Solidification Stress Model in Abaqus

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Objectives

- To predict the evolution of temperature, shape, stress and strain distribution in the solidifying shell in continuous casting mold by using world's leading nonlinear commercial multipurpose finite element package with an accurate approach.

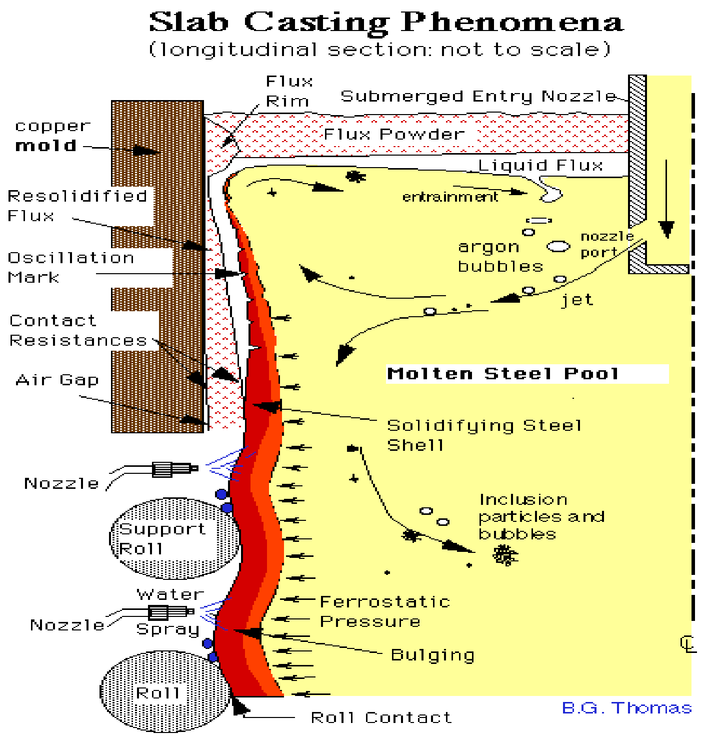
- Validate the model with available analytical solution and benchmarks with in-house code CON2D.

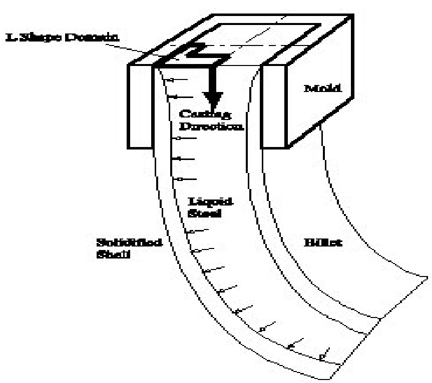
- To apply new Abaqus model to our real problems with even more complex phenomena.

Why ABAQUS ?

- If its convergence problems can be overcome, ABAQUS offers a wide range of capabilities.
- It is relatively simple to use, other modelers in this field can largely benefit from this work, including our final customers – the steel industry.
- Abaqus has imbedded pre and post processing tools supporting import of the major CAD formats. All major general purpose pre-processing packages like Patran and I-DEAS support Abaqus.
- Abaqus is using full Newton-Raphson scheme for solution of global nonlinear equilibrium equations and has a powerful contact algorithm.
- Abaqus has a rich library of 2D and 3D elements.
- Abaqus has parallel implementation on High Performance Computing Platforms which can scale wall clock time significantly for large 2D and 3D problems.
- Abaqus can link with external user subroutines (in Fortran and C) linked with the main code than can be coded to increase the functionality and the efficiency of the main Abaqus code.

Basic Phenomena



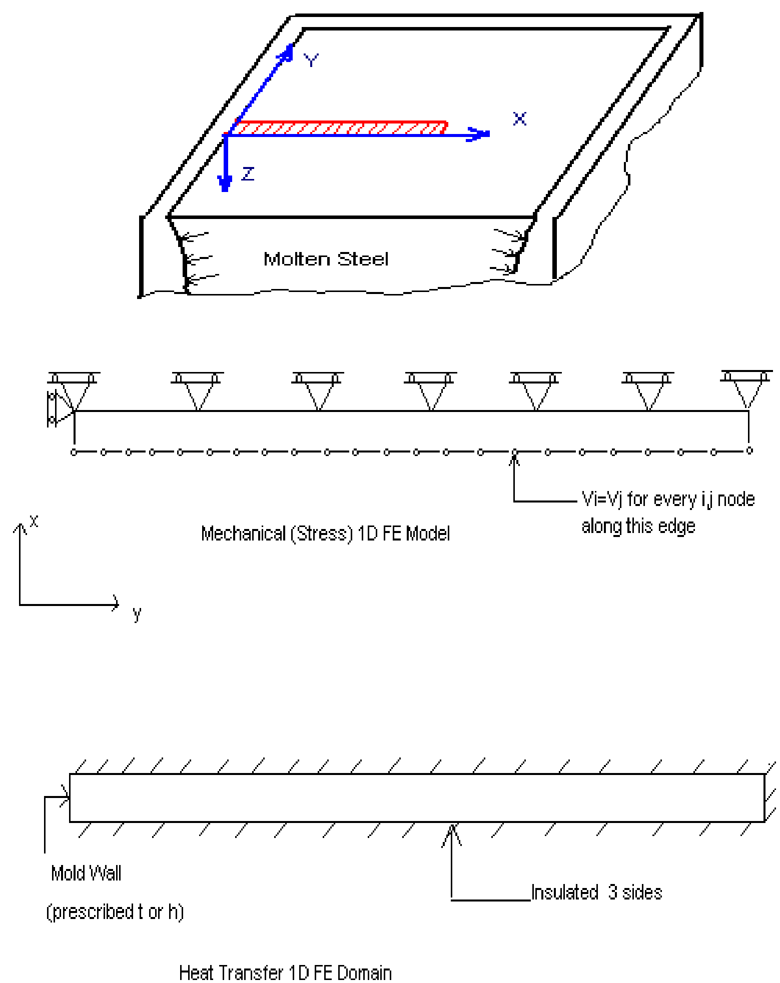


- Initial solidification occurs at the meniscus and is responsible for the surface quality of the final product.
- Thermal strains arise due to volume changes caused by temp changes and phase transformations.

