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FERMI 1st Quarter of Project Report (May-June 2021) LLNL Contribution (short version)

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FERMI

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I. Introduction

This work delineates the work accomplished in the 2nd quarter of CY 2021, which consists of the first quarter of funding for LLNL in the FERMI project (Fusion Energy Reactors Modeling Initiative), a project of the GAMOW (Galvanizing Advances in Market-Aligned Fusion for an Overabundance of Watts) program under ARPA-E. LLNL is responsible for the structural mechanics component of FERMI, concentrating on fusion first wall and blankets.

The remainder of this document consists of the following sections:

1) Material Model Progress
2) PreCICE and Diablo
3) Modeling of CFS Vacuum Chamber
4) Summary and Future Work

II. Material Model

We are currently extending the Diablo model 8 (thermal creep) and 8rsc (irradiation creep) to a consolidated multi-term model along the lines of Murakami [8], which should account for irradiation-induced secondary creep and swelling. We are evaluating including terms for primary creep as in Kloc [9].

$$\begin{aligned}
&\dot{\mathbf{e}} = \frac{1}{G_T}\dot{\mathbf{s}} + \sum_{i=1}^{N}\left(a_T^i \|\mathbf{s}\|^{b_T^i}\right)\mathbf{n} + c_T \|\mathbf{s}\|^{d_T} \|\phi\|^{k_T}\,\mathbf{n}; \mathbf{n} = \frac{\mathbf{s}}{\|\mathbf{s}\|} \\
&\dot{\boldsymbol{\varepsilon}} = \dot{\mathbf{e}} - \frac{1}{3K_T}\dot{p}\mathbf{I} + (A+Qp)\|\phi\|^{h_T}; \\
&p = -tr(\boldsymbol{\sigma})
\end{aligned} \tag{1}$$

We assume that classical plastic flow can be ignored as the design envelope should be quite below thresholds for plastic deformation.

III. PreCICE and Diablo

Much existing work has already been done in a side branch of Diablo, documented in the Argonne report [13]. In this application, we use fluid pressure calculated in the computational fluid dynamics software OpenFoam[14] , interpolated and communicated via the PreCICE coupling library [15] to create pressures along the fluid-solid interface for computational solid mechanics calculations by Diablo [16]. In the current implementation, full two-way coupling is supported using radial basis functions, since direct interpolation in PreCICE is only supported for tets currently. Because we use pressures not forces (better for consistency), we have to do the mapping operation on the “Diablo” side in order to work with MPI, which is slightly different order-of-operations than the standard templates for coupling, which use forces: o.k. for node-on-node, but not so good when the meshes are quite disparate. This implementation has been validated with reference to the standard “Turek” benchmark, see Figure III-1.

Current work involves (a) Transitioning the extant code in the side-branch of Diablo into the main branch, (b) getting the main branch of Diablo to compile with compilers compatible with PreCICE (gcc), (c) working with HyperComp and ANL to communicate coupling strategies and code sections, to facilitate coupling with HyMAG, and (d), preparing for volumetric coupling as that feature becomes available in PreCICE (imminent). Volumetric coupling will be necessary to map radiation fluxes and JxB forces, as well as capture temperature data from HyMAG.

