Modeling of the Influence of a Damaged Thermally Grown Oxide (TGO) Layer in an Environmental Barrier Coating System

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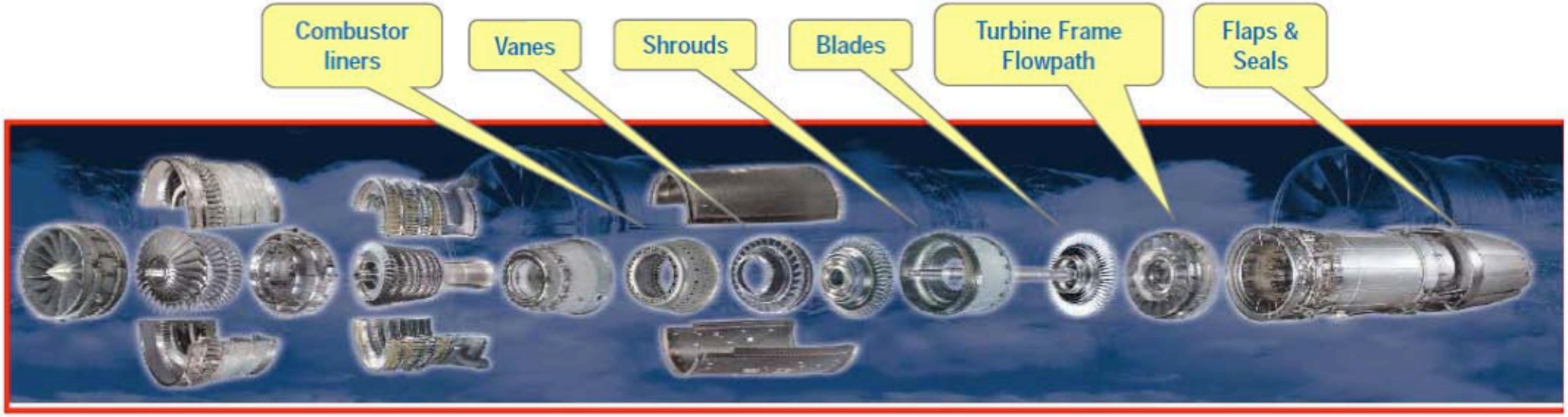
American Society of Composites (ASC) 34th Technical Conference, Atlanta, GA
Sep. 23-25, 2019

CMCs for Gas Turbine Engines



Courtesy of GE Aircraft Engines

Benefits:

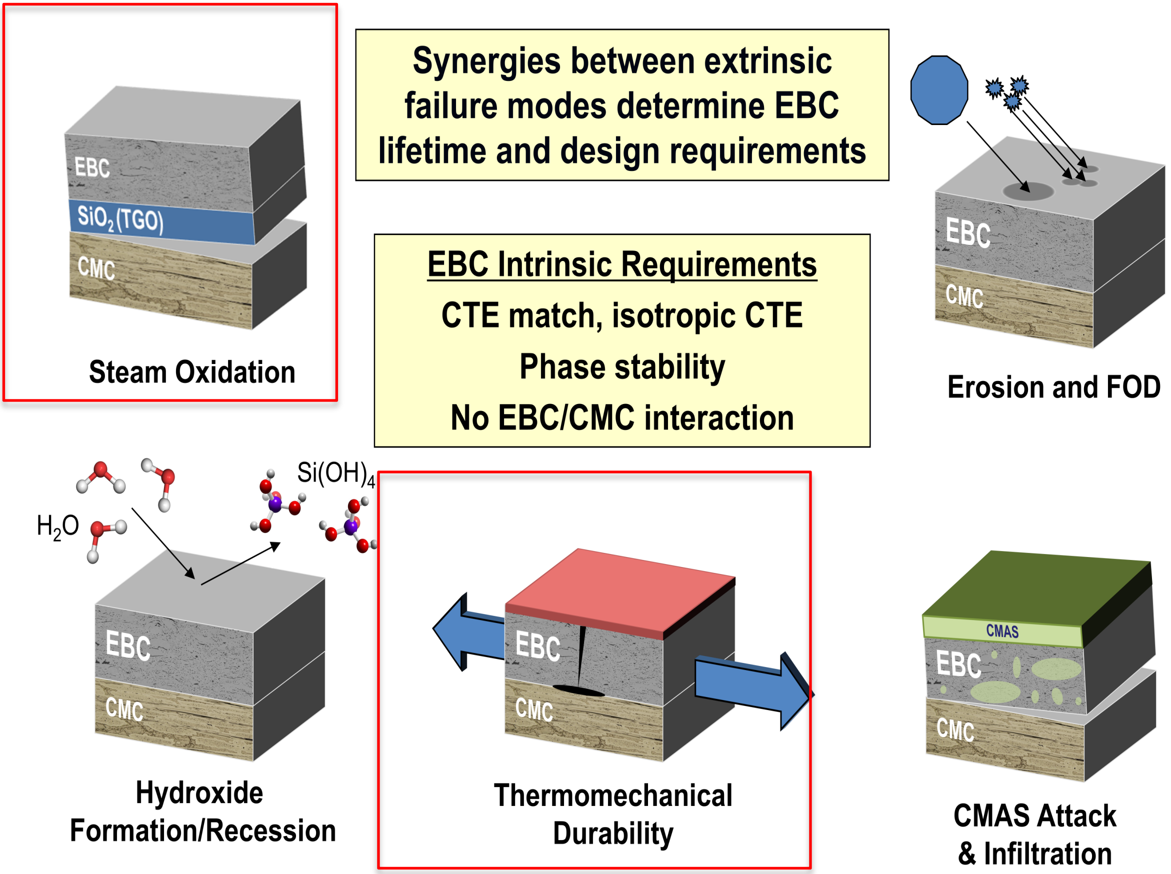
- Enabling for high OPR engines (high turbine inlet temperatures)
  - 200 to 500+ °F temperature advantage over metals
  - Reduce cooling air
  - Reduce fuel burn (up to 6%) - CO_2 emissions
- Weight – 1/3 of metals and 1/2 titanium aluminides
- CMC combustor liner and first stage turbine vane reduce 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.



Steam Oxidation

Synergies between extrinsic failure modes determine EBC lifetime and design requirements

