# ROBUST FAILURE PREDICTION IN FIBER REINFORCED POLYMER RODS USING FREQUENCY ENTROPY OF CLUSTERED ACOUSTIC EMISSION EVENTS

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**Keywords:** acoustic emission signal, fiber reinforced polymer rod, failure prediction, fuzzy c-means clustering, frequency entropy

**Abstract**
This work presents a procedure for failure prediction in fiber reinforced polymer (FRP) rods based on analysis of acoustic emission (AE) signals. As damage increases in FRP rods, AE events are produced that are due to damage accumulated from independent mechanisms. This leads to wide spectrum AE events that are expected to have increased entropy. For each AE event detected during tensile tests the frequency entropy, duration, peak amplitude, energy, counts and rise time features were determined. Using these features, a fuzzy C-means algorithm classified the AE events into two clusters. For the second cluster, the frequency entropy histograms were compared versus the percent of ultimate load. The entropy of AE events was compared to the mean for histograms measured at less than 10-20% of the ultimate load. AE events more than two standard deviations from the mean are categortized as high entropy events. The results for six different FRP rods show a significant rise high entropy events occurs around 50%, 35% and 60% of ultimate load for glass FRP size 6, glass FRP size 4 and carbon FRP size 2, respectively. Results represent a threshold equal to 20% for the precent of high entropy AE events in the process of failure prediction in FRP rods. This work demonstrates that monitoring high entropy events is a promising approach to predict failure in FRP rods.

Excerpt from ISBN 978-3-00-053387-7

## 1. Introduction

Fiber reinforced polymer (FRP) rods have been extensively used in pre-stressing applications and they have replaced the steel as reinforcement for structures [1]. However, because of the lack of ductility, development of techniques for prediction of failure in FRP rods is required.

When FRPs are loaded they deform elastically. This deformation produces sudden microstructural damage that releases elastic energy as acoustic emission (AE) waves that propagate through the material. These vibrations are sensed using an AE sensor mounted on the surface of material. Acoustic emission signal analysis has been proved to be a promising technique for monitoring the progress of damage mechanisms in FRPs [2]. A large number of studies have been done on FRPs where common AE features including peak amplitude, duration, energy and so on used for damage characterization. In a study by Barre´ et al. [3] the peak amplitude distribution of AE events combined with scanning electron microscopy (SEM) was used for identification of different damage mechanisms in FRP. Other studies [4-6] used pattern recognition techniques including fuzzy C-means clustering (FCM), k-means, kohonen's self-organizing map (SOM) and so on to classify the AE events based on the group of mentioned features and then each of the resulting clusters was correlated to a kind of damage mechanism. In some studies the frequency features of AE events were used for damage characterization in FRPs. Gutkin et al. [7] used pattern recognition techniques based on peak frequency of AE events and assigned different frequency ranges to each damage mechanism. Li et al. [8] extracted the first and second peak frequencies of AE events using fourier transform and then they characterized different damage mechanizms based on these frequencies by applying the kohonen's SOM and FCM algorithms. Although, there have been a lot of experiments on mechanical behavior of different damage mechanisms in FRPs, non of them provide a robust method for prediction of impending failure in FRP rods. It is well-known that different type of damage produce different acoustic power spectral density patterns. Therefore, it might be expected that the most damaging events in FRPs may simultaneously contain several different AE patterns and tend to be distributed in more frequencies. A common way to quantify this change is using the entropy of the spectrum. When the spectrum is concentrated in few frequencies, the entropy is small. On the other hand, a widespread spectrum has large entropy. In a study conducted by Unnthorsson et al. [9] four different entropies of AE events were used to predict failure in carbon FRPs. They concluded that average evolution of AE entropy is not useful for failure prediction.

In this paper, frequency entropy is identified for each AE event detected during the FRP rod tensile test. The Fuzzy C-means clustering algorithm based on AE features including the frequency entropy, duration, peak amplitude, energy, counts and rise time is used in different percent of ultimate load to discriminate the AE events into two clusters. The frequency entropy histogram of the second cluster is used for prediction of failure in FRP rods.

## 2. Experimental Procedure

The test specimens used in this work consisted of two different type of FRP rods including glass FRP and carbon FRP. These specimens are prepared based on the CSA S806-06 (2006) Annex B standard. Table 1 lists the properties of the FRP rods used in this experiment.

