Development of a Combined Cohesive and Virtual Crack-Closure Approach to Represent R-Curves

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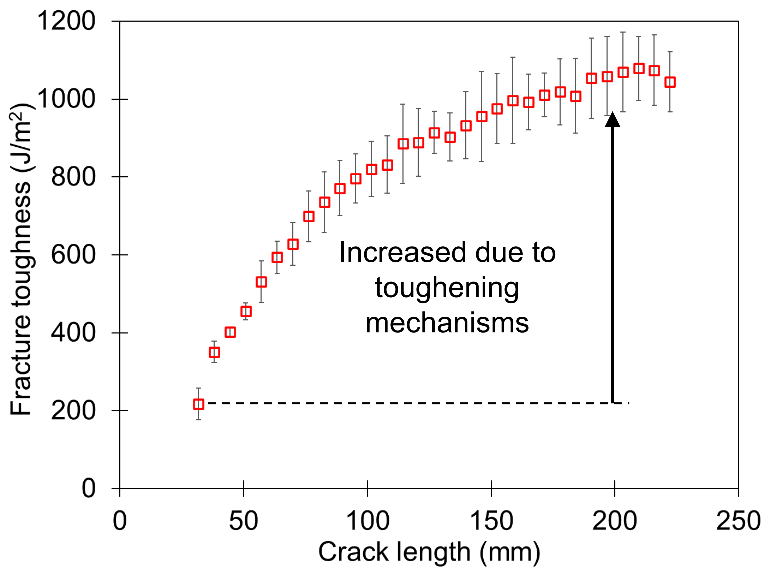
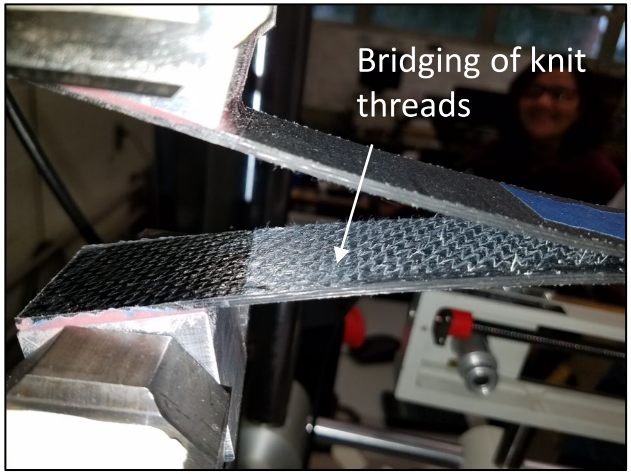
Motivation and Objective

- Delamination in composites is highly influenced by resistance-curve (R-curve) effects, but computationally expensive to simulate
- The objective is to increase element size to evaluate structural-scale damage tolerance by developing an approach that takes advantage of the virtual crack-closure technique (VCCT) and cohesive zone modeling (CZM)
- Compared three analysis types: VCCT, CZM, and a combined VCCT/CZM approach



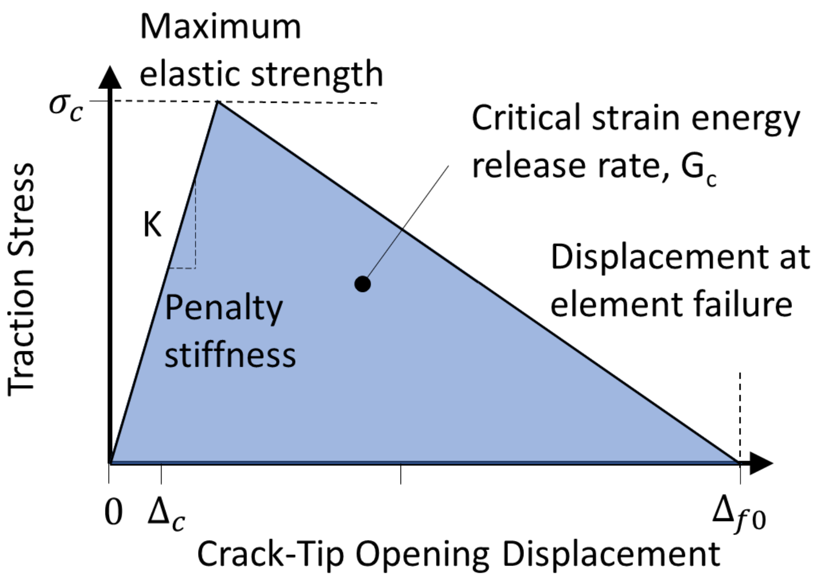
R-Curve



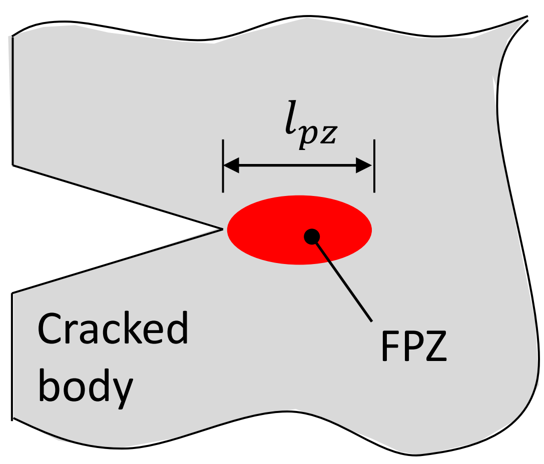
Double cantilever beam (DCB) test

Cohesive Zone Modeling (CZM)

- **CZM approaches utilize a traction-separation law (TSL), which is often depicted as a bilinear law**
- **The TSL shape describes the elastic/softening responses as a function of the crack-tip opening displacement**
- **Under linear elastic conditions, the crack propagation is dominated by G_c and has small fracture process zone (FPZ) length (l_{pz})**
- **Typically need 3 to 5 elements to represent FPZ**



Bilinear TSL

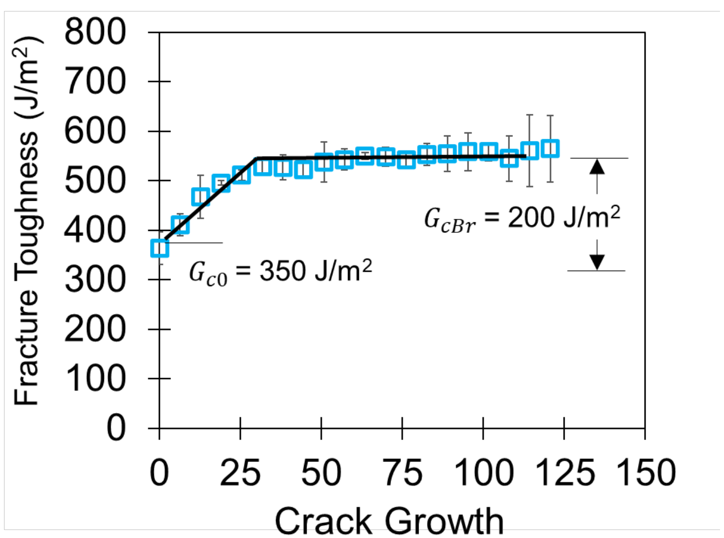


Fracture Process Zone (FPZ)

