Traction-separation relationship for polymer-modified bitumen under Mode I loading: Double cantilever beam experiment with stereo digital image correlation

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A R T I C L E   I N F O

Article history:
Received 16 September 2017
Received in revised form 19 December 2017
Accepted 20 December 2017
Available online 21 December 2017

Keywords:
DCB fracture experiments
StereoDIC measurements
Asphalt shingle
Polymer modified bitumen
CZM traction-separation law

A B S T R A C T

The traction-separation law under Mode I loading for a polymer modified bitumen commonly used as an adhesive for 3–tab roofing shingles is quantified. Double cantilever experiments are performed at three different loading rates (0.03 mm/min, 0.3 mm/min and 3 mm/min). Load-displacement measurements are synchronized with speckle image acquisition and the data analyzed to determine (a) J-integral, (b) cohesive zone end opening displacement and (c) the crack opening displacement (COD) as a function of crack extension. Imaging is performed using two stereo vision systems equipped for capturing speckle images of the DCB specimen at two different magnifications with fields of view of (a) 14 mm × 12 mm and (b) 170 mm × 140 mm. The stereo vision system used to acquire data at higher magnification is mounted on a translation stage and focused on a region close to the crack tip as the crack propagated. This stereo vision system is used to measure the strain fields near the crack tip and for measurement of crack opening displacement (COD) at 1 mm behind the current crack tip for a range of crack extensions. The second stereo vision system is used to visualize the process zone size and measure the strain fields over larger fields of view ahead of the crack tip. Assessment of the fracture surface for lower loading rates (0.03 mm/min and 0.3 mm/min) revealed a ductile type fracture (rough surface due to void growth in the process zone). For the highest loading rate (3 mm/min), the fracture surface is typical of the type seen during brittle fracture (shiny surface with striations), with intermittent rapid crack propagation events followed by crack arrest along clearly visible arrest fronts.

Analysis of the data obtained for the two slower loading rates that exhibited ductile fracture throughout the entire growth process shows that the energy release rate $G_c^d = 70 \text{ J/m}^2$, and the final separation, $d_c^d = 250 \mu m$ for the slowest loading rate of 0.03 mm/min and, $G_c^b = 120 \text{ J/m}^2$, and the final separation, $d_c^b = 250 \mu m$ for 0.3 mm/min loading rate. For the highest loading rate, which exhibited nominally brittle fracture, the energy release rate $G_c^b = 10 \text{ J/m}^2$, and the final separation $d_c^b = 1.5 \mu m$. The peak cohesive stresses during ductile and brittle fracture are determined to be $\sigma_c^d = 0.7 \text{ MPa}$ and $\sigma_c^b = 9.6 \text{ MPa}$, respectively, for loading rates of 0.3 mm/min and 3 mm/min, respectively. Finally, COD at the onset of crack growth measured at 1.00 mm behind the moving crack tip for the loading rate of 0.3 mm/min, $\text{COD}_c^d \approx 0.30 \text{ mm}$, remaining constant for crack lengths, $a$, in the range 25 mm ≤ $a$ ≤ 165 mm.

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https://doi.org/10.1016/j.engfracmech.2017.12.031
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1. Introduction

1.1. The problem

The recent increase in hurricane activity, and the damage incurred during these intense storms, has highlighted the importance of residential and commercial building structural resiliency. A specific area of concern is the survivability of modern asphalt roofs when subjected to sustained hurricane level winds. Fig. 1a shows a schematic of a modern three-tab asphalt roof. For such roofing systems, the upper shingle is “attached” to the lower one by a self-sealing adhesive layer known as the “sealant strip”. The sealant strip material is a form of bitumen, an organic thermoplastic material widely used as a binding material in asphalt concrete, pavements and roofing shingles.

Asphalt roofing systems, such as the one shown during construction in Fig. 1a, can be purchased that are experimentally rated\(^1\) to withstand sustained 150 mph winds. However, there is a wealth of data today\(^{[1,2]}\) indicating that these asphalt roofing systems incur premature failure under sustained hurricane force winds that are much less than 150 mph. Careful review of both video recordings and first-hand observations of these failures provides prima facie evidence that the mechanisms of failure occur in the following order. First, the front edge of an asphalt shingle begins to slightly uplift after being exposed to hurricane force winds for up to 1 h. The uplift results in increasing pressure on the underside of the front portion of the shingle due to increased drag forces. Secondly, the process of increased pressure resulting in additional shingle uplift continues until the sealant layer slightly separates (typically near the free edge). Thirdly, further uplift occurs due to the reduced stiffness of the shingle-sealant structure causing increased pressure on the shingle. Fourthly, the process of continued separation and increased uplift cascades into catastrophic failure of the roofing system\(^{[5]}\). Fig. 1b shows the failed sealant strip and the loss of the upper shingle during high winds. Based on these observations, the mechanical response and separation resistance of the sealant strip has a fundamental role in the performance of asphalt shingle systems when exposed to high wind conditions.

