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Modelling The Fracture Energy of Polymer Nanocomposites

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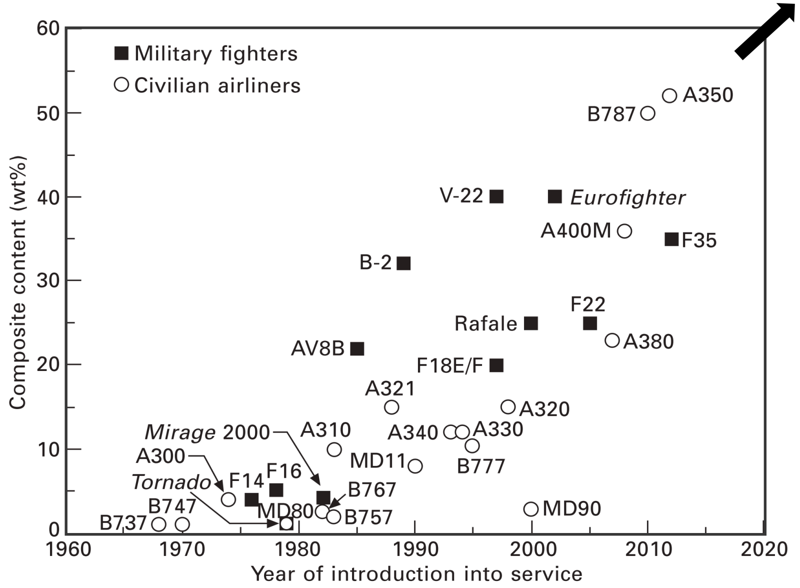
1 Background

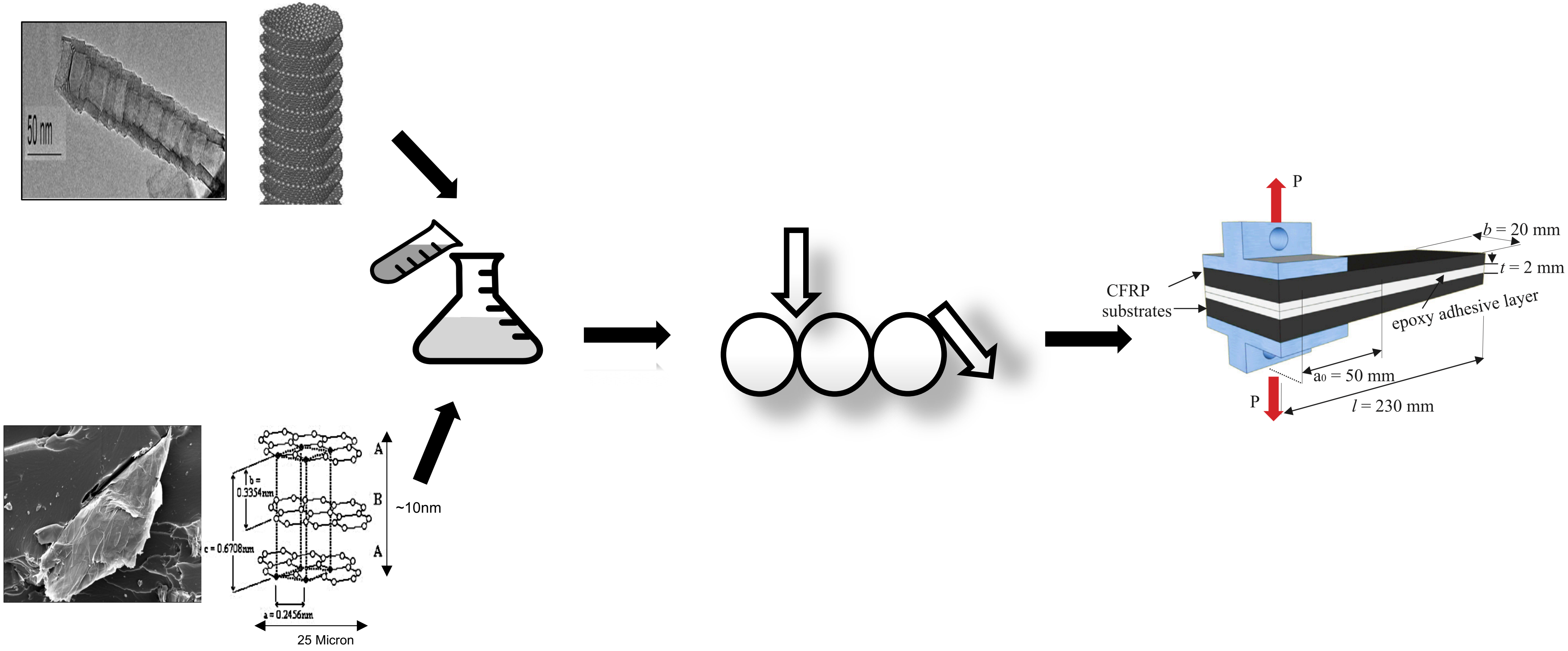
Relatively low toughness And Poor cyclic fatigue resistance

Can led to **rapid** and **large-scale** cracking.