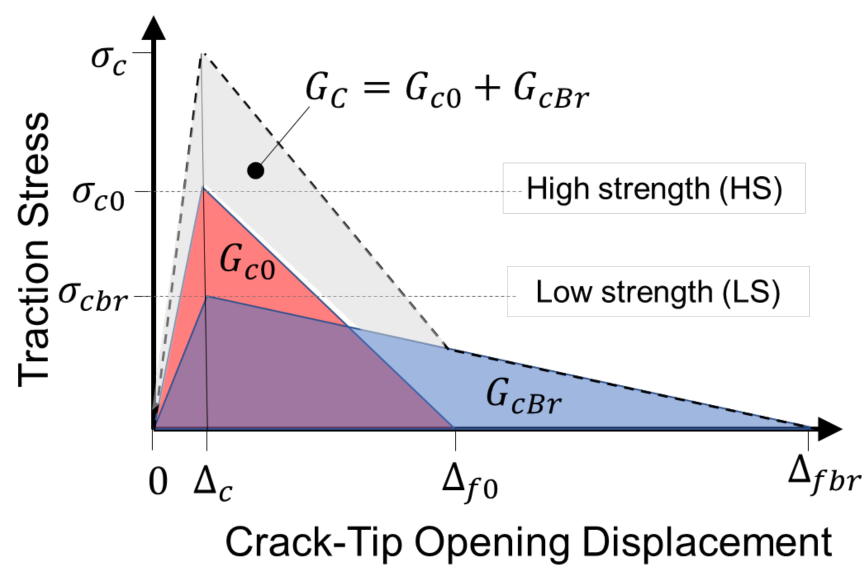
Representing Bridging in CZM

- **Under large-scale bridging conditions, the shape of the TSL is an important feature to capture**
- **R-curves can be represented by superposing two or more bilinear TSLs**
  - An initial linear elastic response representing interfacial debonding
  - Additional TSLs are secondary bridging law(s) that are typically low strength
- **Fracture process zones lengths (l_{pz}) are inversely proportional to the maximum elastic strengths (traction stress, σ_c)**

$$l_{pz} \propto \frac{1}{\sigma_c^2}$$

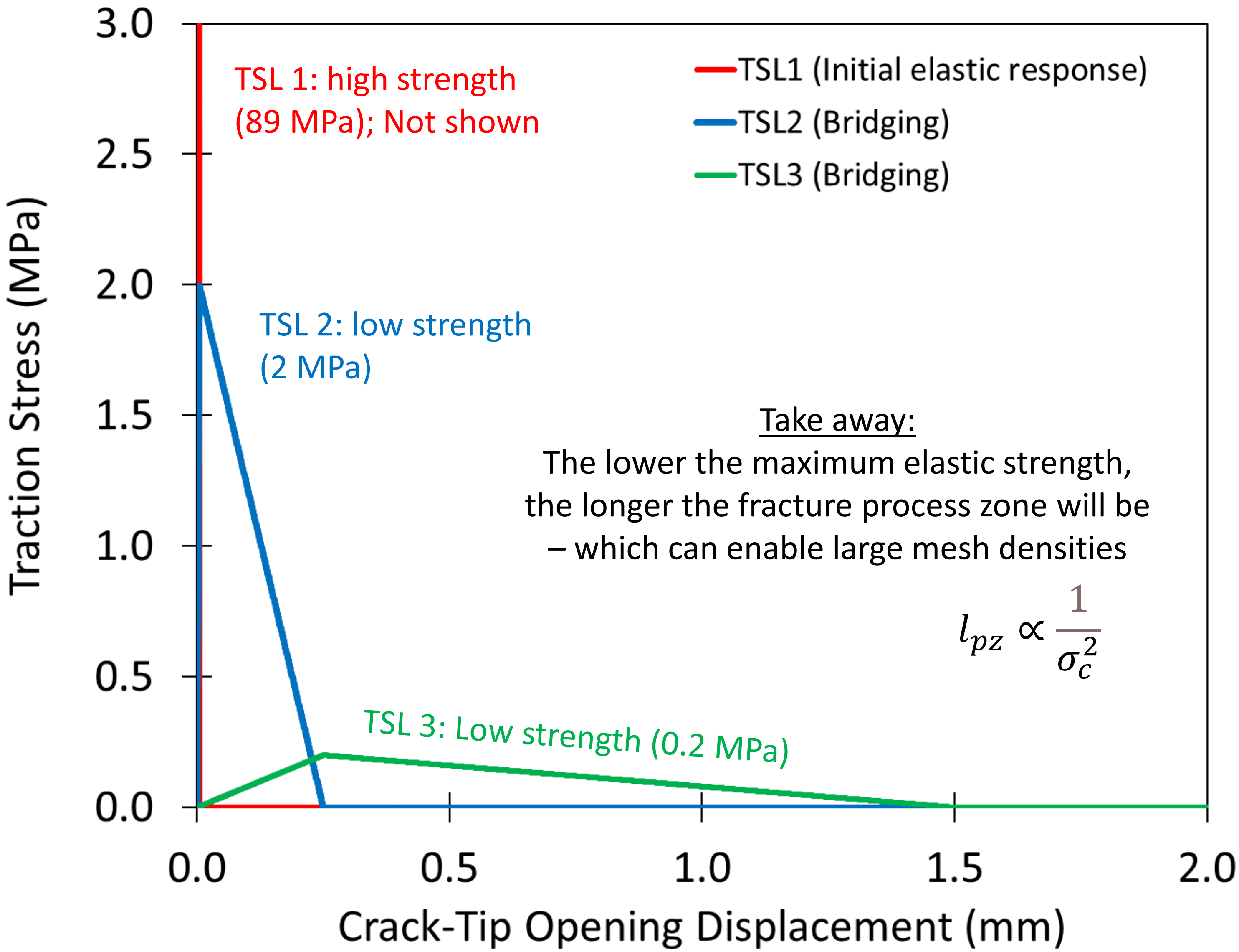


R-curve



Superposed cohesive law

Superposed TSL Example (CZM)



