Composite Thermal Damage Measurement with Handheld FT-IR

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FAA Sponsored Project Information

Principal Investigators & Researchers
- Brian Flinn (PI)
- Tucker Howie (Post Doc, UW-MSE)
- Ashley Tracey (PhD student, UW-MSE)

FAA Technical Monitor
- David Westland (year 4)
- David Galella (year 3)
- Paul Swindell (year 1 & 2)

Industry Participation
- The Boeing Company (Paul Shelley, Paul Vahey)
- Sandia National Lab (Dennis Roach)
- Agilent (formerly A2 Technologies)

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Project Motivation

Motivation and Key Issues

- Damage detection in composites requires different techniques than metals
- Incipient thermal damage (ITD) occurs below traditional non-destructive evaluation (NDE) detection limits
    - ITD is chemical damage. NDE detects physical damage such as delaminations and microcracking

Objective

- Determine if handheld Fourier transform infrared (FTIR) spectroscopy can detect ITD and guide repair

Approach

- Characterize panels with controlled thermal damage and perform repair based on FTIR inspection

Project Background

Continuation of existing project (year 4 of 4)

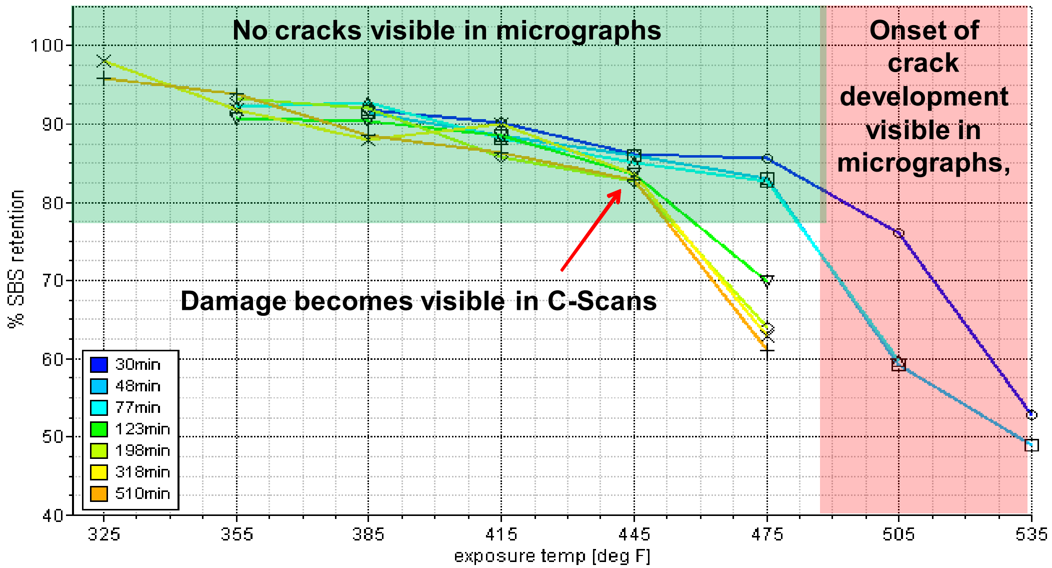
Years 1 and 2 (A2 Technologies, Boeing and U of DE)

- Characterization of homogeneous thermal damage
  - Ultrasound
  - Short beam strength (SBS)
  - Microscopy
  - Handheld Fourier transform infrared (FTIR) spectroscopy (ExoScan)
- Calibration curve for FTIR detection of thermal damage (SBS data)
- Mapped surface of localized thermal damage on resin rich surface

Year 3 & 4 (UW and Boeing)

- Contact angle and fluorescence spectroscopy
- 3-D characterization of localized thermal damage
- FTIR guided scarf repair
- Mechanical testing of locally damaged and repaired panels

Thermal Damage vs. Detection Method



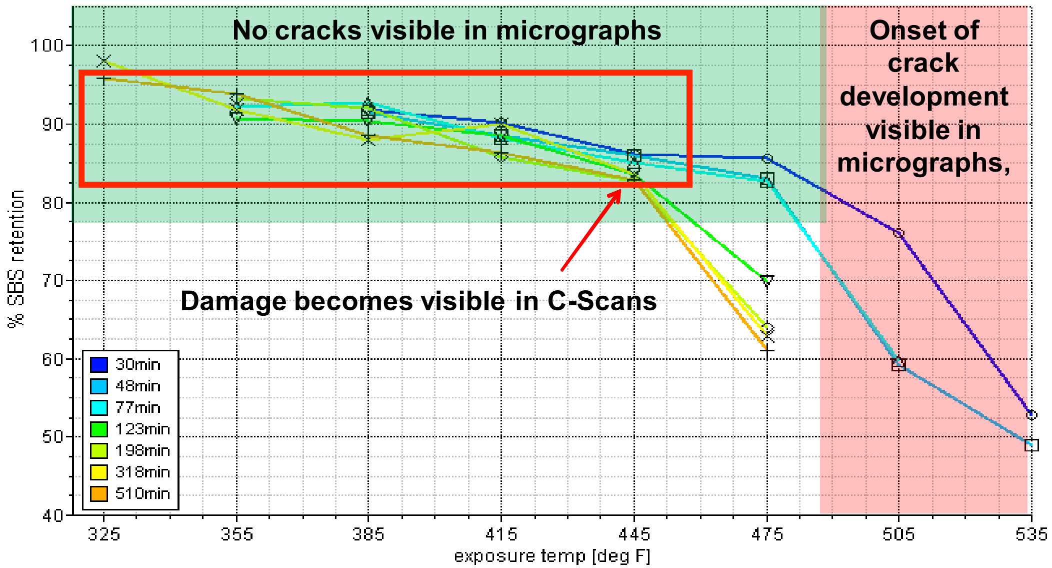
Short beam strength (SBS) degrades before detection possible with ultrasound or visual inspection

- Damage termed ITD

Need a method to detect ITD

- FTIR?

