

Development of Automated Model Generation and Analysis of Surface Cracked Plates in Bending for Interpolated Elastic-Plastic J -integral Solutions

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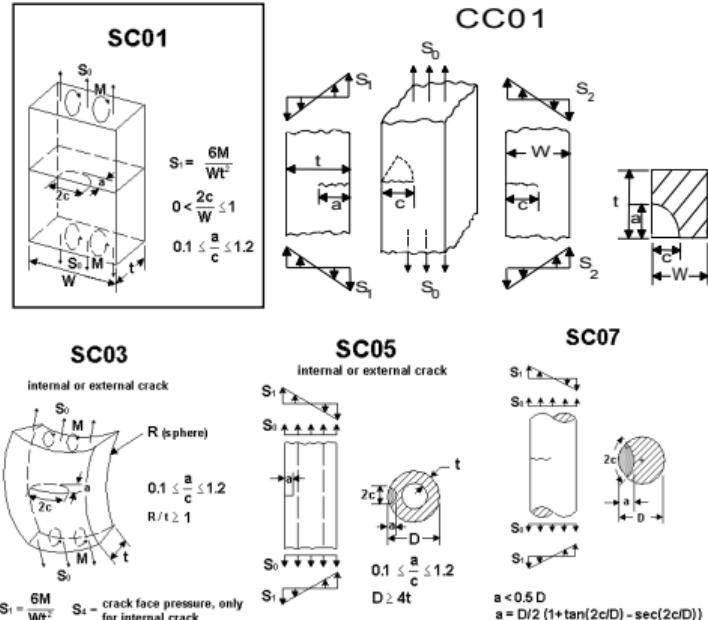
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- ▶ Introduction
- ▶ Literature Review
- ▶ Modeling Preparation for Research Tasks
- ▶ Research Plan for Bending Models and Modified TASC Program
- ▶ Results and Discussion
- ▶ Conclusions and Recommendations for Future Work
- ▶ Appendix

Introduction

- ▶ Constraint and stress states can get pretty involved.
- ▶ Semi-elliptical surface cracks (SC01) are among the simplest part-through crack cases, and are the subject of ASTM E2899.
- ▶ Handbook or curve-fit solutions exist for the other geometries, but only for linear elastic materials.
- ▶ NASA's TASC program covers elastic-plastic surface cracks in tension, but **not** in bending.



Research goals

- ▶ High quality set of elastic-plastic finite element analysis results as a basis for curve-fit or handbook calculations
- ▶ Modified TASC program for bending or tension analysis

Literature Review

For a surface crack in bending, stress intensity at a given location:

$$K_I = (H\sigma_b F_b) \left(\frac{\pi a}{Z} \right)^{0.5}$$

$$\sigma_b = \frac{6M}{Wt^2}$$

$$Z = 1 + 1.464 \left(\frac{a}{c} \right)^{1.65}$$

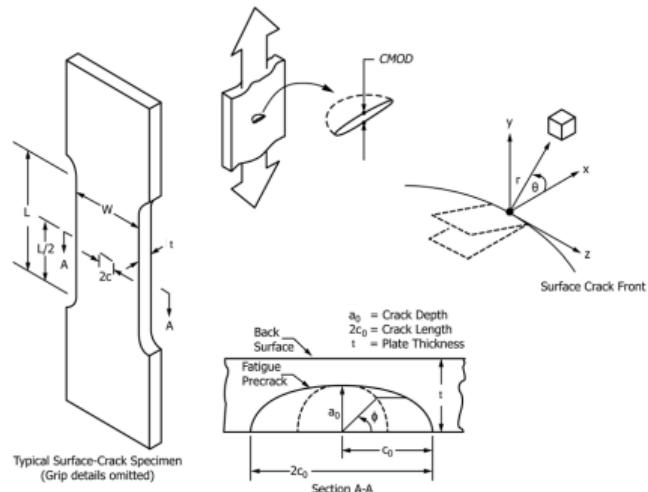
$$F_b = \left[M_1 + M_2 \left(\frac{a}{t} \right)^2 + M_3 \left(\frac{a}{t} \right)^4 \right] f_\phi f_{wb} g$$

For surface cracks in tension, we need “only” 10 equations.

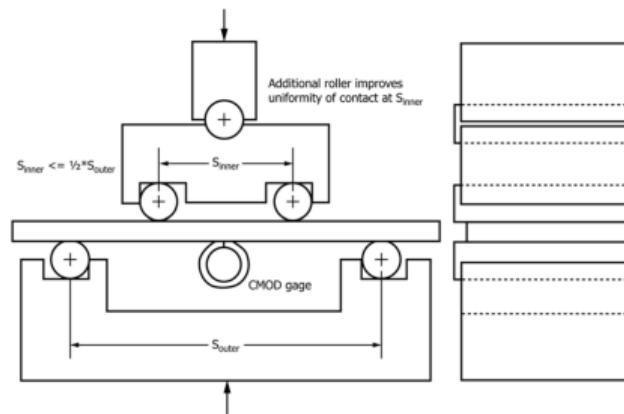
No such curve fit exists for elastic-plastic materials.

...plus another 12 equations, and that's just for linear elastic materials.

ASTM E2899: Standard Test Method for Measurement of Initiation Toughness in Surface Cracks Under Tension and Bending



Test specimen and crack configurations



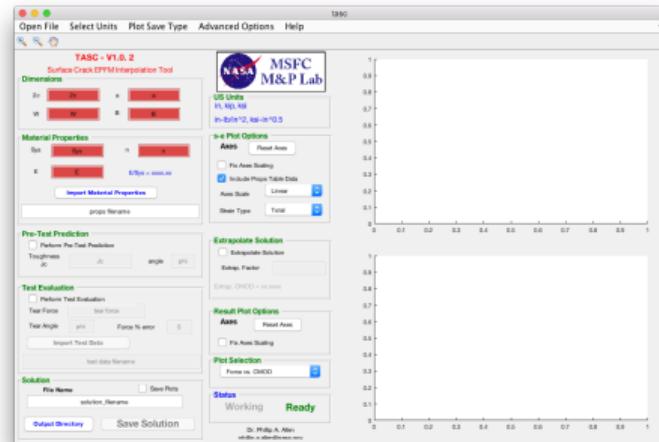
Four-point bend test configuration

- ▶ Starter crack machined into flat plate, fatigued to sharpen crack front
- ▶ CMOD monitored as tension or bending load increased monotonically
- ▶ Either specimen fails or start of stable crack tearing is detected
- ▶ Location where crack growth occurs is recorded
- ▶ Conditions classified as linear elastic, elastic-plastic, or fully-plastic
- ▶ If LEFM or EPFM, calculate constraint from tables
- ▶ If LEFM, calculate K from series of provided equations
- ▶ If EPFM, **use nonlinear FEA** to calculate J

