Innovative Mechanical characterization of CFRP by using acoustic emission technique

Original Citation:
Innovative Mechanical characterization of CFRP by using acoustic emission technique / Barile, Claudia. - In: ENGINEERING FRACTURE MECHANICS. - ISSN 0013-7944. - STAMPA. - 210:(2019), pp. 414-421. [10.1016/j.engfracmech.2018.02.024]

Availability:
This version is available at http://hdl.handle.net/11589/123220 since: 2022-06-22

Published version
DOI:10.1016/j.engfracmech.2018.02.024

Publisher:

Innovative Mechanical characterization of CFRP by using acoustic emission technique

Abstract

Carbon Fiber Reinforced Plastic materials (CFRP) offer high specific mechanical properties that make them extremely attractive for aeronautical and aerospace applications. Anyway, their damaging mechanical response is very negative and, if these damages are not visible on the surface their use could become deeply dangerous if not properly monitored. It is therefore essential to detect, evaluate and analyze the several types of propagation of damage caused by static, cyclic and environmental effects. Acoustic Emission technique (AE) is an innovative methodology that is finding good evidence in detecting and identifying CFRP damage mechanisms. In this paper, the AE technique was applied to CFRP specimens subjected to open hole testing and mode I delamination.

Keywords: Carbon Fiber Reinforced Polymers (CFRP), Acoustic Emission, Mechanical Characterization, delamination.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

1. INTRODUCTION

In the last years the diffusion of composite laminates significantly grew up in many different field also in consideration of the possibility to be designed for the specific purpose. Carbon Fiber Reinforced Polymers (CFRP), in particular, have several advantages such as good stiffness/weight ratio and good resistance/weight ratio. Due to these reasons they are frequently used in structural applications for the automotive and aeronautic fields. However, this class of materials is subjected to several damage mechanisms that can severely affect their application even if no externally visible damage is present. A critical issue is related with the absence of mathematical models which can describe, with an appropriate level of reliability, the behavior of composites. A particularly dangerous damage mechanism is delamination. This is a critical phenomenon due to due fact that it introduces separation in two or more pieces and, at the same time, it reduces drastically mechanical resistance. It worth noting that good design with composite materials must consider the resistance performances in presence of a defect, that is to say the capability of the material to maintain its integrity also in presence of a not visible damage. The knowledge of the resistance of composites to interlaminar fracture is essential both in the design stage and in the stage of material selection [1]. It is fundamental the capability to detect, evaluate and analyze various kinds of damage propagation due to static load, fatigue end environmental effects. Two approaches are possible to address this problem. First one requires to improve accuracy of detection techniques in order to reduce the minimum detectable size of the damage so that inspection window can be extended. Second one aims to increase the critical dimension of the defect by using a larger quantity of materials and so reducing the achievable advantages in terms of costs and weight reduction. Traditional non-destructive techniques can allow to detect damage when it has reached a certain extension, but they fail in detecting nucleation and initial stage of propagation during exercise especially in the case of opaque materials. Acoustic Emission technique (AE) is an innovative approach which has given promising results in the detection and identification of damage mechanisms in CFRP. It is a non-destructive technique that analyzes the emission of wave sounds as a consequence of activation of a damage mechanism such as nucleation or damage propagation. This approach has been successfully used for metals [2-4] and in the case of Glass Fiber Reinforced Polymer (GFRP) [5, 6] but no many results can be found in literature about its application to fiber carbon composites [7].

In this paper AE technique was applied to CFRP specimen subjected to two kinds of mechanical tests: open-hole and mode I delamination. These tests are typically performed in the automotive and aeronautic fields. In these tests the defect propagation is connected to the specimen's geometry so that it is easily observable externally and it requires a low amount of activation energy [8]. The acoustic emission of the material was characterized by recording some typical feature such as number of events, amplitude, energy and signal duration. Crack propagation was also contemporarily monitored by a calibrated CCD camera. Data were used to correlated AE signal features to damage mechanisms by keeping in mind that several studies confirm the presence of a relationship between small amplitudes and matrix cracks. In the same way big amplitude can be put in relationship with fiber breaking and delamination.

2. MATERIALS AND METHODS

2.1. Open-hole tensile tests

The open-hole tensile tests were performed over 7 samples obtained by two different laminates employing different resins reinforced by carbon fibers. Four specimens were obtained by a laminate obtained by soaking carbon fiber by thermosetting resin. The last three specimens were manufactured starting from a laminate obtained by soaking carbon fibers by a thermoplastic resin. Both laminates have the same symmetric lay-up $[(0,90)_4]s$. The sample were all tested by following the ASTM 5766 standard [9]. For simplicity the set of samples obtained from the first laminated will be indicated by A, while those obtained by the second laminate will by indicated by B.

Specimen have a rectangular transverse section whose width is 36 mm, while the thickness is uniform and equal to 3.04 mm for specimens A and 2.48 mm for specimens B. Test were performed on a servo-hydraulic loading machine under controlled environmental conditions, at 23 °C, in displacement control mode with a crosshead constant speed set at 2 mm/min.

2.2. Mode I delamination tests

For testing mode I, 9 double cantilever beam (DCB) specimens were prepared by using epoxy resin reinforced by carbon fibers. Following the ASTM D5528-01 [10], they were made up with an odd number of unidirectional layers and delamination propagation was along the 0° direction. A non-adhesive insert was put in the centerline of the laminate while manufacturing the lay-up in order to simulate the nucleation of the delamination. The thickness of the film was less than 13 μm and its length was 45 mm. All specimens have a rectangular section with uniform thickness (25 mm x 3 mm) and the are 125 mm long. Tests were performed under environmental controlled conditions at 23 °C. An Instron 1342 servo-hydraulic loading machine was used in displacement control mode at velocity v=1 mm/min. In Figure 1 the schematic of the loading system and of the specimen are shown.

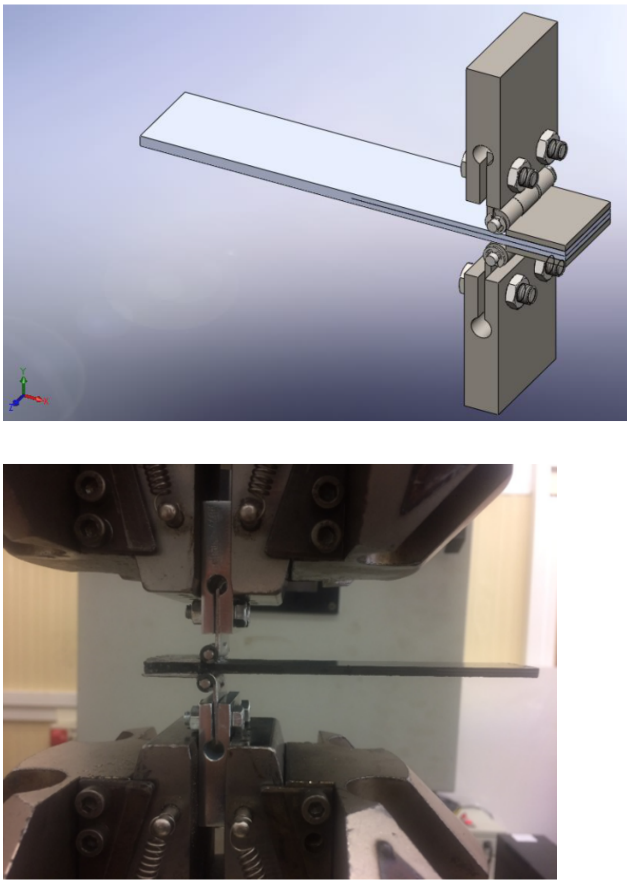
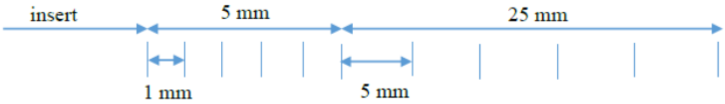
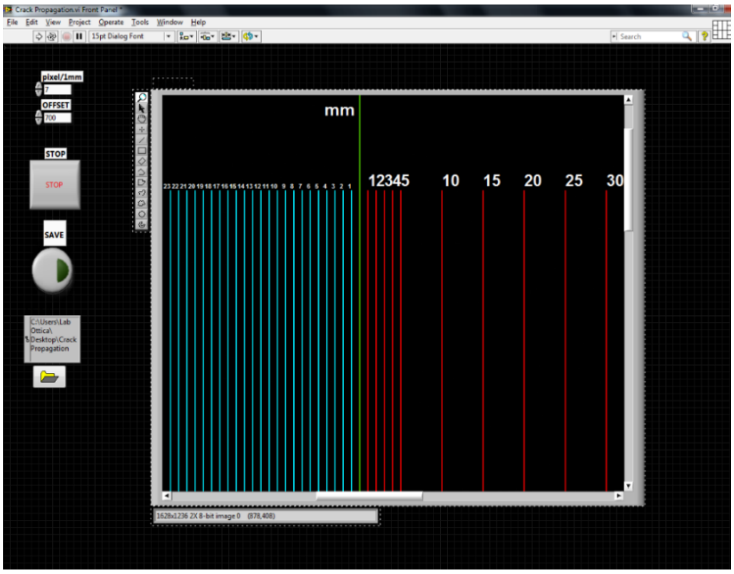


Figure 1. Schematic of the loading frame and its placement inside the loading machine

In order to monitor the crack propagation during the test a digital calibrated grid was used to measure, time by time, the position of the damage.





pixel/1mm 7

OFFSET 700

C:\Users\Lab Ottica\Desktop\Crack Propagation

1628x1236 2X 8-bit image 0 (878,408)

Figure 2. Screenshot of the software use for monitoring damage propagation

The digital grid was superimposed on the image recorded live by the CCD camera (Fig.2). This was a MarlinAVT firewire, black and white camera with a 1636x1252 pixel matrix and it was run a 12.75 fps. The insert was not externally visible so that, by following the standard [10], it was necessary to evaluate preliminary the initial delamination length (a_0). Grid lines in blue are referred to the part of the insert while red lines cover the part of the specimen where real aperture of the specimen occur. The optical system employed for the measurement was placed in front of the specimen for the whole test and acquired images in continuous mode.

