Stiffness, Strength, and Damage Tolerance of Irregular Suture Interfaces

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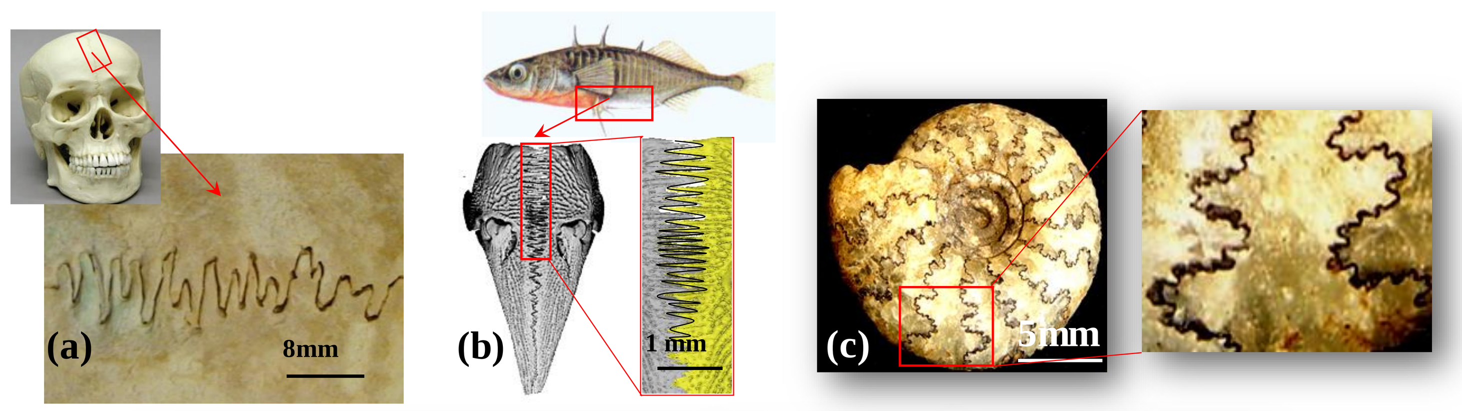
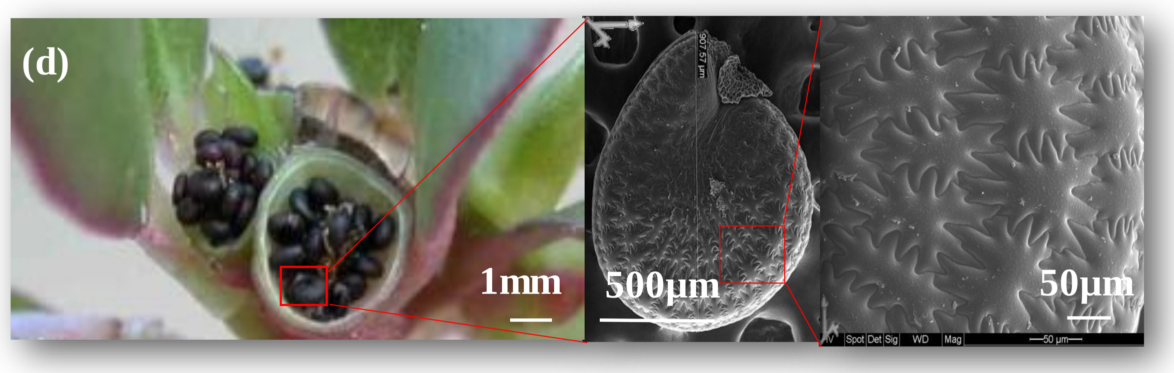
Background and Motivation

- **Irregular sutures in nature**
  - Mechanical models of regular sutures were developed [1-3]
  - However, many suture interfaces in nature show an irregular morphology instead of a regular repeating one:



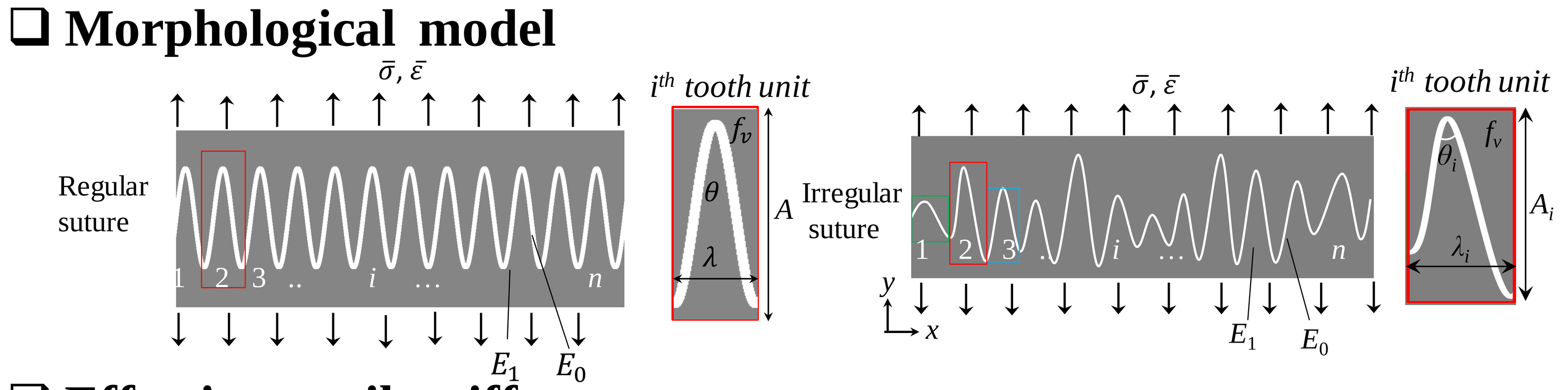


(a) cranial sutures of adult, (b) the pelvic suture of stickleback, (c) ammonite suture, (d) the suture in seed coat of *Portulaca*.

- **The goal of this research** is to determine the influences and underlying mechanisms of morphological irregularity on the mechanical properties of suture interfaces.

Analytical Model

- **Morphological model**



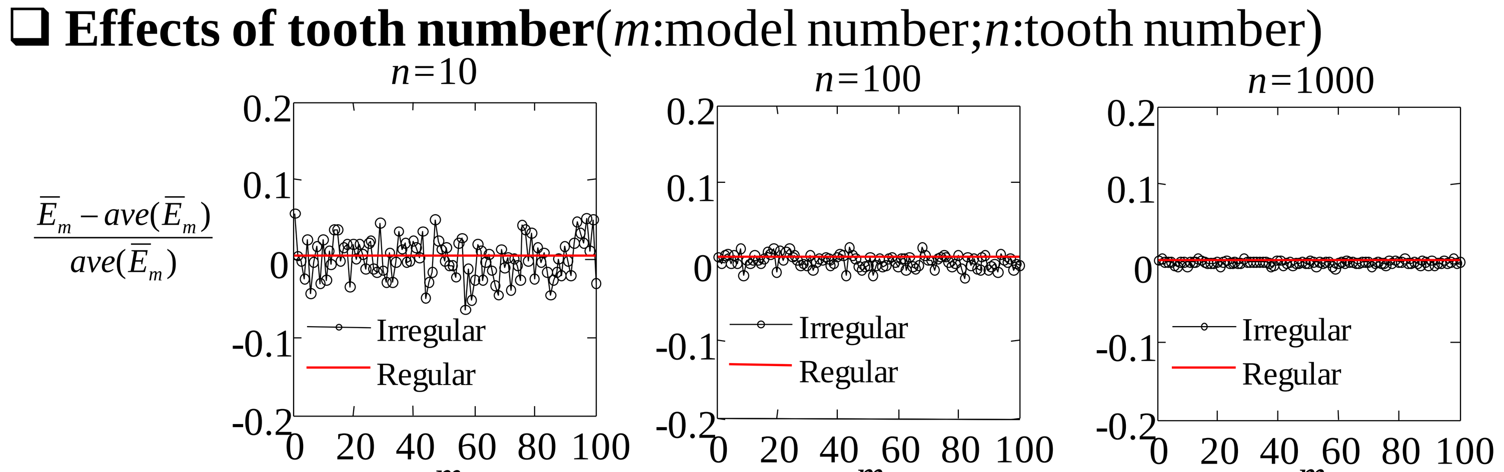
- **Effective tensile stiffness:**

$$\frac{E_i}{E_1}(f_v,\theta_i)=\frac{f_v^2}{(1-f_v)\left(\frac{E_1}{G_0}sin^2\theta_i cos^2\theta_i+\frac{E_1}{E_0}sin^4\theta_i\right)+f_v} \qquad \bar{E}=\frac{\sum_{i=1}^n A_i\lambda_i E_i}{\sum_{i=1}^n A_i\lambda_i}$$

