THE EFFECT OF FATIGUE DAMAGE ON VISCOELASTIC PROPERTIES OF ANGLE-PLY GFRP LAMINATES

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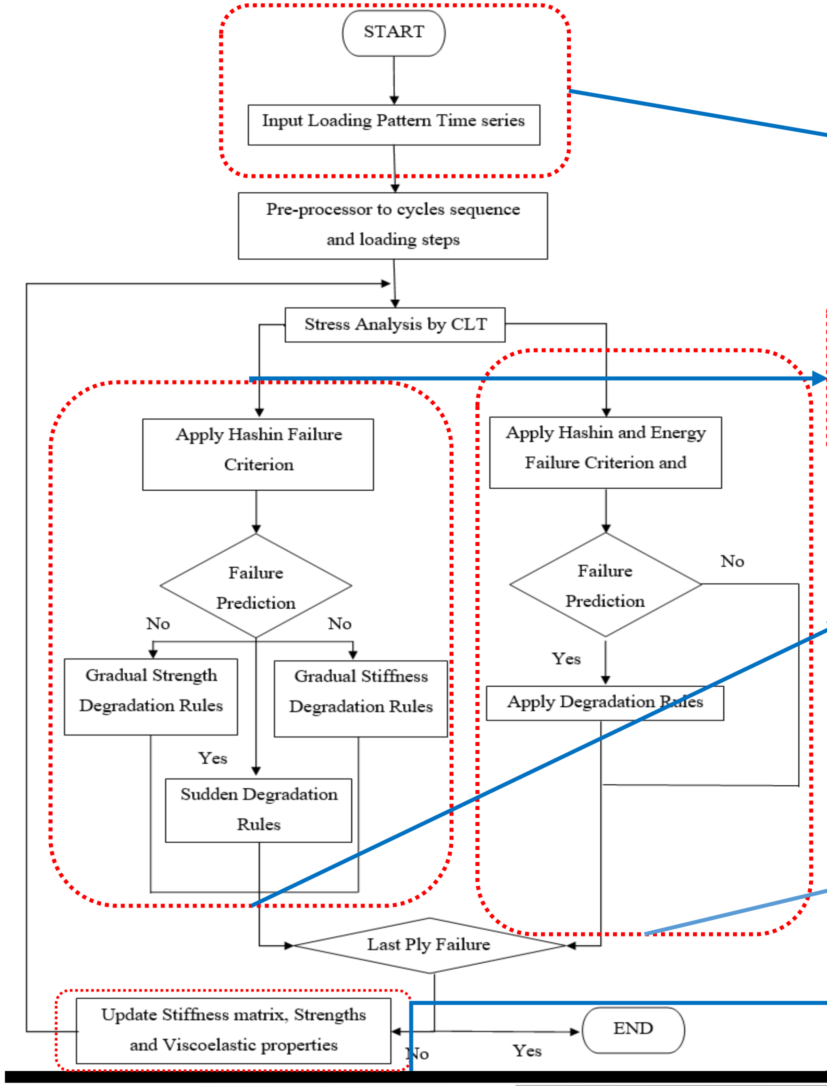
- Motivation
- Methodology
- Results and discussion
- Conclusion

Progressive Damage Modelling Including Viscoelastic behavior



Inputs and preprocessing:

- Input the initial mechanical properties including viscoelastic and strengths of material in lamina level for fiber, matrix and shear direction
- Preprocessing for variable amplitude loading using Rainflow Algorithm

Time-dependent failure and degradation:

- Hashin and energy-based failure criteria
- Degradation rules for strength and stiffness of material

Cycle-dependent failure and degradation:

- Hashin failure criterion
- Residual strength model
- Residual stiffness model

Schapery viscoelastic law:

$$\varepsilon(t) = g_0 S_0 \sigma(t) + g_1 \int_0^t \sum_{k=1}^{n} S_k (1 - e^{-\lambda_k(\psi - \psi')}) \frac{dg_2 \sigma}{d\tau} d\tau$$

Constitutive law for lamina using Schapery law:

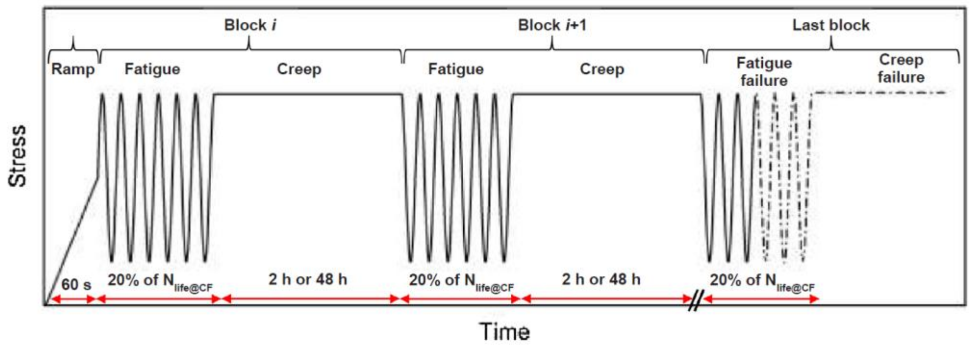
$$\begin{Bmatrix} \varepsilon_{11}(t) \\ \varepsilon_{22}(t) \\ \gamma_{12}(t) \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & 0 \\ S_{21} & g_{0,22} S_{0,22} & 0 \\ 0 & 0 & g_{0,66} S_{0,66} \end{bmatrix} \begin{Bmatrix} \sigma_{11}(t) \\ \sigma_{22}(t) \\ \tau_{12}(t) \end{Bmatrix} + \begin{Bmatrix} 0 \\ g_{1,22} \int_0^t \sum_{k=1}^{n} S_{k,22} (1 - e^{-\lambda_{k22}(\psi - \psi')}) \frac{dg_{2,22} \sigma_{22}}{d\tau} d\tau \\ g_{1,66} \int_0^t \sum_{k=1}^{n} S_{k,66} (1 - e^{-\lambda_{k66}(\psi - \psi')}) \frac{dg_{2,66} \tau_{12}}{d\tau} d\tau \end{Bmatrix}$$