  Inelastic Strains develop due to both strain-rate independent plasticity and time dependant creep.
- At inner side of the strand shell the ferrostatic pressure linearly increasing with the height is present.
- The mold taper has the task to compensate the shell shrinkage yielding good contact between strand shell and mold wall.
- Many other phenomena are present due to complex interactions between thermal and mechanical stresses and micro structural effects. Some of them are still not fully understood.

1D Solidification Stress Problem for Program Validation

- **Analytical Solution exists (Weiner & Boley 1963)**
- **1D FE Domain used for validation**
- **Generalized plane strain both in y and z direction to give 3D stress/strain state**
- **Yield stress linearly drops with temp. from 20Mpa @ 1000C to 0.07Mpa @ Solidus Temp 1494.35C**
- **Tested both internal PLASTIC Abaqus procedure and a special high-creep function to emulate Elastic-Prefect Plastic material behavior**



Governing Equations

Heat Transfer Equation:

$$\rho\left(\frac{\partial H(T)}{\partial T}\right)\left(\frac{\partial T}{\partial t}\right)=\frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k(T)\frac{\partial T}{\partial y}\right)$$

Equilibrium Equations 2D:

$$\frac{\partial \Delta\sigma_x}{\partial x}+\frac{\partial \Delta\tau_{xy}}{\partial y}=\Delta F_x$$

$$\frac{\partial \Delta\sigma_y}{\partial y}+\frac{\partial \Delta\tau_{xy}}{\partial x}=\Delta F_y$$

$$\int \Delta\sigma_z dA=\Delta F_z$$

$$\int x\Delta\sigma_z dA=\Delta M_x$$

$$\int y\Delta\sigma_z dA=\Delta M_y$$

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More Equations:

Constitutive Equations:

$$\{\Delta\sigma\} = [D]\{\Delta\varepsilon_e\} + [\Delta D]\{\varepsilon_e\}$$

where,

$$\{\sigma\} = \{\sigma_x \quad \sigma_y \quad \sigma_z \quad \tau_{xy}\}^T$$

$$\{\varepsilon\} = \{\varepsilon_x \quad \varepsilon_y \quad \varepsilon_z \quad \varepsilon_{xy}\}^T$$

$$[D] = \frac{E(T)}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & 0 & \nu \\ \nu & 1-\nu & 0 & \nu \\ 0 & 0 & \frac{1-2\nu}{2} & 0 \\ \nu & \nu & 0 & 1-\nu \end{bmatrix}$$

Generalized Plane Strain

$$\Delta\varepsilon_x = \frac{\partial \Delta u_x}{\partial x}$$

$$\Delta\varepsilon_y = \frac{\partial \Delta u_y}{\partial y}$$

$$\Delta\varepsilon_{xy} = \frac{1}{2}\left(\frac{\partial \Delta u_y}{\partial x} + \frac{\partial \Delta u_x}{\partial y}\right)$$

$$\Delta\varepsilon_z = a + bx + cy$$

Finite Elements Implementations

$$[K]\{T\} + [C]\{\dot{T}\} = \{Q\}$$

$$[K]\{\Delta u\} = \{\Delta F_{\varepsilon_{th}}\} + \{\Delta F_{\varepsilon_{pl}}\} + \{F_{fp}\} + \{F_{el}\}$$

Incremental Total Strain

$$\{\Delta\varepsilon\} = \{\Delta\varepsilon_e\} + \{\Delta\varepsilon_{th}\} + \{\Delta\varepsilon_{pl}\}$$

Constants Used in Abaqus Numerical Solution of B&W Analytical Test Problem

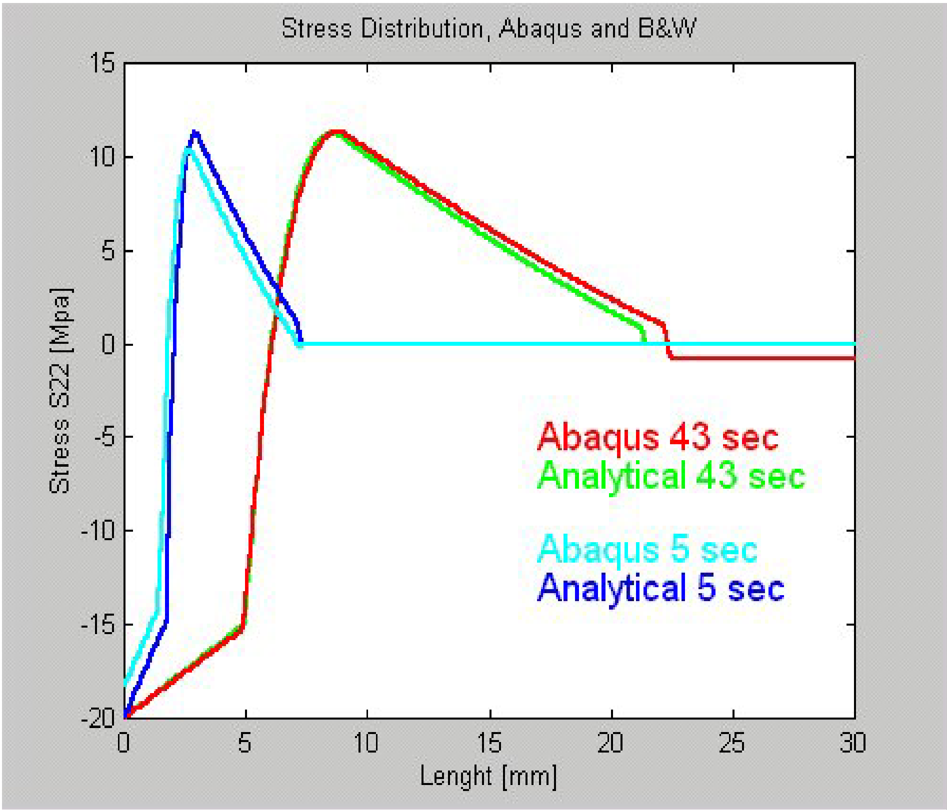
Conductivity	[W/mK]	33.
Specific Heat	[J/kg/K]	661.
Elastic Modulus in Solid	[Gpa]	40.
Elastic Modulus in Liq.	[Gpa]	14.
Thermal Linear Exp.	[1/k]	2.E-4
Density	[kg/m^3]	7500.
Poisson's Ratio	0.3	
Liquidus Temp	[^{O} C]	1494.48
Solidus Temp	[^{O} C]	1494.38
Initial Temp	[^{O} C]	1495.
Latent Heat	[J/kgK]	272000.
Number of Elements		300.
Uniform Element Length [mm]		0.1

