QUALITY CONTROL PROCEDURES

JOHN GOLDAK, PRESIDENT
GOLDAK TECHNOLOGIES INC.
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1. **Introduction**

1.1. **Background on Computational Weld Mechanics (CWM).** Arc welding is a complex manufacturing process in which an electric arc generates heat in an area approximately one cm$^2$ while travelling at speeds of approximately 1 to 5 mm/s to form a pool of liquid metal with volume usually slightly less the 1 cm$^3$. As the liquid metal on the trailing edge of the weld pool solidifies, a weld joint or weld overlay is created. The transient temperature field drives metallurgical phase changes, thermal expansion-contraction and changes temperature dependent properties of the materials. The microstructure evolves as it is heated and cooled with phase changes, annealing, recrystallization and grain growth. The strain due to thermal expansion-contraction, phase changes and restraint of the structure and fixtures generates stress and plastic deformation. The plastic deformation leads to residual stress and deformation.
During the welding process, various defects such cracks can occur. Because cracks are usually a function of the stress-strain history, to assess the risk of cracking, it is important for design engineers to have reliable estimates of the transient stress and strain fields in the neighbourhood of each weld joint in the repair operation. In addition, the residual stress from welds can play a role in a fracture mechanics analysis of the risk of cracking due to in-service loads.

The physics and mechanics of welding can be separated into the physics of the arc and weld pool on the one hand and the physics of the solid surrounding the weld pool on the other hand. The physics of the arc and weld pool primarily involve magneto-hydrodynamics and fluid flow with length scales less than 1 mm and time scales less than 0.1 second. The physics of the solid surrounding the weld pool primarily involve solid mechanics with length scales greater than 1 mm and time scales greater than 1 second. The coupling between the physics and mechanics of the weld pool and the physics and mechanics of the solid is almost entirely though the transient temperature field in the solid.

There are various parametric models to compute the heating effect of the arc and weld pool. Since 1984, the most popular model in CWM has been a power density distribution function with net weld power and the weld pool shape, size and position as a function of time [1]. The development of this model was led by John Goldak. The weld pool shape and size parameters are usually estimated from macro-graphs of cross-sections of the weld joint.

A computer model to predict the behaviour of this complex process can save time, money and explore what if scenario’s that are difficult, expensive and time consuming to assess by experiment. The arguably best computer models of the welding process, solve the conservation of energy, mass and momentum, i.e., three coupled partial differential equations, with realistic 3D geometry of the structure and the welding process and the most realistic constitutive equations and weld process models available. Because the welding process is transient, non-linear and usually involves complex geometry, the best model are based on
3D transient non-linear Finite Element Analysis (FEM). Because such models require complex numerical algorithms and sophisticated software, the first models did not emerge until the 1980s. Reference [2] is good reference on the state of the art of CWM as it emerged in 1985. References [3] and [4] discuss progress in CWM in 1995 and 2008 respectively. Professor John Goldak’s research in computational weld mechanics that has contributed to the development of CWM has been funded by the National Research Council of Canada since 1972. VrWeld is largely based on his research.

2. Background on Professor John Goldak

Internationally John Goldak is best known for his research in computational mechanics of welds. In particular for the development of a heat source model for arc welds that is widely known as the Double Ellipsoid Weld Pool Model. In 2011, The Welding Science and Engineering Conference created the ‘The Pioneers of Computational Weld Mechanics’ award to honor the contributions of Professor Yukio Ueda, Japan and John Goldak to the development of computational weld mechanics. In 2014 he was awarded the American Welding Society Comfort A. Adams award and the Canadian Welding Association (CWA) Fellowship Award that honors one individual each year with exemplary reputation and service to advancements of welding sciences, technology application, research, education, publication of papers, books, Journal articles and peer recognition. In 2017, CWA gave him the Michael Vuchnich Award for the person who has done the most to advance the science, technology and application of arc welding in Canada in their Career. He is a member of the Canadian Academy of Engineering. He is Founder and President of Goldak Technologies Inc. (GTI), (http://goldak-vrweld.com/about_vrweld.html), a company dedicated to developing software for design-driven analysis and optimization of welds and welded structures. GTI was awarded the John S. Hewitt Team Achievement Award by the Canadian Nuclear Society in 2011 as a major player for its computational weld mechanics analysis that
contribute to the successful repair of AECLs NRU reactor in 2009. GTI customers include leading multinationals in the agricultural machinery industry, the Canadian Navy on computational mechanics for weld repair of submarines and leading organizations in the nuclear power industry.

