Numerical Analysis of Strong Buckling Behavior of Square Thin Membranes using ABAQUS

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ES240 Project

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Outline

- Motivation: design of thermomechanically stable thin films
- Project goal
- Method : pressure application
- Results
  - Code validation: comparison with experiments
  - Stress evolution with geometry change
  - Effect of Poisson’s ratio
  - Stress evolution with temperature change
- Discussion: deviation of FEM results from experimental/analytical results
- Conclusion: effectiveness of this model
- Suggested future work

Motivation

- Released thin film structure for micro solid oxide fuel cell (μSOFC) to increase efficiency
- Residual stress in the film due to fabrication process
- Operation at high temperature required for the electrolyte (Yttria-stabilized Zirconia)

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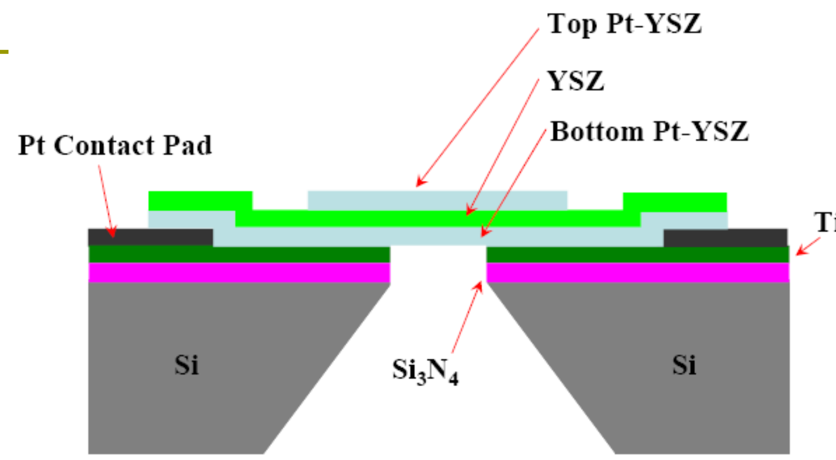
- Failure of thin membranes
- Design (geometry, material property, residual stress) to avoid high stress concentration/failure is critical



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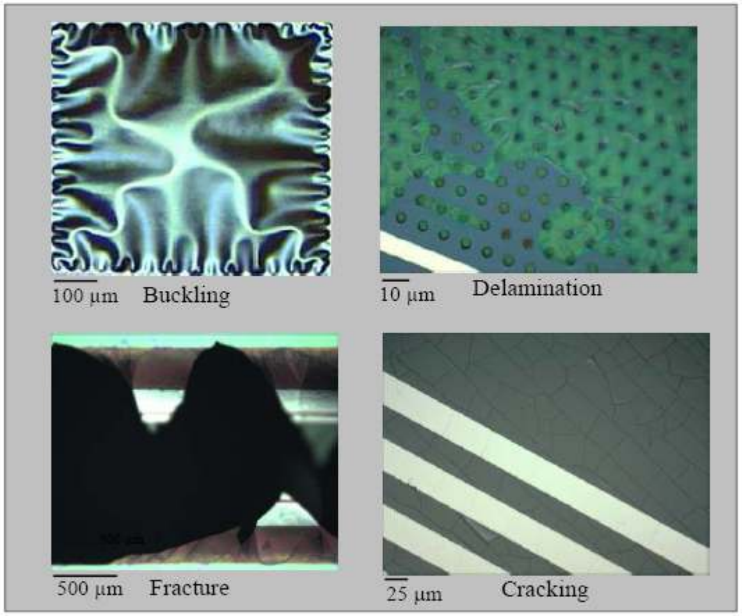
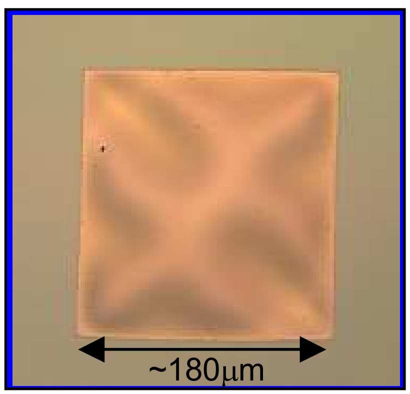


