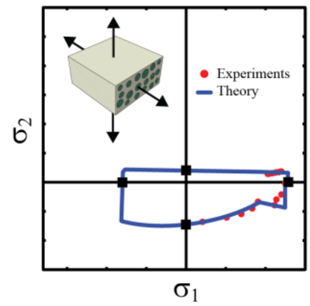
Benchmarking of lamina failure tests from WWFE-I and WWFE-II with a three parameter micromechanics based matrix failure theory



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Application of composite materials

- Composites widely used in various industries
- Tailor material properties according to needs of end product
- Increase strength, reduce weight and costs
- Design tools to accurately predict failure

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1. Types of failure modeling techniques
2. World Wide Failure Exercises I,II
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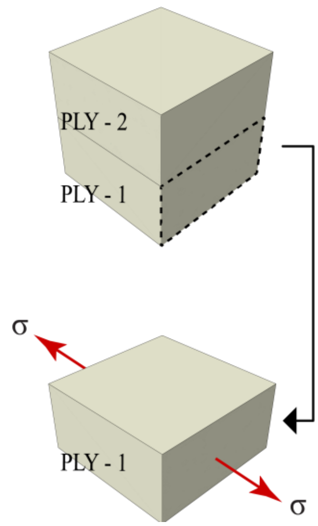
Mesomodeling

- Considers <u>lamina</u> layers (plies) as building blocks of laminates
- Use <u>volume average lamina quantities</u> (stresses & strains) to predict failure
- Examples Maximum stress/strain, Tsai-Wu[1], Tsai-Hill, Hashin[2] etc.
- Don't use physics to predict failure
- **How do look stresses look in constituents ?**
- **Any other kind of stresses ?**

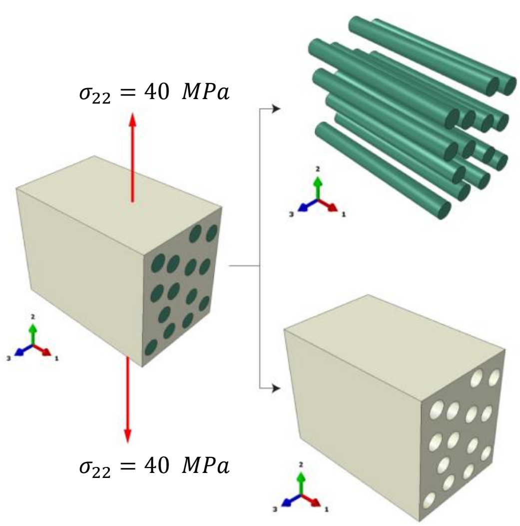


Volume average constituent stresses

Composite Lamina

$\sigma_{11} = 0\ MPa$
$\sigma_{33} = 0\ MPa$

$\sigma_{22} = 40\ MPa$



$\sigma_{22} = 40\ MPa$

Fibers

$\sigma_{22} = 46.005\ MPa$

$\sigma_{11} = -7.892\ MPa$
$\sigma_{33} = -2.321\ MPa$

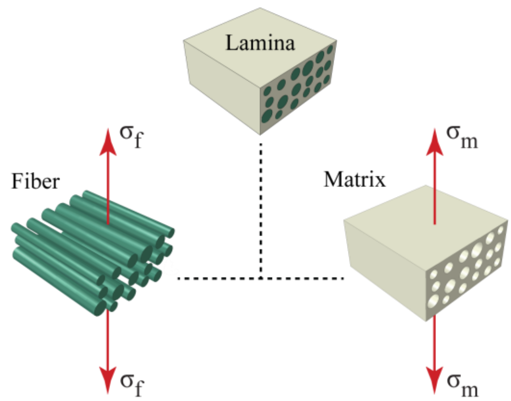
Matrix

$\sigma_{22} = 31.178\ MPa$

$\sigma_{11} = 11.593\ MPa$
$\sigma_{33} = 3.410\ MPa$

Multiscale micromechanical modeling

- Use average constituent quantities to predict failure
- Can use physics
- Can predict the response of the entire composite using just constituent properties
- Examples are Chamis[3], [4]Mayes and [5]Huang.