Erosion and FOD

<u>EBC Intrinsic Requirements</u>

CTE match, isotropic CTE

Phase stability

No EBC/CMC interaction

Hydroxide Formation/Recession

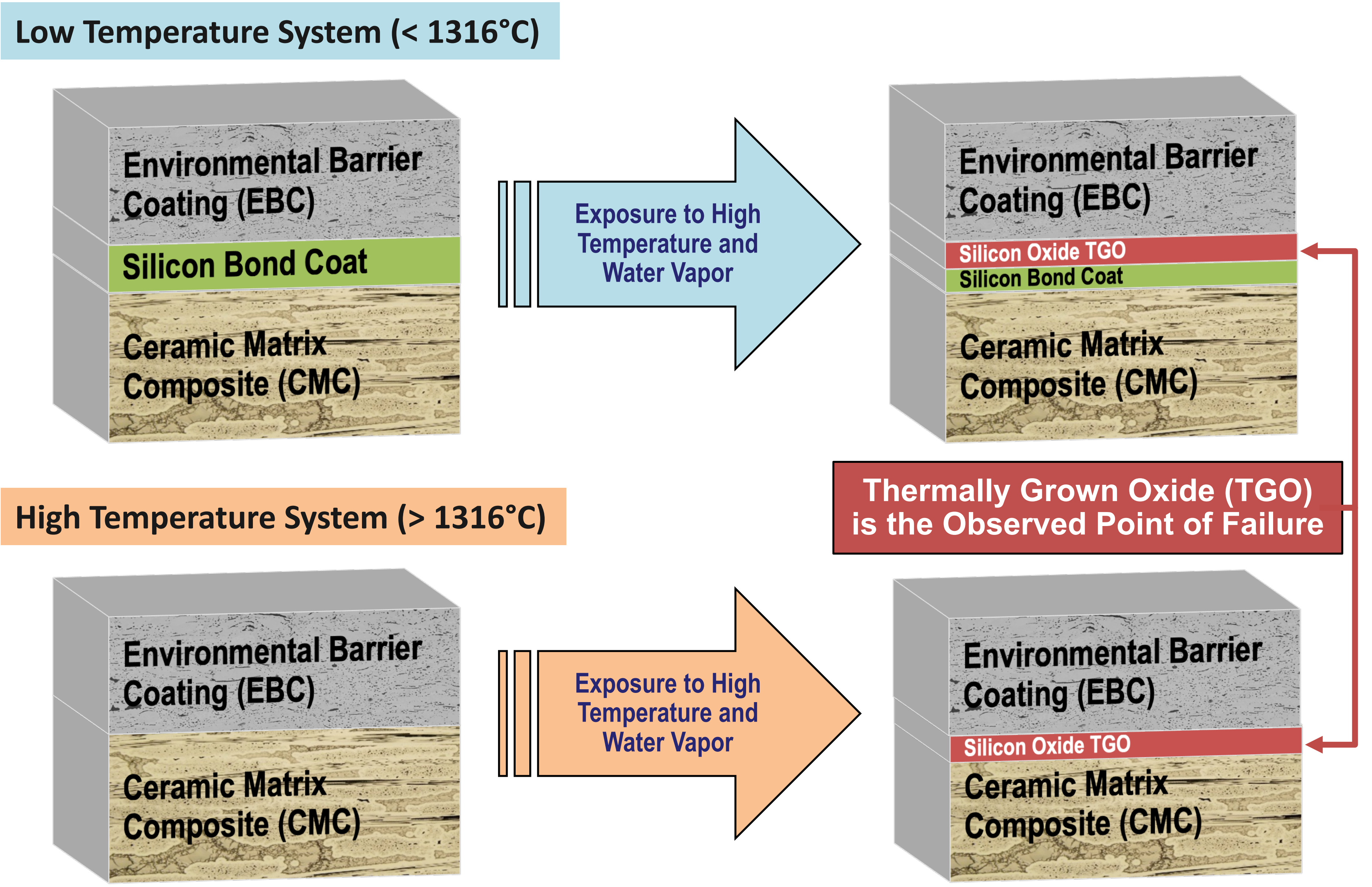
Thermomechanical Durability

CMAS Attack & Infiltration

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)

Environmental Barrier Coating (EBC)

Silicon Bond Coat

Ceramic Matrix Composite (CMC)

Exposure to High Temperature and Water Vapor

Environmental Barrier Coating (EBC)

Silicon Oxide TGO

Silicon Bond Coat

Ceramic Matrix Composite (CMC)

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

High Temperature System (> 1316°C)

Environmental Barrier Coating (EBC)

Ceramic Matrix Composite (CMC)

Exposure to High Temperature and Water Vapor

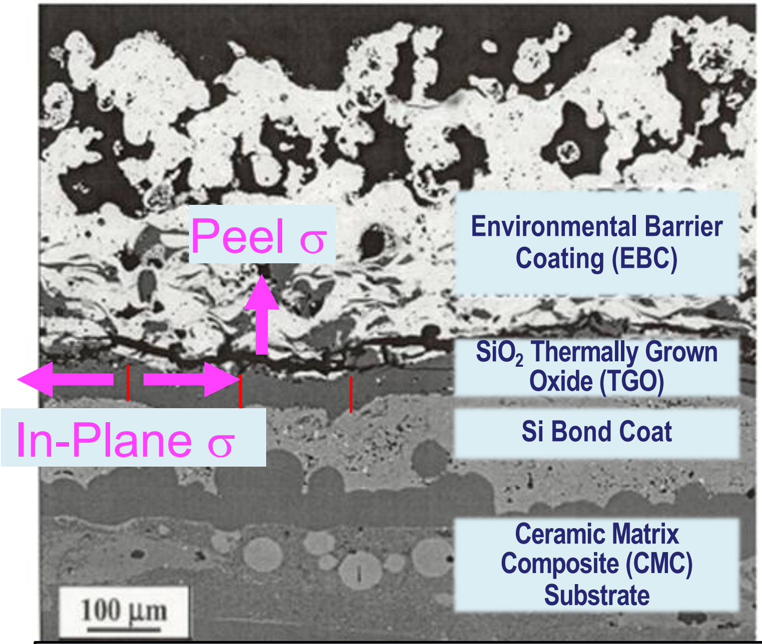
Environmental Barrier Coating (EBC)

Silicon Oxide TGO

Ceramic Matrix Composite (CMC)

Environmental Barrier Coating (EBC) Systems

- 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 microns)
  - Can vary due to exposure temperature, microstructure, composition, etc.



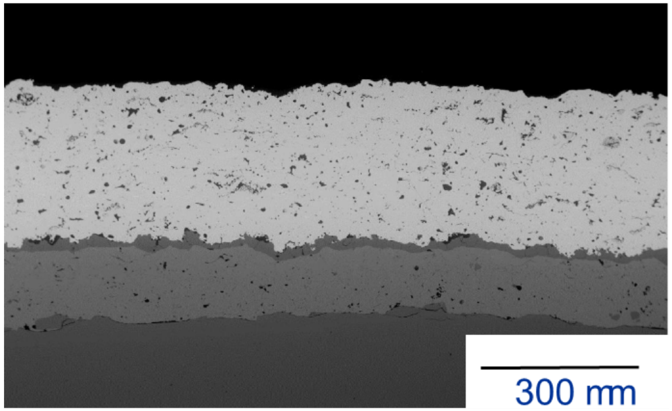
Environmental Barrier Coating system after 15,144h test

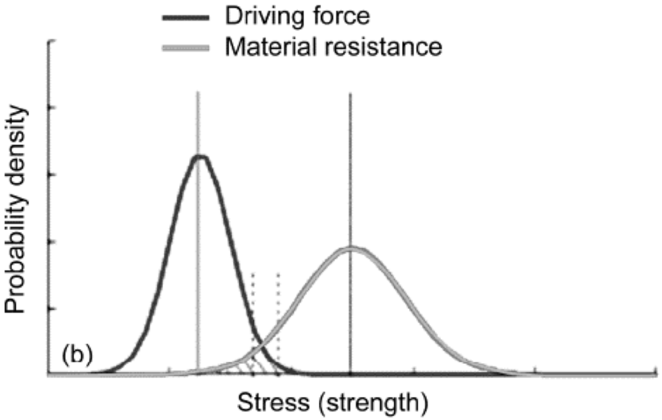
Ultimate Goal: Predict the durability of EBC/CMC system when subjected to harsh environments

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

Current Study Objective

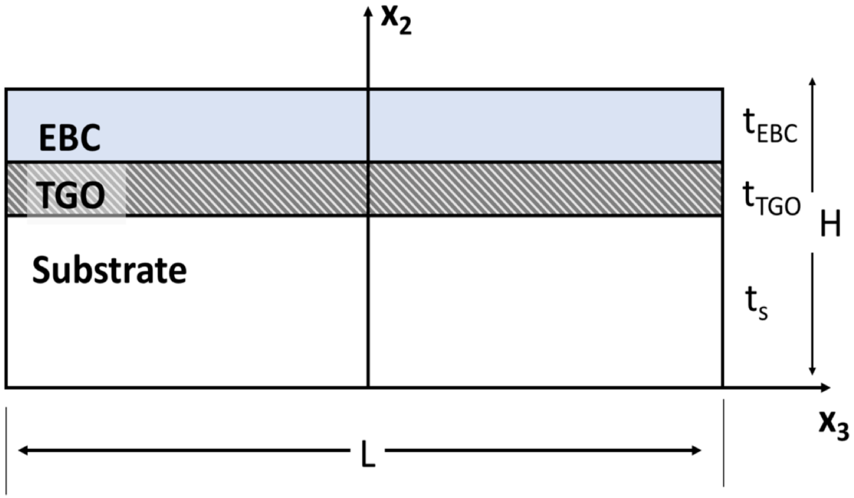
- Perform **finite element analyses** to examine the influence of uniformly and nonuniformly grown oxide layers on the associated driving forces leading to mechanical failure (spallation) of EBC layer when subjected to isothermal loading
- **Assess the effect of damage** in the TGO layer in the form 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



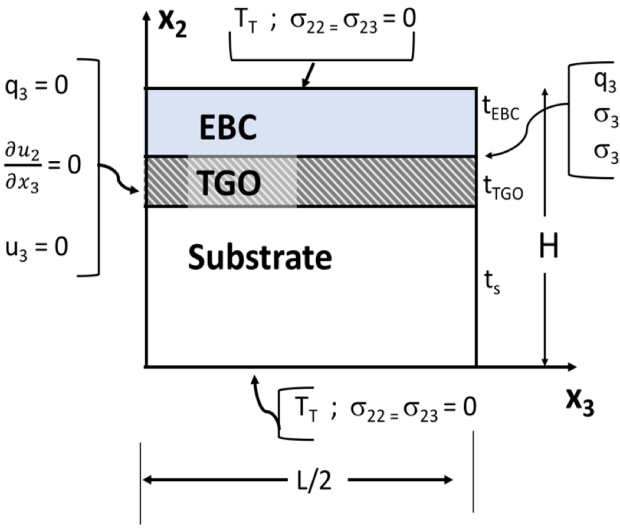


Idealization Of Three Layer System

With Geometry And Applied Thermal And Mechanical Boundary Conditions



Boundary Conditions



- **Global loading is cool-down from 1482 ºC to 38.7 ºC (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.

