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Adoption of High Performance Computational (HPC) Modeling Software for Widespread Use in the Manufacture of Welded Structures

to

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by

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EXECUTIVE SUMMARY

Many US manufacturing companies have moved fabrication and production facilities off shore because of cheaper labor costs. A key aspect in bringing these jobs back to the US is the use of technology to render US-made fabrications more efficient overall with higher quality. A new initiative of the current administration has the goal of enhancing competitiveness to retain manufacturing jobs in the US. One significant competitive advantage that has emerged in the US over the last two decades is the use of virtual design for fabrication of large structures in the light and heavy materials industries. Industries that have used virtual design and analysis tools have reduced material parts size, developed environmentally-friendly fabrication processes, improved product quality and performance, and reduced manufacturing costs. Indeed, Caterpillar Inc. (CAT), one of the partners in this effort, continues to have a large fabrication presence in the US because of the use of weld fabrication modeling to optimize fabrications by controlling weld residual stresses and distortions and improving fatigue, corrosion, and fracture performance.

This report describes Engineering Mechanics Corporation of Columbus' (Emc^2's) DOE SBIR Phase I results which extended an existing, state-of-the-art software code, VFT®, currently used to design and model large welded structures prior to fabrication - to a broader range of products with widespread applications for small and medium-sized enterprises (SMEs). VFT® helps control distortion, can minimize and/or control residual stresses, control welding microstructure, and pre-determine welding parameters such as weld-sequencing, pre-bending, thermal-tensioning, etc. VFT® uses material properties, consumable properties, etc. as inputs. Through VFT®, manufacturing companies can avoid costly design changes after fabrication. This leads to the concept of joint design/fabrication where these important disciplines are intimately linked to minimize fabrication costs. VFT® currently is tied to a commercial solver which makes it prohibitively expensive for use by SMEs, as there is a significant licensing cost for the solver - over and above for the relatively minimal cost for VFT®. Emc^2 developed this software code over a number of years in close cooperation with CAT (Peoria, IL), who currently uses this code exclusively for worldwide fabrication, product design and development activities. The use of VFT® has allowed CAT to move directly from design to product fabrication and helped eliminate (to a large extent) new product prototyping and subsequent testing. Additionally, CAT has been able to eliminate/reduce costly "one-of-a-kind" appliances used to reduce distortion effects due to fabrication. In this context, SMEs can realize the same kind of improved product quality and reduced cost through adoption of the adapted version of VFT® for design and subsequent manufacture of new products.

Emc^2's DOE SBIR Phase I effort successfully adapted VFT® so that SMEs have access to this sophisticated and proven methodology that is quick, accurate and cost effective and available "on-demand" to address weld-simulation and fabrication problems prior to manufacture. The open source code, WARP3D, a high performance finite element code mainly used in fracture and damage assessment of structures, was modified so that computational weld problems can be solved efficiently on multiple processors and threads with VFT®. The thermal solver for VFT®, based on a series of closed form solution approximations, was enhanced for solution on multiple processors greatly increasing overall speed. In addition, the graphical user interface (GUI) has been tailored to integrate these solutions with WARP3D. The GUI is used to define all the weld pass descriptions, number of passes, material properties, consumable properties, weld speed, etc. for the structure to be modeled. The GUI was improved to make it user-friendly for engineers that are not experts in finite element modeling. Finally, a plan for porting VFT® onto the Ohio Supercomputer Center (OSC) through its hosted Manufacturing and Polymer Portal has been developed. This access route will permit SMEs to perform weld modeling to improve their competitiveness at a reasonable cost. All of these improvements are detailed in this report.

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1 INTRODUCTION

The use of virtual design computational tools in the fabrication of large structures has enjoyed significant success in the heavy materials industry for almost two decades. Industries that have used virtual design and analysis tools have reduced material parts size, developed environmentally-friendly fabrication processes, improved product quality and performance, and reduced manufacturing costs.

This project leveraged the existing, state-of-the-art weld simulation software code, *Virtual Fabrication Technology, known as* VFT®, used to design and model large welded structures prior to fabrication - to a broader range of applications and products for widespread use by small and medium-sized enterprises (SMEs). The use of such a code helps control distortion, minimize residual stresses, control welding microstructure, and pre-determine welding parameters such as weld-sequencing, pre-bending, thermal-tensioning, using material properties, consumable properties, etc. as inputs. By doing this, manufacturing companies avoid costly design changes after fabrication. Emc^2 staff developed this software code over a number of years in close cooperation with Caterpillar Inc. (CAT) of Peoria, IL, who currently uses this code exclusively for their fabrication and product design and development activities worldwide.

Emc^2 has licensed VFT® for a variety of other applications including those for nuclear industry regulatory reviews (US NRC), national laboratory work (KAPL), shipbuilding (US NAVY), etc. The current limitation of VFT® is that it requires the use of a commercially available finite-element analysis (FEA) software package as its "core solver." This makes it prohibitively expensive for use by SMEs, since there is a significant licensing cost for the solver - over and above the minimal license costs for VFT®.

The effort successfully adapted VFT® so that SMEs have access to this sophisticated and proven methodology which, upon successful completion of the proposed Phase II SBIR effort is envisioned to be a quick, accurate and cost effective tool available "on-demand" to address weld-simulation and fabrication problems prior to manufacture.

2 PROBLEM DEFINITION

The need to join metallic parts/pieces to achieve final product configuration often employs welding as the parts' joining process. Welding is the preferred joining process for many reasons but to some extent depends on the application. For example, construction of buried pipelines that transport high pressure gases and other energy products typically employs welding of pipe sections because of the inherent leakage problem associated with pipe sections joined by bolted flanges. Also, products that are weight sensitive use welding to join structural parts/pieces because of added weight associated with other joining processes. Indeed, next generation commercial space flight vehicles are using welded aluminum super structures which require light weight construction[*]. Additionally, welding is the only joining process that can be used in some applications because of geometry or restricted space associated with the product, e.g. stiffeners used in construction of ship panels.

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[*] Emc^2 is currently working with a private company on this proprietary matter.

However, welding has some inherent drawbacks and, if not accounted for in early product design, can lead to time consuming, non-value activities that add cost and lengthen time to achieve final product configuration. Distortion and residual stress states are two primary anomalies that can, and often do, occur as a result of welding metal parts/pieces. In particular, distortion due to welding usually requires some sort of re-work such as mechanical pressing, flame straightening, and others (see for instance [3]) to reduce welding effects on final product configuration. Residual stresses induced by welding can, at a minimum, reduce useful life of the structure (corrosion and fatigue) and increase susceptibility to fracture. In the past, and still to a significant degree for the present, effects of distortion due to welding have been addressed by extensive examination of welding processes (torch speed, heat input, consumables, sequencing, fixturing, etc.). These studies result in an expensive and time consuming iterative physical process with no guarantee of achieving final optimal product configuration and performance goals.

Nonetheless, virtual (computational-based) weld modeling/simulation design and analysis tools have been used in the heavy materials industry sector over the past 10 to 15 years and the few companies that use such technology have enjoyed significant success in fabrication of products through improved product performance with lower costs to manufacture. Weld modeling tools permit the designer to address distortion and residual stress concerns due to welding prior to fabrication. Also, use of weld modeling tools allows distortion control strategies to be determined in a matter of a few days, not weeks or months as is required when only an iterative, physical approach is employed. Weld modeling and analysis methods can be used very effectively to determine best practices for weld repair and this methodology has been successfully employed for joining (welding) dissimilar metal applications. Members of the industrial sector that have employed virtual design and analysis tools have realized products that have reduced material parts size, more environmentally-friendly fabrication processes, improved product quality and performance, and reduced costs. Indeed, Emc^2 has seen a surge of requests for VFT® from off-shore manufacturers which have been rejected in order to keep this technology's competitive advantages situated in the US.

3 PROGRAM ACCOMPLISHMENTS AND GOALS OVERVIEW

VFT® is a sophisticated, mathematical and physics-based computer code system that simulates the weld process[†]. The weld process is a highly non-linear and difficult phenomenon to capture. The weld process involves (for example) melting, removal and re-depositing of material, continuous deposition of new weld material, and annealing in the heat affected zone. Prior to this DOE SBIR Phase I award, VFT® exclusively employed a commercially available software code as the system solver. As such, the user must have a license for this commercial code (pay a fee) to solve the welding problem via VFT®. For large fabrications with many welds, the user must have access to multiple processors and corresponding license access for these additional processors in order to obtain results in a high performance environment. Also, the major method to input data and produce the necessary files to perform the computational weld analysis (weld

[†] Note: Cutting and forming analyses may also be performed via VFT® but only as a subsidiary goal.

pass description, number of passes, material properties, consumable properties, etc.) is through a graphical user interface (GUI) tied to the commercial solver.

In order for SMEs to be able to access a version of VFT® that is cost effective and efficacious for manufacturing problems where welding plays a major role in fabrication, we adapted VFT® during the DOE SBIR Phase I program as describe in the following discussion. The four main tasks in Phase I were to (i) tailor VFT to an open source solver, (ii) tailor the GUI to interface with the open source solver and improve the user friendly nature of the GUI, (iii) investigate the possibility of tailoring VFT to an adaptive mesh refinement algorithm, (iv) evaluate the potential hardware/software platform for VFT use with access to SMEs. All goals were achieved, along with additional goals, in the Phase I program as summarized below and elaborated upon later on.

- The VFT system was successfully tied to an open source code called WARP3D. WARP3D is a high performance nonlinear finite element code mainly used for damage and fracture mechanics modeling under both static and dynamic conditions. Tying VFT to WARP3D required modification of the nonlinear solution procedure to accommodate thermal plasticity problems, procedures to efficiently handle the weld induced temperatures, and tailoring of the weld specific material routines (UMAT) to work efficiently with WARP3D on multiple processors and threads,. The high performance computing performance is found to be superior in solution speed to the commercial solver (ABAQUS) for solving weld problems.
- The VFT GUI was tailored to interface with WARP3D, including writing out the necessary files for weld analysis. In addition, we improved the GUI to a "road map" style to reduce the need to be "a computational expert" to use VFT® effectively.
- During the welding process the torch location is typically where highly non-linear phenomena occur, i.e. in the weld and the heat affected zone (HAZ). The finite element (FE) mesh representing the structural (material) part in the weld and HAZ needs to have a very fine discrete description (mesh) while the torch is present but can be a coarse description when the torch is not present. This behavior suggested that implementation of an "adaptive mesh refinement" (AMR) methodology might be useful. A study was made to determine the feasibility of tailoring VFT to an adaptive scheme based on some US Government open source routines. Because of the speed enhancements to VFT from the new thermal solver, the inclusion of WARP3D as the FE solver, and the great difficulty of economically tailoring VFT to an adaptive scheme (with minimal failure risk) due to accuracy errors during interpolations of both the thermal and structural solver, it was determined that this was not necessary at this time. This topic may be revisited during a SBIR Phase III effort once the system has been loaded on the Portal.
- The Ohio Supercomputer Center through the Manufacturing and Polymer Portal was evaluated as the platform to launch the adapted version of VFT for use by SMEs. The portal is currently used for other software platforms and has been found to be able to provide SMEs access to VFT. In addition, staff responsible for developing and maintaining the portal has experience in marketing this type of software platform.

Several technical advancements to VFT were made that were not included in the original DOE SBIR Phase I proposal. These features were addressed as they were determined to be important to improve the code.

- The thermal solver, Comprehensive Thermal Solution Process (CTSP), was improved to permit solution on multiple processors to improve speed. CTSP is a series-based closed form solution procedure which is about an order of magnitude faster than numerical solution of the weld temperature fields. Its speed was enhanced by permitting solution on different threads/processors and then merging at the end.
- The Paraview post processor, an open source code, can now be used to visualize VFT results (stresses, distortions, temperatures). Visualization of results is important for design of weld solution strategies.

Finally and to complement previous comments, the use of VFT® has allowed CAT to move directly from design to product fabrication. This should be a goal of all manufacturing fabricators in the US. This improved process has eliminated (to a large extent) new product prototyping and subsequent testing along with elimination/reduction of costly "one-of-a-kind" appliances used to reduce distortion effects due to fabrication. In this context, small- and medium-size manufacturing and engineering firms can realize the same kind of improved product quality and reduced cost (as CAT has achieved) by adoption/use of an adapted version of VFT® in the design and subsequent manufacture of their products.

3.1 Anticipated Public Benefits

Anticipated public benefits by use of an adapted version of the virtual design and analysis tool, VFT®, by SMEs include:

Product weight reduction by eliminating and reducing weld distortion and residual stresses in US manufactured fabrications. Product structural parts/pieces can be thinner because the need to control/reduce distortion by having a thicker part has been eliminated through controlling distortion before the structure is fabricated. Reduce stock material for fabrication. Thus, more material resources are available for other applications.

Improved environmental-friendliness of the manufacturing process. Fewer consumables required in product fabrication which eliminates prototyping and subsequent testing due to implementation of distortion control strategies in early product design process.

Improved product safety. More robust structural strength and performance metrics; increased fatigue life and less susceptible to fracture due to control of residual stresses. Thus, less likelihood of product failure in the field and which translates to safer workplace environment.

US Competitive Advantage is improved. The use of computational weld modeling as part of the complete design/build strategy of US manufacturers makes companies more efficient. This can result in total product costs that are less than off shore fabrications that take advantage of a cheap labor pool to be cost competitive.

4 ADVANTAGES OF WELD MODELING

Computational weld modeling is challenging because many welding processes are highly nonlinear. Materials melt and re-solidify; very high transient thermal gradients are experienced;

non-linear temperature dependent plastic straining and phase transformations can occur; these are among the multiple sources of nonlinearity that must be addressed in any weld modeling effort. Moreover, for weld modeling to have practical advantages in industrial production, computational solution times must be manageable since an optimum weld design of large, complex fabrications and nuclear piping systems requires numerous separate analyses. Figure 1 illustrates three advantages of computational weld modeling. On the first level, weld residual stresses can cause or lead to subcritical cracking. Both fatigue and stress corrosion crack growth is strongly affected by tensile weld residual stresses. The second concern is distortions caused by welding (middle illustration in Figure 1). Distortion control can lead to tremendous fabrication cost savings, especially for large fabrications since rework to 'straighten' structures can be very expensive. Finally, microstructure control (phases, hardness), as illustrated in the bottom illustration in Figure 1, is sometimes of concern. The advantages of computational weld modeling include: (i) Greatly reduced fabrication costs by developing weld procedures to control distortions, (ii) Improved stress corrosion cracking, fatigue, and fracture response of structural components by control of residual stresses, and (iii) Control of microstructure.

There are many methods to control all three of these weld fabrication concerns. These include weld sequencing, pre-camber, heat-sink welding, weld parameter control (heat input), pre-tensioning, and overlay welding, among many others [1,2,3]. Computational weld models can be used to design proper weld parameters and procedures to control weld residual stresses, distortions, and micro-structure. Most commercially-available computational weld models are mathematics and physics based. The following provides a brief description of computational weld models developed and used by Emc^2. These models use ABAQUS for two-dimensional (2D) solutions and the VFT® code (Virtual Fabrication Technology) to model three-dimensional (3D) weld problems. The general approach of the two programs is similar but VFT permits rapid 3D solutions. Many more details can be found in recent book chapters [2,3].

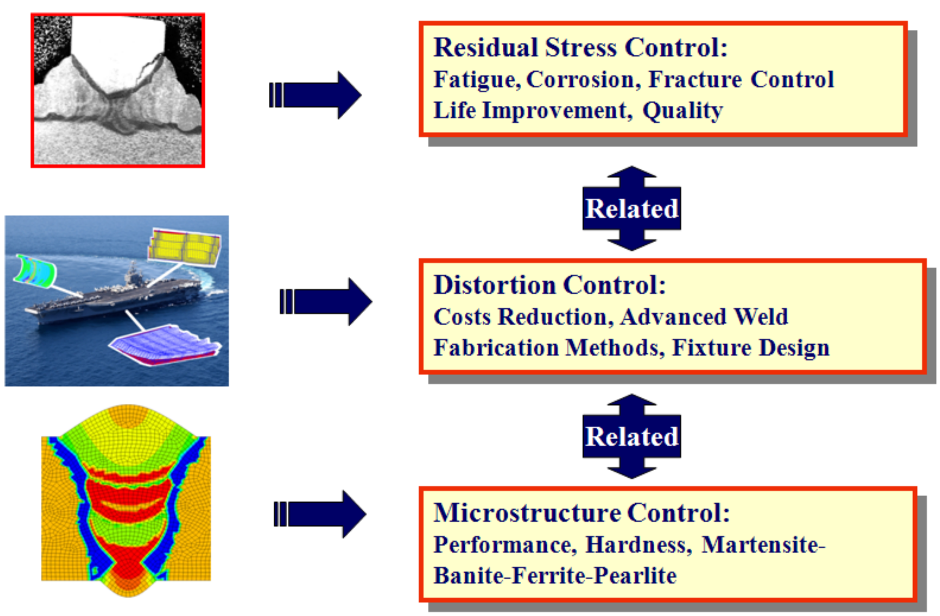

Figure 1 Purpose of computational weld models

5 HISTORY OF COMPUTATIONAL WELD MODELING AND VFT

No attempt is made here to provide a complete overview of the development of weld process models over the years. Perhaps the first attempt to predict residual stresses induced by the welding process was conducted by Rodgers and Fletcher [4] using an analytical approach in 1938. A number of other analytical approaches were developed from this time through the early 1970's to predict distortions and residual stresses (see for instance the survey paper by Masubuchi [5]). These approaches were quite novel and often provided reasonable predictions when compared with experimental measurements, but were often limited to single pass welds.

Such analytical approaches were replaced by numerical approaches in the early 1970's as the power of the finite element method was realized. The earliest published finite element models for predicting the residual stresses induced by the weld process were developed independently by Kamichika et al. in Japan [6] and Friedman [7] in the USA. Researchers (Brust, Barber, Mishler, Kanninen) [8], McGuire [9], and Brust, Rybicki, and Kanninen et al. {[10], [11], [12] and references cited therein}) extended these models in the late 1970's and early 1980's to account for (among other features) multiple pass welds, material re-melting and annealing, phase changes, and heat sinks. This work was also perhaps the first to use closed-form analytical solutions to develop accurate high-speed weld thermal analysis procedures for finite thickness (including thin) plates. These models were used extensively in studies for the nuclear power industry to develop weld procedures to mitigate heat-affected zone (HAZ) inter-granular stress corrosion cracking (IGSCC) in stainless steel piping systems in Boiling Water Reactors (BWR). Therefore, computational weld models were first used to help control weld residual stresses caused by welding to mitigate service cracking problems. Methods such as Heat Sink Welding (HSW [8]), Induction Heating for Stress Improvement (IHSI [9]), and Backlay Welding (BW [10]) were developed and optimized using these early weld models. The methods are still used in many industries today. In fact, feasibility studies for the early forms of the mechanical stress improvement process (MSIP) were examined in these programs [12]. As such, this work probably represented the first industrial application of a weld process model to aid in solving a manufacturing fabrication problem.

Since the early 1990's, weld process models have been extensively developed and are being used by many different organizations. Fricke, Keim, and Schmidt [13]; Goldak et al. [14]; Yang and Feng [15]; and Buchmayr [16] summarize methods used by organizations in Germany, Canada, USA (Edison Welding Institute), and Austria, respectively, to model weld induced residual stresses and distortions. No attempt to summarize the methods used by these and other organizations is made here; rather the interested reader can consult these references and references cited therein and below for details. Most of these models were used to solve small problems and the tools were not sophisticated enough to solve the very large problems encountered in the large fabrication and ship building industries.

In the early to mid 1990's, the present authors worked to improve all of these weld analysis tools. In particular, the high-speed thermal solution procedures and the structural procedures such as local annealing, melt element detection, etc., were extensively updated and improved for the nuclear industry, the aerospace industry, the Department of Energy, and the automotive industry, among others. During this time period (circa 1995), Caterpillar approached Dr. Brust and his development team with a very large program to develop a simple to use and rapid computational weld modeling process that could be used on large fabrications necessary in the heavy equipment industries. This 5 year development resulted in the code now called VFT®. Caterpillar and other organizations now routinely use VFT to greatly reduce fabrication costs and to reduce metal requirements since many of their designs are limited by fatigue life issues. Indeed, by carefully controlling the weld process not only can one control distortions (greatly reducing fabrication costs) but by producing compressive weld residual stresses at critical weld locations the fatigue life, corrosion life, and fracture response of these structures can all be improved.

A summary of computational weld models and numerous industrial applications of computational weld models can be found in the book edited by Feng [17]. In particular, chapters by Chen, Brust, and Yang [2] and Brust and Kim [3] discuss mitigation methods for both weld residual stress and distortion control with numerous applications. In fact, a recent problem in the nuclear power industry (primary water stress corrosion cracking (PWSCC)) has led Dr. Brust and his colleagues to develop weld residual stress, distortion, and cracking sessions at the ASME Pressure Vessel and Piping conferences from circa 2000 to the present [18]. This year's sessions at the July 2013 ASME PVP Conference in Paris had more than 35 papers devoted entirely to distortion and residual stress control. The current methods used are completely documented in these references and those cited therein. Computational weld modeling has come a long way since the early analytically based Rodgers and Fletcher models [4].

There continues to be improvement in computational weld models from both basic research developments to improvements in solution speed for very large problems. In particular, Feng et al [19] have been improving the constitutive models which account for the annealing effect when a weld heats up a base metal or heat affected zone region to high temperature before cooling down in order to improve the final plastic strain predictions. This is a feature we plan to consider implementing in the DOE SBIR Phase II models. Improvements in speed and tailoring the code to open source solvers are the subjects of this report.

6 THE ORIGINAL VFT CODE

Weld distortion control must be performed on three dimensional models. With VFT development, extensive full-scale experiments have validated the accuracy and predictive power of models. Successful models can be used to reduce fabrication cost and improve quality by minimizing and controlling distortions.

The following is a brief description of the original VFT® (Virtual Fabrication Technology, VFT, Reference [20]) code. This represents the code prior to improvements made during the course of this DOE SBIR Phase I program. As seen in Figure 2, the modeling tool consists of a weld graphic user interface (WGUI), a comprehensive-thermal solution procedure (CTSP) (or numerical DFLUX code), and a structural model (UMAT). The WGUI is a 3-D graphics user interface program developed for welding process simulation, with particular emphasis on maximizing the modeling engineer's productivity. It provides a visual tool for the user to define welding simulation procedures for CTSP and UMAT. CTSP and UMAT are two main analysis modules for thermal and structural analysis in this software.

The thermal model (CTSP) was developed based on superposition of complicated closed form analytical expressions and developed heat source theories. CTSP is rapid and is used for large problems. This CTSP is protected by four (4) international patents. The structural model is tied to the ABAQUS Finite Element Analysis program (Dassault Simulia) with the use of a special weld specific user material routine which can account for material melting, phase changes, and other parameters.