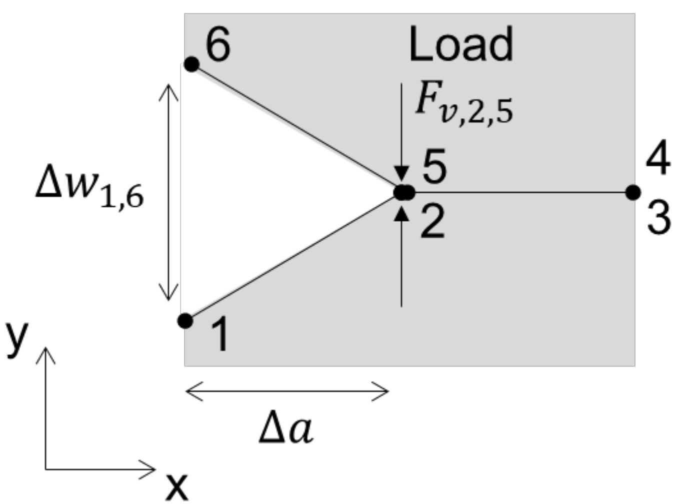
Take away:

The lower the maximum elastic strength, the longer the fracture process zone will be – which can enable large mesh densities

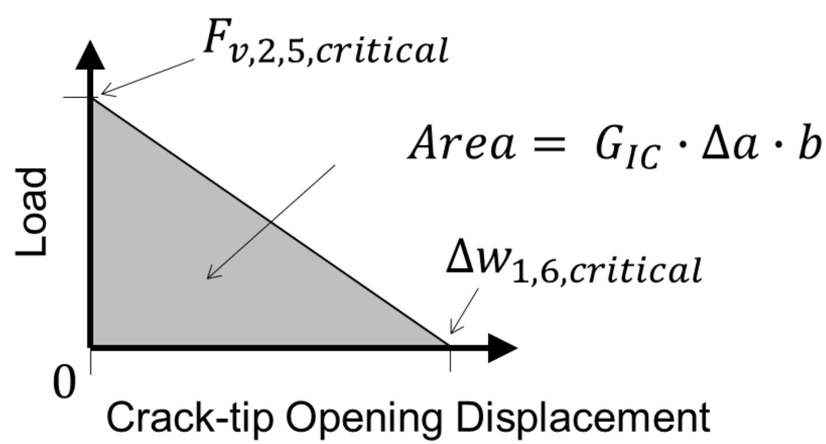
$$l_{pz} \propto \frac{1}{\sigma_c^2}$$

Virtual Crack-Closure Technique (VCCT)

- VCCT is a linear elastic fracture mechanics method that can be used to simulate delamination using relatively coarse meshes
- Tied nodal pairs (2,5) are released after $G_I \geq G_{IC}$
- VCCT can represent R-curves by specifying $G_{IC}(x, y)$, but is not a satisfactory general solution
- Unable to account for changes in the R-curve with specimen thickness



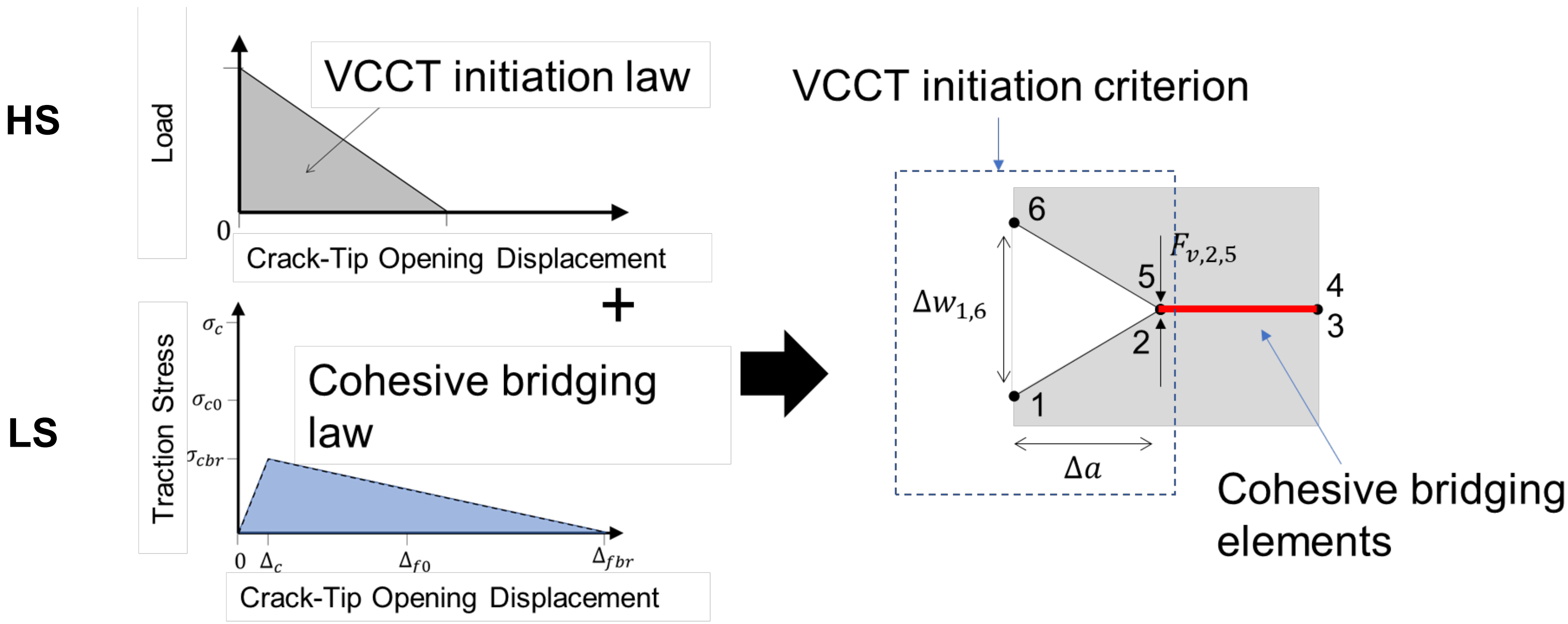
Delaminated body



Progressive release curve

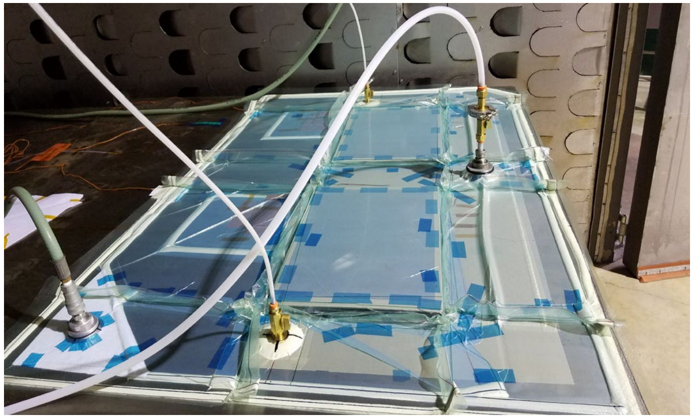
Combining CZM and VCCT

- Mesh requirements are determined based on the size of the fracture process zone, typically with the shortest l_{pz} (High strength)
- Replacing high strength (HS) TSLs with VCCT can enable significantly larger cohesive elements to be used to represent large fracture process zones (Low strength; LS)
- VCCT considers initiation criterion based on critical strain energy release rate (SERR)

