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Application of Wavelet Analysis for Measurement of Fracture Energy in Drop Weight Tear Testing of API X65 Steel

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Abstract

Determination of fracture energy is one of the most important aims in drop weight tear testing (DWTT) for assessment of material properties. The purpose of this study is to investigate a new experimental method for measuring fracture energy of tested steel. In doing so, the wavelet transformation was applied for API steel for the first time to analyze acceleration signals from impact tests. The acceleration signal from DWTT on API X65 steel was captured and studied using wavelet transformation. The DWT tests were conducted on three specimens with chevron notch according to API 5L standard. After the impact test, the noisy acceleration signal from each specimen was smoothed using discrete wavelet transformation. Then, force-displacement response was derived for each specimen from which fracture energy was calculated using the area under each plot. The obtained average fracture energy was 6326 J and the peak load was 219 kN. It was found that about 39% of the total fracture energy was used in crack initiation while 61% used in crack propagation. The comparison of the obtained results with previous data from similar research showed the effectiveness of wavelet transformation for accurate measurement of fracture energy using DWTT.

Keywords: Drop Weight Tear Test, Accelerometer, Discrete Wavelet Transform, Fracture Energy, API X65 Steel.

1. Introduction

The Drop Weight Tear Test (DWTT) is a destructive test to determine the mechanical properties of the tested material such as its fracture energy and characteristics of the fracture surface [1]. This experiment is widely used in steel gas transportation pipelines. It should be mentioned that the Charpy impact test is also a widely used impact test. In DWTT, the dimensions of the laboratory specimen are larger than the Charpy impact specimen and are close to the full thickness of the pipe. This feature makes DWTT results more representative of real-world conditions. [2].

In DWTT, accelerometers are commonly used for the indirect measurement of impact force, displacement, and hammer velocity. Several studies have investigated the fracture behavior of materials under various conditions. For instance, Panin et al. [3,4] explored the effect of temperature and notch type on the fracture energy of a plain carbon steel using Charpy impact tests equipped with strain gauges and acoustic emission sensors. Eremin et al. [5] examined the fracture behavior of welded aluminum alloy specimens under Charpy impact tests equipped with acoustic emission sensors. Fathi and Hashemi [6] experimentally and numerically calculated the absorbed energy of standard API X65 steel specimens in the DWTT equipped with a strain gauge. Three standard specimens were subjected to the DWTT and the average fracture energy of API X65 steel was measured to be 6187 J. Fathi and Hashemi [7] investigated the effect of low-velocity impact on the fracture energy of a DWTT specimen with a chevron notch in API X65 steel. Khosrovi and his co-workers [8] obtained the fracture energy of API X65 steel specimen in the DWTT equipped with an accelerometer. The fracture energy of the specimen was obtained as 6791 J in this research.

Wavelet transformation has rarely been used in the analysis of impact testing. This research aims to apply wavelet analysis to the acceleration signal obtained from DWTT on API X65 steel for the first time. Using accelerometers and wavelet transformation provides a more efficient, cost-effective, and accurate method for determining fracture energy in DWTT.

2. Methodology

2.1. Specimen Preparation and Test Procedure

In this study, the tested specimens were made of API X65 steel, according to the American Petroleum Institute (API) standards. The specimens were extracted from a natural gas transmission pipe with an outer diameter of 1219 mm and a wall thickness of 14.3 mm.

The impact tests were conducted using a DWTT machine equipped with accelerometer and strain gauges, located at University of Birjand. The machine had a hammer with a mass of 700 kg and a maximum drop height of 3 meters, which provides an impact energy capacity of up to 21 kJ. The setup of the testing machine is illustrated in Figure 1.

Figure 1. The Laboratory specimen in the DWTT.

The specimen was placed on the support anvils of the testing device. The hammer was then released from a height of 2 meters to impact and fracture the specimen.

2.2. Wavelet Transformation

Wavelet transformation is currently one of the efficient methods in processing vibration signals. This transformation uses wavelet functions instead of sine functions. Wavelet transformation can be used in many cases. Among them, signal denoising, time-frequency analysis, non-stationary analysis, data compression, discontinuity finding and fault detection can be mentioned [9]. In the wavelet transformation method, the variable windowing method is used, which is one of the most advanced windowing methods. This is the most important advantage of the wavelet transformation over short-time Fourier transformation method. Wavelet transformation can achieve high frequency resolution and low time resolution at low frequencies, where frequency behavior is very important. In contrast, at high frequencies, where the time and place of occurrence of the frequency are important, it has a high time resolution and a low frequency [10].

