Influence of Thermally-Grown Oxide (TGO) Layer on the Driving Forces Associated with Failure in Environmental Barrier Coating (EBC) Systems

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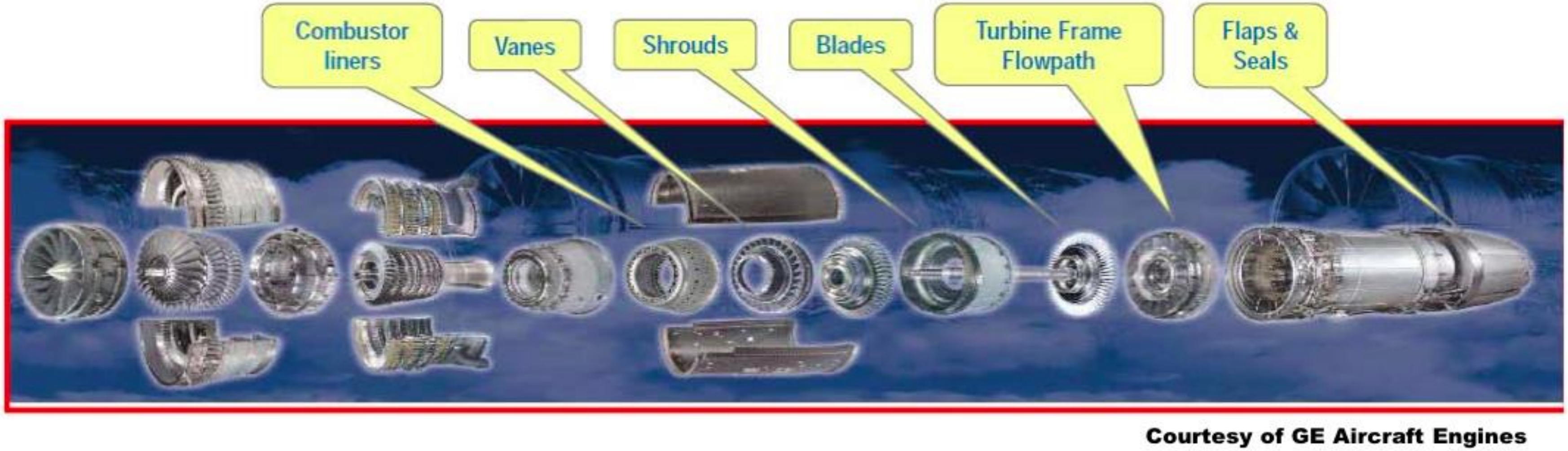
CMCs for Gas Turbine Engines



Benefits:

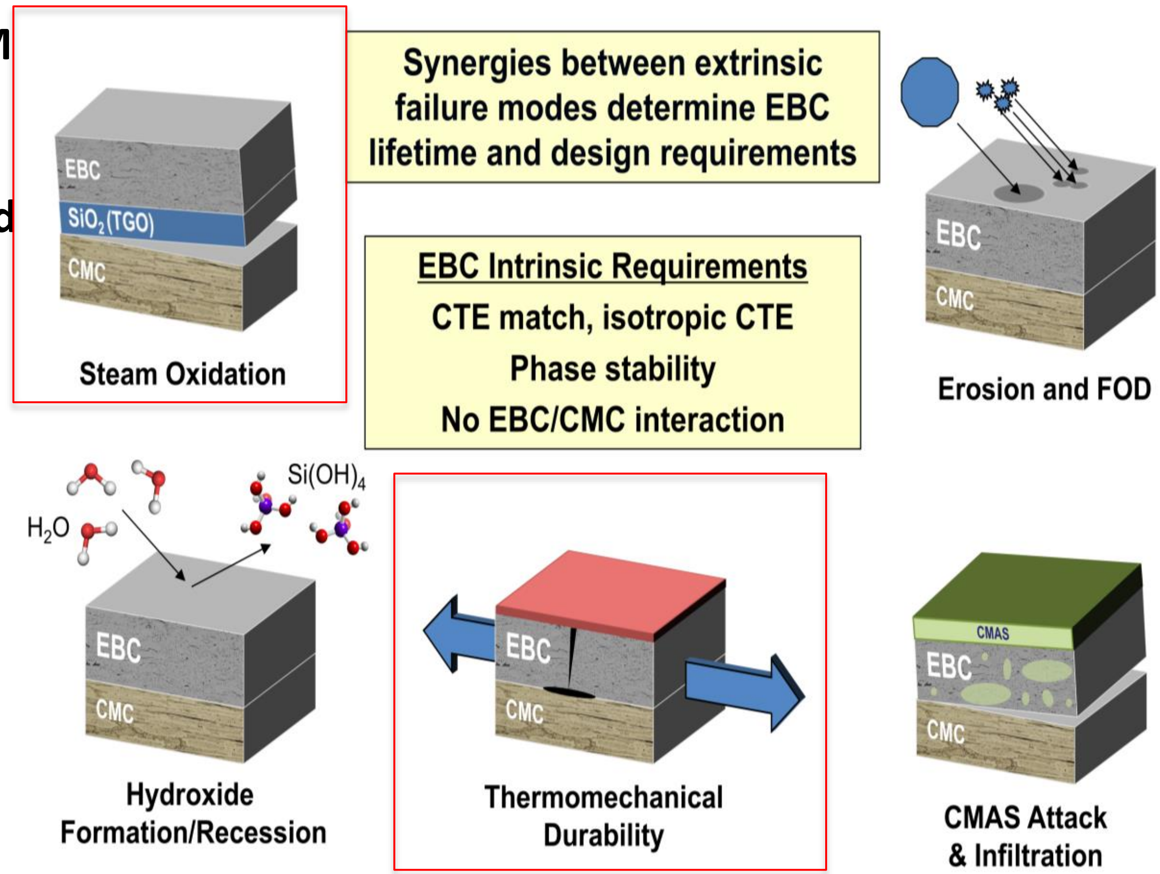
- Enabling for high OPR engines (high turbine inlet temperatures)
  - 200 to 500+ °F temperature advantage over metals
  - Reduce cooling air
  - Reduce fuel burn (up to 6%) - NO_2 emissions
- Weight – 1/3 of metals and 1/2 titanium aluminides
- CMC combustor liner and first stage turbine vane reduce NO_X
- **An external environmental barrier coating (EBC) made of layers of oxides/silicates is required to achieve long-term stability and component life.**

Environmental Barrier Coating (EBC) Systems

- 1st Gen of EBCs were developed in 1990s under NASA's HSCT-EPM (High Speed Civil Transport – Enabling Propulsion Materials) program consisting of mullite and BSAS materials.

- 2nd Gen EBCs were developed under NASA's UEET (Ultra Efficient Engine Technology) program in early 2000s. Most of the current EBCs are some variation of 2nd Gen EBCs.

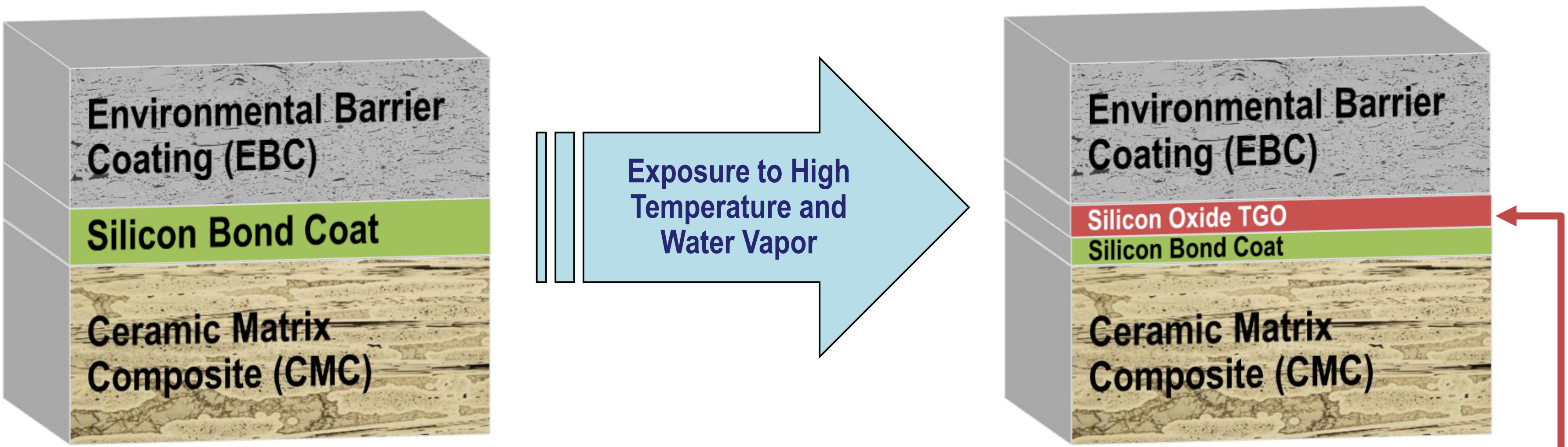
EBCs have various failure modes.