- **Effective strength $\left(\bar{\sigma}_i^f\right)$ of each cell in suture:**

$$\frac{\bar{\sigma}_i^f}{f_v\sigma_1^f}=\begin{cases}1, & \theta_i\le\theta_0: tooth\ failure\\ \frac{sin\theta_0 cos\theta_0}{sin\theta_i cos\theta_i}, & \theta_i>\theta_0: interface\ shear\ failure\end{cases}$$

- **Effects of tooth number**(m:model number;n:tooth number)



References

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[2]Y.N. Li, C. Ortiz, M.C. Boyce, Physical Review E, 85(2012).
[3]Y.N. Li, C. Ortiz, M.C. Boyce, Journal of Mechanics and Physics of Solids, 61, 1144(2013).
[4]J.H.Song, M.C.Boyce,C.Ortiz, et al. Journal of Structural Biology,171 (2010), 318-331.
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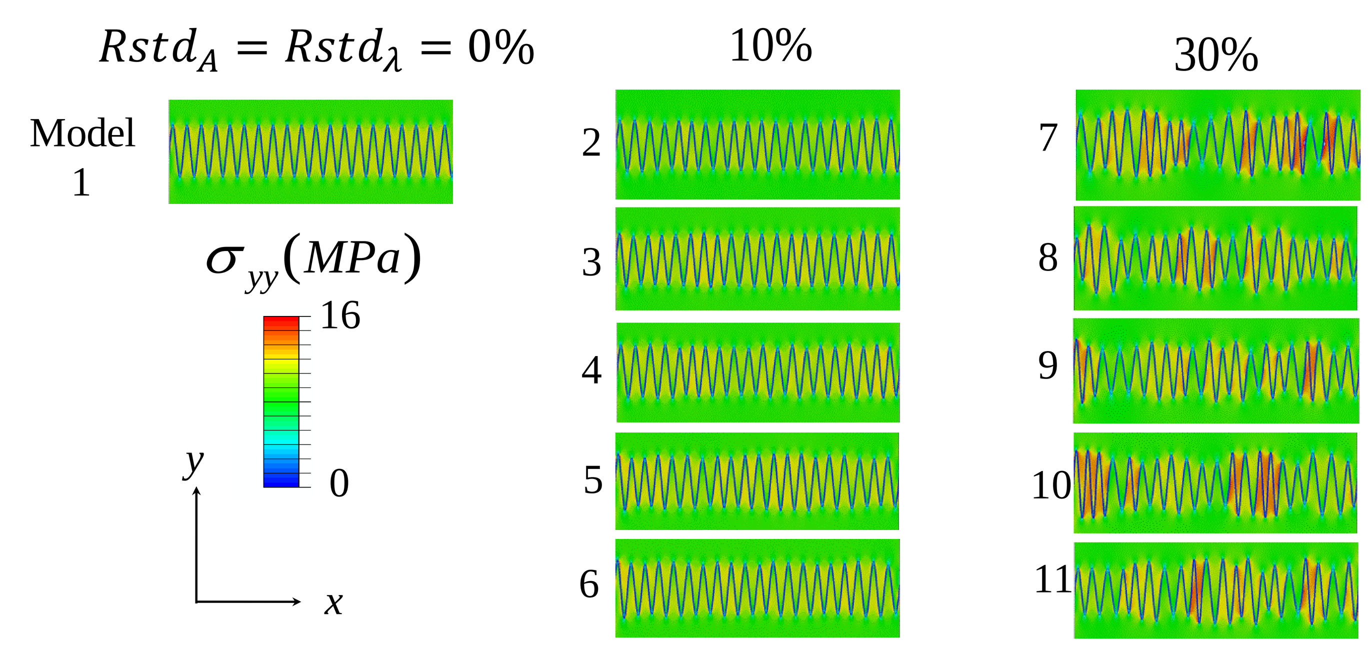
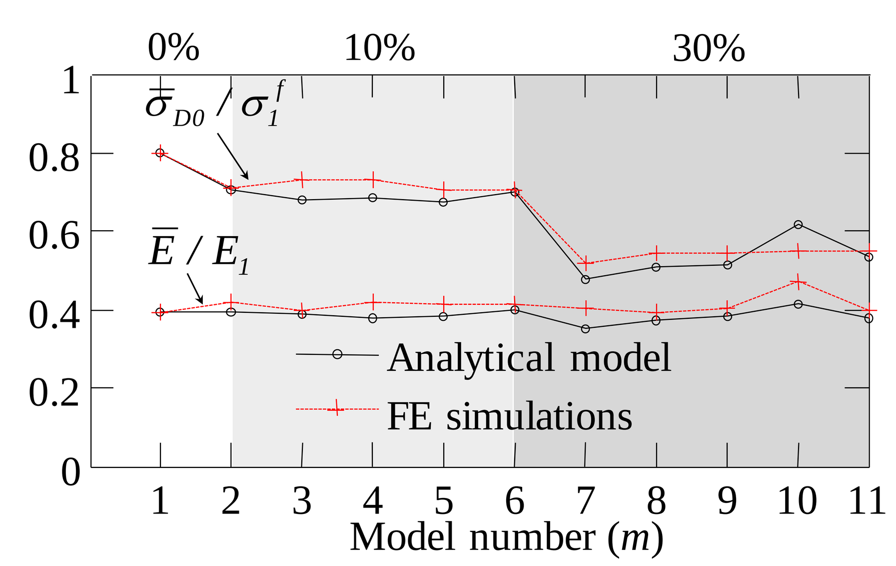
Finite Element Simulations