The discrete wavelet transformation is commonly implemented using multiresolution analysis (MRA). This involves successive filtering operations, where the signal is passed through a series of low-pass (G) and high-pass (H) filters, followed by downsampling. This process results in the decomposition of the signal into approximation (low-frequency content) and detail (high-frequency content) coefficients at each level. The approximation coefficients contain the main features of the signal, while the detail coefficients capture the rapid variations or noise. The relationship of low-pass filters with the scale function (ϕ) and high-pass filters with the wavelet function (ψ) is shown in relations 1 to 3 [11].

$$H(n) = (-1)^n G(1-n) \tag{1}$$

$$\phi(x) = \sum_n G(n)\sqrt{2}\,\phi(2x-n) \tag{2}$$

$$\psi(x) = \sum_n H(n)\sqrt{2}\,\phi(2x-n) \tag{3}$$

In this study, the goal was to use the wavelet transformation to analyze the acceleration signal obtained from the DWTT. Given the noisy nature of the signal due to the high impact and specimen oscillations, the discrete wavelet transformation was applied to remove unwanted noise and obtain a smooth signal.

The smoothed acceleration signal was then double-integrated to derive the velocity and displacement of the hammer during the impact. Using Newton's second law, the force applied to the specimen was calculated and the force-displacement curve was obtained to calculate the fracture energy.

2.3. Data Extraction Process

After the hammer dropped from 2m height and fractured the specimen, the impact data were collected. To ensure the repeatability of the results, the experiment was performed on three identical specimens under the same conditions. The acceleration data obtained during the impact test contained significant amounts of noise due to the high impact force and the resulting oscillations of the specimen.

To accurately measure the fracture energy, the acceleration signal needed to be filtered to remove any noise. One of the common methods for noise reduction is the use of discrete wavelet transformation, also known as the filter bank method. This method decomposes the signal into high-frequency (details) and low-frequency (approximations) components using high-pass and low-pass filters. Given that the primary signal characteristics were expected to reside in the low-frequency range, the analysis focused on filtering out high-frequency components that corresponded to noise. Several mother wavelets were tested, including Coiflet, Biorthogonal, Reverse Biorthogonal, and Daubechies, with different levels of decomposition. Based on the analysis, the Symlet8 wavelet at the seventh decomposition level was found to be the most suitable for this experiment. This choice was based on the wavelet's ability to reduce noise and retain the essential characteristics of the signal. Figure 2 shows the filtered acceleration signal using the Symlet wavelet at level 7.

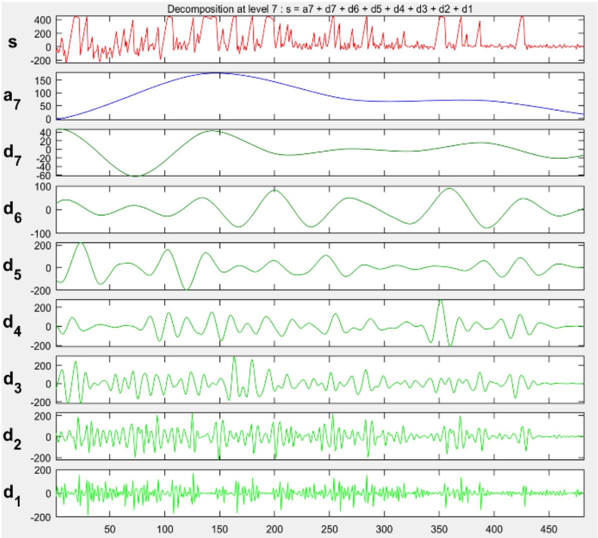

Figure 2. Decomposition of the acceleration signal of the DWTT in 7 levels with Symlet wavelet.

3. Results and Discussion

After the acceleration data processed and the force-displacement curves obtained for all three specimens, the fracture energy for each specimen was calculated by measuring the area under each curve. The specimens were labeled as G1, G2 and G3. The force-displacement curves for the three specimens, along with the mean curve, are shown in Figure 3.

Based on the force-displacement curves in Figure 3, the fracture energies for the specimens G1, G2 and G3 were found to be 5994 J, 6339 J, and 6646 J, respectively. The average fracture energy for the three specimens was calculated to be 6326 J. Additionally, the analysis revealed that approximately 39% of the total fracture energy was used for crack initiation, while 61% was used for crack propagation. This indicated a higher resistance to crack growth, signifying the material's toughness.

The peak force and displacement data during the impact test provided crucial insights into the material's toughness and energy absorption capacity. The peak forces for specimens G1, G2 and G3 were found to be 196 kN, 243 kN, and 217 kN, respectively, with an average peak force of 219 kN. This indicated the force required for the onset of crack growth.