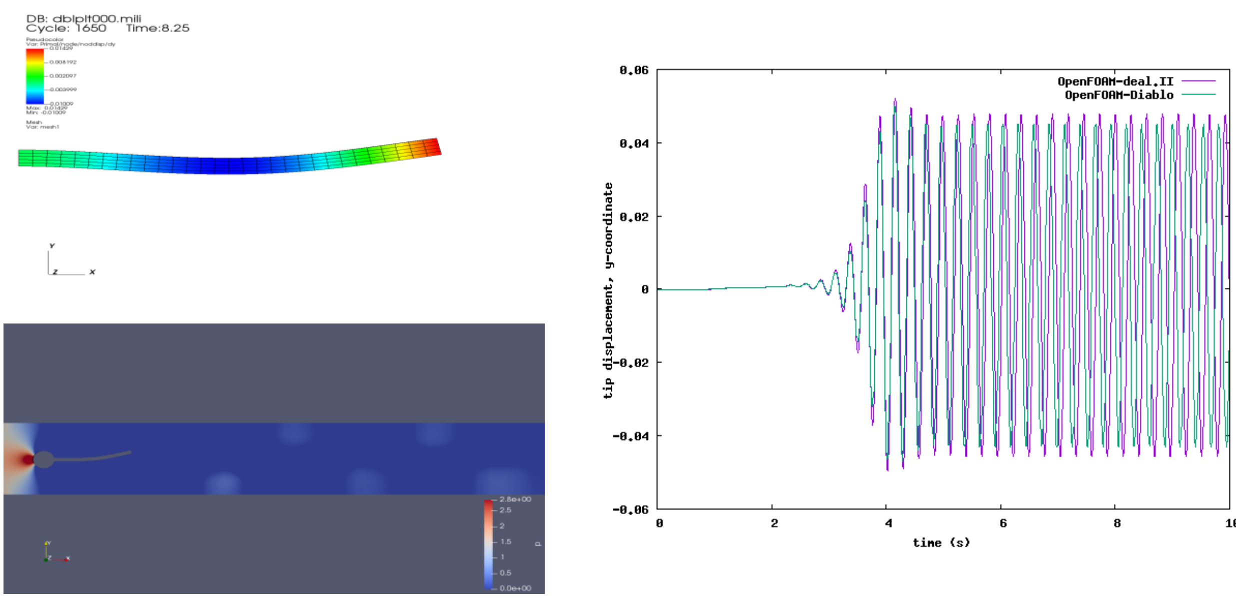

Figure III-1 - Validation of Diablo-OpenFoam coupling via the Turek benchmark, compared to OpenFoam/deal.II, from [13]

IV. Modeling of the CFS Vacuum Chamber

To assess the existing structural design of the CFS vacuum chamber, Diablo was used to calculate the structural response of the baseline design. A solid model was provided by CFS, from which a hexahedral finite element model was developed. Boundary condition data was drawn from the thesis of Segantin [17]. Some temperature data was also cross-checked with members of the FERMI team.

The following thermal boundary conditions were imposed:

- Initial temperature of everything: 300K
- Inner Vacuum vessel inner wall: 1045 K
- Inner Vacuum vessel outer wall: 980 K
- Outer Vacuum vessel inner wall: 950 K
- Outer Vacuum vessel outer wall: 890 K (the same as the Flibe tank)

The Thermal and Structural problem was solved implicitly at each step. Symmetry conditions were imposed for the modeled 10-degree section in theta, symmetric along the vertical (Z) axis.