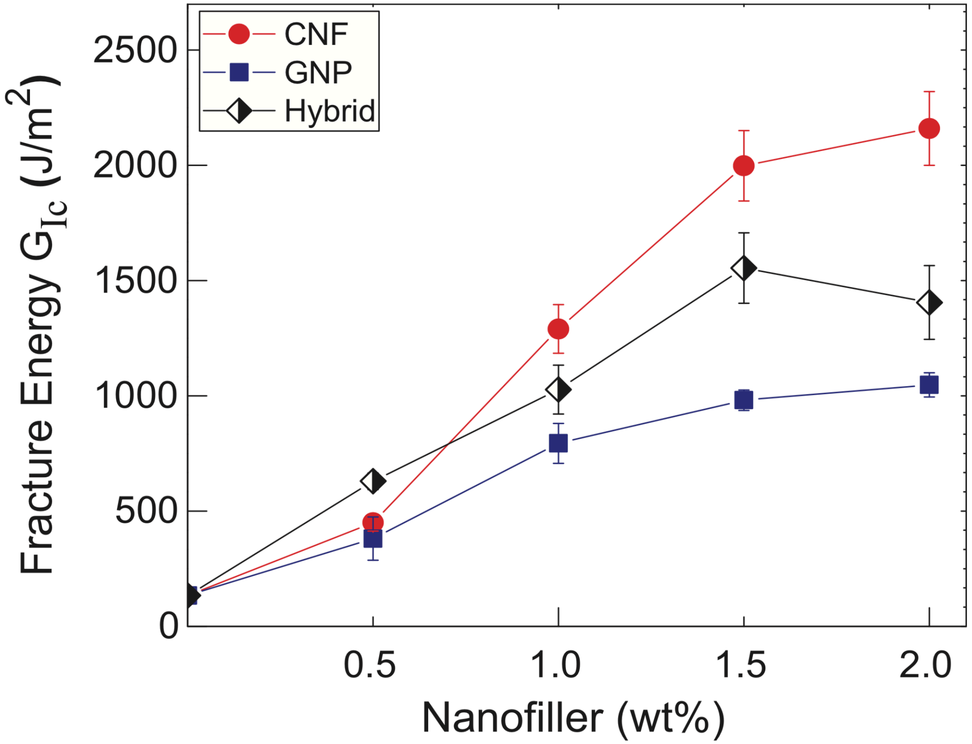
National Transportation Safety Board. NTSB Aircraft Accident Report- Aloha Airlines, Flight 243, Boeing 737-200, N72711, near Maui, Hawaii. Washington, D.C.: 1988.

2 Materials and Method



3.1 Experimental Results: G_{Ic}

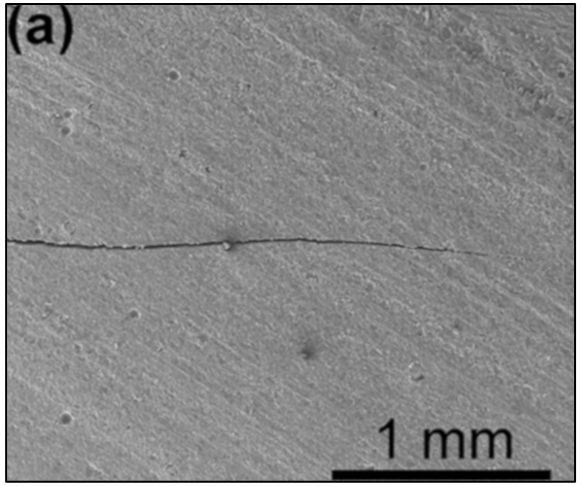
- **Linear increase** up to a nanofiller concentration of 1.5 wt.%
- Toughness **increase is larger for CNF** compared to GNP and hybrid counterparts.
- Difference due to **extent of toughening** mechanisms induced.