Thermal Damage vs. Detection Method



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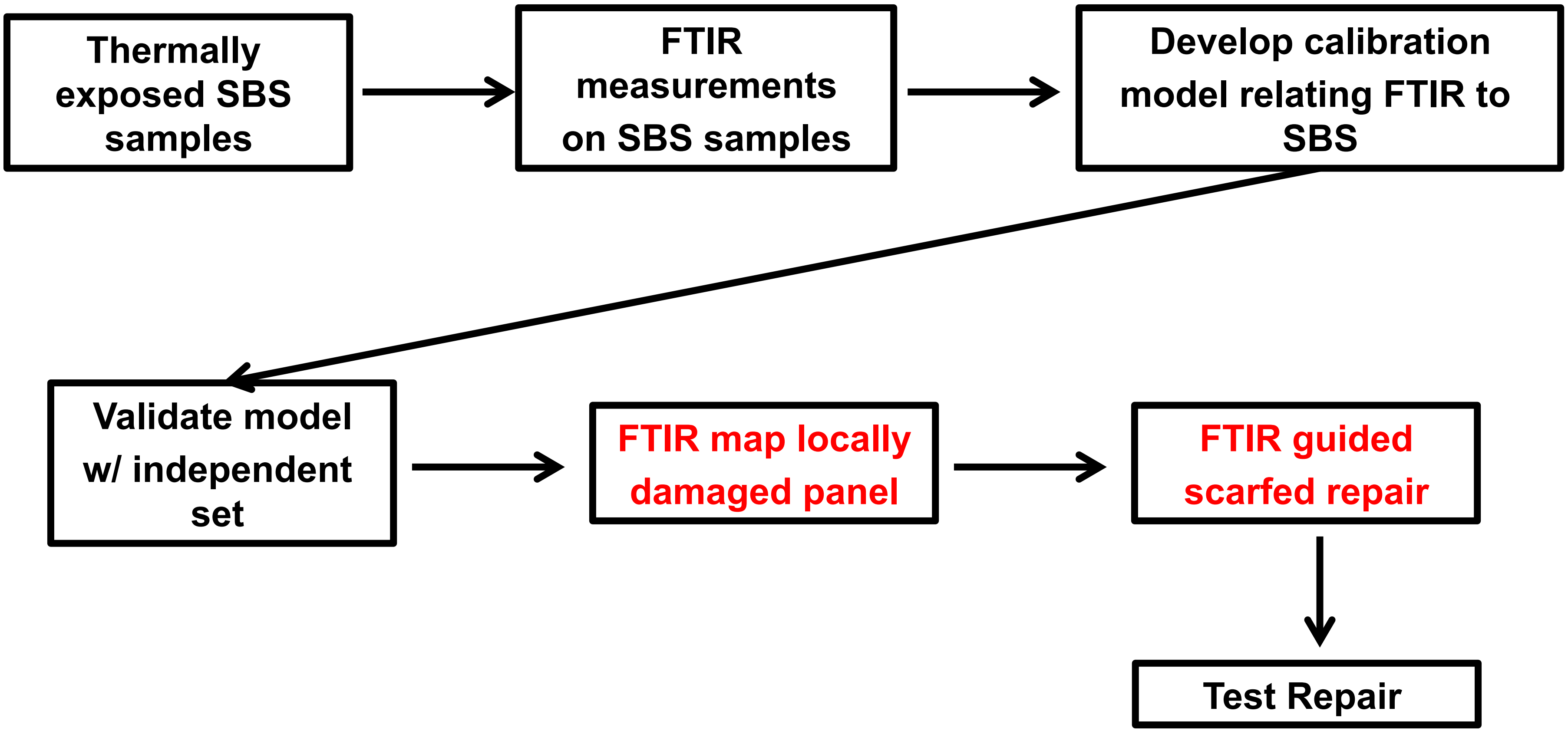
- FTIR?

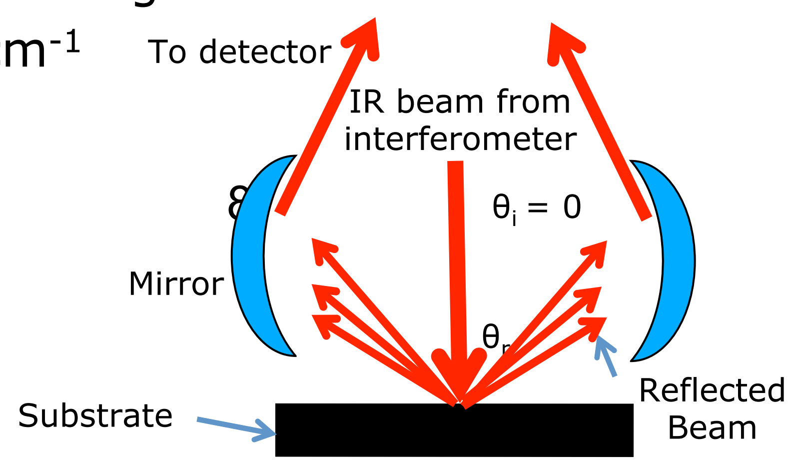
Experimental Overview



Materials and Process

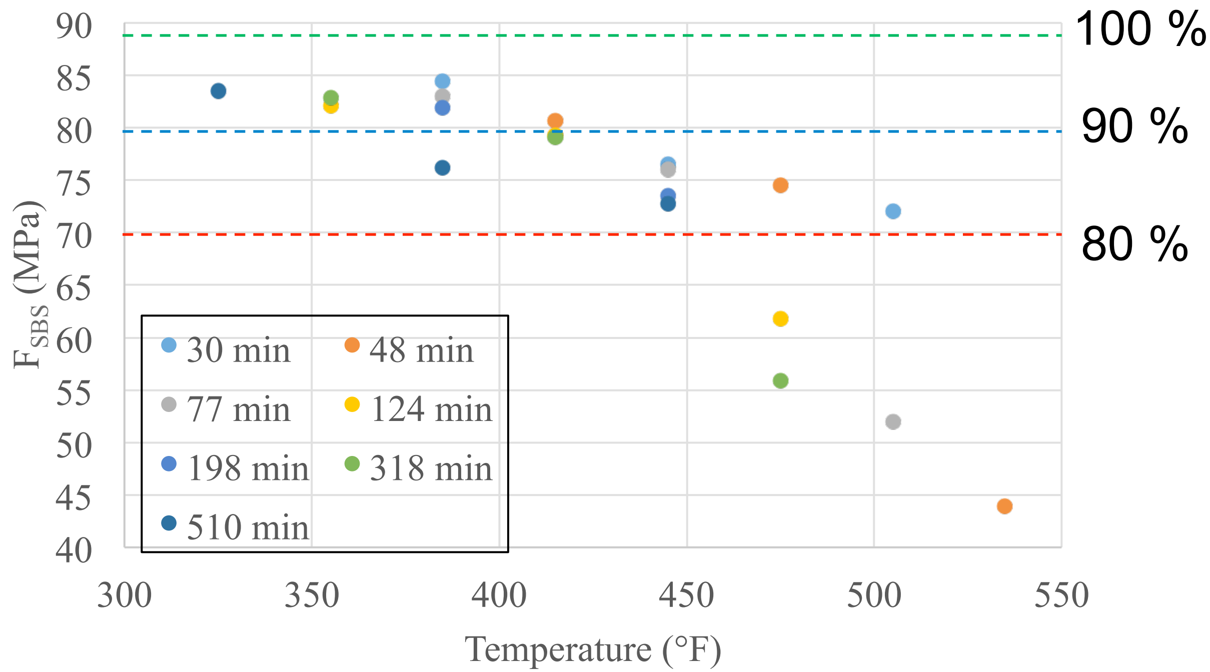
- Toray T800/3900 composites with various levels of thermal damage
  - SBS calibration samples thermally exposed in convection oven
  - Panels with localized damage from heat blanket and insulation
- Sand surfaces with 180 grit Al_2O_3 sanding pads using pneumatic orbital sander to simulate repair
- FTIR spectra taken with Exoscan FTIR using diffuse reflectance
  - Mid-IR range: 4000 cm^{-1} to 650 cm^{-1}
  - 90 scans, 16 cm^{-1} resolution


