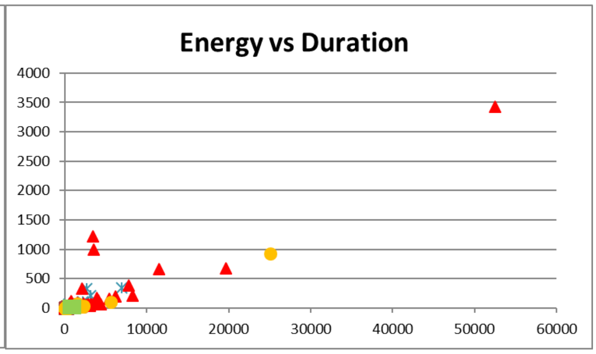

The Series-A scatter graphs showing the green square "safe zone" where all AE activity from the high J_R test specimens is contained. Only specimens with low J_R generate any AE outside this zone.

Specimen	AE profile	J_R (N/mm)
A-01 A-04	All hit characteristics in "safe zone"	1.3 – 1.4
A-02 A-03	No AE hit fully violates the "safe zone", several "partial" violations	1.1 – 1.2
A-05 A-06	Several full hit violations	0.8 – 0.9

Table summarising the correlation between variation in J_R value and variation in Acoustic emission characteristics observed in the Mode I, DCB test series A

The comparison of data sets like this can only be clumsily achieved by human operators; instead various automated pattern recognition tools exist that can quickly identify and quantify the extent to which any set of data deviates from a known or given template. This kind of analysis has also been previously used to identify different damage types occurring in composite material failure using Acoustic Emission waveforms [Torres-Arredondo *et al*.

AE to confirm the effect of DACOMAT interface modification

Before integrating structural damage tolerance enhancement into operating polymer composite structures, DACOMAT modified material interface effects need to be tested and demonstrated in various laboratory tests like the Mode I DCB specimens discussed in this report.

We have observed how an “untreated” DCB interface can return a natural “wide” spread of J_R values across a test series and how the AE waveform characteristics obtained during crack propagation varies based on the distribution of returned J_R values.

It is proposed that DACOMAT modified interface Mode I DCB tests that successfully and reliably return a “high” J_R value can be confirmed during testing (and potentially in operating structures) by AE measurements showing that all AE data is confined to a “safe zone” of activity.

And similarly, that DACOMAT modified interface Mode I DCB tests that successfully and reliably return a “low” J_R value can be confirmed during testing (and potentially in operating structures) by AE measurements showing AE data violating the prescribed “safe zone” of activity.

This proposal remains to be tested and confirmed.

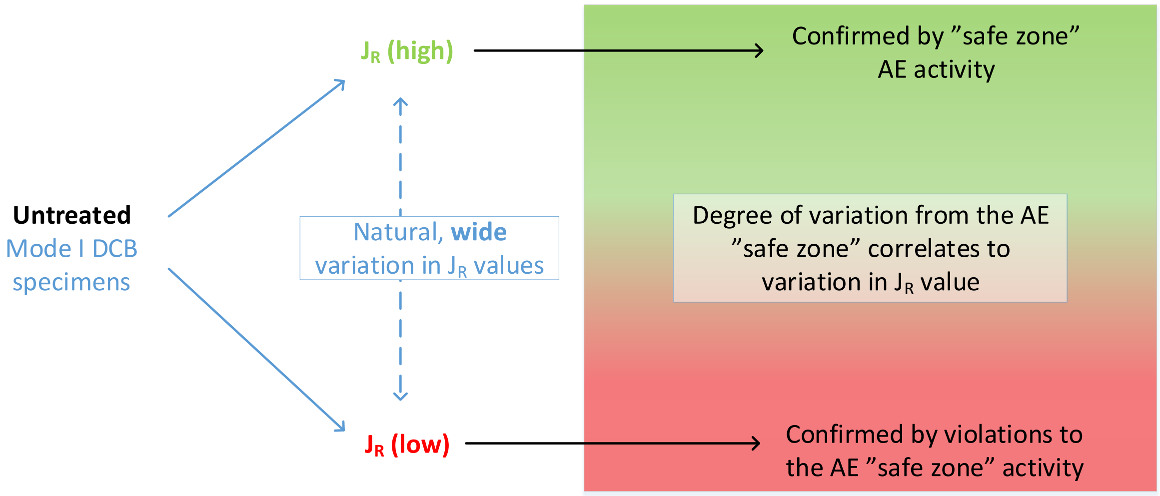

Illustration of the “natural, wide” distribution of J_R values that can be confirmed in laboratory testing using AE measurements