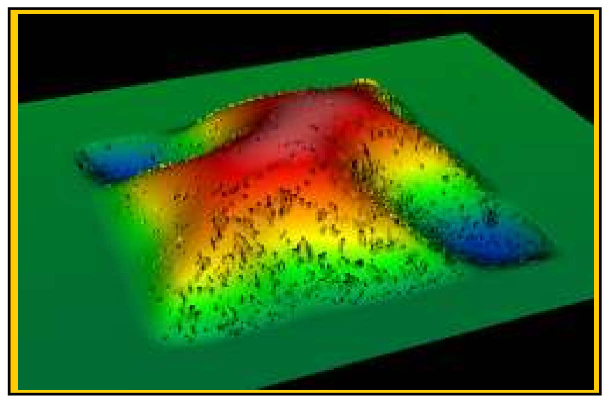
Project Goal

To achieve thermomechanically stable membrane design

- Analytical prediction is hard due to non-linearity
- Experiments require significant efforts

- *Model square thin membranes under in-plane stress with finite element method, and predict their buckling behavior including deflection and stress states*





Yttria-stabilized Zirconia (YSZ), ~500nm-thick, buckled after cooling from ~600C after fabrication

Numerical Simulation Method

- Software: ABAQUS v6.6
- 3D deformable shell plate

sidelength 5-1000μm >> thickness ~300-600nm

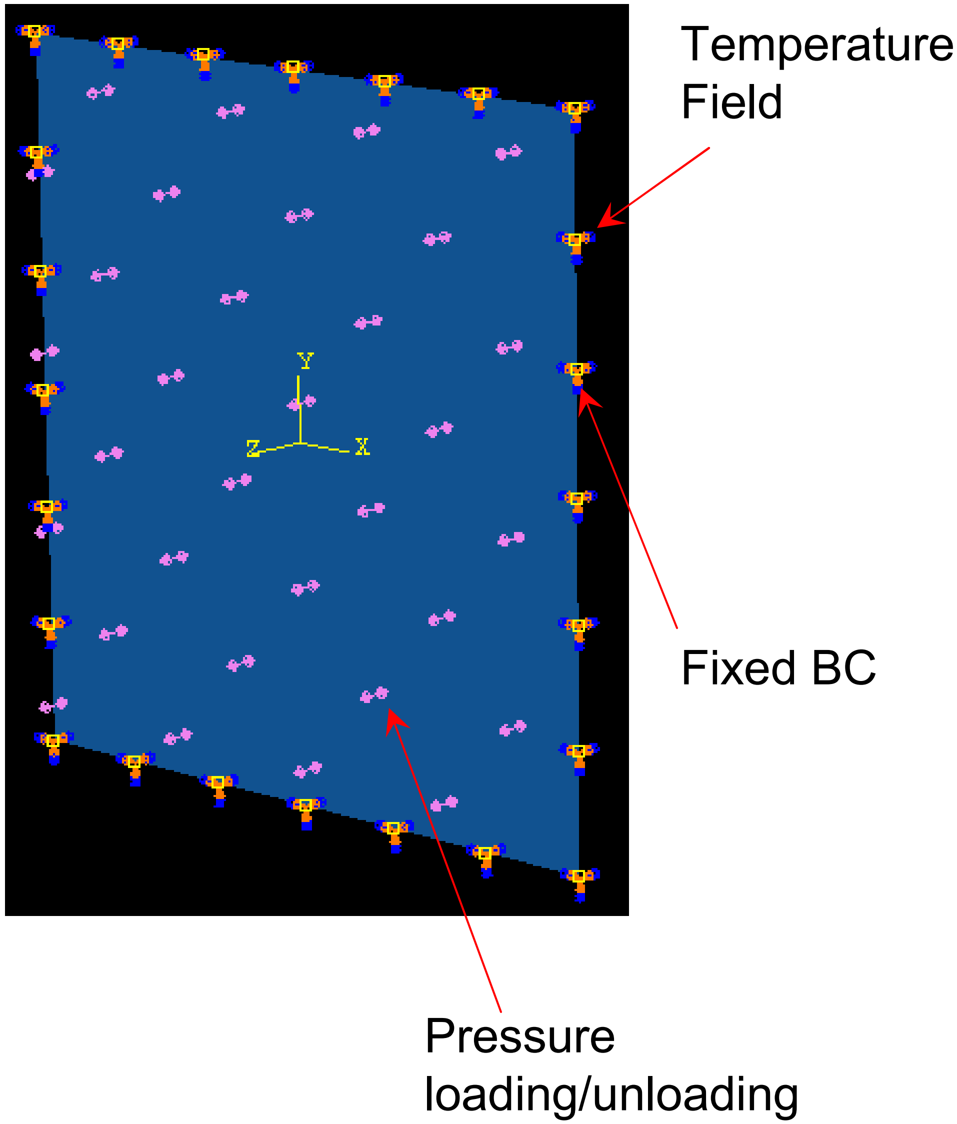
- Assumption: isotropy, no plastic deformation, single-layer
- Material Properties of YSZ
  - Young's modulus: 64 [GPa]
  - Poisson's ratio: 0.2
  - CTE: 11.4 [10^{-6}/K]
- Boundary condition: 4 sides fixed
- Mesh number: ~10x10