ExoScan FTIR



An infrared beam path for diffuse reflectance

SBS Calibration Samples

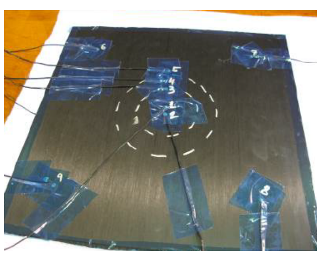


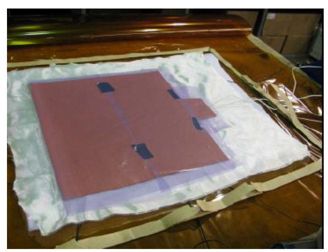
- Range of thermal exposure chosen using Design of Experiments (DOE) in ITD region
- F_{SBS} values ranged from 43.9 Mpa to 84.4 MPa (undamaged F_{SBS} = 88.8 MPa)

* SBS testing performed at University of Delaware

Locally Heated Panel Setup

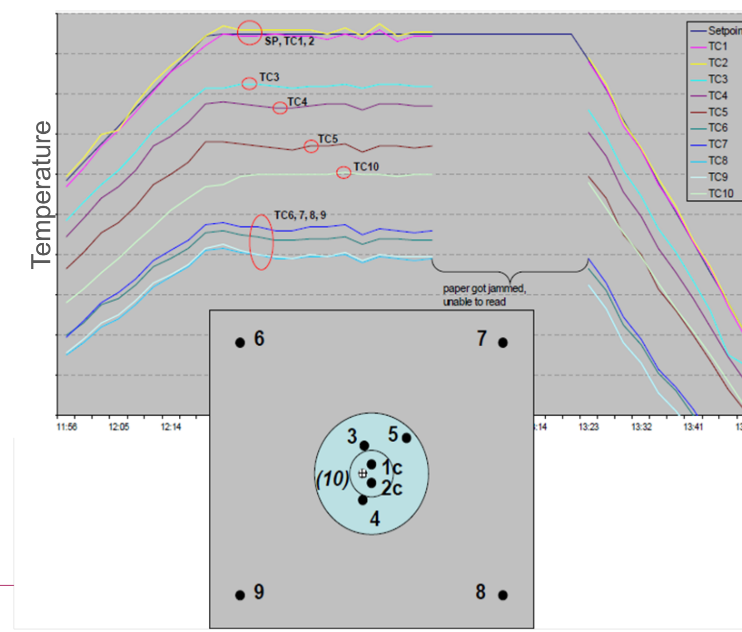
- 24-ply unidirectional 12 in x 12 in panels subjected to localized hotspot
- Local hotspot from heat blanket + extra insulation layers in center of panel
- Panels exposed for 1 hour at one of three peak temperatures (440 °F, 465 °F, 490 °F)
  - Panels referred to as low, medium, and high exposure respectively





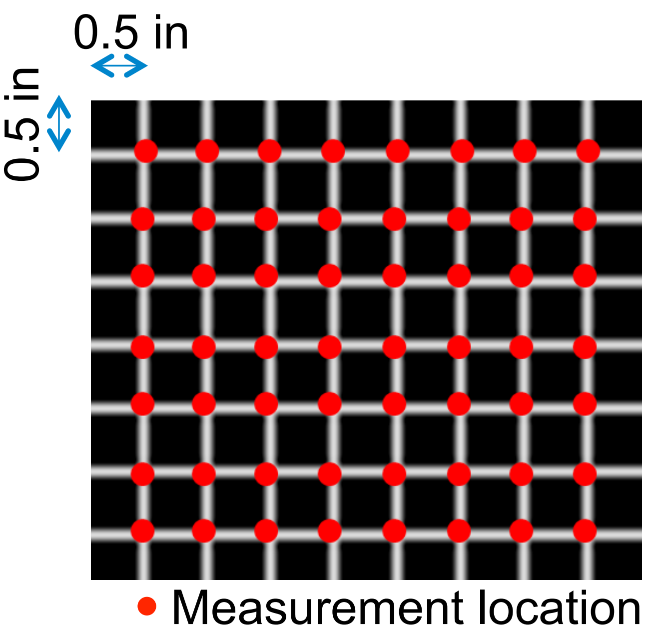
Insulation Stacking

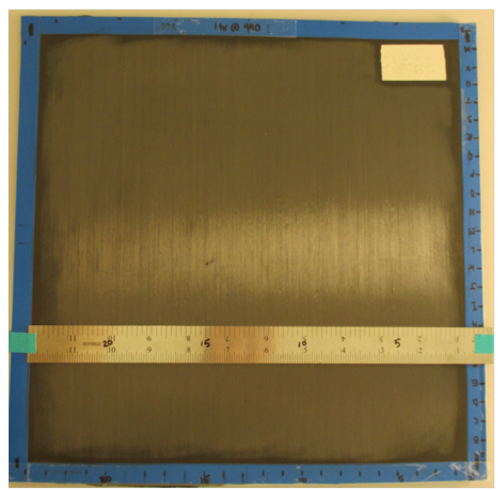
Small
Small
Small ~ 7.0 cm
Intermediate ~ 9.5 cm
Large ~ 12.1 cm

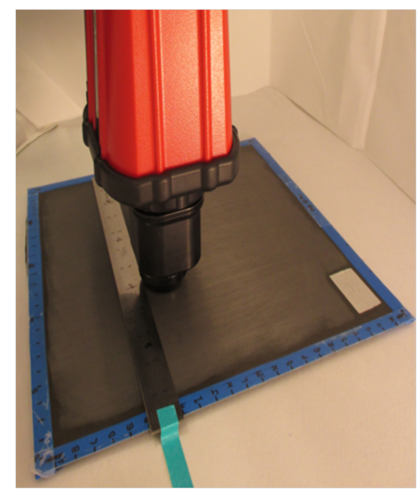


Panel Mapping Procedures

- Grid with 0.5 in between points marked on edges of panel
- FTIR positioned using rulers to align with grid
- Measurements taken at every point on grid
  - 3 measurements taken at every point