K. N. Lee, "Environmental Barrier Coatings for CMC's"; in *Ceramic Matrix Composites*, Wiley, New York (2015)
K. N. Lee, J Am Ceram Soc. 2019:1507-1521

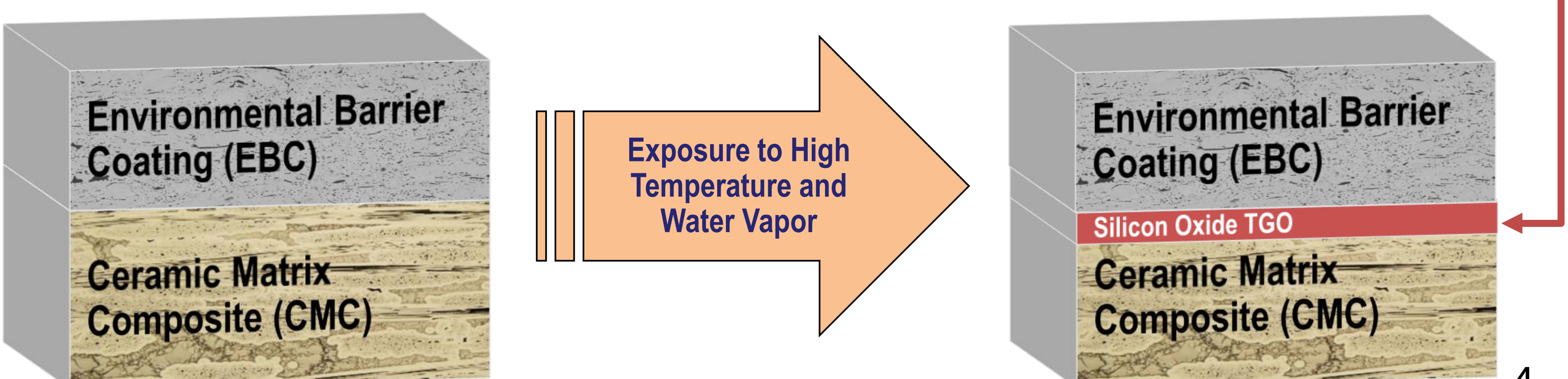
Environmental Barrier Coating (EBC) Systems

Low Temperature System (< 1316°C)



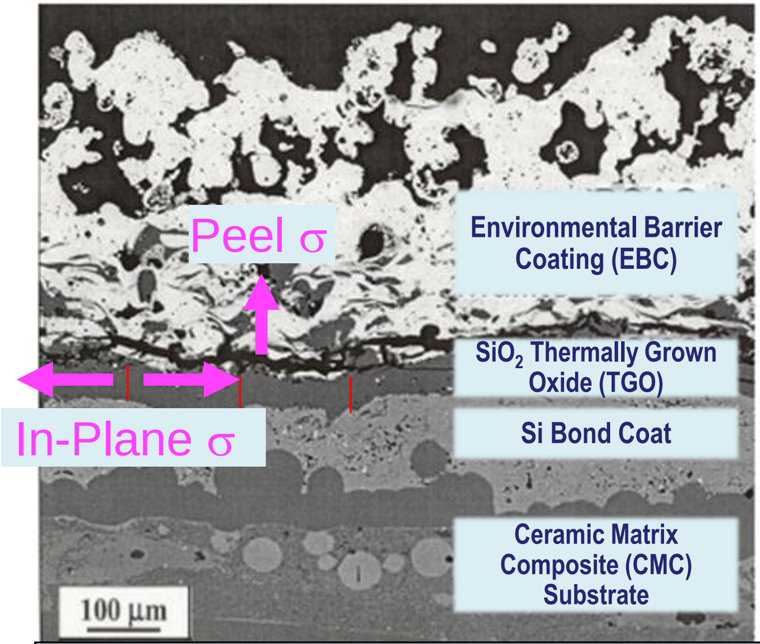
Thermally Grown Oxide (TGO) is the Observed Point of Failure

High Temperature System (> 1316°C)



Environmental Barrier Coating (EBC) Systems (contd.)

- Although durable, EBC systems must survive for 10,000+ hours
- Lifetime of EBC/CMC systems is limited by the formation of a thermally grown oxide (TGO)
  - SiO_2 TGO can grow on either silicon bond coat or SiC substrate
- Observed failures
  - Vertical Cracks **(~10 μm spacing at failure).**
  - Horizontal Cracks (Delamination)
- EBC fails when TGO reaches some critical thickness (~ 20-40 microns)
  - Can vary due to exposure temperature, microstructure, composition, etc.



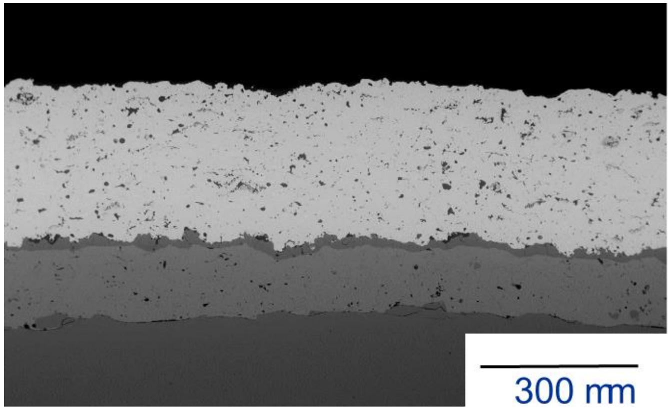
Environmental Barrier Coating system after 15,144h test

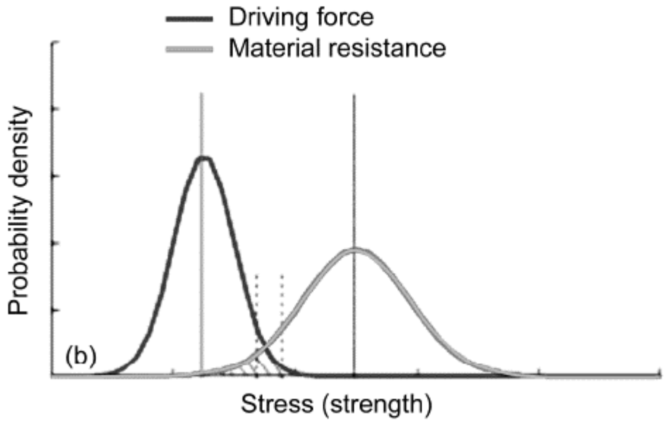
Ultimate Goal: Predict the durability of EBC/CMC system when subjected to harsh environments

J. Kimmel et al., ASME paper GT2003-38920, ASME TURBO EXPO, Atlanta, GA, USA, June 16-19, 2003.

Current Study Objective

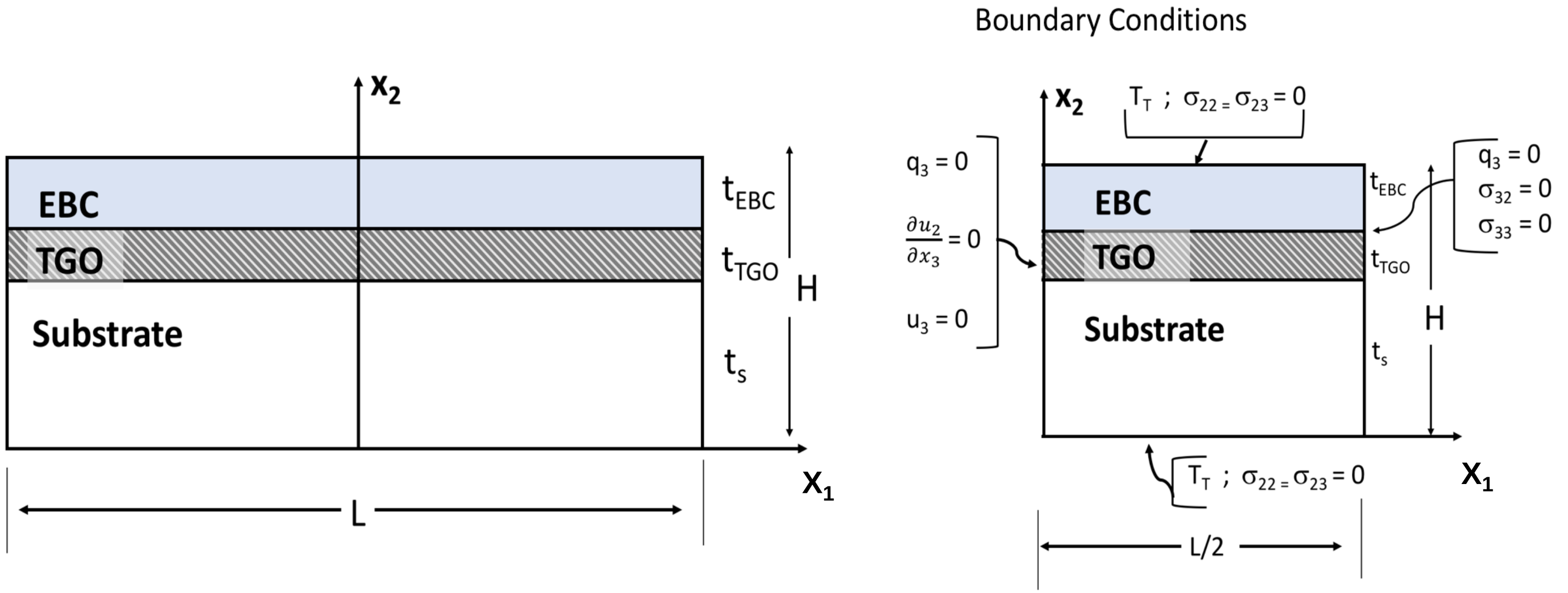
- Perform **finite element analyses** to examine the influence of uniformly and nonuniformly grown oxide layers on the associated driving forces leading to mechanical failure (spallation) of EBC layer when subjected to isothermal loading
- **Assess the effect of damage** in the TGO layer in the form of vertical cracks for both uniform and non-uniform TGO layers**.**
    - Ignore residual stresses due to processing, cyclic loading effects, growth rate of TGO as well as any time dependent behavior (creep/relaxation)
    - **Qualitative** not quantitative study
    - What influences critical TGO thickness
- Examined 3 layer and 4 layer systems





Idealization of Three Layer System

With Geometry And Applied Thermal And Mechanical Boundary Conditions



- Global loading is cool-down from 1482ºC to 38.7ºC (2700 °F to 102 °F)
- Applied in one step since material assumed to be linearly elastic
- Stress state is generated due to geometry and mismatch in constituent material properties

Two-dimensional finite element analyses are performed using ABAQUS finite element program.