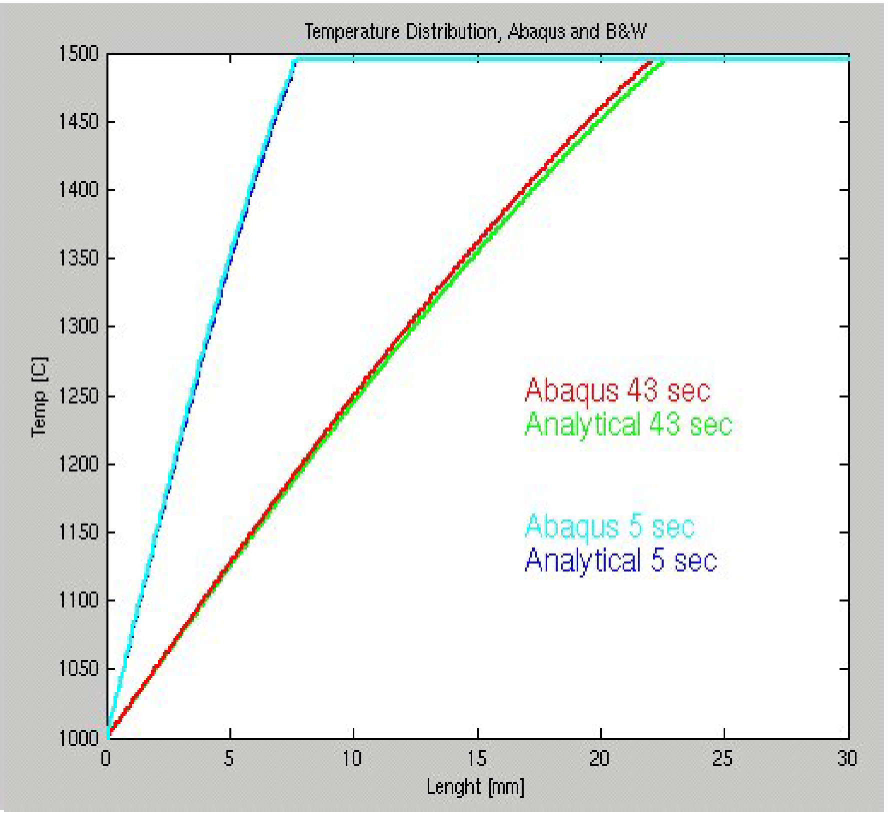
Artificial and non-physical thermal BC from B&W (slab surface quenched to 1000C), replaced by a convective BC with h=220000 [W/m^{2}K]

Simple calculation to get h, from surface energy balance at initial instant of time:

$$-k\frac{\partial T}{\partial x} = h(T - T_{\infty})$$ and for finite values $$33\frac{495}{0.0001} = h\,495$$

Temperature and Stress Distributions for 1D Solidification
Abaqus and Analytical (Weiner-Boley)Solutions



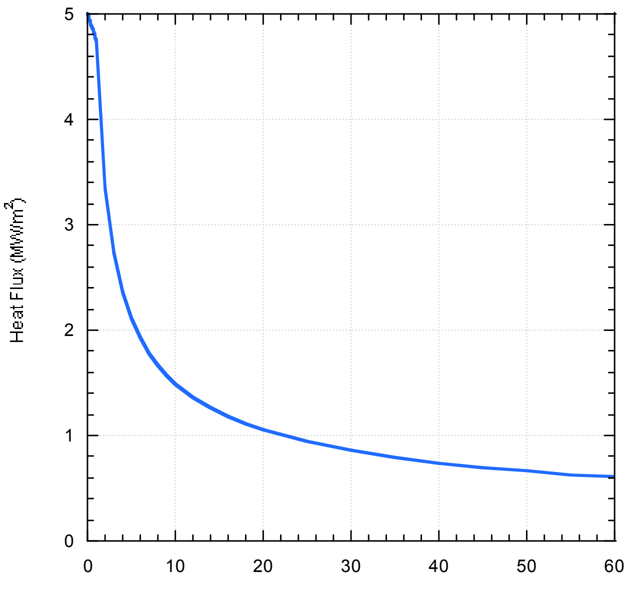


- **The numerical representations from MATLAB and Abaqus produces almost identical results**
- **Model is numerically consistent and has acceptable mesh**

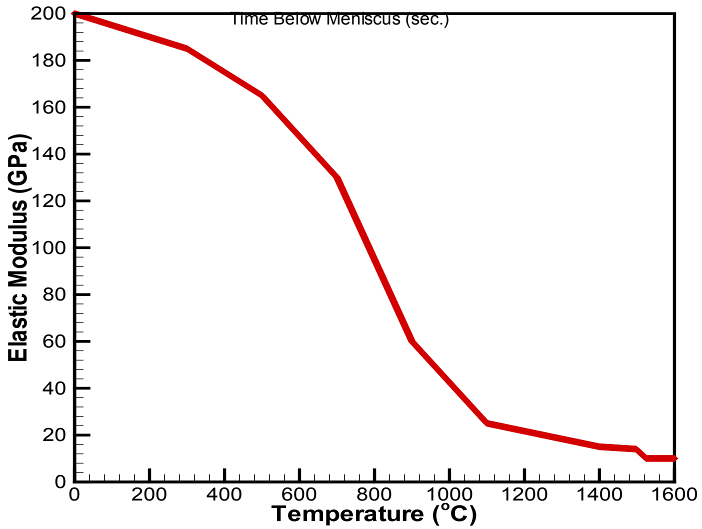
Add more complexity (physics) to the Abaqus model by means of user subroutines

Applied instantaneous Heat Flux from a real plant measurements:

$$q\left(MW/m^3\right)=\begin{cases}5-0.2444t\left(\text{sec.}\right) & t\leq 1.0\,\text{sec.}\\ 4.7556t\left(\text{sec.}\right)^{-0.504} & t>1.0\,\text{sec.}\end{cases}$$



Elastic modulus decreases as temperature increase:



The only difference between solid and liquid is a large creep rate in the liquid

$$\dot{\varepsilon} = \begin{cases} \mathbf{10} \quad (|\sigma| - \sigma_{yield}) & \textbf{\textit{if}} \quad |\sigma| > \sigma_{yield} \\ \mathbf{0} & \textbf{\textit{if}} \quad |\sigma| \le \sigma_{yield} \end{cases}$$

(this is still a "milder" version of the liquid creep function used in CON2D)

Elastic visco-plastic model of Kozlowski for solidifying plain-carbon steel as our constitutive model:

$$\dot{\varepsilon}(1/\sec.) = f(\%C)\left[\sigma(MPa) - f_1\left(T\left({}^oK\right)\right)\varepsilon\left|\varepsilon\right|^{f_2\left(T\left({}^oK\right)\right)-1}\right]^{f_3\left(T\left({}^oK\right)\right)} \exp\left(-\frac{4.465\times10^4\left({}^oK\right)}{T\left({}^oK\right)}\right)$$

where

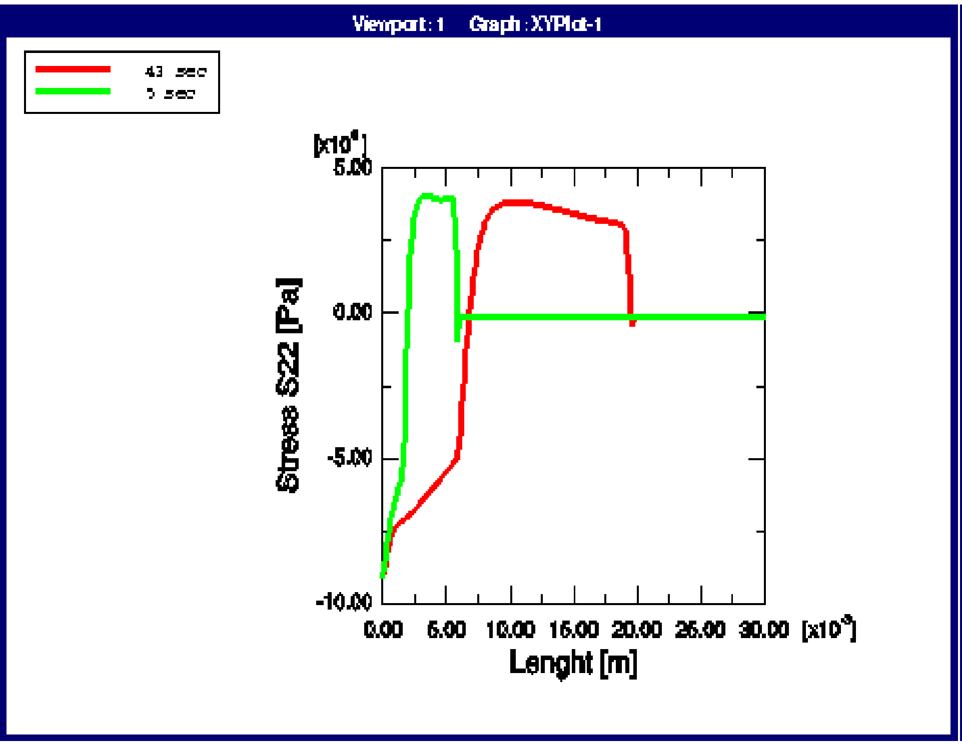
$$f_1\left(T\left({}^oK\right)\right) = 130.5 - 5.128\times10^{-3}\,T\left({}^oK\right)$$

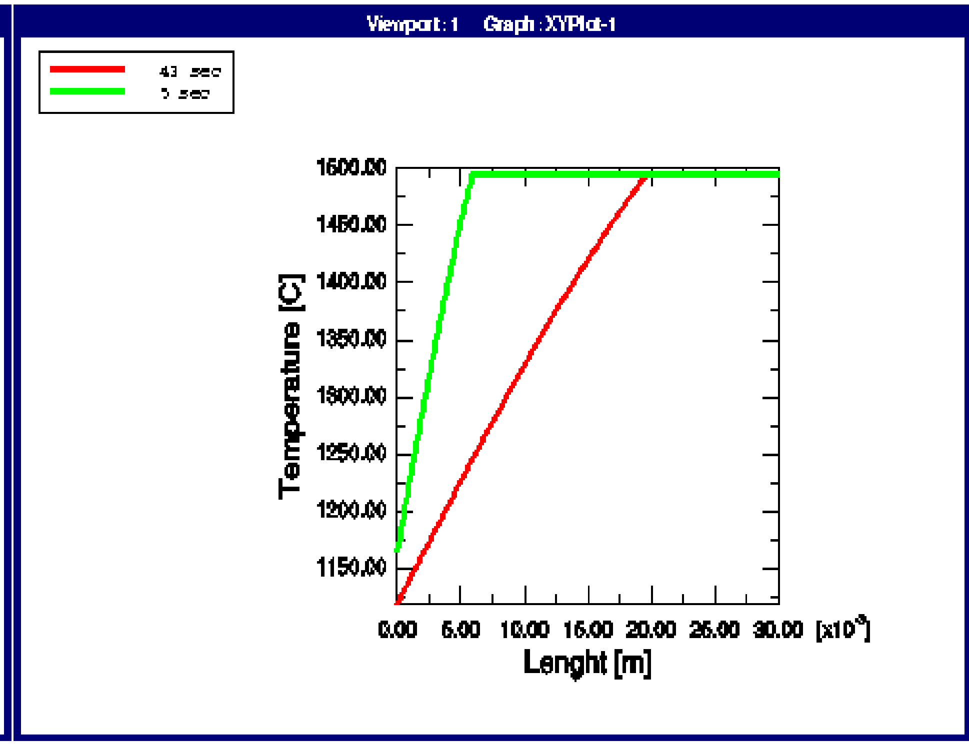
$$f_2\left(T\left({}^oK\right)\right) = -0.6289 + 1.114\times10^{-3}\,T\left({}^oK\right)$$

$$f_3\left(T\left({}^oK\right)\right) = 8.132 - 1.54\times10^{-3}\,T\left({}^oK\right)$$

$$f(\%C) = 4.655\times10^4 + 7.14\times10^4\%C + 1.2\times10^5\left(\%C\right)^2$$