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WWFE-I and WWFE-II

- WWFEs are composite failure benchmarks for GRPs and CFRPs
- Various failure theories were tested against experimental evidence
- Experiments include strength envelopes for laminas and laminates
- stress-strain curves for laminas and laminates
- Only lamina strength envelopes were predicted

Outcomes WWFE-I and WWFE-II

Exercise	Leading theories
WWFE-I	Puck [6], Zinoviev [7], Tsai [8] and Bogetti [9]
WWFE-II	Carrere [10], Pinho [11], Cuntze [12] and Puck [13]

- Usage of lamina quantities don't permit the use of physics
- Calibration is cumbersome due to large number of input parameters (50-75) parameters[14]

[14] **Dr. Richard M. Christensen** - http://www.failurecriteria.com/theworldwidefail.html

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Fertig matrix failure theory

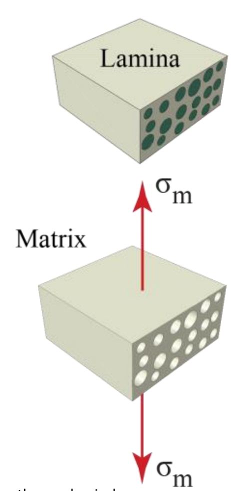
$$B_t\{I_t\}^2 + \frac{1}{1-\frac{\beta}{\tau_0}\{-I_h\}}\left[B_{s1}I_{s1} + B_{s2}I_{s2}\right] = 1$$

$$I_t = \frac{\sigma_{22}^m + \sigma_{33}^m + \sqrt{\left(\sigma_{22}^m + \sigma_{33}^m\right)^2 - 4\left(\sigma_{22}^m\sigma_{33}^m + \sigma_{23}^m\sigma_{23}^m\right)}}{2}$$ (Tension)

$$I_{s1} = \sigma_{12}^{m\,2} + \sigma_{13}^{m\,2}$$ (Longitudinal Shear)

$$I_{s2} = \frac{1}{4}\left(\sigma_{22}^m - \sigma_{33}^m\right)^2 + \sigma_{23}^{m\,2}$$ (Transverse Shear)

$$I_h = \sigma_{22}^m + \sigma_{33}^m$$ (Effect of pressure on shear plane)



[15] C. P. Hoppel, T. A. Bogetti, and J. W. Gillespie, "Literature Review-Effects of hydrostatic pressure on the mechanical behavior of composite materials," *Journal of Thermoplastic Composite Materials*, vol. 8, no. 4, pp. 375–409, 1995

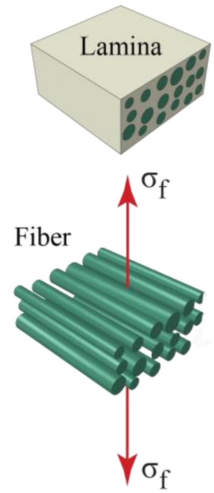
Fiber failure theory

The Maximum stress criterion used

$$\frac{\sigma_{11}^{f}}{S_{11}^{f+}} = 1 \qquad \text{or} \qquad \frac{\sigma_{11}^{f}}{S_{11}^{f-}} = 1$$

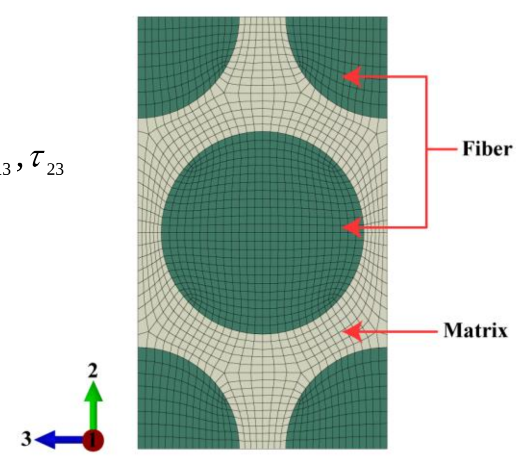
S_{11}^{f+} longitudinal tensile strength of the fiber