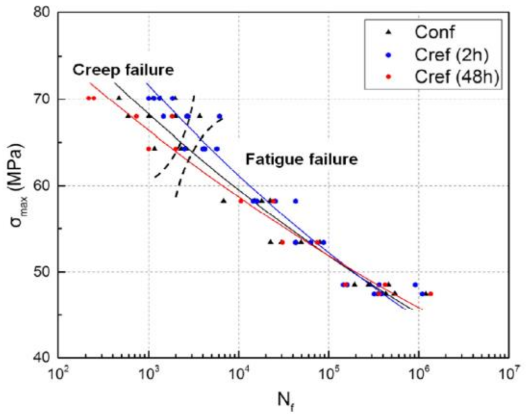
Creep-fatigue interaction:

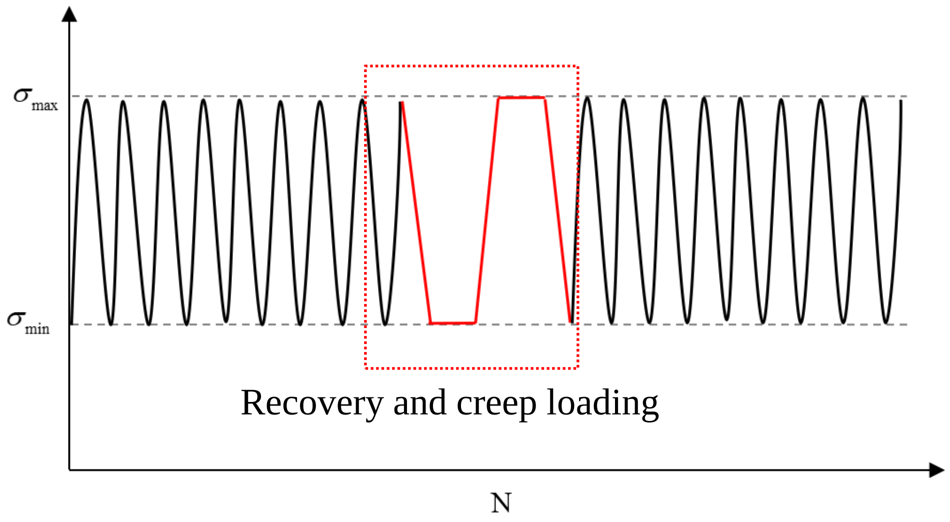
- Modeling time-dependent (viscoelastic) properties in terms of fatigue damage level under loading
- Modeling viscoelastic deformation effect on cycle-dependent properties (fatigue stiffness, strength)

Time- and cycle-dependent behavior Interaction

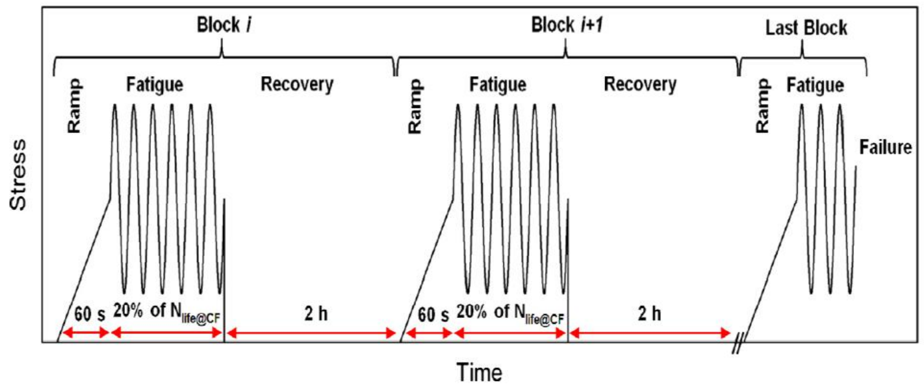
- Creep-fatigue interaction:

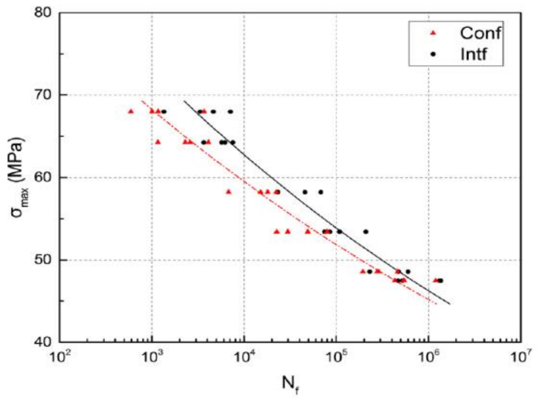






- Recovery-fatigue interaction:





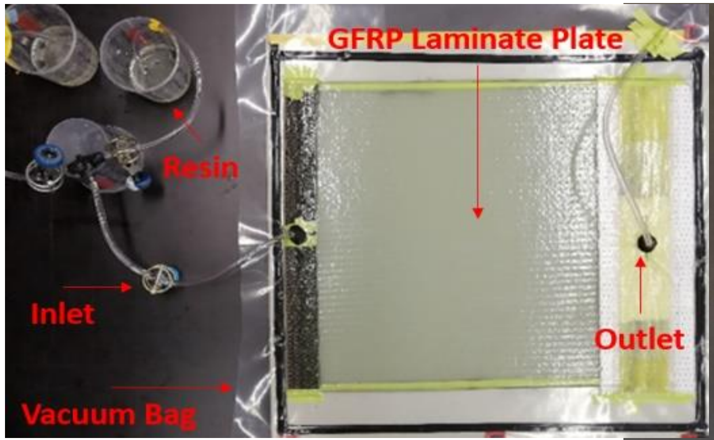
(Movahedi-rad, et al., 2019)