Temperature and Stress Distribution
Elastic-visco-plastic model by Kozlowski

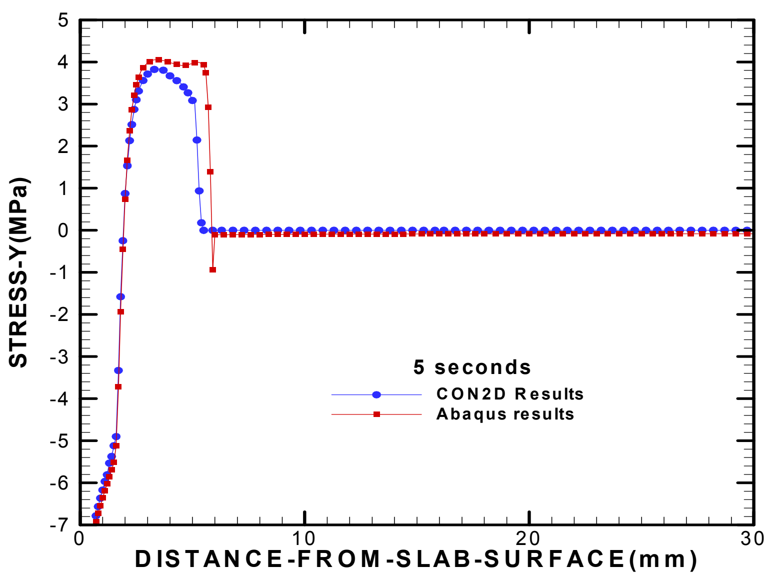


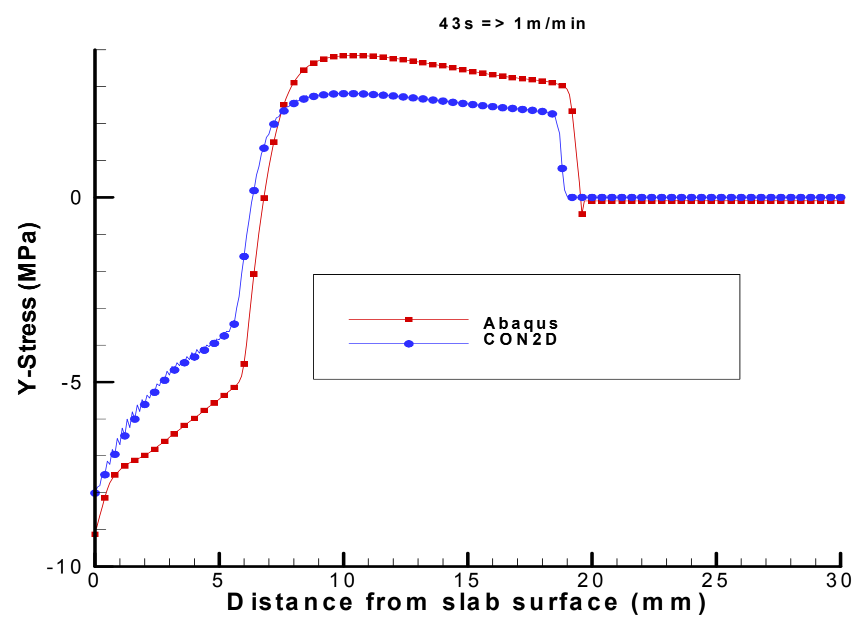


- **Different residual stress values due to different creep rate function**
- **Lower temperatures due to real flux data**

Comparison of Abaqus and CON2D for previous complex model

	CON2D	ABAQUS/Native Explicit
Element type	6 node triangular	4 node rectangular
Number of elements	400	300
Number of nodes	1803	603
Initial time step	1.E-4	1.E-11
RAM used	350Mb	450Mb
Wall clock on IBMp690	**5 minutes**	**5760 minutes (96 hours)**





Conclusions (Past Work):

- Nowadays, It is possible to perform numerical simulations of steel solidification process in the Continuous Casting Mold with multipurpose commercial finite element code-Abaqus.
- ~1000 x more CPU resources are needed with Abaqus explicit creep integration compared to in-house code CON2D for identical problem due to superior CON2D robust integration scheme
- Main culprit for Abaqus slow performance is the integration of the in creep functions.
- Abaqus native implicit creep integration has failed completely for this class of problems.
- Quantitatively results are matching well, qualitative differences are under investigation.

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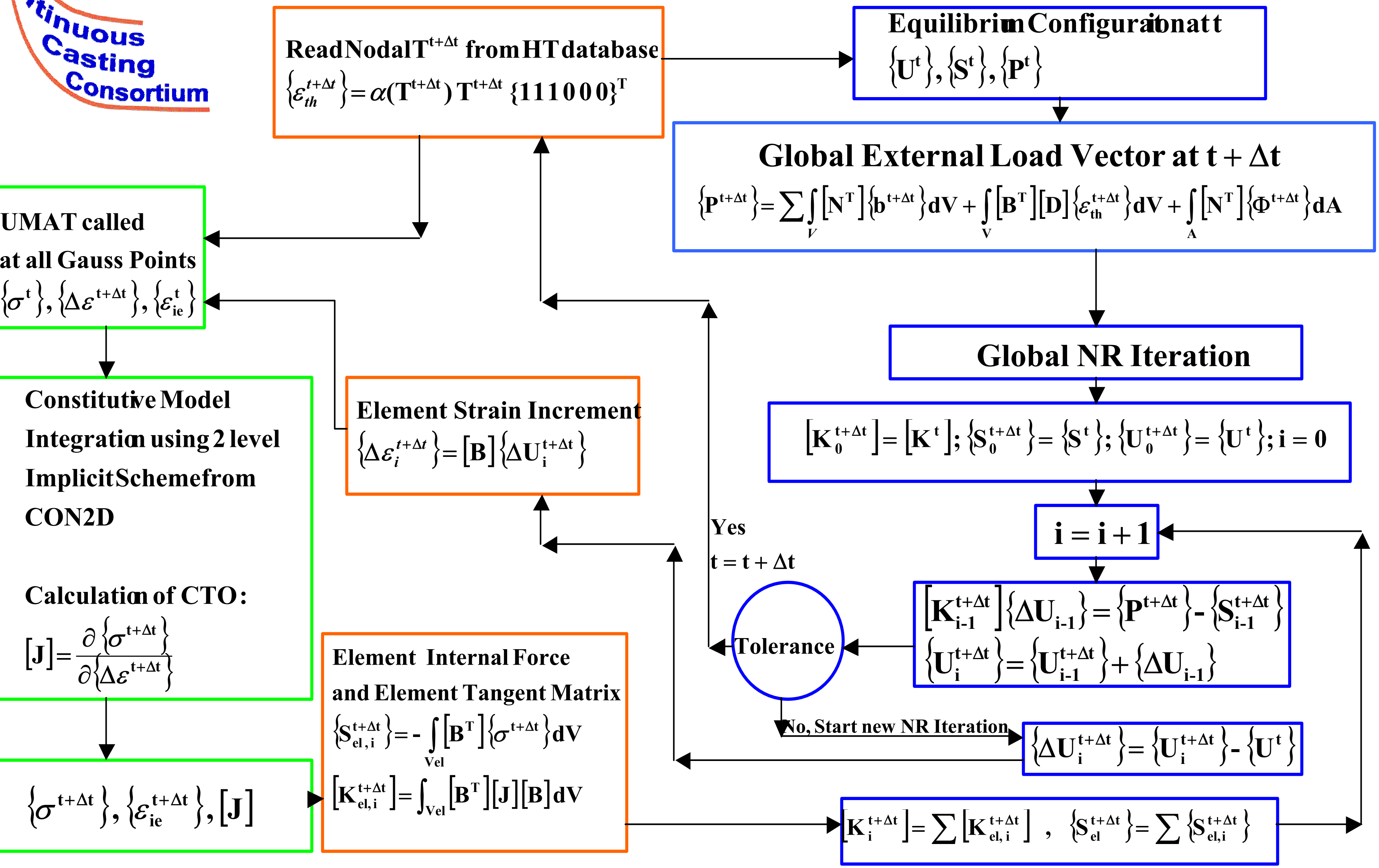
Solutions to Abaqus Slow Performance