**Table 1.** FRP test specimens.

| Bar Type | No. of Specimens | Diameter (mm) | Gauge Length (mm) | Modulus of Elasticity (GPa) | Surface Coating |
|---|---|---|---|---|---|
| GFRP size 6 | 2 | 19 | 760 | 46 | Undulation and sand coated |
| GFRP size 4 | 2 | 13 | 520 | 46 | Undulation and sand coated |
| CFRP size 2 | 2 | 6 | 240 | 124 | Sand coated |

For the tensile test, using the Instron 300DX universal testing machine and a 30kip Baldwin universal testing machine a ramping load is applied to the FRP rods until the failure. Two resonant piezoelectric tranducers ARI5I-AST of operating frequency 80kHz to 200kHz with 40dB low noise preamplifier

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built in, mounted on the surface of FRP rods to detect AE events. A USB data acquisition (DT9816-S, 16-bit, 750 kHz per channel) connected to the sensors, is used to sample the outputs of the sensors. Figure 1 represents a schematic of the experimental setup.

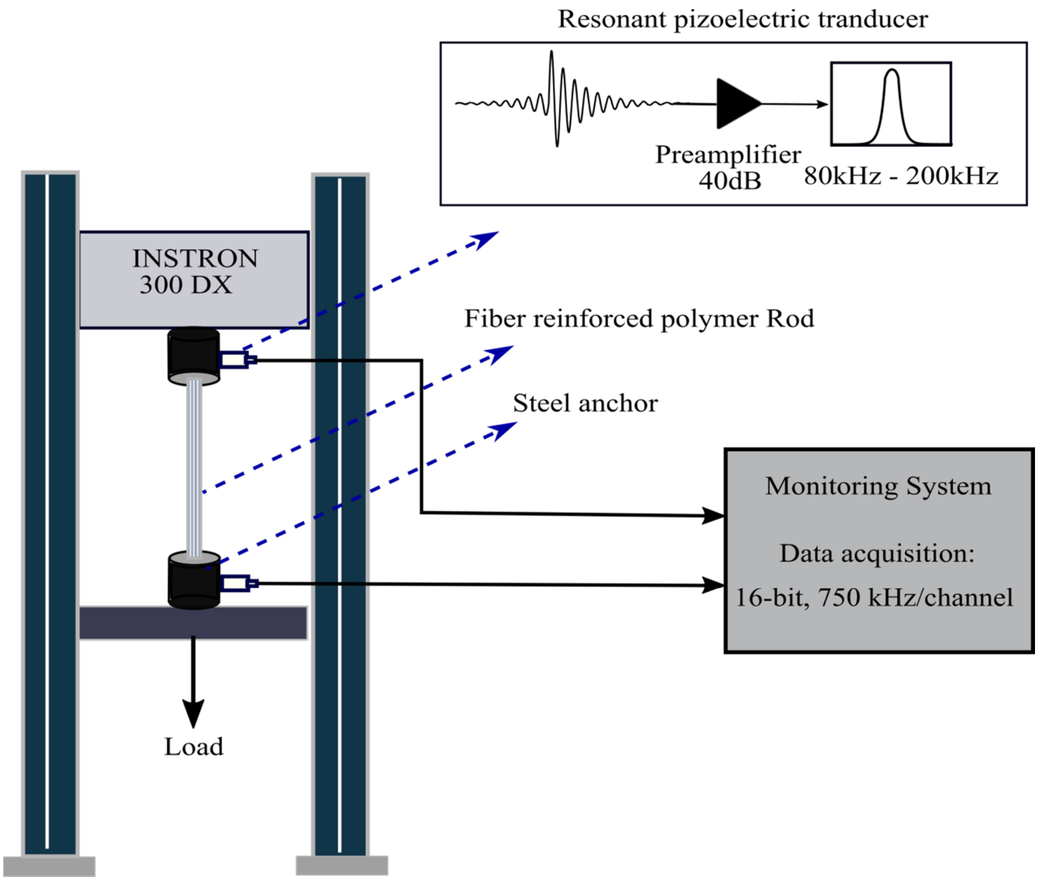


**Figure 1.** A schematic representation of the FRP rods tensile test setup

For facilitating the transfer of AE waves to the sensors the Proceq couplant gel (P.No. 71010031) is used as a coupling agent between the ceramic face of the sensors and the surface of the steel anchor. Table 2 shows the load information applied to the FRP rods during the tensile test.