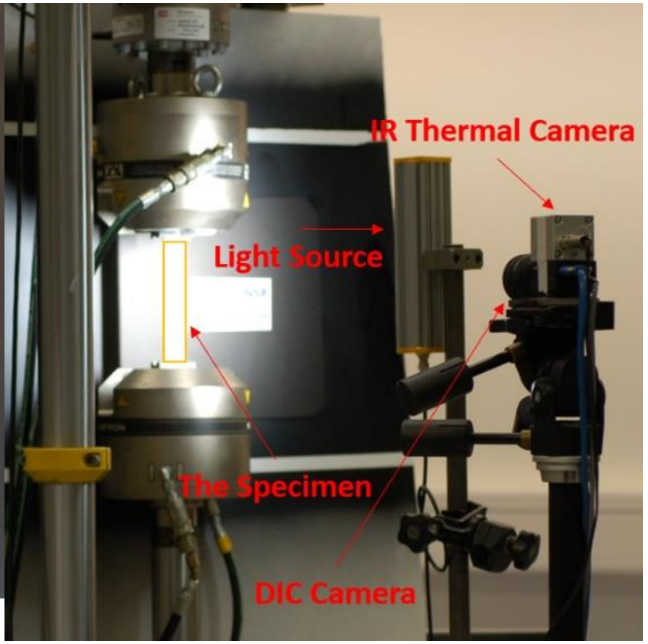
Time- and cycle-dependent properties interaction

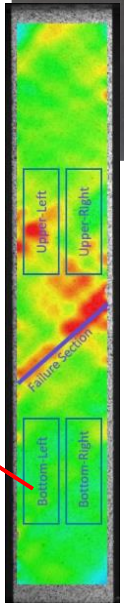
- Cycle-dependent properties:
  - Study the effect of relatively large deformation caused by viscoelastic behavior on S-N curves
  - Investigate quantitatively the effect of fiber reorientation as a result of creep deformation to refine residual stiffness models
- Time-dependent properties:
  - Modeling the evolution of viscoelastic properties depends on the state of damage caused by fatigue
  - Using the failed specimen to cut damaged sample for DMA testing and adopting TTSP to obtain creep master curves
- Testing:
  - Quasi-static tests
  - CA Fatigue tests
  - DMA tests

Experimental Procedure

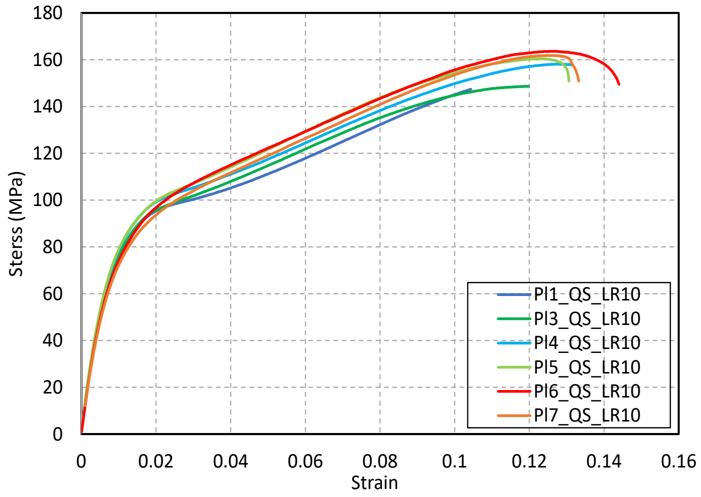
- Fabrication:
  - Specimen layup: $[\pm 45]_{2s}$
  - Material: Glass/epoxy
  - Method: Vacuum infusion
- Measurements:
  - DIC
  - IR thermal camera
- Testing:
  - Quasi-static tests
  - CA Fatigue tests
  - DMA tests