3. **VrWeld**

VrWeld is part of a software framework called VrSuite that has been developed Goldak Technologies Inc. All of the software in VrSuite has been developed by GTI. All of the analyses reported in references [3], [4] [5] [6] [7] and [8] were done exclusively with VrWeld or other packages in VrSuite. It contains complete coupled nonlinear FEM analysis software for thermal, microstructure and stress analysis. It also includes a powerful package for design optimization and statistical analysis. VrWeld has a rich infrastructure for welding including support for welding procedures and weld joints. VrWeld has excellent microstructure evolution in the HAZ and FZ for low-alloy steels. VrHeatTreat has a rich infrastructure for heat treating steels including carburization of parts such as gears. A brief overview of inputs-outputs, the main equations solved and Verification & Validation are given below. More detail can be provided on request.

3.1. **VrWeld Inputs and Outputs.** The input data to VrWeld are:

1. The 3D geometry of the structure being welded can be provided as Stereolithographic (STL) files or neutral IGES or STEP files generated from CAD files. The position of each weld pass, its starting point, arc speed and ending point is required information. Macro-graphs of the cross-sections of each weld pass that define the geometry of the weld pool and filler metal added can be measured in flat coupon test plate. GTI then transforms this geometric data into an FEM mesh of the full welded structure with weld joints and filler metal added in each weld pass. The sequence of welds and fixtures or clamps is defined by the user.
The 3D geometry of the original design of the NRU Reactor vessel was provided by AECL as Stereolithographic (STL) files. In addition, AECL provided wall thickness data measured by ultrasonics. The geometry of a flat and a curved coupon test was provide by AECL. The geometry of patch plates used in the weld repair of the thinnest areas of the wall was provided by AECL. The position of each weld pass, its starting point, arc speed and ending point was provided by AECL. Macro-graphs of the cross-sections of each weld pass in the flat coupon test plate that define the geometry of the weld pool and filler metal added were provided by AECL. GTI transformed this geometric data into an FEM mesh of the full vessel including the base ring that has a seal and the detailed geometry of each overlay weld block.

(2) Temperature dependent thermal and mechanical material properties are required for base metals and filler metals. Temperature dependent thermal and mechanical material properties were provided for the Aluminum 5052 irradiated base metal and the Aluminum 4047 filler metal. For the Aluminum 5052 irradiated base metal median, upper bound and lower bound estimates of the temperature yield stress stress was provided.

(3) The weld process parameters including weld current, weld voltage, weld speed, filler metal wire size and speed were provided. The start time of each weld pass was computed based on the start time of the first weld pass, the time to weld each weld pass based on the length of the weld pass and the weld speed and a delay time between the end of one weld pass and the start of the next weld pass.

(4) The delay time between completing each weld pass and starting the next weld pass and time to allow the structure to cool to room temperature is important information. VrWeld can compute the delay times as a function of the maximum interpass temperature.

The output data from VrWeld include the following 3D global fields:
(1) Transient temperature field.
(2) Transient displacement field.
(3) Transient stress tensor field and principal stress fields.
(4) Transient elastic, thermal, plastic and total strain tensor or vector field.

VrWeld has a rich environment for visualizing this data as images and as plots and generating reports for a VrWeld analysis.

3.2. What Equations Does VrWeld Solve?

3.2.1. Conservation of Energy or Heat Equation. With specific enthalpy $h$, thermal flux $q$ and a power density function $Q$, temperature $T$, temperature gradient $\nabla T$, thermal conductivity tensor $\kappa$ specific heat $c_p$, the heat equation can be be written in the following form:

$$\dot{h} + \nabla \cdot q + Q = 0$$

$$q = \kappa \nabla T$$

$$dh = c_p dT.$$ 

VrWeld solves this partial differential equation on a domain defined by an FEM mesh. The domain is dynamic in that it changes with each time step as filler metal is added to the weld pass. The initial condition is assumed to be a constant temperature of 300 K. The material properties $\kappa$ and $c_p$ are usually temperature dependent. If microstructure is computed, then such as $\kappa$ and $c_p$ dependent on the microstructure phase..

