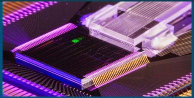
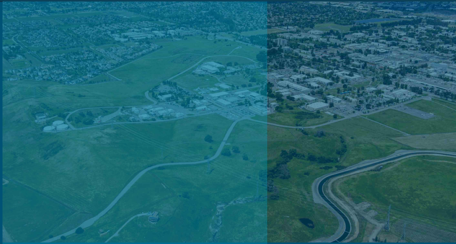
Cohesive surface elements compatible with 10-node composite tetrahedral elements





18th U.S. National Congress on Computational Mechanics

Presented by:

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Abstract

12-node composite wedge cohesive surface finite elements:

- Developed to be compatible with 10-node composite tetrahedral finite elements.
- Used for interfacial fracture analysis, especially hard-to-mesh scenarios.

Performance comparisons with respect to 8-node hexahedra and 4-node tetrahedra:

- Exemplary problem is an asymmetric double-cantilever beam specimen.
- 10-node composite tetrahedra perform similarly to 8-node hexahedra.
- Unsurprisingly, 4-node tetrahedra are not the best choice.

Currently implemented in the latest release of Sierra/Solid Mechanics:

- Somewhat of a cinch to implement after the composite tetrahedral element.
- Will be crucial for modeling delamination within complicated microstructures.

Cohesive surface elements

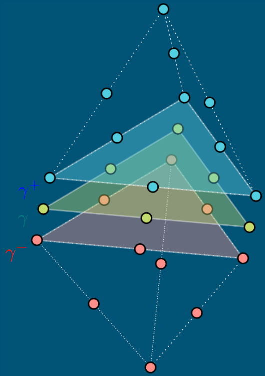
Finite elements for interfaces:

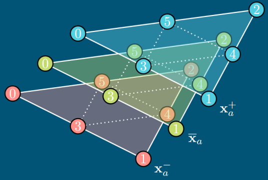
- Initially overlapping surface elements.
- Nodal forces from displacement jumps.
- Regularizes interfacial fracture.
- Seamless fracture surfaces.

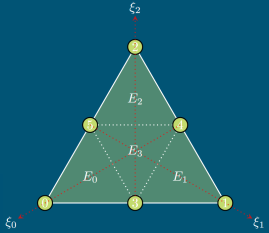
Robust and well-established tool [1].

- Insertion on internal mesh surfaces.
- Relatively simple finite element.
- Works for tetrahedra and hexahedra.
- Now, works for composite tetrahedra.

How well do composite wedge CSEs perform?







Cohesive zone models

Material models for interfaces:

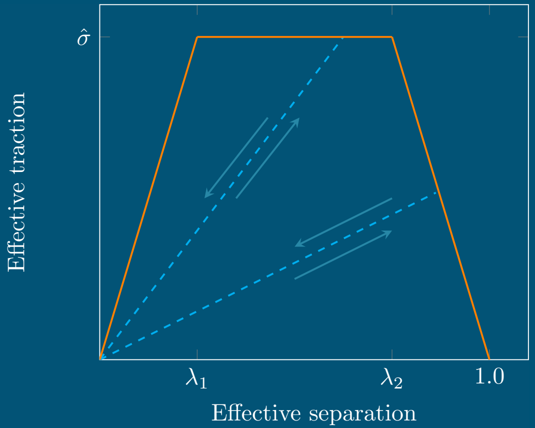
- Traction as a function of separation.
- Toughness is the integrated area.
- Non-trivial loading and unloading.
- Distinct from continuum models.

Tvergaard-Hutchinson [2] model:

- Trapezoidal traction-separation law.
- Extended to 3D in Sierra/SM [3].

Toughness, element stiffness, process zone [4].

- $\hat{\sigma} \approx 0.03\% \, E = 20.7$ MPa.
- $\delta_c = (2\Gamma/\hat{\sigma})/(1 + \lambda_2 - \lambda_1) = 4.8$ µm.
- $\lambda_1 = \lambda_2 = (\hat{\sigma}/\delta_c)(s/E) \approx 4\%$ to 9%.