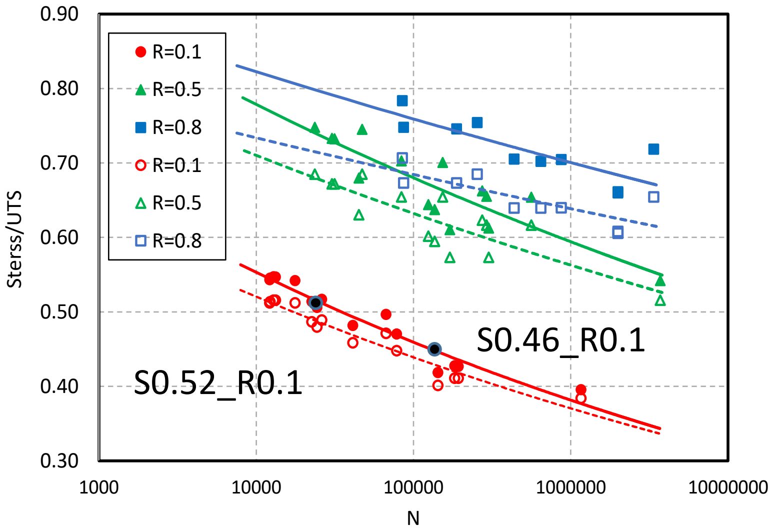


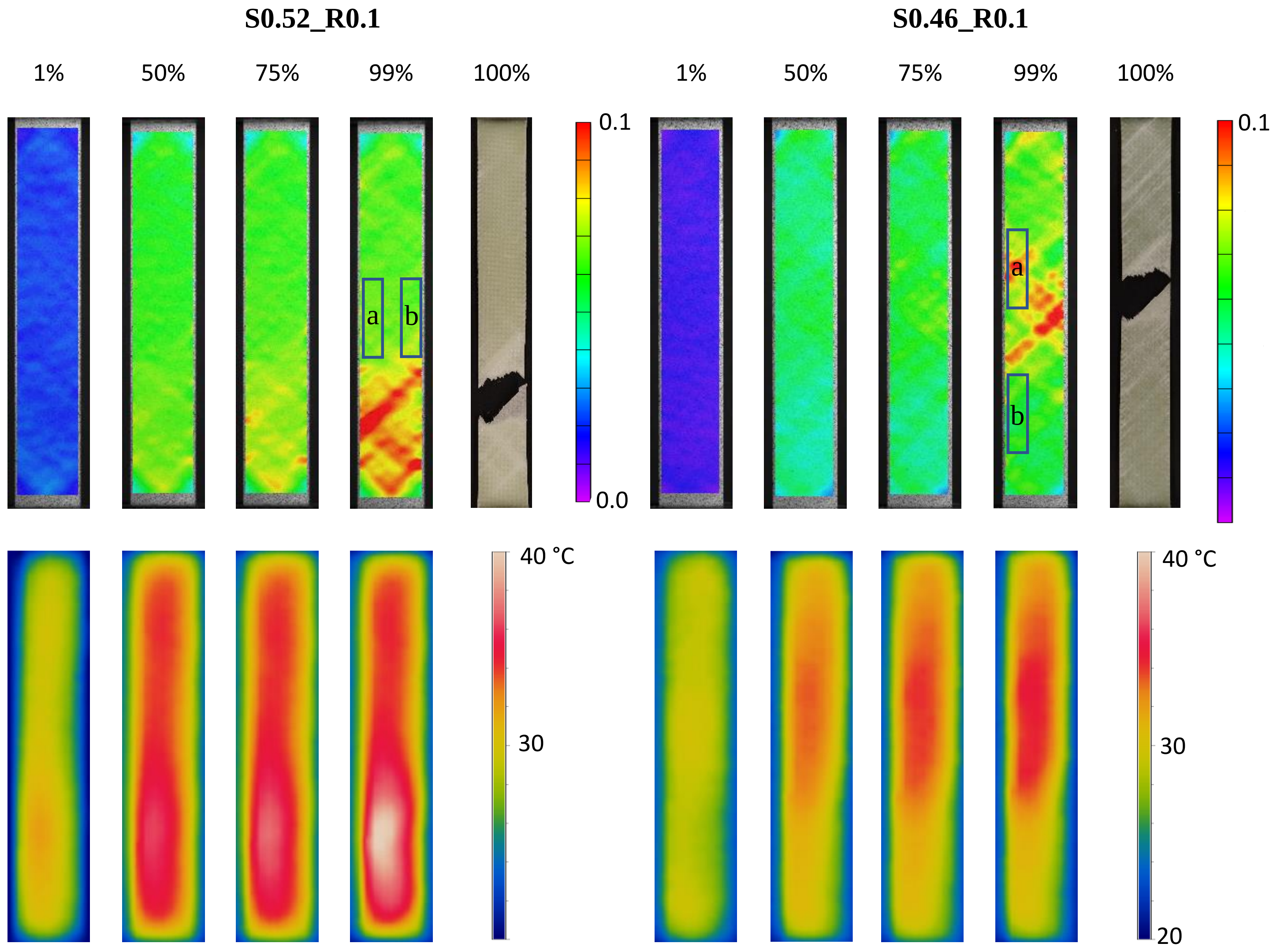




CA Fatigue Tests, S-N Curves, and DIC results







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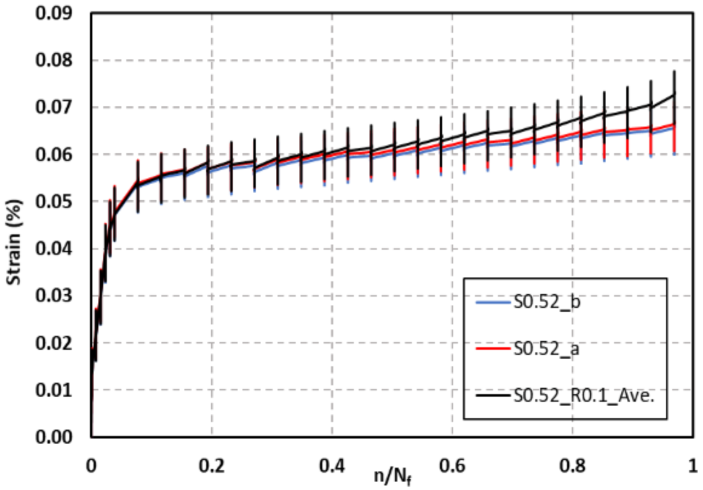
DMA Testing

- DMA testing for Temperature in range of 35 to 115 °C and frequency sweeps
- Single Cantilever Fixture

- Modeling time-dependent (viscoelastic) properties in terms of fatigue damage level under loading
- Increasing Damping ratio and decreasing T_g
- The Modulus values for DMA testing and Fatigue stiffness comparable



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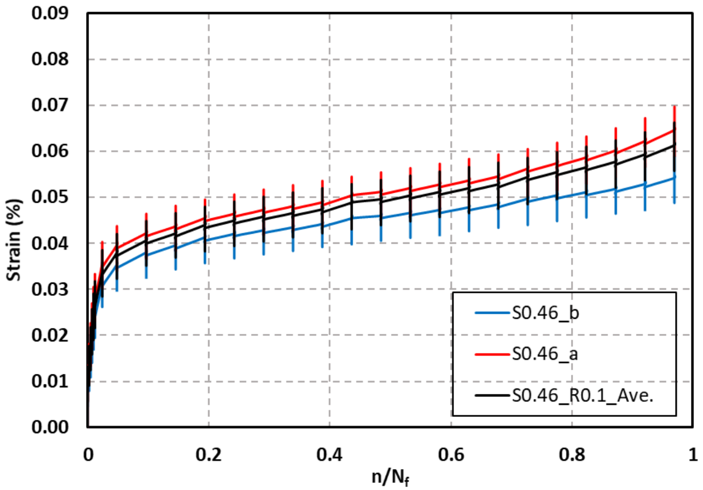

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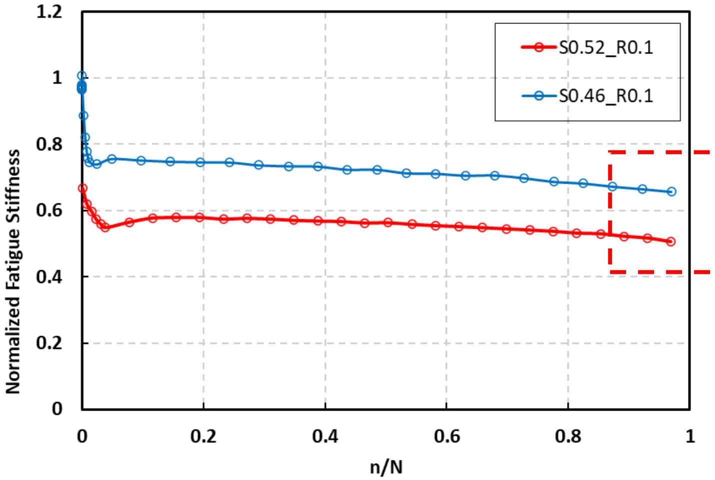