Constituent's Material Parameters

- Assume isotropic thermoelastic properties

Material	Thickness (mm)	Modulus (GPa)	Poisson Ratio	CTE ($x10^{-6}$ K^{-1})	Strength (MPa)
$Yb_2Si_2O_7$ (EBC)	0.175	200*	0.27	4.5	45-65 (?)
SiO_2 (TGO)	0.001 0.002 **0.004** 0.008 **0.016**	35*	0.17	10	45-75 (200)
Si ** (Bond Coat)	0.075	97*	0.21	4.5	40-55 (?)
Hexoloy SiC (Substrate)	3.000*	400	0.17	5.25	380-550

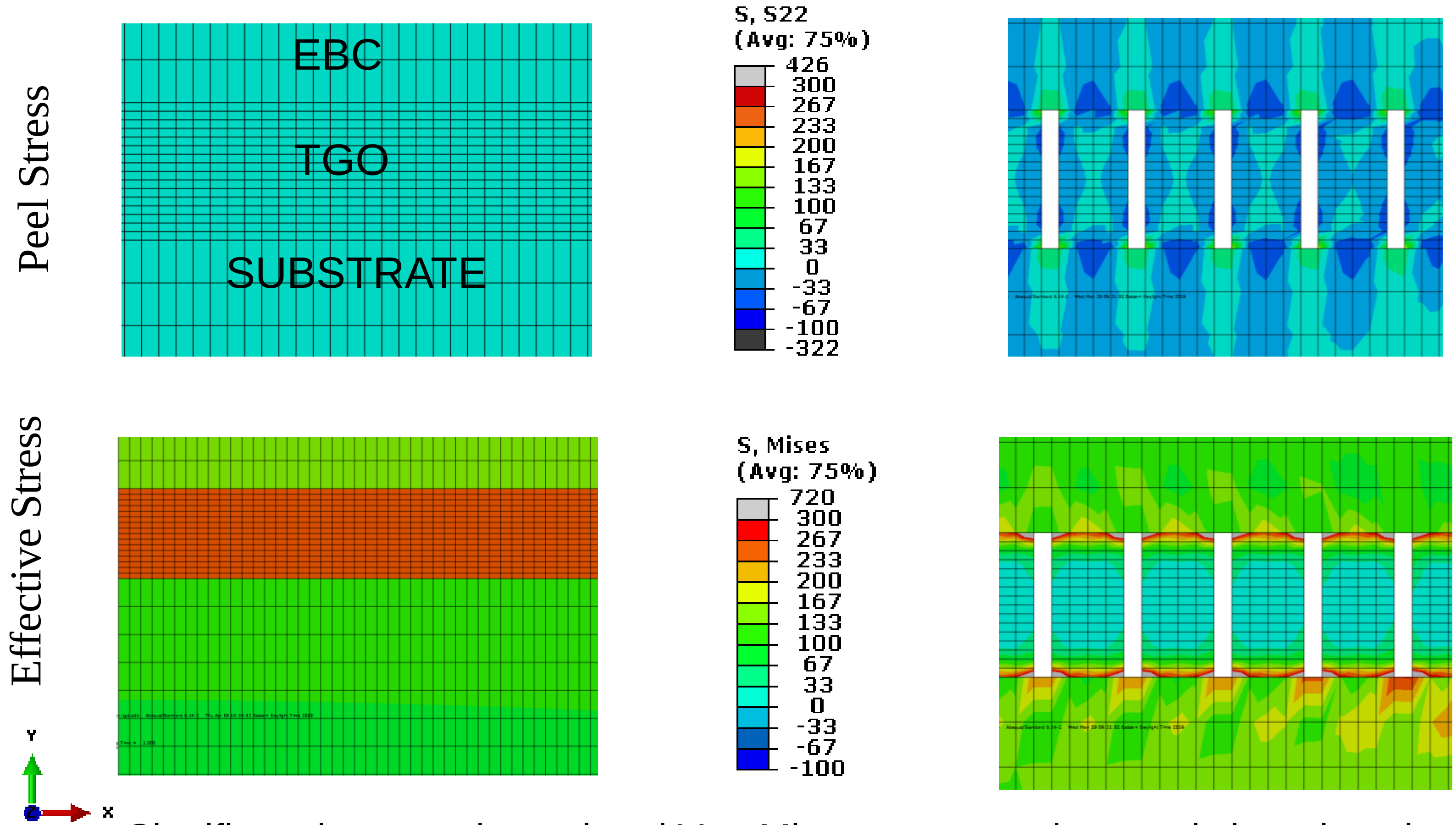
* Initial thickness assuming no TGO, bond coat

** If present

Two TGO thicknesses (4 and 16 µm) have been analyzed here with both uniform and non-uniform TGO layer thickness.

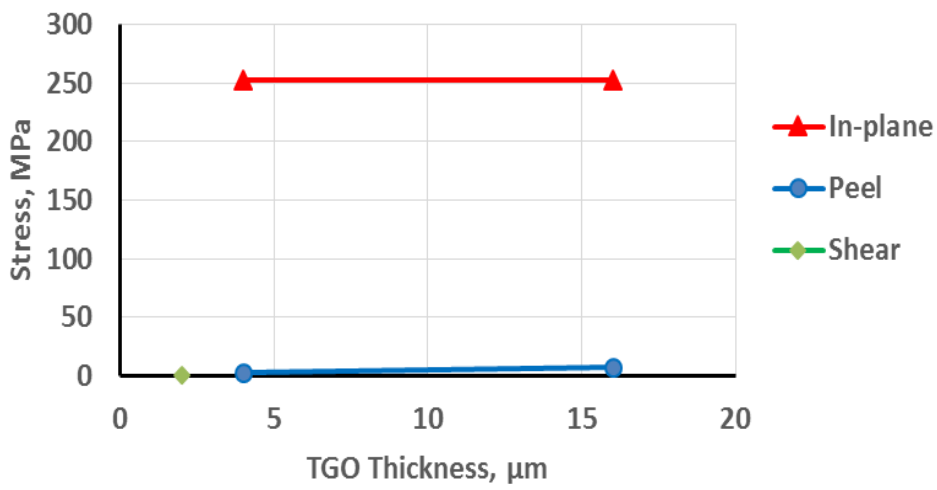
Results: Uniform 3 Layer System

Undamaged (16 μm TGO Layer) | **Damaged (16 μm TGO Layer)**

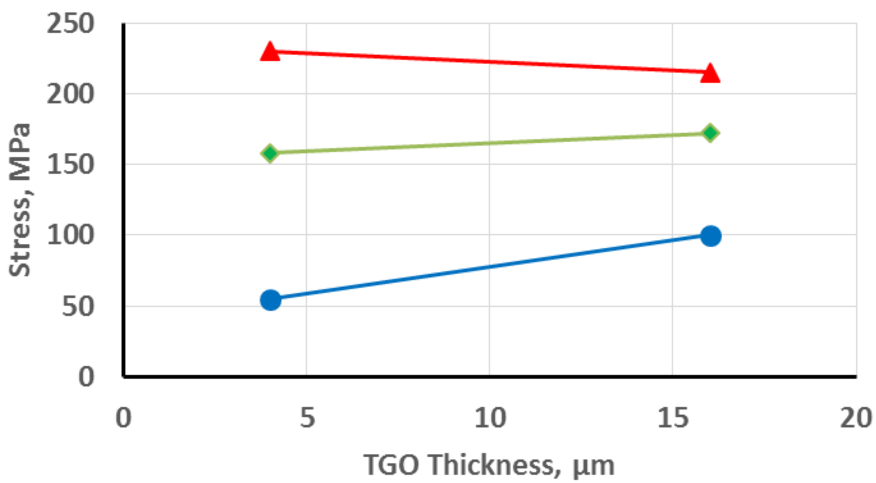


- Significant increase in peel and Von-Mises stress as damage is introduced. Peel stress increases from a negligible value when there is no damage to **~100 MPa** at EBC/TGO interface **when damage is present**.

Maximum Stresses in Uniform TGO Layer 3-layer System



No Damage

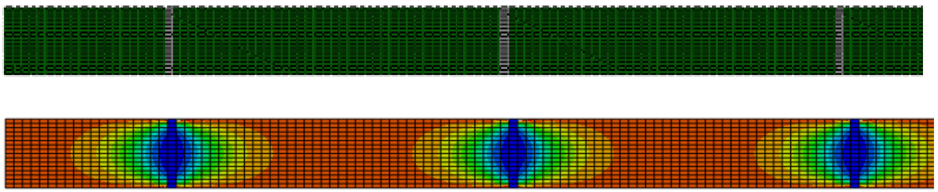


Vertical cracks @10 µm spacing

- TGO thickness has **no significant (< 1%) effect** on the resulting stress state in the system when there is **no damage**. Only significant stresses are in-plane stresses that cause vertical cracks
- When **damage is present**, *peel and shear stresses increase with increase in TGO layer thickness*

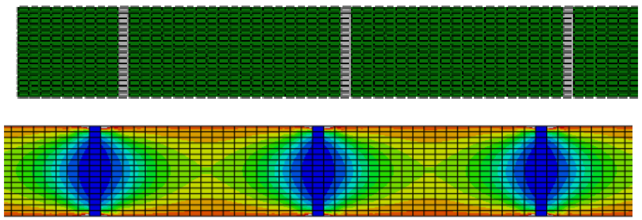
Maximum In-plane Stress in TGO layer Versus Crack Spacing- 3 Layer System

