Novel Approach in Fracture Characterization of Soft Adhesive Materials Using Spiral Cracking Patterns

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Article

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NOVEL APPROACH IN FRACTURE CHARACTERIZATION OF SOFT ADHESIVE MATERIALS USING SPIRAL CRACKING PATTERNS

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ABSTRACT
A transformative and radically different approach for fracture characterization of soft adhesive materials through use of spiral cracking patterns is presented. This research particularly focuses on hydrocarbon polymeric materials such as asphalt binders. Five different asphalt materials were utilized in this study. An innovative integrated experimental-computational framework coupling Acoustic Emissions (AE) approach along with machine learning-based Digital Image Analysis (DIA) method is employed to determine the crack geometry and to accurately characterize fracture behavior of the material. Various image processing and machine learning techniques such as Convolutional Neural Networks (CNN), skeletonization, segmentation, and regression were used in DIA to automatically analyze spiral patterns. A new parameter called the “Spiral Cracking Energy ($E_{Spiral}$)” to assess fracture performance of soft adhesives is introduced in this work. This study also explores the relationship between $E_{Spiral}$ and fracture energy of the material.

Keywords: Soft Adhesives, Spiral Cracking Pattern, Acoustic Emission, Digital Image Analysis, Machine Learning, Convolutional Neural Networks (CNN)
1. INTRODUCTION

As a common phenomenon in materials, fracture can create various cracking patterns. It is specially prevalent in thin coatings under residual stresses, forming a network of cracking similar to patterns observed in dried mud layers and old paintings, see Fig. 1(a). Some of the well-studied examples of fractures are straight type cracks, a.k.a mud(channeling) cracks commonly observed in fragmented dried out fields, dried mud layers, coatings, and paintings. In addition to mud fracture patterns, which is the most common type, a rare spiral-shaped cracking patterns have been observed in some soft adhesive materials, see Fig. 1(b).

Spiral cracks usually occur in thin layer of soft materials coated on rigid substrates. Some distinct processes such as: drying, cooling, syneresis, or stretching of a substrate are attributed as the cause of formation of this type of cracks. Fig. 2 schematically illustrates the mechanism of spiral crack development. Deformation mismatch between the coating layer and the substrate induces biaxial tensile stresses within the coating/substrate system which will act as the driving force behind the crack propagation in the material. As the magnitude of the induced stresses increases, first a network of channeling cracks (a.k.a. mud cracks) appears hierarchically, dividing the layer into several polygonal sections. After formation of mud cracks, partial detachment of the material from the substrate (partial delamination) takes place within the polygonal sections. Delamination front begins from the edge of the polygonal cell and grows towards the center of the cell. While partial delamination occurs, the spiral crack starts at the border of the adhering region of the fragmentation from some initial imperfection or a weak interface and propagates along a spiral trajectory.

Spiral cracks have been observed and reported in several materials including: thin brittle adhesive layers bonding glass plates together [1, 2]; inside biaxially stressed films of certain polymers such as polyethylene terephthalate bonded to glass substrate [3]; inside thin TiN, and NbN monolayers deposited onto steel or stainless steel substrates [4]; inside delaminated areas of drying precipitates of different compounds, including nickel phosphate, ferric hydroxide [5, 6]; inside the silicate sol-gel films [7]; inside the thin film of Mo/Si multilayer system [8]; in diamond-like carbon (DLC) film on a ductile steel substrate [9]; inside thin films of silicate materials widely used as a coating in laser technologies [10]; inside hydrogenated nickel coatings [11, 12]; and on the surface of melt-grown poly (L-lactic acid) (PLLA) spherulites [13], see Fig. 3. Behnia et al reported formation of spiral fracture patterns inside a thin layer of hydrocarbon polymeric materials such as asphalt binders and further investigated these patterns [14]. The logarithmic spiral function was found to be the best fit to mathematically represent 3D spirals, see equation (1) where: “A” is the apparent length scale, “b” is the spiral tightness parameter, is the initial spiral crack depth, is the angle from the x-axis, and is the final angle corresponding to the outmost point of spiral in the sample:

\[
\mathbf{p}(r, \theta, z) = Ae^{b\theta}\cos(\theta)\mathbf{i} + Ae^{b\theta}\sin(\theta)\mathbf{j} + \frac{\theta}{2\theta_f}D_0 \mathbf{k}
\]  