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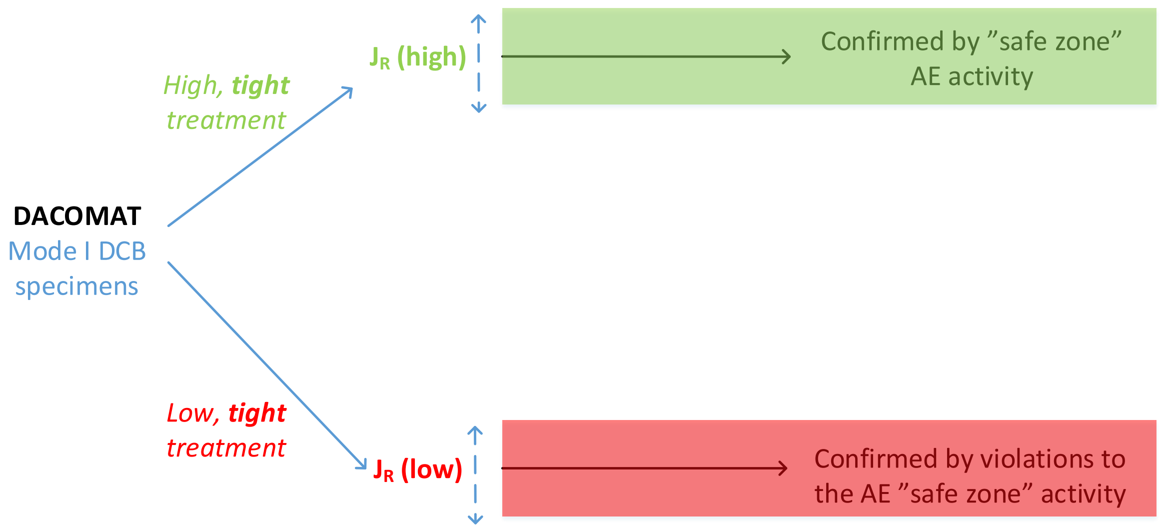

Illustration of the DACOMAT interface modifications to achieve a "high, tight" or "low, tight" distribution of J_R values, and confirmation of the effect via the laboratory test AE measurements

Application of AE damage evaluation monitoring

In all mechanical test laboratories certain limit levels can be assigned in the test machine set up based on maximum and minimum load levels (load control), actuator displacement (position control), or some other relevant measurable parameter. This improves safety and control over the progression of the test specimen response to its' mechanical testing.

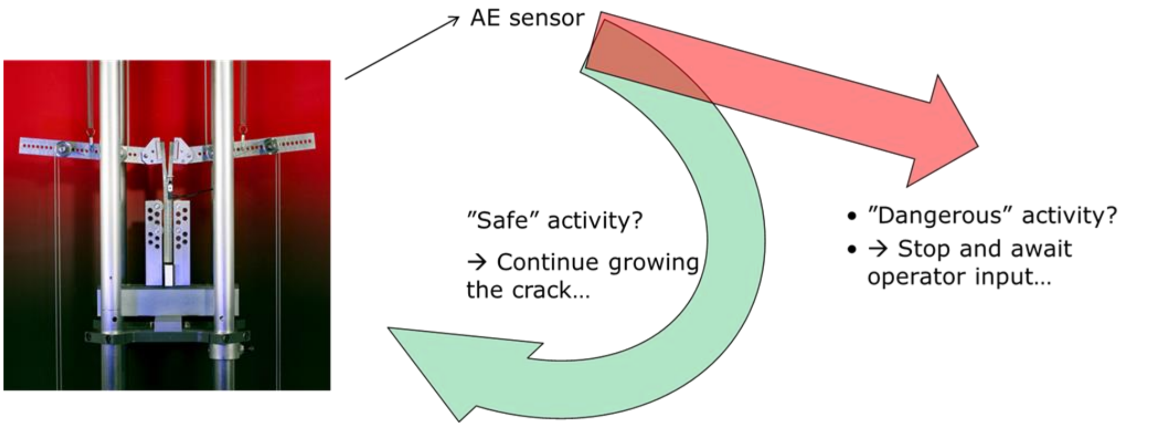

Illustration of an automated damage control mechanical test

The development of sensor systems that can track characteristics of the damage evolution during test progression suggests that a "damage control" limit trigger could also be developed that would allow a DCB test specimen to be automatically paused when the characteristics of the crack progression changed. Or a fatigue test that paused when a new composite material damage mechanism was initiated within that specimen.

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For the monitoring of damage in structural components it is common to use exception analysis to warn when a new local condition exists within the structure. This could be characterised as Level 1 damage monitoring when the presence of a new damage (for example at a critical structural location) activates the local sensor and allows for operation to be paused for an inspection and characterisation of the severity of this new damage.