ASTM E2899 is unusual in its analysis requirements

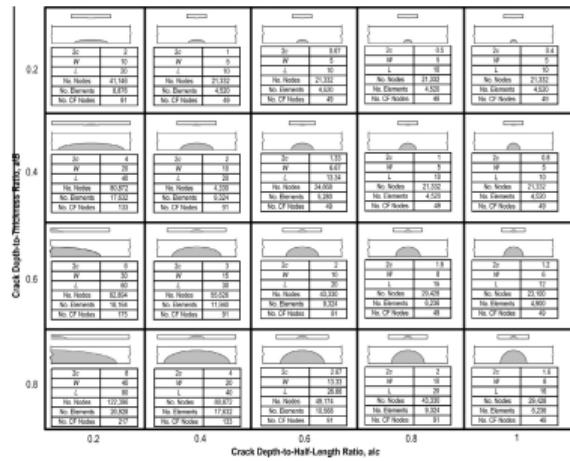
- ▶ requires results of elastic-plastic finite element analysis
- ▶ other standards require much simpler calculations or graphical constructions
- ▶ NASA TASC program satisfies requirements, but only for tension

Mechanics of bending is more complex than for tension (constraint, crack closure)

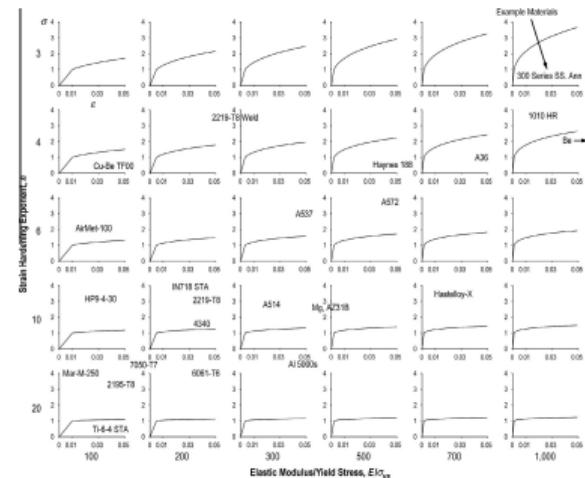


NASA TASC program

TASC: interpolation code using database of 600 EPFM results for flat plates in tension



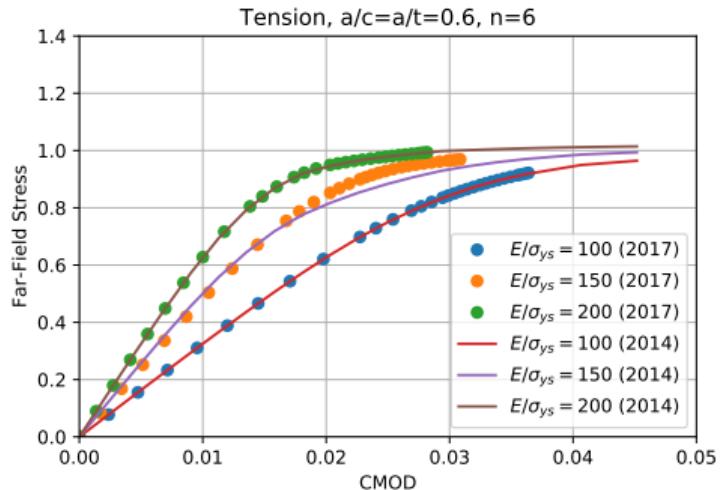
20 normalized geometries:
 $0.2 \leq \frac{a}{c} \leq 1.0, 0.2 \leq \frac{a}{t} \leq 0.8$



30 normalized materials:
 $100 \leq \frac{E}{S_{ys}} \leq 1000, 3 \leq n \leq 20$

Modeling Preparation for Research Tasks

Verification of two TASC cases,
applying procedure to a new
material ($\frac{E}{\sigma_{ys}} = 150$)



Comparison of normalized FEA results, interpo-
lated result, and TASC raw data

Research Plan for Bending Models and Modified TASC Program

Creating Plate Models
Solving Plate Models, Optimizing Boundary Conditions
Verification and Validation
Updates to TASC

$$t = 1 \quad 0.2 \leq \frac{a}{c} \leq 1.0 \quad 0.2 \leq \frac{a}{t} \leq 0.8$$

$$W = 5 \max(c, t) \quad S_{\text{inner}} = W \quad S_{\text{outer}} = 2W \quad L = 1.1S_{\text{outer}}$$