(1)
This study presents a transformative and radically different approach using spiral cracking patterns as a powerful diagnostic tool to obtain valuable information about the fracture characteristics of soft adhesives particularly hydrocarbon polymeric materials. Accurate fracture characterization of soft adhesive materials have remained a challenging task. Implementation of conventional testing methods such as compact tension \( C(T) \) test (to evaluate fracture characteristics) and the Peel test (to measure adhesive strength) of such materials is quite challenging. Due to the soft nature of these materials, large creep deformations usually occur in the material during the experiment. Moreover, another concerning issue is that the Linear Elastic Fracture Mechanics-based (LEFM) theories are not suitable to describe the fracture of soft and highly stretchable materials. Research studies have demonstrated that due to large deformations during fracture process, the stress field near crack tip in soft materials is significantly different from that of used for LEFM (The LEFM is based on the assumption of infinitesimal deformations) [15].

2. MATERIALS
The present work focuses on fracture characterization of hydrocarbon polymeric materials such as asphalt binders. It should be noted that the proposed research approach is not limited to hydrocarbon polymers and it is applicable to other soft adhesives with some minor adjustments in sample geometry and type of substrate material, etc. Five asphalt materials with different fracture properties and varying performance grades (PG) including: PG58-16, PG64-16, PG64-22, PG70-22, and PG58-28 were utilized. The standard notation of PG \( XX-YY \) is used for asphalt grading where “\( XX \)” and “\( YY \)” are known as the PG high and low temperatures, respectively. The PG high temperature is the average seven-day maximum temperature (°C) of asphalt road and PG low temperature is the minimum temperature (°C) that asphalt road will likely experience during its service life [16].

3. SPIRAL CRACKING EXPERIMENT
Cylindrical-shaped specimens bonded to rigid substrate is proposed to use as the testing specimen for semi-solid soft adhesives, Fig. 4(a). Depending on the type of the adhesive material being tested, the diameter \( D \) and thickness \( h \) of the specimen as well as the type of substrate material (such as glass, aluminum, etc) can be different and they should be carefully selected to ensure there are no delamination and no mud cracks within the spiral specimen. For hydrocarbon polymeric materials, various geometries with different thicknesses (ranging from 1mm to 30mm) were investigated. Results demonstrated that cylindrical
specimens with $D=25\text{mm}$ and $h=20\text{mm}$ bonded to an aluminum substrate showed the most promising results (i.e. no debonding & no mud cracks). Lack of mud cracks in the proposed testing configuration is an advantage which minimizes variation in spiral results (better repeatability). Experience showed that presence of mud cracks in spiral samples are the source of variability (number of mud cracks, their lengths, and their formation locations vary from one sample to another).

Spiral cracks are produced in the lab under a controlled condition. Depending on the type of material, they could be thermally-induced, solvent-induced, or caused by drying. In case of hydrocarbon polymeric materials, spiral cracks are thermally-induced and produced by cooling the sample. In the preliminary study, various cooling rates including: 0.3, 0.5, 1, 1.5, and 2°C/min were investigated. Results showed that cooling rates higher than 1°C/min resulted in sample delamination from substrate before spiral crack even gets a chance to develop. Thus, the average cooling rate of 1°C/min was applied for testing asphalt materials. Asphalt samples were prepared by pouring heated material into a cylindrical-shaped silicon mold mounted on the substrate. Samples are let to reach room temperature before testing. To conduct the experiment, sample was cooled down from 0 to -50°C at the average rate of 1°C/min. The -50°C was selected to make sure spiral crack is fully developed inside the sample. Results showed that formation of spiral crack in asphalt samples subjected to 1°C/min cooling rate completes at temperatures ranging from -40°C to -50°C for various types of asphalt. As the temperature reduces, differential thermal contraction between rigid substrate and asphalt creates thermally-induced stresses within the material which eventually leads to formation of an inward-growing spiral crack nucleating from some initial imperfection or a weak interface near edge of the specimen.