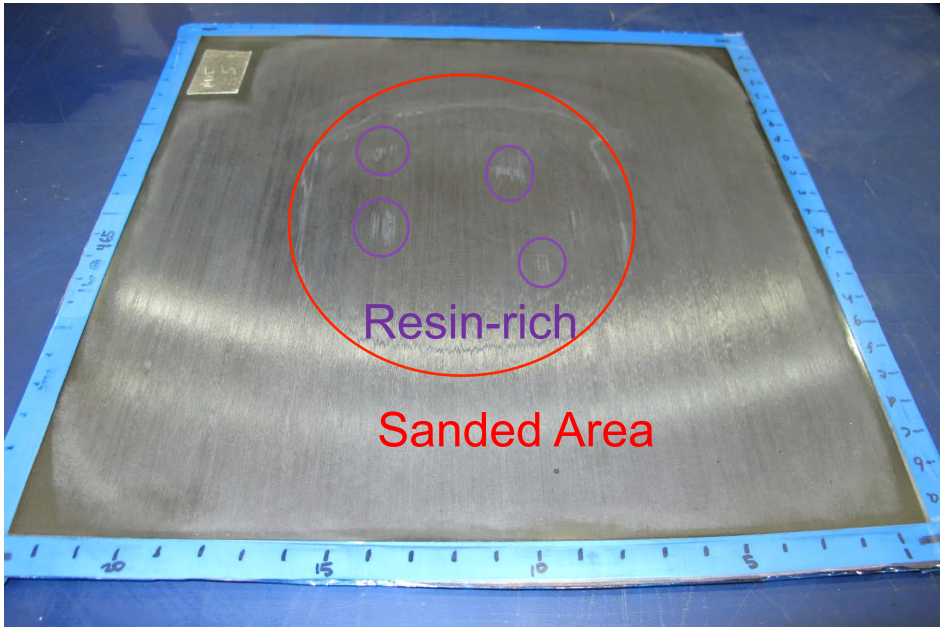




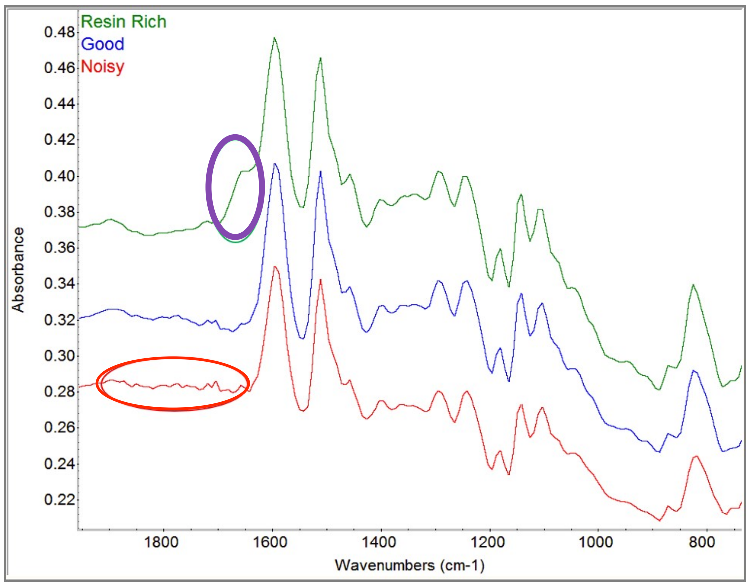


Panel Sanding

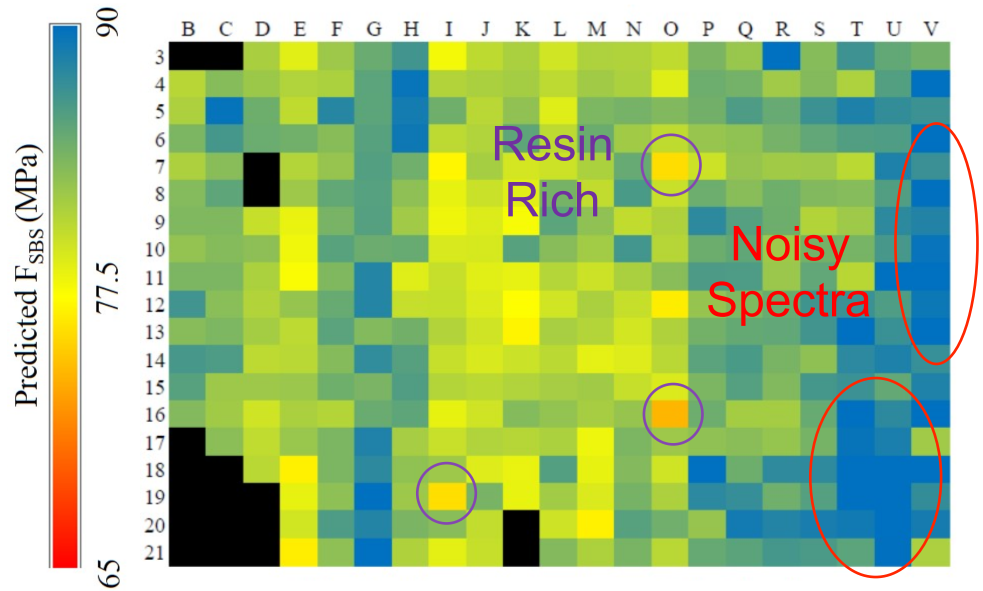
- Located damage based on FTIR inspection and sanded down to next ply
  - Small areas of over-sanding leading to resin rich spots