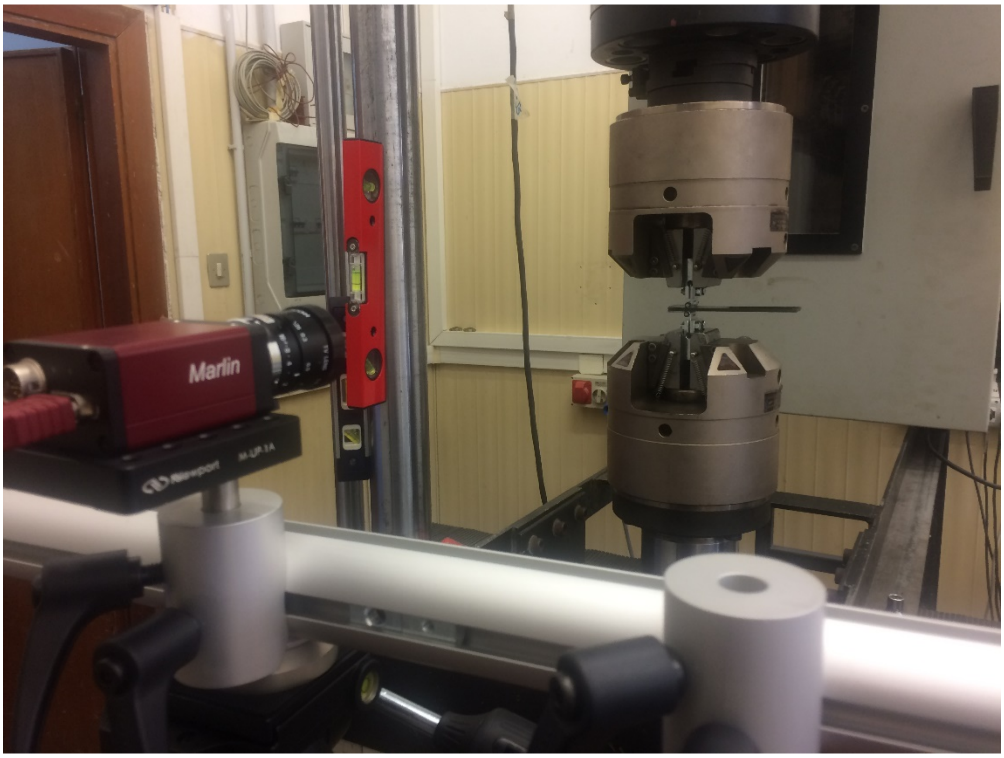


Figure 3. Optical set-up for crack evolution recording

2.3. Acoustic Emissions

Acoustic emissions were recorded by the acquisition system software Physical Acoustic Corporation (PAC) PCI-2 and elaborated by AEWin software. Detection of the signal was performed by placing a piezoelectric sensor on the specimen after application of silicon coupling gel. Acoustic piezoelectric sensor was a single crystal resonance transducer [11,12] whose main features are reported in Tab.1:

Table 1. Main characteristics of the Acoustic Emission sensor

Acoustic sensor characteristics	
Peak sensitivity	54 dB
Operation range	200 – 750 kHz
Resonance frequency	250 KHz

Temperature Range	-65 to 177 °C
Size	5 x 4 mm

Acquisition frequency was chosen based on the test duration and, in these tests, was set to 100 kHz. Furthermore a 34 dB threshold value was set. Signals were recorded by the sensors and amplified by a 20/40/60-AST pre-amplifier with the gain set to 40 dB.

For the case of the open-hole tensile tests two sensors were symmetrically applied at 40 mm with respect to the hole and transversally centered as indicated in Figure 4. Disposition of the sensors and preliminary evaluation of the wave sound speed by the pencil test allowed on line localization of the

crack.

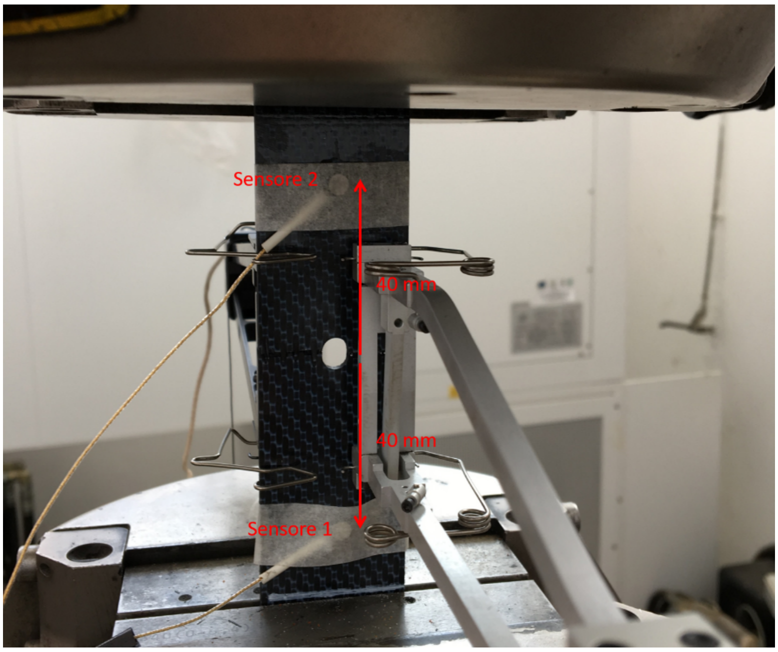


Figure 4. Positions of the sensors during the Open-hole tensile tests

In the case of the mode I delamination tests only one sensor was employed, and it was applied at 10 mm from the edge of the sample in the opposite side with respect to the insert. It should be pointed out that delamination mechanism in a material characterized by a linear elastic behavior introduce a release of energy that can be expressed like:

$$G = \frac{-\, dU}{B\, da} \tag{1}$$

Where a is the crack length, B is the length of the specimen and U is the total elastic deformation energy of the sample. The released energy rate for mode I is evaluated, by following the standard and, in analogy with the simple beam theory, can be described as it follows:

$$G_{I}^{BT} = \frac{3P\delta}{2Ba} \tag{2}$$

Where P is the maximum load while δ is the deflection at the maximum load.

3. RESULTS

3.1. Open hole tensile test

By looking at the graphs reported below it is interesting to observe that there is a relevant difference in terms of Energy if the two kinds of laminates are compared. For A laminate Energy reaches 16000 a.u. while for B laminate the maximum value is 450 a.u. However, in spite of this difference, trends are similar for the two laminates. It is possible, in fact, to identify three different zones: first one (up to 40% of duration of the test) is characterized by low energy values almost near to zero; in the second zone (from 40% to 80 % of duration of the test) the energy values grow up with a given rate; in the third region (from 80 % to 100 % of duration of the test) the rate is much higher so that total amount of energy grows faster.

Moreover, by observing Fig. 5, it is possible to obtain another essential information connected with the specificity of the thermosetting matrix of A laminate. Thermoset resins, in fact, are generally more resistant and hard that thermoplastic ones but, at the same time, more fragile. This behavior is put in evidence also by the acoustic signal analysis where big jumps are observed and a generally more consistent release of energy.

