Drilling Rotation Constraint for Shell Elements in Implicit and Explicit Analyses

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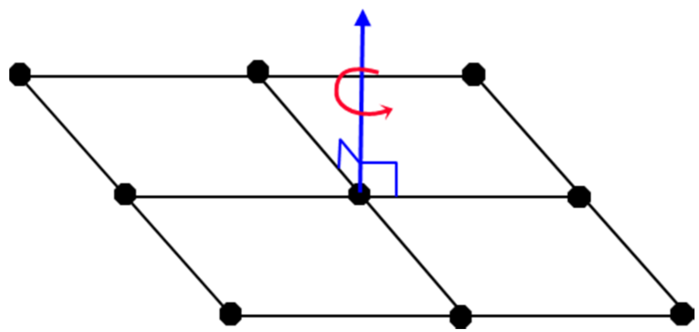
DYNAMORE

Motivation

- Standard (LS-DYNA) shell elements, e.g. the under integrated Belytschko-Lin-Tsay shell (element type 2) or the fully integrated shell with assumed strain interpolation (element type 16), do not possess stiffness in the **normal rotational (drilling) degree of freedom**.



- In **implicit analyses**, this missing stiffness would lead to a singular system matrix. Therefore, a small amount of torsional stiffness aka drilling rotation constraint is added. What should be the amount of this stiffness?

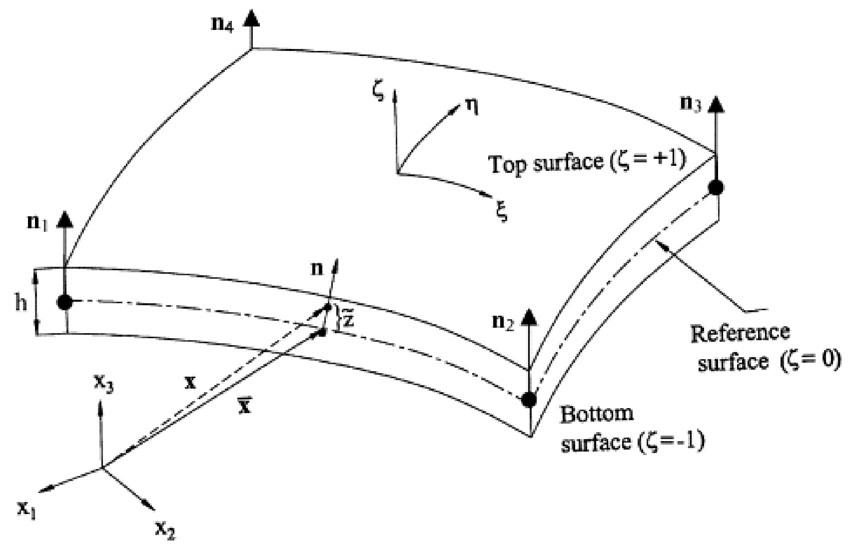
- The same approach is now available for **explicit analyses** since version R7. In which situations could this be helpful?

Overview

- Theoretical background of drilling rotation constraint method
- Associated LS-DYNA keyword input parameters
- Example 1: Flat vs. curved geometry
- Example 2: Pre-twisted cantilever
- Example 3: Simplified crashrail
- Example 4: Metal forming
- Example 5: Spot weld connections
- Example 6: Screw
- Summary

Drilling rotation degree of freedom

- Shell elements are defined by their thickness and a reference surface



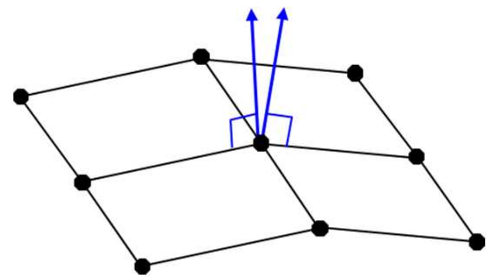
- Load is carried by membrane/bending action

- 6 degrees of freedom at each node: 3 translational and 3 rotational

- Two rotations about in-plane axes describe bending and twisting

- Third rotational d.o.f. allows easy connection to other shells or beams, but it is not needed for shell kinematics itself; no stiffness is associated

- This drilling d.o.f. is resisted in curved shell topologies by bending stiffness of adjacent elements



- Flat shell topologies allow **unconstrained drill rotation**.

Constraint methods

AUTOSPC: automatic single point constraint method

- Global stiffness matrix examined for unattached degrees of freedom
- Generate additional constraints as necessary to avoid negative eigenvalues
- Tolerance value AUTOTOL: smallest singular value / largest singular value

Local constraint method

- Kinematic constraint (local SPC) added on element level
- SPC added or deleted depending on local curvature criterion

DRCM: drilling rotation constraint method

- Rotational stiffness in form of a fictitious torsional spring
- Same amount regardless of shell topology (curved or flat)

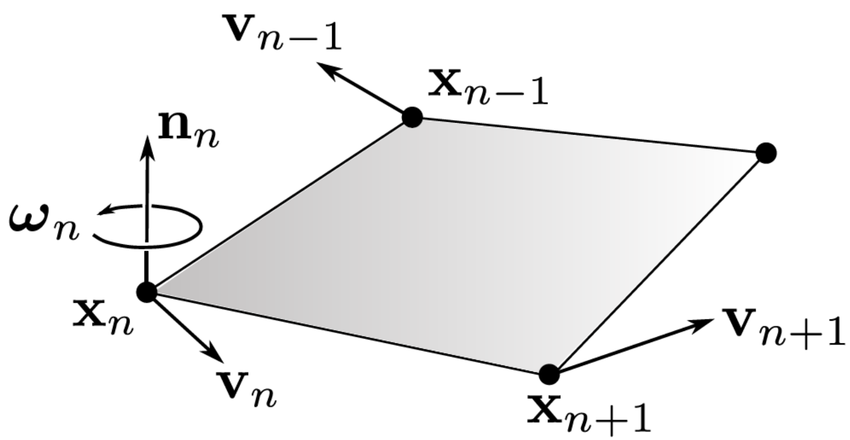
Drilling rotation constraint method

- Kinematics on element level:

  - nodal coordinates

  - nodal velocities

  - rotational velocity



- Generalized drilling strain rate for node n can be defined as:

$$\dot{\varepsilon}_n^{\text{drill}} = \boldsymbol{\omega}_n \cdot \mathbf{n}_n - \frac{(\mathbf{v}_{n+1} - \mathbf{v}_n) \cdot \mathbf{n}_n \times (\mathbf{x}_{n+1} - \mathbf{x}_n)}{2\|\mathbf{x}_{n+1} - \mathbf{x}_n\|^2} - \frac{(\mathbf{v}_{n-1} - \mathbf{v}_n) \cdot \mathbf{n}_n \times (\mathbf{x}_{n-1} - \mathbf{x}_n)}{2\|\mathbf{x}_{n-1} - \mathbf{x}_n\|^2}$$

- Associating a rotational stiffness leads to generalized stress rate:

$$\dot{\sigma}_n^{\text{drill}} = 0.0005\ k\ E\ \ \dot{\varepsilon}_n^{\text{drill}}$$

where k = user defined scaling parameter DRCPRM (1.0 by default)
and E = Young's modulus of shell element

Drilling rotation constraint method

- Internal drilling forces from principle of virtual work:

$$\mathbf{f}_n = V\sigma_n^{\text{drill}}\,\mathbf{B}_n^T$$

needed in explicit and implicit calculations

- With element volume V and corresponding B-operator

$$\mathbf{B}_n^T = \begin{bmatrix} \mathbf{n}_n \\ \dfrac{\mathbf{n}_n \times (\mathbf{x}_{n+1} - \mathbf{x}_n)}{2\|\mathbf{x}_{n+1} - \mathbf{x}_n\|^2} + \dfrac{\mathbf{n}_n \times (\mathbf{x}_{n-1} - \mathbf{x}_n)}{2\|\mathbf{x}_{n-1} - \mathbf{x}_n\|^2} \\ -\dfrac{\mathbf{n}_n \times (\mathbf{x}_{n+1} - \mathbf{x}_n)}{2\|\mathbf{x}_{n+1} - \mathbf{x}_n\|^2} \\ -\dfrac{\mathbf{n}_n \times (\mathbf{x}_{n-1} - \mathbf{x}_n)}{2\|\mathbf{x}_{n-1} - \mathbf{x}_n\|^2} \end{bmatrix}$$

- Finally, the stiffness matrix is given by

$$\mathbf{K}_n = 0.0005\; k\; E\; V\; \mathbf{B}_n^T\, \mathbf{B}_n$$

needed in implicit calculations

LS-DYNA keyword input

- **IMPLICIT** - DRCM is **default behavior** for the whole model

***CONTROL_IMPLICIT_SOLVER**

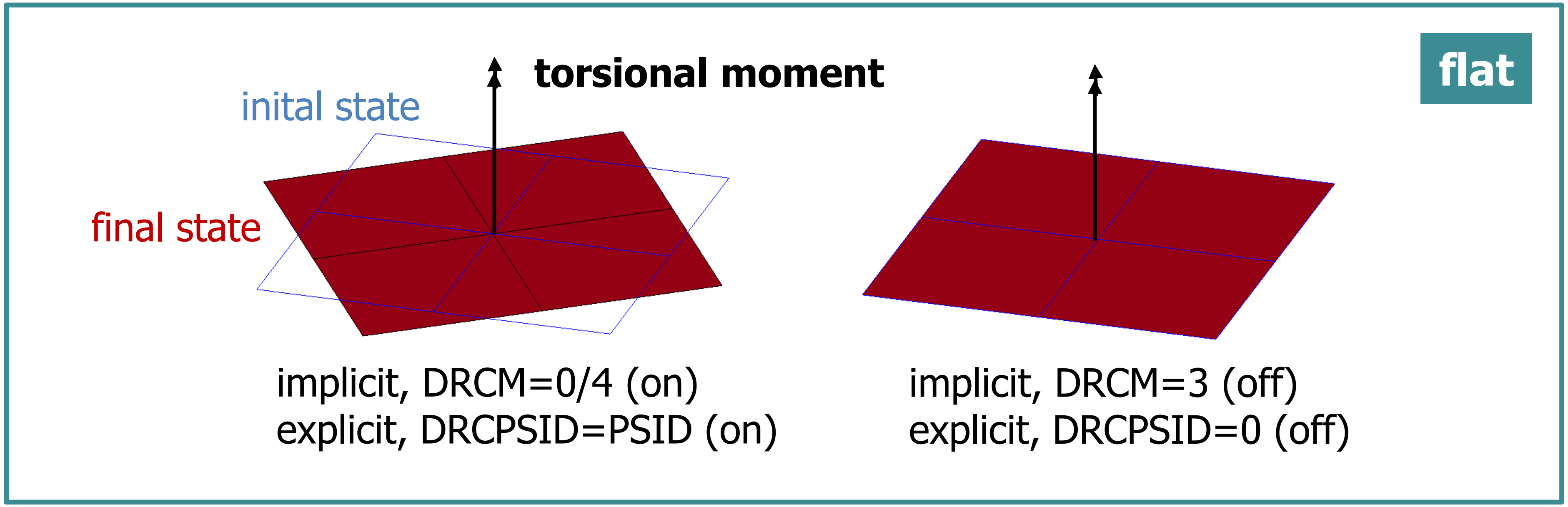
Card 1	1	2	3	4	5	6	7	8
Variable	LSOLVR	LPRINT	NEGEV	ORDER	**DRCM**	**DRCPRM**	AUTOSPC	AUTOTOL
Type	I	I	I	I	**I**	**F**	I	F
Default	4	0	2	0	**4**	**depends…**	1	see below

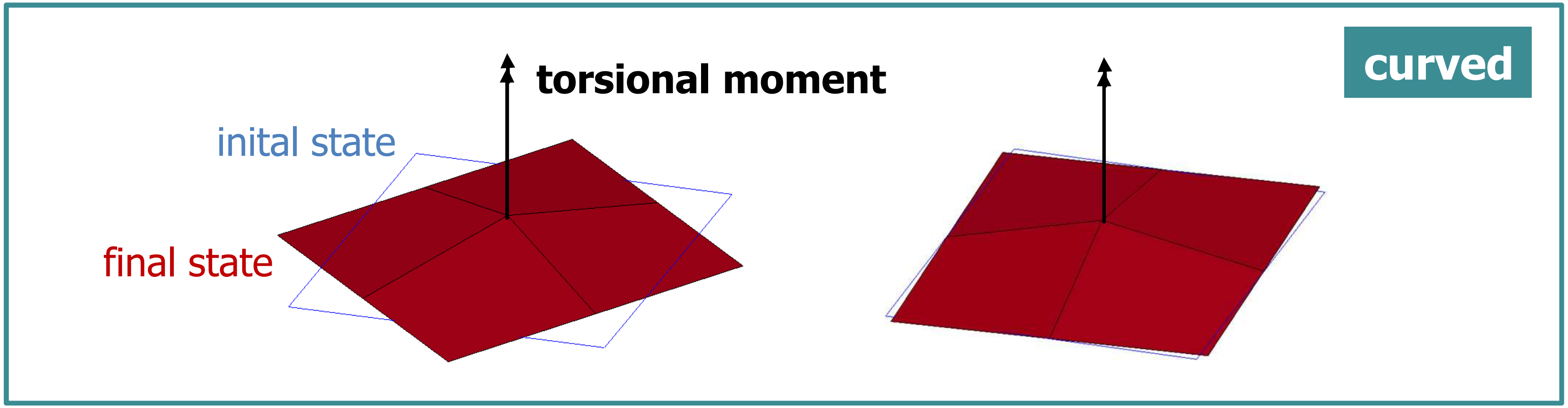
- **EXPLICIT** – DRCM is **optional** for defined part set since R7.0.0

***CONTROL_SHELL**

Card 4	1	2	3	4	5	6	7	8
Variable	NFAIL1	NFAIL4	PSNFAIL	KEEPCS	DELFR	**DRCPSID**	**DRCPRM**	
Type	I	I	I	I	I	**I**	**F**	
Default	inactive	inactive	0	0	0	**0**	**1.0**	

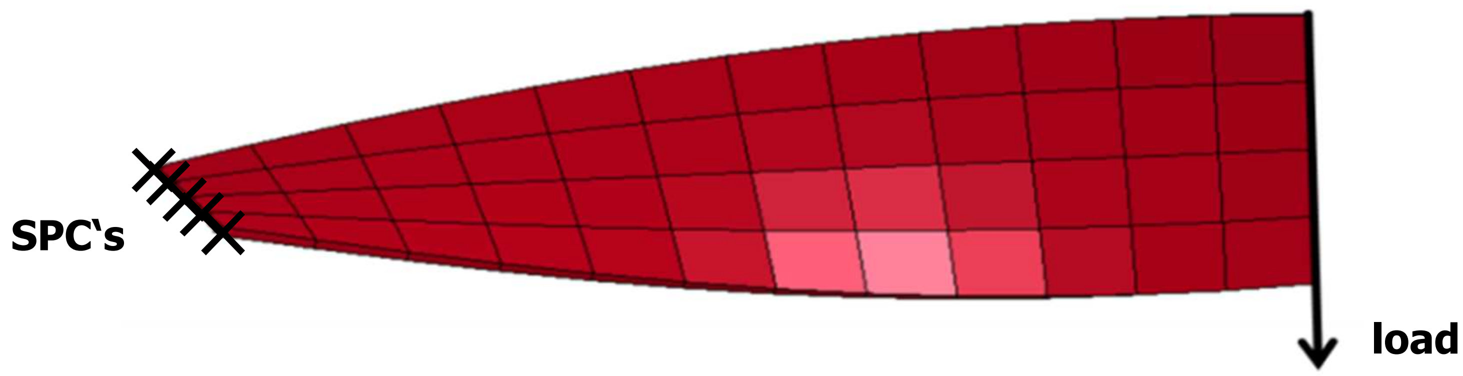
Example 1: Flat vs. curved geometry





Example 2: Pre-twisted cantilever

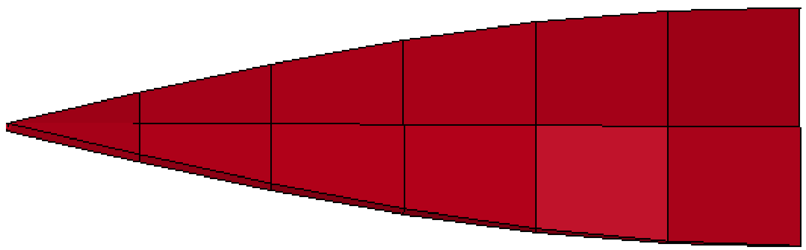
- Common test problem for shell elements
- Features a large initial twist such that its opposite edges are at a 90° angle with respect to each other



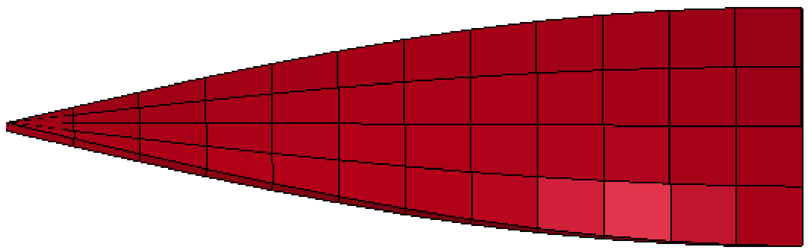
- Warping results in bending-membrane coupling
- The pre-twisted beam is commonly used to evaluate the ability of quadrilateral elements to handle double curvature geometries

Example 2: Pre-twisted cantilever

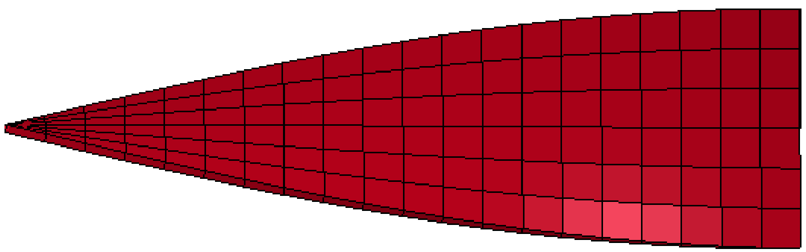
- **Convergence study** with 6 different discretizations



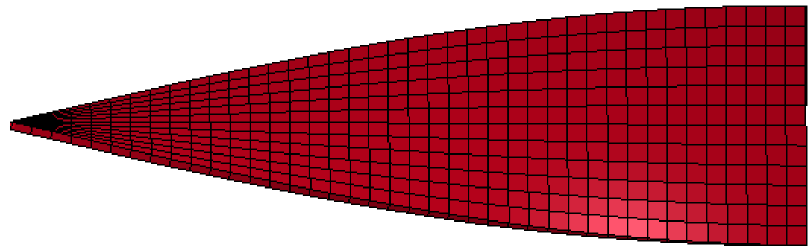
12 elements, warpage angle = 20°



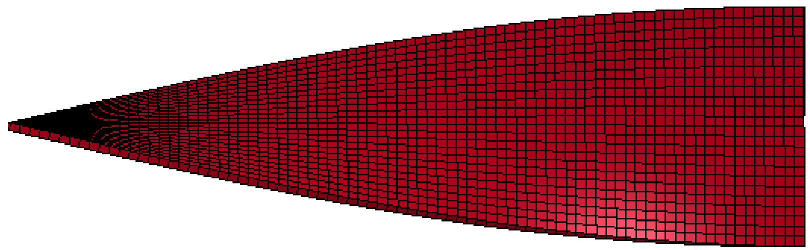
48 elements, warpage angle = 10°



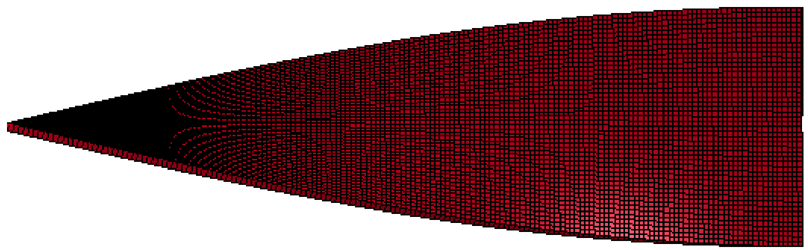
120 elements, warpage angle = 6°



480 elements, warpage angle = 3°



1920 elements, warpage angle = 1.5°

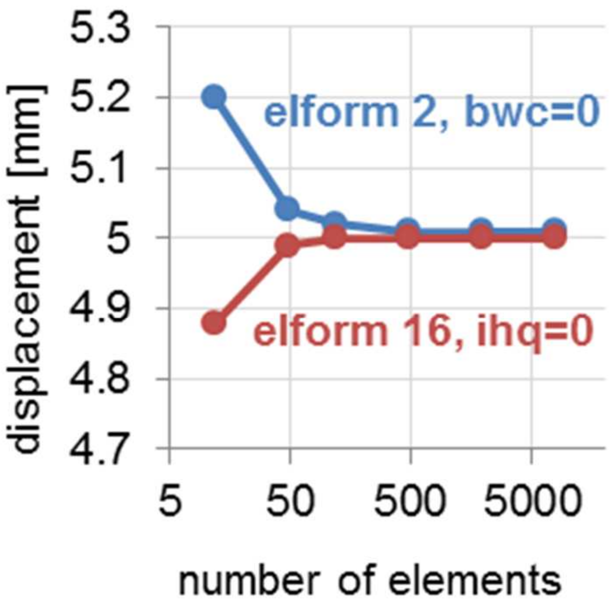


7680 elements, warpage angle = 0.8°

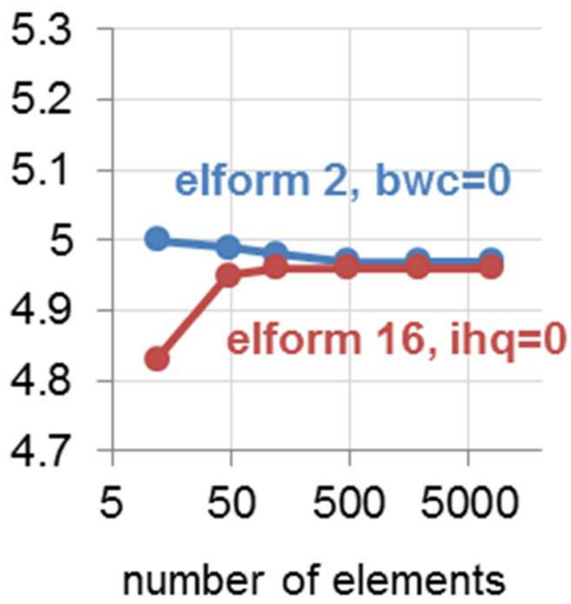
Example 2: Pre-twisted cantilever

- Results with different scaling parameters (DRCPRM)
- Belytschko-Tsay shells (#2) with default warping stiffness (BWC=0)
- Fully integrated shells (#16) with default warping stiffness (IHQ=0)

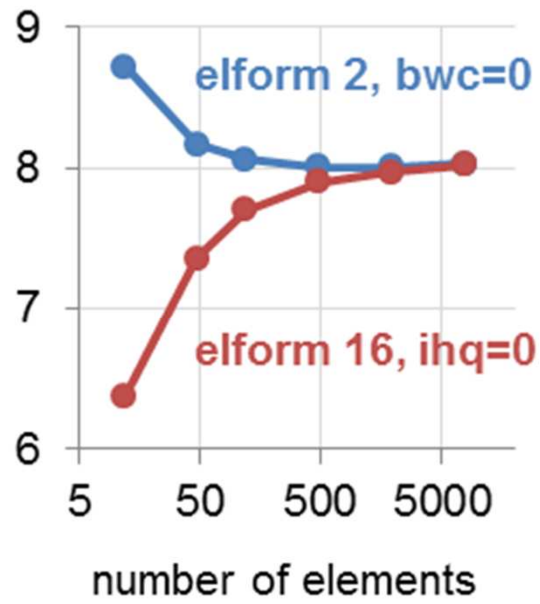
DRCPRM = 1.0 (default)



DRCPRM = 100.0



DRCPRM = 0.01

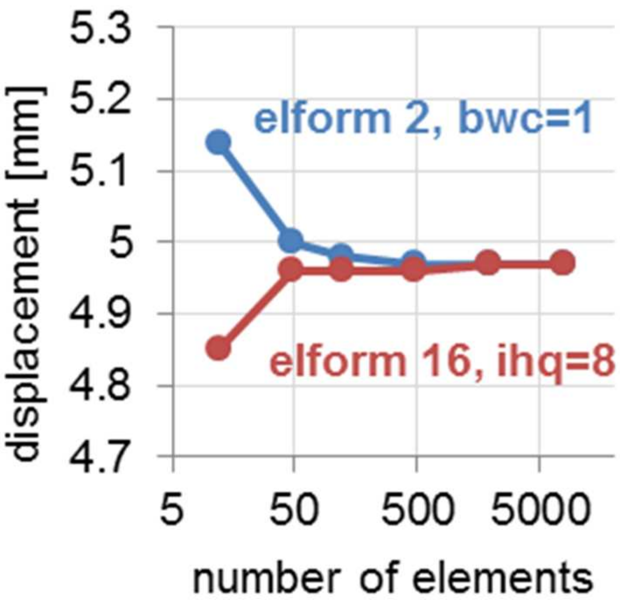


Example 2: Pre-twisted cantilever

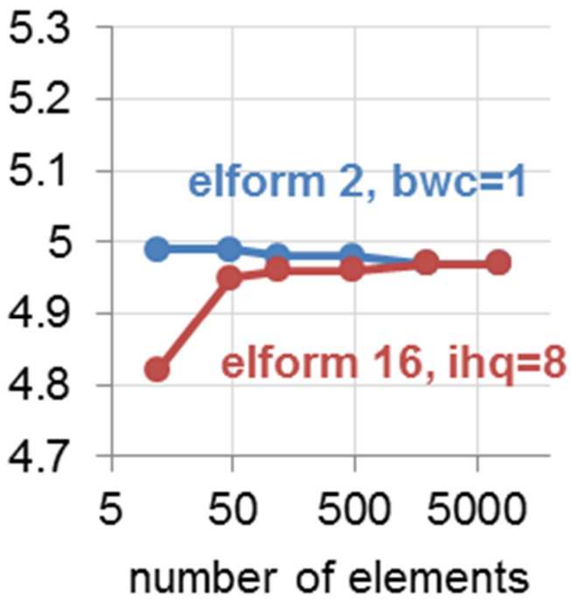
- Results with different scaling parameters (DRCPRM)
- Belytschko-Tsay shells (#2) with enhanced warping stiffness (BWC=1)
- Fully integrated shells (#16) with full projection warping stiffness (IHQ=8)

recommended for best results in most situations

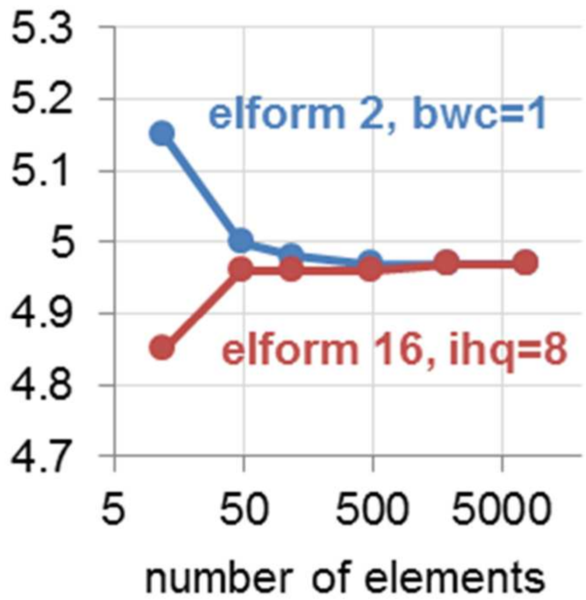
DRCPRM = 1.0 (default)



DRCPRM = 100.0

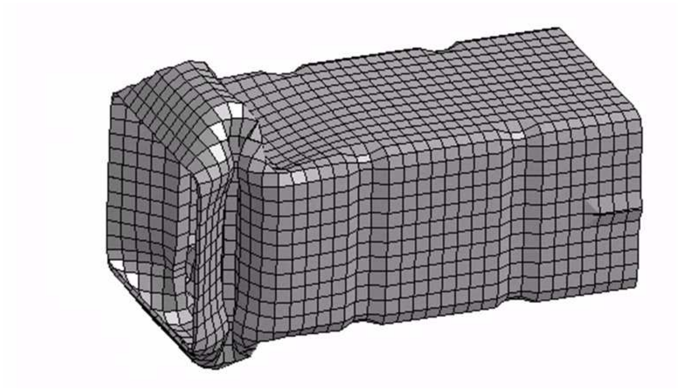


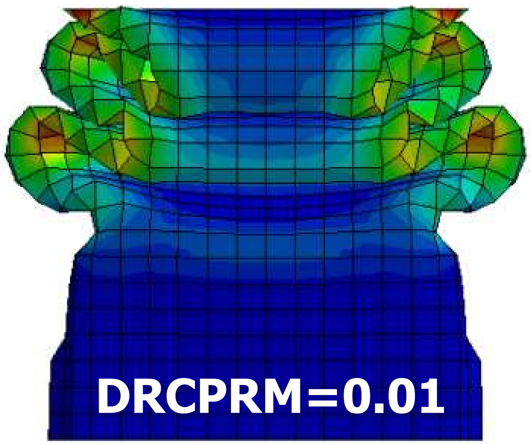
DRCPRM = 0.01

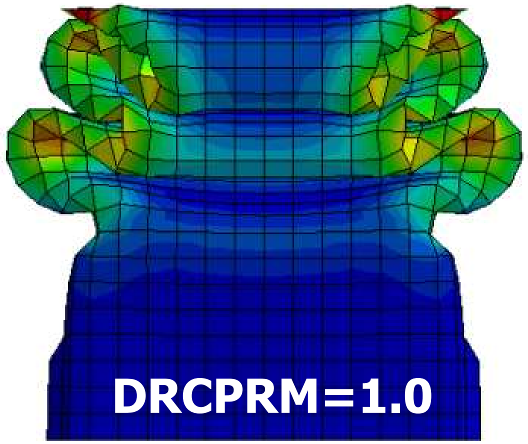


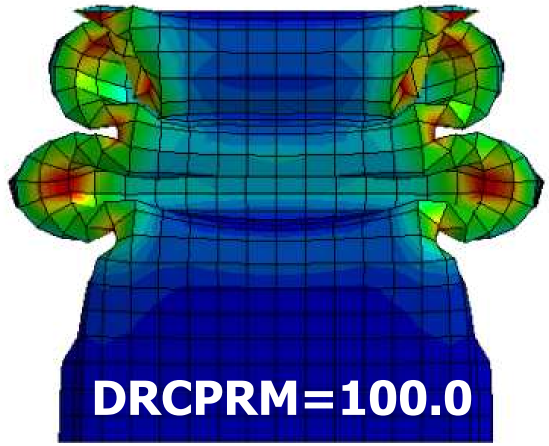
Example 3: Simple crashrail

- Quarter model of steel front rail gets deformed in axial direction
- (Implicit) study of different **scaling parameters** for the drilling stiffness









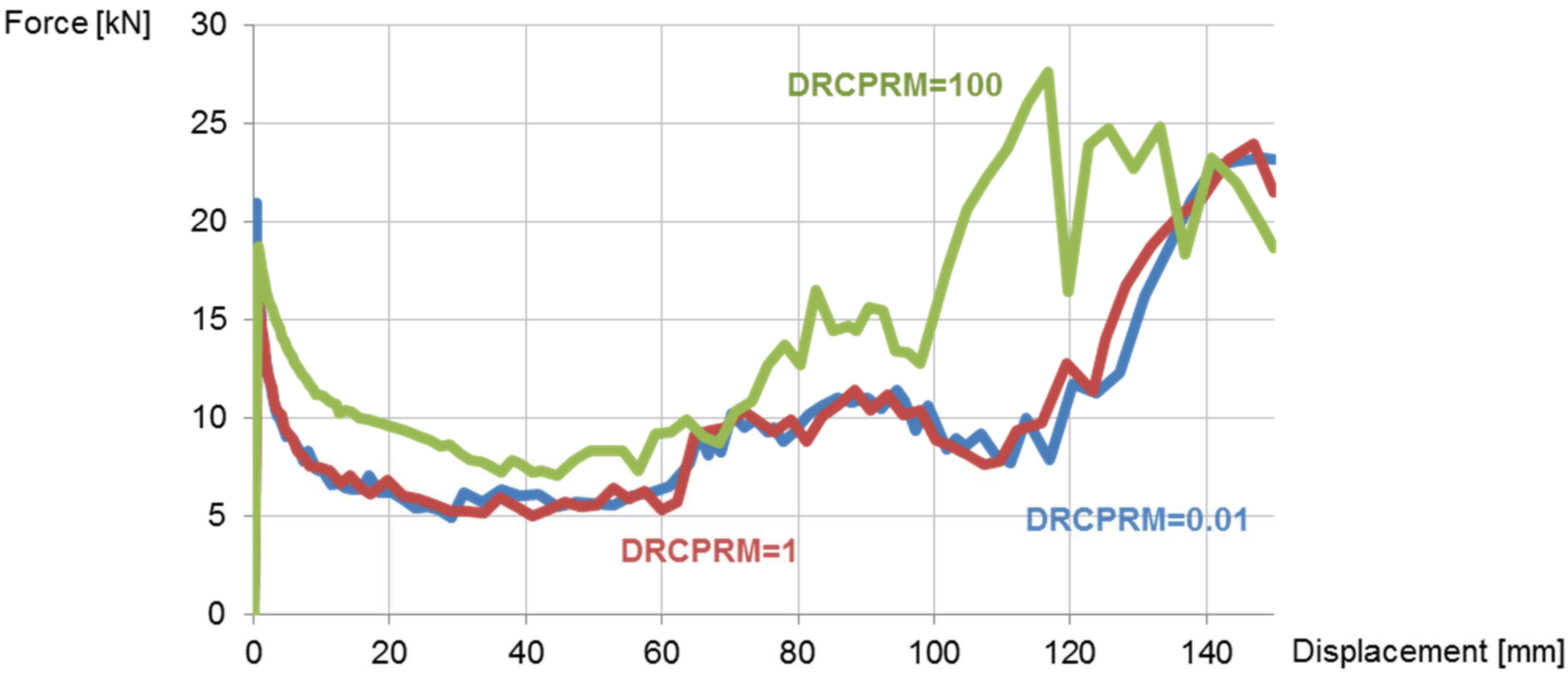
Reduction does not improve the result, CPU cost increases by factor of 2 (inferior convergence)

Default value, reference for now

Higher artificial stiffness affects solution, same CPU time as before

Example 3: Simple crashrail

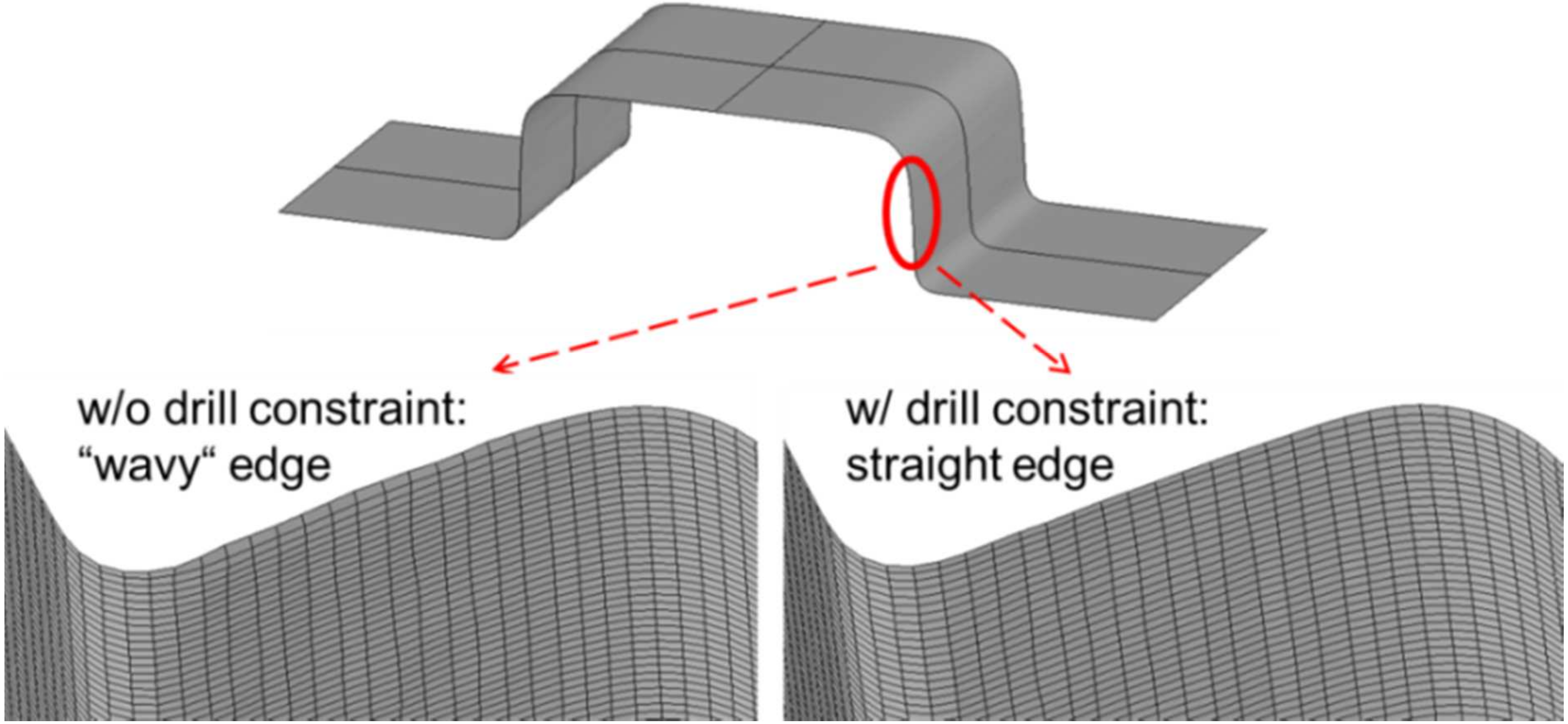
- Same conclusion from load-displacement curve:



➡ Default value of **DRCPRM = 1.0** seems to be a good choice

Example 4: Metal forming

- Explicit analysis of channel forming process (quarter model)



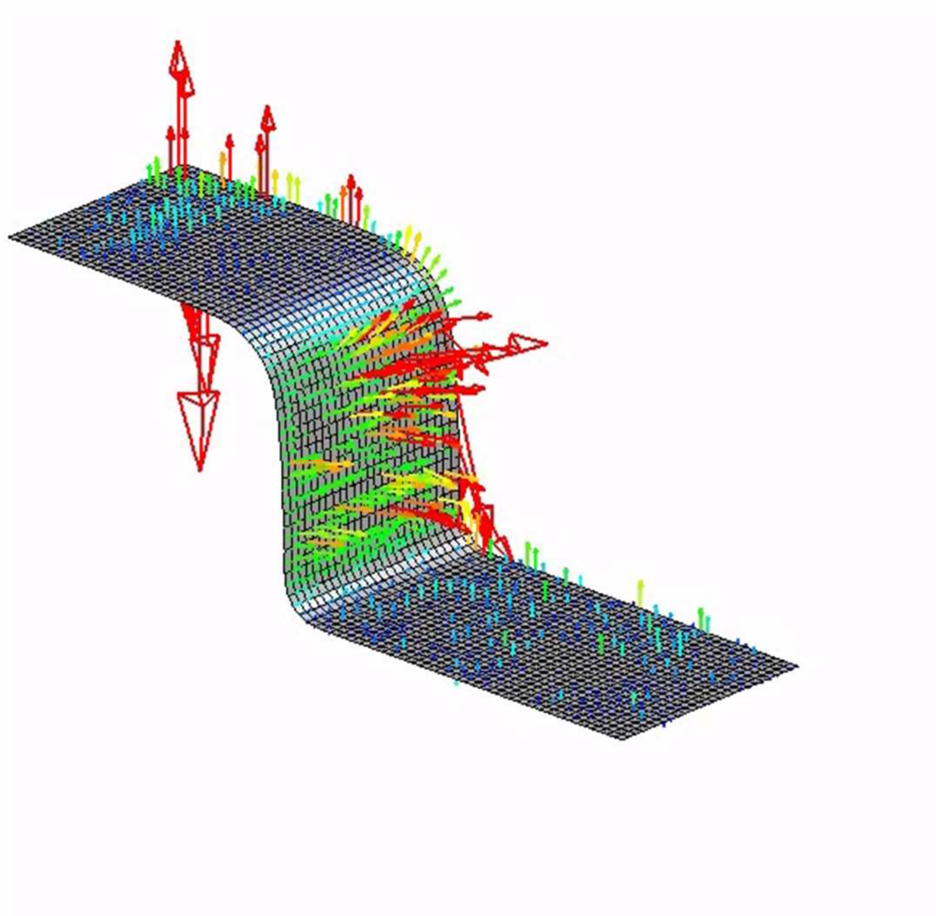
➡ Initially flat geometry gets deformed: drawn over 90° radius

➡ Free spinning drill rotations get involved in bending mode

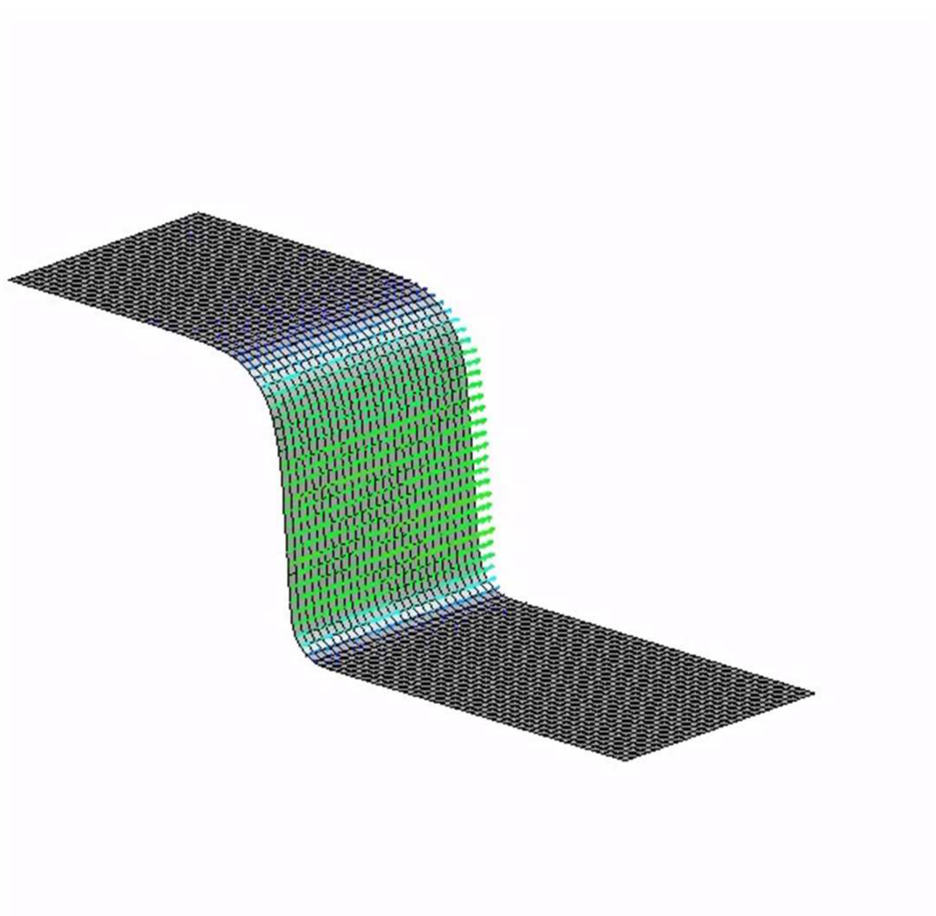
Example 4: Metal forming

- Observation of nodal rotations (0…3.14) as vector plot:

DRCM = off

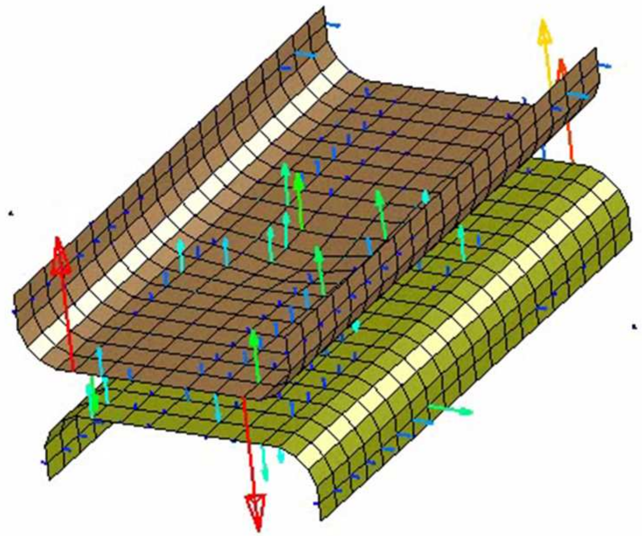


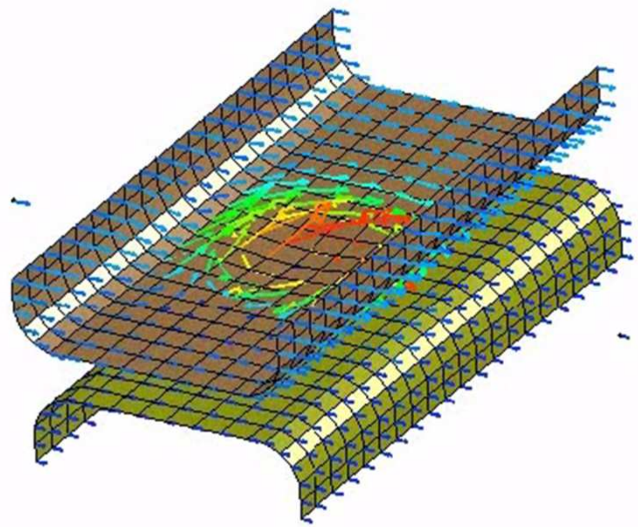
DRCM = on



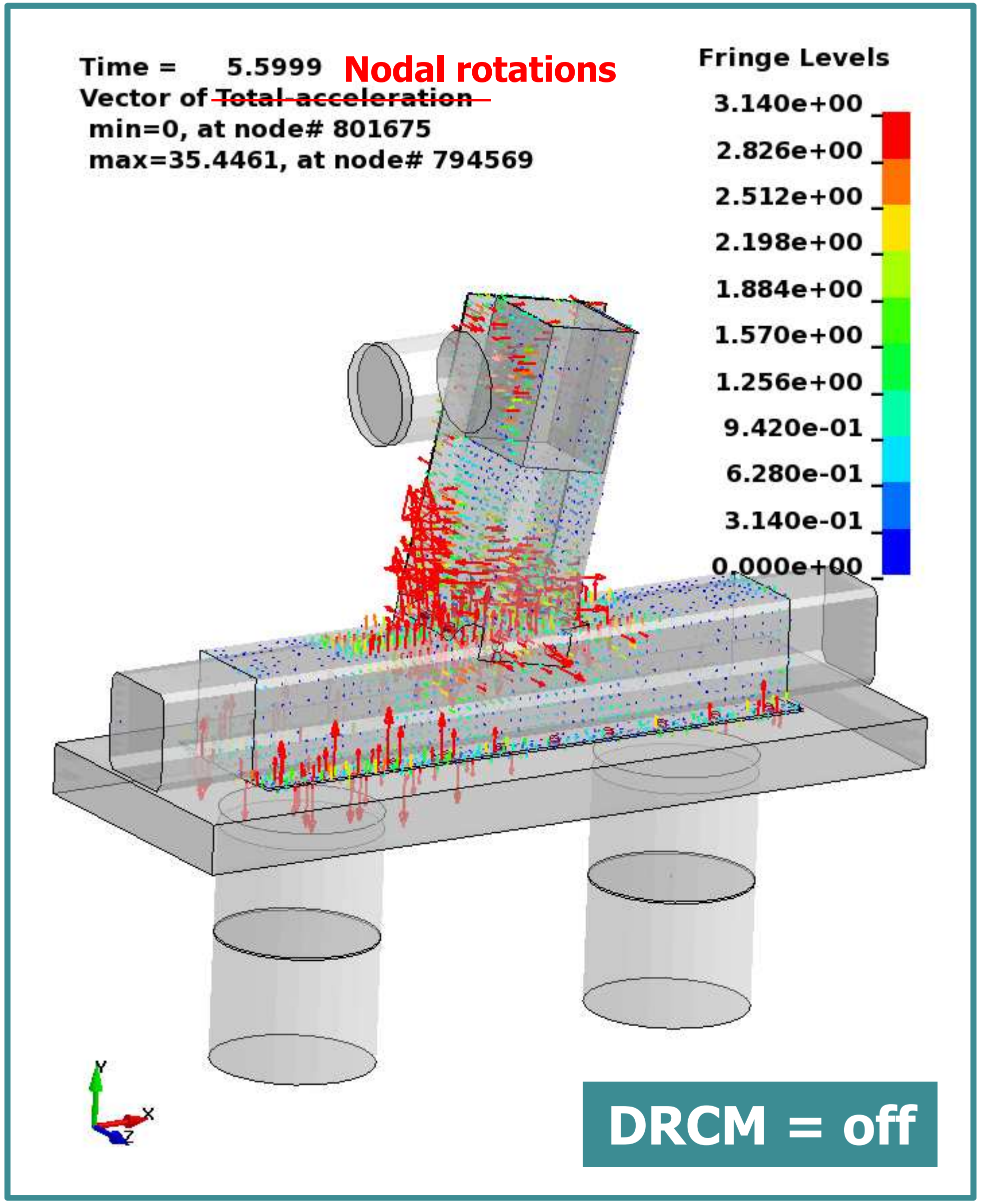
Example 5: Spot weld connections

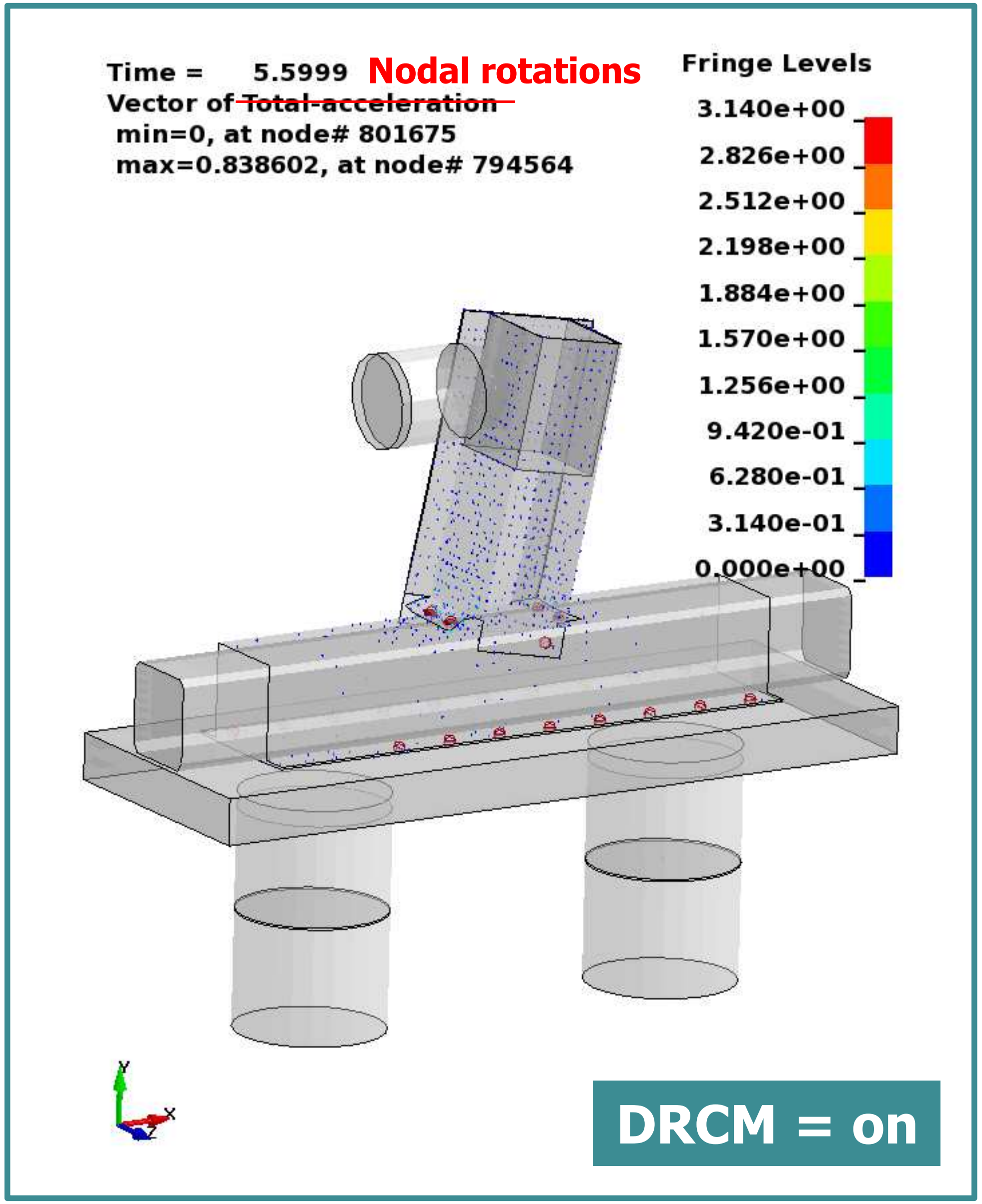
- Punctual connection between metal parts, e.g. spot welds or rivets, are often modeled by SPR constraints, single beams or solid elements fastened to shell components
- Local forces and moments acting on shell elements, where nodal rotations can become important: often these areas are geometrically flat at the beginning, but get highly deformed during crash loading
- In fact, idea for DRCM option in explicit came from SPR investigations:



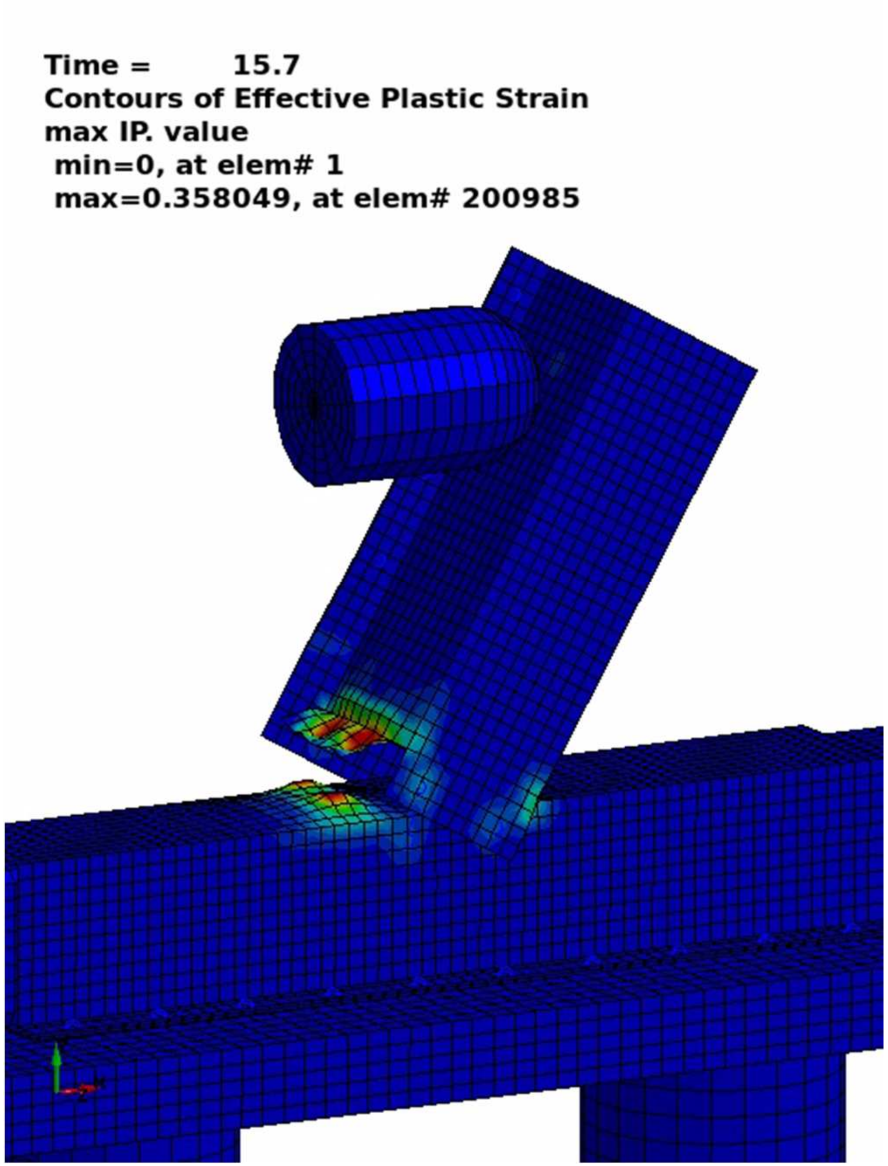


Example 5: Spot weld connections

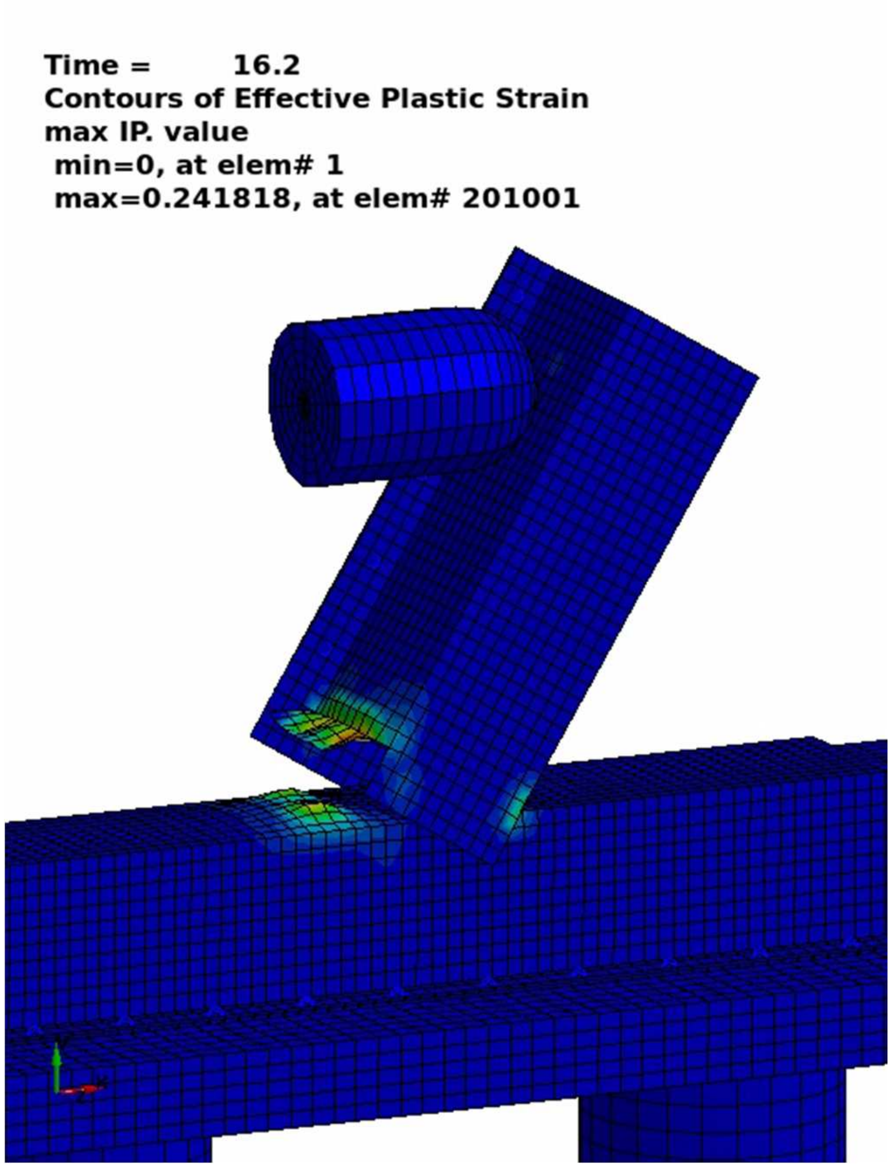




Example 5: Spot weld connections



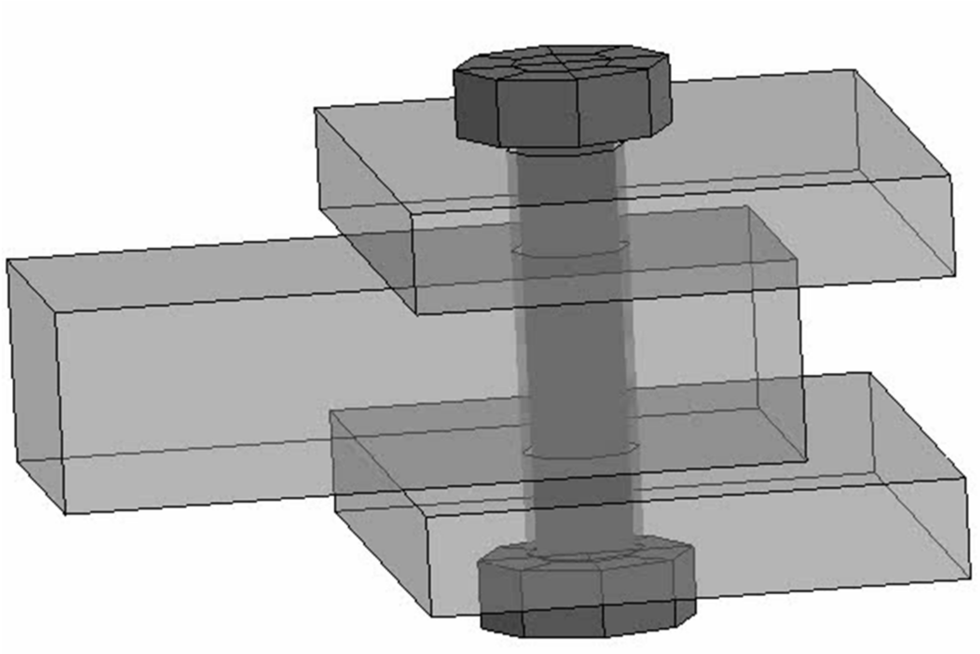
DRCM = off



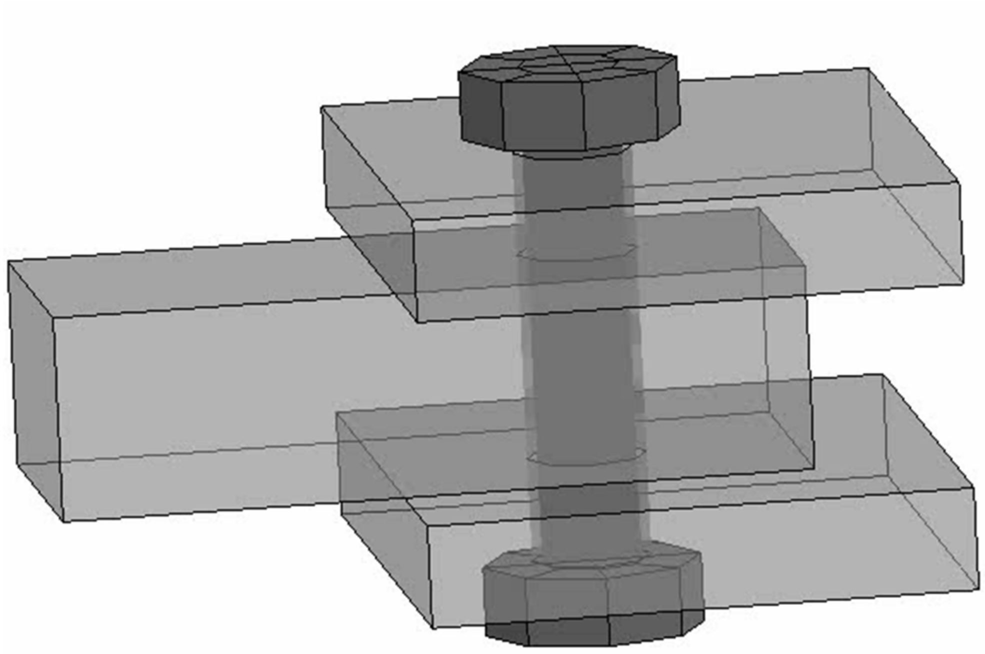
DRCM = on

Example 6: Screw

- Screw modeled as beam type 9 with heads modeled as shells
- Pre-stressed with *INITIAL_AXIAL_FORCE_BEAM
- Upper bolt head is rotated by external load
- Lower bolt head rotates only with drilling stiffness activated



DRCM = off



DRCM = on

Summary

- Attempt to provide more insight into topic of **shell‘s drilling d.o.f.**
- Constraint method necessary in **implicit**: default setting in LS-DYNA
- Now optional for **explicit** analyses since R7.0.0: part set can be defined (CPU cost can increase by up to 20%)
- Might be helpful in some situations as shown in the examples, but more investigations necessary, **please try in your applications!**
- Default value for DRCPRM seems to be a good choice, but always bear in mind that this is a non-physical additional stiffness that might have an influence on the structural response