Stress Load Application [Ziebart and Paul, 1999]

- Possible numerical instability at critical buckling points (eigenvalue calculations)
- Thermal simulation of in-plane residual stress
  - Pressure loading to buckle a membrane
  - Thermal loading with temperature field to apply corresponding prestress

$$\sigma_0 = -(\Delta T)E\alpha/(1-\nu)$$

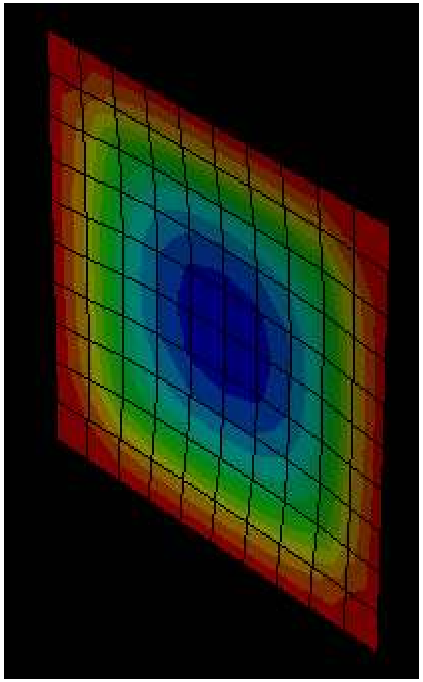
  - Pressure unloading



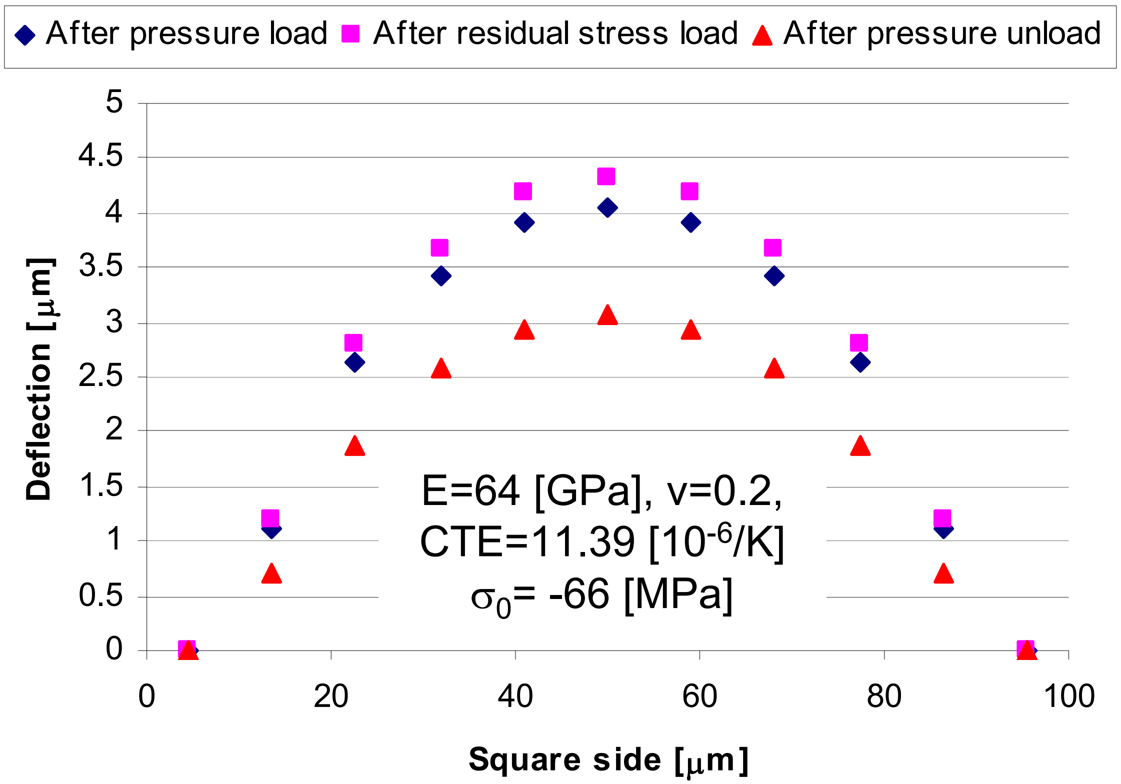
Results: Deflection Profile after Each Step