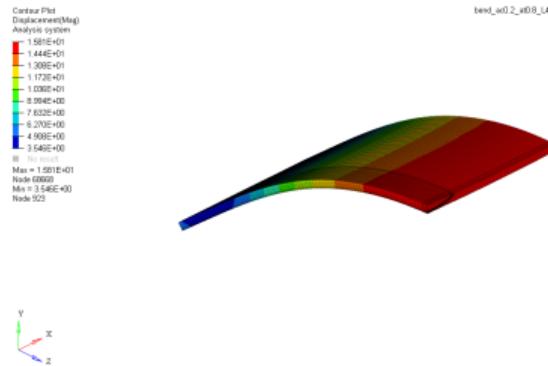


Plate model, $\frac{a}{c} = 0.2, \frac{a}{t} = 0.8$

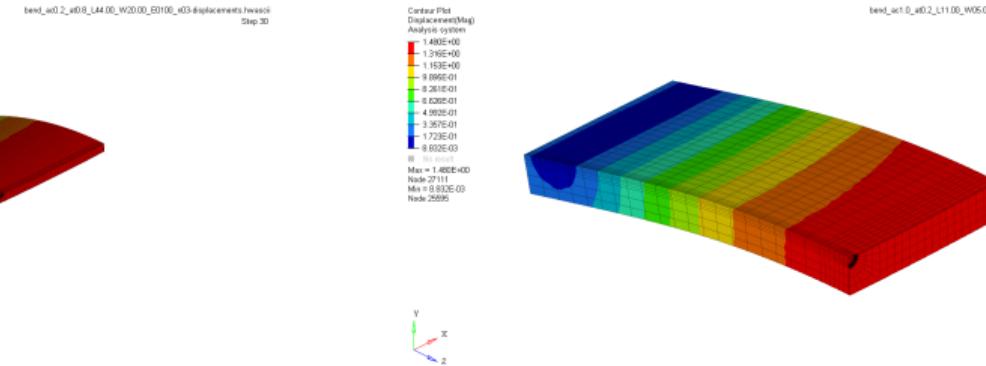
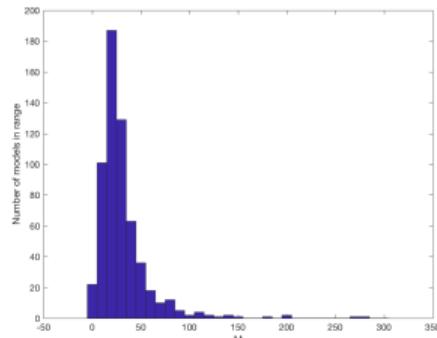
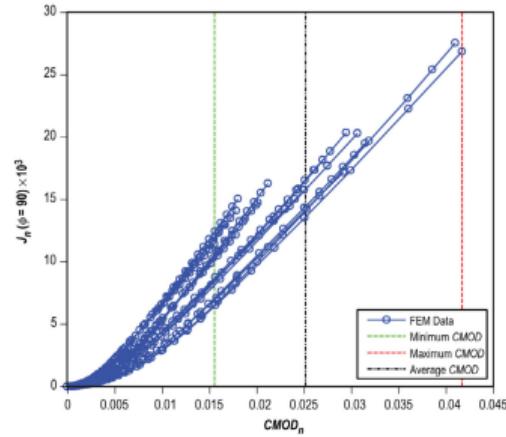


Plate model, $\frac{a}{c} = 1.0, \frac{a}{t} = 0.2$

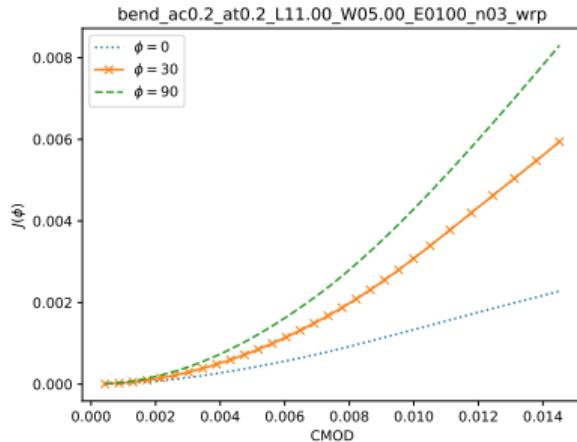
Allen and Wells (2014) reported $M = \frac{r_\phi \sigma_{ys}}{J} < 25$ for tension



Histogram of M results from TASC tension model database



J-CMOD graph used for extrapolation



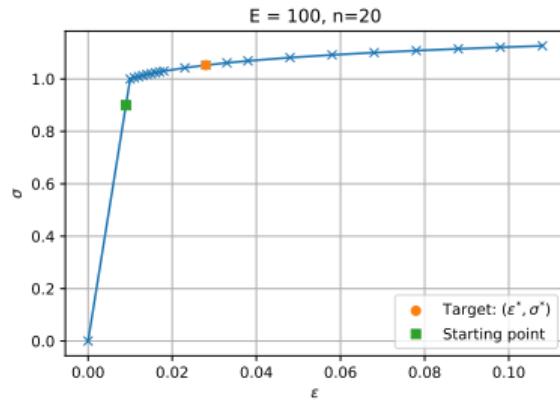
$$\frac{a}{c} = 0.2, \frac{a}{t} = 0.2, E = 100, n = 3$$

Adjust boundary conditions until

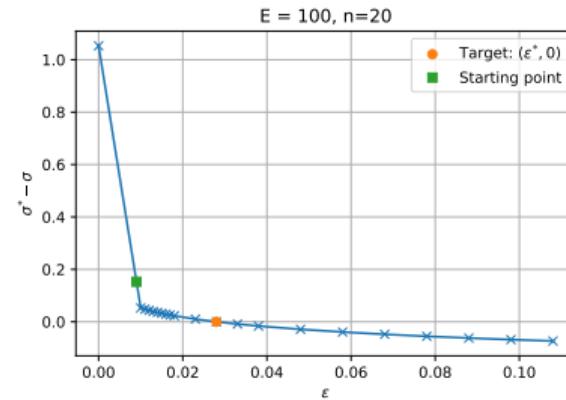
- ▶ slope of last 20% of J -CMOD curve is $20\times$ larger than initial slope
- ▶ slope of last 20% of J -CMOD curve is $< 10\%$ different than slope of previous 20%

at $\phi = 30^\circ$

Displacement control for tension models makes optimization easier

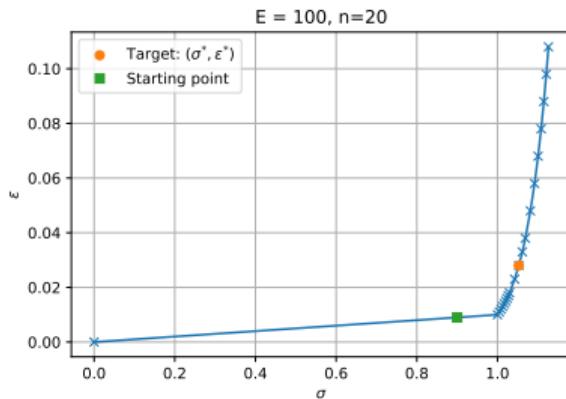


Example stress-strain curve using linear plus power law (LPPL) formulation

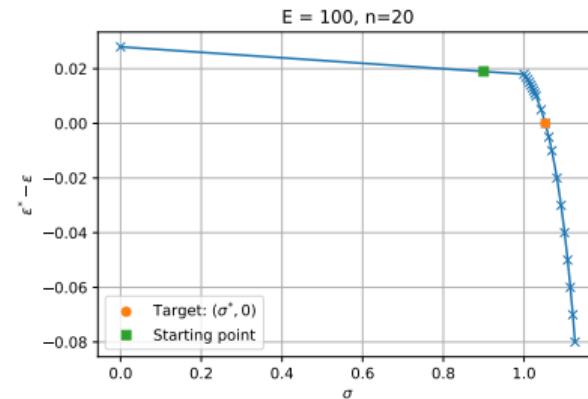


Transformed to find required strain level

Load control for bending models makes optimization more difficult

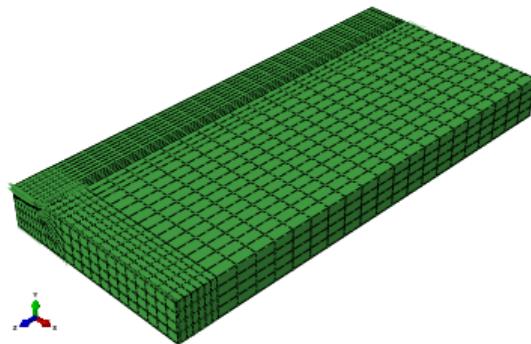


Example stress-strain curve using LPPL formulation, transformed to stress-controlled