S_{11}^{f-} compressive strength of the fiber



Computing constituent stresses

- RVE with hexagonal fiber packing
- Loads $\sigma_{11}, \sigma_{22}, \sigma_{33}, \tau_{12}, \tau_{13}, \tau_{23}$
- Mapping ${}_{L}X_{i}^{a} = \dfrac{\sigma_{i}^{a}}{\sigma_{L}^{C}}$
- Can obtain constituent stresses for any composite stress state



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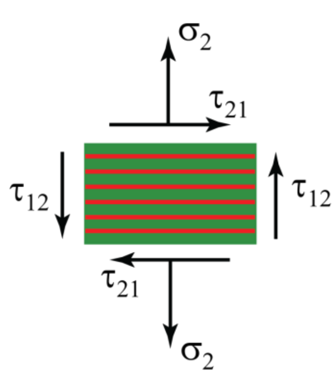
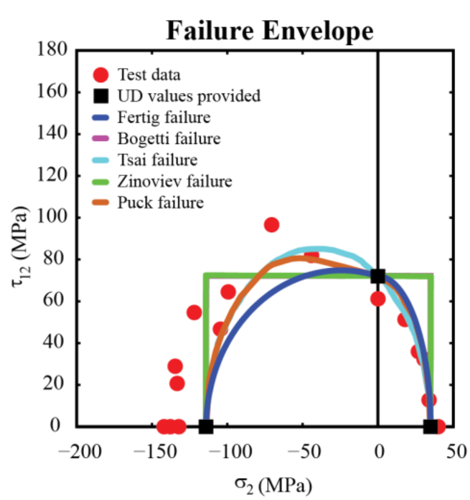
GRP lamina under combined transverse and shear loading





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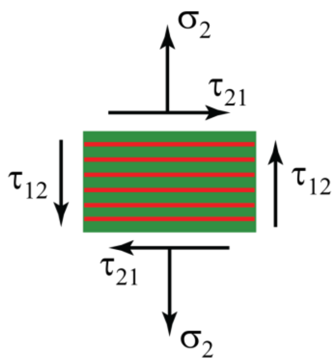
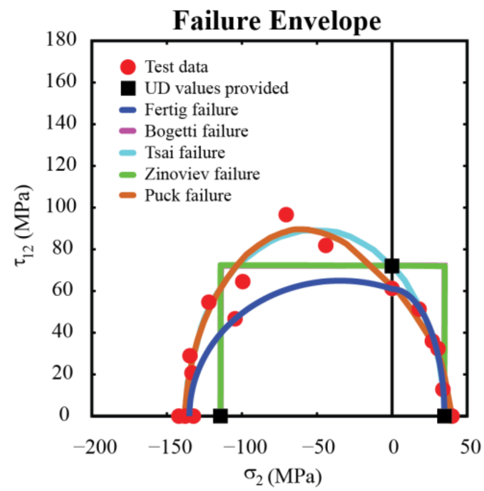
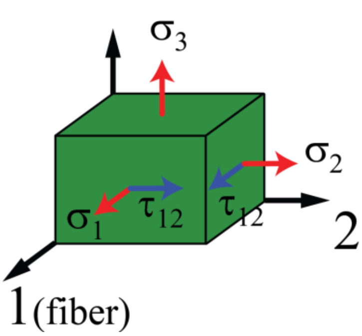
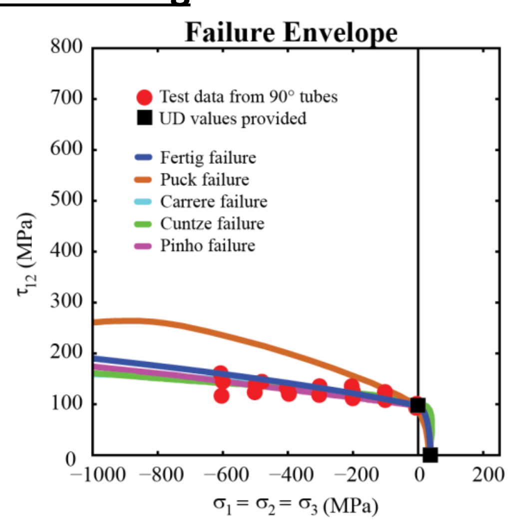