80 μm spacing



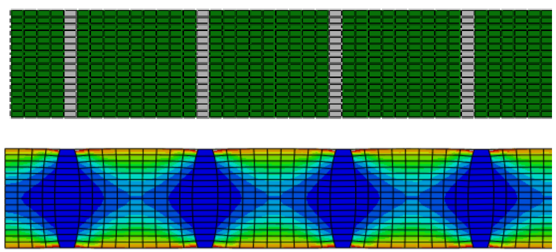
In-plane stress

40 μm spacing

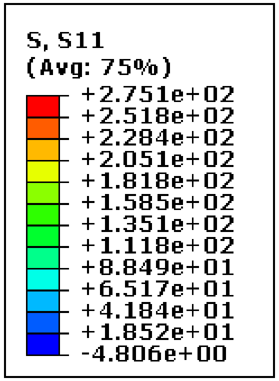


In-plane stress

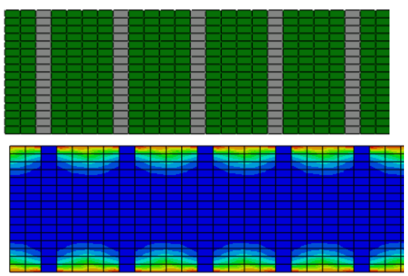
20 μm spacing



In-plane stress



10 μm spacing

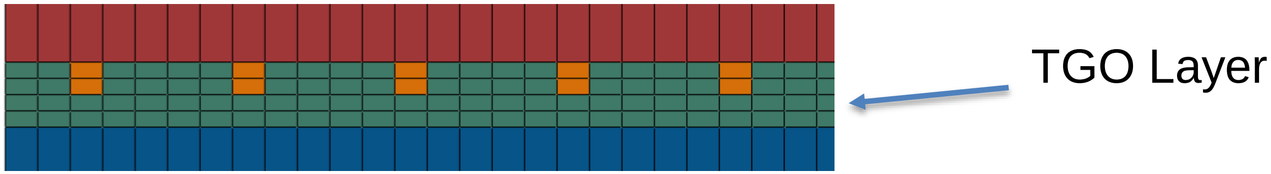


In-plane stress

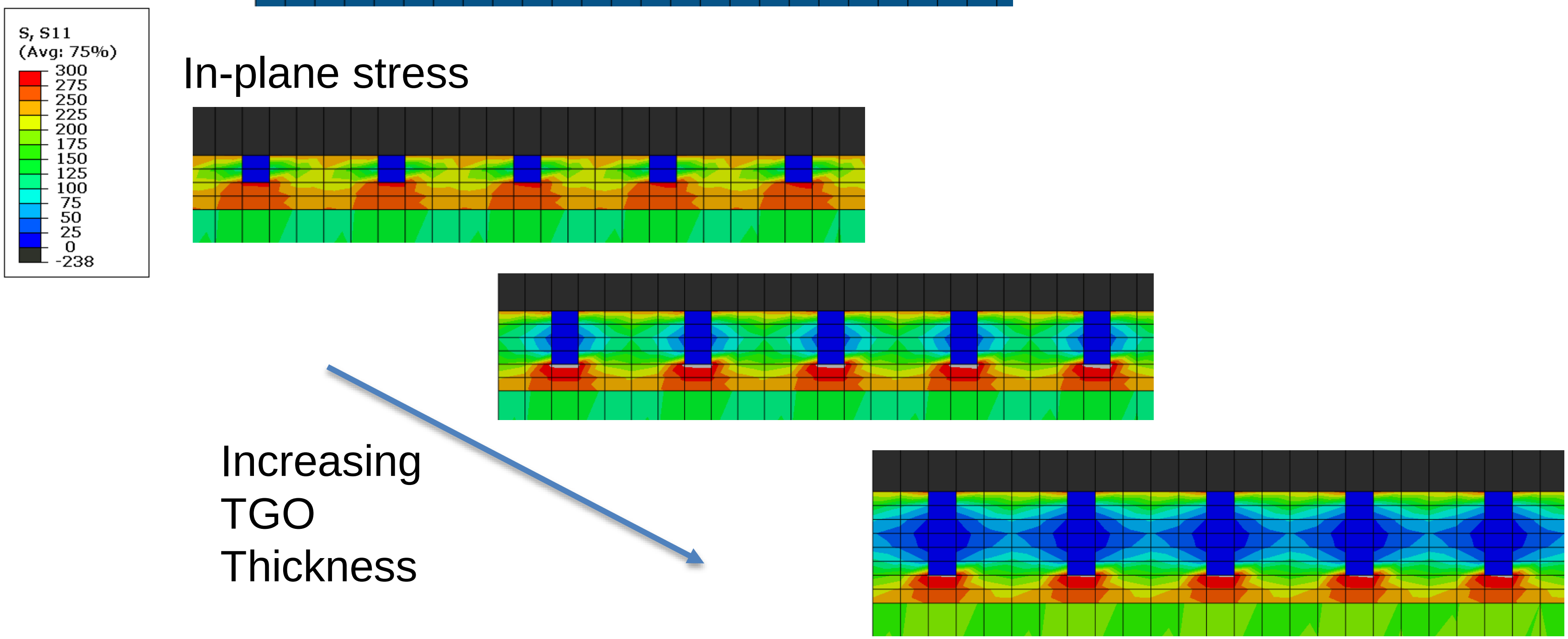
- Elements representing cracks are shown in gray
- TGO has a Uniform thickness of 16 μm
- Current idealization suggests that strength of pristine TGO material should be ~ 200 MPa

Geometry and Contours of In-plane Stress for Partial Cracks in TGO Layer of 3-Layer System

Geometry



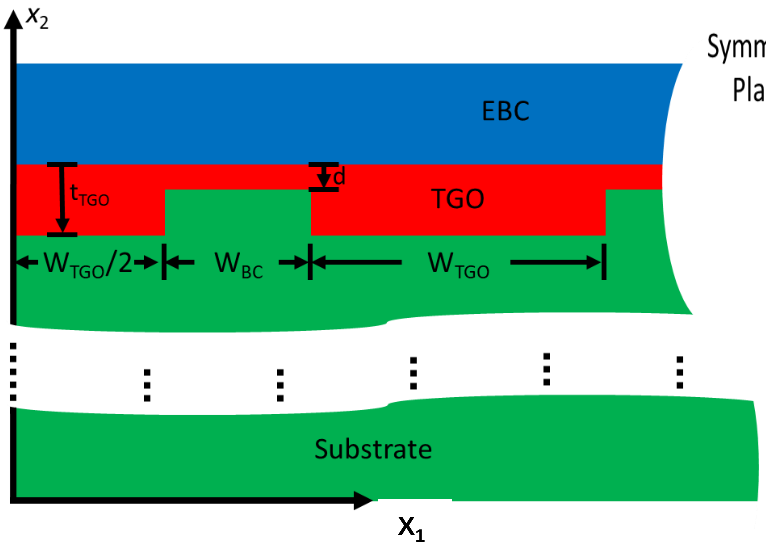
In-plane stress

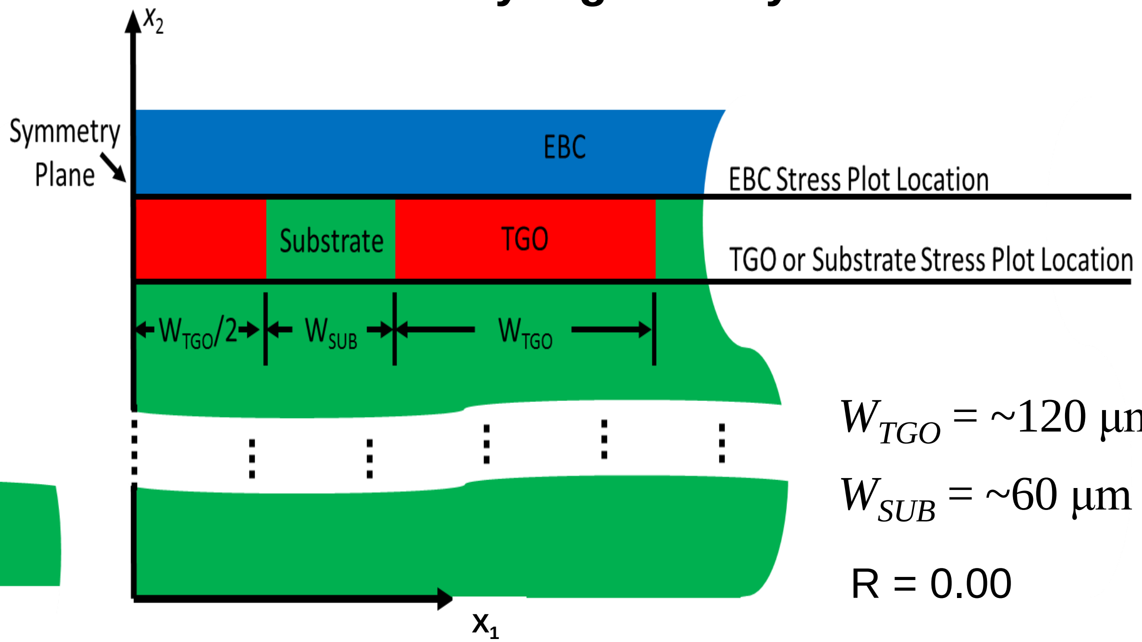


- In-plane stress at the tip of the partial cracks is very high (> 300 MPa), suggesting that partial cracks are likely to propagate and coalesce into a full vertical crack almost instantaneously.

Nonuniform Layer Idealization
3 Layer System

Schematic showing discontinuous TGO layer geometry





W_{TGO} = ~120 µm

W_{SUB} = ~60 µm

R = 0.00

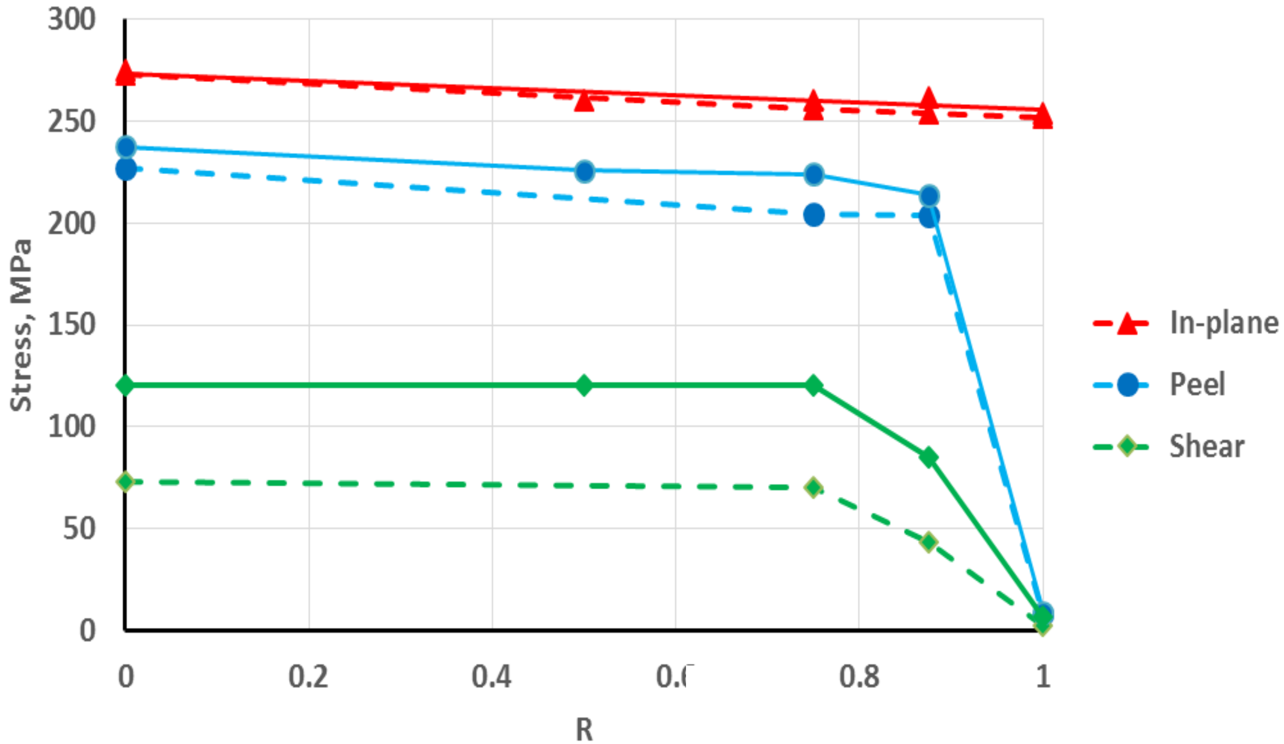
$R = d/t_{TGO}$ ⇒ R = 0.00, 0.75, 1.00

t_{TGO} = 1, 4, 16 µm

- EBC, TGO, and CMC substrate involving only the first ~550 µm out of 5000 µm (*L*/2) in the x_1-direction
- Discontinuous TGO “islands” inserted between the substrate and EBC interface
- Severity of nonuniformity considered by adjusting R factor
- Initial TGO island width was set to half its full width (symmetry boundary conditions)