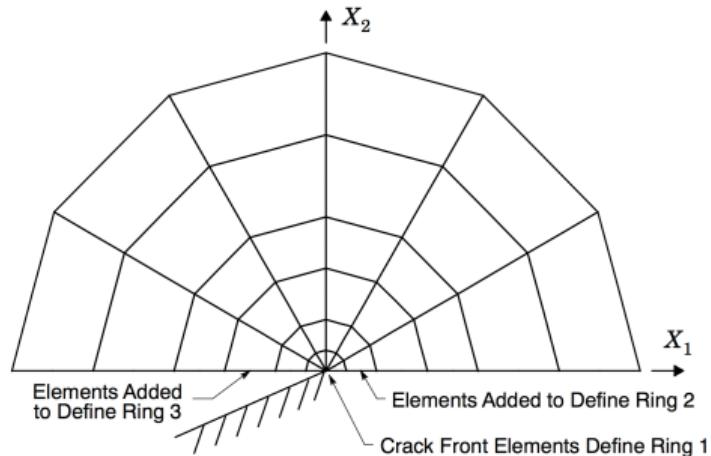
Transformed to find required stress level

Abaqus validation



Example Abaqus bending model from
FEACrack

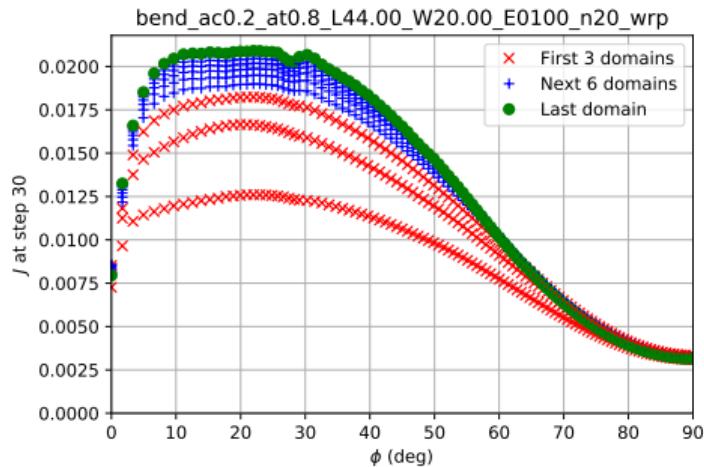
J convergence



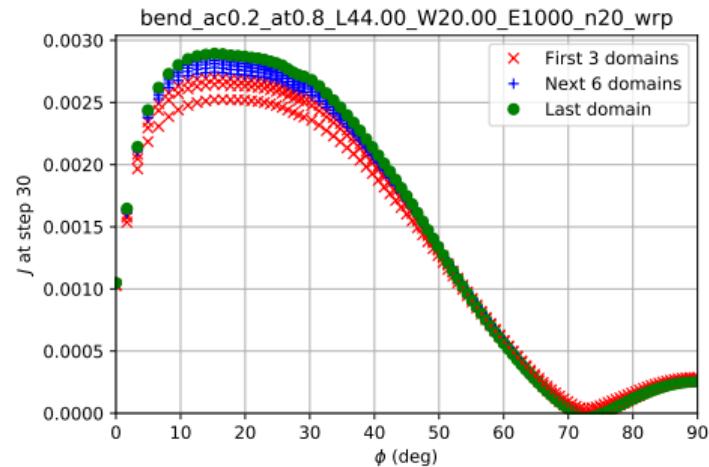
Elements used in WARP3D J calculations

- ▶ Don't break anything already working for tension
- ▶ Make a `results_bending` database alongside the existing `results` database for tension
- ▶ Identify any equations only valid for tension models
- ▶ Replace with conditionals checking for model type, then use tension or bending equations as required
- ▶ Interpolation method should need no changes
- ▶ Validate a load-CMOD curve against existing bending experimental data

Results and Discussion

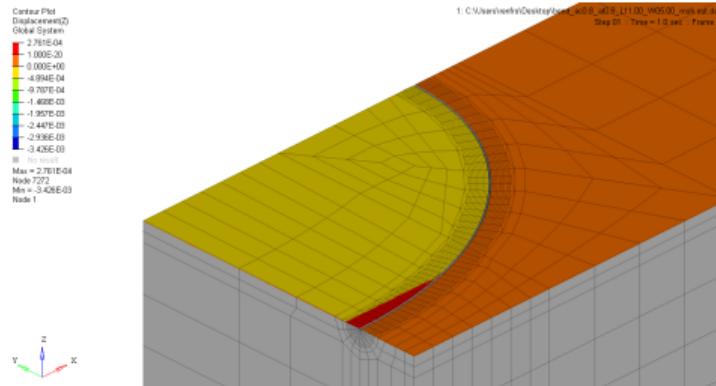


Convergence of J across 10 domains

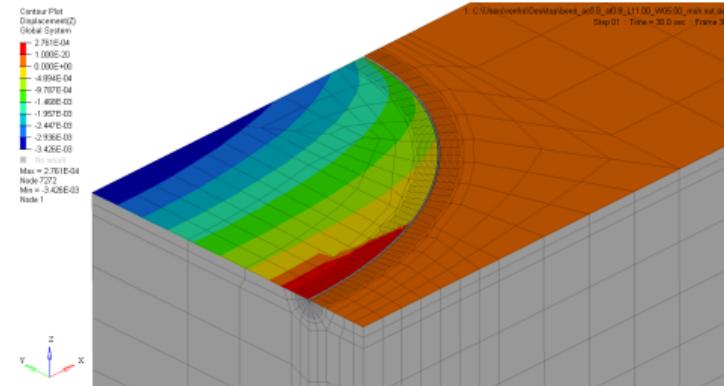


Anomalous J convergence graph

Why is J higher at $\phi = 90$ in some cases? What happens to plate deflection?