The heating affect of the arc is modelled by a double ellipsoid power density distribution that approximates the weld pool as measured from macro-graphs of the cross-section of several weld passes. A convection boundary condition $q = h(T - T_{amb})$ is applied to external surfaces. The FEM formulation of the heat equation leads to a set of ordinary differential equations that integrated in time using a backward Euler integration scheme. Thermal contact between parts can modelled with
thermal contact elements to compute the jump in temperature across a contact interface.

3.2.2. Conservation of Momentum Equation. Given the density, $\rho$, the elasticity tensor as a $6 \times 6$ matrix, the body force $b$, the Green-Lagrange strain $\varepsilon$, VrWeld solves the conservation of momentum equation that can be written in the following form in which inertial forces, $\rho \ddot{x}$ are ignored.

$$\nabla \cdot \sigma + b = 0$$

$$\sigma = D\varepsilon$$

$$\varepsilon = (\nabla u + (\nabla u)^T + (\nabla u)^T\nabla u)/2$$

VrWeld solves this partial differential equation for a visco-thermo-elasto-plastic stress-strain relationship using theory and algorithms developed by J.C. Simo and his colleagues [10]. The initial state is assumed to be stress free. However, if the initial stress state is known, it can be initialized in VrWeld. The Dirichlet boundary conditions constrain the rigid body modes. The system is solved using a time marching scheme with time step lengths of approximately 1 second during welding and usually an exponentially increasing time step length when welding stops and the structure cools toward ambient temperature.

3.3. Guidelines for verification and validation for use in the NRU Repair. The Preface of the ASME standard [11] states: This document provides general guidelines for implement V&V of computational models for complex systems in solid mechanics. The guidance is based on the following key principles:

1. Verification (addressing programming errors and estimating the numerical errors) must precede validation (assessing a model’s predictive capability by comparing calculations with experiment).
2. The need for validation and the associated accuracy requirements for computational model predictions are based on the intended...
use of the model and should be established as part of the V&V activities.

(3) Validation of a complex system should be pursued in a hierarchical fashion from the component to the system level.

(4) Validation is specific to a particular computational model for a particular intended use.

(5) Simulation results and experimental data must have an assessment of uncertainty to be meaningful.

Although the state of the art of V&V does not yet lend itself to writing a step-by-step performance code/standard, this guide provides the computational solid mechanics (CSM) community with a common language and conceptual framework to enable managers and practitioners of V&V to better assess and enhance the credibility of CSM models. Implementation of a range of V&V activities is discussed, including model development for complex systems, verification of numerical solutions for governing equations, attributes of validation experiments, accuracy requirements, and quantification of uncertainties. Remaining issues for further development of a V&V protocol are identified.

An overview of the process of verification and validation is shown in Fig. 1.

3.4. Verification of VrWeld for use in the NRU Repair. Verification of VrWeld software is done by comparing results computed by VrWeld with relevant mathematical problems for which the exact solution is known. (Occasionally when mathematical problems with exact known solutions are not available, numerical solutions that are considered to be highly accurate are sometimes used.) This is done for all mathematical equations in VrWeld. Goldak Technologies Inc. (GTI) does verification by creating Test Suites that are collections of problems for which the exact solution is known for a particular solver such as the solver for the transient heat equation or the solver for transient visco-elastic-plastic stress analysis. These Test Suites are run automatically and the sum of squares error in the solution of each
test problem in the Test Suites is contained in a report. This report is generated automatically and sent by email to all software developers at GTI. These Test Suites of verification problems are run routinely
to ensure that bugs have not been introduced into VrWeld during the software development process. Appendices D and E have examples of these reports for transient visco-elastic-plastic stress analysis and for transient thermal analysis.