Effect of Spectral Features on Model Predictions



Surface Map of Low Exposure Panel



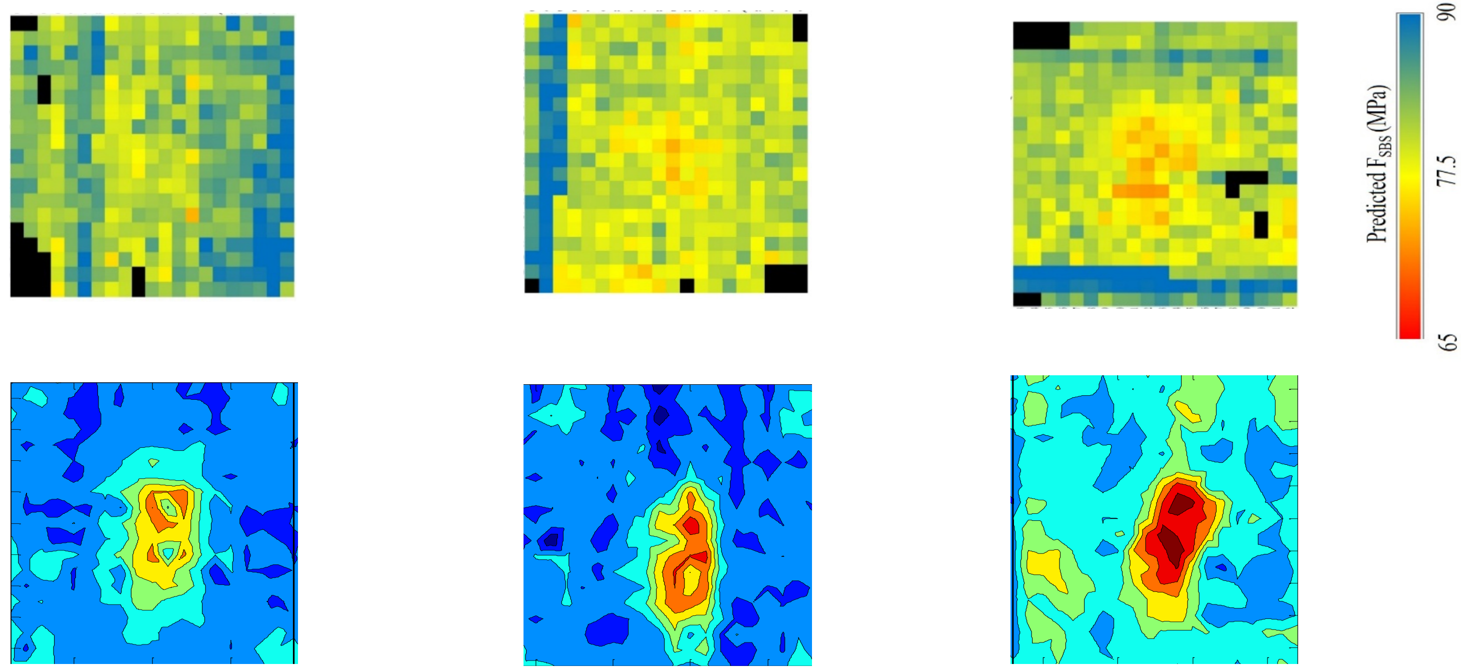
- Resin rich spectra exhibit broad carbonyl peak between 1600-1690 cm^{-1}
  - Predicted lower F_{SBS} values
- Noisy spectra were observed by an increase in noise in the baseline
  - Predicted higher F_{SBS} values
  - Can be mitigated by taking a new background reference

Comparison of Surface Mappings Predictions

Low Exposure | Med. Exposure | High Exposure

Sanded Surface (Model 4)

Resin Rich Surface (1st year)*

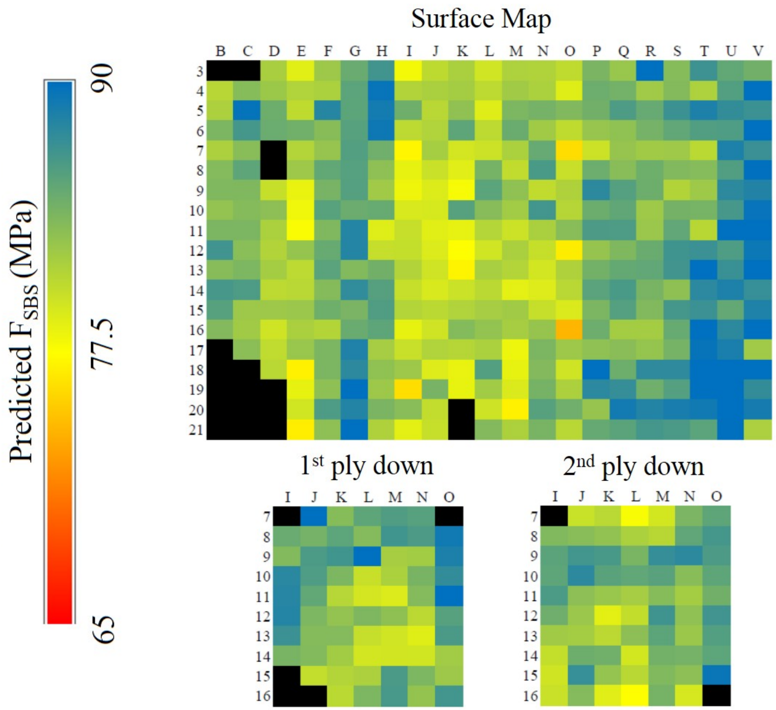


Note: Scaling, panel orientation, and color scheme are different

- Reasonable agreement between predictions results on the two surfaces

* Measurements performed by A2 Technologies and Boeing

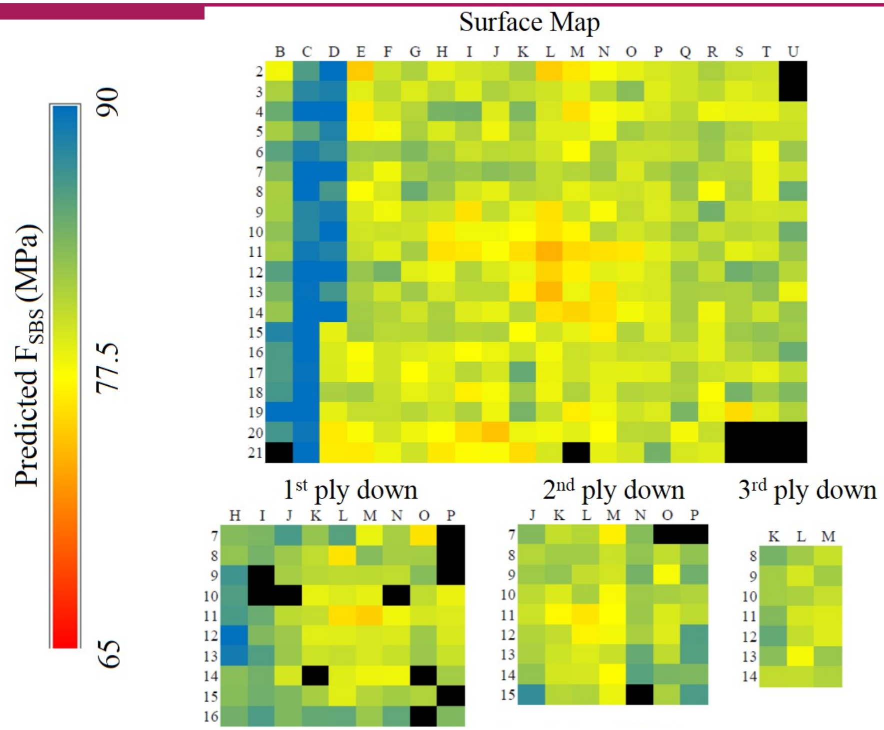
Inspection of Low Exposure Panel



□ 0.5 in x 0.5 in

- Low exposure panel used to establish a Go/No Go threshold to damage removal
- Sanded down 2 plies to evaluate prediction variance
  - 79.5 MPa (90% retention of undamaged F_{SBS}) chosen as the threshold (Green or blue color on the map)