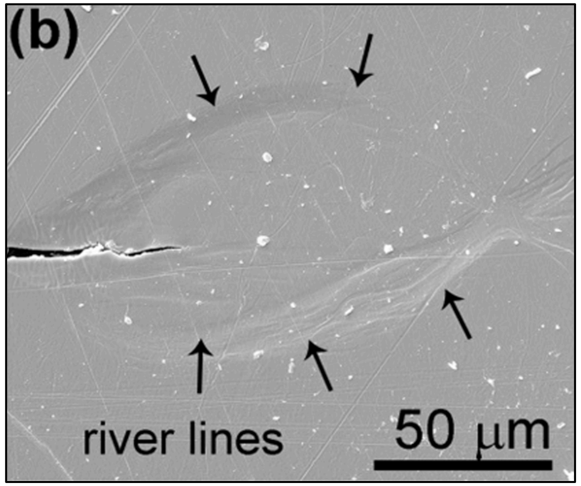
: Common to both

: Unique

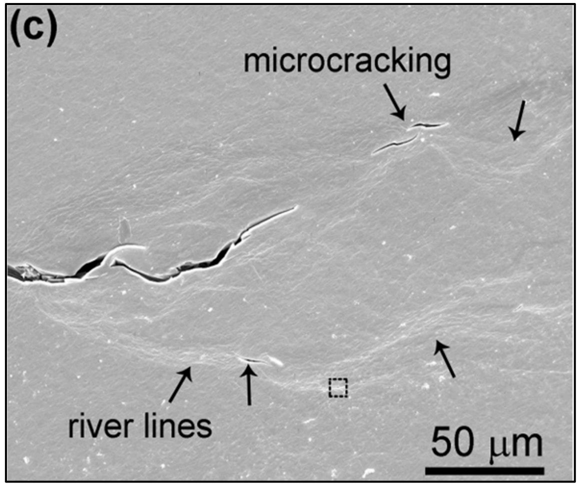
3.2 Intrinsic Mechanisms

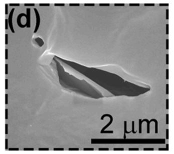


Unmodified



CNF Doped





GNP Doped

- No microscale damage in process zone
- Well-defined crack tip
- No evidence of intrinsic or extrinsic toughening mechanism.

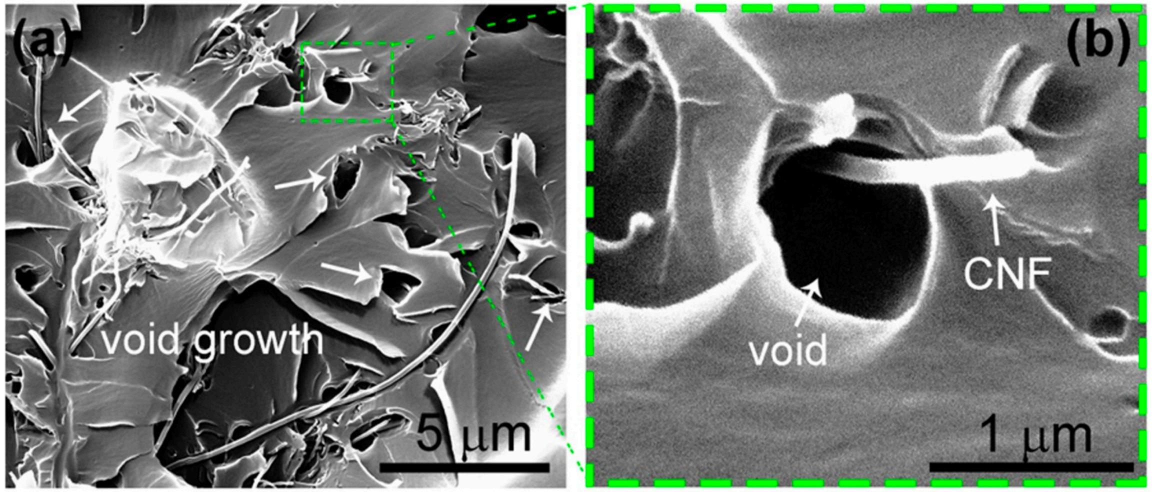
← Microscale damage in process zone for CNF and GNP composites →

- Interfacial debonding CNFs and epoxy)