1.2. Previous bitumen fracture studies

There have been several research studies related to the use of asphalt in pavements. Failure of the asphalt system occurred in the form of fracture that initiates between the aggregate and a thin layer of bitumen binding agent\(^{[6]}\). To perform fracture analysis of such thin bitumen films, several investigators have modeled the film using a cohesive zone\(^{[7–11]}\). To account for the viscoelastic nature of bitumen, Yong-Rak Kim et al.\(^{[10]}\) developed a viscoelastic cohesive zone model (CZM) that incorporated (a) a time dependent damage variable, (b) a characteristic length for the cohesive zone and (c) linear viscoelastic constitutive relation of the bitumen. In their work, the damage variable is assumed to have a power law evolution and the traction-separation relationship is obtained from a series of tensile experiments on asphalt binder that is sandwiched between two metal plates and loaded at constant rate in displacement control.\(^2\)

In related work, Harvey et al.\(^{[11]}\) performed tensile experiments on bitumen butt joints and double cantilever beam (DCB) specimens to extract the CZM traction-separation law at various temperatures (−30°C to 20°C) and strain rates. The authors determined a temperature compensated strain rate based on time-temperature superposition and the Arrhenius relationship to compare fracture energy values for bitumen films at different temperatures. The authors observed qualitatively similar trends in the energy release rate with strain rate for both the butt joint and DCB samples, with the DCB samples yielding a lower energy release rate for a given strain rate. Of particular importance for this work are their observations that (a) a transition from ductile to brittle behavior occurs with increasing strain rate during loading, (b) the energy release rate (G) in the brittle region is independent of strain rate, (c) a normalized energy release rate (G/2h; 2 h is the thickness of the adhesive layer) follows a power law relationship with strain rate and (d) the estimated failure strains in the ductile fracture regime and the brittle fracture regime are individually independent of the strain rate, with the brittle fracture strain approximately two orders of magnitude less than the strain during ductile fracture. Based on these experimental observations, Porto et al.\(^{[9]}\) implemented a finite element formulation with a CZM to represent the bitumen layer to simulate bitumen fracture. In their studies, the authors assumed (a) a triangular traction-separation law that increases linearly to a maximum at separation and (b) a linear-exponential law for ductile fracture.

1.3. Traction-separation laws and CZMs: fundamentals and recent applications

As noted above, several investigators have employed a CZM to represent the behavior of thin bitumen layers. The foundational concepts for development of cohesive zone models (CZMs) for adhesive layers such as the bitumen sealant strips are first introduced in the independent work of Dugdale\(^{[13]}\) and Barenblatt\(^{[14]}\). After the pioneering work of Needleman\(^{[15]}\) and Knauss\(^{[16]}\) using a CZM to describe the process of void nucleation and decohesion in an isotropically hardening, elastic-viscoelastic plastic matrix, CZMs have been extensively employed by researchers performing a variety of analyses including (a) determining the fracture strength of adhesive materials\(^{[17,18]}\), (b) interface fracture studies for bi-material corners\(^{[19]}\), fiber reinforced composites\(^{[20,21]}\) and (c) for static as well as dynamic crack propagation\(^{[22]}\). The success of CZMs for

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1. Ratings are based on experiments that have met ASTM standards such as ASTM D7158\(^{[3]}\) or ASTM D3161\(^{[4]}\).
2. The authors calculated the experimental traction by assuming constant damage throughout the cross-sectional area of the binder material, though such conditions have been observed to be difficult to obtain\(^{[12]}\).
Fracture analysis is, in part, because of its effectiveness in modeling nonlinear fracture when the failure process zone size is much larger than geometric dimensions, particularly when the process zone size is much larger than the transverse dimensions of the fracture specimen. An additional reason for its broad use is the relative ease with which it can be implemented in a finite element code, resulting in its inclusion in commercial codes such as ABAQUS.

To employ a CZM in fracture analysis requires that the traction-separation relationship for the material be known. As noted by Park et al., there are several displacement-based and potential-based traction-separation laws in existence, each having specific advantages and limitations. There are two established approaches for extracting traction-separation relationships for a cohesive interface: a direct method and an iterative method. In the direct method, the traction-separation relationship is obtained by simultaneous measurement of energy release rate (J-integral) and the “end-opening displacement”. The traction-separation relation can be extracted by taking the first derivative of the J-integral with respect to the end opening displacement. In the iterative method, the cohesive zone parameters (cohesive strength, critical separation at which damage initiates, separation at fracture, exponential softening factor, etc.) for an assumed shape of the traction-separation law are obtained by performing numerical simulations (e.g., finite element analyses) with an assumed traction-separation law and iteratively comparing the numerical and experimental results until a satisfactory match of the cohesive zone size, global load-displacement curve and crack opening displacement are achieved.