Inspection of Medium Exposure Panel



□ 0.5 in x 0.5 in

- Medium exposure panel exhibited moderate damage in 3″ x 3″
  - Low F_{SBS} values around 74-75 MPa (~ 82 % of undamaged F_{SBS})
- Most of the damage was removed after sanding to the first ply down
- Panel passed Go/No Go threshold after sanding 3 plies down

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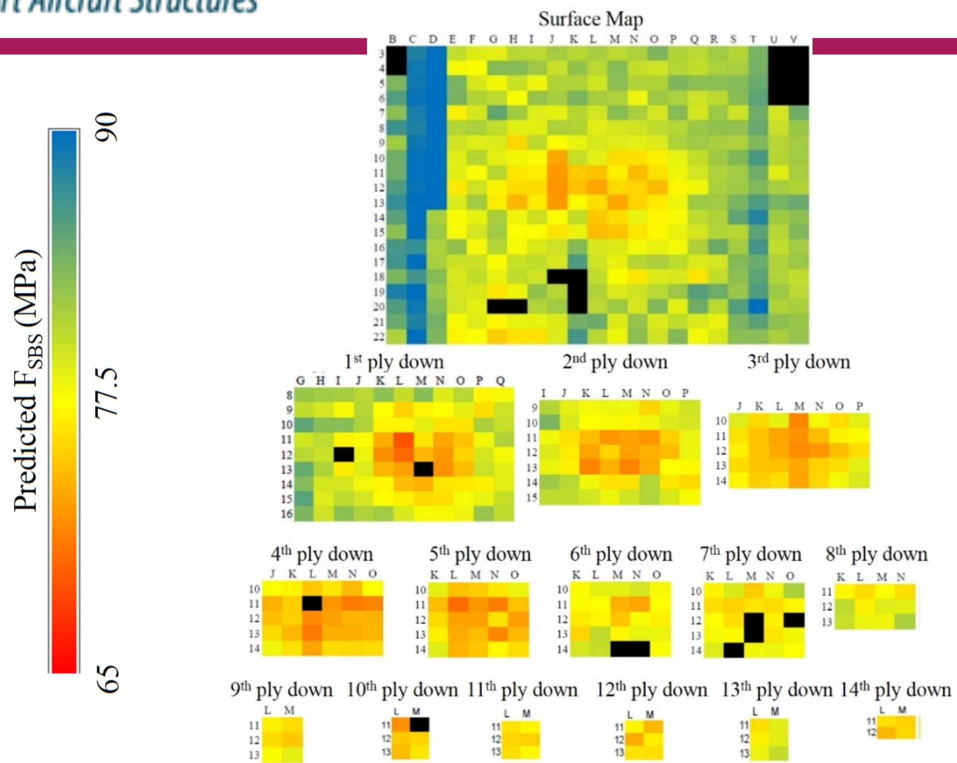
Inspection of High Exposure Panel

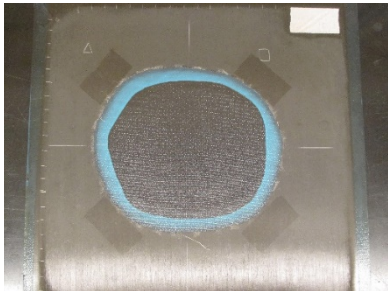


☐ 0.5 in x 0.5 in

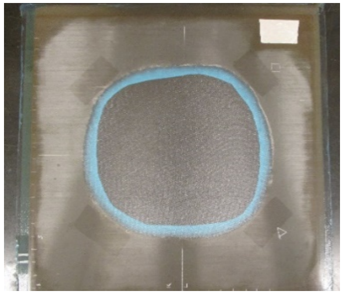
- High exposure panel had large damage region ~ 5″ x 5″
  - Low F_{SBS} values around 72-73 MPa (~ 80 % of undamaged F_{SBS})
- Go/No Go threshold not passed in the center of the panel after sanding down 14 plies
- Inspection stopped due to repair size restriction

Repair Process

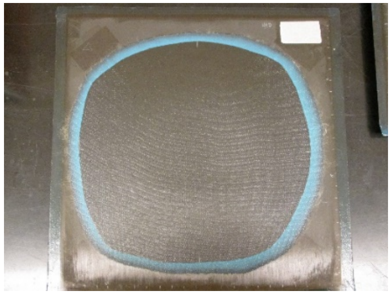
- After inspection was completed panels were sanded to a 30:1 scarf angle
- Patch plies were cut from Toray T800/3900 unidirectional prepreg
  - The high exposure patch was double vacuum debulked (DVD) to help removal volatiles that could be trapped in a thick patch
- MetlBond 1515-3M adhesive
- Patches were cured under a vacuum using a heat blanket controlled by a hot bonder at 350 °F for 2.5 hours



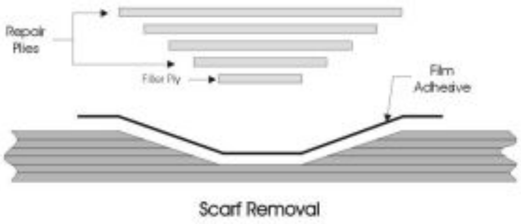
Low Exposure (2-plies)



Medium Exposure (3-plies)