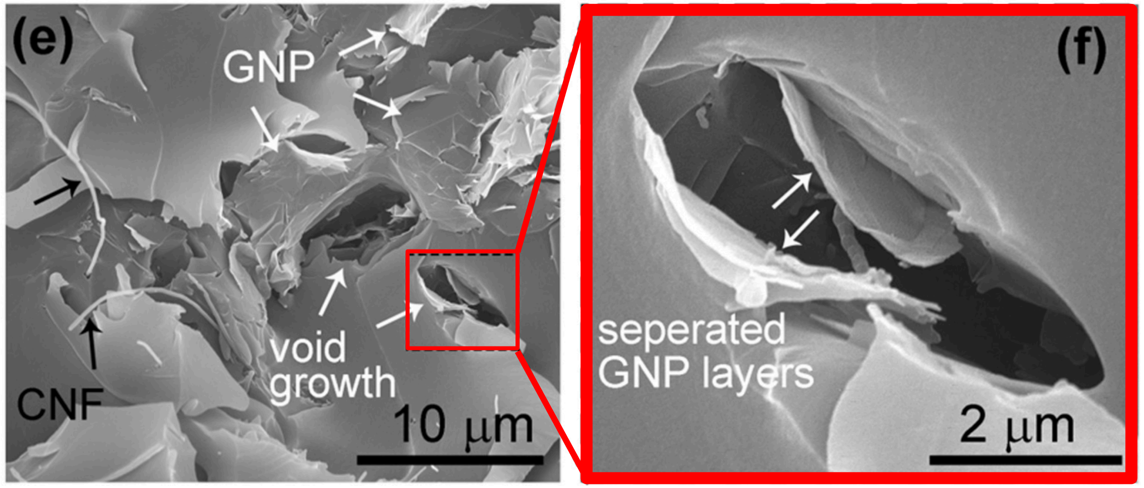
- Interfacial debonding (GNPs and epoxy)

High Triaxial Stress state → Separation of Graphene layers → Micro-cracking ahead of the crack-tip.

3.3 Intrinsic Mechanisms



CNF and Epoxy Plastic Void Growth



GNP and Epoxy Plastic Void Growth

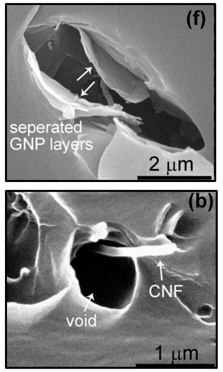
3.4 Intrinsic Mechanisms: Prominence

1. GNP microcracking
2. Nanofiller-epoxy interfacial debonding
3. Microcrack coalescence

} ⬆ Relatively minor toughening mechanisms

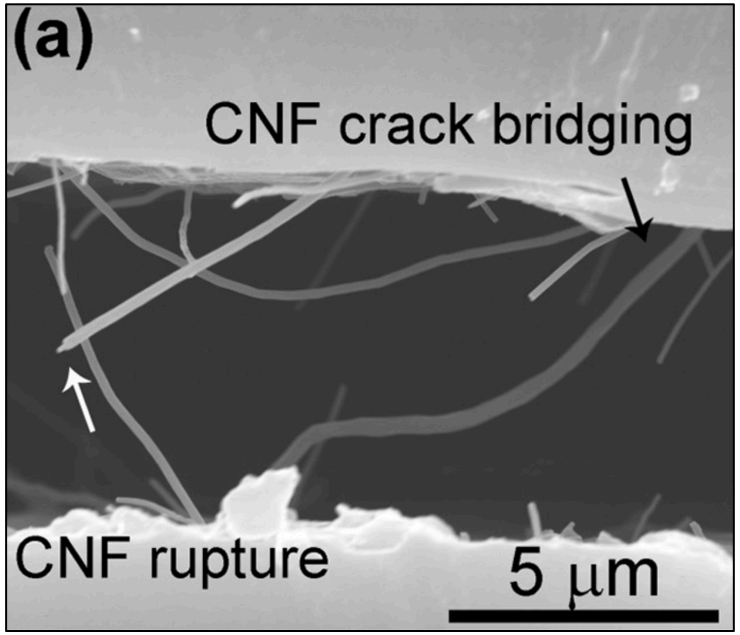
4. Plastic void growth

   Due to significantly higher elastic modulus of nano filler compared to epoxy.

