Evaluation of the Stress and Displacement Behavior of Different LS-Dyna Element Types in Combination with Different Anti-Hourglassing Formulations and Initial Element Deformations

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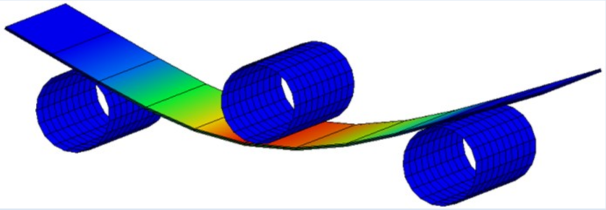
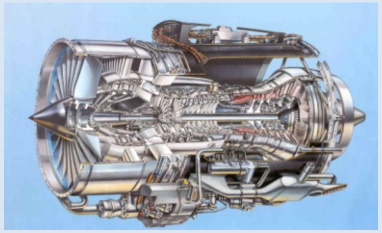
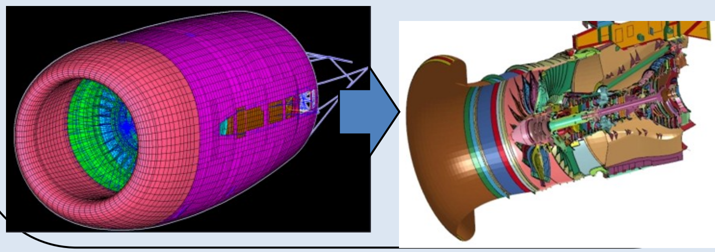


Outline

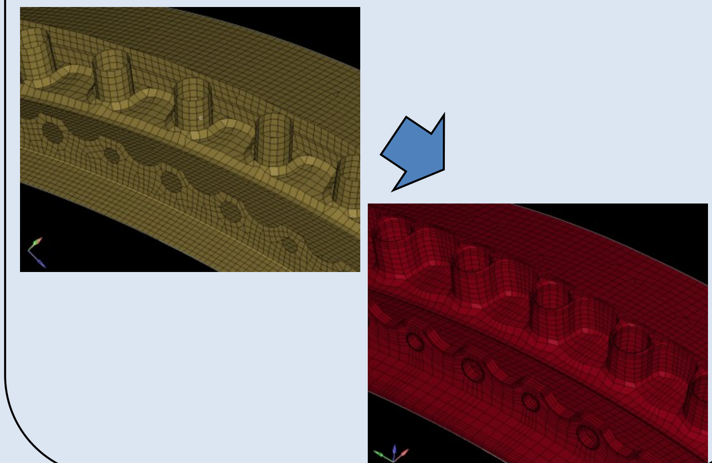
1. Motivation

More and more details are taken into account in FE models in recent times

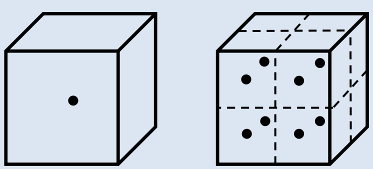




Often shell and beam elements are substituted by solid elements



Which solid element type and which anti-hourglassing formulation is suitable for thin-walled structures?



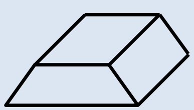
Solid ELFORM 1, 2, -1, -2, …
T-Shell ELFORM 1
Shell ELFORM 1, 2, 16, …

↔ HG 4, 5, 6

$$\dot{Q}_\alpha^M = \frac{QM \cdot E\, tA}{8} B_{\beta I} B_{\beta I} \dot{q}_\alpha^M$$

$$\dot{Q}_\alpha^B = \frac{QB \cdot E\, t^3 A}{192} B_{\beta I} B_{\beta I} \dot{q}_\alpha^B$$

$$\dot{Q}_3^W = \frac{QW \cdot \kappa\, G t^3 A}{12} B_{\beta I} B_{\beta I} \dot{q}_3^B$$



What happens for initially deformed elements?

2. Elements under consideration

Solid elements

ELFORM 1:
- Underintegrated constant stress element (standard solid element)
- Fastest element in this test

ELFORM 2:
- Fully integrated element (tendency for locking)
- Slower than ELFORM 1

ELFORM -1:
- Similar to ELFORM 2, but accounted for poor aspect ratios on order to reduce shear locking
- Slower than ELFORM 2

ELFORM -2:
- Similar to ELFORM 2, but accounted for poor aspect ratios on order to reduce shear locking
- Higher costs than for ELFORM -1 because of more accurate formulation

T-Shell elements

ELFORM 1:
- Underintegrated element
- Appears to the user as 8-node brick element (but plane stress is assumed)

Shell elements

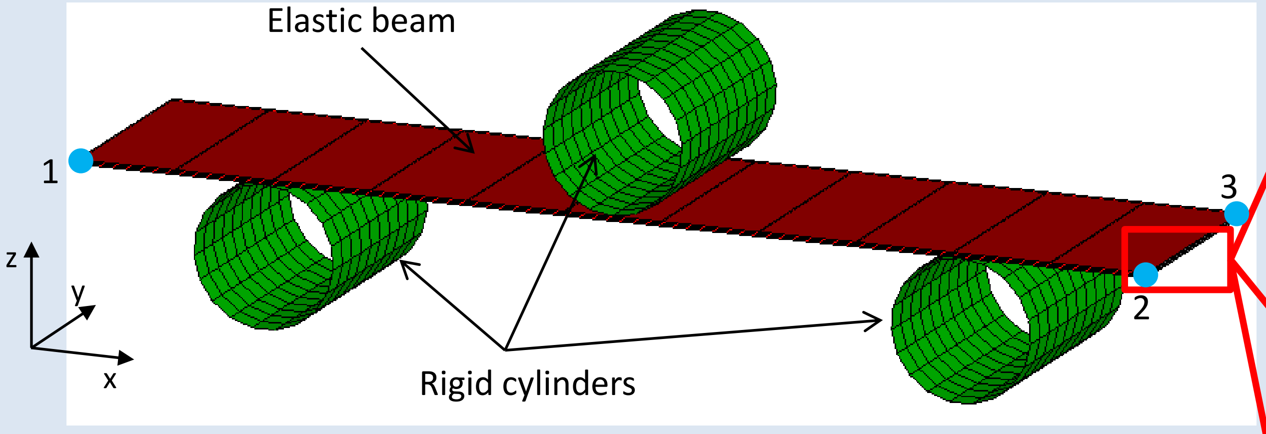
ELFORM 1:
- Underintegrated element (Hughes-Liu formulation)

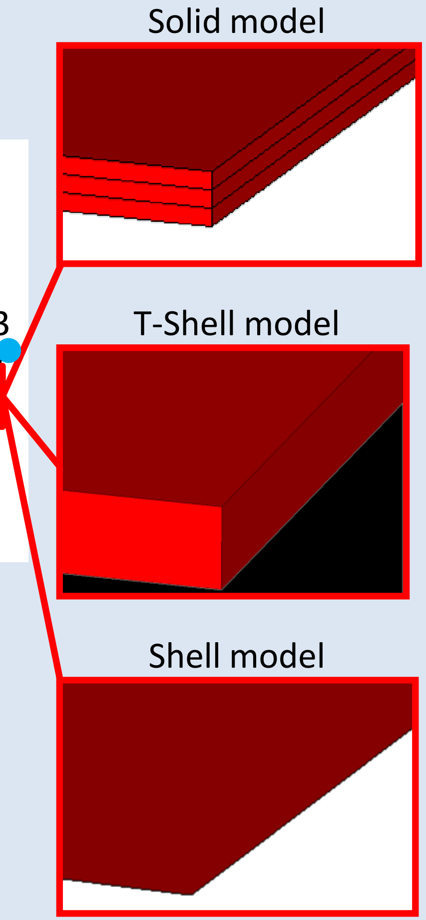
ELFORM 2:
- Underintegrated element (Belytschko-Tsai formulation, standard shell element)

ELFORM 16:
- Fully integrated element
- Higher computational costs than ELFORM 1 and 2
- Preferred for implicit calculations

For more details please refer to: Hallquist, J. O.: “LS-DYNA Theory Manual”, Livermore Software Technology Corporation, 2006

3. Model and boundary conditions





Dimensions:

- Length x width x thickness = 23 mm x 5 mm x 0.1 mm
- Diameter of cylinders = 3 mm
- Aspect ratio of solid elements: 150 x 63 x 1

Material: E=210.000 N/mm^2, ν=0.3, ρ=7.9e-9 t/mm^3 (*MAT_ELASTIC)

Contact: Automatic single surface between beam and cylinders

Boundary conditions:

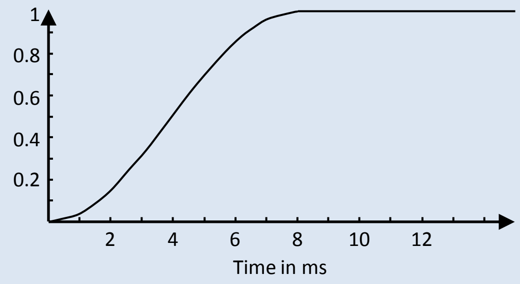
- Node 1 and node 2 are fixed in y-direction, node 2 and node 3 are fixed in x-direction
- Lower cylinders are fixed, upper cylinder is loaded

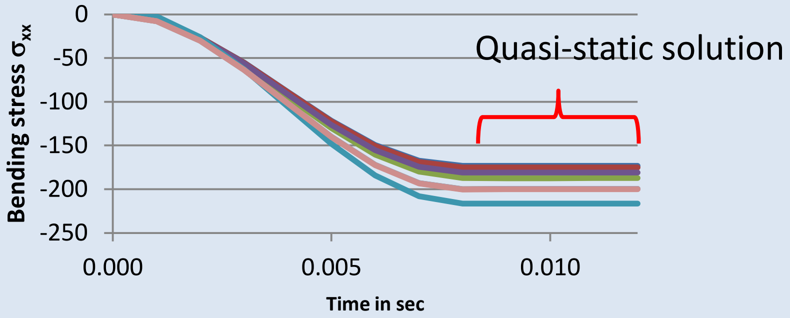
Loading:

- Upper cylinder is loaded by a force of 0.1 N in negative z-direction or with a prescribed displacement of 0.5 mm in negative z-direction resp.

3. Model and boundary conditions

Load curve:

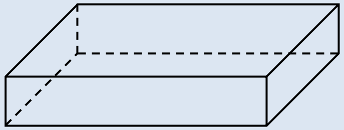




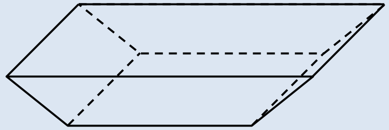
Time integration: All computations are done with explicit time integration (mpp solver)

Damping: Global damping of 10e4 s^{-1} is applied (to achieve quasi-static solution)

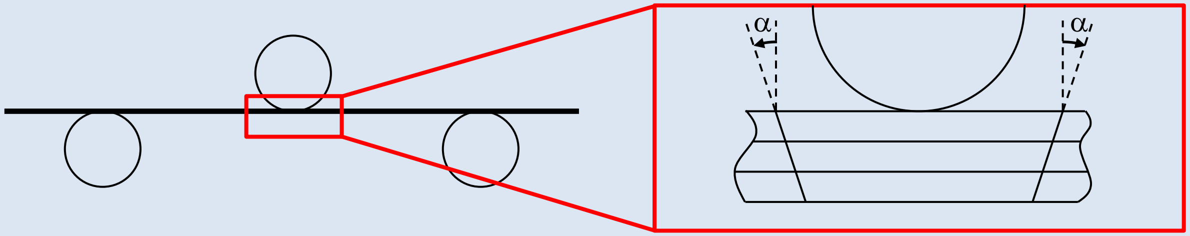
Initial element deformations: All computations are done without and with initial element deformations:



Undeformed element



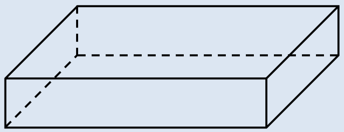
Initially deformed element



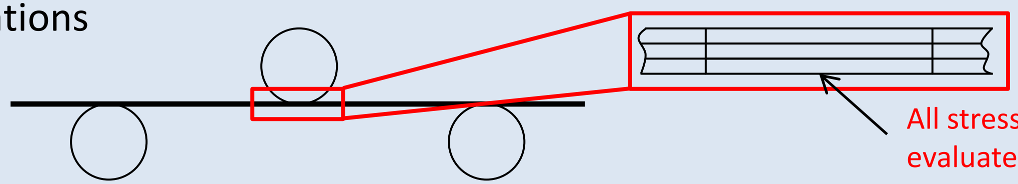
To achieve initial element deformations, the taper angle α of the middle elements is varied between α=0°, α=5°, α=10° and α=20°.

Hourglass Control: All computations are done with HG 4, 5 and 6 with default control coefficients

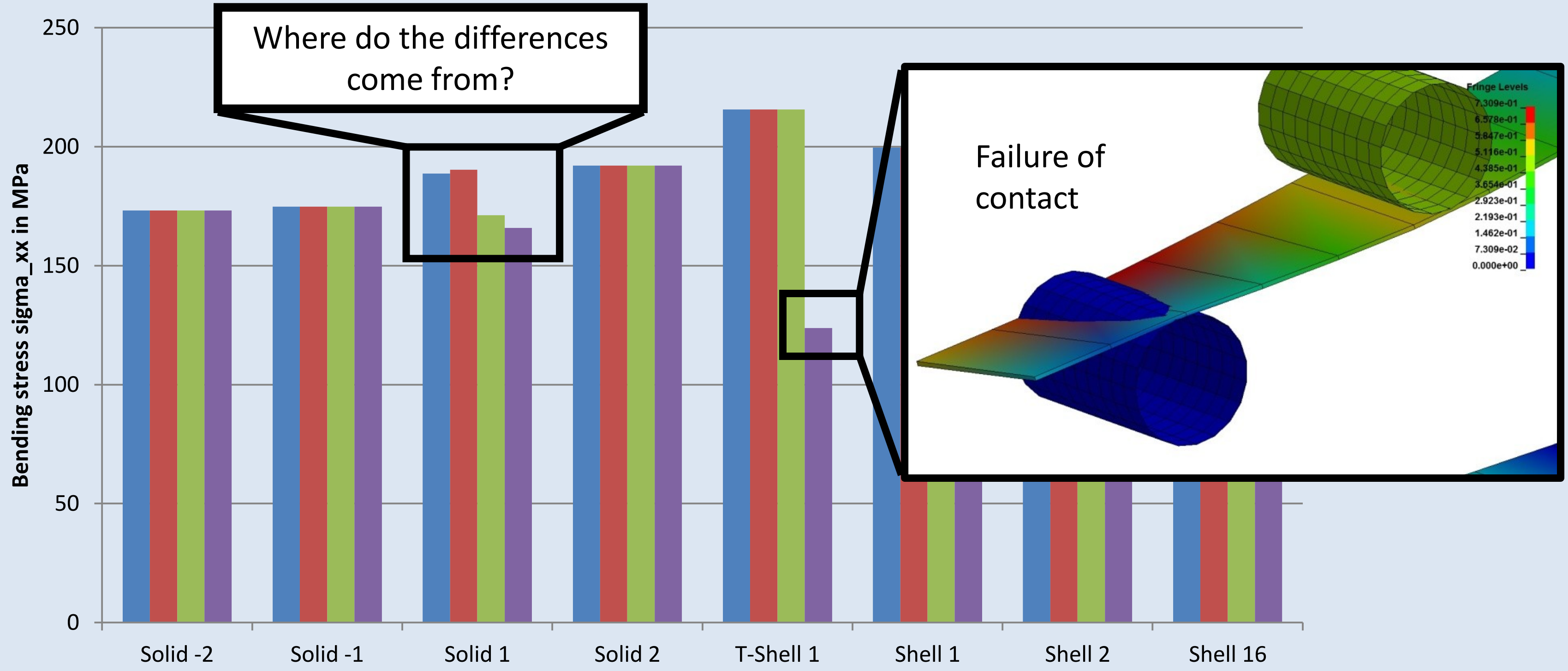
4. Test results with undeformed elements



4.1 Max. bending stresses for **DISPLACEMENT-BASED** loading and different anti-hourglassing formulations

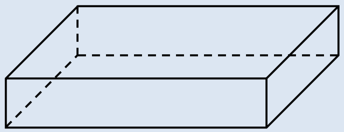


All stresses in all diagrams are always evaluated at the lowest integration point in the middle of the beam



- Influence of hourglass control onto computed stresses only for solid ELFORM 1
- Shell elements compute more accurate results due to position of integration point

4. Test results with undeformed elements



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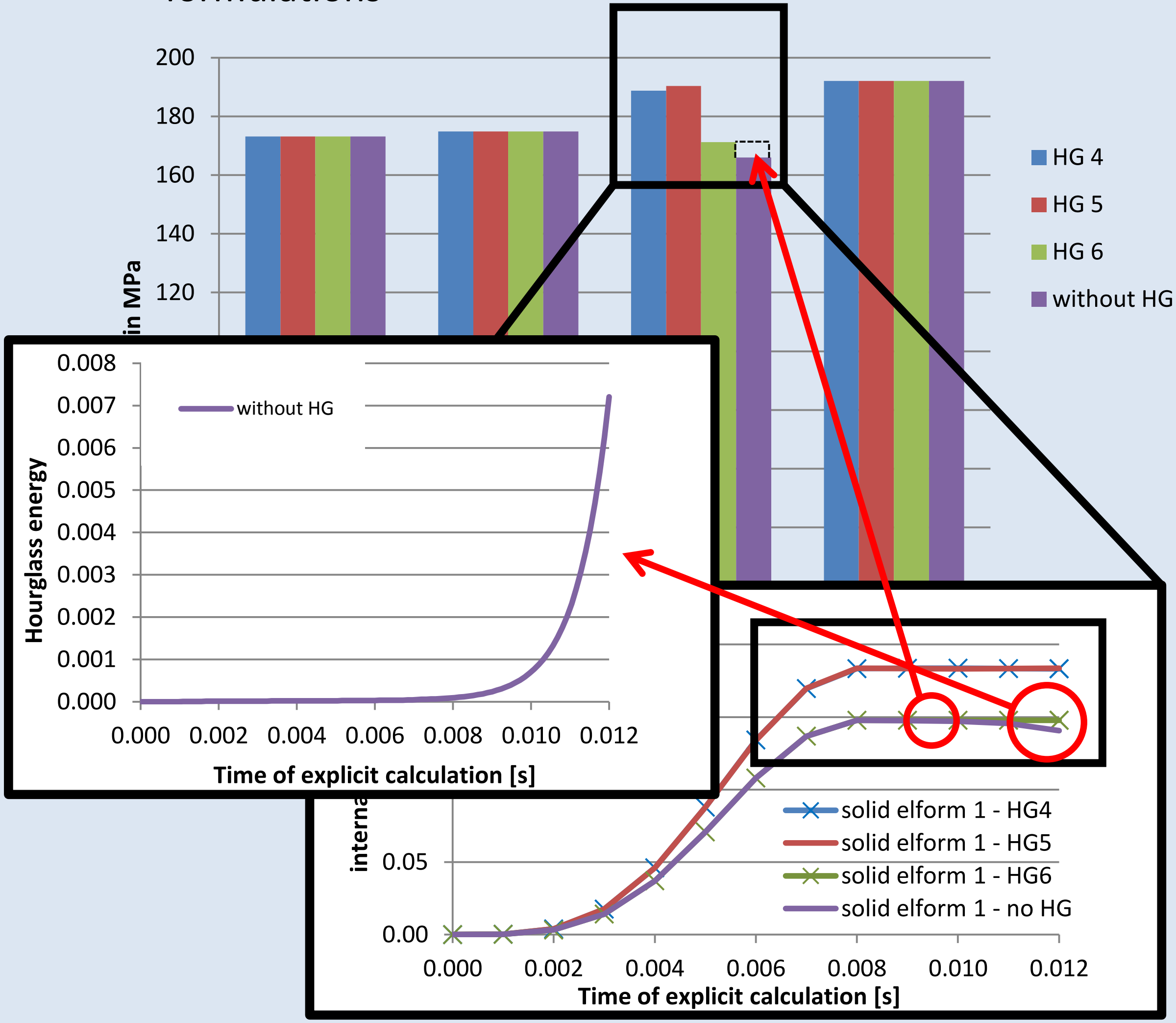
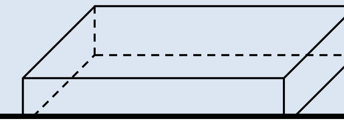


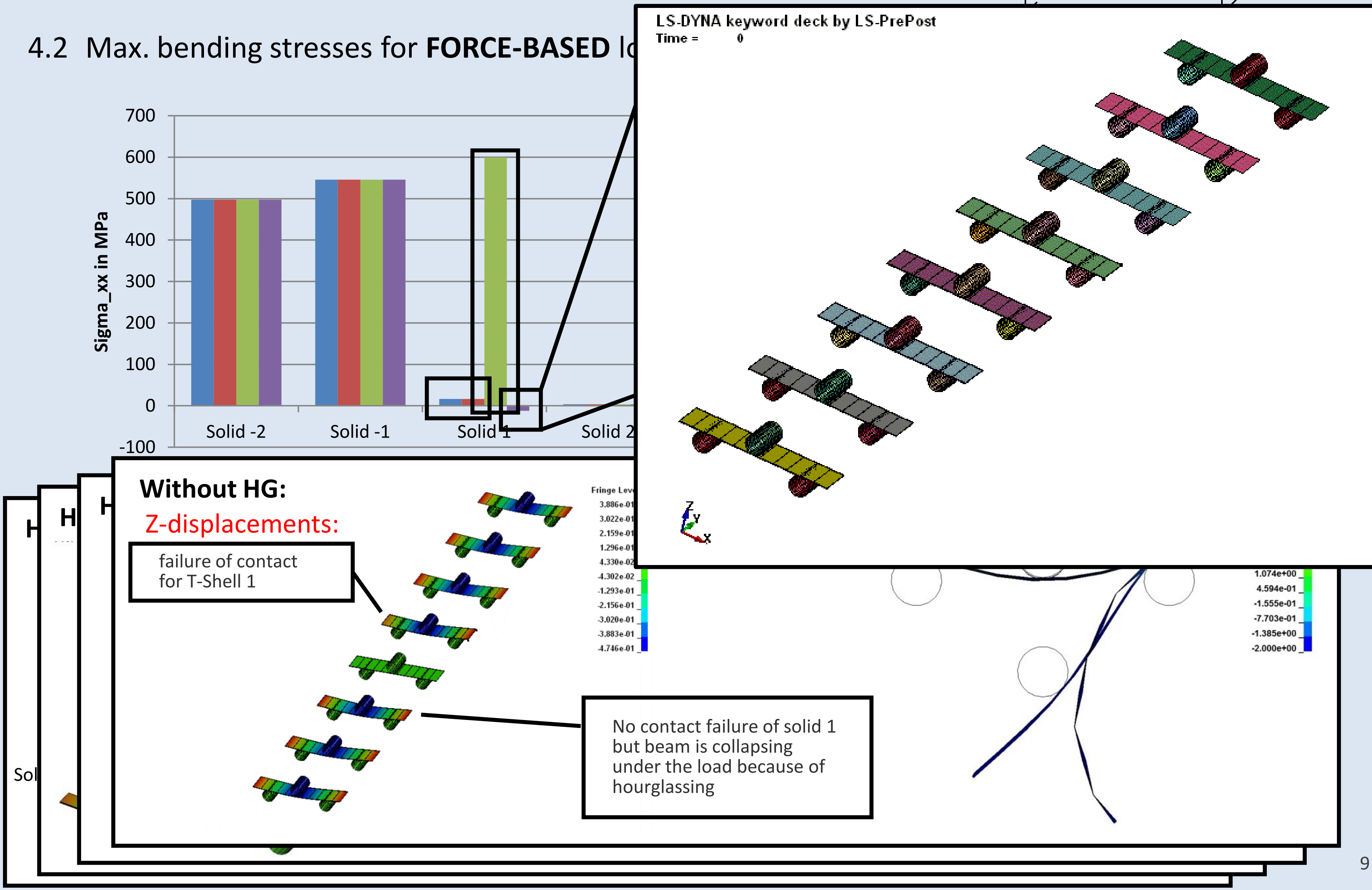
Solid ELFORM 1:

- HG 4 and HG 5 cause an increase of the stiffness which results in higher stresses (especially in y-direction)
- This specific reaction can also be observed for the internal energy functions
- The decrease of the internal energy of the model without HG control results from an increase of the hourglass energy
- Without hourglassing, model with no HG control would lead to the same result like model with HG control 6

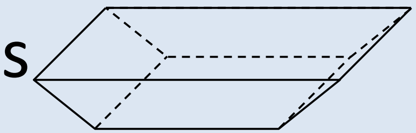
4. Test results with undeformed elements

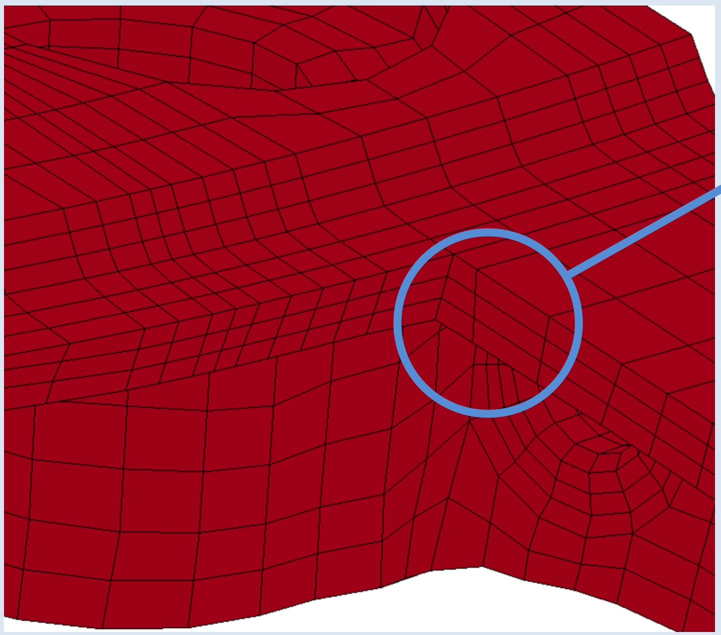


4.2 Max. bending stresses for **FORCE-BASED** l



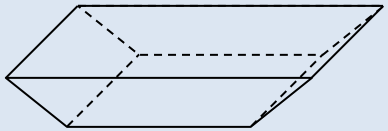
5. Test results with initially deformed elements



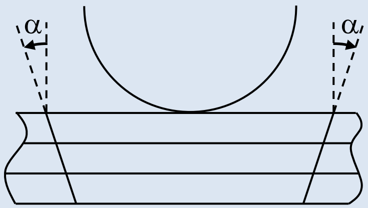


Most meshes of real parts do not contain only perfectly brick-shaped elements, where all edges are perpendicular to each other.

How do such initially deformed solid elements behave in the 3-point-bending test?

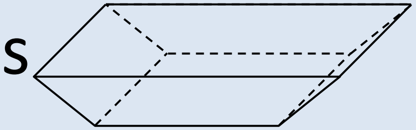


Here, variation of so-called taper angle:

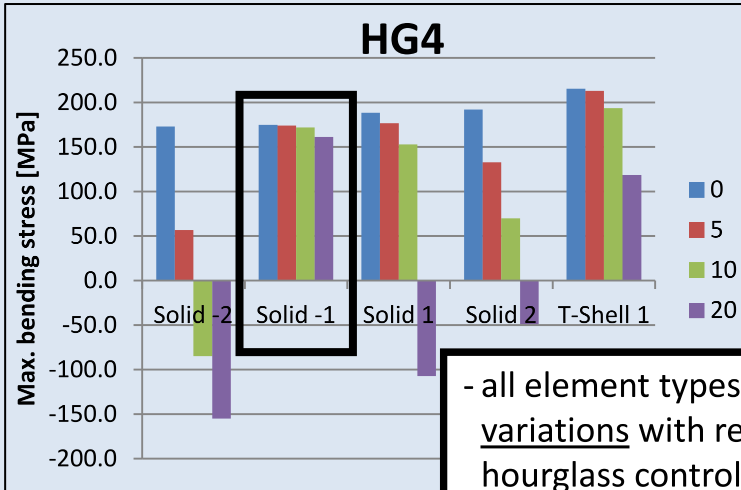


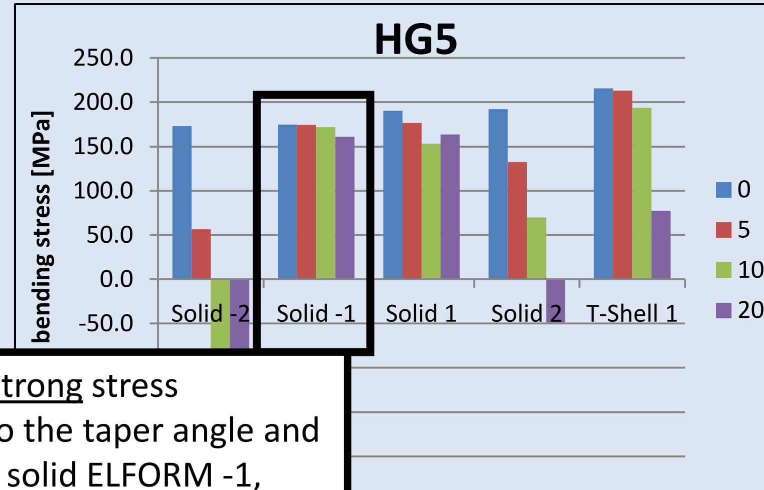
α=0°, α=5°, α=10° and α=20°

5. Test results with initially deformed elements



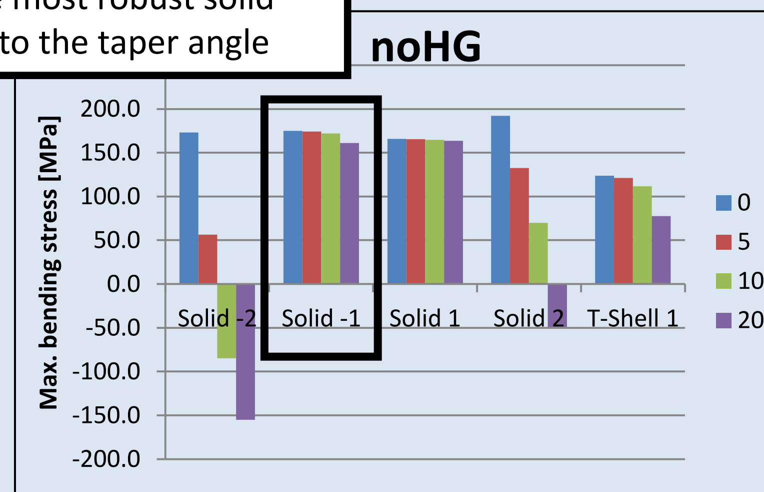
5.1 Max. bending stresses for **DISPLACEMENT-BASED** loading





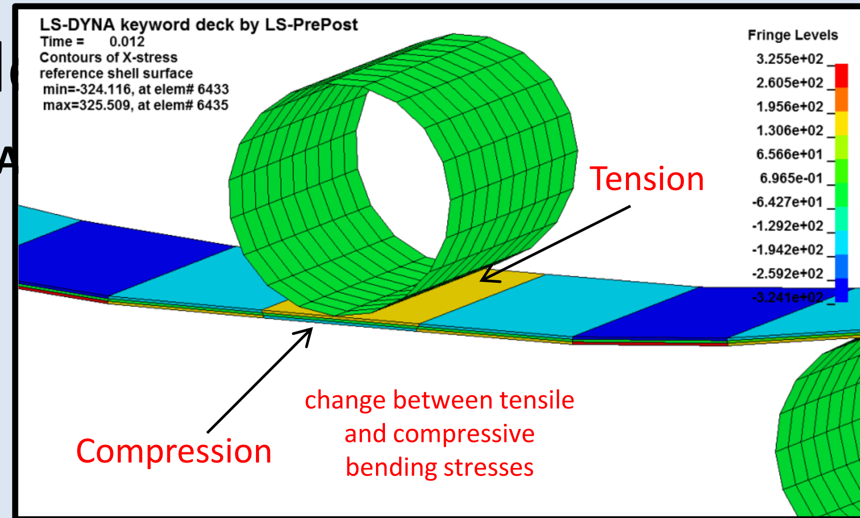
- all element types show <u>strong</u> stress <u>variations</u> with respect to the taper angle and hourglass control <u>except solid ELFORM -1</u>,

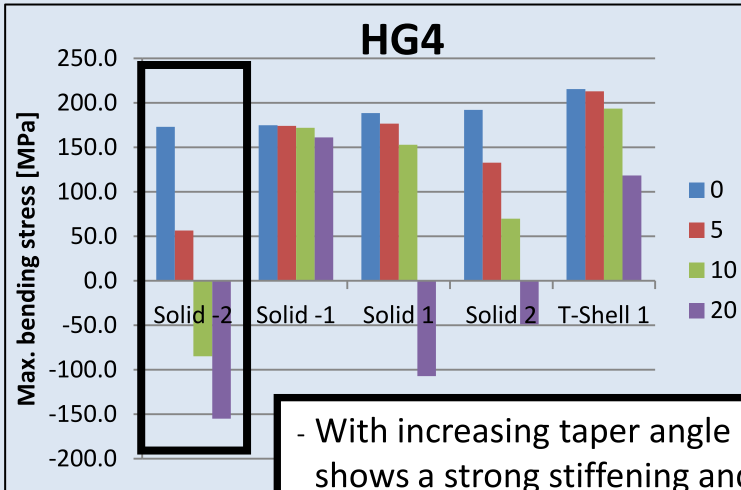
→ solid ELFORM -1 is the most robust solid element with respect to the taper angle

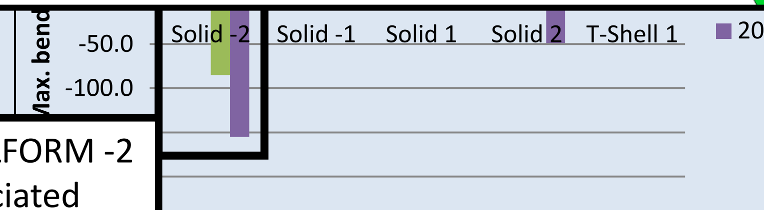


5. Test results with initially d

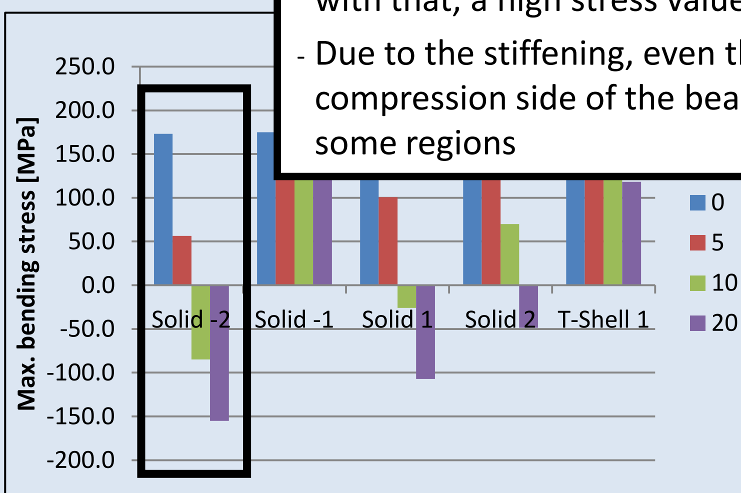
5.1 Max. bending stresses for **DISPLACEMENT-BA**

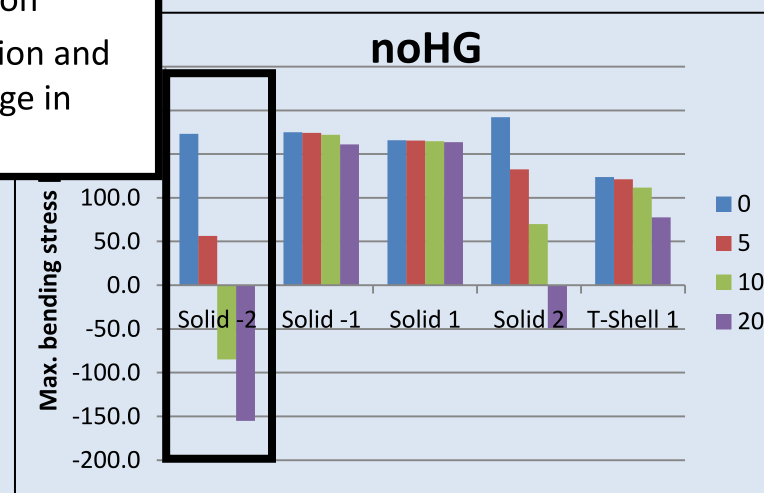




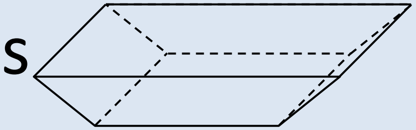


- With increasing taper angle solid ELFORM -2 shows a strong stiffening and, associated with that, a high stress value variation
- Due to the stiffening, even the tension and compression side of the beam change in some regions

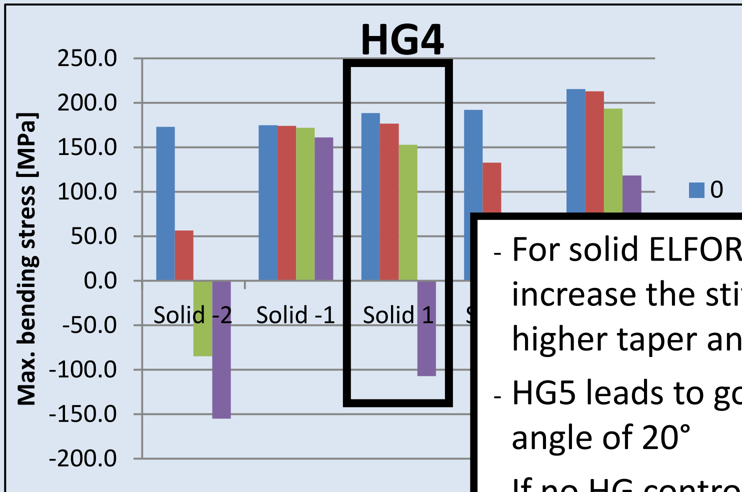


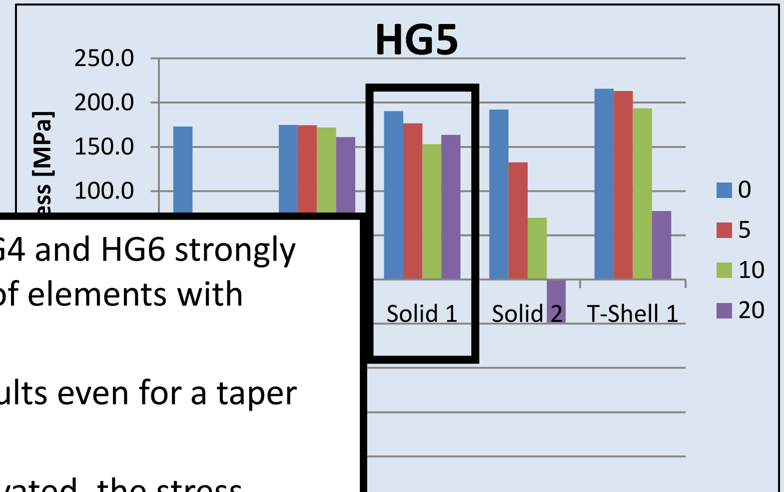


5. Test results with initially deformed elements

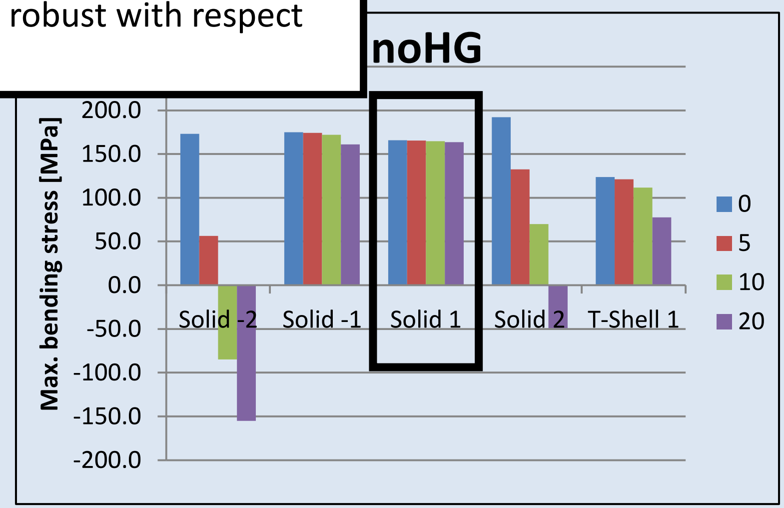


5.1 Max. bending stresses for **DISPLACEMENT-BASED** loading

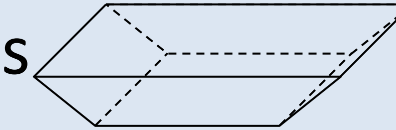




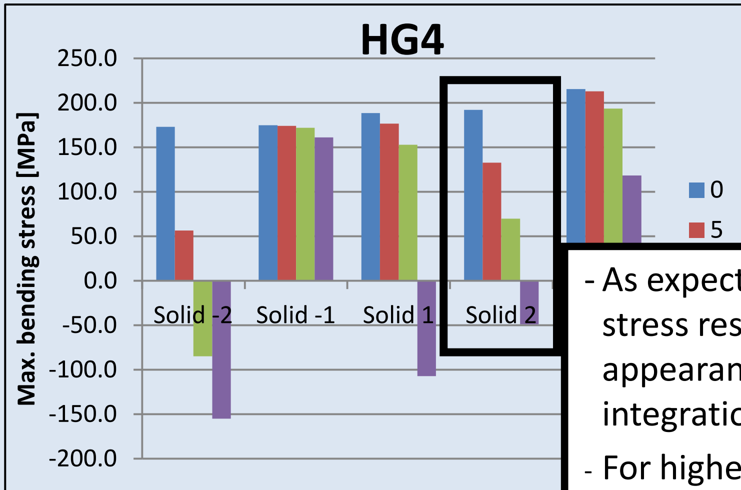
- For solid ELFORM 1 HG4 and HG6 strongly increase the stiffness of elements with higher taper angles
- HG5 leads to good results even for a taper angle of 20°
- If no HG control is activated, the stress results are much more robust with respect to the taper angle

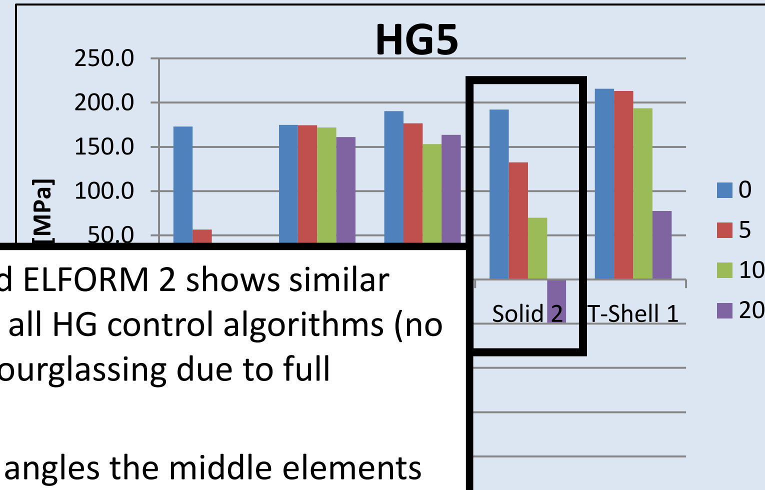


5. Test results with initially deformed elements

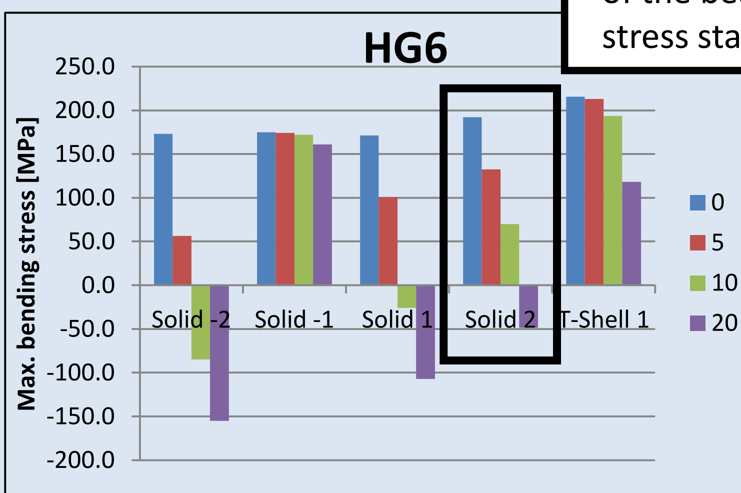


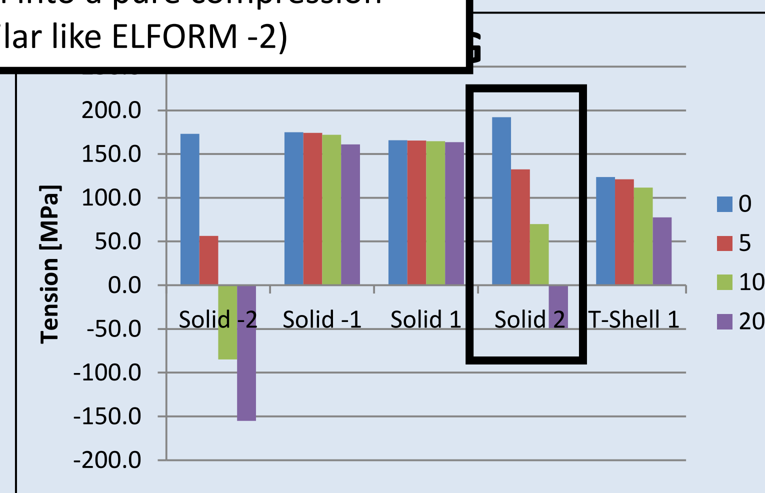
5.1 Max. bending stresses for **DISPLACEMENT-BASED** loading



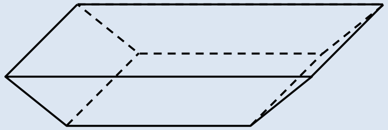


- As expected solid ELFORM 2 shows similar stress results for all HG control algorithms (no appearance of hourglassing due to full integration)
- For higher taper angles the middle elements of the beam turn into a pure compression stress state (similar like ELFORM -2)

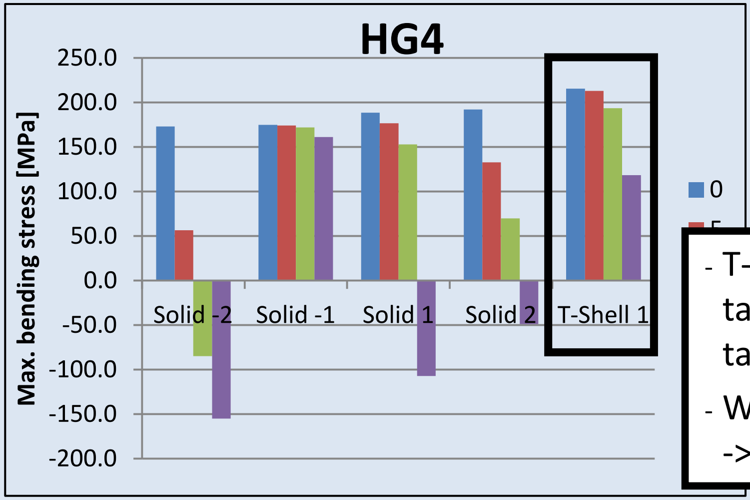


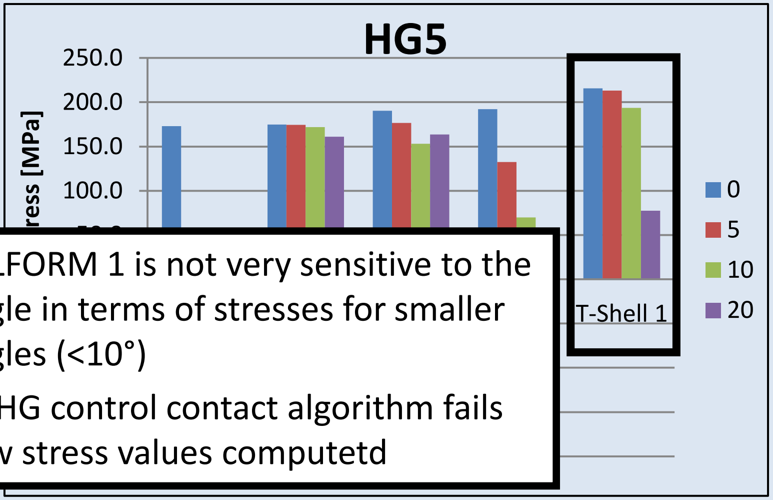


5. Test results with initially deformed elements

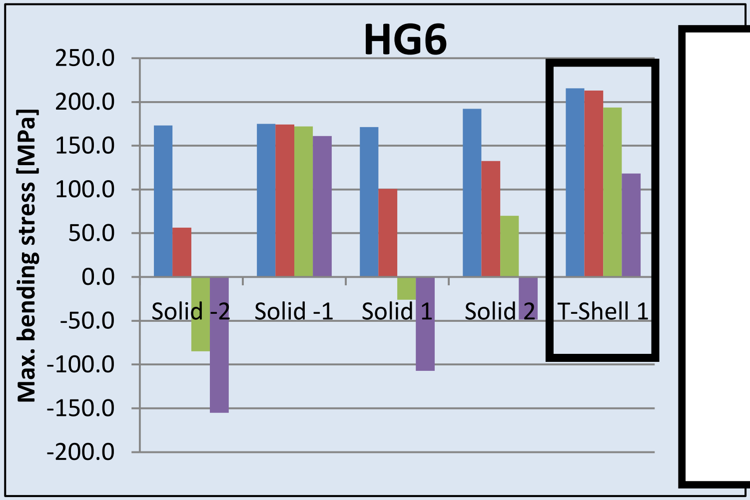


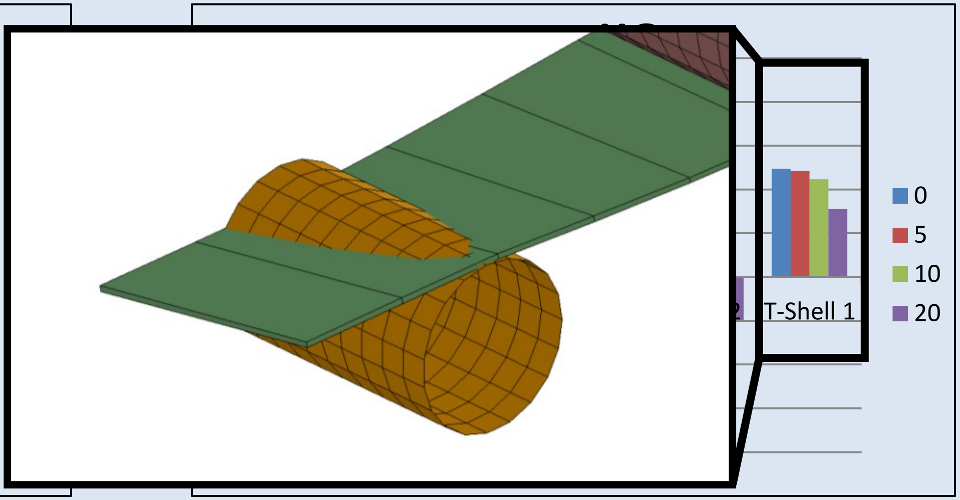
5.1 Max. bending stresses for **DISPLACEMENT-BASED** loading



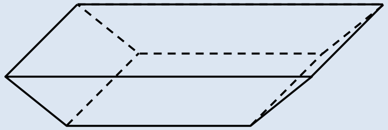


- T-Shell ELFORM 1 is not very sensitive to the taper angle in terms of stresses for smaller taper angles (<10°)
- Without HG control contact algorithm fails -> too low stress values computetd

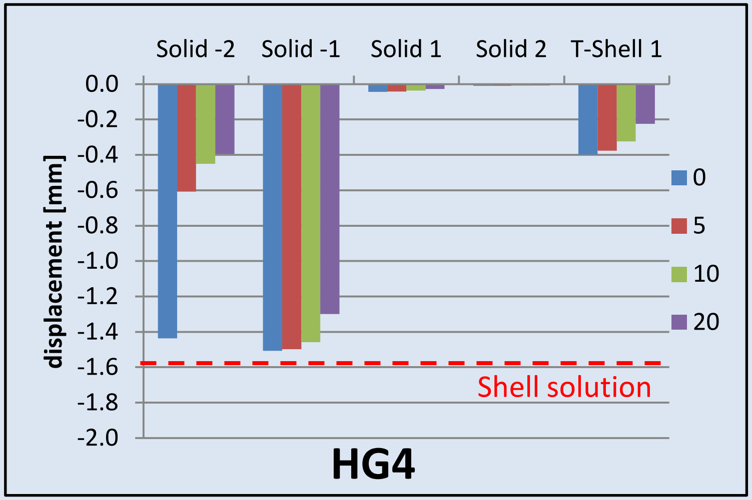


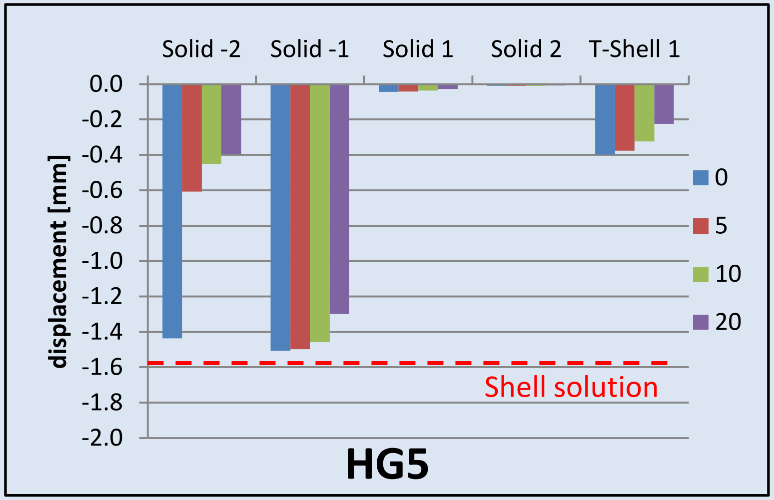


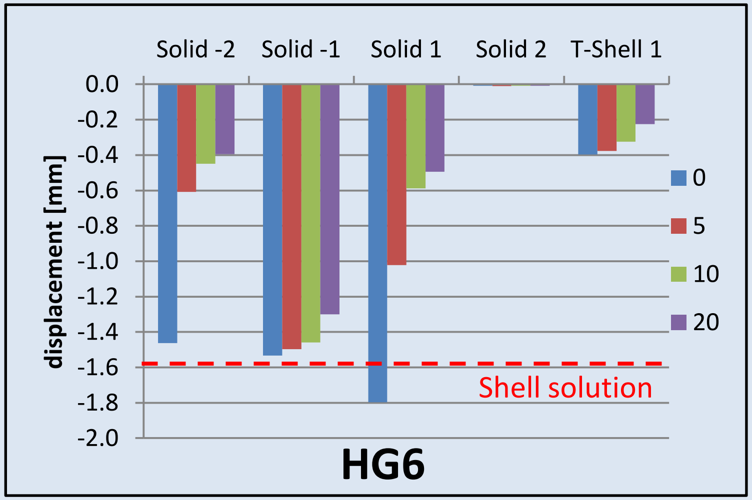
5. Test results with initially deformed elements

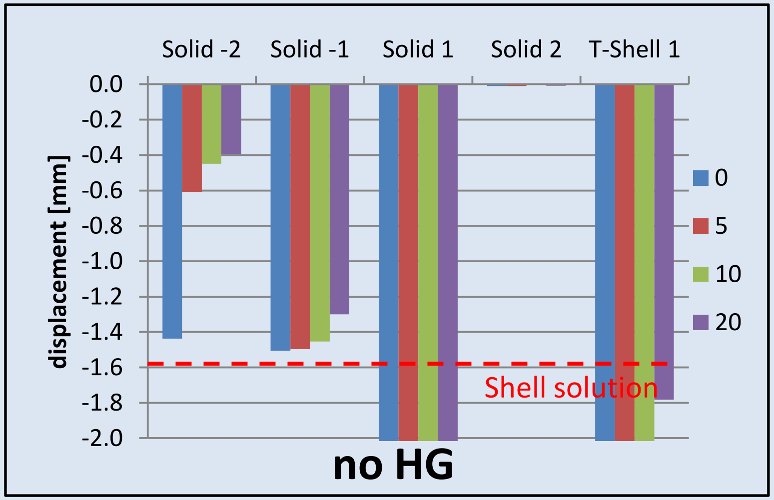


5.2 Max. displacements for **FORCE-BASED** loading

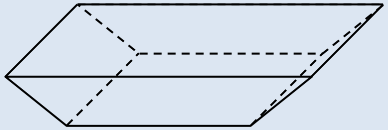








5. Test results with initially deformed elements



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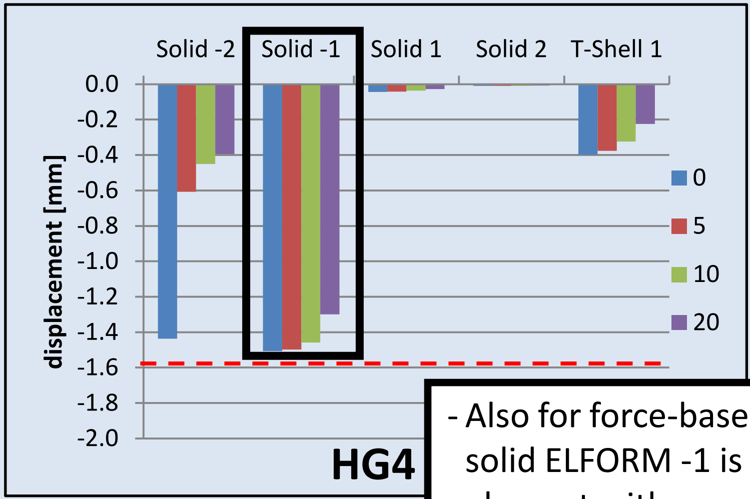
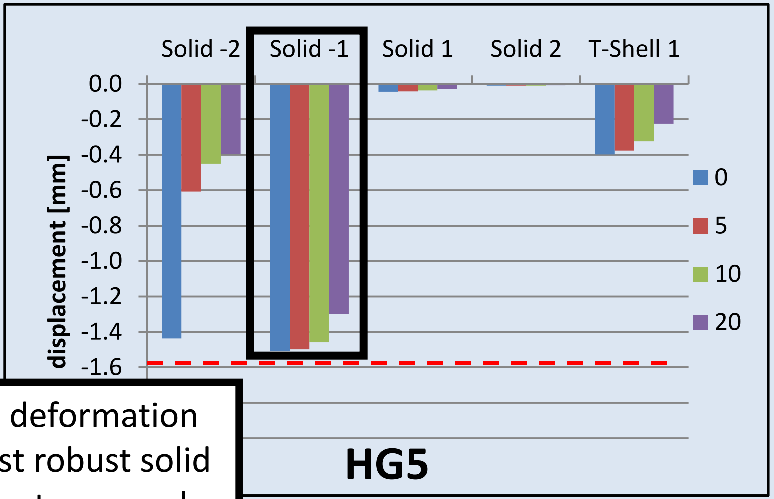
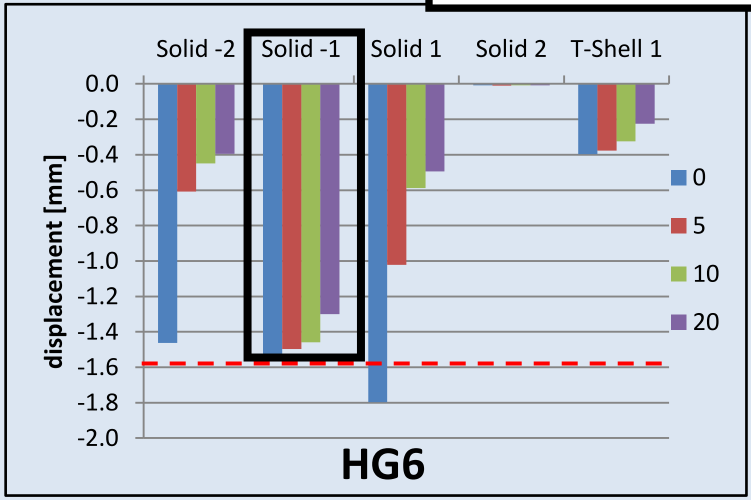
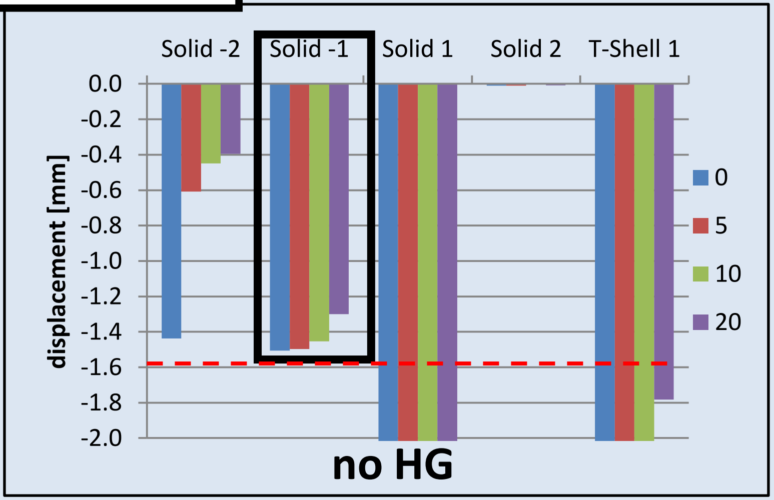




- Also for force-based beam deformation solid ELFORM -1 is the most robust solid element with respect to the taper angle





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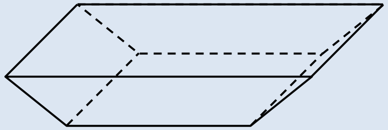

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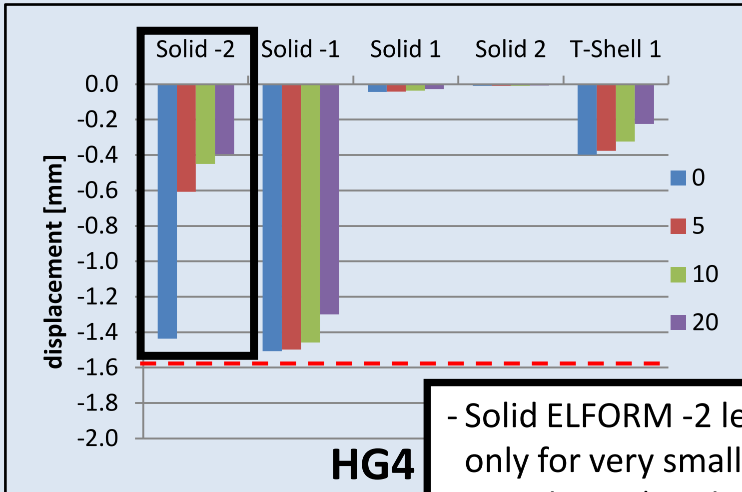
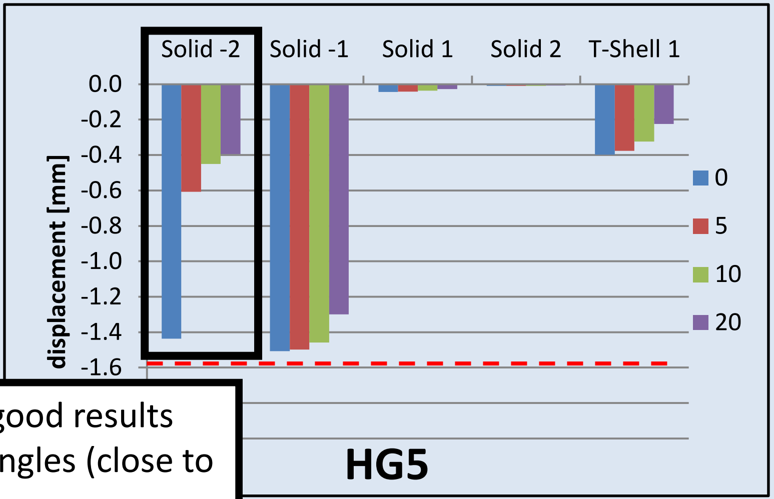
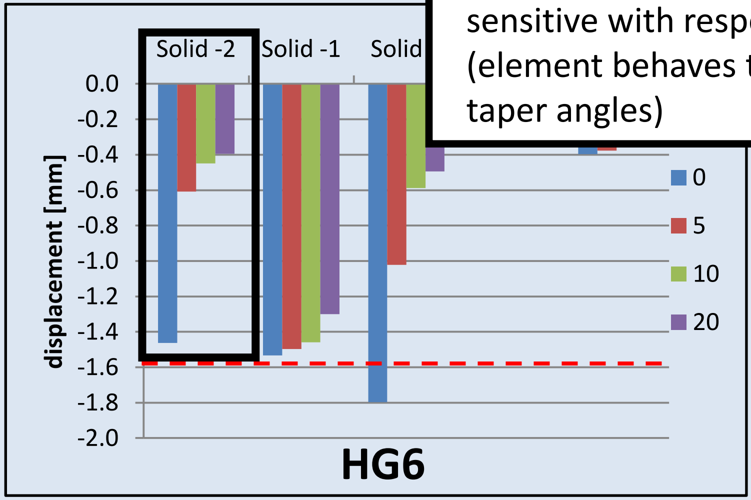
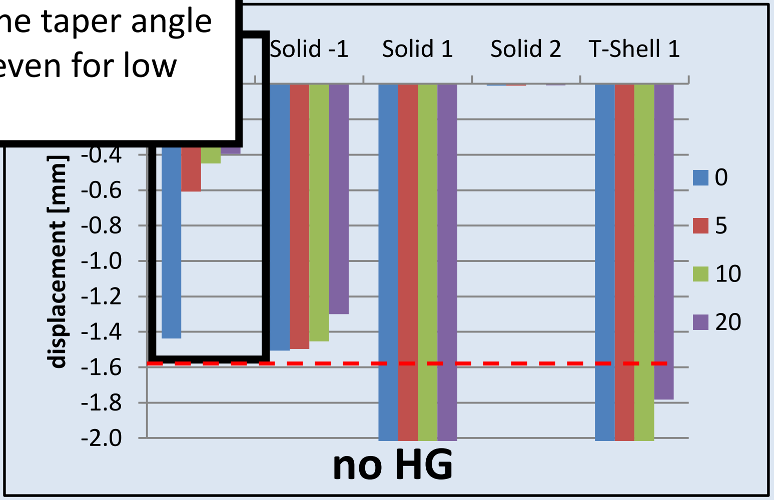


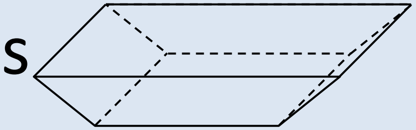


- Solid ELFORM -2 leads to good results only for very small taper angles (close to zero degree) and is therefore very sensitive with respect to the taper angle (element behaves to stiff even for low taper angles)

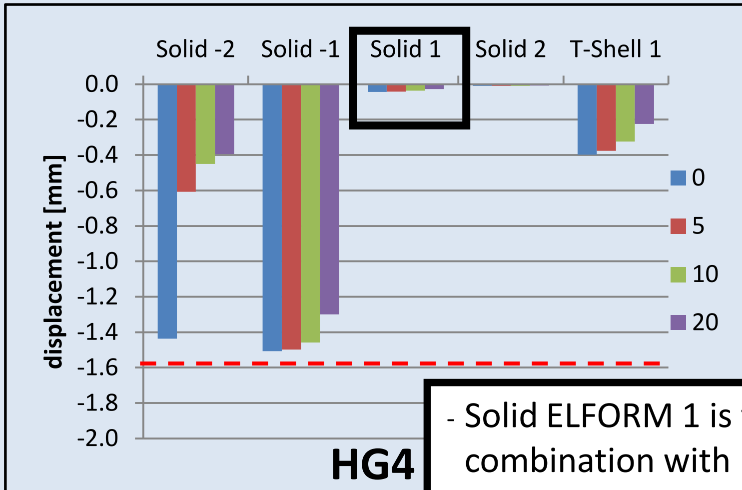


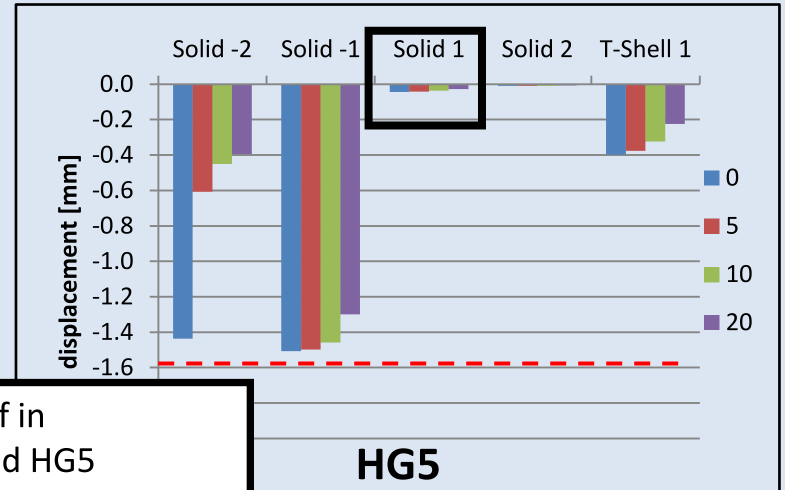


5. Test results with initially deformed elements

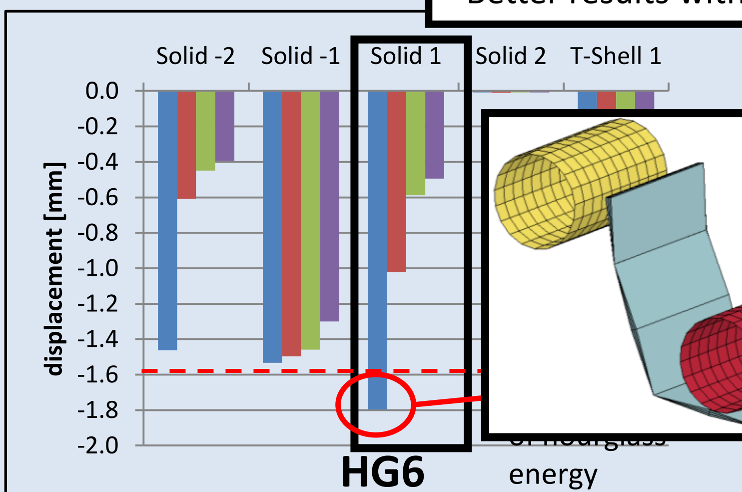


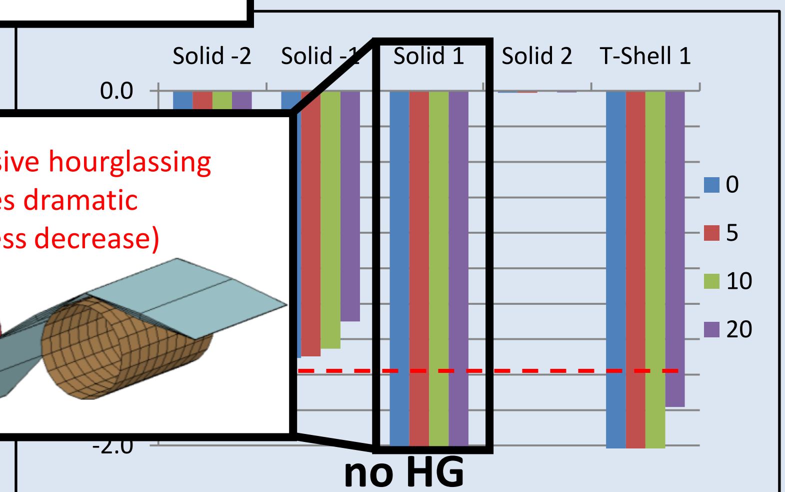
5.2 Max. displacements for **FORCE-BASED** loading

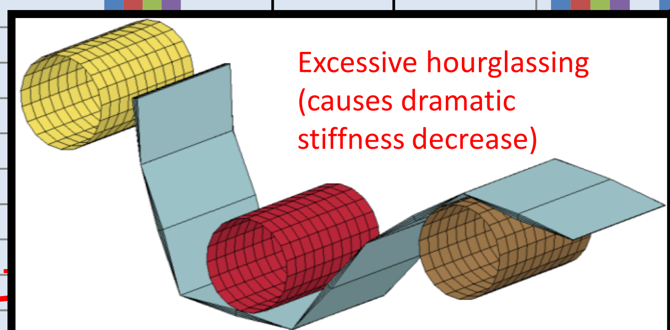




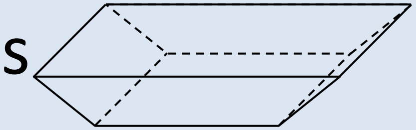
- Solid ELFORM 1 is too stiff in combination with HG4 and HG5
- Better results with HG6



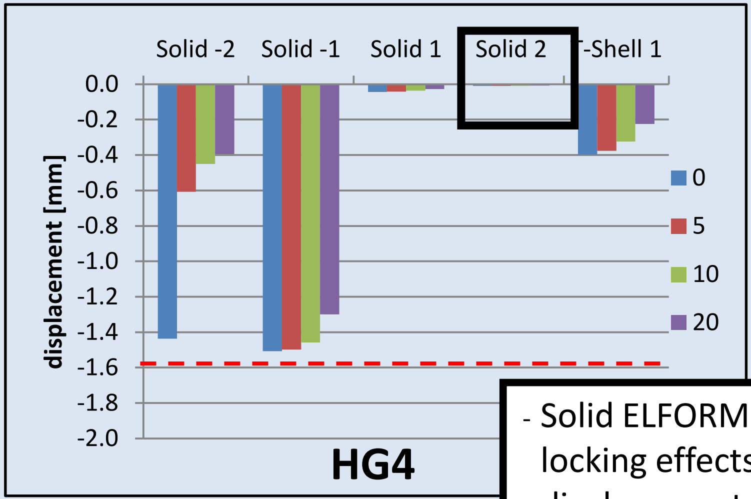


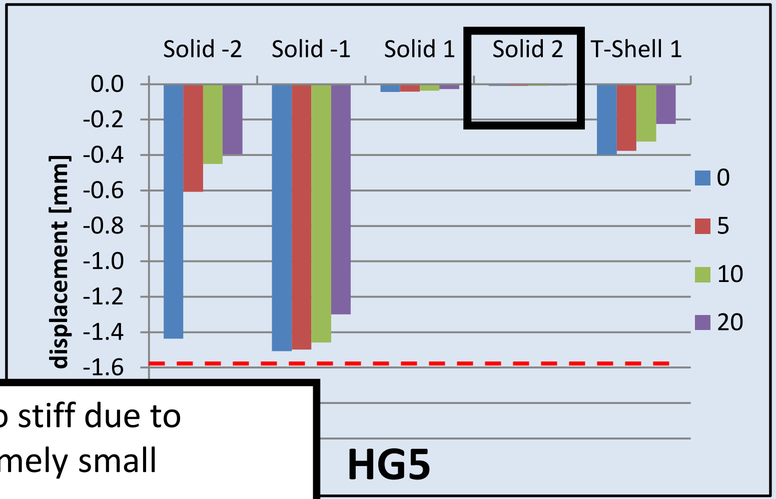


5. Test results with initially deformed elements

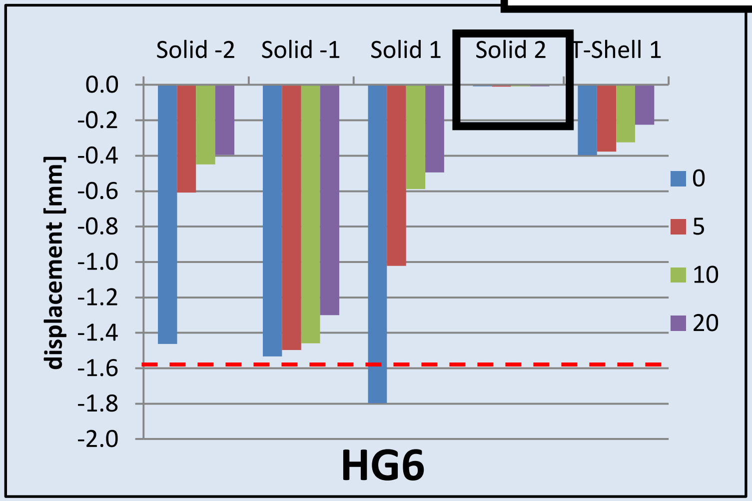


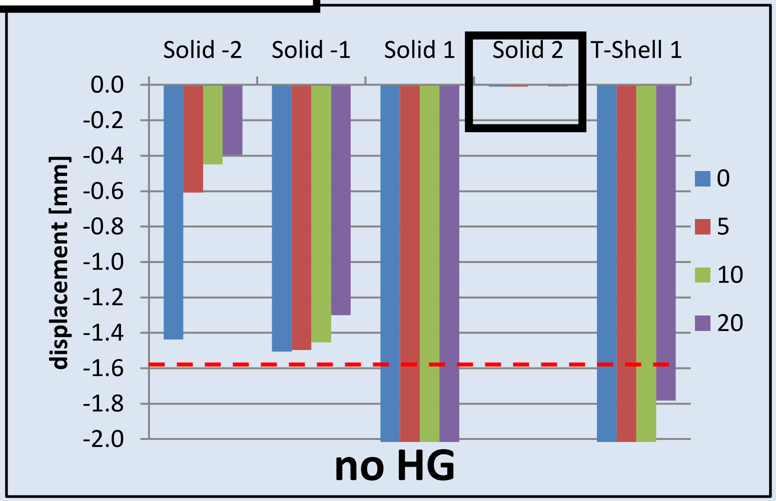
5.2 Max. displacements for **FORCE-BASED** loading



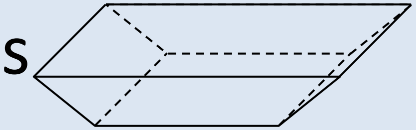


- Solid ELFORM 2 is too stiff due to locking effects (extremely small displacements)

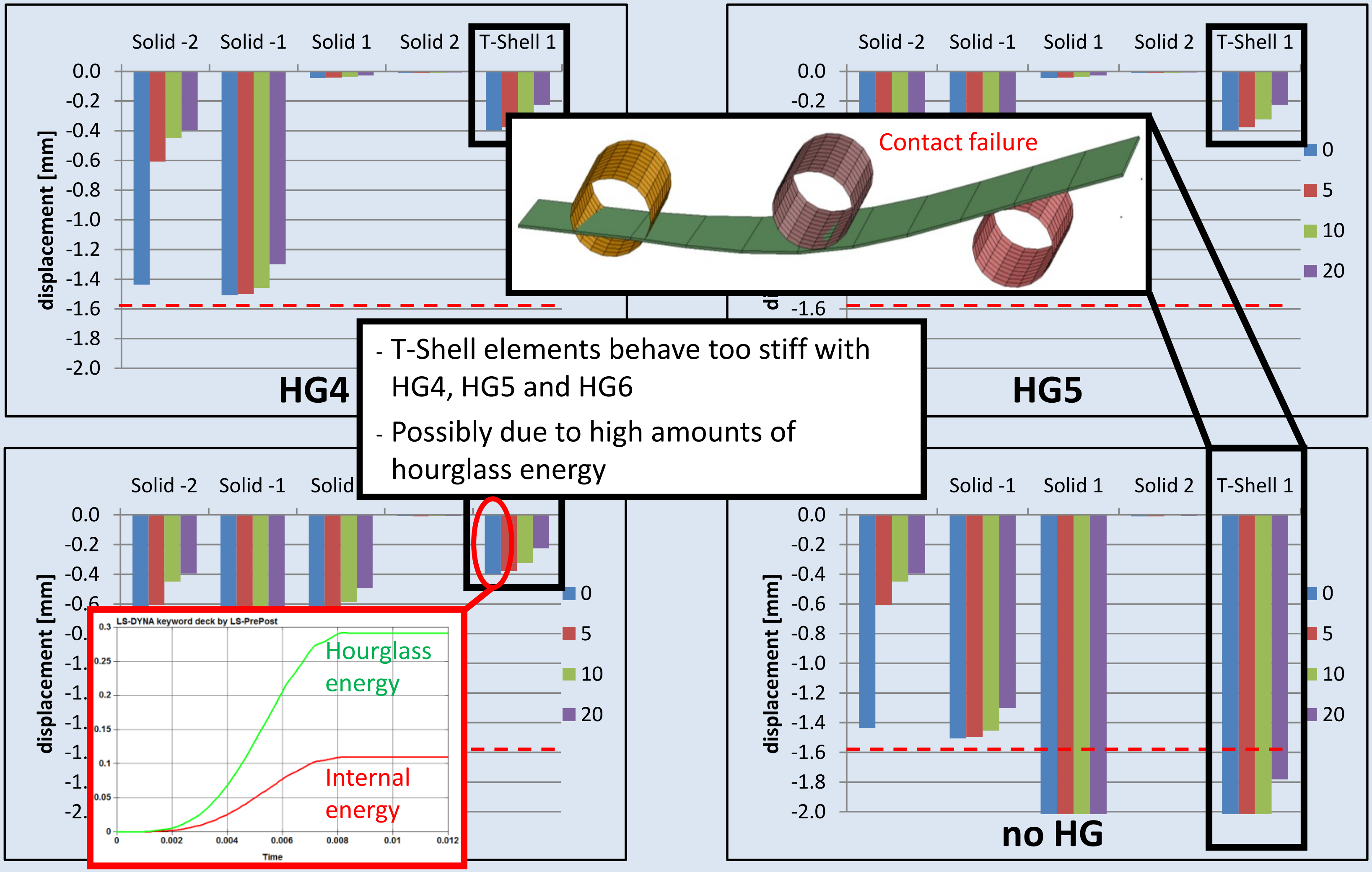




5. Test results with initially deformed elements



5.2 Max. displacements for **FORCE-BASED** loading



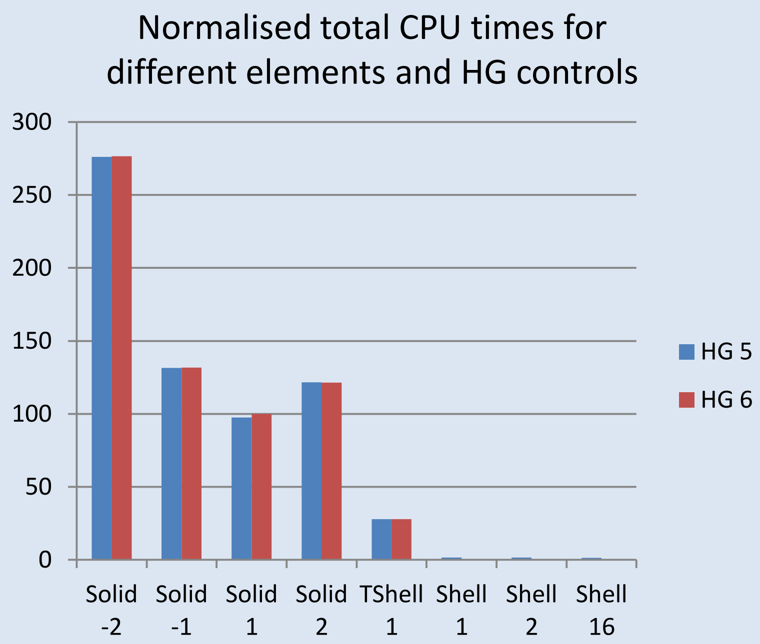
- T-Shell elements behave too stiff with HG4, HG5 and HG6
- Possibly due to high amounts of hourglass energy

6. Comparison of computation time

- The table given below shows the total CPU times [sec] (elapsed time of d3hsp files) for all force-based calculations with a taper angle of 0°deg and hourglass controls 5 or 6
- Because HG6 is not implemented for shell elements, they are not listed in the second table.
- All CPU times are normalised with respect to solid ELFORM 1 (HG6).
- As expected, shell elements are much faster than solid elements (less DOF, bigger time-step size).
- Solid ELFORM 1 is the fastest solid element but ELFORM -1 is only about 30% slower
- There is nearly no difference in the computation time between hourglass control 5 and 6 in LS Dyna.

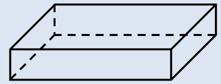
HG5:		Total CPU time [s]	Total CPU time - normalised
Solid	ELFORM -2	1917.700000	276.1
	ELFORM -1	913.280000	131.5
	ELFORM 1	677.950000	97.6
	ELFORM 2	845.120000	121.7
T-Shell	ELFORM 1	193.450000	27.8
Shell	ELFORM 1	11.157000	1.6
	ELFORM 2	11.156000	1.6
	ELFORM 16	9.031000	1.3

HG6:		Total CPU time [s]	Total CPU time - normalised
Solid	ELFORM -2	1920.200000	276.5
	ELFORM -1	915.170000	131.8
	ELFORM 1	694.450000	**100**
	ELFORM 2	843.550000	121.5
T-Shell	ELFORM 1	192.830000	27.8



Summary

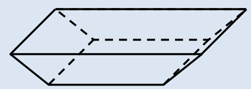
Initially undeformed elements



Displacement-based computations:
- Shell elements compute most accurate stress results due to position of integration points
- Stress results of solid ELFORM 1 strongly depend on the used hourglass control algorithm

Force-based computations:
- Only HG control 6 leads to good results in terms of stresses and displacements for solid ELFORM 1
- HG control 4 and 5 lead to too stiff structures and too low stresses for solid ELFORM 1

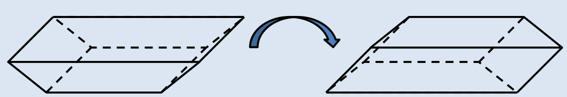
Initially deformed elements (taper angle > 0°)



Displacement-based computations:
- Results of solid ELFORM 1 are highly sensitive with respect to the taper angle
- For taper angles > 0° Solid ELFORM 1 leads to good results only in combination with HG 5
- Solid ELFORM -1 leads to very good results for all taper angles

Forced-based computations:
- Solid ELFORM 1 reacts to stiff in combination with HG control 4 or 5 (good results in combination with HG 6 but only for taper angle =0°)
- Solid -1 leads to good results for all taper angles in terms of stresses and displacements

- All test have also been carried out with negative taper angles and led to quantitatively similar results



Thank you for your attention!

Markus Kober[1], Arnold Kühhorn[1], Benjamin Kästner[1], Akin Keskin[2]

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