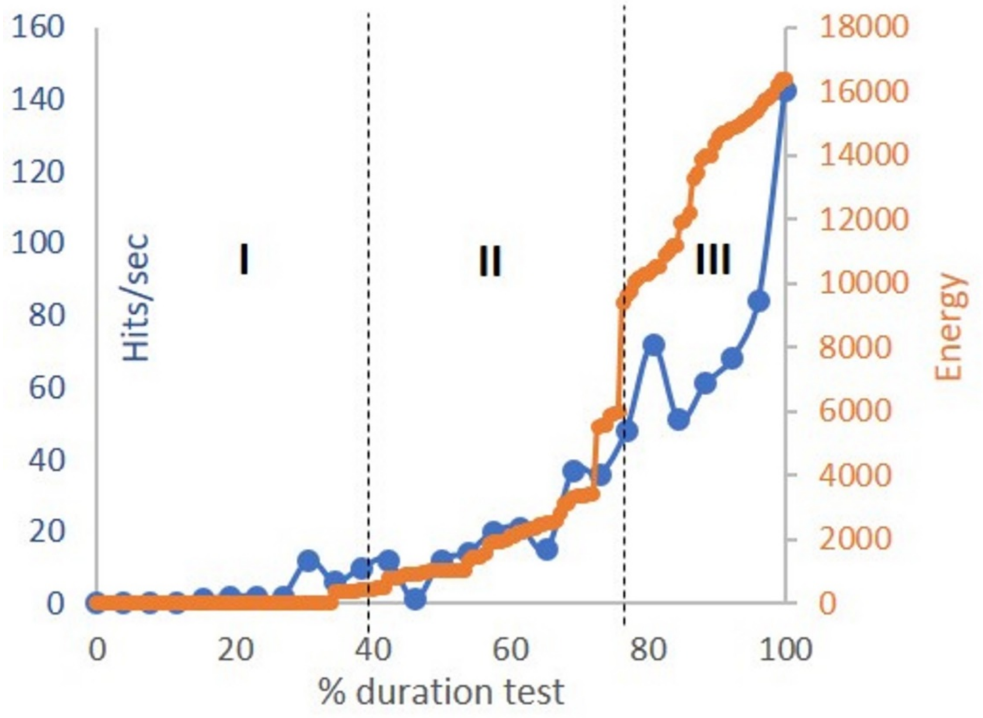


Figure 5. Hits/sec e Energy for laminate A

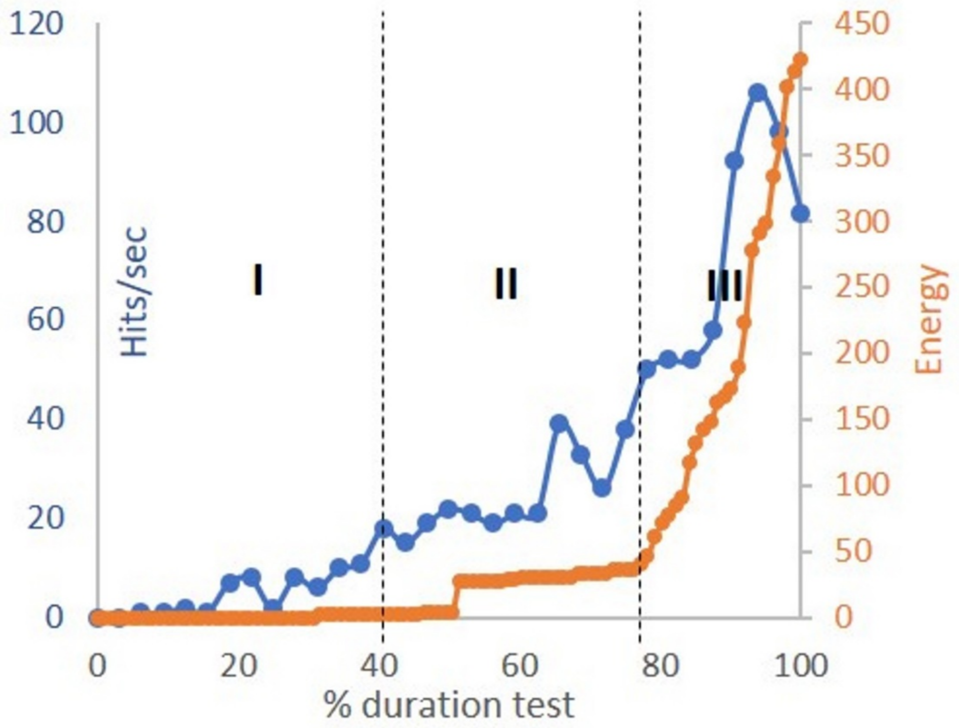


Figure 6. Hits/sec e Energy for laminate A

Finally, by looking at Fig.6, it is possible observe different effects connected with fiber and matrix in terms of acoustic emission. According with literature, low energy values are associated with events occurring in the matrix (zone I) while higher energy values can be associated to fibers (zone III). In the zone II is observable a mix of events that produces an increment in terms of Energy and Hits/sec that is higher if compared to zone I and lower if compared to zone III. Great part of the signals in zone III can be referred to damage and complete rupture in fibers.

3.2. Mode I delamination tests

In Fig.7 is reported a combined plot where the load vs displacement behavior is presented along with the crack progression. Figure refers to one specimen, but it is representative of results obtained in all the other tests.

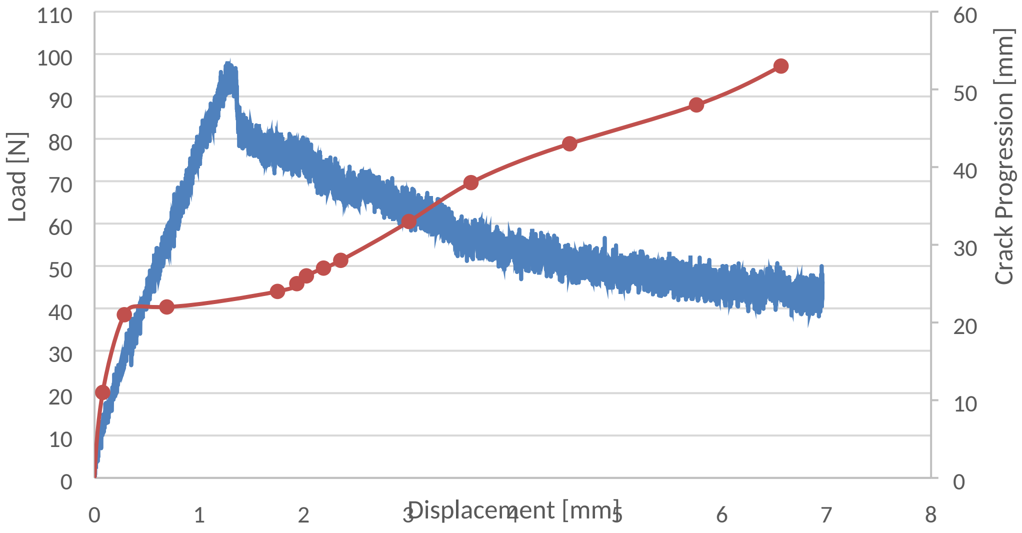


Figure 7. Load and crack progression as a function of the displacement

By looking at Figure 7 it can be observed that deformation energy is accumulated in the sample up to 98 N load. For that value the accumulated energy (G_I) reaches the critical value (G_{IC}) so that delamination starts. At that point the material response becomes non-linear. Delamination propagation doesn't seem to be affected by the fiber bridging that is generally observed in fiber glass reinforced composites (GFRP) [5]. It is also interesting to observe the crack progression behavior; it can be observed that when maximum load is exceeded also an increment of the crack propagation slope is observed; that slope remains almost constant for the rest of the test. An important aspect, connected with the aim of this work, is the capability of detecting the onset of the crack just by looking at the acoustic emission signals. In Figure 8 the graphs *cumulative hits* vs *time*, *cumulative energy* vs *time* and *hit derivative* vs *time* are reported for a given specimen and they are representative of what observed on the other samples. In the region I, it can be observed that hits, energy and hit derivative are low. The initiation of delamination generates then a rapid increment of hits and energy. Also, the hit derivative increases in a consistent way in the time period occurring from 90 s and 110 s after the starting of the test. In this interval, at 101 s, the maximum load for the calculation of G_{IC} following ASTM 5528-01 [10] is achieved. Finally, the zone III is characterized by delamination propagation which relates to high acoustic activity but with a reduced rate of Hit/s if compared to zone II. These considerations confirm capability of AE in monitoring fracture by delamination in a much more powerful way with respect to simple external observation as reported in the standard [10]. It must be underlined that most evident and readable information about defect nucleation can be retrieved by the analysis of the hit derivative while more detailed information about delamination propagation are obtainable by cumulative graphs.

