Modeling and simulation of mechanical effects in two-photon lithography

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Introduction and Motivation

- Two-photon lithography (TPL) has emerged as a pivotal technique for fabricating highly intricate micro-and nanoscale structures with diverse applications.
- During the development stage, forces exerted by the solvents significantly affect the structural integrity, quality, and throughput of the fabricated components.
- Pre-fabrication collapse risk assessment would be of great significance to the

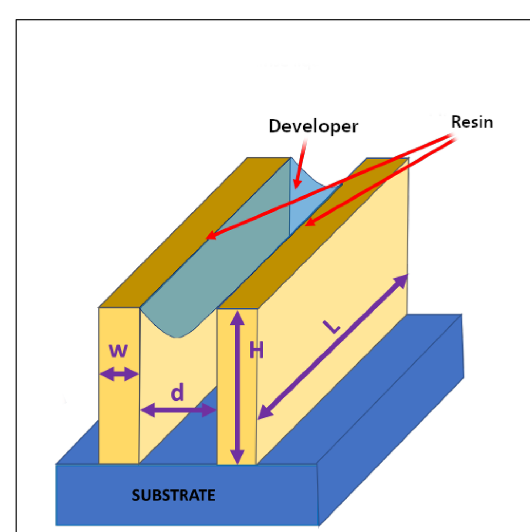
Goal

To develop a first-principles framework predicting mechanical stability limits in TPL fabricated structures.

Mathematical modeling

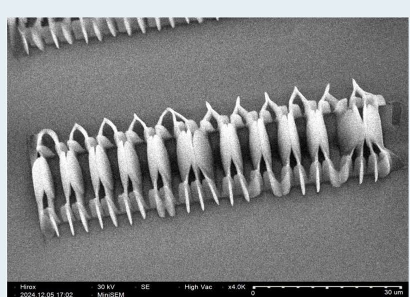
- Two approaches were considered during the formulation depending on the material properties of the resin.
  - **Structural model**
  - **Rheological model**
- The structural model considered the **Surface Tension Force (STF)** and **Laplace pressure (P)** due to the fluid present in between two pillars.
  - The critical aspect ratio was calculated to be as follows,