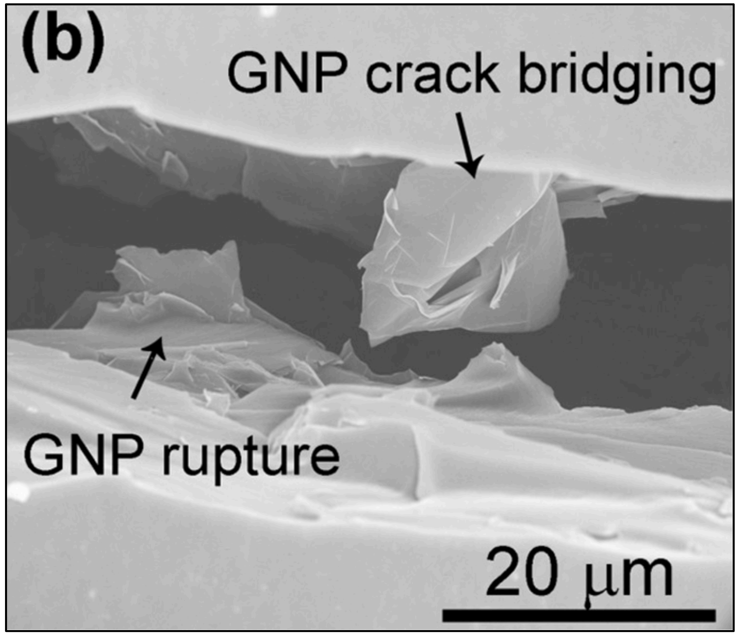


} ⬆⬆⬆ Prominent toughening mechanism

3.5 Extrinsic Mechanisms



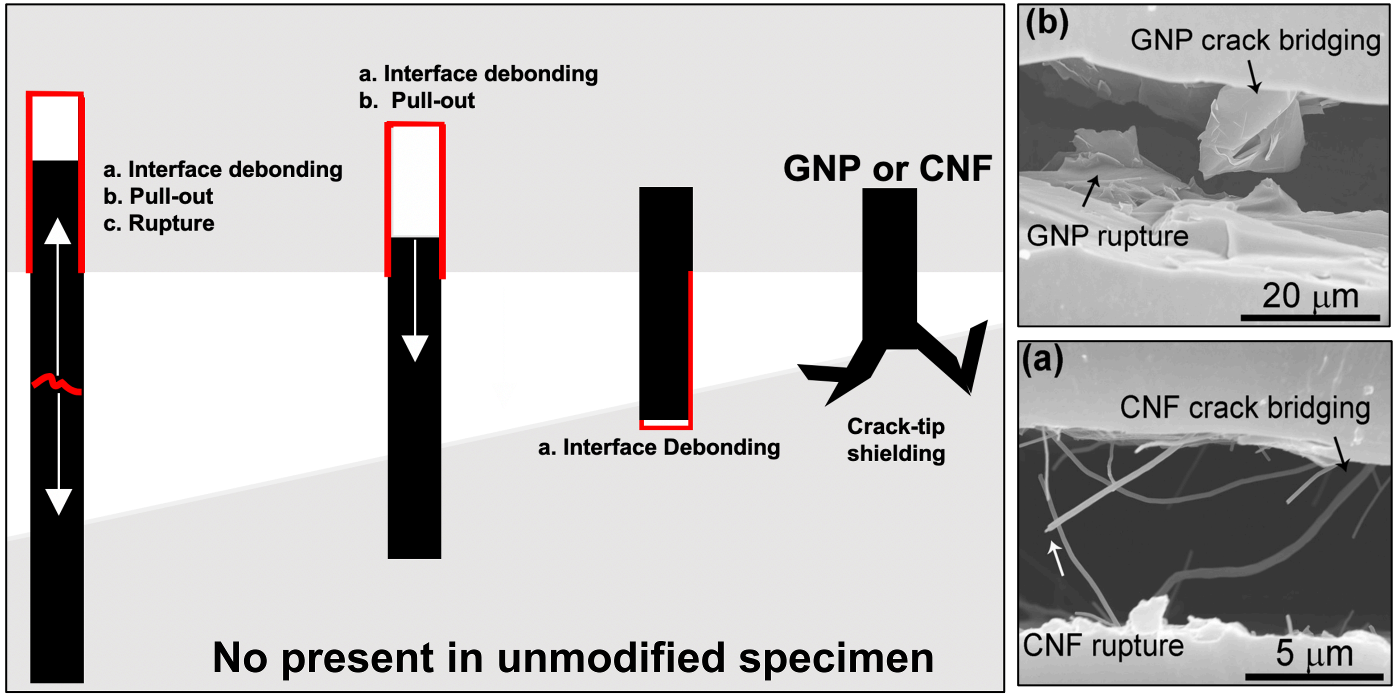
CNF Crack-Bridging



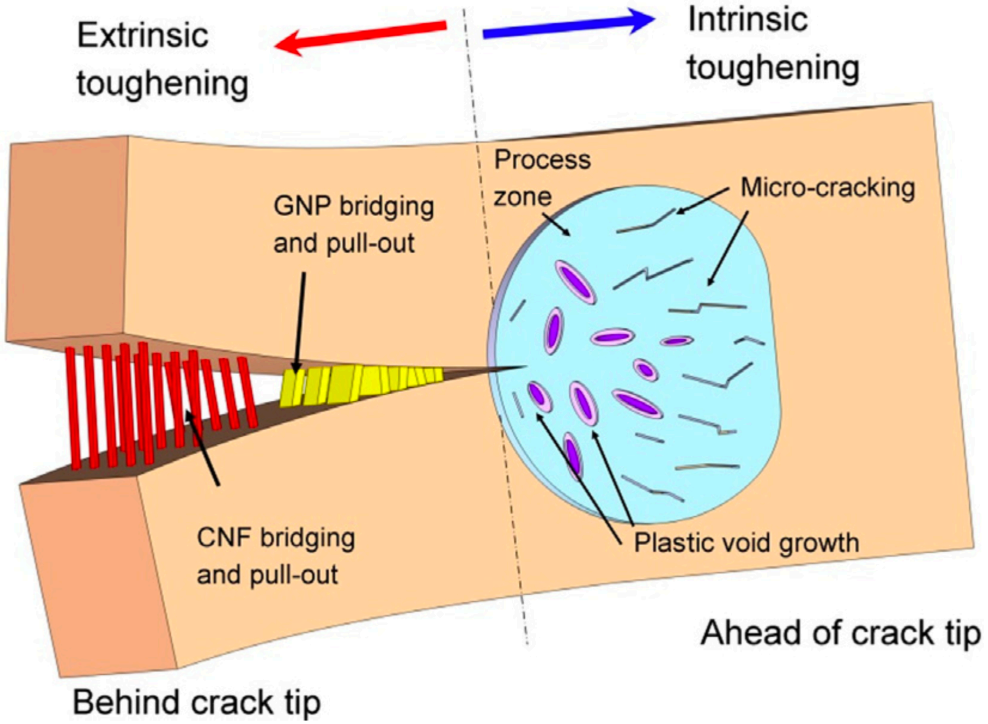
GNP Crack-Bridging

Crack front passes across the nanofillers →

- Shorter embedded lengths → Crack bridging zone → Shield the crack tip from the applied stress → Increases fracture energy
- Medium embedded lengths → Debond → Pull-out → Increases fracture energy
- Long embedded lengths → Nanofiller rupture → Increases fracture energy



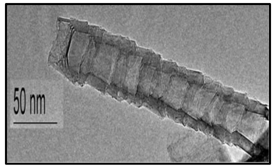
3.6 Summary



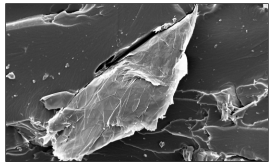
Extrinsic toughening
Intrinsic toughening
Process zone
Micro-cracking
GNP bridging and pull-out