In many cases computational weld models use the assumption of two dimensional modeling because of the complexities of full moving arc three dimensional modeling. There are many cases where the 2D assumptions produce erroneous results but this assumption can be workable for some problems. Axis-symmetric weld modeling of pipe in particular has been used successfully to provide conservative predictions of both axial and hoop weld residual stresses [21]. Numerous large scale weld models have been analyzed in order to control weld distortions, residual stresses, and micro-structure. While the two dimensional models can provide reasonable predictions of weld residual stresses for some cases, three dimensional solutions must be used for distortion predictions and most fabrications that are more complicated that a simple plate or pipe weld. The weld models can be used to control weld distortions and residual stresses. References [2 and 3] discuss many of these example problems, validation cases for large real world structures, and summarize mitigation strategies. Some typical examples are presented later before discussing changes made during this program.

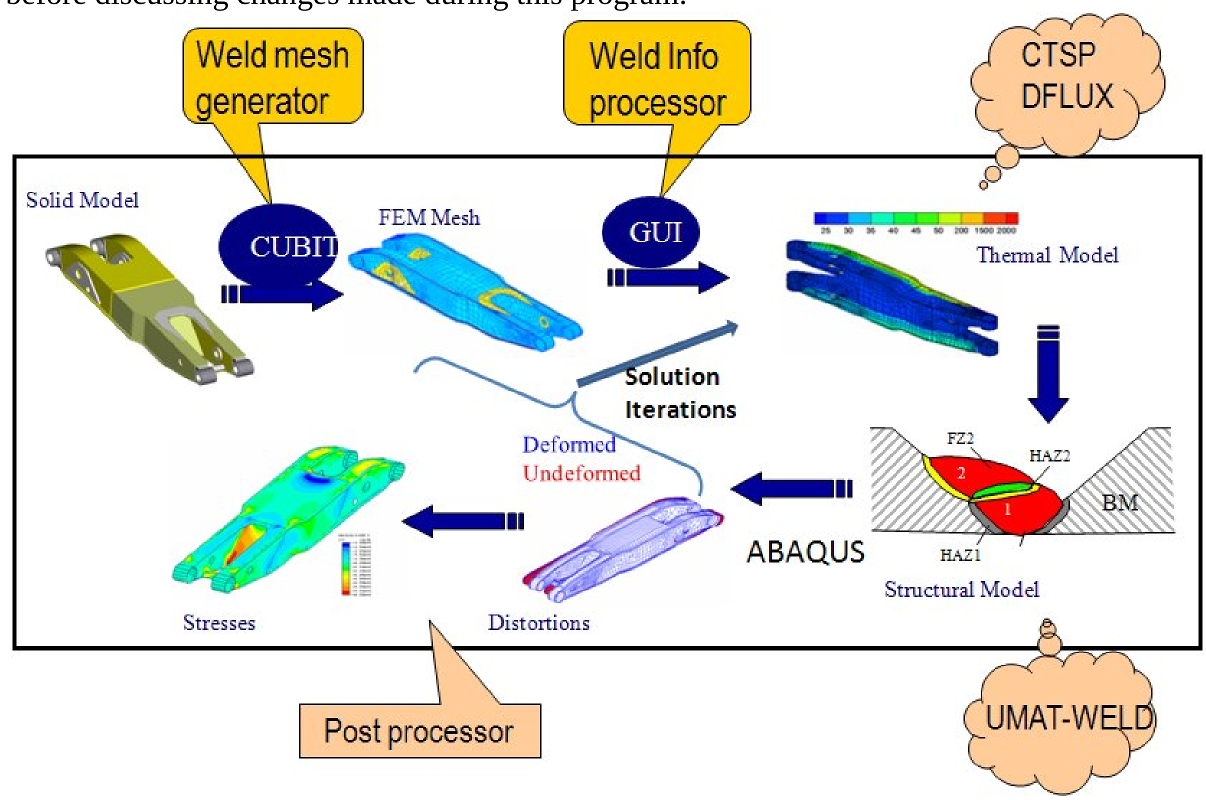

Figure 2 VFT weld modeling procedure

6.1 Comprehensive-Thermal Solution Procedure

The CTSP permits most welding features, from weld start/stop effects, multiple passes, and base plate cutouts, to trailing heat and cooling sources and moving weld torches on complex structures. It was developed based on superposition of complicated closed form analytical expressions and previously developed heat source theories [22,23,24][‡]. It can be used to obtain extremely rapid thermal solutions for complicated (and arbitrary) weld geometries compared with traditional numerical thermal solutions. The CTSP detailed solution scheme includes transient heating and cooling, curved weld paths, and multiple pass welds. CTSP is indeed the key enabler of the VFT software.

6.2 Structural Model

The UMAT includes a constitutive law [25] developed specifically for welding applications. The overall modular structure of UMAT-WELD is shown in Figure 3. An outline of the constitutive framework can be found in References [2,3,and 25]. The developed UMAT-WELD routine extends ABAQUS capabilities in material modeling and significantly improves numerical convergence for welding applications.

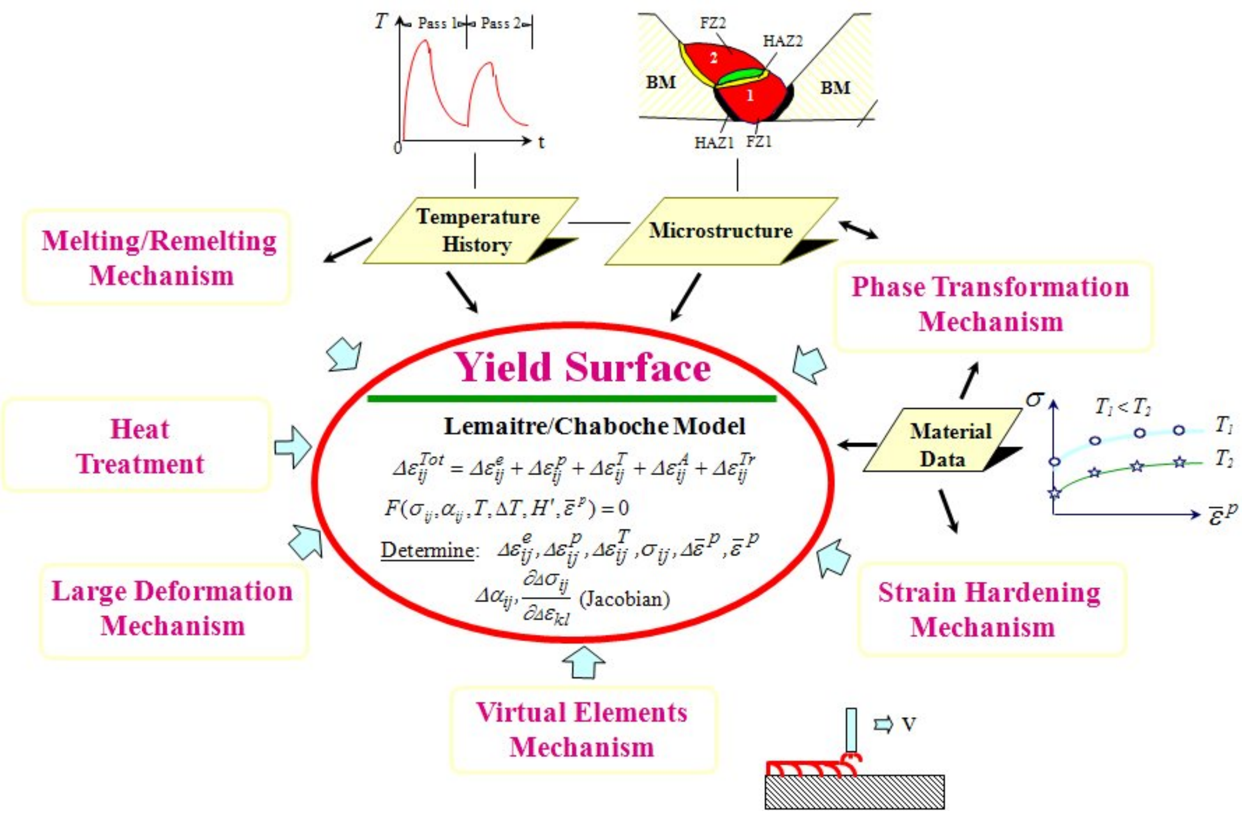

Figure 3 User routine UMAT-WELD global module weld material law

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[‡] Since CTSP is protected by international patents full details of the development and equations are not presented in these or any references. Full details can be provided to DOE if confidentiality is maintained.

The constitutive law permits stress relief due to weld melting/re-melting effects, strain hardening effects, large deformation mechanisms and a scheme of virtual element detection (VED) for modeling continuous weld element deposition associated with a moving arc. The structural model was developed based on ABAQUS commercial finite element codes.

Some of the main features of UMAT-WELD include:

- Using a field variable to trace temperature histories at material points and store the maximum temperatures experienced at these points for weld fusion line visualization;
- Using solution-dependent state variables to trace thermal and mechanical strain evolution for yield surface determination;
- Using solution-dependent state variables to trace yielding locus evolution;
- Allowing user to choose either isotropic or kinematic or combined strain hardening model with annealing;
- Several models that account for phase transformation plasticity are included;
- Post weld heat treatment can be modeled;
- Incorporating an initial stress self-equilibrating scheme for pre-welding initial stress considerations, etc.

6.3 Weld Modeling Advantage Example - Motor Grader Drawbar

This example comes from a heavy manufacturing application. More details of this example can be found in References [3,26]. The component motor grader to be welded is shown in Figure 4 where the motor grader machine is shown to the left. It consists of a yoke welded to a grader plate with 16 single pass welds. The welds are mainly Tee-fillet welds (with several lap joints), most of which are deposited on one side. A number of weld sequence studies were performed using the VFT code. However, it became clear that sequencing alone would not solve the distortion control problem. Figure 4(b) shows a side view of the distortion pattern which results from the optimum weld sequence. It is seen that the distortion is 5.9 mm. The tolerance requirement for the grader is +- 0.75 mm, so this is too much distortion.

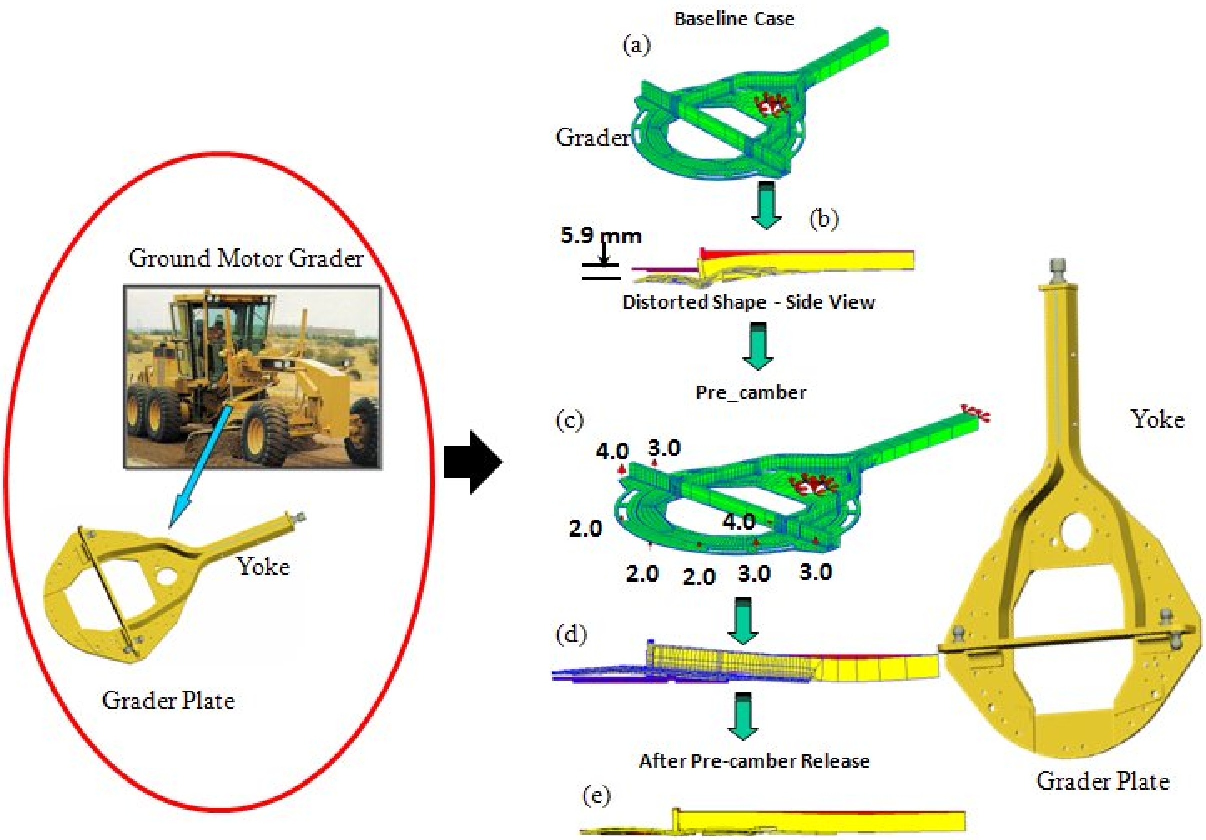

Figure 4 Motor Grader Weld Distortion Control Example

The previously existing manufacturing process for this motor grader drawbar required welding, then mechanical straightening and machining. Moreover, the cutting process led to distorted parts before the weld even began. The plate material supplied by a steel manufacturer arrives with a history of residual stresses which are introduced by the rolling and thermal manufacturing processes. When one cuts parts out of plate that has prior residual stresses, these are rearranged, and an initial distortion in the part to be welded is introduced. Welding and cutting simulations using the VFT® software were employed to predict the distortion of the drawbar during welding and to develop a better production process. From Figure 4(b) it is clear that the distortion using the standard baseline weld process of 5.9 mm was not adequate. This 5.9-mm distortion was after optimization of the weld sequence to minimize distortions. It was clear that weld sequencing alone was only a partial solution to control distortions.

A pre-camber fixture was designed using VFT which elastically pre-cambers the yoke and grader plates during welding. The pre-camber scheme that resulted was designed to control the flatness of drawbar in the design range of 1.5 mm (+ - 0.75 mm). Stress and distortion analyses of the fixture were carried out to adjust the pre-cambering scheme, and Figure 4(c) shows the effect. The numbers on the ‘pre-cambering’ solution are the final field values of pre-camber displacement, in millimeters, after optimizing the procedure.

Functionally, the process was optimized as follows. The distortion pattern from the optimized sequencing study, Figure 4(b), served as the initial pre-camber estimate. One half of these predicted distortion values were assumed to be applied as pre-camber for the next analysis. Then one-half the final distortion pattern increment from the current iteration was applied to the original pattern (in the opposite direction). After about 5 analysis iterations, the final pre-camber distortions applied to the grader plate (in mm) are seen in Figure 4(c). The arrows indicate the direction of the pre-camber. Figure 4(d) shows the distortion pattern prior to release of the pre-camber fixture. Figure 4(e) shows the final distortion pattern after release of the fixturing. This results in a motor grader that is within the tight distortion control tolerances required. *It is important to note that methods to control and manage weld distortions also have a profound effect on weld residual stresses since they are intimately connected [27].*

The analysis led to a number of other benefits. The sizes of the welds in the drawbar were reduced and their locations regularized, and in several locations the plate thickness was reduced as well. The manufacturer has been using the pre-camber fixture in its factories since this work. Significant cost savings (in the seven figure range) from this solution including the elimination of large straightening presses on the shop floors and a yearly recurring savings from reduced material and fabrication costs. The cost and efficiency of computational weld modeling has been realized in greater than one hundred products at Caterpillar at present.

7 PHASE I DOE PROGRAM VFT CODE DEVELOPMENT

The VFT code was significantly modified during the course of this DOE SBIR Phase I program. The effort successfully adapted VFT® so that small and medium-size firms have access to this sophisticated and proven methodology which is a quick, accurate and cost effective tool available "on-demand" to address weld-simulation and fabrication problems prior to manufacture.

This section is organized into subsections discussing the topics which are summarized below.

1. The GUI is used to define all the weld pass descriptions, number of passes, define material properties, consumable properties and weld speed, etc. for the welded structure to be modeled. The GUI was improved to make it amenable for use by an engineer that is not an expert with finite element modeling so that VFT can be used seamlessly. In addition, the graphical user interface (GUI) has been tailored to integrate these solutions with WARP3D.
2. The open source code, WARP3D, which is a high performance finite element code mainly used in fracture and damage assessment of structures, was modified so that the computational weld problem can be solved very efficiently on multiple processors and threads with VFT.
3. In addition, the thermal solver of VFT, which is based on a series of closed form solution approximations and is extremely rapid, has been enhanced for solution on multiple processors greatly enhancing the overall speed.
4. Results and VFT system performance on the open source system are summarized.

5. The plan for porting the VFT system to the Ohio Supercomputer Center has been developed. This will provide SMEs inexpensive access to VFT in order to perform weld modeling to improve their competitiveness at a reasonable cost.
6. Finally, the results are tailored so that they can be visualized using the open source code Paraview.

7.1 The Graphical User Interface (GUI)

This section summarizes the improvements and modifications made to the graphical user interface during this program. A pictorial overview of the new VFT system is illustrated in Figure 5. A weld specific finite element mesh is developed, which has appropriate refinement near the weld joints. The GUI writes out input files specific to the thermal solution module (CTSP) and a separate file for the structural solution (open source code WARP3D). Improvements to the GUI performed in this program were to make it more user friendly with solutions tailored to parallelize the thermal solution as well as tailoring structural solutions to WARP3D and its efficient multi-processor solution procedure.

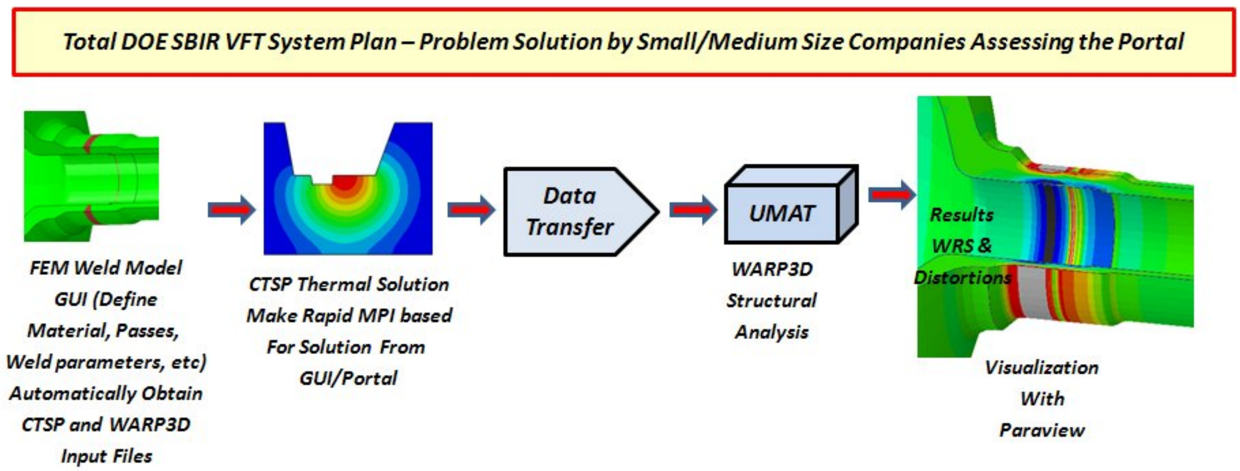

Figure 5 VFT weld modeling procedure with open source solution process

The GUI permits easy simulation of the structure, analysis by HPC, rapid modification of weld process parameters, sensitivity study of parameters, and overall optimization. The GUI is the portal to these procedures. The VFT® GUI exports model and temperature results files in the WARP3D distortion solver format, as well as subdividing the weld model for multiprocessor execution of CTSP. By suitable linearization of the temperature solutions, CTSP becomes a "perfectly parallel" HPC analysis and the GUI serves to post-process its output by consolidating the results from multiple cores.

The GUI contains special-purpose graphical features which allow welding engineers to conveniently specify weld length, sequence, direction, and number of passes. However, the sequence must be specified manually for each weld which is a laborious procedure. The goal of this task is to ultimately enhance user productivity by automating the VFT® weld specification process, building "best practice" optimization heuristics into the GUI for both manual and automated multi-pass welding. In Phase I we established that improved user productivity can be accomplished through simple weld problem solutions (e.g. bead-on-plate, Tee fillet weld) which will provide the strategy for implementing this user friendly feature for VFT® for a wider range of weld problem solutions.

7.1.1 Details of the VFT GUI for Open Source Solution

In an industrial context, components are frequently modeled with a view toward CFD/thermal process modeling as well as stress/weld/fatigue analysis. Accordingly, the versatile finite element method (FEA) is preferred over, for instance, meshless methods for this reason. VFT imports a user-generated FEA mesh either in the popular ABAQUS **.inp/*.abq* file format or as a native VFT **.msh* file. All that is needed in the VFT *.msh format is the nodes, elements, and weld groups. Figure 6 illustrates an example mesh of a component used in an actual piece of construction equipment to prevent operator damage due to roll over. This example will be used later in the context of the WARP3D development to provide results of the final design. As can be seen on the blow up illustration at the bottom left of Figure 6 there are a number of options. This illustrates the importation of the model into the VFT system with the File-ImportSolidMesh option where either the ABAQUS or VFT mesh format can be chosen. Each of the menu items across the top (bottom left blow up in Figure 6), that is ‘File’, ‘Mesh’, ‘Query’, ‘View’, ‘Weld’, and ‘Help’, have pull down menus to perform tasks necessary to develop the input data necessary to perform a weld analysis. The ‘File’ menu pull down items are listed in Figure 6. The ‘File’ pull down menu shown here does the following things:

- *ImportSolidMesh* – imports the finite element model
- *Import_VFTr* – import a previously saved VFT model. This might have partial passes defined, or might need to have the weld model re-sequenced, etc. and is in native VFT format.
- *Save VFTr* – saves a file in VFTr format for future read and use.
- *Export* – exports a thermal file (CTSP) and/or WARP3D file after the weld process has been defined to permit analysis.
- *Timeshift* – this shifts absolute times for virtual element detection (VED) and CTSP needed for some applications for WARP3D format analysis.
- *Merge Timeshifter Nonoverlap* – specialized feature needed for some applications.
- *WARP 3D tools* – this creates the temperature format from the CTSP analysis required for WARP3D analysis and/or produces the input file for WARP3D analysis.
- *Combine multiple CTSP results* – advanced feature used to merge CTSP results. For instance, for multiple welders at the same time.
- *Merge CTSP Multi-core* – used to define the number of cores desired to perform the CTSP analysis and sets up the solution process.
- *FileClose and Exit* – closes the file or exits the VFT GUI.