$$AR_{critical} = \sqrt[3]{\frac{Ed}{3PH+8\gamma \sin\theta}},$$

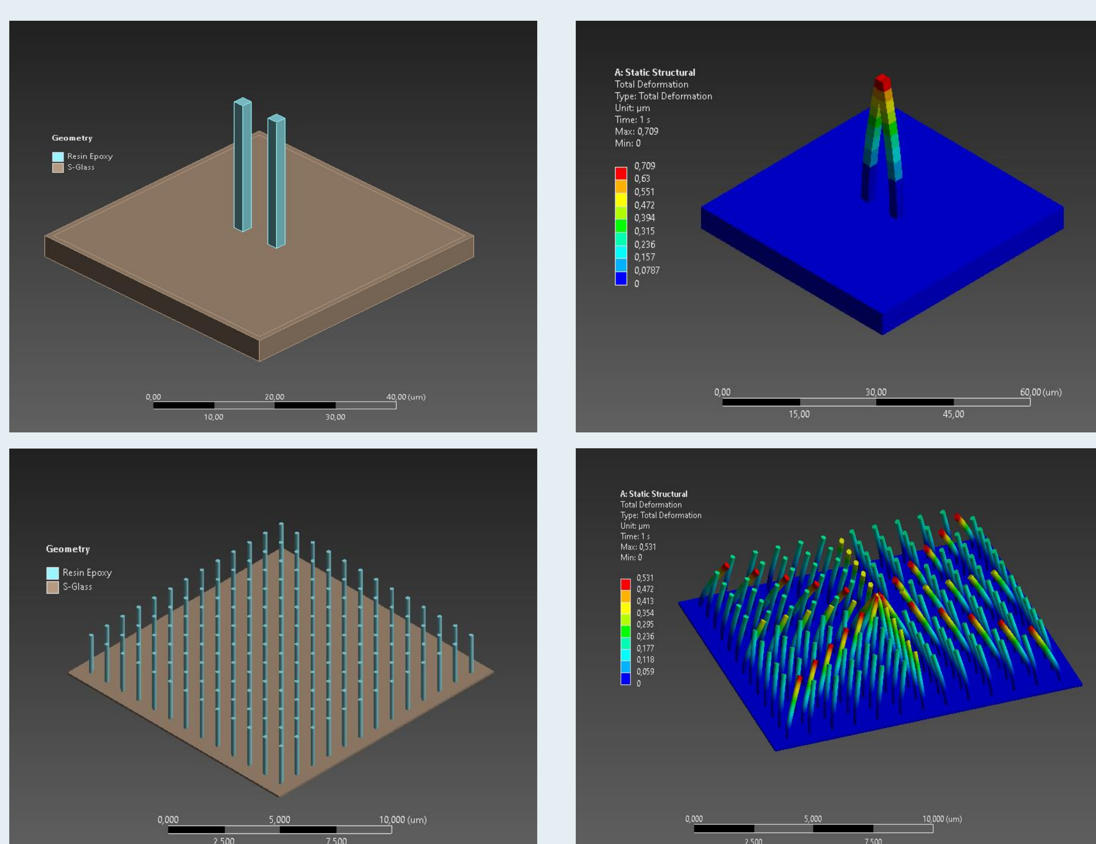


- The rheological model was formulated based on the assumption that the resin behaves as a non-Newtonian fluid.
  - It uses the finite volume method with a **non-linear viscosity model** to capture the flow behaviour of the resin.

Finite element simulations



Simulations show comparable results to the experimental data (shown above).



Model applications

- Both **analytical and FEM models (Figure 1)** show that total deformation of pillars increases rapidly with aspect ratio, and structures with lower Young's modulus are far more prone to collapse at high aspect ratios.
- **Stability map (Figure 2):** Visualizes how the critical aspect ratio for collapse depends on both pillar spacing and aspect ratio, clearly separating stable and unstable fabrication regions.