3.5. Validation of VrWeld for use in the NRU Repair. Excellent examples of validation are given in the references [3,4,5,7,8]. In [5] two examples are an overlay weld analysis with 27 weld passes in two layers covering a 100x100 mm block in a 400x400 mm square plate 30 mm thick and an overlay weld analysis with 51 weld passes two layers covering a 100x100 mm block in a 400x400 mm square plate 30 mm thick. The experimental data was gathered from 6 thermocouples and 22 strain gauges. In addition, distortion was measured by a coordinate measuring machine and compared to computed distortion or displacement. The agreement between measured and computed data values was considered to be remarkably good. In [6], the transient displacement field was measured with a high precision stereo camera and compared with the transient displacement computed with VrWeld. Again the agreement was considered to be exceptionally good. In [2] the residual stress measured by neutron diffraction and x-ray synchrotron diffraction was compared with the residual stress computed with VrWeld. Again the agreement was considered good.

How large sets of experimental data for a weld provided by recent developments in sensor technology and data acquisition systems such as distributed fibre optic temperature and strain sensing optical fibre, in addition to full field and transient data such as thermographic and Digital Image Correlation (DIC) cameras can be correlated with predictions from VrWeld are discussed [13].

In all of these validation tests except [6], only one experiment has been done. As discussed in [3, 7], it is desirable to conduct multiple experiments and use statistics to assess the accuracy statistics of the experiments. In the one case [6], where repeat experiments were available, the errors in the experiment were of the same order of magnitude
as changes induced in the values computed by VrWeld by reasonable changes in the input parameters, e.g., 10% changes in weld power or weld speed.

The inputs to VrWeld are the geometry of the domain or structure, the temperature and microstructure dependent thermal and mechanical material properties, the initial conditions and boundary conditions. In Computational Weld Mechanics (CWM) the geometry of the filler metal added and the weld pool are important. The sensitivity of the computed solutions to errors in these inputs can be computed by solving the problem with variations in the inputs. For example, for the overlay weld repair of the NRU reactor, this has been done for median, upper bound and lower bound estimates of the temperature dependent yield stress of Al-5052 irradiated. It can be done for any input parameter.

The analyses have all assumed the initial state of the structure being welded had zero initial stress and the geometry was the exact geometry of the original design except for wall thinning due to corrosion. If estimates of the initial state or deviations from the original geometry were available, then ‘what if analyses could be run to estimate their effect.

In addition to errors in the inputs, truncation errors can arise because the mesh size or spatial discretization is finite and the time step size is finite. These errors can be estimated by running analyses with a finer mesh or shorter time steps. The analyses have been done with linear FEM elements. The analyses could be run with either a finer mesh or with a mesh with higher order elements such as quadratic brick elements to obtain an estimate of the truncation error due to finite size of elements. Errors can also be bounded by using duality, e.g., the Prager-Synge Hyper-circle theorem. It can also be useful to form a sub-project on a small sub-domain that has an above average error norm. Then mesh the sub-domain with a finer mesh and solve this small sub-domain with time dependent boundary conditions obtained from a previous solve with a coarser mesh and possibly coarser time
steps. If the sub-domain is smaller than the global domain, it is usually feasible to solve it with a much finer mesh and possibly much shorter time steps than the larger global domain.

4. Flat Coupon Weld Validation Test

A Flat Coupon Weld Test can be used to validate an overlay welding procedure. An example is shown in Fig. 2. It can also be used as a lower cost test for multi-pass welds in thicker plates. In [8] an Al-6061-T6 base plate was chosen as the available material with the closest properties to the Al-5052-irradiated material in the NRU vessel wall. The thickness was 12.5 mm which is slightly thicker than the 8 mm wall thickness of the NRU vessel wall. The four weld passes were designed to allow macro-graphs of the cross-section of each weld pass before it was covered with the next weld pass. From these macro-graphs the double ellipsoid parameters, see Fig. 3, can be estimated to specify the distribution of heat in the weld pool for the transient thermal analysis of each weld pass. Results of the analysis of this test with VrWeld can be found in [8] [9].