Sierra/Solid Mechanics

Sierra/SM [3] currently has three CSEs:

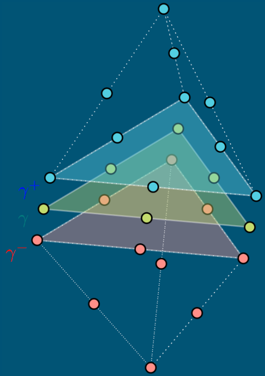
- Hex8, compatible with Hex8s.
- Wedge6, compatible with Tet4s.
- Wedge12, compatible with Tet10s [5, 6].

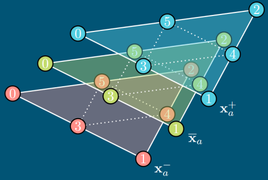
Distinct library of interface material models:

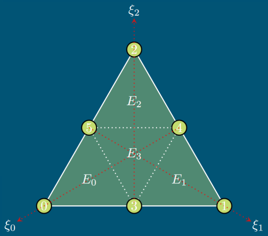
- Tvergaard-Hutchinson [2].
- Thouless-Parmigiani [7].
- Mixed-mode dependent toughness [8].
- Simple traction decay.

Currently under consideration:

- Park, Paulino, and Roesler [9].
- Camanho and Dávila [10].







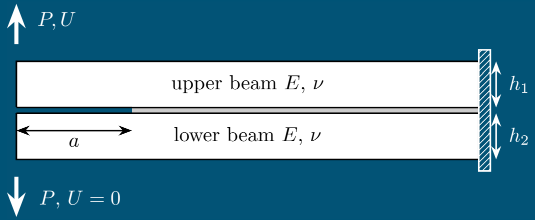
Double cantilever beam

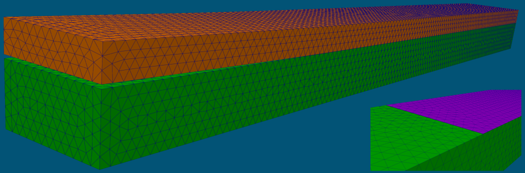
Asymmetric DCB [4] analysis:

- Linearly elastic ($E = 69$ GPa, $\nu = 0.33$).
- Approximate G from compliance C:

$$G = \left(\frac{P^2}{2w}\right)\left(\frac{a^2}{EI}\right), \quad a = (3EIC)^{1/3}$$

- Epoxy ($G_c = 50$ mJ/mm^2) from CSEs.
- $h_1 = 4.5$ mm, $h_2 = 2h_1$, $w = 4h_1$, $a = 10h_1$, $L = 4a$, $U = a/90$, $N = 50$.
- Absolute/relative tolerance = 10^{-7}.
- Sierra 5.24.1 with 32 cores on Ubuntu.
- CSEs insertion using Exomerge [11].





Comparison 1

Similar total number of elements:

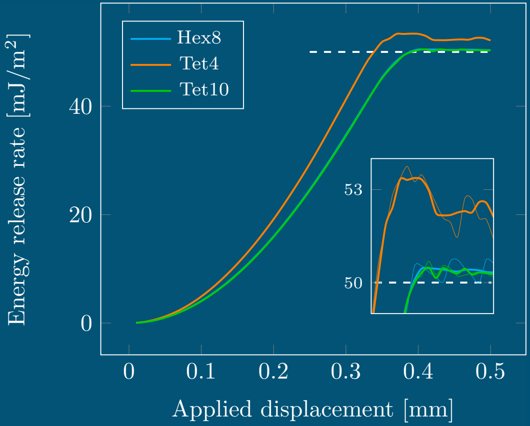
- 108,000 for Hex8 (120,500 nodes).
- 111,373 for Tet4 (23,192 nodes).
- 111,373 for Tet10 (164,799 nodes).

Predictions from 0.4 mm to 0.5 mm:

- 50.40 ± 0.04 mJ/m^2 for Hex8 (218 s).
- 52.37 ± 0.25 mJ/m^2 for Tet4 (48 s).
- 50.34 ± 0.10 mJ/m^2 for Tet10 (547 s).

Underintegrating cohesive elements:

- 50.40 ± 0.28 mJ/m^2 for Hex8 (204 s).
- 52.20 ± 0.51 mJ/m^2 for Tet4 (46 s).
- 50.35 ± 0.16 mJ/m^2 for Tet10 (510 s).