- Successfully buckled membranes with center deflection in the right order

3.07 μm (FEM) vs. average 2.46 μm (Experiment)

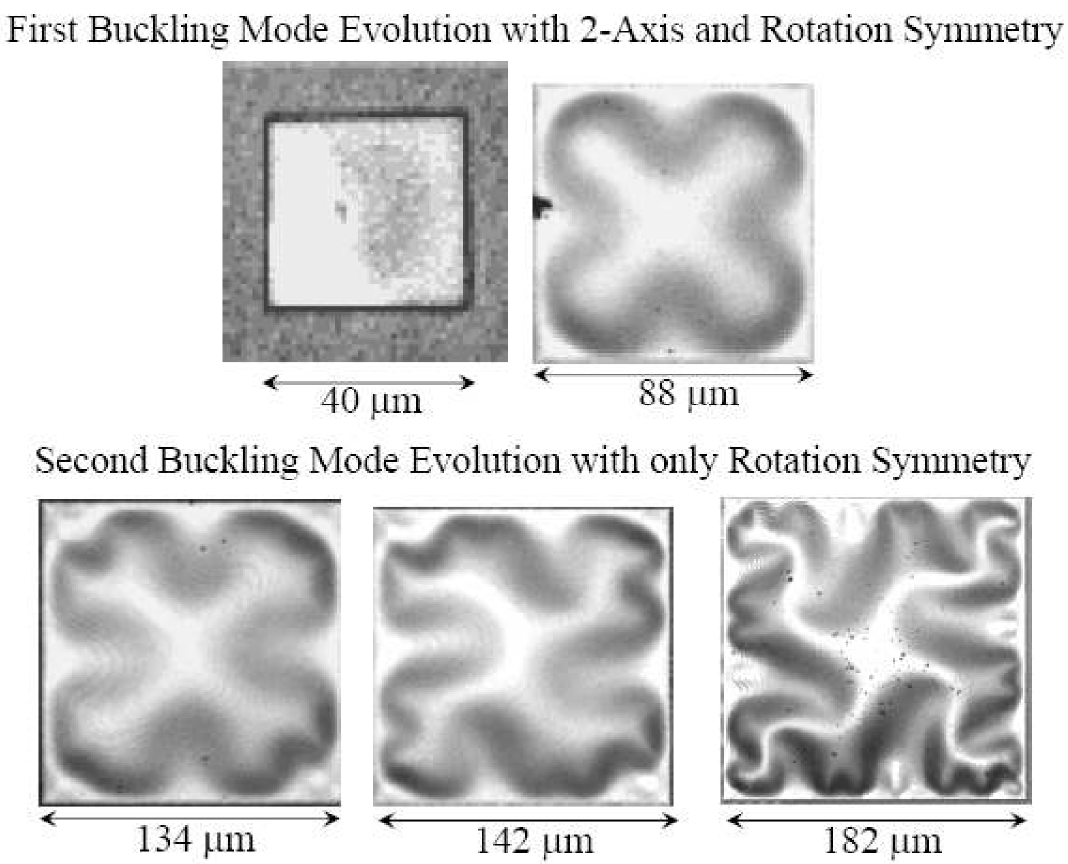


Deflection distribution
Sidelength 100 [μm]
Thickness = 625 [nm]



Results: Buckling Pattern Evolution with Sidelength (Experimental)

- First buckling mode : 2-axis and rotation symmetry
- Second buckling mode: only rotation symmetry