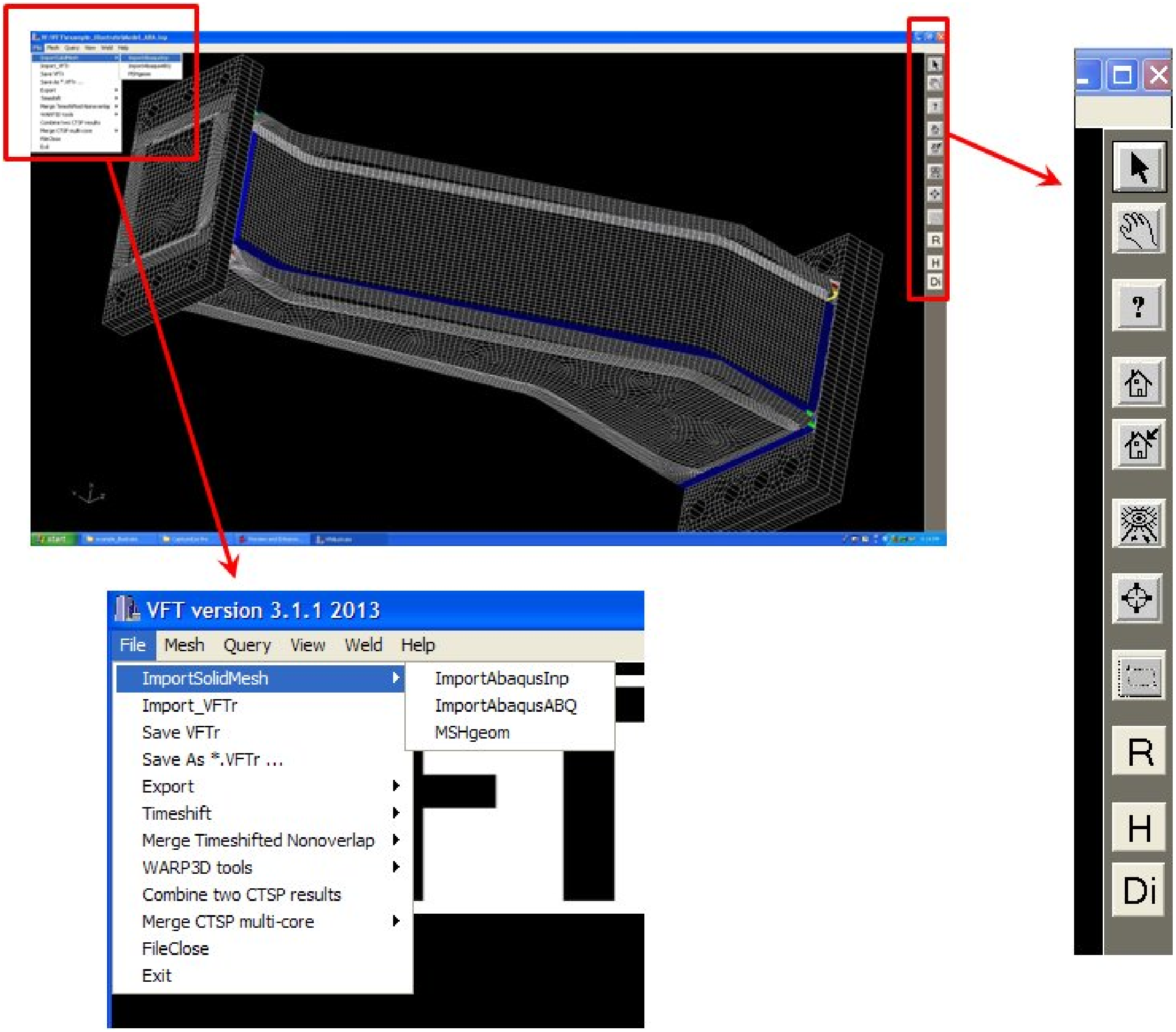

Figure 6 VFT-GUI imports Abaqus **.inp/*.abq* or native VFT **.msh* models

Many of these items will be discussed in further detail below. In addition, each of the other menu items (i.e. Mesh, Query, View, Weld) have a large pull down list to perform other chores necessary for weld analysis, some of which are discussed in detail later. The ‘Help’ menu provides help for the user. The right hand side in Figure 6 shows a number of model manipulation processes, some of which will be defined later.

The goal is to design a structure that has manageable weld residual stresses at critical locations to enhance fatigue life as well as distortion control to permit easy fabrication. This mesh should contain the weld groups (shown colored), on which the user will specify weld passes of suitable length, direction, and sequence. The user has several main objectives in any weld simulation including (i) compute residual weld stresses for use in a fatigue life, corrosion, fracture assessment or design, and (ii) minimize overall weld distortions, which is an important factor in the alignment of large welded subassemblies

Weld modeling begins with specifying the parameters of the torch by means of the *Weld/WeldParameter/Create* menu dialog box (see Figure 6 and Figure 7). Heat input per unit weld length is the critical input in welding, given by the expression

$$HI = I\ V/v$$

where, I = welding current (Amps), V = welding voltage (volts), v = torch traveling speed (mm/s). Arc efficiency for MIG welding varies from as high as 0.85 to as low as 0.45. For MIG we usually recommend an efficiency setting of 0.75.

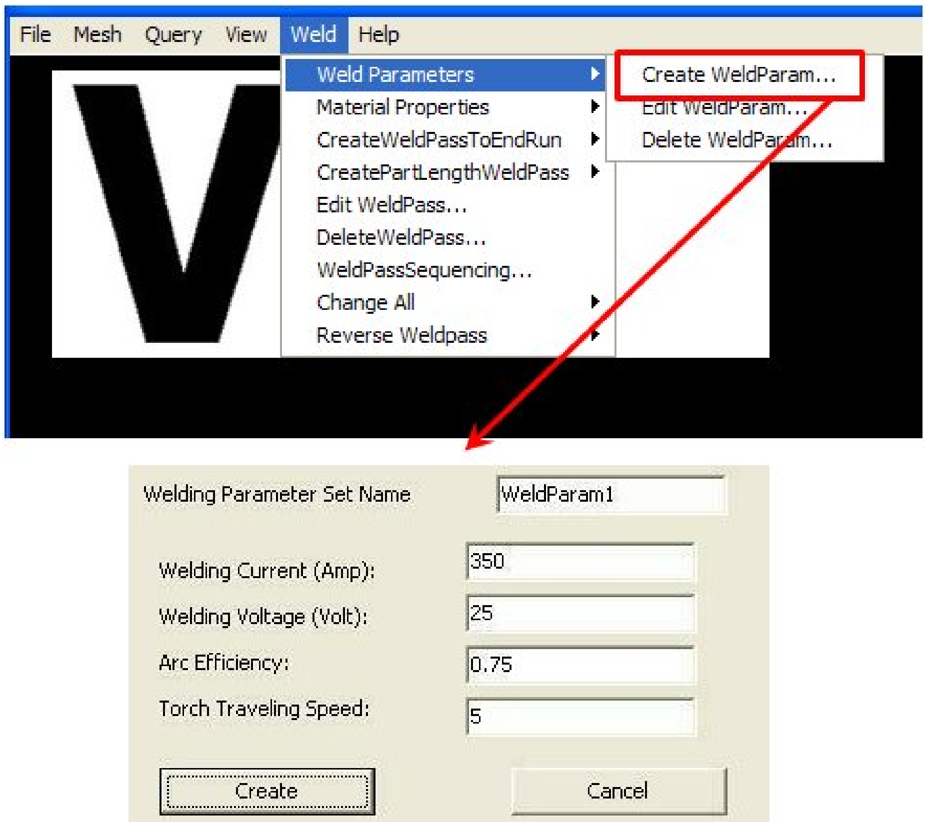

Figure 7 Dialog box for weld torch parameters

Next, the user enters the material parameters for weld metal by means of the *Weld/Material Properties/Create* dialog box (Figure 8). Thermal conductivity, specific heat and density are fundamental physical properties of thermal conduction. Weld simulation involves high-temperature elastic-plastic material behavior so the user must choose among six material constitutive relations at this point.

- Isotropic (multi-linear)
- Combined hardening (linear)
- Combined hardening (multi-linear)
- Elastic-Plastic-Creep (Isotropic, multi-linear)
- Simple Phase Transformation

- Complete Phase Transformation

Isotropic and combined hardening (linear) are well known constitutive models but it has been shown that the “mixed” Lemaitre-Chaboche combined hardening (multi-linear) model is best for most applications. Multi-linear data is imported from the user-specified (e.g.) *material.dat* file. There is an option to include annealing in the weld simulation, with appropriate annealing temperature parameters. VFT uses ‘progressive annealing’ which means that there is a start temperature for annealing and an end temperature with history completely removed at the anneal end temperature. There is also an option to include the VED procedure, which can be explained as follows. The user-generated FEA mesh represents the final as-welded geometry of the component. However, the initial state has no welds (i.e. weld elements are fictitious). The progressive conversion of fictitious elements to solid elements, during welding, is recorded in a VED (Virtual Element Detection) data file which is used in the WARP3D structural analysis. Nonetheless, VED adds execution time and the user has the option to select a faster but less accurate result without it. VED essentially adds the weld elements when they become active and this is handled in the UMAT weld material routine discussed later.

VFT-GUI offers a number of labor-saving techniques for weld pass (WP) specification. The user can divide an existing weld group into several WPs along its length, by means of menu item *Weld/CreatePartLengthWeldPass*, or the WP can run the full length of the weld group by selecting *Weld/CreateWeldPassToEndRun*. Furthermore, the user can acquire the entire weld group as a WP (“Full section…”), or create several WPs on the group section (“Partial section…”). The following discussion applies to the economical *Weld/CreateWeldPassToEndRun/Full section…* menu option.

Launch the WP Creation dialog box by menu item *Weld/CreateWeldPassToEndRun/Full section…* Figure 9 shows the first of three tabs, which seeks information on the weld pass type (T-Fillet, V-Groove, Lap Joint, Box Type) and shape (Non-Circular, Full Circle, Partial Circle, Girth (Full Circle), Girth (Partial Circle)). Time step control has critical process parameters: InterPass Cooling Time & Steps. Inter-pass cooling time is much shorter for automated welding. It is also essential to enter the thickness of adjacent plates.

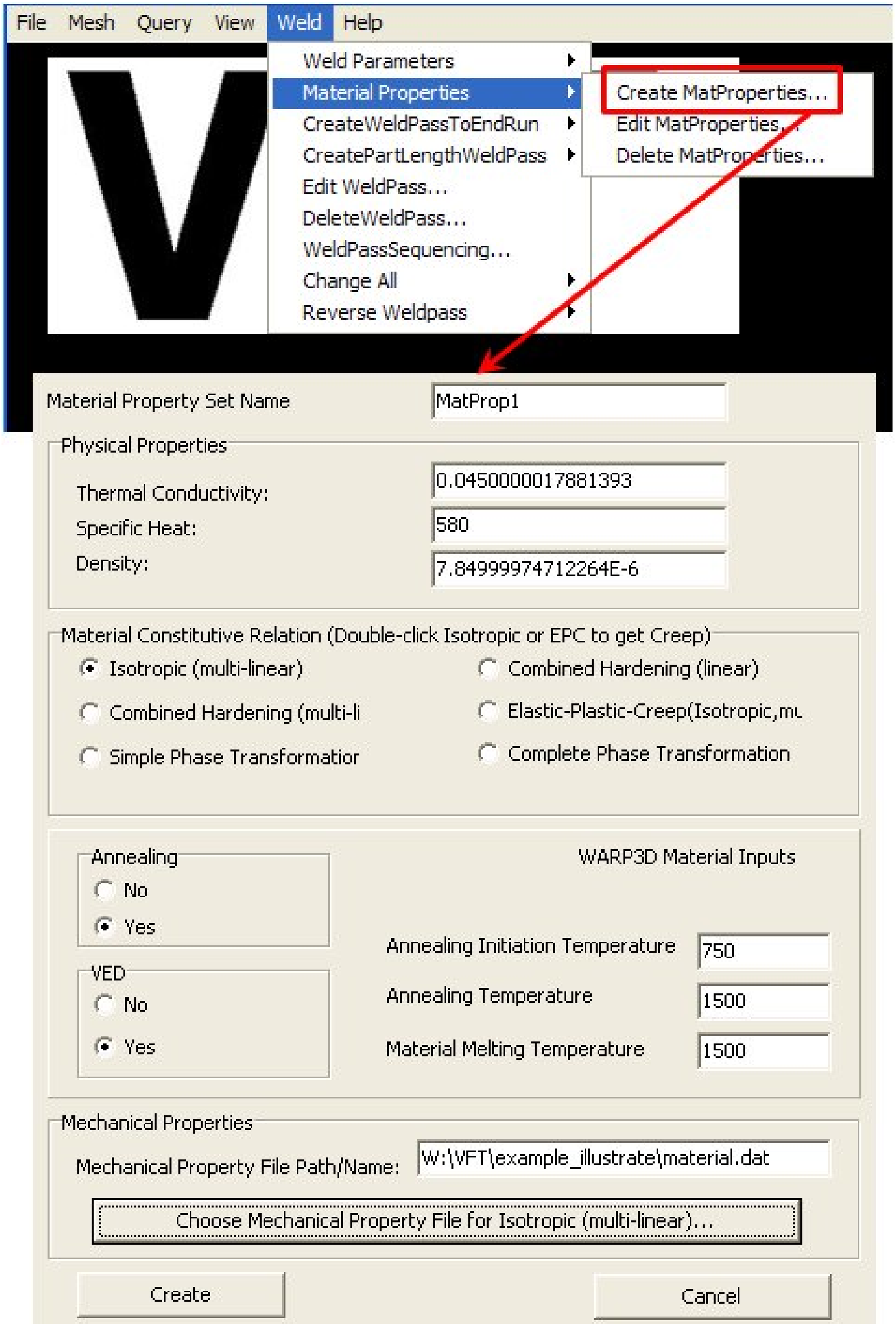

Figure 8 Material properties of base and weld metal

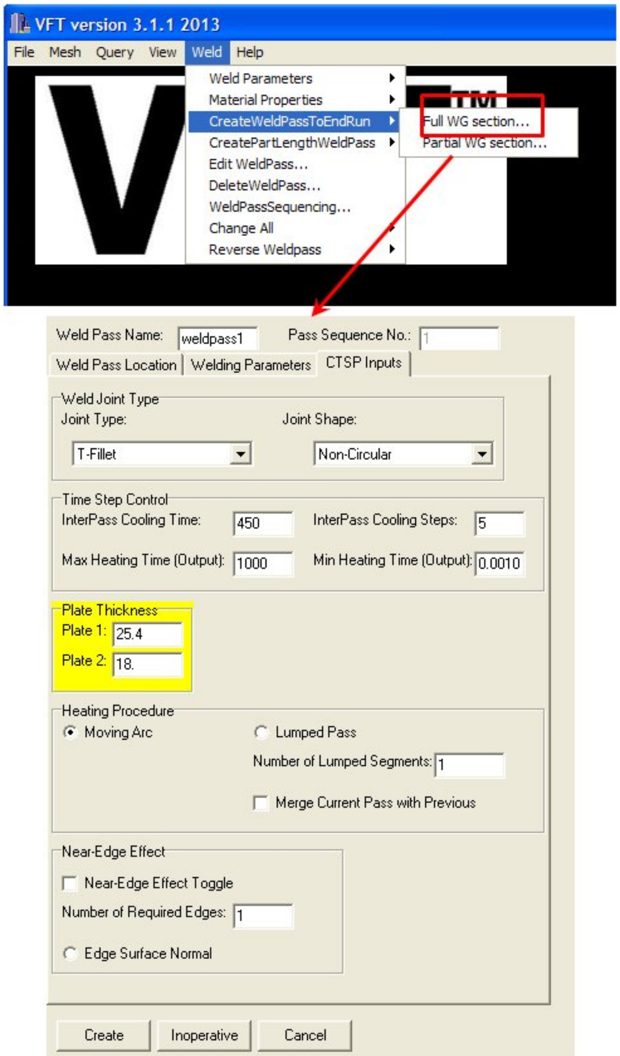

Figure 9 CTSP inputs for weld pass creation

Welding parameters are entered in the second tab (Figure 10). The user specifies the weld pass by means of the third tab (Figure 11), in which the user is required to select a material property set and weld color definition. VFT permits up to 10 materials to be used. To specify a weld pass on a weld group of elements, the user maneuvers the image to view the start element facets. Then select First item (One start element) and click on any facet on the start face (Figure 12). Select Second item (Auto-gen to end run) and click anywhere on the weld group to capture the elements of the WP, shown in yellow. Lastly, the user selects the Third & Fourth items (Figure 13), which involve clicking on the adjacent plates to establish normals.

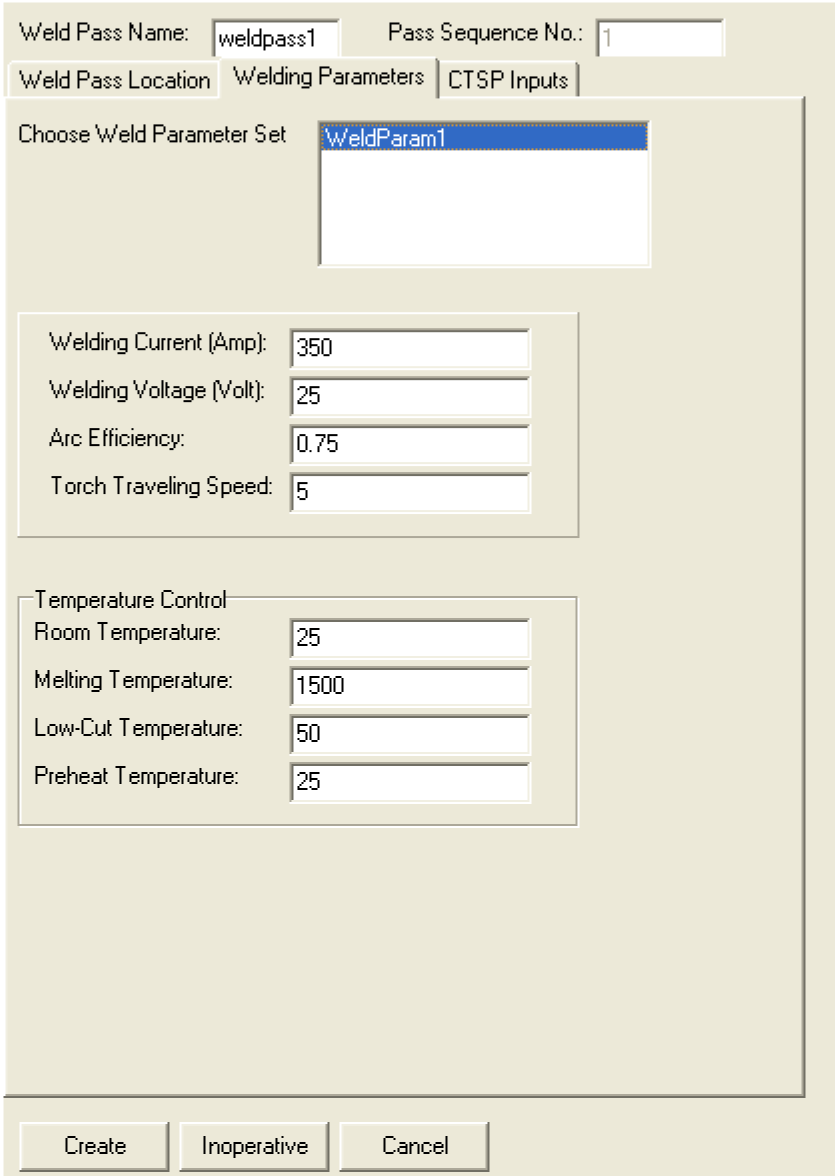

Figure 10 Weld parameters for this pass

CTSP obviates the need for an expensive transient finite element thermal analysis by using asymptotic mathematical functions to represent actual temperature distributions around a welding torch (CTSP is discussed later). In particular, it uses the classical error function solution of one-dimensional thermal solidification/conduction. The foregoing plate normal's definition serve the purpose of orienting the functions appropriately in the mesh for the thermal analysis. The user clicks the Create button to create this WP and repeats the procedure for any others. *It is noted that WARP3D does not have a numerical thermal solver so that the use of an independent thermal solver like CTSP was critical to this project.*

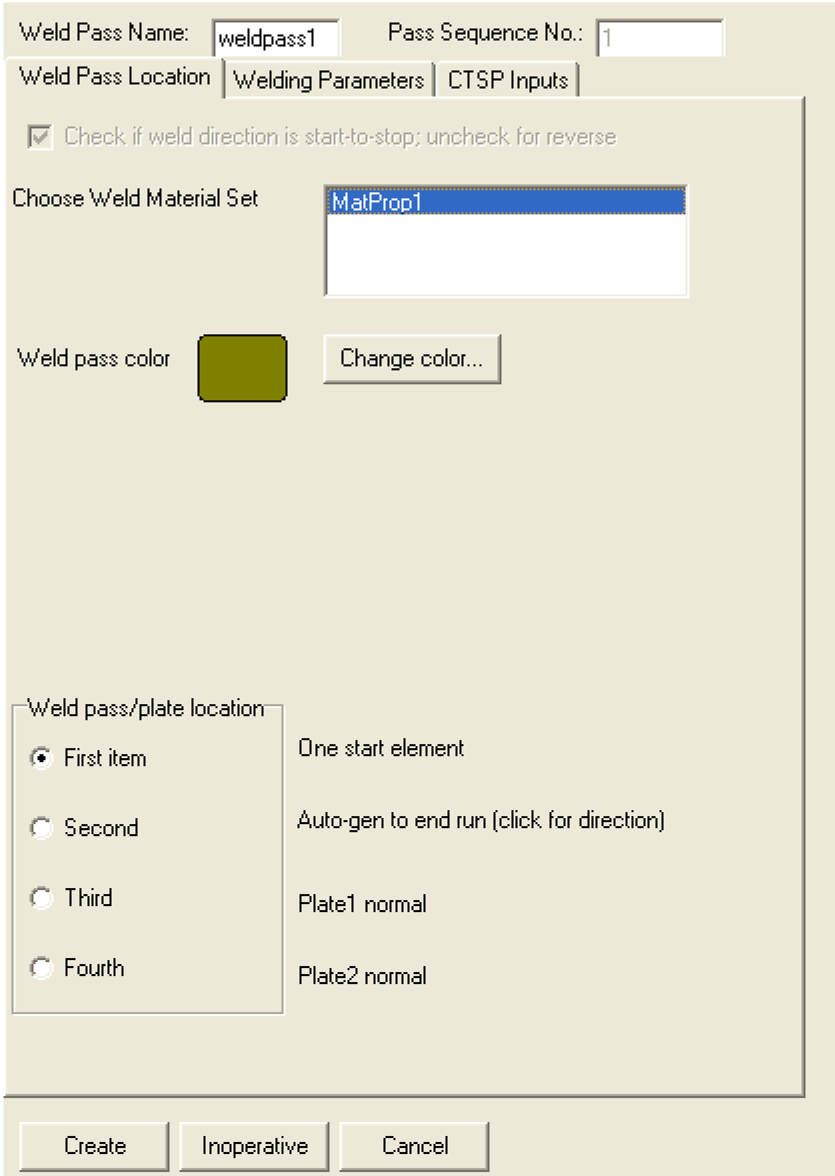

Figure 11 Tab for weld pass specification

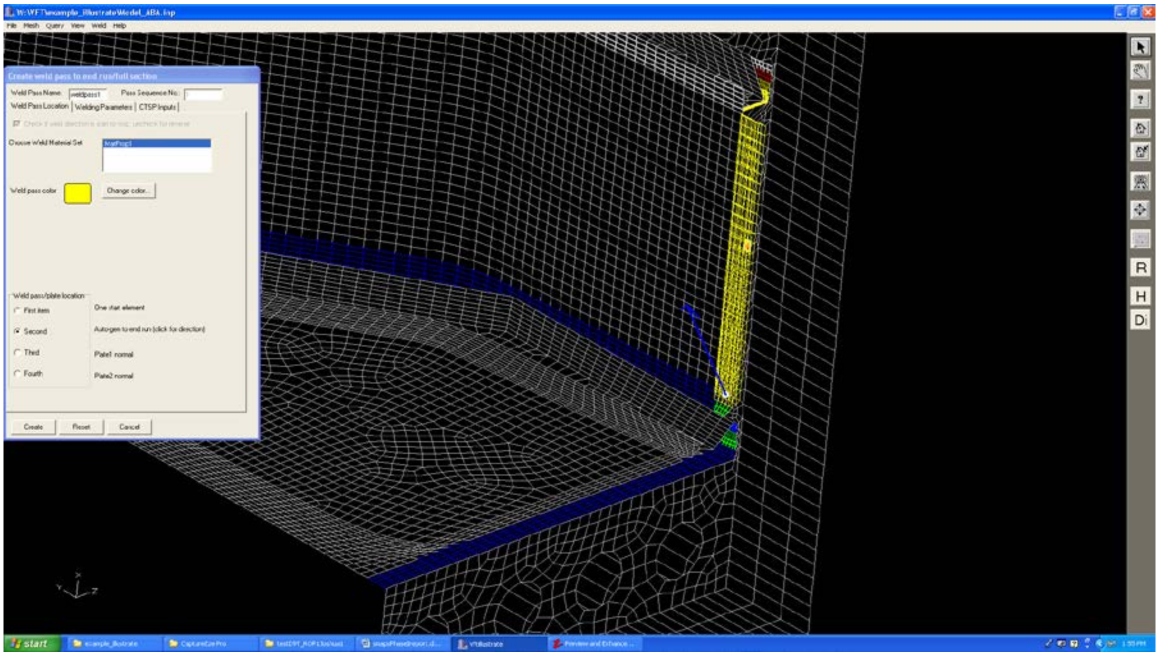

Figure 12 Yellow WP after First item (start element) and Second (direction)