The Flat Coupon Weld Test used the welding procedure to be used in the NRU weld repair [8]. The base plate was Al-5052-32 was chosen as the available material with the closest properties to the Al-5052-irradiated material in the NRU vessel wall. The thickness is 12.5 mm which is slightly thicker than the 8 mm wall thickness of the NRU vessel wall. The four weld passes were designed to allow macro-graphs of the cross-section of each weld pass before it was covered with the next weld pass. From these macro-graphs the double ellipsoid parameters can be estimated to specify the distribution of heat in the weld pool for the transient thermal analysis of each weld pass. The double ellipsoid parameters specified were Front = width = depth = 3.5 mm; rear = 7 mm.

A convective boundary condition to account for cooling was applied with $T_{amb} = 300K$ and
Figure 2. Parameters for the double ellipsoid heat source model are shown.

\[
\begin{align*}
  h(T) &= 1.5 \times (5 + 0.05 \times (T - 300) + (6 \times (10^7 - 7))) \times ((T - 300)^3)) \\
  q(T) &= h(T)(T - T_{amb}) \\
\end{align*}
\]

The Flat Coupon Test was instrumented with nine thermocouples to record the transient temperature and nine strain gauges to record the X and Y-strains. See Fig 3.

The Flat Coupon Test plate was clamped at each of the four corners in a vertical position. The welds were made vertically up. The delay time between weld passes was set at 60 seconds. When the weld started, a delay time 8 seconds was applied.

The filler metal is added dynamically in the analyses as it is in the real welding process.
VrWeld analyses were run with a mesh that had 3240 elements and 5425 nodes. The filler metal element size was $5 \times 10 \times 2$ mm.

The output or results of the VrWeld analysis of the Flat Coupon Validation Test are the transient temperature for each thermocouple and the transient X and Y strain for each strain gauge for the fine and the coarse mesh.

The objective of this Coupon Test was to validate the capability of the software package VrWeld to predict transient temperatures and strains in a welded structure. The test weld was done on a 12x18x0.5 Aluminum 6061-T6 plate with four weld passes. See Fig. 1A in Appendix A for the location of weld passes, the thermocouples and the strain gauges. The test was designed to simulate on a small test as closely as possible the overlay weld procedure to be used in the NRU repair. The plate was vertical and the welds were made vertically up. There was approximately a one minute delay between weld passes.

Each of the four corners was held by a clamp. Because the details of the clamping were not provided, analyses were run with three different constraints to try to emulate the clamping. On each of the four corners, four nodes were constrained to zero displacement. This prevented the corners from translational or rotational or bending motion. This is the most severe restraint. On each of the four corners of the plate, one node was constrained to zero displacement. This does not restrain rotation about the constrained node. This is an intermediate restraint. see Fig. 1a and 1b. One each of the four corners, one node was constrained to prevent motion normal to the plane of the plate, i.e., the y-direction. In addition, rigid body motion in the X and Z directions in the plane of the plate was constrained. This provides the least restraint.

The analysis was first run with the welding parameters given to GTI by AECL. These parameters were supplied to AECL by Liburdi. After running the thermal analysis, GTI took the following steps to improve the agreement between measured and computed thermocouple results.

(1) adjusted the welding start time by matching the time of the first pass peak temperature in TC3;
(2) adjusted the power by matching the peak temperature of the first pass in TC3;
(3) adjusted the welding speed by matching the time of the first pass peak temperature in TC1;
(4) re-adjusted the power by matching the peak temperatures of the first pass in TC1 and TC2;
(5) adjusted the start dwell time by matching the peak temperature of the first pass in TC3;
(6) adjusted the convection coefficient function by matching cooling curves after the first pass in all TCs;
(7) adjusted delay times after each pass by matching the times of all peak temperatures in TC3;
(8) re-adjusted the convection coefficient function by matching cooling curves after all passes finished in all TCs.

Possible improvements which we didn’t make because the above procedure provided a very close match for all TCs:

(1) use different weld procedure parameters for each pass, e.g., weld power, and weld speed. Then repeat steps 2 to 4.
(2) use a different start dwell time period for each pass;
(3) use decreased power at the end of each pass (not implemented yet but easy to add);
(4) change coefficients for each term in the convection coefficient function (we only played with the global scale);
(5) different convection coefficient functions after each pass.

In the opinion of the author, the agreement between measured and predicted transient temperatures and measured and predicted transient X-strain and Y-strain is acceptable.

