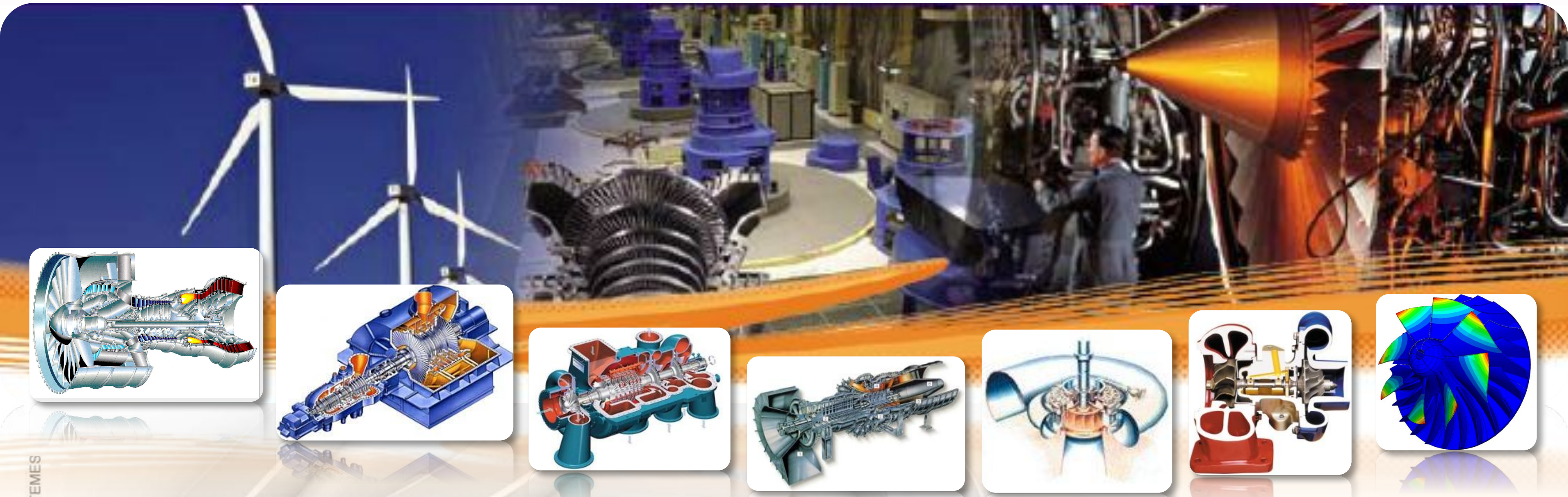
SIMULIA Solutions for Turbomachinery

Update and Workshop - March/April 2011

Jack Cofer, Industry Lead – Turbomachinery
Dr. Youngwon Hahn, Engineering Specialist



Agenda

- **Turbomachinery update – Jack Cofer**
  - Vision for next three years
  - Mechanisms for prioritizing product enhancements
  - Future roadmaps
  - Improvements in progress
    - Rotordynamics enhancements and collaboration with ROMAC
    - Mapping
    - Cavity radiation
  - Abaqus 6.11 preview
  - Isight 5.5 preview
  - 2011 SIMULIA Customer Conference
- **Turbomachinery applications using Abaqus – Youngwon Hahn**
  - Rotordynamics analysis
    - Procedures, Campbell diagram plug-in, ROMAC benchmarks and integration
  - Coupled structural-acoustic analysis
  - Blade stress and vibration analysis
    - Model building, mapping, meshing, stress analysis, XFEM, blade untwist
  - Blade-out containment analysis
  - Foreign object impact analysis

Agenda (Siemens)

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  - Major RFE status
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SIMULIA Turbomachinery Vision – Next 3 Years

Where we are headed

- **Major components of the Turbo Industry vision:**
  - Work closely with customers to gather enhancement requirements
  - Implement enhancements to Abaqus specifically for turbomachinery workflows
  - Develop tighter integration between Abaqus and 3rd-party turbo design software through co-simulation and Isight components
  - Forge strong relationships with key strategic partners
- **Focus areas:**
  - Rotordynamics
  - Blade design - stress and vibration analysis, aero/mechanical MDO
  - General usability for turbomachinery workflows
  - Fracture and failure (XFEM)
  - Thermal analysis and cavity radiation heat transfer
- **Key partners:**
  - Advanced Design Technology
  - CD-adapco
  - Concepts NREC
  - University of Virginia Rotating Machinery and Controls Lab (ROMAC)

Mechanisms for Prioritizing Requests for Enhancements

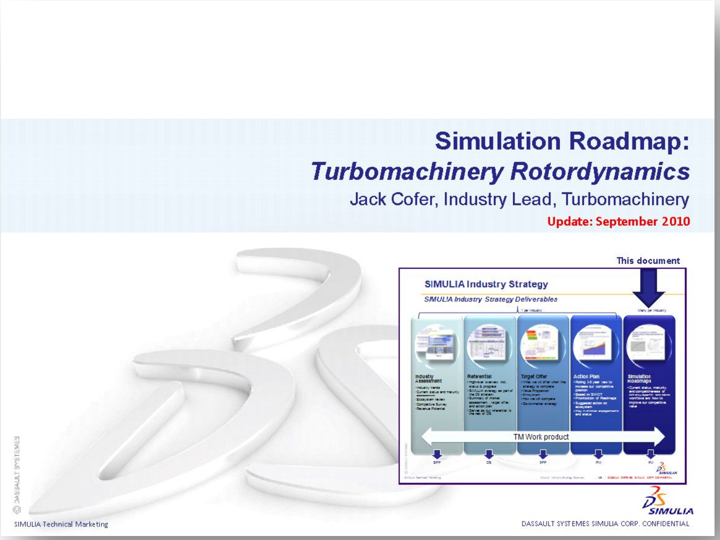
Caveat: The number of RFEs and suggestions that are submitted by customers far exceeds the capacity of our R&D resources, so prioritization is necessary

1. **Customers submit RFEs through their local offices**
   - Offices review them to decide if they should be entered in the RFE database, and then they vote on them.
   - Items that get the most votes from multiple offices have a bigger chance of getting into the R&D plan, but this is not guaranteed. Some items are created as plug-ins by the local offices.
   - The vast majority of the smaller RFEs are handled this way.
2. **Major enhancements captured in Simulation Roadmaps**
   - Created by Industry Leads in Technical Marketing and submitted to Product Management at an annual review in September.
   - This is the primary mechanism by which we identify the major needs for improvement, and probably the most reliable way to increase the chances of an item actually getting into the R&D plan.
   - The roadmaps are normally organized by specific industry workflows, such as rotordynamics analysis or blade vibration and stress analysis, or by specific functionalities needed by the industry such as thermal analysis, cavity radiation heat transfer, and fracture and failure.
   - When creating a roadmap, we gather all of the RFEs submitted by our industry customers, and try to categorize them into major workflows. For example, out of more than 130 turbo-related suggested improvements, nearly 50 were related to rotordynamics.
   - TM also submits a “Super Priority” list that prioritizes RFEs submitted across multiple industries – these go to the top of the list.
3. **High level advocacy by account managers and major customers**
   - Many smaller RFEs, such as “nice to have” usability issues, either do not generate sufficient votes in the offices or don’t find their way into the roadmaps.
   - However, if the account manager in the field – or the customer - can find an advocate at HQ (such as in Technical Marketing, Customer Support, or R&D), the advocate can fight to get higher priority.
4. **Paid services engagements** to implement high priority RFEs

Future Simulation Roadmaps

- **Simulation Roadmaps drive product development to increase our competitiveness per industry**
  - Owned and written by Technical Marketing in conjunction with Sales & Customer Support
  - Feed into the Product Strategy and R&D plans
- **Key elements of the roadmap:**
  - Competitive assessment
  - Requirements list – what to do to increase our competitiveness *(based on customer input)*
  - Alliance landscape
  - Key customer engagements
- **Future roadmaps being planned:**
  - Blade stress and vibration analysis, aero/mechanical MDO
  - General usability for turbo workflows
  - Fracture and failure (XFEM)
  - Thermal analysis and cavity radiation heat transfer

(Blade stress and vibration analysis, aero/mechanical MDO; General usability for turbo workflows) — To be submitted in September 2011



Abaqus Enhancements for Turbomachinery in Progress

- **Rotordynamics**
  - Plug-in to automatically generate Campbell diagrams – see Abaqus Answer #4721
  - Plug-in to enable direct import of bearing coefficients from ROMAC bearing codes THPAD and SQFDAMP (Target completion: May 2011)
  - 6.10-EF (Nov. 2010) and 6.11 (June 2011): Improvements to direct matrix input capability to enable import of fully generalized stiffness, mass, and damping matrices (including non-symmetric, frequency-dependent, cross-coupled dynamic coefficients)
  - 6.12 (June 2012): Improved capability for distributed load definition (DLOAD) to provide the capability to define loads with respect to a stationary reference frame with frequency dependency and perform rotordynamic analyses on fully detailed 3-D solid models created within (or imported into) Abaqus/CAE
  - 6.12+: Expanded plug-in for more plots (interference diagrams, orbit depiction, critical speed maps, and unbalance response plots)
  - Training class: December 2011
- **Mapping**
  - Undocumented in 6.10-EF for testing with full release in 6.11 (June 2011): Full interactive capability in /CAE to map spatially varying surface data (pressure, temperature, film coefficients, etc.) from 3rd party products into Abaqus attribute definitions (b.c.'s, loads, shell thickness, etc.) and visualize it
  - 6.12 (June 2012): Full contour visualization in /CAE without running datacheck with pre.exe
- **Cavity radiation**
  - 6.10: New adaptive view factor calculation to dramatically improve accuracy
  - Long-term: looking at revamping the whole method to make many improvements

UVA Rotating Machinery and Controls Laboratory (ROMAC) Industrial Program

- In June 2010, SIMULIA joined the University of Virginia Rotating Machinery and Controls Laboratory (ROMAC) Industrial Program.
- This program supports cooperative research efforts conducted by faculty, staff, and students in the Mechanical and Aerospace Engineering Department and the Electrical Engineering Department at the University of Virginia.
- The ROMAC Industrial Program emphasizes theoretical and experimental research in general areas of rotordynamics, turbomachinery, structural dynamics, magnetic bearings, the application of automatic controls to the dynamics of rotating machinery, internal incompressible flows, the coupling of internal flows to the dynamics of rotating machinery, fluid film bearings, and seals.
- The interaction between industry and university professionals through the medium of ROMAC provides the university researchers with an understanding of practical industrial problems with rotating machinery while the industrial participants obtain very timely research results and access to a full suite of world-leading rotordynamics and bearing analysis codes.
- More than 40 companies are currently members of the Industrial Program, most of whom are listed on the ROMAC web site at http://www.virginia.edu/romac/current_members.htm.

Joint Rotordynamics Work with ROMAC

- **Dr. Youngwon Hahn is currently working with two Ph.D. students at ROMAC. This work will be reported at the ROMAC Annual Meeting in June 2011.**
- **Project #1: Create an Abaqus/CAE plug-in to allow automated import of bearing properties from the ROMAC bearing codes**
  - Focused initially on tilting pad oil film bearings (commonly used in gas and steam turbines) - squeeze film damper bearings (commonly used in aircraft engines) to be added later.
  - The plug-in will provide two options:
    1. Direct import of bearing properties (stiffness, damping coefficients) from the ROMAC codes THBRG, THPAD, and MAXBRG so that the user doesn't have to manually enter and convert them
    2. Manual input of individual bearing stiffnesses and damping coefficients in the plug-in GUI
  - Status: In testing, to be released May 2011
- **Project #2: Provide reference data and further insight for development efforts that will improve the ability of Abaqus to handle full 3D non-axisymmetric rotor models, including the rotor blades.**
  - ROMAC will perform their own rotordynamics analyses and generate mode shape plots for both 3D axisymmetric and non-axisymmetric rotor models to compare to SIMULIA models and results using Abaqus.
  - Status: 3D bladed wheel models created by SIMULIA and sent to ROMAC, 3D rotor models under development.
- **In the long term, we will investigate ways in which SIMULIA's Isight software can be used to automate the rotordynamics analysis simulation process to achieve optimal designs for rotor/bearing systems.**

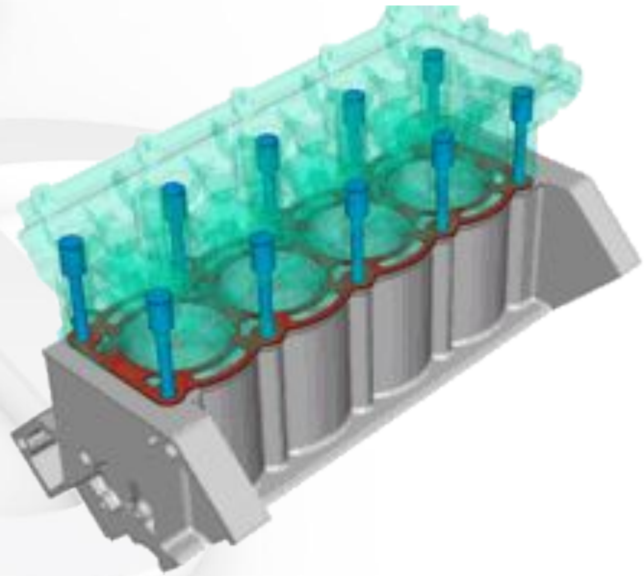
Major RFE Status (Siemens)

1. **Mapping issues**
   - Displaying contour plots of all loads/boundaries/fields (including film conditions) in pre processing and post processing.
   - For post processing, need FILM in the .odb file.
   - FILM for uniform loads, not applied by user subroutines – need to write the data to ODB.
   - Non-uniform FILM loads applied via user subroutine FILM (relevant for DLOAD)
   - Mapping for 2D models (50% of their work.
   - Mapping along one single variable and along a path
   - Status:
2. **Support for local coordinate system by the Pro/E associative interface from Elysium**
   - Status:
3. **Rotordynamics issues**
   - Beam element gyroscopic effect;
   - Damping matrix with unsymmetrical cross coefficients
   - Unbalance mass response
   - Campbell-diagram
   - Status:

Abaqus 6.11 Preview

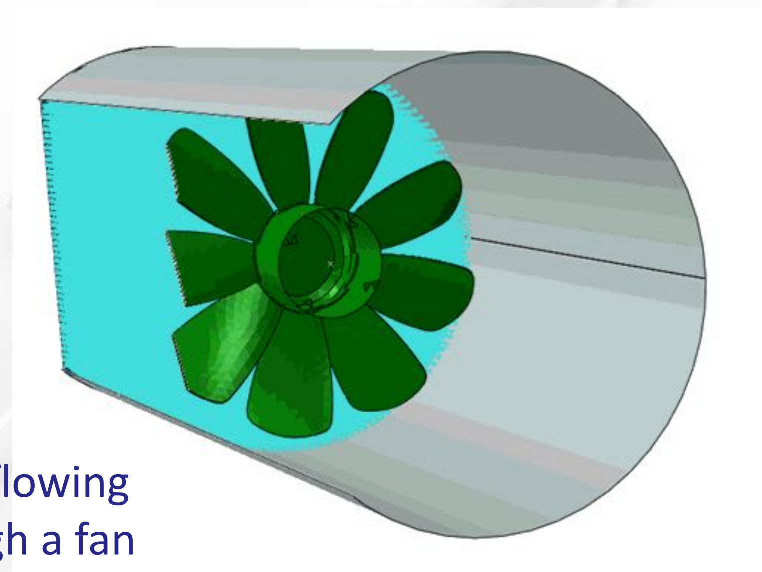
GPGPU Acceleration

- Direct solver acceleration using GPGPU's
- Speed-ups of 2-3x have been observed
- Benefits generally limited to larger problems > 1M

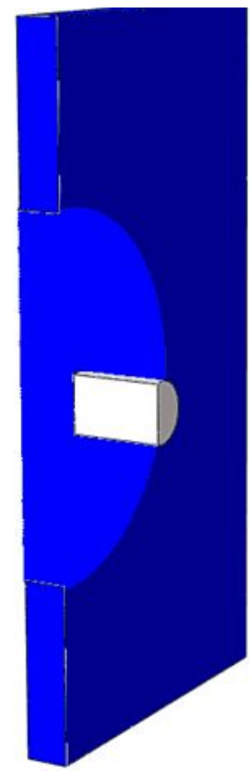


Smoothed Particle Hydrodynamics (SPH)

- Suitable for large deformation problems involving damage/fragmentation
- Increases competitiveness in aerospace and defense industries
- Limited parallel scalability in the first release



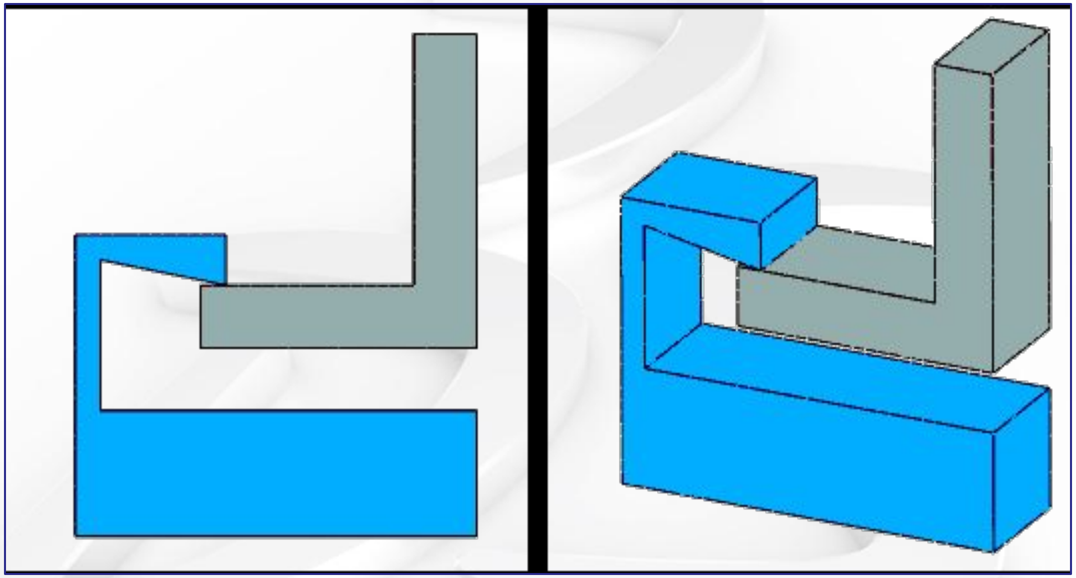
Fluid flowing through a fan



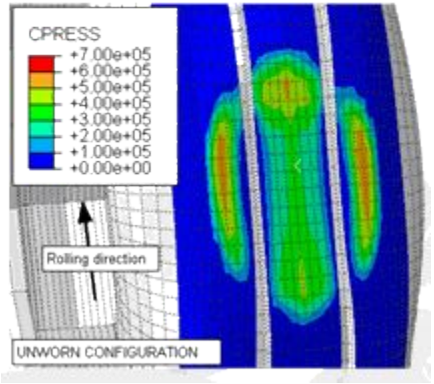
Ballistic impact

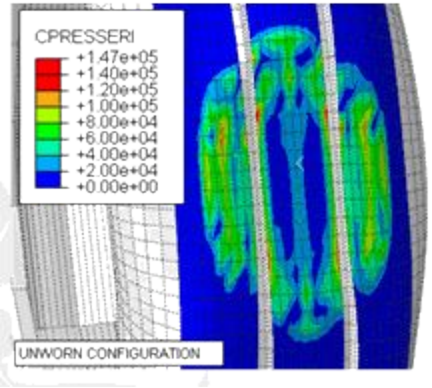
Contact Enhancements

- Contact pressure error indicators increase confidence in results quality
- Edge-surface contact expands the class of problems that can be solved robustly



Edge-surface contact

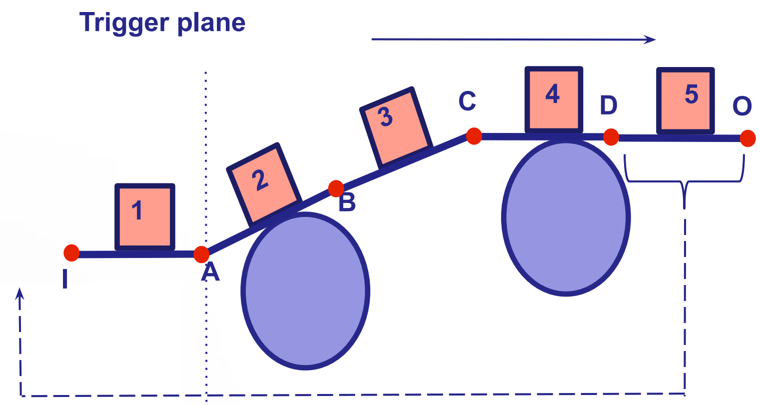


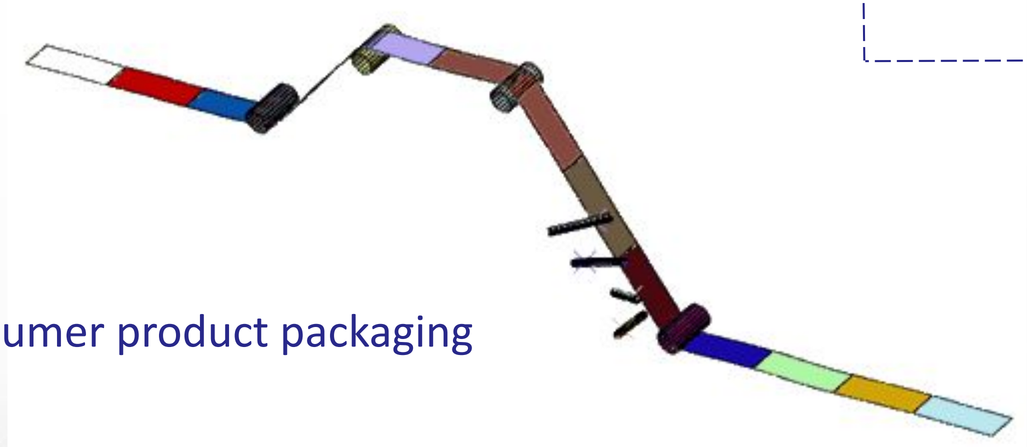


Error indicators

Conveyer Belt

- Specialized technique for simulating continuous processes
- Limited to periodic geometries
- Unique in the industry

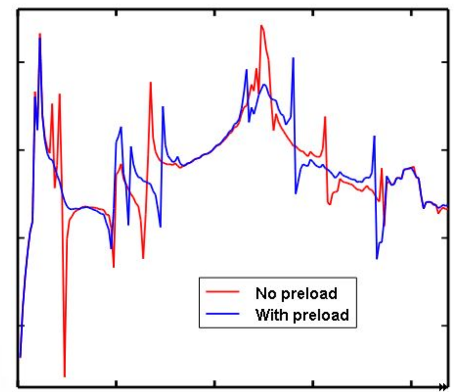


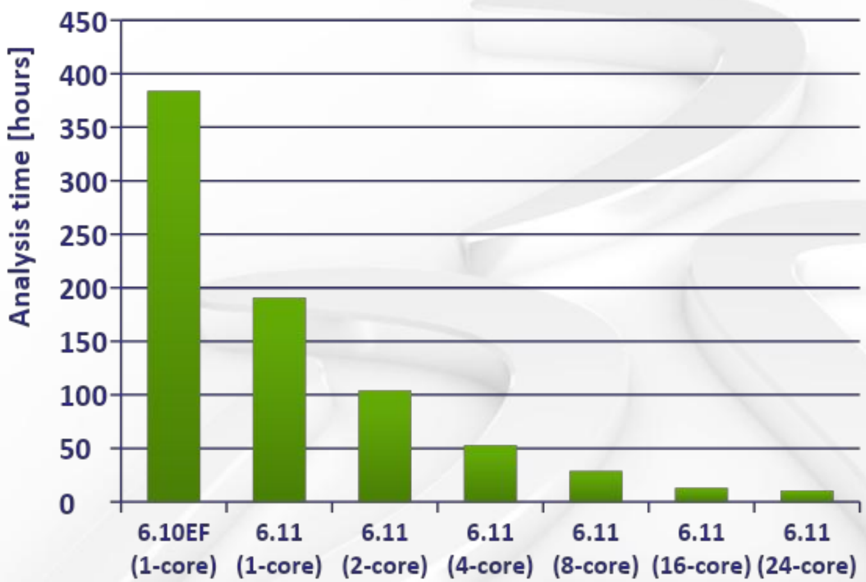


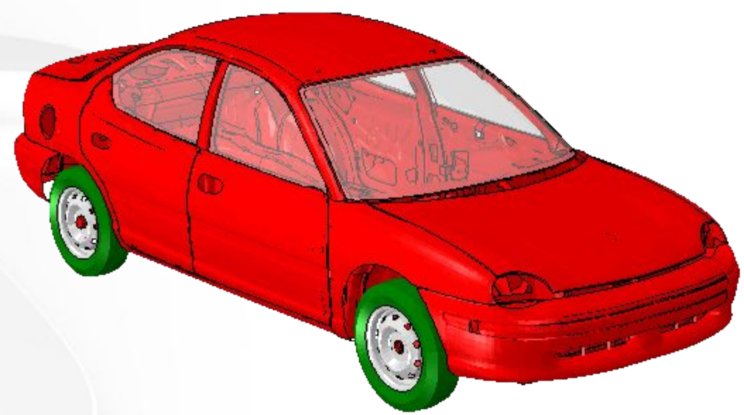
Consumer product packaging

Parallel Frequency Response Solver

- Targeted towards automotive NV market
- Supports SMP w/ up to 24 cores
- Provides class-leading performance

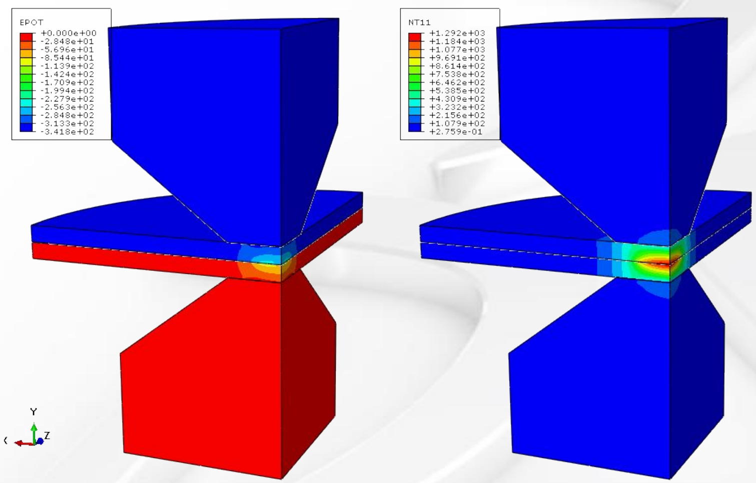


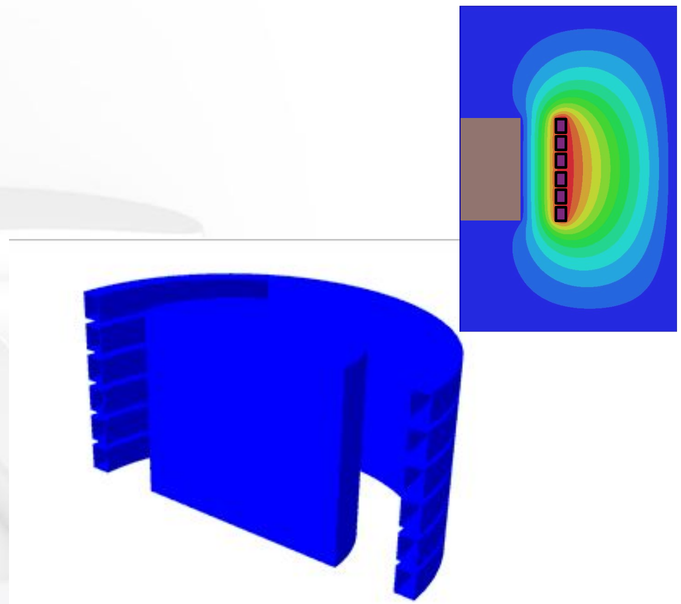




Multiphysics

- **New solution procedures for:**
  - Thermal-electrical-structural (ETS)
  - Low-frequency electromagnetics (EM)
- **Sequential thermal-stress following EM**
- **Applications span the range of industries**

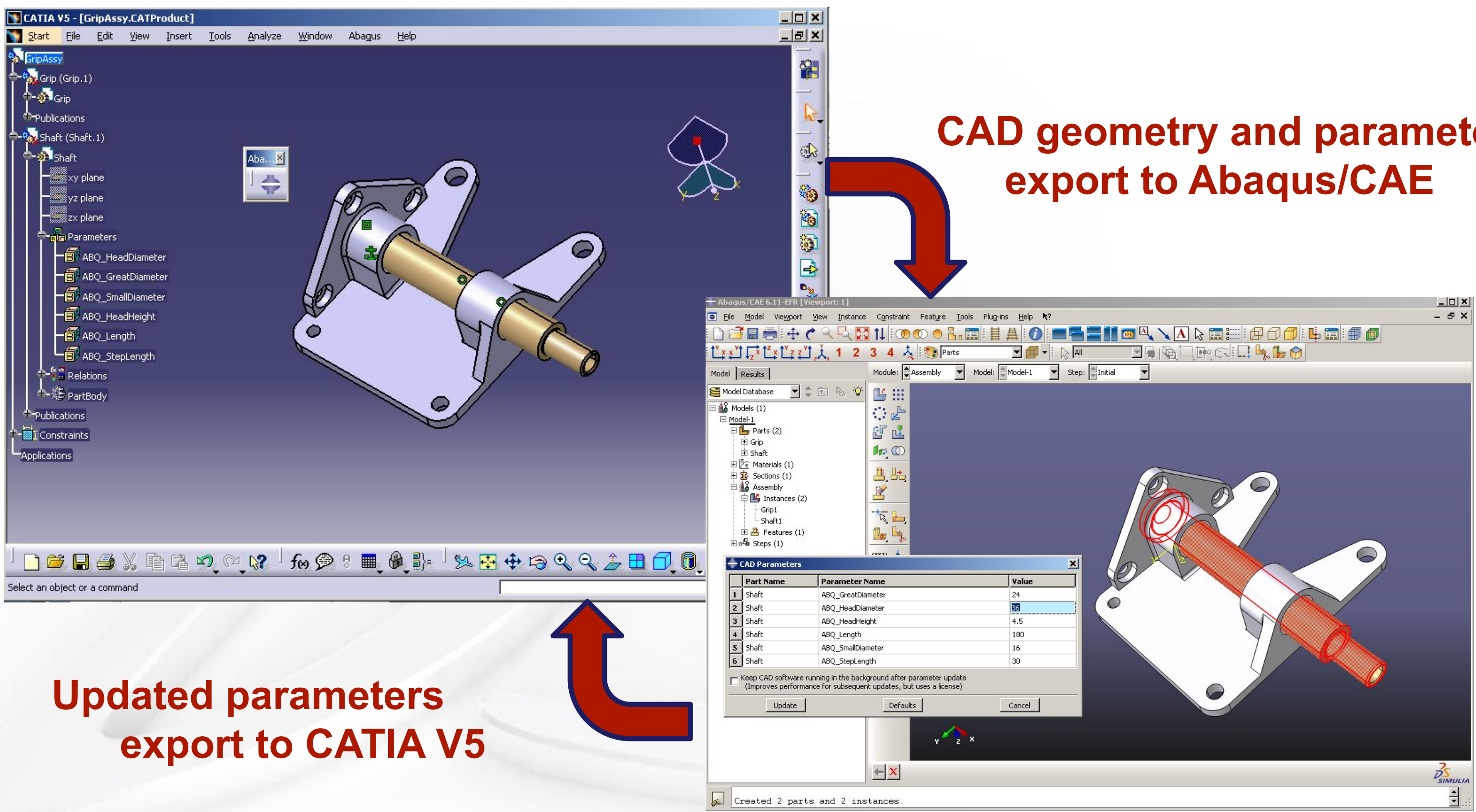




Spot welding

CAD Interfaces

- **CATIA V5 Bidirectional Associative Interface**
  - CATIA parameters can be modified from Abaqus/CAE
    - Model updated automatically
  - Support for CATIA V5 R20



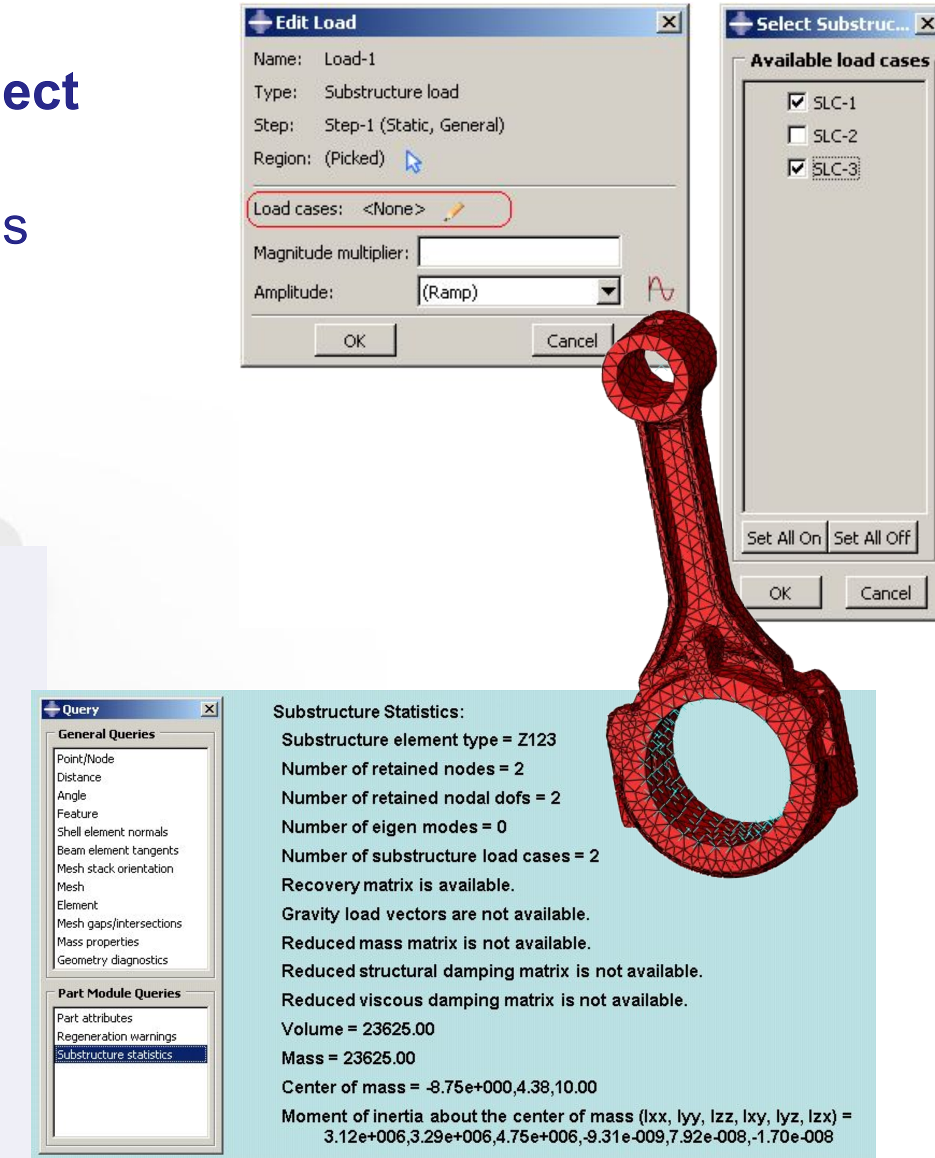
CAD geometry and parameters export to Abaqus/CAE

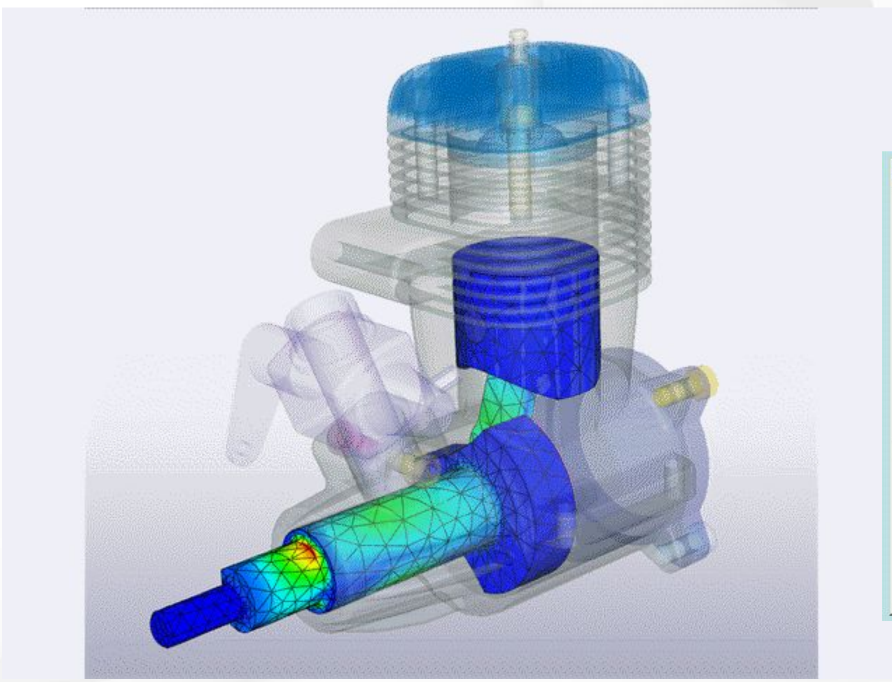
Updated parameters export to CATIA V5

SIMULIA

Substructures

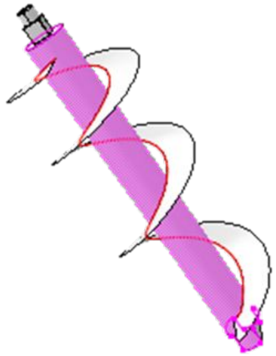
- **Continuation of 6.10-EF project**
  - Support for:
    - Substructure load cases
    - Substructure load
  - Improved display
  - Substructure statistics query

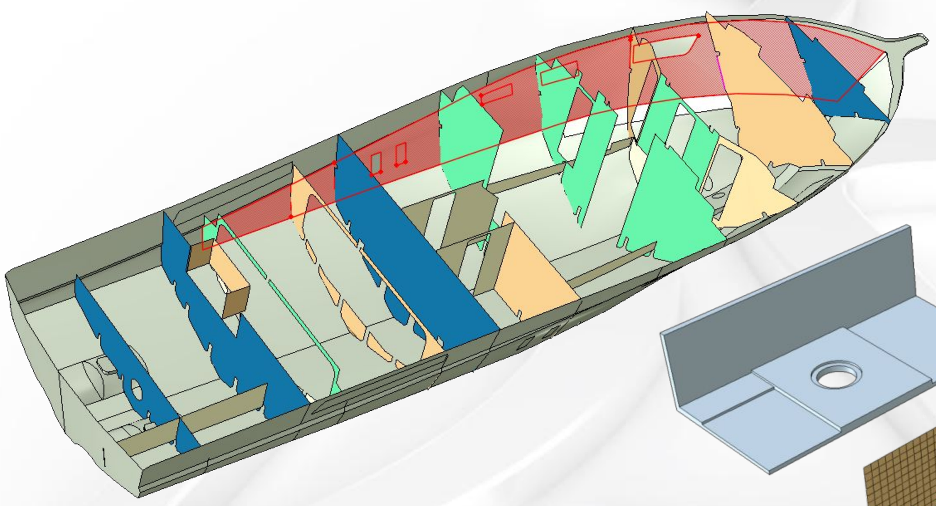


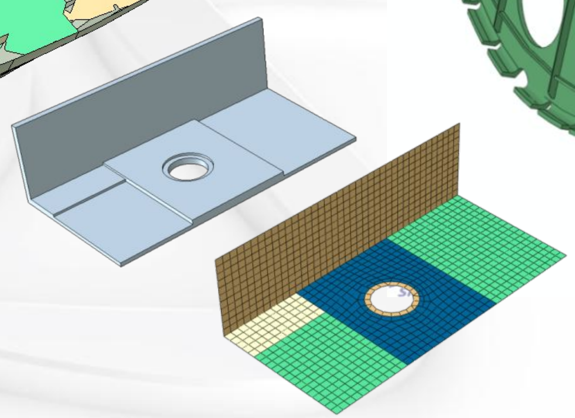


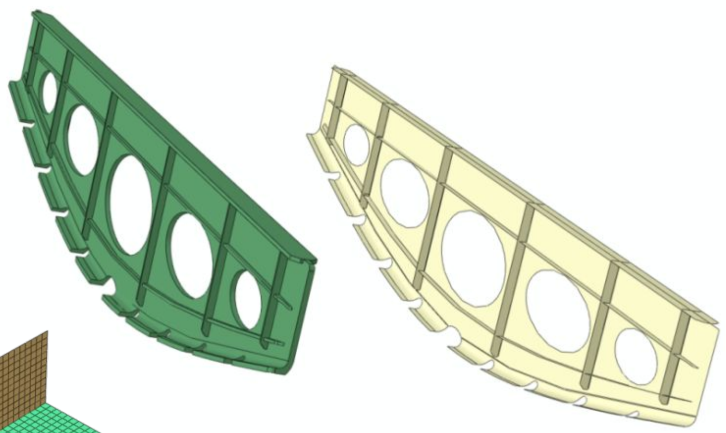
Mid-surfacing Enhancements

- **Reduce picking needed to create mid-surface**
  - Improved robustness
    - **Offset** operation performance
    - Feature regeneration
  - Enhanced heuristics for **Extend** and **Blend** geometry tools
  - New tool for partitioning faces by edge projection