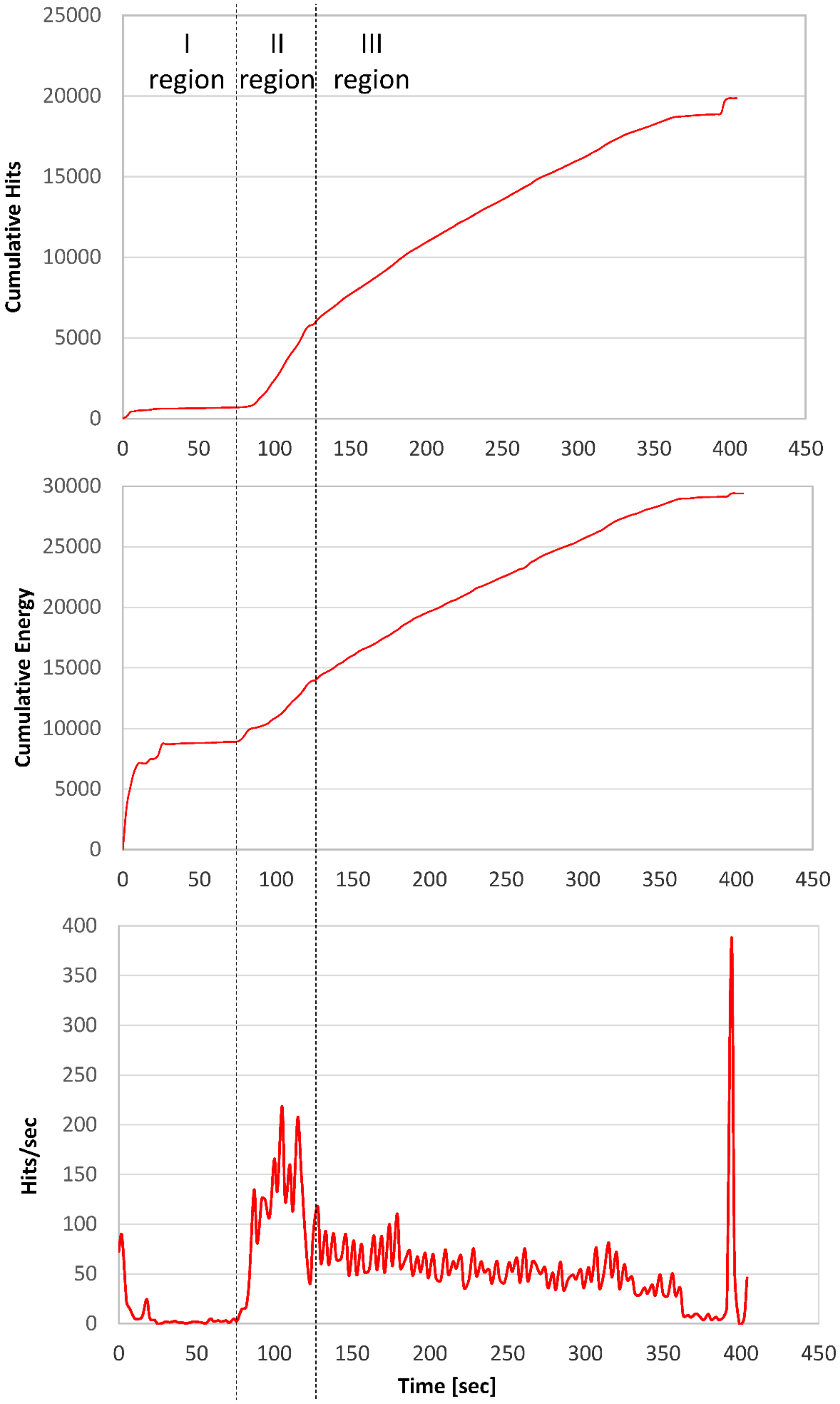

I
region
II
region
III
region
Cumulative Hits
25000
20000
15000
10000
5000
0
0
50
100
150
200
250
300
350
400
450
Cumulative Energy
30000
25000
20000
15000
10000
5000
0
0
50
100
150
200
250
300
350
400
450
Hits/sec
400
350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350
400
450
Time [sec]

Figure 8. *Hit cumulative-time* (UP)*, energy cumulative-time* (Middle), *derivative hit-time* (Bottom). The three regions are indicated by dashed lines

4. CONCLUSIONS

In this paper the acoustic emission technique was applied to CFRP composites to obtain information about the state of the material subjected to two different tests: tensile open-hole and mode I delamination. Acoustic signals analysis remarkably show that it is possible to distinguish between nucleation and defect propagation and between effects connected with events occurring in matrix and fibers. It was also observed that the two different matrices generate different AE signature. Based on these data future studies are possible in the direction of introduce an innovative approach that can provide more complete information about the state of the mechanically stressed materials [13, 14] as done for the case of GFRP [15].

REFERENCES

[1] Oskouei AR, Zucchelli A, Ahmadi M, Minak G. Using Acoustic Emission to Evaluate Fracture Toughness Energy Release Rate (GI) at Mode I Delamination of Composite Materials. In Acoustic Emission, Ed. Wojciech Sikorski, ISBN 978-953-51-0056-0 (2012).

[2] Barile C, Casavola C, Pappalettera G, Pappalettere C. Acoustic emission analysis of aluminum specimen subjected to laser annealing. Conference Proceedings of the Society for Experimental Mechanics Series 2014; 8:309-315.

[3] Barile C, Casavola C, Pappalettera G, Pappalettere C. Hybrid thermography and acoustic emission testing of fatigue crack propagation in Aluminum Samples. Conference Proceedings of the Society for Experimental Mechanics Series 2015; 66(5):247-252.

[4] Barile C, Casavola C, Pappalettera G, Pappalettere C. Analysis of crack propagation in stainless steel by comparing acoustic emissions and infrared thermography data. Eng Fail Anal 2015; 69:35-42.

[5] Saeedifar M, Fotouhi M, Najafabadi MA, Toudeshky HH, Minak G. Prediction of quasi-static delamination onset and growth in laminated composites by acoustic emission Compos Part B 2016; 85:113-122.

[6] Fotouhi M, Najafabadi MA. Acoustic emission-based study to characterize the initiation of delamination in composite materials. J Thermoplast Compos Mater 2016; 29(4):519–537.

[7] Mohammadi R, Saeedifar M, Toudeshky HH, Najafabadi MA, Fotouhi M. Prediction of delamination growth in carbon/epoxy composites using a novel acoustic emission-based approach. J Reinf Plast Compos 2015; 34(11):868–878.

[8] Silversides I, Maslouhi A, LaPlante G. Acoustic emission monitoring of interlaminar delamination onset in carbon fibre composites. Struct Health Monit 2013; 12(2).

[9] ASTM 5766 - Standard Test Method for Open-Hole Tensile Strength of Polymer Matrix Composite Laminates, 2011.

[10] ASTM D5528-01 Standard test method for mode I interlaminar fracture toughness of unidirectional fiber-reinforced polymer matrix composites" West Conshohocken, PA: ASTM International, 2007.

[11] Enoki M, Kishi T, Kohara S. Determination of Microcracking Moment Tensor of Quasi-Cleavage Facet by AE Source Characterization. Progress in Acoustic Emission III, Proceedings of the Eighth International Acoustic Emission Symposium, The Japanese Society for Non-Destructive Inspection 1983; 763-770.

[12] www.mistrasgroup.com.

[13] Refahi Oskouei A, Zucchelli A, Ahmadi M et al. An integrated approach based on acoustic emission and mechanical information to evaluate the delamination fracture toughness at mode I in composite laminate. Mater and Des 2011; 32:1444–1455.

[14] Minak G, Zucchelli A. Damage evaluation and residual strength prediction of CFRP laminates by means of acoustic emission techniques In: Durand LP (ed.) Composite materials research progress. New York: Nova Science Publishers Inc 2008; 165–207.