- **Stiffness and strength (pre-failure analysis)**
  - Finite element models (the same volume fraction)

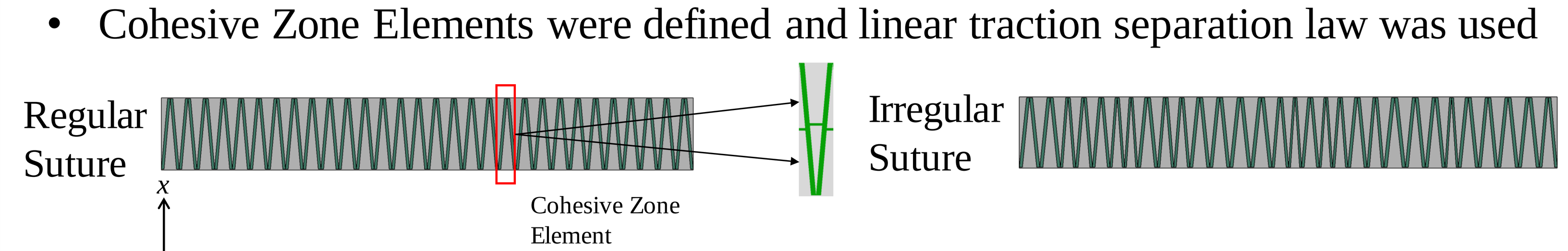


  - When the degree of irregularity increases,



  - stress distribution in each tooth becomes more and more non-uniform
  - the maximum stress is always in the sharpest tooth
  - tensile strength decreases
  - stiffness barely changes

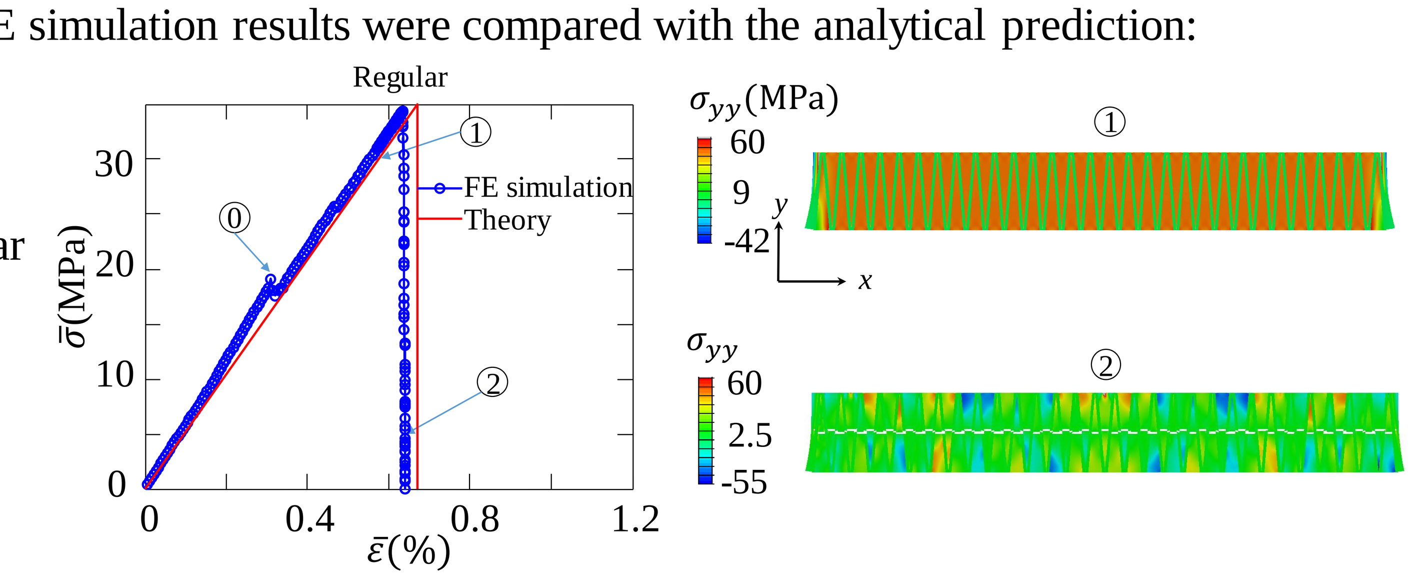
- **Damage tolerance (post-failure analysis)**
  - Cohesive Zone Elements were defined and linear traction separation law was used



