Effect of surface roughness of the adherend on the stress field at the crack tip of the adhesive joint

Introduction

Adhesive bonding is essential in engineering for joining dissimilar materials. While high-performance adhesives are important, surface treatment of adherends strongly affects joint reliability.

Even under cohesive failure, Mode I fracture toughness varies with surface structure, as shown experimentally [1,2] and numerically [3,4]. Our earlier work showed that **periodic geometries alter fracture resistance** [4]. Surface-induced minima in the strain energy release rate (SERR) serve as fracture initiation points. However, it addressed only local effects and lacked spatial modeling of SERR.

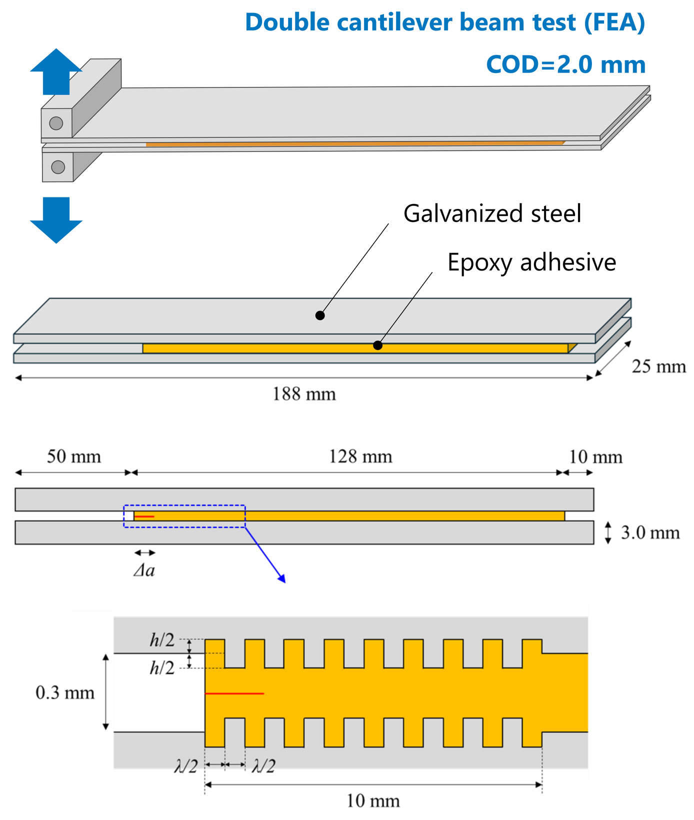
This study models **SERR as a function of periodic geometry**—pitch and height—enabling **spatially resolved,** geometry-based control of cohesive failure behavior.

Surface engineering to boost cohesive fracture resistance!

Methods

This study uses finite element analysis (FEA) to simulate crack propagation in adhesive joints with **periodically patterned** adherend surfaces. The adherend surface is modeled with **rectangular patterns defined by height h and pitch λ.**

The SERR g was first computed using the **J-integral** at varying crack extensions. Based on the obtained values, a parametric model $g(\Delta a, \lambda, h)$ was constructed. To **represent SERR fluctuations quantitatively**, the model includes a periodic sine term and was fitted using **response surface methodology**.



Results

Periodic surface roughness on the adherend causes spatial fluctuation in SERR, which is otherwise uniform for smooth surfaces (as shown in prior studies). This study newly shows that the fluctuation can be **quantitatively expressed using geometric parameters λ and h**, enabling spatial design of fracture resistance.