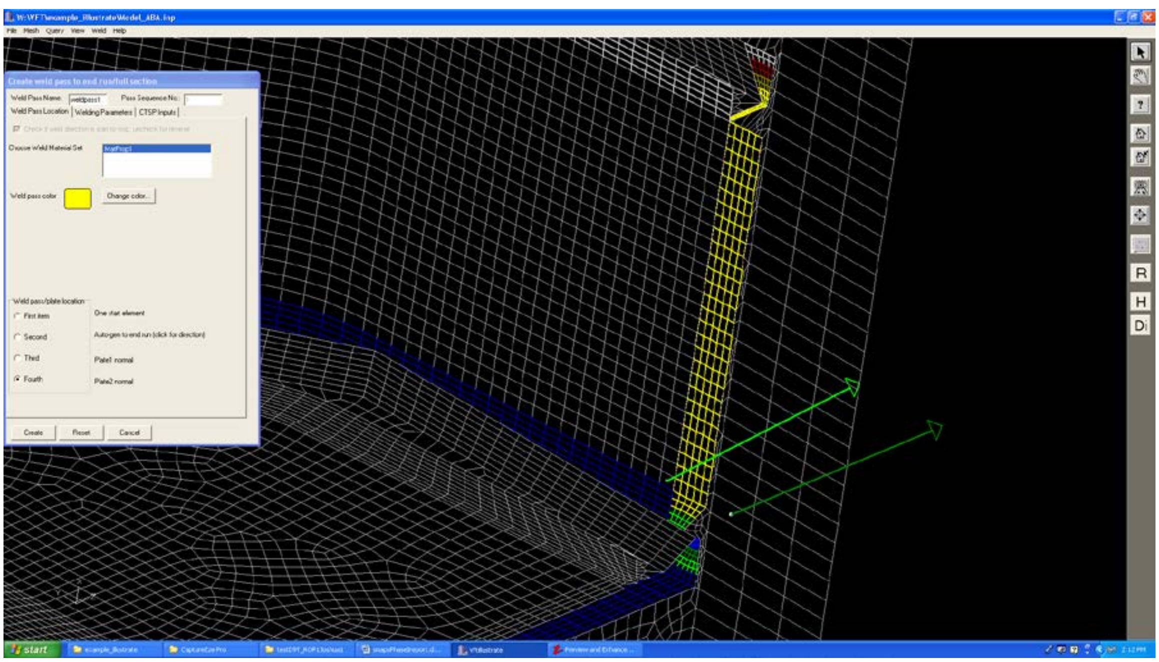

Figure 13 Third & fourth items (normals to the adjacent plates)

Welding residual stress and distortion is strongly influenced by weld sequence on one or other side of a large plate. Accordingly, VFT-GUI provides a convenient dialog box (Figure 14) to facilitate changing weld pass order or direction.

Once the model is ready, the user specifies #cores and exports a multi-core CTSP data file set by means of the menu item *File/Export/exportCTSP* and dialog box (Figure 15).

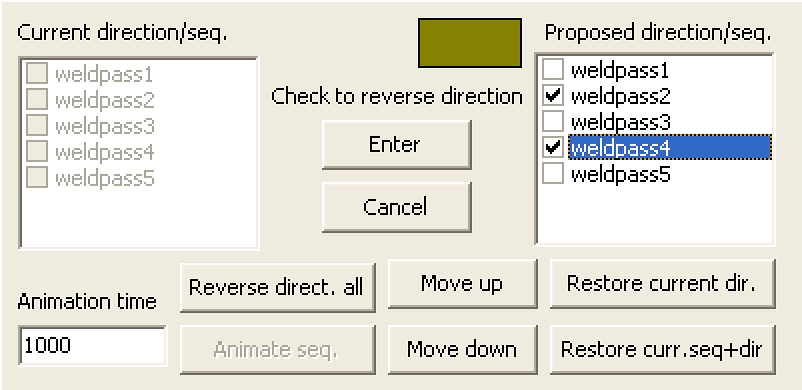

Figure 14 Dialog box to specify weld pass sequence and direction

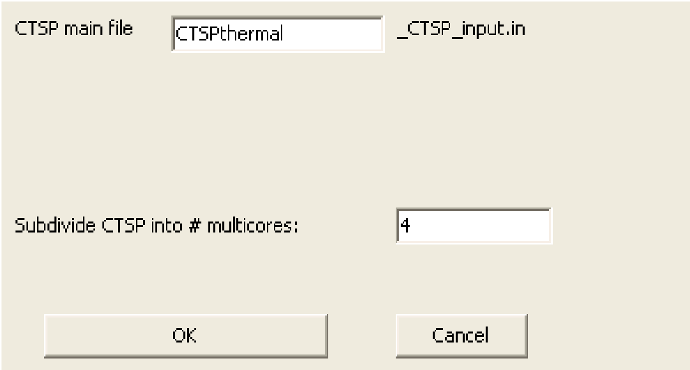

Figure 15 Dialog box to specify #cores and write CTSP datafile set

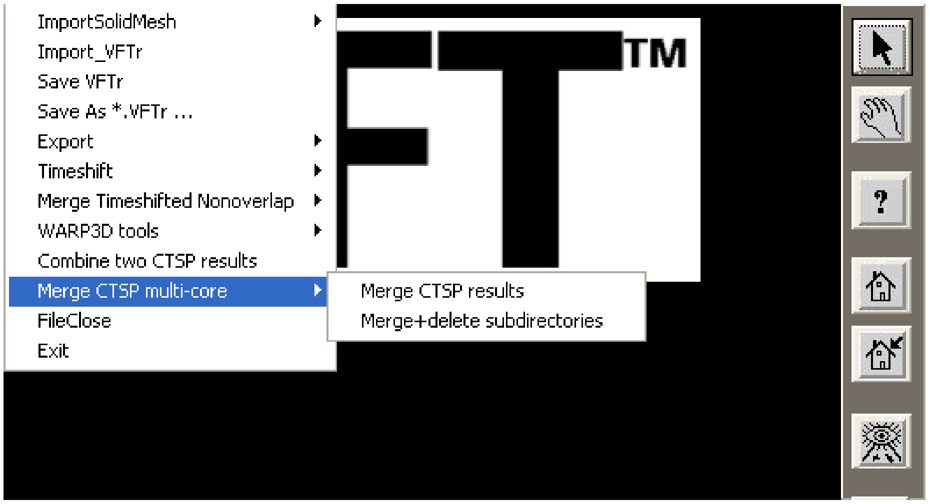

Figure 16 Menu item for merge of multi-core CTSP results

After multi-core CTSP has executed, the user merges the multi-core CTSP results by *File/Merge multi-core* menu item (Figure 16). Details of the MPI CTSP merge feature are presented in Section 7.2.2.

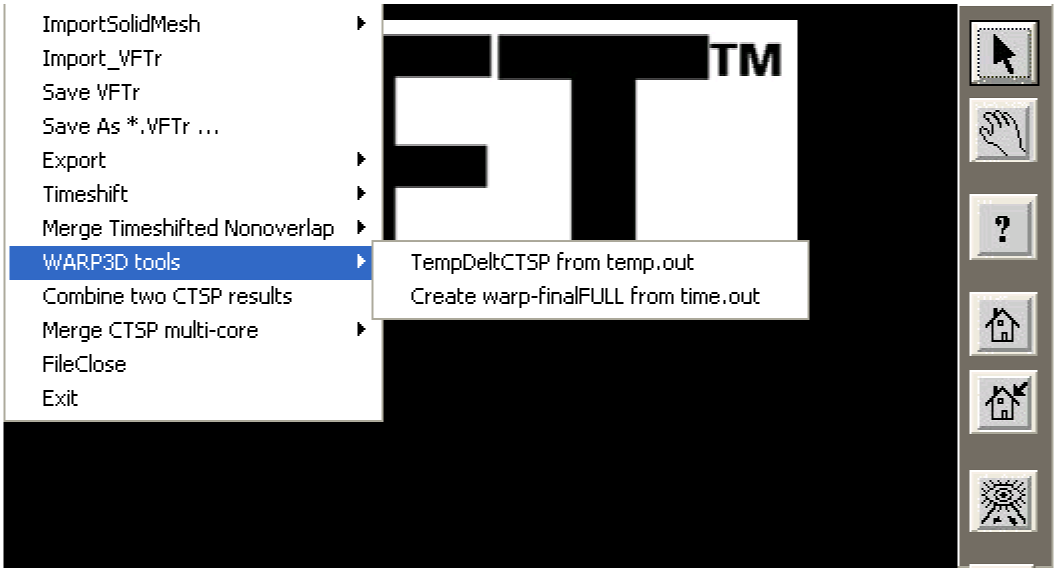

Figure 17 Menu item for WARP3D-specific datafiles

The non-linear structural analysis code WARP3D has unique input file requirements. In particular, it operates on incremental temperatures rather than CTSP *temp.out* temperature sequences, so VFT-GUI provides the menu item *File/WARP3D tools/TempDeltCTSP from temp.out* (Figure 17) to generate suitable input files. Secondly, WARP3D's control file contains time information which must be derived from CTSP *time.out* data file content, so VFT-GUI creates the control file by means of *File/WARP3D tools/Create warp-finalFULL from time.out.* VFT-GUI has its own special **.VFTr* model file format to allow the user to store and edit weld models effortlessly. VFTr commands appear in the main menu in Figure 17.

Since weld simulation involves a long sequence of non-linear analyses, VFT-GUI provides a *Mesh/FEstats…* menu item to inform the user of model size and likely execution time. It also has a set of mesh *Query* capabilities to help estimate plate thickness et al.

7.1.2 Initial Development of Mesh Generation for VFT-GUI

The meshes required to perform a weld analysis using VFT require refinement and swept meshes along the welds. A simple mesh generator (for simple meshes such as butt weld or Tee-fillet weld) was developed as a standalone routine. This will be implemented, and extended in the Phase II effort.

The user can choose to import a mesh generated using a favorite mesh generator, or VFT-GUI can generate a suitable mesh by its super-element capability. The mesh generator is only applicable for simple models and most users develop their own mesh first before reading into the VFT-GUI for weld definition. A super-element is a coarse plate- or weld-group-sized element which is user-subdivided into a large number of hexagonal finite elements. VFT-GUI generates a FEA mesh from an assembly of interlocking super-elements, enforcing subdivision-compatibility among them. The *Mesh/AddSuperelement…* menu item launches the dialog box in Figure 18. First, the user enters the ELSET name of this super-element (e.g. base metal, WG1, WG2, etc.) and the granularity of subdivision. The user is notified if the granularity, as entered, conflicts with information on preceding super-elements. Next, the user enters geometry data for the eight corners. This procedure is repeated for all super-elements in the coarse model. Super-element data is saved in a special-purpose *.sed file.

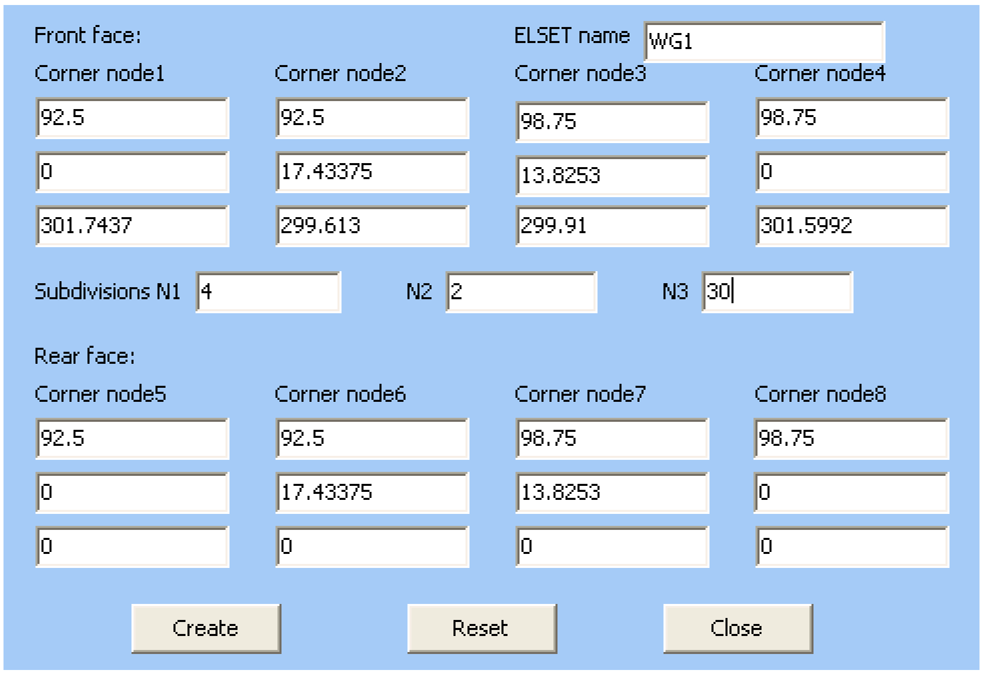

Figure 18 Dialog box for super-element data

Mesh generation occurs when the user selects menu item *Mesh/Generate Mesh*, and VFT-GUI automatically tests the mesh for degenerate elements. Figure 19 shows a weld group generated by the data in the dialog box above.

Note: If the user generates a mesh using their favorite mesh generator, they must conform to the particular requirements of VFT-CTSP. Namely, weld groups must have hexagonal elements and must be prismatic with respect to number of elements per longitudinal cross section (Figure 20).

By means of VFT-GUI, the user can easily add and/or reconfigure weld passes, as shown in the right fillet weld (Figure 20). The mesh generator is not user-friendly at present (although Emc^2 specialists can easily use it). However, user-friendly features and improvements are planned for the Phase II effort and beyond into Phase III.

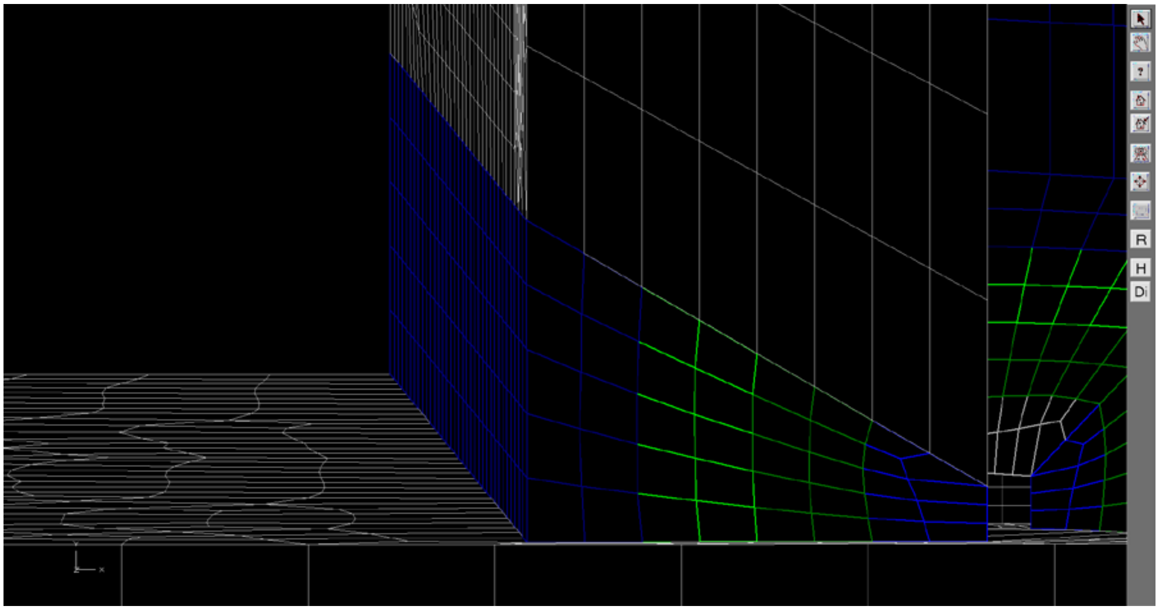

Figure 19 Dark blue weld group (left) generated by foregoing super-element

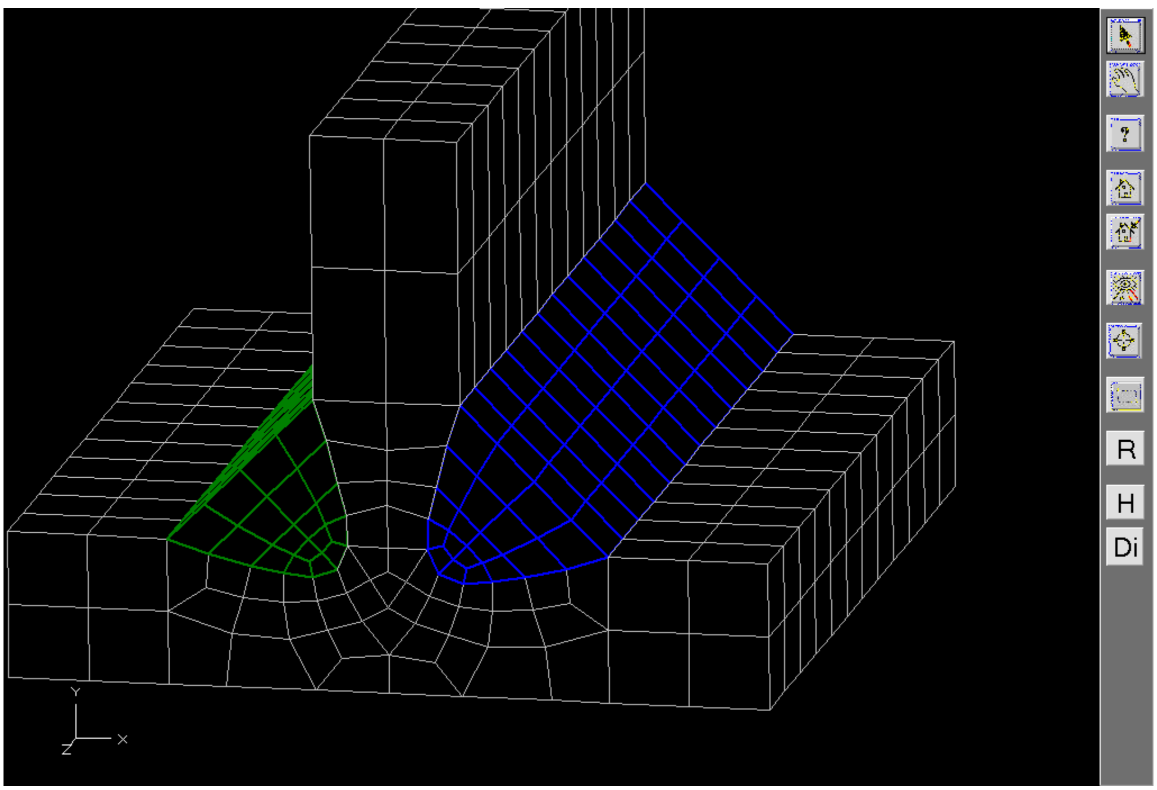

Figure 20 User-generated mesh of component, showing two weld group ELSETs.