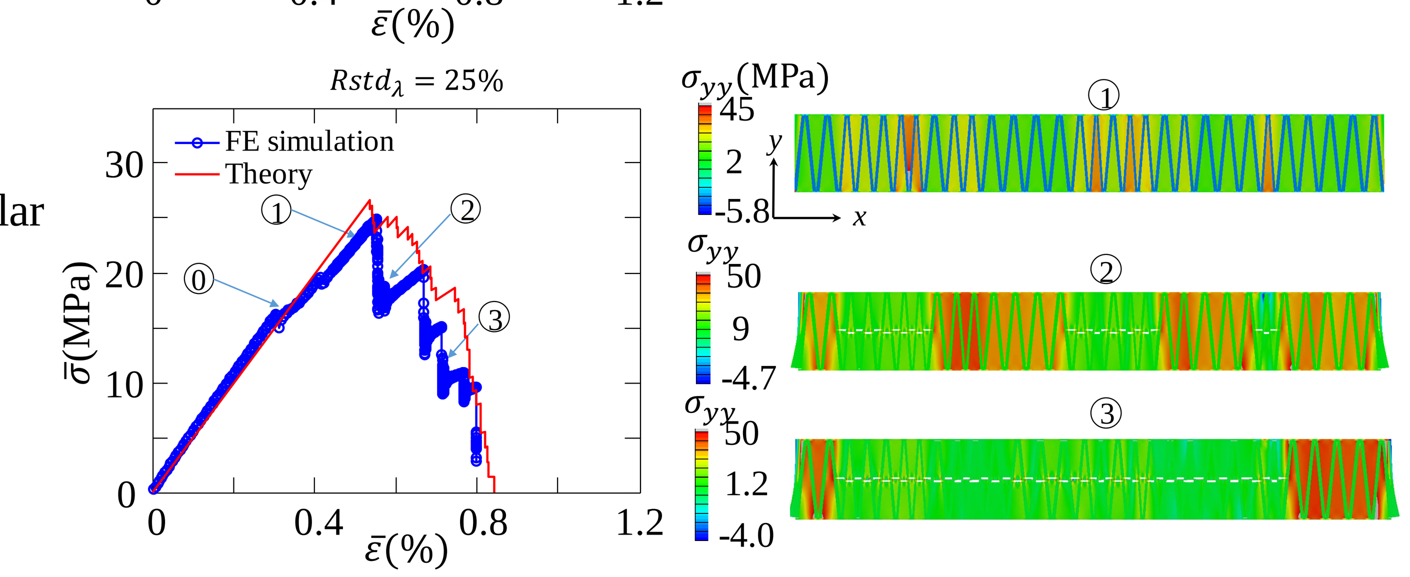
The diagram of FE model and cohesive element

  - The FE simulation results were compared with the analytical prediction:

  - Regular suture



  - Irregular suture



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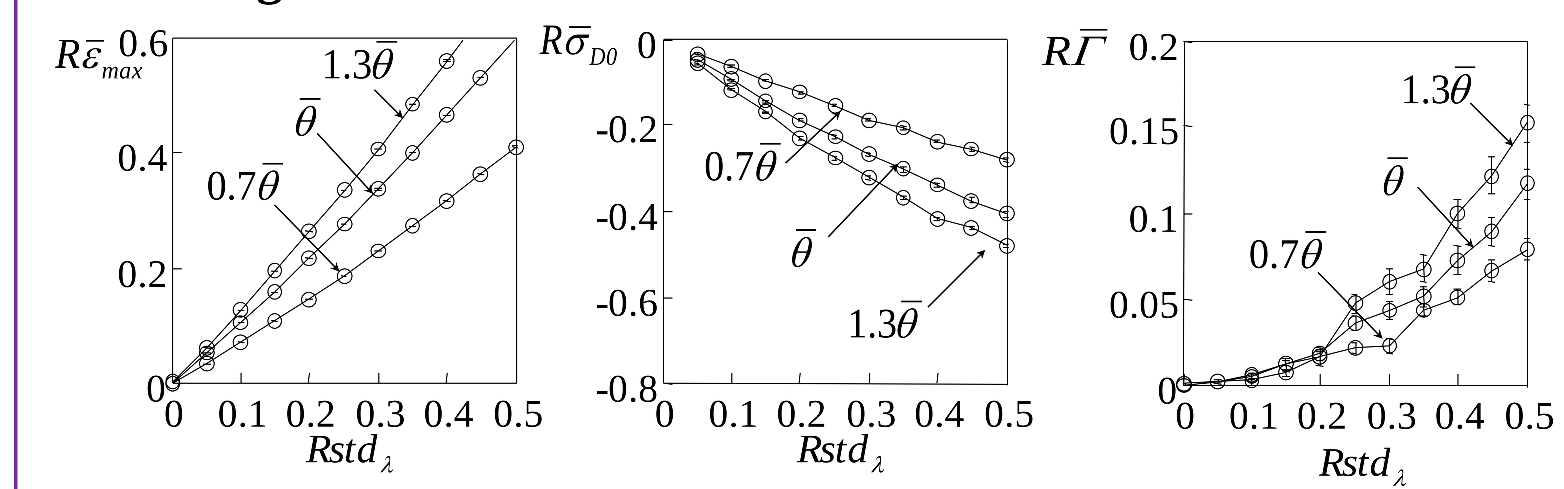
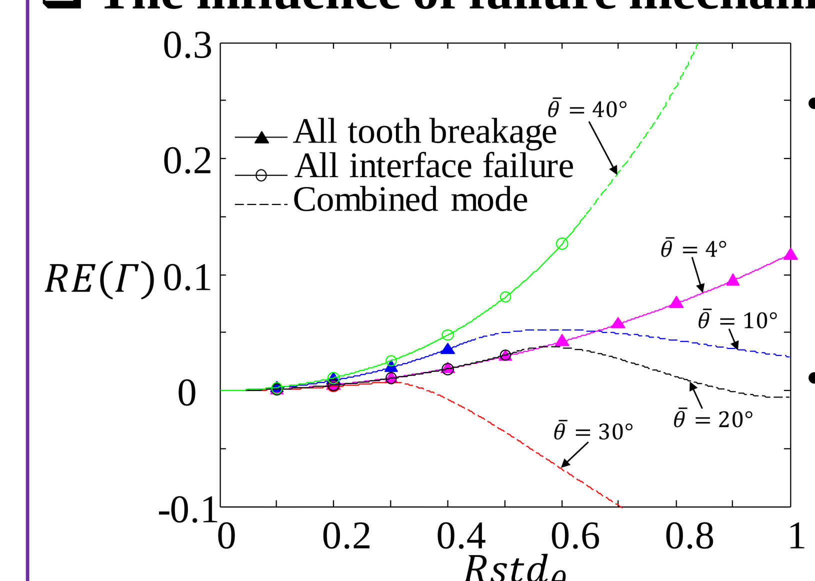
Parametric Study

- **Influences of morphological irregularity on fracture strain, strength and toughness**