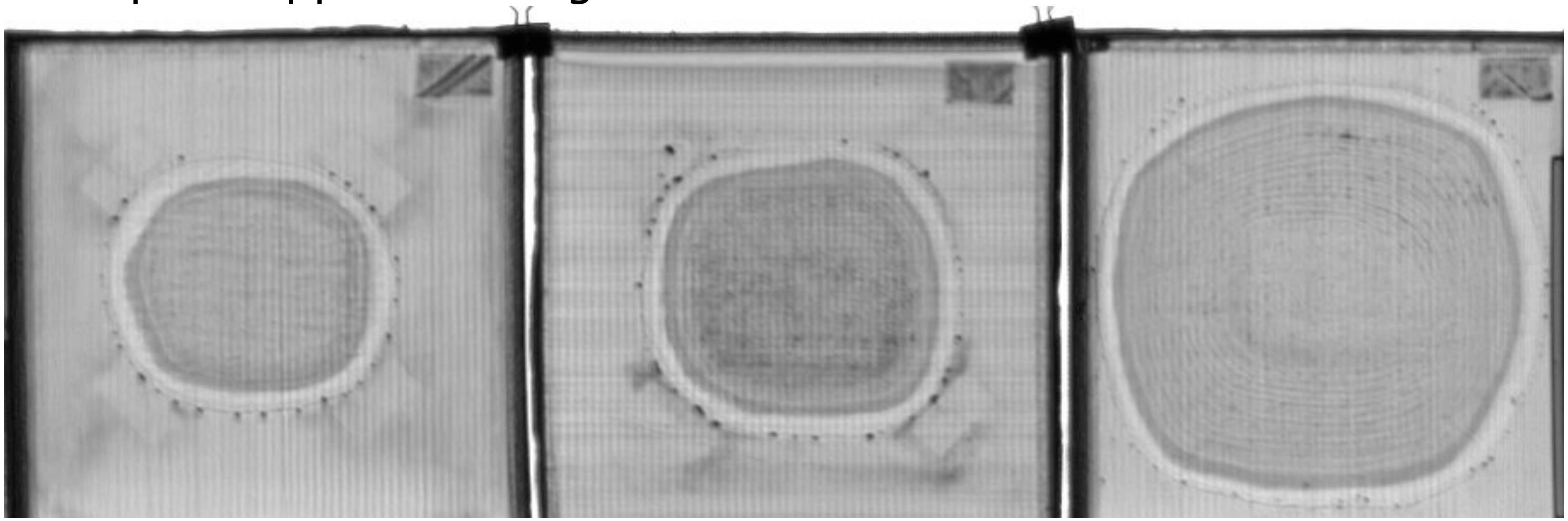
High Exposure (14 plies)



Scarf repair diagram from http://www.netcomposites.com/

Inspection of Repairs

- Repaired panels inspected using ultrasound
  - 5Mhz 2.5" Focused TTU
  - 6" Water Path
  - .04 Resolution
- Repairs appear to be good



Low Exposure (2-plies) Medium Exposure (4-plies) High Exposure (14 plies)

Ongoing Work

- Mechanical testing of repaired and duplicate damage panels to evaluate removal of ITD
  - Short beam strength
    - Gives interlaminar shear stress and is known to be sensitive to incipient thermal damage
    - Max shear stress occurs at center of the sample, but most damage is on the plies near surface
  - Tension test with 45° samples
    - Sensitive to matrix dominated properties
    - May not be sensitive to damage in ITD range
  - Compression after impact
    - Sensitive to ITD
    - Potentially sensitive to surface damage
    - Number of test samples

Positive properties of test Negatives properties of test

Ongoing Work

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Positive properties of test Negatives properties of test

Ongoing Work

- Making three additional panels to determine effectiveness of testing method prior to testing panels
  - Undamaged Panel
  - Undamaged Panel with large repair
  - Extra damage panel exposed at ~ 480 °F for 1 hr
- If tensile test can detect ITD the remaining six panels (3 repaired and 3 damaged) panels will be tested
- This work should be completed by December 31, 2014

Positive properties of test Negatives properties of test

Summary

- Improved consistency of model predictions
- Go/No Go Threshold set at prediction of 90 % F_{SBS} retention
- Used FTIR to map and guide repair of thermally damaged panels
  - Low exposure panel exhibited almost no damage
  - Medium exposure panel had moderate damage which was removed after sanding down 3 plies
  - Part of high exposure panel did not reach Go/No Go threshold after removing 14 plies
    - Stopped to repair size restrictions
- Panels repaired using scarf repair process
- Repaired panels inspected with ultrasound and repaired panels look good
- Mechanical testing of panels is currently ongoing

Acknowledgements

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Sandia National Labs

Agilent Technologies

- John Seelenbinder

UW MSE

- Edward Roberts, Jake Plummer, David Pate, Jonathan Morasch

University of Delaware

Looking Forward

- Benefit to Aviation
  - Improved damage detection
  - Greater confidence in repairs
- Future needs
  - Application to other composite systems
  - Other applications of handheld FTIR
    - Chemical damage
    - Surface prep for bonding

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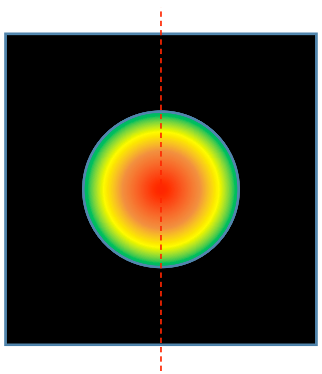
QUESTIONS?

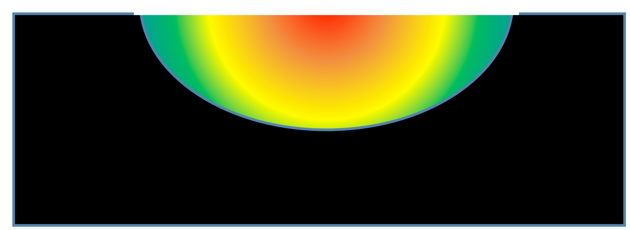
Considerations for Mechanical Testing

- Properties desired for mechanical testing
  - Need to test both repaired and damaged panels to compare results
  - Tests matrix dominated properties
  - Preferably large area such that it contains a significant portion of damaged region
  - Prefer failure of composite rather than bondline in repaired panels
- Damage distribution in the panels
  - Highest damage on surface in the center of the panel
  - Damage decreases radially outward from the center on the panel
  - Damage into the depth of panel has ellipsoidal form

Top View of Damage Panel



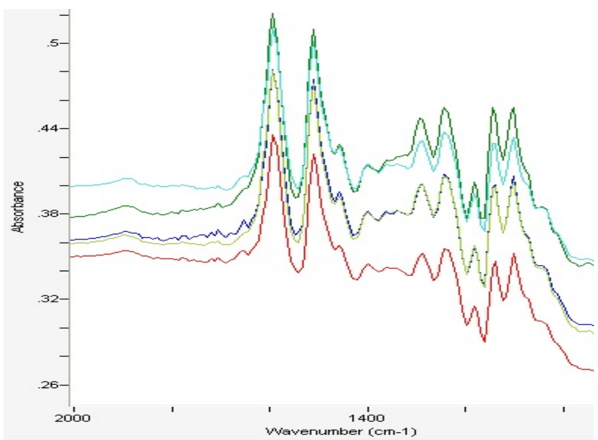
Representative cross-section of damage area taken along red dashed line