Using a direct method, the traction-separation relation can be extracted with relative ease compared to the iterative method. However, accurate measurements for both the J-integral and the opening displacement with adequate resolution are essential requirements. Sørensen et al. employed the direct method for experimental determination of the traction-separation law for unidirectional carbon/epoxy composite splitting and polyurethane adhesive and steel adherend using a DCB loaded with pure bending moment. In their work, the authors observed significant difference in the shape of the traction-separation law at different loading rates. Recently, Yong Zhu et al. used the direct method for extracting the traction-separation of polyurea/steel interface undergoing Mode I and Mode II fracture loading conditions at various loading rates. In their work, the authors employed digital imaging with two-dimensional digital image correlation (2D-DIC) to measure the opening displacement, the rotation of the adherend above and below the crack tip and the load line displacement; motion measurements are relatively coarse, with displacement resolution on the order of 2 μm. Employing an end loaded split (ELS) specimen, Chenglin Wu et al. obtained a mixed mode traction-separation law for a silicon/epoxy interface using infrared crack opening interferometry to measure normal opening displacement and digital image correlation to measure both the normal as well as the tangential crack opening displacement. A comparison of the direct and iterative methods for traction-separation law for a silicon/epoxy interface is given by Gowrishankar et al.
1.4. Enclosed experimental study for bitumen

Since modeling the fracture process described in Section 1.1 for an asphalt shingle roofing system is key to understanding
the mechanism of failure during real world loading conditions, and such modeling requires the separation response of
the bitumen sealant strip, this paper reports on our measurement of the traction-separation relationship for a polymer modified
bitumen (PMB) used as a self-sealant adhesive in 3-tab shingles. To the best of the author’s knowledge, traction–separation
relationship for a self-sealing adhesive commonly employed in 3-tab shingles (PMBs) is not reported in the open literature.3
The paper also reports the crack opening displacement (COD) measured 1 mm ahead of the crack tip for 0.3 mm/min loading
rate. The paper is organized as follows. Section 2 describes the experimental methods and materials. Section 3 presents
the experimental results. Section 4 gives a discussion of the findings. Section 5 provides concluding remarks.

2. Experimental methods and materials

2.1. Bitumen material

The material used in our experimental program is a polymer modified bitumen extracted from sealant layer in Supreme®
AR 25415 3-tab shingles manufactured by Owens Corning. The self-sealing adhesive material contains Styrene-Butadiene-
Styrene block copolymer (5–10 wt%) that forms a polymer network within the bitumen [30]. The specific amounts and poly-
mer structure details for the additive used in the mixing process for the PMB sealant layer are not provided by the
manufacturer.

2.2. Sample preparation

To obtain the CZM traction–separation relationship for the bitumen cohesive zone model, the Double Cantilever Beam
(DCB) specimen shown in Fig. 2 is used in the fracture experiments. The sample dimensions are chosen as per the ASTM
D3433–99–13 standard [31]. In this study, two essentially rigid aluminum plates having nominal dimensions with a length
of 365 mm, width of 25.4 mm and thickness of 12.7 mm are used as adherends joined by a layer of the PMB adhesive. Before
applying the adhesive, the adherend faying surfaces are treated as follows. First, coarse grit sand paper (P50) is used to create
a rough surface on both the adherends. Secondly, the surfaces are cleaned in water and acetone and air dried. After the sur-
faces have dried, the adherends are placed on top of a heating plate and heated to 150 °C. Once the adherends reached steady
state temperature, the PMB sealant material extracted from a shingle sealant in the form of small solid flakes are distributed
evenly on the faying surfaces of both the adherends. Additional sealant material is added to ensure that a given thickness of
the adhesive can be obtained. Thirdly, once the sealant is completely melted on the adherends, the adherends are allowed
to cool to a temperature of 40 °C; at this temperature the sealant is in its rubbery state. Fourthly, shims of required thickness
are placed on both ends of the bottom adherend (see Fig. 2) and the adherends are joined together, with Teflon tape placed
on both the top and bottom adherend surfaces to form a pre-crack of length a0. The sample is then clamped in a fixture with
low applied pressure between the top and bottom adherends and heated to 150 °C until the sealant on the top and bottom
adherends completely melts and bond to both surfaces, forming an adhesive layer of uniform thickness4 between the adher-
ends. The excess sealant that squeezes out of the adherends is removed and collected for future use. Dimensions for the DCB
specimen components are measured at six different locations. Table 1 shows the measurement of dimensions for the DCB sam-
ple, with all measurements obtained using a Vernier caliper having a least count of 0.025 mm (0.001 in.).

2.3. Sample loading and data acquisition

Each DCB specimen is loaded in displacement control using an Instron 5566 test frame with a 5 kN load cell. A schematic
of the experimental configuration is shown in Fig. 3. As shown in Fig. 3, the DCB specimen is attached to the upper and lower
pin grips using 3 mm diameter pins. Vertical loading is applied to the DCB sample by displacing the top grip at a constant
displacement rate. Three different loading rates (0.03, 0.3 and 3 mm/min) are selected in this study to provide quantitative
data regarding the effect of loading rate on both fracture behavior and the traction–separation relationship for the adhesive.