- **Solution1: Apply Kozlowski III model everywhere (liquid and solid) through the CREEP subroutine with its explicit integration, and apply Abaqus native perfect plasticity for liquid. Currently Abaqus Plasticity works only coupled with implicit creep integration. This issue has been addressed to HKS developers.**

- **Solution 2: Replace Abaqus native local integration model with fully implict local integration from CON2D followed by its robust two level bounded NR integration scheme coded in another user defined subroutine UMAT. This work is currently under way. HKS has showed interest in our UMAT work.**

- **Solution 2 is the focus of our current work !**

Materially Non-Linear FEM Solution Strategy in Abaqus with UMAT

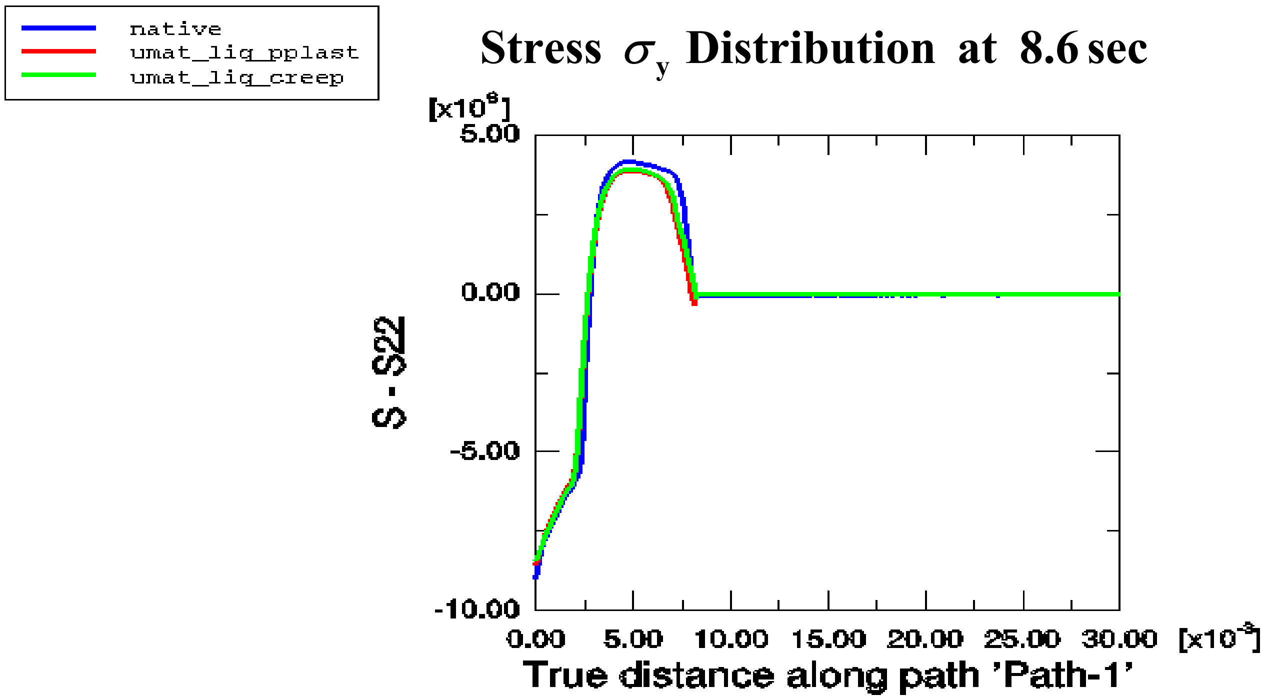


Early Results with UMAT

- Wall clock while keeping liquid creep function is ~25min,
  230x Improvement compared with Abaqus Native Explicit Integration, but still 5x slower then CON2D.

- Elastic-Perfectly Plastic constitutive law with very low Yield Stress coded for liquid phase replacing aggressive creep function and avoiding its integration. This implementation is actually faster then CON2D, 4min for this problem size and more then 1000x faster then Abaqus native explicit creep integration.