Constituents' Material Parameters

- Assume isotropic thermoelastic properties

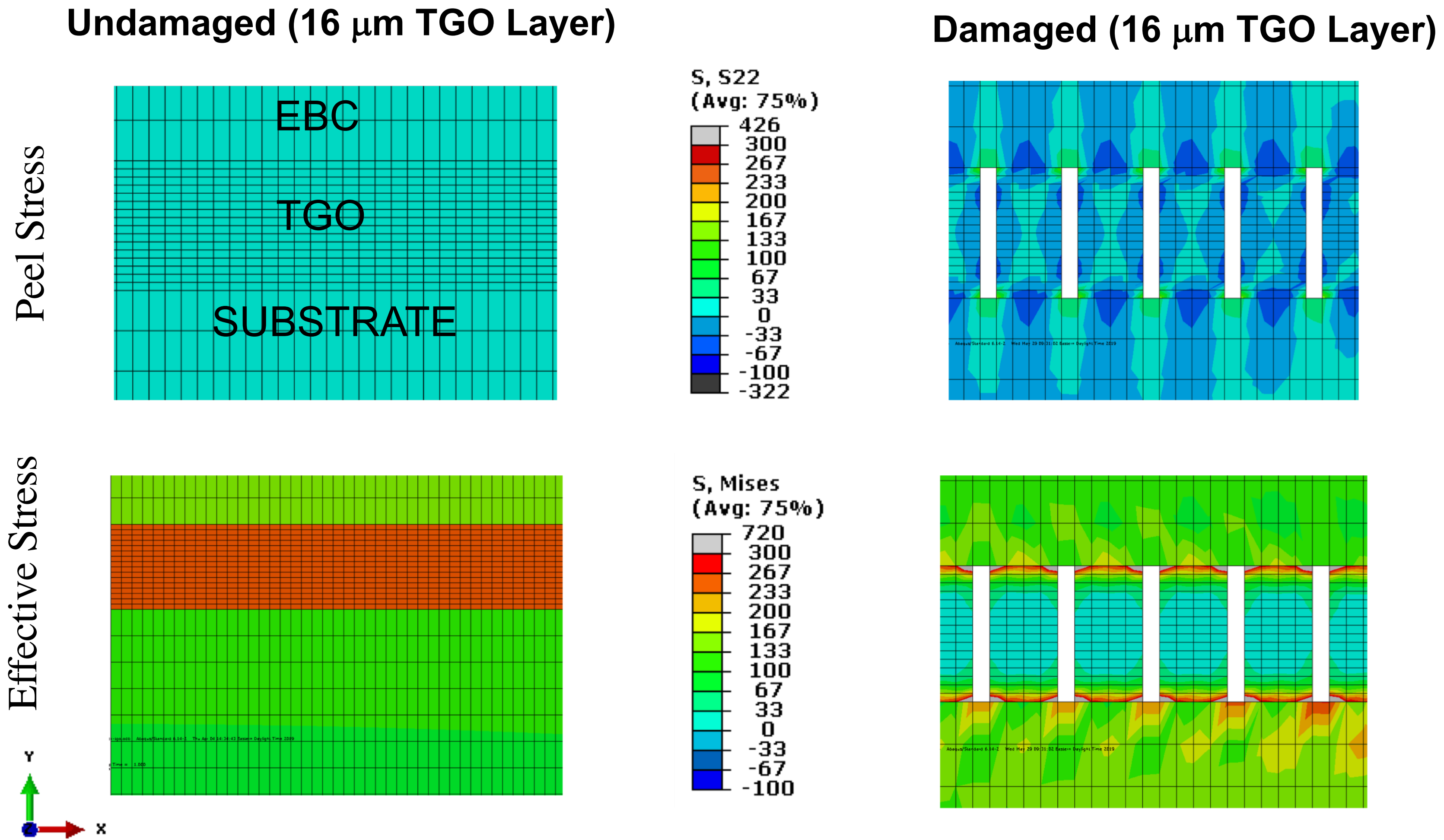
Material	Thickness (mm)	Modulus (GPa)	Poisson Ratio	CTE ($\times 10^{-6}$ K^{-1})	Strength (MPa)
$Yb_2Si_2O_7$ (EBC)	0.175	200	0.27	4.5	45-65 (?)
SiO_2 (TGO)	0.001 0.002 **0.004** 0.008 **0.016**	**35**	0.17	**10**	45-75 (?) (200)
Si ** (Bond Coat)	0.075	97	0.21	4.5	40-55 (?)
Hexoloy SiC (Substrate)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



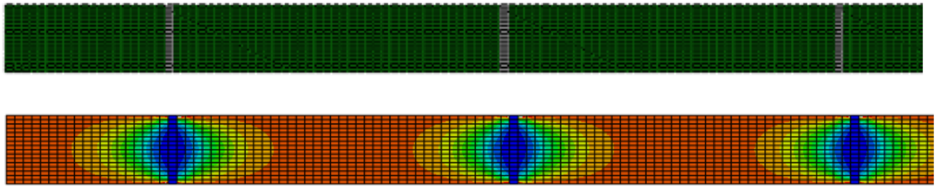
Undamaged (16 μm TGO Layer)

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**.

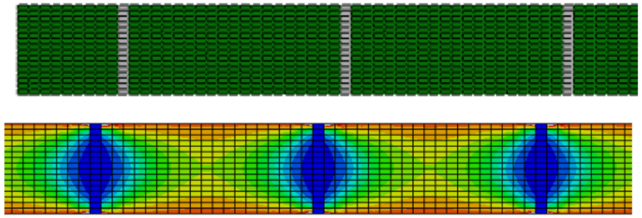
Maximum In-plane Stress in TGO layer Versus Crack Spacing