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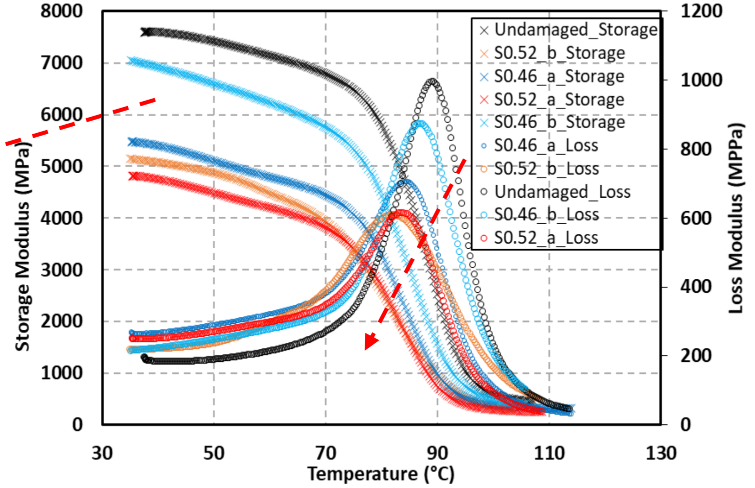
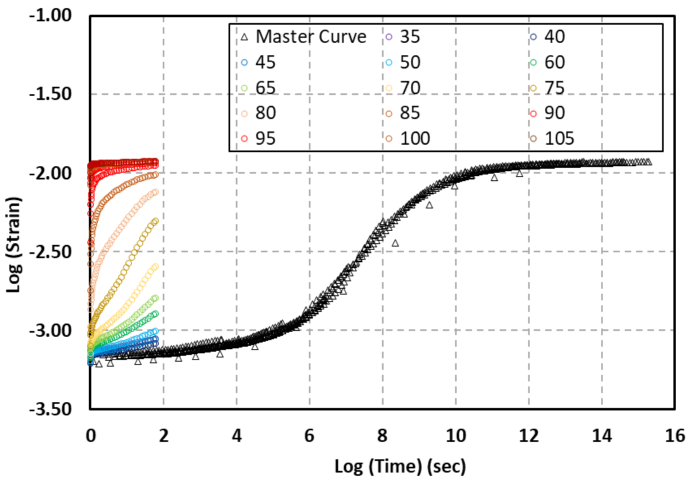


(d)

DMA Testing and TTSP

- Creep-recovery tests with 60 and 30 minutes for creep and recovery parts
- TTSP for the temperatures range from 35 to 115 °C

- Modeling viscoelastic properties in terms of fatigue damage
- Besides the vertical shift observing by fatigue stiffness degradation, we have considerable horizontal shift
- Feasibly developing an extension of TTSP, called time-temperature-fatigue damage to model evolution of viscoelastic properties for different fatigue damage level



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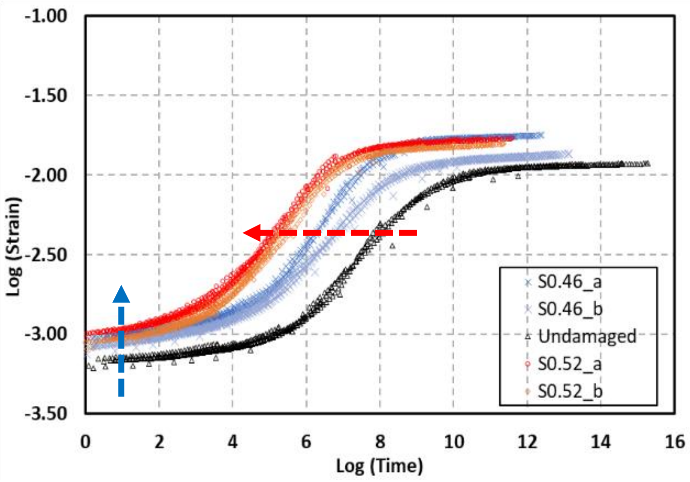

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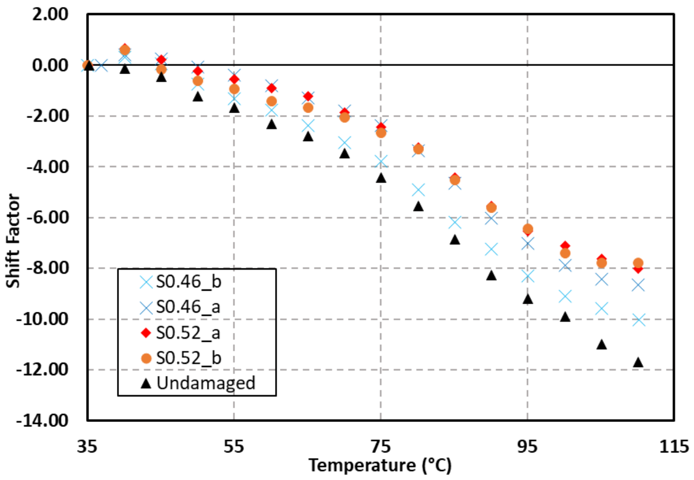