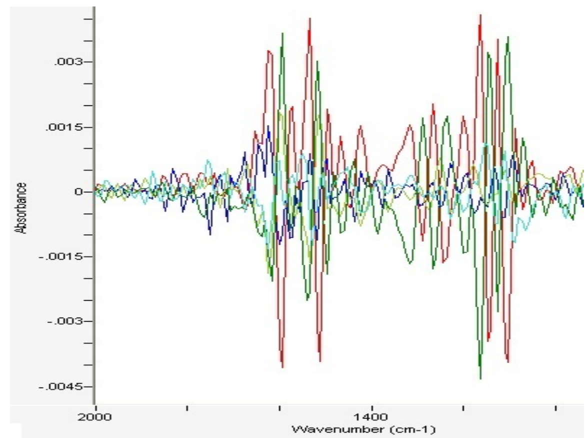
Red = high damage
Blue/Green = light damage
Black = no damage

Generating Calibration Model

- Model needed to correlate FTIR spectra to F_{SBS} data
- Spectra preprocessed using Savitzky-Golay 1st derivative and 7-pt smoothing
  - Removes baseline effects
  - Accentuates differences in spectra
- Partial Least Squares (PLS) model generated using Principal Components Analysis (PCA) in GRAMS IQ software



Raw Spectra



Processed Spectra

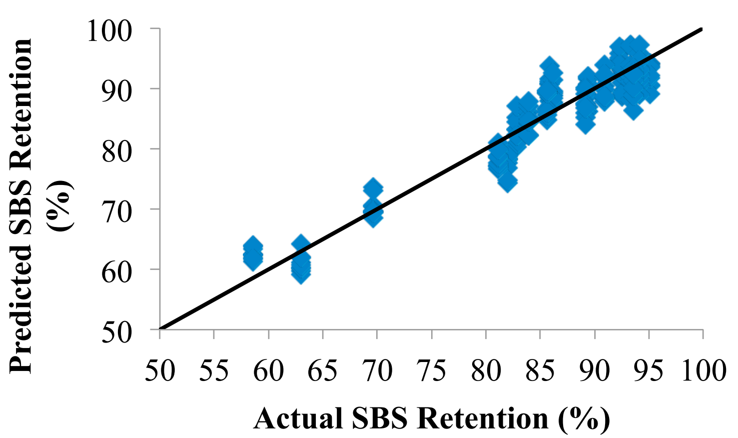
Calibration Model and Model Validation

Model validated by predicting independent evaluation set

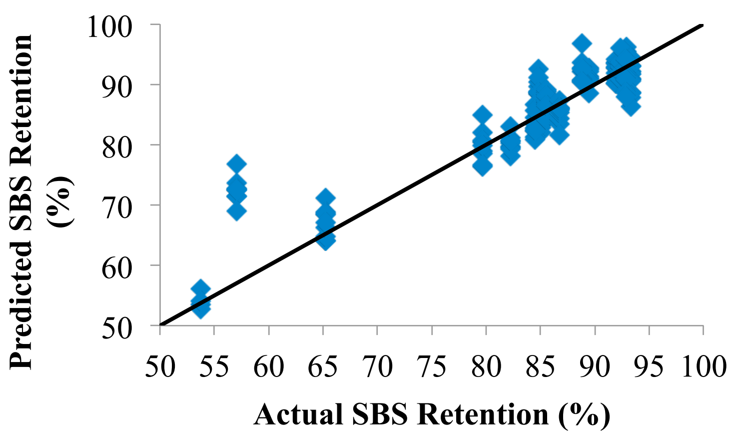
- Model showed good predictive capabilities of evaluation set (~85% of samples had < 5% error)

$$\%Error = \frac{predicted - actual}{actual} * 100\%$$

Cross-validation of calibration set using leave-one-out method



Prediction of independent evaluation set



✓ PLS model relating the SBS measurements to FTIR spectra successfully generated

Model Development

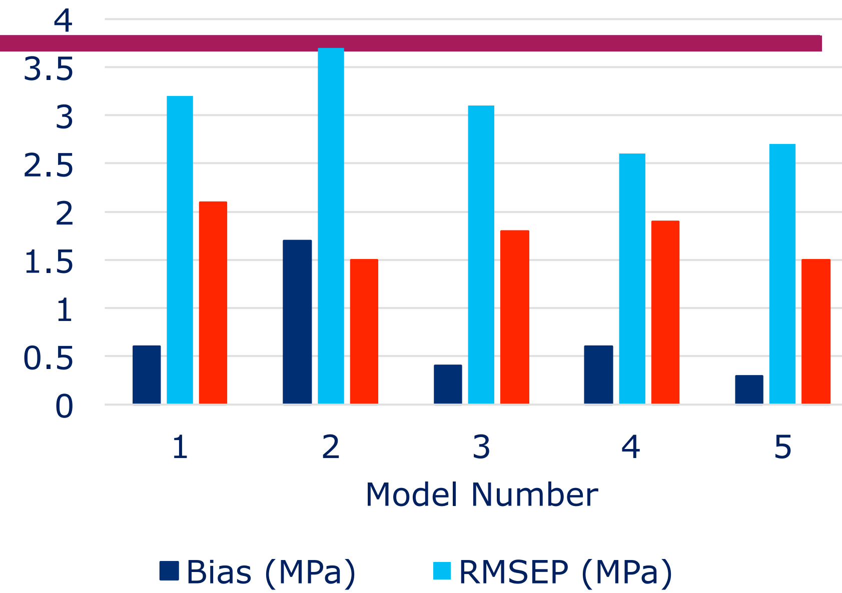
Model	F_{SBS} Values in Calibration Set	# of Principal Components	Frequency Range (cm^{-1})
1	All	5	1700-950
2	All	3	1700-950
3	All	4	1700-950
4	F_{SBS} > 60.0 MPa	4	1700-950
5	F_{SBS} > 60.0 MPa	4	1600-950

Models generated by altering 3 variables

- Sample Set→ lower F_{SBS} values may skew model (physical damage not chemical)
- Principal components → overfitting vs. underfitting
- Restrict frequency range → reduce influence of certain peaks

Model Analysis

Model	F_{SBS} Values in Calibration Set	# of Principal Components	Frequency Range (cm^{-1})
1	All	5	1700-950
2	All	3	1700-950
3	All	4	1700-950
4	F_{SBS-} > 60.0 MPa	4	1700-950
5	F_{SBS-} > 60.0 MPa	4	1600-950



Model predictions of independent sample set evaluated on three criteria:

- Bias: $\sum_{i=1}^{n} (x_i^{pred} - x_i^{actual}) / n$
- Root mean square error of prediction: $\sqrt{\sum_{i=1}^{n} (x_i^{pred} - x_i^{actual})^2 / n}$
- Average Mahalanobis Distance (M-distance): Measure of the spread of the data

Models 4 and 5 show best performance