The results from this study were compared with previous research conducted by Fathi and Hashemi [6] and Khosravi [8]. The comparison showed that the difference in total fracture energy between this study and the previous research was low, with an approximate 2.2% difference. This comparison validated the efficiency of wavelet transformation in accurately measuring fracture energy in DWTT.

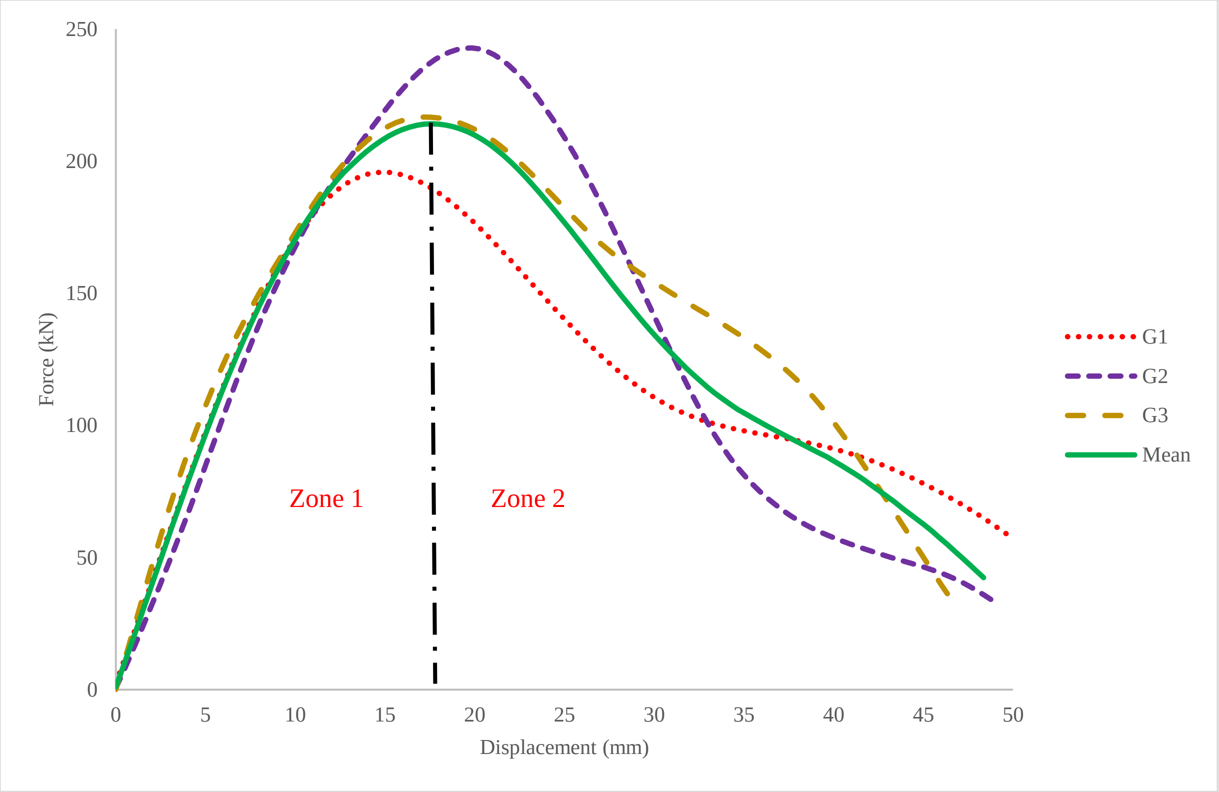

Figure 3. The force-displacement curves for the three specimens

4. Conclusions

In this study, wavelet transform was used for the first time to analyze the acceleration signals obtained from DWTT on API X65 steel. The analysis demonstrated the effectiveness of wavelet transformation in extracting the fracture energy from acceleration signals.

The key findings of this research are summarized below:

1. The use of accelerometers and wavelet transformation provided a new method for analyzing DWTT results, effectively determining the fracture energy.
2. Discrete wavelet transformation was shown to be an appropriate tool for analyzing acceleration signals, with the ability to smooth the signals and remove noise.
3. The Symlet 8 wavelet at the seventh decomposition level was found to be the most suitable for extracting fracture energy from acceleration signals.
4. Accelerometers offer several advantages over strain gauges, including ease of installation, a higher signal-to-noise ratio, and the ability to be reused, making them suitable for DWTT.
5. The average fracture energy of API X65 steel measured using DWTT and wavelet transformation was found to be 6326 J.
6. The material's toughness was confirmed, with approximately 61% of the total fracture energy used for crack propagation, indicating high resistance to crack growth.

5. Acknowledgement

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