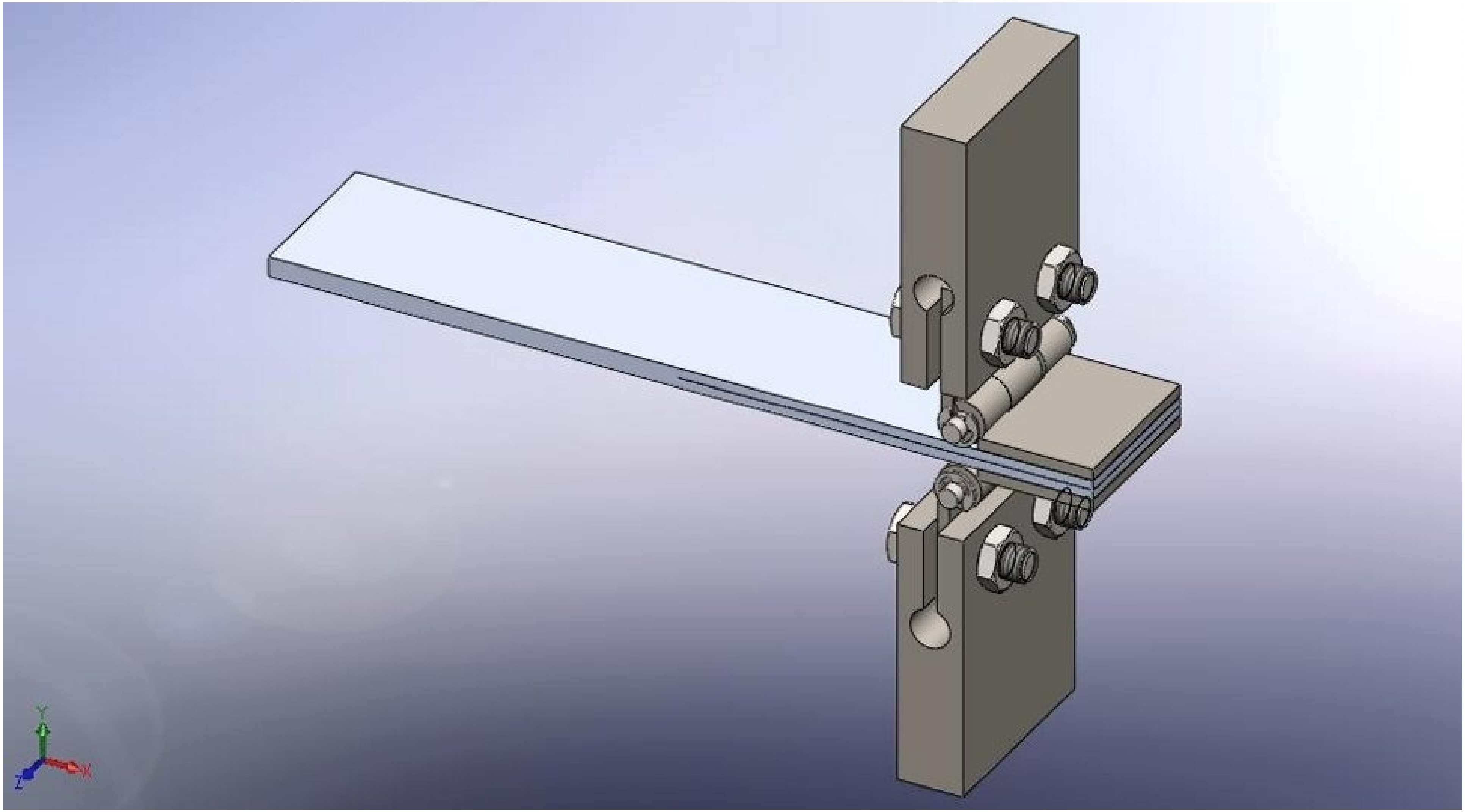
[15] Cesari F, Dal Re V, Minak G et al. Damage and residual strength of laminated carbon–epoxy composite circular platesloaded at the centre. Compos Part A 2007; 38:1163–1173.

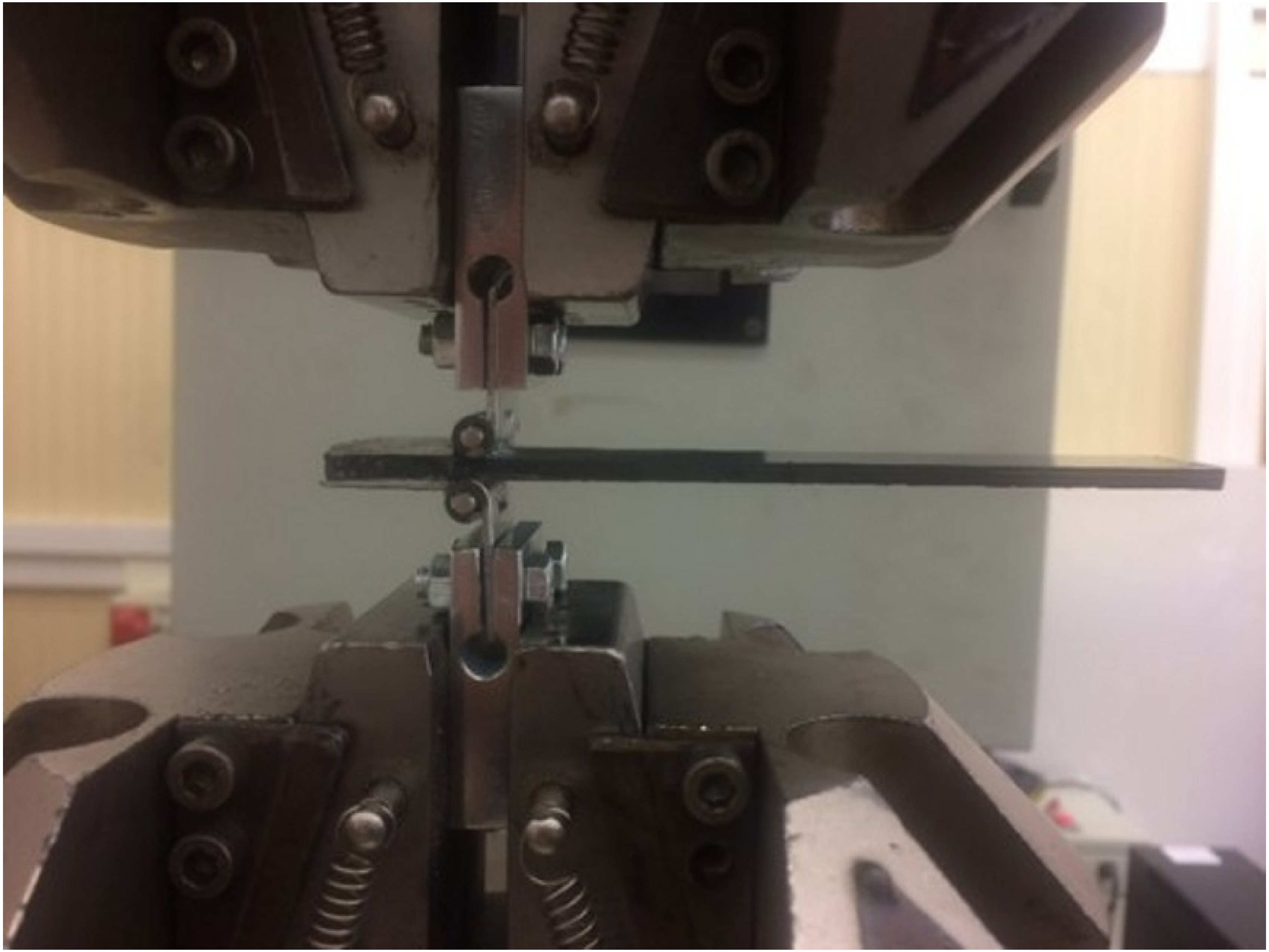
List of figures

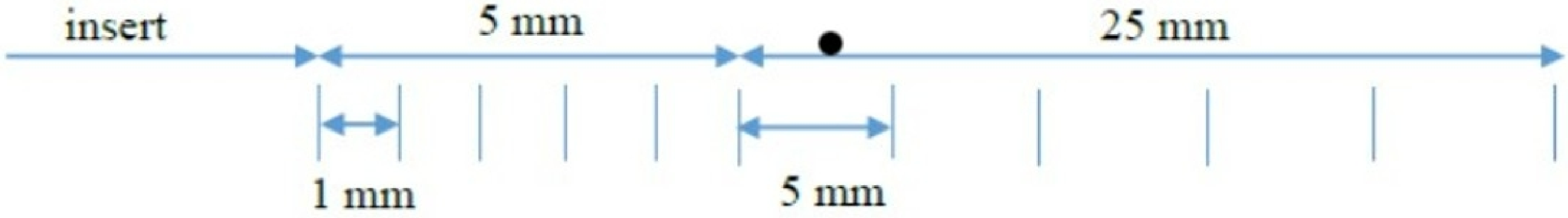
- Figure 1. Schematic of the loading frame and its placement inside the loading machine
- Figure 2. Screenshot of the software use for monitoring damage propagation
- Figure 3. Optical set-up for crack evolution recording
- Figure 4. Positions of the sensors during the Open-hole tensile tests
- Figure 5. Hits/sec e Energy for laminate A
- Figure 6. Hits/sec e Energy for laminate A
- Figure 7. Load and crack progression as a function of the displacement
- Figure 8. *Hit cumulative-time* (UP)*, energy cumulative-time* (Middle), *derivative hit-time* (Bottom). The three regions are indicated by dashed lines