Maximum Stresses in TGO Layer with No Damage Three-Layer System (EBC/TGO/Substrate)

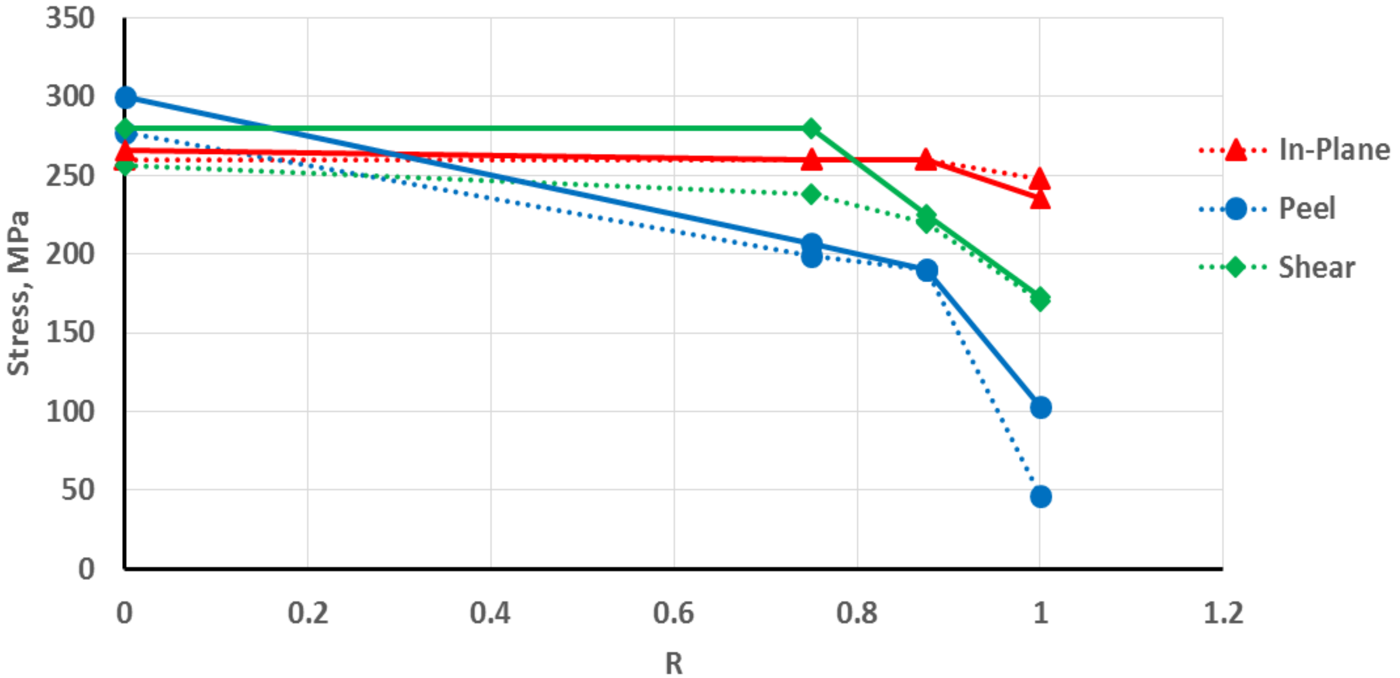
Solid lines represent thick (16 μm) TGO
Dash lines represent thin (4 μm) TGO



- Significant peel and shear stresses develop even at slight non-uniformity.
- Magnitude of stress is independent on the severity of non-uniformity
- As the TGO thickness grows, peel and shear stresses will cause initiation and propagation of delamination/horizontal cracking leading to EBC spallation.
- Change in shear is greater than peel with TGO growth

Max. Stresses in Non-uniform TGO Layer
Vertical Cracks @ 10 μm Spacing; 3 Layer System

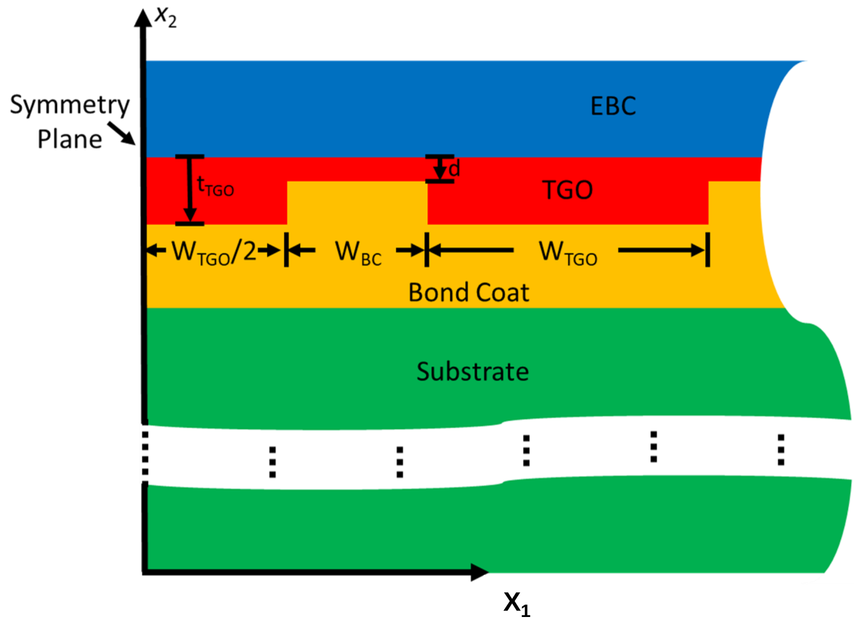
Solid lines represent thick (16 μm) TGO
Dash lines represent thin (4 μm) TGO



- In the presence of **damage and non-uniformity**, there are significant shear and peel stresses for delamination to initiate and propagate causing spallation of the coating (particularly when the TGO becomes thick, e.g., 16 μm (solid curves).
- Nonuniformity magnifies residual stress by up to a factor of 5-6x.

Non-uniform Idealization – 4 Layer System

Lower temperature system



t_{TGO} = 1, 4, 16 µm

W_{TGO} = ~120 µm

W_{BC} = ~60 µm

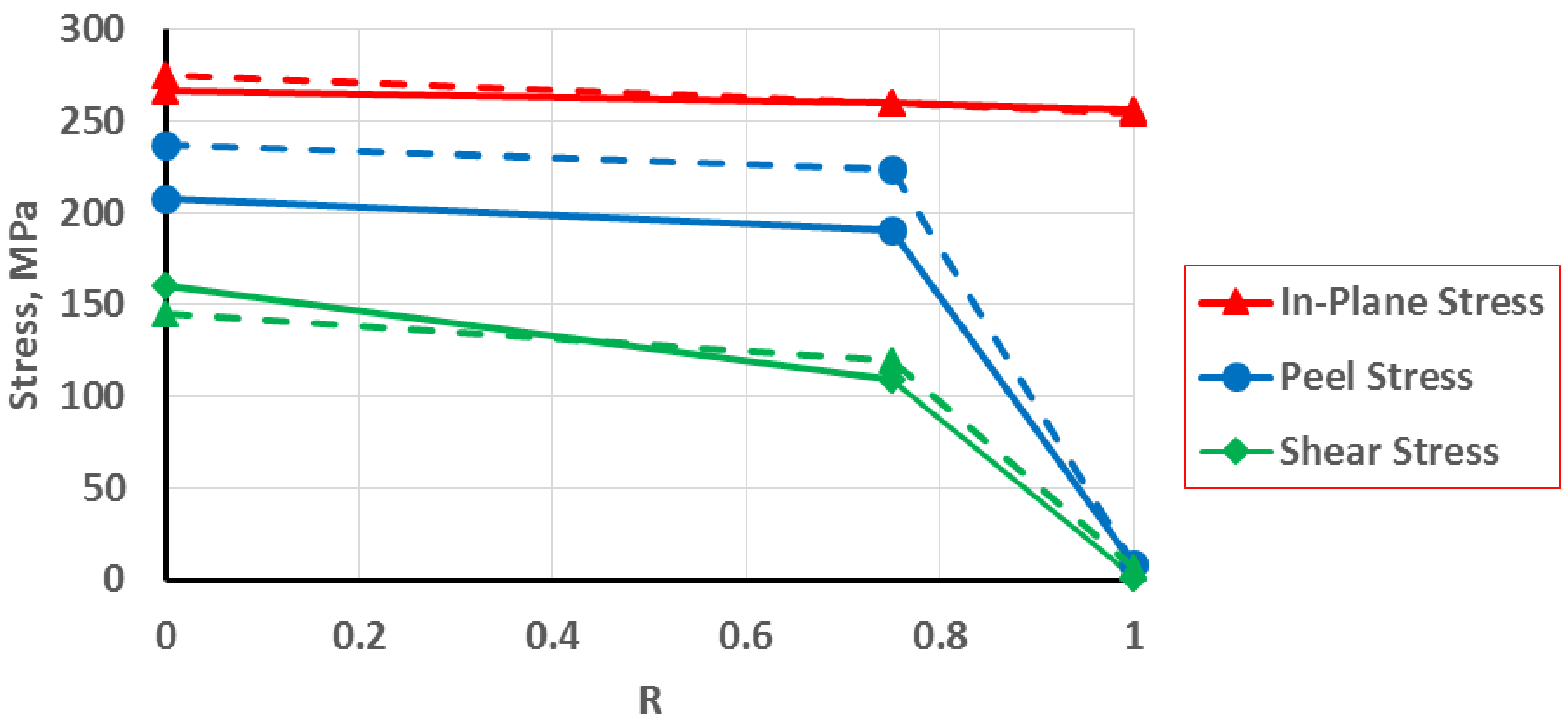
$R = d/t_{TGO}$

R = 0.00, 1.00

- Discontinuous TGO “islands” inserted between the substrate and EBC interface
- Severity of nonuniformity considered by adjusting R factor