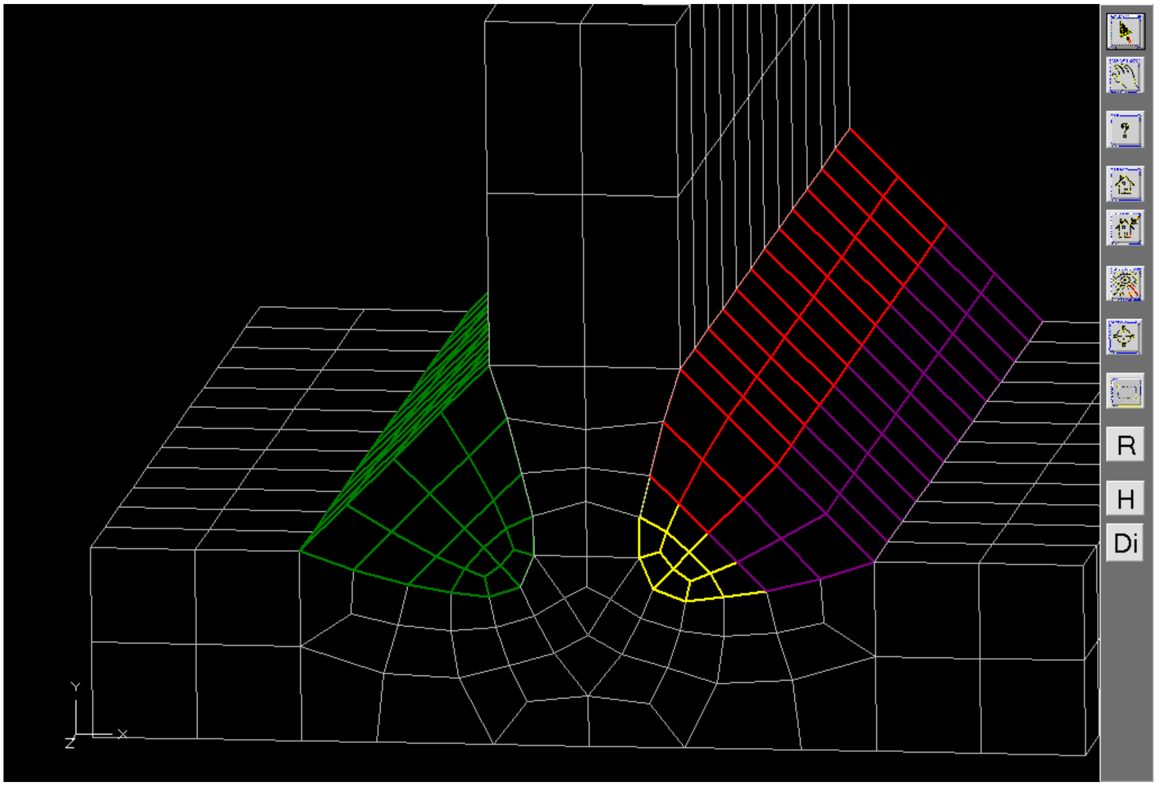

Figure 21 Three weld passes specified in right fillet weld group

7.2 Open Source Finite Element Solver Implementation (WARP3D)

Prior to this Phase I DOE SBIR program, the VFT computational weld modeling system used the ABAQUS solver. The temperature versus time histories produced by the CTSP thermal module for each weld pass were originally read into ABAQUS and the corresponding weld distortions, residual stresses, and microstructure were calculated for a 'baseline' weld fabrication process. Distortion and residual stress control strategies are then investigated in subsequent analyses to achieve the fabrication goals. The weld modeling process is inherently highly nonlinear, requiring extensive solution times for large welded fabrications. This requires solution with ABAQUS using multiple processors and additional license 'tokens'. For instance, for large problems one may want to use 36 processors to achieve a solution in a reasonable period of time. This would require up to ~40 or so license tokens using the commercial code ABAQUS. The cost for a SME to hold such a large volume of license tokens is prohibitive.

The goal of this task was to tailor the VFT system to permit solution with an open source, nonlinear, finite element solver. There are a number of publicly available Government developed solvers which could be considered for this purpose. After a rather extensive search of such available solvers, we chose to tailor VFT to permit use of the WARP3D public domain nonlinear finite element solver. Emc^2 has used WARP3D for solving a variety of highly nonlinear fracture mechanics analyses in the past and found it to be easy to adapt to our needs. WARP3D has been tailored for rapid solutions using parallel computers and benchmark solutions compared with commercial codes (including ABAQUS) show similar and even more rapid solution performance.

The work required for this task is summarized in the following bullets. Dr. Robert Dodds, developer of WARP3D, was involved with this task in order to tailor WARP3D to VFT solutions and to make many other improvements necessary for rapid solution.

1. Modify the CTSP thermal files to permit the solution format of WARP3D. This included a 'merge' procedure to perform the thermal solution efficiently on multiple processors on a computer cluster.
2. VFT uses a weld specific user constitutive routine, which permits material melting and re-solidification, material deposition as the weld torch moves along, phase transformation plasticity for materials where it is needed, user choice of six material constitutive laws, among other features. WARP3D had implemented a process whereby one can use it with a material USER routine (as is done with ABAQUS). This activity required re-write and tailoring the weld UMAT to WARP3D and permit rapid parallel solutions. This turned out to require extensive effort but was successful.
3. Developing nonlinear solution parameters with WARP3D to permit rapid solution of the weld problem. This includes specifying the equation solver for weld problems. WARP3D has a variety of direct and iterative solvers that the user can choose. It is anticipated that the direct solver will suffice for most problems and a conjugate gradient iterative solver may suffice for huge problems, but this needs to be studied.
4. WARP3D permits writing out output results in a format that is readable by an open source Government code (Paraview). This will permit the proper visualization of results (currently ABAQUS viewer is used).after some modifications in order to permit writing out of some of the solution dependent variables calculated within the USER weld routine.

7.2.1 CTSP Temperature Files for WARP3D

With ABAQUS the total temperatures are required at each time step while WARP3D requires the temperature changes at each node. A file converter was written to perform this task and is invoked using the GUI as discussed in Section 7.1. In addition, WARP3D defines the temperature load in a format called 'load patterns'. The load patterns are defined for each compute step separately, which meant that a separate load pattern was required for each pass at each location of the torch where temperatures are defined by CTSP. This results in definition of thousands of temperature files for large problems which must be managed by the system. The original adaptation of VFT to WARP3D used this format and wrote out WARP3D input files which read each of these. Because of the inconvenience of this approach, it was decided that a 'USER LOAD' routine would make this process easier. This is particularly important when we port the code to the portal so that SMEs can use this simplified analysis procedure. With the USER LOAD routine, one large file is read by WARP3D which defines the temperatures at each node as each moving arc pass is deposited throughout the weld process. Because CTSP only writes out temperatures for nodes that are actively being affected by the weld torch, and assigns room temperature to all other nodes, the size of this file is manageable. It is noted that the GUI permits one to perform the analysis using the multiple load step process or using the USER LOAD routine by user choice.

7.2.2 MPI CTSP Merge Feature

The thermal solver used within the VFT system is based on a series solution of closed form solutions which is briefly discussed in Section 6.1 and References [22, 23, 24]. The CTSP permits most welding features, from weld start/stop effect transients, multiple passes, and base plate cutouts, to trailing heat and cooling sources and moving weld torches on complex structures. It was developed based on superposition of complicated closed form analytical expressions and developed heat source theories. It can be used to obtain extremely rapid thermal solutions for complicated (and arbitrary) weld geometries compared with traditional numerical thermal solutions. A detailed solution scheme has been developed which includes transient heating and cooling, curved weld paths, and multiple pass welds.

It is noted that the decision to use WARP3D as the VFT solver was predicated on the fact that a separate thermal solver was available since WARP3D does not include thermal solution[§]. CTSP is weld-specific thermal conduction software which simulates welding efficiently by using asymptotic mathematical temperature distributions in place of a formal transient finite element analysis of torch heat flow. Although the weld metal's elastic-plastic material properties are temperature-dependent, the dependence is relatively weak and the overall weld sequence can reasonably be decomposed into a set of independent, super-imposable weld pass analyses (see Section 7.2.3). Hence CTSP is amenable to multi-core High Performance Computing (HPC).

When writing CTSP input files, VFT-GUI allocates weld passes to cores in weld order, but it promotes load balancing by ensuring that each core has approximately an equal number of time steps. After executing CTSP on multi-cores, it is necessary to merge each core result into the overall *temp.out* result file. Final results are desired at the "single-core-analysis" time points, which are termed the hierarchical times. Examining the plot of temperature vs. time as the torch passes the end of a weld pass (Figure 22), there is an immediate precipitous drop in temperature and a long exponentially declining tail. Time points are clustered after each weld pass to capture the rapid reduction.

As an example, for a 48 pass weld, one might want to perform the CTSP analysis on 8 cores. This would mean that Passes 1 to 8 are on Core 1, Passes 9 to 16 on Core 2, and so on. After completion, there are then 8 sets of temperatures that must be merged to obtain the correct temperature file that results in the exact same file as if the entire solution is made on one core. Hence, for the Core 1 results the cooling at the end of the 8^{th} pass continues for a period of time, for Core 2 the cooling continues for a period of time, etc. These then are merged using a rather complicated algorithm that ensures minimal interpolation errors. This greatly speeds up the solution and results in accurate temperature fields.

[§] VFT can be used with numerical thermal analyses using a DFLUX routine when using ABAQUS as the solver. However, this is rarely done since numerical thermal solution times are long and CTSP has been shown to be just as accurate (see Section 7.2.3).

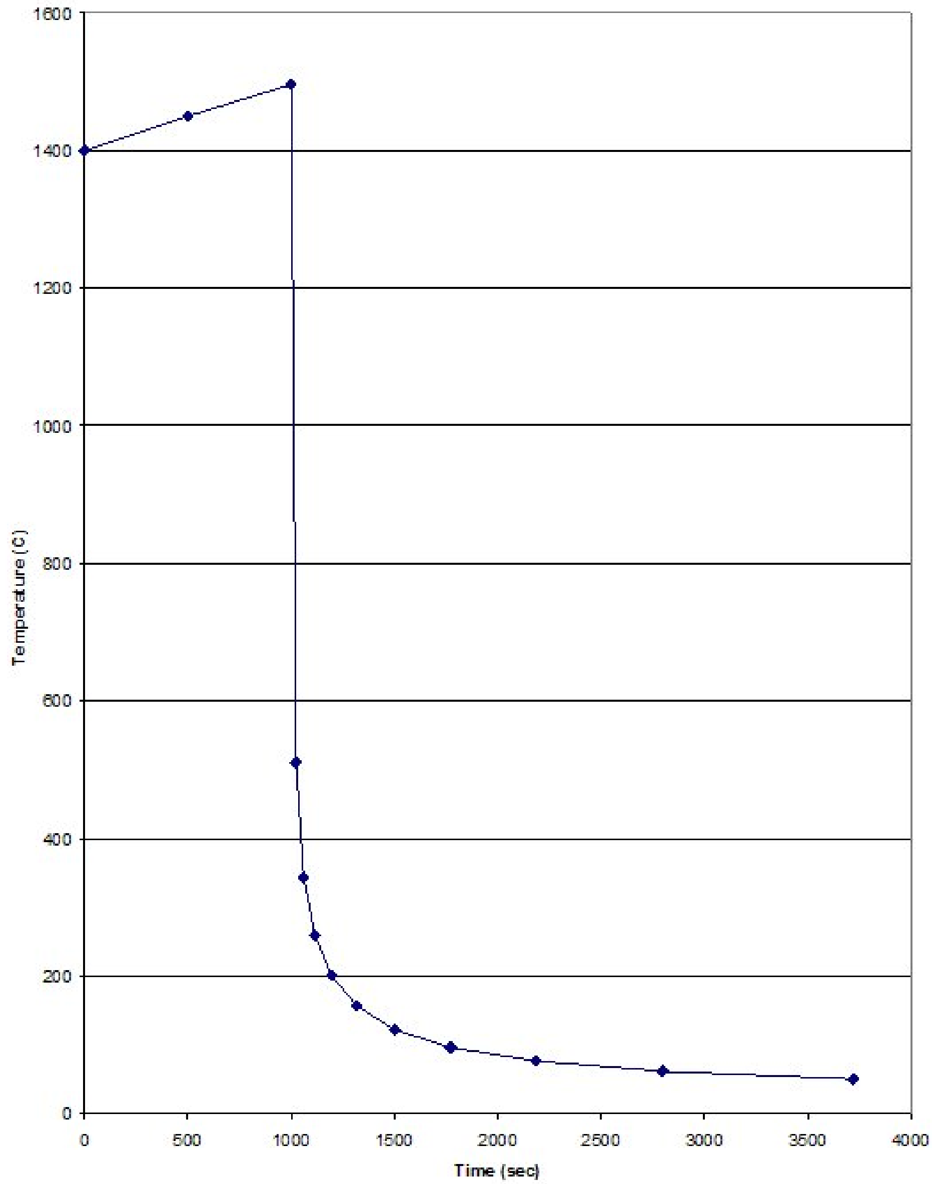

Figure 22 Temperature vs. time plot as the torch passes the end of a weld pass

7.2.3 CTSP Validation with Numerical Solutions and Measurements

Theoretically, finite difference methods (FDM) and finite element methods (FEM) are likely to obtain more accurate results than analytical solutions since the analytical solutions require additional assumptions, such as temperature-independent material properties and ignorance of latent heat effects. Therefore, it is necessary to compare the CTSP solutions with the finite difference method (FDM) and finite element method (FEM) numerical results to show its appropriateness.

Figure 23 shows the temperature comparison between the CTSP and the FDM, which is a fluid mechanics model of the weld pool developed by some of the current authors [22, 23, 24]. This FDM model includes fluid flow within the weld pool, latent heat effects, convection, radiation within the molten pool, temperature dependent material properties, among many other detailed features. Three different views of temperature distribution from the top, transverse cross section and the longitudinal cross section have been displayed in the figure. It can be seen that temperature distributions from two methods are very close to each other. Temperature difference is more obvious in the weld pool shapes and less significant outside the heat affected zone. It was shown in Reference [24] that such a small difference has a second order effect on displacement and residual stress predictions. Extensive validation with other FDM solutions was made in developing and perfecting this CTSP model as well.

In addition, the CTSP results are compared with the FEM results. The temperature history at three nodal points is compared between FEM and the CTSP solution (as shown in Figure 24). The nodal point 25 is located at the weld root, and the nodal points 31 and 45 are located farther from the weld. The temperature differences on these three points between FEM and the analytical solution are all small, which means that the CTSP results have good agreement with FEM results.

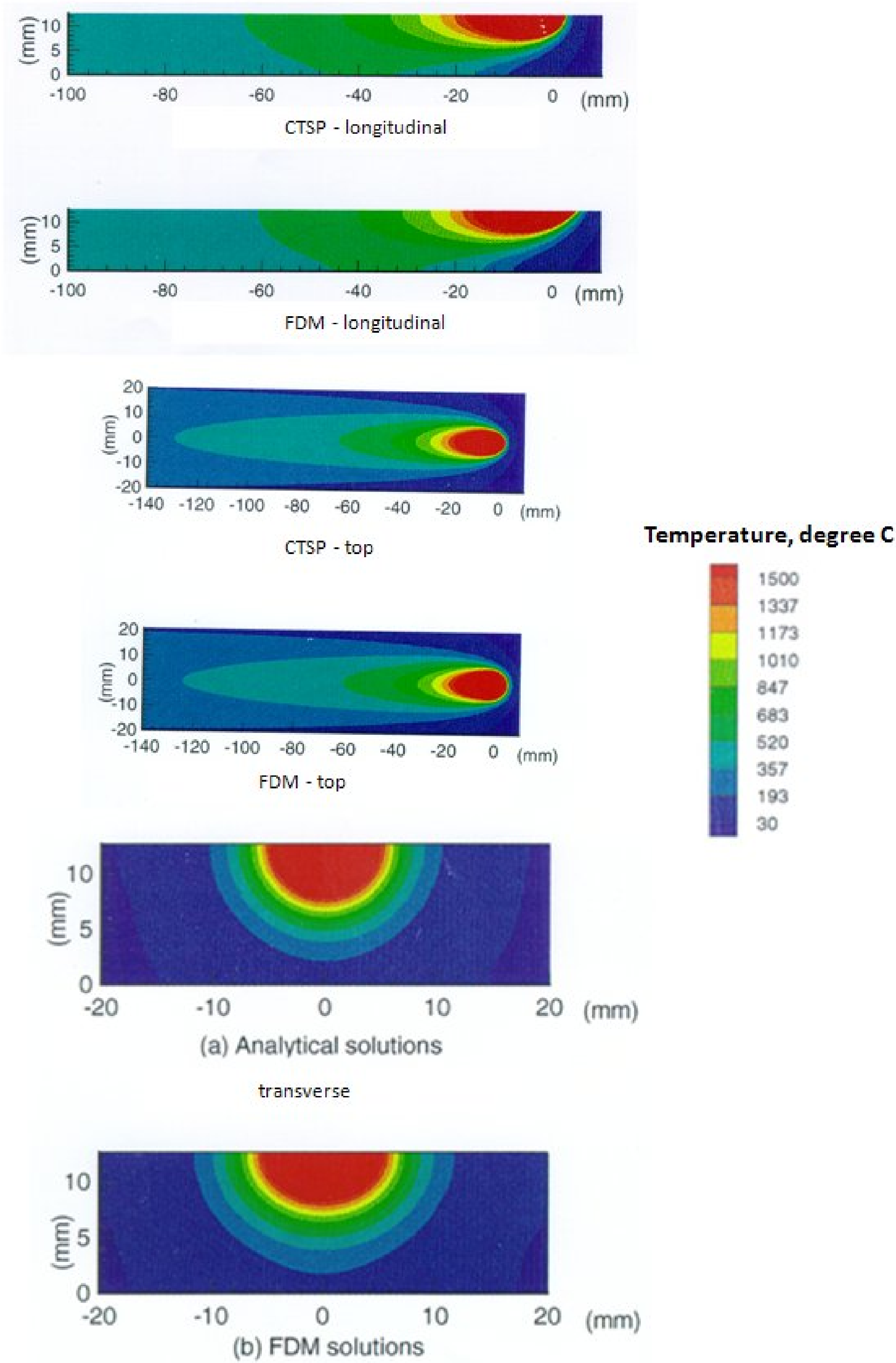

Figure 23 Temperature comparison between CTSP and finite difference methods

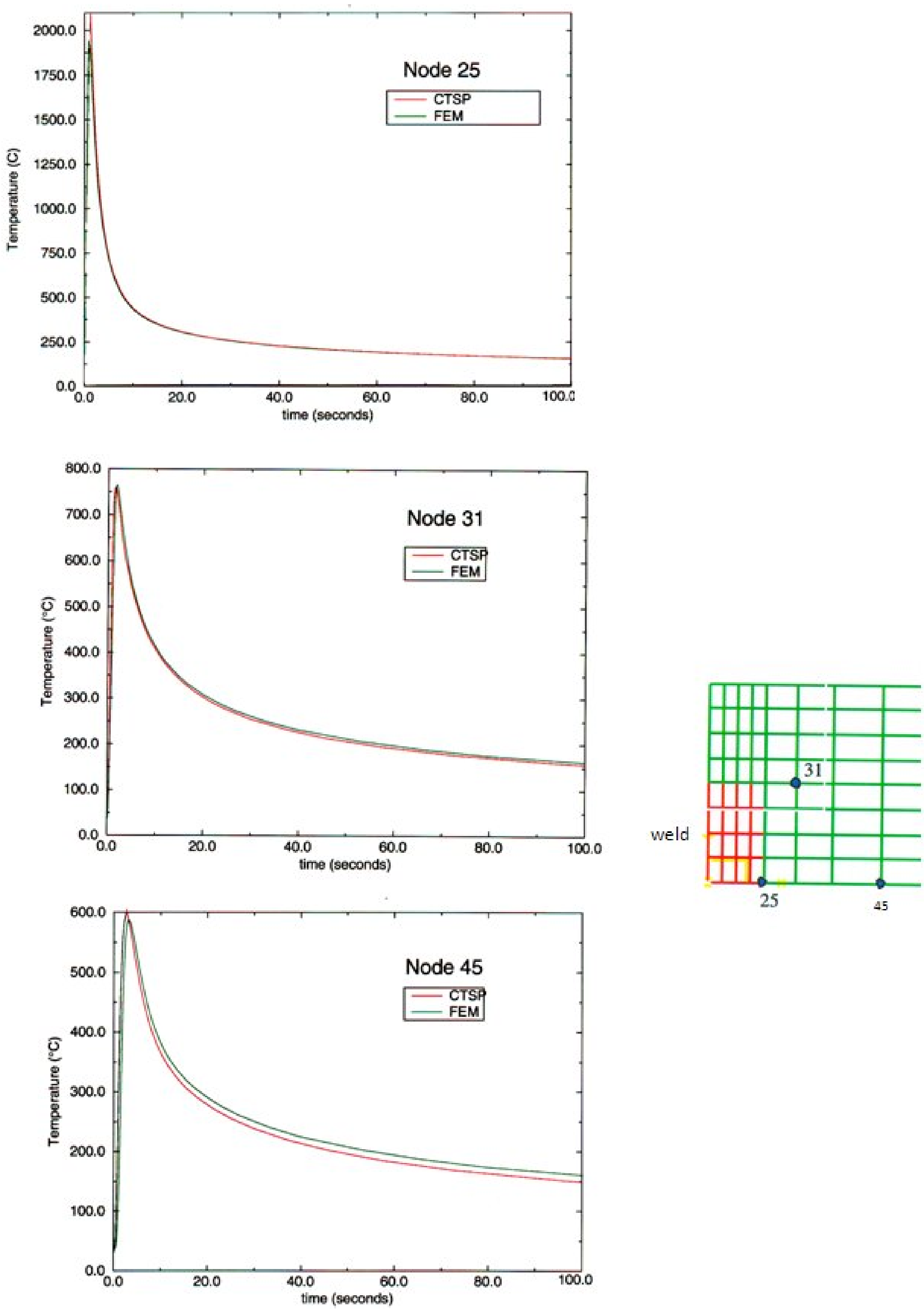

Figure 24 Predicted temperature history between CTSP and FEM for bead-on-plate case

In addition to the numerical validation comparisons of the CTSP model, a series of experimental tests were performed to compare temperature history with predicted results. Figure 25 and Figure 26 are temperature history comparisons between the CTSP predictions and experimental results for bead-on-plate and T-fillet welds, respectively. It can be seen that the predictions have good agreement with experimental measurements.