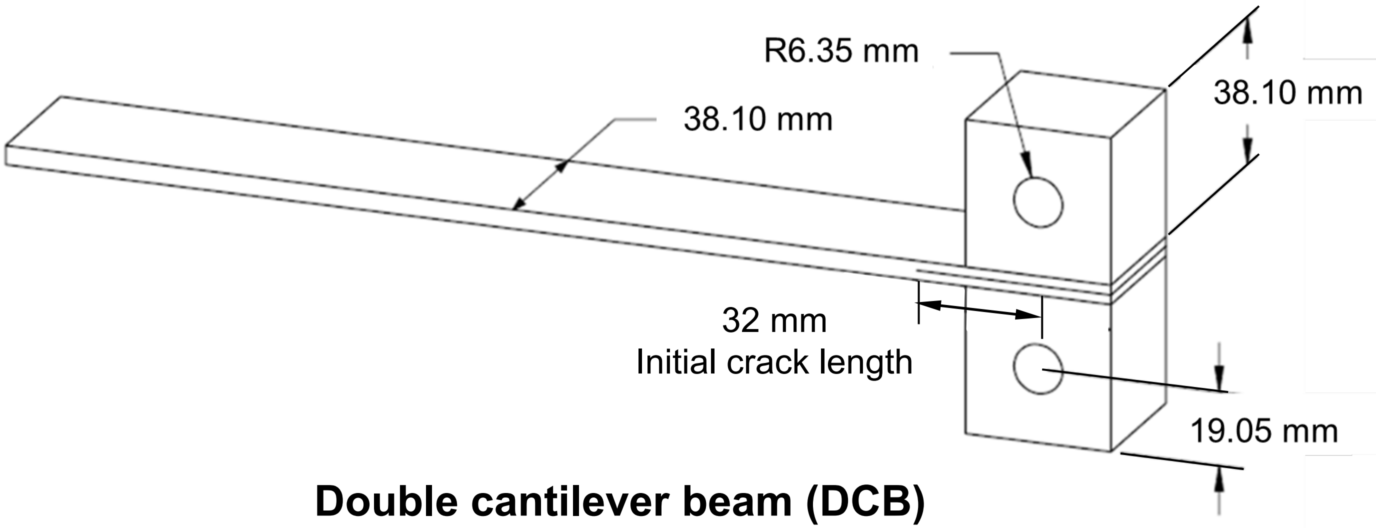


Material System and Fabrication

- **Carbon/Epoxy Composite**
  - Saertex Biaxial [0/90] fabric
  - Hexcel 1078 aromatic epoxy resin system
- **Two layup configurations**
  - $[0/90/90/0]_{3s}$: 5-mm thick
  - $[0/90/90/0]_{9s}$: 15-mm thick
- **Manufactured using vacuum-assisted resin transfer molding (VARTM) technique**



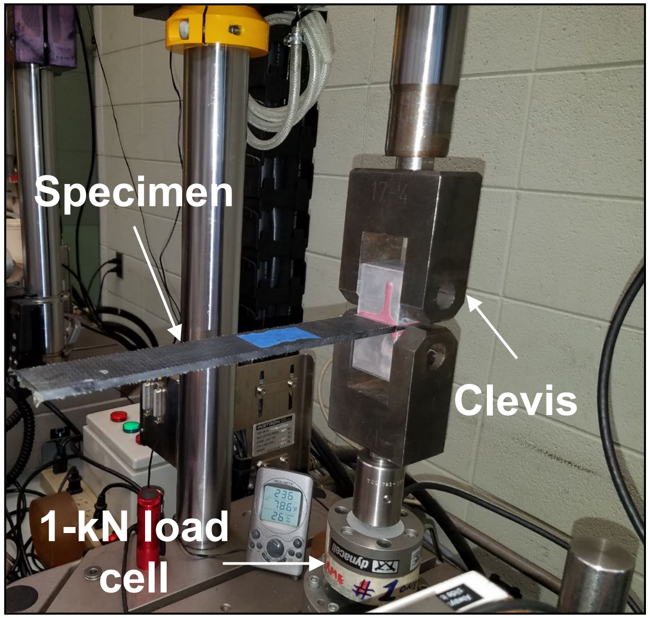
VARTM



Double cantilever beam (DCB) Specimen configuration

Experimental Test

- Double cantilever beam tests were performed in accordance with ASTM D5528
- Teflon film was used as the crack initiator
- Displacement rate of 0.5 mm/min with a 1 kN load cell
- Three replicates were performed per laminate configuration
- Crack length was visually recorded using a camera system



Test setup

Experimental Characterization of R-Curve Response

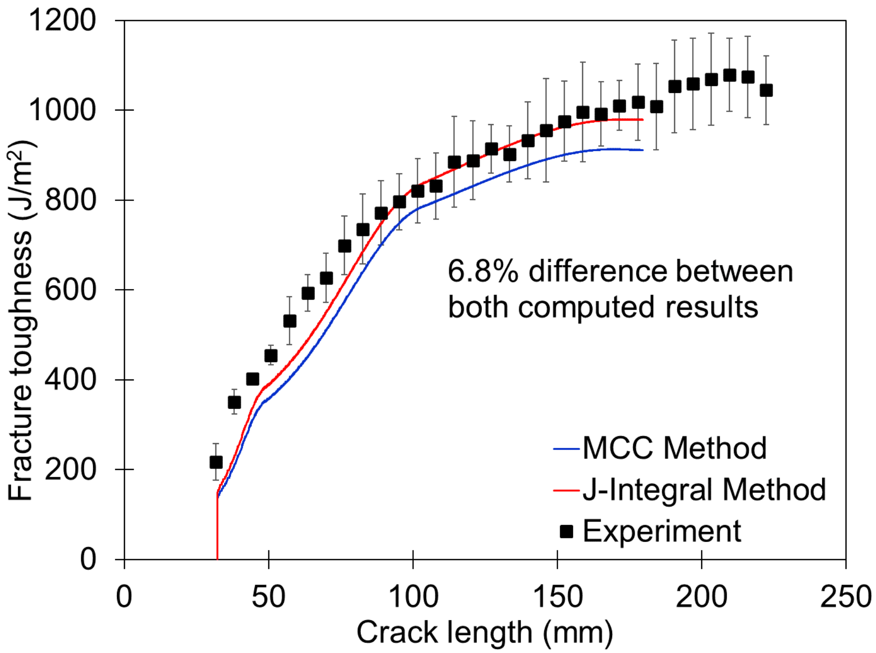
- Experimental SERRs were initially obtained using the modified compliance calibration (MCC) approach
- Computed MCC was compared to computed J-integral results and was found acceptable (based on a numerical example)