Comparison of Max Stresses in 3 and 4 Layer Systems with Undamaged TGO Layer (16 µm)

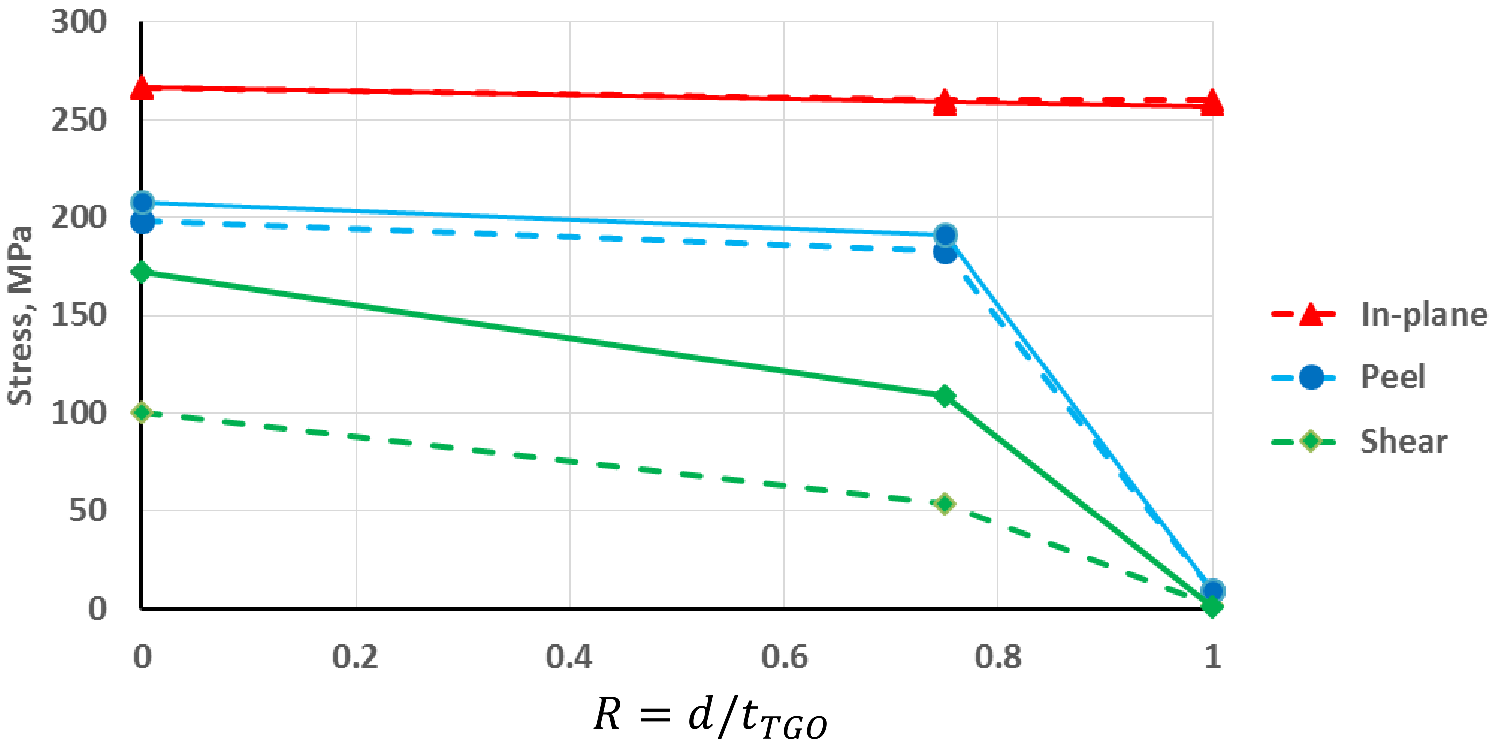
Solid lines represent **4 layer** EBC system (Low Temp System)
Dash lines represent **3 layer** EBC system (High Temp System)



- Stresses are lower overall for 4 layer system compared to 3 layer
  - Peel stresses significantly lower (10%)
  - In-plane and Shear stresses are similar but slightly lower

Max. Stresses in Undamaged TGO Layer
4 Layer System (EBC/TGO/BondCoat/Substrate)

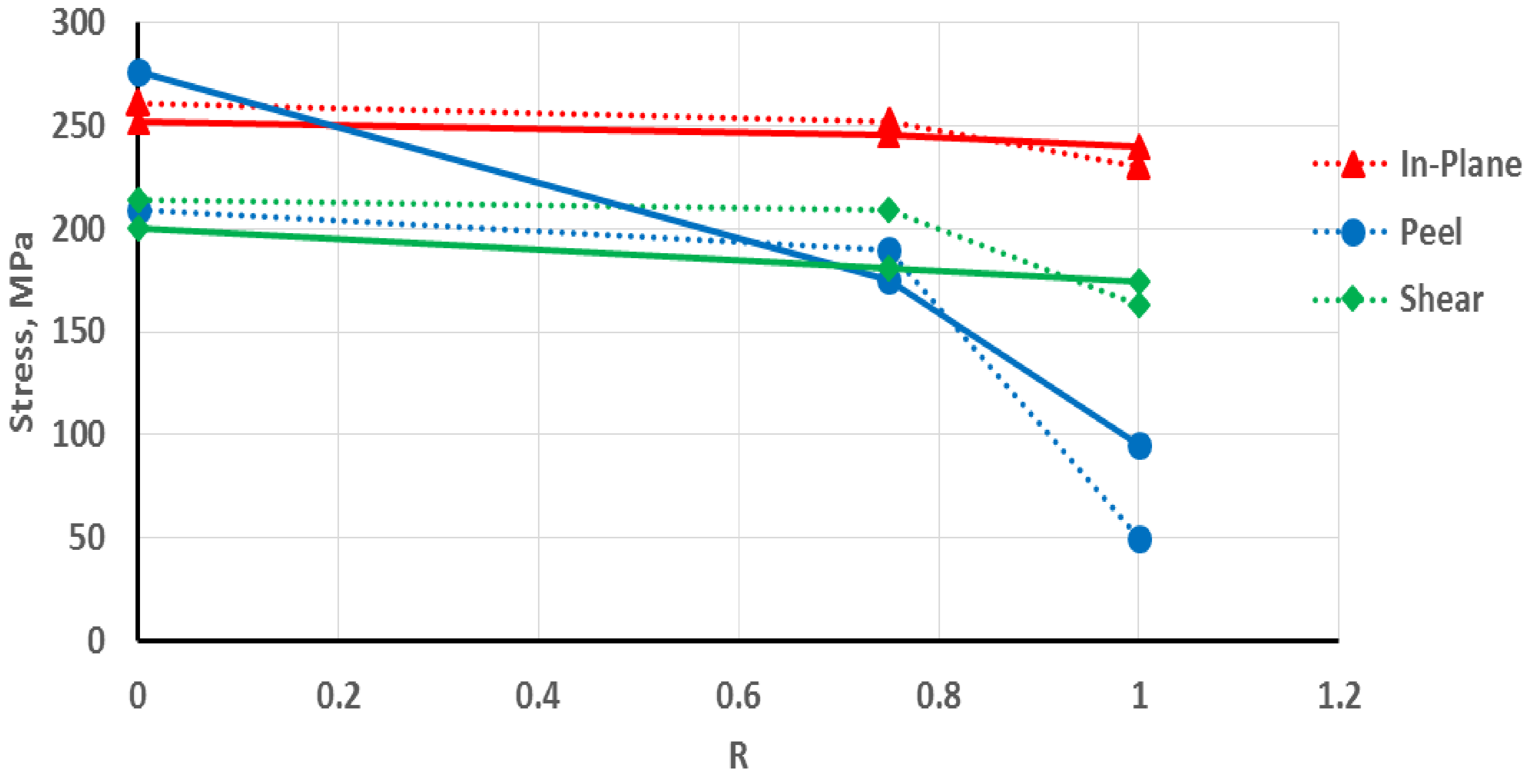
Solid lines represent **thick** (16 μm) TGO
Dash lines represent **thin** (4 μm) TGO



- R=0 (island); R=1 (uniform); R=0.75 (step island)
- Similar trends in peel and shear as with 3 layer system – yet sensitivity to nonuniformity appears greater