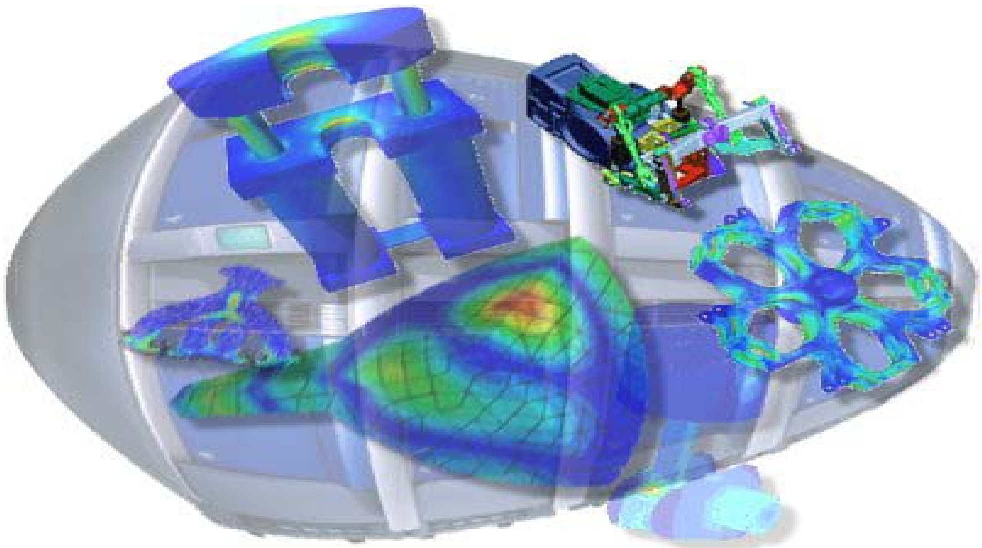
- Almost identical results for Stress Distribution for both cases with UMAT and Native Explicit Creep Integration



Future Work

- More work on validation of results and comparison with CON2D.
- Add constitutive model for steels with delta-ferrite and temp dependant thermal linear expansion.
- Move to 2D and perhaps 3D FE domains with Abaqus to increase process understanding.
- Derive and add Consistent Tangent Operator for temperature to UMAT and fully couple HT and Stress analysis.
- Add more Complexity (Physics) to the model: Internal BC with Ferrostatic Pressure, contact and friction between mold and shell, input mold distortion data, effects of superheat…
- If there are enough dofs (3D), parallel Abaqus features can be applied (each time increment solved in parallel).

New Engineering Computational Resources at the National Center For Supercomputing Applications at the University Of Illinois



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NCSA Terascale Linux Clusters

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•Intel Xeon Linux Cluster of Parallel PC-s

(currently #4 with 6.12 Tflops on the top 500 list of supercomputers)

- 1280 3.06 GHz dual processor nodes
- Myrinet 2000 interconnect between PC-s
- 3GB /node of RAM

•Intel Itanium2 Linux Cluster of Parallel Itanium PC-s

- 256 1.3Ghz dual processor nodes
- Myrinet 2000 interconnect beween PC-s
- 4 and 12 GB/node of RAM

•Can solve a million equations with million unknowns in less then a minute by performing 350×10^9 floating point operation per second

NCSA machine room expansion

– capacity to 20 TF and expandable

– dedicated September 5, 2001

•Great Potential to solve large scale problems in computational fluid dynamics and computational solid mechanics

Shared Memory NCSA Capabilities:

- Shared memory systems IBM Regatta, Power 4
  - 2+ TF of clustered SMP
  - 32 SMP CPUS, 1.3 Ghz
  - large, 256 GB memory
  - AIX IBM Unix OS

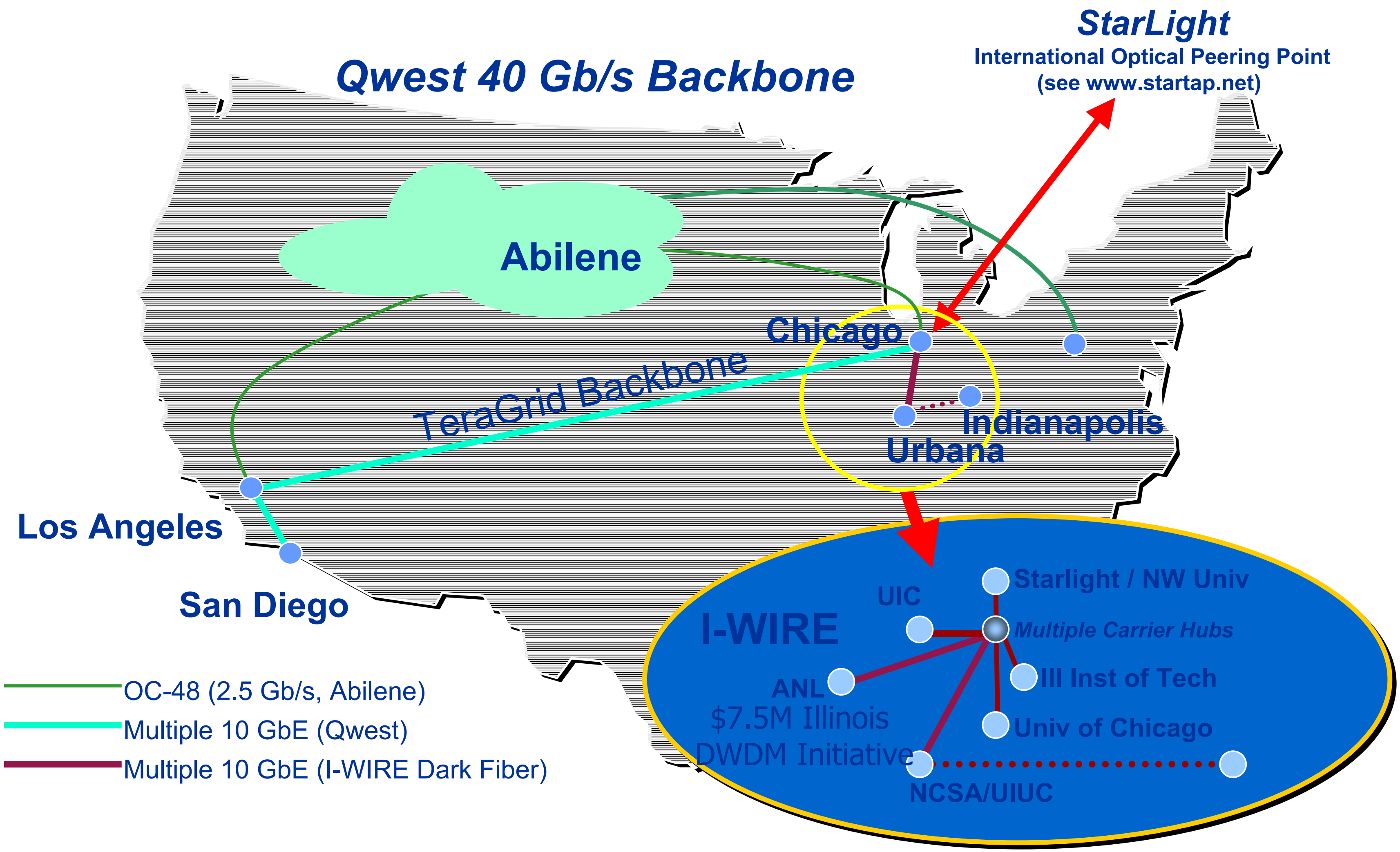
  Perfect for engineering commercial software like:

  Abaqus, Ansys, Fluent, LS-Dyna, Marc, PRO/E..

