USE OF THE TAPERED DOUBLE-CANTILEVER-BEAM GEOMETRY FOR FRACTURE TOUGHNESS MEASUREMENTS AND ITS APPLICATION TO THE QUANTIFICATION OF SELF-HEALING

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ABSTRACT

A decade ago a new class of materials was demonstrated in the form of self-healing polymer composites [1], which posses the inherent functionality to recover toughness following the occurrence of damage. In addition to the work of White *et al*. [1] serving as the seminal paper to demonstrate the successful implementation of autonomous function in a material, that work also introduced the necessity for rigorous quantification of healing efficiency defined as the ratio of healed to virgin fracture toughness, $\eta = K_{\mathrm{IC\ healed}}/K_{\mathrm{IC\ virgin}}$ [2]. Early work employed a Tapered Double-Cantilever Beam (TDCB) fracture geometry where the crack length independence simplified calculation of healing efficiency to the ratio of healed to virgin critical loads, $\eta = P_{\mathrm{C\ healed}}/P_{\mathrm{C\ virgin}}$ [2]. In the intervening years this work has spawned an entire new field of research, encompassing a growing array of both the mechanisms of damage that provide the stimulus for *in situ* self-healing to occur and the strategies by which *in situ* self-healing is achieved. The preponderance of work in the field continues to focus on damage from mechanical loading and has employed various fracture geometries. The current work investigates the application of four common fracture test geometries—the TDCB, Compact Tension (CT), Single Edge Notch Bend (SENB) and Single Edge Notch Tension (SENT) geometries—to the measurement of healing efficiency. While the crack length independence of the TDCB negates the need to measure the virgin and healed crack lengths, the importance of accurately determining the measurement of the virgin and healed crack lengths when employing the CT, SENB or SENT geometries to calculate healing efficiencies is pointed out [3]

In addition to the geometry parameters and measurement of the critical load for crack extension P_C needed for the TDCB geometry, calculation of K_{IC} with the CT, SENB or SENT geometries require accurate knowledge of the initial crack length a to solve for the fracture toughness. The TDCB, CT, SENB and SENT geometries all exhibit a dependence on crack length where the TDCB does not, and that dependence is quite strong varying by approximately an order of magnitude for the range of crack lengths. As the field of self-healing has grown, a variety of fracture specimens—to included TDCB, CT, SENB and SENT geometries—have been applied to quantifying the healing efficiency. A number of recent manuscripts in the literature that employ specimens such as the CT, SENB or SENT fail to fully solve for healing efficiency by simply taking the ratio of critical loads, thus making the implicit assumption that $a_{healed} = a_{virgin}$. A key point to this paper is to question this assumption. The virgin crack length a_{virgin} is determined by the propagation of the precrack, which depends on the virgin fracture toughness of the sample and the tactile control of the person tapping the razor blade in the specimen. Conversely, the healed crack length a_{healed} is determined by the healing functionality of the self-healing material being studied. For liquid-based self-healing materials—where liquid healing agents tend to wick towards the crack tip under capillary action—the healed region is dependent on the volume of healing agent released (i.e. dependent on the size and concentration of microcapsules or semi-infinite for micro-fluidic based systems) versus the volume of the crack to be healed (i.e. dependent on the length and width of the crack and gap between the crack surfaces). Depending on the available volume of healing agent released and volume of the crack to be healed, a_{healed} can be much longer or much shorter than a_{virgin}. For solid-based self-healing materials the healed region is generally dependent only on the cracked surfaces being in close contact (possibly under external

intervention in the form of pressure, temperature or solvent). Depending on the alignment of crack surfaces, a_{healed} can be much longer or much shorter than a_{virgin}.

For the current work the error in reported healing efficiency when the healed crack length is not accounted for is defined to be $(\eta_{reported} - \eta_{actual})/\ \eta_{actual}$ (%) where $\eta_{reported}$ is calculated with $a_{healed} = a_{virgin}$ and η_{actual} is calculated with the actual value of a_{healed}. The crack length independence of the TDCB geometry results in zero error for all combinations of virgin and healed crack lengths as shown in Fig. 1a. The CT, SENB and SENT specimen on the other hand exhibit significant errors for all cases where the virgin and healed cracks are not identical, as shown in Figs. 1b-d. For all three geometries the reported healing efficiency is over predicted when the healed crack is shorter than the virgin crack, which according to the literature is the most common situation. When the virgin crack is in the middle of the range and healed crack is the minimum length (i.e., at the prenotch), the CT and SENB over predict by approximate 100% and the SENT over predicts by closer to 200%. One way to reduce this error is to make the virgin precrack extend as short a length as possible from the prenotch in an effort to physically force $a_{healed} \approx a_{virgin}$. However, if the virgin precrack is very short and the healed crack is long, the healing efficiency can be under predicted by as much as 90%. Moreover, it is worth noting that representative W values for CT, SENB and SENT specimens are 51, 10, and 10 mm respectively. An inaccuracy in the healed crack length of as little as 1 mm can result in healing efficiency errors of 7, 33% or 45% for the CT, SENB or SENT respectively. However, all of these errors need to be mitigated to enable an accurate measurement of the healing efficiency. One way is clearly through the use of the TDCB geometry, which inherently has no error arising from crack length measurements.

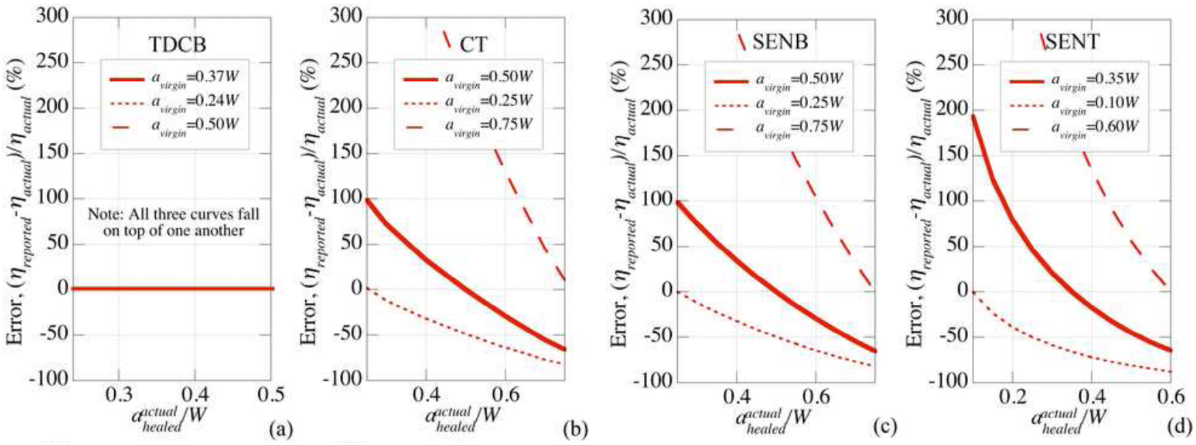

Figure 1. The dependence of error in reported healing efficiency as a function of the actual healed crack length (a) CT, (b) TDCB, (c) SENB and (d) SENT geometries.

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