**Table 2.** Rate of loading and displacement for FRP rods tensile test

| Bar Type | Loading Rate $(\frac{kN}{min})$ | Displacement Rate $(\frac{mm}{min})$ | Ultimate Load (kN) |
|---|---|---|---|
| GFRP size 6 | 71.25- 142.5 | 6 | 228 |
| GFRP size 4 | 31.67- 63.35 | 4 | 117 |
| CFRP size 2 | 7.92-15.84 | 0.8 | 78 |



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## 3. Methodology

### 3.1 Acoustic Emission Features

Acoustic emission signal is a transient stress wave due to sudden release of energy during damage development within material [5]. Several time-based features are defined for each detected AE events. Figure 2 represents common time-based features for AE events.

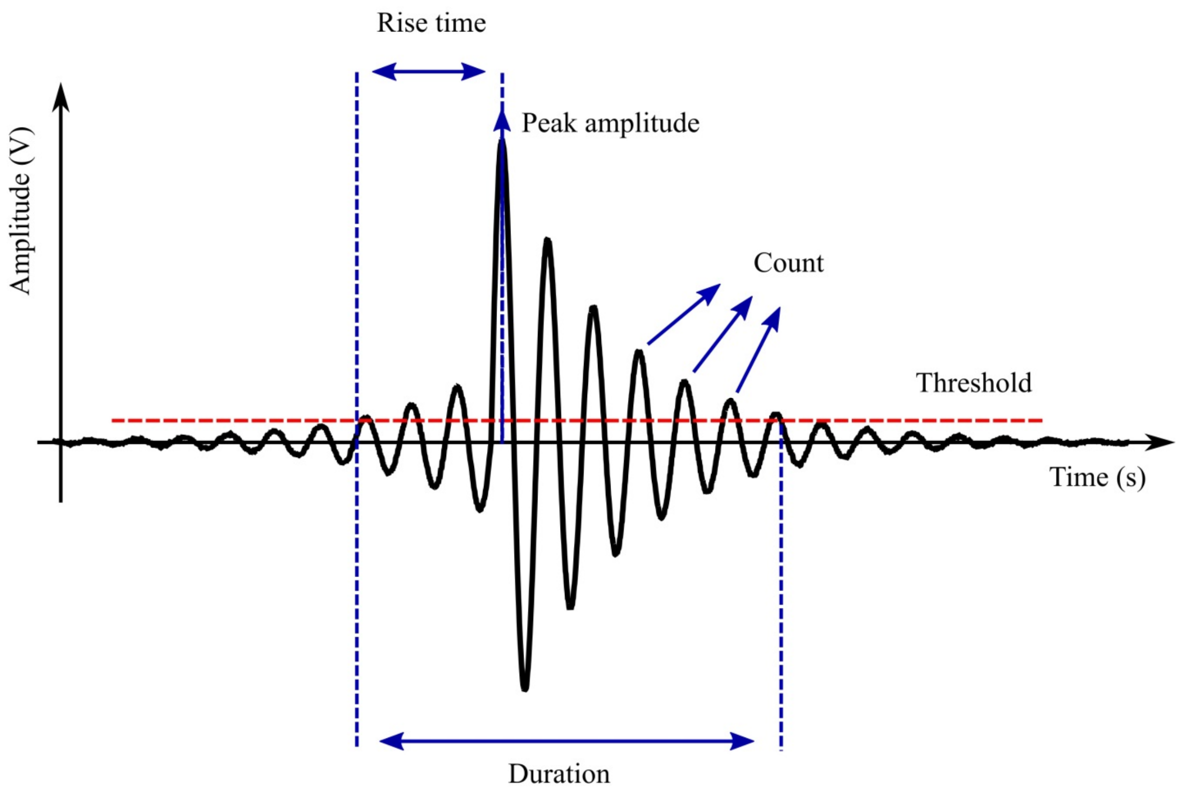


**Figure 2.** Common time-based features of acoustic emission event

In addition to these time-based features, frequency entropy can be defined for each AE event using following equation [9].

$$H = -\sum_{i} Pr(x = x_i)\, log(Pr(x = x_i)), \qquad Pr(x = x_i) = \frac{|x_i|}{\sum_j |x_j|} \tag{1}$$

Where $H$ is the frequency entropy and $|x_i|$ is the magnitude of i$^{th}$ frequency in the spectrum of AE event. This feature investigates the uncertainity about the energy distribution of AE event in different frequencies. When the energy is distributed in few frequencies, the entropy is small. On the contrary, distribution of energy over many frequencies provides large entropy.

In the next section, a combination of the mentioned time-based features and frequency entropy are used within the Fuzzy C-means clustering algorithm for failure prediction in FRP rods.