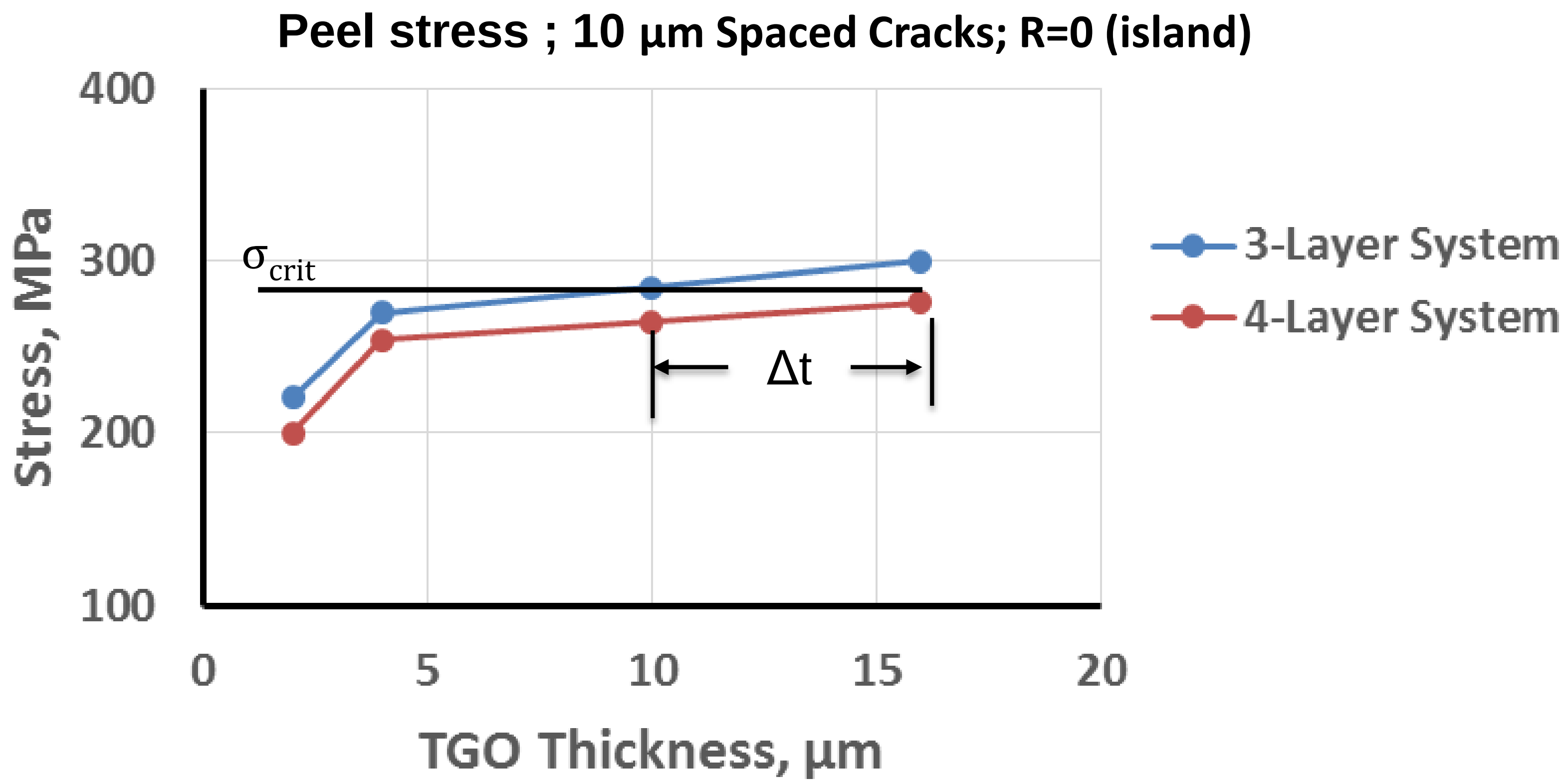
Maximum Stresses in Damaged TGO Layer
10 μm Spaced Cracks; 4 Layer System

Solid lines represent **thick** (16 μm) TGO
Dash lines represent **thin** (4 μm) TGO



- Uniform (R=1), damaged system has nonzero peel and shear stresses
- Peel significantly increases with increasing TGO
- Shear slightly decreases with increasing TGO

Presence of Si Bond Coat Reduces Driving Forces



- Decrease in peel stress when bond coat added
- **Given critical failure stress, Si bond coat (i.e., four layer system) enables thicker TGO layer prior to failure**
- **Suggests bond strength between EBC and TGO >290 (MPa)**
- Shear stresses similar but reduction in magnitude larger !

Summary

- A three layer (EBC/TGO/Substrate) and a four layer (EBC/TGO/Bond coat/Substrate) were analyzed subjected to an isothermal cooldown.
- The influence of damage in the TGO layer in the form of vertical cracks and two thicknesses for both uniform and non-uniform TGO layer were examined.

Uniform TGO layers

- With no damage, the stress state is independent of TGO layer thickness.
- When damage was introduced in the form of vertical cracks, **significant peel and shear stresses** developed.
- Given an average experimentally observed crack spacing in the TGO layer of 10 μm; suggests the tensile strength of the pristine TGO material should be around 200 MPa.

Non-uniform TGO layers

- **Even a slight non-uniformity in the TGO thickness resulted in significant peel and shear** stresses increasing the possibility of delamination and spallation of EBC when a critical thickness is reached.
- When damage is introduced, there was an increase in peel and shear stresses.

- The presence of damage (vertical cracks caused by in-plane stresses) enhances the stresses that are present due to non-uniformity. However, the presence of non-uniformity itself is still the main factor influencing the magnitude of peel and shear stresses.

Summary (contd.)

- As TGO thickness increases with exposure time; peel and/or shear stresses will exceed the material resistance (strength) and lead to EBC failure. That is a critical thickness will be reach whereupon delamination/spallation will occur.

- Presence of a bondcoat layer reduces the driving forces. For a given critical failure stress, silicon bondcoat in four-layer system enables a thicker critical TGO and thus increased life prior to failure.

- Note when characterizing constituent, interface, etc. strengths its important to account for localization features such as damage, microstructure, residual, etc.!!

<u>Future Work</u>

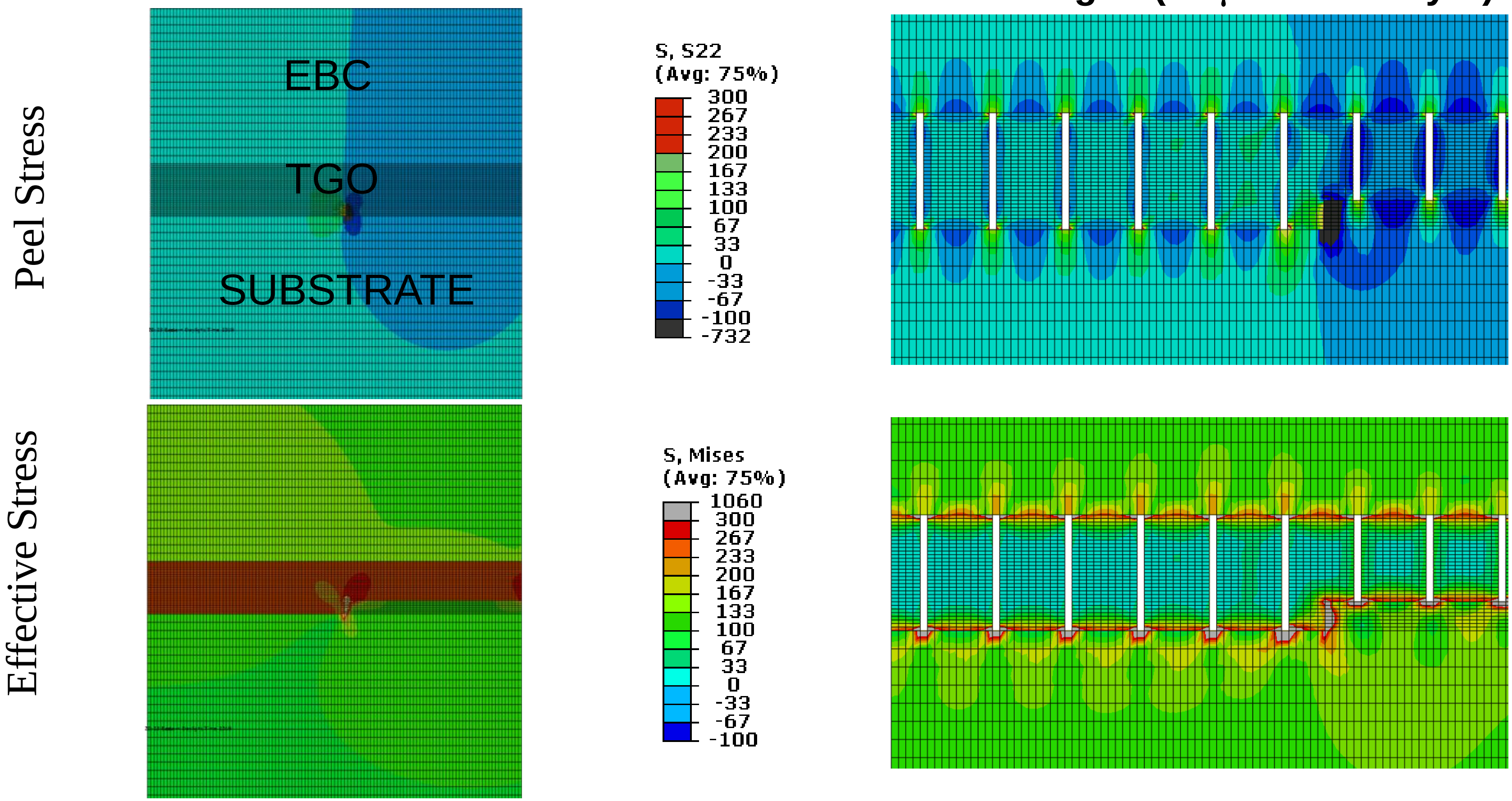
- Material behavior (e.g. creep/relaxation), TGO growth rate
- Constituent material and interfacial bond strength

Backup Charts

Results: Non-Uniform 3 Layer System

R=0.75

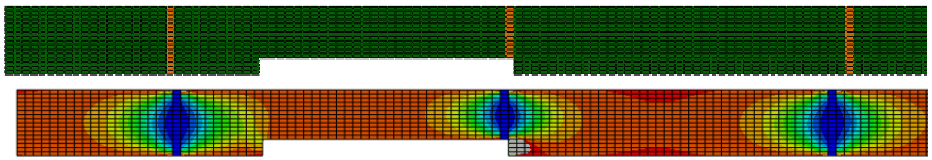
Undamaged (16 μm TGO Layer) **Damaged (16 μm TGO Layer)**



- Significant increase in peel and Von-Mises stress as damage is introduced. Peel stress at undulation is similar to crack tips. TGO/Sub interface higher values than TGO/EBC interface.