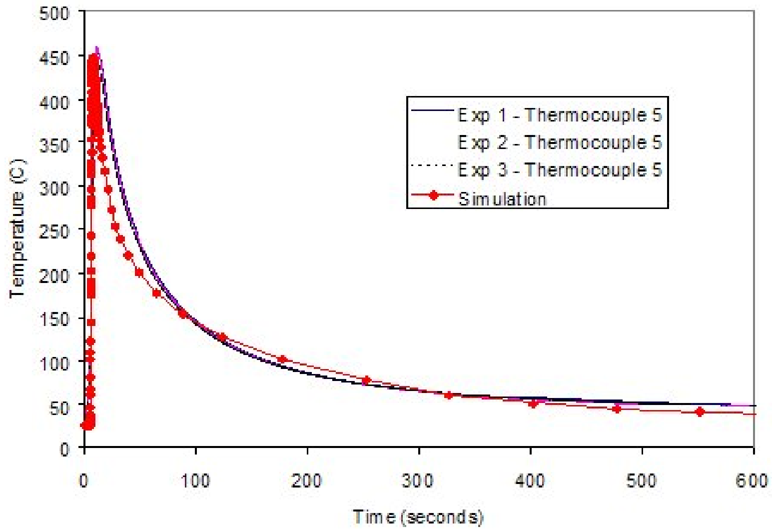

Figure 25 Temperature history comparison between CTSP and experiments at bead-on-plate welds (255A, 22.4V, 16.93mm/sec, 3mm thick, 6.5 mm from the weld center line)

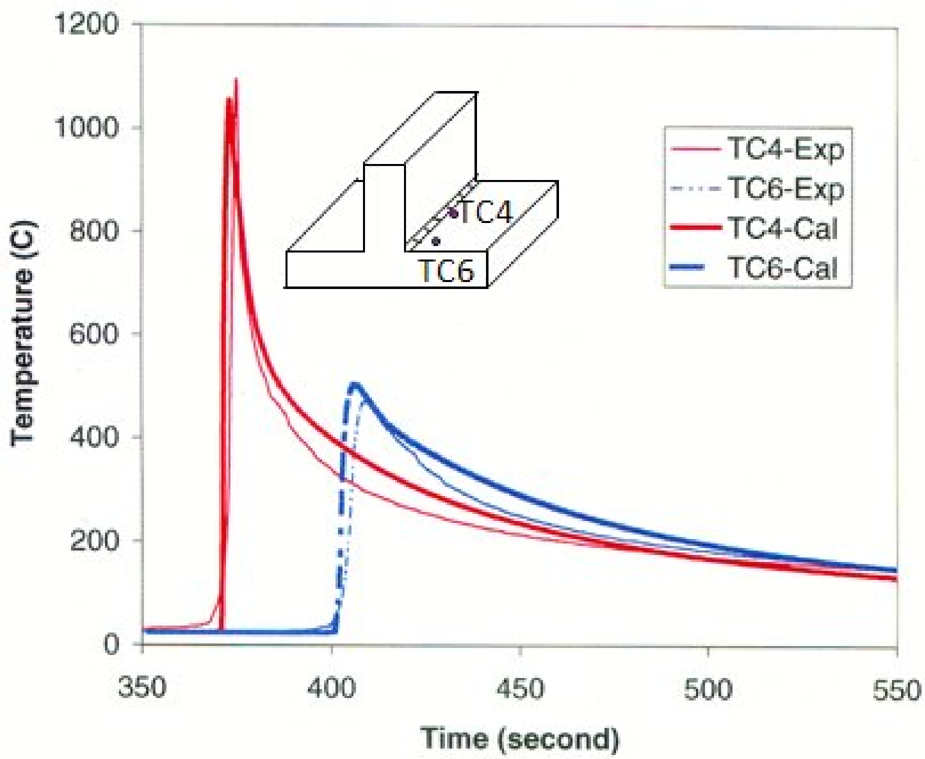

Figure 26 Temperature history comparison between CTSP and experiments at T-fillet welds (TC4: 0.5mm from weld toe; TC6: 4.5mm from weld toe)

Using the CTSP solution package, a number of models have been tested on many welded structures. Figure 27 shows temperature distributions during the welding process for several test pieces. Figure 27(a) is a T-joint structure with a solid back plate and Figure 27(b) is with a square cutout. A set of reflected heat sources is used to prevent heat loss from the cutout, and these sources are located at the mirror position with respect to the near cutout surfaces. The temperature in Figure 27(b) is higher than that in Figure 27(a) since there is more heat accumulation near the cutout.

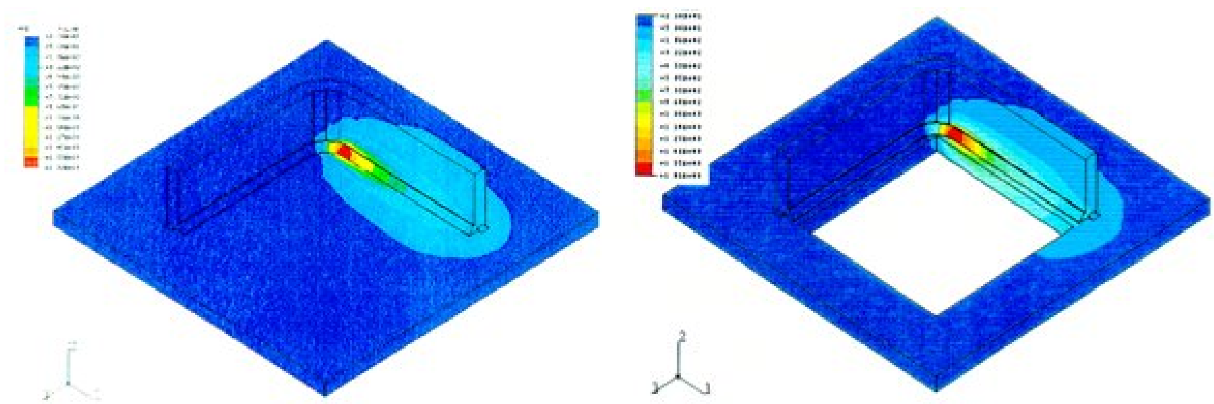

Figure 27 Predicted temperature distribution on different welded structures (a) without cutout; (b) with cutout

Many thermocouples were used to measure temperature history on the structure of Figure 27(a) during welding. Thermocouple placement has been shown in Figure 28(a). Temperature history comparisons between measurement and prediction have been shown in Figure 28(b) and (c), respectively. It indicates that overall there is good agreement between measurement and prediction for all thermocouples, although there is small discrepancy at peak temperature for thermocouple 2 which has negligible effect on residual stress predictions. It is emphasized that numerous additional full-scale validations of CTSP were performed during this Phase I development. Groove welds in plates, Tee-fillet specimens, lap joints, as well as full scale large components with cutouts, etc., were instrumented and used to validate and improve the effectiveness of CTSP.

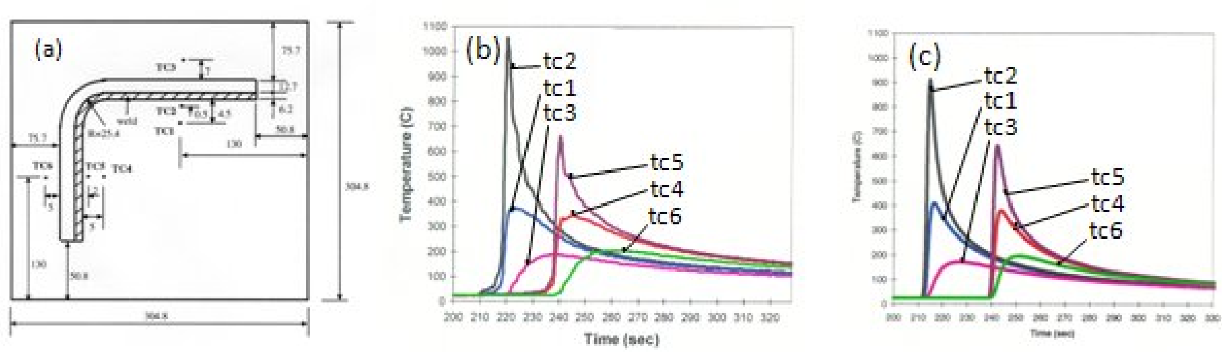

Figure 28 Temperature history comparison between prediction and measurement (a) thermocouple placement; (b) measurement; (c) prediction

7.2.4 Tailoring the VFT Weld Specific Constitutive law to WARP3D

The weld process is highly nonlinear with material melting, annealing, and material being deposited as the weld torch moves along, cyclic straining, etc. This can lead to unique material phenomena for some materials such as phase transformation plasticity, among other complications. Indeed, general purpose commercial codes such as ABAQUS do not have these features or the features are inconvenient to use. As such, VFT has a weld specific USER routine to perform these tasks with ABAQUS. This UMAT routine was extensively modified in order to work properly with WARP3D.

After the implementation of the UMAT to WARP3D solution, the UMAT portion of the WARP3D solution could only perform in serial mode while other solution processes such as matrix reduction and inversion could be performed using either Message Passing Interface (MPI) on multiple processors each with multiple threads, or on multiple threads alone. This was because the architecture of the UMAT was not compatible with the WARP3D MPI/thread solution process. The solution for this was quite difficult and time consuming. Initially, we considered re-writing the entire UMAT using modern coding procedures (the original code architecture was developed in the late 1990's). Since this is a very large task (the UMAT is a very large FORTRAN code) an alternative solution was pursued. A UEXTERNAL procedure was written for WARP3D which transferred certain material parameters to the UMAT one time (up front). After much effort this procedure resulted in complete MPI/thread performance of VFT with WARP3D with solution speeds that are much superior to ABAQUS. Re-write of the UMAT is something that will be needed in the future, perhaps in a Phase III program, but the immediate problem was overcome for this Phase I effort. This was perhaps the most difficult part of merging VFT with WARP3D!

7.2.5 Nonlinear Solution Parameter Definition and WARP3D Modification

WARP3D has been mainly used in the solution of fracture and damage mechanics problems in recent years. As such, the definition of the nonlinear solution parameters so that an optimum solution could be performed without divergence was critical. When VFT was first converted to run on WARP3D computational weld problems, it often diverged due to the unique aspects of the weld problem (for instance, material melting, being deposited, being annealed, etc.). When this happened, the user often had to modify the step sizes and perform a restart analysis. This is not acceptable for a code that is to be used by novice modelers in SMEs. The solution must not diverge for the casual user of VFT.

This required extensive studies of the necessary nonlinear solution parameters most efficient for using WARP3D for the weld problem. These were carefully determined and were added to the GUI so that when the WARP3D input file is written out for solution the proper parameters are defined. However, even with this fix some problems diverged as the solution was not robust. As such, the nonlinear solution process for WARP3D was modified to be more appropriate for VFT weld problems. This has essentially eliminated divergence and the solution is now robust.

It is noted that WARP3D has both direct and iterative solvers permitted with only the change of one solution parameter. For all of our solutions to date we have used the direct solver, which is appropriate for smaller problems. For huge problems (perhaps with one million elements or larger) the iterative solver may increase solution speeds. This will be investigated within the Phase II program.

7.2.6 VFT WARP3D Post Processing

The Paraview open source (DOE) code was obtained for use in visualizing results. This will be part of the VFT system on the Manufacturing and Polymer Portal (M&PP). This required some modification of WARP3D in order to write out parameters necessary. In particular, the temperatures can be written out and viewed in Paraview now. This is important to visualize whether the temperature fields obtained from CTSP look reasonable.

7.3 Adaptive Mesh Refinement Study

VFT weld modeling is ideally suited to Adaptive Mesh Refinement (AMR) for two reasons.

- Most of the structure is linear elastic, with non-linear behavior confined to the small regions of weld metal and heat affected zones.
- Weld modeling involves a long sequence of time-consuming non-linear structural analyses, so economizing on mesh size is very important.

The existing formulation of VFT-CTSP, using mathematical functions for torch heat flow, imposes a number of requirements upon the finite element mesh. The functions are oriented in the mesh by computing the weld pass direction and by user-input plate normals. In its present form CTSP insists upon hexagonal weld group elements for these purposes. Robust mesh refinement algorithms tend to generate a variety of hexagonal, wedge, and tetra elements, making it impossible to implement them without an extensive rewrite of CTSP.

There is also some question about the criterion to use in driving the AMR process. Weld residual stresses, strains, and distortions are very sensitive to material properties, so further study is warranted to elucidate a stable statistic for AMR in weld regions. Also, due to the severe nonlinear nature of the computational weld problem, the necessary interpolations of the field variables (in the case of phase transformation plasticity there are a total of 27 field variables that must be managed) would likely render convergence problems with the WARP3D format. Moreover, as will be seen later, solution speeds with WARP3D on MPP/threads are superior and quite useful for the M&PP. In addition, the implementation of an AMR scheme to the VFT process using WARP3D, would be intensely time consuming and costly without knowing whether the performance would result in a robust solution process.

Therefore, the process of adapting AMR to VFT is abandoned for Phase I and II. It may be considered for Phase III.

7.4 Plan For Porting VFT to Ohio Supercomputer System

We evaluated the capability of the Ohio Supercomputer Center through the PolymerOhio via the Manufacturing and Polymer Portal to house the adapted HPC version of VFT® for use (adoption) by SMEs in the US. The plan includes use of the current format of the M&PP but in an extended form to include the US and Ohio's (other than polymer-based) manufacturing industries. Thus, the extended version of this portal will provide outreach to industries for technologies that improve processes and lower costs to manufacture products.

We envision that use of such an expanded portal would involve (at a minimum) three major aspects:

1) With the Ohio Supercomputer Center (OSC), the feasibility of installing VFT® on the M&PP has been established. This would house or provide a repository for the adapted version of VFT® and makes this version of VFT® easily accessible to industries in Ohio and other states. The use of the current M&PP (primarily polymer-based) industries over the past number of years has demonstrated and proven the feasibility of this technology outreach approach.
2) Identified the best approach to develop the interface between user and the computational resources at OSC to efficiently access the VFT® software. Ohio (and other states) industries will have access to the adapted HPC version of VFT® using the format/method that is in place in the current M&PP. This particular technology, modeling/simulation software for analysis and design of welded structures, can have on-line and/or in classroom training available for members. Both modes of training (on-line and classroom) for use of new technologies are currently available through the M&PP. By negotiating a special license with the provider of particular simulation software, the M&PP is allowed to provide access to the software, training in its use and personalized support. Affordable, pay-for-use prices are arranged with time intervals appropriate for users to easily complete simple and/or complex projects using the particular software. For example, the M&PP's mainstay software, Moldex3D, simulates the mold-filling process during plastic injection molding. Whereas a conventional license for use of the Moldex3D software costs approximately $30,000 per seat per year, Moldex3D can be accessed through the M&PP for $200/day, $800/week, and $2400/4 month. A two day classroom course costs $500 and on-line training, including a theoretical background on the process, costs $200.
3) Completion of an extended survey of Ohio manufacturing firms to gauge interest and current capability of potential companies for use of an adapted version of VFT®. Ohio is a rational choice as a pilot area for this program because it is the one state within the U. S. with the largest number of employees and revenues from manufacturing.

8 PERFORMANCE OF VFT AND VALIDATION

As described in earlier sections, VFT computational weld analyses can now be performed using WARP3D. The packages for the WARP3D code have a number of manuals associated with them. The user should become familiar with these manuals prior to using this tutorial. However, the following procedure with the use of the GUI should permit the VFT user to use WARP3D to solve weld problems with minimal need for the WARP3D manuals.

The procedure for a VFT based computational weld analysis is summarized in the steps below.

Step 1. Read the weld based finite element mesh into the GUI.
Step 2. Define the material definition sets and weld parameter sets. Up to 10 materials can be used and as many weld set parameters as desired although there are usually only a few of these required. Moreover, each weld parameter can be redefined during pass definition.
Step 3. Define all of the weld passes. This includes the cooling times desired for each pass.
Step 4. Define boundary conditions.

Step 5. Write out the input file for the thermal analysis (CTSP) along with the number of cores desired for CTSP solution.
Step 6. Perform CTSP analysis, merge results, and write the files in the format required for WARP3D analysis. This is all done automatically with the GUI.
Step 7. Write out the input file for WARP3D. The preferred nonlinear solution parameters for weld analysis, and all other parameters needed for the WARP3D analysis are automatically set. The user chooses the number of output plot files and restart files desired. This also writes out utility routines such as VED needed for the analysis. While it is useful for the user to be familiar with WARP3D and the corresponding User manuals this is not necessary as the complete input file is written necessary for analysis.
Step 8. Perform the WARP3D analysis. This usually requires porting the input files to a Linux cluster and performing the analysis on as many threads as possible.
Step 9. Run a utility routine to convert the WARP3D output to Paraview for viewing.
Step 10. Examine results in Paraview.
Step 11. If distortion goals or weld residual stress goals are not met, use the GUI to modify pass sequence, boundary conditions, pre-camber definition, etc and go to Step 5 and repeat to achieve the desired goals.

8.1 Example Analyses

A number of example cases were run and results compared to ABAQUS results. Below we present three of the smaller example problems that were solved with both ABAQUS and WARP3D during the development and validation phase of this program. We only present three small examples as exemplars. The new VFT system was then exercised on an actual Caterpillar component, called a 'pant leg' that represents a component in a heavy fabrication where the weld sequence was optimized. The details of the optimization scheme cannot be discussed due to the proprietary nature. However, one of the sequences examined, which did not result in an optimum sequence in terms of distortion control is discussed in detail. The final example is a very large problem that was solved with the new open source VFT code only. After this a summary of speed enhancements with the WARP3D solution are presented and compared to ABAQUS.

8.1.1 Tee-Fillet Example

The first example is a simple Tee-fillet weld as seen in Figure 29 and Figure 30. Figure 29 compares distortion magnitudes and Figure 30 compares stresses. The left plot is using reduced (1-point) integration (ABAQUS), the middle plot is full integration (ABAQUS) and the right plot is the WARP3D solution. WARP3D handles element locking using a B-BAR approach, while ABAQUS (for 1-point integration) uses reduced integration with hour glass control. The full integration used no locking control but it seemed to produce reasonable results here. Good comparison is observed verifying the implementation scheme into WARP3D.

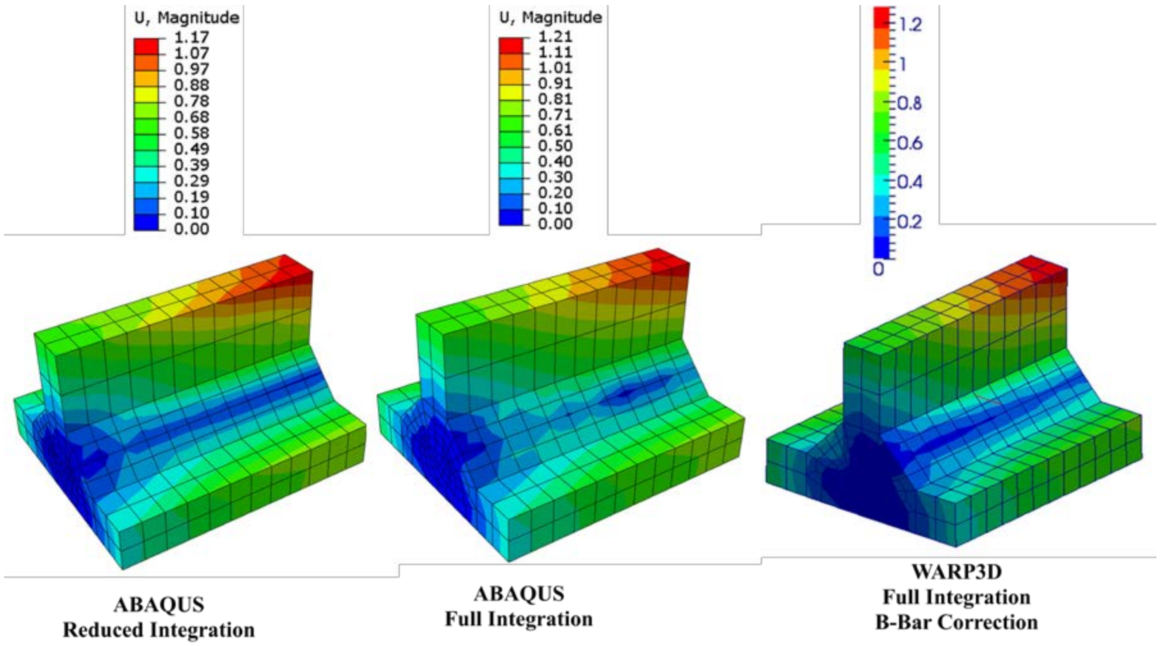

Figure 29 Distortion magnitude comparisons

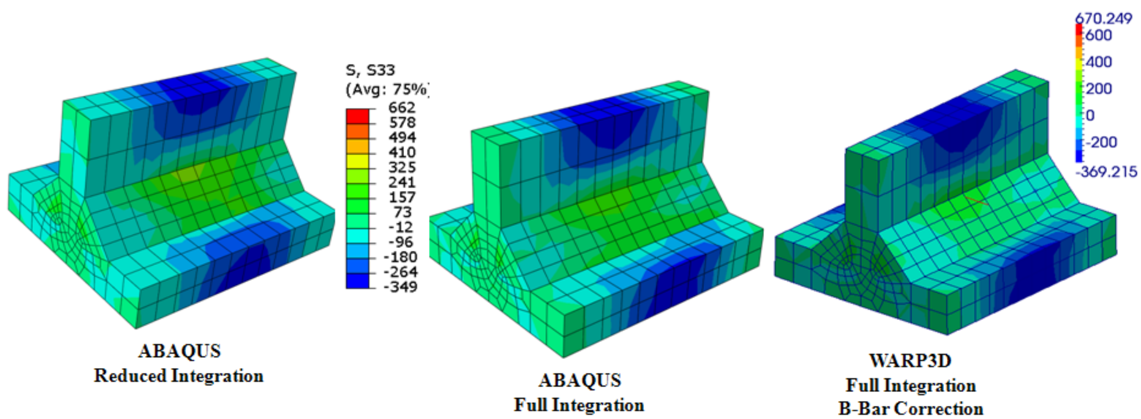

Figure 30 Weld direction stress comparisons

8.1.2 Coarse Pipe Model

The very coarse pipe model was considered next. This is a coarse mesh but examines the ability of VFT-WARP3D to handle curved pipe type welds (girth welds). The mesh is shown in Figure 31 and the axial stress comparisons are shown in Figure 32, which is a cut at about half way along the length. The torch start/stop points are seen in Figure 32 where the compression is shown. This is typical of the effect of torch start/stop on weld residual stresses where the stress typically reverses sign. It is seen that the comparison is again very good. Note that some slight contour differences appear and this is mainly due to the contour interpolation methods used between Paraview and ABAQUS. The actual values at the Gauss Points were checked as well with excellent comparison.

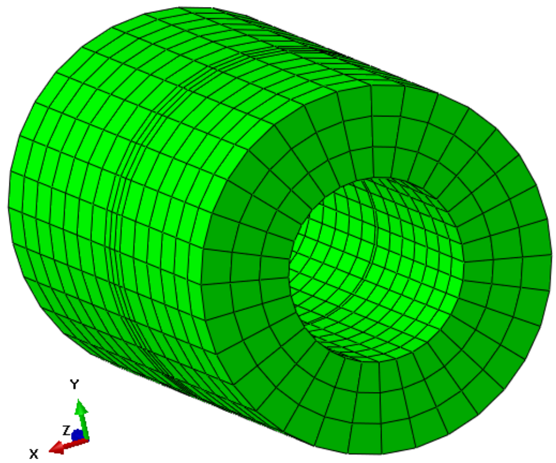

Figure 31 Coarse pipe model example – circumferential girth weld

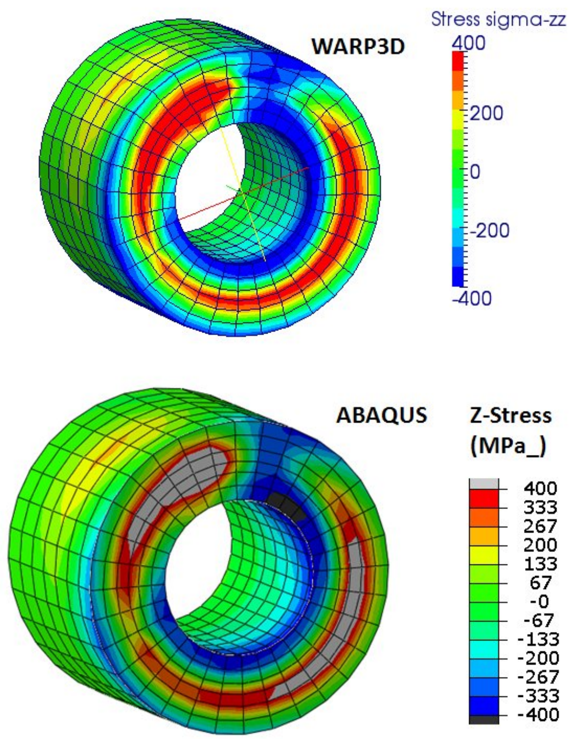

Figure 32 Axial (Z-component) stress comparisons between ABAQUS and WARP3D

8.1.3 Circular 'Boss' Weld in Plate

A boss is a typical weld used in many cases in light and heavy construction fabrication to reinforce a plate. An example is shown in Figure 33 where the lap weld is shown in blue. This is actually an important component that is used to reinforce certain regions of structures where fatigue life in the weld is important. Often holes are drilled after fabrication through the reinforcement where distortions that occur during the drilling process because the WRS are rearranged may become important. All of this can be modeled. The welds are shown in 'blue' in Figure 33.