### 3.2 Failure Prediction

When FRP rods are under loading, matrix cracking is normally the first and most dominant damage mechanism happening in them. By extending of this damage mechanism accros the FRP rod, more loads are transferred to the fibers that gradually leads to other damage mechanisms including fiber-matrix debonding and fiber breakage.

Fuzzy C-means clustering algorithm [10] based on frequency entropy, duration, peak amplitude, energy, counts and rise time is used to cluster AE events into two clusters. It is believed that each cluster represents a type of damage mechanism [4,5,7]. The first cluster that has larger population and contains AE events with smaller peak amplitude and smaller duration is the most dominant damage mechanism. On the other hand, the second cluster having smaller population especially at the early stages of loading contains stronger AE events (see figure 3). For the second cluster the entropy histogram is examined in different percent of ultimate load. On the entropy histogram those AE events that fall further than two standard deviations away from the mean, are considered as the high entropy events. The amount of high entropy AE events in the second cluster for different percents of ultimate load is found and rapid change in the number of high entropy AE events is correlated to exceeding service load.

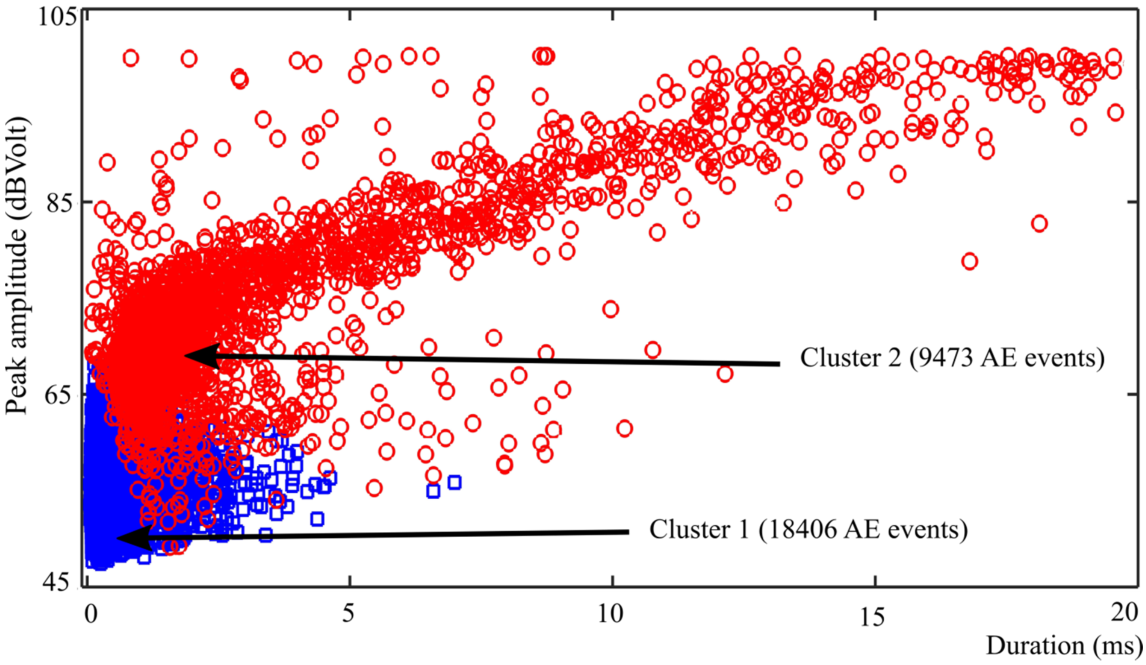


**Figure 3.** Representation of clusters using peak amplitude and duration of AE events

## 4. Results and Discussion

The FRP tensile test was done on six different FRP rods. Based on the frequency range of the sensors, a sampling frequency of 400 kHz was selected for the data acquisition system. The noise signals were filtered by assigning a threshold equal to the ten times of noise level, such that just those AE events that cross the threshold were detected. For entropy calculation, 2048-points discrete Fourier transform (DFT) was applied to each AE event and finally the FCM clustering algorithm using time-based features and frequency entropy was used to discriminate the AE events into two clusters. Figure 4 represents the frequency entropy histogram of the second cluster in different percent of ultimate load.



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From this figure it can be seen that for the second cluster the number of AE events with high entropy increases considerably after some percent of load.