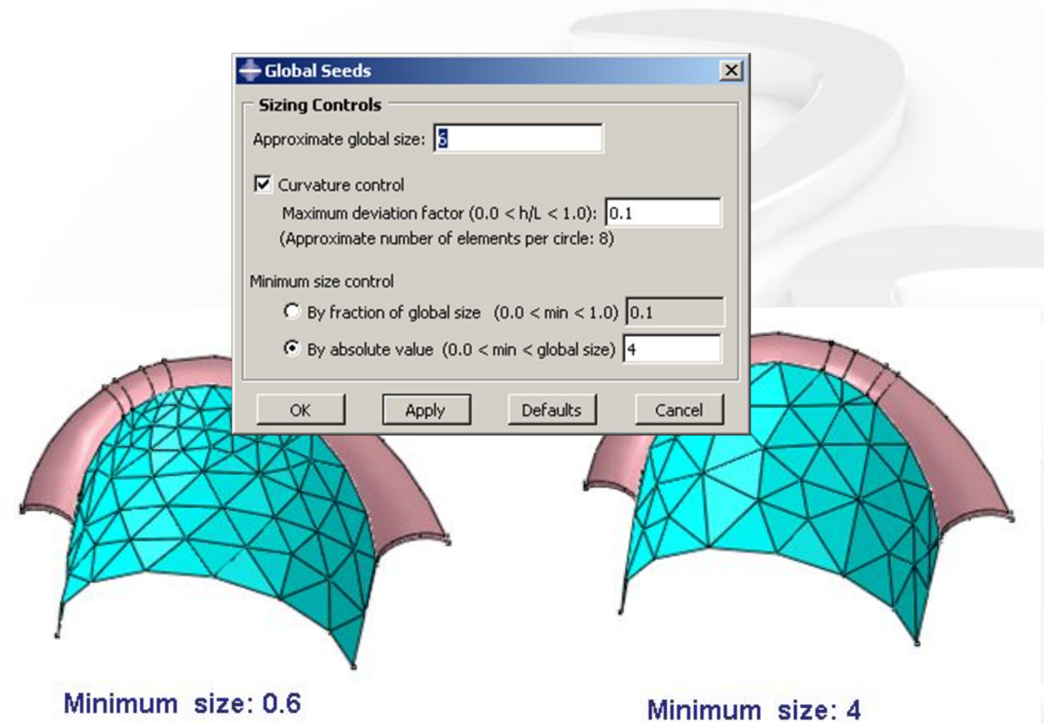




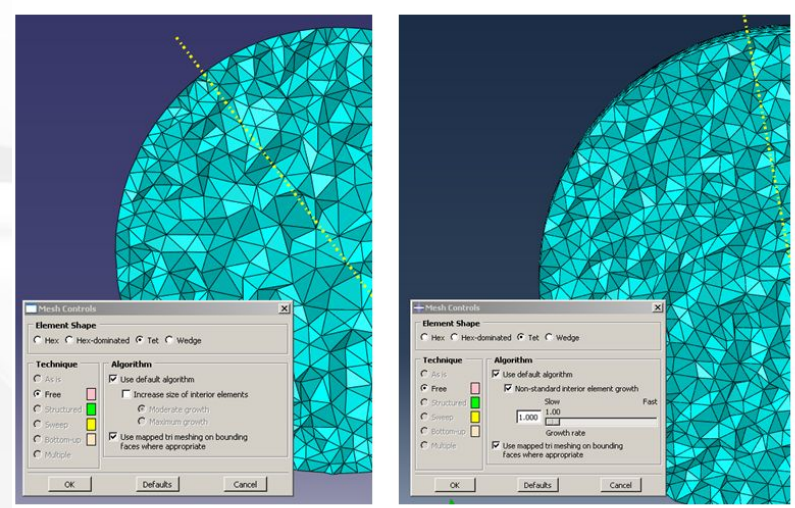


Tet Meshing

- Minimum element size specification
- Tetrahedral element size growth control for interior volume
- Improved quality and robustness
  - Control deviation between boundary mesh and surface geometry
  - Reduced likelihood of creating short element edges
  - Better gradation on surface meshes



Mesh Growth Comparison

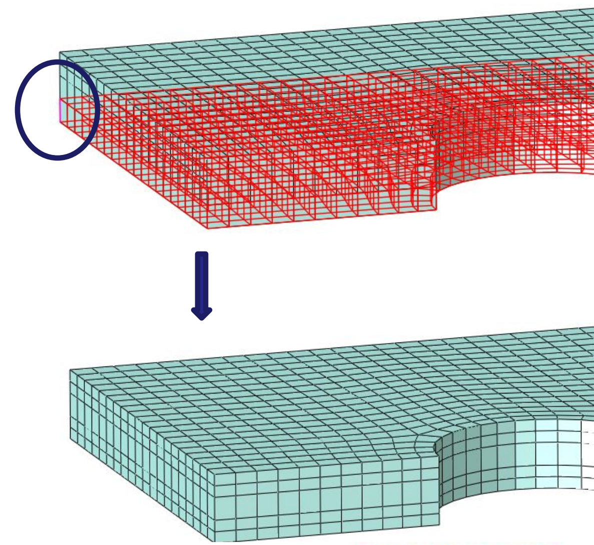


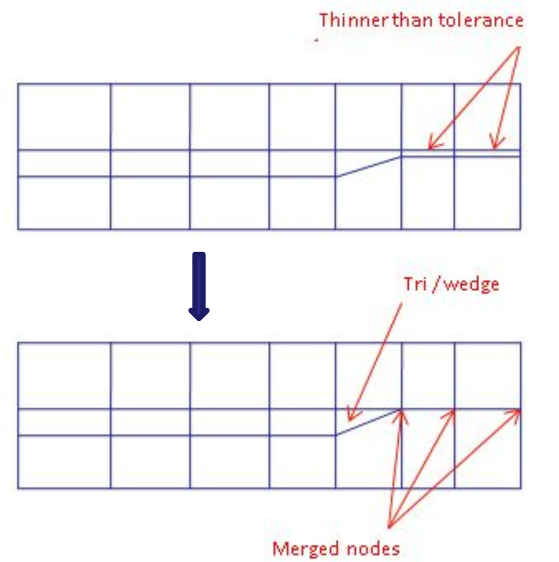
6.9EF

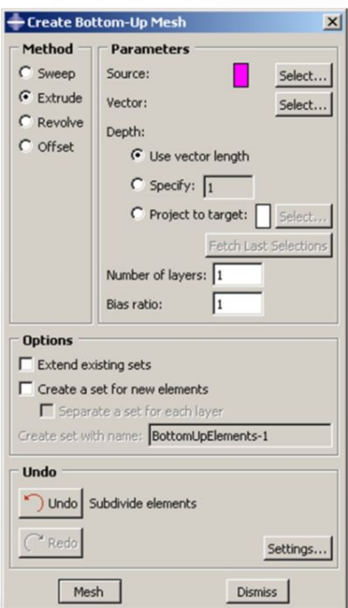
DEV 6-11

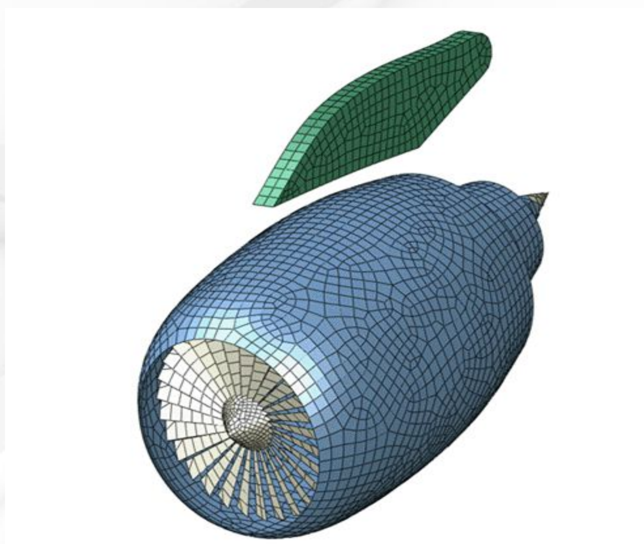
Mesh Editing

- **New mesh edit functions**
  - Merge/subdivide elements
  - Grow/collapse short element edges
- **Bottom-up meshing**
  - Now available for orphan meshes
  - Generate elements by offsetting
  - Additional options for extrude method





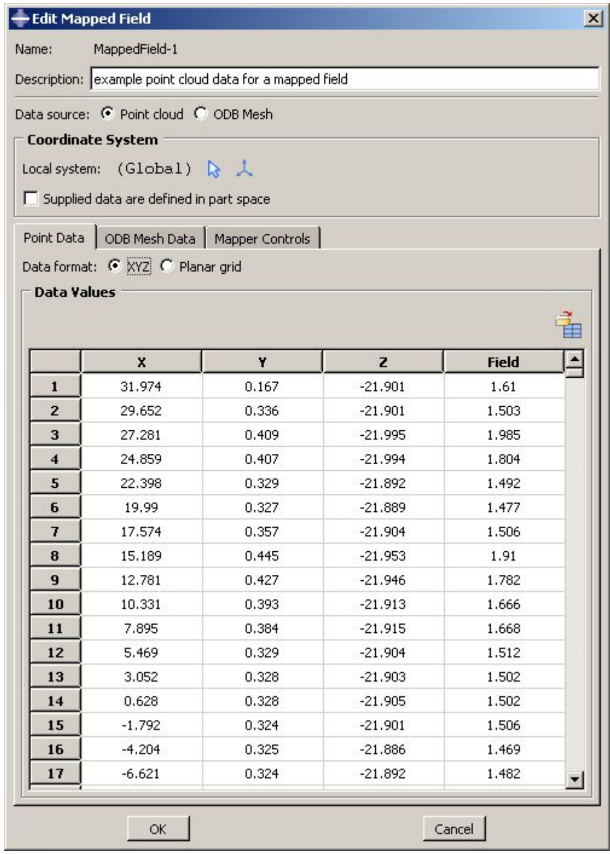


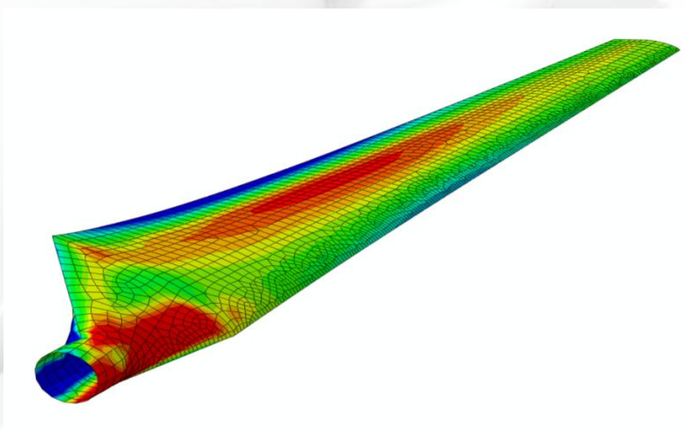


Mapping Capability

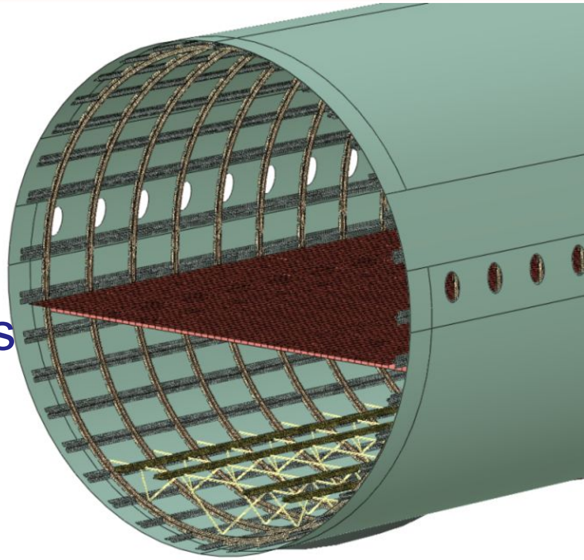
- **Interface for:**
  - Importing spatially varying point cloud field data
  - Applying data sets as loads, predefined fields and interactions

  Examples:
  - Pressure, temperature & film coefficients
  - Shell thickness, density
- **Import data using**
  - Text files & spreadsheets
  - Existing Abaqus output database
- **Mapping options & controls**
  - Default value, algorithm, search tolerance

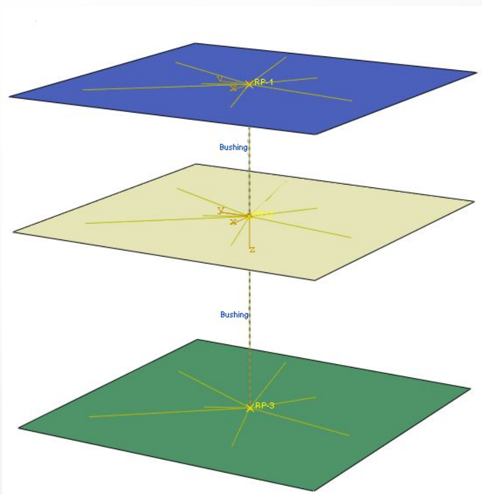




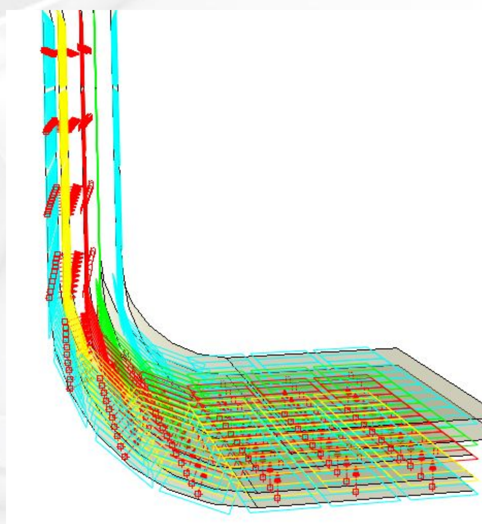
Assembled Fasteners

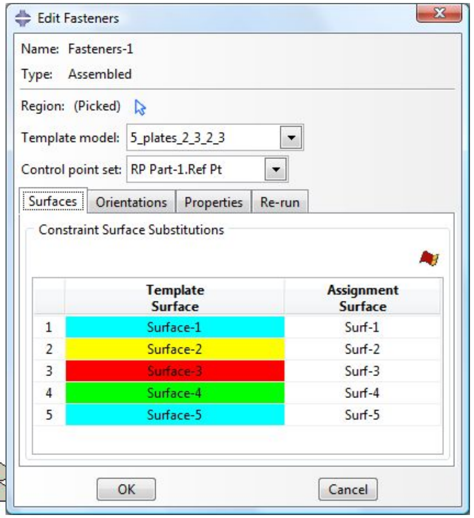


- **Capabilities for realistic modeling of fasteners**
- **Create Template model**
  - Separate from actual analysis model.
  - Contains surfaces, constraints and connectors
- **Assign to a region**
  - Attachment points, orientations, and surfaces specified to create an “assembled fastener”.
  - Allows specification of a calibration script.



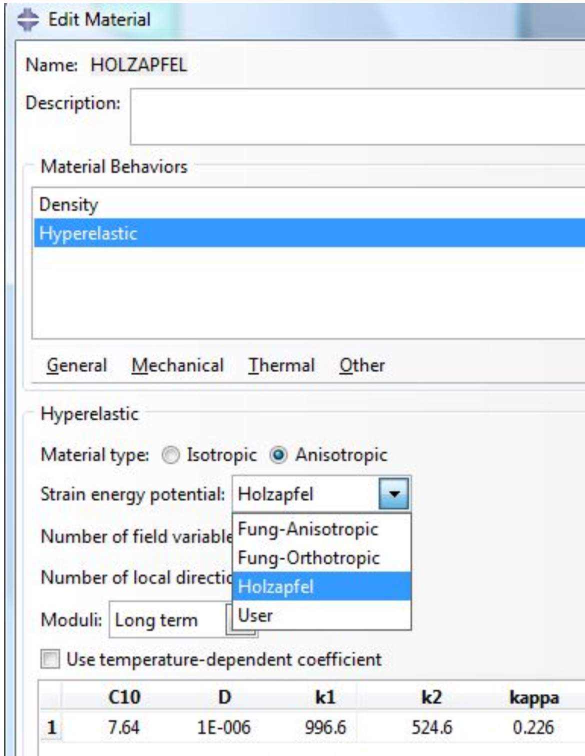
3 plate template model

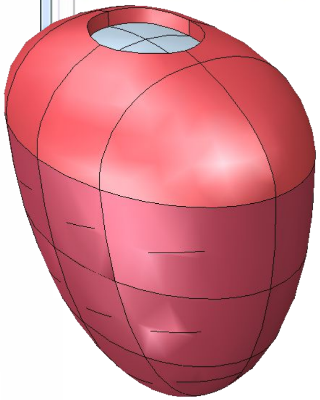


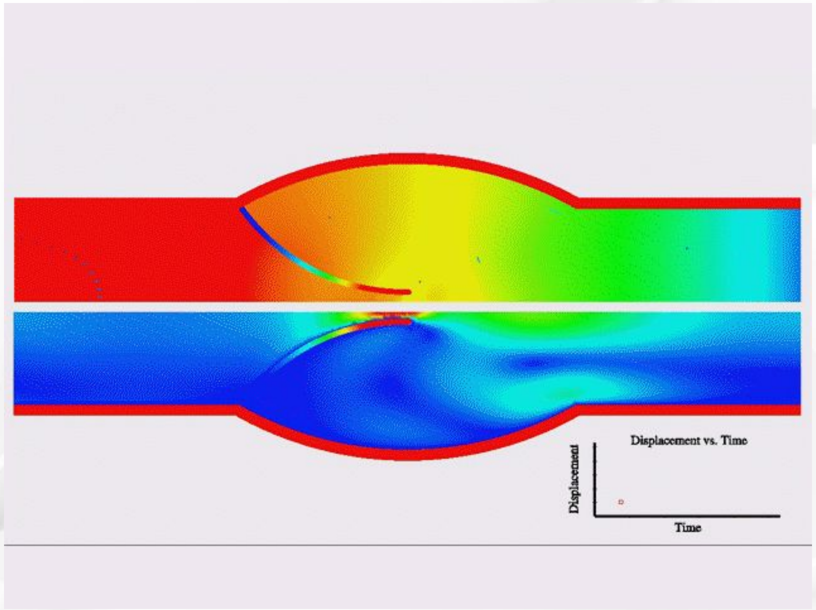


Analysis Coverage

- **Interface for Anisotropic Hyperelasticity**
  - Highly anisotropic and nonlinear elastic material behavior
    - Model soft biological tissues and fiber-reinforced elastomers
- **Abaqus/CFD**
  - Distributions to velocity
    - Inlet, outlet and wall BC







Abaqus Topology Optimization Module (ATOM)

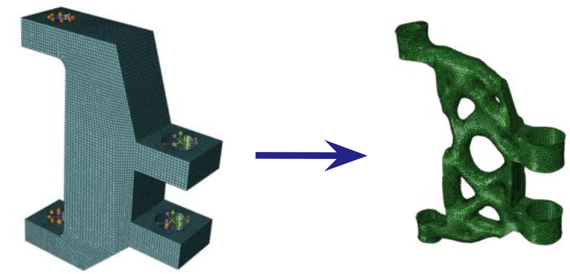
- **Topology optimization**
  - Modify stiffness
  - Good for evolving optimum shape
- **Shape optimization**
  - Moves nodes
  - Good for fine tweaking of shape

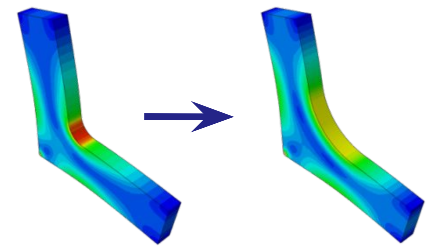
Both support:

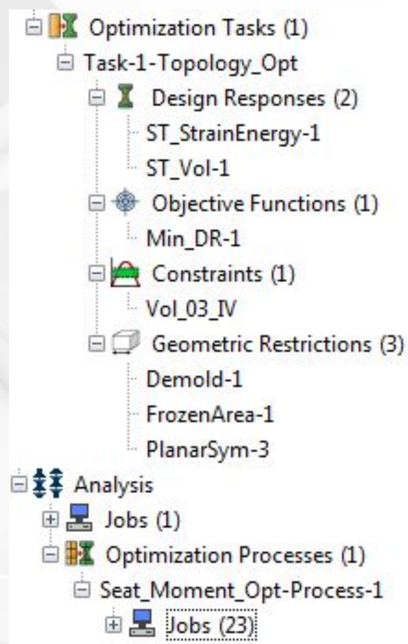
Contact

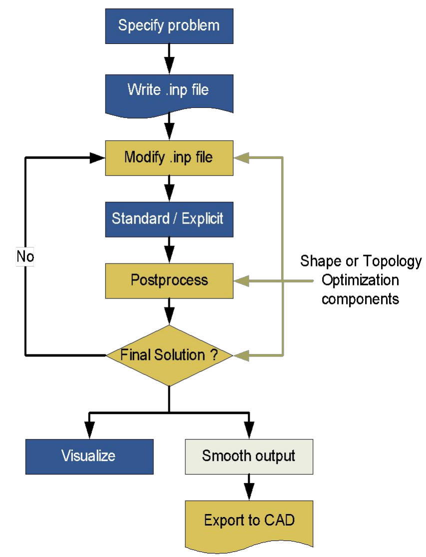
Geometric non-linearity

Nonlinear materials



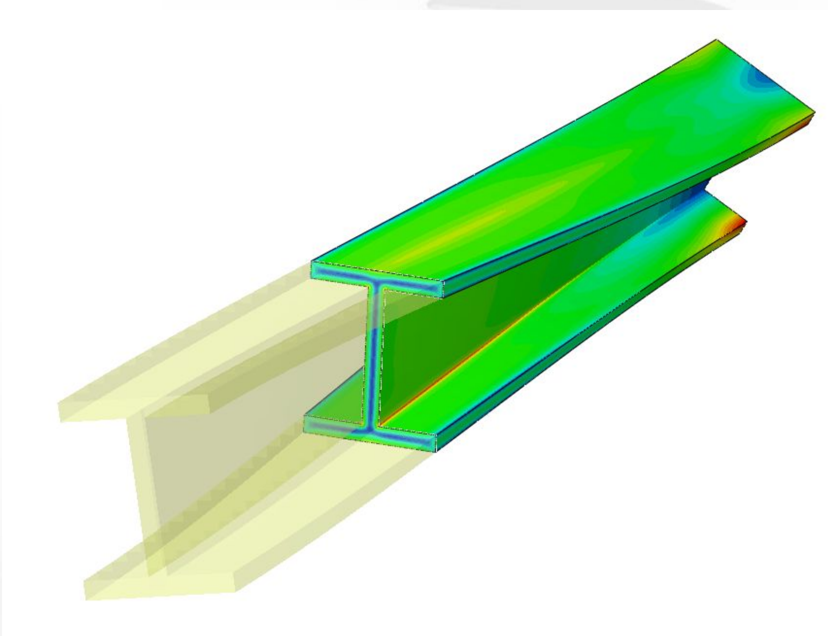


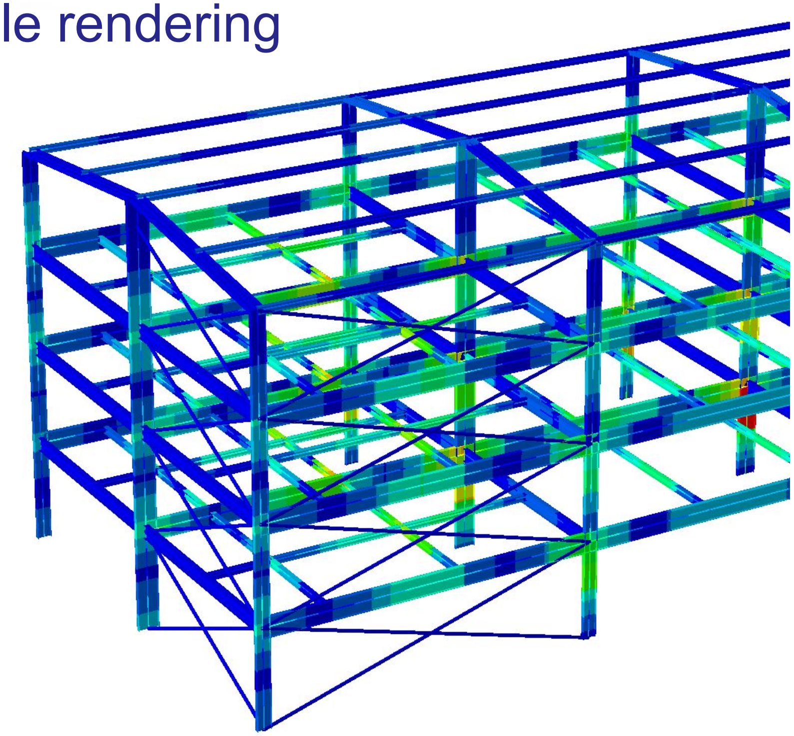




Visualization

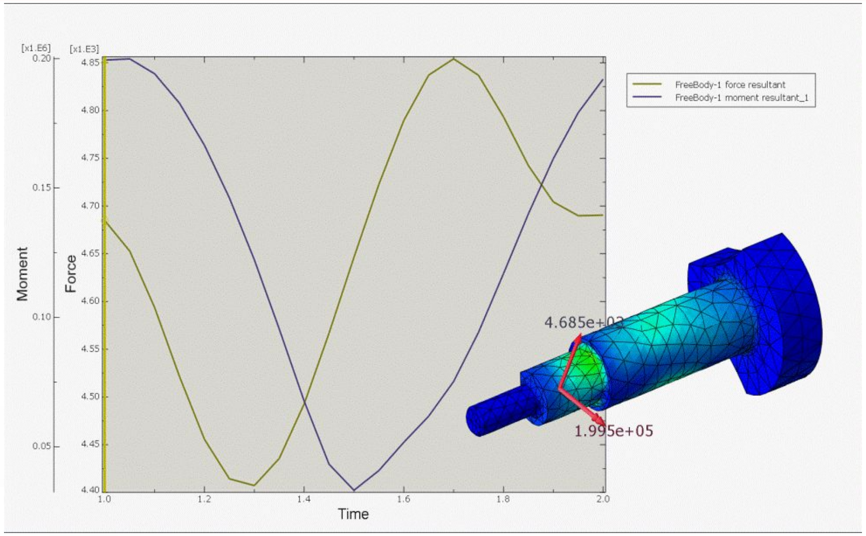
- **Contour plots on beam sections**
  - Available for Box, Rectangle, Circle, Pipe, I and L sections
  - New 'BEAM_STRESS' field output variable
    - SF and SM required
  - View cuts enabled with beam profile rendering

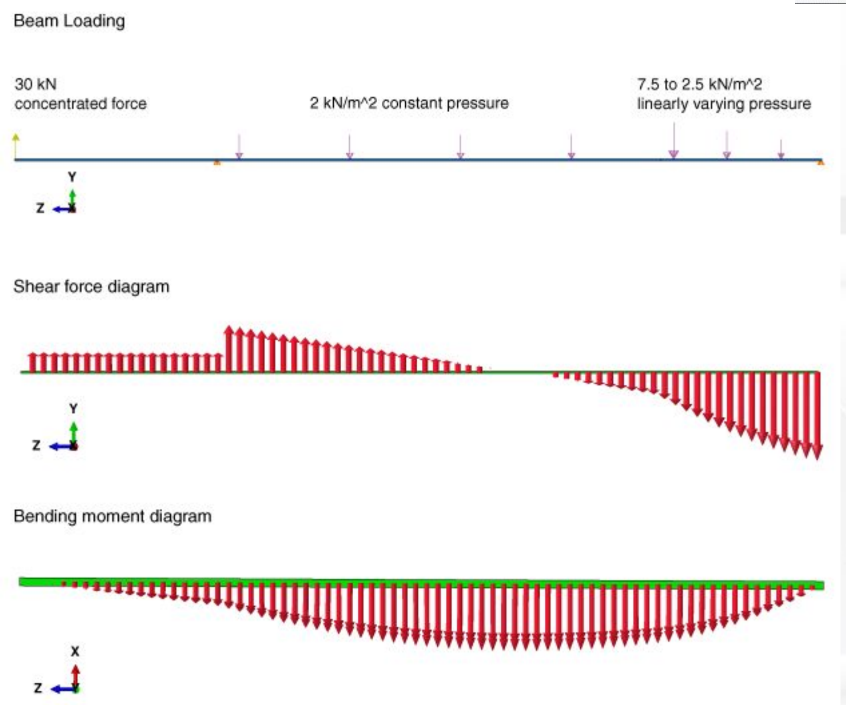


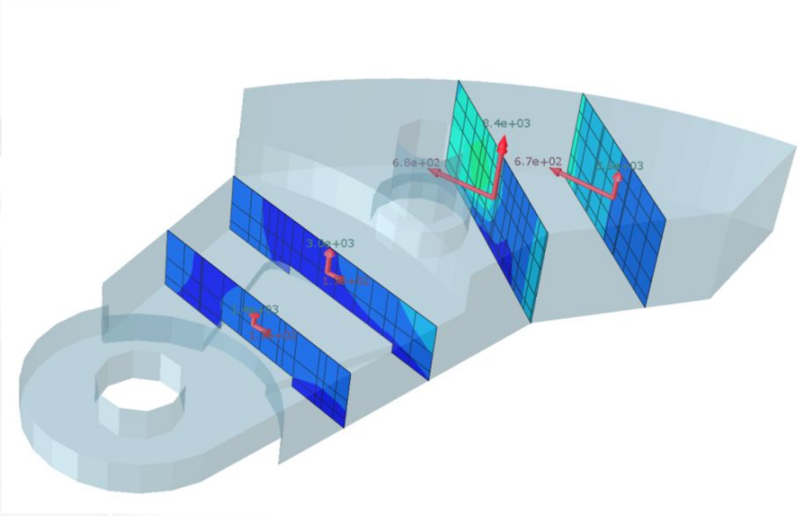


Free Body Diagram Enhancements

- Section force/moment history output
- Section force/moment display on multiple view cuts
- Multiple free bodies on a single view cut





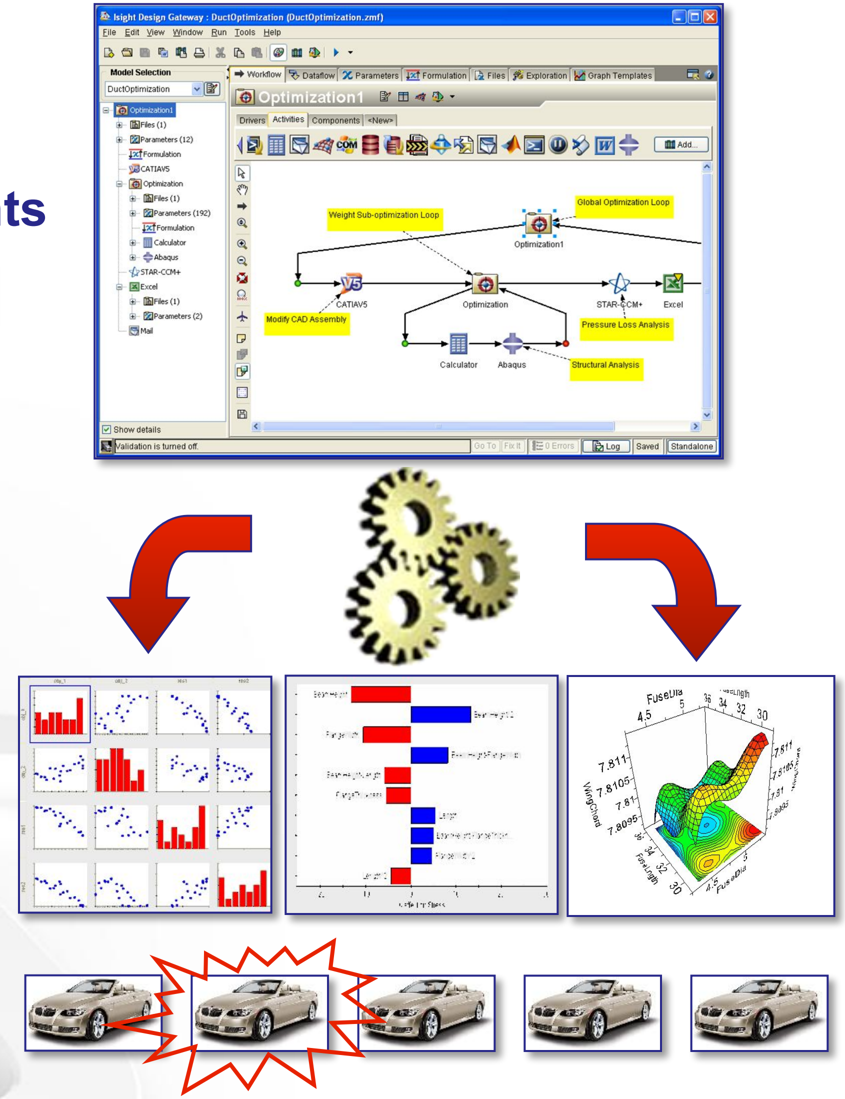


Isight 5.5 Preview

Isight 5.5 – Desktop Process Integration & Optimization

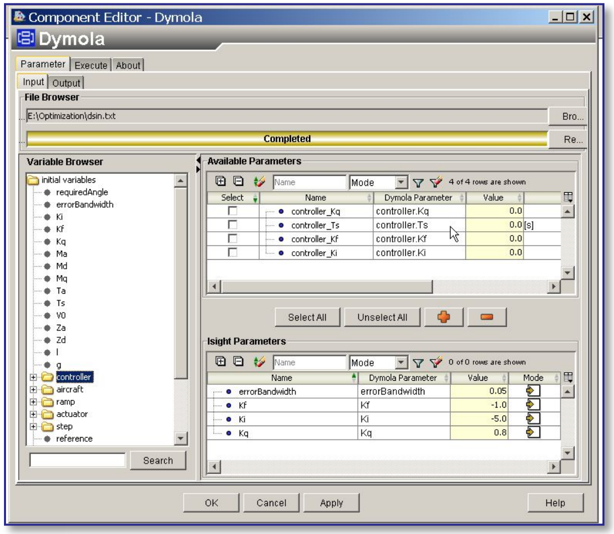
- **Intuitive graphical interface**
- **Integrate applications and automate simulation processes using components**

- **Full suite of powerful exploration tools**
  - Optimization
  - Design for Six Sigma
  - Design of Experiments
  - Reliability and Robustness
  - Approximation models
  - Nested exploration / MDO
- **Interactive data visualization for post processing of multi-run jobs and results interpretation**
- **Grid execution with SEE**
- **Helps identify the best design**



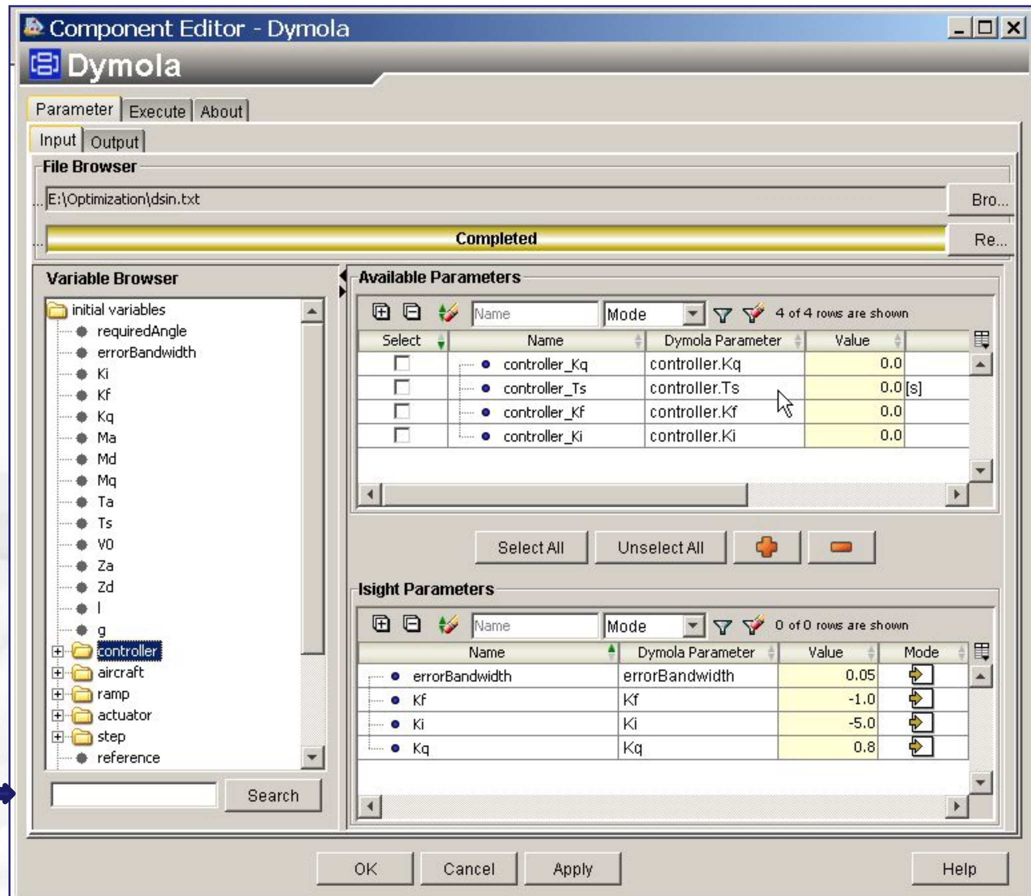
Isight 5.5 Enhancements

- **Model & Simulation Integration**
  - Dymola component
  - Model comparison tool
- **Optimization**
  - MISQP
  - Custom exploration strategy
- **Postprocessing**
  - Overlaid constraints graph
  - Carpet charts



Isight 5.5 Enhancements: Model & Simulation Integration

- Dymola Component allows users to modify a Dymola input file, simulate the Dymola model, and extract the results from the Dymola output file
- Model Comparison Tool allows users to quickly compare Isight sim-flow models in order to determine differences in the problem definition, sim-flow, and coupled-simulation models



Parameters of the selected component

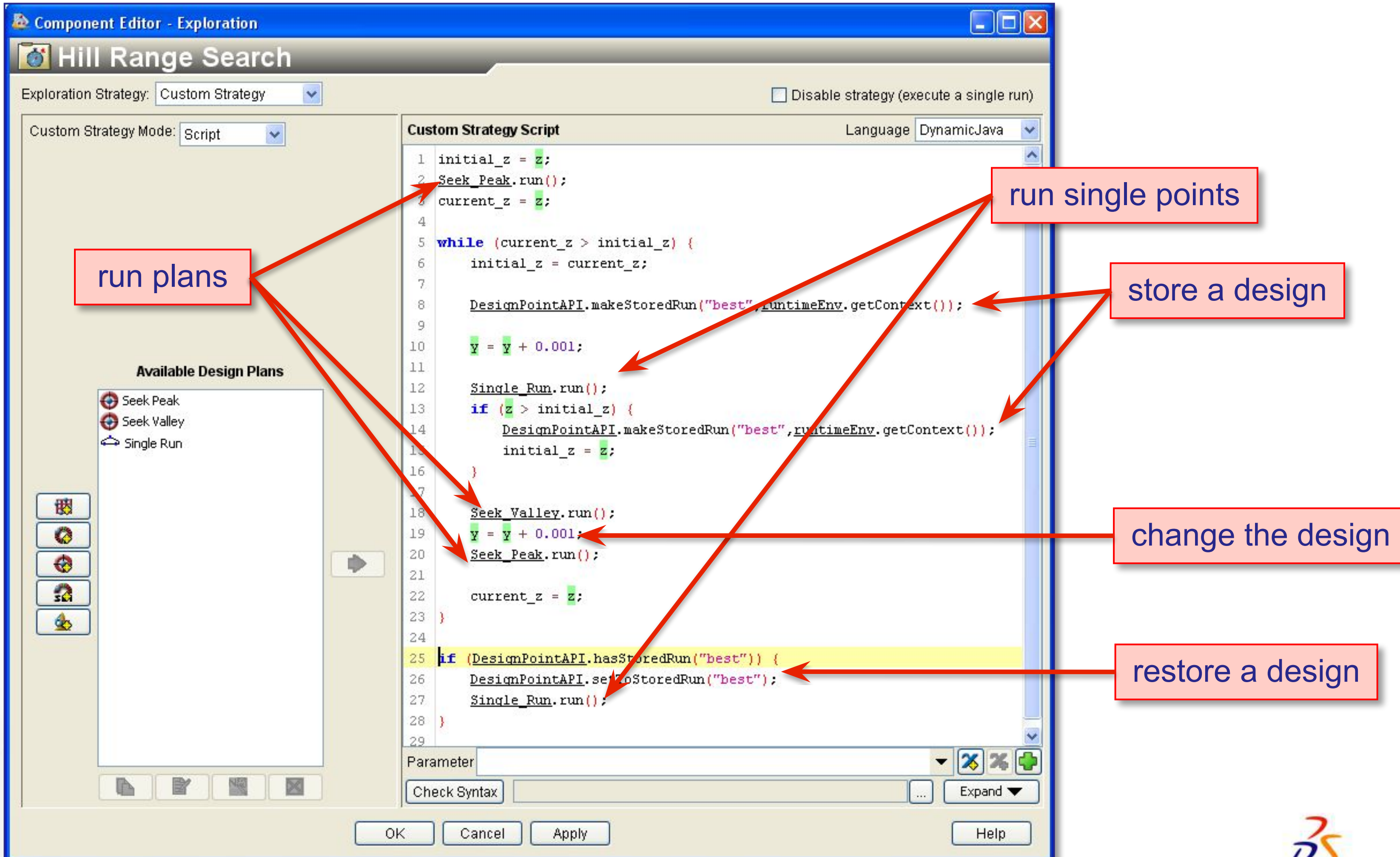
Parameters and initial condition of variables of the whole model

Mapping of Isight parameters to the Dymola model parameters

User can search for an input parameter by its name

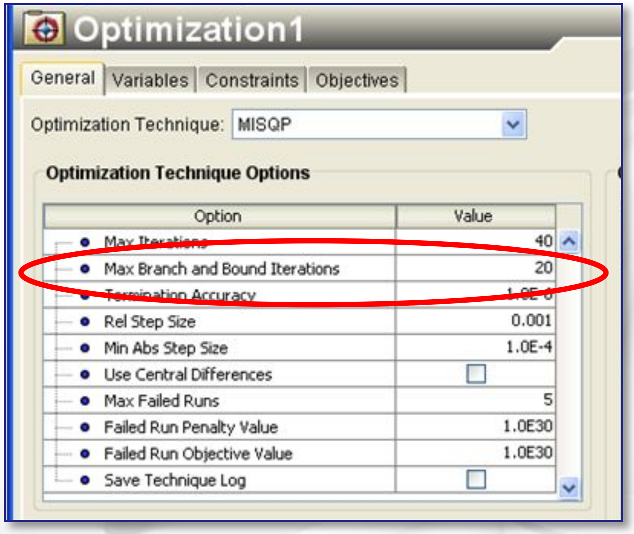
Isight 5.5 Enhancement: Custom Exploration Strategy

- **Python/Jython, Java script mode offers complete flexibility to impose any desired logic on the optimization process**
- **Leverage existing DOE, Optimization, Approximation and Monte Carlo**



Isight 5.5 Enhancement: Mixed-Integer Sequential Quadratic Programming Algorithm (MISQP)

- MISQP is a cutting edge optimization technique in Isight for mixed real and integer variables developed by Klaus Schittkowski.
- This algorithm combines the SQP technique used in NLPQL with a branch-and-bound technique for integers.
- Behaves identically to NLPQL for problems without integer variables.



Excellent benchmark results:

#function calls for each problem and each method

	0. Math. Function	1. Bolt-Nut-Plate	2. Pressure Vessel	3. Cantilever
Hooke-Jeeves	401	135	249	861
Downhill Simplex	319	321	362	828
MOST	64	64	674	17
ASA	1015	1023	1013	2023
MIGA	961	961	961	3601
MISQP	169	47	260	1249

white: optimal Grey: feasible red: fail

SIMULIA

2011 SIMULIA Customer Conference | BARCELONA, SPAIN • May 16-19

Advanced Seminars - May 16; Conference - May 17-19, 2011
Barcelona, Spain

- **138 abstracts received**
  - **Resulting in 80+ Customer Papers / Presentations**
  - **Representing all industries and SIMULIA products; including Abaqus, Isight, and SLM**
- **Goal of 200+ Customer Attendees and 20+ Partner Exhibitors**
- **6 Industry Special Interest Groups** (including Turbomachinery)
- **4 Advanced Seminars**
- **5 General Lectures**
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For more information

- www.simulia.com/solutions/turbomachinery.html
  - New site still under development, new content added periodically
- **SIMULIA Customer Conference paper references and online videos**
- **Case studies, tech briefs, flyers, webinars**
  - Eblade webinar, September 2010
  - New Features in Isight/SEE 4.5, September 2010
  - New Features in Abaqus 6.10-EF, January 2011
  - Replays now available at www.simulia.com
- **Jan/Feb 2010 issue of *INSIGHTS* magazine**
- **Latest issue of Realistic Simulation News**
  - Download at www.simulia.com/RSN
- **ASME and other conference papers on Abaqus and Isight applications for turbomachinery**
  - List provided upon request *(just updated)*
- **Regional User Meetings (RUMs)**
  - Schedules posted at simulia.com/events/rums.html
- **Contact Jack Cofer, Industry Lead for Turbomachinery, at jack.cofer@3ds.com**

Turbomachinery Applications using Abaqus

Youngwon Hahn

Ver. OCT 2010

Who Is Dr. Youngwon Hahn?

