Hydrothermal Loading Effects on the Dynamic Fracture Behavior of Carbon Fiber Composites

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Abstract. This study focuses on the evaluation of the effect of hydrothermal conditioning on the dynamic fracture behavior of unidirectional carbon fiber composites. Specifically, the Mode-I (opening) fracture response as a function of moisture uptake and the role of saline on the critical dynamic stress intensity factor (SIF) was investigated. Samples were soaked in an elevated temperature bath of 70°C of either ASTM standard sea water or distilled water for durations ranging from hours to months with their moisture uptake monitored. A unique long-bar striker device was used to impact pre-cracked specimens and digital image correlation combined with ultra high-speed imaging was used to capture the evolution of the kinematic fields ahead of the crack tip. A transversely isotropic elastodynamic solution was used to extract the SIF as a function of time. Overall, the ambient condition samples exhibited on the order of double the critical SIF relative to the any soaked samples, regardless of duration or saline presence. The SIF reduction is thought to be driven by matrix and interface degradation, as evidence by post-mortem X-ray microtomography.

Introduction

Fiber reinforced polymer composites are widely used in engineering applications due to their advantageous mechanical performance with relatively low density. At the same time, the effect of hygrothermal aging on composites have shown that their properties can degrade, resulting in irreversible deterioration of performance and durability [1]. Specifically, moisture penetration in composites via the matrix or voids may induce swelling, develop internal stresses and instigate the formation of microcracks and the expansion of voids [2]. The generation of microcracks and enlargement of voids could further increase f moisture ingress rate and effectively accelerate composite degradation [3]. Additionally, moisture uptake has been shown to be detrimental to the matrix-fiber adhesion strength [4,5] and the adhesion strength [6]. As such, it is important to characterize their failure behavior as a function of weathering conditions, particularly under dynamic conditions of relevance to real-world loading environments.

Methods

Commercially available specimens from Dragonplate composed of UTS 700 unidirectional carbon fiber, infused with NCT 304-1 epoxy resin were used. Specimens were composed of approximately 16 plies at 4.76 mm thick. Specimens were 55% fiber volume fracture and were cut to 45 by 100 mm coupons, notched and pre-cracked.

Prior to fracture experiments, hygrothermal aging was performed by submerging samples in tanks held at 70°C, allowing for accelerated mass absorption [7]. Manufacturer provided moduli were used in the fracture analysis and moduli of the soaked sample were calculated following the Chamis model [8] based on weight percent moisture uptake. Samples were soaked in either ASTM sea water or distilled water at intervals that ranged from 3.5 hours, 2 days, 2 weeks to over 4 months. A subset of samples was desiccated after soaking to remove the absorbed moisture from the material.

For fracture characterization, specimens were mounted to a unique long-bar striker device, held in place by clay on both vertical ends to reduce boundary wave reflections. A small steel projectile was impacted on the opposite end of the pre-crack at about 4 m/s to induce a stress-wave loading pulse in the sample. The compressive pulse reaches the free end with the pre-crack and reflects as a tension wave. When enough stress has built up at the crack tip, the crack is pulled open in a dominantly Mode-I (opening) manner. Ultra high-speed imaging with a Shimadzu HPV-X at 1 million frames per second was used in conjunction with MatchID, a commercially available digital image correlation software, to track the evolving surface kinematic fields at the crack tip. Leveraging a transversely isotropic elastodynamic solution, the dynamic stress intensity factor (SIF) is tracked until crack initiation. At that point, the SIF is considered the critical SIF and is akin to a dynamic fracture toughness [9].

Results

Results indicate that the ambient samples have consistently higher resistance to fracture than any soaked samples, as shown in Figure 1 below. The difference between the ambient and soaked conditions was approximately 60% for the 3.5 hour soaked samples, 40% for 2 day soaks, 50% for 2 week soaks and 80% for soaks longer than 4 months. The deterioration is thought to be due to dominant matrix and interface degradation and in the case of long term soaking, surface degradation is also though to play a critical role. The slight increase in the critical SIF between the 3.5 hour and the 2 day soaks is thought to be due to matrix plasticization which allows the composite to absorb greater deformation before fracture. Comparing the desiccated samples to those of 2 week soaked indicates that the moisture absorption leads to irreversible matrix damage.