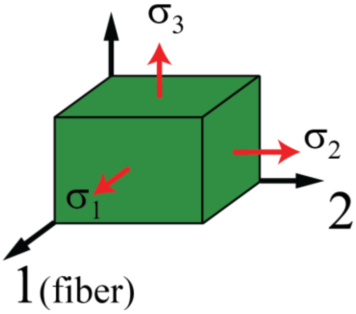


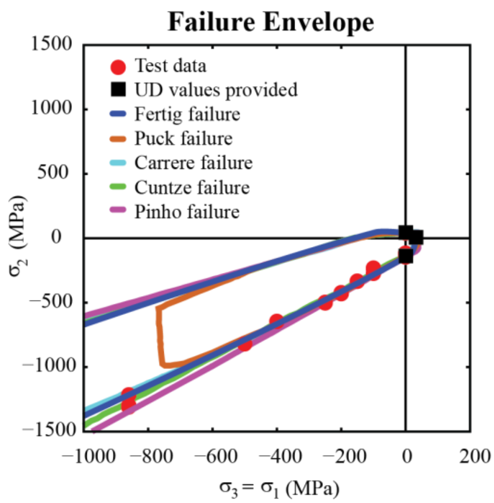
CFRP lamina under combined hydrostatic and shear loading



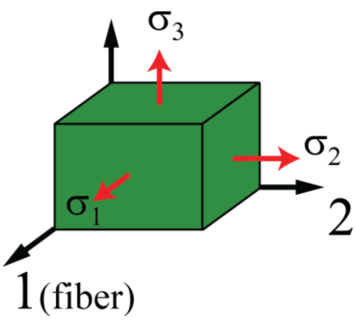


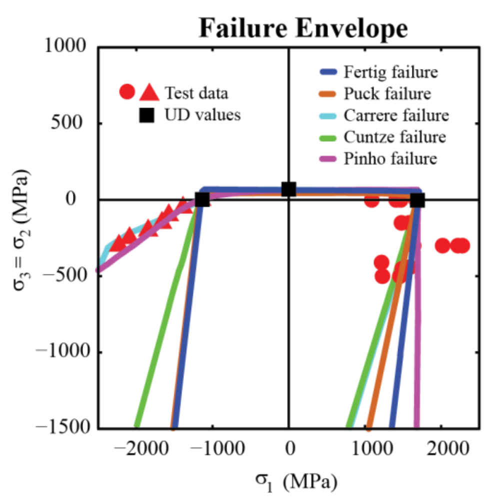
GRP lamina under combined transverse and through thickness loading



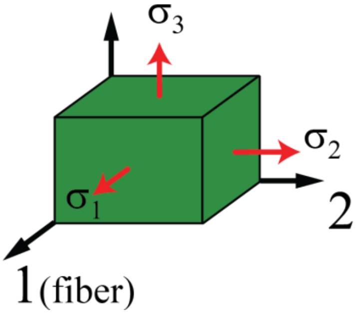


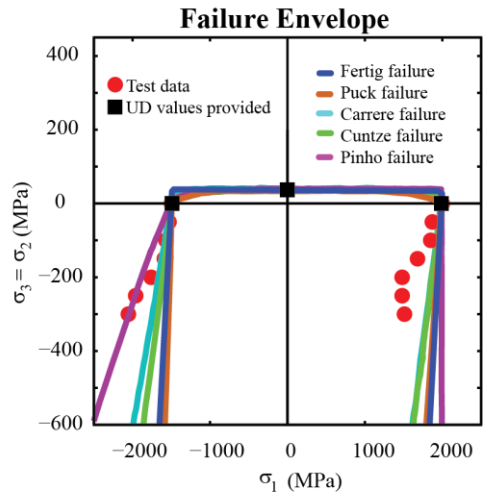
GRP lamina under combined through thickness and longitudinal loading