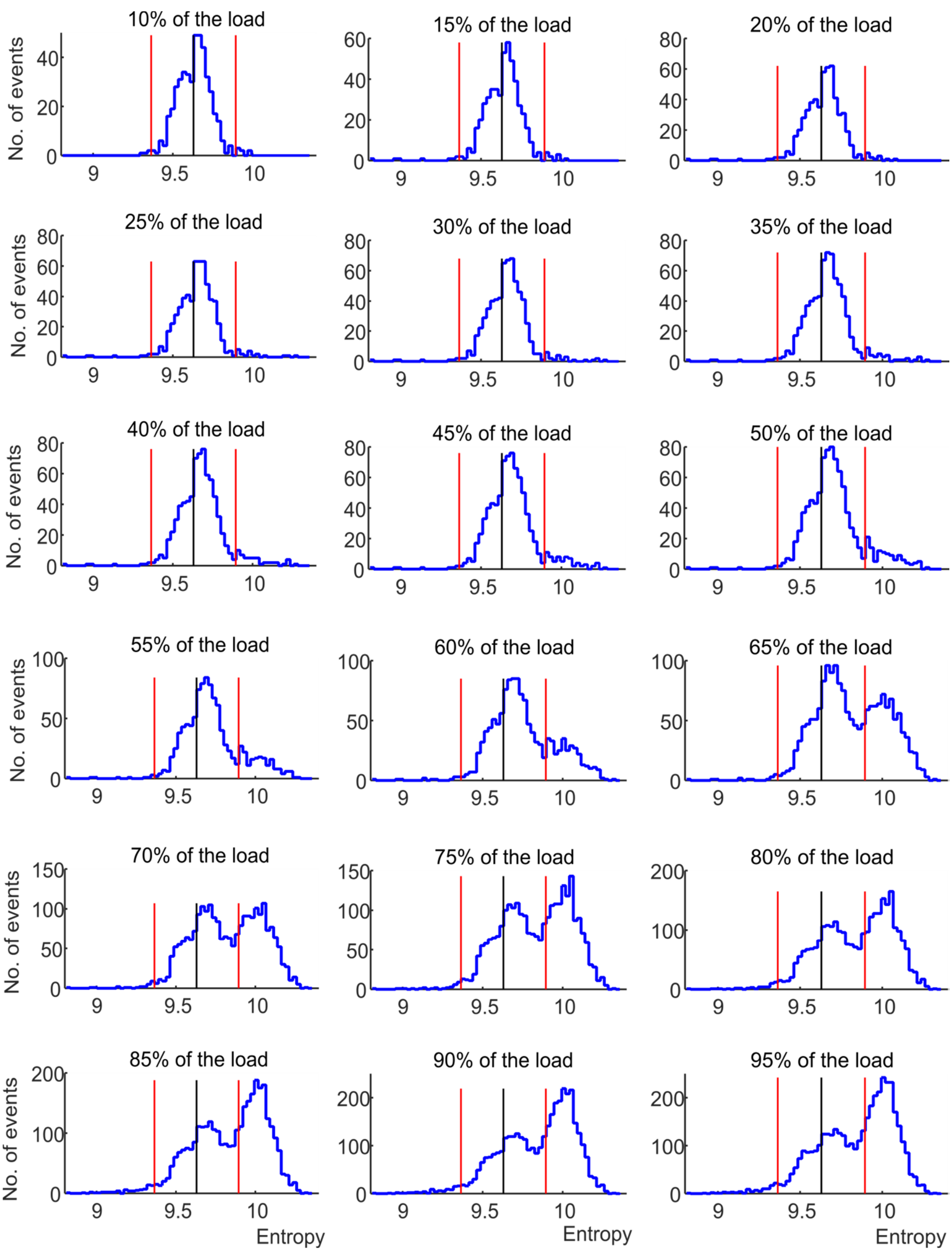


**Figure 4. .** Histogram of the frequency entropy for the second cluster in different percent of ultimate load for CFRP rod size 2 ( The middle black line is the mean of histogram in 10% of ultimate load and the region restricted to the two red lines is within two times of standard deviation from the mean)

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As a matter of fact, at the early stages of load the frequency spectrum of AE events contains a few frequencies that can be related to one damage mechanism. Therefore, the AE events have small entropy. Applying more loads to FRP rods generates more damage mechanisms with different frequencies [7]. When a combination of these damage mechanisms appears in AE events, the frequency spectrum of AE events contains more frequencies that leads to high entropy. It means that for more damaged FRP rods the entropy of AE events is higher, thus monitoring the number of high entropy AE events can provide information about the status of FRP rods under loading. Figure 5 shows the amount of high entropy AE events in the second cluster versus the load, for FRP rods with different sizes.