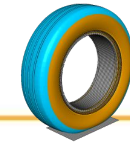
Overview

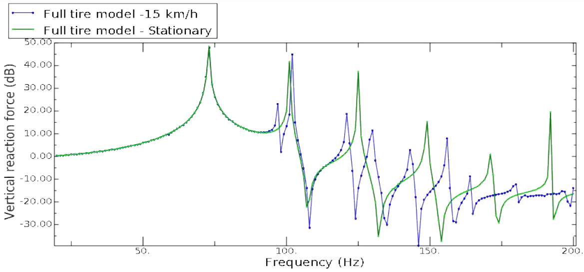
- **Rotordynamics**
  - Gyroscopic Effect
  - Bearing Modeling
  - Frequency Extraction and Frequency Response
  - Campbell Diagram Plug-in
  - Other Plug-in in development (including interface with ROMAC bearing code)
  - Substructure
- **Coupled Structural-Acoustic Analysis**
- **Blade Analysis**
  - Modeling in A/CAE
  - Cyclic Symmetric Model
  - Modal Analysis
  - Stress Analysis
  - New Mapping Capability in A/CAE (6.11)
  - XFEM
  - Displacement Analysis (i.e. untwist) for given pre-loading condition
- **Bird Strike Analysis**
  - Lagrangian Approach
  - SPH: New functionality in 6.11 (in-progress)
- **Blade-out Analysis**
  - Case Study of Blade Containment

SIMULIA

Rotordynamics

Rotordynamics





Gyroscopic Effect

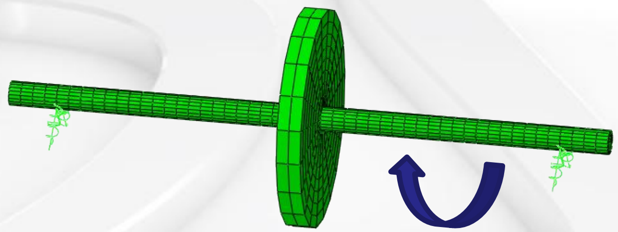
- Abaqus provides two approaches for gyroscopic effect.
  - Eulerian approach
    - This technique was required by a tire application.
    - User can apply transport velocity as a spin speed in steady state transport procedure in order to obtain gyroscopic effect for the spinning structure.
    - This requires axi-symmetric model which was created by special modeling technique called symmetric model generation (SMG). SMG requires a prior 2-D model result.
    - This approach is recommended for rotordynamic analysis now.

Apply spin speed with *transport velocity in steady state transport procedure

Rotordynamics

Gyroscopic Effect

- Lagrangian approach
  - General approach.
  - User can apply body force as the function of the spin speed in general static procedure in order to obtain gyroscopic effect for the spinning structure.
    - DLOAD with CENTRIF and CORIO load type is supported as a body force.
  - CORIO load type, one of body forces, only supports solid and truss elements now.
  - The body force DLOAD is calculated in moving reference frame.
    - The whirl frequency can be obtained by manual calculation of result frequency and applied spin speed.
  - This approach is not recommended now since subsequent steady state dynamic analysis is not applicable.
  - We are planning to enhance this method in 6.12.



Apply spin speed with CENTRIF and CORIO load type in general static procedure

Rotordynamics

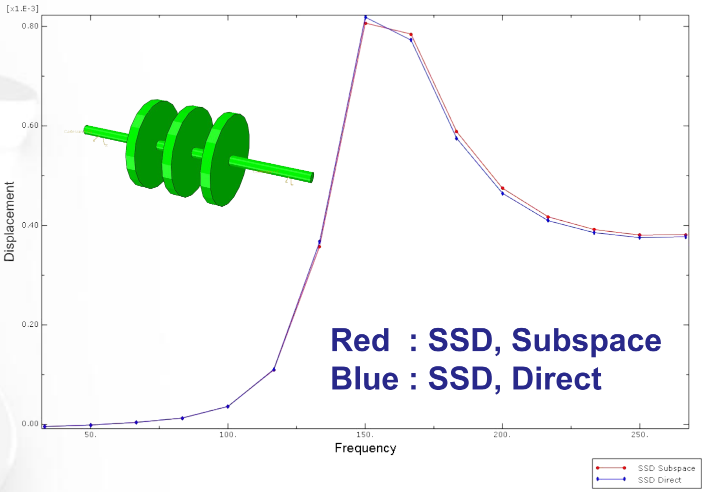
Bearing Modeling

- **Bearing is a flexible component to support shaft.**
  - Bearing has stiffness and damping coefficient
  - Abaqus provides two types of element for bearing modeling.
    - Spring and Dashpot elements
      - Kxx, Kzz, Cxx or Czz is supported
      - Frequency dependency is supported
    - Connector elements with elastic and damping behavior
      - Kxx, Kxz, Kzx, Kzz, Cxx or Czz is supported.
      - Frequency dependency is supported only for Kxx, Kzz, Cxx, and Czz.
  - We are planning to enhance this capability in 6.12

Rotordynamics

Frequency Extraction and Frequency Response

- **Real frequency extraction**
  - Lanczos and AMS solver is supported.
    - AMS (Automatic Multi-level Substructuring) method
      - Well-suited to very large systems where a large subset of eigenvalues are needed.
      - The finite element model is projected onto a reduced multi-level substructure modal space to solve a global eigenproblem.
- **Complex frequency extraction**
  - Prior real frequency extraction step is required, since projection method is used for complex frequency extraction step.
- **Frequency response analysis**
  - Steady-state dynamic procedure is supported.
    - Direct method and subspace-based method are supported for gyroscopic effect.
  - Unbalanced load can be considered with *CLOAD, loadcase=# keyword.



Rotordynamics

Unbalance Load

- **Rotational Loads**
  - Defined by a prior SST Step
- **Unbalance Load Definition**
  - Are assumed of same frequency and sign as Rotor Rotation
  - Are proportional to the rotational velocity squared

$$F = \underline{me\omega^2}\,\underline{e^{j(\omega t+\phi)}}$$

Where
m = unbalance mass
e = unbalance eccentricity
ω = rotational velocity [rad/s]

Another load for phase angle

It can be defined in amplitude definition.
***Amplitude, name=unbalance**

$$f_1, me\omega_1^2, f_2, me\omega_2^2, \ldots$$

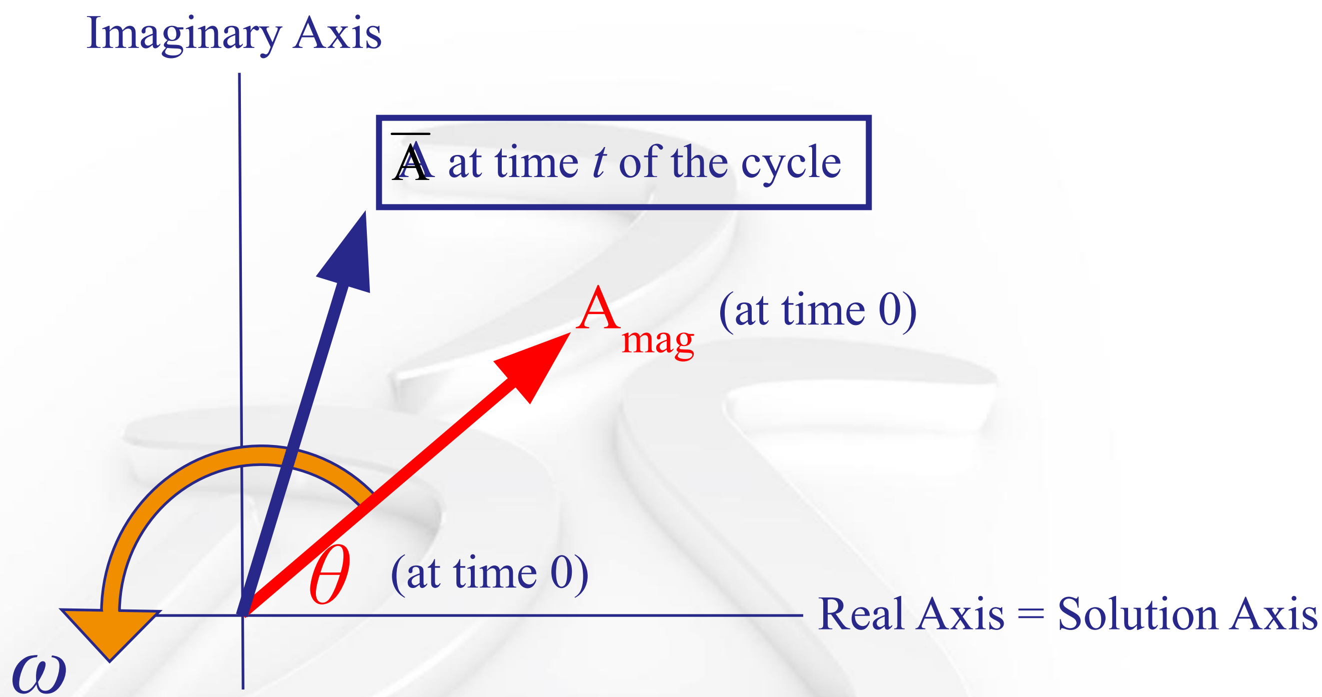
- **Rotational Loads**
  - are defined by specifying two simultaneous loads
    - of equal Magnitude
    - In orthogonal planes
    - With a Phase angle of 90 degrees

SIMULIA

Introduction

Unbalance Load

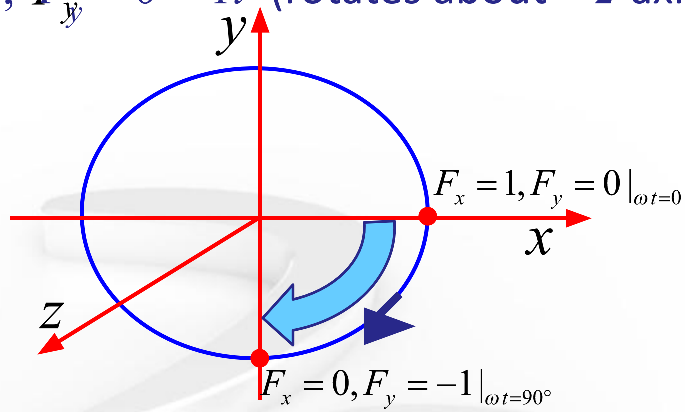
- **Complex plane**
  - The time variation of an excitation or output quantity during a cycle of response is equal to its projection on the "Solution Axis."



Rotordynamics

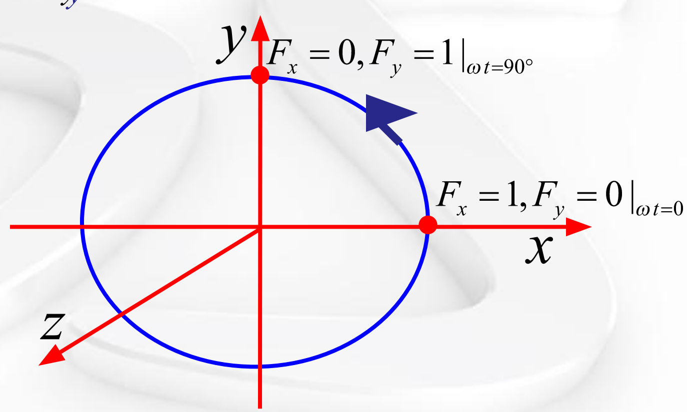
Unbalance Load

- **Complex axes to physical axes**
  - Example: Unit force due to an imbalance for a z-axis rotation.
    - $\overline{F}_x = 1 + 0i$, $\overline{F}_y = 0 + 1i$ (rotates about − z-axis)



$$F_x = \mathrm{Re}(\overline{F}_x e^{i\omega t}) = \cos(\omega t)$$
$$F_y = \mathrm{Re}(\overline{F}_y e^{i\omega t}) = -\sin(\omega t)$$

- $\overline{F}_x = 1 + 0i$, $\overline{F}_y = 0 - 1i$ (rotates about + z-axis)

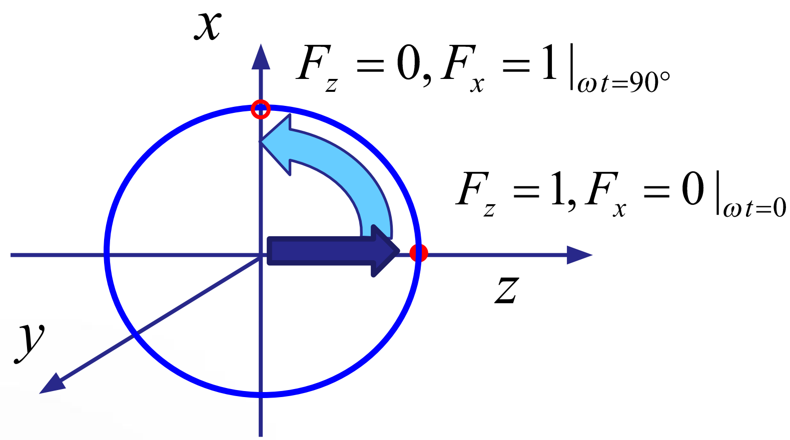


$$F_x = \mathrm{Re}(\overline{F}_x e^{i\omega t}) = \cos(\omega t)$$
$$F_y = \mathrm{Re}(\overline{F}_y e^{i\omega t}) = \sin(\omega t)$$

Rotordynamics

Defining Positive Rotation: Load

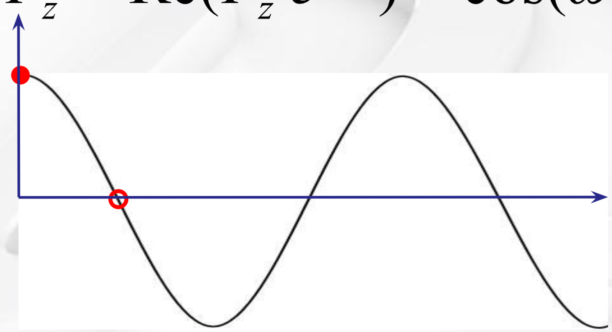
- Use right-hand rule
  - To define 1-axis in the direction of real force at time=0
  - and 2-axis in the direction of real force at time=T/4
  - 3-axis is then your axis of rotation
- Complex Unit Load Vectors at time=0

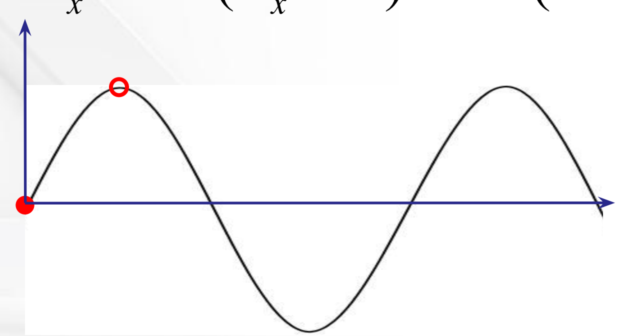


Rotation about +y-axis

$$\overline{F}_z = 1 + 0i$$
$$\overline{F}_x = 0 - 1i$$

$$F_z = \mathrm{Re}(\overline{F}_z e^{i\omega t}) = \cos(\omega t) \qquad F_x = \mathrm{Re}(\overline{F}_x e^{i\omega t}) = \sin(\omega t)$$



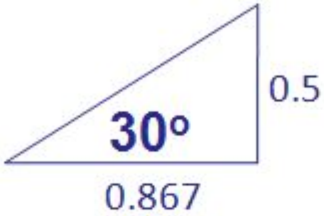


Rotordynamics

Example: Load

General Case: 30º

- To define a load 30º ahead of original load



$$\overline{F}_z = 1 + 0i$$
$$\overline{F}_x = 0 - 1i$$

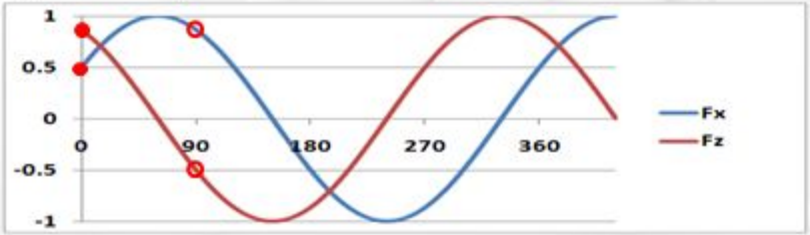
Multiply by (0.867 + 0.5i)

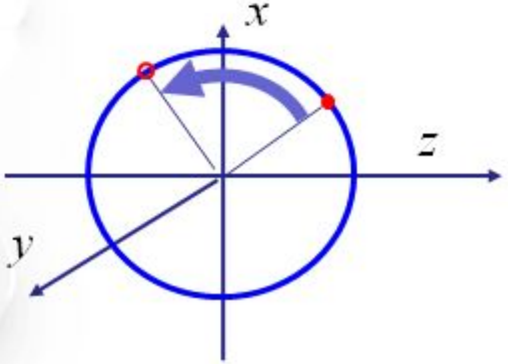
$$\overline{F}_z = 0.867 + 0.5i$$
$$\overline{F}_x = 0.5 - 0.867i$$

LC	DOF	Value	DOF	Value
1	1	0.5	3	0.867
2	1	-0.867	3	0.5

$$F_z = -0.5, F_x = 0.867 \,|_{\omega t=90°}$$
$$F_z = 0.867, F_x = 0.5 \,|_{\omega t=0}$$

$$F_z = \mathrm{Re}(\overline{F}_z e^{i\omega t}) = 0.867\cos(\omega t) - 0.5\sin(\omega t)$$
$$F_x = \mathrm{Re}(\overline{F}_x e^{i\omega t}) = 0.5\cos(\omega t) + 0.867\sin(\omega t)$$





Rotordynamics

Frequency Extraction and Frequency Response

- **Comparison with reference paper**

Reference Results*

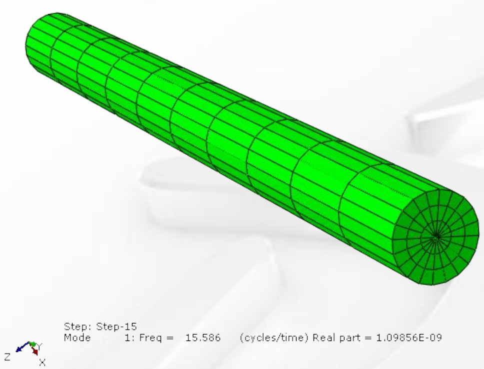


Table 2 Nondimensional first backward and forward critical speeds $\omega = (\rho l^2\ \Omega^2/E\sigma^2)^{1/4}$ of uniform shaft

σ=r/(2L)

	Ratio σ	Current work			Hermitian elements	
		Linear elements	Quadratic elements	Cubic elements	Ref. (1)	Ref. (2)
Backward mode	0.02	3.1362	3.1234	3.1234	3.1252	3.1253
	0.04	3.0851	3.0728	3.0728	3.0792	3.0796
	0.06	3.0111	2.9993	2.9993	3.0116	3.0125
	0.08	2.9244	2.9132	2.9132	2.9313	2.9328
	0.10	2.8329	2.8224	2.8224	2.8455	2.8475
Forward mode	0.02	3.1482	3.1354	3.1354	3.1373	3.1374
	0.04	3.1292	3.1168	3.1167	3.1240	3.1246
	0.06	3.0976	3.0856	3.0856	3.1016	3.1027
	0.08	3.0539	3.0425	3.0425	3.0696	3.0715
	0.10	2.9991	2.9885	2.9884	3.0282	3.0311

(1) Rouch and Kao (1979), (2) Nelson (1980)

***T.C. Gmur and J.D. Rodrigues, "Shaft Finite element for Rotor dynamics Analysis," ASME J. Vib. Acoust. 113 (1993) 482-493**

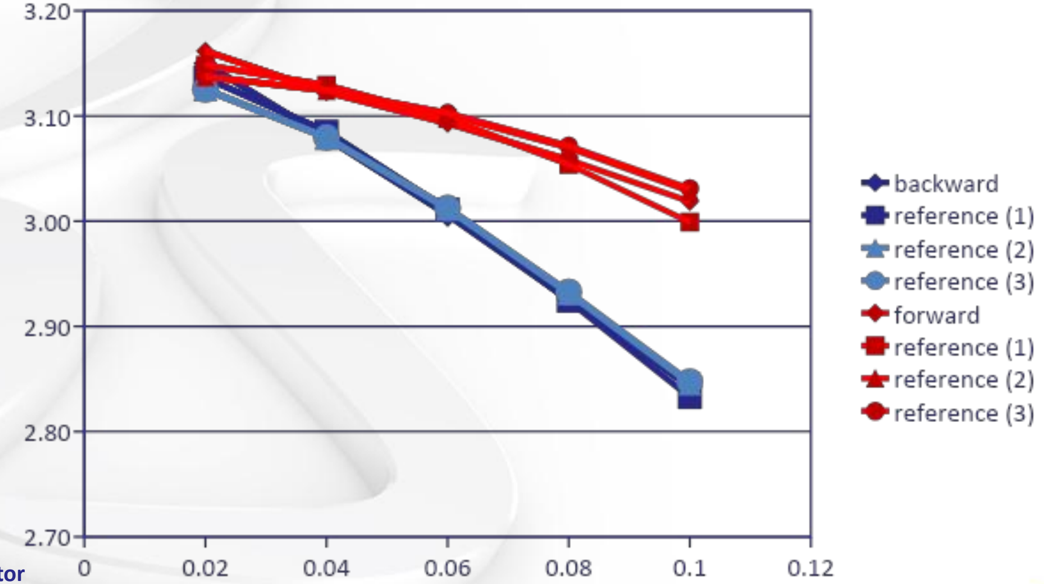
Rotordynamics

Frequency Extraction and Frequency Response

- **Comparison with reference paper**

Dimensionless critical forward/backward speed

Ratio	0.02	0.04	0.06	0.08	0.1
backward	3.1498	3.0790	3.0059	2.9254	2.8418
reference (1)*	3.1362	3.0851	3.0111	2.9244	2.8329
reference (2)*	3.1252	3.0792	3.0116	2.9313	2.8455
reference (3)*	3.1253	3.0796	3.0125	2.9328	2.8475
Forward	3.1617	3.1226	3.0929	3.0583	3.0185
reference (1)*	3.1482	3.1292	3.0976	3.0539	2.9991
reference (2)*	3.1373	3.1240	3.1016	3.0696	3.0282
reference (3)*	3.1374	3.1246	3.1027	3.0715	3.0311

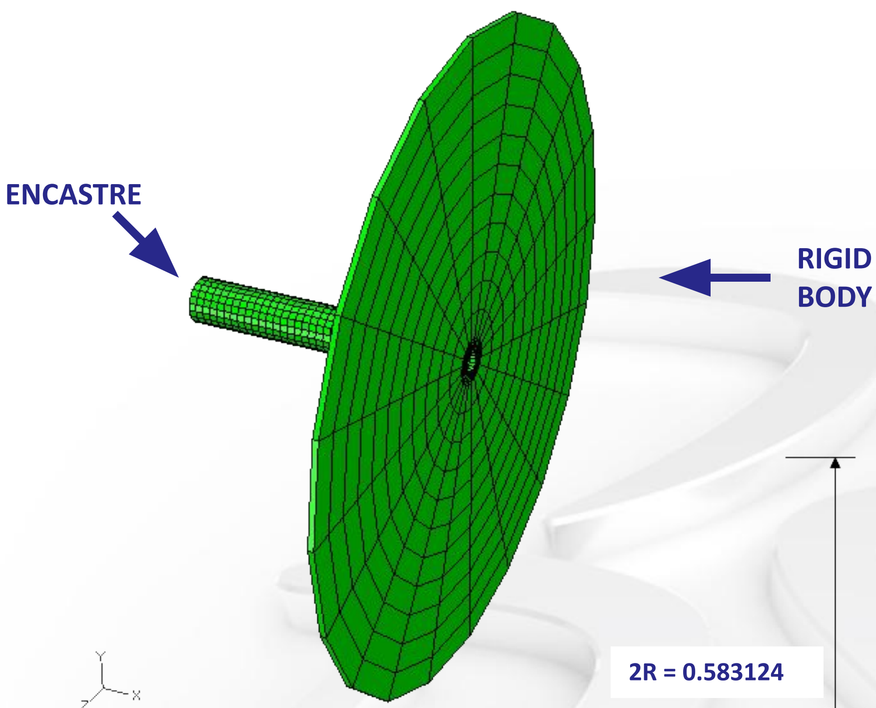


***T.C. Gmur and J.D. Rodrigues, "Shaft Finite element for Rotor dynamics Analysis," ASME J. Vib. Acoust. 113 (1993) 482-493**

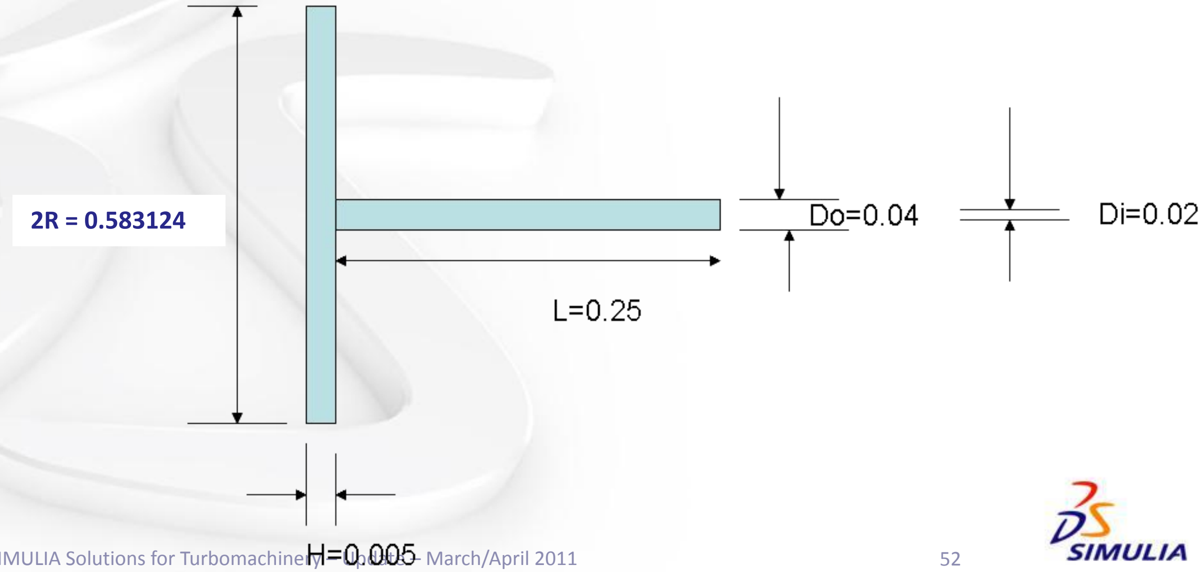
Rotordynamics

Frequency Extraction and Frequency Response

- **Comparison with analytical solution**



- **Shaft assumed Massless, but Flexible**
- **Disk is assumed Rigid**
- **Units in m, Kg, N, s**
- **Radius of Disk has been chosen such that:**
  - $I_t = ml^3/3$
  - Where
  - I_t = Disk transverse moment of inertia
  - m = Disk mass
  - l = Shaft length
  - E = 2.1e11 Pa
  - Disk density = 7800 kg/m^3



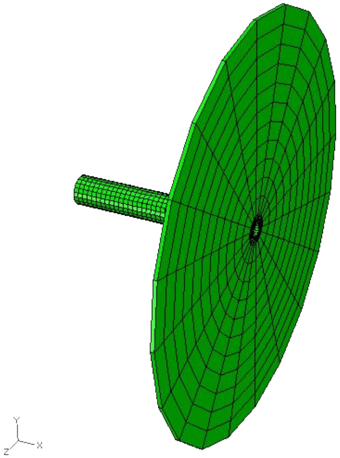
Rotordynamics

Frequency Extraction and Frequency Response

- **Comparison with analytical solution**

@ 400 rad/s	Classical Result*		Abaqus	
	Backward	Forward	Backward	Forward
1	51.6	112.9	53.507	110.69
2	268.3	334.4	264.08	331.80

@ 1400 rad/s	Classical Result*		Abaqus	
	Backward	Forward	Backward	Forward
1	23.3	170.9	24.85	164.31
2	234	541.1	237.49	535.2

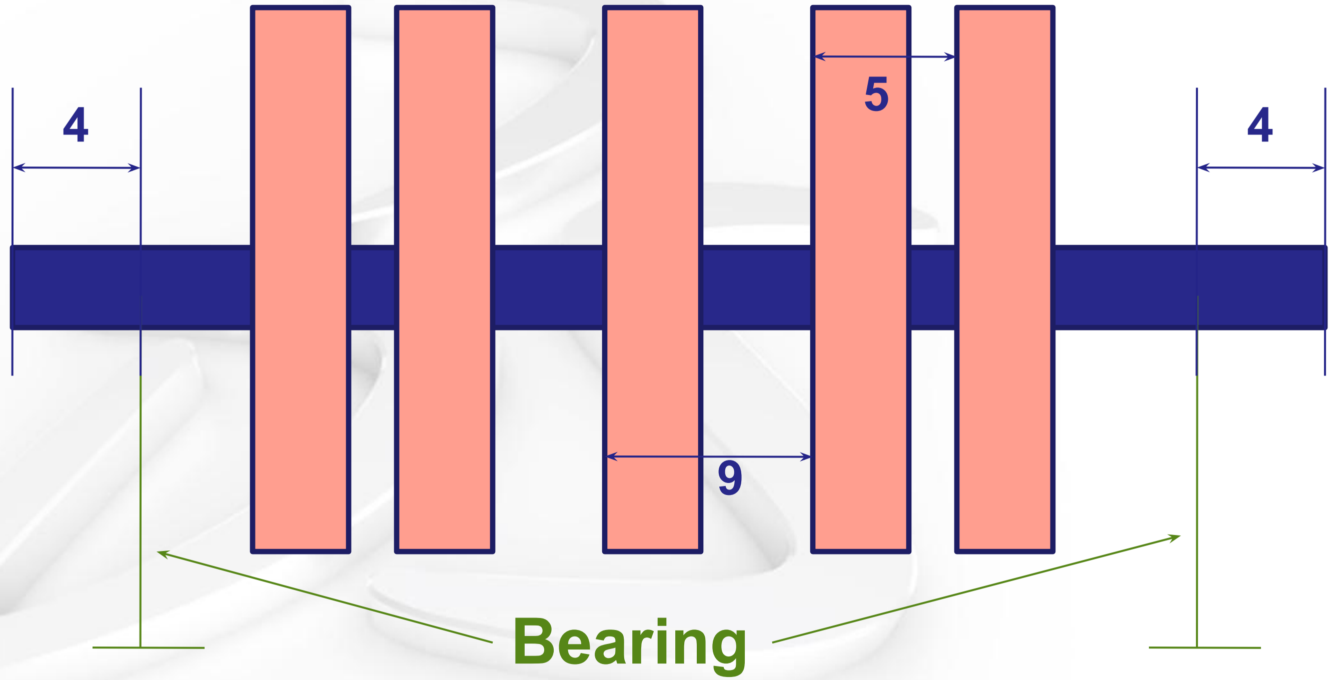


*J.P. Den Hartog, "Mechanical Vibrations," Dover Publication, Inc, New York, 1985

Rotordynamics

Frequency Extraction and Frequency Response

- **Comparison with ROMAC results**
  - Shaft: L=50, Do=2, Di=0.1
  - Disk: L=2, Do=18, Di=2
  - Bearing location: 4 inches away from the each end
  - E=30e6, Poisson's ratio=0.3, Density=0.284(lb/in^2)/386.4 = 7.35e-4 (lbm/in^2)
  - Three cases: one disk, three disks, and five disks



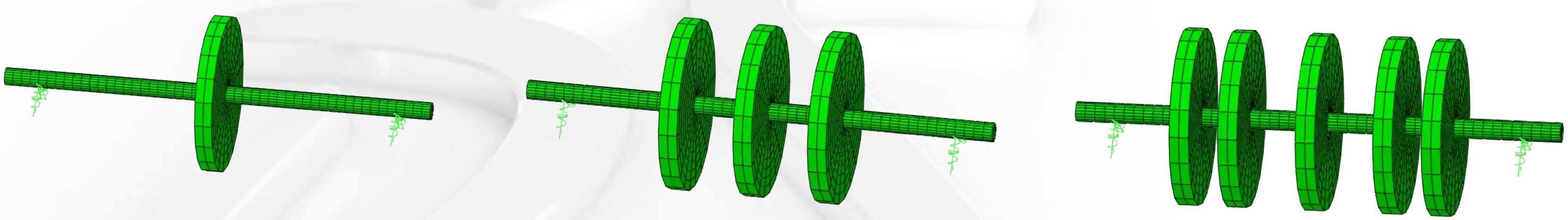
Rotordynamics

Frequency Extraction and Frequency Response

- **Comparison with ROMAC results**
  - With uncoupled bearing (no Kxy/Kyx)
    - Kxx = 1000, Kzz = 2000
    - Cxx = 300, Czz = 400

Damped Natural Frequency								
One Disk Rotor			Three Disks Rotor			Five Disks Rotor		
ROMAC	Abaqus	ERROR	ROMAC	Abaqus	ERROR	ROMAC	Abaqus	ERROR
30.35 (B)	30.30	0.18%	19.23 (B)	19.31	0.38%	15.55 (B)	15.66	0.75%
30.37 (F)	30.31	0.19%	21.02 (F)	21.07	0.25%	19.70 (F)	19.77	0.33%
172.00 (F)	170.88	0.65%	72.57(B)	73.06	0.67%	67.62 (F)	68.15	0.79%
114.05 (B)	114.17	0.11%	89.15 (F)	89.48	0.37%	56.90 (B)	57.50	1.06%
544.83 (F)	547.56	0.50%	134.47 (B)	135.51	0.78%	110.15 (B)	111.42	1.15%
544.17 (B)	546.95	0.51%	163.25 (F)	164.40	0.70%	138.35 (F)	139.37	0.74%
550.33 (B)	553.40	0.56%	177.83 (B)	178.34	0.28%	148.38 (B)	149.72	0.90%
557.17 (F)	560.10	0.53%	227.17 (F)	226.92	0.11%	201.67 (F)	204.62	1.46%

Log Dec								
One Disk Rotor			Three Disks Rotor			Five Disks Rotor		
ROMAC	Abaqus	ERROR	ROMAC	Abaqus	ERROR	ROMAC	Abaqus	ERROR
0.4381	0.4321	1.36%	0.5924	0.5881	0.73%	0.6599	0.6587	0.19%
0.3281	0.3236	1.37%	0.7368	0.7282	1.16%	1.1410	1.1260	1.31%
0.0765	0.0761	0.53%	0.4321	0.4267	1.24%	0.6927	0.6892	0.51%
0.1397	0.1372	1.76%	0.2994	0.2983	0.35%	0.5834	0.5808	0.44%
0.0641	0.0629	1.81%	0.2869	0.2826	1.50%	0.5903	0.5877	0.44%
0.0505	0.0496	1.68%	0.1284	0.1260	1.87%	0.4162	0.4199	0.89%
0.0516	0.0506	1.89%	0.1518	0.1520	0.15%	0.4474	0.4376	2.18%
0.0503	0.0494	1.85%	0.0625	0.0622	0.45%	0.5497	0.5505	0.14%



Solver Difference

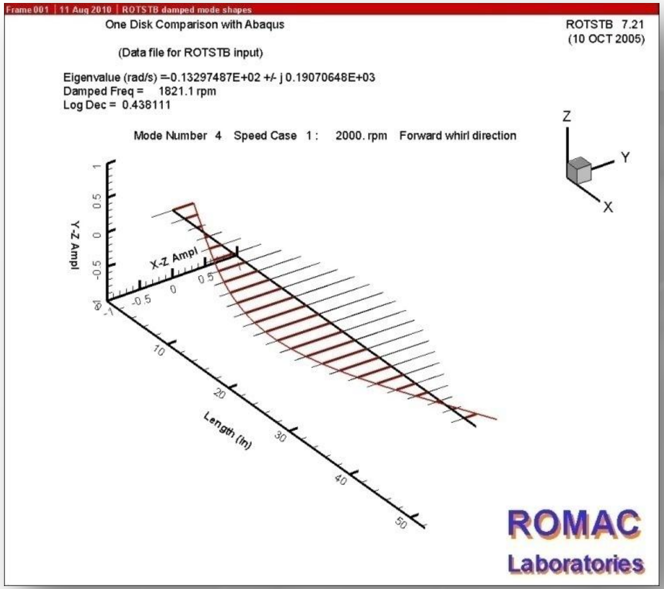
Abaqus: Projection method. Frequency extraction step is required.

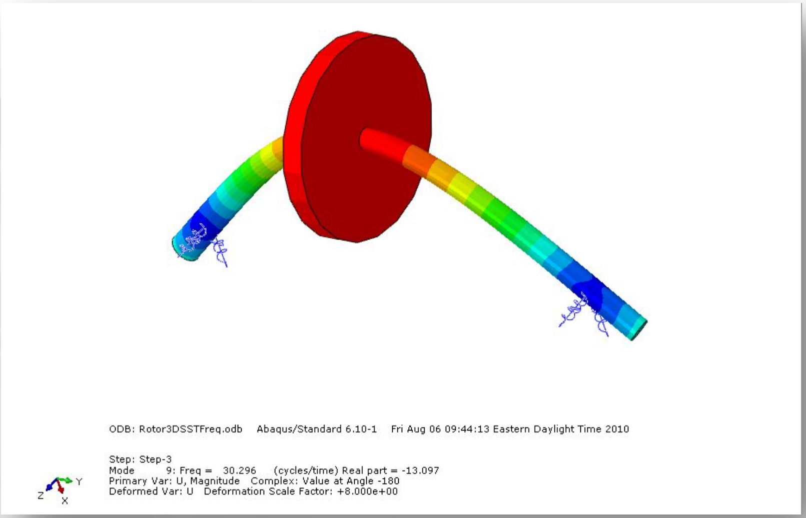
ROMAC: Direct method (Complex Hessenberg QR algorithm) in EISPACK

Rotordynamics

Frequency Extraction and Frequency Response

- **Comparison with ROMAC results**
  - With uncoupled bearing (no Kxy/Kyx)
    - Kxx = 1000, Kzz = 2000
    - Cxx = 300, Czz = 400



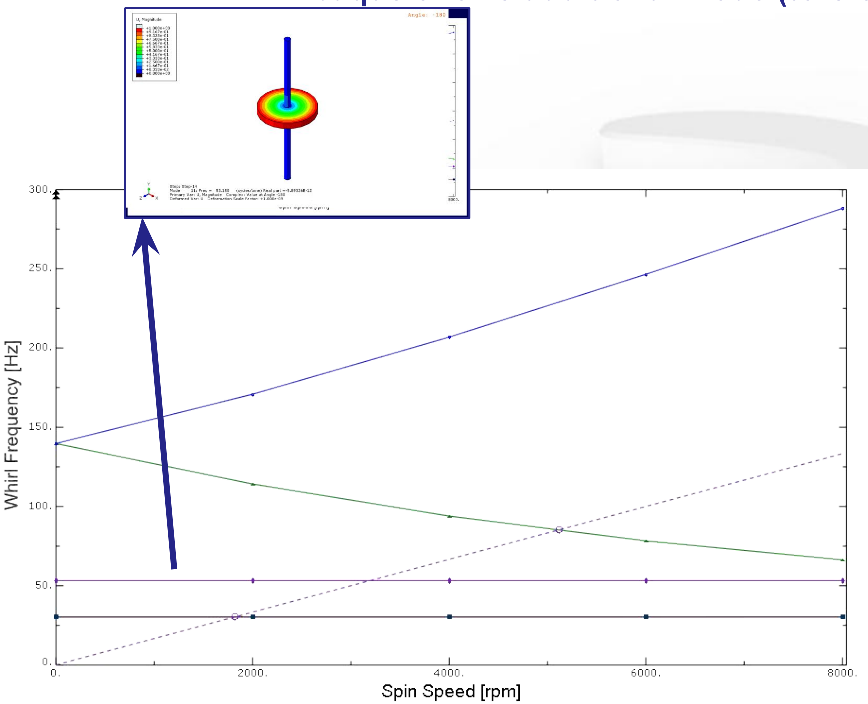


Rotordynamics

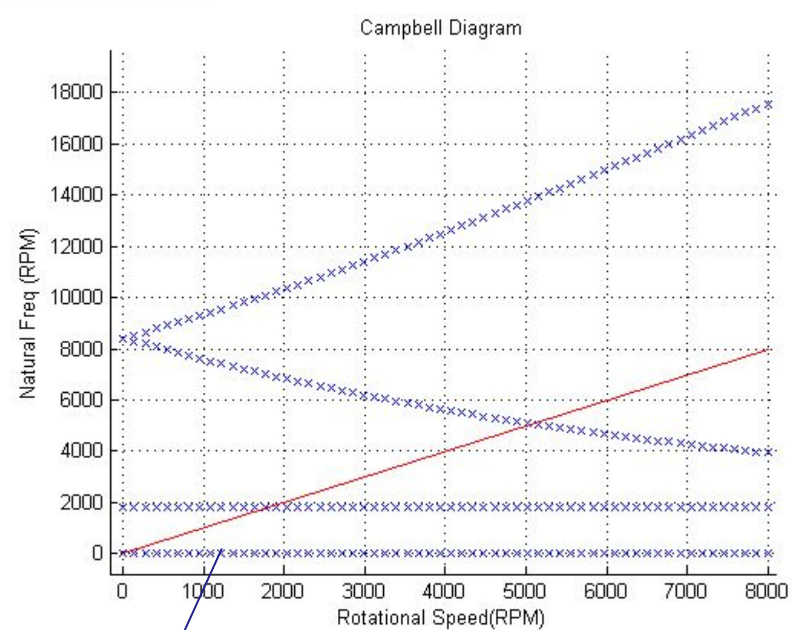
Frequency Extraction and Frequency Response

- **Comparison with ROMAC results**
  - With uncoupled bearing (no Kxy/Kyx)
    - Kxx = 1000, Kzz = 2000
    - Cxx = 300, Czz = 400

Abaqus shows additional mode (torsional mode)