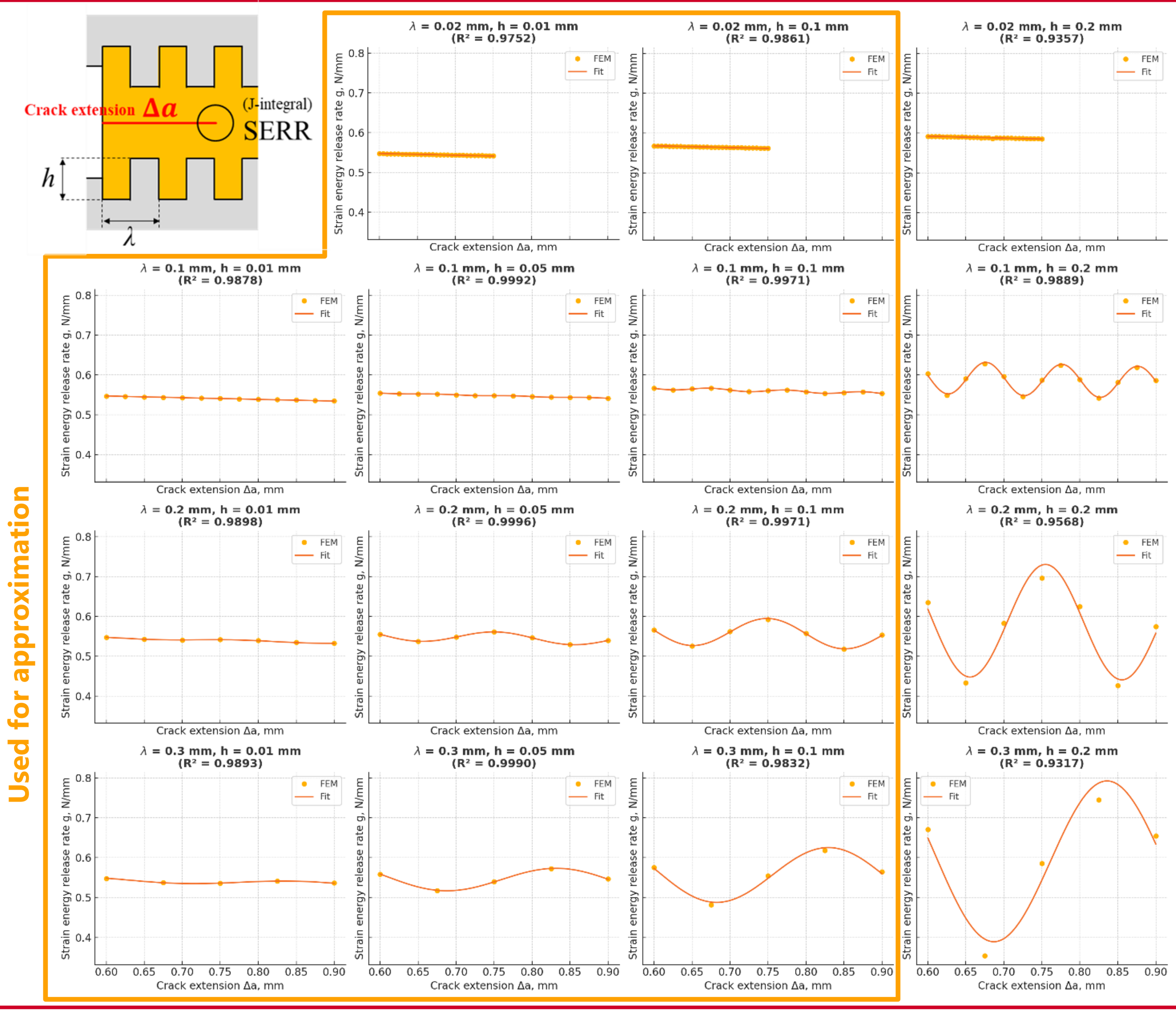
- The spatial variation of SERR $g(\Delta a, \lambda, h)$ was expressed as a function of crack extension Δa and surface geometry parameters λ, h:

$$g(\Delta a, \lambda, h) = \frac{\alpha K}{(\Delta a + 50)^4} \cdot \left(1 + \beta \cdot sin\left(\frac{2\pi}{\lambda}(\Delta a + 50) + \phi\right)\right)$$

  α, β, ϕ are geometry-dependent coefficients, $K = 3.58 \times 10^6$ is the baseline SERR for a smooth surface.
- These three parameters were approximated via response surface methodology as follows:

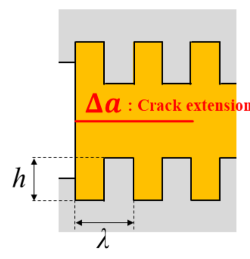
$$\alpha(\lambda, h) = 1.001 - 0.02092\lambda + 0.2796h + 0.02796\lambda^2 - 0.1498\lambda h + 1.233h^2$$
$$\beta(\lambda, h) = -0.0136 + 0.249\lambda + 0.496h - 0.737\lambda^2 - 4.92\lambda h - 2.25h^2$$
$$\phi(\lambda, h) = 3.303 - 20.200\lambda + 5.962h - 212.314\lambda^2 - 149.420\lambda h - 142.866h^2 + 850.553\lambda^3 + 2037.674\lambda^2 h - 127.301\lambda h^2 - 22.897h^3$$

- The approximation, based on FEM results within $0\,\mathrm{mm} < h < 0.10\,\mathrm{mm}$ and $0\,\mathrm{mm} < \lambda < 0.30\,\mathrm{mm}$, showed excellent fit with all R^2 values exceeding 0.97, ensuring high reproducibility and accuracy.