80 µm spacing



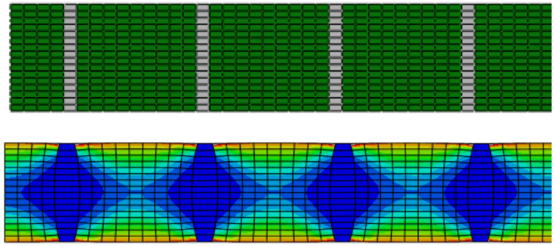
In-plane stress

40 µm spacing

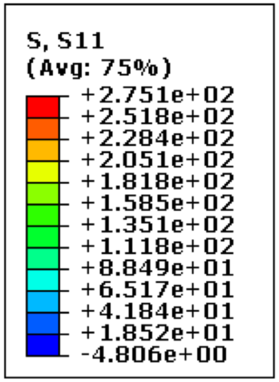


In-plane stress

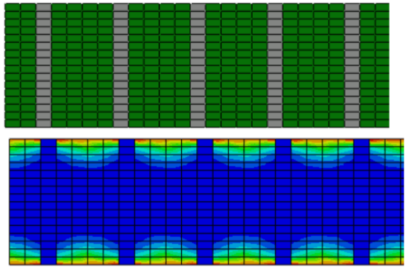
20 µm spacing



In-plane stress



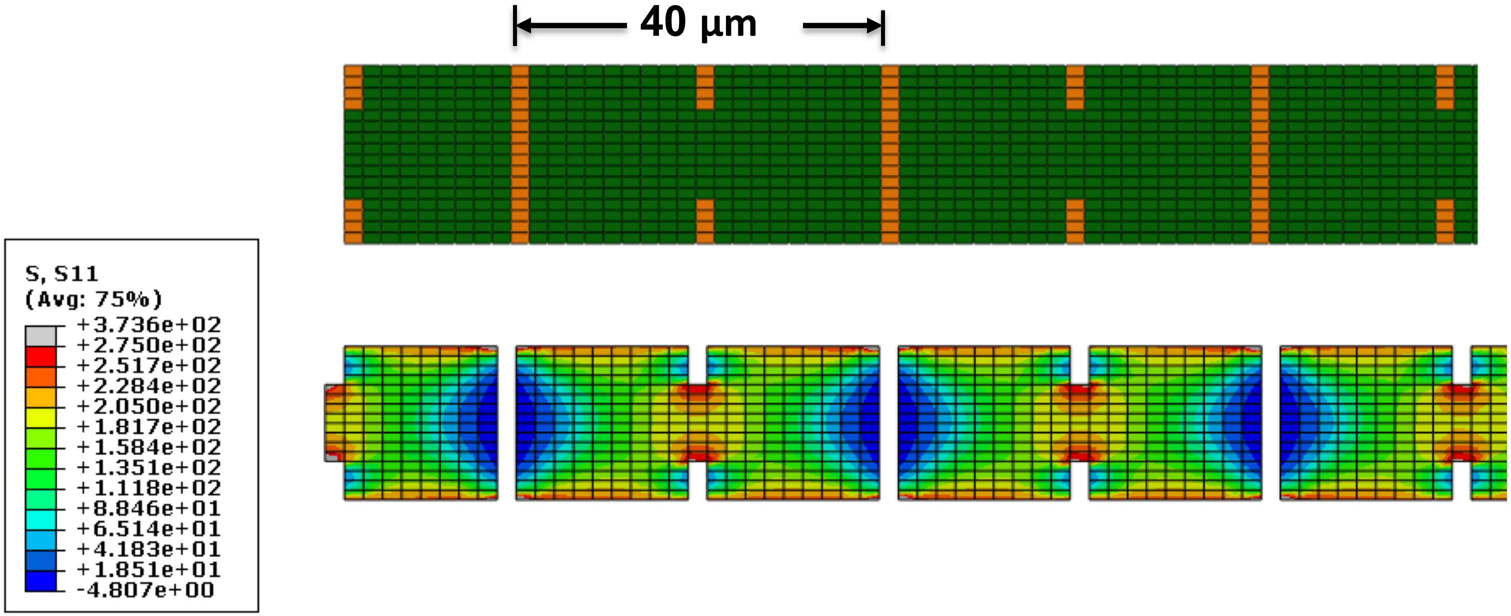
10 µm spacing



In-plane stress

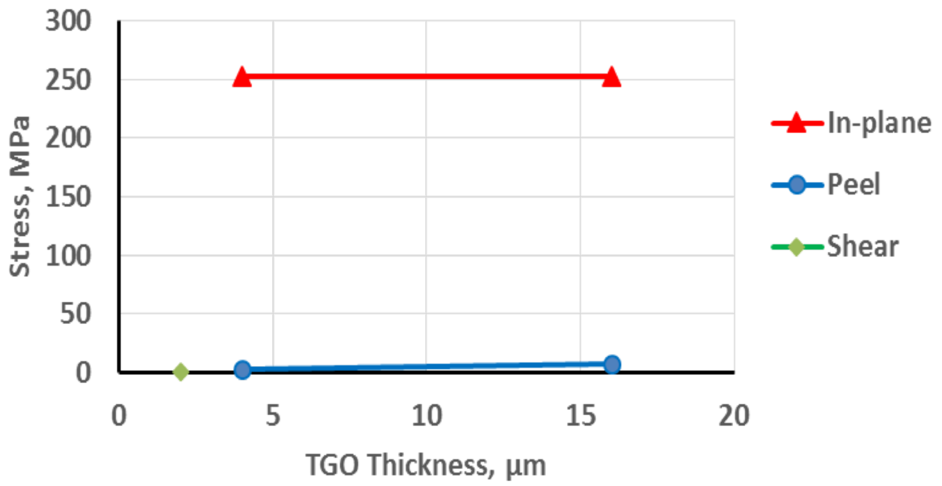
- TGO has a Uniform thickness of 16 µm
- Elements representing cracks are shown in gray
- Current idealization suggests that strength of pristine TGO material should be ~ 200 MPa

Geometry and Contours of In-plane Stress for Full and Partial Cracks in the TGO Layer

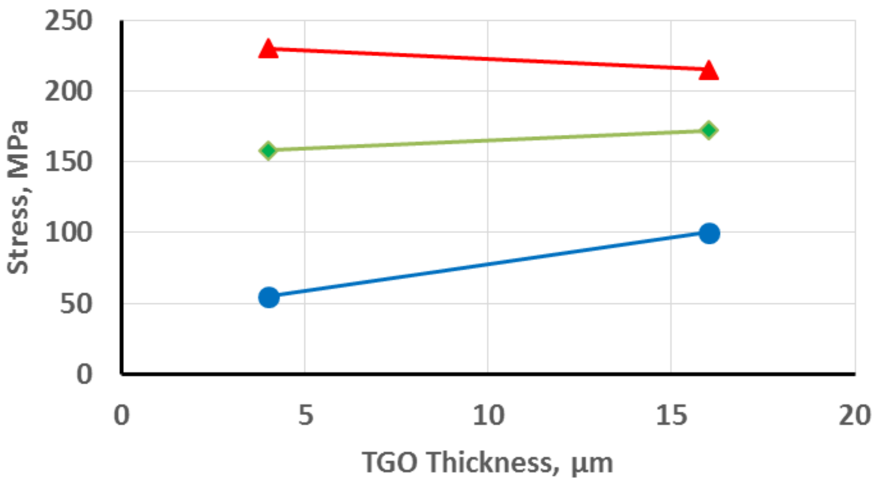


- In-plane stress at the tip of the partial cracks is very high (> 300 MPa), suggesting that partial cracks are likely to propagate and coalesce into a full vertical crack almost instantaneously.