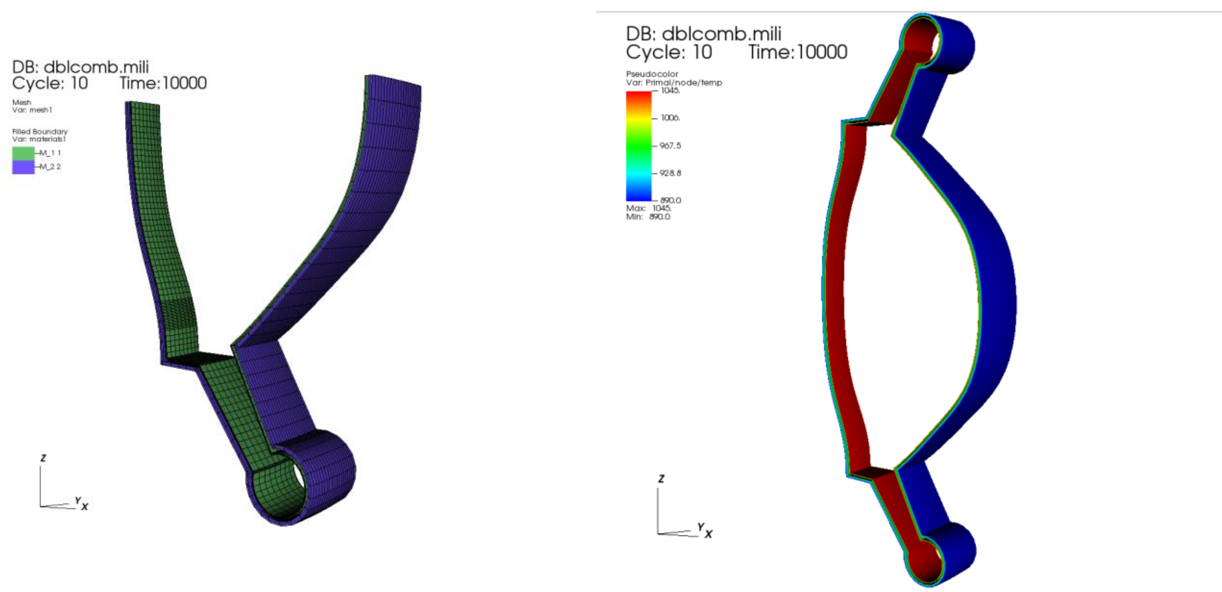

Figure IV-1 - Finite element mesh and thermal boundary conditions for initial analysis of CFS vacuum chamber