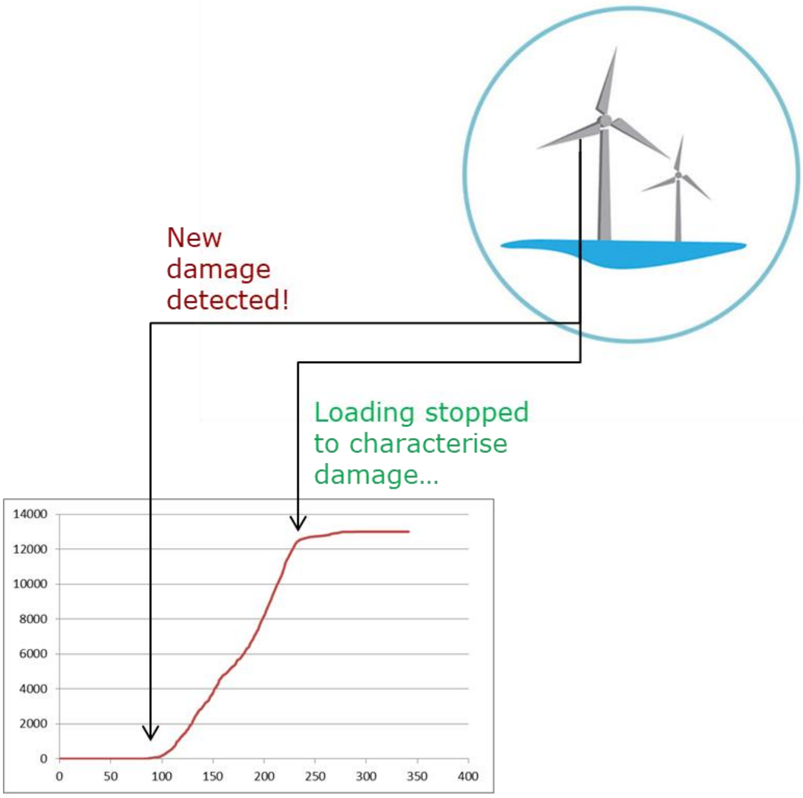

Illustration of the Lvl 1 SHM monitoring concept warning that new damage has been detected within the structure

When implemented, the DACOMAT concept means that operating structures will have areas where damage is known to exist. But this damage will be no threat to the designed performance of the structure due to the modified interface properties in the material around this damage. In order to ensure that the DACOMAT modified damage tolerance effect is successful in every case, it is proposed to use structural health monitoring sensors that can confirm the required micromechanical mechanisms have been activated, and provide a warning if they are not.

This we can classify as Level 2 SHM monitoring where AE activity from a known damage area is detected as the structure is in operation. As all the AE is contained in the established "safe zone" of activity, the SHM system can confirm that the fracture resistance properties of the DACOMAT modified interfaces are as intended. If, however, violations to the AE "safe zone" begin to be detected then the operator can no longer be confident that the desired damage tolerance index for that structural section is being achieved.

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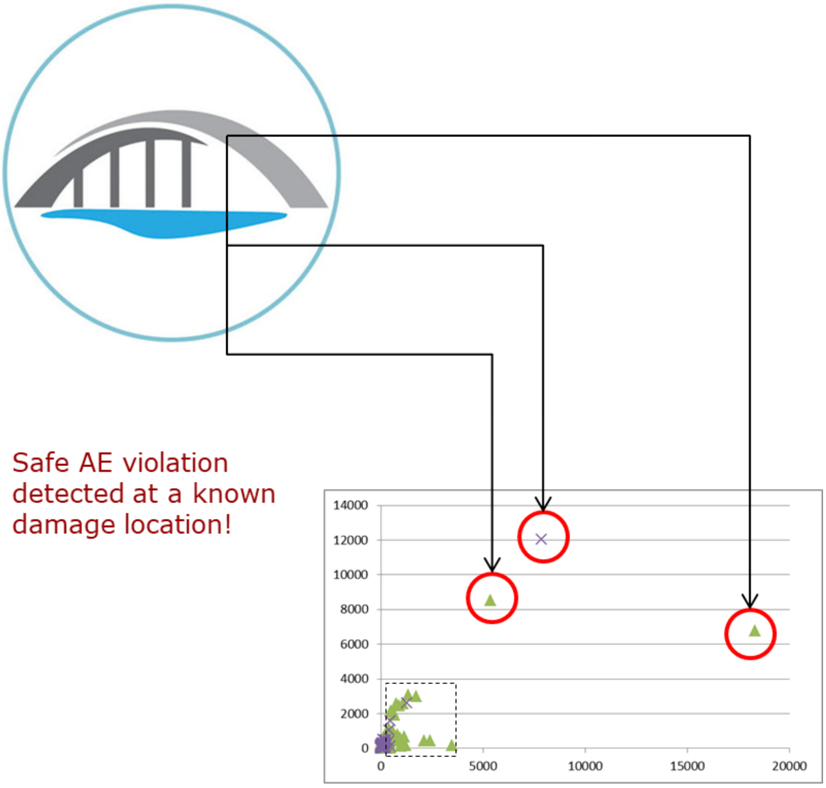

Illustration of the Lvl 2 SHM monitoring concept warning that a known damage area is violating the DACOMAT "safe zone" for AE activity and possibly no longer providing the desired damage tolerance

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