Full field displacement and strain measurements on the side surface of the DCB are obtained at two different magnifica-
tions using two separate, but synchronized, stereo vision systems. Synchronized recording of both the stereo image pairs and
the load cell signal is performed using a National Instrument data acquisition system and VIC-Snap software [32]. The high
magnification stereo vision system shown in Fig. 3 consists of two 9 MP CCD PointGrey cameras and a pair of Nikon 50 mm
lens with 40 mm extension tubes. The 9 MP CCD camera sensor has 3376 × 2704 array of pixels with a physical sensor size of
3.69 μm × 3.69 μm. The imaging system is mounted on a translation stage and configured to focus on a region close to the

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3 The viscoelastic constitutive relations of the shingle, sealant and fracture parameters of the adhesive (sealant) are important properties required as input to
the model. The authors have measured and reported recently the viscoelastic creep compliance of shingle and sealant material from creep test at different
temperature using dynamic mechanical analyzer [29].

4 Both aluminum adherends are machined to achieve a nominally planar surface with variability of ±/− 50.8 μm over the 256 mm length. The two shims,
located at opposite ends of the DCB specimen, are used to obtain consistent thickness of the adhesive along the length of the DCB.
crack tip with a field of view of 14 mm × 12 mm. The translation stage provides additional freedom to move the stereo system parallel to the DCB side surface and continuously monitor the crack tip fields for a moving crack. This allows the measurement of crack opening displacement for different amounts of crack extension levels. In this work, the digital magnification factor for the high magnification stereo system is 4.15 µm on the object per pixel. To acquire accurate deformations with the high magnification imaging system, the side surface of the DCB sample is lightly coated with flat white paint and Xerox toner powder is applied to the surface while the paint is still wet to ensure proper adhesion of the speckle pattern. Once the paint is dried, compressed air is used to blow away any loosely bonded toner powder. This process resulted in a random pattern with an average speckle size of 15 µm. Fig. 4 shows both the as-applied pattern and its gray-scale intensity distribution.

The low magnification stereo vision system shown in Fig. 3 is used to record the speckle images on the opposite side of the DCB specimen (opposite to the side viewed by the high magnification stereo system) with a field of view of 170 mm × 140 mm. The low magnification system employs two 5 MP low noise CMOS Point Grey cameras and two 28 mm Nikons lens. The 5 MP CMOS camera sensor has a 2448 × 2048 array of pixels with physical size of 3.45 µm for each pixel. Digital magnification for the secondary stereo system is 70 µm on the object/pixel. The random speckle pattern for the low magnification system is produced by applying a thin coat of flat white paint followed by over-spraying flat black paint from a compressed air paint can. The resulting random speckle pattern has an average size of 0.25 mm. The low magnification system’s speckle pattern with grayscale intensity distribution are shown in Fig. 5.

The low magnification system provides overall visualization to (a) quantify the displacement and strain field in the large process zone ahead of the crack tip and (b) obtain accurate measurement of the load line displacement applied to the specimen. The high magnification system is employed for measurement of both the CZM opening displacement and the COD with sufficient resolution. The displacement resolution achieved in the current system is on the order of 40 nm. Fig. 6 shows a photograph of the experimental setup.

Since experiments are performed at three different displacement rates, synchronized stereo images are acquired by both systems at the frame rates shown in Table 2.

### Table 1
Measurement of DCB sample dimensions.

<table>
<thead>
<tr>
<th>Distance of measurement location from crack tip (mm)</th>
<th>Thickness of DCB sample: H (mm)</th>
<th>Width of DCB sample: b (mm)</th>
<th>Thickness of top adherend: ( h_{d1} ) (mm)</th>
<th>Thickness of bottom adherend: ( h_{d2} ) (mm)</th>
<th>Thickness of adhesive: ( h_a = H - h_{d1} - h_{d2} ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>27.025</td>
<td>25.500</td>
<td>12.725</td>
<td>12.725</td>
<td>1.575</td>
</tr>
<tr>
<td>50</td>
<td>27.050</td>
<td>25.500</td>
<td>12.750</td>
<td>12.725</td>
<td>1.575</td>
</tr>
<tr>
<td>100</td>
<td>27.050</td>
<td>25.475</td>
<td>12.725</td>
<td>12.750</td>
<td>1.575</td>
</tr>
<tr>
<td>150</td>
<td>27.025</td>
<td>25.425</td>
<td>12.750</td>
<td>12.750</td>
<td>1.575</td>
</tr>
<tr>
<td>200</td>
<td>27.025</td>
<td>25.425</td>
<td>12.750</td>
<td>12.725</td>
<td>1.550</td>
</tr>
<tr>
<td>250</td>
<td>27.050</td>
<td>25.425</td>
<td>12.750</td>
<td>12.750</td>
<td>1.550</td>
</tr>
</tbody>
</table>

The J integral, containing the traction-separation relation, can be calculated by taking the contour integral around the cohesive zone (along the dotted line in Fig. 8). The integral is given in Eq. (1) as

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5. The working distance of high magnification system is less than 60 mm. Hence, it is difficult to set up both systems on the same side of the DCB as the high magnification system blocked the field of view of the low magnification system.