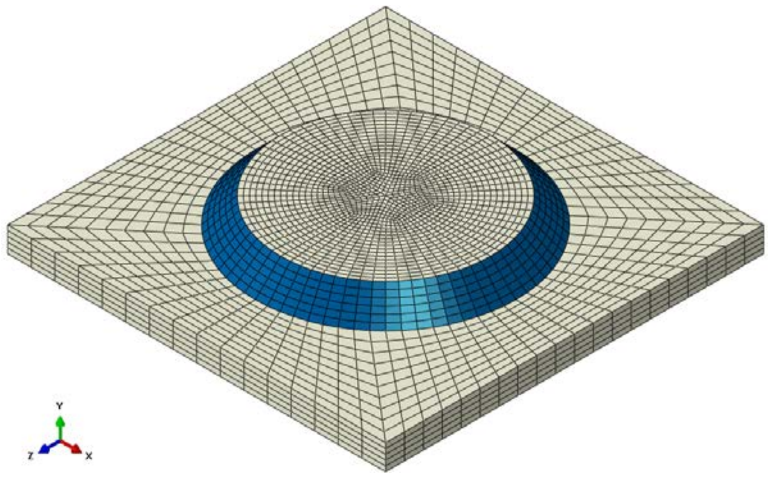

Figure 33 'Boss' reinforced plate weld model (lap weld)

Figure 34 compares distortion magnitudes. The left plot is using reduced (1-point) integration (ABAQUS), the middle plot is full integration (ABAQUS) and the right plot is the WARP3D solution. WARP3D handles element locking using a B-BAR approach, while ABAQUS uses reduced integration with hour glass control. The full integration used no locking control but it seemed to produce reasonable results here.

The x-direction stress comparison is shown in Figure 35. Again, good comparison is observed with the full integration ABAQUS solution considered to be less accurate. The WARP3D solution times were improved during the solution of this problem by optimizing the step size definitions and the step size was too fine to ensure convergence. Finally, Figure 36 shows comparisons of Z-component stress along a cut plane. Good comparison is observed again showing that the VFT conversion to WARP3D was successful.

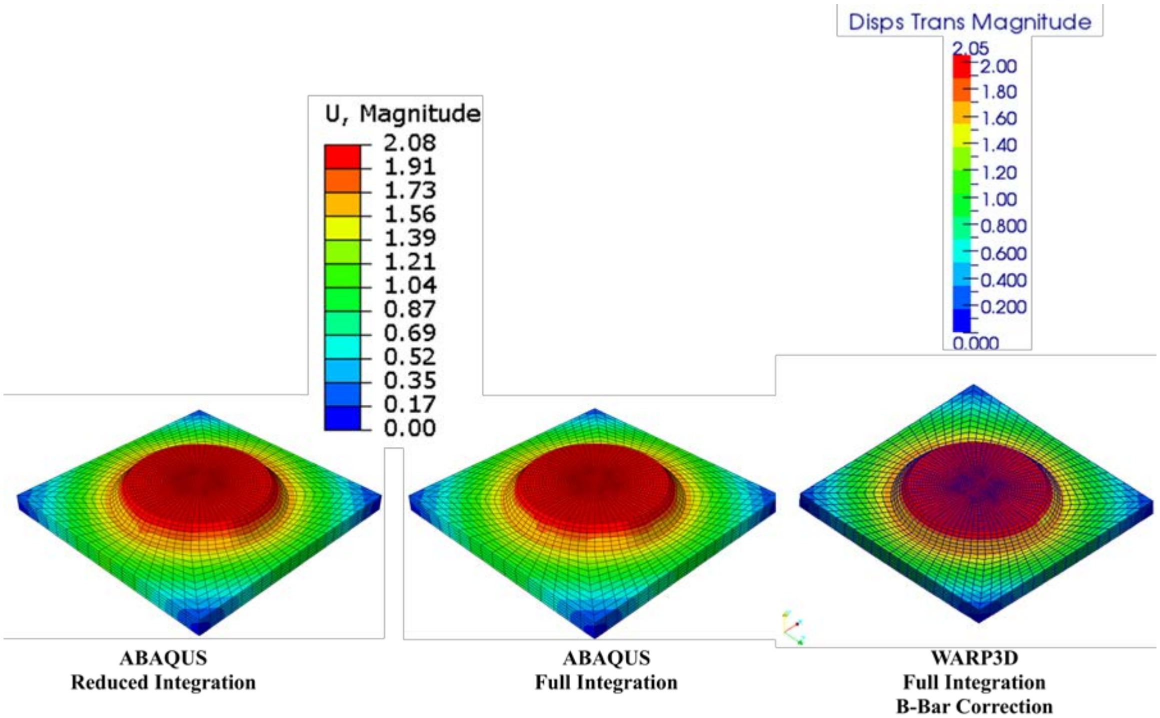

Figure 34 Distortion magnitude comparisons)

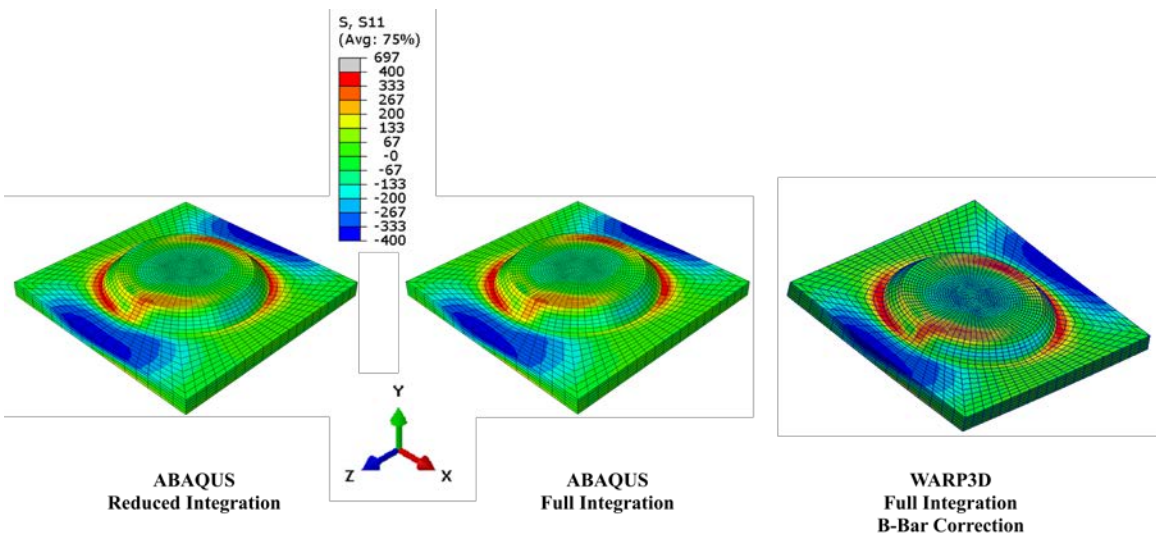

Figure 35 X-Component Stress comparisons on cut plane

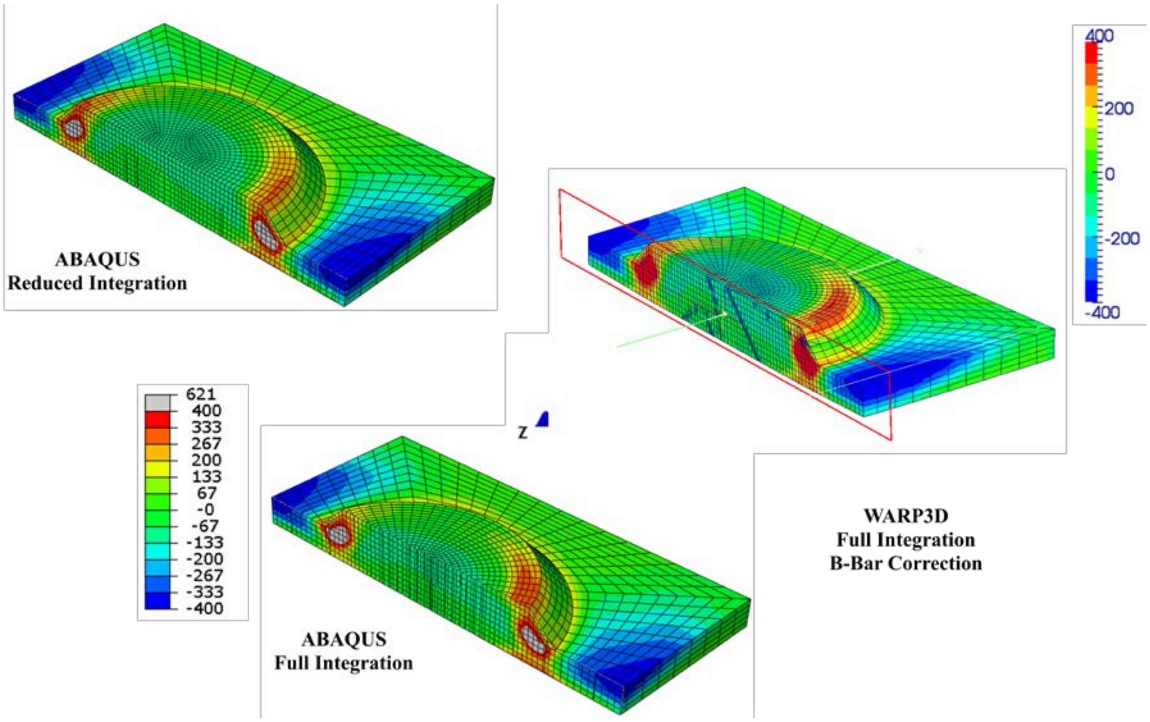

Figure 36 Z-Component Stress comparisons on cut plane

8.1.4 'Pant Leg' Solution

After implementation of VFT into the open source format of WARP3D and validation with a number of smaller problems (three of these were summarized in Sections 8.1.1, 8.1.2, and 8.1.3 above) an actual component was considered. The goal for this component is distortion control so that expensive and time consuming component straightening operations could be avoided after fabrication. Indeed, control of such distortions (and/or weld residual stresses) is a key competitive advantage to organizations that use weld modeling tools. Due to the proprietary nature of this, only some details are presented and the final solution sequence and how this was obtained are not discussed.

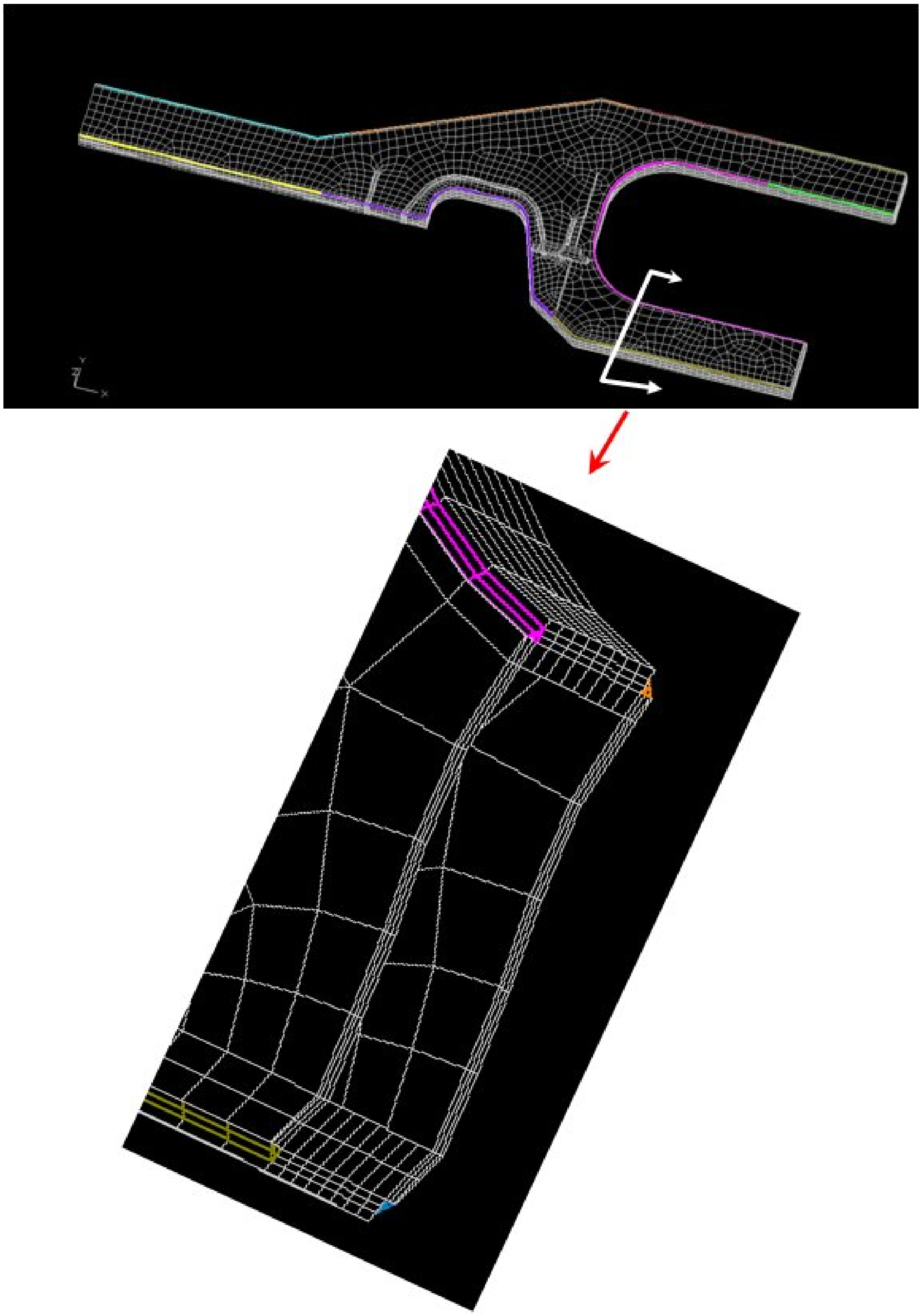

Figure 37 Pant leg problem showing welds and cross section

Figure 37 illustrates the component which is shaped like a large tuning fork or 'pant leg'. The component mesh was developed and read into the VFT GUI. The materials, weld passes, sequence, etc. were defined and the CTSP and WARP3D files were developed and the weld analysis was performed. The weld pass definitions for this example are shown in Figure 37 with different colors. The model consisted of 32594 nodes and 24892 8-node brick elements with 18 passes that needed to be optimized. The lower cut illustration in Figure 37 shows that the cross section is 'box-like' with lap fillet and Tee-fillet welds. This mesh is rather coarse but was adequate for this problem since distortion control was the main aim. After analysis, if the distortion goals are not met, the weld sequence is modified within the GUI and another analysis is performed.[**] It is noted that the results of the optimized sequence were verified with shop measurements and the solution was implemented on the shop floor for this component.

Figure 38 compares the predicted distortions from the VFT with open source WARP3D and ABAQUS. The comparison is very good with the WARP3D solution considered a little more accurate because of the 1-point reduced integration used with the ABAQUS model with hour glass control since the mesh was rather coarse. The maximum distortion magnitude is just less than 3 mm for this sequence, which was not the final goal.

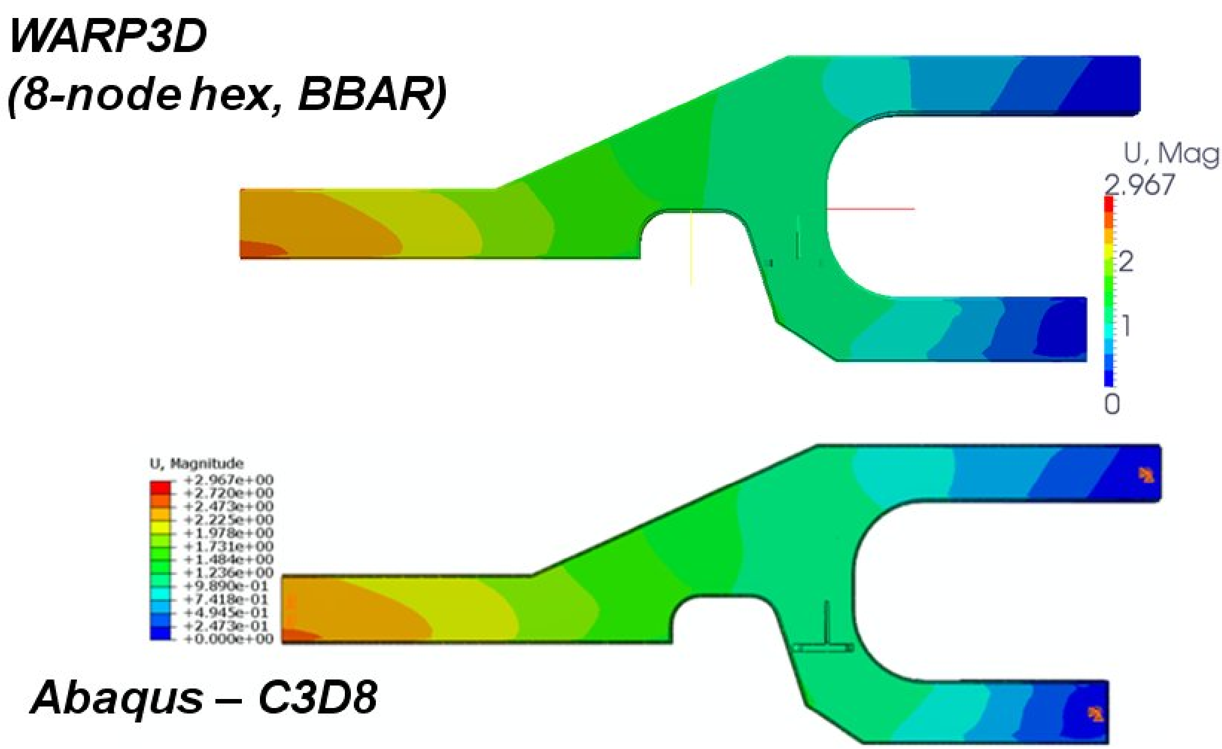

Figure 38 Pant leg problem distortions

[**] The specific process for weld sequence optimization cannot be discussed here.

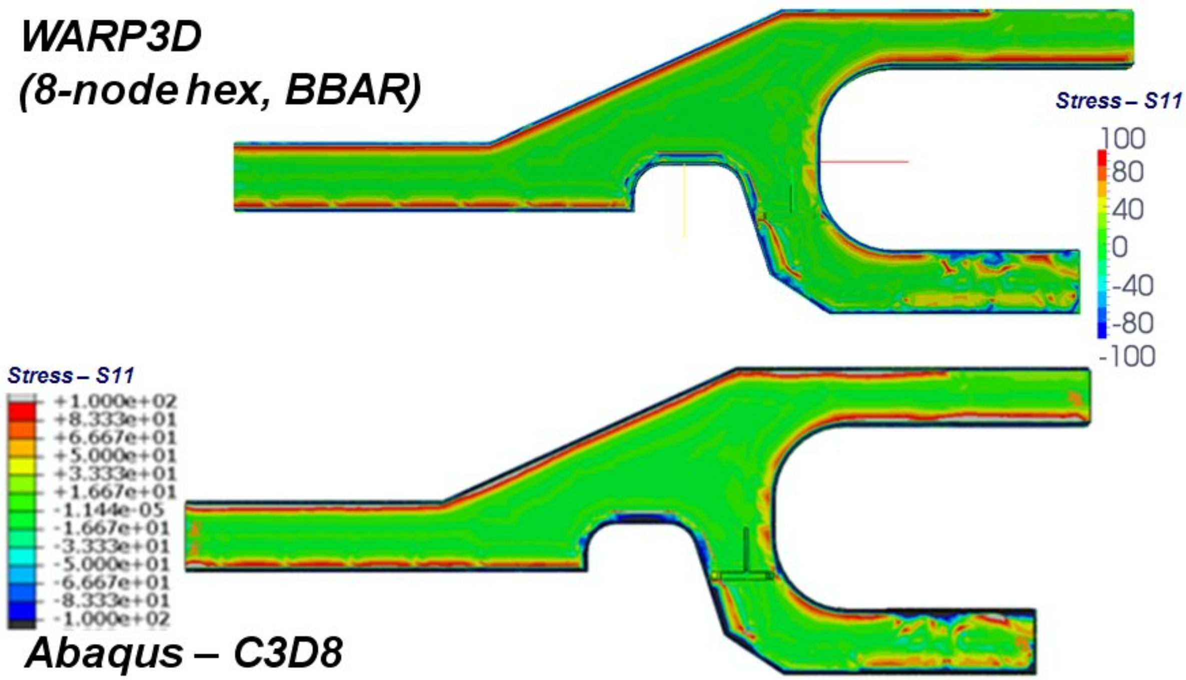

Figure 39 Pant leg stresses in major weld direction

Figure 39 compares the stresses in the long weld direction, which are most important for this problem. Comparison is good (note that the applied boundary conditions appear in the ABAQUS results with the 'orange' characters). A rather complete study of the convergence and speed comparisons between ABAQUS and WARP3D solutions is summarized in Section 8.2.

8.1.5 'ROP' Solution

The final example shown is a very large problem illustrated in Figure 40. This component consists of 48 welds and the model has 210908 nodes, 186150 8-node brick elements, and a total of 48 passes. The component mesh was developed and read into the VFT GUI. The materials, weld passes, sequence, etc. were defined, the CTSP and WARP3D files were developed, and the weld analysis was performed. The weld pass definitions for this example are shown in Figure 40 with different colors. The lower illustration in Figure 40shows that the cross section is 'box like' with groove and Tee-fillet welds. This mesh is quite fine (one of the largest problems solved to date with VFT) since prediction of weld residual stresses necessary to accurately perform a fatigue analysis was the main aim. Full details of this problem are not presented due to the proprietary nature of the analysis. However, this is an actual production component.

Figure 41 shows the predicted final distortion pattern. The bottom of the ROP was fixed during welding for this example and thus the displacements are zero in this region. The maximum distortions are near the top, as expected.