Maximum Stresses in Uniform TGO Layer



No Damage

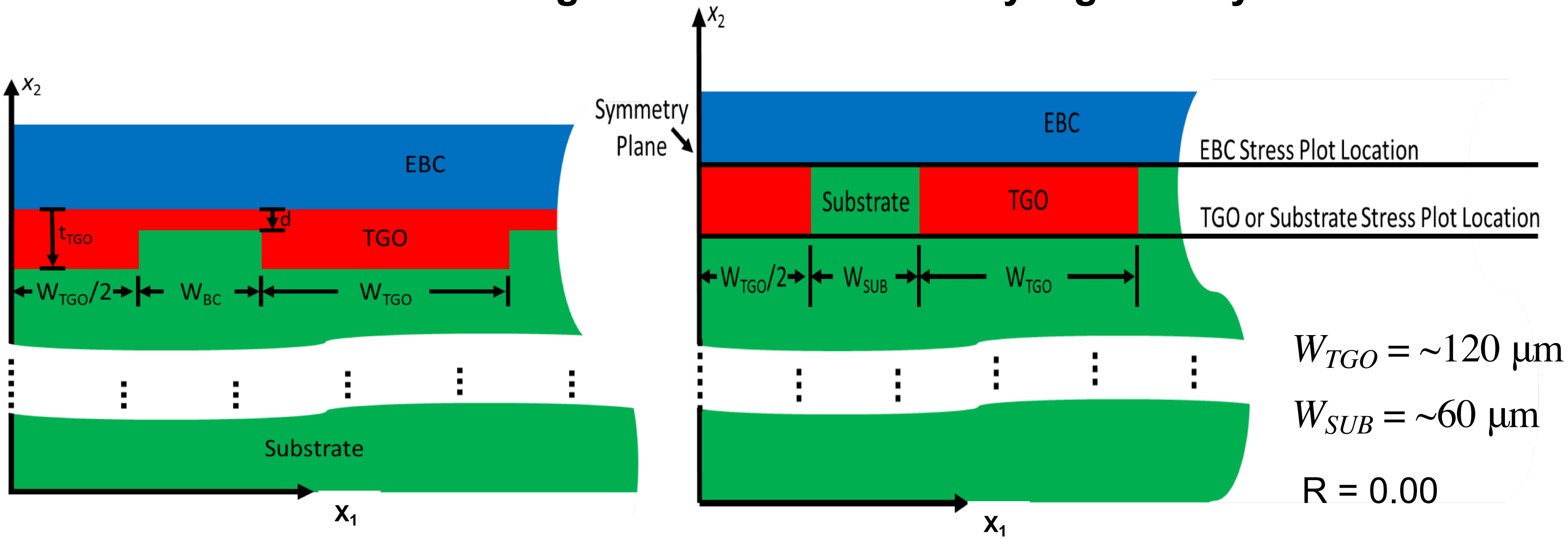


Vertical cracks @10 µm spacing

- 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*

Nonuniform Layer Idealization

Schematic showing discontinuous TGO layer geometry



$W_{TGO} = \sim 120\ \mu m$

$W_{SUB} = \sim 60\ \mu m$

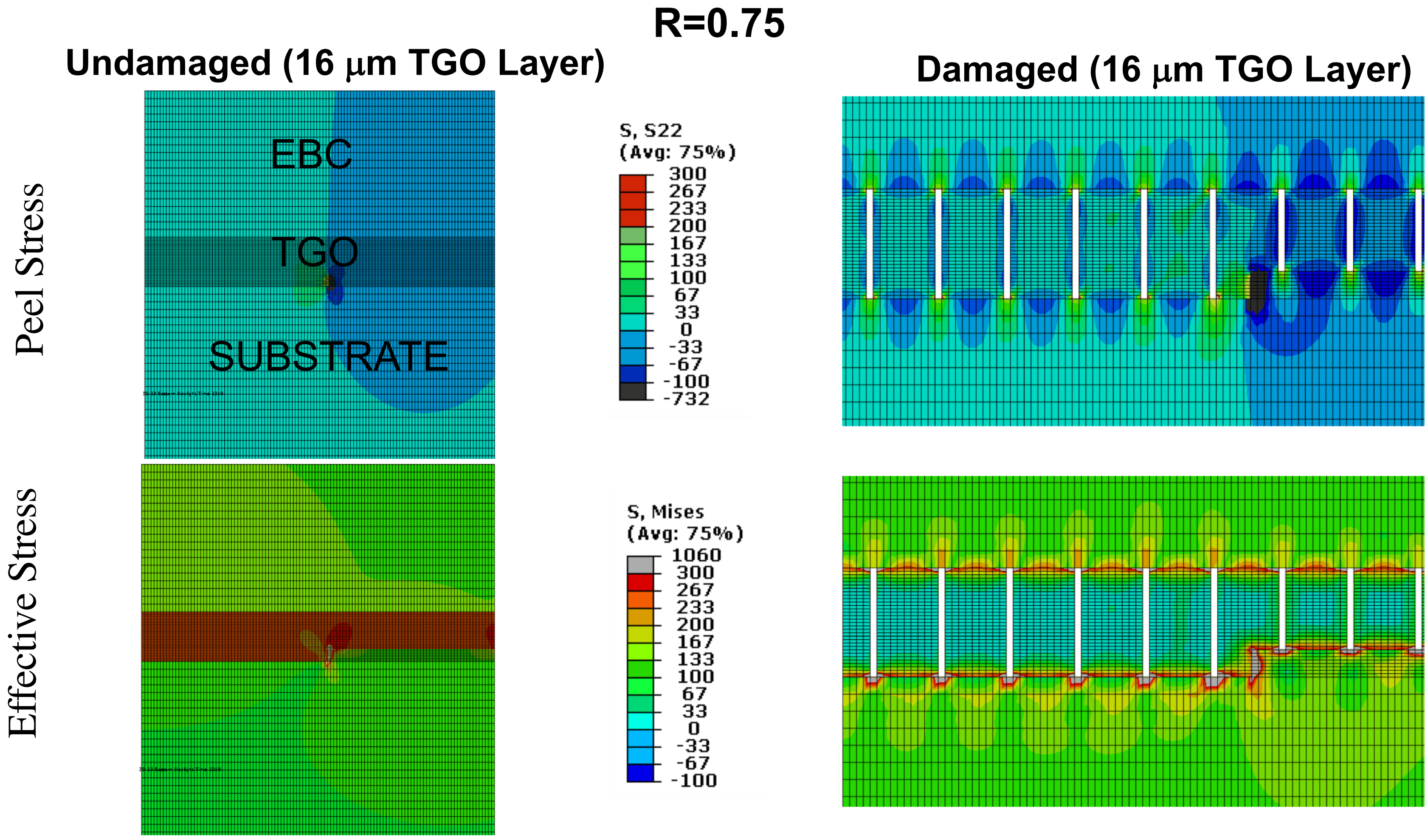
R = 0.00

$R = d/t_{TGO}$ ⇨ 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)

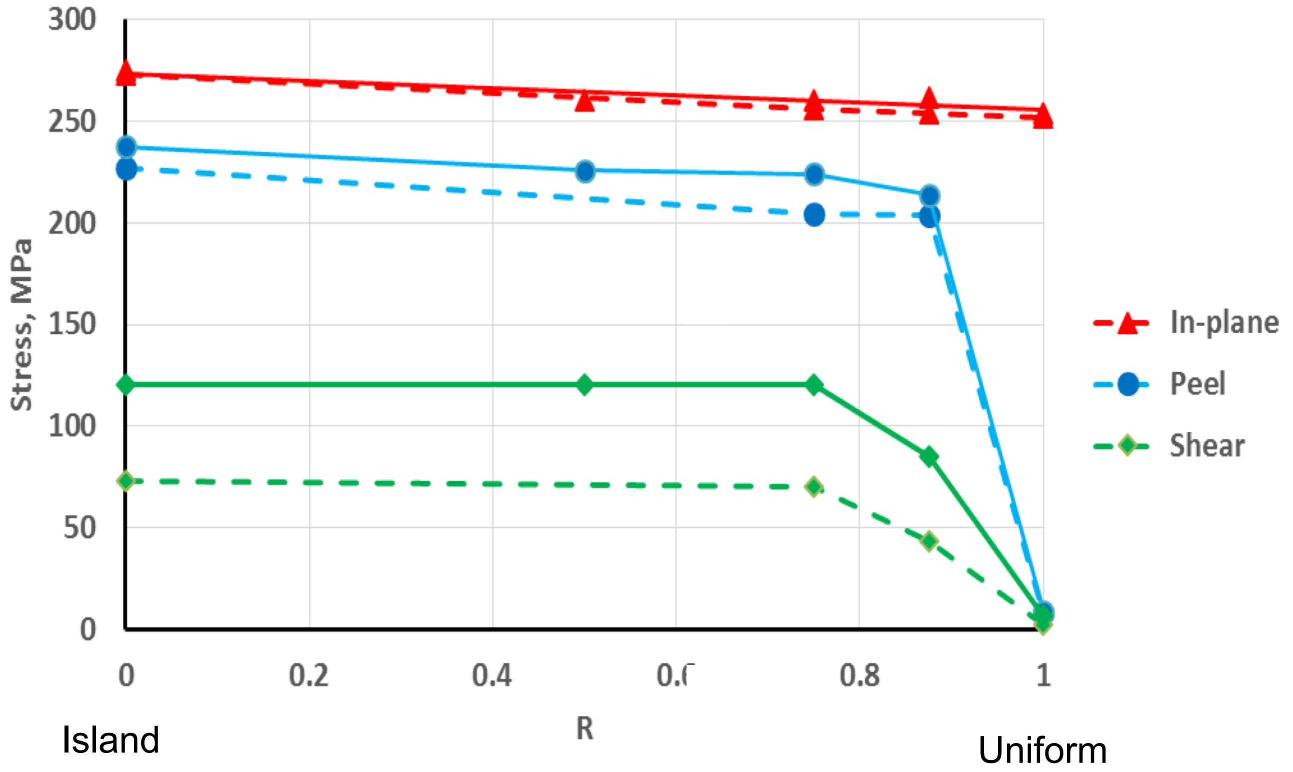
Results: Non-Uniform 3 Layer System



- 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 Stresses in TGO Layer with No Damage

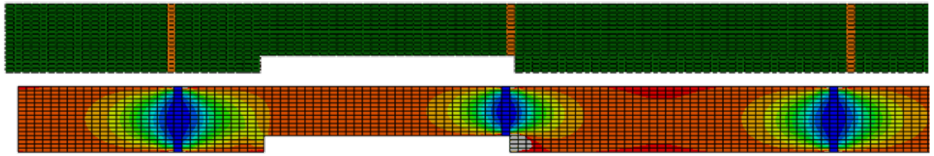
Solid lines represent thick (16 μm) TGO
Dash lines represent thin (4 μm) TGO