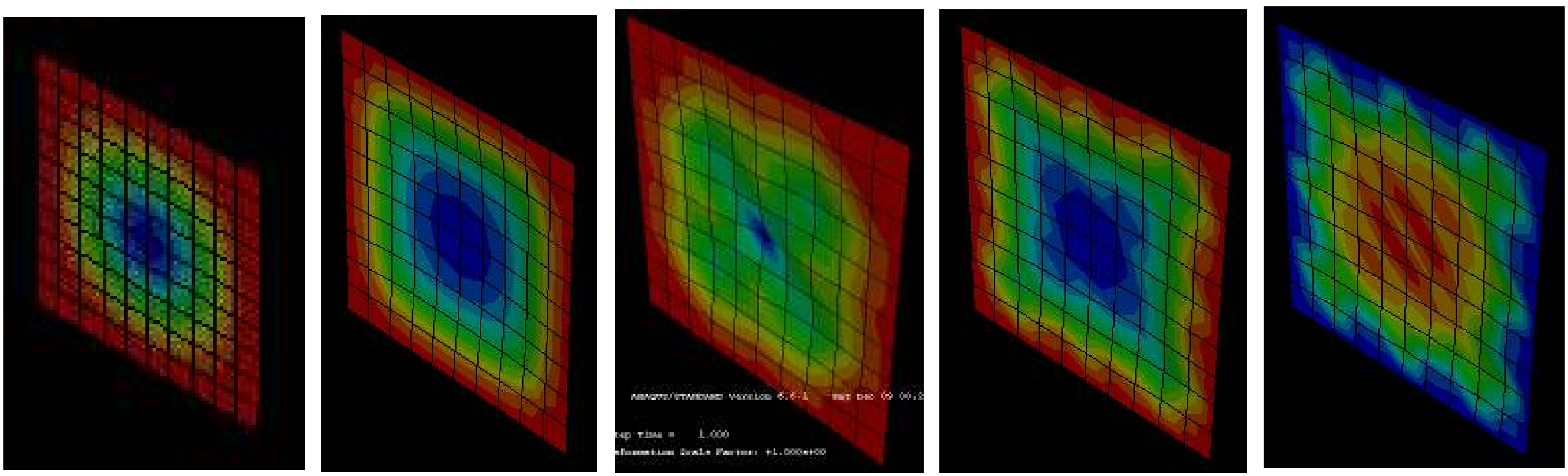


E=24 [GPa], v=0.2,
CTE=9.74 [10^{-6}/K]
σ_0= -38 [MPa]
thickness= 368 [μm]

Results: Buckling Pattern Evolution with Sidelength (FEM)

- Followed first and second buckling modes with increasing sidelength as experiments

E=64 [GPa], v=0.2, CTE=11.39 [10^{-6}/K] σ_0= -66 [MPa] thickness=625 [nm]