First load step



Last load step

Improvements to Initial Bending Models
Validation of Purpose-Built Model Results
Validation of Modified TASC Output
Validation of J Values between WARP3D and Abaqus

J Convergence Study
Addition of Elastic Boundary at Crack Face

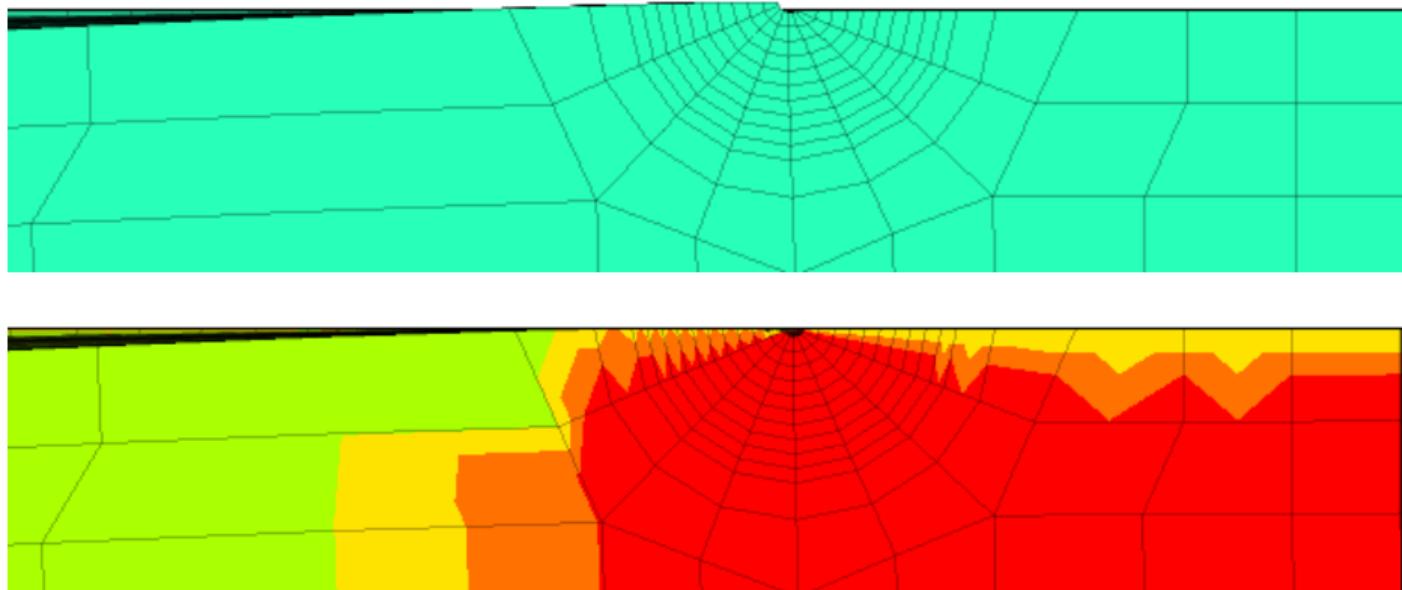
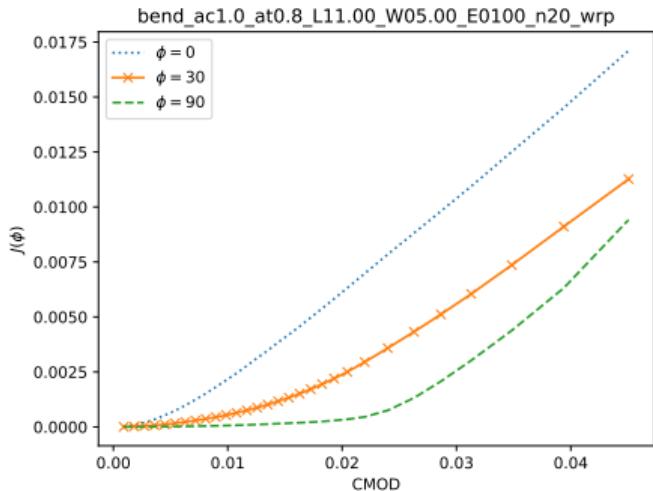


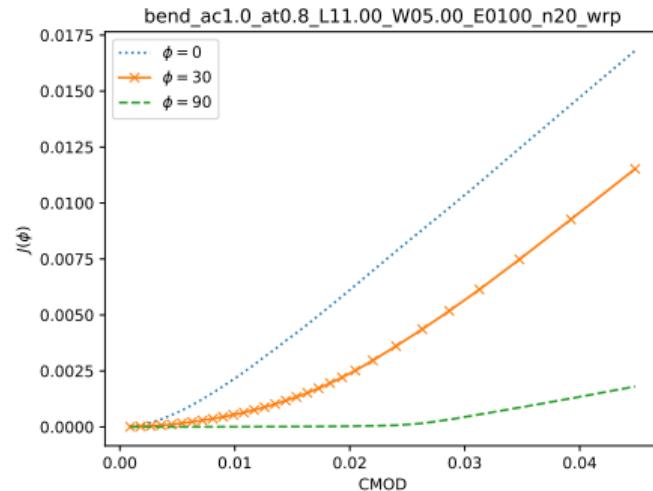
Plate deflection before and after addition of elastic boundary

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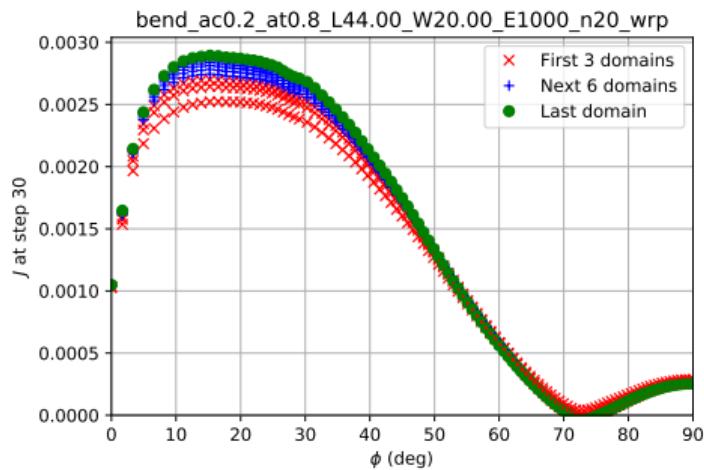
Before addition of elastic boundary