- Significant peel and shear stresses develop even with slight non-uniformity.
- Magnitude of stress is independent of 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

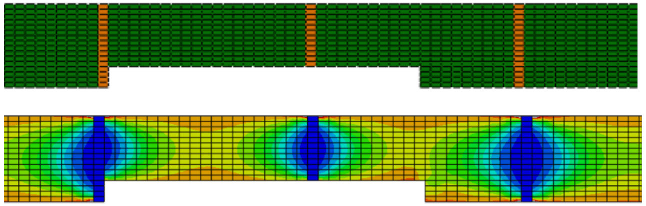
Maximum In-plane Stress in Non-uniform TGO layer Versus Crack Spacing

80 µm spacing



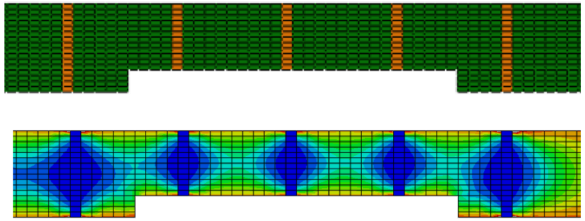
In-plane stress

40 µm spacing

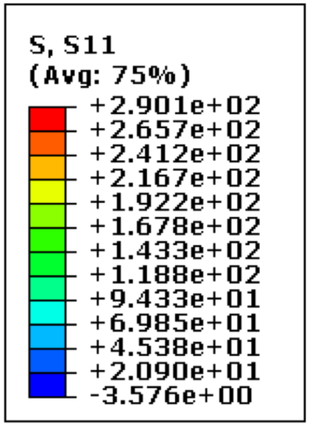


In-plane stress

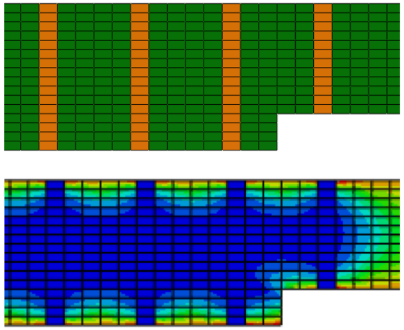
20 µm spacing



In-plane stress



10 µm spacing

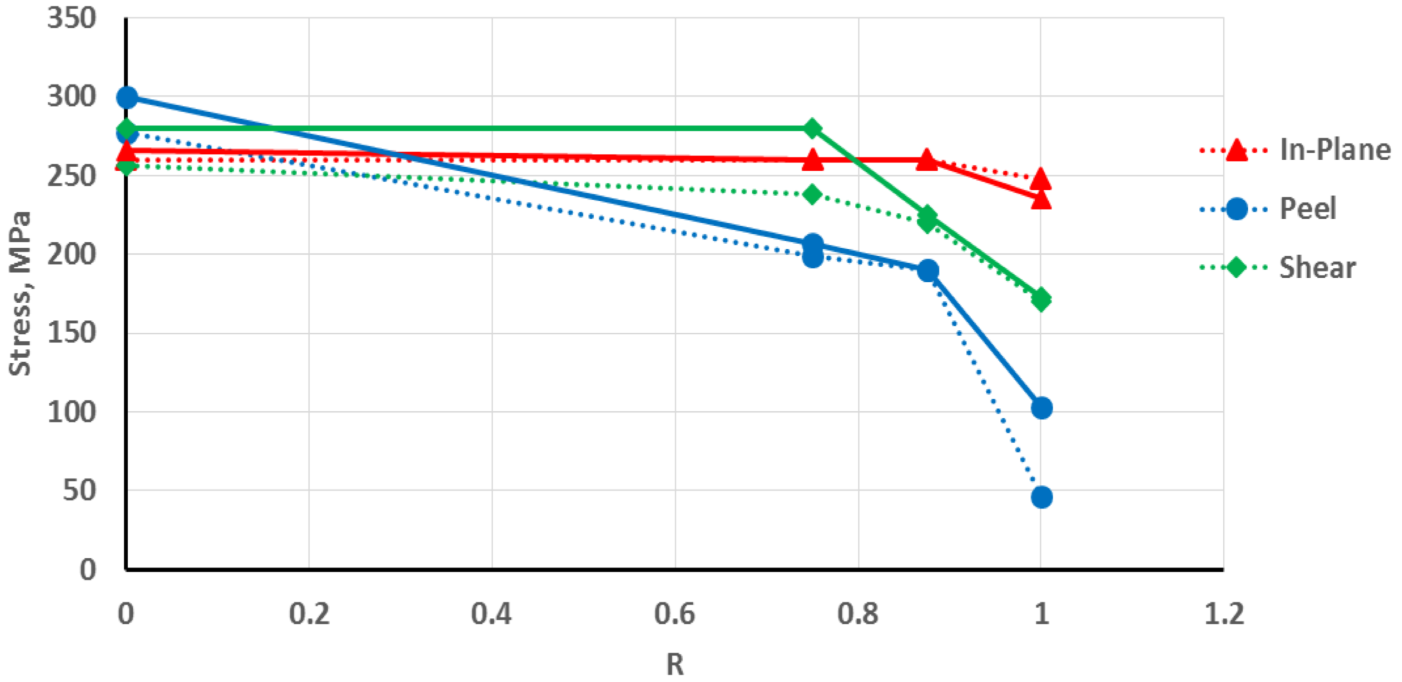


In-plane stress

- 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

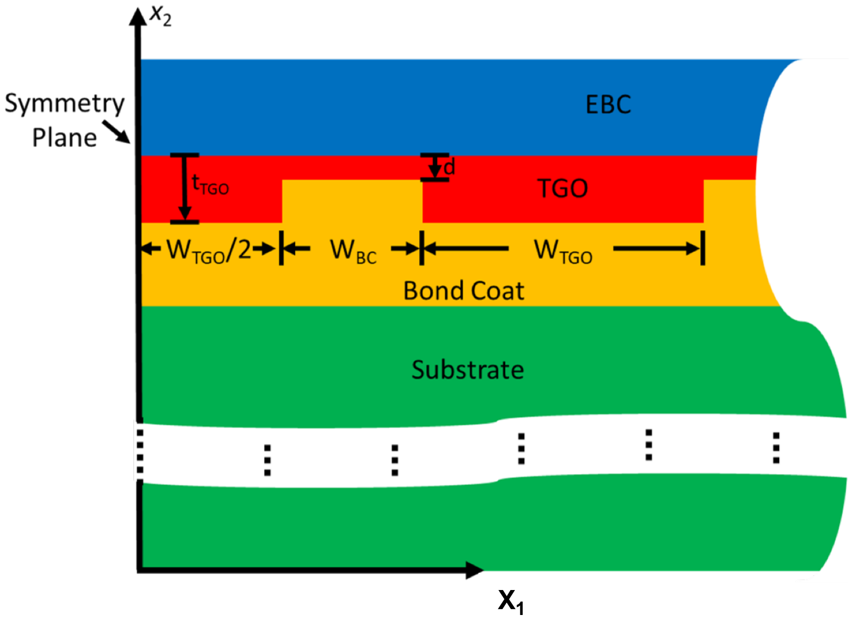
Maximum Stresses in Non-uniform TGO Layer Vertical Cracks @ 10 µm Spacing

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).