Abaqus



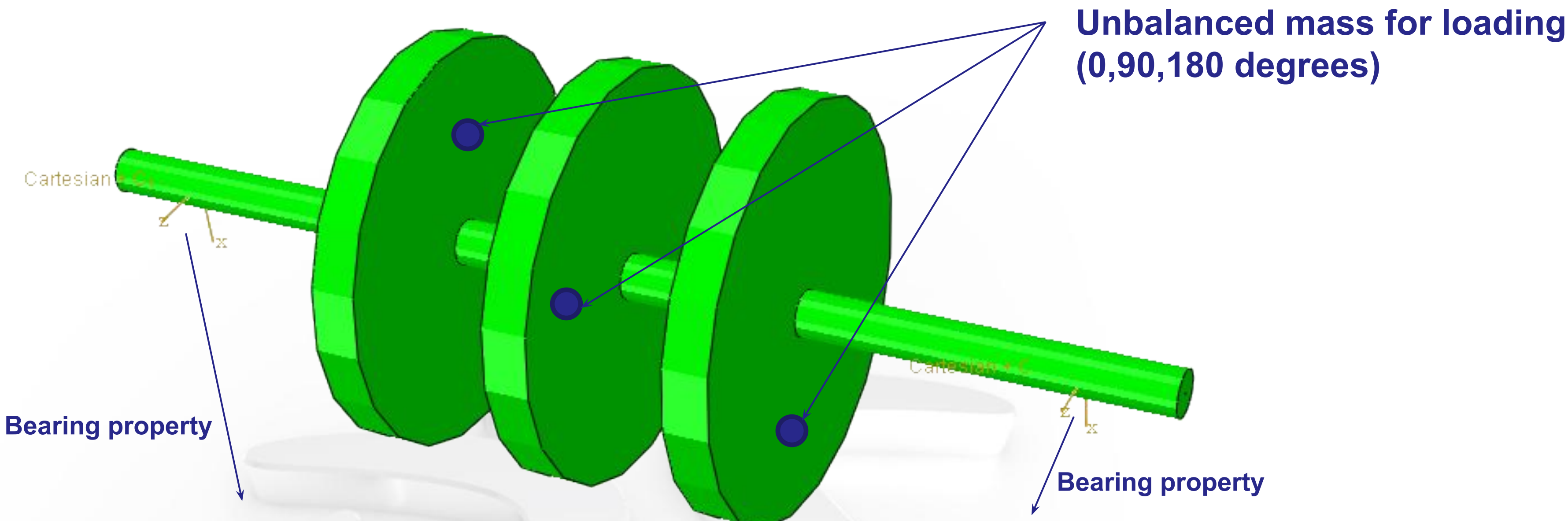
ROMAC

Zero mode

Rotordynamics

Frequency Extraction and Frequency Response

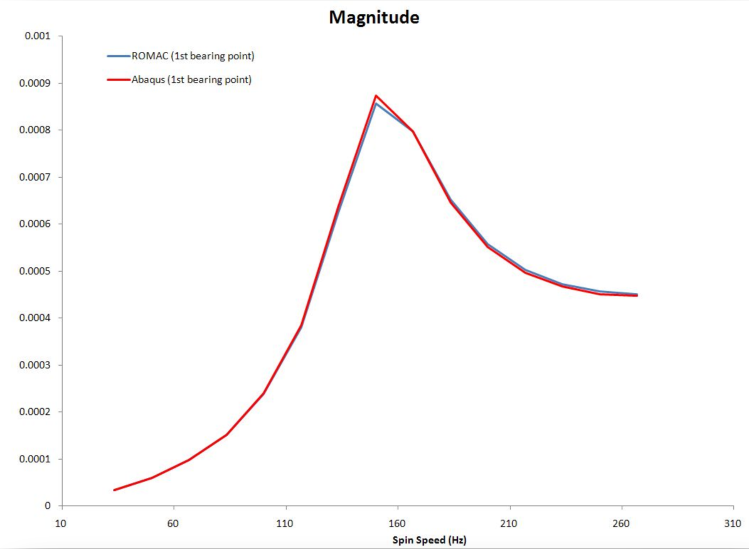
- **Load Definition (unbalance load)**
  - 1 oz-in at 0,90, and180 degrees (X-axis is 0 degree)

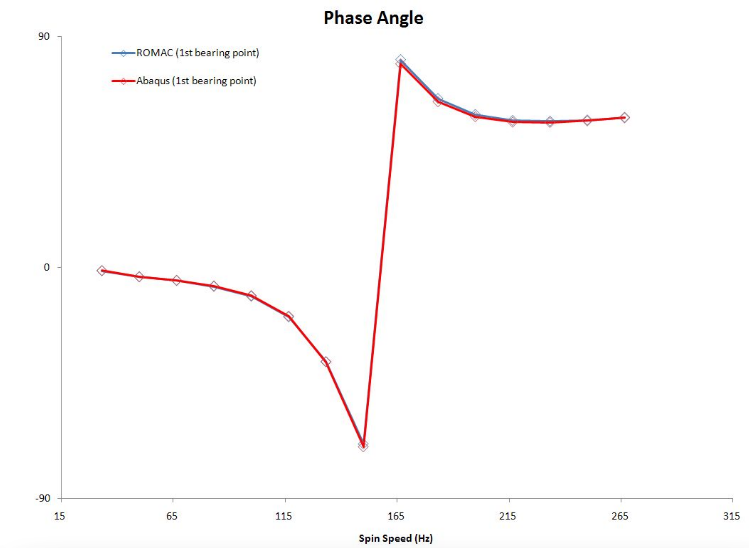


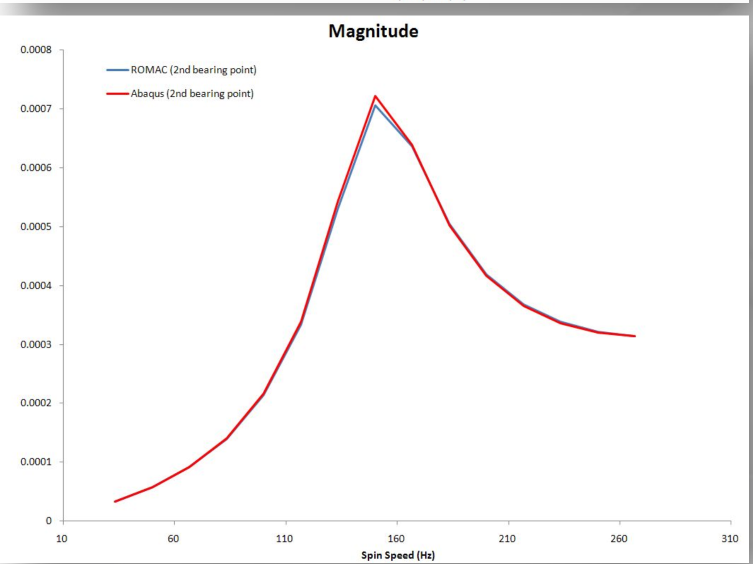
Kxx	Kxz	Kzx	Kzz	Cxx	Cxz	Czx	Czz
38601.54	0	0	52588.27	544.5408	0	0	496.1638
57810.68	0	0	68011.77	449.5349	0	0	474.8226
75565.91	0	0	83794.3	391.7378	0	0	404.688
91934.54	0	0	99067.23	350.412	0	0	358.4907
105787.4	0	0	112254	315.4584	0	0	321.0936
117891.2	0	0	123904.6	286.6295	0	0	290.8449
128550.6	0	0	134217	262.4451	0	0	265.7449
139211.9	0	0	144593	243.596	0	0	246.2656

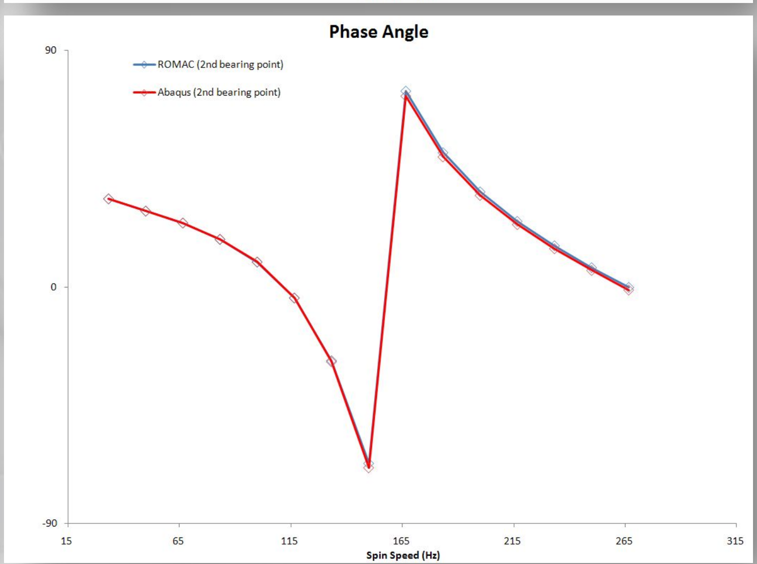
Simple Rotor (Three Disks)

Frequency Extraction and Frequency Response





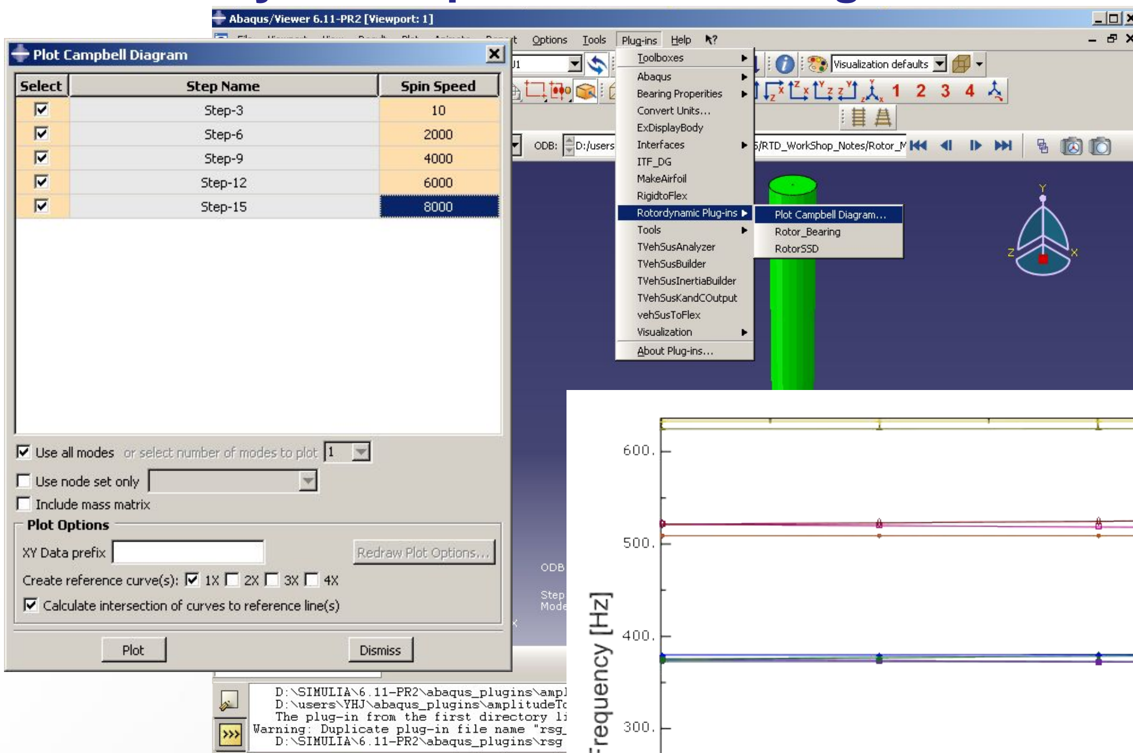


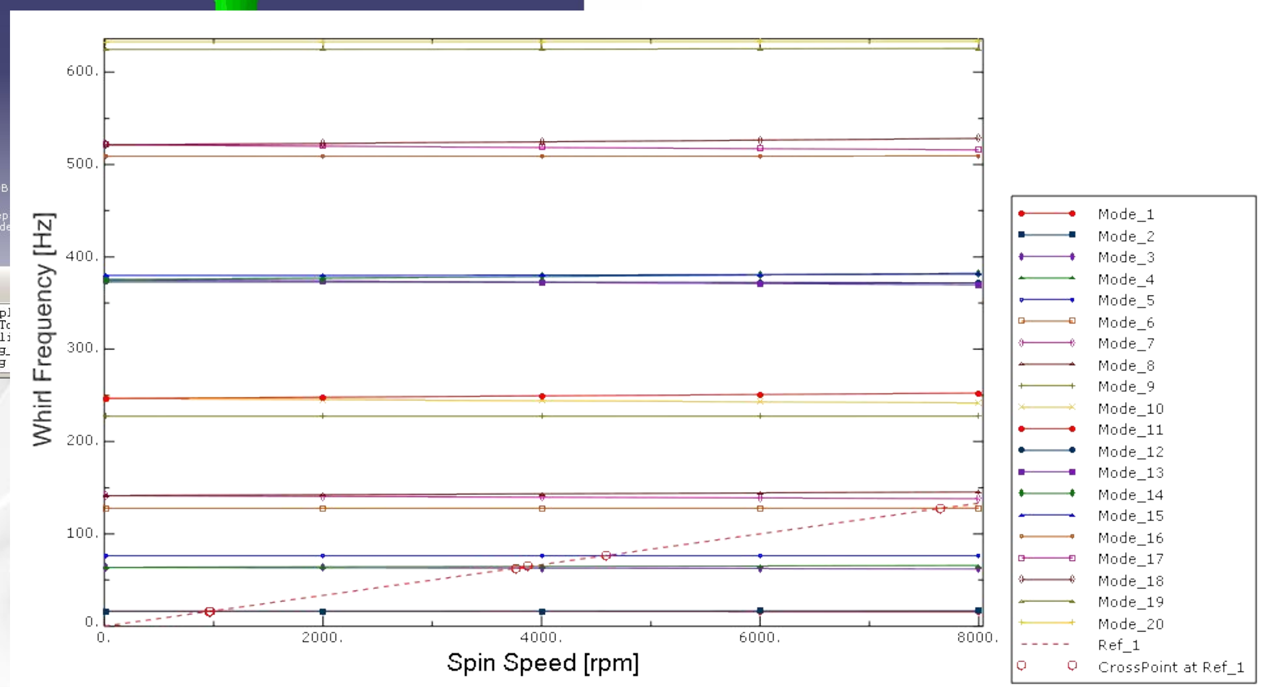


Rotordynamics

Campbell Diagram Plug-in (ANSWER 4721)

- **Newly developed A/Viewer Plug-in for rotordynamic application**

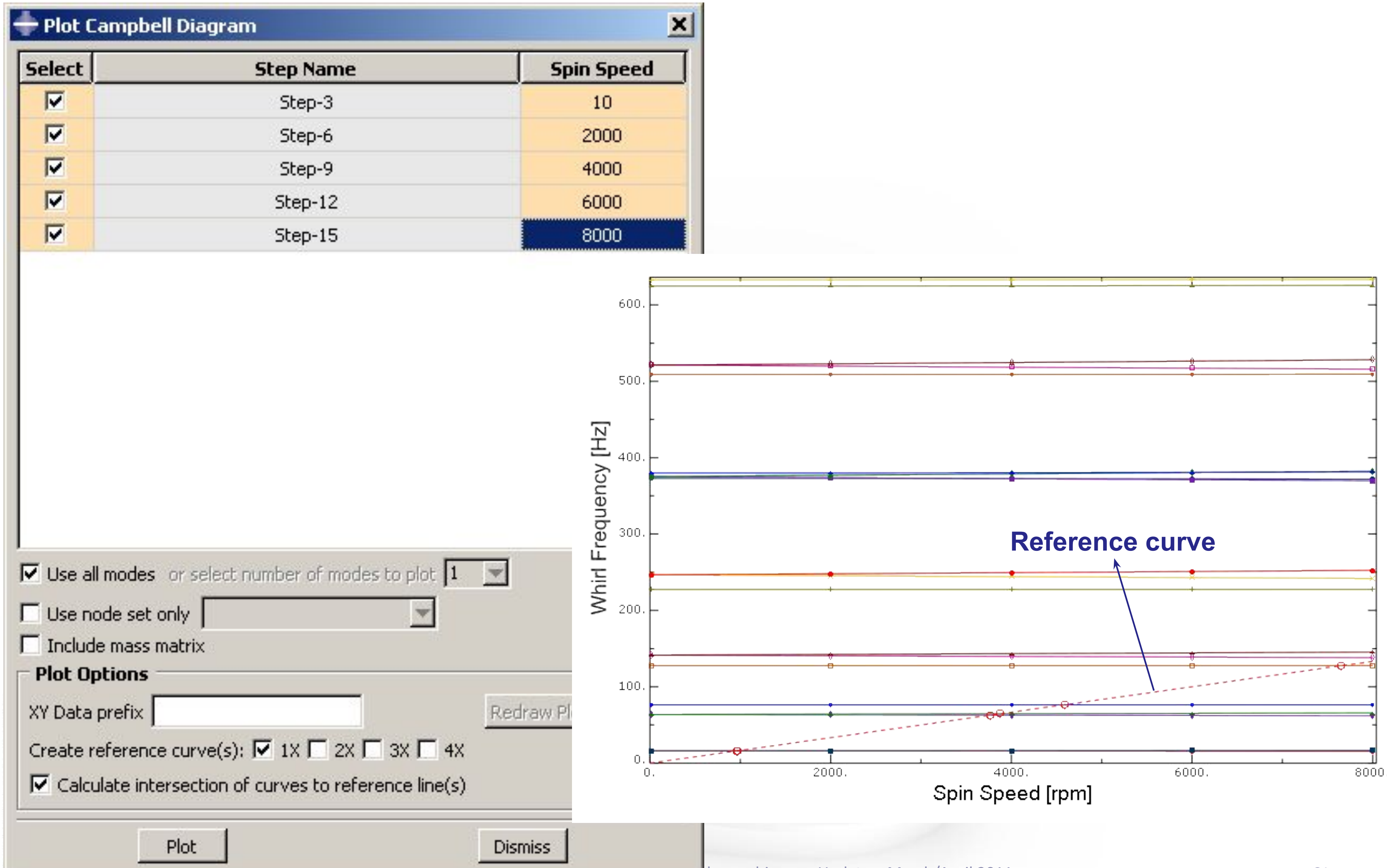




Rotordynamics

Campbell Diagram Plug-in

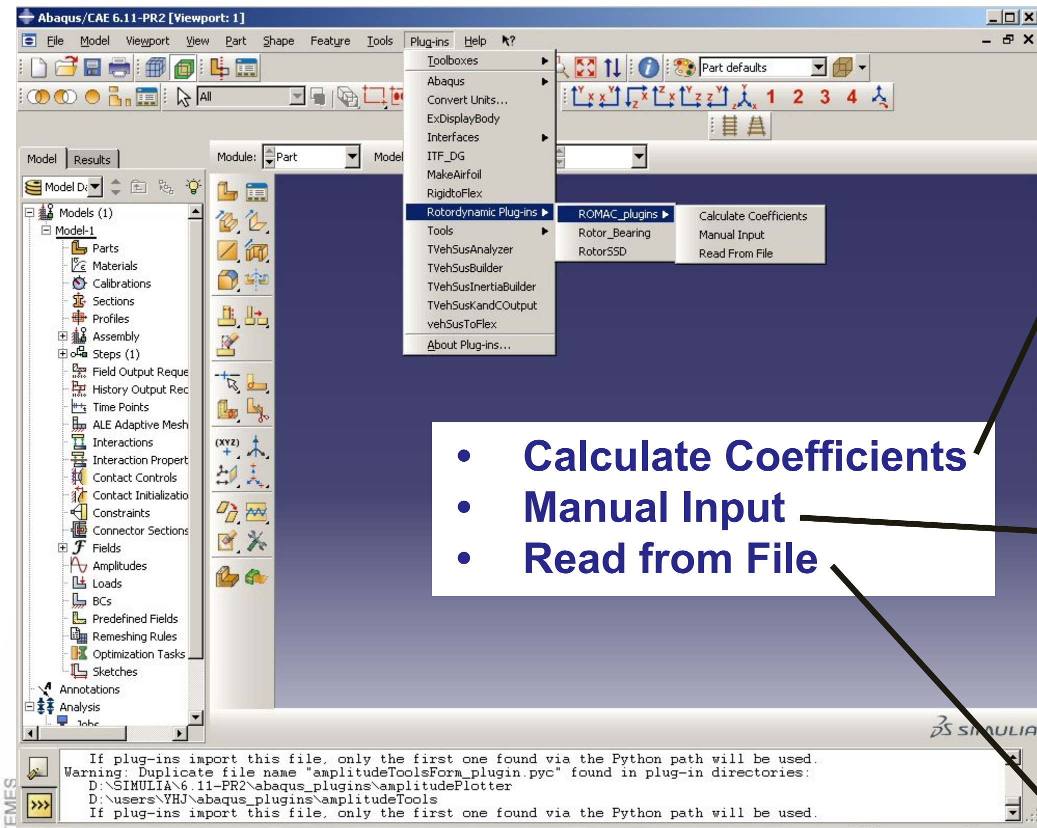
- **Newly developed A/Viewer Plug-in for rotordynamic application**



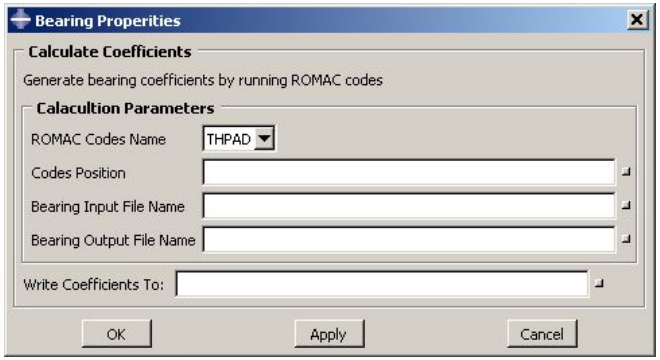
Rotordynamics

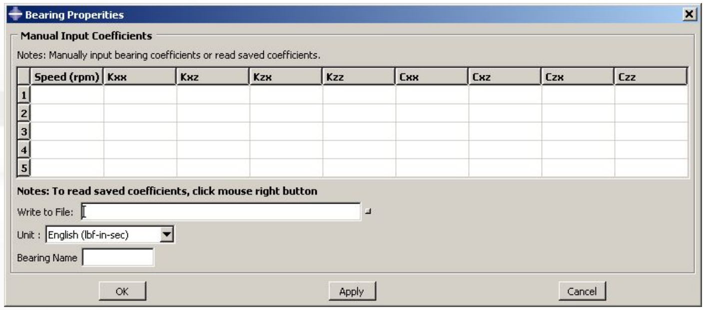
Other Plug-in in Development

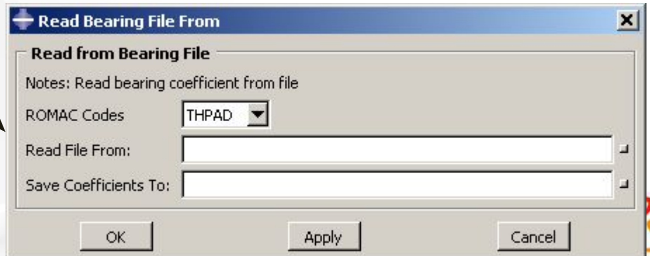
- **Plug-in to import bearing property from ROMAC Bearing Code (THBRG, THPAD, and MAXBRG)**



- **Calculate Coefficients**
- **Manual Input**
- **Read from File**



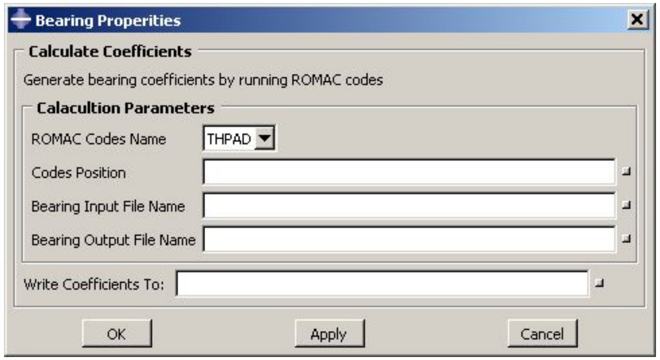


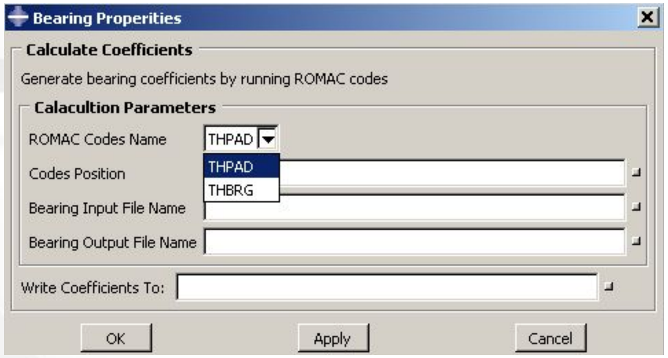


Rotordynamics

Other Plug-in in Development

- **Plug-in to import bearing property from ROMAC Bearing Code (THBRG, THPAD, and MAXBRG)**
  - Calculate Coefficients
    - Read input file for bearing code
    - Run the ROMAC bearing code
      - THPAD
      - THBRG
    - Save the bearing coefficient to Abaqus input file format.

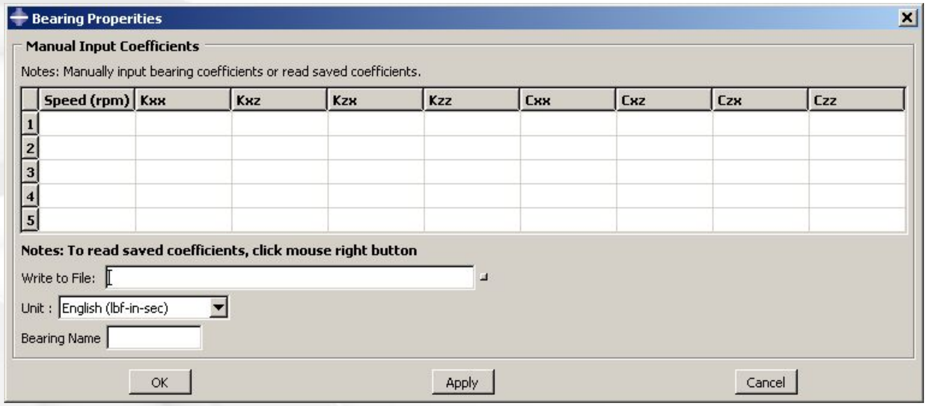




Rotordynamics

Other Plug-in in Development

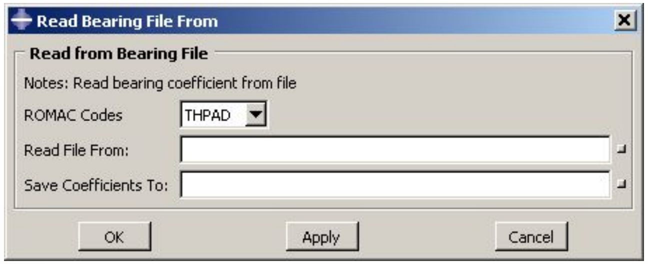
- **Plug-in to import bearing property from ROMAC Bearing Code (THBRG, THPAD, and MAXBRG)**
  - Manual Input
    - Bearing property manual input
    - Save the bearing coefficient to Abaqus input file format.

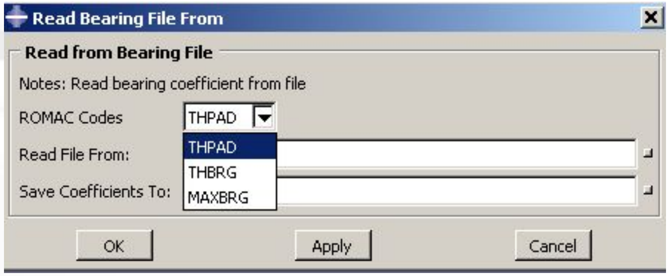


Rotordynamics

Other Plug-in in Development

- **Plug-in to import bearing property from ROMAC Bearing Code (THBRG, THPAD, and MAXBRG)**
  - Read from File
    - Read input file for bearing code
    - Run the ROMAC bearing code
      - THPAD
      - THBRG
      - MAXBRG
    - Save the bearing coefficient to Abaqus input file format.

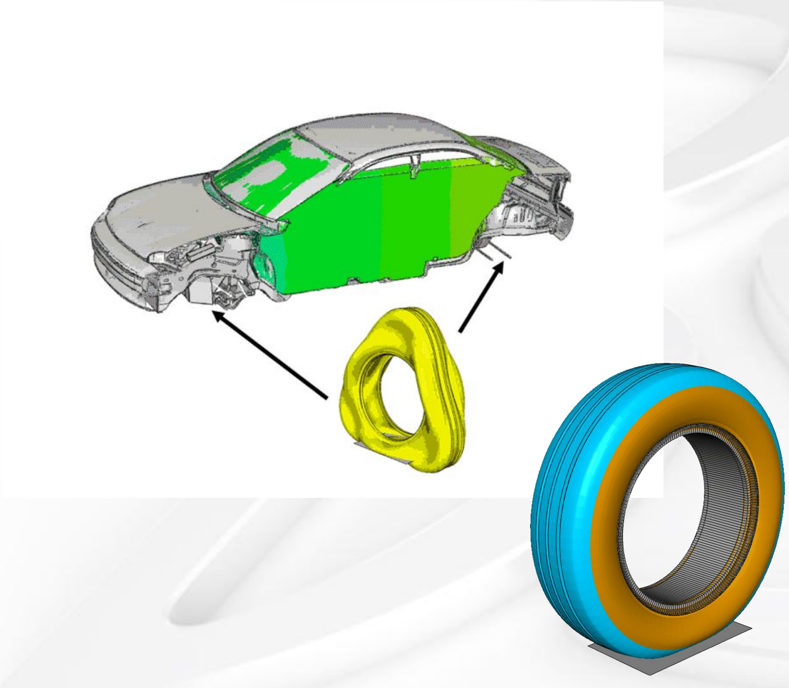


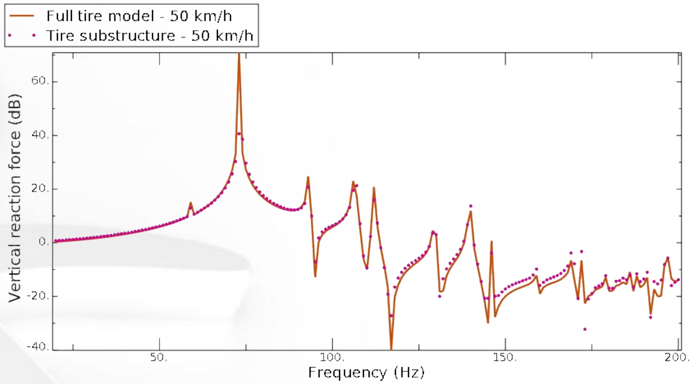


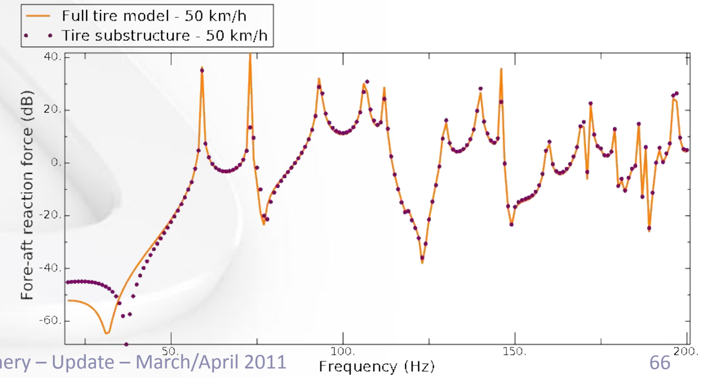
Rotordynamics

Substructure

- **Abaqus provides substructuring capability (superelement).**
- **Gyroscopic effect is handled as a damping matrix.**
- **Abaqus supports reduced damping matrix generation for substructure**
  - Viscous damping
    - Viscous damping matrix can be unsymmetric due to coriolis forces
  - Structural damping



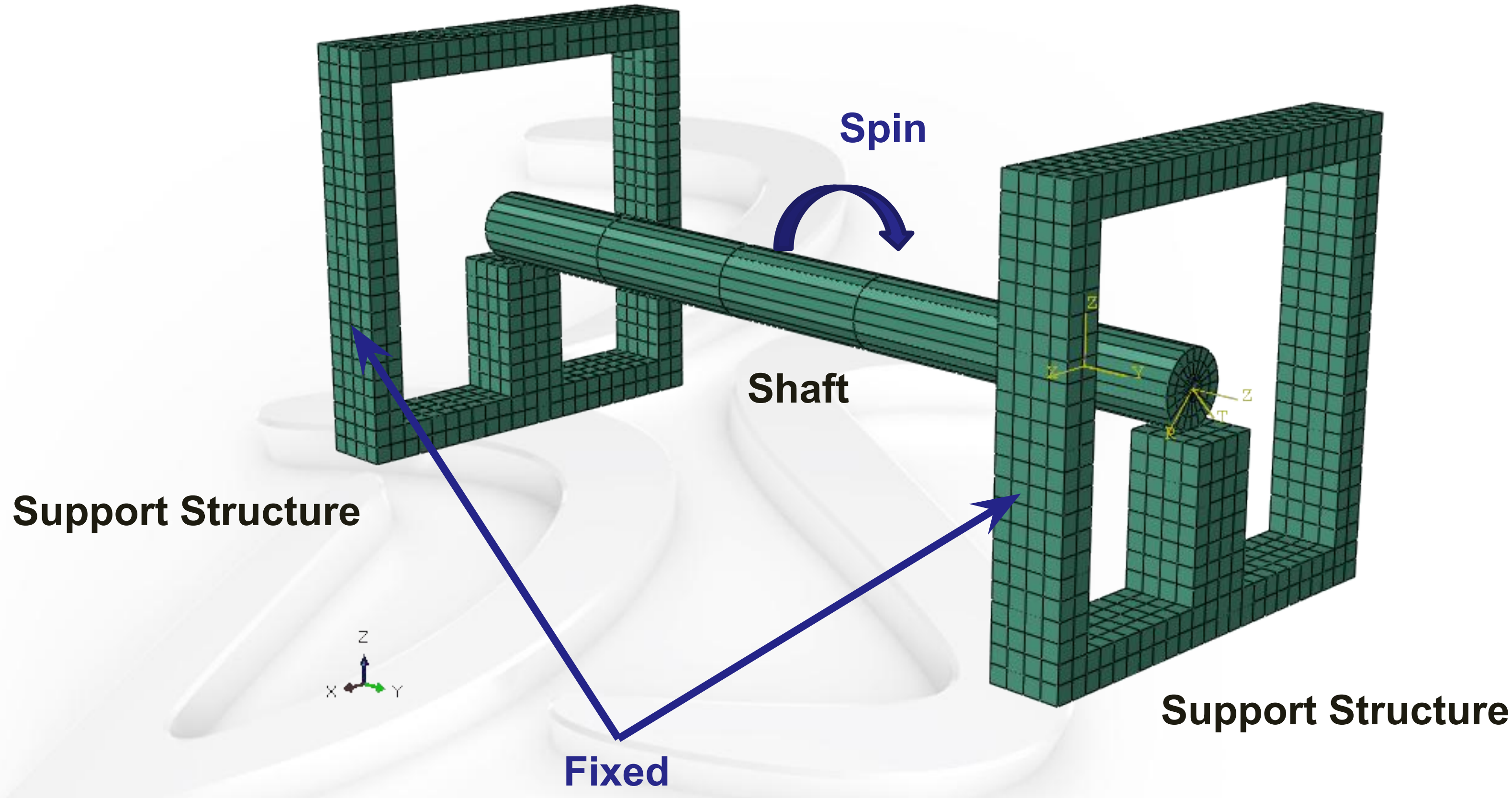




Rotordynamics

Substructure

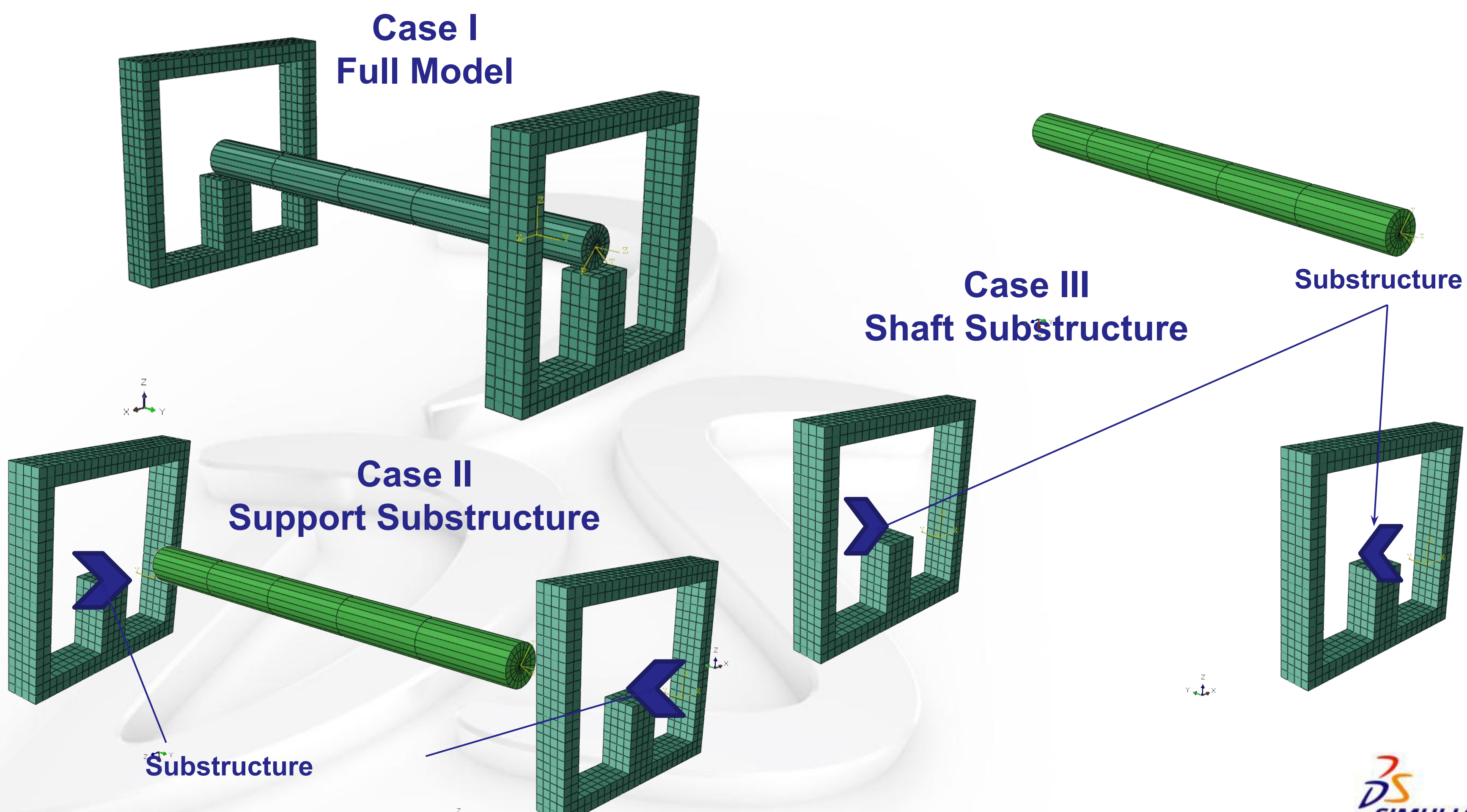
- **Example: Rotor-bearing system with support structure.**
  - Modal analysis considering spin speed (261 rad/s)
  - Bearing with elastic behavior is defined between shaft and support structure



Rotordynamics

Substructure

- **Rotor-bearing system with support structure.**
  - Three different cases: full model, support substructure, and shaft substructure

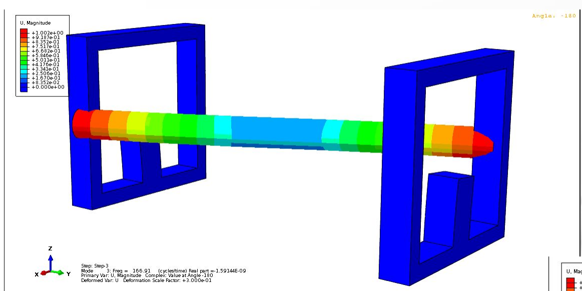


Rotordynamics

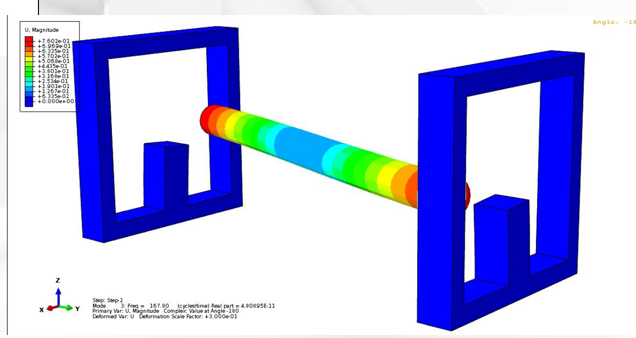
Substructure

- **Rotor-bearing system with support structure.**
  - Three different cases: full model, support substructure, and shaft substructure

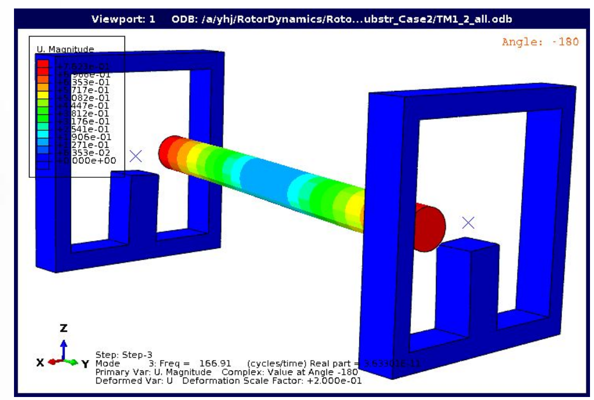
Number	Case I		Number	Case II		Diff. with Case 1 in IM	Number	Case III		Diff. with Case 1 in IM
	RE	IM		RE	IM			RE	IM	
1	-1.38E-08	85.214	1	1.23E-11	87.371	2.53%	1	-7.60E-11	85.214	0.00%
2	1.46E-08	87.207	2	-1.26E-11	89.54	2.68%	2	7.44E-11	87.207	0.00%
3	-1.59E-09	166.91	3	4.81E-11	167.8	0.53%	3	3.63E-11	166.91	0.00%
4	2.19E-09	172.63	4	-4.90E-11	173.62	0.57%	4	-3.63E-11	172.63	0.00%
5	7.62E-10	338.46	5	1.30E-10	369.37	9.13%	5	-3.87E-11	338.46	0.00%
6	-2.34E-09	342.72	6	-1.30E-10	373.58	9.00%	6	4.05E-11	342.72	0.00%



Case I: mode 3



Case II : mode 3



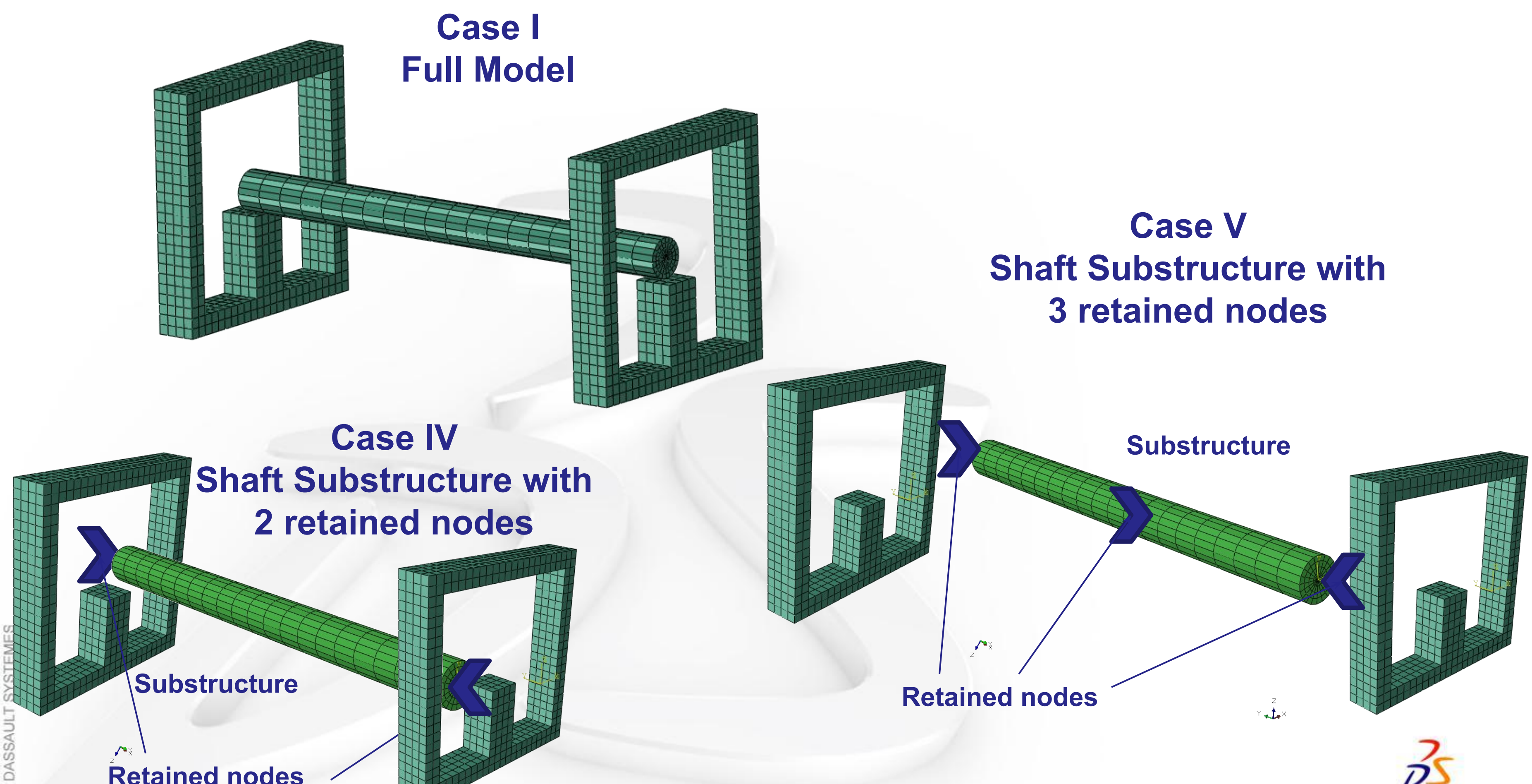
Case III : mode 3

SIMULIA

Rotordynamics

Substructure

- **Rotor-bearing system with support structure (refined model)**
  - Three different cases: full model, shaft substructures with 2 and 3 retained nodes