$$G_I = \frac{3P^2C^{2/3}}{2A_1bh} \qquad \text{(MCC)}$$

$$J_I = \frac{2P}{b} sin(\theta) \qquad \text{(J-Integral)}$$

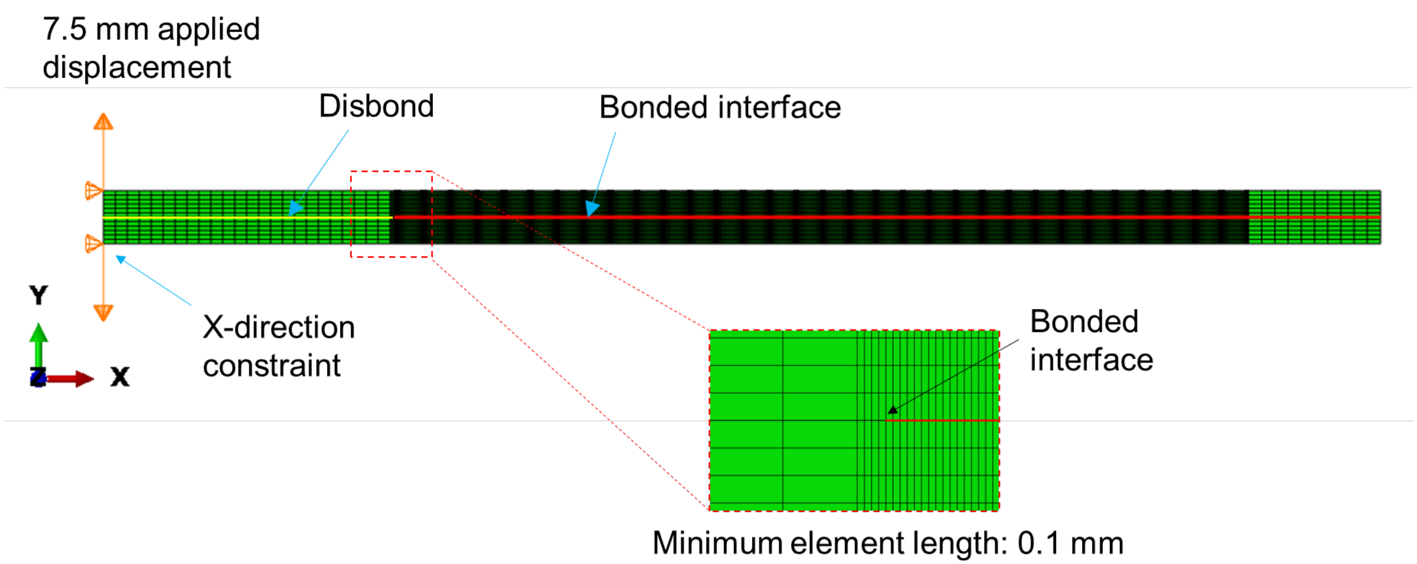
P: Load
θ: Rotation of the specimen arms at load-application point
b: Specimen width
h: Specimen thickness
C: Compliance (displacement/load)
A_1: Calibration parameter