Results showed a gradual reduction in spiral crack depth (penetration depth) from almost 50% of sample thickness ($h$) at the edge to almost zero at the center of the specimen, see Fig. 4(b). This phenomenon could be linked to gradual reduction in the amount of stored strain energy as the crack spirals from the edge towards the center of the sample. During the fracture process, stored strain energy in the specimen is consumed for creation of new fractured surfaces. At the beginning of the fracture process, the stored strain energy in the specimen is at the highest level, leading to nucleation of spiral crack at the interface with a maximum penetration depth, $D_0$. As spiral crack grows, strain energy is gradually diminished to create new fractured surfaces. As a result, crack penetration depth continuously decreases until it reaches almost zero at the center of sample. Careful inspection of fully grown 3D spiral showed that the gradual change in spiral crack depth is almost linear. Fig. 4(c) schematically shows the hypothetical unwrapped shape of 3D spiral crack in the form of a triangle.

![Spiral Crack Diagram](image)

Figure 4: (a) Testing configurations for semi-solid soft adhesives (b) 3D spiral crack developed in the sample (c) Unwrapped spiral crack in the form of triangle

### 4. INTEGRATED EXPERIMENTAL AND COMPUTATIONAL FRAMEWORK

An overview of the integrated experimental and computational framework consisting of multi-sensor AE method coupled with Digital Image Analysis (DIA) approach to evaluate fracture characteristics of soft adhesive materials is illustrated in Fig. 5 (technical details of these methods are provided in sections 4.1 and 4.2). In this approach, the total area of spiral-shaped fractured surfaces ($A_{\text{Fracture}}$) inside the specimen is calculated through application of coupled AE-DIA approach where total length of spiral crack ($L_{\text{Spiral}}$) is...
measured using DIA and the initial depth of spiral crack, $D_0$ is determined using AE source location. For the DIA analysis a novel machine learning-based image processing framework is applied. The AE energies of individual events (i.e. AE event is a rapid physical change such as microcracks appearing as acoustic signal) will be added up to measure the total amount of released AE energy due to formation of spiral crack within the sample. A new parameter (index) called the Spiral Cracking Energy ($E_{\text{Spiral}}$) is introduced which is defined as the amount of released AE energy per unit of newly formed fracture surface area of spiral cracks. It should be noted that this fracture index is not the same as the fracture energy of the material due to the fact that the measured AE energy is not equal to the strain energy released during crack propagation. During the spiral cracking process, part of the strain energy released in the specimen is used to create new fractured surfaces, and the rest is released as transient elastic waves which can be picked up by AE sensors (a portion of transient waves can be dissipated by attenuation before reaching AE sensors). The former is related to the fracture energy and the latter is captured by AE method. The $E_{\text{Spiral}}$ index quantifies fracture resistance of soft adhesives materials using their AE activities during spiral cracking. Unit of $E_{\text{Spiral}}$ is $V^2 \mu s/mm^2$ and it can be calculated by dividing the total released AE energies of fracture-induced signals by the total fractured surface area within the sample, equation (2) where, $N$ is the total number of recorded AE signals, $V_i(t)$ is the voltage of the $i^{th}$ recorded signal in volts, $A_{\text{Fractured}}$ is the total surface area of fractured faces measured from AE-DIA analysis.

$$E_{\text{Spiral}} = \frac{\sum_{i=1}^{N} \int_{0}^{t} V_i^2(t) dt}{A_{\text{Fractured}}} \quad (2)$$

Figure 5: Integrated AE-DIA approach to assess fracture characteristics of soft adhesives
4.1. Multi-Sensor Acoustic Emission Testing

The multi-sensor Acoustic Emission (AE) technique was employed to continuously monitor acoustic activities of the specimen during the course of the spiral cracking experiment and also to measure the initial depth of spiral crack, \(D_0\), see Fig. 6. Broadband AE sensors with a relatively flat response over the target frequency range capable of working properly at target range of test temperatures will be utilized. For asphalt materials broadband AE sensors with flat responses in frequency ranging 20kHz-1MHz are used. To minimize extraneous noise (i.e. separating genuine fracture-originated AE signals from noise) signals are pre-amplified 20 dB using broadband pre-amplifiers. Signals are then further amplified by 21 dB (for a total of 41dB) and filtered using low-pass (LPF) and high-pass (HPF) filters of 500 kHz and 20 kHz, respectively, with the Fracture Wave Detector (FWD) signal condition unit. The signals are digitized using a 16-bit analog-to-digital converter (ICS 645B-8) and a sampling frequency of 1 MHz and a length of 2048 points per channel per acquisition trigger. At the post processing stage, all AE signals with energy lower than 4 V^2*μs are filtered out. Moreover, the standard pencil-lead break (PLB) test is performed routinely before conducting the experiments in order to calibrate AE system as well as the AE sensors and to make sure variation within the AE channels is negligible.