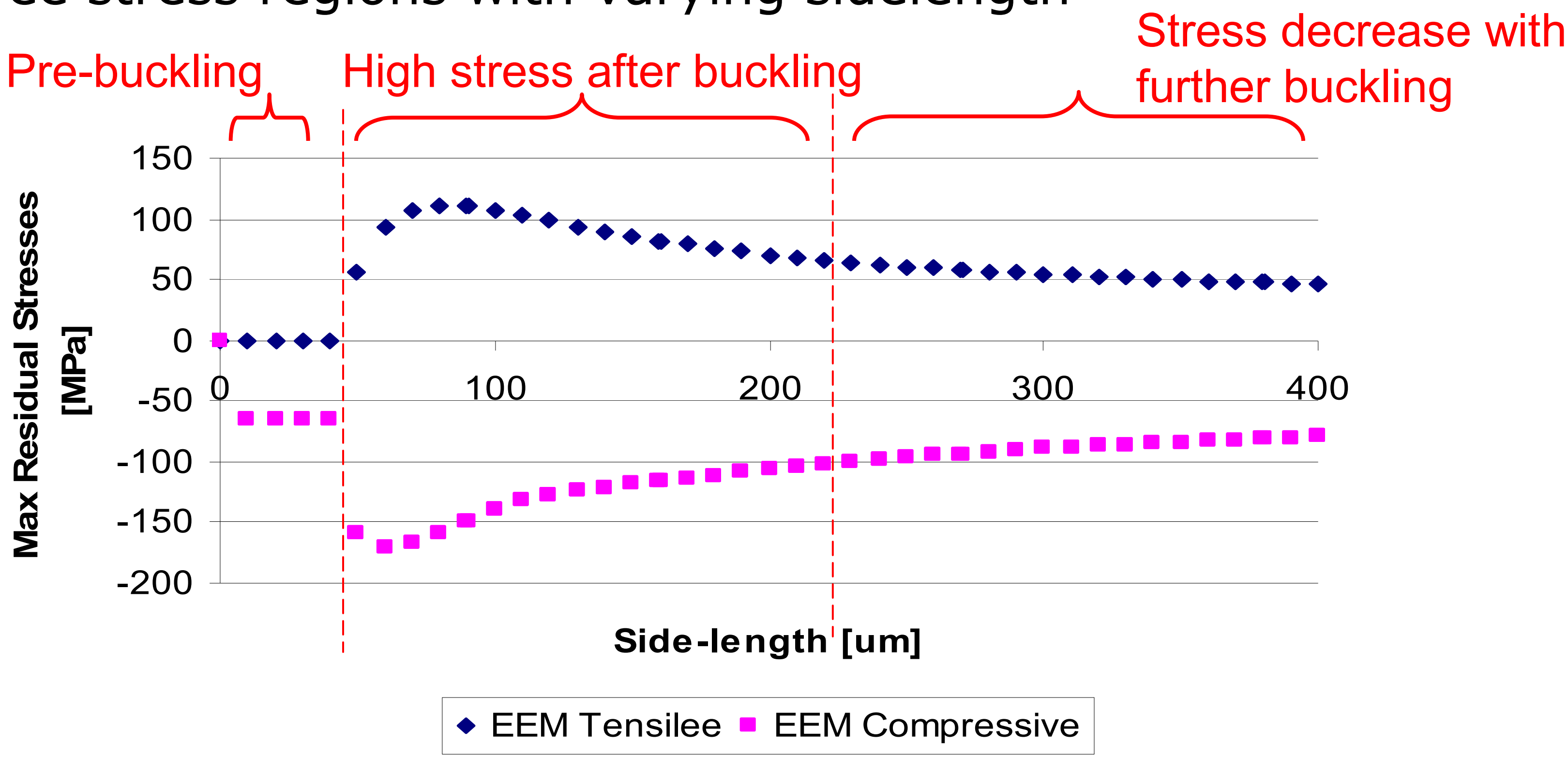


Sidelength: [not in scale]

20μm 100μm 300μm 500μm 1000μm

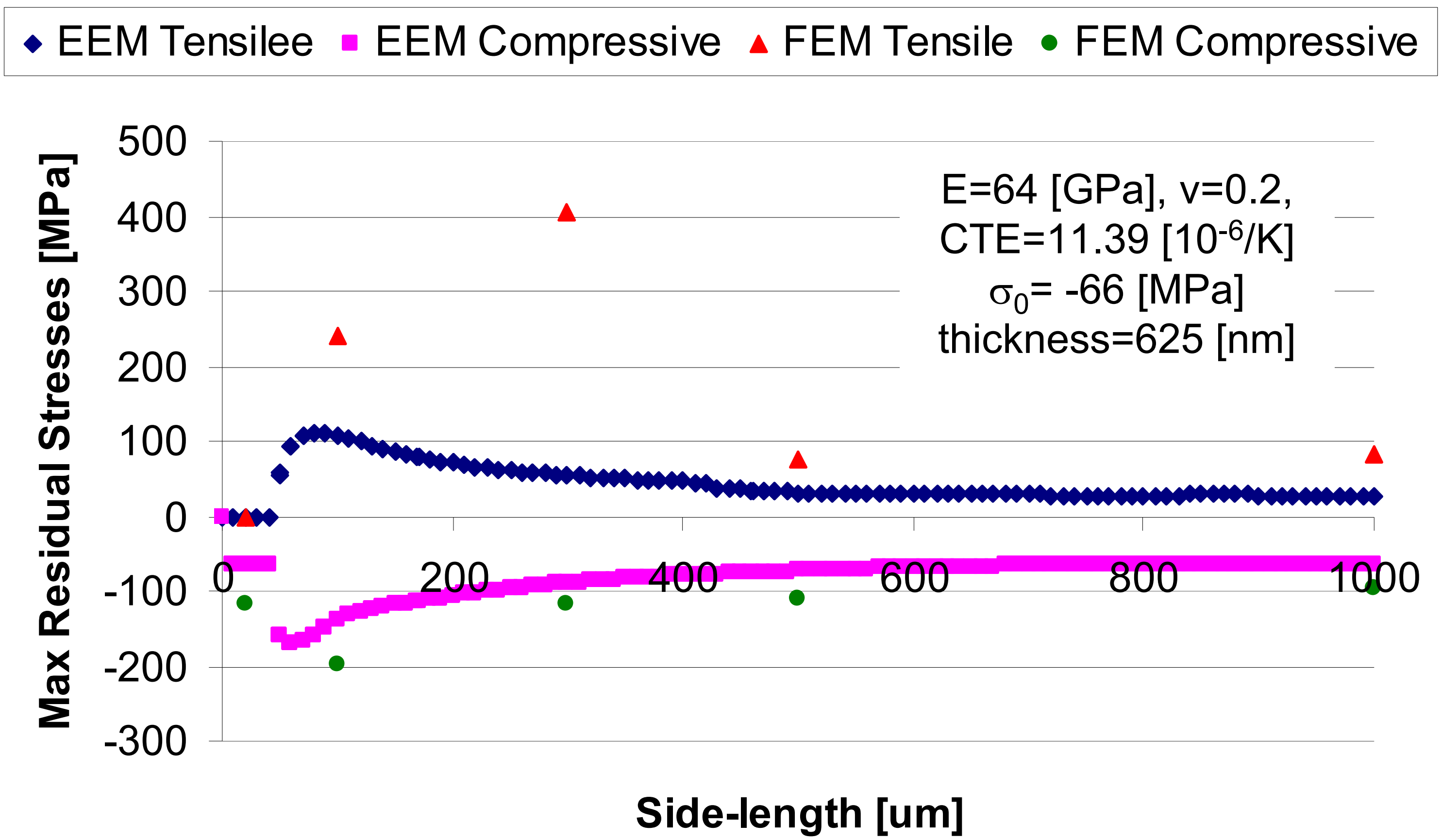
Results: Stress Evolution with Sidelength (EMM)