6. Actuator displacement measurements include the effect of machine compliance, which made it difficult to interpret the displacement data during data reduction process.
Fig. 3. Schematic of the DCB experimental setup.

Fig. 4. (a) Random speckle pattern for high magnification stereo system, (b) gray-scale intensity distribution for the random pattern.
Fig. 5. (a) Random speckle pattern for low magnification stereo system, (b) gray-scale intensity distribution for the random pattern.

Fig. 6. Photograph of the DCB experimental set up. High magnification system imaging system mounted to translation stage is clearly visible. Low magnification system is partially obscured by specimen and loading frame components.

Table 2
Stereo camera recording speed for different loading rates.

<table>
<thead>
<tr>
<th>Displacement rate (mm/min)</th>
<th>Camera frame rate (frames/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.00</td>
<td>5.0</td>
</tr>
<tr>
<td>0.30</td>
<td>1.0</td>
</tr>
<tr>
<td>0.03</td>
<td>0.1</td>
</tr>
</tbody>
</table>
\[
J = \int_0^{\delta_n} \sigma(\delta) d\delta, \tag{1}
\]

where \(\delta_n\) is the normal opening displacement; \(\sigma(\delta)\) is the traction in the cohesive zone at a normal separation of \(\delta\). Differentiating the \(J\) integral expression in Eq. (1) with respect to \(\delta_n\) gives the traction-separation relation as,

\[
\frac{\partial J}{\partial \delta_n} = \sigma(\delta_n). \tag{2}
\]

For the DCB specimen shown in Figs. 2 and 3 that is subjected to nominally Mode I load, a closed form expression for the \(J\)-integral has been developed previously [33] for longer cracks using modified beam theory assumptions. Considering the effect of finite rotation of the adherends at the crack tip location, the expression is written in the following form;

\[
J = 12\left(\frac{Pa_0}{Edh_d}\right)^2 + P(w'_1 - w'_2), \tag{3}
\]

where \(P\) is the applied load per unit width of the DCB; \(a_0\) is the crack length; \(E_d\) (71 GPa) is Young’s modulus for the aluminum adherend; \(h_d\) is the thickness of the adherend; \(w'_1\) and \(w'_2\) are the in-plane rotations of the top and bottom adherends at the crack tip location relative to the specified x-y coordinate system in Fig. 8. Local in-plane rotations on the surface of the adherend are calculated from DIC by spectral decomposition of the two-dimensional displacement gradient tensor on the surface (Eq. (4)).

\[
|F| = |R| |U|, \tag{4}
\]

where \(F\) is the two-dimensional displacement gradient tensor on the surface; \(R\) is the local in-plane rotation matrix; \(U\) is the two-dimensional right stretch tensor. The displacement gradient tensor on the surface is calculated from the projected displacement components onto the surface. The calculated local rotations are shown in Fig. 9b. It is noted that the local rotations calculated at points along a line element perpendicular to the neutral surface of the top and bottom adherends are observed to be constant to within measurement error of \(6.2 \times 10^{-5}\) rad (one standard deviation) for all load levels. Hence, the overall rotation of the top and bottom adherends, \(w'_1\) and \(w'_2\), at each displacement are obtained by averaging the rotations of a line element perpendicular to the ‘x’ axis and passing through points 1 and 2, as shown in Fig. 8. A distinct advantage of this approach is that noise in the slope measurements is reduced.

As noted by Li et al. [34], Eq. (3) is generally appropriate when the crack length is relatively long (e.g., \(a/h_d > 10\)). Since the crack is relatively short in this study (\(a/h_d = 2\)), it is necessary to confirm that predictions using Eq. (3) are accurate for this application. The most direct approach for validation is to compare the load-line displacement predictions using beam theory and the experimental DIC measurements, with agreement indicating that the beam theory predictions via Eq. (3) are reliable. Assuming root rotation occurs at the crack tip, an estimate for the beam theory prediction of load line displacement can be written in the form;

\[
\Delta = a_0(w'_1 - w'_2) + (v_2 - v_1) + \frac{8P(a_0)^3}{Edh_d^2}, \tag{5}
\]

where \(\Delta\) is the load line displacement; \(v_1\) and \(v_2\) are the vertical displacements of points 1 and 2, respectively; “\(a_0\)” is the crack length or distance between load line and crack tip (see Fig. 8). Figs. 7a and 7b compare \(\Delta\) predictions based on Eq. (5) to direct DIC measurements for all three loading rates. As shown in Figs. 7a and 7b, there is excellent agreement in these independent measurements, confirming for this application, where \(E_d/E_a > 100\) with \(E_a\) representing the modulus of the adhesive material, that the use of Eq. (3) is appropriate.