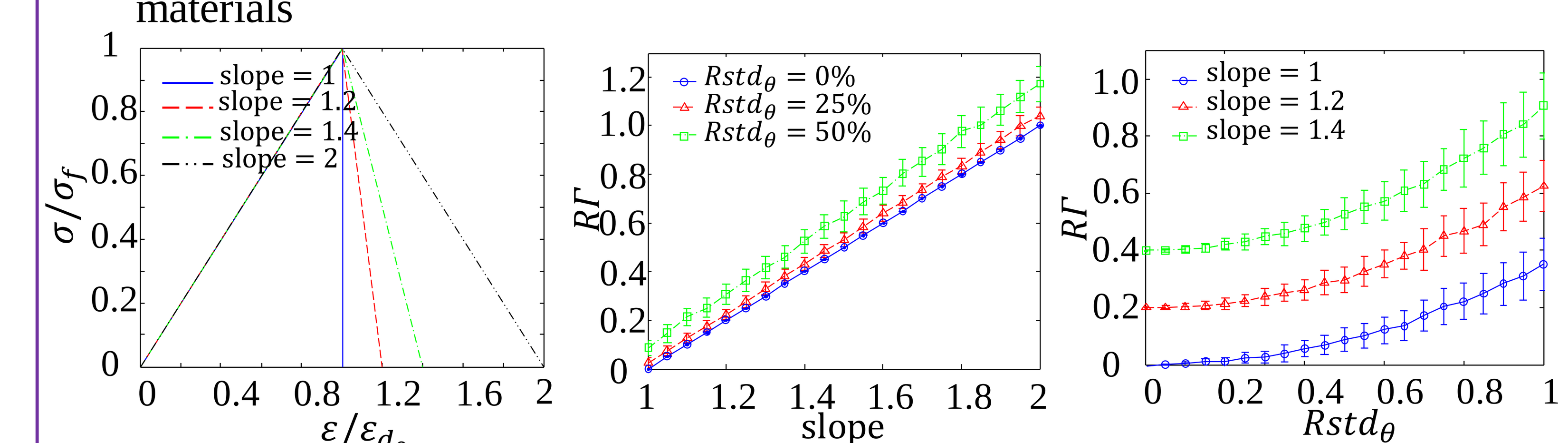
  - When $Rstd_\lambda$ increases,
    - fracture strain $\bar{\varepsilon}_{max}$ and toughness $\bar{\Gamma}$ increases
    - strength $\bar{\sigma}_{D0}$ decreases

- **The influence of failure mechanism transition on damage tolerance**



  - When $Rstd_\theta$ increases, the failure mechanism will transfer from purely tooth breakage or interface failure to combined tooth &interface failure.
  - For most value of $\bar{\theta}$, the failure mechanism transition decreases the damage tolerance.

- **The influence of post-failure slope of material on damage tolerance**
  - The toughness of suture increases with the post-failure slope of component materials

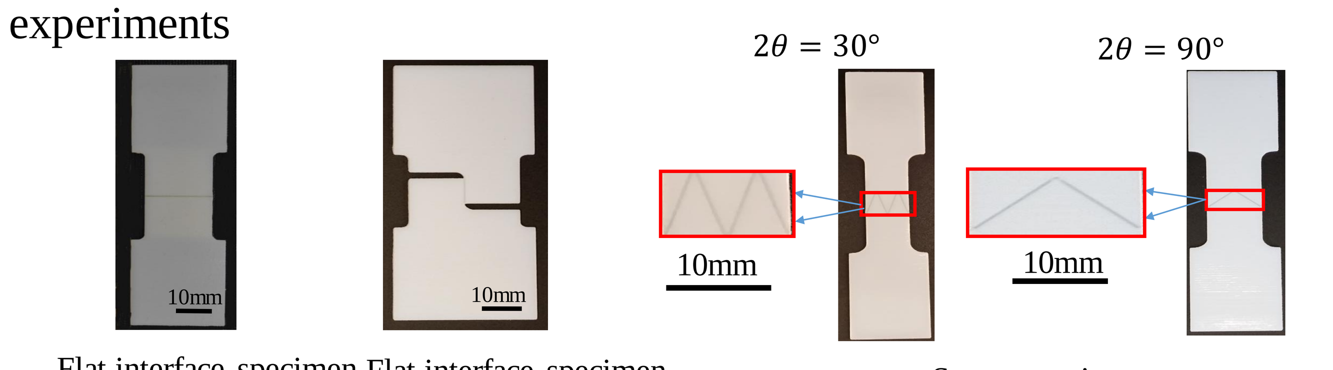


Conclusions

- The irregularity in morphology of suture interfaces can increase the ductility and damage tolerance;
- Regulating the morphological irregularity will be a powerful way to provide tunable ductility and damage tolerance to sutures.

Ongoing and Future work

- To calibrate the mixed-mode failure criteria of interfacial layer by 3D printing and experiments



- To quantify the effects of morphological irregularity through the number of hierarchy.