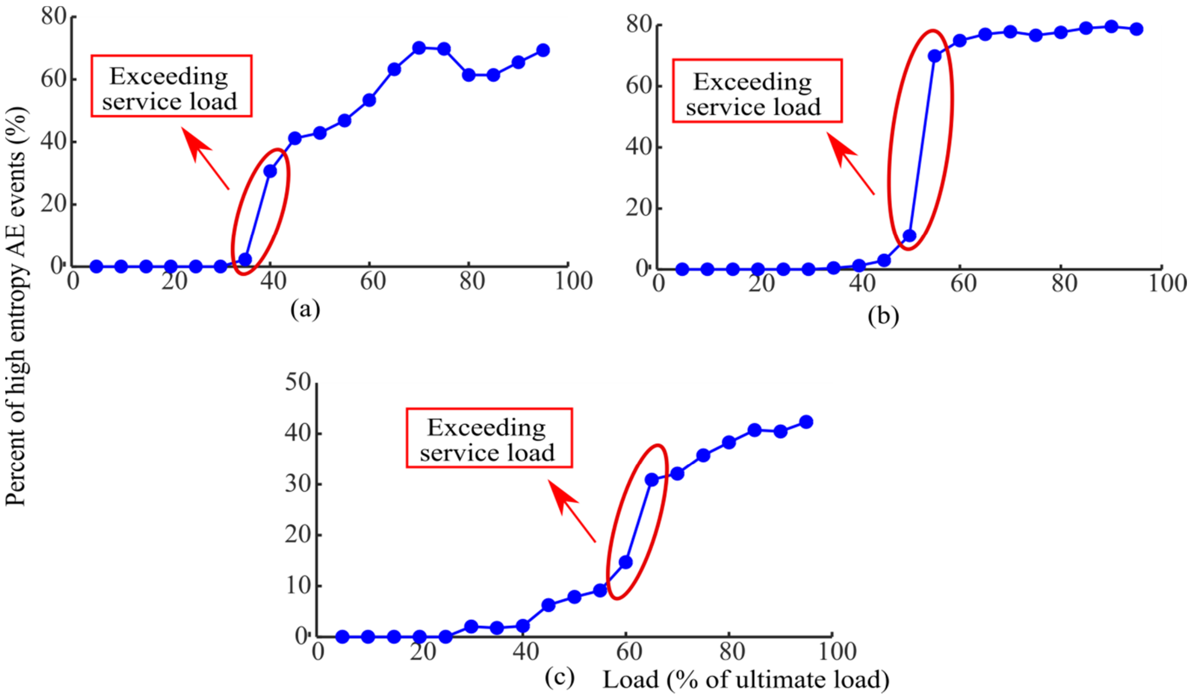


**Figure 5. N**umber of high entropy AE event in different percent of ultimate load (a) GFRP rod size 4 (b) GFRP rod size 6 (c) CFRP rod size 2

From the figure 5 as one can observe, the number of high entropy AE events in the second cluster increses rapidly around 50%, 35% and 60% of ultimate load for glass FRP size 6, glass FRP size 4 and carbon FRP size 2, respectively. This figure provides a threshold equal to 20% for the precent of high entropy AE events in the process of failure prediction in FRP rods.

## 3. Conclusions

In this paper, a robust method for prediction of impending failure in fiber reinforced polymer rods was presented based on the frequency entropy of clustered AE events. For each detected AE event during the tensile test, frequency entropy and time-based features including peak amplitude, duration, energy, counts and rise time were determined and then at different percent of ultimate load the fuzzy c-means clustering algorithm based on these features was used to discriminate the AE events into two clusters. For the second cluster, that contains higher energy AE events, the histogram of frequency entropy was investigated in different percent of ultimate load. Those AE events that fall further than two standard deviations away from the mean, were considered as the high entropy events. The evolution of amount



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of high entropy AE events in the second cluster showed a rapid change around 50%, 35% and 60% of ultimate load for glass FRP size 6, glass FRP size 4 and carbon FRP size 2, respectively and this change was correlated to exceeding service load in FRP rods. From the results a threshold equal to 20% was determined for the precent of high entropy AE events in the process of failure prediction in FRP rods. As a conclusion, the frequency entropy of clustered AE events can be used for prediction of failure in FRP rods, however the type of damage mechanisms cannot be determined.

## Acknowledgments

The authors would like to express their gratitude to the the Natural Sciences and Engineering Research Council of Canada, the Government of Manitoba, Research Manitoba and Centre for Structural Innovation and Monitoring Technologies (SIMTReC).

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