Also shown schematically in the Inset to Fig. 8 is a local crack tip coordinate system, \((\zeta, \delta)\). For the purposes of estimating COD, the coordinate system, moves with the crack tip as the crack propagates. Since the release of energy during the fracture process occurs in the process zone ahead of the crack tip, where various irreversible processes occur (e.g., void nucleation, ligament formation and inelastic deformation), the resisting stresses in the deforming material ahead of the crack tip is replaced by an equivalent traction acting to close the crack; this is shown schematically in the inset to Fig. 8.

Inspection of Eqs. (1)(3) shows that the \(J\)-integral formula in Eq. (3) is sufficient to determine the traction-separation law for the material. Furthermore, the key parameters required to calculate \(J\), which includes the crack length, load, cohesive zone opening displacement and in-plane rotations of the two adherends, can be measured experimentally (see Section 2). Based on this discussion, the authors employed the direct approach to develop the traction-separation law for the bitumen material system.

It is important to note that the \(J\)-integral is path independent for a stationary crack. Thus, in the direct extraction of the traction-separation law, measurement of opening displacement and the \(J\) integral are performed for the DCB specimen with a stationary crack. As the CZM opening displacement increases, the cohesive zone length increases with an increase in \(J\)-integral (see Fig. 8 schematic). Once the cohesive zone is fully developed, the \(J\) integral reaches a steady state value \(J_{ss}\), which is equal to the area under the traction-separation curve. In this study, the cohesive zone opening displacement in the y-direction, \(\delta_n\), is calculated by finding the relative displacement components of points 3 and 4, which are the points...
0.78 mm above and below the crack tip location, respectively, and shown schematically in the Inset to Fig. 8. It is noted that the investigators also computed the Crack Opening Displacement (COD) at 1.00 mm behind the crack tip using vertical displacements at points which are 0.78 mm above and below the moving crack tip (points 5 and 6 in Fig. 8).

Fig. 7a. Load versus load line displacement from beam theory and DIC for loading rates of 0.03 mm/min and 0.3 mm/min.

Fig. 7b. Load versus load line displacement from beam theory and DIC for loading rate of 3 mm/min.

Fig. 8. Schematic of the fracture process zone ahead of crack tip.
3. Experimental results

Full-field, three-dimensional displacements and surface rotations are measured on both the front and back surfaces simultaneously using the Point Grey stereo image pairs\footnote{It must be emphasized that stereovision is essential for accurate measurements in this case due to the large out-of-plane cupping response of the bitumen layer and the relatively small field of view required to accurately measure the CZM crack opening displacement, $\delta_{\text{CZM}}$, near the initial crack tip. Errors > 50% of the measured value are observed when using a single camera system. See [35–37] for additional details regarding the effects of out-of-plane displacement when using a single camera with 2D-DIC to extract measurements.} and commercial software, VIC-3D\footnote{For the x-y coordinate system shown in Fig. 8, clockwise rotation of the adherend corresponds to positive slope. Thus, for the configuration shown in Fig. 8, $w' > 0$ and $w_2 < 0$.}. In all of the stereo image analyses, the following StereoDIC image analysis parameters are used to obtain the displacement measurements:

- subset size of $25 \times 25$ pixels$^2$.
- step size of 7 pixels between subset centers.
- Gaussian weighted filter size of $9 \times 9$ [36].

For a loading rate of 0.30 mm/s, at load $P \approx 380$ N and $t = 304$ s that corresponds to an instant near maximum load, Figs. 9a and 9b show the full-field opening mode displacement field and the in-plane rotations for the DCB specimen with crack length, $a_0 = 25.4$ mm respectively. Similarly, but with a different scale for the contours due to the large difference in response, for a loading rate of 3 mm/min, a load $P \approx 310$ N and time $t = 20$ s which again corresponds to an instant near the initial maximum loading at this rate, Figs. 10a and 10b show the full-field opening mode displacement field and the in-plane rotations, respectively, for the highest loading rate, 3 mm/min. As shown in Figs. 9 and 10, there are large gradients in both variables. Thus, care must be taken to identify the crack tip location to measure the adherend slopes $w_1^0$ and $w_2^0$ and the opening mode displacement, $\delta_n = v_4 - v_3$, at each time and corresponding load. In this study, the crack tip location is identified through visual inspection by marking the end of the Teflon layer. Sensitivity of the $J$ integral to error in locating the exact position of the crack tip is investigated by comparing $J$ integral values corresponding to crack tip locations which are $+/-.0.5$ mm from the current position. Figs. 11a and 11b show that the $J$ integral values change only by a small fraction (< 5%) due to slight errors in identifying the crack tip location.

Figs. 12–14 show the calculated $J$-integral versus $\delta_n$ for loading rates 0.03 mm/min, 0.3 mm/min and 3 mm/min, respectively, along with a best fit third order polynomial fit. Inspection of Figs. 12–14 indicate that the $J$-integral reaches steady
Fig. 10. Full field (a) normal opening displacement and (b) in-plane rotations of DCB sample for a stationary crack of length 25.4 mm at a loading rate of 3 mm/min.