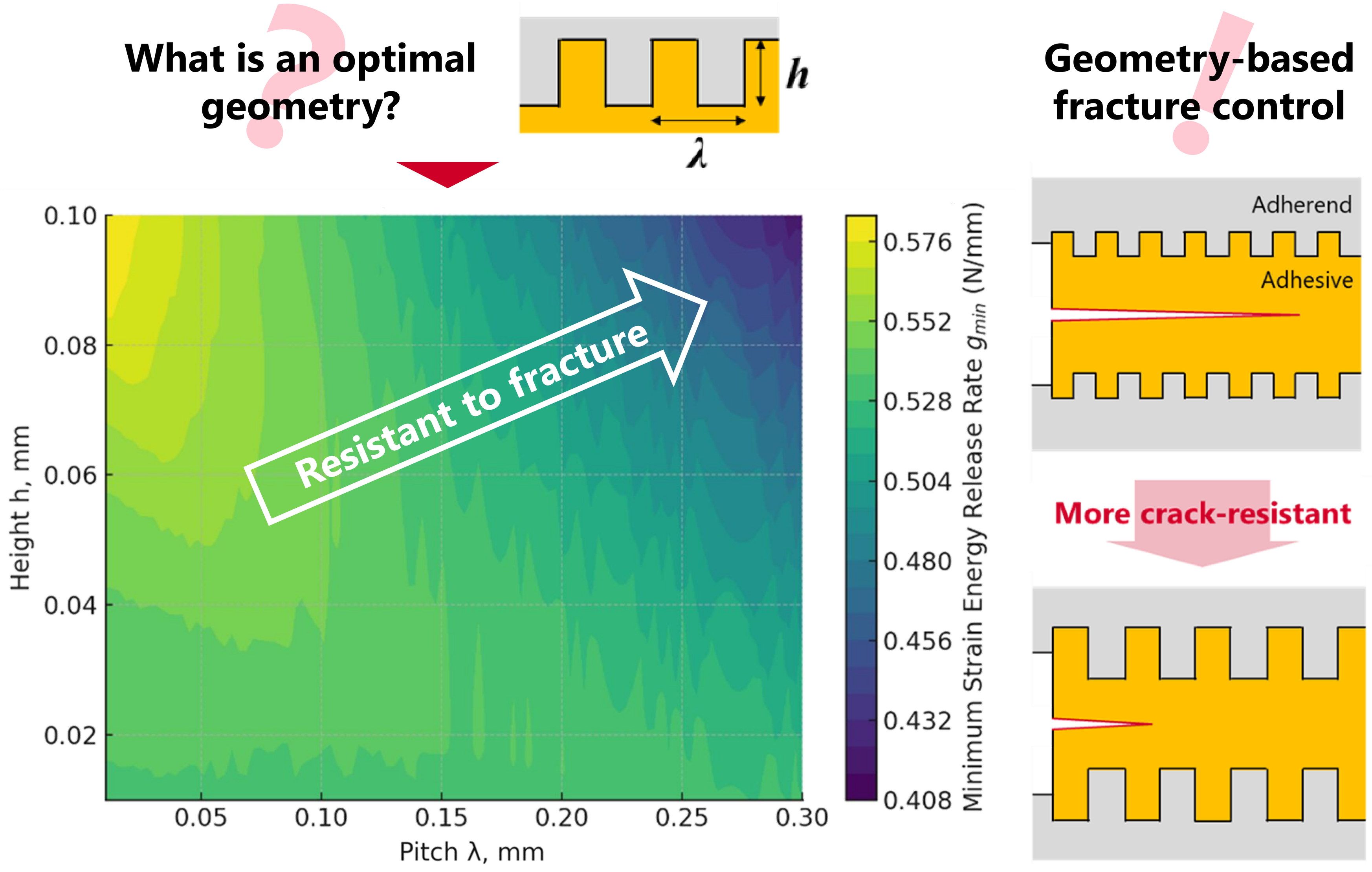


Discussion

- **Geometric dependence of SERR distribution:**
  - The **driving-side SERR** under cohesive failure exhibits **periodic spatial fluctuation** when periodic surface roughness is introduced.
  - The waveform—including amplitude and phase—of this fluctuation is quantitatively **governed by the surface geometry parameters λ (pitch) and h (height).**
- **Implications for fracture control:**
  - Variation in SERR implies that, even under identical external energy input, the **energy concentrated at the crack tip differs with geometry.**
  - This enables **intentional modulation of crack propagation** behavior through surface design.



- **Critical role of local minima in SERR:**
  - Prior work showed that local minima in $g(\Delta a, \lambda, h)$ act as rate-limiting points for fracture, based on both FEA and apparent toughness [4].
  - The right figure reveals **optimal roughness geometries** within $0.60\,\mathrm{mm} < \Delta a < 0.75\,\mathrm{mm}$ that minimize SERR—offering direct insight for crack-resistant surface design in this region.



Conclusion

- Developed a framework expressing **Mode I SERR as a function of surface geometry** (height and pitch), enabling spatial design of fracture energy **along the interface**.
- Demonstrated that surface roughness can enhance **cohesive fracture toughness**, not just prevent interfacial failure.
- Reframed fracture resistance as a designable parameter, **beyond relying solely on adhesive toughness.**

➡ Enabling spatial design of SERR via surface geometry

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STRI Sensing Technology Research Institute

R HIRAKAWA*, N TERASAKI, Y MIZUTANI, S Hartwig
*Manufacturing Sensing Research Group, Sensing Technology Research Institute

Contact: hirakawa.rio@aist.go.jp

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