Comparison of Computed MCC and J-Integral



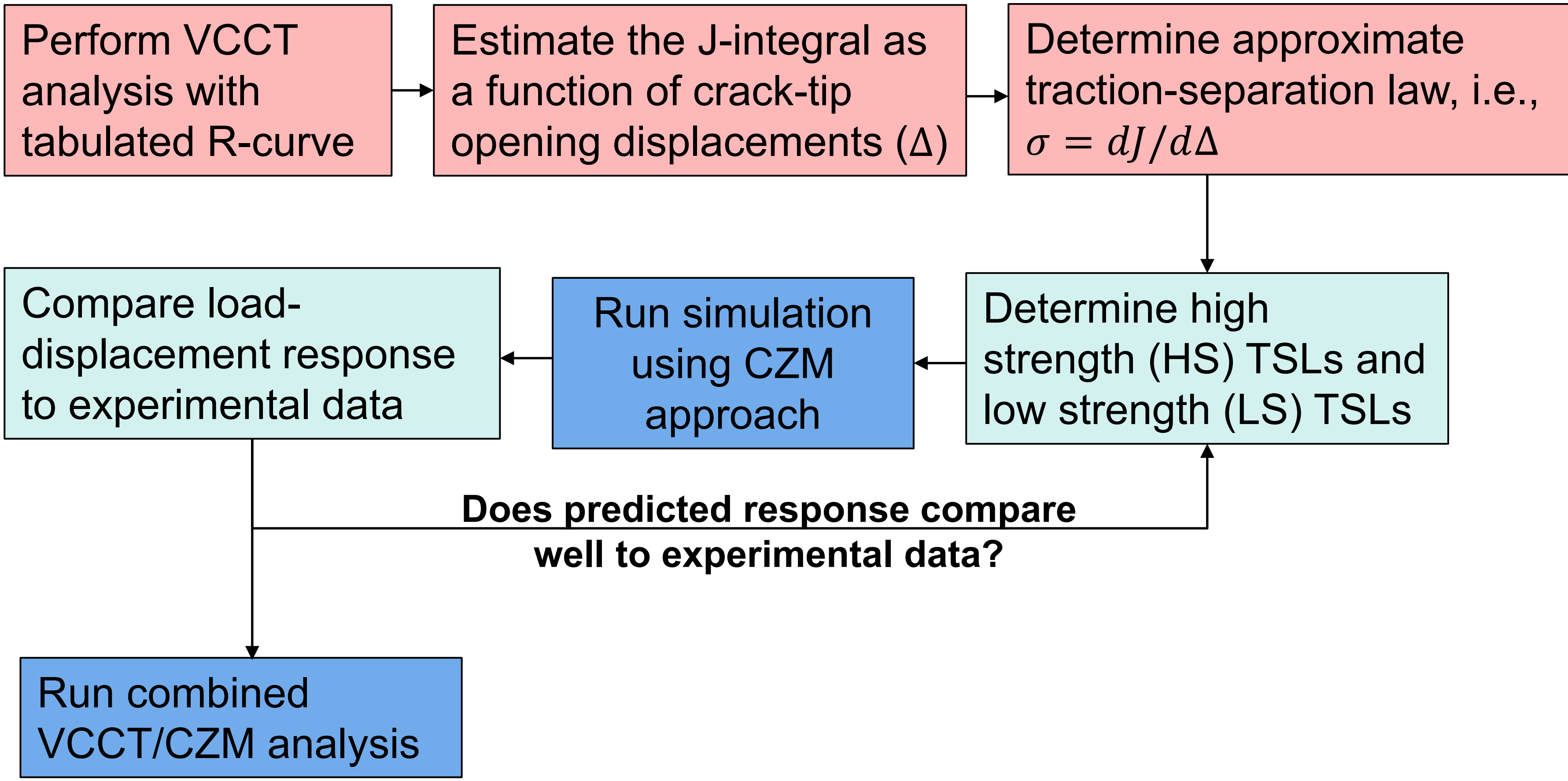
Computational Approach

- **Implicit finite element analysis using Abaqus/Standard v2022 software**
  - Hexahedral (C3D8I) elements with incompatible modes
  - Viscoelastic regularization of 1.0E-6 was used
- **Three analysis types: VCCT, CZM, and a combined VCCT/CZM**
  - VCCT analysis used an SERR as a function of position to estimate R-curve effects
  - CZM used superposed TSLs to estimate R-curve effects
- **Varied element length from 0.1 mm to 10 mm to determine computational time**



Finite element model

Determination of Bridging Laws



Fracture Properties

Fracture Properties using a $[0/90/90/0]_{3s}$ (5-mm thick) layup configuration

Model	*SERR* (N/mm)	*Strength* (MPa)	*Stiffness* (MPa/mm)
VCCT (HS)	0.150	-	-
Cohesive			
TSL-1 (HS)	0.150	89.0	2.00E+05
TSL-2 (LS)	0.250	2.00	4.47E+02
TSL-3 (LS)	0.150	0.20	8.00E-01

Combined VCCT/CZM

- TSL-1 (HS) → **Replaced with VCCT**
- TSL-2 (LS), TSL-3 (LS) → **Superposed CZM**

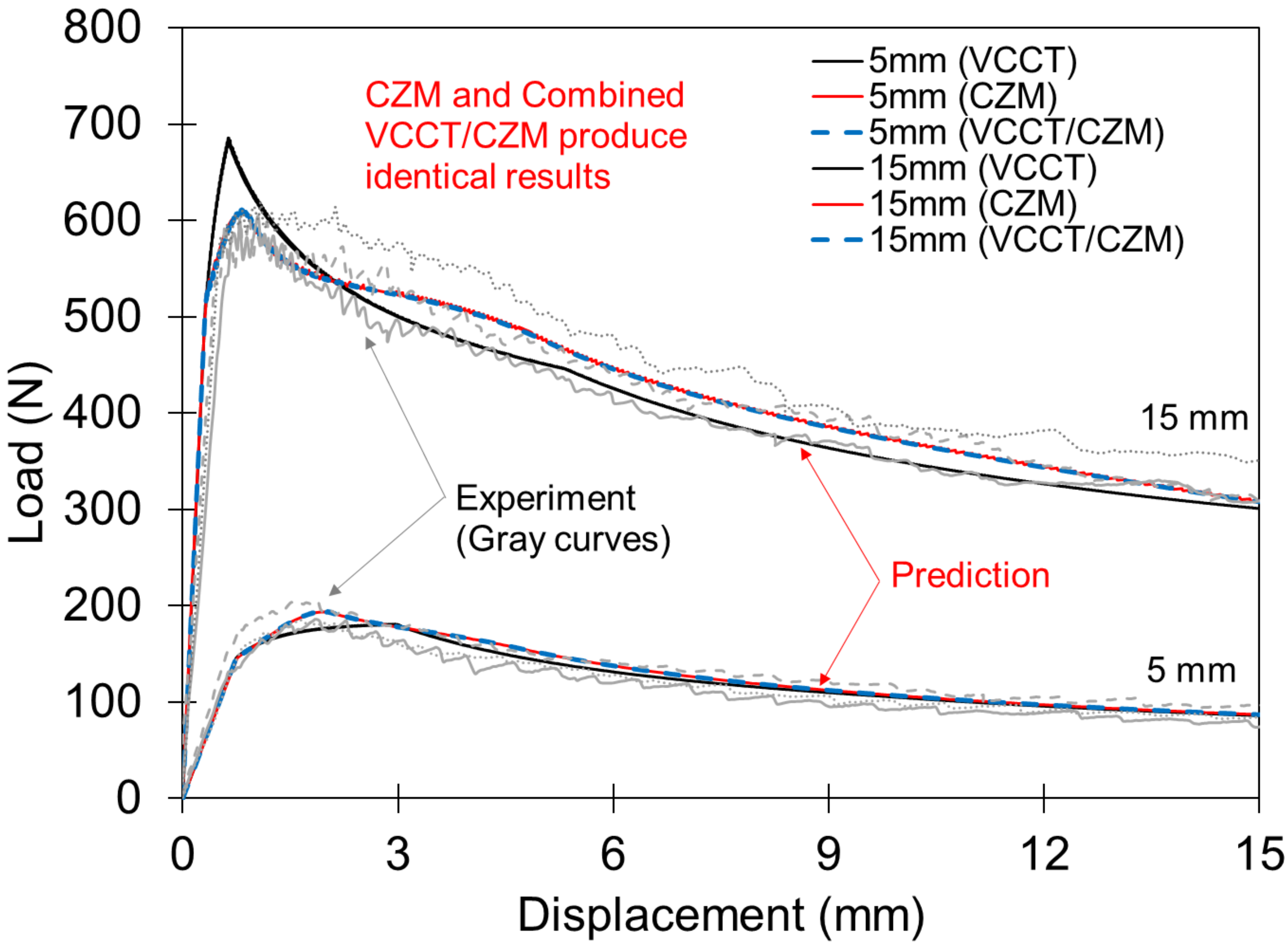
Fracture Properties using a $[0/90/90/0]_{9s}$ (15-mm thick) layup configuration

Model	*SERR* (N/mm)	*Strength* (MPa)	*Stiffness* (MPa/mm)
VCCT (HS)	0.150	-	-
Cohesive			
TSL-1 (HS)	0.150	89.0	2.00E+05
TSL-2 (LS)	0.300	25.0	5.59E+03
TSL-3 (LS)	0.350	0.30	1.25E+01
TSL-4 (LS)	0.200	0.03	1.29E-02