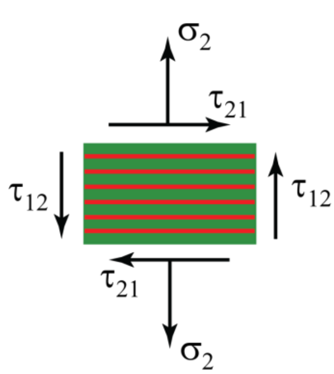


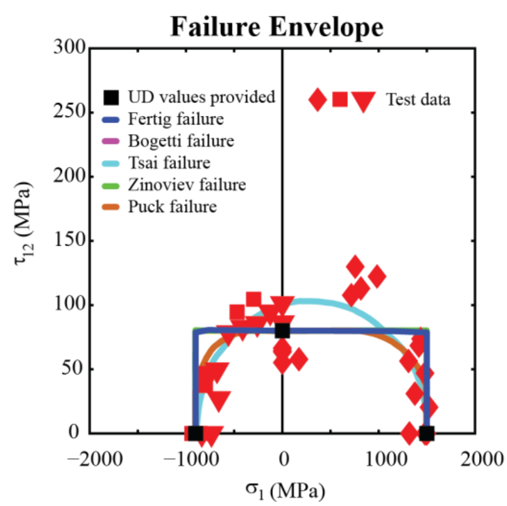
CFRP lamina under combined through thickness and longitudinal loading



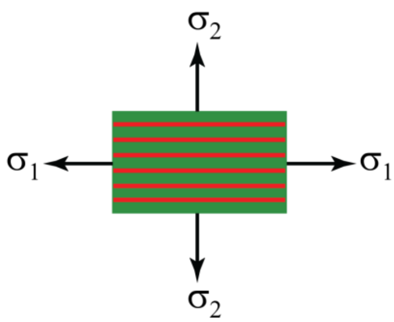


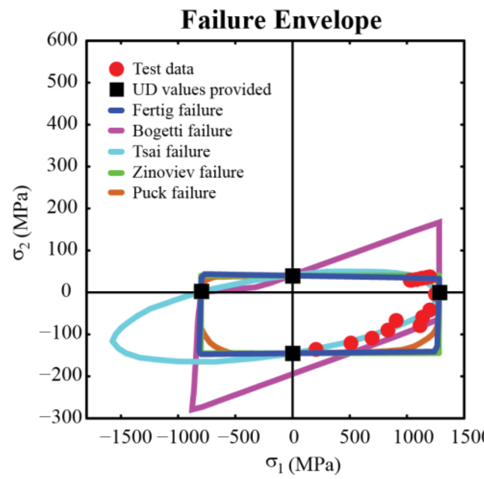
CFRP lamina under combined transverse and shear loading



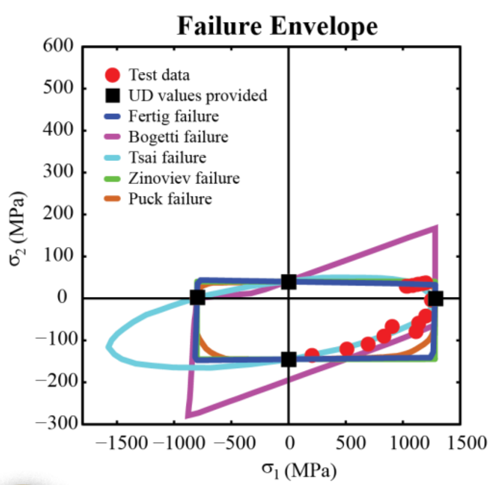


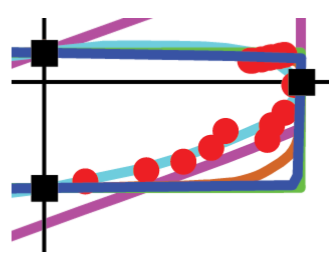
GRP lamina under combined longitudinal and transverse loading