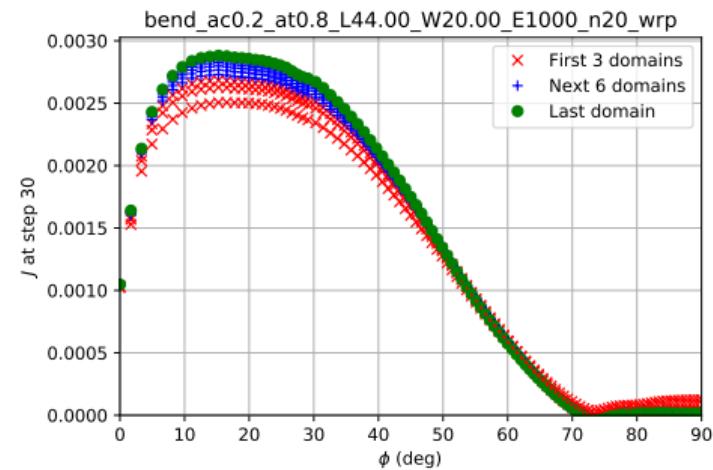
After addition of elastic boundary

Improvements to Initial Bending Models
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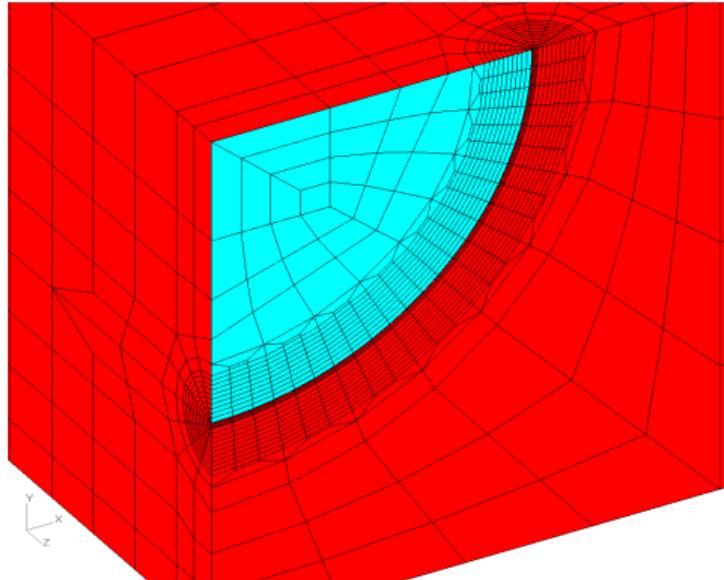
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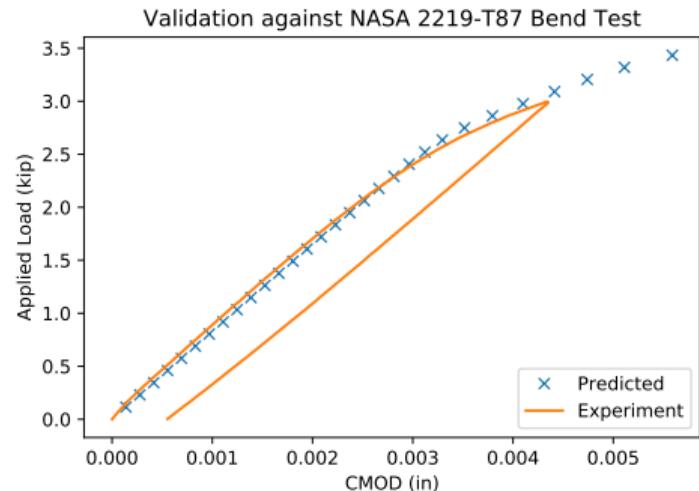
Before addition of elastic boundary



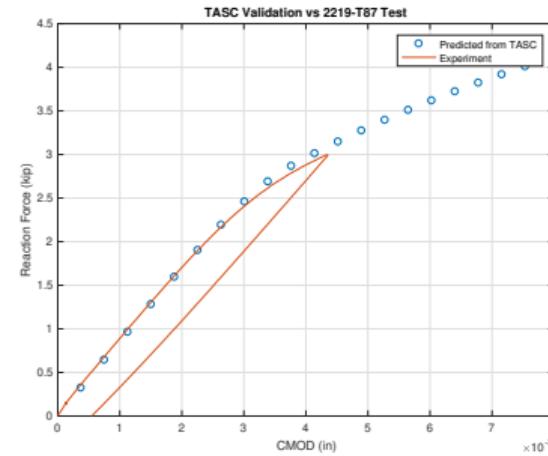
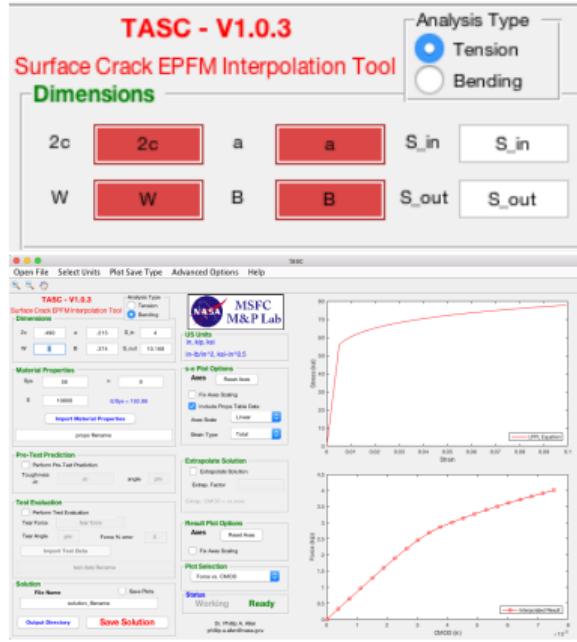
After addition of elastic boundary