- Energy Minimization Method (EMM)
  - Model deflection from observed symmetry (only 1st mode)
  - Minimize strain energy to obtain coefficients of deflection function
  - Calculate stress from the deflection
- Three stress regions with varying sidelength



Results: Stress Evolution with Sidelength (FEM)

- Maximum in-plane stress obtained from FEM showed similar tendency with EMM results, but higher compressive stress



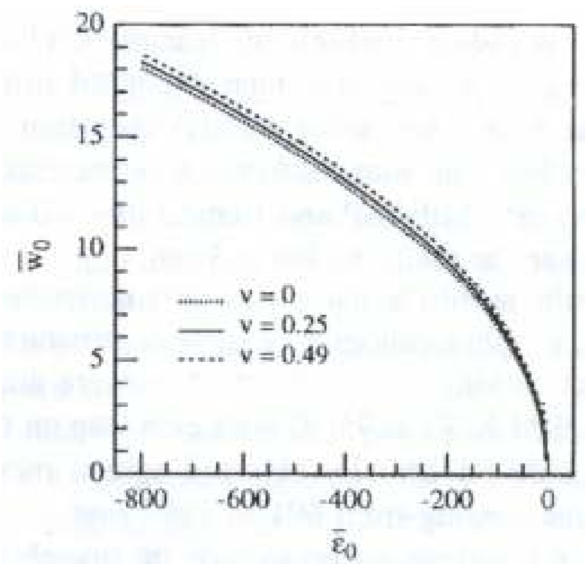
Results: Effect of Poisson's Ratio on Center Deflection

- Calculated the center/max deflection of membranes with varying Poisson's ratio
  - Poisson's effect has little effect on the center deflection
  - This result coincides with Ziebart and Paul's analysis (Journal of MEMS, 1999)

E=64 [GPa], v=0.2, CTE=11.39 [10^{-6}/K]

σ_0= -66 [MPa] thickness=625 [nm]