- Further SMP Expansions coming this year with newest SMP platform(s)
- Secondary and tertiary storage
  - 500 TB secondary storage SAN
  - 3.4 PB tertiary storage

Computing in 21St Century, a story of TeraGrid

Computing Resources: Anytime, Anywhere



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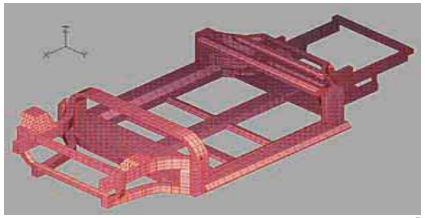
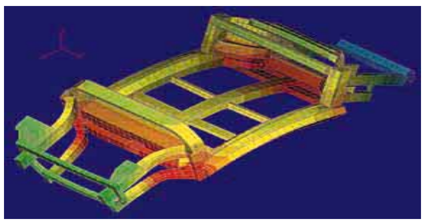
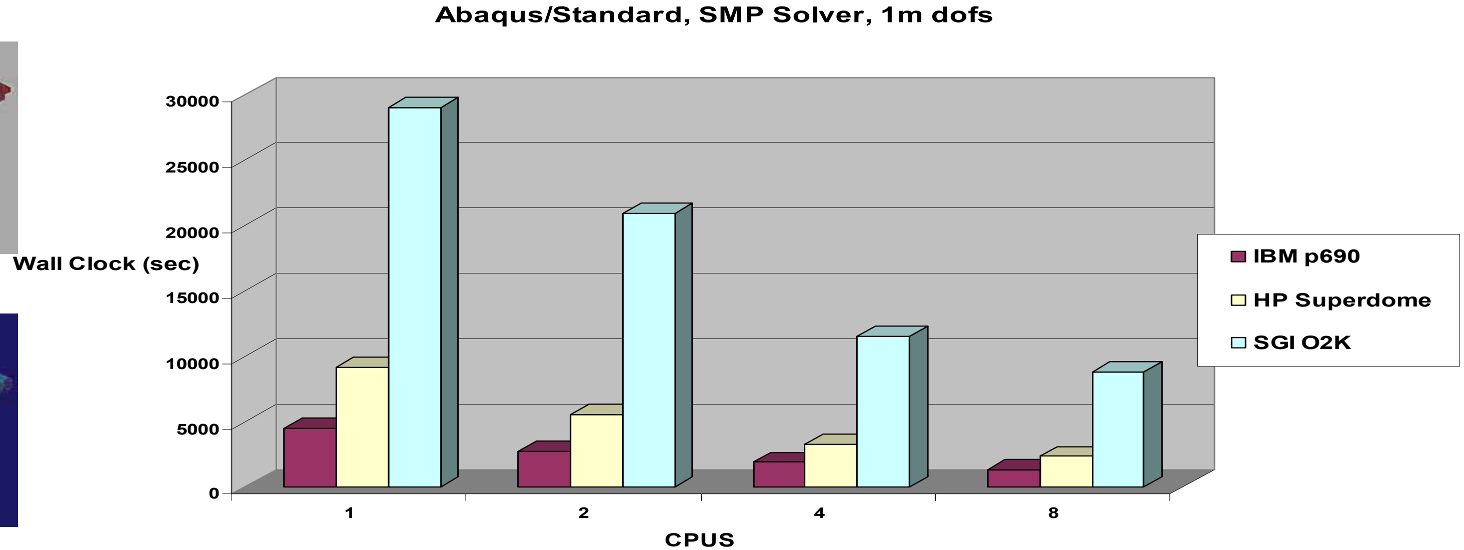
Some CSM and CFD Applications on NCSA machines

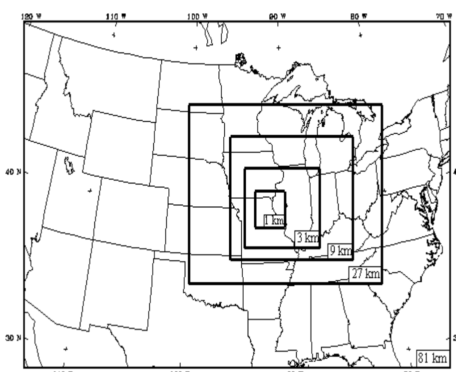


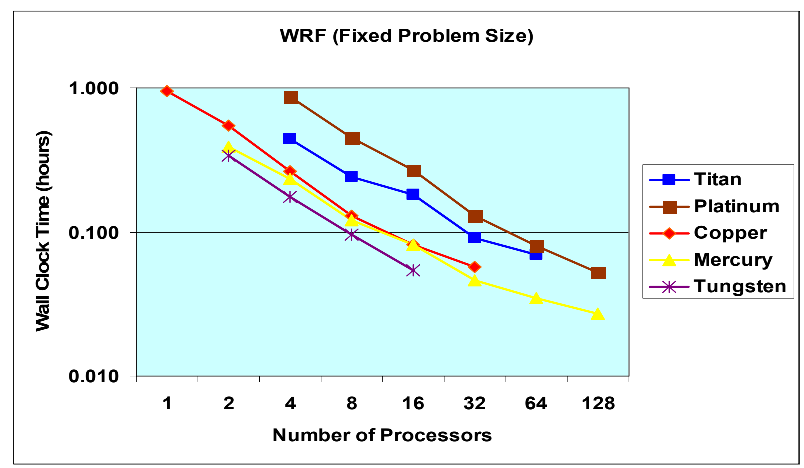




Reference: Bob Wilhelmson (NCSA)

Severe Weather Forecast





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