CNF bridging and pull-out
Plastic void growth
Ahead of crack tip
Behind crack tip

4.1 Model: CNF, GNP and Hybrid

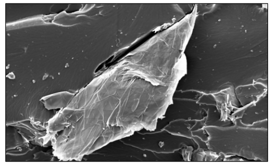
$$G_{Ic} = G_{CU} + \Delta G_{pull-out} + \Delta G_{rupture} + \Delta G_{db} + \Delta G_{v}$$



$$G_{Ic,CNF} = G_{CU} + \frac{V_f \sigma_f^2 d_f}{8\tau_i} + \frac{V_f \sigma_f^2 l_f}{2E_f} + \frac{V_f l_{po} G_i}{d_f} + \left(1 + \frac{\mu_m}{\sqrt{3}}\right)^2 V_f \left(\frac{d_v^2}{3d_f^2} + \frac{d_v}{3d_f} - \frac{2}{3}\right) \sigma_y r_{yu} K_{vm}^2$$



$$G_{Ic,GNP} = G_{CU} + \frac{V_f tW\sigma^2}{2(t+W)\tau_G} + \frac{V_f l\sigma^2}{2E_G} + \frac{2V_f (t+W) l_{po} G_i}{tW} + \left(1 + \frac{\mu_m}{\sqrt{3}}\right)^2 [V_{void} - V_f] \sigma_y r_{yu} K_{vm}^2$$