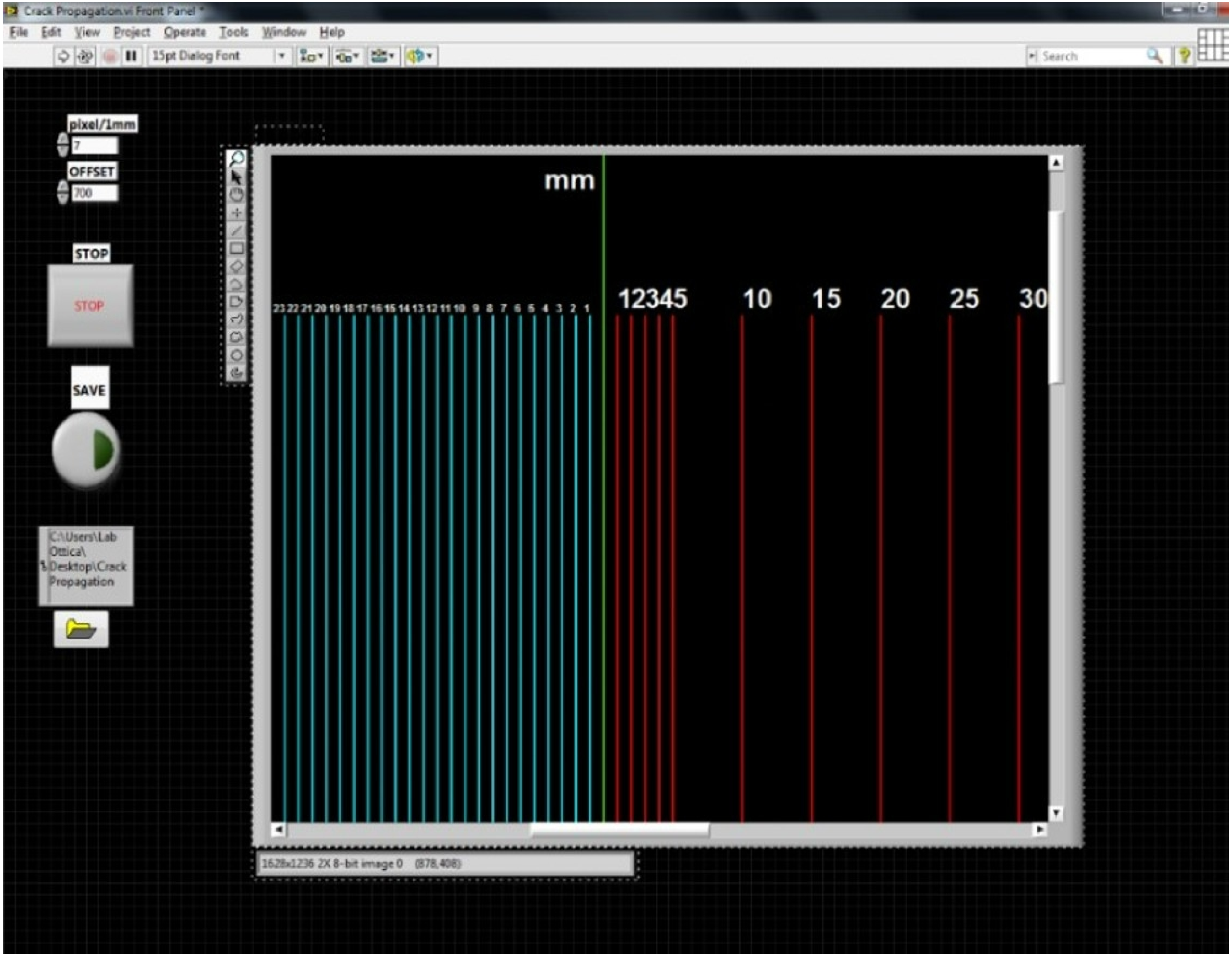
List of tables

- Table 2. Main characteristics of the Acoustic Emission sensor


Y
X
Z




insert
5 mm
25 mm
1 mm
5 mm

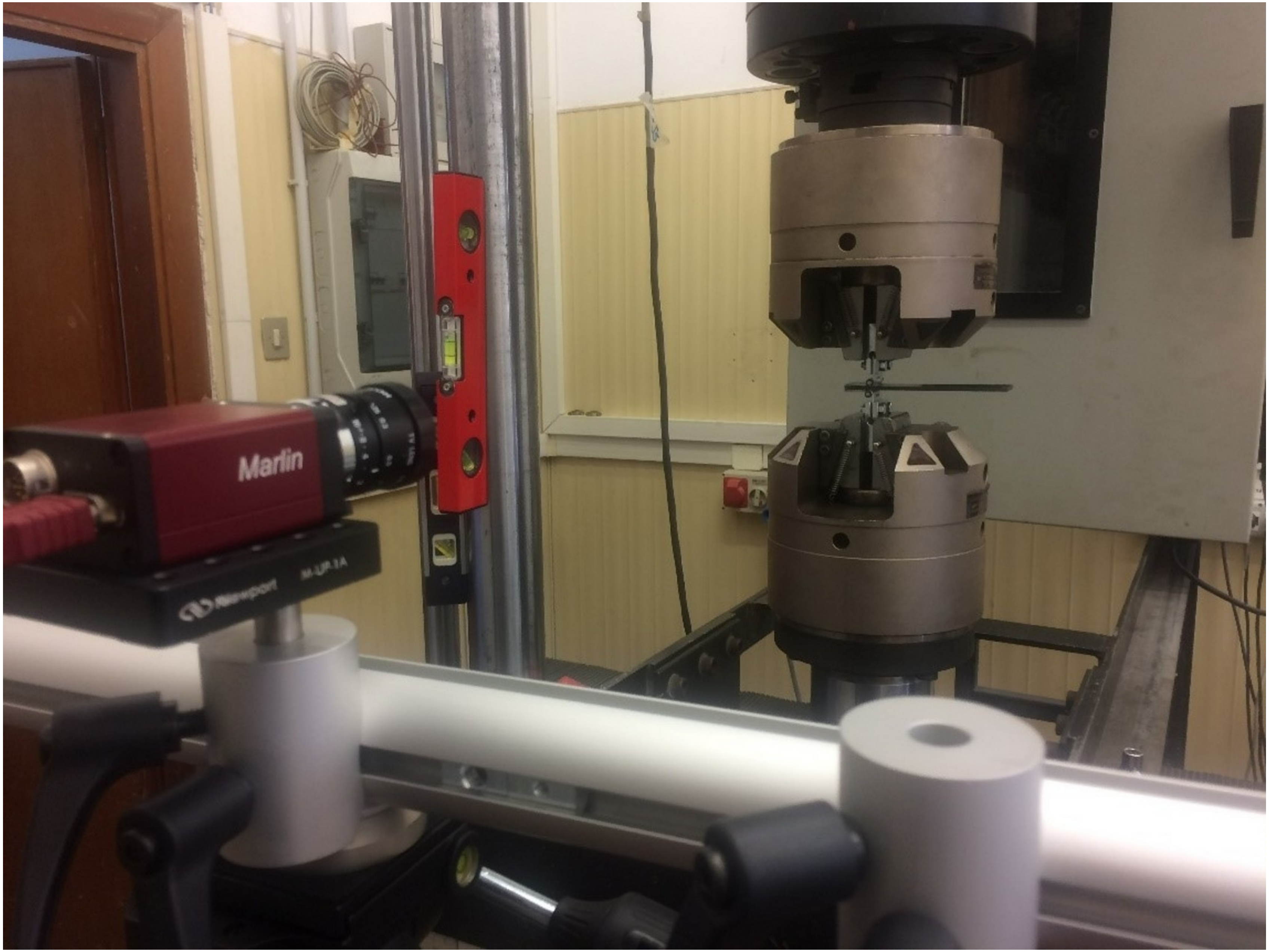


pixel/1mm 7