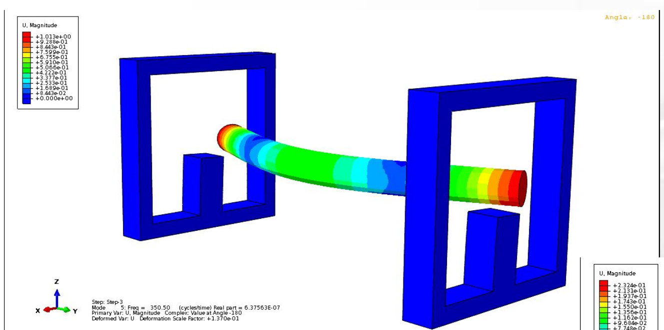


Rotordynamics

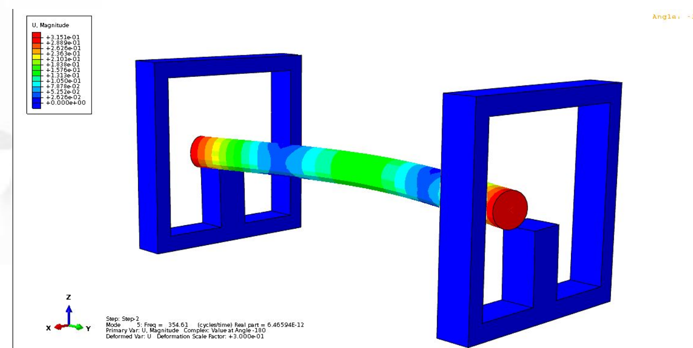
Substructure

- **Rotor-bearing system with support structure.**
  - Three different cases: full model, shaft substructures with 2 and 3 retained nodes

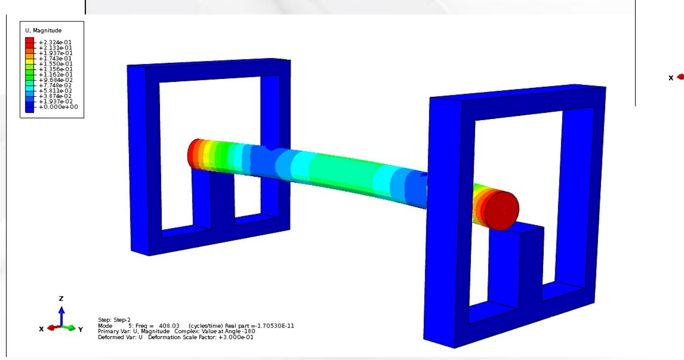
Number	Case I		Number	Case IV with 2 retained nodes		Diff. with Case 1 in IM	Number	Case V with 3 retained nodes		Diff. with Case 1 in IM
	RE	IM		RE	IM			RE	IM	
1	2.08E-08	81.653	1	-6.70E-12	84.531	**3.52%**	1	4.18E-12	82.064	**0.50%**
2	-2.06E-08	83.397	2	7.80E-12	86.492	**3.71%**	2	-3.89E-12	83.836	**0.53%**
3	-4.82E-08	169.71	3	-1.30E-11	171.83	**1.25%**	3	5.41E-12	170.95	**0.73%**
4	4.54E-08	175.28	4	1.31E-11	177.64	**1.35%**	4	-6.96E-12	176.66	**0.79%**
5	2.95E-08	350.5	5	-2.94E-11	408.03	**16.41%**	5	1.25E-11	354.62	**1.18%**
6	-2.53E-08	355.29	6	2.89E-11	413.16	**16.29%**	6	-1.11E-11	359.46	**1.17%**



Case I: mode 5



Case V : mode 5



Case IV : mode 5

Coupled Structural-Acoustic Analysis

Coupled Structural-Acoustic Analysis

Frequency Extraction and Frequency Response

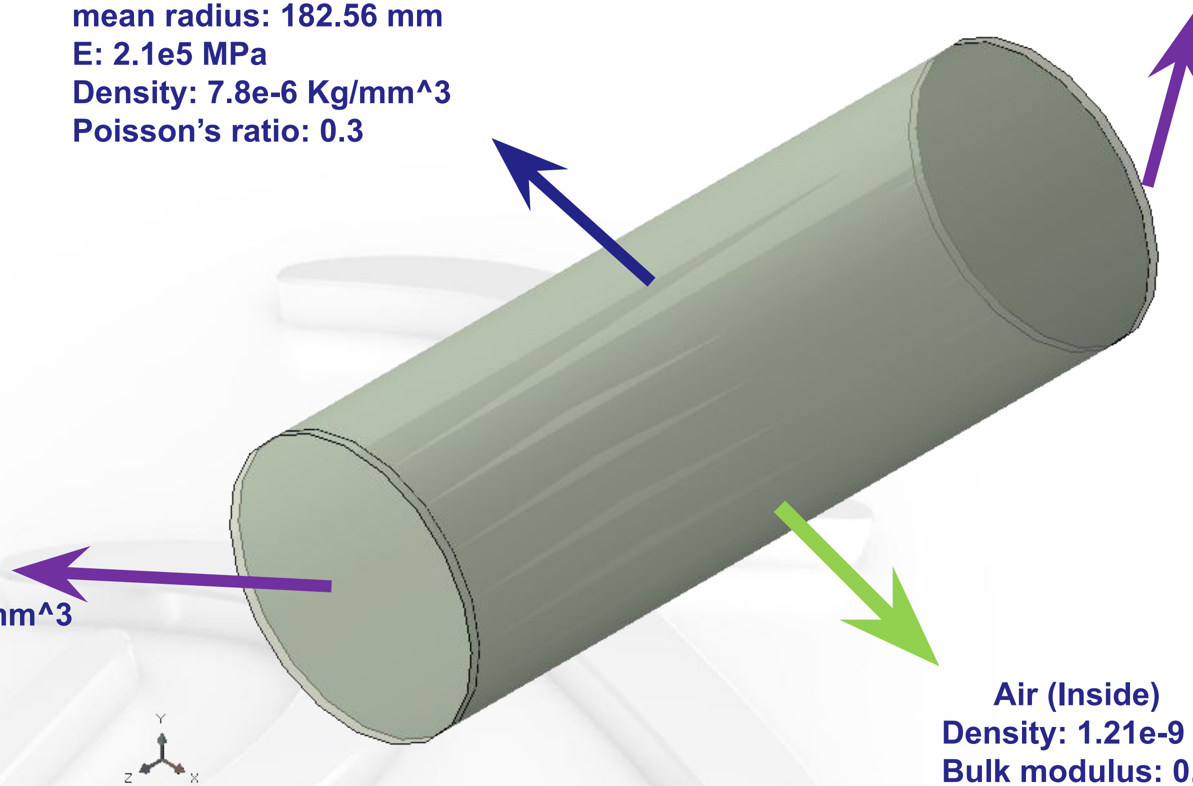
- **Lanczos and AMS solvers support coupled structural-acoustic analysis.**
  - We have two kinds of architectures: SIM and ADB.
    - ADB-based Lanczos solver provides fully coupled method.
    - SIM-based Lanczos and AMS solvers provide project method.
- **Steady State Dynamic (SSD) analysis can be applied for frequency response analysis.**
  - SSD, direct
    - Direct solution
  - SSD, mode-based
    - Mode superposition
  - SSD, subspace-based
    - Subspace projection method

Coupled Structural-Acoustic Analysis

Coupled Structural Acoustic Model

Steel
thickness: 1.219 mm
length: 1010 mm
mean radius: 182.56 mm
E: 2.1e5 MPa
Density: 7.8e-6 Kg/mm^3
Poisson's ratio: 0.3

Aluminum
thickness: 25.4 mm
E: 7.e4 MPa
Density: 2.7e-6 Kg/mm^3
Poisson's ratio: 0.3



Aluminum
thickness: 25.4 mm
E: 7.e4 MPa
Density: 2.7e-6 Kg/mm^3
Poisson's ratio: 0.3

Air (Inside)
Density: 1.21e-9 Kg/mm^3
Bulk modulus: 0.14 Mpa
Sound of speed: 340 m/s

free-free boundary condition

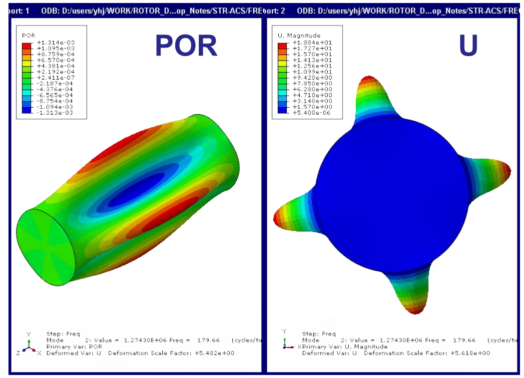
Element length <= speed of sound / (n*(max. Freq.)), n= 6~10
Element length set-up: 10 mm for STR (for higher ND)

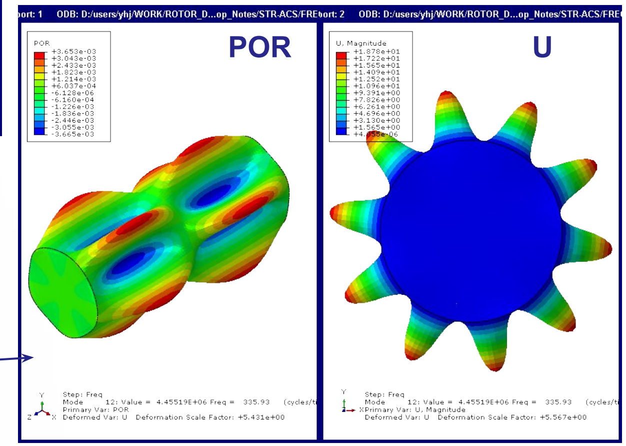
Coupled Structural-Acoustic Analysis

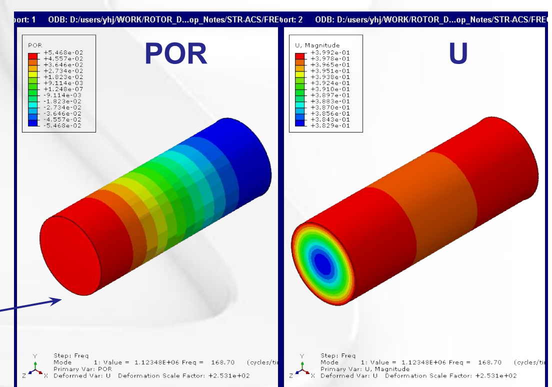
Coupled Structural Acoustic Model

- **Result**
  - Frequency range:
    - 80-480 Hz

Structural Mode			
Mode(n,m)**	Experiment*	Abaqus	Err
(4,1)	172.7	179.66	4.0%
(4,1)	173.8	179.66	3.4%
(3,1)	178.6	185.04	3.6%
(3,1)	179.1	185.04	3.3%
(5,1)	232.8	236.11	1.4%
(5,1)	233.5	236.12	1.1%
(2,1)	294.8	299.15	1.5%
(2,1)	297.7	299.15	0.5%
(6,1)	326.8	329	0.7%
(6,1)	-	329.01	-
(5,2)	328.3	335.93	2.3%
(5,2)	330.4	335.94	1.7%
(6,2)	368.6	375.31	1.8%
(6,2)	370.3	375.31	1.4%
(4,2)	377	379.29	0.6%
(4,2)	-	379.3	-
(7,1)	444.1	447.65	0.8%
(7,1)	-	447.65	-
(7,2)	471.1	475.74	1.0%
(7,2)	471.9	475.74	0.8%
Acoustic Mode			
Mode(p,q,r)***	Experiment	Abaqus	
(0,0,1)	172	168.7	-1.9%
(0,0,2)	343	336.56	-1.9%







** n and m are the mode orders with respect to the circumference and length of the shell.
*** p, q and r are the mode orders with respect to the circumference, radius and length of the cylindrical cavity

***S. Boily and F. Charron, "The vibroacoustic response of a cylindrical shell structure with viscoelastic and poroelastic materials," Applied Acoustics, 58, 1999, pp 131-152**

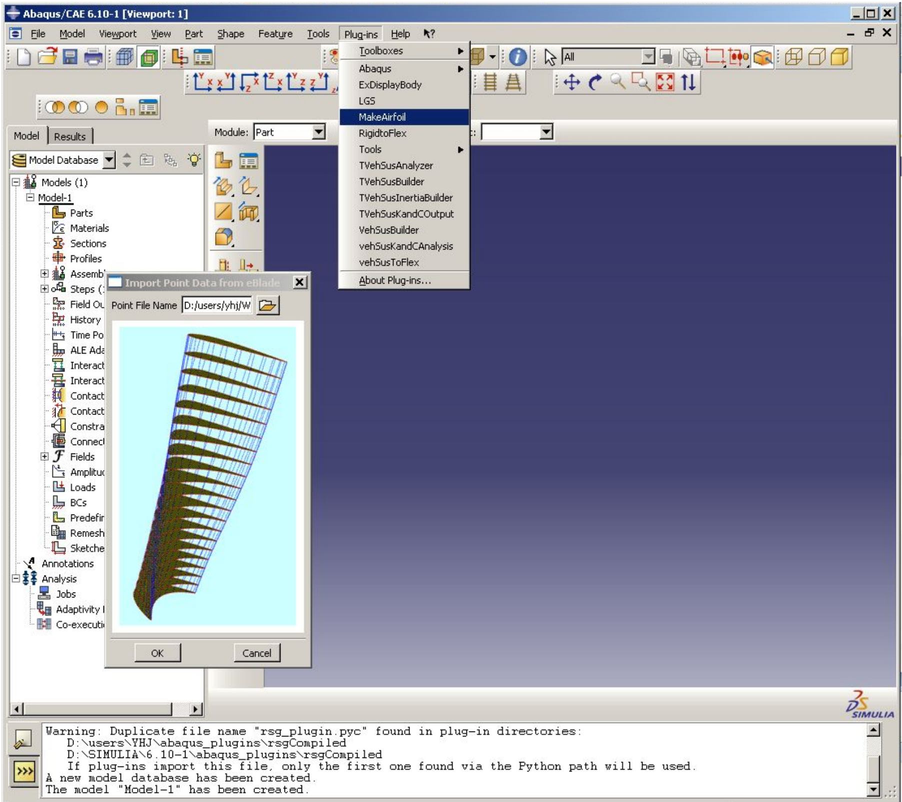
Blade Analysis

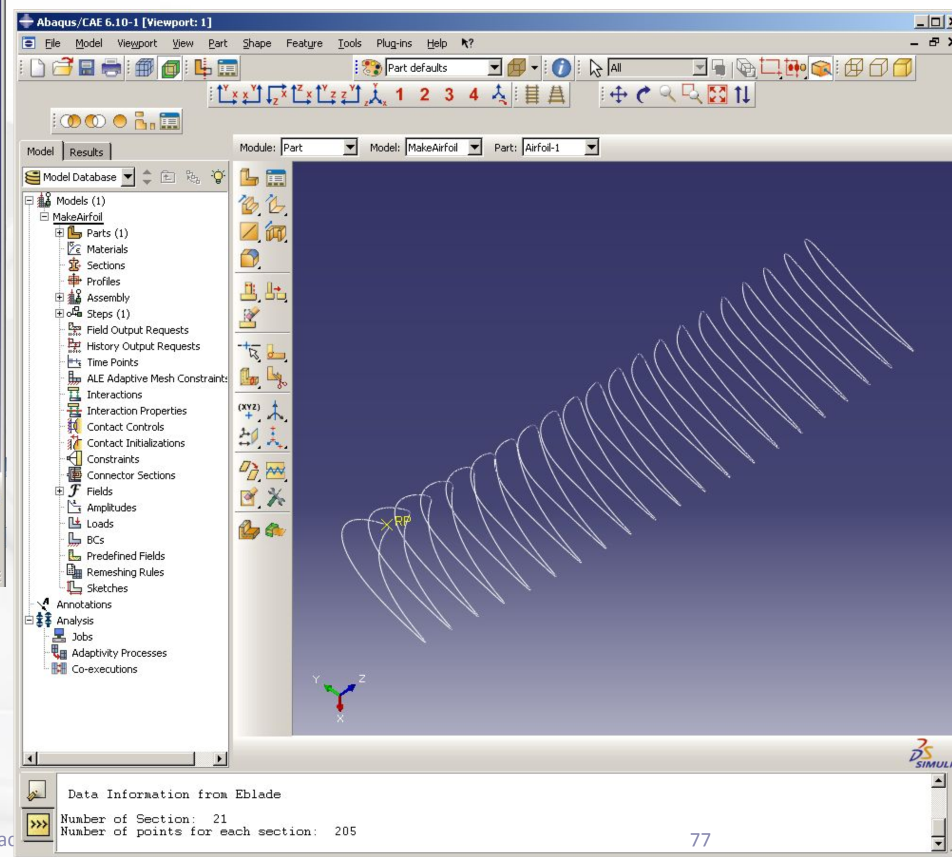
SIMULIA

Blade Analysis

Modeling in A/CAE

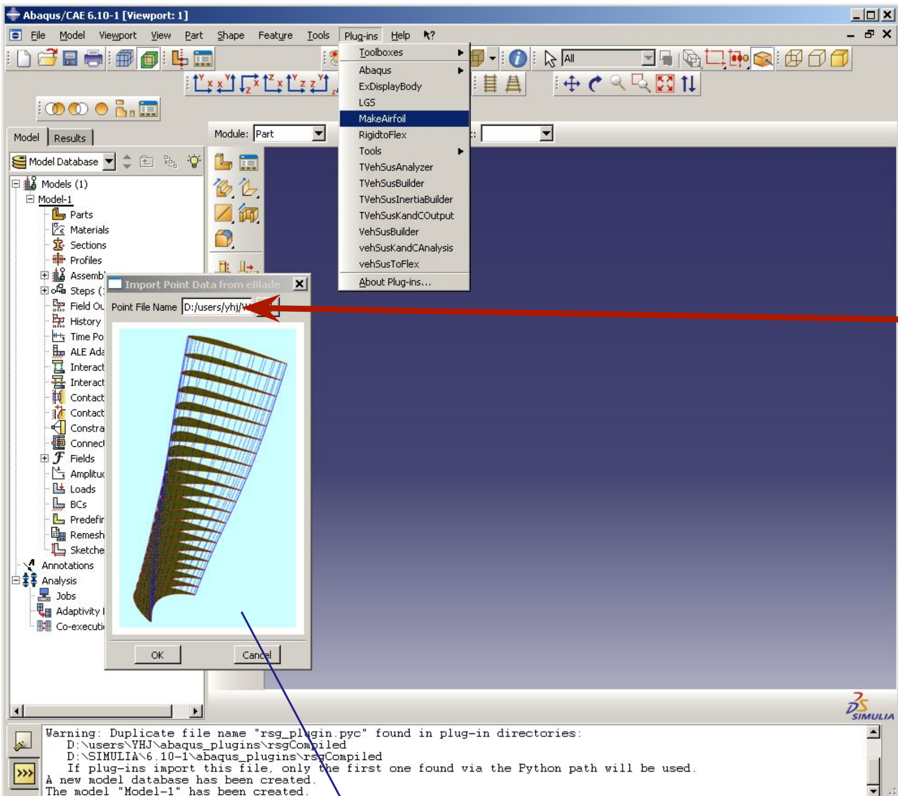
- **Blade Geometry from Eblade (see appendix for more details)**





Blade Analysis

- **Import Eblade data to A/CAE: Plug-in**



Number of section

Number of points

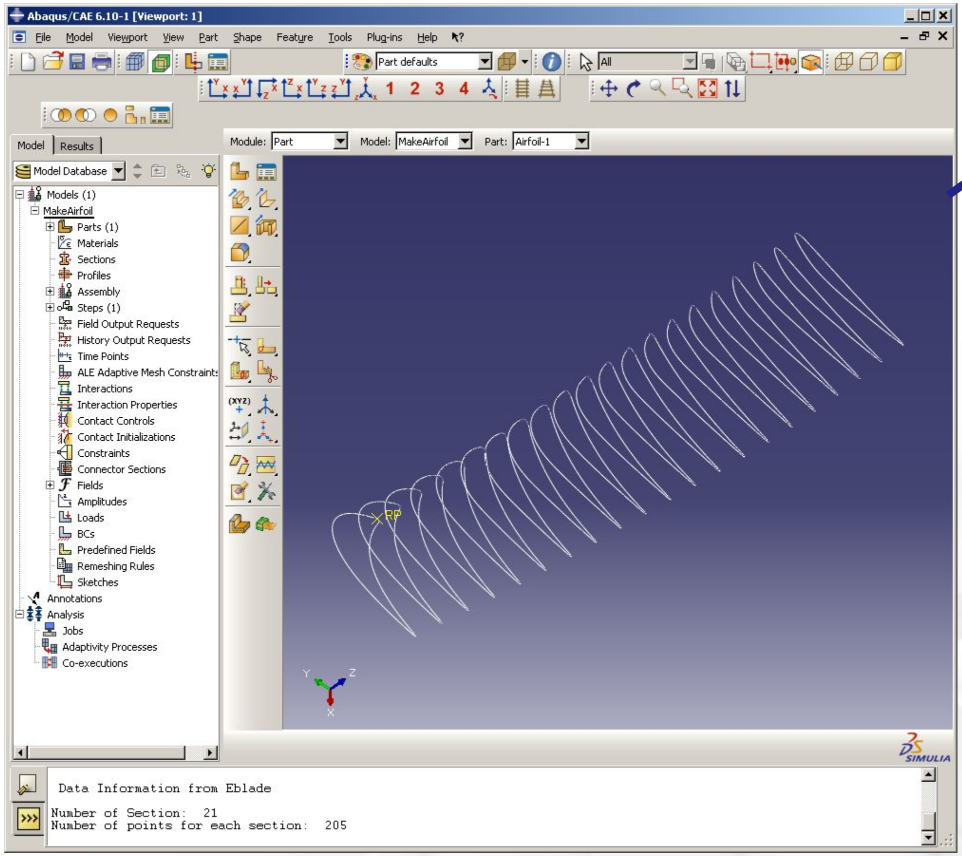
```
Training Blade-NP33- smoothed with 21 interpo
21        1
205
6.3043E01      -2.5928E01      0.0000E00
6.2921E01      -2.5950E01      0.0000E00
6.2781E01      -2.5937E01      0.0000E00
6.2637E01      -2.5879E01      0.0000E00
6.2507E01      -2.5766E01      0.0000E00
6.2442E01      -2.5662E01      0.0000E00
```

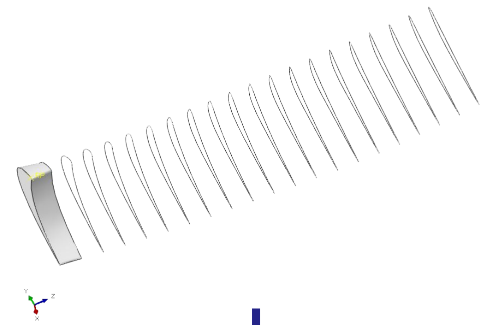
coordinates

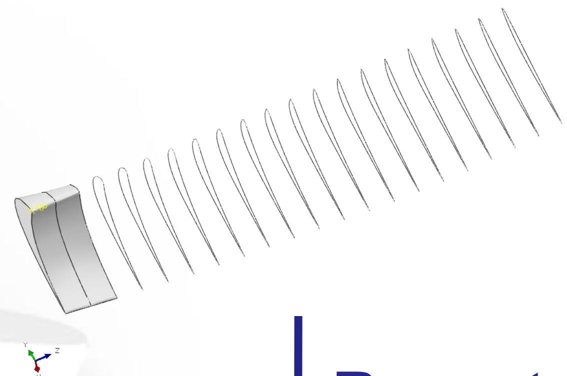
The plug-in reads the input files generated from Eblade and creates the splines shown in next slide.

Blade Analysis

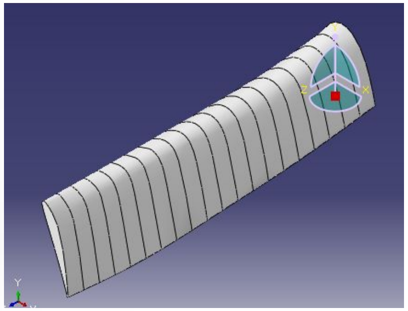
- **Create geometry by Loft**







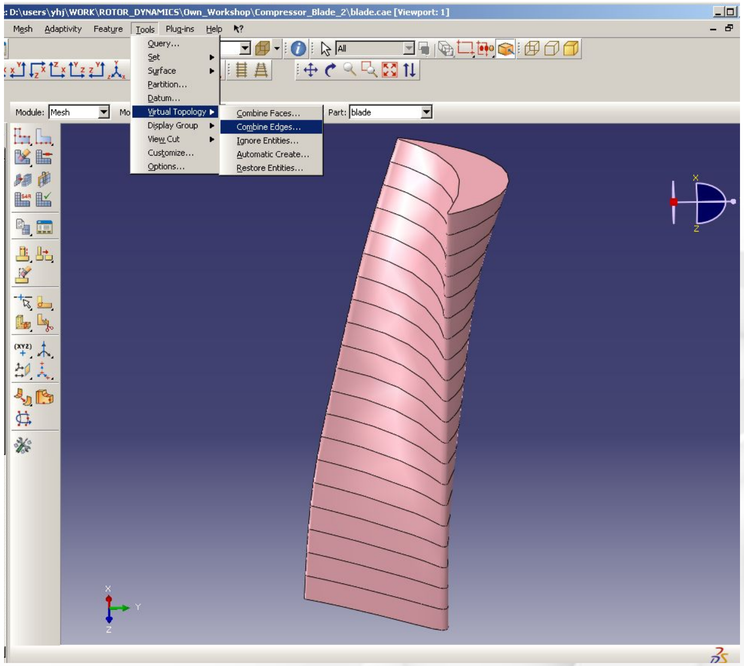
Repeat…

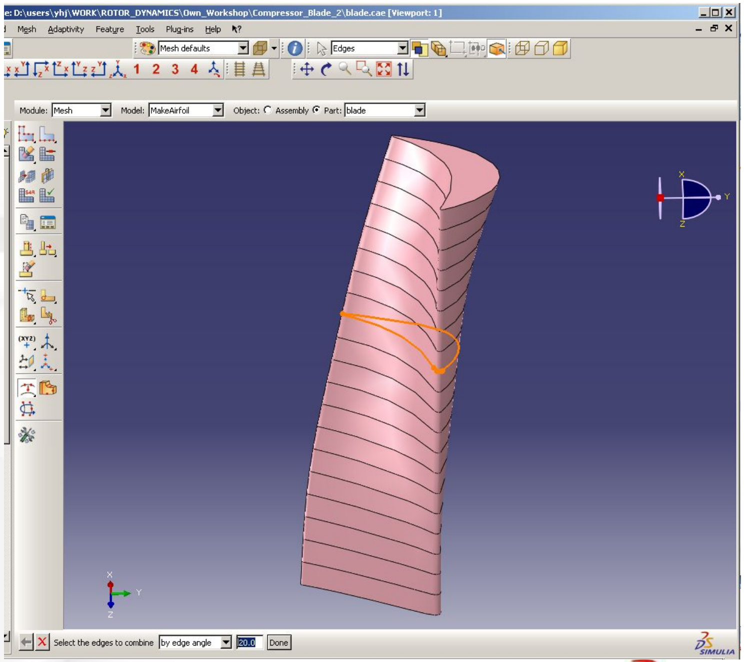


SIMULIA

Blade Analysis

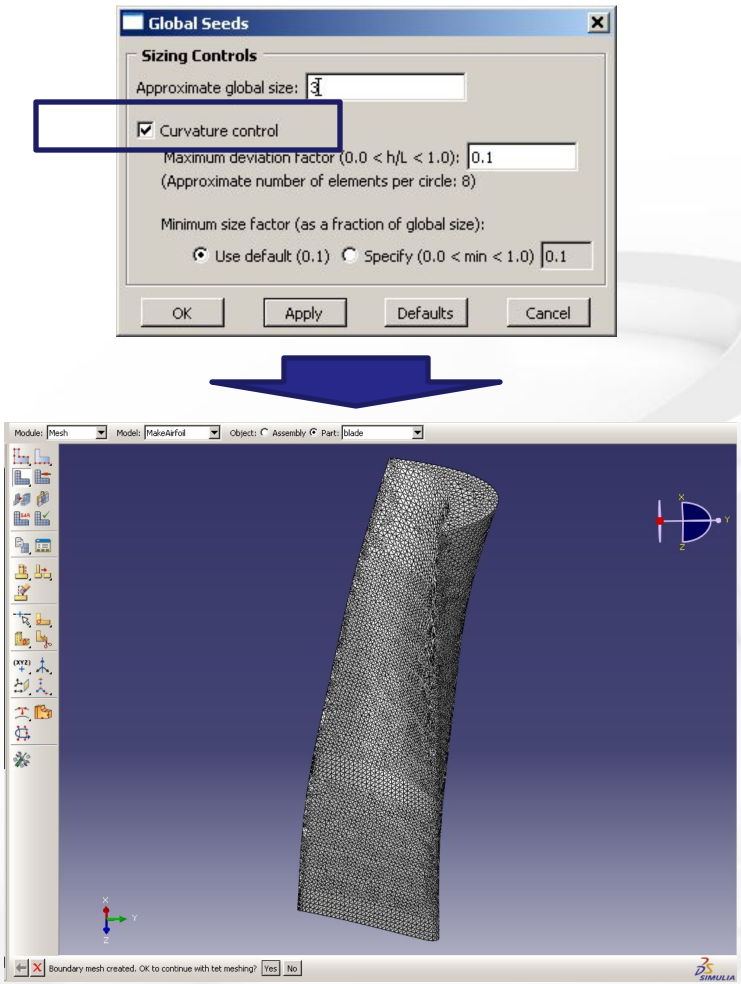
- **Meshing**
  - Before meshing, do “combine edge” under “Virtual Topology” in “tool” menu.

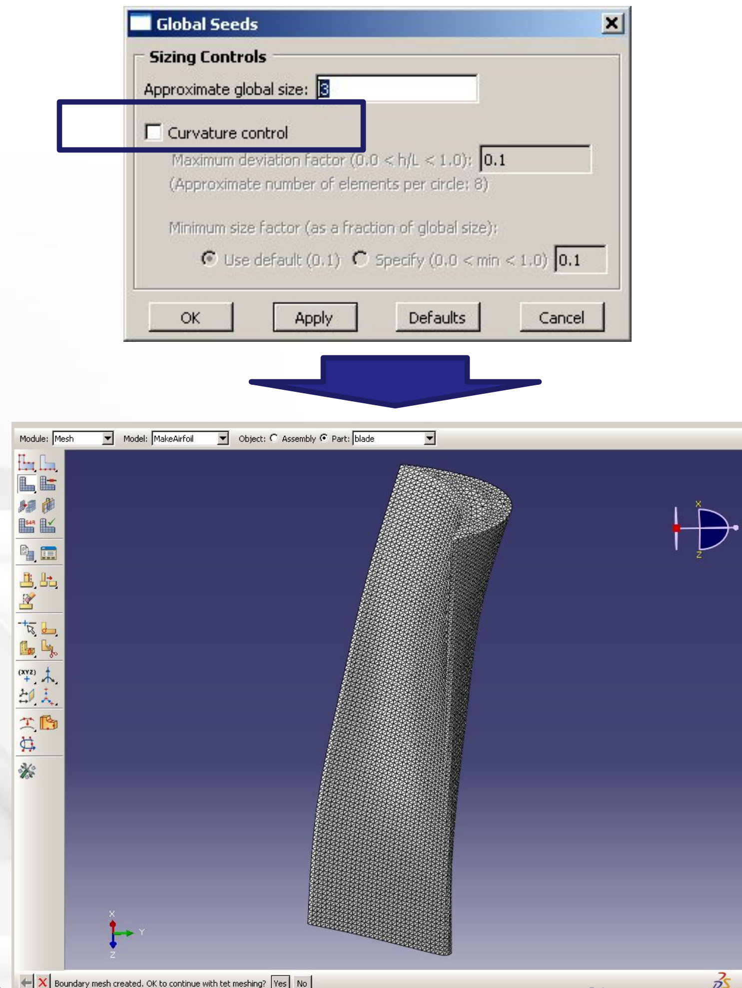




Blade Analysis

- **Meshing**
  - Then, DO NOT check the curvature control in seed to get the same size of mesh.

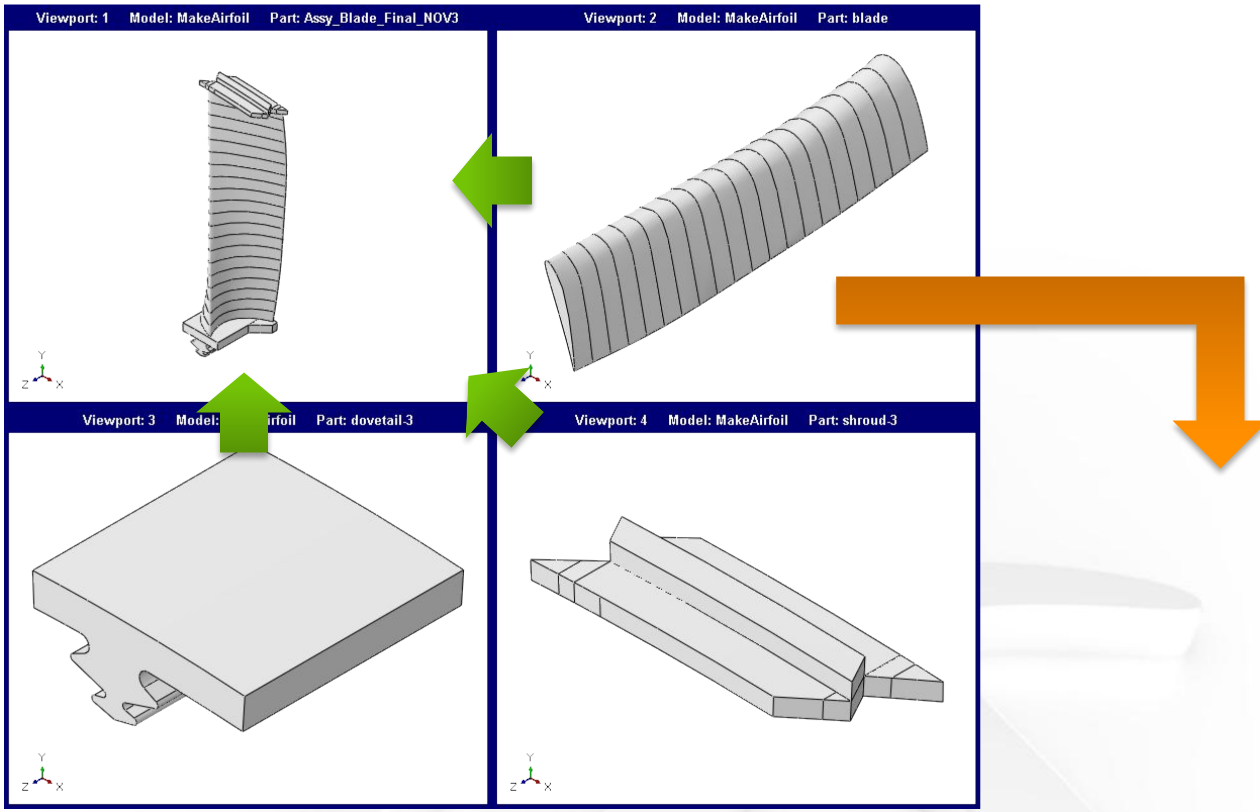


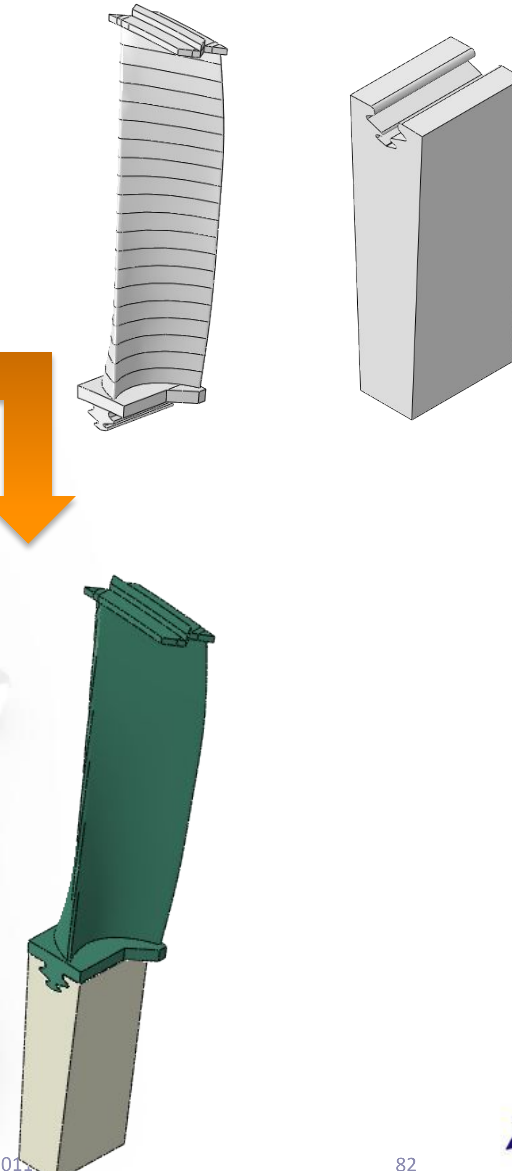


Blade Analysis

Modeling in A/CAE

- **Blade Geometry**



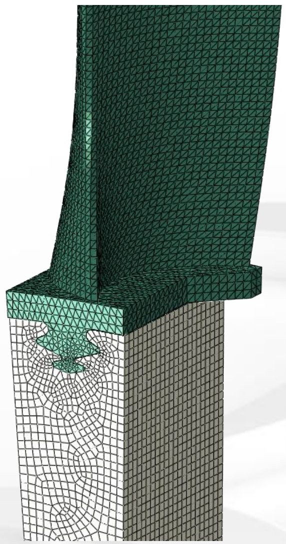


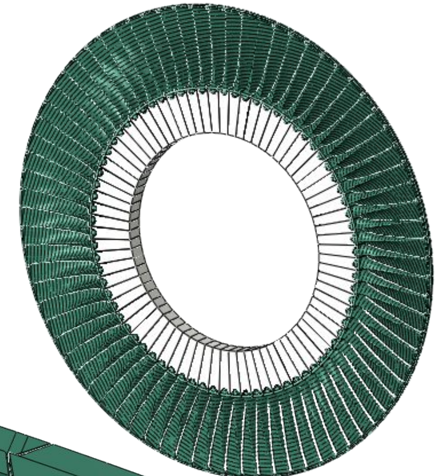
With "*merge*" in Assembly level, one new part can be generated.