Non-uniform Idealization – 4 Layer System



t_{TGO} = 1, 4, 16 μm

W_{TGO} = ~120 μm

W_{BC} = ~60 μm

$R = d/t_{TGO}$

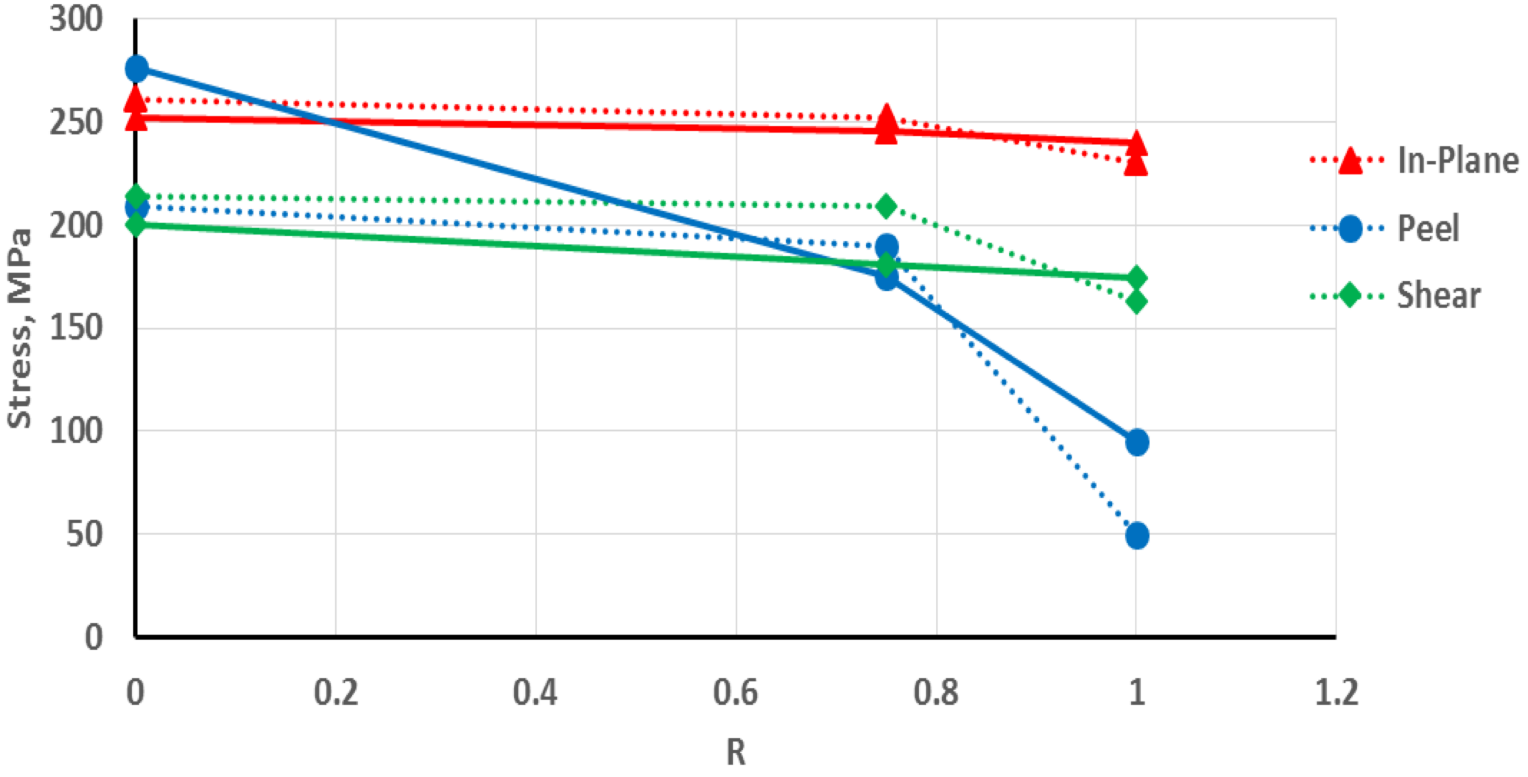
R = 0.00, 1.00

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

Maximum Stresses in Damaged TGO Layer

10 µm Spaced Cracks

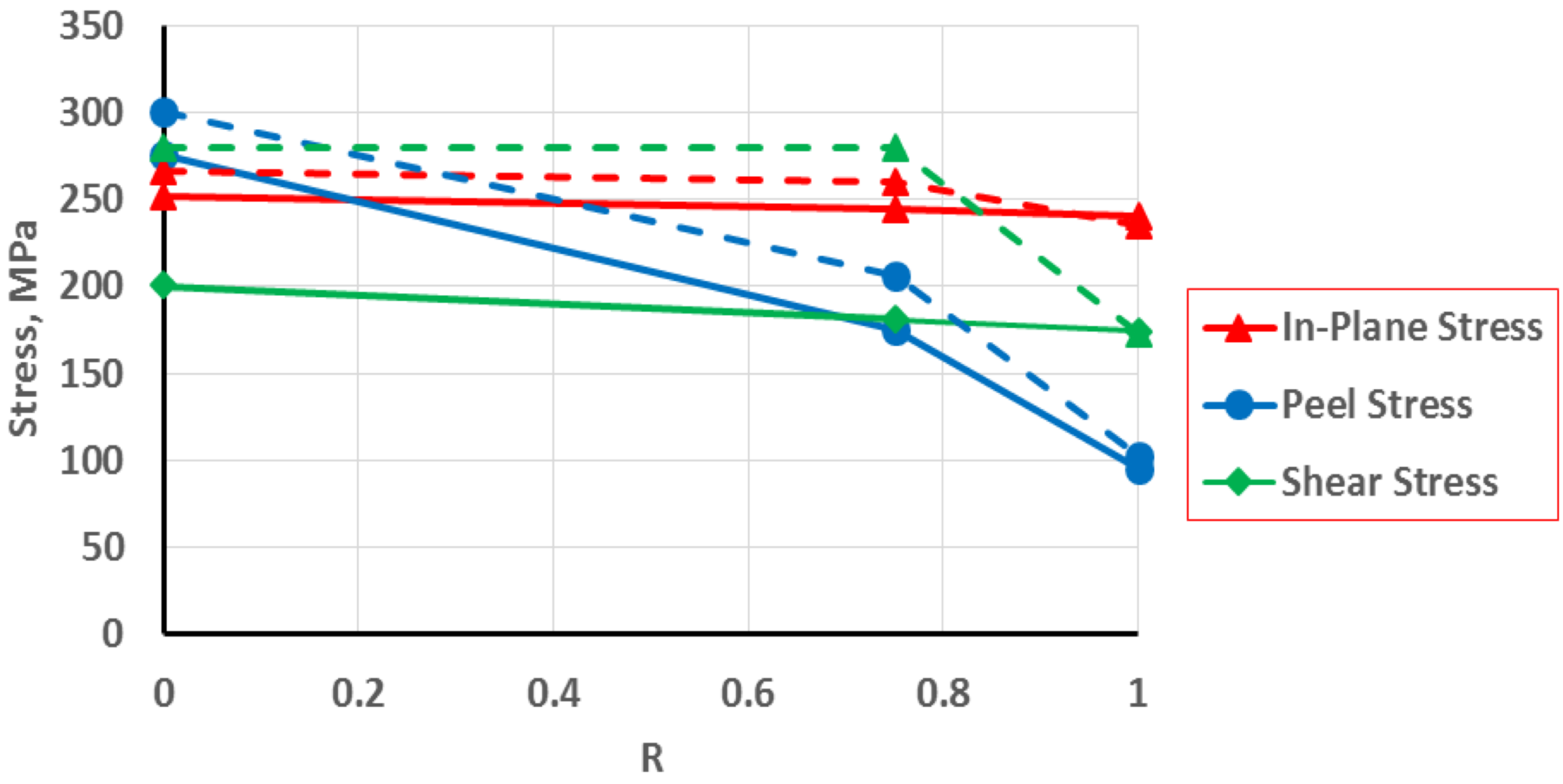
Solid lines represent **thick** (16 µm) TGO
Dash lines represent **thin** (4 µm) TGO