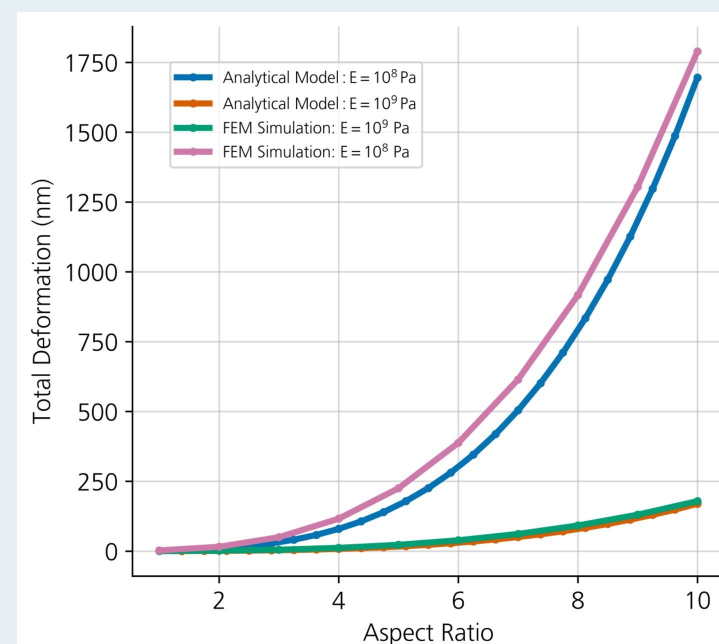


Figure 1: Comparison of the analytical and finite element model

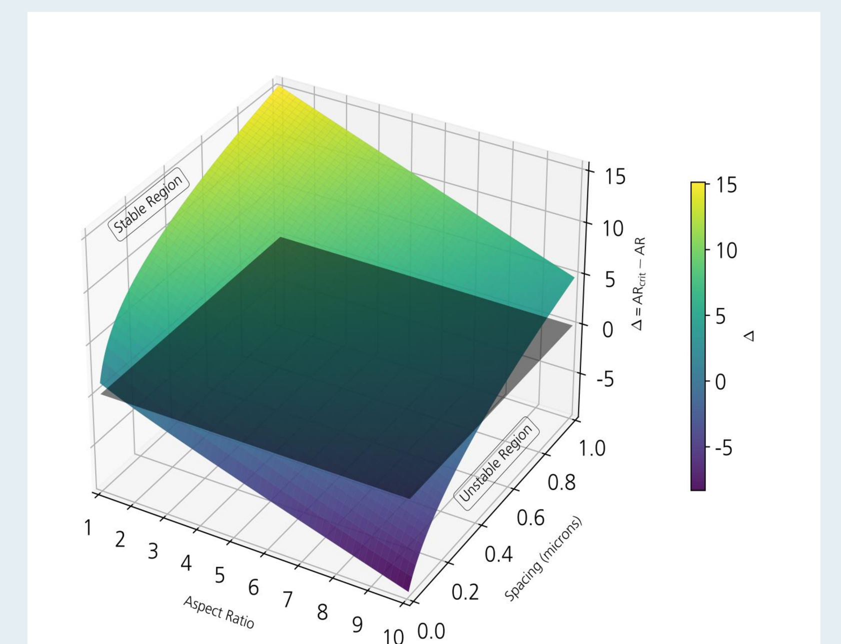
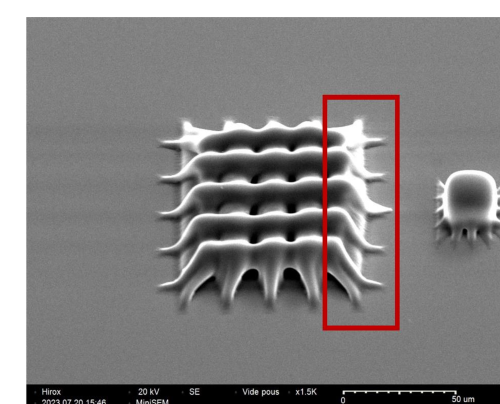
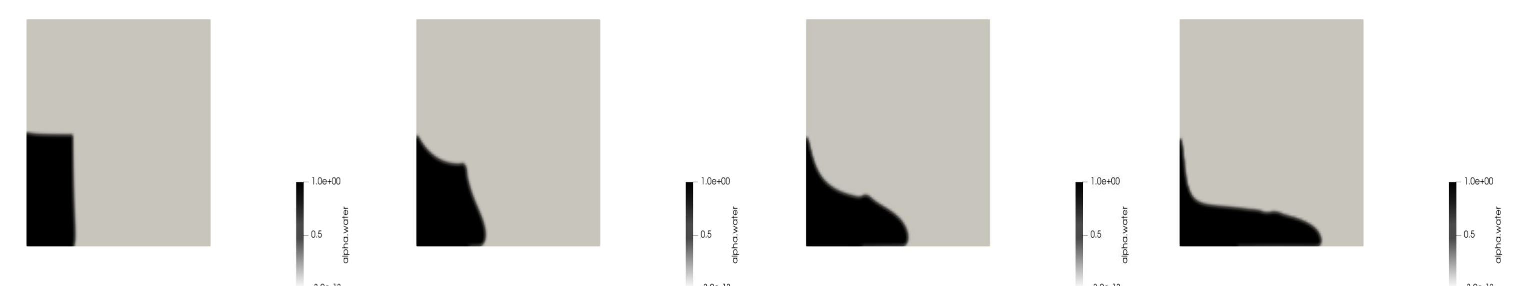


Figure 2: Stability map based on the critical aspect ratio

Rheological simulations

- The softer resins tend to show a gradual collapse, mainly due to the external forces acting on the sidewalls.
- The **Bird-Carreau model** was chosen to capture the non-linear behaviour.





Conclusion

- Pillar collapse is a highly non-linear process that could depend on a variety of factors apart from the capillary forces considered here.
- The analytical model shows agreement with the finite element simulations performed on ANSYS, thereby helping in verification.
- The critical aspect ratio can be used as a guidline for experimentalists to mitigate collapse in their structures.

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