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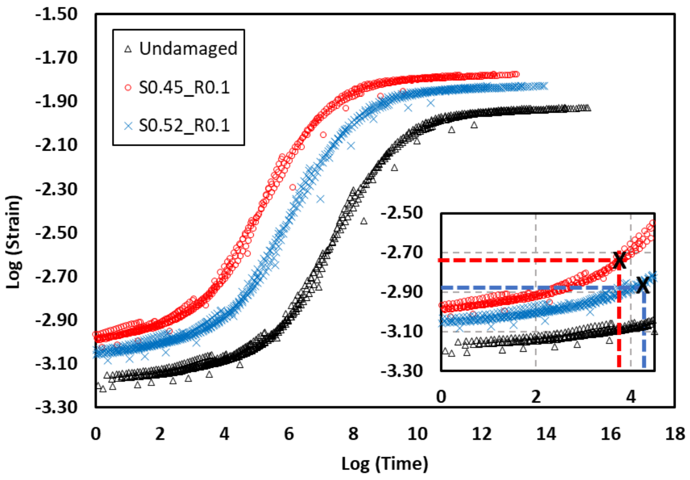
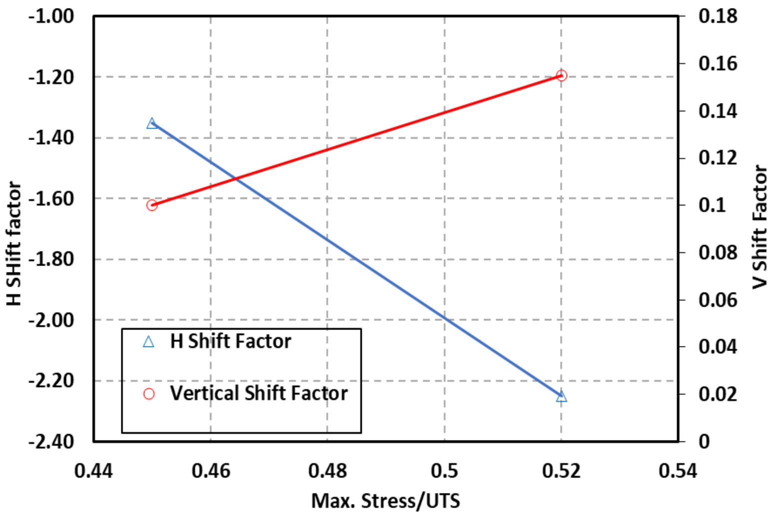


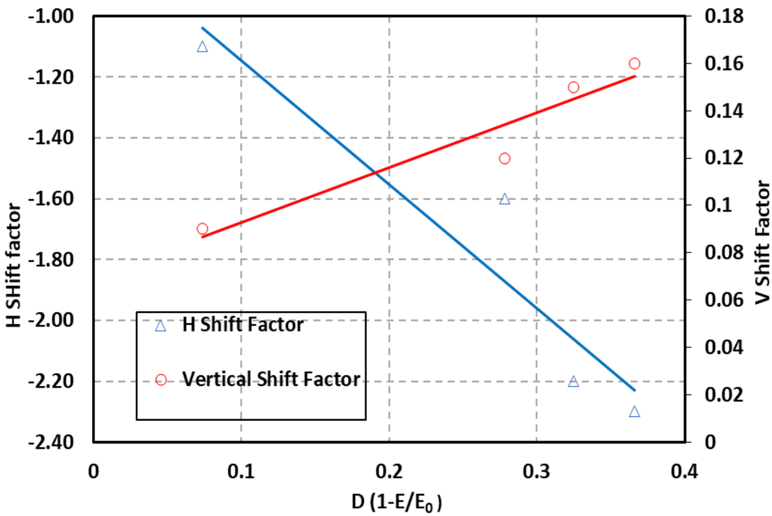
(d)

Residual Viscoelastic Properties Models

- Modeling viscoelastic properties and shifting factor in terms of fatigue damage state
- Besides the vertical shift observing by fatigue stiffness degradation, we have considerable horizontal shift
- Feasibly developing an extension of TTSP, called time-temperature-fatigue damage to model evolution of viscoelastic properties for different fatigue damage level



(a)



(b)

DMA Sample ID	Storage modulus (MPa)	Damping Ratio	T_g	D = 1-(E/E$_0$)	H Shift Factor (a_T)	V Shift Factor (b_e)
S0.52_a	4810	0.0498	75	0.3663	-2.3	0.16
S0.52_b	5125	0.4839	78	0.3248	-2.2	0.15
S0.46_a	5480	0.0462	80	0.2780	-1.6	0.12
S0.46_b	7030	0.0304	82	0.0738	-1.1	0.09
Undamaged	7600	0.0255	85	--	--	--

Conclusion

- Conducting DMA tests on damaged and undamaged material to study the effect of fatigue damage on viscoelastic properties
- Distinguish the more severe damage under higher stress level and effect on viscoelastic properties
- Suggesting to develop TTSFD principle, to obtain viscoelastic properties depends on damage state as observed for higher stress level we observed more vertical and horizontal shifts
- Completing the DMA tests for other R-ratios and stress levels to finally model generalized residual viscoelastic properties
- Developing the suitable viscoelastic model to capture time-dependent deformations for FEM and extending in PDM of elastic material to viscoelastic

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Thanks for your attention!

- Hashin failure criterion:

$$\text{Fiber failure in tension}: 1 = \left(\frac{\sigma_{11}}{\sigma_A^+}\right)^2 + \left(\frac{\tau_{12}}{\tau_A}\right)^2$$

$$\text{Fiber failure in compression}: 1 = \left(\frac{\sigma_{11}}{-\sigma_A^-}\right)^2$$

$$\text{Matrix failure in tension}: 1 = \left(\frac{\sigma_{22}}{\sigma_T^+}\right)^2 + \left(\frac{\tau_{12}}{\tau_A}\right)^2$$

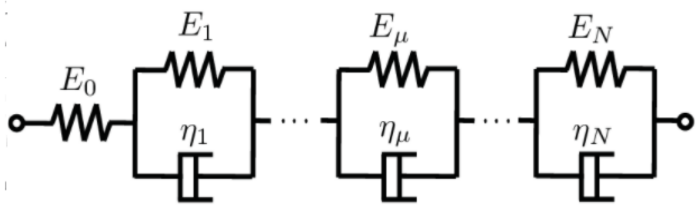
$$\text{Matrix failure in compression}: 1 = \left[\left(\frac{\sigma_{22}}{2\tau_T}\right)^2 + \left(\frac{\tau_{12}}{\tau_A}\right)^2\right] + \left[\left[\left(\frac{\sigma_T^-}{2\tau_T}\right)^2 - 1\right]\frac{\sigma_{22}}{\sigma_T^-}\right]$$

Time-dependent failure prediction

- Reiner–Weissenberg failure criterion (R-W):

$$\varepsilon(t) = g_0 S_0 \sigma(t) + g_1 \int_0^t \sum_{k=1}^{n} S_k \left(1 - e^{-\lambda_k(\psi - \psi')}\right) \frac{\mathrm{d} g_2 \sigma}{\mathrm{d}\tau} \mathrm{d}\tau$$