Fig. 11a. Sensitivity of $J$ integral values on crack tip location for 0.03 mm/min and 0.3 mm/min loading rate.

Fig. 11b. Sensitivity of $J$ integral values on crack tip location for 3 mm/min loading rate.
state near the end of the experiment. At the end of the experiment, comparison of the J-integral values for the two loading rates shows that there is a 12X decrease with increasing loading rate (120 J/m² for 0.3 mm/min and 10 J/m² for 3.0 mm/min).

Using derivatives of the best-fit third order polynomial fit to the J-$\delta_n$ data shown in Figs. 12–14 (continuous line) to obtain the traction, $\sigma(\delta_n)$. Figs. 15–17 show the resulting traction-separation relationship for bitumen for 0.03 mm/min, 0.3 mm/min and 3 mm/min loading rates, respectively. What is most obvious when reviewing Figs. 15–17 is the distinct difference in shape of the traction-separation laws when bitumen is subjected to a different load rate. For the higher loading rates, the results are convex shaped traction-separation law. For the highest loading rate, the maximum traction occurs for an extremely small displacement, $\delta_n \approx 700$ nm. The shape for the traction-separation law for the highest loading rate is similar to the form obtained by Zhu et al. [26] for a polyuría/steel interface undergoing nominally Mode I loading. For the lowest loading
rate (0.03 mm/min), the results closely approximate an idealized triangular form, with the peak traction occurring near the beginning of the loading for extremely small values of \( \delta_n \). The form of this traction-separation law for the lower loading rate is close to a linear softening model commonly used to represent a CZM in finite element analysis [38]. As shown in Figs. 15–17, the critical end opening displacement at the point of crack growth, \( \delta_c \), for the two lower loading rates is \( \approx 0.25 \text{ mm} \), which are over two orders of magnitude larger than \( \delta_c \approx 0.0015 \text{ mm} \) for the highest loading rate.

### 4. Discussion

Inspection of the results in Figs. 12 and 14 show that the J-integral and \( \delta_c \) at failure are 70 J/m² and 0.25 mm, respectively, for the lowest loading rate (0.03 mm/min). The J integral value for 0.03 mm/min loading rate is 40% less than the values obtained for 0.3 mm/min loading rate with similar \( \delta_c \). Though the values are similar for both lower loading rates, there is a remarkable difference in the shape of the traction-separation law between the 0.30 mm/min and 0.03 mm/min loading rates. Since the cubic polynomial fit to the J–\( \delta_n \) in Fig. 12 does not appear to reflect some of the trends in the measurements, additional analysis of the data may be required to improve confidence in the results.

Relative to previous work, it is noted that the bitumen traction-separation law for both slow and fast rates of loading can be viewed as having “finite traction” at zero separation [26]. This form is similar to the traction-separation relationship used in numerical simulations by Xu and Needleman [39]. From a physical standpoint, the traction at zero separation should be zero. The “finite traction” could be due to either (a) insufficient resolution in the opening displacement in a portion of the traction-separation relation which is very stiff and/or (b) insufficient temporal resolution to capture the initial response of the material. Since the resolution of the DIC method is on the order of 40 nm, it seems more likely that the temporal resolution must be increased. Fortunately, advances in high speed imaging ensure that we can obtain very high temporal resolution during this early transient response region.9

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9 Experiments using a high-speed stereo imaging system (e.g. Photron SA-2X) that has very good spatial resolution while acquiring images at 20 kHz or higher are being planned to obtain data during the early transient stage and determine whether temporal or spatial resolution are the source of the initial finite traction.
The significant difference in cohesive zone parameters for loading rates ≤ 0.30 mm/min and 3 mm/min led the investigators to seek plausible reasons for these findings. The most obvious source for the change in bitumen response is the presence of different fracture processes that occurred in these cases. As shown in Fig. 18a, the fracture surfaces for lower loading rates have the appearance expected for ductile separation processes. For loading rates ≤ 0.30 mm/min, the fracture surfaces are rough, with the entire thickness of the bitumen layer involved in the process. Inspection of the high magnification images of the crack tip region shows the presence of void growth occurring just ahead of the crack tip for the slower loading rates, with connecting ligaments being deformed until separation occurred (see Fig. 19).

When the loading rate reaches 3.0 mm/min, as shown most clearly in Fig. 18b the fracture surface is nearly flat, as expected when nominally brittle separation occurs. The fracture surface shows evidence of striations and crack arrest fronts as the flaw extended. For this higher loading rate, the investigators observed steady crack growth, followed by periods of fast fracture and crack arrest. The process is visible as discrete jumps in the load vs cross head displacement plot (see Fig. 20). Conversely, for slow loading rates, the load vs cross head displacement data shows a gradual reduction in the load with increasing displacement.