Comparison 2

Similar total number of nodes:

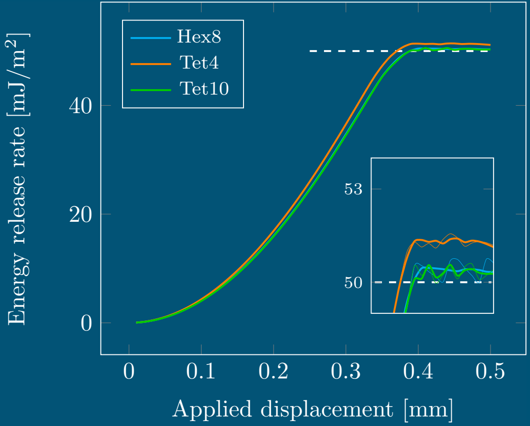
- 120,500 for Hex8 (108,000 elements).
- 122,283 for Tet4 (661,083 elements).
- 120,845 for Tet10 (81,630 elements).

Predictions from 0.4 mm to 0.5 mm:

- 50.40 ± 0.04 mJ/m^2 for Hex8 (218 s).
- 51.30 ± 0.07 mJ/m^2 for Tet4 (311 s).
- 50.34 ± 0.13 mJ/m^2 for Tet10 (313 s).

Underintegrating cohesive elements:

- 50.40 ± 0.28 mJ/m^2 for Hex8 (204 s).
- 51.29 ± 0.13 mJ/m^2 for Tet4 (310 s).
- 50.30 ± 0.19 mJ/m^2 for Tet10 (310 s).



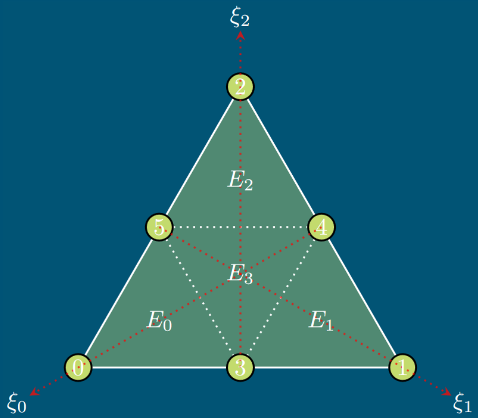
Implementation

12-node composite wedge cohesive elements:

- Displacement on Tet10s is piecewise-linear.
- Cohesive zone models just need displacement.
- No projected quantities seem to be required.
- Just use four linear wedge cohesive elements!

$$\mathbf{f}_a^{\pm} = \mp \sum_{e=1}^{4} \sum_{g=1}^{3} \mathbf{t}(\boldsymbol{\delta}_g^e)\, N_a(\boldsymbol{\xi}_g)\, J_a^e$$

- Working perfectly well so far!
- Agglomeration should be more efficient.
- May consider alternatives in the future.



Conclusion

12-node composite wedge CSEs:

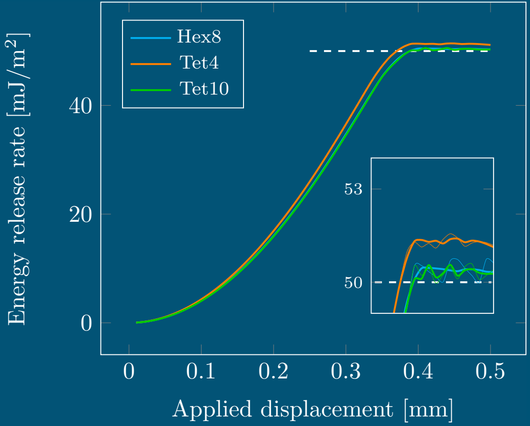
- Compatible with Tet10s.
- Interfacial fracture analysis.
- Simple to develop or implement.

Performance comparable to Hex8s in DCBs:

- Similar for similar node counts.
- Only structured hexes considered.
- Tet4s are not the best choice.

Underintegration is not that beneficial:

- Small fraction of CSEs, small speedup.
- Worsens accuracy, possibly convergence.



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