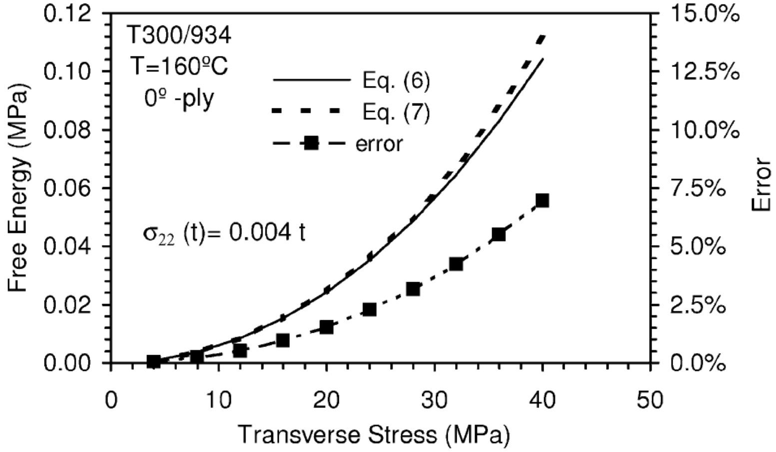
$$\psi = \int_0^t \frac{\mathrm{d}t'}{a_\sigma}, \psi' = \psi(\tau) \int_0^\tau \frac{\mathrm{d}t'}{a_\sigma}$$



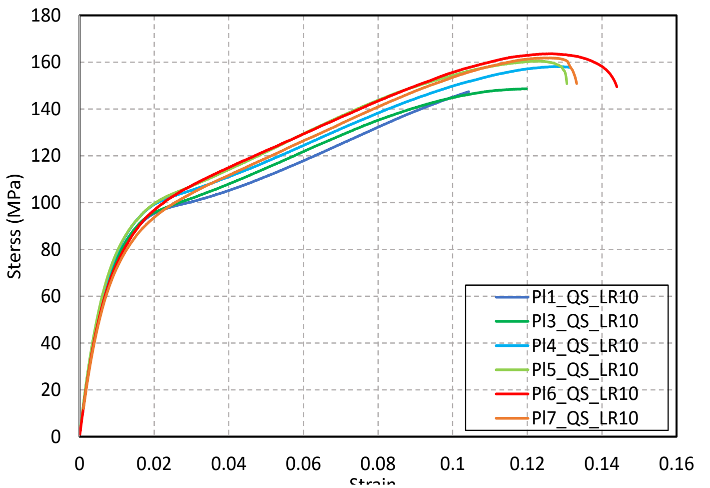
$$\varepsilon_{k,ij}(t) = S_{k,ij} \int_0^t \left(1 - e^{-\lambda_{k,ij}(\psi - \psi')}\right) \frac{\mathrm{d}(g_{2,ij}\sigma_{ij})}{\mathrm{d}\tau} \mathrm{d}\tau$$

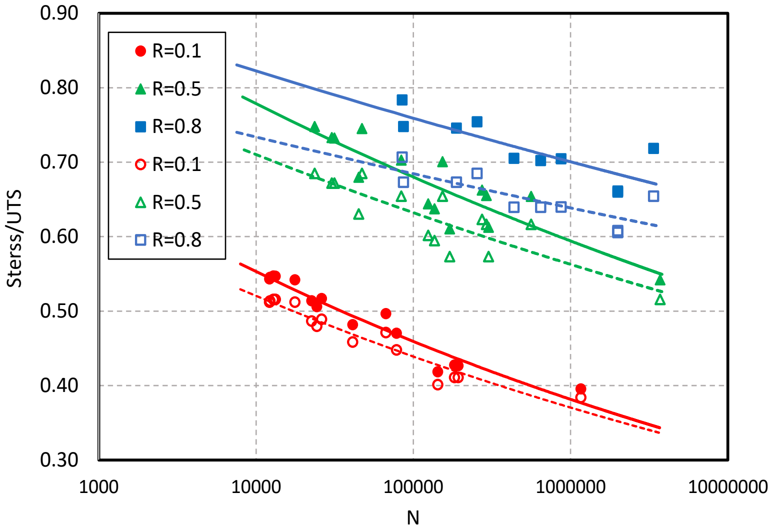
$$\varepsilon_{ij}(t) = g_{0,ij} S_{0,ij} \sigma_{ij}(t) + g_{1,ij} \sum_{k=1} \varepsilon_{k,ij}(t)$$

$$w_{s,ij}(t) \simeq g_{0,ij} S_{0,ij} \frac{[\sigma_{ij}(t)]^2}{2} + g_{1,ij} \sum_{k=1}^{n} \frac{1}{g_{2,ij} S_{k,ij}} \frac{[\varepsilon_{k,ij}(t)]^2}{2}$$