GRP lamina under combined longitudinal and transverse loading



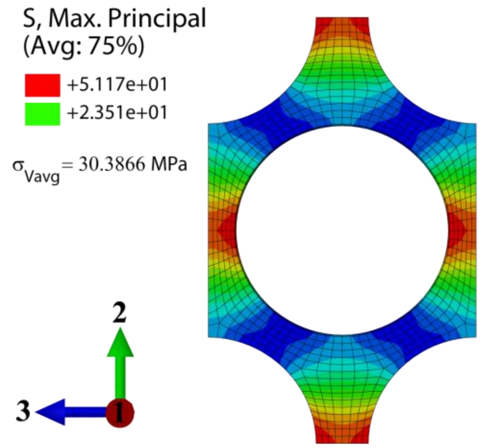


Modified Fertig failure theory

- RVE subjected to transverse failure load.
- $\alpha_m = \frac{\sigma_{max\ principal}}{\sigma_{Vavg}}$
- Matrix failure theory is

$$\frac{\sigma^m_{max\ principal}}{S^m_{+t}\alpha_m} = 1 \quad \text{or} \quad \frac{\sigma^m_{VM}}{S^m_{VM}} = 1$$

- Fiber failure criterion is same.



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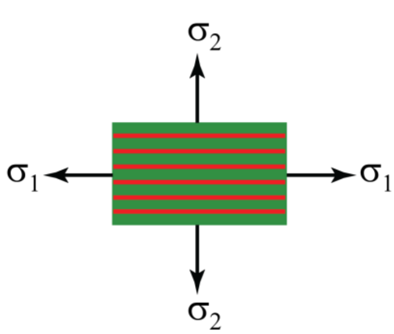

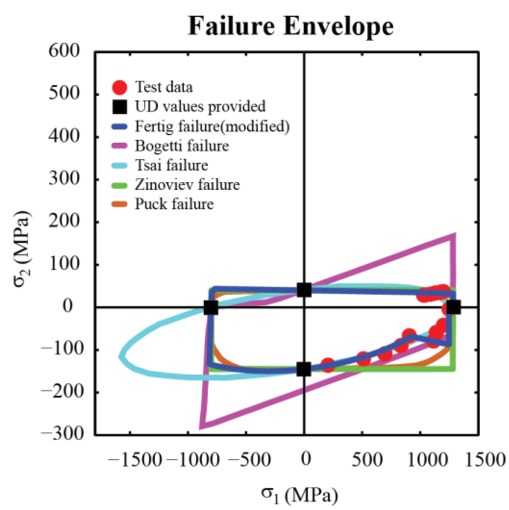

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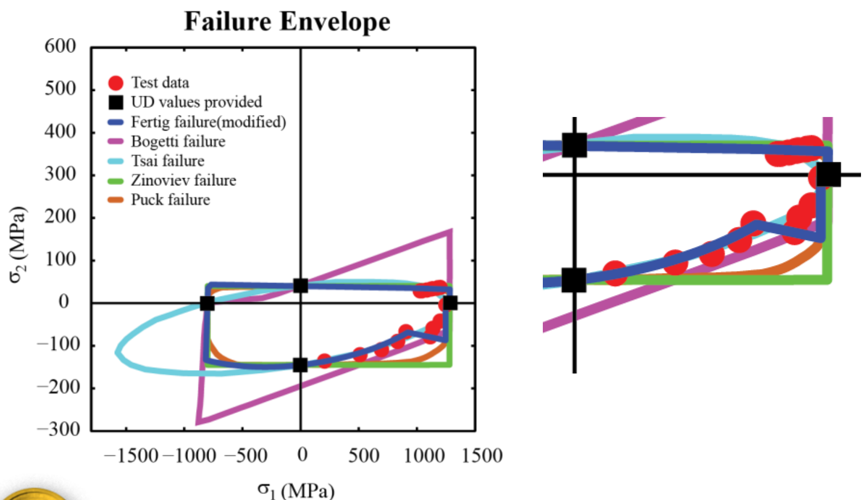

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Conclusions

- For most of the test cases, predictions of Fertig failure agreed with the test data.
- Fertig failure theory has just three parameters and so is very easy to calibrate.
- Modified Fertig failure theory performed better than any failure theory for one case in particular.

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Future work

- The original Fertig matrix failure theory needs to be augmented with the missing strain energy.
- Incorporate non-linearity to predict the stress-strain curves from the WWFEs.
- Fertig failure needs to benchmarked against laminate level failure test data from the WWFEs.

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Thank you.

QUESTIONS ?