Poisson's ratio	Center deflection [μm]
0.15	3.11
0.2	3.06
0.25	3.01

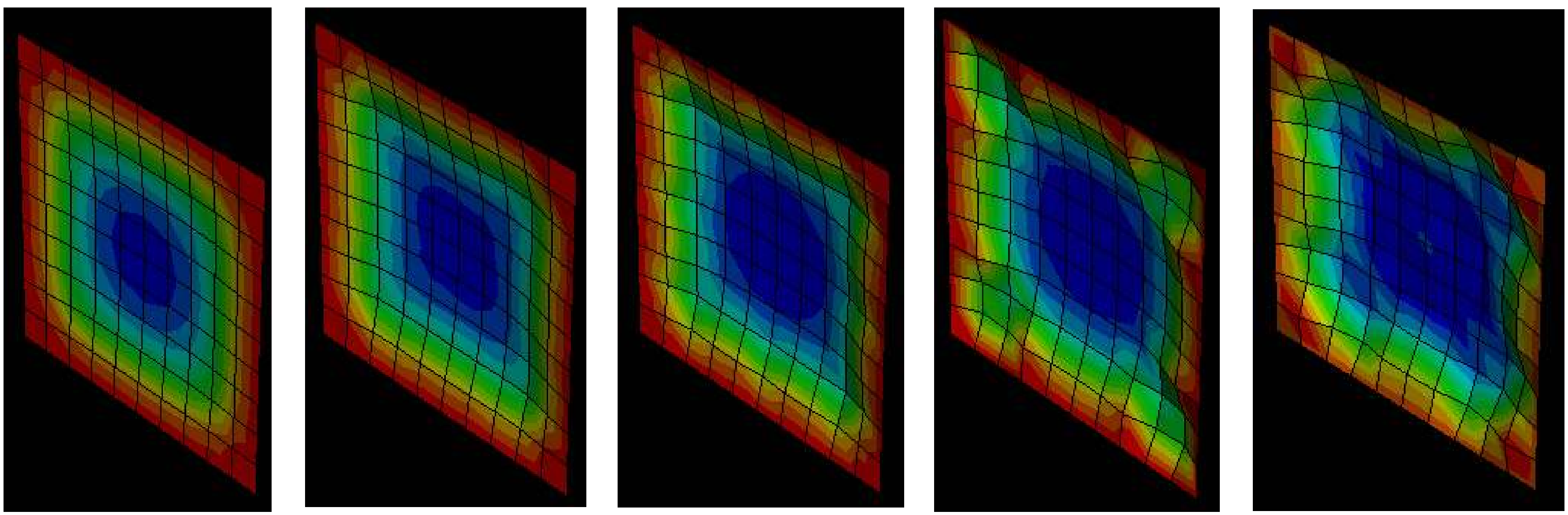


[Ziebart and Paul, 1999]

Results: Pattern Evolution with Temperature

- Again, followed the first and second buckling modes with increasing temperature

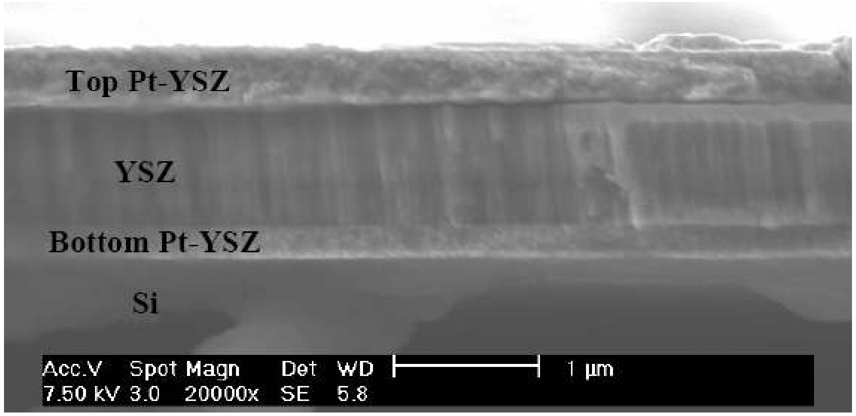
E=64 [GPa], v=0.2, CTE=11.39 [10^{-6}/K], thickness=625 [nm], sidelength = 100 [μm]



ΔT: 100C 1000C 1500C 2000C 2500C

Discussions

- Deviation of FEM results from EEM/experimental results is possibly due to
  - Assumptions: no plastic deformation (observed), no expansion of Silicon substrate, uniformity (thickness variation)
  - Small number of meshes
  - Experimental measurement errors
  - EMM analysis which includes only 1st mode buckling



Conclusions

- Buckling behaviors due to residual stresses were successfully modeled with thermal loading.
- Pattern evolutions ($1^{st,}$ 2^{nd} order) with increasing sidelength were predicted.
- Stress evolutions with increasing sidelength, including three regions, were predicted.
- Effect of Poisson's ratio on center deflections of buckled membranes was confirmed to be weak.
- Stress/deflection evolutions with increasing temperature were predicted.

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This simple FEM analysis can produce preliminary prediction of buckling behavior (stress, deflection) of thin membranes under residual stress or thermal loading.

Suggested Future Work

- Improvement in modeling
  - Mesh size, number
  - Material property (include plasticity)
  - Modeling of substrates
- Modeling of tri-layers structure (Pt-YSZ/YSZ/Pt-YSZ) of μSOFC

Thank you!