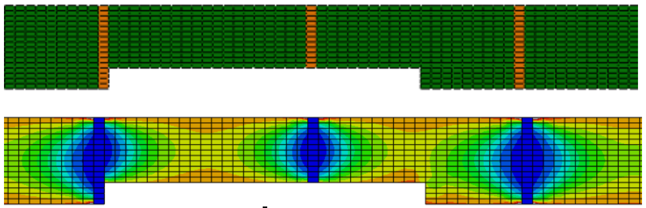
Maximum In-plane Stress in Non-uniform TGO layer Versus Crack Spacing

80 µm spacing



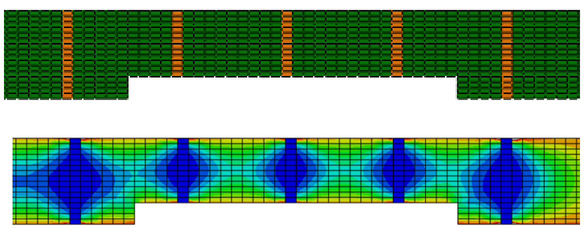
In-plane stress

40 µm spacing

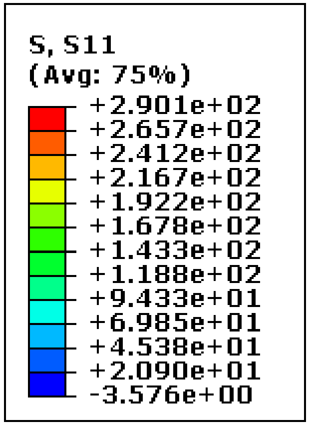


In-plane stress

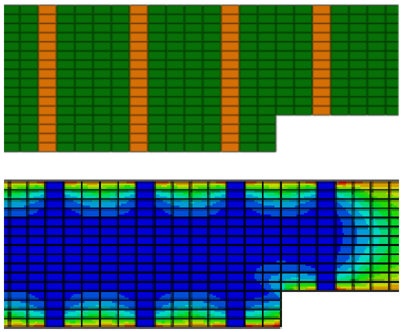
20 µm spacing



In-plane stress



10 µm spacing

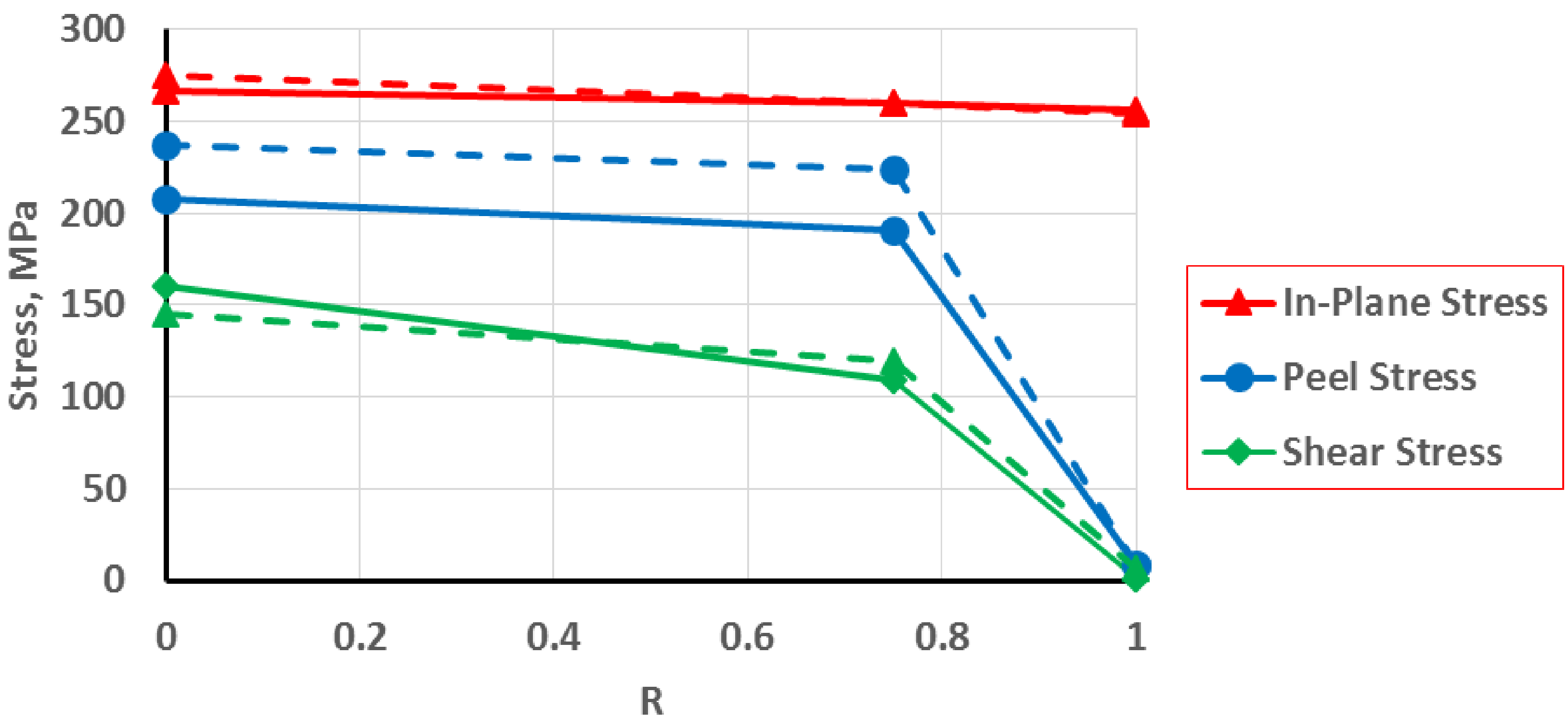


In-plane stress

- Elements representing cracks are shown in gray
- **TGO has a Non-uniform thickness of 16 µm; R=0.75**
- At 10 µm crack spacing observed experimentally, maximum in-plane stress in the TGO material is ~ 190 MPa

Comparison of Max Stresses in 3 and 4 Layer Systems with Undamaged TGO Layer (16 μm)

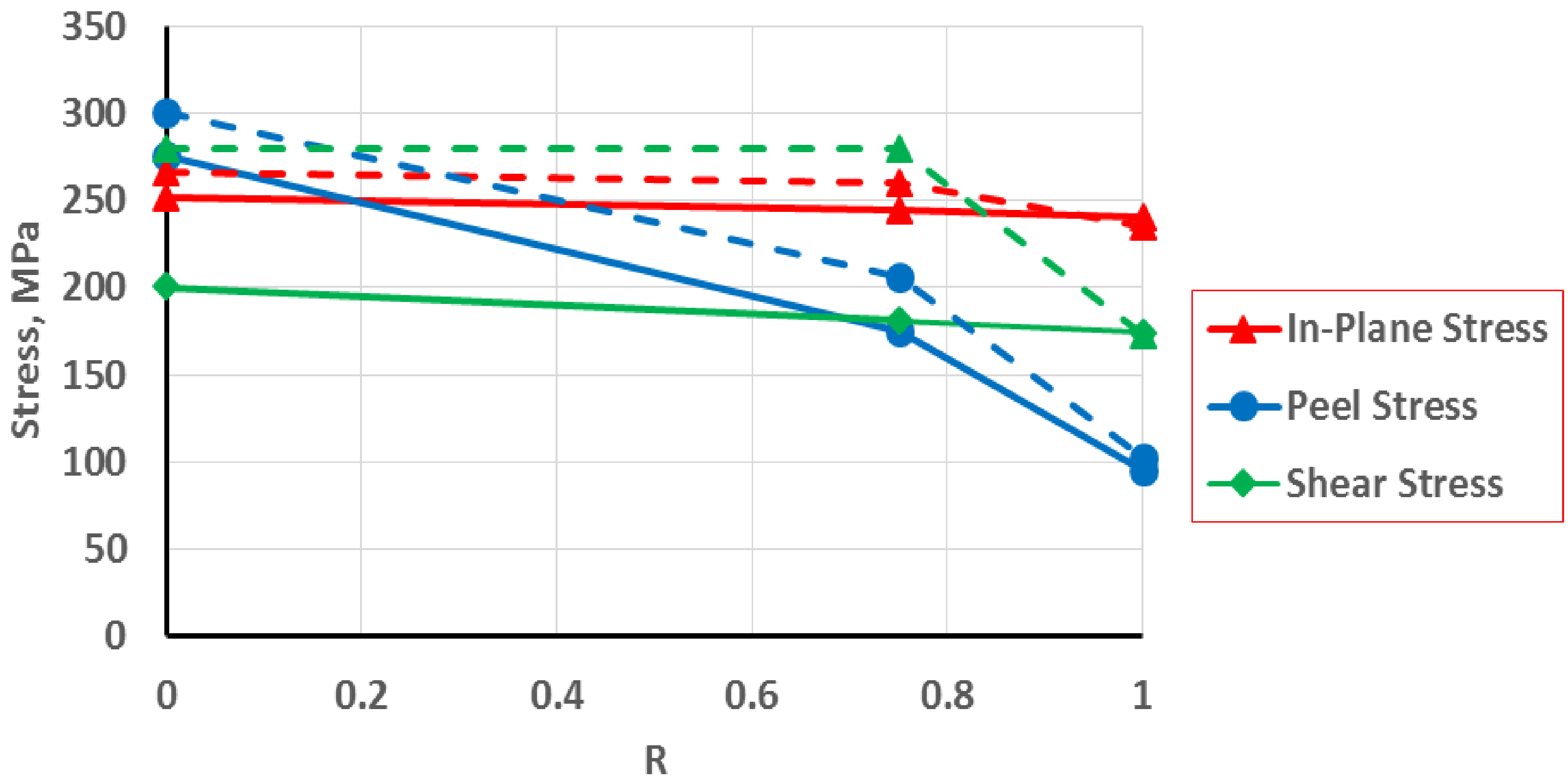
Solid lines represent **4 layer** EBC system (Low Temp System)
Dash lines represent **3 layer** EBC system (High Temp System)



- Stresses are lower overall for 4 layer system compared to 3 layer
    - Peel stresses significantly lower (10%)
    - In-plane and Shear stresses are similar but slightly lower

Comparison of Max Stresses in 3 and 4 Layer Damaged Systems; 16 μm TGO Layer, 10 μm Cracks

Solid lines represent **4 layer** EBC system (Low Temp System)
Dash lines represent **3 layer** EBC system (High Temp System)



- Stresses are lower overall for damaged 4 layer system compared to 3 layer
  - Shear stresses significantly lower (~30%)
  - Peel stresses lower (~10%)