4.1. Compare Measured and Computed Transient Thermocouple Temperatures. Plots of measured vs computed temperatures for the nine thermocouples are shown in ?? for times from 0 to 1000 s to resolve the peak transient temperatures. Plots of measured vs computed temperatures for the nine thermocouples are shown in 6 for
Figure 3. The four weld passes are shown. Thermocouples are on the weld face and the strain gauges (measuring Y and X-strain) are on the other face.

Figure 4. The macro-graphs for the 1st, 2nd, 3rd and 4th weld passes were made at the cut positions shown in this figure.
times from 0 to 6000 s to resolve temperature as they cool to ambient temperature.

**Figure 5.** The temperature measured by thermocouples shown in Figure 3 is shown in green. The temperature computed with VrWeld is shown in red. The horizontal axis is time from 0 to 1000 seconds. The vertical axis is temperature in degrees K.

**Figure 6.** The temperature measured by thermocouples shown in Figure 3 are shown on the green curves. The temperature computed with VrWeld is shown in red. The horizontal axis is time from 0 to 6000 seconds. The vertical axis is temperature in degrees K.
4.2. **Compare measured vs computed strains.** The strains measured with each of the strain gauges shown in Figure 3 were compared with the computed transient strains. Each of the four corners of the coupon was fixed to zero displacement in the y-direction, i.e., normal to the coupon plate. In addition, the remaining the rigid body modes in the plane of the plate were constrained to zero displacement. Raw data from strain gauges must be post-processed to account for the change in the temperature of the strain gauge and then for the thermal expansion in the body. For example, a strain gauge that is intended to measure elastic strain in a body that is changing temperature, must account for thermal expansion of the body. A good test of a well-calibrated strain gauge would be to attach say eight strain gauges to a plate of Al5052-H32 and slowly heat the plate to the maximum operating temperature and then cool slowly. If the plate is not restrained and the temperature gradients in the plate can be neglected, then the elastic strain in the plate is zero and all eight strain gauges should report zero elastic strain. Since the algorithm used for post-processing the strain gauge data was not available, the thermal strain factor was assumed that computes the transient elastic-plastic strain by subtracting 0.55 of the transient thermal strain from the transient total strain. The agreement between measured and computed values was good.

Figures 7, 8, 9, 10 shows plots of the measured vs computed transient X-strain and Y-strain for each of the nine strain gauges on the flat weld coupon with 4 passes. The plots are for times from 0 to 1000 s to resolve peak strains and times from 0 to 6000 s to resolve the strain as the temperatures cool to ambient temperatures. On all figures the red plot is measured strain and the green plot is computed total strain minus 0.55 of the thermal strain. The displacements at the four corners of the coupon are constrained to zero in the vertical direction. In addition rigid body modes in the horizontal directions are constrained.

The following figures shows plots of the measured vs computed transient X-strain and Y-strain of a flat weld coupon with 4 passes. On all figures:
The red plot is measured strain. The blue plot is computed total strain minus thermal strain (clamp 4 corners, 4 nodes XYZ at each corner). The green plot is computed total strain minus thermal strain (clamp 4 corners, 1 node XYZ at each corner). The pink plot is computed total strain minus thermal strain (clamp 4 corners, 4 nodes Y at each corner, plus RBM in XZ).

REFERENCES

Figure 9. The Y-strain measured by strain gauges is shown in red. The computed Y-strain is shown in green. The horizontal axis is time from 0 to 1000 seconds. The vertical axis has units of micro-strain.

Figure 10. The Y-strain measured by the nine strain gauges is shown in red. The computed Y-strain is shown in green. The horizontal axis is time from 0 to 6000 seconds. The vertical axis has units of micro-strain.