Another indication that there is a clear change in the fracture processes is the process zone size. Using the transverse strain magnitude as a metric for process zone size, Fig. 21 compares the full-field distributions for εyy for both loading rates ≤ 0.30 mm/min and 3 mm/min. As shown in Fig. 21, not only is the process zone size for a loading rate of 0.30 mm/min far larger but also the strain levels are an order of magnitude larger for lower loading rates. In addition, the shape of the process zone for lower load rates is similar to the strip yield plastic zone model of Dugdale and Barenblatt [13,14]. A final indicator that lower loading rates correspond to ductile separation processes is the measured COD during crack extension. As shown in Fig. 22, the measured COD ≤ 0.30 mm is essentially constant as the crack extends in the bitumen layer, an observation that is consistent with conditions typically associated with steady state ductile crack growth [40–44].

The initial high compliance in the load vs cross head displacement in Fig. 20 is the result of slackness in the pin connections of the DCB. The load vs displacement obtained from the DIC measurement shows an initial linear load displacement relation as predicted by the beam theory (Figs. 7a and 7b). Since the DIC data is not available after the crack growth for the high rate of loading (3 mm/min), the cross-head displacement is used Fig. 20 to show the crack growth and arrest phenomena.
It is noted that previous studies for pure bitumen [8,9] have observed (a) a power law increase in the energy release rate with strain rate in the ductile region, (b) the energy release rate and end opening displacement at fracture for brittle fracture are independent of loading rate and (c) the energy release rate depends on the adhesive layer thickness. Though the trends shown in this work for PMB appear to be qualitatively consistent with findings (a) and (b), additional experiments for a larger range of loading rate and PMB specimen thicknesses are needed for quantitative comparisons to previous research results.

Since separation of bitumen materials has been shown to be a function of strain rate [9,11], it is of interest to estimate the average strain rate at the crack tip. The average crack tip strain rate prior to the onset of crack extension in the adhesive is determined by dividing the opening displacement between points 3 and 4 (see Fig. 8) by the adhesive thickness at each time. The temporal derivative of a least square polynomial fit to the strain-time data is used to obtain the time-varying strain rate. Fig. 23 shows the experimental average crack tip strain rate data for all three loading rates up to crack extension. For a loading rate of 3 mm/min, as shown in Fig. 21b and Fig. 23 crack extension occurs after about 20 s for an average strain of 700 με and an average strain rate of 220 με/s. For a loading rate of 0.3 mm/min, as shown in Figs. 21(a) and 23 crack extension initiates at ≈304 s when the strain reached ≈60,000 με and the strain rate rises to ≈1000 με/s. For a loading rate of 0.03 mm/min, crack extension occurs at ≈2250 s at even higher strain and a strain rate of ≈320 με/s. Though such results are nominally consistent with the underlying viscoelastic nature of bitumen (i.e. rapid loading impedes viscoelastic deformations), what is most compelling is the sudden, dynamic, brittle fracture of the bitumen when subjected to a relatively low average strain in the crack tip region. In this regard, inspection of the traction-separation law in Fig. 17 for the highest displacement rate indicates that

11 As shown in Fig. 21, near the onset of crack extension the average crack tip strain is a reasonable estimator for local conditions since the StereoDIC measurements showed that the εyy field is reasonably uniform in this region. Damage such as shown in Fig. 19 results in relatively uniform crack tip strains much earlier in the loading process, so that the average crack tip strain metric is quite reasonable for estimating local conditions, especially in the regions where rapid increases in strain rate are present.
Fig. 21. Normal strain in the transverse direction in the cohesive zone at the onset of crack extension for (a) ductile fracture corresponding to 0.3 mm/min loading rate and for (b) brittle fracture process corresponding to loading rate of 3 mm/min.

Fig. 22. Crack opening displacement versus crack extension for at loading rate of 0.3 mm/min.

Fig. 23. Average crack tip strain rate in the adhesive for three loading rates.
the stresses in the crack tip region are quite high, suggesting that separation in this case may be due to the large stresses incurred during rapid loading.

5. Conclusions

The traction-separation relationships for polymer modified bitumen (PMB) used as a self-sealing adhesive for commonly used 3-tab asphalt shingles are obtained at room temperature (25 °C) from DCB experiments performed at three different loading rates. Results clearly show that traction-separation parameters (energy release rate, end opening displacement, peak cohesive stress) are a strong function of loading rate and the associated crack tip strain rate. This rate dependence of the fracture process in PMB is expected due to its viscoelastic nature at room temperature.

The strong dependence of the traction-separation parameters on far-field displacement rate shown in Table 3 is consistent with observations of the fracture processes in the material; lower displacement rates result in ductile separation after extensive straining has occurred. Higher displacement rate results in conditions that induce brittle separation of the material.

Acknowledgements

Financial support provided by NASA through the NASA Cooperative Agreement NNX13AD43A is gratefully acknowledged. In addition, the support provided by the Center for Mechanics, Materials and NDE at the University of South Carolina is deeply appreciated.

References


Table 3

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<tr>
<th>Load rate (mm/min)</th>
<th>J-integral (J/m$^2$)</th>
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