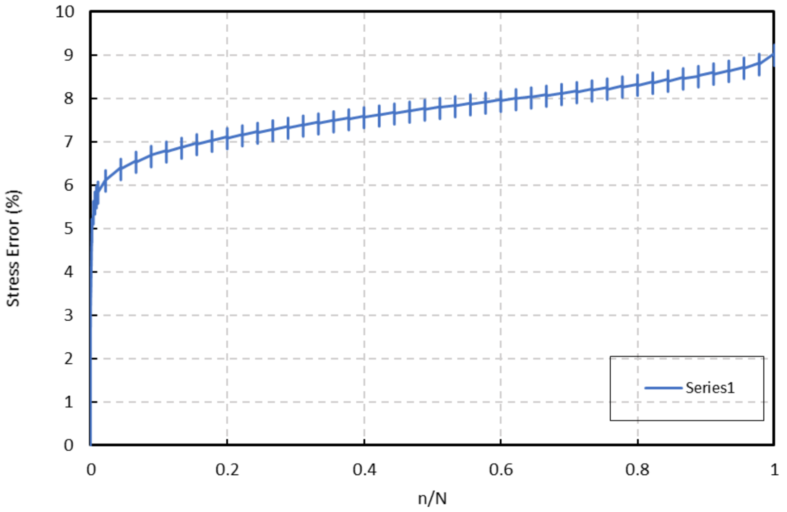


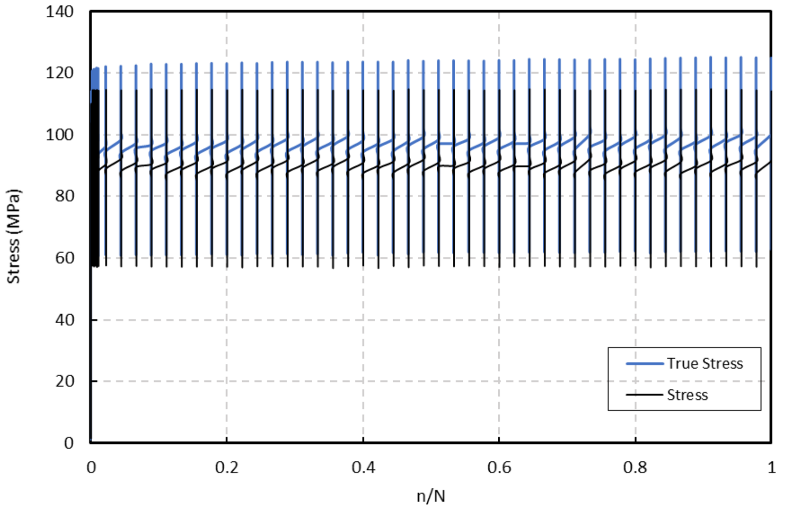
Cycle-dependent properties: S-N Curves



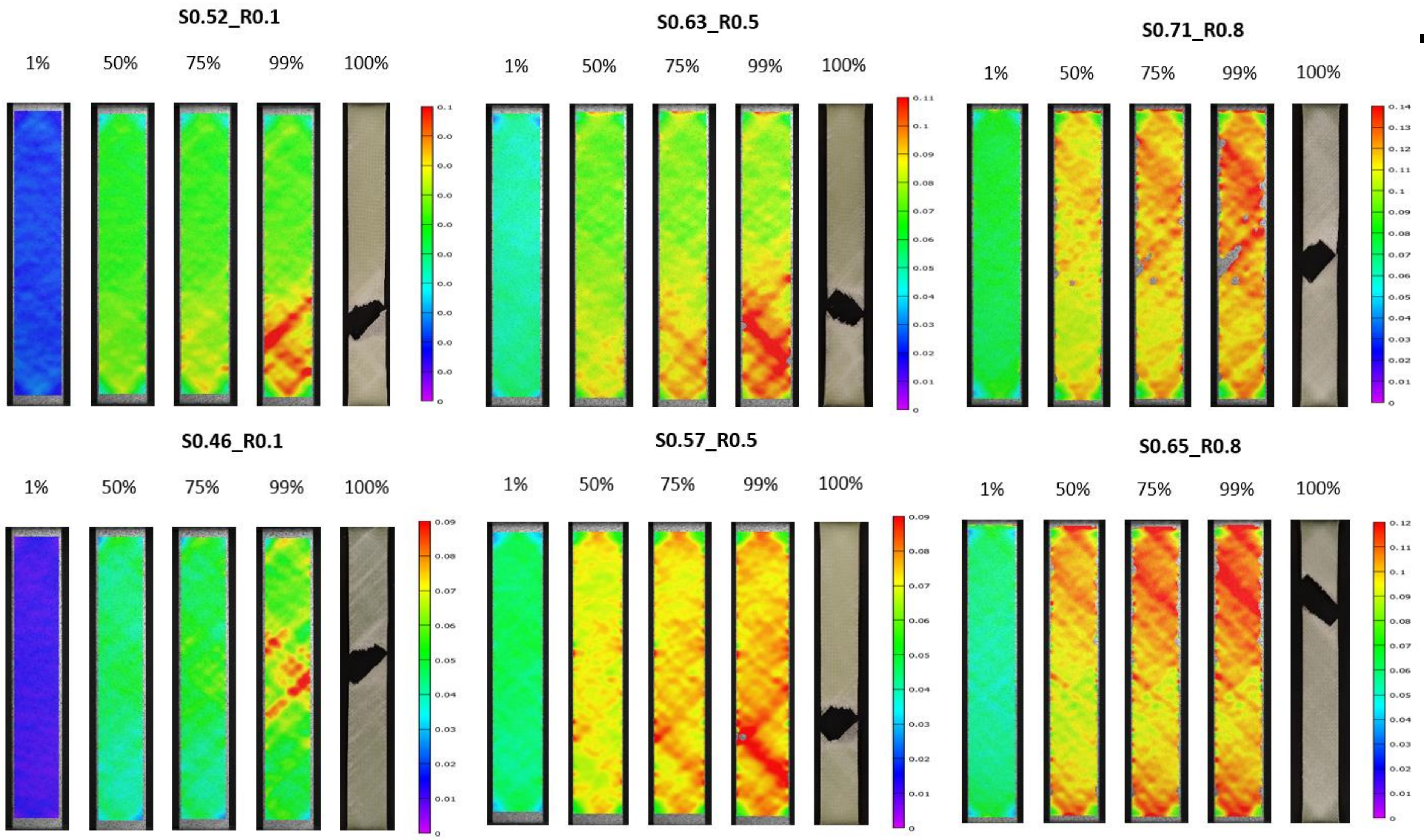


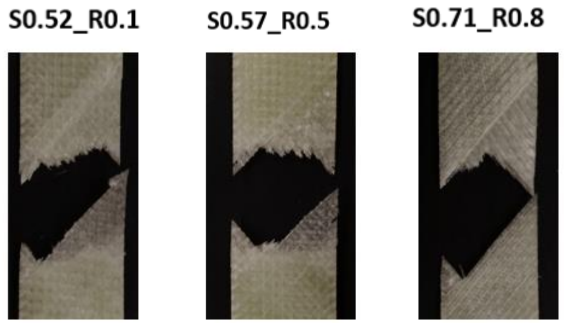
- Fiber reorientation for S0.63-R0.5
- Dashed line: Not- considering deformation
- Solid Line: Excluding the effect of fiber reorientation





Damage propagation and failure modes





Fiber breakage | Mixed fiber breakage and pull-out | Fiber pull-out

Cycle-dependent properties: Fatigue Stiffness

- Fiber reorientation for S0.63-R0.5
- DIC $\Delta\theta_{av} = \arctan\left(\frac{1+\varepsilon_x}{1-\varepsilon_y}\right) - 45$