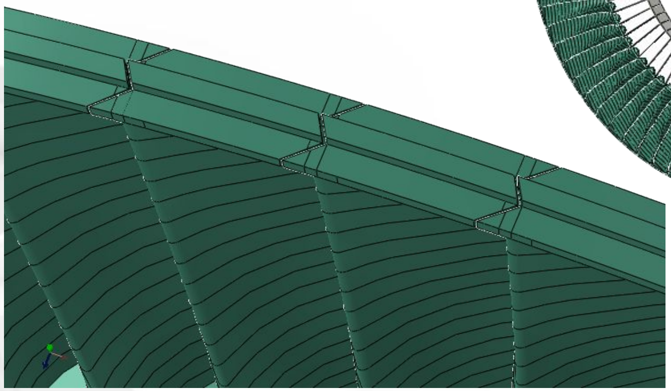
Blade Analysis

Modeling in A/CAE

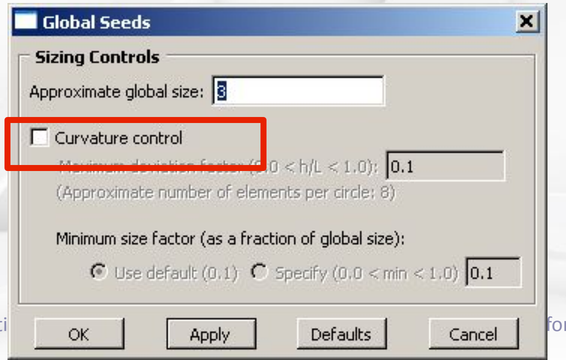
- **FE Model for a Blade Section and Full Model**

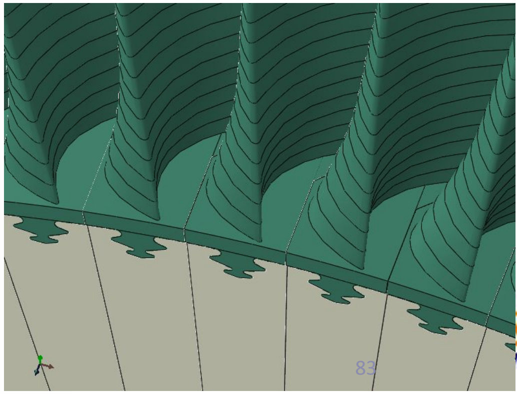






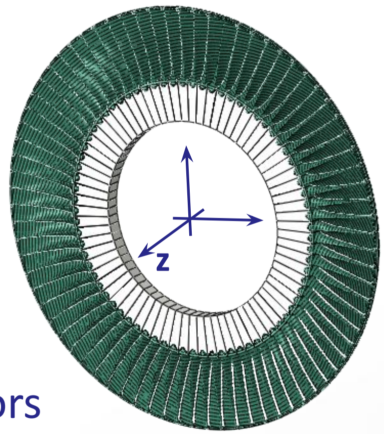
No curvature control for blade in "*seed*" menu



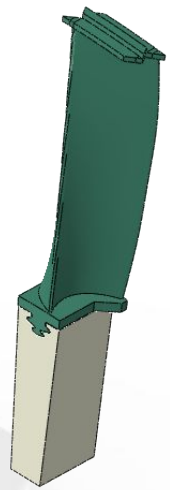


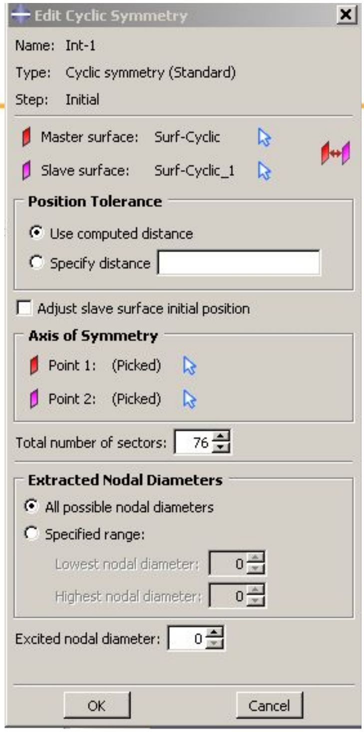
Blade Analysis

Cyclic Symmetric Model

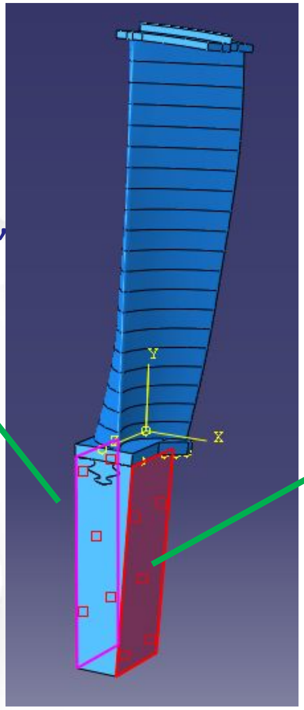


76 sectors





Surface "slave"



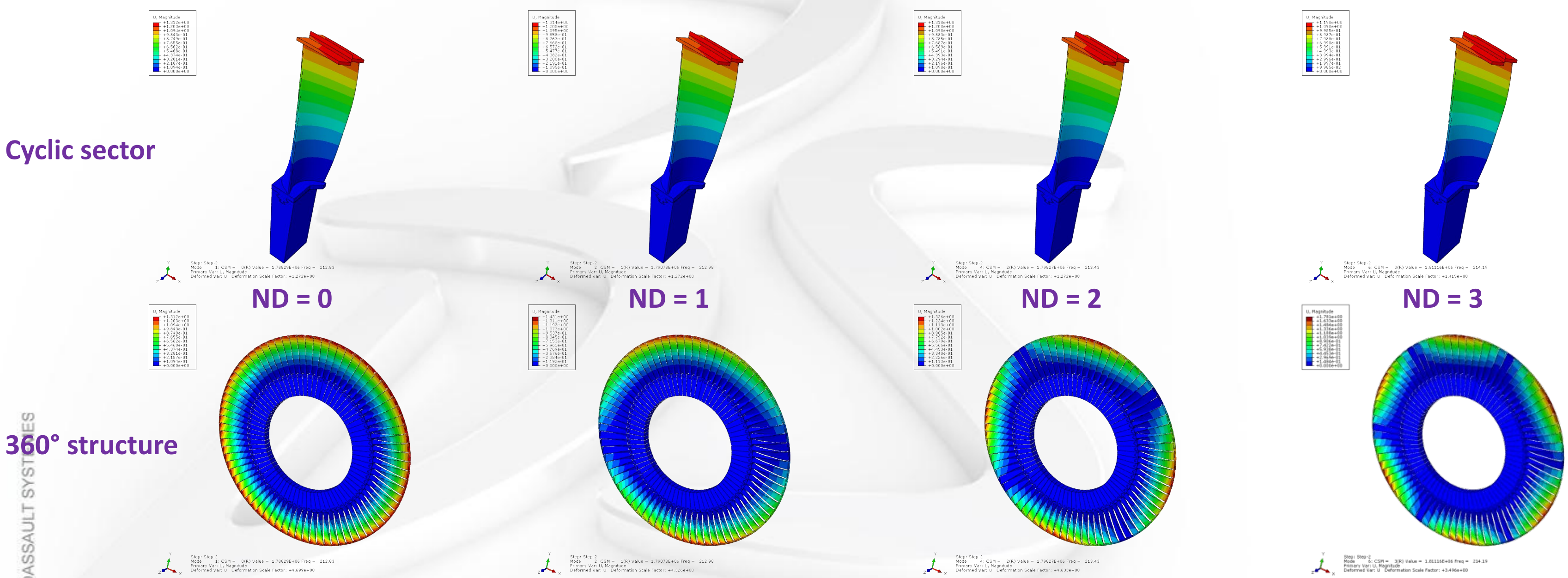
Surface "master"

SURFACE, NAME=*master
SURFACE, NAME=*slave
TIE, CYCLIC SYMMETRY, NAME=*cyclic
slave, master

Blade Analysis

Modal Analysis

- **Frequency extraction capability is supported with Lanczos solver only for cyclic symmetric model.**
  - One of the output in frequency extraction for cyclic symmetric model is cyclic symmetry mode number, which is also called “nodal diameter (ND)”
  - Nodal diameter (ND) indicates the number of waves along the circumference in a basic response.



Blade Analysis

Modal Analysis

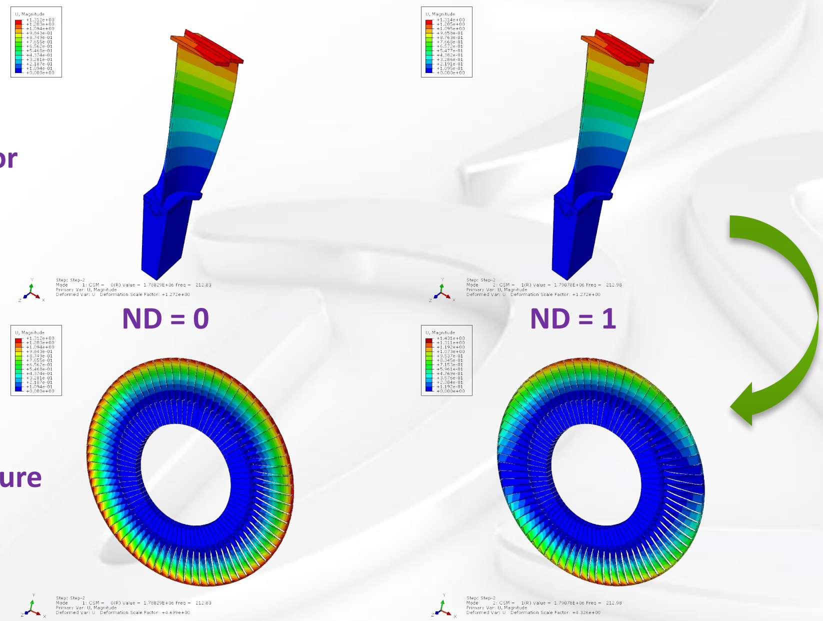
- **Frequency extraction capability is supported with Lanczos solver only for cyclic symmetric model.**
    - ND number is one of outputs in .dat file.
    - Abaqus/Viewer has capability to show the modeshape of 360° structure from cyclic symmetric model.

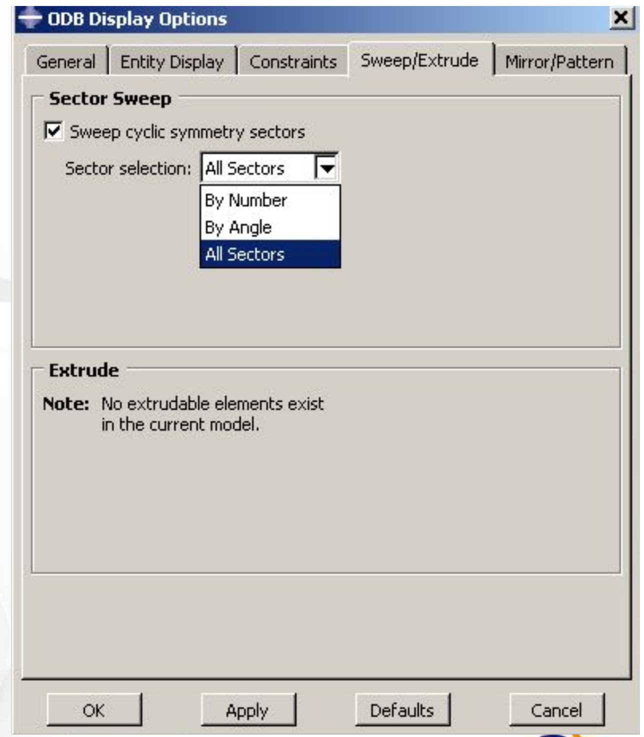
Cyclic sector

360° structure

ND = 0

ND = 1



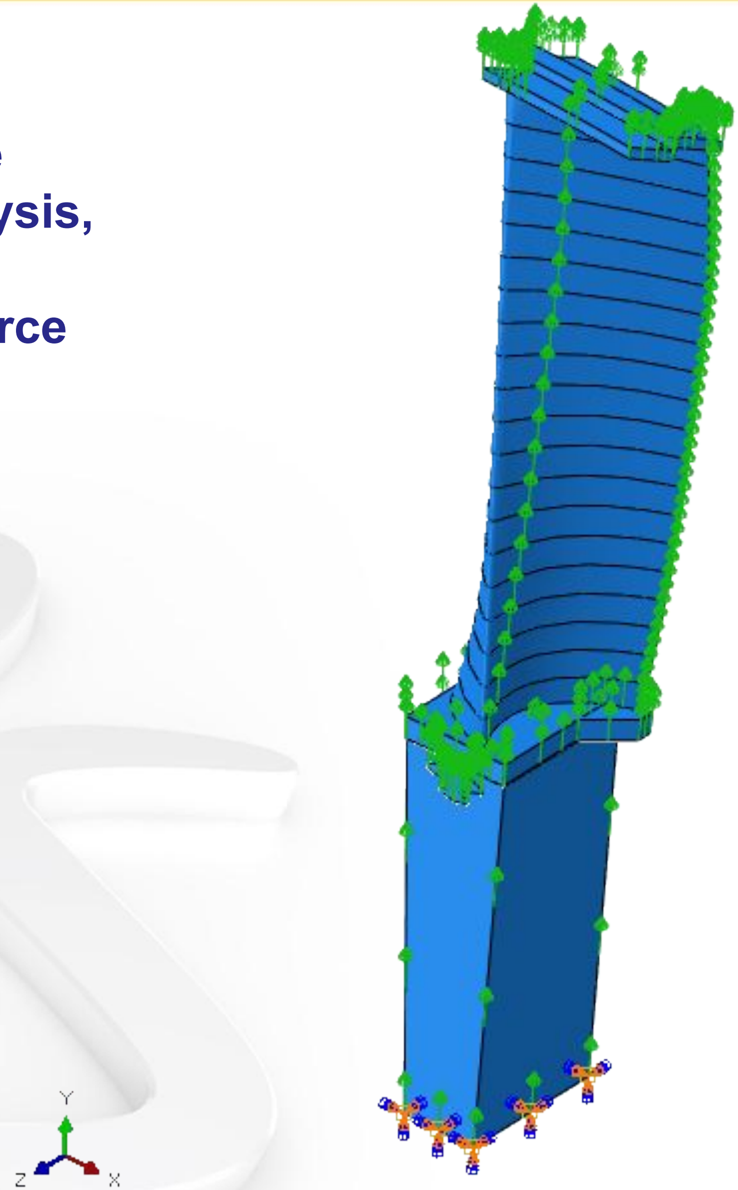


Blade Analysis

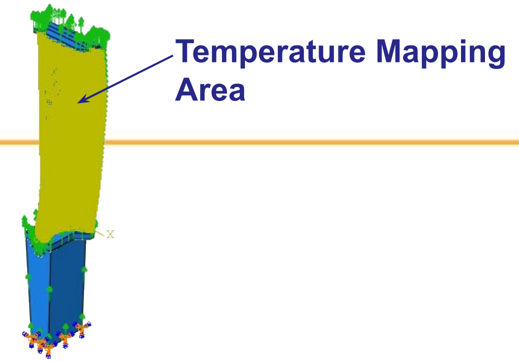
Stress Analysis

- **After mapping the temperature results from the previous analysis, stress analysis considering temperature and centrifugal force is performed.**
- **The bottom surface is fixed.**

- **Sequentially coupled thermal-stress analysis is only available for cyclic symmetric model.**

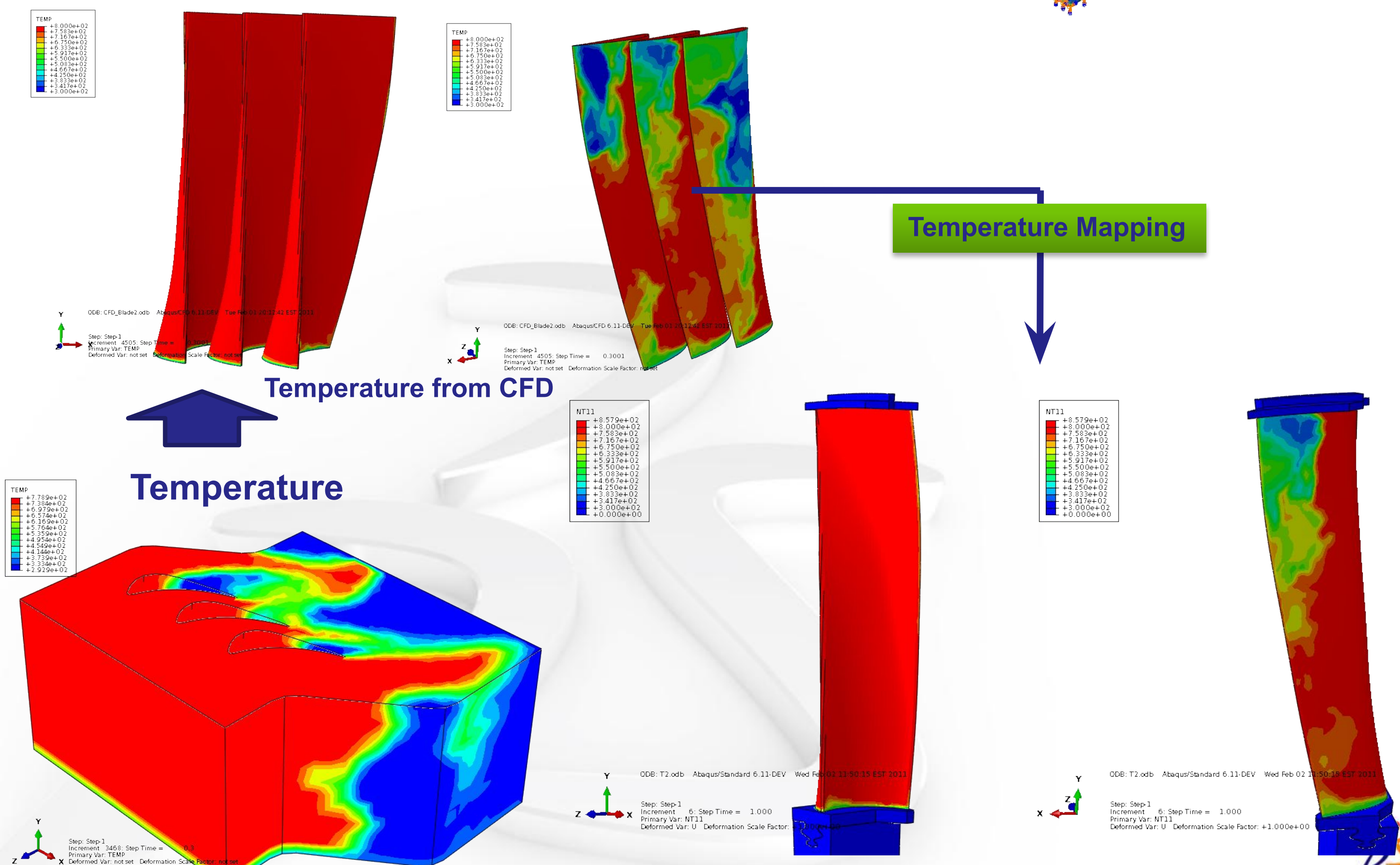


Blade Analysis



Stress Analysis

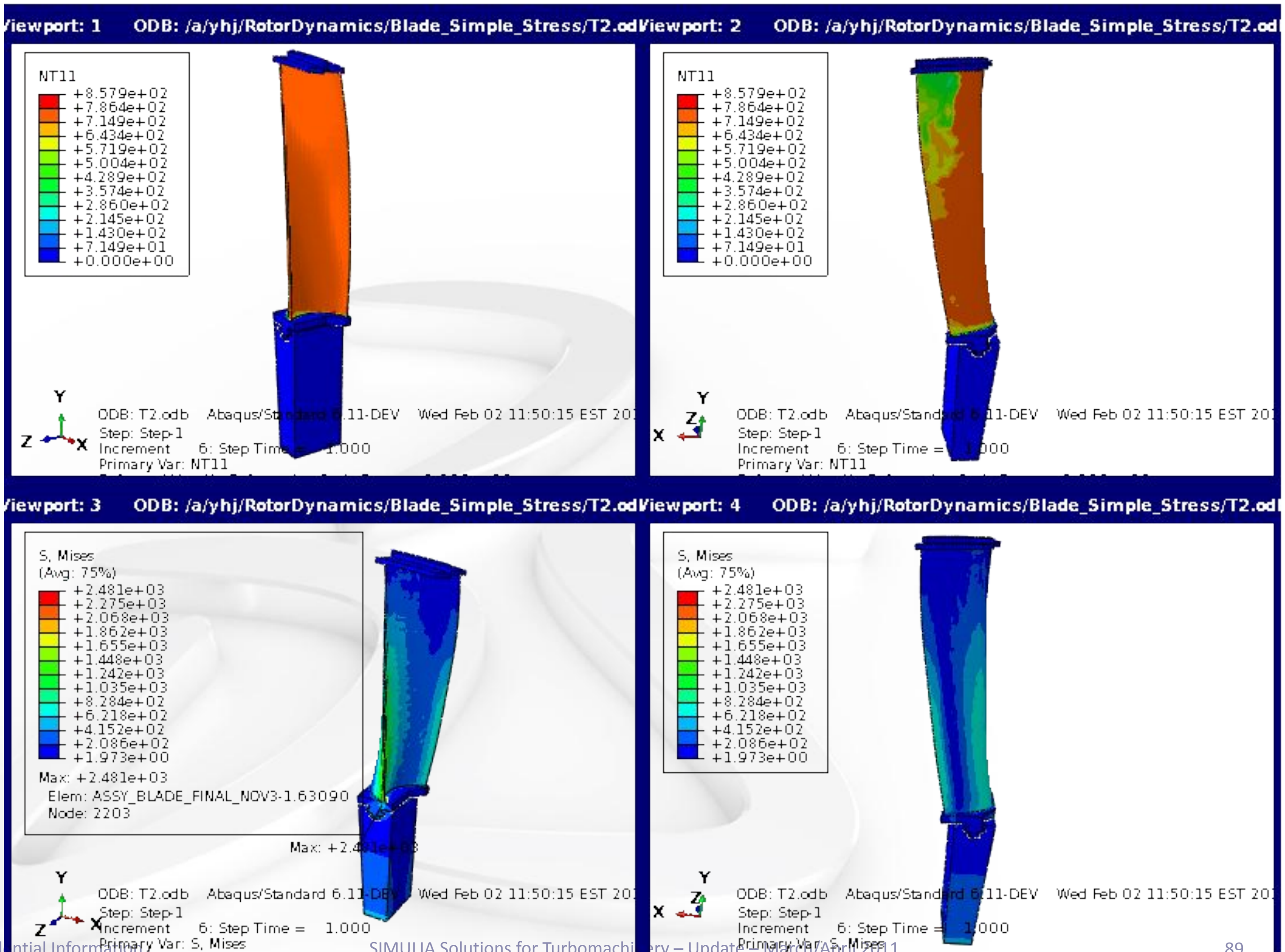
- **Stress analysis after mapping temperature**



Blade Analysis

Stress Analysis

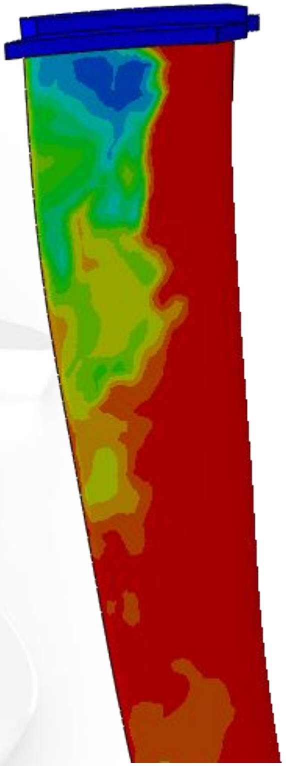
- **Stress analysis after mapping temperature**



Blade Analysis

New Mapping Capability with A/CAE in 6.11

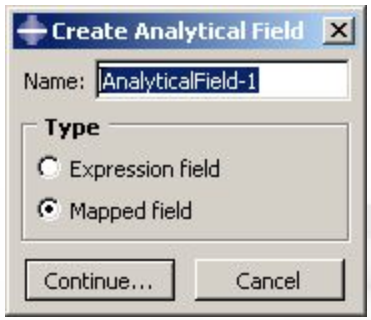
- **Sources of the data can be (but are not limited to):**
  - A previous Abaqus analysis
  - XYZ data
- **Supports mapping for scalar values for:**
  - Nodes, elements and element faces
  - Surfaces and Volumes



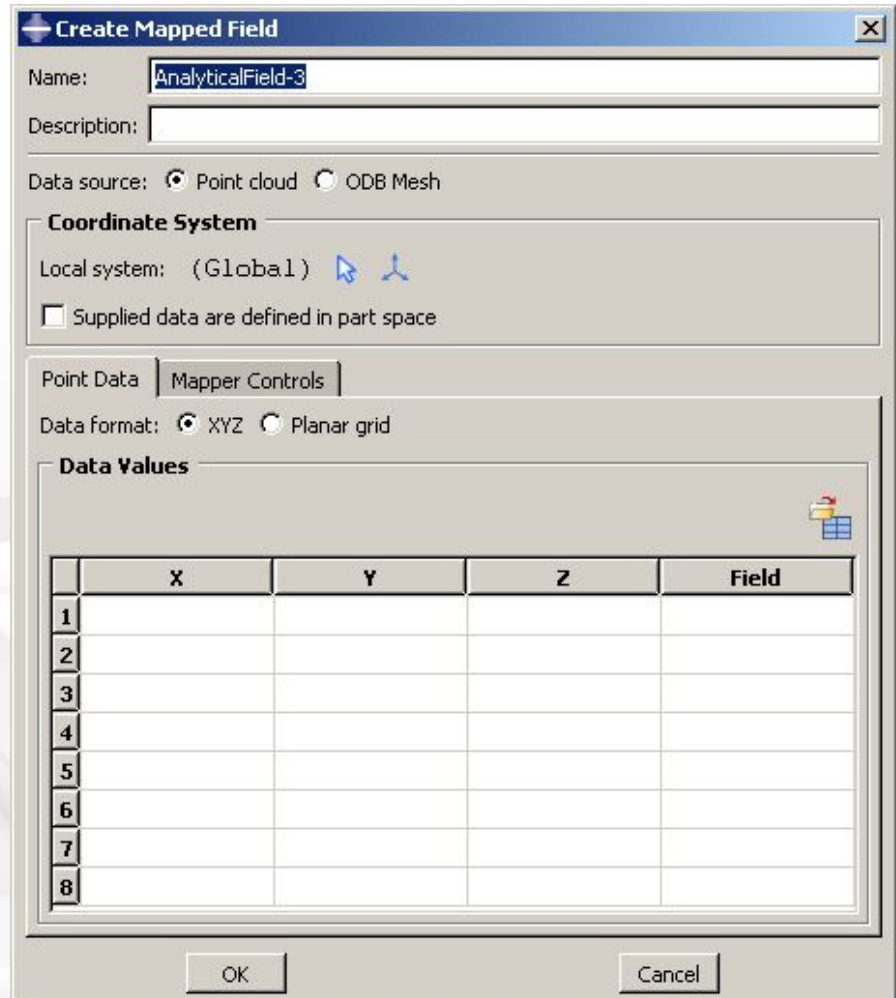
Blade Analysis

New Mapping Capability with A/CAE in 6.11

- **Mapping Fields:**
  - **A new type of analytical field**



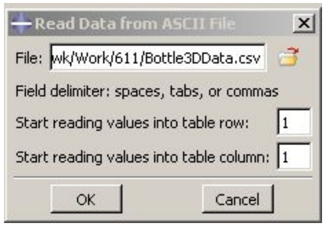
  - **Defines the source field data values**
    - Two input formats are supported in 6.11
      - Point Cloud
      - Odb Mesh
  - **Support for local systems to localize and orient the supplied data**
  - **Mapping options & controls**



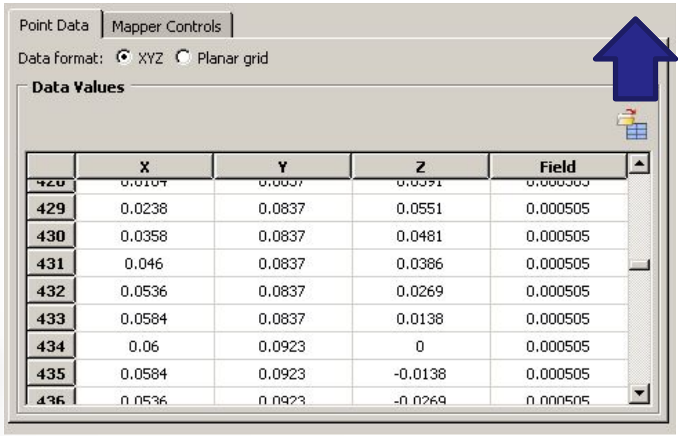
Blade Analysis

New Mapping Capability with A/CAE in 6.11

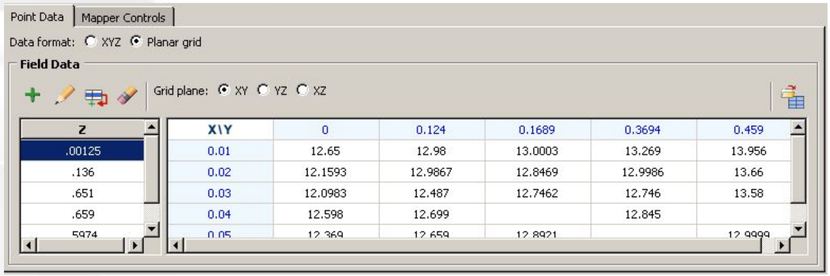
- **Point Cloud**



- **XYZ Format**
  - Coordinate data associated with a field value
  - User supplies X,Y,Z values and a value for each location to be mapped
    - Read from file
    - Typed in(???)



- **Grid Format**
  - Also called tabular format in other products
- **Defines XYZ data based on planes**
  - XY, YZ or XZ
  - User supplies plane location and a value for each coordinate pair in that plane
- **Read from file support** (see docs for formatting requirements)

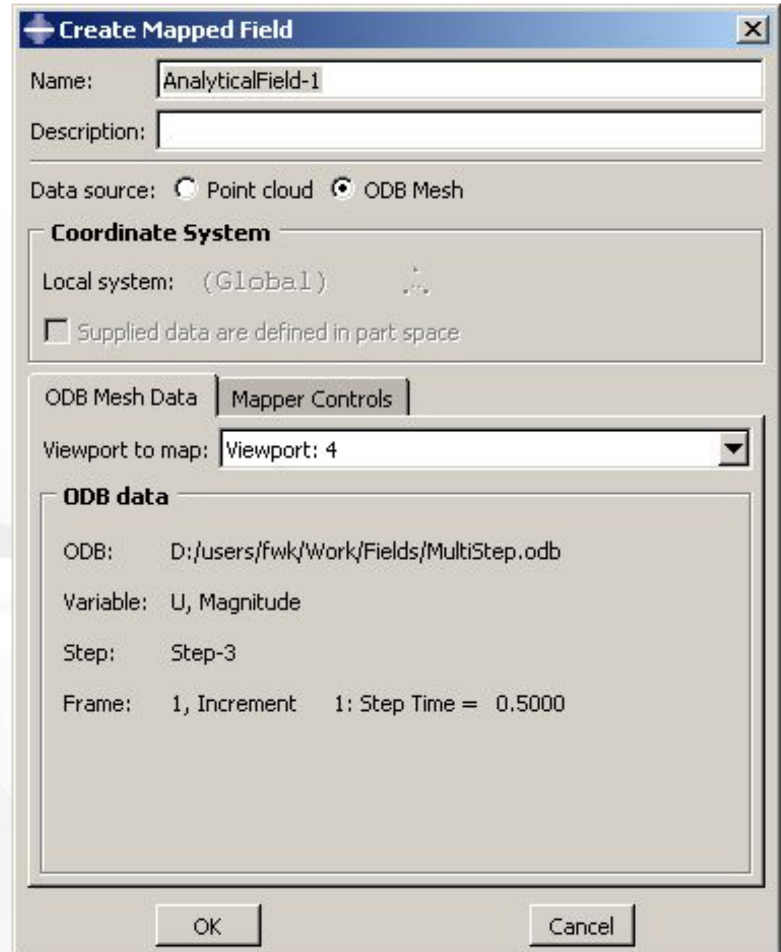


SIMULIA

Blade Analysis

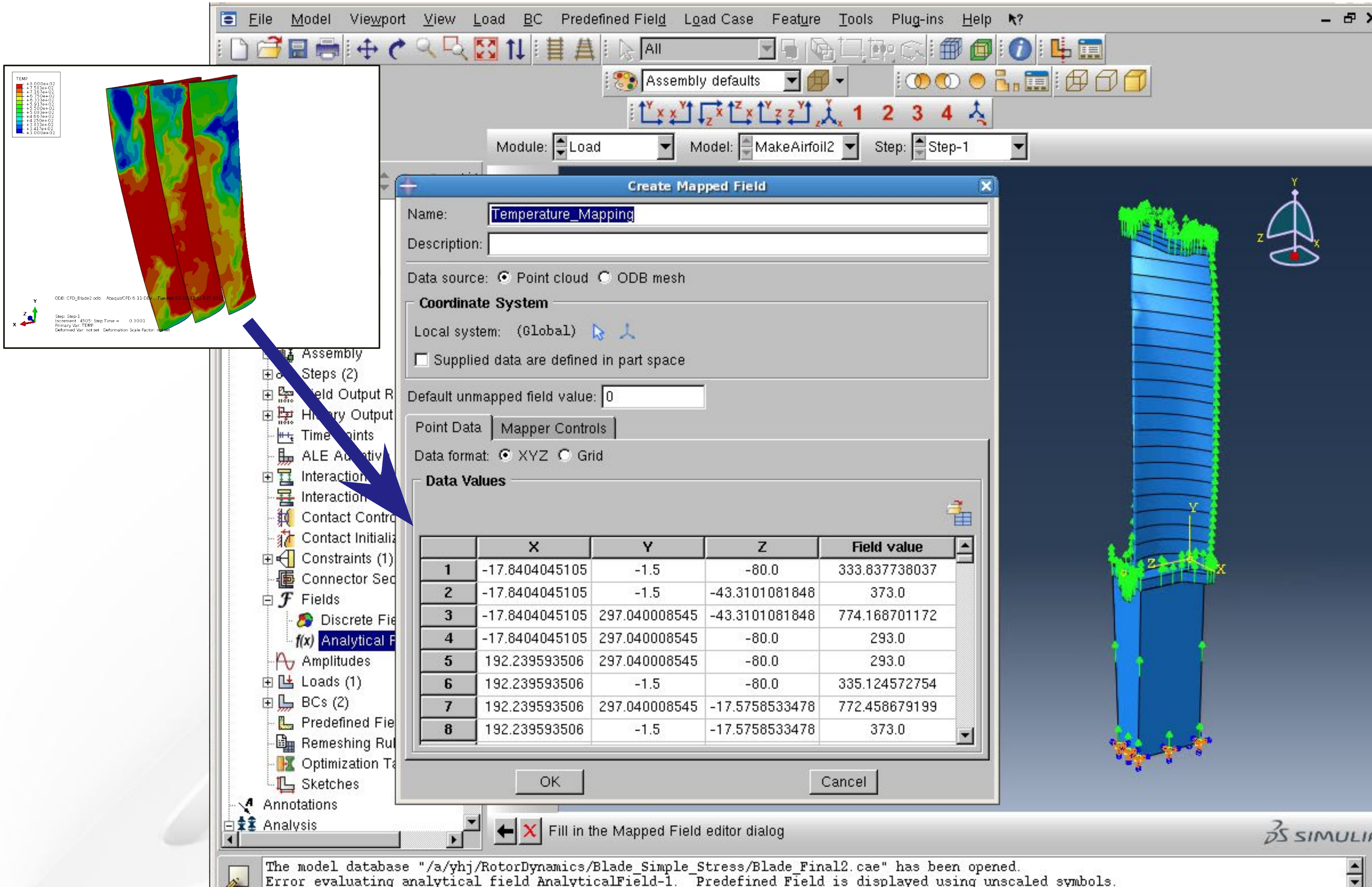
New Mapping Capability with A/CAE in 6.11

- **Odb Mesh**
  - **Supports mapping from an ODB to the current model**
    - Nodal, Whole element, or integration point data
    - Dissimilar meshes are supported
  - **User selects a viewport with an open and displayed ODB to indicate mapping settings**
    - All settings of the viewport will be used in the mapping
      - Primary Variable
      - Step/Increment
      - Averaging
      - Section Points (top or bottom)
      - Etc.



Blade Analysis

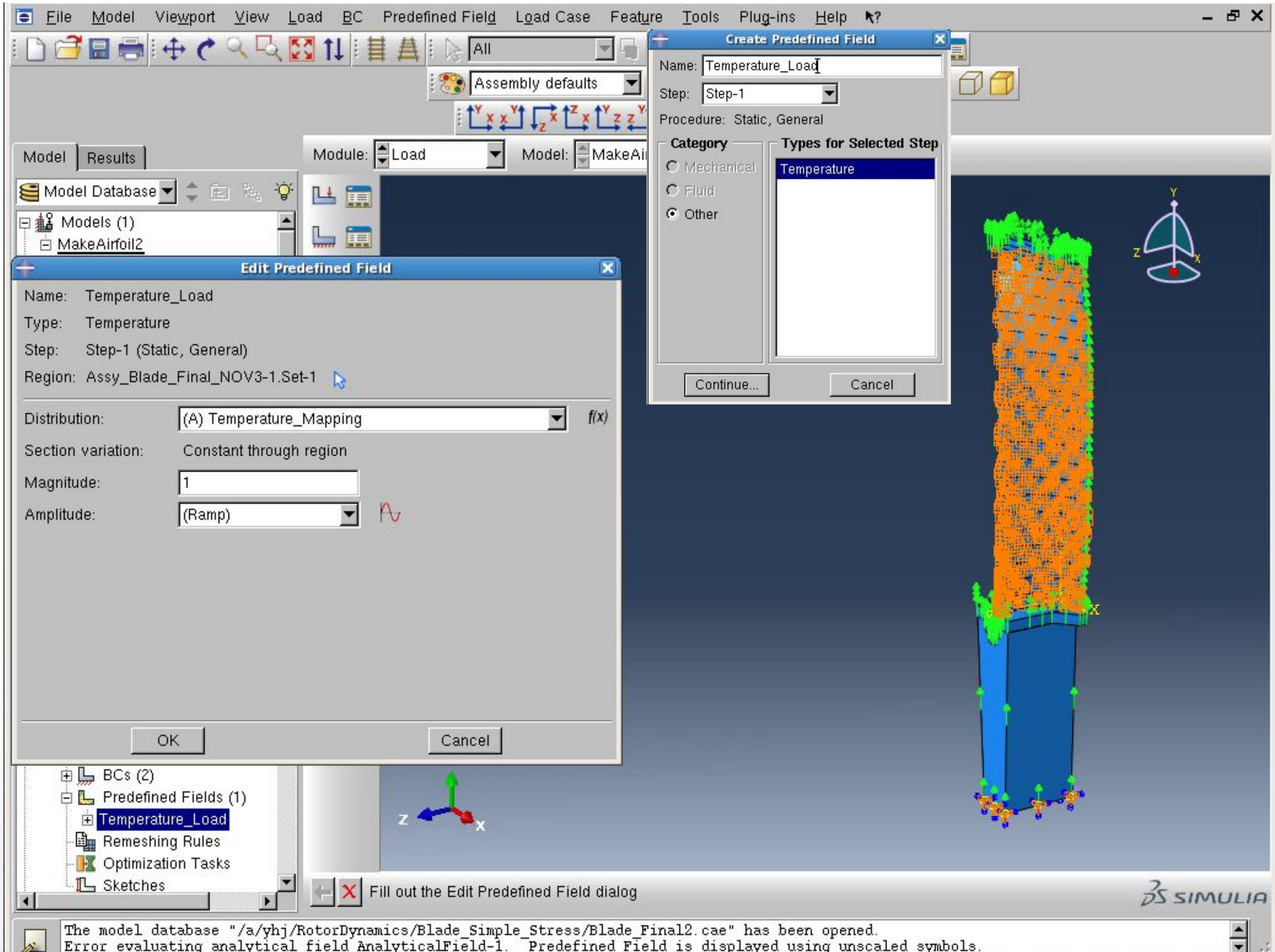
New Mapping Capability with A/CAE in 6.11



SIMULIA

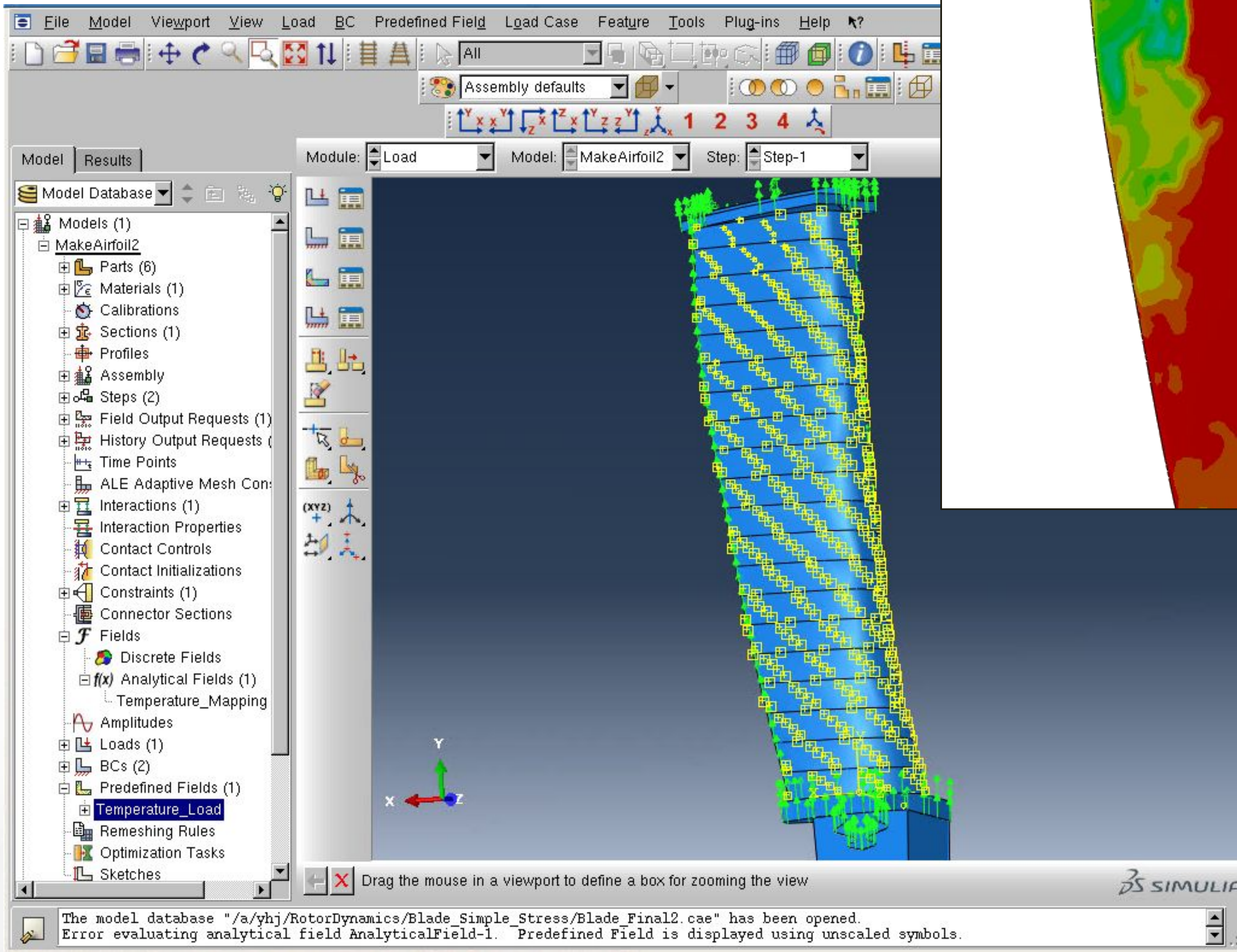
Blade Analysis

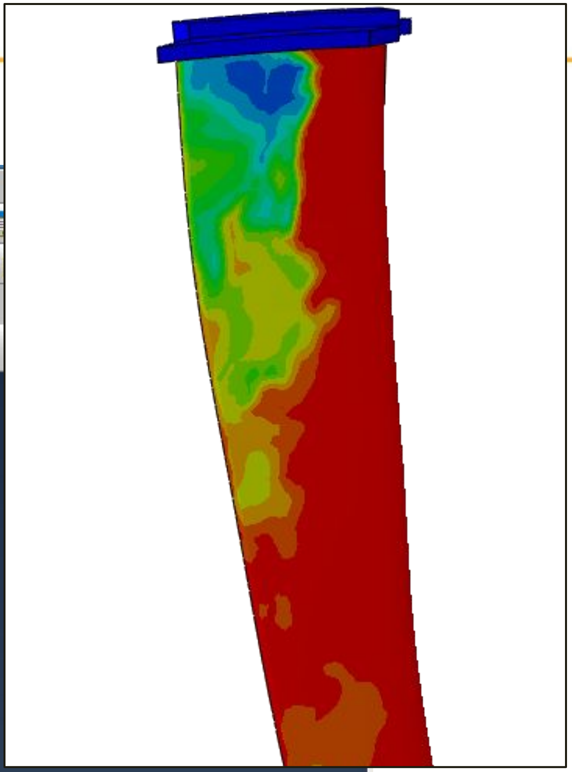
New Mapping Capability with A/CAE in 6.11