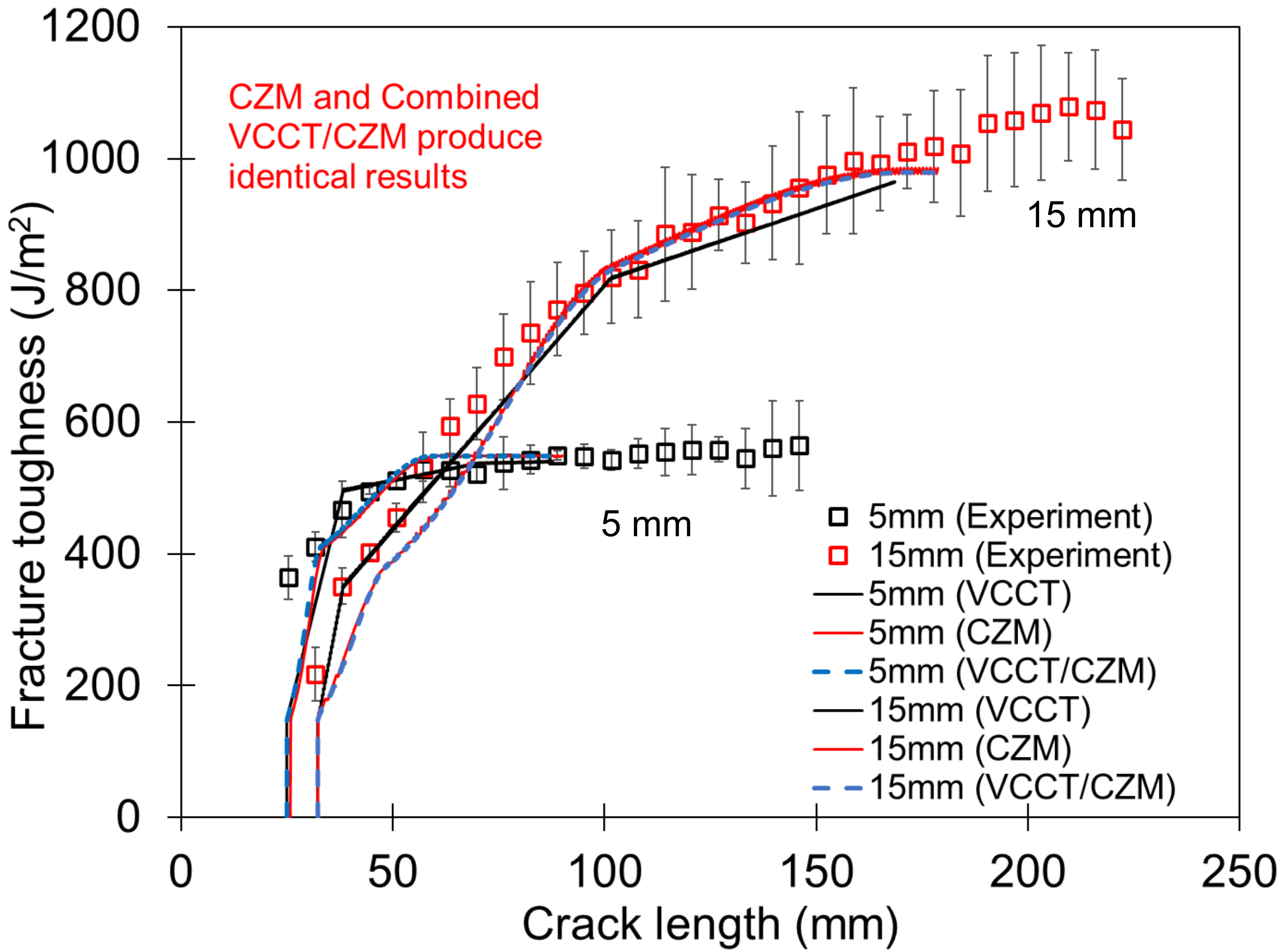
Combined VCCT/CZM

- TSL-1 (HS) → **Replaced with VCCT**
- TSL-2 (LS), TSL-3 (LS), TSL-4 (LS) → **Superposed CZM**

Load-Displacement Results



R-Curves



CZM and Combined
VCCT/CZM produce
identical results
Fracture toughness (J/m^2)
Crack length (mm)
1200
1000
800
600
400
200
0
0
50
100
150
200
250
15 mm
5 mm
5mm (Experiment)
15mm (Experiment)
5mm (VCCT)
5mm (CZM)
5mm (VCCT/CZM)
15mm (VCCT)
15mm (CZM)
15mm (VCCT/CZM)

Computational Time

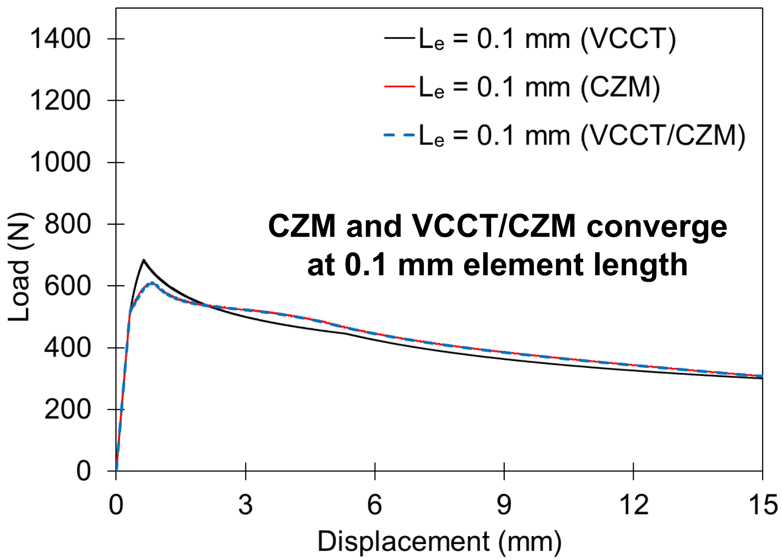
- CZM approach took approximately twice as long as the VCCT finite element model for a 0.1-mm element length
- CZM did not reach convergence for element lengths greater than 1 mm
- VCCT and combined VCCT/CZM solution had nearly equivalent computational times for large element lengths (5 mm and 10 mm)
- Computational time can be reduced by up to 92% using a 10 mm element length

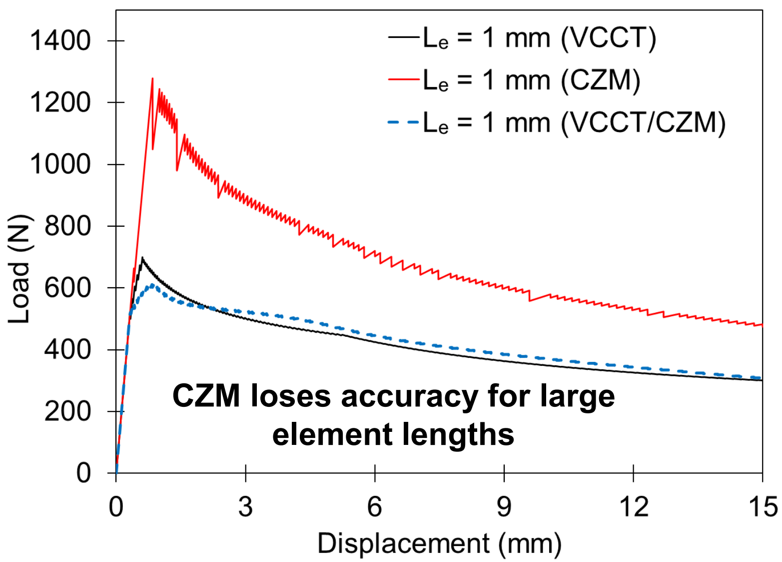
Computational time for each method and element length