Crack front mesh of purpose-built experimental validation model

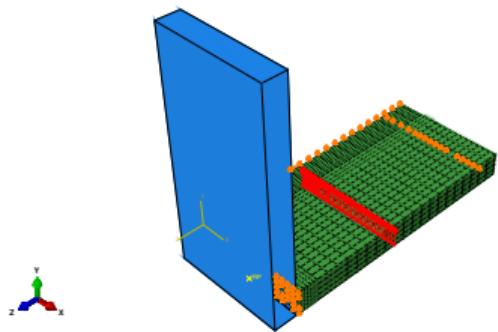


Comparison of predicted load and CMOD between purpose-built model and experiment

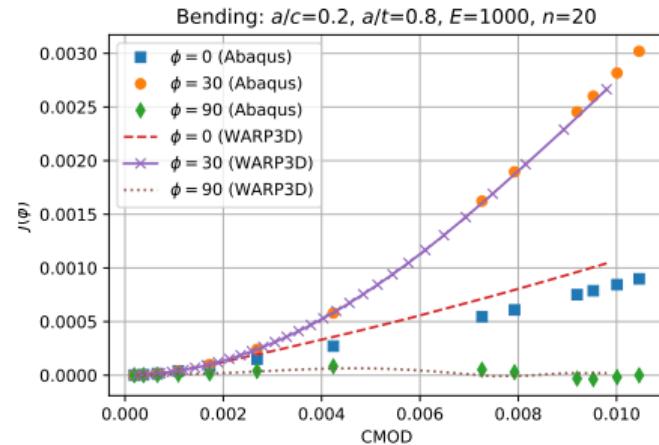


Comparison of TASC and experiment

Modified TASC Program



Sample Abaqus validation model

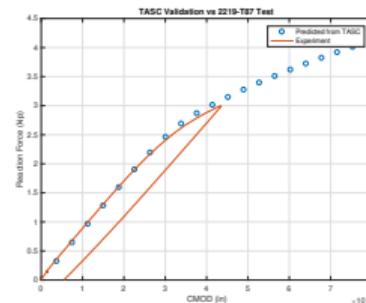
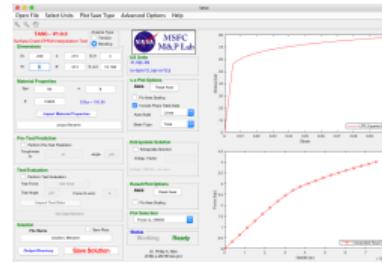


Sample J comparison between Abaqus and WARP3D

Conclusions and Recommendations for Future Work

Database of 600 elastic-plastic finite element results for surface cracks in bending

- ▶ More challenging than tension models
- ▶ Subset of results verified and validated against Abaqus and experimental data
- ▶ Modified TASC program
- ▶ Possible to satisfy requirements of ASTM E2899 for tension **and** bending without constructing purpose-built EPFM models
- ▶ Greatly reduces analytical burden on anyone doing ASTM E2899 tests



1. TASC and E2899

- ▶ Finish integrating bend data into TASC, beyond load-CMOD validation
- ▶ Additional values for material and/or crack geometry
- ▶ Investigate other interpolation methods (piecewise cubic?)
- ▶ Replace traction boundary conditions with rigid rollers and contact modeling

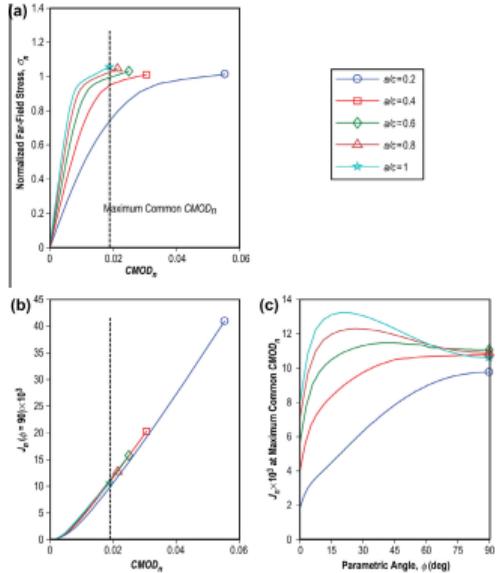
2. More experimental data needed for these.

Thanks to:

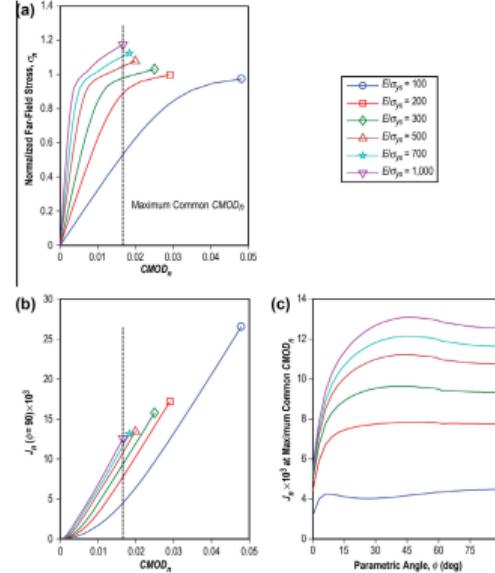
- ▶ Tennessee Tech University's:
 - ▶ Center for Manufacturing Research (Computer Aided Engineering)
 - ▶ Information Technology Services (High Performance Computing)
- ▶ Quest Integrity's FEACrack
- ▶ UIUC's WARP3D
- ▶ Dassault's Abaqus
- ▶ Anaconda's Python distribution

Appendix

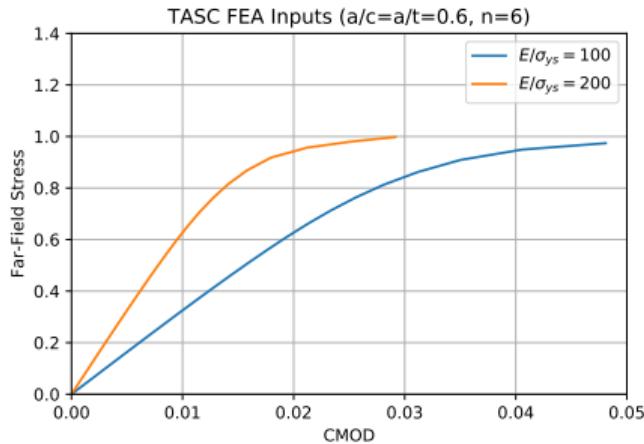
Initial Verification of Two Tension Cases from Allen and Wells (2014)