Blade Analysis

New Mapping Capability with A/CAE in 6.11



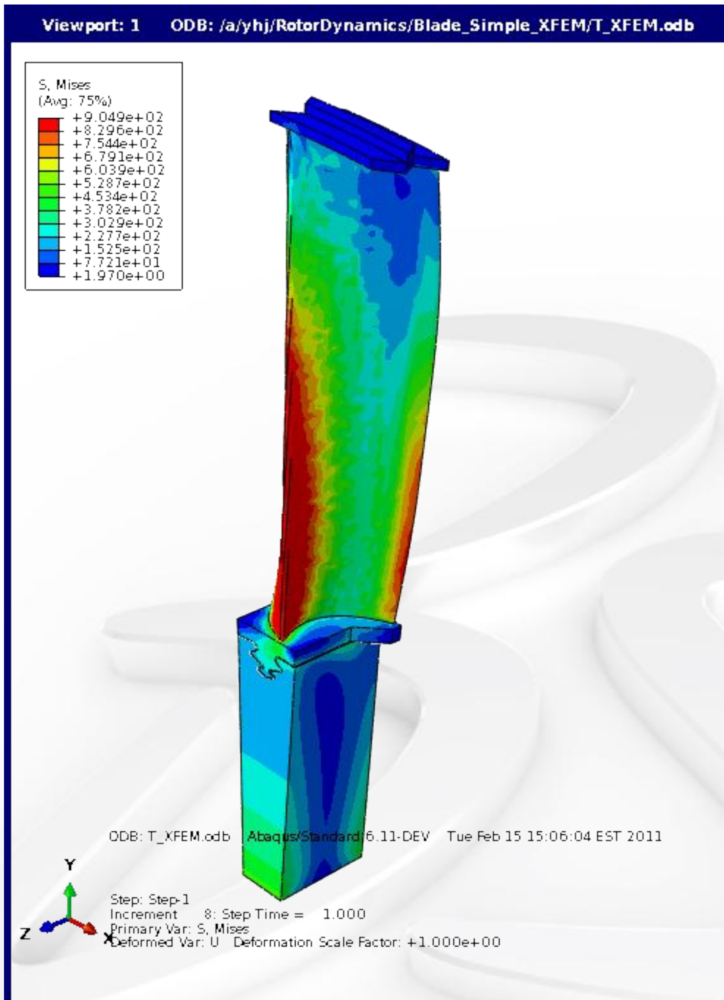


SIMULIA

Blade Analysis

XFEM

- **Crack initiation and propagation in stress analysis**



Viewport: 2 ODB: /a/yhj/RotorDynamics/Blade_Simple_XFEM/T_XFEM.odb

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Surf-tie_master, Surf-tie_slave
*Nset, nset=_PickedSet5979_PP_, internal, instance=disk-3-1
+-- 18 lines: 54,    55,    56,    57,    58,   278,   279,   280,   281,
*Tie, name=Int-1, cyclic symmetry, adjust=no
Surf-Cyclic1, Surf-Cyclic
*Enrichment, name=Crack-1, type=PROPAGATION CRACK, elset=_PickedSet5981
*End Assembly
**
** MATERIALS
**
*Material, name=Material-1
*Damage Initiation, criterion=MAXPS, tol=0.05
 950.,0.,0.
*Damage Evolution, type=displacement
0.1,
*Damage Stabilization
1.e-3
*Density
 2.6e-09,
*Elastic
200000., 0.3
*Expansion
 2.8e-06,
*Plastic
+--  2 lines: 900, 0.------------------------------------------------------
**
** BOUNDARY CONDITIONS
**
** Name: BC-3 Type: Symmetry/Antisymmetry/Encastre
*Boundary
_PickedSet5961, ENCASTRE
                                                      160782,12
```

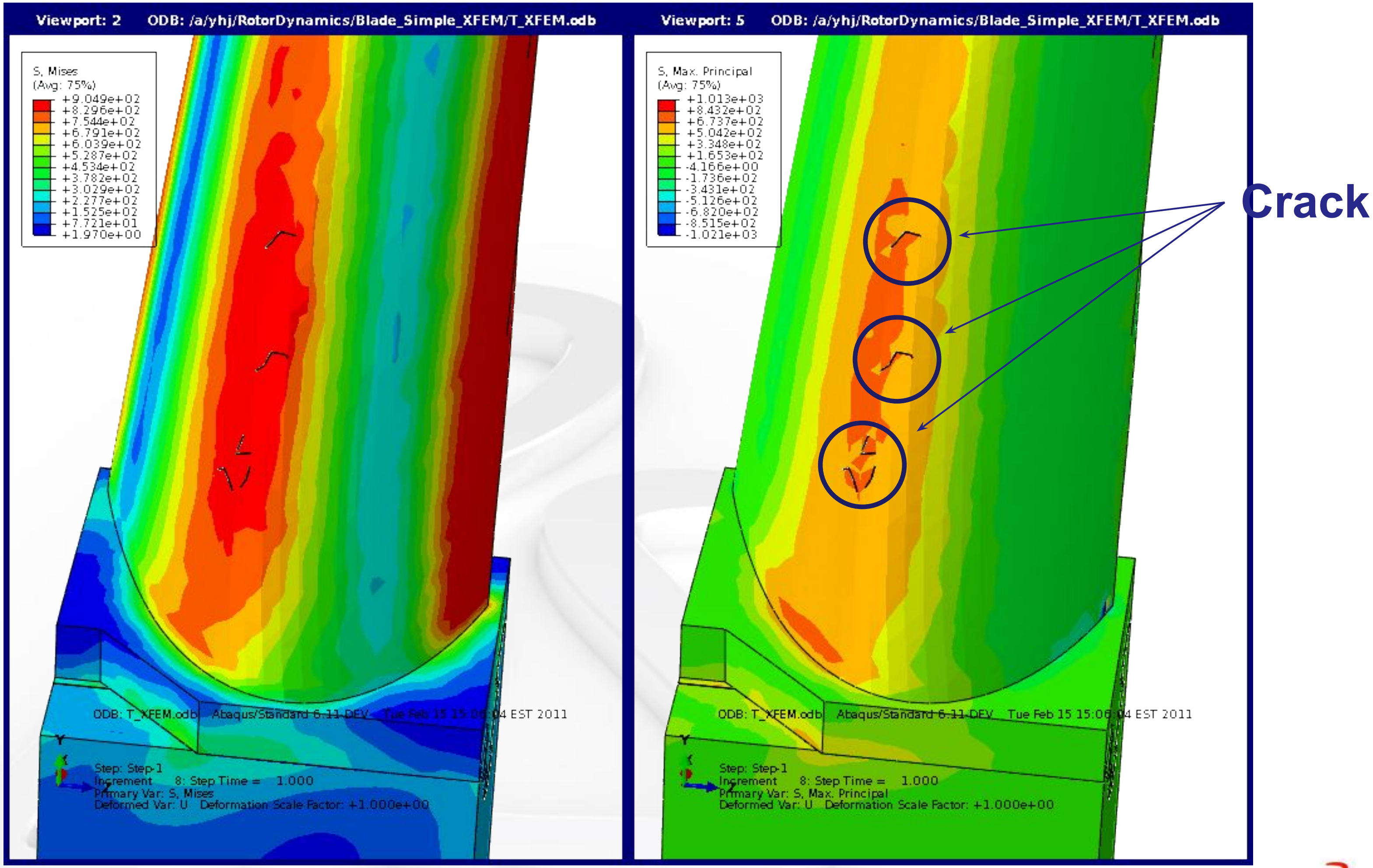
Von Mises

SIMULIA

Blade Analysis

XFEM

- **Crack initiation and propagation in stress analysis**



Blade Analysis

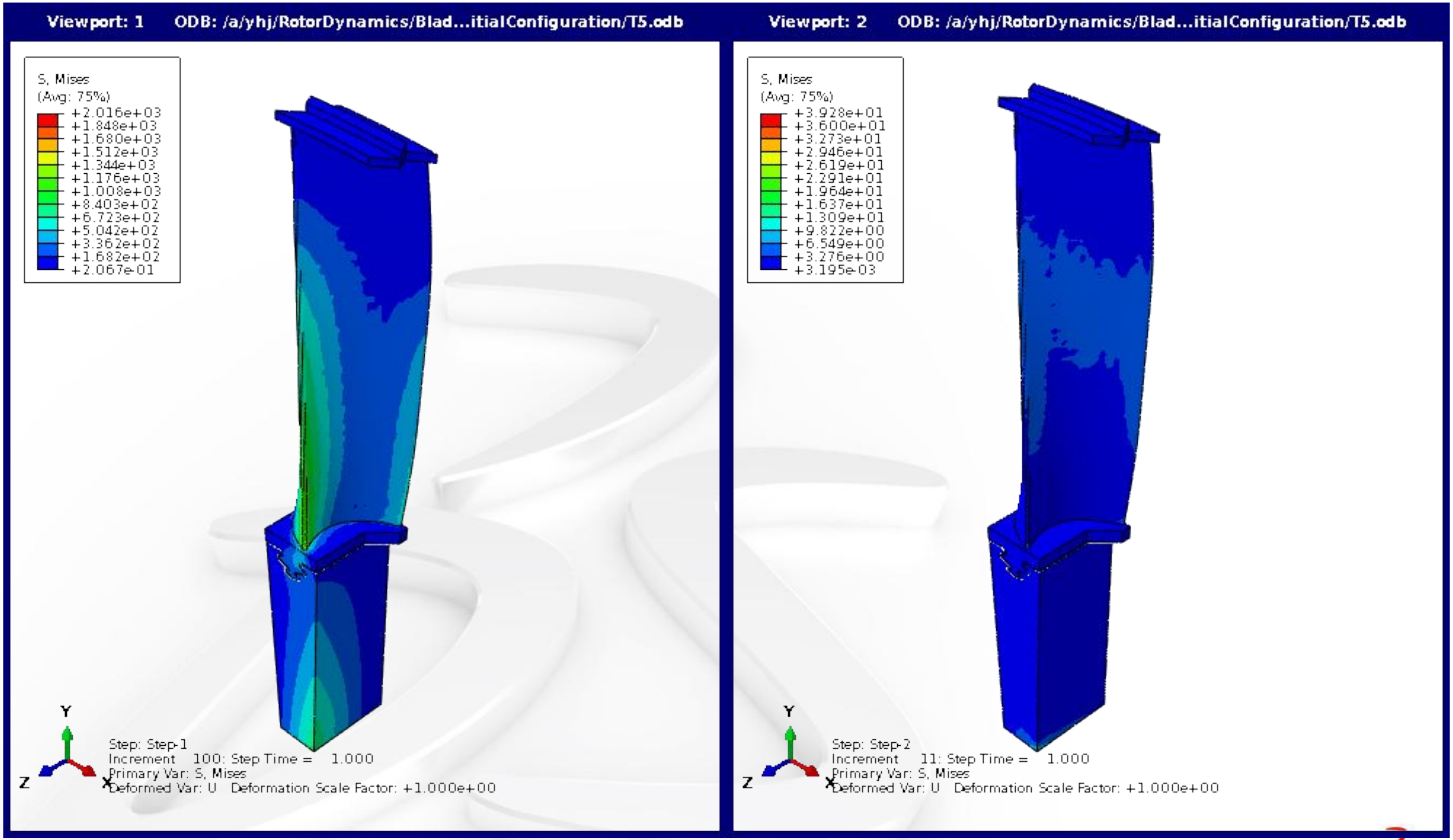
Displacement Analysis at given pre-loading condition

- **To find the initial configuration for manufacturing in case that the shape in numerical mode has pre-loading stage.**
- **This capability is already requested by geostatic industrial field to verify that the initial geostatic stress field is in equilibrium with applied loads and boundary conditions and to iterate, if necessary, to obtain equilibrium**
  - *GEOSTATIC
    - In most geotechnical problems a nonzero state of stress exists in the medium.
      - This typically consists of a vertical stress increasing linearly with depth, equilibrated by the weight of the material, and horizontal stresses caused by tectonic effects.
    - The active loading is applied on this initial stress state.
      - Active loading could be the load on a foundation or the removal of material during an excavation.
    - Except for purely linear analyses, the response of the system will be different for different initial stress states.
      - This illustrates a point of nonlinear analysis:
        - The response of a system to external loading depends on the state of the system when that loading sequence begins (and, by extension, to the sequence of loading).
        - The linear analysis concept of superposing load cases does not apply.

Blade Analysis

Displacement Analysis at given pre-loading condition

- **Blade Application (Centrifugal Force is considered)**



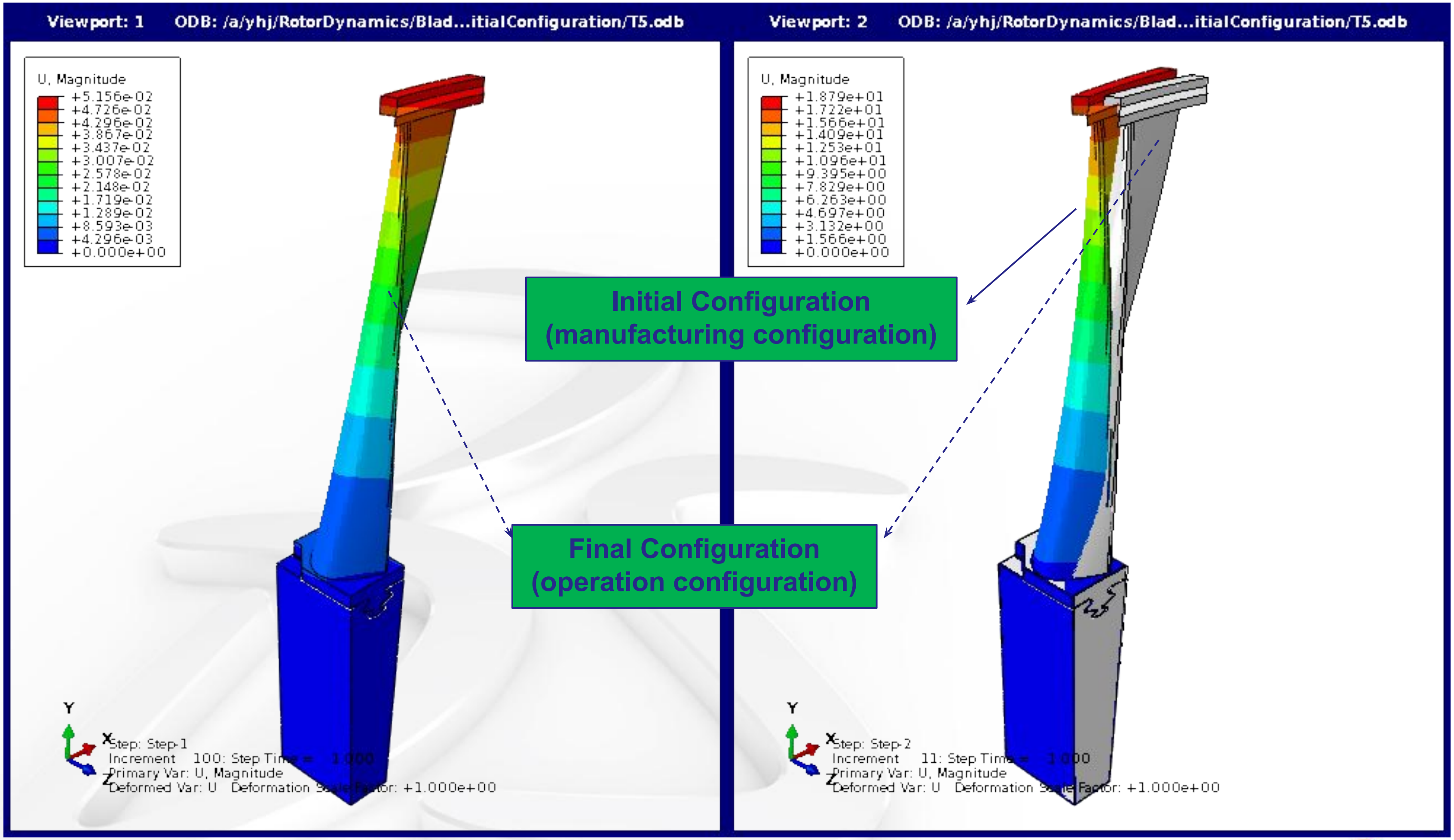
After *GEOSTATIC step

Releasing the loading in *STATIC step: Initial Configuration

Blade Analysis

Displacement Analysis at given pre-loading condition

- **Blade Application (Centrifugal Force is considered)**



After *GEOSTATIC step

Releasing the loading in *STATIC step: Initial Configuration

Blade-out Containment Analysis

Blade-out

Preliminaries

- **Fan Blade Out (FBO) is a requirement by FAA (Federal Aviation Administration).**
  - In a commercial jet engines, a system must exist which will not allow any compressor or turbine blade to perforate the engine case in the event that it is released from a disk during engine operation*.
    - Due to this requirement, the fan case is the heaviest single component of a jet engine.

- **The character of a blade off impact is repeatable.**
- **The most severe blade-out occurs when a 1st stage fan blade in a high-bypass gas turbine engine is released.**
- **Pre-loading effect should be considered (centrifugal loading).**
  - Spin speed
- **Fan Blade Out**
  - Disconnecting rigid connection between blade and rotor at a particular time.
- **High strain dependent material model is necessary.**
- **Simulation Target:**
  - Adequacy of the containment to resist blade penetration

*K.S. Carney, J.M. Pereira, D.M. Revilock, P. Matheny, "Jet engine fan blade containment using an alternate geometry," International Journal of Impact Engineering, 36, pp 720-728, 2009

Blade-out

Model in reference (Flat and Curved Plates)*

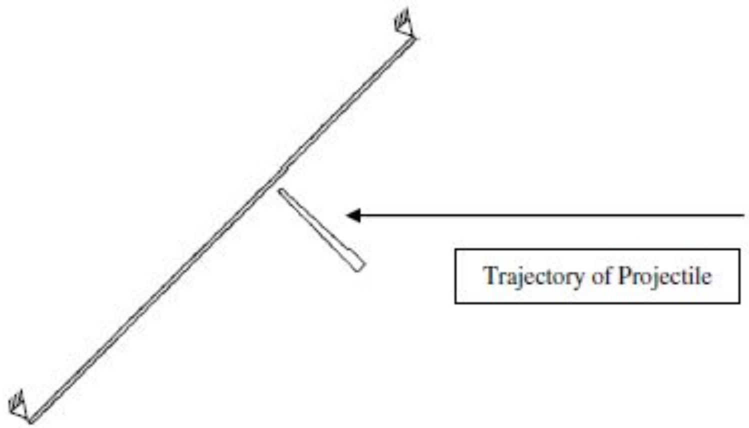


Fig. 6. The orientation of the blade simulating projectile as it impacts the plate.

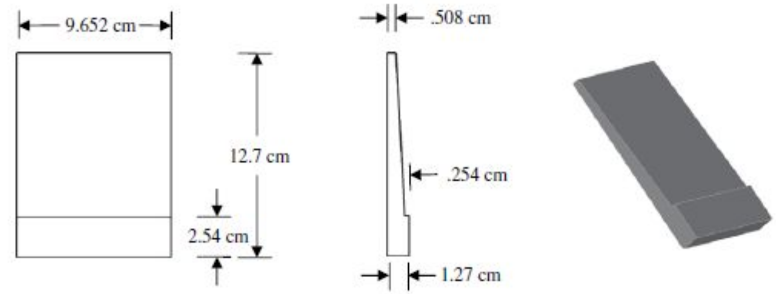


Fig. 5. The blade simulating projectile, which is made of Ti–6Al–4V titanium.

Table 1
Material model properties of Ti–6Al–4V titanium.

ρ	Density	4650.22 kg/m³ (0.168 lbs/in³)
E	Young's modulus	110.316 GPa (16.0×10^6 lbs/in²)
ν	Poisson's ratio	0.31
σ_y	Yield stress	1.00663 GPa (1.46×10^5 lbs/in²)
E_T	Tangent modulus	1.59269 GPa (2.31×10^5 lbs/in²)
ε^p_{fail}	Plastic strain to failure	0.22

Table 2
Material model properties of 304L stainless steel.

ρ	Density	7750.373 kg/m³ (0.280 lbs/in³)
E	Young's modulus	193.053 GPa (28.0×10^6 lbs/in²)
ν	Poisson's ratio	0.305
σ_y	Yield stress	339.222 MPa (4.92×10^4 lbs/in²)
E_T	Tangent modulus[a]	~165 MPa (~2.4×10^5 lbs/in²)
ε^p_{fail}	Plastic strain to failure	0.36

[a] Approximate value. Plastic behavior defined by tabular stress–strain curve.

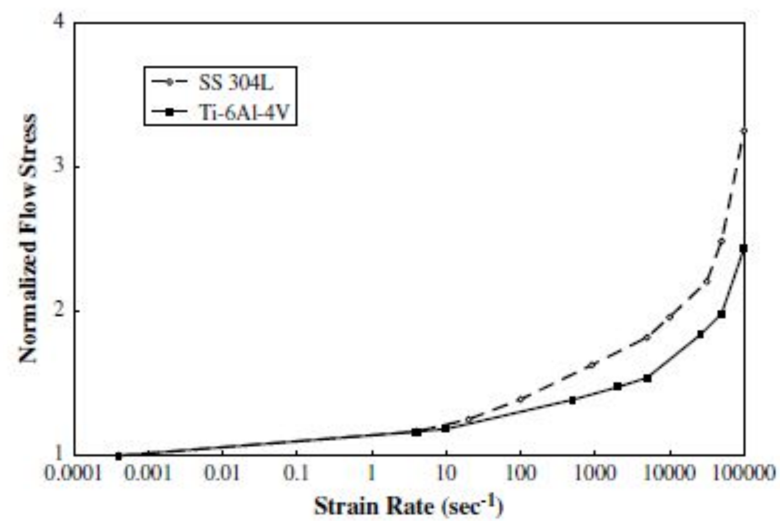


Fig. 7. The strain rate sensitivity of Ti–6Al–4V and SS-304L utilized in the analytical model.

*K.S. Carney, J.M. Pereira, D.M. Revilock, P. Matheny, "Jet engine fan blade containment using an alternate geometry," International Journal of Impact Engineering, 36, pp 720-728, 2009

Blade-out

Results in reference 3 (Flat and Curved Plates)

Table 3
Ballistic impact test results.

Test ID	Geometry	Projectile weight	Velocity	Damage description
LG456	Curved	465.8 gm (1.027 lbs)	358.4 m/s (1176 ft/s)	*Contained*; small perforations on both slap down corner locations
LG455	Flat	459.9 gm (1.014 lbs)	358.4 m/s (1176 ft/s)	*Contained*
LG457	Flat	463.1 gm (1.021 lbs)	394.4 m/s (1294 ft/s)	*Contained*; perforation at initial contact location
LG458	Curved	463.1 gm (1.021 lbs)	395.3 m/s (1297 ft/s)	*Contained*; perforations on both slap down corner locations
LG480	Flat	468.1 gm (1.032 lbs)	423.1 m/s (1388 ft/s)	*Uncontained*; complete projectile size hole with a massive tear running almost the length of the plate
LG477	Flat	459.9 gm (1.014 lbs)	426.7 m/s (1400 ft/s)	*Uncontained*; complete projectile size hole
LG459	Curved	464.0 gm (1.023 lbs)	430.4 m/s (1412 ft/s)	*Contained*; perforations on both slap down corner locations meet forming single tear
LG479	Flat	462.2 gm (1.019 lbs)	457.2 m/s (1500 ft/s)	*Uncontained*; complete projectile size hole with a massive tear running almost the length of the plate
LG461	Curved	459.9 gm (1.014 lbs)	460.2 m/s (1510 ft/s)	*Contained*; perforations on both slap down corner locations meet forming single tear
LG462	Curved	462.2 gm (1.019 lbs)	490.1 m/s (1608 ft/s)	*Uncontained*; complete projectile size hole with tear beginning on initial contact

Flat Plate

Fig. 10. Flat at 394 m/s (1294 fps).

394 m/s

Fig. 12. Flat at 457 m/s (1500 fps).

457m/s

Curved Plate

Fig. 13. Curved at 430 m/s (1412 fps).

430 m/s

Fig. 15. Curved at 490 m/s (1608 fps).

490 m/s

Blade-out

Abaqus result comparison for flat plate

Table 3
Ballistic impact test results.

Test ID	Geometry	Projectile weight	Velocity	Damage description
LG456	Curved	465.8 gm (1.027 lbs)	358.4 m/s (1176 ft/s)	*Contained*; small perforations on both slap down corner locations
LG455	Flat	459.9 gm (1.014 lbs)	358.4 m/s (1176 ft/s)	*Contained*
LG457	Flat	463.1 gm (1.021 lbs)	394.4 m/s (1294 ft/s)	*Contained*; perforation at initial contact location
LG458	Curved	463.1 gm (1.021 lbs)	395.3 m/s (1297 ft/s)	*Contained*; perforations on both slap down corner locations
LG480	Flat	468.1 gm (1.032 lbs)	423.1 m/s (1388 ft/s)	*Uncontained*; complete projectile size hole with a massive tear running almost the length of the plate
LG477	Flat	459.9 gm (1.014 lbs)	426.7 m/s (1400 ft/s)	*Uncontained*; complete projectile size hole
LG459	Curved	464.0 gm (1.023 lbs)	430.4 m/s (1412 ft/s)	*Contained*; perforations on both slap down corner locations meet forming single tear
LG479	Flat	462.2 gm (1.019 lbs)	457.2 m/s (1500 ft/s)	*Uncontained*; complete projectile size hole with a massive tear running almost the length of the plate
LG461	Curved	459.9 gm (1.014 lbs)	460.2 m/s (1510 ft/s)	*Contained*; perforations on both slap down corner locations meet forming single tear
LG462	Curved	462.2 gm (1.019 lbs)	490.1 m/s (1608 ft/s)	*Uncontained*; complete projectile size hole with tear beginning on initial contact