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

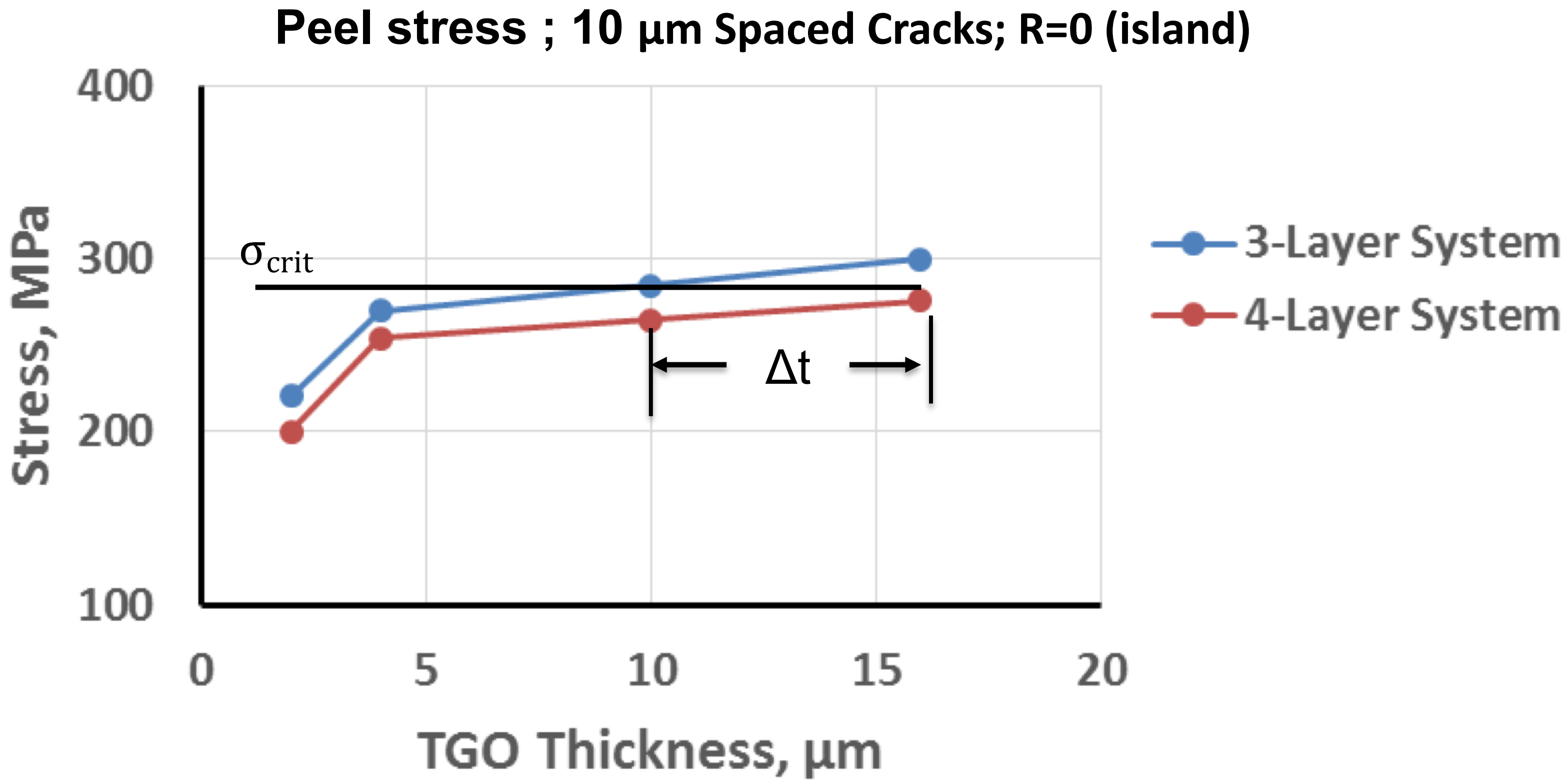
Comparison of Max Stresses in 3 and 4 Layer Damaged Systems; 16 µm TGO Layer, 10 µm Cracks

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%)

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 few cases of 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; analyses suggest that 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.

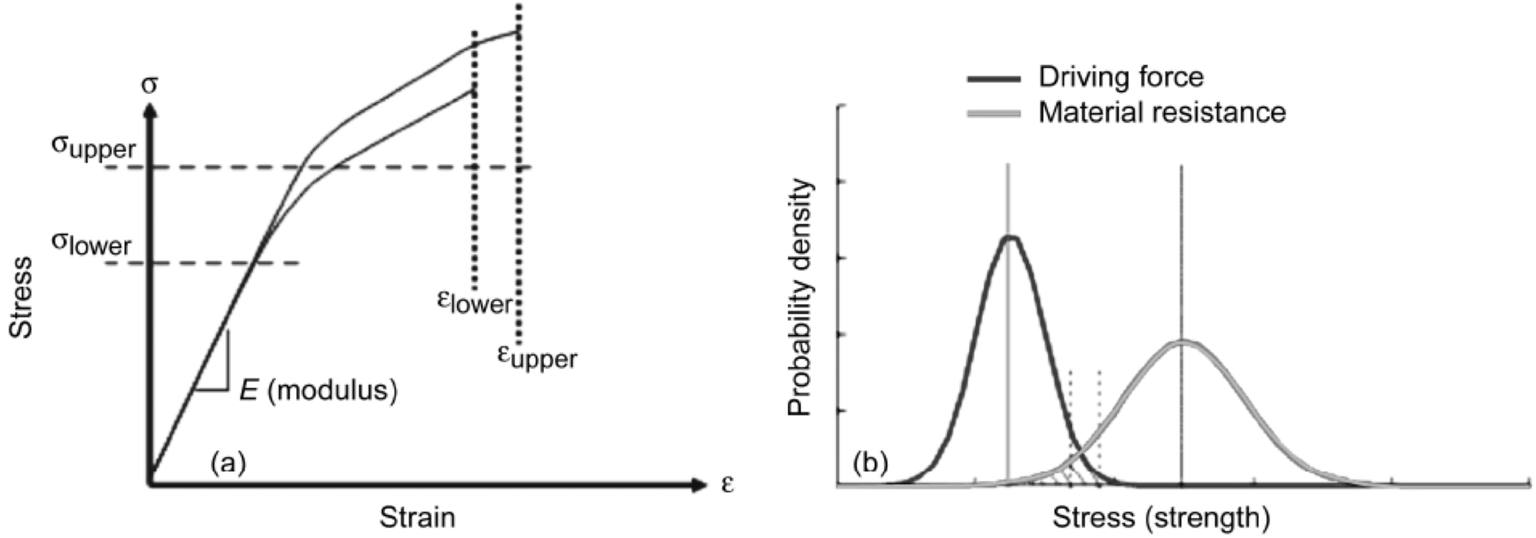
<u>Future Work</u>

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

Thank You For Your Attention

Email: Steven.M.Arnold@nasa.gov

Modeling Philosophy: Trade Offs



Actuality both driving force (applied loads and local architecture**) and material resistance** (dependent upon both local architecture and processing methodology) **are spatially varying throughout a given component/specimen.**

1) Assume a fixed (pristine) architecture (Driving Forces) with specific architectural parameters that can be varied (e.g., tow spacing, tow shape, etc.) to obtain a statistical distribution of resulting stresses. These stresses then can be compared with statically and spatially varying material strength values (Resistance).
2) Alternatively, one can analyze local architecture (e.g., ply shifting, ply rotation, nesting, etc.) and the flaw and porosity distribution in great detail using high-fidelity numerical analyses to obtain detailed local stresses (i.e., driving forces). These stresses can be compared with a fixed value of material strength (resistance).

Prior Study Results related to Thermally Induced Stresses in TBC-Protected Plate

- **Effect of geometry on free-edge interlaminar stresses: no effect of L/H, significant effect of t_{BC}/H**
- **Effect of bond coat properties on free-edge interlaminar stresses: significant effect of α_{BC} and E_{BC}, small effect of κ_{BC}**
- **Effect of top coat properties on free-edge interlaminar stresses: smaller effect of α_{TC} and E_{TC} relative to α_{BC} and E_{BC}**
- **Effect of substrate properties on free-edge interlaminar stresses: relatively small effect of α_S and E_S along TC/BC interface, with substantially greater effect along BC/S interface**
- **Effect of through-thickness thermal gradient on free-edge interlaminar stresses: the magnitude of the gradient has significant effect**
  - **Change in sign of the peel stress with increasing gradient from tension to compression**

* "Thermally-Induced Interlaminar stresses in TBC-Protected Plate: A Material and Geometric Parametric Study"; Arnold et al., HITEMP Review 1995, Vol. II, CP 10178, pp. 34:1-14

Lessons Learnt

- **Type of Analysis**: Compared 2-D plain stress, 2-D generalized plain strain and full 3-D analyses. All analyses gave comparable results. 2-D plain stress and 2-D plain strain can bound the problem.

- **Mesh Density**: Results are sensitive to mesh density. Size of the element is governed by the case with smallest undulations (when considering non-uniform layers). One should maintain the same element size for subsequent analyses.

- **Modeling of Corners:** When modeling non-uniform layers, results were compared with models with sharp corners to those where corners were rounded off. The difference in resulting stresses was not significant.

- **Size of the Model:** Symmetry was used with appropriate boundary conditions. If the edges are constrained appropriately, the size of the model can be reduced.