5. APPENDICES

5.1. Appendix D: Example of Results of a VrSuite Test Suite For Stress Analysis.

From: Jianguo Zhou <jzhou@mrco2.carleton.ca>
Subject: SMT: StressTests errors (51:51:51)
Date: November 14, 2006 2:55:18 PM EST
To: Daniel Downey <downey@mrco2.carleton.ca>,
    jgoldak@mrco2.carleton.ca,
    Jianguo Zhou <jzhou@mrco2.carleton.ca>,
    swang@mrco2.carleton.ca,
    Stanislav Tchernov <tchernov@mrco2.carleton.ca>

CompatibleDirichletZero: err: 0.000000
CompatibleDirichletShift: err: 0.000000
CompatibleDirichletUniaxX: err: 0.000000
CompatibleDirichletUniaxY: err: 0.000000
CompatibleDirichletUniaxZ: err: 0.000000
CompatibleDirichletShearXY: err: 0.000000
CompatibleDirichletShearYZ: err: 0.000000
CompatibleDirichletShearXZ: err: 0.000000
CompatibleDirichletZeroThermalStrain: err: 0.000000
CompatibleDirichletZeroThermalStress: err: 0.000000
CompatibleDirichletVolumetricStrain: err: 0.000000
ContactDirichletZero: err: 0.000000
ContactDirichletShift: err: 0.000000
ContactDirichletUniaxX: err: 0.000000
ContactDirichletUniaxY: err: 0.000000
ContactDirichletUniaxZ: err: 0.000000
ContactDirichletShearXY: err: 0.000000
ContactDirichletShearYZ: err: 0.000000
ContactDirichletShearXZ: err: 0.000000
AMGDirichletZero: err: 0.000000
AMGDirichletShift: err: 0.000000
AMGDirichletUniaxX: err: 0.000000
AMGDirichletUniaxY: err: 0.000000
AMGDirichletUniaxZ: err: 0.000000
AMGDirichletShearXY: err: 0.000000
AMGDirichletShearYZ: err: 0.000000
AMGDirichletShearXZ: err: 0.000000
CompatibleNeumannZero: err: 0.000000
CompatibleNeumannZeroZero: err: 0.000000
CompatibleNeumannUniaxX: err: 0.000000
CompatibleNeumannUniaxY: err: 0.000000
CompatibleNeumannUniaxZ: err: 0.000000
CompatibleNeumannShearXY: err: 0.000000
CompatibleNeumannShearYZ: err: 0.000000
CompatibleNeumannShearXZ: err: 0.000000
ContactNeumannZero: err: 0.000000
ContactNeumannZeroZero: err: 0.000000
ContactNeumannUniaxX: err: 0.000000
ContactNeumannUniaxY: err: 0.000000
ContactNeumannUniaxZ: err: 0.000000
ContactNeumannShearXY: err: 0.000000
ContactNeumannShearYZ: err: 0.000000
ContactNeumannShearXZ: err: 0.000000
AMGNeumannZero: err: 0.000000
AMGNeumannZeroZero: err: 0.000000
AMGNeumannUniaxX: err: 0.000000
AMGNeumannUniaxY: err: 0.000000
AMGNeumannUniaxZ: err: 0.000000
AMGNeumannShearXY: err: 0.000000
AMGNeumannShearYZ: err: 0.000000
AMGNeumannShearXZ: err: 0.000000
5.2. Appendix D: Example of Results of a Test Suite For Transient Thermal Analysis.

From: Jianguo Zhou <jzhou@mrco2.carleton.ca>
Subject: SMT: EnergyTests errors (21:21:21)
Date: November 16, 2009 4:02:19 PM EST
To: Daniel Downey <downey@mrco2.carleton.ca>, jgoldak@mrco2.carleton.ca

CompatibleDirichletZero: err: 0.000000
CompatibleDirichletShift: err: 0.000000
CompatibleDirichlet: err: 0.000000
CompatibleConvection: err: 0.000000
CompatibleFlux: err: 0.000000
ContactDirichletZero: err: 0.000000
ContactDirichletShift: err: 0.000000
ContactDirichlet: err: 0.000000
ContactConvection: err: 0.000000
ContactFlux: err: 0.000000
AMGDirichletZero: err: 0.000000
AMGDirichletShift: err: 0.000000
AMGDirichlet: err: 0.000000
AMGConvection: err: 0.000000
AMGFlux: err: 0.000000
TransientDirichlet: err: 0.000000
TransientConvection: err: 0.000000
TransientFlux: err: 0.000000
TransientContactDirichlet: err: 0.000000
Solidification: err: 0.000000
ConvSolidification: err: 0.000000