As the spiral crack propagates inward, new fractured surfaces are formed which are accompanied by release of stored strain energy in the form of transient mechanical stress waves inside the specimen. The AE piezoelectric sensors mounted on the surface of the specimen as well as on the substrate adjacent to specimen will continuously monitor and detect these mechanical waves and convert them into AE signals. The AE signals carry valuable information about the spiral fracture process occurring in the material. Therefore, AE signals were recorded, carefully analyzed, and key features of signals such as: signal amplitude, energy, frequency, hit counts, arrival time, and duration were extracted.

In addition, the AE source location technique was applied to measure the starting penetration depth of spiral crack (\(D_0\)). An integrated approach combining the two-step Akaike Information Criterion (AIC) method [17] and Simplex algorithm (a.k.a Nelder-Mead algorithm) was implemented. The AIC approach was used for precise automatic determination of time of arrival (ToA) of AE signals. The autoregression-based AIC function divides the AE signal, \(\{X_1, X_2, \ldots, X_k\}\), into two vectors at the time \(k\): \(\{X_1, X_2, \ldots, X_k\}\) and \(\{X_{k+1}, X_{k+2}, \ldots, X_N\}\). The method then compares the signal variance of prediction errors before and after the time \(k\) in a predetermined time window. The AIC value at point \(i = k\) is calculated using equation (3) where \(N\) is the number of amplitudes of a digitized AE wave; \(X_i\) is an amplitude of a signal \((i = 1, 2, \ldots, N)\); \(\text{var}(X[1, k])\) is the variance of \(X\) between \(X_1\) and \(X_k\); and \(\text{var}(X[k + 1, N])\) is the variance of \(X\) between the \(X_{k+1}\) and \(X_N\). The ToA of an AE signal is the time at which the AIC function becomes a global minimum. In the two-step AIC process, at the first step the global minimum of AIC function is employed to obtain the first estimation of the ToA. In the second step, the time interval is narrowed down and focused on neighborhood of the first ToA estimation. The final value of the ToA of the signal is computed using the global minimum of recalculated AIC function.

\[
\text{AIC}_k = k \cdot \log\{\text{var}(X[1, k])\} + (N - k - 1) \cdot \log\{\text{var}(X[k + 1, N])\}
\]  

After calculating the ToAs of AE signals, the Simplex algorithm was used for source location. In this method, for any point in the medium an error \((E)\) was computed by comparing the calculated and observed arrival times. As such, an error space is created in which each point is an error associated with a point in the specimen. The point with the minimum error is the event location. Equation (4) is used to calculate the location error using the least squares method (\(L_2\) norm) where: \(E\) is the least squares error (\(L_2\) norm error);
\( t_i \) is the ToA obtained from the AIC picker; \( tt_i \) is the travel time from the location of interest to the \( i^{th} \) sensor; \( n \) is number of AE sensors; \( m \) is number of equations; and \( q \) is the degree of freedom. The error space is created by computing \( E \) for every point in the medium and the point with the minimal error is localized as the source location of the AE event.

\[
E = \sqrt{\sum_{m-q} \left[ (t_i - \frac{\sum t_i}{n}) - (tt_i - \frac{\sum tt_i}{n}) \right]^2}
\]  

(4)

The accuracy of source localization was assessed using the Euclidean Distance Error (EDE) in which the PLB procedure (Hsu–Nielsen source) is used to artificially generate AE signals at various locations of the sample. Source of AE activities was located and compared with the actual locations. The EDE was measured by calculating a distance between the actual source location and the estimated source location. Results showed around 92% accuracy of the source location approach in spiral specimens.

In addition to determining the crack initial penetration depth, the AE source location was also implemented to measure 3D shape and size of fracture process zone (FPZ) ahead of spiral crack tip. Results showed that unfortunately the source location didn’t have the sufficient spatial resolution to map out the accurate 3D geometry of FPZ in spiral specimens.