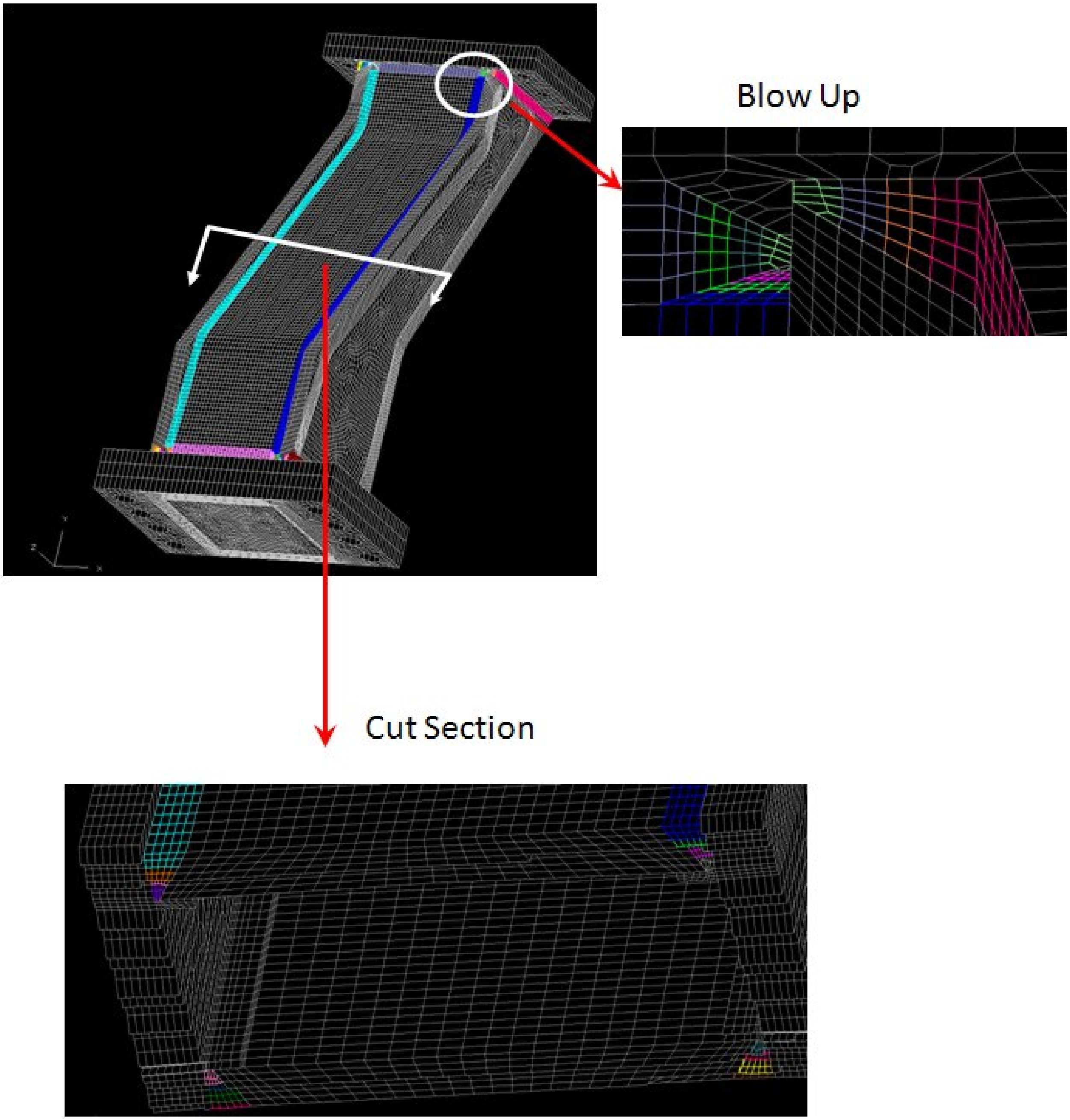

Figure 40 ROP problem

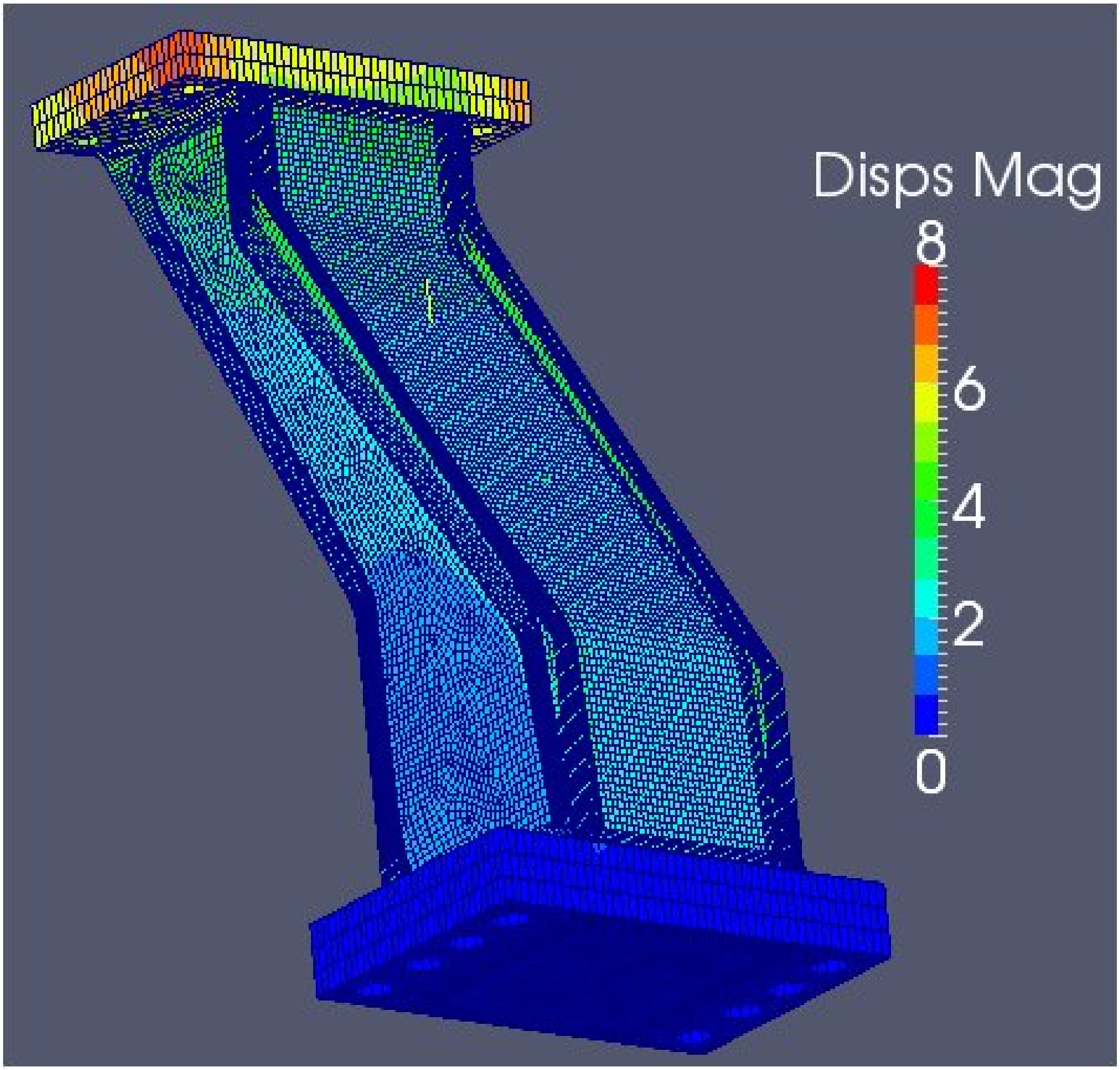

Figure 41 ROP problem displacements

Figure 42 shows the Von Mises stress produced after welding is complete. It is seen that this weld sequence results in regions of high stress. Figure 43 shows the 'Y-component' stresses or those stresses in the direction of the long welds in the ROP. The stress in the weld direction, where solidification shrinkage occurs, tends to produce the highest weld residual stresses. These stresses could contribute to reduced fatigue life when combined with the service loads. The bottom illustration in Figure 43 shows a blow up of the most critical weld residual stress region.

These stresses would then be used to perform a fatigue assessment. The mean stress effect with high tensile stresses plays a key role in both fatigue design and fatigue crack growth. During design, the weld process might be modified to reduce tensile stresses, or produce compressive weld residual stresses in regions where the service cyclic stresses are highest (or the critical fatigue locations). The process of engineering the weld residual stresses by controlling the weld process, weld sequence, and other methods (see Reference [3]) has become an important design consideration and will become more important in the future. Indeed, the locations of high tensile weld residual stresses should not be near the regions of high cyclic stresses for efficient design.

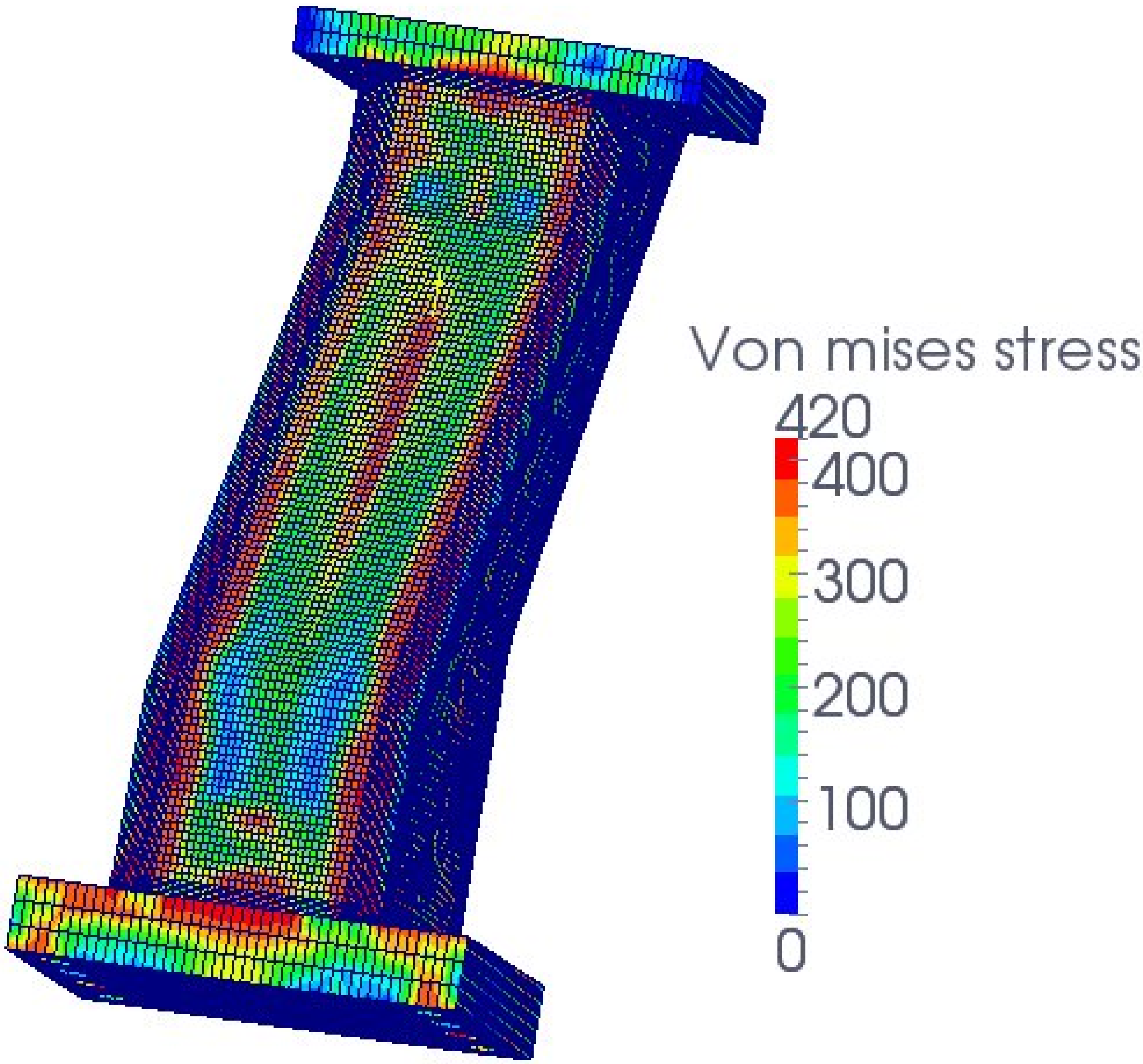

Figure 42 ROP problem Von Mises Stress

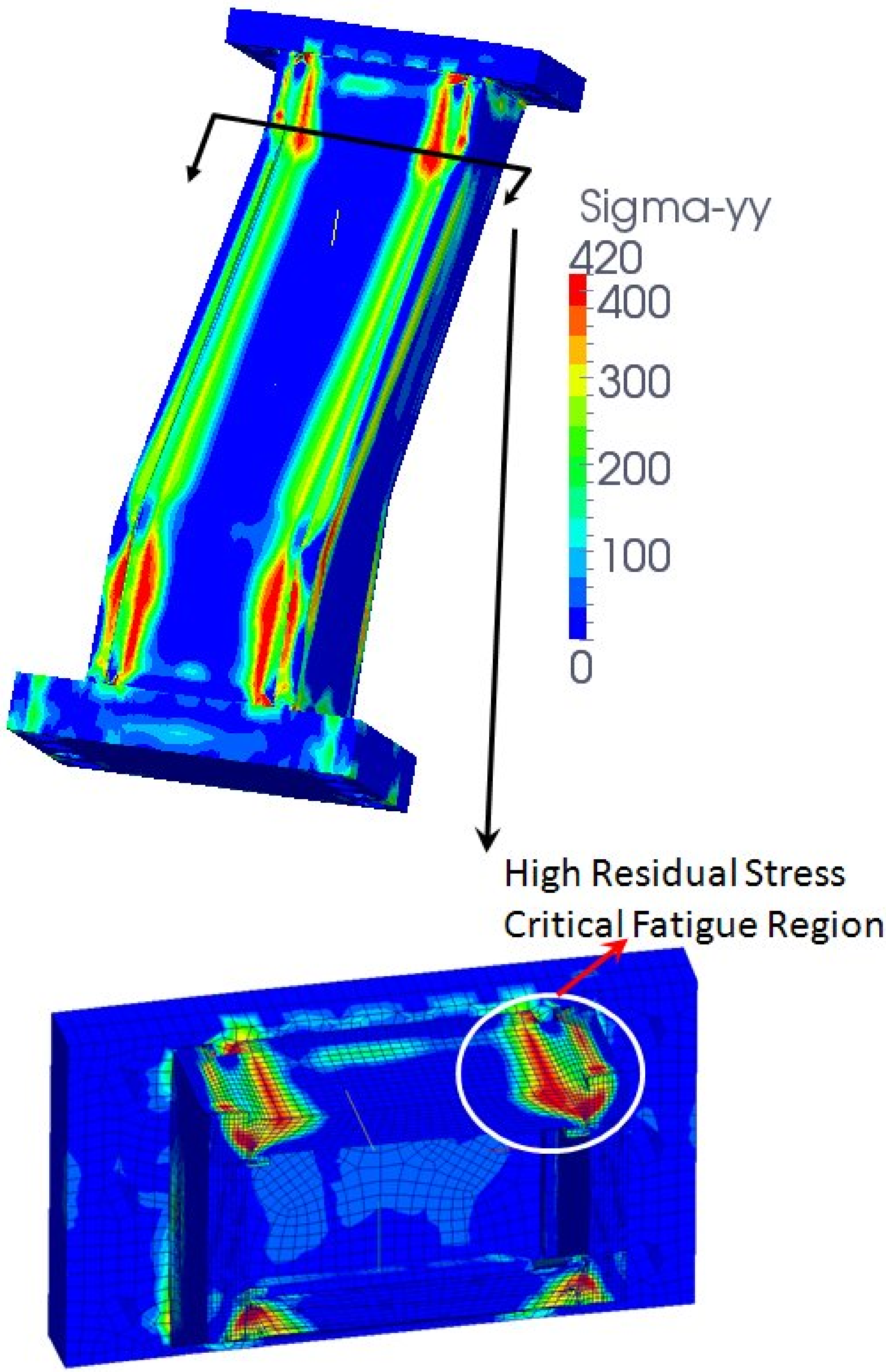

Figure 43 Long weld component stresses (important for fatigue)

8.2 Solution Speed Comparisons

The pant leg problem discussed in 8.1.4 was used to perform a rather detailed study of solution speed and convergence between WARP3D and ABAQUS. Table 1 summarizes the series of analyses that were performed for both ABAQUS and WARP3D. The number of cores used ranged from 1 to 16. The portions of the solution times were also summarized. Figure 44 plots these results. In general the speed of solution using WARP3D is nearly 68% faster than solutions using ABAQUS as the solver. These results were indeed surprising and welcome.

Table 1 Summary of speed comparison

Solver	Number of cores	Wall Clock Time [sec]	Speedup (Serial Time / Parallel Time)	Efficiency (Speedup / p)	Time: Abaqus / WARP3D	Time: WARP3D / Abaqus	Abaqus solver iterations	WARP3D solver iterations	Iterations: Abaqus / WARP3D	Iterations: WARP3D / Abaqus	WARP3D % time in stress	WARP3D % time in solver
Abaqus	16	6901	6.46	0.40	2.95		4448		1.60			
WARP3D	16	2338	6.12	0.38		0.34		2775		0.62	9%	33%
Abaqus	8	8329	5.35	0.67	2.59		4448		1.60			
WARP3D	8	3211	4.45	0.56		0.39		2775		0.62	10%	45%
Abaqus	4	13173	3.38	0.85	2.63		4448		1.60			
WARP3D	4	5009	2.86	0.71		0.38		2775		0.62	12%	55%
Abaqus	2	23845	1.87	0.93	2.87		4448		1.60			
WARP3D	2	8307	1.72	0.86		0.35		2775		0.62	13%	63%
Abaqus	1	44561	1.00	1.00	3.12		4448		1.60			
WARP3D	1	14304	1.00	1.00		0.32		2775		0.62	14%	67%
Abaqus:	Direct solver (threaded), UMAT (threaded), adaptive time increments, C3D8 (full integration)											
WARP3D:	Pardiso direct solver (threaded), UMAT (threaded), fixed time increments (cutback allowed), 8-node Bbar (full integration)											

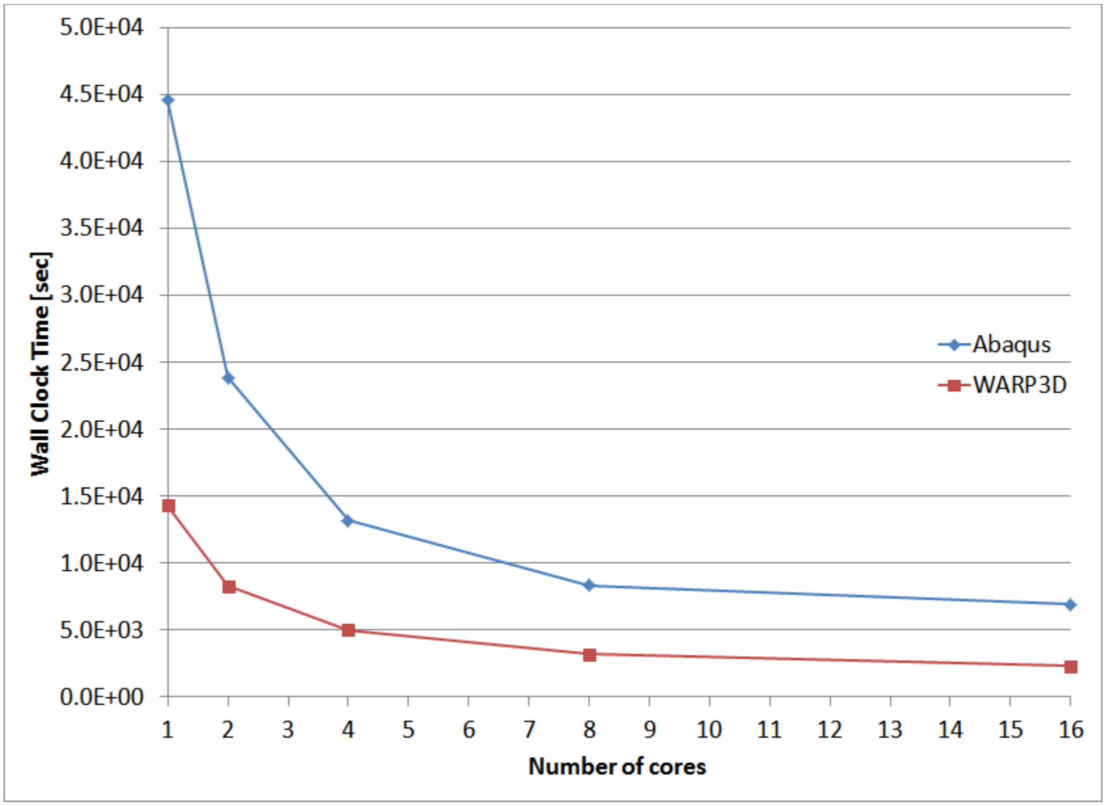

Figure 44 Solution time comparisons for VFT using either WARP3D or ABAQUS

9 SUMMARY

Through this DOE SBIR Phase I program, the computational weld modeling system, VFT, has been modified and adapted by including modules from US Government developed open source software. The code is now capable of being ported to a high performance computing system at the Ohio Supercomputer Center on The Ohio State University campus for access and use by small and medium size businesses on a fee-for-service basis. The DOE SBIR Phase II effort will require efficiency improvements in all areas developed in the Phase I program before the portal will be available for use by non-weld modeling experts. This Phase I program was a great success and fits well into the DOE SBIR plan for this initiative.

Many US manufacturing companies have moved fabrication and production facilities off shore because of cheaper labor costs. A key aspect in bringing these jobs back to the US is the use of technology to render US-made fabrications more efficient overall with higher quality. A new initiative of the current administration has the goal of enhancing competitiveness to retain manufacturing jobs in the US. One significant competitive advantage that has emerged in the US over the last two decades is the use of virtual design for fabrication of large structures in the heavy materials industry. Industries that have used virtual design and analysis tools have reduced material parts size, developed environmentally-friendly fabrication processes, improved product quality and performance, and reduced manufacturing costs. Indeed, Caterpillar Inc. (CAT), one of the partners in this effort, continues to have a large fabrication presence in the US because of the use of weld fabrication modeling to optimize fabrications by controlling weld residual stresses and distortions and improving fatigue, corrosion, and fracture performance.

Emc^2's DOE SBIR Phase I effort successfully adapted VFT® so that SMEs have access to this sophisticated and proven methodology that is quick, accurate and cost effective and available "on-demand" to address weld-simulation and fabrication problems prior to manufacture. The open source code, WARP3D, a high performance finite element code mainly used in fracture and damage assessment of structures, was modified so that computational weld problems can be solved efficiently on multiple processors and threads with VFT®. The thermal solver for VFT®, based on a series of closed form solution approximations, was enhanced for solution on multiple processors greatly increasing overall speed. In addition, the graphical user interface (GUI) has been tailored to integrate these solutions with WARP3D. The GUI is used to define all the weld pass descriptions, number of passes, material properties, consumable properties, weld speed, etc. for the structure to be modeled. The GUI was improved to make it user-friendly for engineers that are not experts in finite element modeling. Finally, a plan for porting VFT® onto the Ohio Supercomputer Center (OSC) through its hosted Manufacturing and Polymer Portal has been developed. This access route will permit SMEs to perform weld modeling to improve their competitiveness at a reasonable cost. All of these improvements are detailed in this report.

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