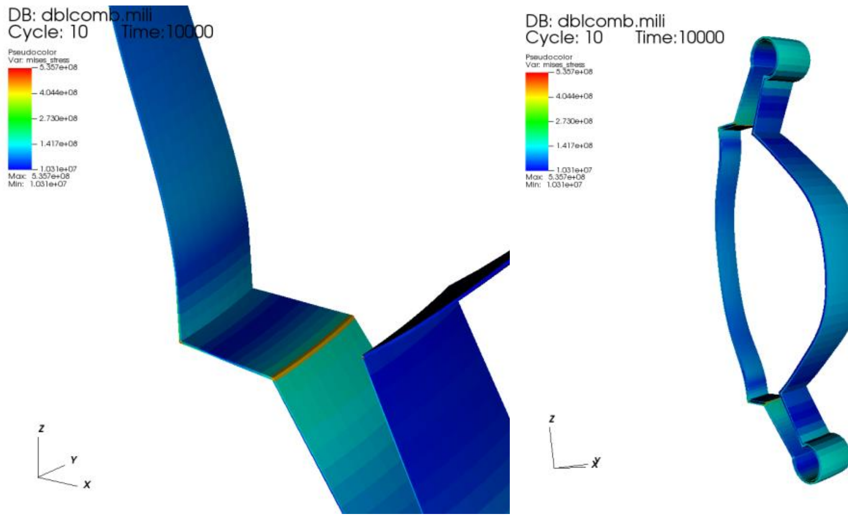

Figure IV-2 - Stress distribution, intial analysis of CFS vacuum chamber

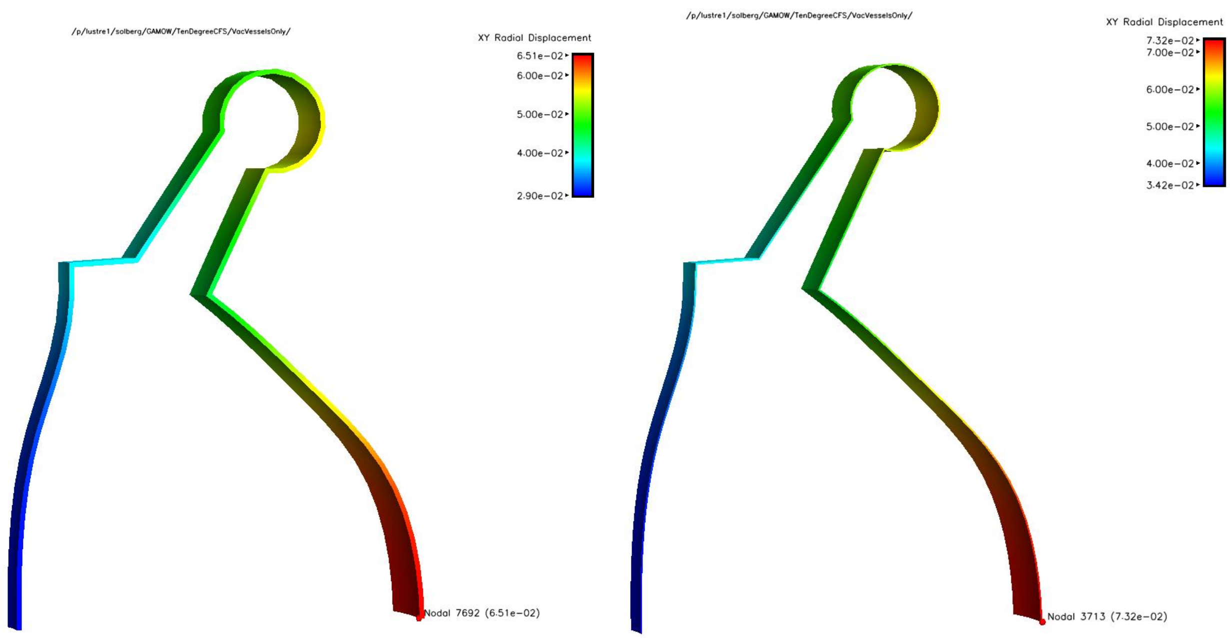

Figure IV-3 - Radial displacement, intial analysis of CFS vacuum chamber

Initial analysis indicates that stress concentration in the inner vacuum vessel is around 538 MPa (outer vacuum vessel has a similar issue but the maximum is lower, 500 MPa). This is over halfway to the nominal 800K value of 970 MPa. However, most of the vessel has a stress level much lower, around 150 MPa max, much lower than yield. Rounding corners would probably do a lot to reduce the bulk stress down to an acceptable level. Still, where temperatures are highest, the stress levels are above those for the 1000 hr creep strain of 0.5%, which is approximately 100 MPa at 1400 F [12]. More troubling, the "gap" between the inner and outer vacuum vessels is closing up, whereas over 7 cm of radial displacement is found at the outer wall centerline for the inner vacuum vessel, while the inner wall of the outer vacuum vessel only displaces 6.51 cm, so the gap between them is closing by over ¾ of a centimeter, again not taking into account thermal creep – this may require additional stiffeners or other features to control the gap between the inner and outer vacuum vessel, or there may be detrimental effects on the thermal hydraulics. Segantin had similar conclusions.

V. Summary and Future Work

In general, much of the work accomplished in the first quarter has been preliminary – investigating the appropriate form for the material model, preparing the codebase for full integration with preCICE/OpenFOAM/HyMag, and performing preliminary calculations. All these steps have proceeded according to plan. It is anticipated that a working creep model will be available with some validation by the end of the second quarter of work. On the coupling front, the volumetric coupling package in PreCICE is "imminent", when this becomes available the appropriate code will be written for the Diablo adapter. It is anticipated that testing with OpenFOAM will occur simultaneously, with testing with HYMAG and the neutronics package to follow as they create their own interfaces. Some interesting issues arise because, in contrast to the previous work with OpenFOAM and Diablo, most of the coupling needed here is essentially one-way, as neither the neutronics packages nor HYMAG can accommodate mesh motion (nor is it anticipated that this is necessary). Hence there may be additional simplifications and strategies (perhaps including file transfer) included within the general coupling strategies. As capabilities are added, the baseline CFS model already constructed will be re-run, and as CFS refines their structural design (e.g. getting rid of stress concentrations) these improvements will be incorporated as well.

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