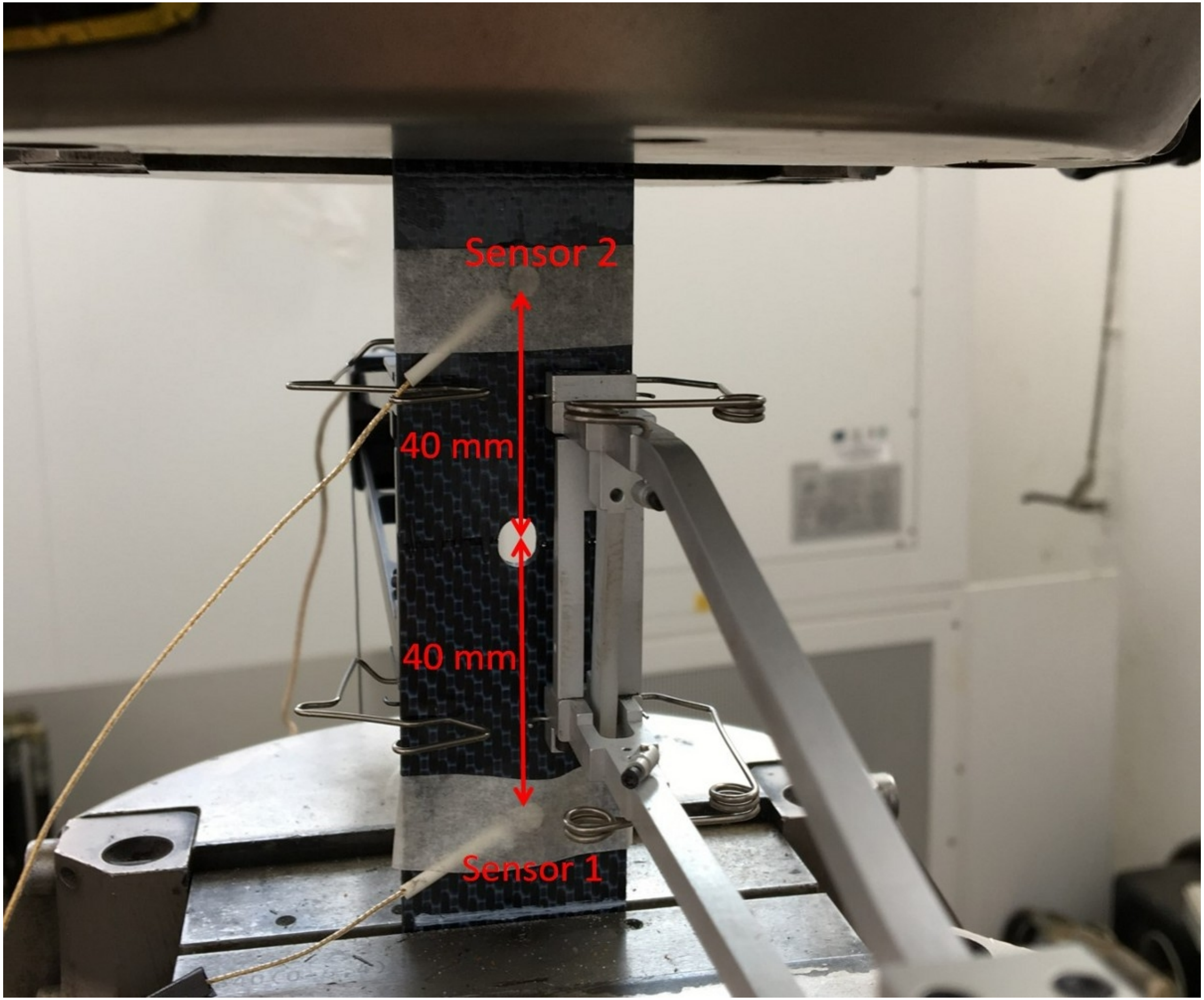
OFFSET 700

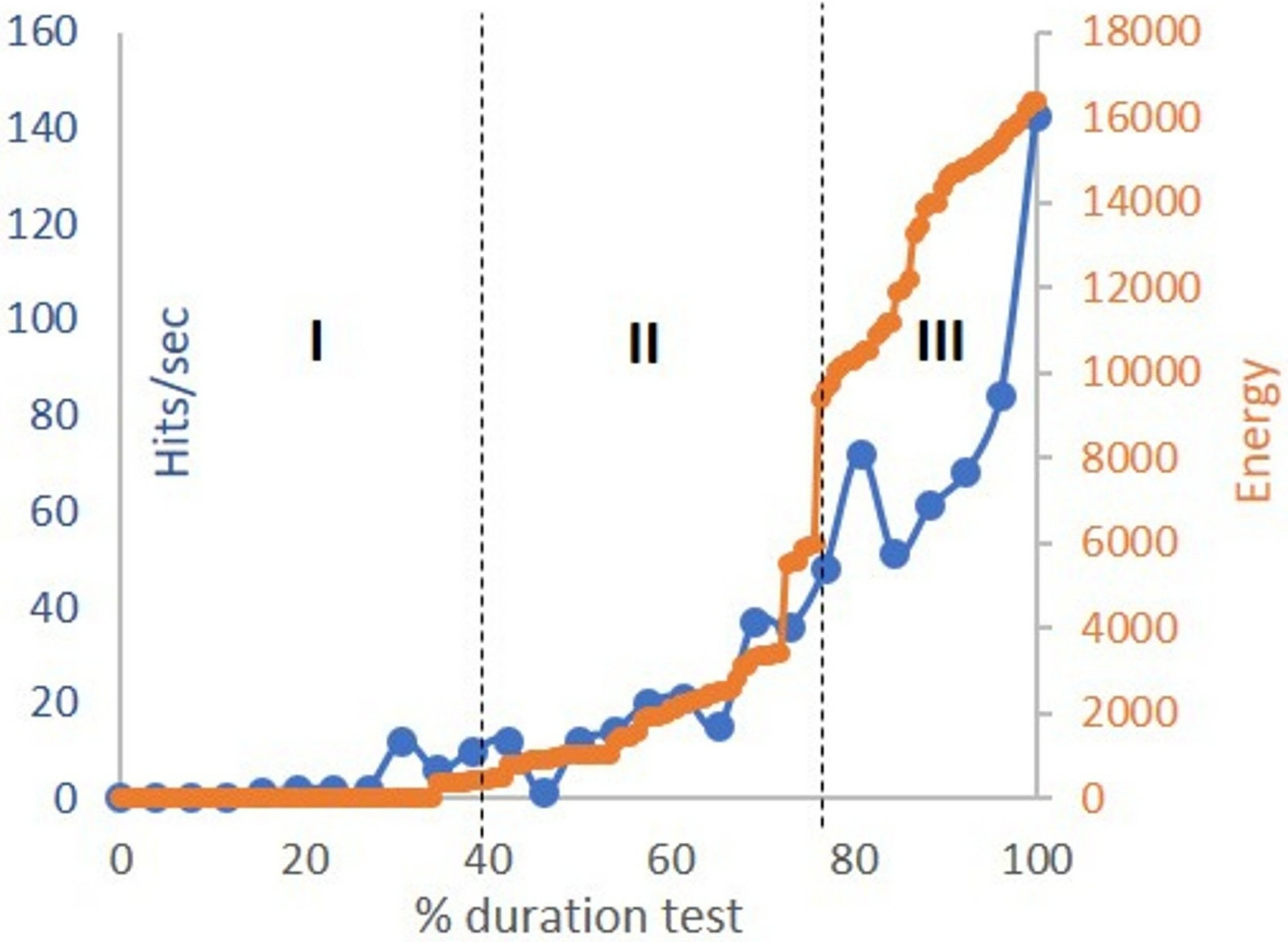
C:\Users\Lab Ottica\Desktop\Crack Propagation

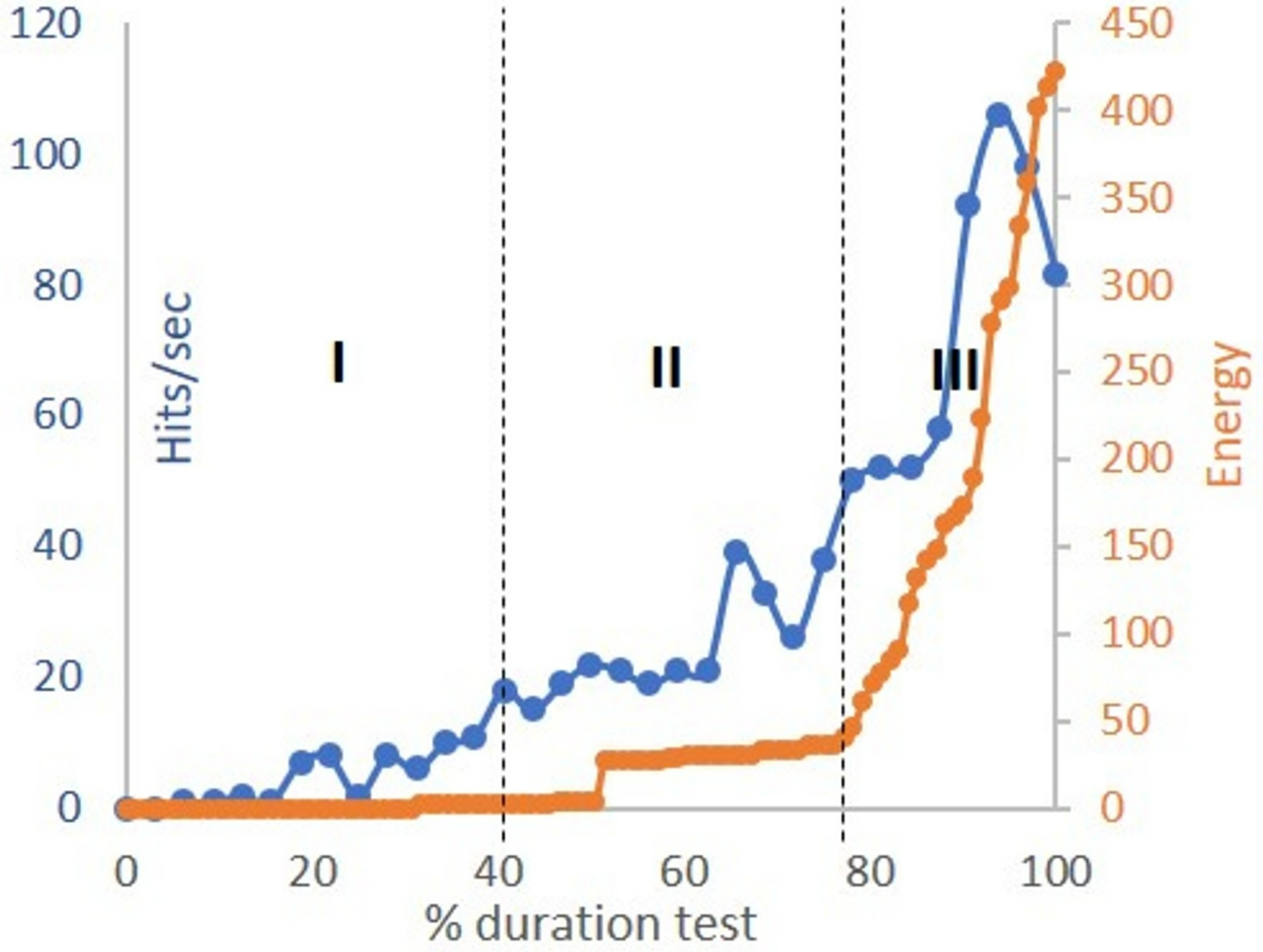
1628x1236 2X 8-bit image 0 (878,408)