The pipeline of the framework used for automated DIA of spiral cracking patterns is illustrated in Fig. 7. It consists of various image processing techniques along with Convolutional Neural Networks (CNN) machine learning approach. In the first step, image skeletonization was applied in which spiral cracking image was reduced to one-pixel thick skeleton of crack path and the output image is converted into grayscale. Skeletonization was done to accelerate the analysis by providing a light skeleton for image processing instead of an otherwise computationally expensive analysis on the original image. After skeletonization, Gaussian blurring filter and Sobel method were applied to remove the inhomogeneous image background illuminations as well as edge detection of cracking patterns, respectively. This was followed by application of the Hough transform method to detect spiral shapes in the image. This approach is capable of detecting shapes in images even if those shapes are slightly broken or distorted [18].

Figure 7: Pipeline of the ML-based DIA framework

The CNN algorithm was implemented for noise reduction of skeletonized images. This algorithm is ideal for image processing tasks as it significantly reduces number of required weights for neurons in the model by using tiling regions, each with the same shared weights. The CNN autoencoder compresses spiral
cracking images in a series of convolutions and then reverse the process during the decoding step. The hidden layers of CNN perform convolutions generating a feature map which contributes to the input of the next layer. Each convolutional layer is followed by a Rectified Linear Unit (ReLU) layer. A regular feedforward neural network consisting of a couple of fully connected layers (+ReLUs) is added at the beginning of the stack and the final layer outputs the prediction using the Softmax activation function. To properly train the CNN model in addition to real spiral crack images, a large number of synthetic images of spiral patterns with various shapes and sizes were generated. Random artificial noise was added to both real and synthesized spiral images. Combination of real and synthesized images with and without artificial noise were used for training the CNN. Once noise was removed from images, segmentation technique was performed to separate and extract the spiral crack path from the original and followed by measuring the total length of spiral crack (L_{Spiral}). Finally, regression analysis was employed to determine spiral parameters: “A” and “b”.

5. RESULTS

Table 1 summarizes the spiral cracking parameters from the AE-DIA approach as well as the fracture energy (G_f) values obtained from compact tension [C(T)] test. Performing C(T) test for semi-solid adhesives is a challenging task due to soft nature of these materials. In this study, for asphalt materials, various temperatures ranging from 0°C to -30°C and loading rates (0.1-1 mm/min) were carefully explored. It was observed that C(T) tests performed at -20°C with loading rate of 0.2 mm/min were satisfactory.

<table>
<thead>
<tr>
<th>Material</th>
<th>Spiral Crack Parameters</th>
<th>C(T) Fracture Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>b (Deg)</td>
<td>A (mm)</td>
</tr>
<tr>
<td>PG58-16</td>
<td>0.0447</td>
<td>2.56</td>
</tr>
<tr>
<td>PG64-16</td>
<td>0.0443</td>
<td>2.54</td>
</tr>
<tr>
<td>PG64-22</td>
<td>0.0444</td>
<td>2.54</td>
</tr>
<tr>
<td>PG70-22</td>
<td>0.0429</td>
<td>2.46</td>
</tr>
<tr>
<td>PG58-28</td>
<td>0.0421</td>
<td>2.41</td>
</tr>
</tbody>
</table>

Experimental results showed that the E_{Spiral} values were positively correlated with fracture energies of asphalt materials meaning that the average amount of released AE energy per unit area of spiral cracks is higher for materials with higher resistance against cracking. Comparison of E_{Spiral} and G_f with spiral tightness, “b”, values demonstrated a different trend in which both E_{Spiral} and G_f were negatively correlated with “b”. This could be explained through understanding the mechanism behind formation and propagation of spiral cracks. It is hypothesized that spiral crack front selects its trajectory in a direction where it could maximize the stored strain energy release rate and also maintain Mode II crack intensity factor zero (i.e., K_{II}=0) [19]. As such, spiral cracks have a constant pitch angle meaning that the orientation of the crack front is constantly bending away from the instantaneous propagation direction. The spiral pitch angle is lower in high fracture resistance materials, because it is more difficult for the crack front to bend away from its instantaneous propagation direction in high fracture resistant materials. Lower spiral pitch angle (φ) results in lower spiral tightness parameter “b” (b = tan(φ)). The C(T) results showed dependency of G_f of
asphalt to its PG low temperature (PGLT) grade where asphalt materials with lower PGLT exhibited higher fracture energies.