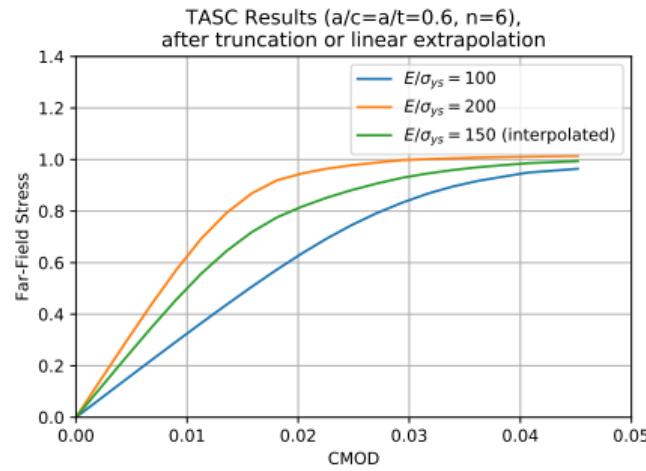
Gap in results for widest aspect ratios



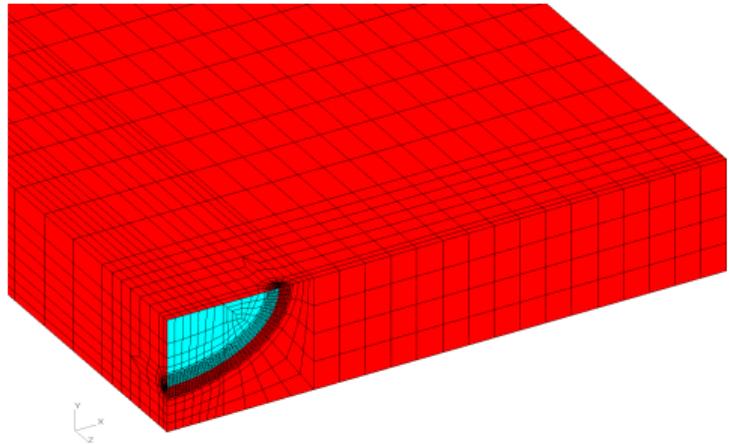
Gap in results for lowest E values



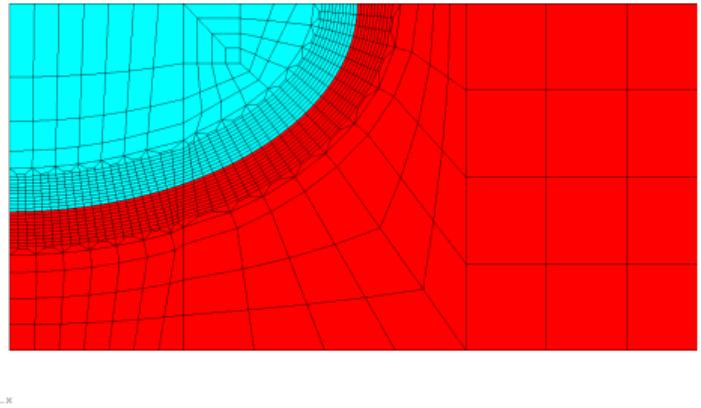
Raw FEA results used in TASC



Interpolated FEA results displayed by TASC



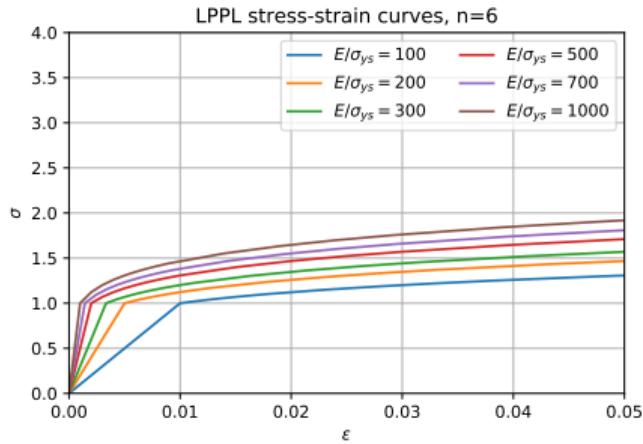
Isometric view of overall mesh



Detailed view of crack front

$$\frac{\epsilon}{\epsilon_{ys}} = \begin{cases} \frac{\sigma}{\sigma_{ys}}, & \epsilon \leq \epsilon_{ys} \\ \left(\frac{\sigma}{\sigma_{ys}}\right)^n, & \epsilon > \epsilon_{ys} \end{cases}$$

where $\epsilon_{ys} = \frac{\sigma_{ys}}{E}$.



Set of LPPL stress-strain curves

$$M = \frac{r_\phi \sigma_{ys}}{J}$$

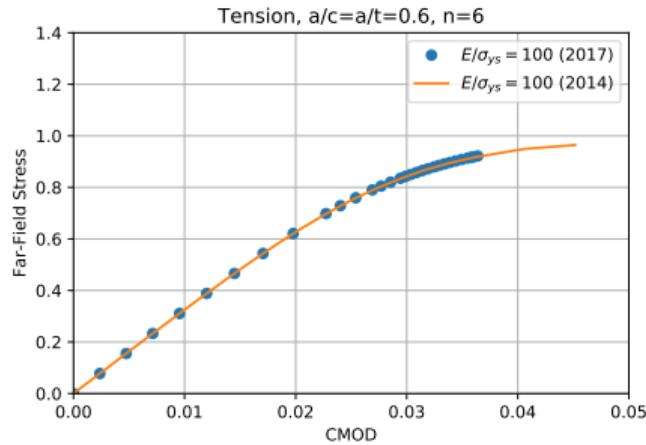
Applied displacement values for verification models

$\frac{E}{\sigma_{ys}}$	Displacement	ϕ	M using $r_{\phi a}$	M using $r_{\phi b}$
100	0.1028	30°	15.9833	36.4241
		90°	22.6234	15.0822
200	0.0550	30°	24.7288	56.3542
		90°	34.9604	23.3069

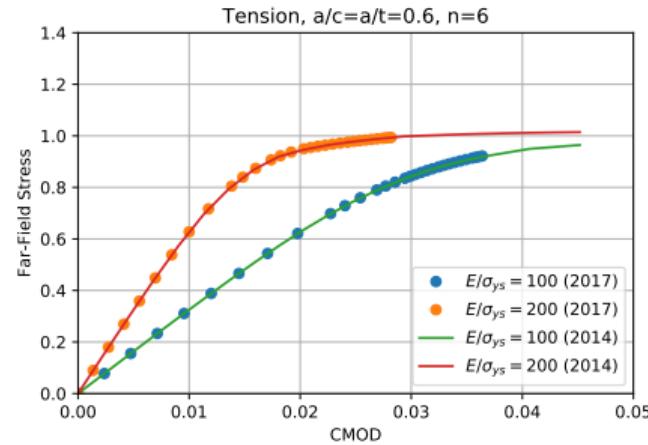
- ▶ 30 load steps
- ▶ `warp3d < file.inp > file.out`
- ▶ 21.6 minutes to solve on laptop, 2.2 minutes on HPC node

Python program

- ▶ run packet_reader to export displacements, forces
- ▶ extract node 1 z displacement, double to get CMOD
- ▶ identify nodes on $z = 0$ from input file
- ▶ extract z reactions from all identified nodes, sum to reaction force
- ▶ divide reaction force by plate cross section area to get stress



Verification of stress and CMOD relationship for first model



Verification of stress and CMOD relationship for second model