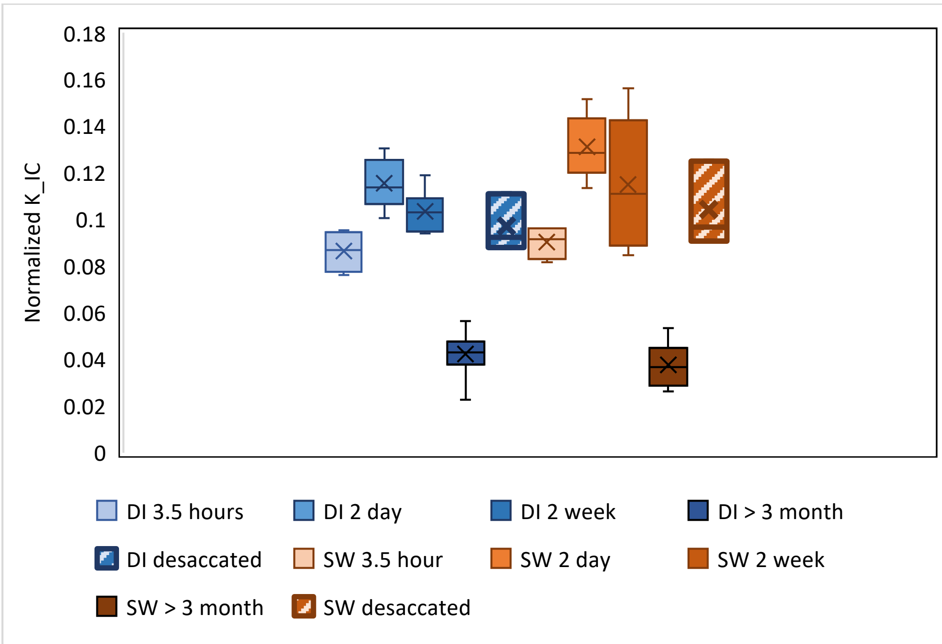

Fig.1 Dynamic fracture values normalized by ambient results, DI = distilled water and SW = sea water.

Conclusion

The effects of saline and moisture absorption on the dynamic Mode-I fracture toughness of unidirectional carbon-epoxy composites was investigated. The presence of saline in the soaking solution appeared to slightly reduce the moisture absorption rate from that observed in the DI water solution, leading to lower mass absorption in the salt water specimens versus the DI specimens. However, there was no statistically significant effect on the resulting SIF between the two. All soaked conditions resulted in a reduction of the dynamic fracture toughness from the pristine condition samples. Short term soaking resulted in an immediate reduction while intermediate term soaking resulted in slight strengthening over the short term condition. This is thought to be due to matrix plasticization. Long term soaks corresponding to significant moisture absorption resulted in significant reductions to the SIF. The moisture absorbed during soaking appears to cause irreversible damage to the matrix.

References

[1] I. Panaitescu, T. Koch, V.-M. Archodoulaki, Polym. Test., 74 (2019), p. 245-256
[2] S.A. Grammatikos, M. Evernden, J. Mitchels, B. Zafari, J.T. Mottram, G.C. Papanicolaou, Mater. Des., 96 (2016), p. 283-295
[3] P. Sun, Y. Zhao, Y. Luo, L. Sun, Mater. Des., 32 (2011), p. 4341-4347
[4] A. Bergeret, L. Ferry, P. Ienny, Polym. Degrad. Stabill., 94 (2009), p. 1315-1324.
[5] S. Wang, W. Liu, Y. Fang, R. Huo, J. Mater. Sci., 54 (2019), p. 2102-2121
[6] A. Hawa, M.S. Abdul Majid, M. Afendi, H.F.A. Marzuki, N.A.M. Amin, F. Mat, A.G. Gibson, Mater. Des., 89 (2016), p.455-464.
[7] W.R. Broughton, A.S. Maxwell, Measurement and Good Practice Guide, Teddington, Middlesex, UK, 2007.
[8] R. Gibson, Principles of Composite Material Mechanics, New York, NY: McGraw Hill, 1994.
[9] K. Ravi-Chandar, Dynamic Fracture, Elsevier, 2004.