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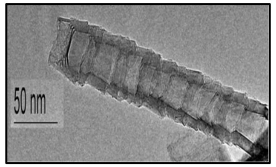
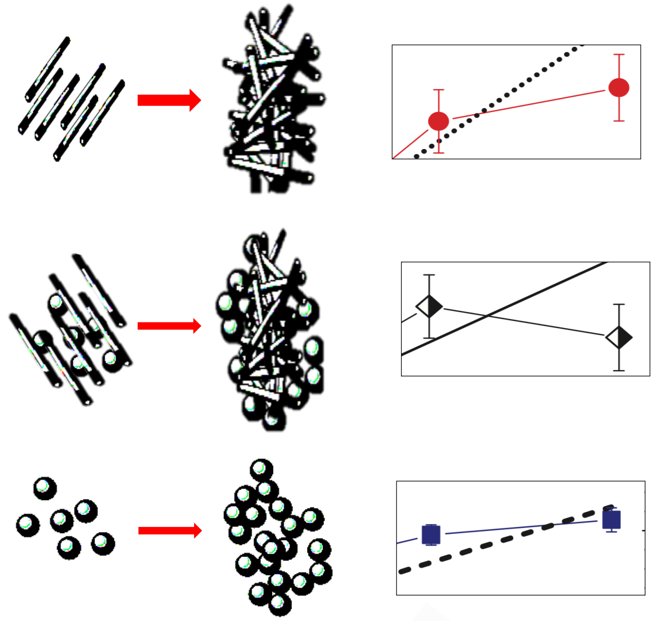
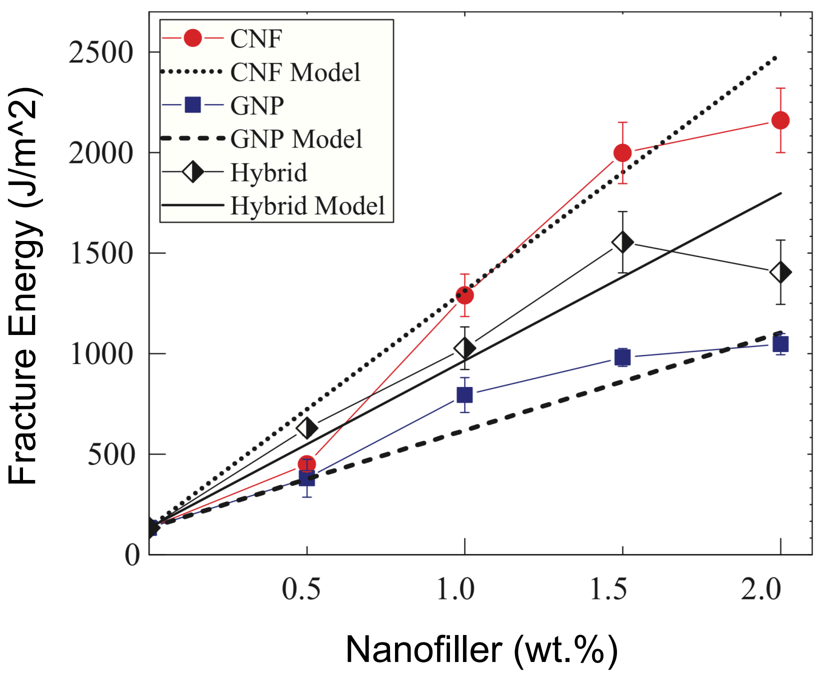


$$G_{Ic,Hybrid} = V_{f,CNF}(G_{Ic,CNF}) + V_{f,GNP}(G_{Ic,CNF})$$

4.2 Modelling and Experiment

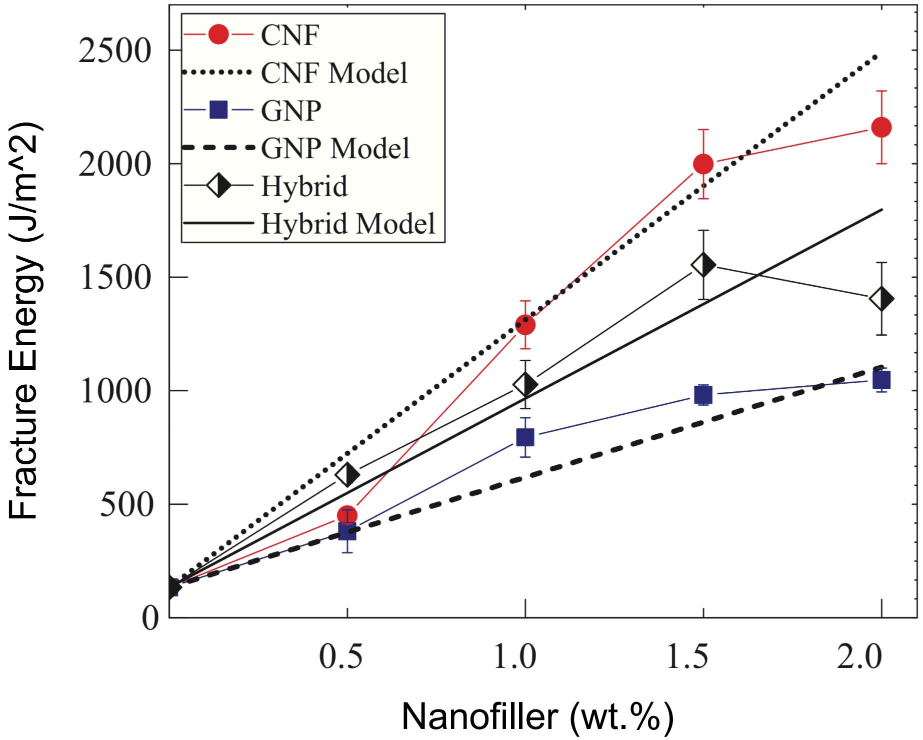
- Predictions by the model in accord, except until increase in agglomeration