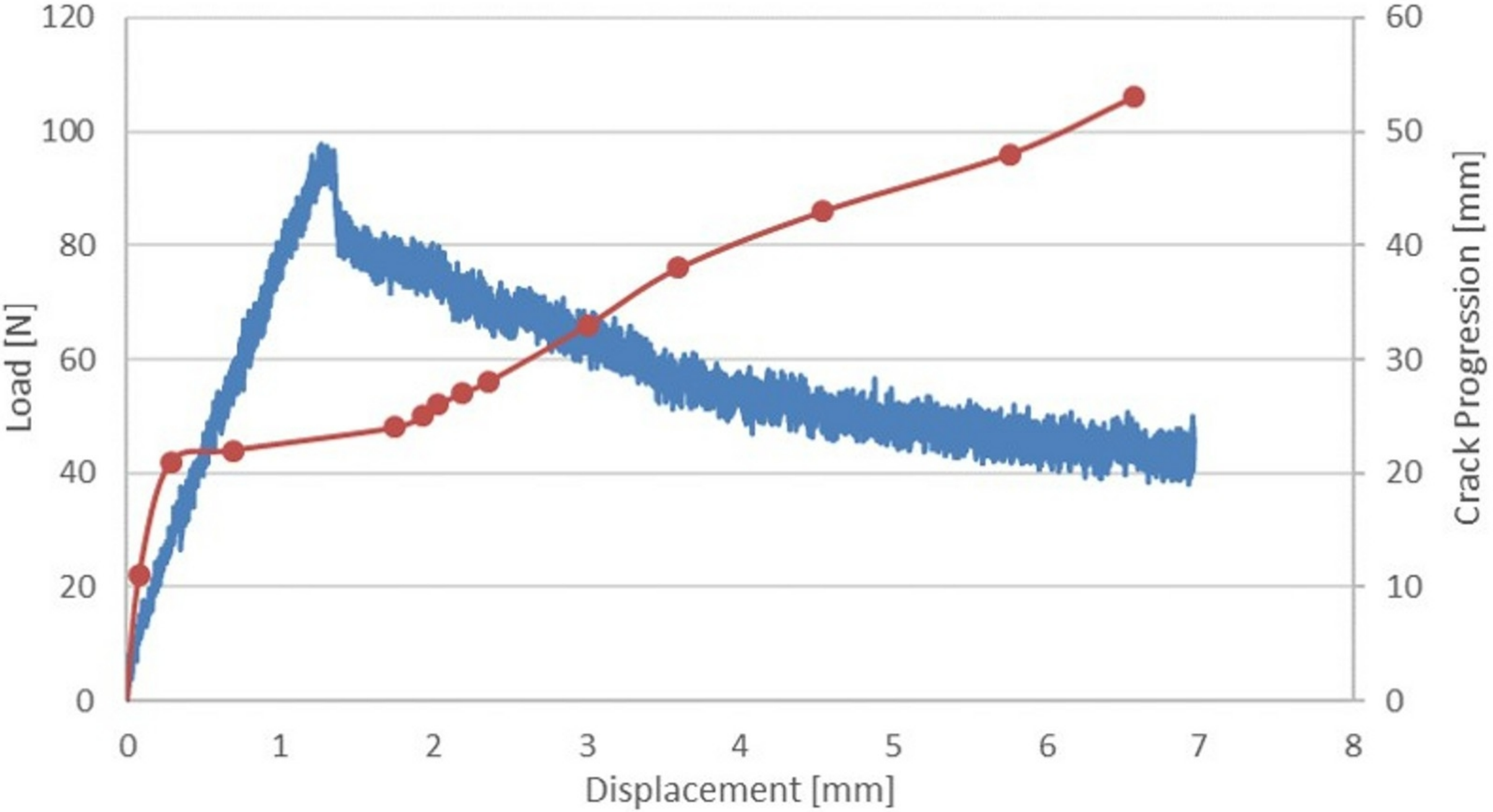


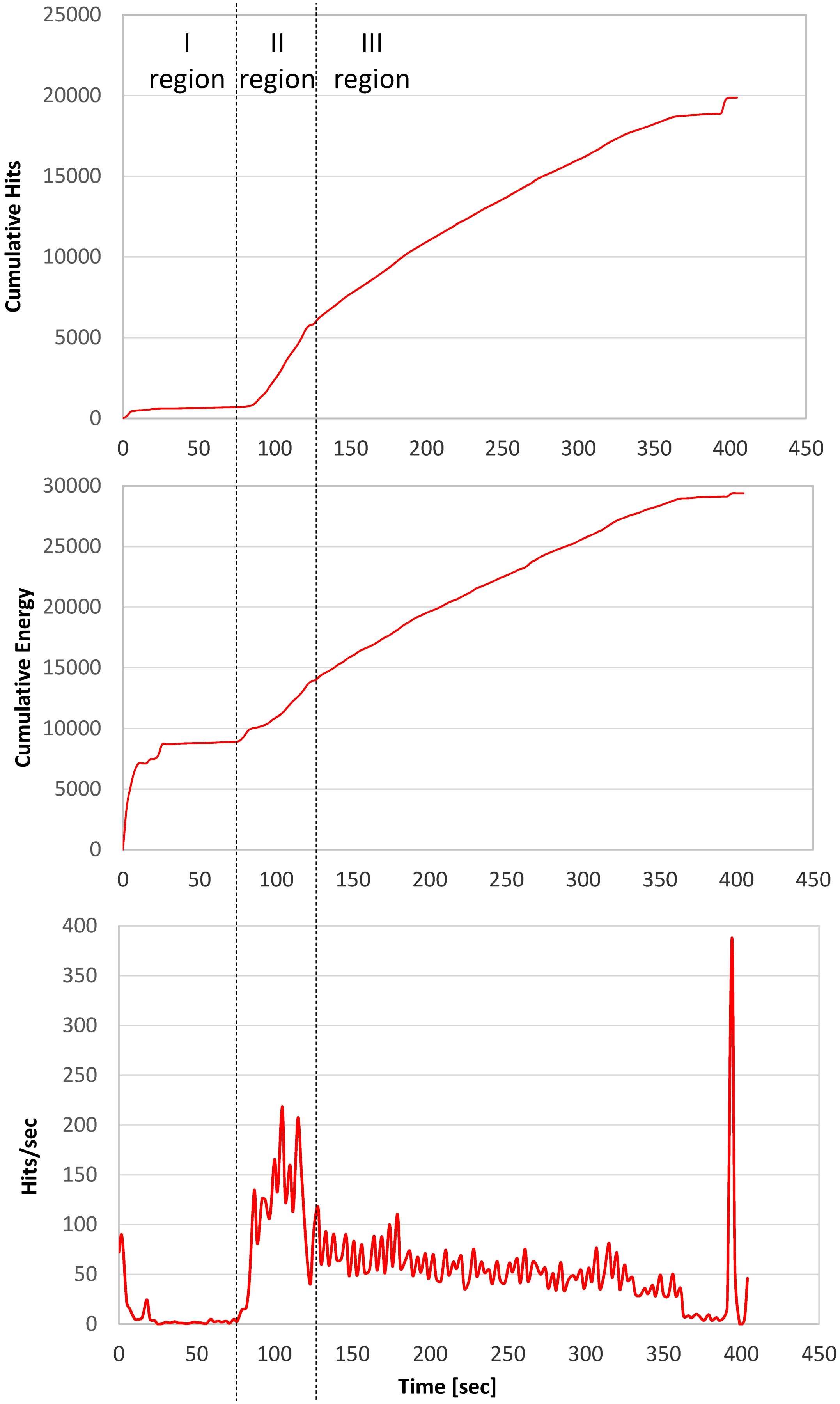
Marlin
Newport
M-UP-1A


Sensor 2
40 mm
40 mm
Sensor 1


160
140
120
100
80
60
40
20
0
Hits/sec
I
II
III
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Energy
0
20
40
60
80
100
% duration test


120
100
80
60
40
20
0
Hits/sec
I
II
III
450
400
350
300
250
200
150
100
50
0
Energy
0
20
40
60
80
100
% duration test


Load [N]
0
20
40
60
80
100
120
Crack Progression [mm]
0
10
20
30
40
50
60
Displacement [mm]
0
1
2
3
4
5
6
7
8


I
region
II
region
III
region
Cumulative Hits
25000
20000
15000
10000
5000
0
0
50
100
150
200
250
300
350
400
450
Cumulative Energy
30000
25000
20000
15000
10000
5000
0
0
50
100
150
200
250
300
350
400
450
Hits/sec
400
350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350
400
450
Time [sec]