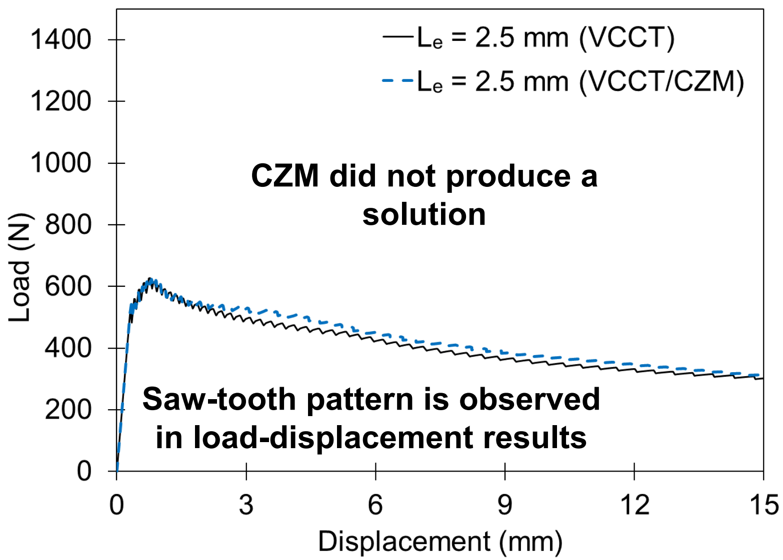
Element Length (L_e)	Time Completed (Hr:Min)*			No. of Degrees of Freedom
	VCCT	CZM	VCCT/CZM	
0.1 mm	1:39	3:04	1:39	54950
1.0 mm	0:24	1:05	0:44	16660
2.5 mm	0:09	n/a	0:20	6790
5 mm	0:10	n/a	0:11	3710
10 mm	0:07	n/a	0:08	1890

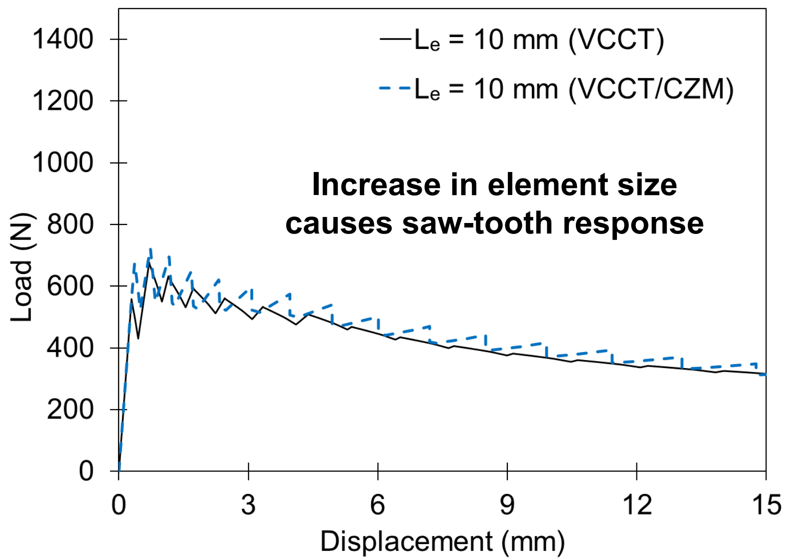
*Assumes a viscosity parameter of 2.0E-6 for all solutions. Improved computational times for the CZM approach can be achieved if increased

Load Response with respect to Element Length (L_e)









Final Remarks

- **A combined VCCT/CZM approach was implemented to take advantage of the VCCT and CZM approaches**
  - Improved computational time
  - Accurate representation of bridging mechanisms
- **Mesh density of CZM is dependent on the TSL with the smallest fracture process zone size (i.e., HS TSL)**
  - Fracture process zone size is inversely dependent on the cohesive strength at the interface
  - Using VCCT in replacement of a HS TSL enables significantly larger cohesive element sizes
- **Significant improvements in computational time using the combined approach can be achieved**
  - Computational time can be reduced by up to 92%
  - The computational time of the combined VCCT/CZM approach is nearly equivalent to a VCCT approach for large element sizes

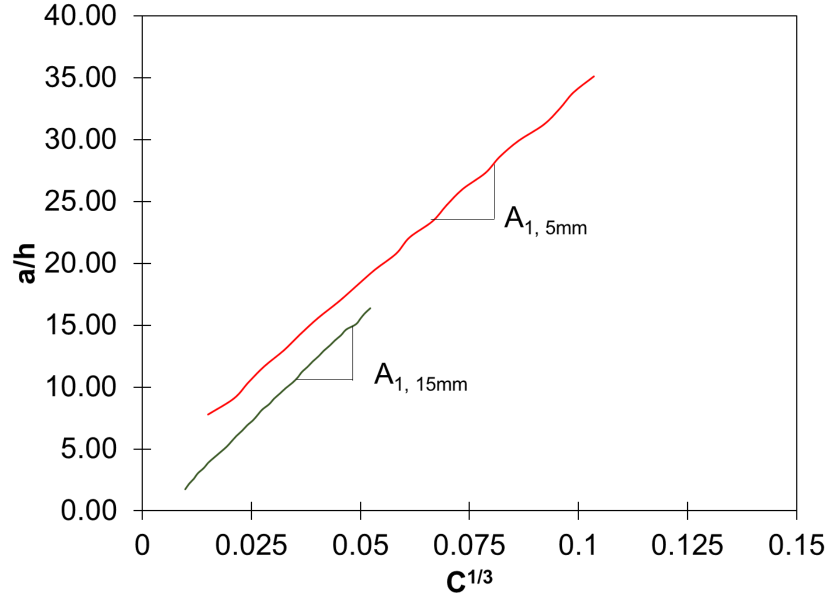
Questions

Estimate of Mode I SERR

- **The experimental mode I SERR (G_I) was calculated using the modified compliance calibration method (MCC) approach**

$$G_I = \frac{3P^2C^{2/3}}{2A_1bh}$$

P: Load
C: Compliance
a: Crack length
A_1: Calibration parameter that is the slope of the normalized crack length (a/h)
B: Specimen width
h: Specimen thickness



Calibration parameter determination

Crack Growth