PTC CREO SIMULATE ENGINE UPDATES

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March 28, 2017

AGENDA

- General improvements/fixes in simulate engine
  - Engine fixes
  - Engine improvements
- Finite friction improvements
  - Algorithm improvements
  - Interface forces
  - Slippage measures
  - Slippage indicators
  - Local/full sliding messages
- SAXSIM16 model discussions
  - Brake system with infinite friction
  - Brake system with finite friction
  - Flywheel axisymmetric model
  - Feedback
- Creo 5.0 Simulate Engine contact projects
- Conclusions

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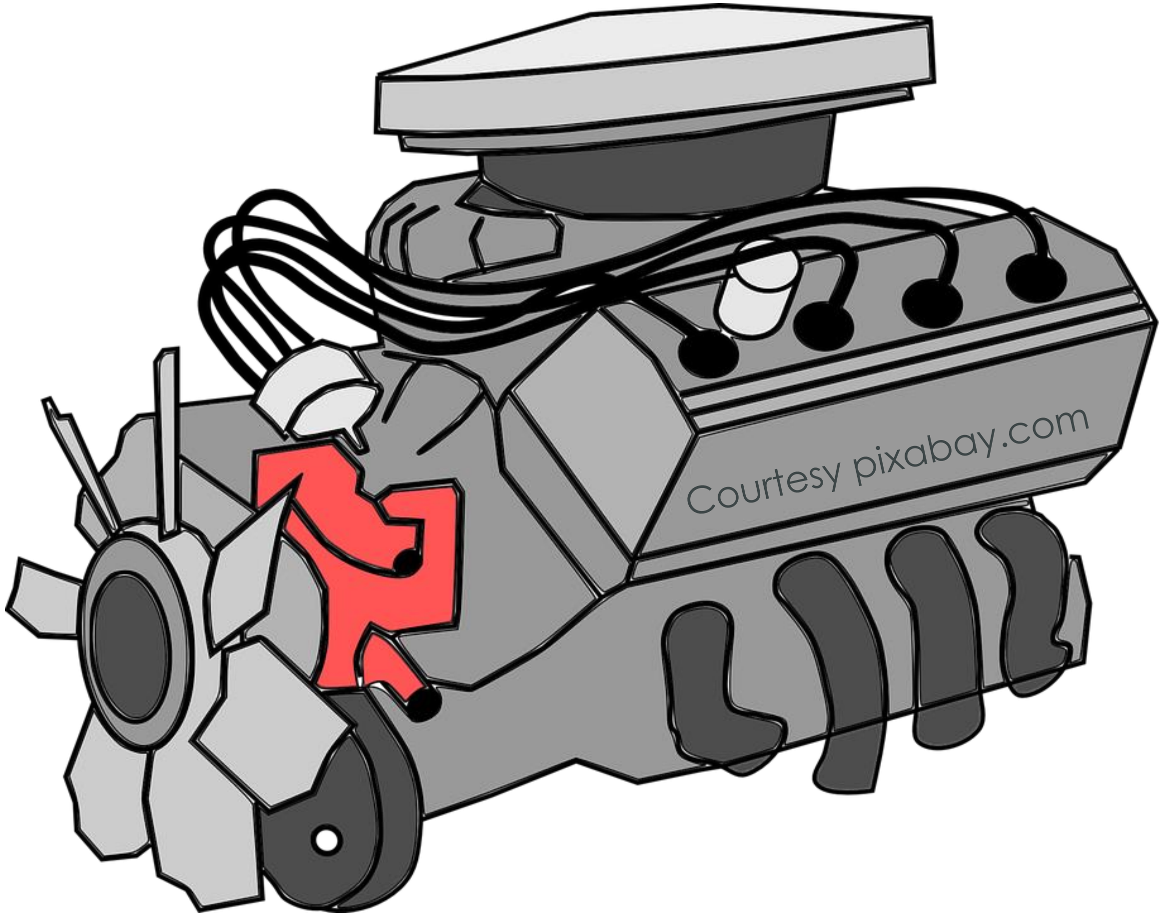
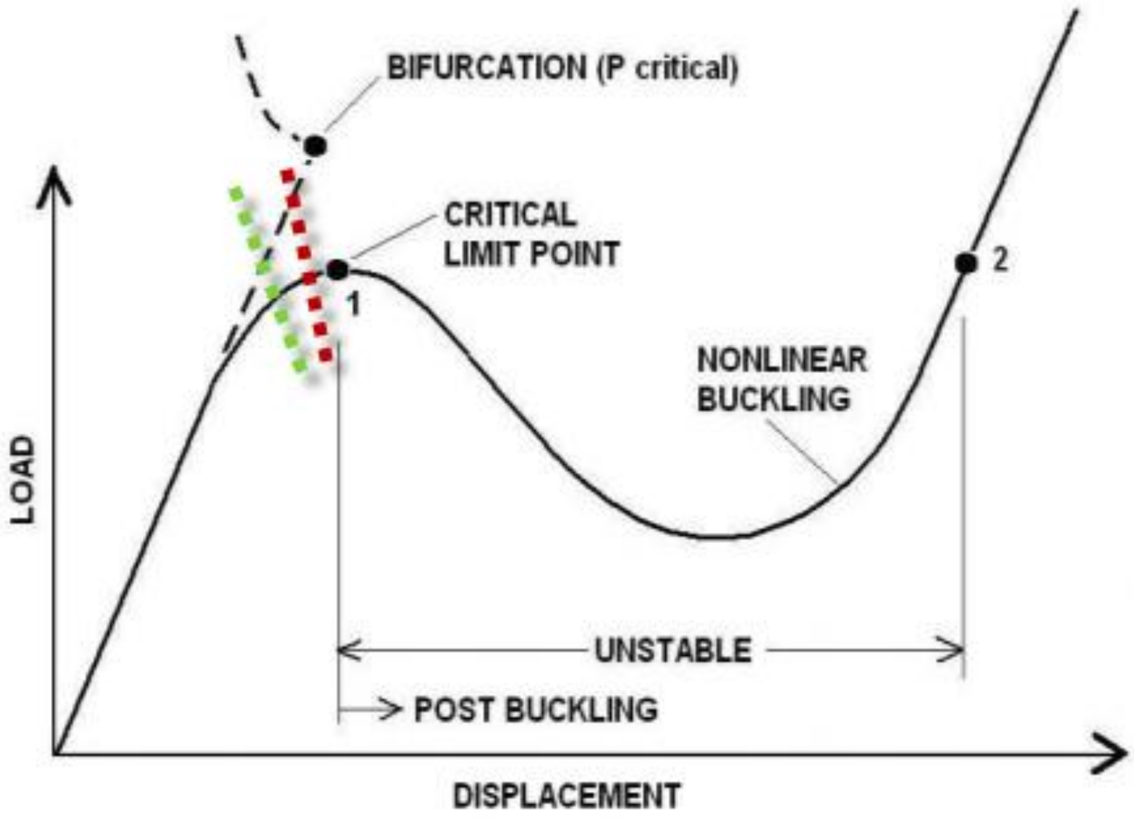
ENGINE FIXES

- Performance with resistance elements.
- Temperature dependent materials.
- Integer overflow, engine crashes.
- Measure calculations for several load cases.
- Fastener measure issue for dynamic shock analysis.
- Mixed shell, solid + contact model constraint issues
- Advanced spring coupling stiffness matrix
- Contact model convergence
- Hyper-elastic, elasto-plastic analysis convergence Etc.



ENGINE IMPROVEMENTS

- Snap-though analysis improvements
  - Algorithm improvements
  - sim_snap_tolerance_factor (sf)
  - sf<1 requesting early start
  - sf>1 requesting delayed start
  - sf=1 default
- NL Solver updates
  - Tuning improvement for finite friction
  - Load displacement curve
    - sim_nl_ldc
  - Accuracy improvements
    - Poor
    - Medium
    - High



Courtesy NASA Langley Research Center

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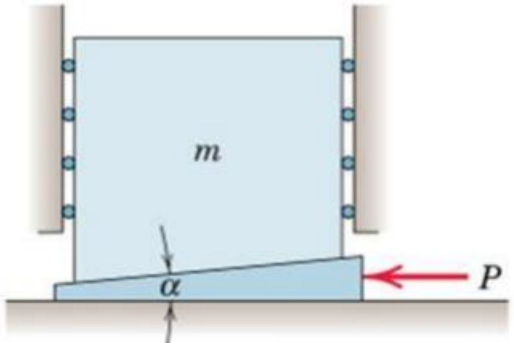
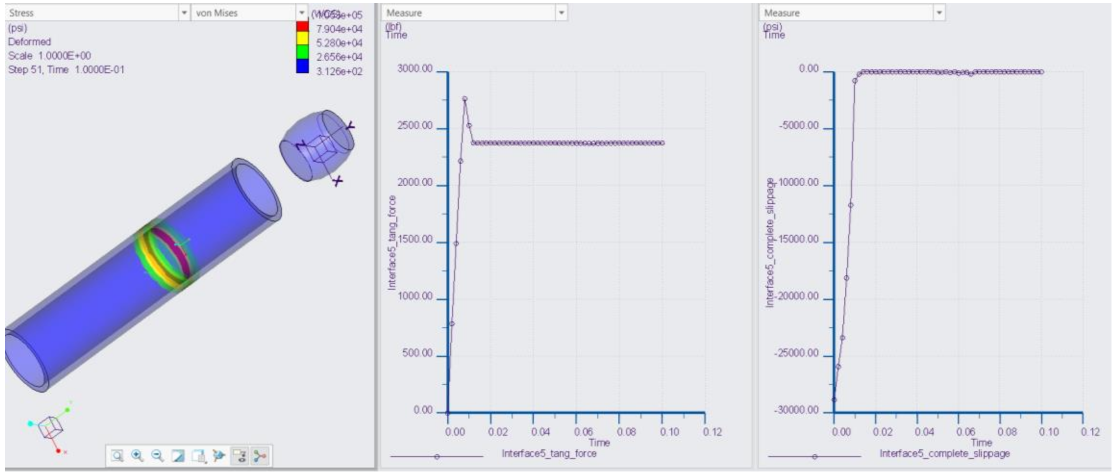
FINITE FRICTION IMPROVEMENTS



- NL Solver algorithm updates
  - Better control on penetration
  - Energy convergence improvement
  - Area/force convergence improvements
- Contact force measures calculation updates
  - Contact interface load measure can be calculated from element stresses on user request
  - Contact interface tangential force measure improvement
- Contact slippage indicator measure updates
  - Any slippage
  - Average slippage
  - Complete slippage
- Contact slippage indicator fringe plot updates
  - Better many-to-few mapping
  - Normalization
  - Sanity checks



- Contact message improvements
  - In RPT file, for every interface, first occurrence of local/full sliding will be intimated
  - In PAS file, for every interface, current state of local/full sliding will be intimated

FINITE FRICTION BASICS

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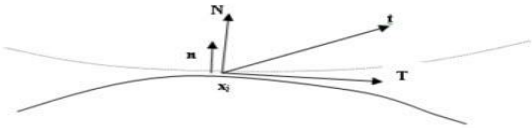
- Friction plays an important role in number of our daily activities and in most industrial processes. Friction not only aids in starting the motion of body but also in changing its direction and subsequently stopping it

- FEM modeling of contacts with friction is of paramount importance for cases where one has to answer questions like:
  - Will sliding occur? When will it occur?
  - What kind of sliding occurs? Local sliding/Full sliding ? Or tipping?

- We will study different scenarios to validate the simulation results
  - Sticking
  - Sliding, and
  - Tipping



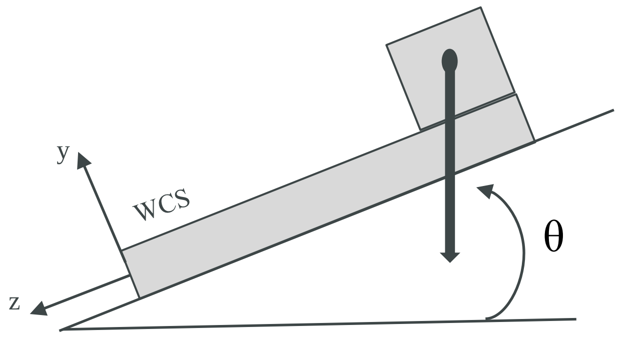
The slippage at a given point $\mathbf{x}_i$ then is $S_i = T - \mu \cdot N \leq 0$

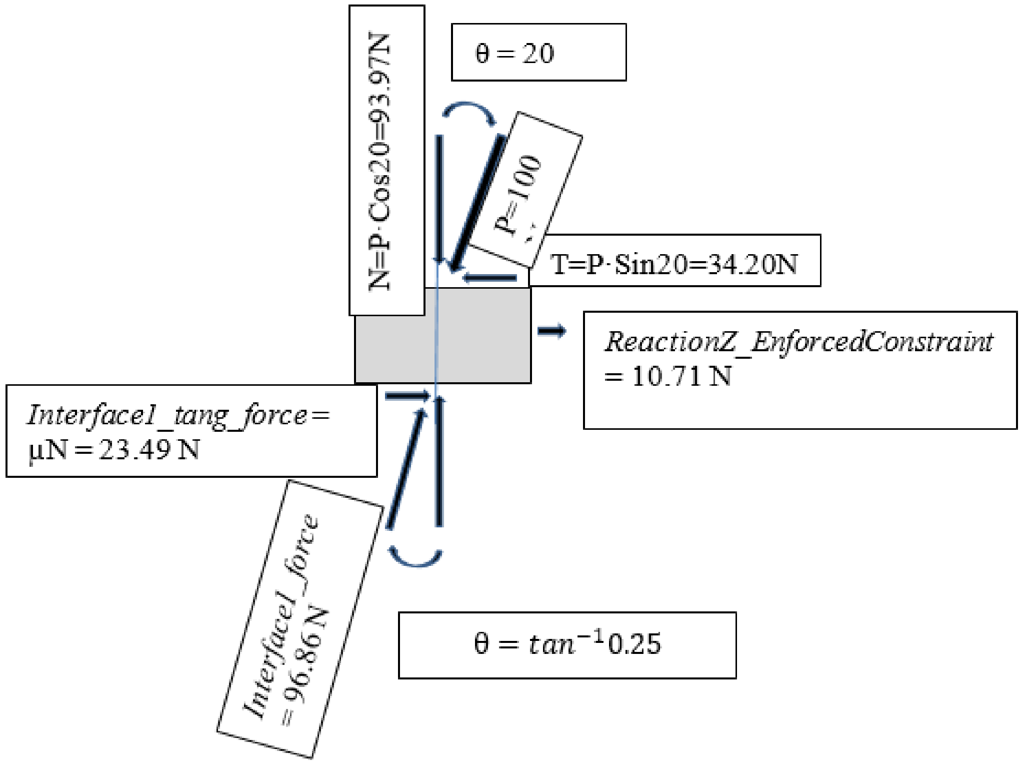
The following measures are available measures for a contact interface:

- *InterfaceName_force – Resultant force*
- *InterfacName_tang_force – Tangential force*
- *InterfaceName_load – Normal force*
- *InterfaceName_any_slippage – Maximum* slippage
- *InterfaceName_complete_slippage – Minimum* slippage
- *Interfacename_average_slippage – Average* slippage
- *InterfaceName_max_tang_traction – Maximum shear stress*

CASE STUDY 1: WHEN WILL SLIDING OCCUR?

Find the minimum angle required (θ) to initiate the sliding of a block on an inclined platform shown below and compare *Creo® Simulate* result to analytical solution. Assume static coefficient of friction as 0.25, W = weight of the block = 100 N. The analytical solution of this case is, $\theta = \tan^{-1}\mu_s \cong 14^0$





Creo® Simulate result

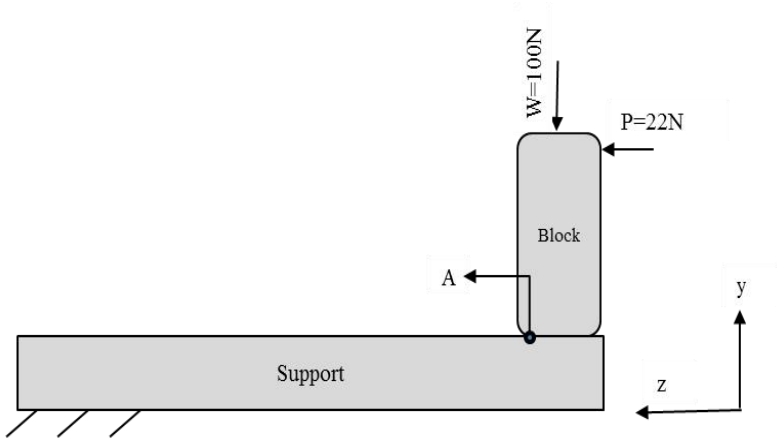
```
Interface1_force:                    9.686116e+01
Interface1_max_tang_traction:        1.144830e-01
Interface1_tang_force:               2.349228e+01
ReactionMag_support:                 9.686128e+01
ReactionY_support:                   9.396926e+01
ReactionZ_EnforcedConstraint:       -1.070990e+01
ReactionZ_support:                  -2.349225e+01
```

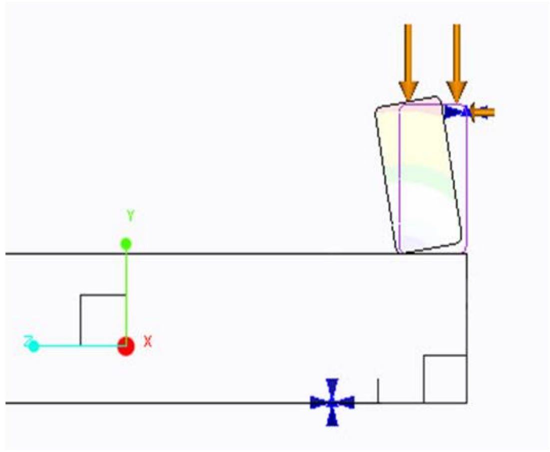
Sr. No.	Measure	θ = 12 deg	θ = 14 deg	θ = 16 deg
1	Interface1_average_slippage	-1.393808e-03	3.421150e-03	1.416395e-02

CASE STUDY 2: WILL TIPPING OR SLIDING OCCUR?

A block is resting on large flat rough support.

Given μ_s=μ_d=0.25, W=100N, P=22N. Will the block slide OR Tip?





Interface1 is stuck, as:

- Measure any slippage is +ve
- Measure average slippage –ve

```
Interface1_any_slippage:        2.535085e+01
Interface1_area:                2.545647e-01
Interface1_average_slippage:   -1.583196e+00
Interface1_complete_slippage:  -3.860591e+01
```

```
ReactionMag_EnforcedDisp:       2.222372e+01
ReactionMag_support:            1.000098e+02
ReactionX_EnforcedDisp:        -1.390416e+00
ReactionY_EnforcedDisp:         0.000000e+00
ReactionY_support:              1.000000e+02
ReactionZ_EnforcedDisp:        -2.218018e+01
ReactionZ_support:              1.801813e-01
```

$$\sum F\_z = \text{ReactionZ\_support} + ReactionZ\_EnforcedDisp + P = 0.18 - 22.18 + 22.0 = 0$$

$$\sum F\_y = \text{ReactionY\_support} + W = 100.0 - 100.0 = 0$$

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SAXSIM 2016: SUMMARY OF ISSUES REPORTED

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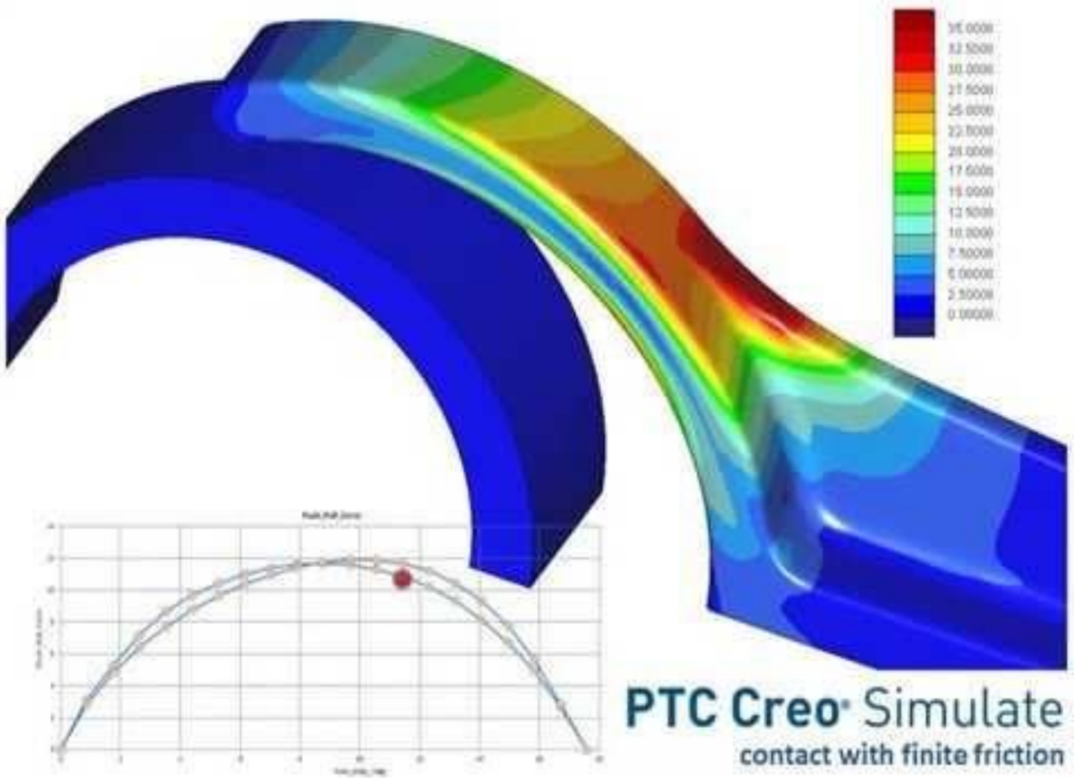
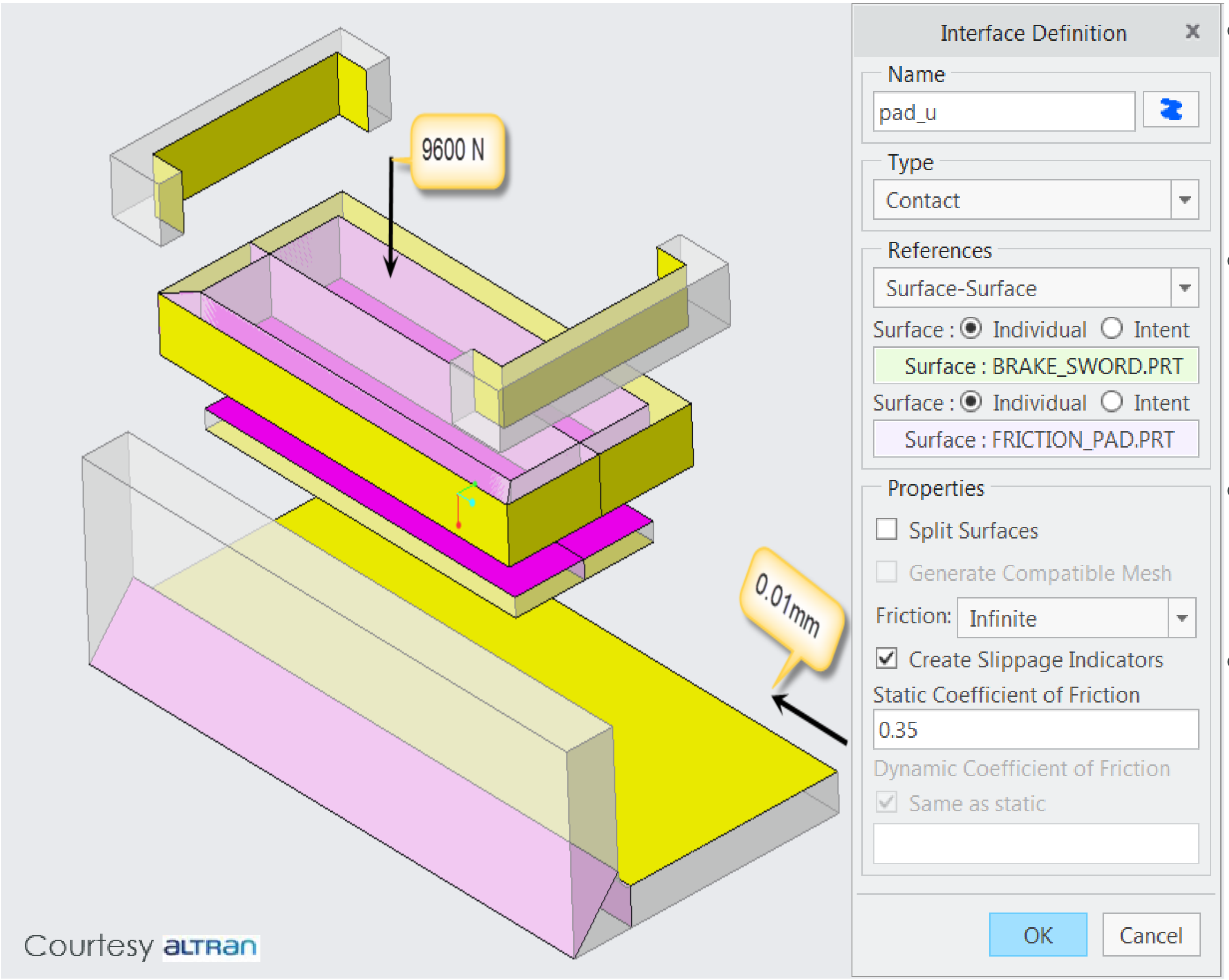
- Finite friction functionality does not work
  - Interface force measure results for SPA are wrong
  - Interface tangential force measure results are not accurate
  - Interface slippage indicator results are not synchronized with RPT/PAS messages
  - Interface slippage measure results are inaccurate
- Infinite friction SDA results are bad
- Engine accepts very loose residual norm
- Contact load measure in Creo 3.0 can not be used as mesh quality checking tool
  - Creo 3.0 calculates it from spring forces
  - Creo 2.0 calculates it from element stresses
- Symmetry constraint and preload scaling issues



Courtesy Urs Simmler

BRAKE SYSTEM: INFINITE FRICTION CASE



- Two pads:
  - pad_u and
  - pad_o
- Both C-frames
  - stiff and
  - fixed
- Given displacement
  - -0.01mm
- Issues raised
  - Contact forces jump in SDA analysis
  - Slippage indicator fringe plots

BRAKE SYSTEM: INFINITE FRICTION CASE

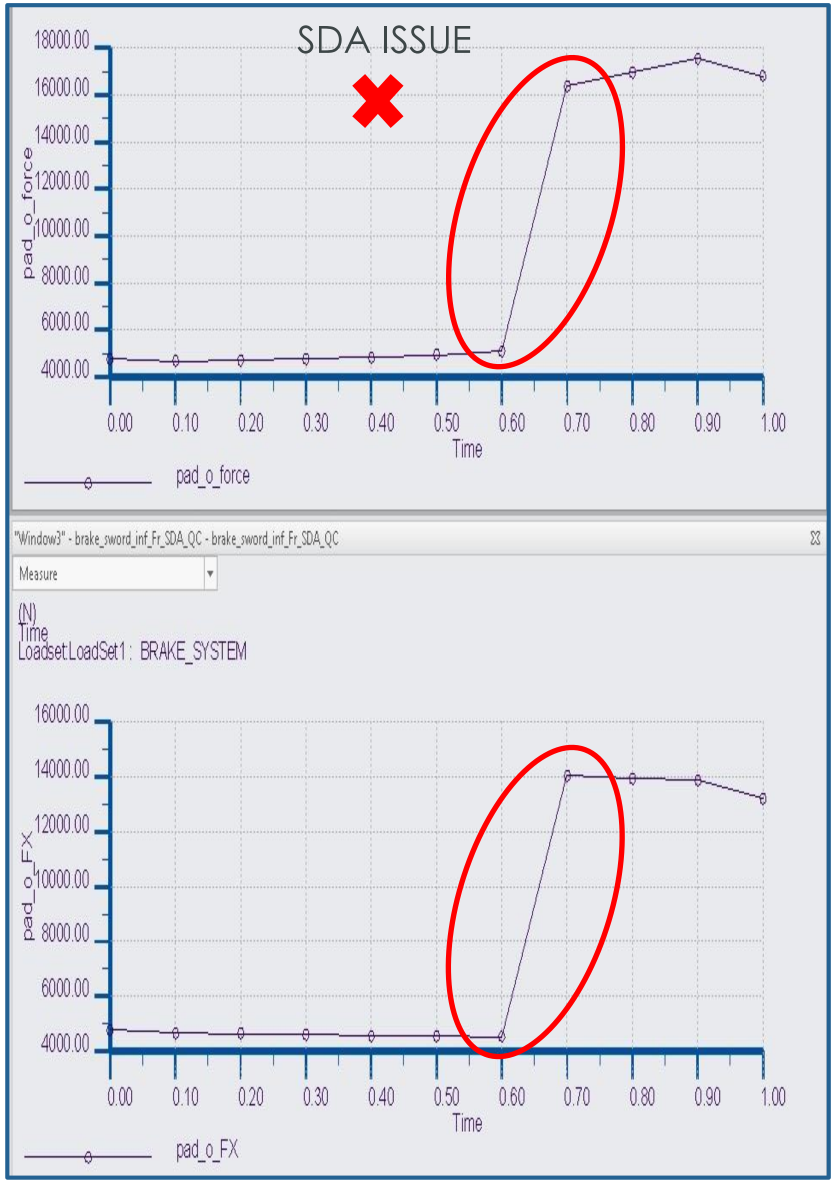
- Infinite friction SDA analysis case
  - When run with increased contact number of iterations (say 500), the Creo Simulate engine delivers interface force measure results that unreasonably jump after some time.
  - A fix is found and will be shipped in next possible build*

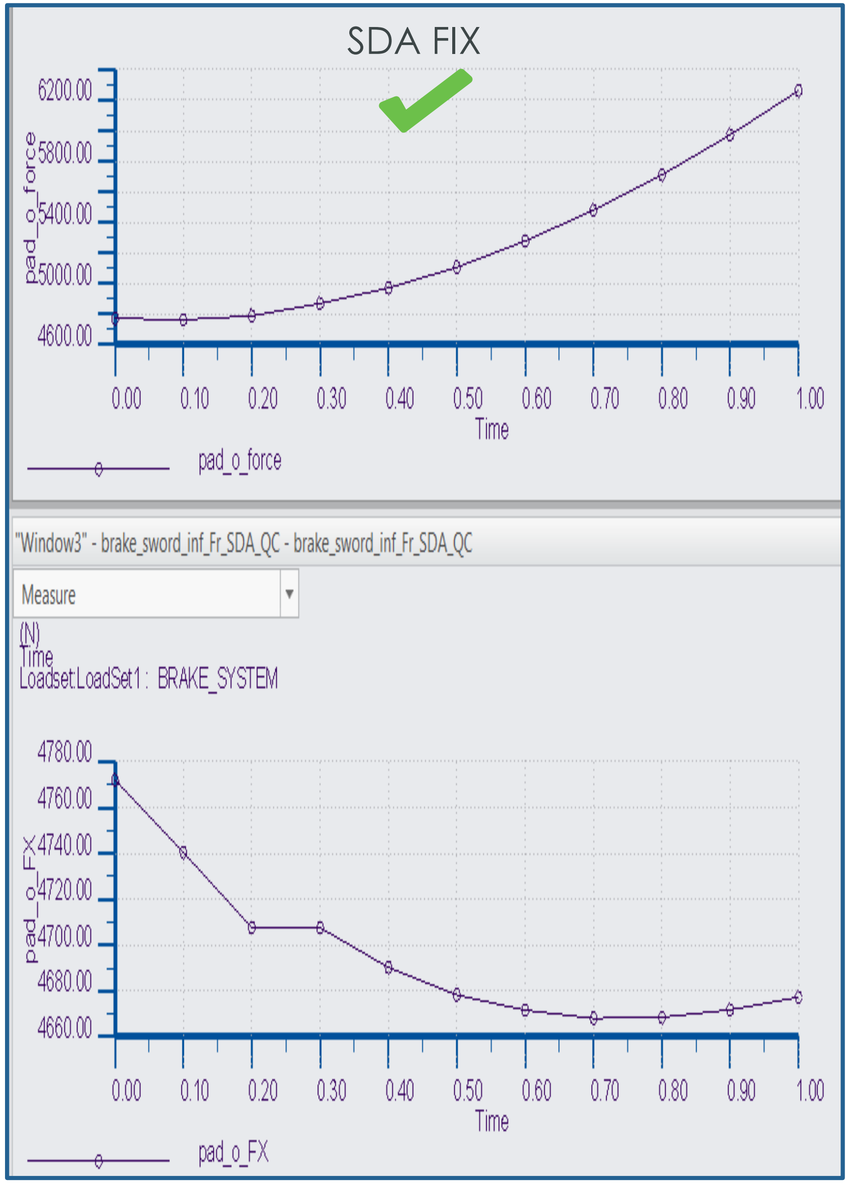
- The work around is to run LDA analysis with an adequate number of output steps (e.g. 11).
  - To ensure the sum of contact normal forces is 9600N, user can create a user defined Interface force measure in WCS:X direction for pad_o and pad_u interfaces and add them.

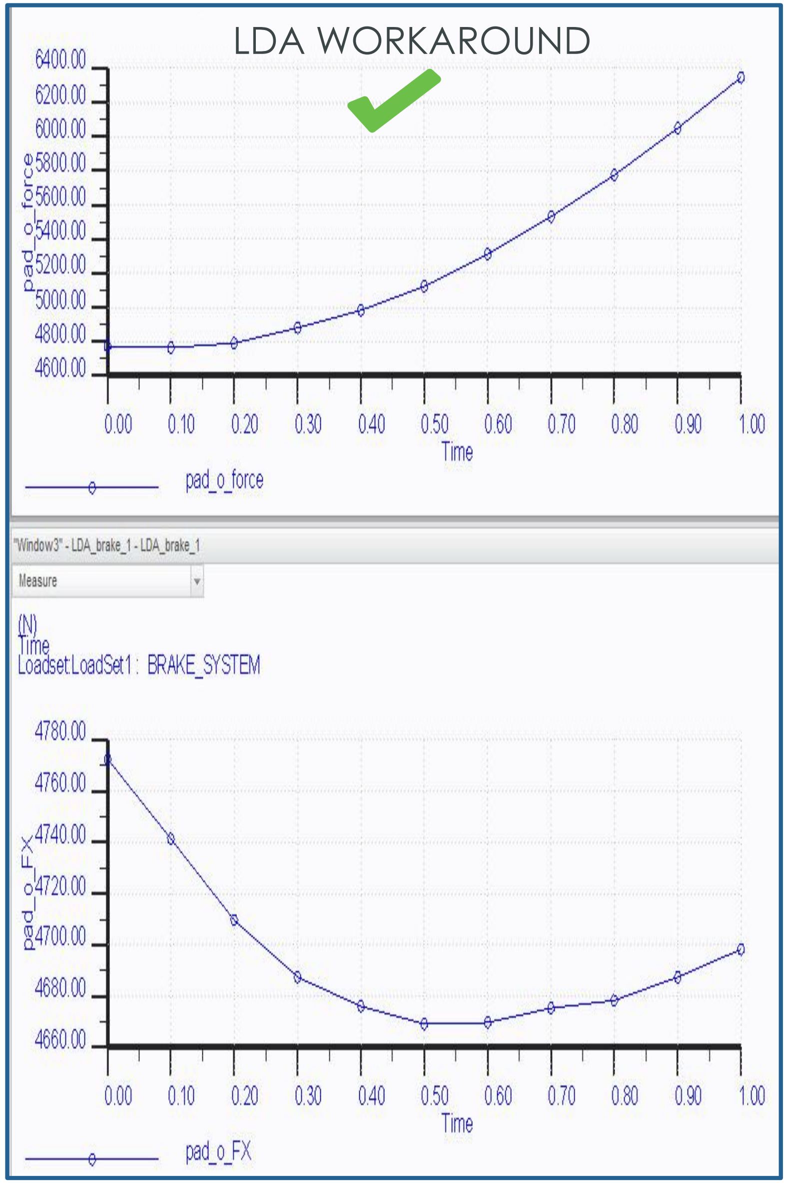
- The Screenshots of related measure plots are shared in next slides

Courtesy pinterest.com

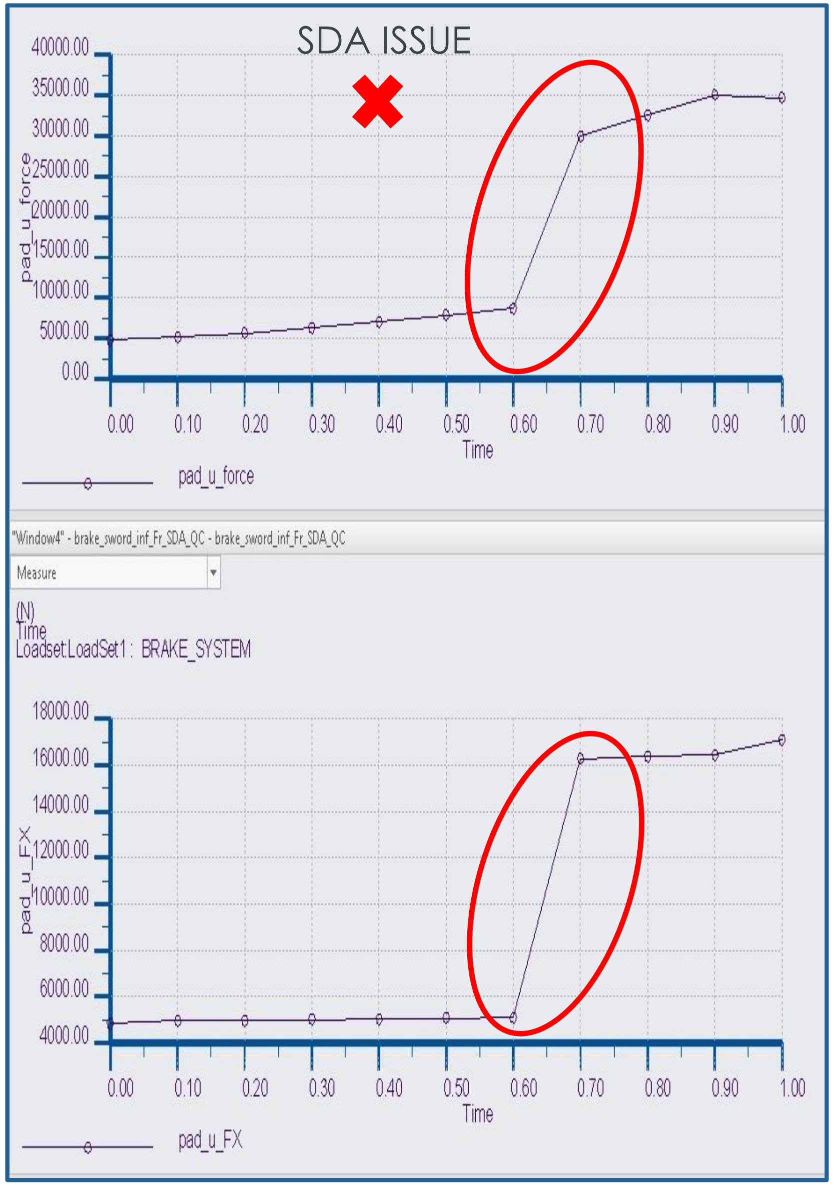
BRAKE SYSTEM: INFINITE FRICTION CASE

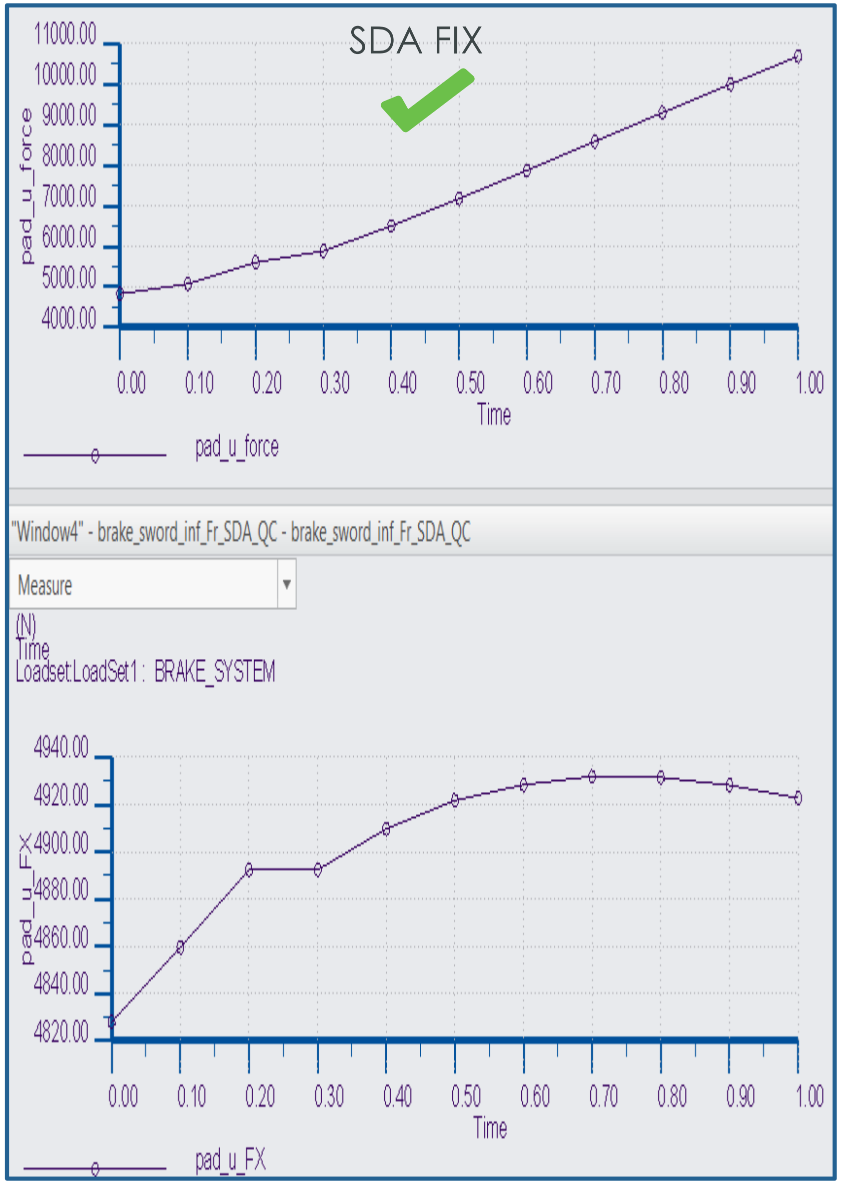


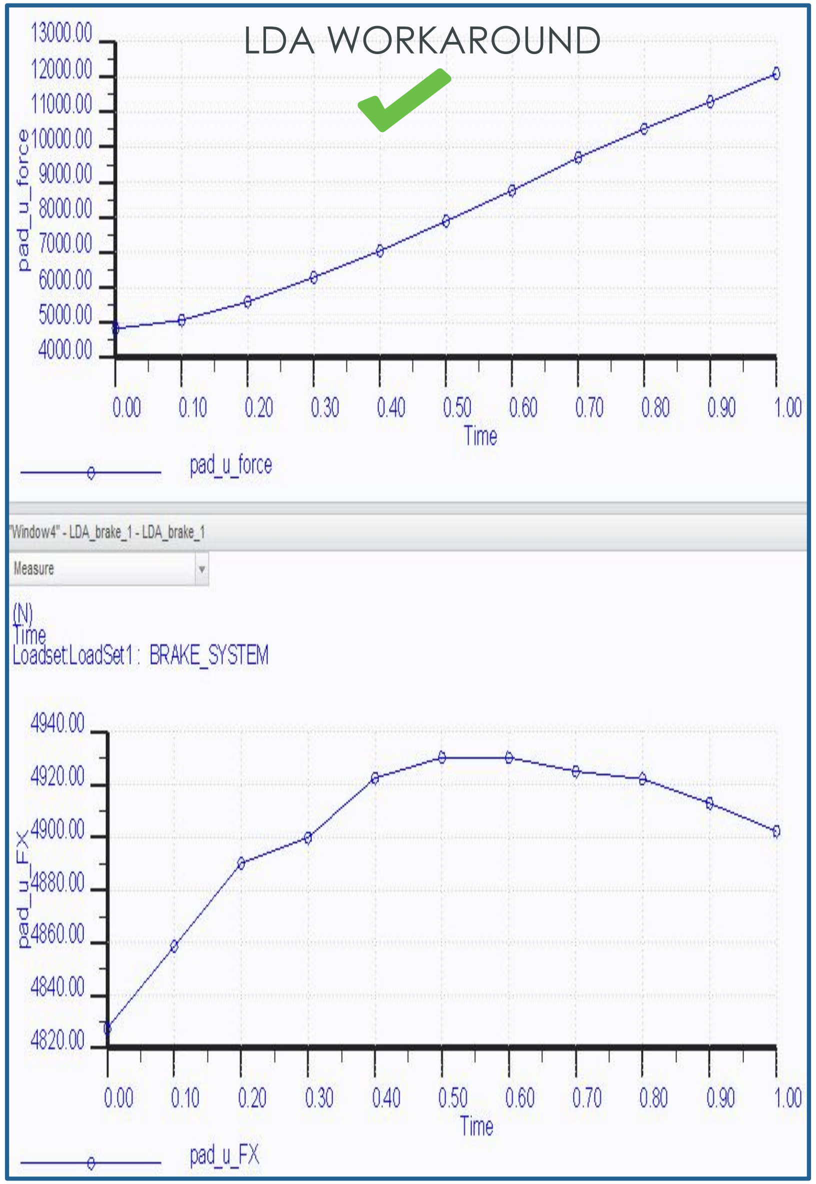




BRAKE SYSTEM: INFINITE FRICTION CASE







BRAKE SYSTEM: FINITE FRICTION RESULTS

```
   >> Pass  2 <<
      Calculating Element Equations          (11:00:43)
         Total Number of Equations:   86309
         Maximum Edge Order:              9
      Solving Equations                      (11:01:00)
      Time Step 1 of 11:   0.00000e+00
      Contact Area:  1.24500e+04
      Calculating Disp and Stress Results    (11:02:28)
      Solving Equations                      (11:02:32)
      Time Step 2 of 11:   1.00000e-01
*** sliding first Occurred
*** pad_u:locally sliding
      Contact Area:  1.15905e+04
      Calculating Disp and Stress Results    (11:03:54)
      Solving Equations                      (11:03:58)
      Time Step 3 of 11:   2.00000e-01
      Contact Area:  1.15682e+04
      Calculating Disp and Stress Results    (11:05:05)
      Solving Equations                      (11:05:09)
      Time Step 4 of 11:   3.00000e-01
*** pad_u:fully sliding
      Contact Area:  1.14659e+04
      Calculating Disp and Stress Results    (11:05:58)
      Solving Equations                      (11:06:02)
      Time Step 5 of 11:   4.00000e-01
```

```
Begin Time Step 1 of 10:  1.00000e-01
Fri Jul 01, 2016   11:02:32

Iteration        Residual norm     contact Area
-------------   -------------   ----------------
            1        0.482314 11607.8      Fri Jul 01, 2016 11:02:52
            2        0.303474 11204.6      Fri Jul 01, 2016 11:02:56
            3       0.0297424 11282.5      Fri Jul 01, 2016 11:02:58
            4       0.0149675 11250      Fri Jul 01, 2016 11:03:00
            5      0.00667361 11088.5      Fri Jul 01, 2016 11:03:02
            6      0.00544438 11259.1      Fri Jul 01, 2016 11:03:03
            7      0.00393995 11151      Fri Jul 01, 2016 11:03:06
            8      0.00227702 11211.6      Fri Jul 01, 2016 11:03:10
            9     0.000786058 11168.1      Fri Jul 01, 2016 11:03:12
           10     0.000771243 11069.8      Fri Jul 01, 2016 11:03:15
           11     0.000436897 11413.6      Fri Jul 01, 2016 11:03:18
           12     0.000538915 11466.7      Fri Jul 01, 2016 11:03:22
           13     0.000411721 11180.2      Fri Jul 01, 2016 11:03:26
           14    6.83751e-005 11187      Fri Jul 01, 2016 11:03:27
           15    5.61147e-005 11412.2      Fri Jul 01, 2016 11:03:30
           16     4.9663e-005 11535.2      Fri Jul 01, 2016 11:03:32
           17    2.29696e-005 11540.3      Fri Jul 01, 2016 11:03:35
           18    1.54079e-005 11547      Fri Jul 01, 2016 11:03:39
           19      6.954e-006 11548.7      Fri Jul 01, 2016 11:03:42
           20     3.4213e-006 11590.5      Fri Jul 01, 2016 11:03:46
***Looser residual tolerance accepted because area and force
   converged for all contacts
*** sliding first Occurred
*** pad_u:locally sliding
```

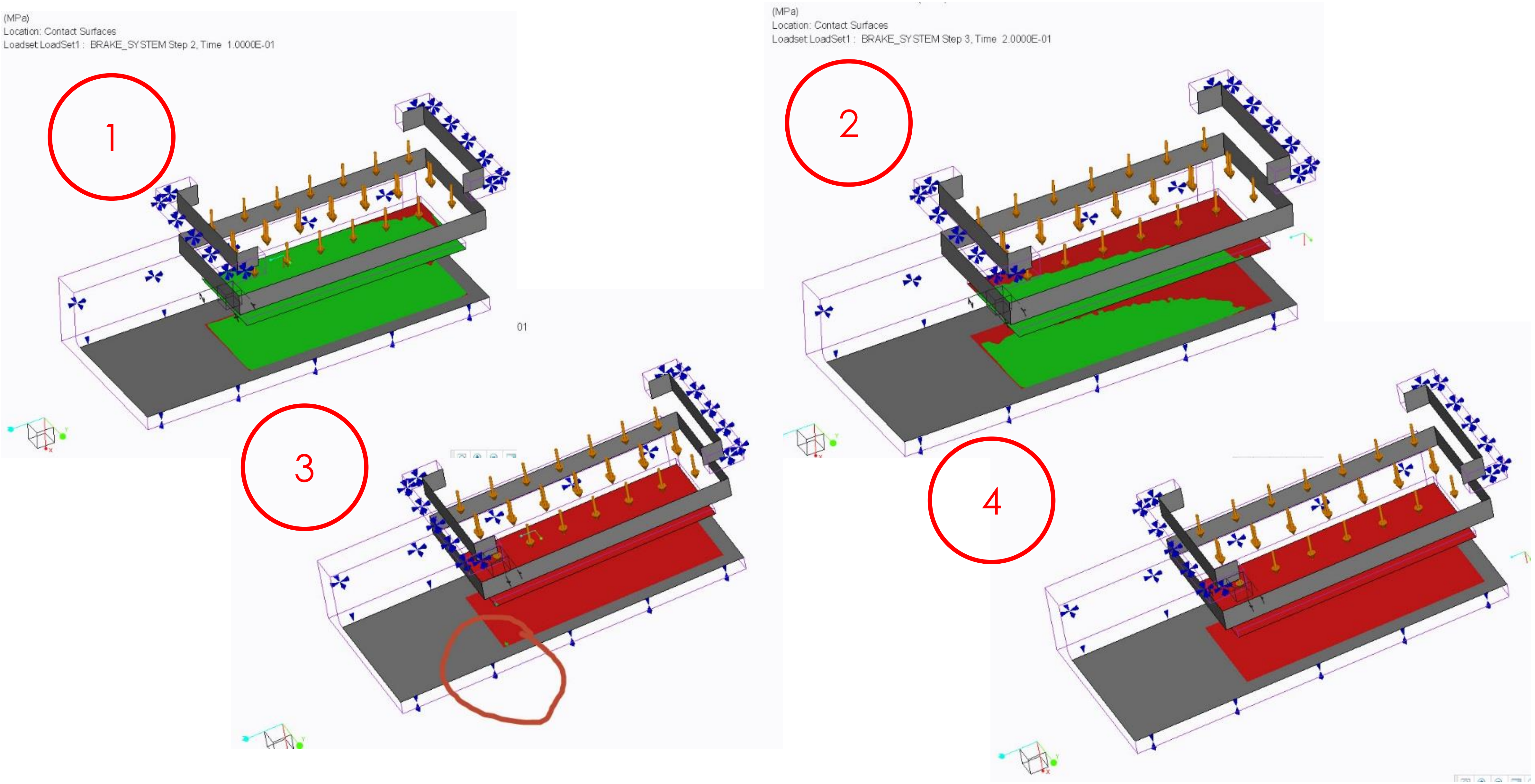
```
Begin Time Step 3 of 10:  3.00000e-01
Fri Jul 01, 2016   11:05:09

Iteration        Residual norm     contact Area
-------------   -------------   ----------------
            1       0.0461888 11560.4      Fri Jul 01, 2016 11:05:28
            2       0.0944069 11475      Fri Jul 01, 2016 11:05:32
            3      0.00971162 11407.9      Fri Jul 01, 2016 11:05:33
            4      0.00221927 11456.9      Fri Jul 01, 2016 11:05:35
            5     0.000904299 11475      Fri Jul 01, 2016 11:05:36
            6      0.00117427 11404.8      Fri Jul 01, 2016 11:05:37
            7     0.000489713 11440      Fri Jul 01, 2016 11:05:39
            8     0.000339117 11440.5      Fri Jul 01, 2016 11:05:42
            9    9.83818e-005 11438.9      Fri Jul 01, 2016 11:05:45
           10    5.89825e-005 11467.9      Fri Jul 01, 2016 11:05:47
           11    2.36539e-005 11465.9      Fri Jul 01, 2016 11:05:50
***Looser residual tolerance accepted because area and force
   converged for all contacts
*** pad_u:fully sliding
```

```
Begin Time Step 4 of 10:  4.00000e-01
Fri Jul 01, 2016   11:06:02

Iteration        Residual norm     contact Area
-------------   -------------   ----------------
            1        0.142417 11565.4      Fri Jul 01, 2016 11:06:21
            2        0.117073 11447.2      Fri Jul 01, 2016 11:06:26
            3       0.0167615 11450.1      Fri Jul 01, 2016 11:06:29
            4      0.00648286 11470.5      Fri Jul 01, 2016 11:06:30
            5      0.00161651 11471      Fri Jul 01, 2016 11:06:31
            6      0.00121884 11465.8      Fri Jul 01, 2016 11:06:33
            7     0.000390819 11483.2      Fri Jul 01, 2016 11:06:35
            8      0.00028584 11505.3      Fri Jul 01, 2016 11:06:39
            9    7.90041e-005 11519.5      Fri Jul 01, 2016 11:06:42
***Looser residual tolerance accepted because area and force
   converged for all contacts
*** pad_u:fully sliding
*** pad_o:fully sliding
```

BRAKE SYSTEM: FINITE FRICTION RESULTS



BRAKE SYSTEM: FINITE FRICTION RESULTS

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Resultant Load on Model:

in global X direction:	9.599973e+03
in global Y direction:	-1.443876e-02
in global Z direction:	-4.043298e-02

Measures:

contact_area:	1.150560e+04
contact_max_pres:	6.037768e+00
max_beam_bending:	0.000000e+00
max_beam_tensile:	0.000000e+00
max_beam_torsion:	0.000000e+00
max_beam_total:	0.000000e+00
max_disp_mag:	1.001098e-02
max_disp_x:	1.436474e-03
max_disp_y:	6.361737e-04
max_disp_z:	-1.001062e-02
max_prin_mag*:	9.522586e+00
max_rot_mag:	0.000000e+00
max_rot_x:	0.000000e+00
max_rot_y:	0.000000e+00
max_rot_z:	0.000000e+00
max_stress_prin*:	9.522586e+00
max_stress_vm*:	9.420534e+00
max_stress_xx*:	-3.489501e+00
max_stress_xy:	2.293706e+00
max_stress_xz:	2.489589e+00
max_stress_yy:	6.127323e+00
max_stress_yz*:	5.278043e+00
max_stress_zz:	-7.759696e+00
min_stress_prin:	-8.878019e+00
strain_energy:	4.145296e+00
F_Z:	-3.359932e+03
Frame_FX:	2.037907e-02
Frame_FY:	-1.157968e+01
Frame_FZ:	3.359972e+03

Frame_IF1_area:	3.850186e+02
Frame_IF1_force:	2.830309e+02
Frame_IF2_area:	6.000035e+02
Frame_IF2_force:	1.682665e+03
Frame_IF3_area:	6.000036e+02
Frame_IF3_force:	1.677305e+03
Frame_IF4_area:	3.205742e+02
Frame_IF4_force:	2.714507e+02
Frame_IF5_area:	0.000000e+00
Frame_IF5_force:	0.000000e+00
Frame_IF6_area:	0.000000e+00
Frame_IF6_force:	0.000000e+00
disp_sword:	1.000000e-02
pad_o_any_slippage:	2.089808e-01
pad_o_area:	4.799999e+03
pad_o_average_slippage:	4.109060e-04
pad_o_complete_slippage:	-1.846389e-01
pad_o_force:	5.031617e+03
pad_o_max_tang_traction:	5.549103e-01
pad_o_tang_force:	1.662197e+03
pad_u_any_slippage:	2.030510e-01
pad_u_area:	4.799998e+03
pad_u_average_slippage:	-1.818560e-03
pad_u_complete_slippage:	-1.922959e-01
pad_u_force:	5.139379e+03
pad_u_max_tang_traction:	5.714244e-01
pad_u_tang_force:	1.697796e+03

pad_o_normal = $\sqrt{pad\_o\_force^2 - pad\_o\_tang\_force^2}$

pad_o_normal = $\sqrt{5031.62^2 - 1662.20^2} = 4749.14$

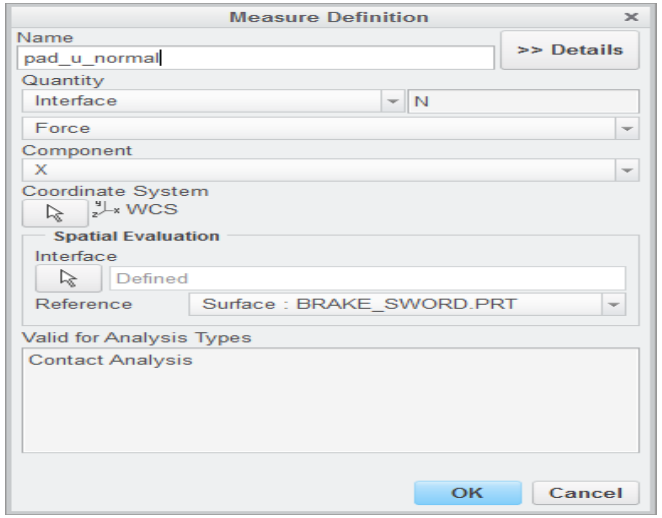
pad_u_normal = $\sqrt{5139.38^2 - 1697.80^2} = 4850.85$

Total normal force = pad_o_normal + pad_u_normal

Total normal force = 9599.99 N

$$\mu_o = \frac{pad\_o\_tang\_force}{pad\_o\_normal} = \frac{1662.20}{4749.14} = 0.35$$

$$\mu_u = \frac{pad\_u\_tang\_force}{pad\_u\_normal} = \frac{1697.80}{4850.85} = 0.35$$



IMPORTANT POINTS FOR FINITE FRICTION RESULTS

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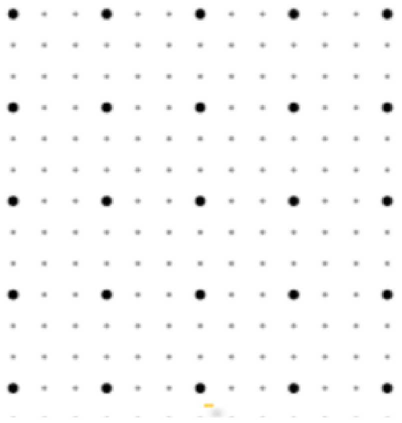
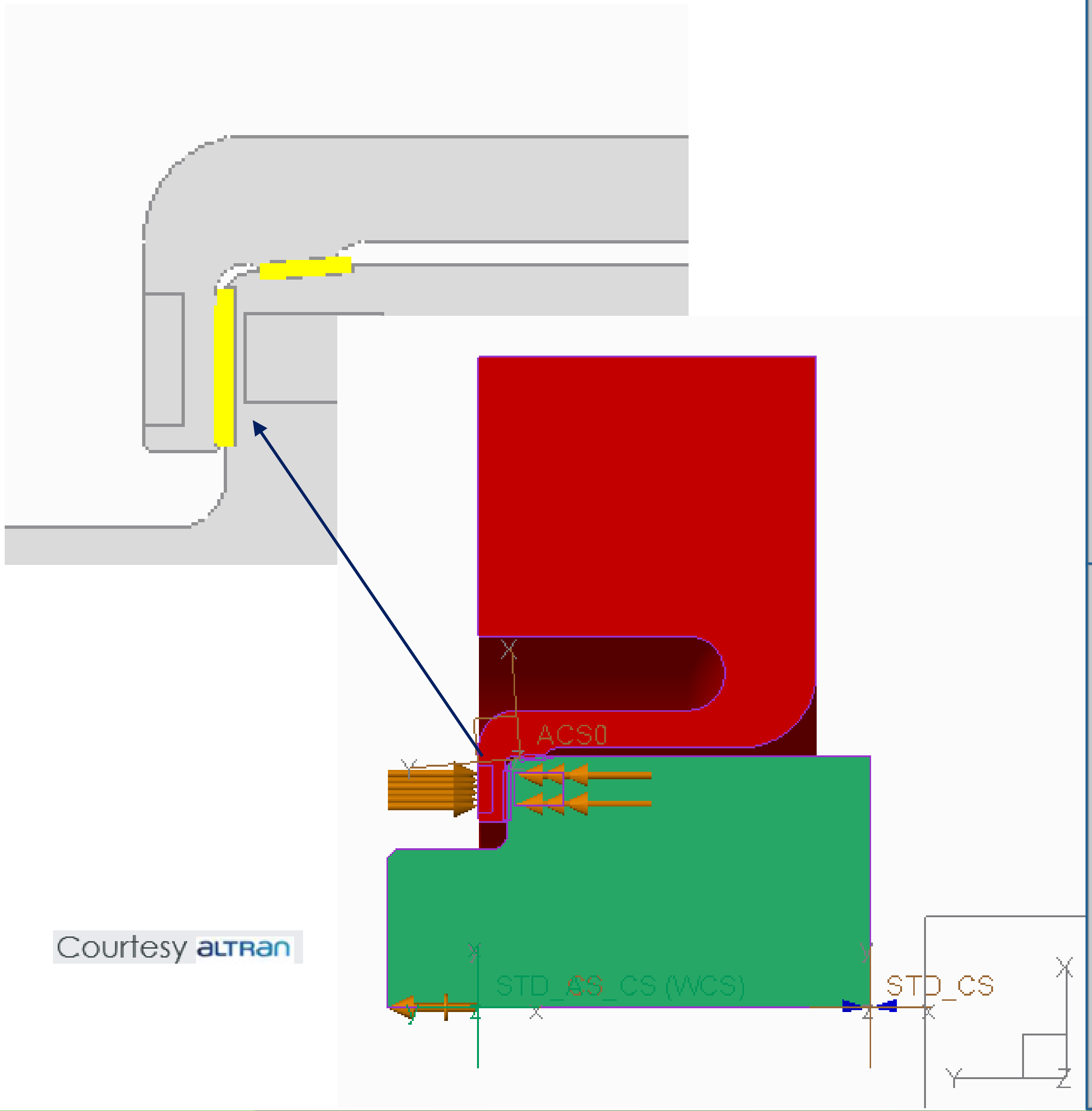
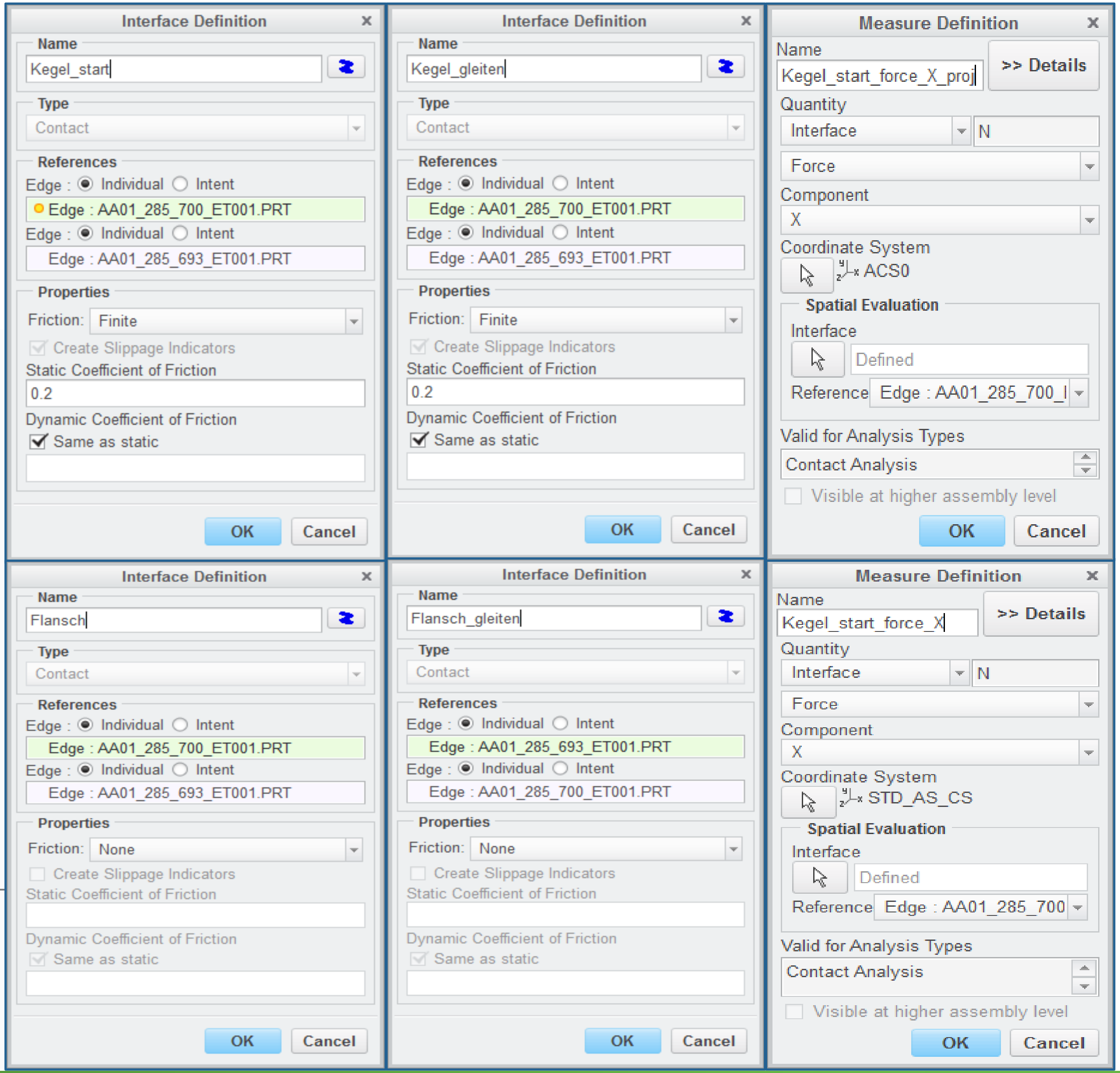
- The contact force measures/slippage measures/slippage indicator calculations
  - are based on contact spring stiffness
  - are based on number of quadrature points (QPs)
  - In general, number of QPs on a given element interface face/interface edge are dense (.) as compared to number of h-nodes (•)on that face/edge
- Contact indicator fringe plots are based on h-node grid
  - The mapping from QPs to h-nodes is many-to-few
  - This is deliberately done for performance reasons
  - May result in loss of information for coarse h-node grid
  - User can change h-nodes grid from Analysis dialog box
- Contact indicator magnitudes are normalized in range [-1,+1]
  - Red color is to indicate sliding
  - Green color is to indicate sticking



FLYWHEEL: FINITE FRICTION



Courtesy ALTRAN



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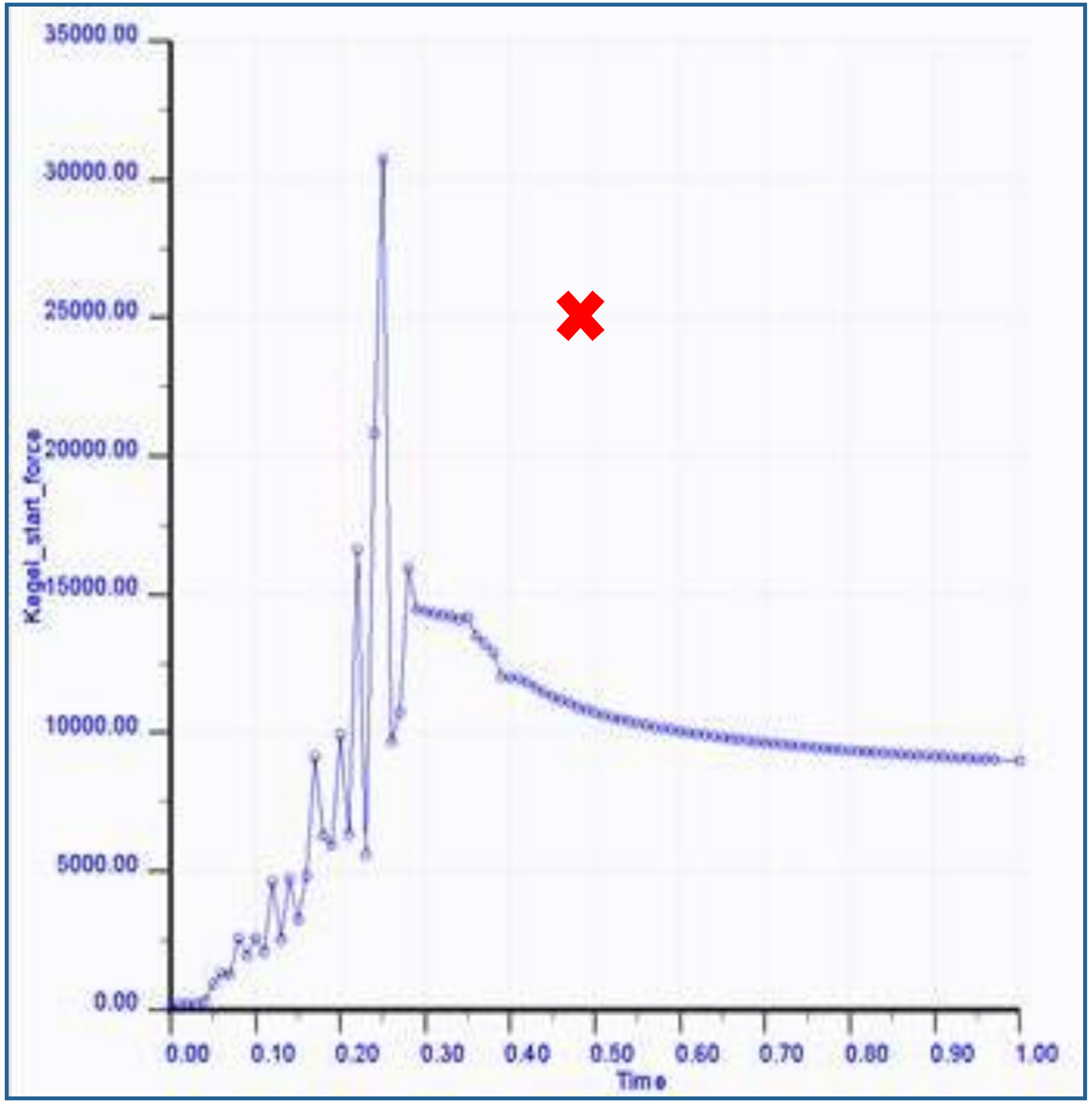
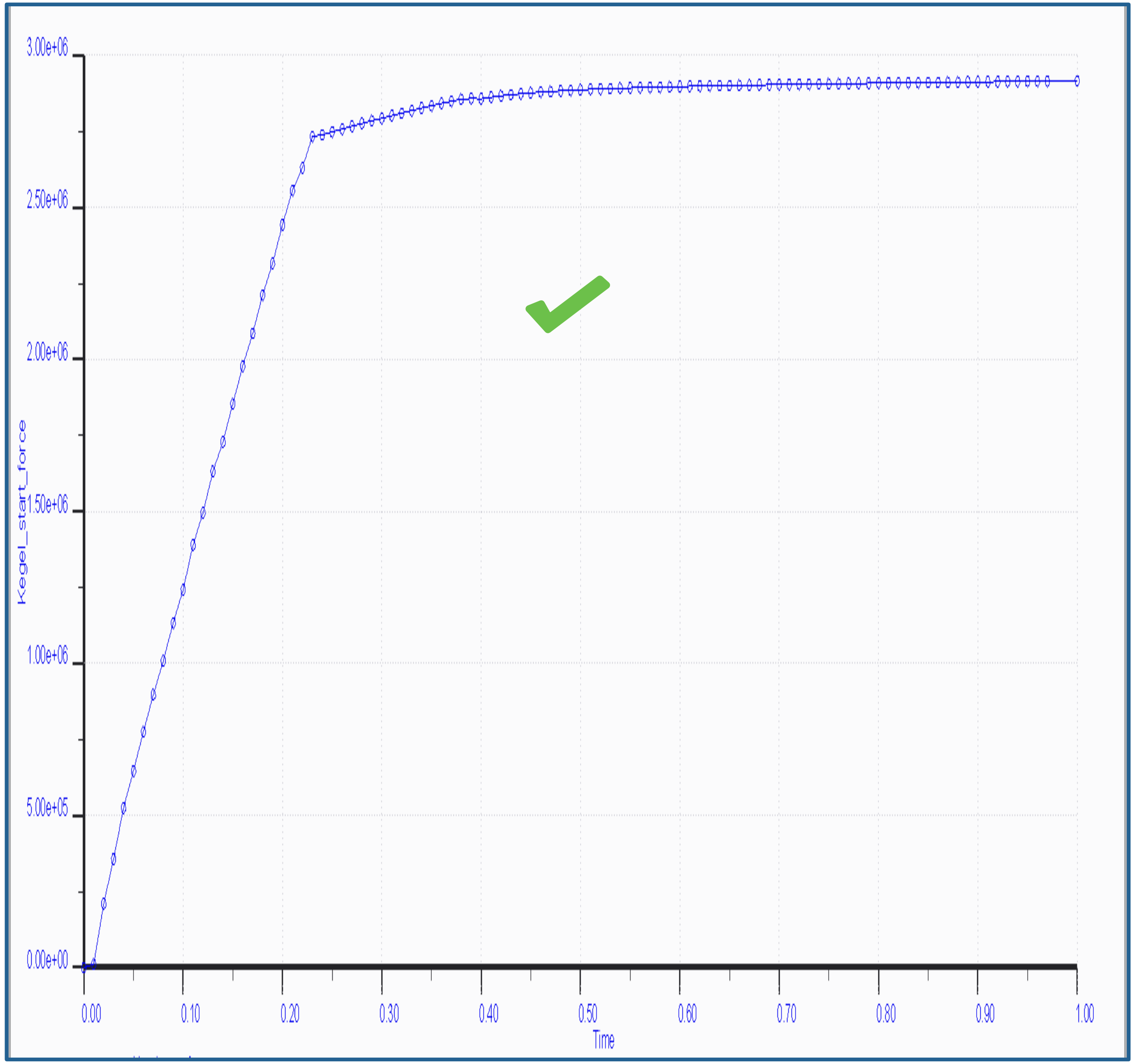




FLYWHEEL: FINITE FRICTION

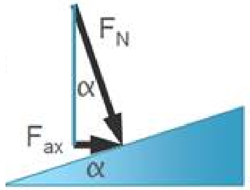
```
Flansch_gleiten_area:                0.000000e+00
Flansch_gleiten_force:               0.000000e+00
Flansch_gleiten_load:                0.000000e+00
Flansch_start_area:                  6.709057e+04
Flansch_start_force:                 2.777301e+06
Flansch_start_load:                  2.777301e+06
Kegel_any_slippage:                  2.575836e+01
Kegel_average_slippage:              2.377562e-01
Kegel_complete_slippage:            -2.596823e+01
Kegel_gleiten_any_slippage:          2.399270e+01
Kegel_gleiten_area:                  2.497448e+03
Kegel_gleiten_average_slippage:     -6.235947e+00
Kegel_gleiten_complete_slippage:    -5.119842e+01
Kegel_gleiten_force:                 5.422545e+05
Kegel_gleiten_force_X:              -5.209540e+05
Kegel_gleiten_force_X_proj:         -5.316519e+05
Kegel_gleiten_force_Y:              -1.504889e+05
Kegel_gleiten_force_Y_proj:         -1.067062e+05
Kegel_gleiten_load:                  5.317243e+05
Kegel_gleiten_max_tang_traction:     6.282911e+01
Kegel_max_tang_traction:             7.510377e+01
Kegel_start_area:                    3.961564e+04
Kegel_start_force:                   2.916440e+06
Kegel_start_force_X:                -2.802505e+06
Kegel_start_force_X_proj:           -2.859860e+06
Kegel_start_force_Y:                -8.072097e+05
Kegel_start_force_Y_proj:           -5.716860e+05
Kegel_start_load:                    2.859805e+06
```

Force magnitude calculations:

Kegel_start_force =
$\sqrt{Kegel\_start\_force\_X\_proj^2 + Kegel\_start\_force\_Y\_proj^2}$

Kegel_start_force = $\sqrt{2.85986E6^2 + 5.716860E5^2}$ = 2.91644E6 OR
Kegel_start_force = $\sqrt{2.802505E6^2 + 8.072097E5^2}$ = 2.91644E6

Axial force verification: Kegel_start_force_Y



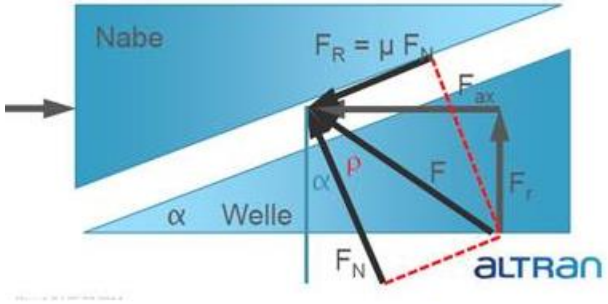
Axial force = $F_{ax} = -F_Y = \frac{F_N \sin(\alpha+\rho)}{\cos\rho}$

Axial force = $\frac{\mathbf{Kegel\_start\_forc\_X\_proj}\,Sin(4.76364+11.31)}{Cos(11.31)}$

Axial force = 8.07498E5

Coefficient of friction Verification

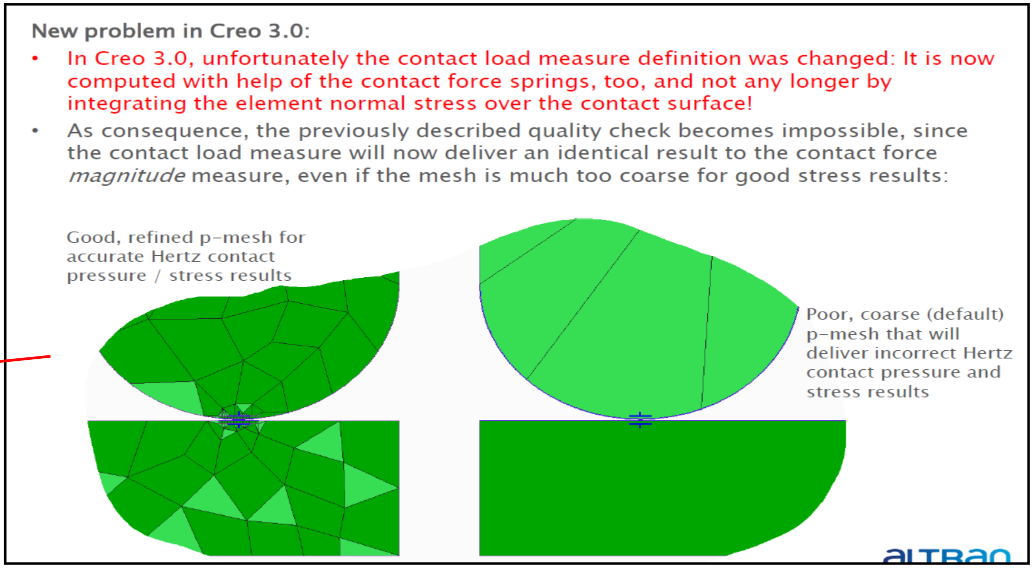
$\mu_{Kegel} = \frac{Kegel\_start\_force\_X\_proj}{Kegel\_start\_force\_Y\_proj} = \frac{5.716860E5}{2.859860E6}$ =0.2



CREO 3.0 (M120) SIMULATE ENGINE ENVS SUPPORTED

- Accuracy:
  - **Poor**: MSE_CONTACT_FULL_LOOSER_CONVERGE: with this new ENV, engine will fully activate looser tolerance acceptance algorithm.
  - **Medium**: MSE_CONTACT_PARTIAL_LOOSER_CONVERGE: With this new ENV, engine will partially suspend the looser tolerance acceptance algorithm – it will make the convergence requirements a bit tighter than default, however it will not fully suspend the looser acceptance algorithm.
  - **High**: MSE_CONTACT_SUSPEND_LOOSER_CONVERGE: with this new ENV, engine will completely suspend the looser tolerance acceptance algorithm and will always seek for 1e-12 default convergence norm

- Contact Interface load measure
  - Creo 2.0, this is calculated from element stress
  - Creo 3.0, this is calculated from spring stiffness
  - Creo 3.0, enable this with engine ENV
    - MSE_CONTACT_LOAD_FROM_STRESS



FEEDBACK ON SAXSIM2016 USER EXPERIENCE

1. Experience regarding the different contact models in Creo 2.0 & 3.0

Contact model:	Friction free	Infinite friction	Finite friction
Experience won with the model	Very good (state Creo 2.0 M200); works quick, robust and reliable in most cases	Contains a significant risk to obtain erroneous or at least inaccurate results (Creo 2.0 M200)	Absolutely unsatisfying and unreliable, wasted time even to test (state Creo 3.0 M080)
Success rate (estimated value from project application experience)	>95 %, at least when used with SDA and linear material	60–70 %	0 %
Typical error examples / problems observed	May underestimate Hertz contact pressure / contact stress with default settings	1. Often shows poor convergence / many iterations necessary (very slow) 2. May typically compute too much penetration and as consequence e.g. too low bolts loads at interpenetrating flanges	1. Fails with fatal error for any reason (stability issues, cuts down load step size until failure,…) 2. If the analysis completes, usually inaccurate or wrong results are obtained, often with too much interpenetration
Possible solutions	usually a refined mesh and reducing contact penetration helps	1. increase allowed number of contact iterations >200 2. Unfortunately, this often cannot be fixed by reducing contact penetration, then try other options shown in this presentation	Non - PTC R&D: Rework and fix the code!

Courtesy ALTRAN

PTC Actions:

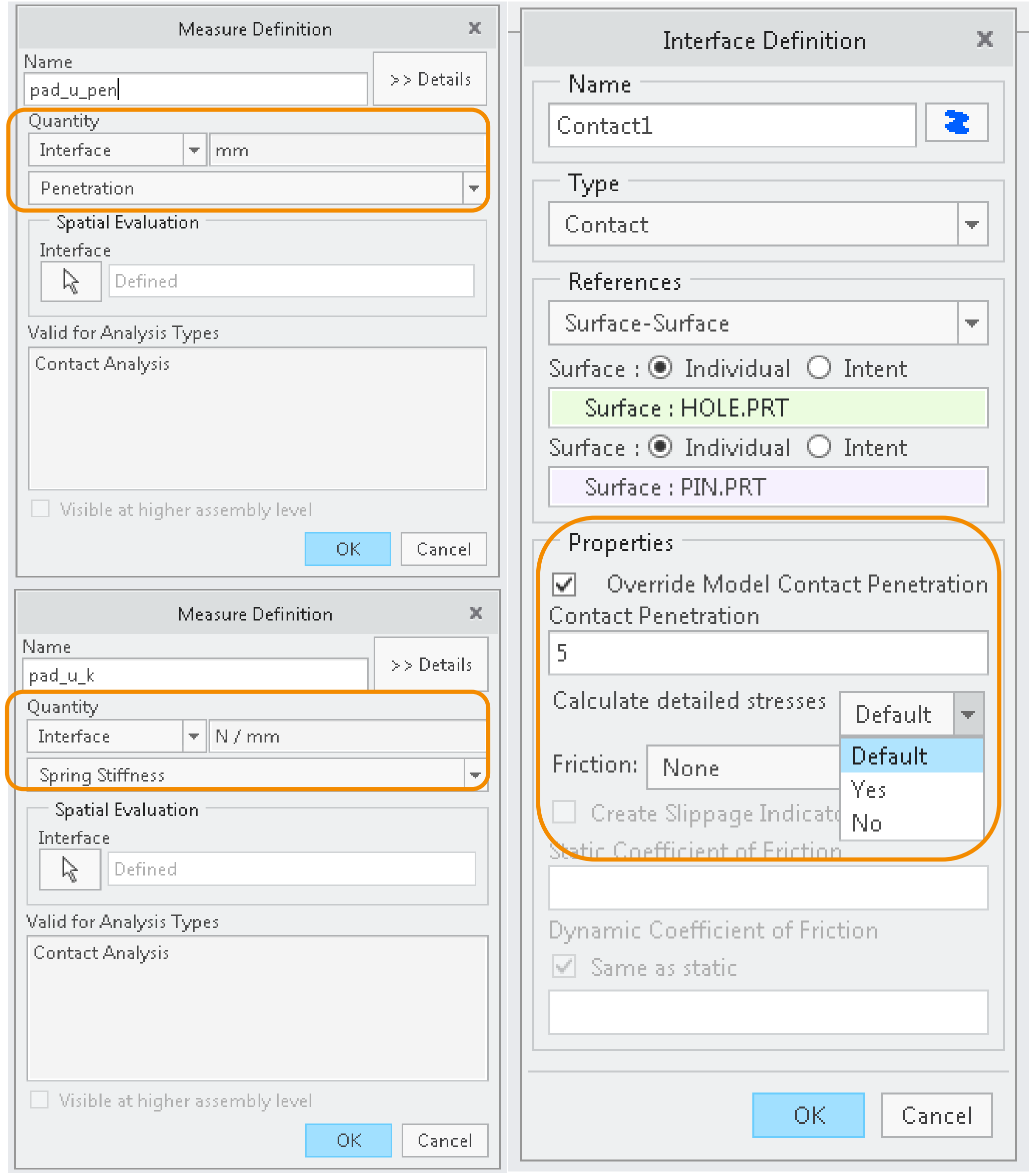
- As outlined in earlier slides, we have already incorporated/fixed several issues reported in the finite friction functionality related to high **penetration** and low **accuracy**
- We have also made available finite friction verification and validation examples to Simulate user community
- We have plans to make available best practice document to users that will primarily focus on addressing general difficulties in contact analysis and possible remedies*.

AGENDA

- General improvements/fixes in simulate engine
  - Engine fixes
  - Engine improvements
- Finite friction improvements
  - Algorithm improvements
  - Interface forces
  - Slippage measures
  - Slippage indicators
  - Local/full sliding messages
- SAXSIM16 model discussions
  - Brake system with infinite friction
  - Brake system with finite friction
  - Flywheel axisymmetric model
  - Feedback
- Creo 5.0 Simulate Engine contact projects
- Conclusions

CREO 5.0 CONTACT PROJECTS*

- New Contact Interface user defined measures
  - Max Penetration
  - Contact Spring stiffness
- New Promotions
  - Config option **sim_contact_penetration** will be promoted to interface dialog, allowing user to input different max penetration caps to each contact interface
  - **Calculate detailed stresses at contact interfaces** checkbox/flag will also be promoted to interface dialog, allowing user to selectively choose this flag based on requirements
- New contact best practice Notes/help/paper will be made available to users



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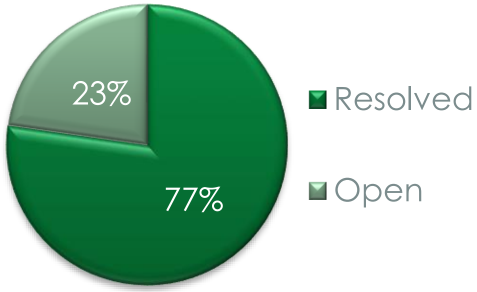
CONCLUSIONS

- Up-to-Feb 2017, 77% simulate engine issues reported are resolved



- Finite friction issues are fixed and result validation/verification study cases are published in NAFEMS international conference last year
- SAXSIM2016 inputs/findings were recorded and appropriate action has been taken to resolve customer concerns
- Engine Enhancements in upcoming Creo 5.0 Simulate release*
  - Roadmap presented this morning by Jose Coronado, PM, Simulate.
  - Contact related projects are being implemented

ptc