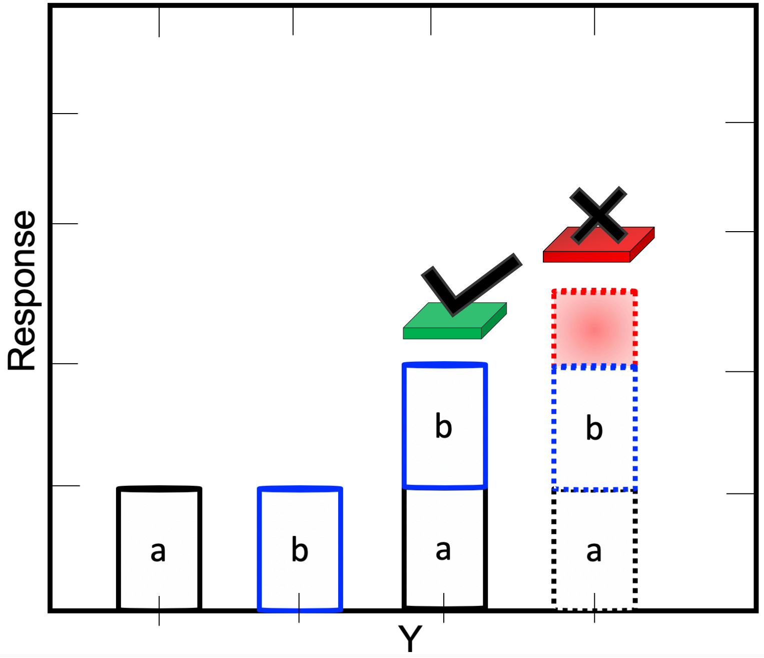




- Prominence of Mechanisms Confirmed

Valiulin AR. Agglomeration versus aggregation. Cheminfographic 2016. https://cheminfographic.wordpress.com/2016/12/20/agglomeration-aggregation/ (accessed July 3, 2019).

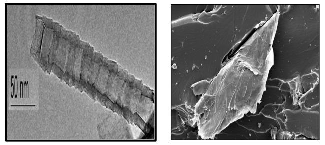




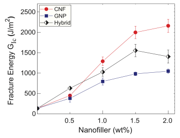
No significant interactions between the two nanofillers with respect to the toughening mechanisms

Conclusion

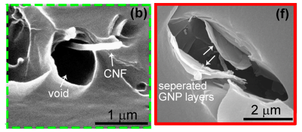
The **effects of the shape** and concentration of nanoscale carbon fillers on the quasi-static fracture energy



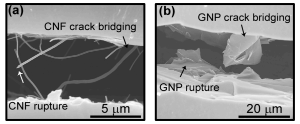
Results show **improvements to the mode I fracture energy**, GIc



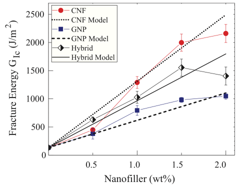
Major **intrinsic** toughening mechanisms: (a) debonding of the nanofillers, (b) plastic void growth initiated by the debonded nanofillers,



Major **extrinsic** toughening mechanisms (c) pull-out and crack bridging of the nanofillers; and (d) rupture of the bridging nanofillers.



Modelling the toughening mechanisms demonstrated to predict fracture energy, G_{Ic}, showed **good agreement** with experimental results.



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$$G_{Ic,GNP} = G_{CU} + \frac{V_f t W \sigma^2}{2(t+W)\tau_G} + \frac{V_f l \sigma^2}{2E_G} + \frac{2V_f (t+W) l_{po} G_i}{tW} + \left(1 + \frac{\mu_m}{\sqrt{3}}\right)^2 [V_{void} - V_f] \sigma_y r_{yu} K_{vm}^2$$

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Relevant Reference:

Ladani RB, Bhasin M, Wu S, Ravindran AR, Ghorbani K, Zhang J, et al. Fracture and fatigue behaviour of epoxy nanocomposites containing 1-D and 2-D nanoscale carbon fillers. Eng Fract Mech 2018. doi:10.1016/j.engfracmech.2018.04.033.

Ladani RB, Wu S, Kinloch AJ, Ghorbani K, Zhang J, Mouritz AP, et al. Improving the toughness and electrical conductivity of epoxy nanocomposites by using aligned carbon nanofibres. Compos Sci Technol 2015;117:146–58.

Ladani RB, Wu S, Kinloch AJ, Ghorbani K, Zhang J, Mouritz AP, et al. Multifunctional properties of epoxy nanocomposites reinforced by aligned nanoscale carbon. Mater Des 2016;94:554–64.