Fig. 18. Flat analysis 396.2 m/s (1300 ft/s).

Fig. 10. Flat at 394 m/s (1294 fps).

394 m/s

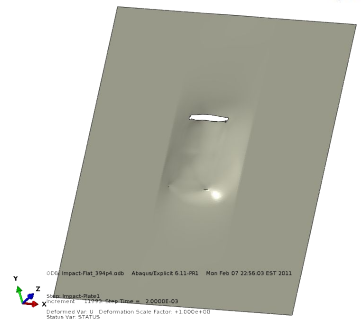
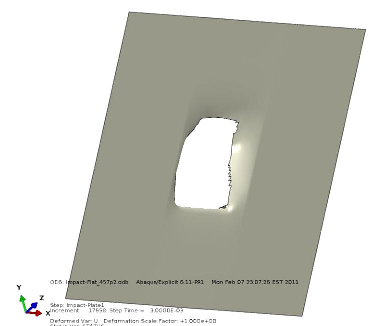


Fig. 12. Flat at 457 m/s (1500 fps).

457m/s



*** Need to adjust damage parameter**

Blade-out

Results in reference 3 (Flat and Curved Plates)

Table 3
Ballistic impact test results.

Test ID	Geometry	Projectile weight	Velocity	Damage description
LG456	Curved	465.8 gm (1.027 lbs)	358.4 m/s (1176 ft/s)	*Contained*; small perforations on both slap down corner locations
LG455	Flat	459.9 gm (1.014 lbs)	358.4 m/s (1176 ft/s)	*Contained*
LG457	Flat	463.1 gm (1.021 lbs)	394.4 m/s (1294 ft/s)	*Contained*; perforation at initial contact location
LG458	Curved	463.1 gm (1.021 lbs)	395.3 m/s (1297 ft/s)	*Contained*; perforations on both slap down corner locations
LG480	Flat	468.1 gm (1.032 lbs)	423.1 m/s (1388 ft/s)	*Uncontained*; complete projectile size hole with a massive tear running almost the length of the plate
LG477	Flat	459.9 gm (1.014 lbs)	426.7 m/s (1400 ft/s)	*Uncontained*; complete projectile size hole
LG459	Curved	464.0 gm (1.023 lbs)	430.4 m/s (1412 ft/s)	*Contained*; perforations on both slap down corner locations meet forming single tear
LG479	Flat	462.2 gm (1.019 lbs)	457.2 m/s (1500 ft/s)	*Uncontained*; complete projectile size hole with a massive tear running almost the length of the plate
LG461	Curved	459.9 gm (1.014 lbs)	460.2 m/s (1510 ft/s)	*Contained*; perforations on both slap down corner locations meet forming single tear
LG462	Curved	462.2 gm (1.019 lbs)	490.1 m/s (1608 ft/s)	*Uncontained*; complete projectile size hole with tear beginning on initial contact

Fig. 13. Curved at 430 m/s (1412 fps).

430 m/s

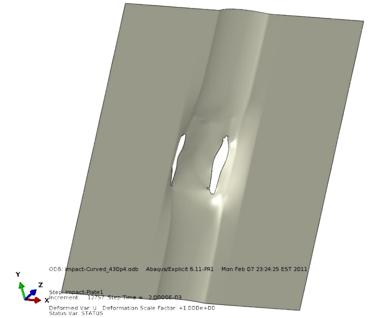
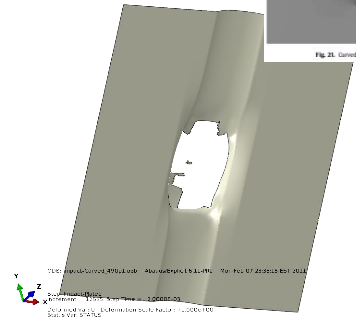
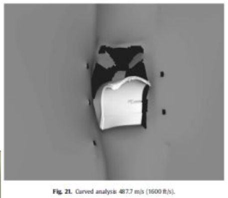


Fig. 15. Curved at 490 m/s (1608 fps).

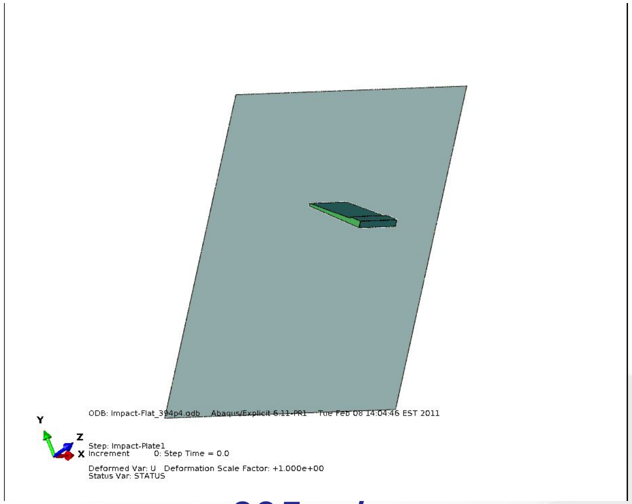
490 m/s

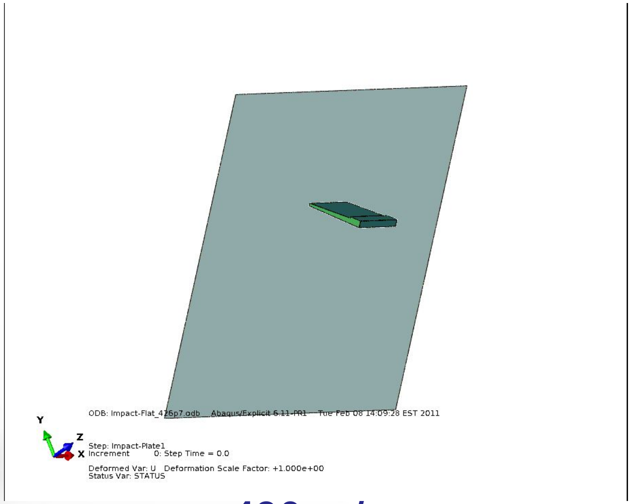




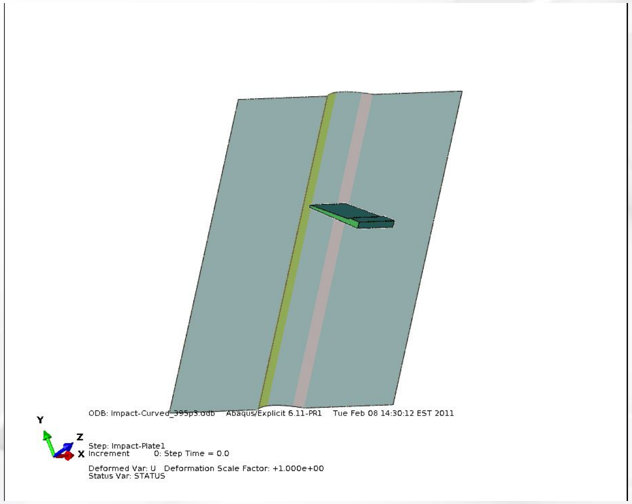
Blade-out

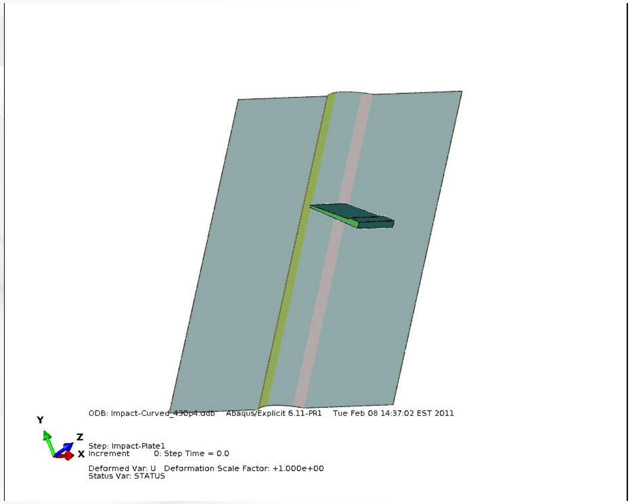
Results in reference 3 (Flat and Curved Plates)





395 m/s **430 m/s**





Blade-out

Results in reference 3 (Flat and Curved Plates)

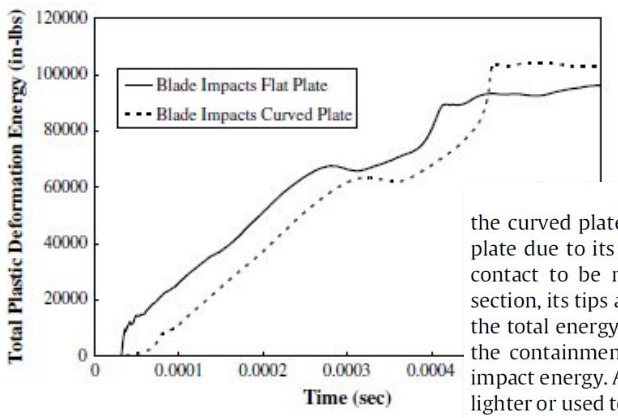
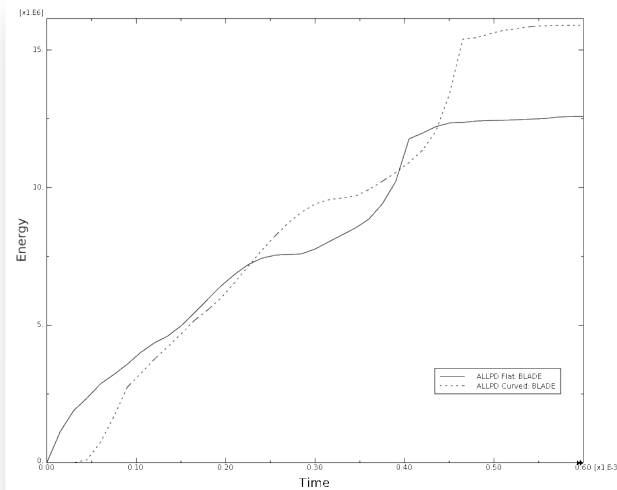


Fig. 16. The running total of plastic deformation energy of the blade projectile, comparing the two geometries, at 457 m/s (1500 fps).

The energy absorbed by the blade in the curved plate case initially lags the energy absorbed in the flat plate due to its having to travel a slightly farther distance for full contact to be made. Then as the blade travels into the curved section, its tips are bent backward, absorbing energy. Since more of the total energy is absorbed by the blades in the curved geometry, the containment structure is required to absorb less of the total impact energy. As a result, the containment structure may be made lighter or used to absorb higher impact velocities.



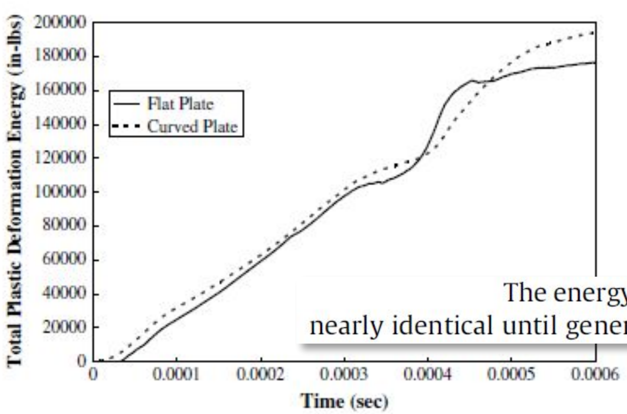
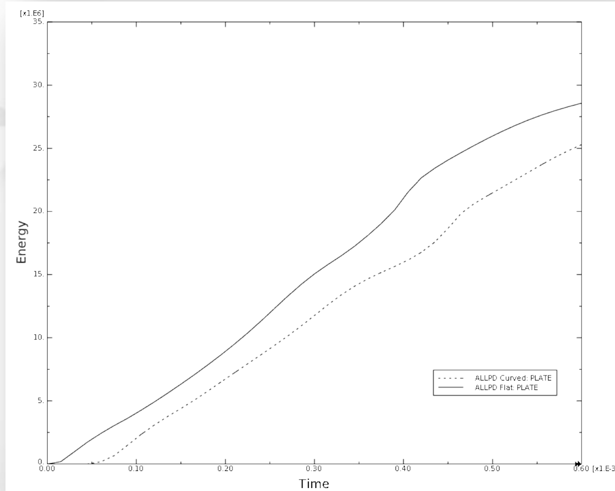


Fig. 17. The running total of plastic deformation energy of the plate, comparing the two geometries, at 457 m/s (1500 fps).

The energy that the flat and curved plates absorb is nearly identical until general failure occurs in the flat plate.

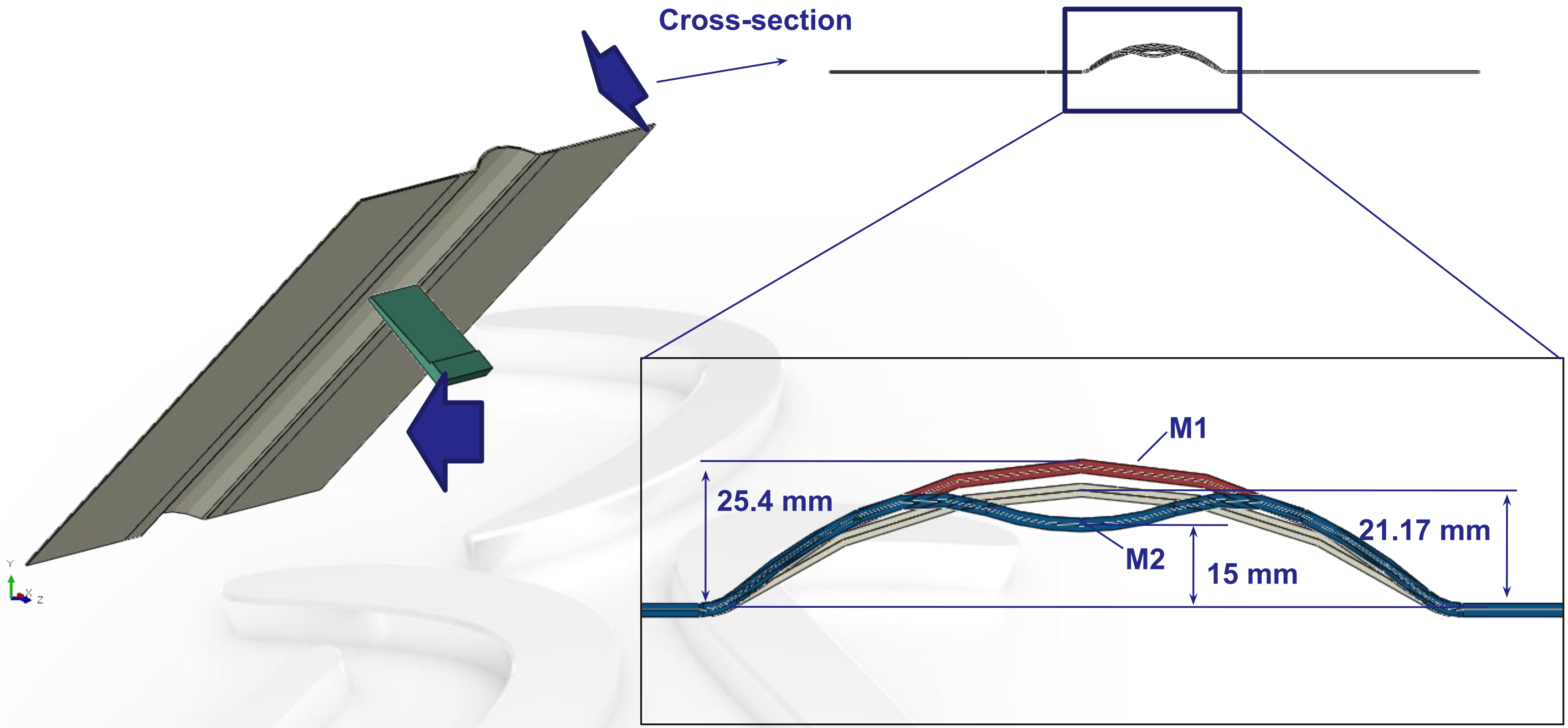


LS-DYNA **Abaqus**

SIMULIA

Blade-out

Further Investigation for reference 3 (Flat and Curved Plates)

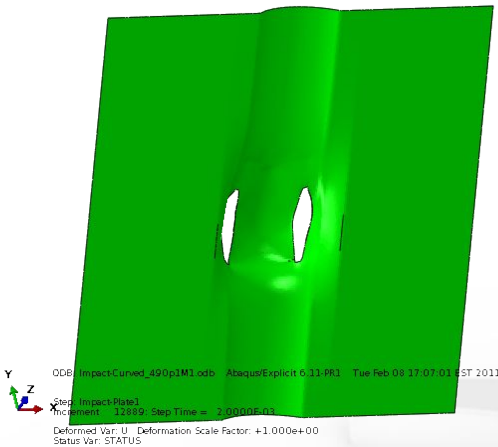


Height:

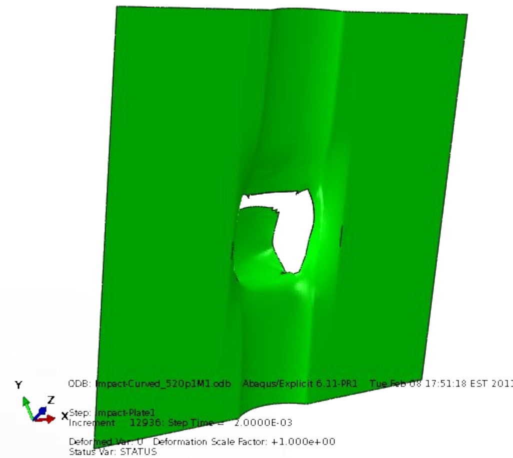
- **21.17 mm: Original Curved Plate**
- **25.4 mm: Modified Curved Plate: Case M1**
- **15.0 mm: Double Curved Plate: Case M2**

Blade-out

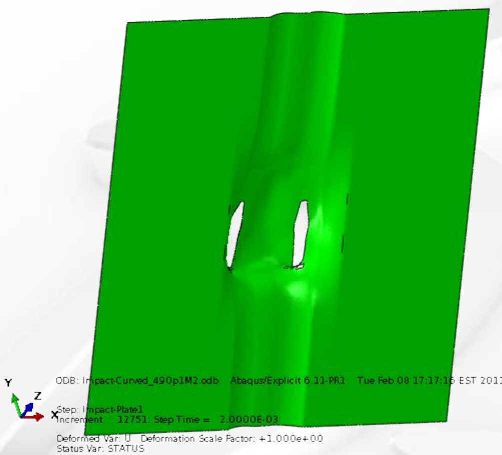
Further Investigation for reference 3 (Flat and Curved Plates)



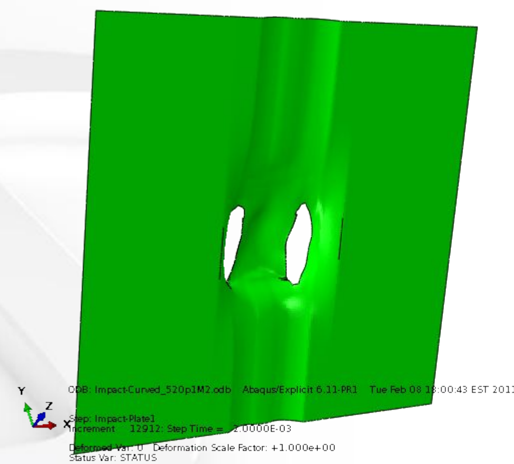
M1: 490 m/s



M1: 520 m/s



M2: 490 m/s

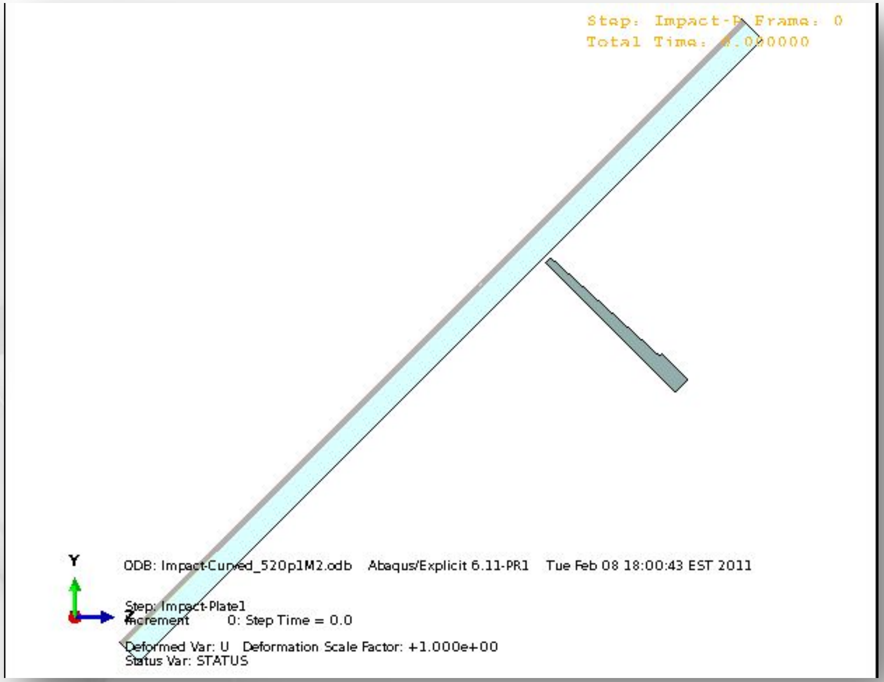


M2: 520 m/s

Blade-out

Further Investigation for reference 3 (Flat and Curved Plates)

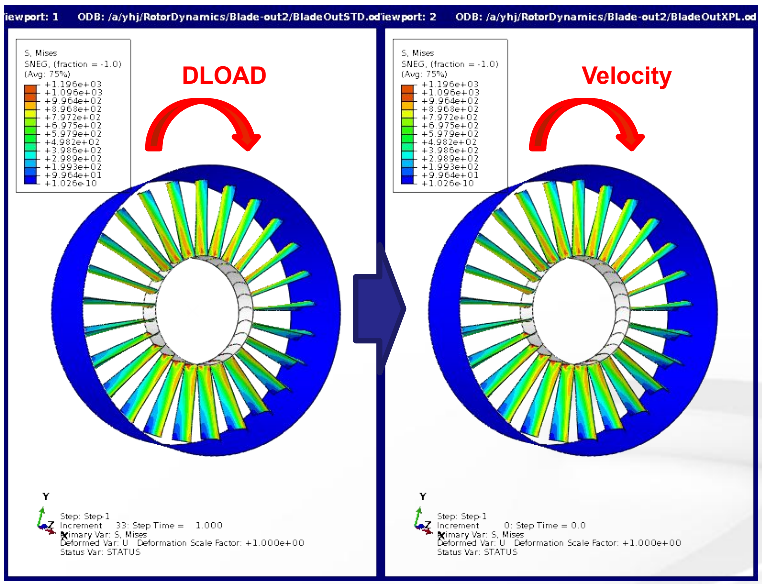
M1: 520 m/s

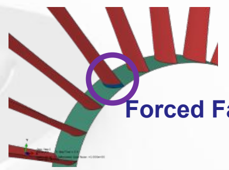


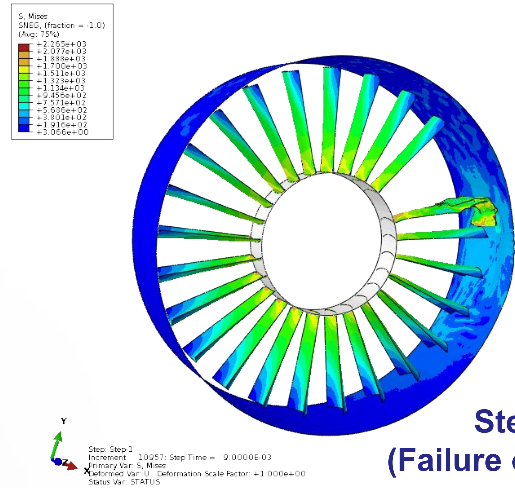
M2: 520 m/s

Blade-out

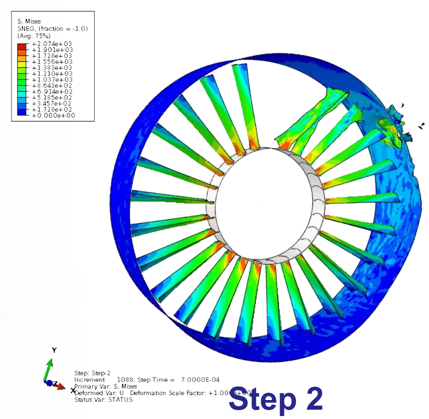
Further Investigation for containment (1000 rad/s spin speed)







Step 1
(Failure on Blade)



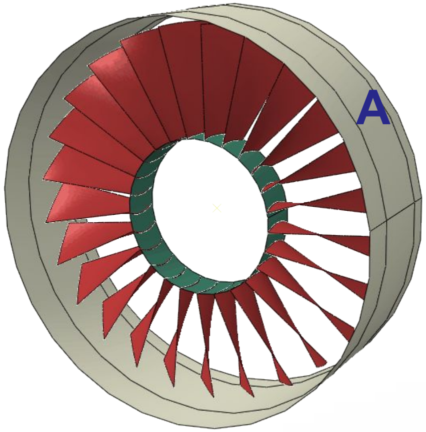
Step 2
(Failure on Containment)

A/Standard

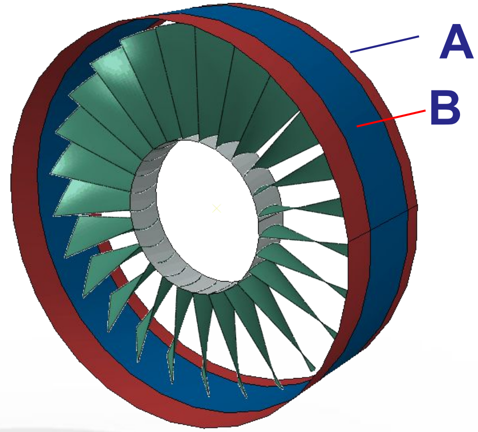
A/Explicit

Blade-out

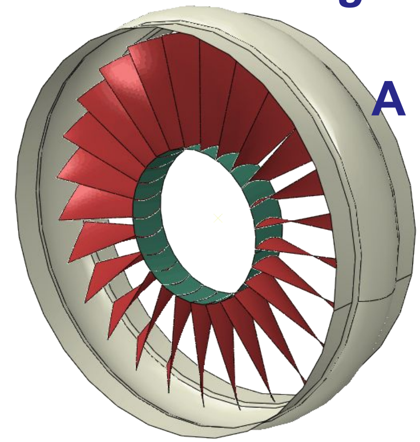
Further Investigation for fan blade-out in simple containment design



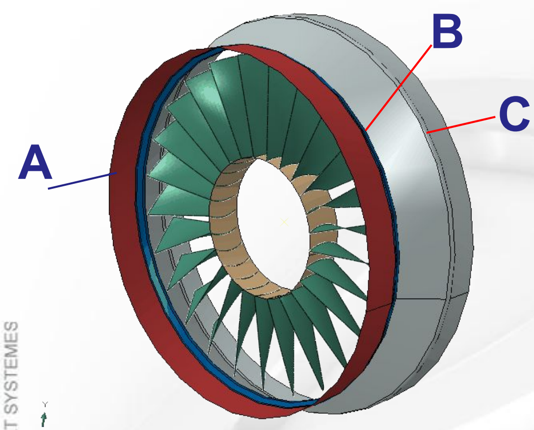
ORG (A=2mm)
Flat with the same thickness



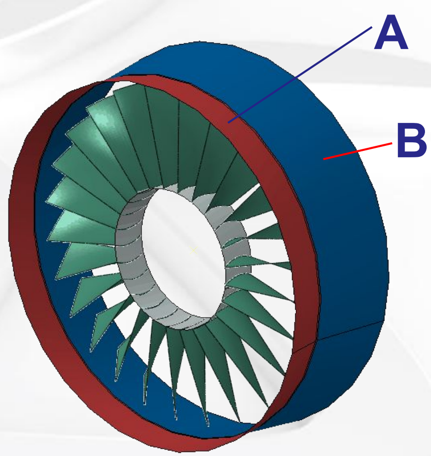
ORG_10 (A=2 mm, B=4mm)
Flat with different thickness



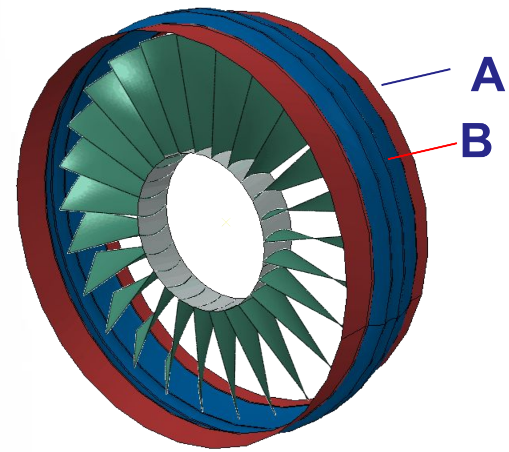
M1 (a=2mm)
Curved with the same thickness



M9 (A=2mm, B=4mm, C=2mm)
Tapered with the different thickness



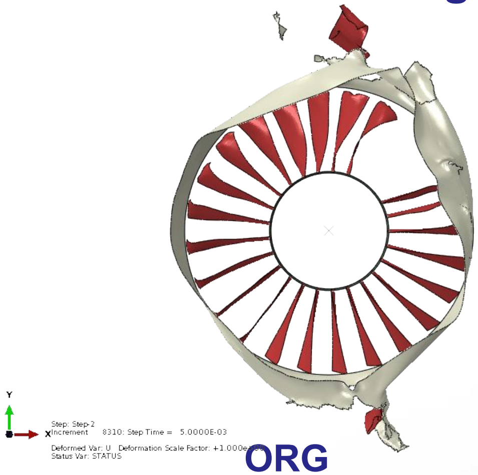
M8 (A=2mm, B=4mm)
Tapered with the same thickness



M7 (A=2mm, B=4mm)
Curved with different thickness

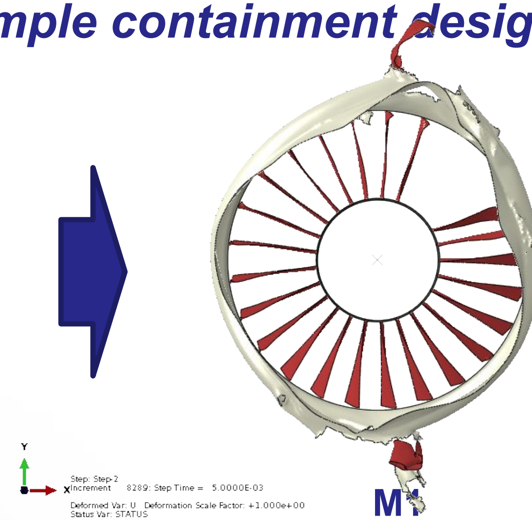
Blade-out

Further Investigation for fan blade-out in simple containment design



ORG
Flat with the same thickness

ORG_10
Flat with different thickness



M1
Curved with the same thickness

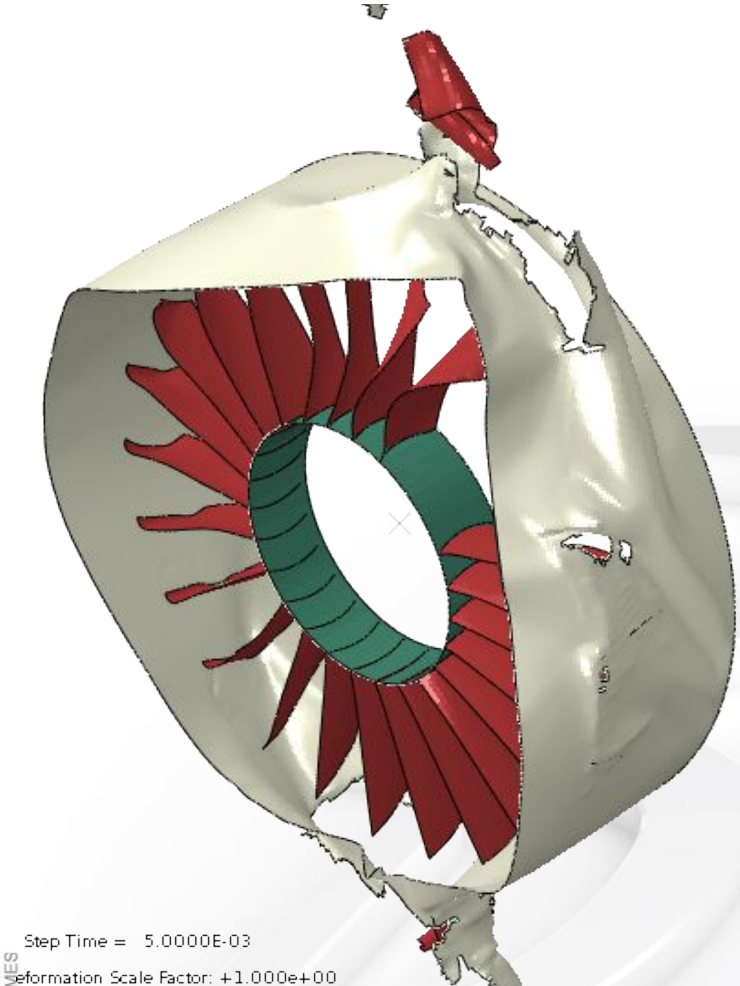
M9
Tapered with the different thickness

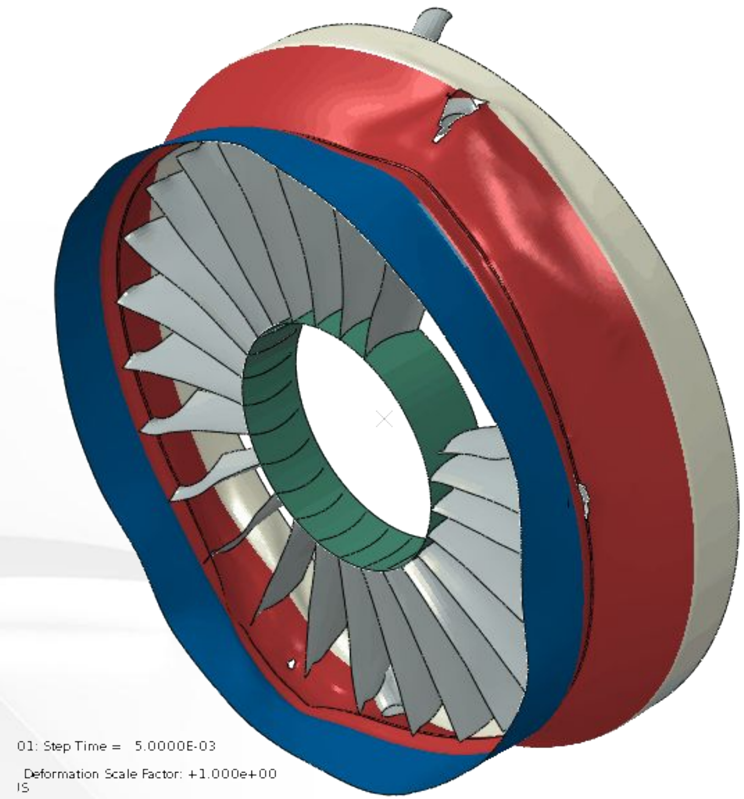
M8
Tapered with the same thickness

M7
Curved with different thickness

Blade-out

Further Investigation for fan blade-out in simple containment design



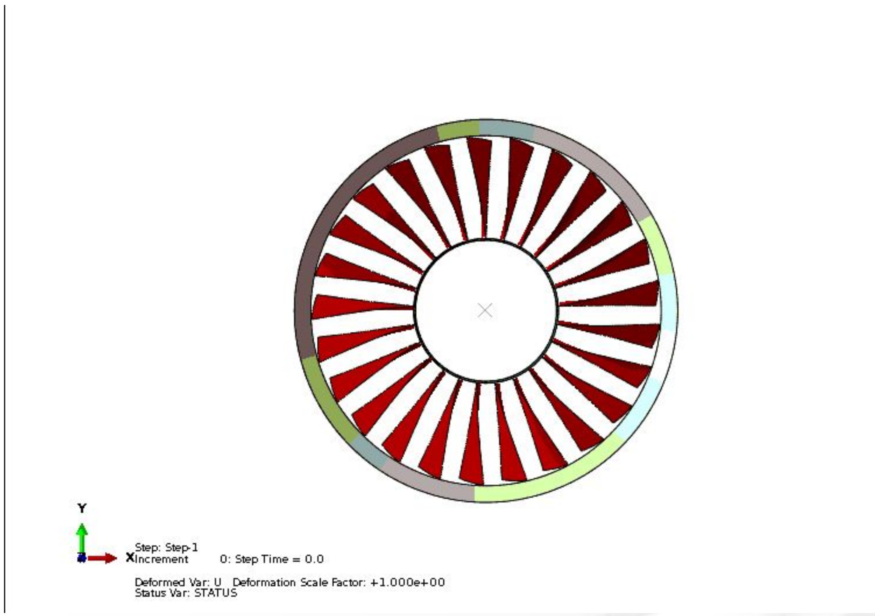


ORG
Flat with the same thickness

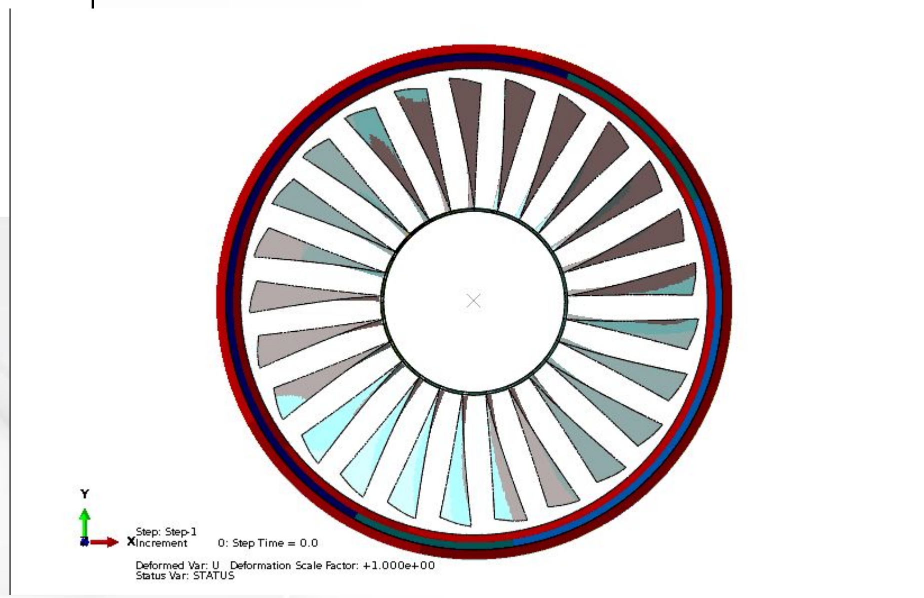
M9
Tapered with the different thickness

Blade-out

Further Investigation for fan blade-out in simple containment design



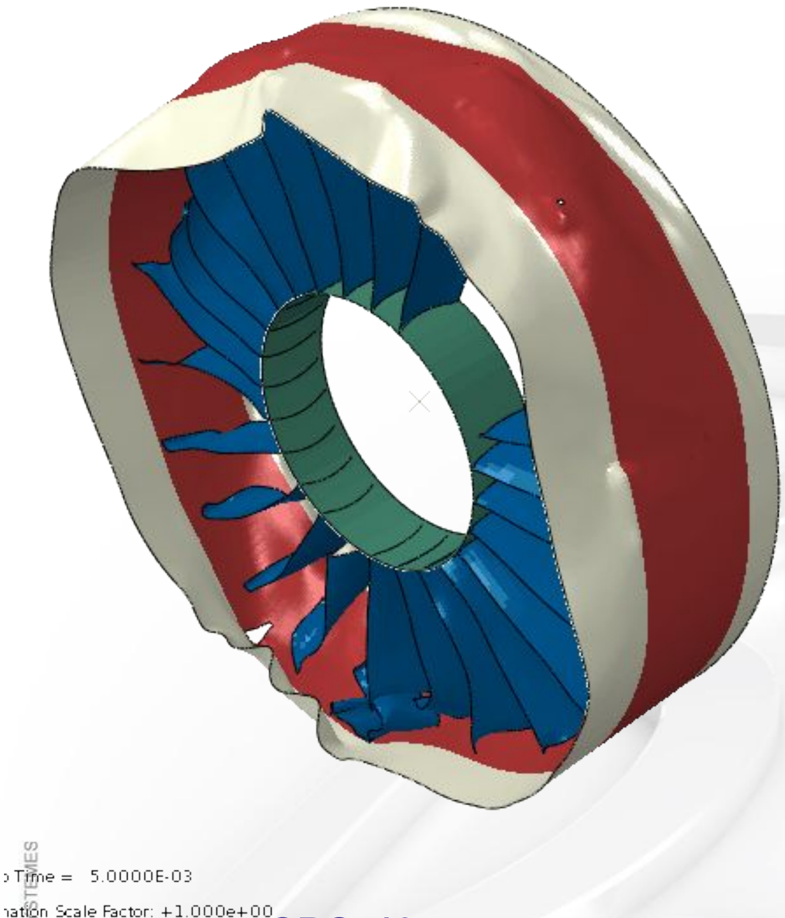
ORG
Flat with the same thickness



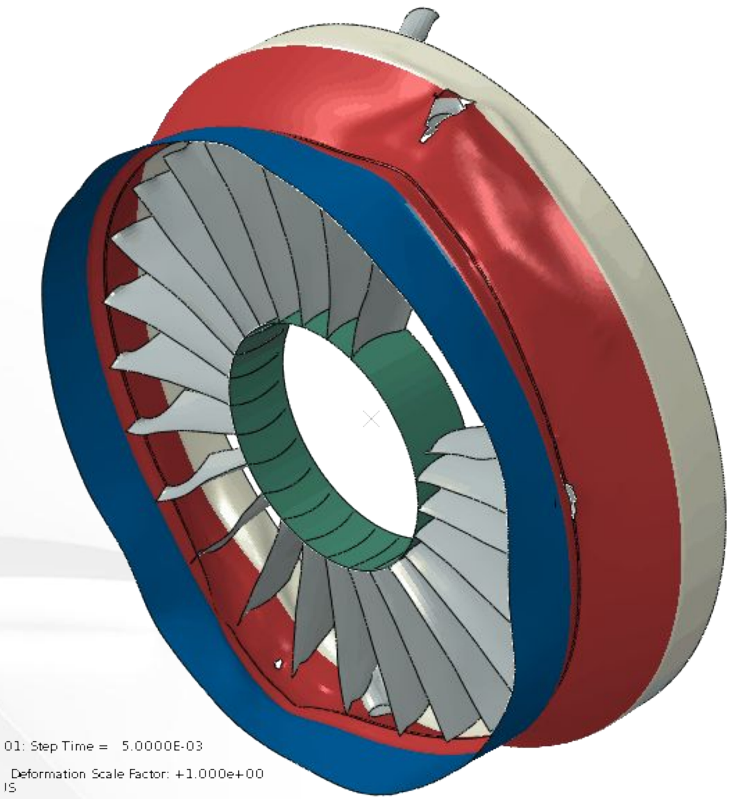
M9
Tapered with the different thickness

Blade-out

Further Investigation for fan blade-out in simple containment design



ORG_10
Flat with different thickness

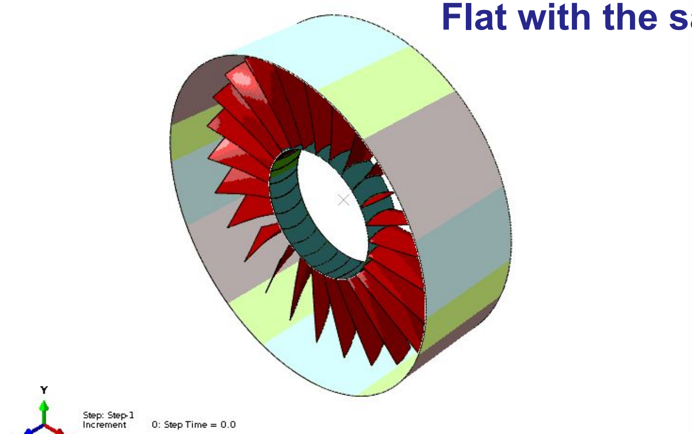


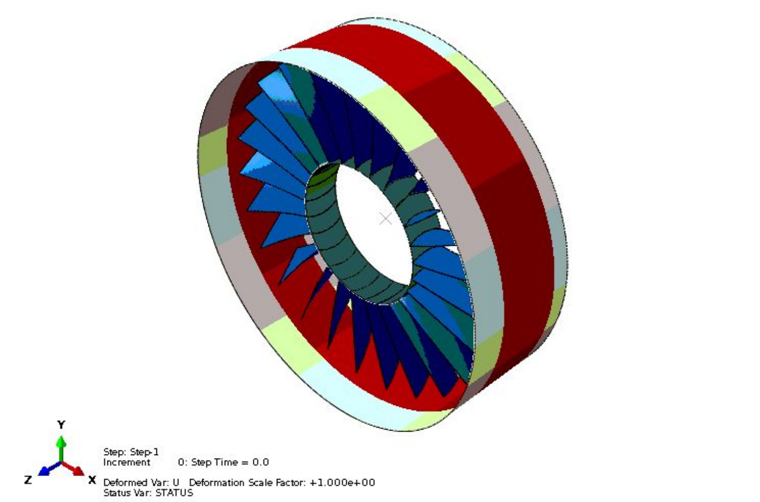
M9
Tapered with the different thickness

Blade-out

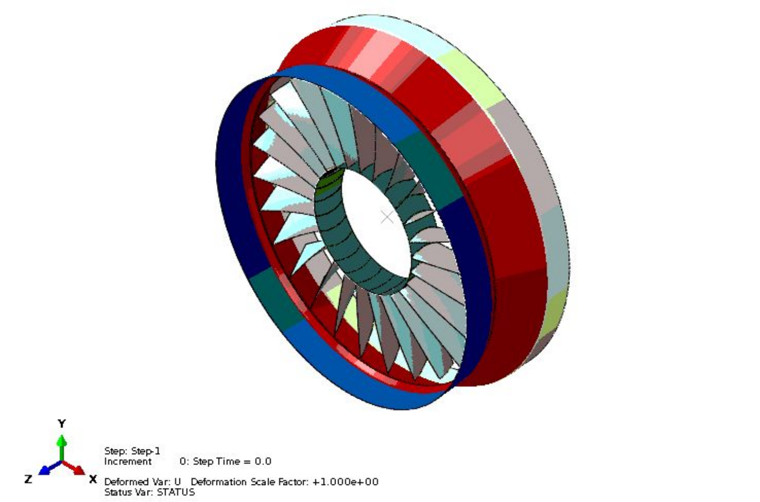
Further Investigation for fan blade-out in simple containment design

ORG
Flat with the same thickness





ORG_10
Flat with different thickness



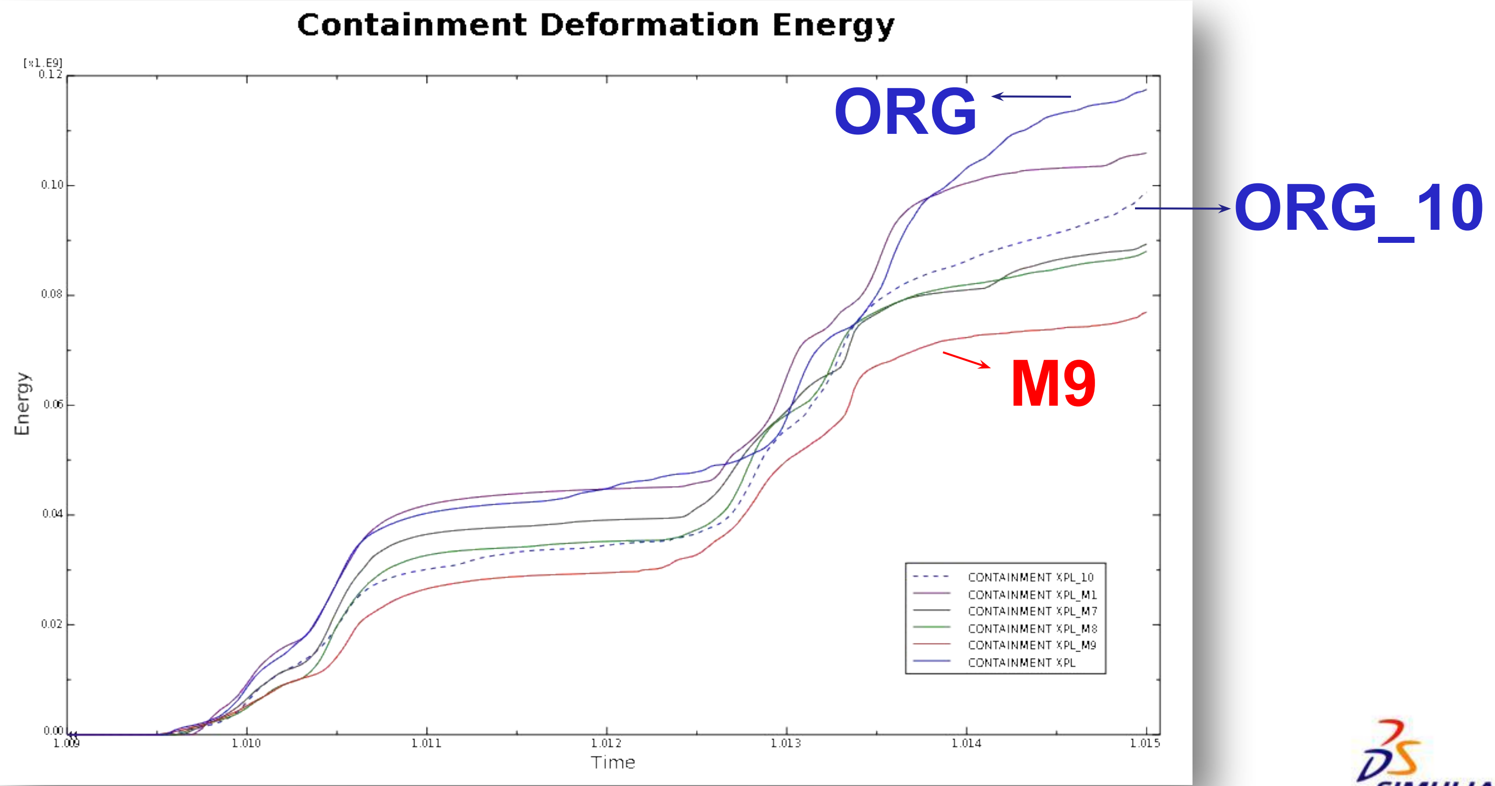
M9
Tapered with the different thickness

Blade-out

Further Investigation for fan blade-out in simple containment design

Thickness

	ORG	ORG_10	M1	M7	M8	M9
Thickness	A = 2 mm	A = 2 mm B = 4 mm	A = 2 mm	A = 2 mm B = 4 mm	A = 2 mm B = 4 mm	A = 2 mm B = 4 mm A = 2 mm
Containment Mass (ton)	0.0234	0.0362	0.025	0.0381	0.0418	0.0386

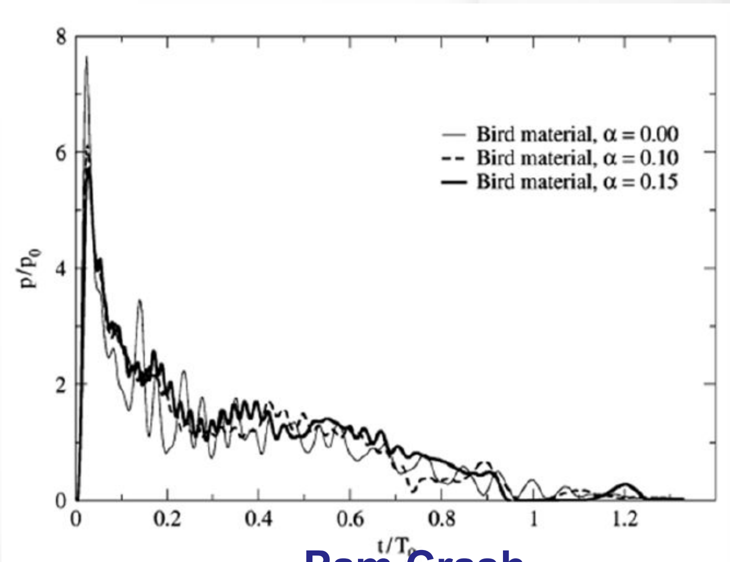


Foreign Object Impact Analysis

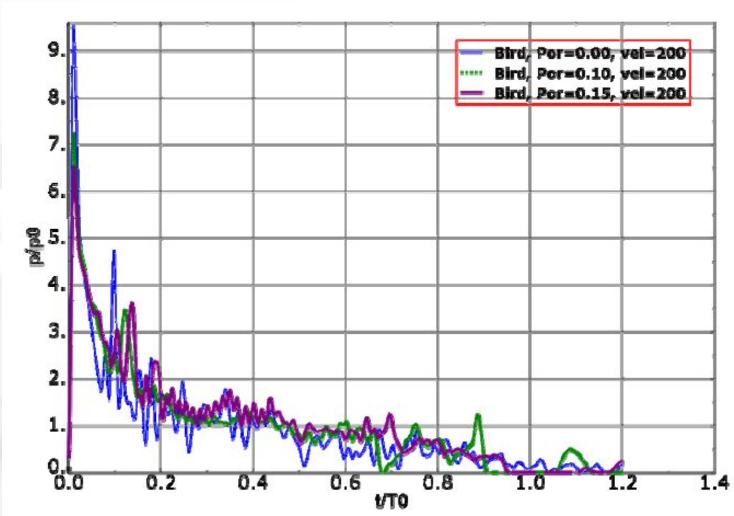
Foreign Object Impact Analysis

Lagrangian Approach

- **Bird Model: ANSWER 4493 Best Practices for Bird Strike Simulations with Abaqus/Explicit**
- **We have bird material model in ready to use for the paid Abaqus users**
  - Correlated with reference papers.
  - CEL and Lagrangian models



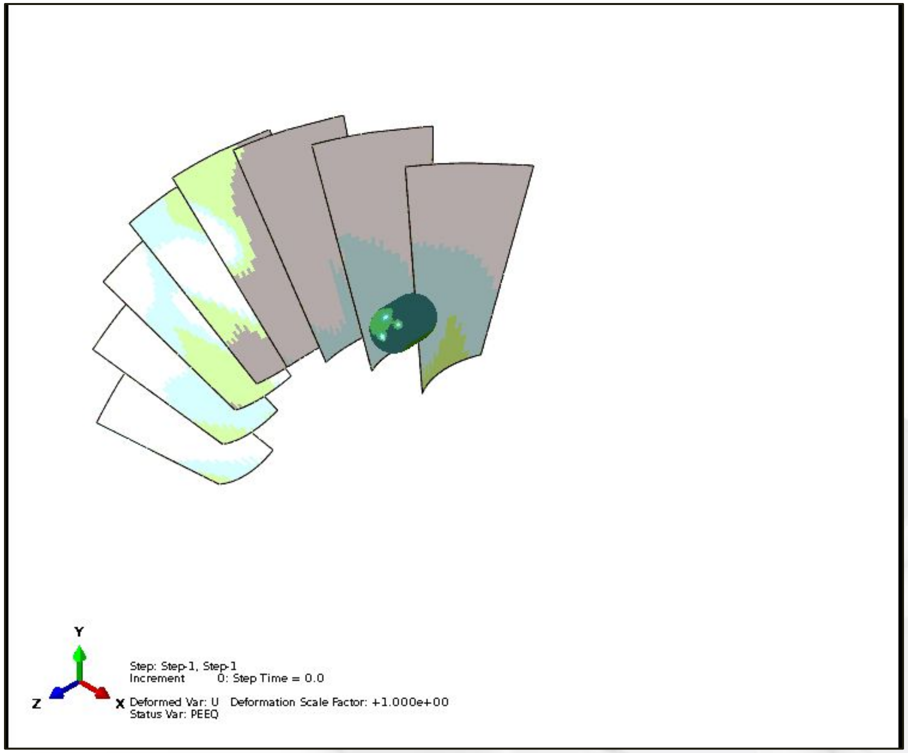
Pam Crash

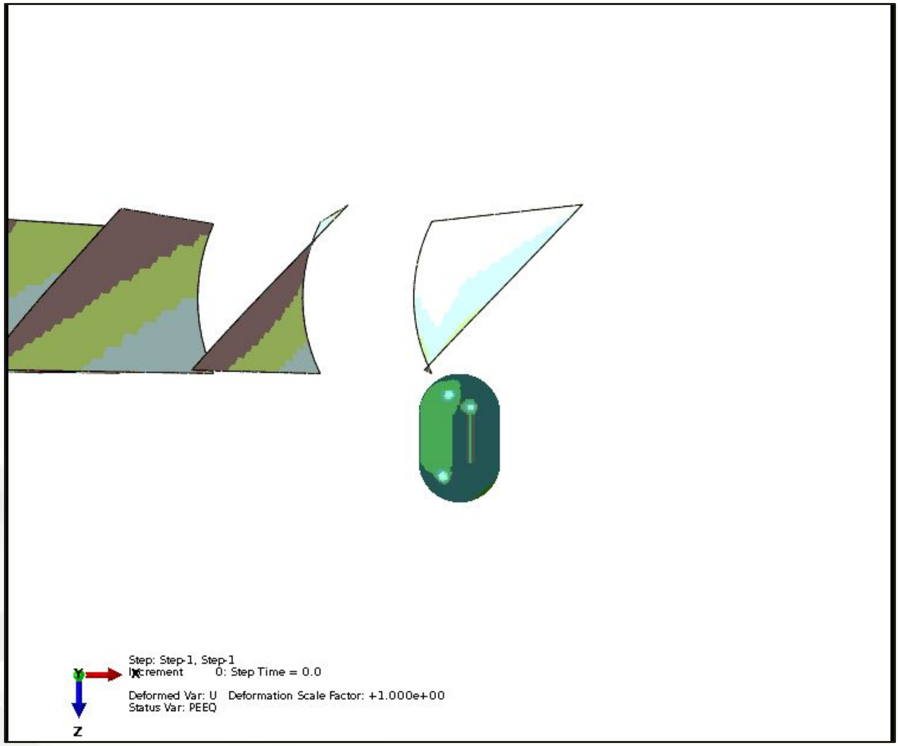


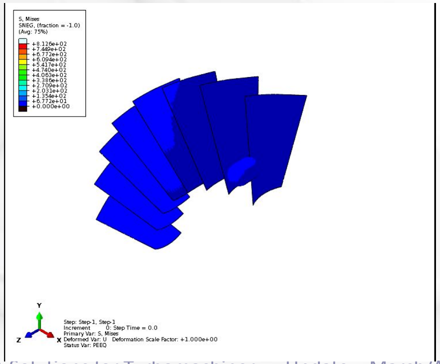
Abaqus

Foreign Object Impact Analysis

Lagrangian Approach



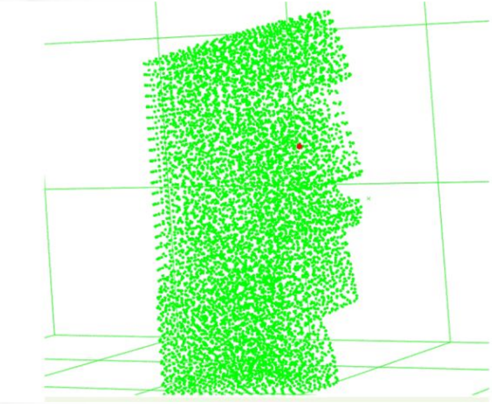




Foreign Object Impact Analysis

SPH: New Functionality in 6.11 (in-progress)

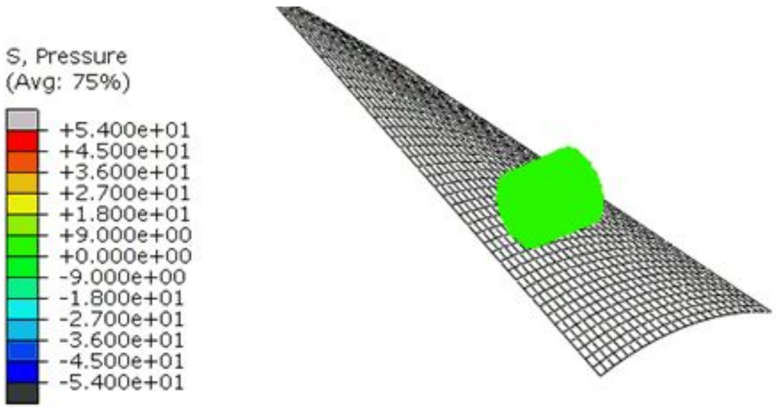
- **Fulfill modeling needs in cases where traditional methods (FEM, FDM) fail or are inefficient:**
  - Extremely violent fluid flows where CFD (mesh or grid-based) cannot cope (free surface)
    - Wave engineering
    - Shallow water flows
  - Extremely high deformations/obliteration where CEL is inefficient and Lagrangian FEM is difficult:
    - Impact fracture: ballistics, shattering, fragmentation
    - Spraying
    - Snow compaction
- **Mesh-free Lagrangian computational method**
  - It is a continuum modeling method (like FEM)

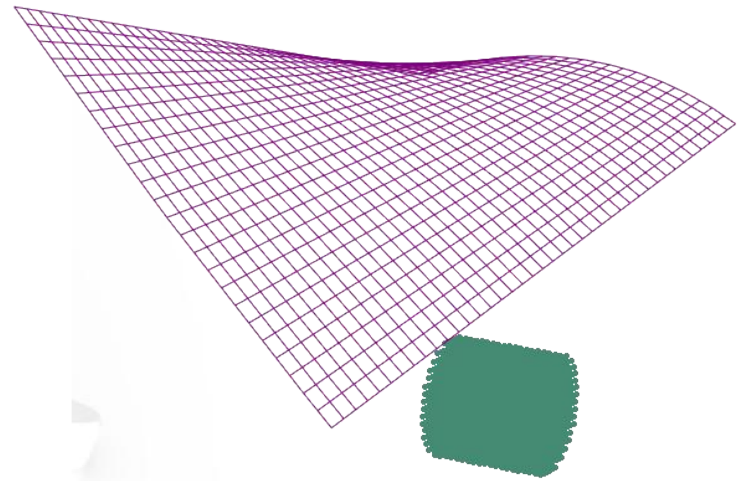


Foreign Object Impact Analysis

SPH: New Functionality in 6.11 (in-progress)

- **A cylindrical bird strikes an initially straight edge of a rotating turbofan blade**
- **The blade deforms and the bird disintegrates**
- **Contour plots of pressure shown**





- **4.2 K particles**
- **0:47 mins on a PC**
- **EOS material with tensile failure**
- **Elasto-plastic blade**

Thank you!
Any questions?

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www.simulia.com

www.3ds.com