Typical plot of AE results including cumulative AE hit counts and AE energy versus temperature is presented in Fig. 8. AE response of the material during spiral cracking showed four distinct regions: region#1 (pre-cracking region), region#2 (transition region from quasi-brittle to brittle state), region#3 (stable cracking region), and region#4 (fully cracked region). Magnitude of emitted AE energies are highest when spiral crack starts to propagate (at the start of region#2). As crack continues to grow, magnitude of emitted AE energies gradually tapers off until it reaches almost zero at the end of region#4 when spiral crack is fully developed. This can be linked to gradual reduction in stored strain energy (as the driving force behind crack propagation) when as the crack front advances from edge towards center of the sample. Fig. 4 schematically shows the 3D spiral cracking pattern with the gradual reduction of crack penetration depths. During the fracture process, stored strain energy in the specimen is consumed for creation of new fractured surfaces. At the end of region#1 (the pre-cracking region) the stored strain energy in the specimen is at highest level, leading to nucleation of spiral crack at the interface with a maximum penetration depth, $D_0$. As crack grows, strain energy is gradually diminished to create new fractured surfaces. As a result, crack penetration depth continuously decreases until it reaches almost zero at the center of sample. Visual inspection of fully grown 3D spiral showed that the gradual change in spiral crack depth is almost linear. Fig. 4 demonstrates the hypothetical unwrapped shape of 3D spiral crack in the form of a triangle.

Further analysis of AE signals was performed to investigate other important AE parameters such as: Signal duration time, Signal rise time (RT), Frequency content, Rise angle ($RA = Signal\ rise\ time/Signal\ peak\ amplitude$), and Average Frequency ($AF = AE\ hit\ counts/Signal\ duration\ time$). An interesting observation was that AE signals recorded at the beginning of spiral crack formation had low rise time, high amplitude values, and high frequency (low $RA$ & high $AF$) (this type of signals are usually observed in fracture Mode I), while signals recorded at lower temperatures exhibited longer duration time, longer rise times, low amplitude, and lower frequency (high $RA$ & low $AF$) (these types of signals are typically observed in fracture Mode II), see Fig. 8(c). These findings suggest that during the course of spiral cracking process, fracture mode changes from Mode I to Mode II. It was observed that the change in $AF$ and $RA$ values mostly occurred at temperatures near the glass transition temperature ($T_g$) of the material where material behavior gradually changes from quasi-brittle to a brittle state ($T_g$ values for asphalt materials utilized in the present study were in the range of -25$^\circ$C to -30$^\circ$C). As a result, it is hypothesized that change in the fracture mode
of spiral cracks happens at temperatures close to the glass transition temperature of the material (within the transition region (region #2)). More in-depth investigation is required to further explore this hypothesis.

6. CONCLUSIONS:
The present work investigates a novel approach for fracture characterization of soft adhesives using spiral cracking patterns. Five different hydrocarbon polymeric materials with different fracture characteristics were utilized in this study. An integrated experimental-computational framework coupling multi-sensor AE and DIA approaches was employed to determine spiral cracking parameters. An efficient image processing framework using various image processing and machine learning techniques such as CNN, skeletonization, segmentation, and regression were used in DIA for automatic analysis of spiral patterns images. A new parameter called the “Spiral Cracking Energy \( E_{\text{Spiral}} \)” was introduced to evaluate fracture performance of soft adhesives. Results showed that \( E_{\text{Spiral}} \) and \( C(T) \) fracture energy \( (G_f) \) values of asphalt material were negatively correlated with its spiral tightness parameter \( ("b") \). It was also observed that the \( E_{\text{Spiral}} \) values were positively correlated with \( C(T) \) fracture energies of asphalt materials. Analysis of AE signals recorded during the course of spiral cracking experiment revealed that at the beginning of cracking process signals exhibited low RA & high AF (usually observed in fracture Mode I) while later on at temperatures lower than glass transition temperature signals were mostly high RA & low AF (typically observed in fracture Mode II). It is hypothesized that change in fracture mode may happen at temperatures near the glass transition temperature \( (T_g) \) of the material at which material behavior changes from quasi-brittle to brittle. Given the current challenges of conducting conventional tests such as \( C(T) \) test to measure fracture properties of soft adhesives, results of this limited study suggest that use of spiral cracking pattern could be considered as a viable alternative for evaluating the fracture performance of such materials.

7. DATA AVAILABILITY
Some or all data that support the findings of this study are available from the corresponding author upon reasonable request.

8. ACKNOWLEDGMENTS
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9. REFERENCES:


