Review of LS-DYNA Cohesive Elements

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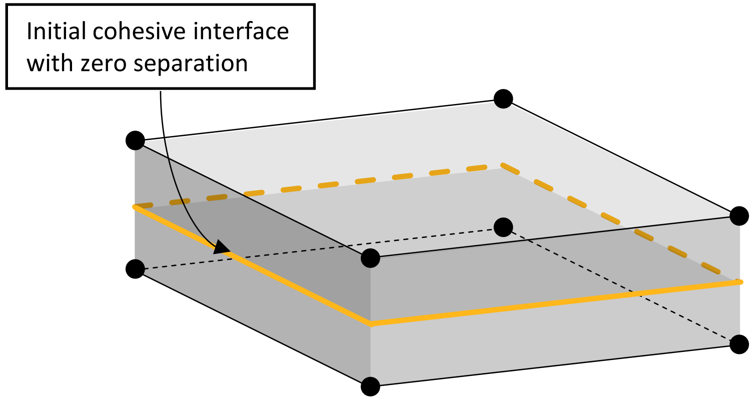
Motivation

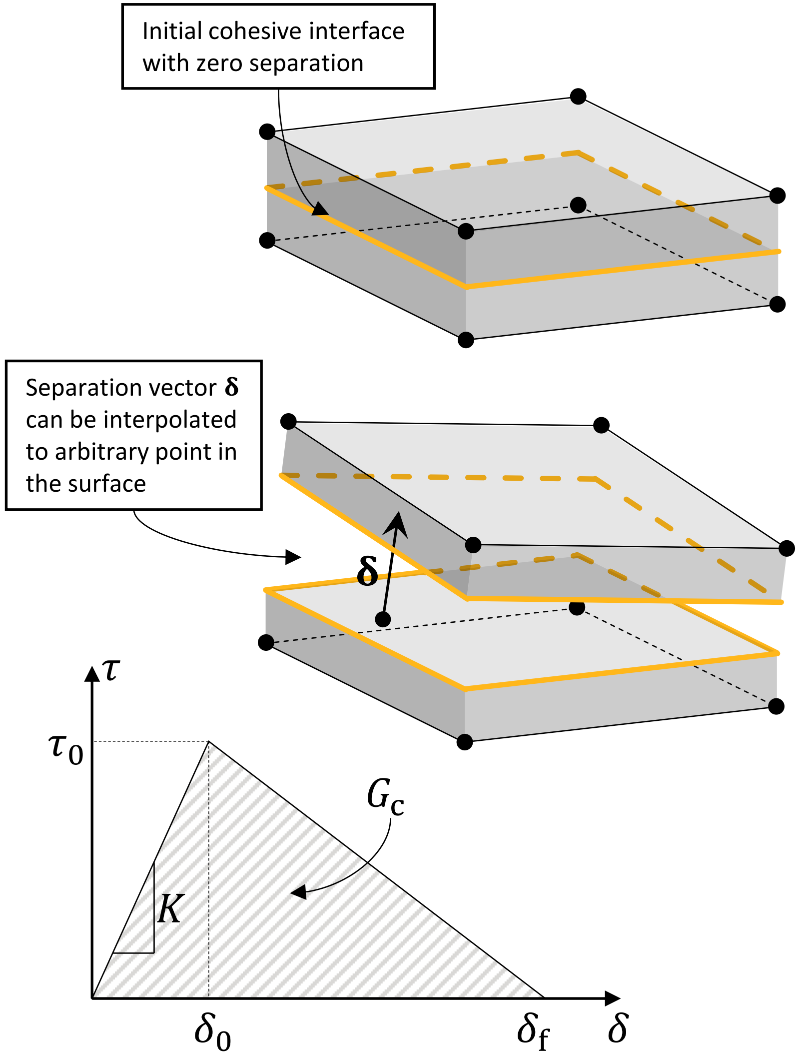
- **Cohesive elements** are used to connect adjacent solid or shell elements by placing a cohesive interface in between.
  - A common application is the modelling of crack initiation and propagation.
  - While the *cohesive element* may initially have a non-zero volume, the *cohesive interface* has zero initial separation.
  - Both solid and shell elements can be connected.
- **Limitations**:
  - Knowledge of where to place the cohesive interface must be known in advance.
  - Especially for brittle material, fine mesh resolution is required to accurately capture the fracture process.
  - An artificial penalty stiffness is introduced in the interface, potentially making models overly compliant.
- **Cohesive tiebreak** contact share most of the properties with their elements counterparts but is not covered in this presentation.



Example of undeformed cohesive element. Even though the element occupies an initial volume, the is no initial separation between the lower and upper surface of the cohesive interface.

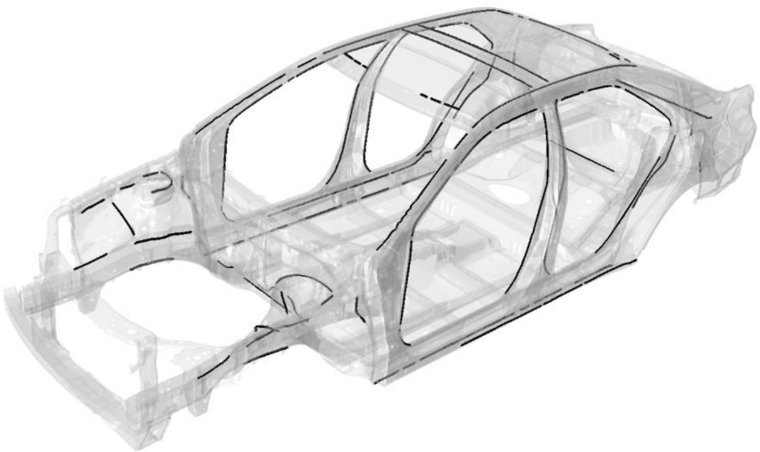
Cohesive Interface

- The *cohesive interface* consists of an upper and lower surface. Initially, these surfaces are coincidental with zero separation. Additionally, the *cohesive element* can have zero thickness and even invert without becoming unstable.
- Instead of strains, the deformation is in terms of the separation $\boldsymbol{\delta}$ (units of length) between the upper and lower surfaces.
- A cohesive constitutive law relates a traction vector $\boldsymbol{\tau}$ (units of stress) with the separation $\boldsymbol{\delta}$, e.g., using a bilinear law.
- The separation and traction vectors are usually formulated as one out-of-plane normal and two in-plane shear components. These are often referred to as mode I (normal) and mode II and III (shear), respectively.
- There are numerous cohesive constitutive models, with various degree of interaction between the components.



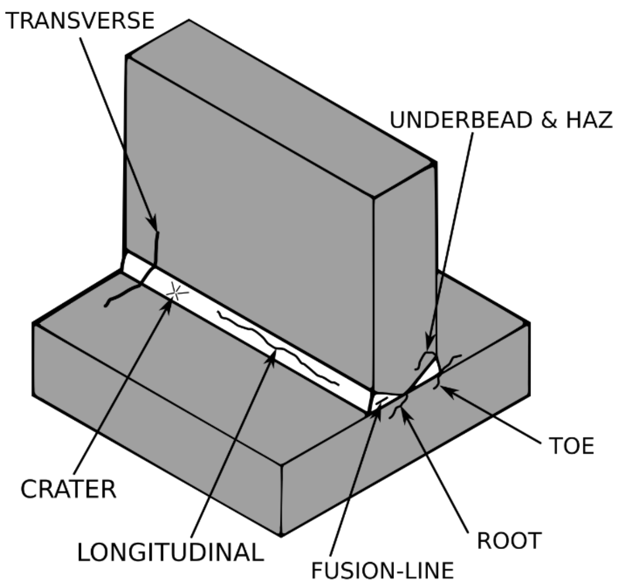
Bilinear traction-separation law. Elastic behavior with penalty stiffness K up to the maximum traction τ_0. Thereafter, the traction decrease linearly to the point of final separation failure δ_f. The integral of the law equals the fracture toughness G_c of the interface.

Applications



Example of structural adhesive bonds in automotive BiW.[1]

Delamination of carbon fiber-reinforced polymer under compression load.[2]



Examples of weld cracks.[3]

Any crack process where the failure path is known in advance.

[1] Public 2012 Toyota Camry FE model, https://www.ccsa.gmu.edu/models/2012-toyota-camry/
[2] Kolossos, CC BY-SA 3.0, https://commons.wikimedia.org/wiki/File:Delamination-CFRP.jpg
[3] Wizard191, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=8678506

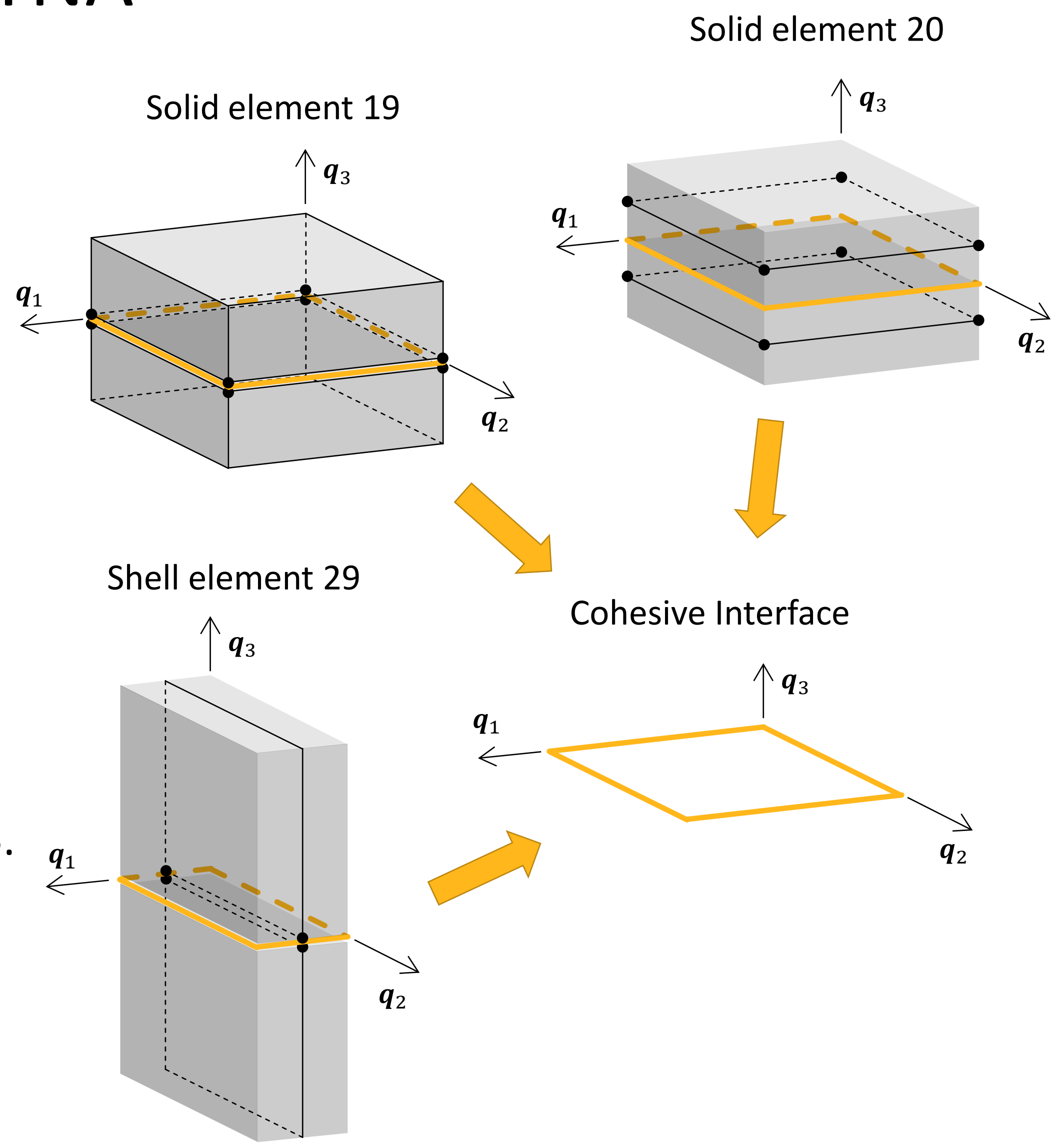
Overview of Cohesive Elements in LS-DYNA

Solid cohesive elements (*SECTION_SOLID)

- ELFORM 19/21: interface between solid hexa/penta faces.
- ELFORM 20/22: interface between shell quad/tria faces.
- ELFORM -19/-21: interface between solid and shell faces.

Shell cohesive elements (*SECTION_SHELL)

- ELFORM ±29: interface between shell edges
- ELFORM 46/47: interface between 2D axisymmetric elements 14/15.



Solid Cohesive Elements

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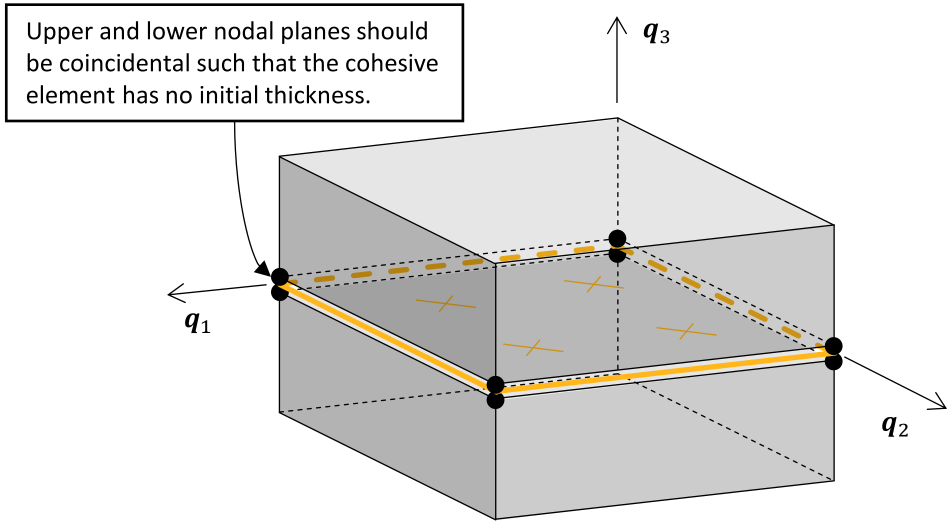
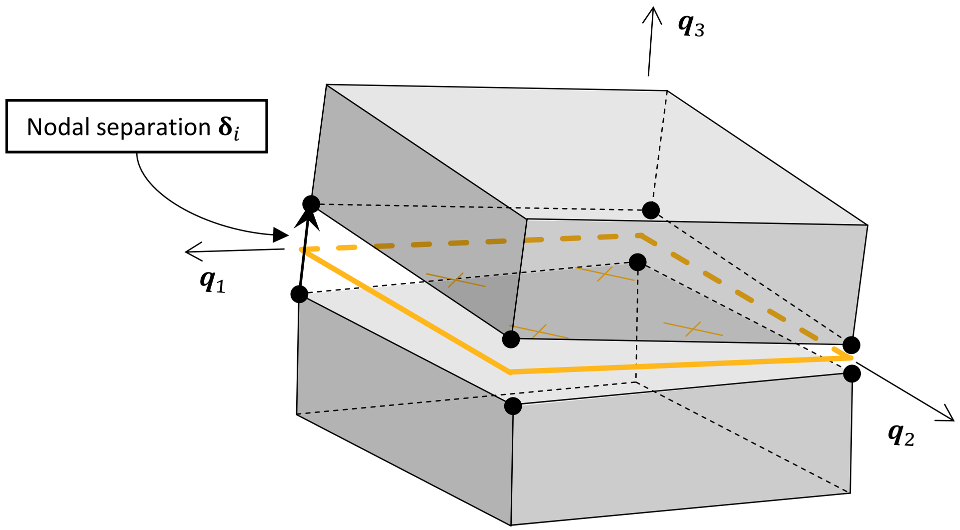
Solid element 19/21

- Used for connecting two solid faces, i.e., each node has three DOF
  - ELFORM 19: 8-noded for use with hexahedral element faces.
  - ELFORM 21: 6-noded for use with pentahedral element faces.
- Total formulation, where separation between layers is computed directly from the interpolation of nodal separations.
- 2-by-2 Gauss or Newton-Cotes integration scheme.
- The element is intended to have zero initial thickness. Otherwise, it will be non-objective. For implicit accuracy (IACC > 0), element can have finite initial thickness.

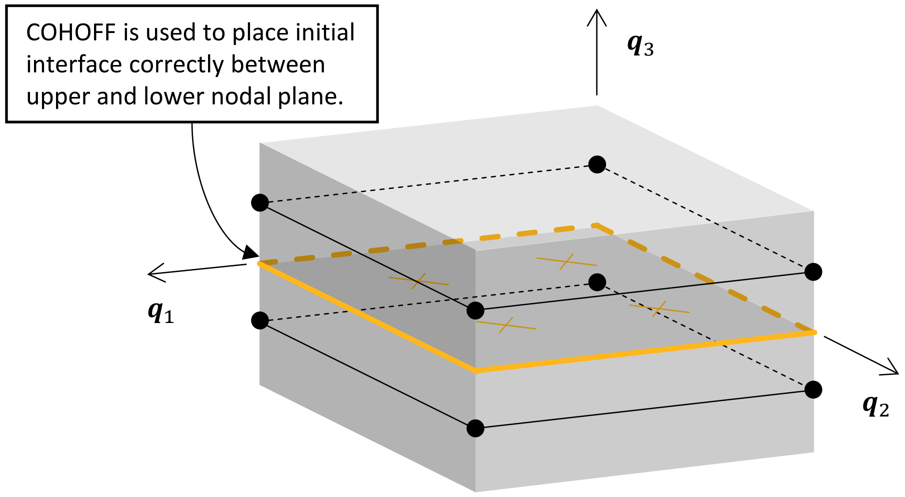


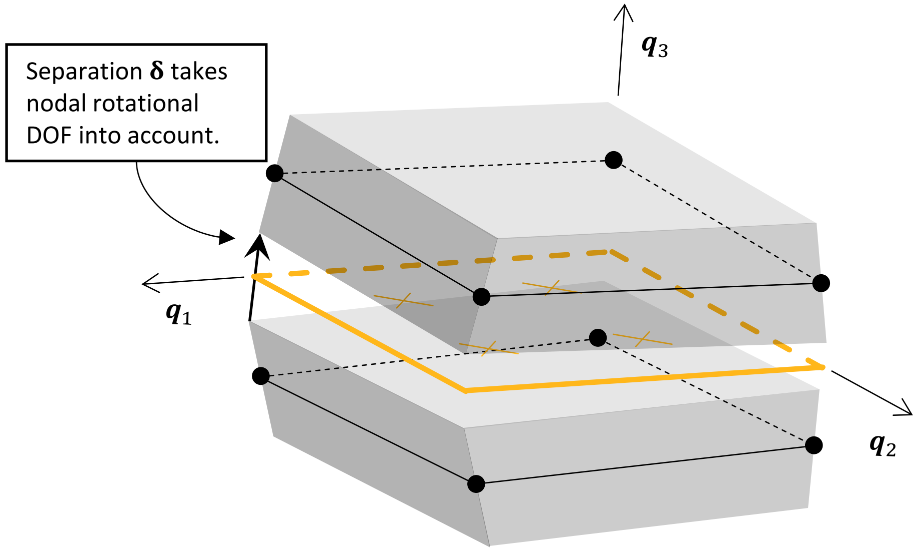


Ansys

Solid element 20/22

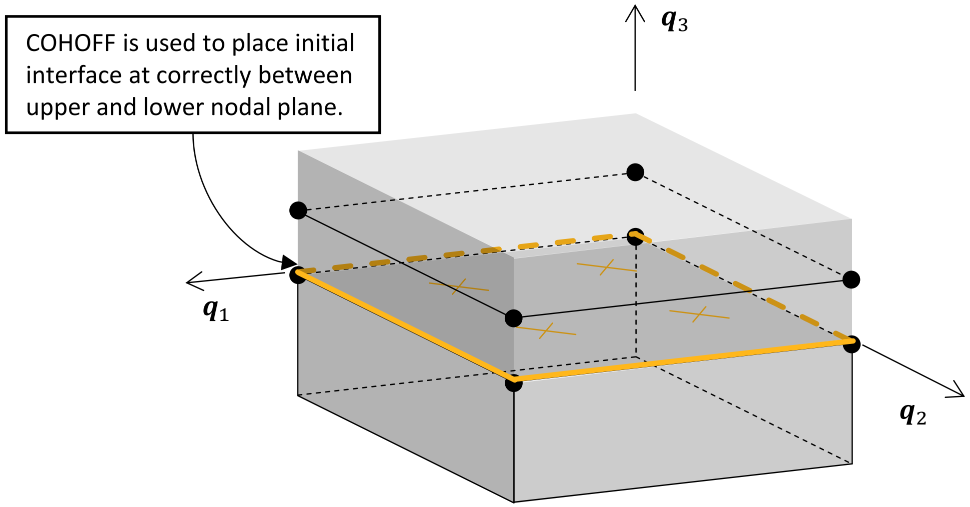
- Used for connecting two shell elements, i.e., each node has six DOF
  - ELFORM 20: 8-noded for use with quadrilateral elements.
  - ELFORM 22: 6-noded for use with triangular elements.
- The top and bottom cohesive surfaces are offset from the nodal planes.
  - By default, the cohesive interface is halfway in between upper and lower nodal planes.
  - For different shell thicknesses, parameter COHOFF is used to place interface correctly. Wrong placement can become non-objective.
- Incremental formulation (separation is computed by integrating the separation rate) due to rotational DOFs.
- 2-by-2 Gauss or Newton-Cotes integration scheme.
- Can be used to connect solid and shell elements. COHOFF then needs to be set such that the interface is placed on the solid surface.

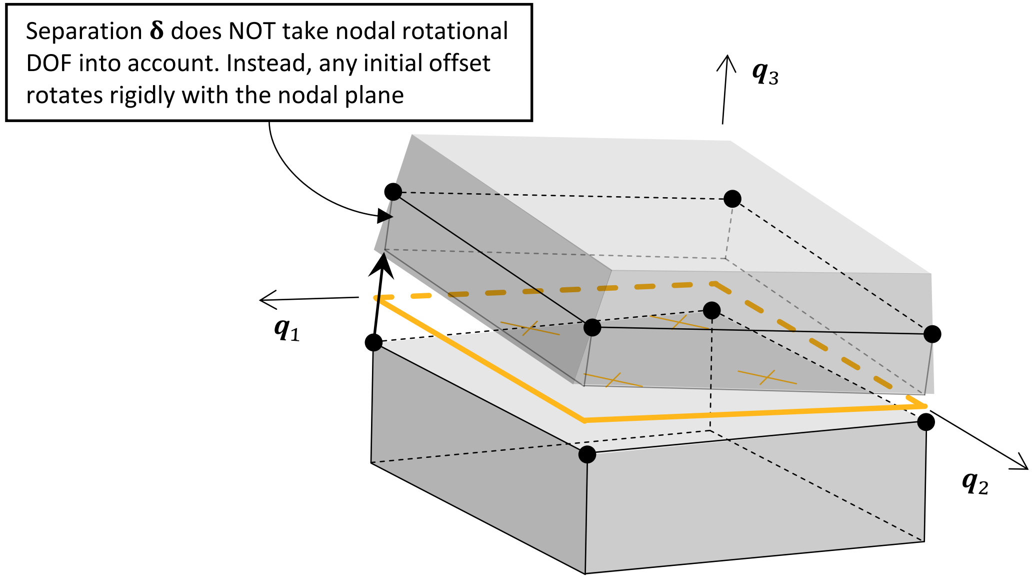




Solid element -19/-21

- Similar to ELFORM 19/21 but allows for offset between nodal planes and interface. Can be used for connecting any combination of solid and shell faces.
  - ELFORM -19: 8-noded for use with hexa/quad element faces.
  - ELFORM -21: 6-noded for use with penta/tria element faces.
- Parameter COHOFF is used to place interface correctly. Wrong placement can become non-objective.
- Total formulation, where separation between layers is computed directly from the interpolation of nodal separations.
  - Any non-zero offset between nodal planes and cohesive interfaces will rotate rigidly with the nodal planes.
  - Each node has three DOF, i.e. nodal rotational DOF are ignored.
- 2-by-2 Gauss or Newton-Cotes integration scheme.

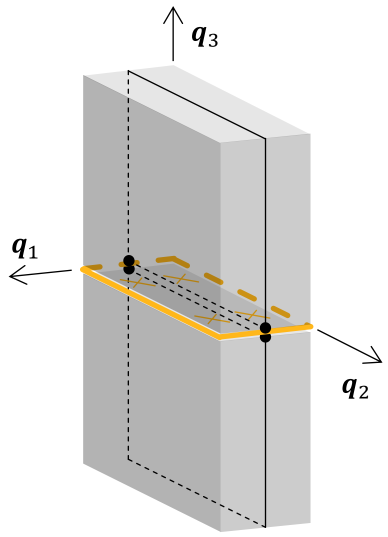


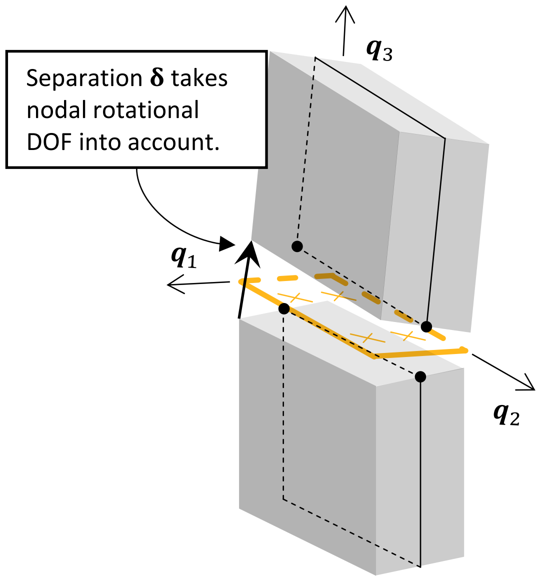


Shell Cohesive Elements

Shell element ± 29

- Used for connecting two shell edges, i.e., 4-noded with six DOF per node.
- ELFORM -29, the same but improved out-of-plane shearing behavior.
- Incremental formulation (separation is computed by integrating the separation rate) due to rotational DOFs.
- 2-by-2 Gauss integration scheme.
- Can have an initial width (cohesive thickness), but this can affect the time step negatively.





Overview Cohesive Materials

Standard Cohesive Materials in LS-DYNA

	Traction Separation	Mixed Mode	Strain rate
***MAT_184:** COHESIVE_ELASTIC	- Linear elastic behavior - Sudden failure (optional)		
***MAT_185:** MAT_COHESIVE_TH	- Trilinear elastic - Completely reversible (no damage)	- Dimensionless quadratic law	

***MAT_186:**
MAT_COHESIVE_GENERAL
	- Arbitrary curve input
	- Damage formulation
		- Three formulations:
		  - Quadratic damage initiation with power or Benzeggagh-Kenane damage evolution law.
		  - Dimensionless quadratic law with damage	

***MAT_138:**
MAT_COHESIVE_MIXED_MODE
	- Bilinear curve (linear softening)
	- Damage formulation
	- Scaling of peak traction w.r.t. element size
		- Quadratic damage initiation
		- Two damage evolution laws:
		  - Power law
		  - Benzeggagh-Kenane law	

***MAT_240:** MAT_COHESIVE_MIXED_MODE_ ELASTOPLASTIC_RATE	- Trilinear curve - Damage formulation - Ideal plasticity (quadratic yield)	- Quadratic damage initiation - Power law for damage evolution	- Linear logarithmic - Quadratic logarithmic

Additional Cohesive Materials in LS-DYNA

***MAT_326:** MAT_COHESIVE_GASKET	- Specially developed for analysis of gaskets. - Modes uncoupled. - No failure.
***MAT_ADD_COHESIVE**	- Allows for using many standard 3D materials with cohesive elements. - To translate the six strains of the 3D material to three cohesive separations it is assumed that no lateral expansion or in-plane shearing is possible ($\dot{\varepsilon}_{xx} = \dot{\varepsilon}_{yy} = \dot{\varepsilon}_{xy} = 0$).

For more details on cohesive materials, please refer to the course on continuous fibre reinforced composites

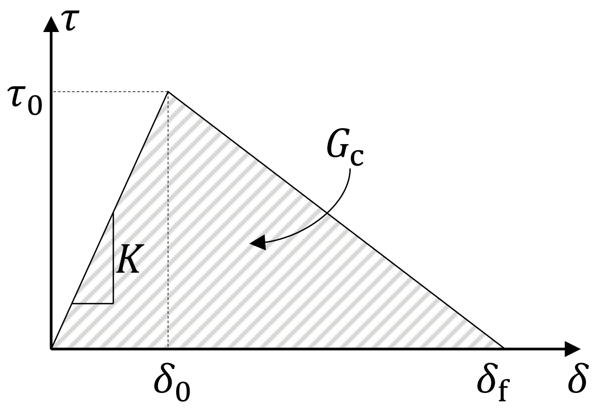
General Remarks

Penalty Stiffness

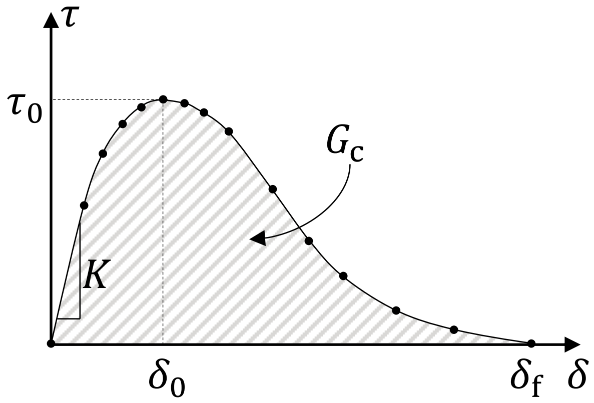
- All LS-DYNA cohesive elements will have an artificial (initial) penalty stiffness (units of stress / length). When modelling adhesives, this can be interpreted as the elastic stiffness.
- In the non-adhesive case, the penalty stiffness will introduce artificial compliance to the structure. Therefore, the stiffness should be set as high as possible (theoretically infinite). However, high penalty stiffness can, in explicit, lead to small critical time steps and, in implicit, poorly conditioned stiffness matrix.
- To minimize compliance, Turon *et al* (2007)[1] proposed a penalty stiffness of

$$K \gg \frac{E_3}{t}$$

  where t and E_3 are the thickness and out-of-plane stiffness of the connected elements above or below. For CFRP the stiffness is typical in the range of $10^6 - 10^7$ MPa/mm.
- When modelling adhesives, the penalty stiffness is $K = \frac{E_a}{t_a}$, where t_a and E_a are the thickness and elastic stiffness of the adhesive.



Bilinear traction-separation law. Elastic behavior with penalty stiffness K up to the maximum traction τ_0. Thereafter, the traction decrease linearly to the point of final separation failure δ_f. The integral of the law equals the fracture toughness G_c of the interface.



General traction-separation law. The penalty stiffness K is the initial slope of the curve. The integral of the law equals the fracture toughness G_c of the interface.

[1] Turon, A, Dávila, CG, Camanho, PP, & Costa, J (2007). An engineering solution for mesh size effects in the simulation of delamination using cohesive zone models. *Eng. Fract. Mech.*, *74*(10). https://doi.org/10.1016/j.engfracmech.2006.08.025

Time Step

- The cohesive element is simplified to a mass-spring system. The highest eigenfrequency for such a system is

$$\omega_{\max} = \sqrt{\frac{2k}{m}} \ ,$$

where the equivalent mass

$$m = \frac{2 m_{\mathrm{b}} m_{\mathrm{t}}}{m_{\mathrm{b}} + m_{\mathrm{t}}}$$

is the harmonic mean of the top and bottom mass and k is the equivalent spring stiffness (units of force / length). The time step is thus limited to

$$\Delta t_{\mathrm{e}} \leq \frac{2}{\omega_{\max}} = \sqrt{\frac{2m}{k}} \ .$$

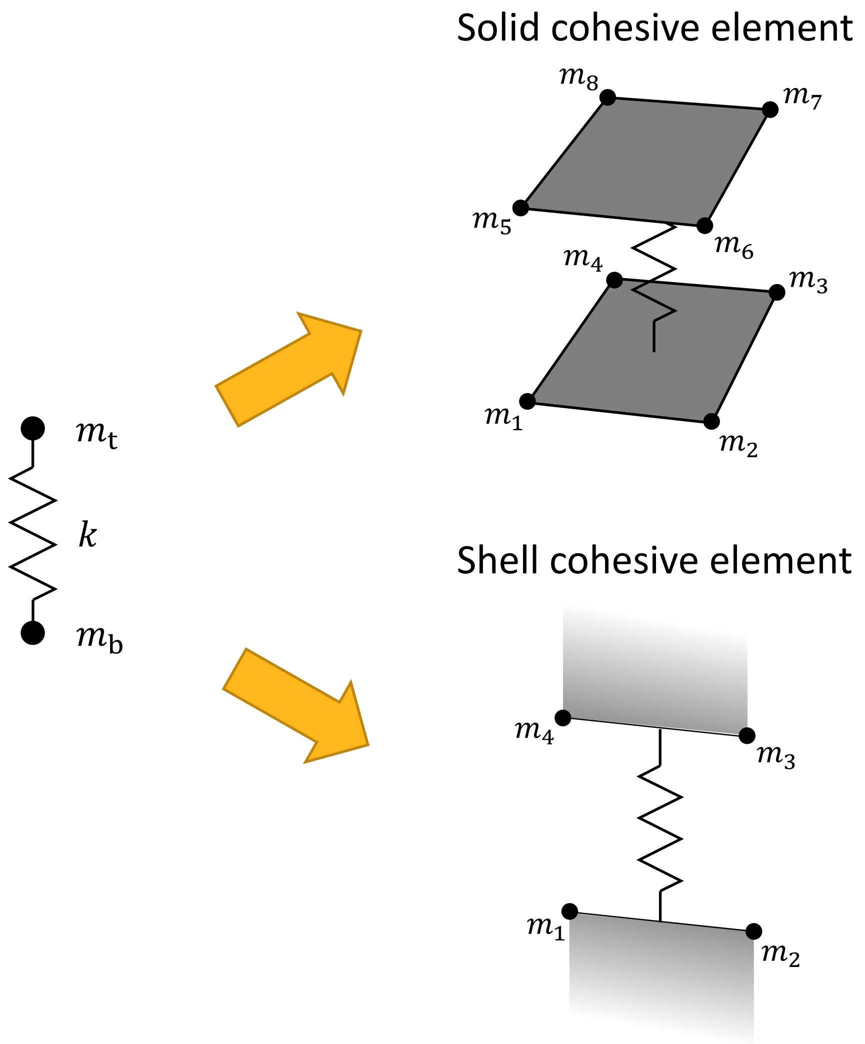
- The equivalent stiffness k is the area integral of the penalty stiffness

$$k = \sum_{i=1}^{N_{\mathrm{IP}}} K w_i J_i = K A_{\mathrm{e}} \ ,$$

where the last step is due to constant stiffness and Jacobian determinant of the element (K is the max of the normal and shear penalty stiffness).

- The equivalent mass m is computed differently for solid and shell elements.

- **Note**: The cohesive time step is not dependent on the element size. Higher resolution will only decrease the time step of connected elements.



Solid Cohesive Time step

- The time step is

$$\Delta t_\mathrm{e} \leq \frac{2}{\omega_\mathrm{max}} = \sqrt{\frac{2m}{k}}$$

with

$$k = KA_\mathrm{e}$$

and the mass m according to the L value of the parameter ICOH on*CONTROL_SOLID.

ICOH	Flag for cohesive elements to control deletion, the time step estimate, and the element type used in implicit and explicit. Breaking LS-DYNA convention, ICOH is interpreted digit-wise, namely as, $\mathrm{ICOH} = [MLK] = K + 10 \times L + 100 \times M$.

- Note that for all cases but $L = 1$, the cohesive element does not need to have any density. That is, the time step is computed from the assembled nodal masses.
- Setting $L = 3$ will result in the theoretical time step for two surfaces connected by cohesive interfaces. Therefore, we recommend using this.
- In some cases, interactions between the cohesive and surrounding elements can decrease the stable time step. If instabilities occur, reducing TSSFAC or the cohesive penalty stiffness (or increasing cohesive mass) might be necessary.

$L = 0$

The cohesive element is treated as a series of mass-spring elements stacked on top of each other. Each top and bottom nodal mass are then shared between two elements, resulting in

$$m_\mathrm{t} = \frac{1}{2} M_\mathrm{t} \ ,$$
$$m_\mathrm{b} = \frac{1}{2} M_\mathrm{b} \ ,$$

where M_t and M_b are the sums of the top and bottom nodal masses. That is,

$$M_\mathrm{t} = m_5 + m_6 + m_7 + m_8 \ ,$$
$$M_\mathrm{b} = m_1 + m_2 + m_3 + m_4 \ .$$

The resulting time step is

$$\Delta t_\mathrm{e} = \sqrt{\frac{2M_\mathrm{t}M_\mathrm{b}}{k(M_\mathrm{t} + M_\mathrm{b})}} \ .$$

$L = 1$

The mass contribution is from the cohesive element only. See manual for details.

$L = 2$

A regular mesh is assumed such that each corner node is shared between four neighboring elements. Thus, we have

$$m_\mathrm{t} = \frac{1}{4} M_\mathrm{t} \ ,$$
$$m_\mathrm{b} = \frac{1}{4} M_\mathrm{b} \ .$$

Resulting in a time step estimation of

$$\Delta t_\mathrm{e} = \sqrt{\frac{M_\mathrm{b}M_\mathrm{t}}{k(M_\mathrm{b} + M_\mathrm{t})}} \ ,$$

which is a factor or $\sqrt{2}$ smaller than the default $L = 0$.

$L = 3$

The element connectivity is used to compute how much (nodal) mass is associated to each cohesive element. That is, no assumption regarding connectivity is made

Shell Cohesive Time Step

- For shell cohesive elements (ELFORM ±29), currently no setting can be made on the ICOH parameter.

- Instead, the top and bottom masses are always assumed to be shared with four elements

$$m_\mathrm{b} = \frac{1}{4}(m_1 + m_2) = \frac{1}{4}M_\mathrm{b}$$
$$m_\mathrm{t} = \frac{1}{4}(m_3 + m_4) = \frac{1}{4}M_\mathrm{t}$$

  giving

$$m = \frac{2m_\mathrm{b}m_\mathrm{t}}{m_\mathrm{b} + m_\mathrm{t}} = \frac{1}{2}\frac{M_\mathrm{b}M_\mathrm{t}}{(M_\mathrm{b} + M_\mathrm{t})}$$

- The time step is limited to

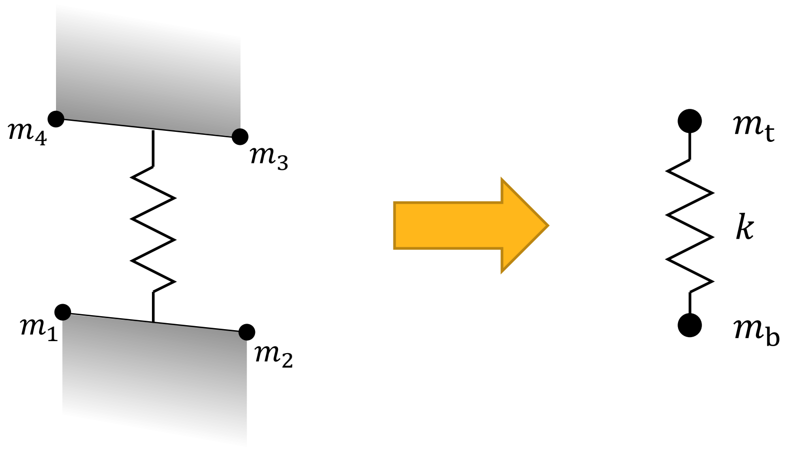
$$\Delta t_\mathrm{e} \leq \frac{2}{\omega_{\max}} = 2\sqrt{\frac{m}{2k}} = \sqrt{\frac{2m}{k}} \;,$$

  with the equivalent stiffness

$$k = KA_\mathrm{e} = KtL \;,$$

  where t is the cohesive shell thickness and L is the length along the cohesive edge.

- As for solid cohesive elements, interactions between the cohesive and surrounding elements can decrease the stable time step. This is especially the case if the cohesive element width is non-zero.



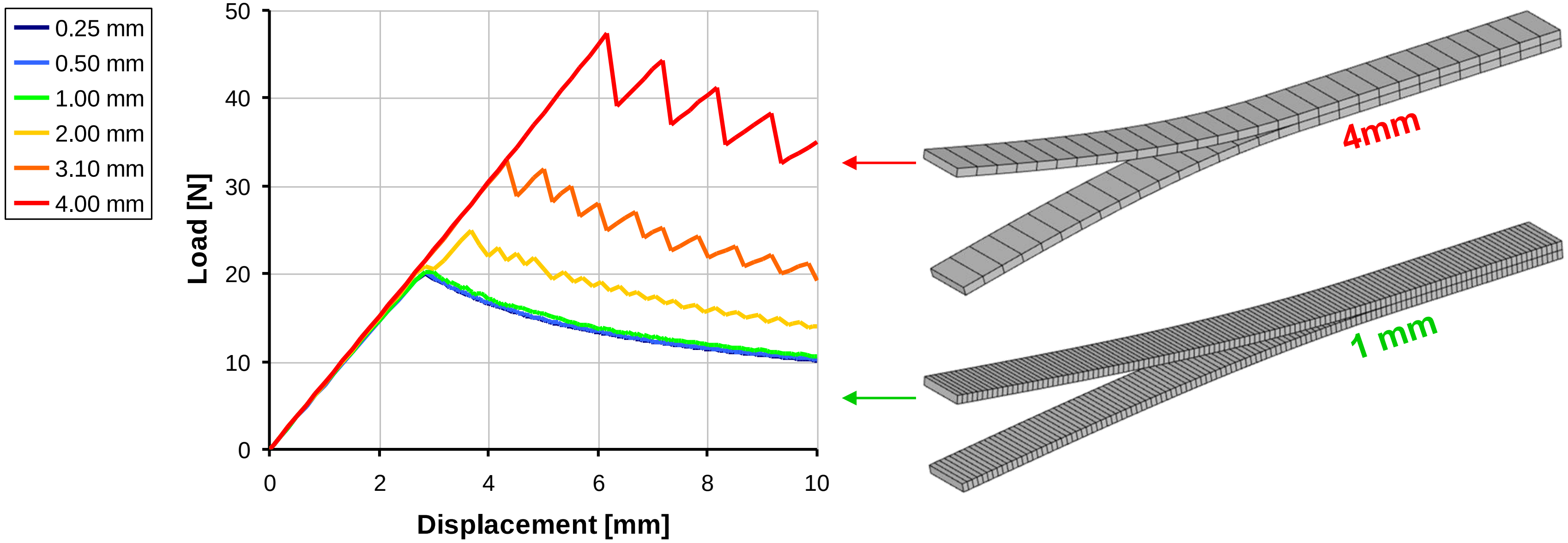
Miscellaneous settings

Parameter	Location	Purpose
INTFAIL	Cohesive material card	Determines integration scheme (Gauss or Newton-Cotes) and number of failed integration points required for element deletion.
COHOFF	*SECTION_SOLID	Used to place the cohesive interface at the correct position between the lower and upper connected elements. By default, the interface is placed at the mid level between the elements. When connecting elements of different thickness (e.g. shell to solid), this parameter needs to be adjusted accordingly.
ICOH	*CONTROL_SOLID	Besides controlling mass for time step estimation, this parameter controls element deletion and allows to enable implicit element formulations also in explicit.
COHEQC	*CONTROL_SOLID	Flag for cohesive element quality checks.
DIR_TIE	*CONTROL_CONTACT	When connecting cohesive elements using (constrained) tied contacts. If set to 1, a SURFA node will not necessarily tie to the closest SURFB segment, but to the “correct” segment. This avoids nonphysical tie situations or even zero solid element volumes as a result. Currently, only for non-groupable MPP contacts.
COHTIEM	*CONTROL_CONTACT	When connecting cohesive elements using (constrained) tied contacts, this controls how the mass from SURFB affects the time step estimation of the cohesive elements. If non-zero, LS-DYNA includes the mass from SURFB when estimating the time step. Currently, only for non-groupable MPP contacts.

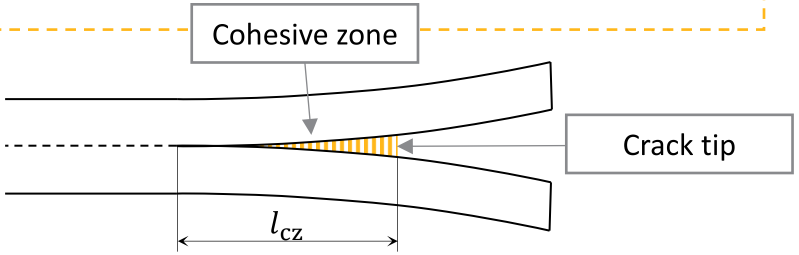
Examples

Mesh Dependance

- **Problem**:
  Forces can be overestimated using coarse meshes



- **Reason**:
  The cohesive fracture zone cannot be described accurately enough by a coarse spatial discretization



Mesh Dependance

Solution: Increase numerical cohesive zone size by scaling strength τ_0, while maintaining the fracture toughness G_c.

- Use analytical formula for length of cohesive zone from Turon *et al* (2007):

$$l_{cz} = \frac{MEG_c}{(\tau_0)^2},$$

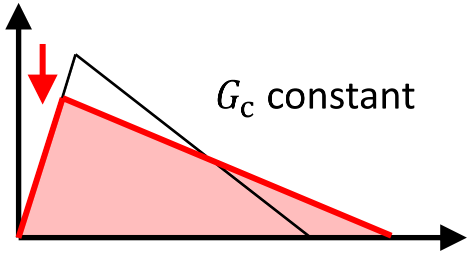
  where E are the Young's modulus of the material. M is a parameter depending on the type of cohesive model.

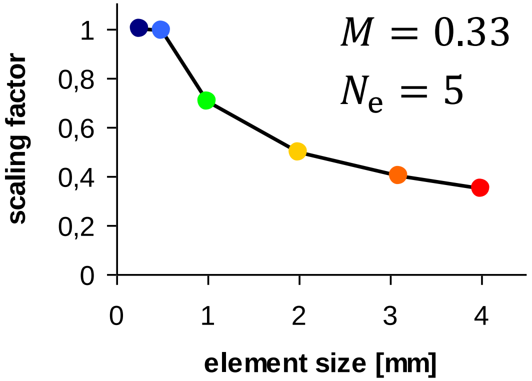
- Define number N_e of elements in cohesive zone (at least three recommended).

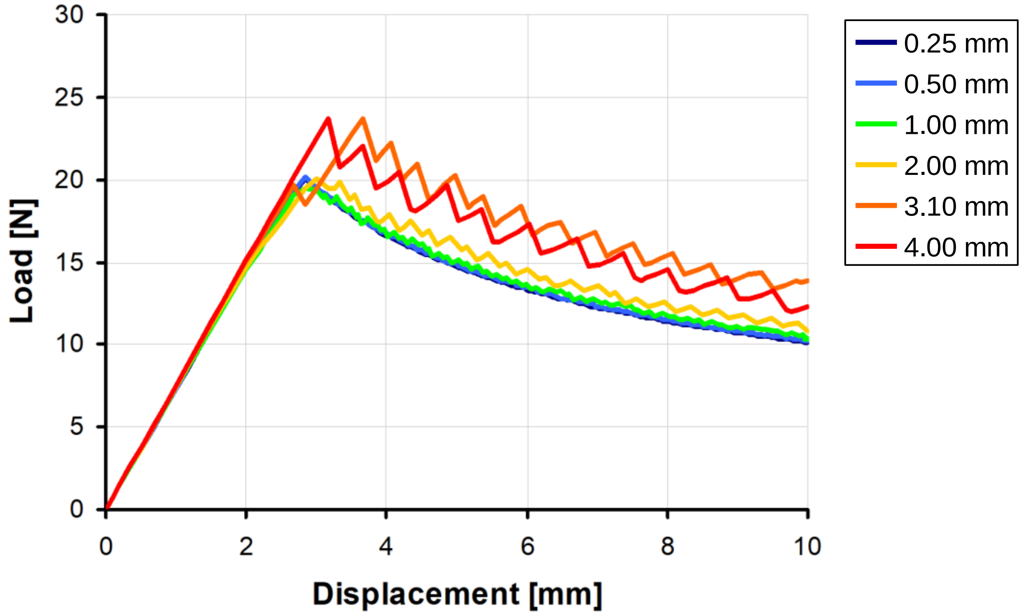
- Formulate strength as function of element size l_e

$$\tau_0(l_e) = \sqrt{M\frac{EG_c}{N_e l_e}}$$

- Note: While long term propagation is rather well predicted, peak load is not.

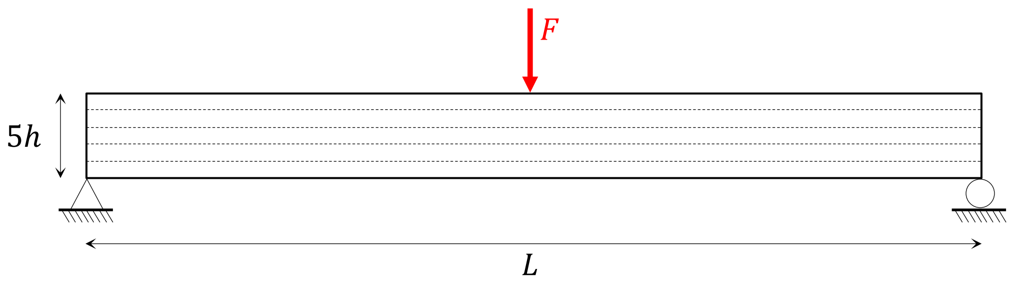


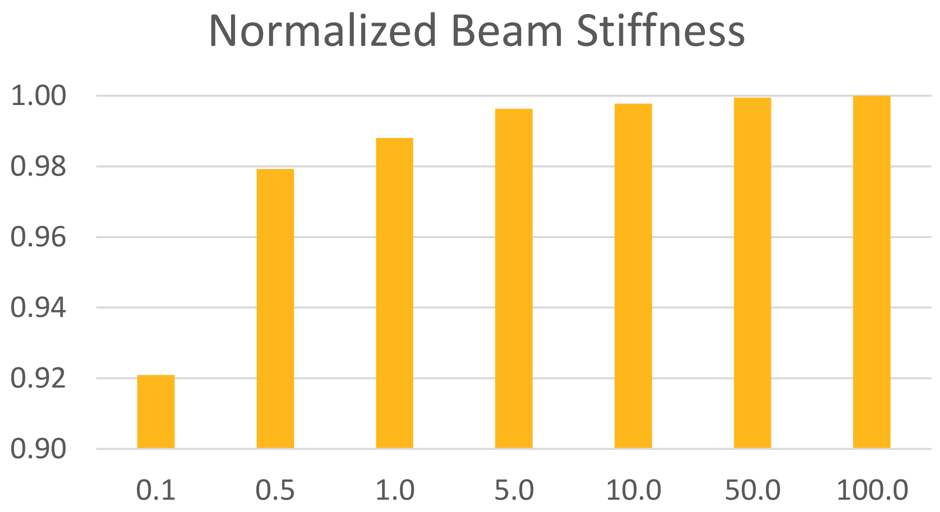


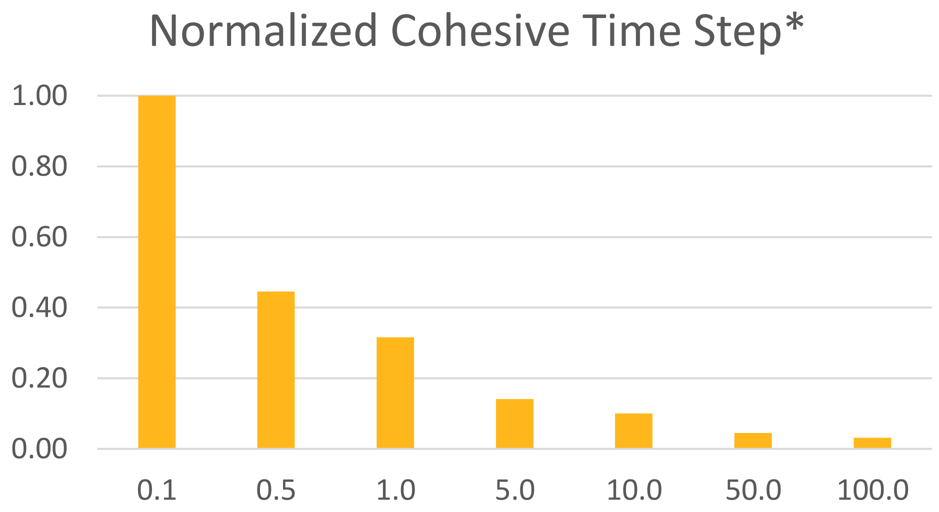


Penalty Stiffness

- Three-point bending of five shell plies (ELFORM 16) connected by cohesive elements (ELFORM 20).
- Cohesive stiffness varied from 0.1 to 100 times $\frac{E}{h}$.
- Cohesive stiffness needs to be high enough to not result in overly compliant response, while also avoiding too small critical time step.







*This does not include the shell element time step, which might be the limiting critical time step.

Summary

Summary

- Cohesive elements are used to connect adjacent solid or shell elements by placing a cohesive interface in between.
- The *cohesive interface* consists of a top and bottom surface. Initially, these surfaces are coincidental with zero separation.
- The *cohesive element* can have zero thickness and even invert without becoming unstable.
- When choosing which cohesive element formulation to use, consideration if to include the rotational DOF of connected shell elements needs to be made.
- The cohesive elements does not need to have any density; the explicit time step is computed based on the mass of connected elements and does not depend on the element size.
- The cohesive element size needs to be small enough to resolve the cohesive fracture zone of the interface. The size of this zone is dependent on the interface strength and fracture toughness.

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