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COUPLED MULTIPHYSICS ANALYSIS OF THE TF COIL STRUCTURE IN THE NSTX UPGRADE

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***Abstract*—**

The National Spherical Torus Experiment (NSTX) is being upgraded to increase plasma current to 2 MA and central toroidal magnetic field to 1 Tesla [1]. The upgrades include a replacement of the centerstack and addition of a second neutral beam. The Inner legs of the TF coil which are at the core of the new larger NSTX upgrade center stack are designed to carry twice the current of the existing TF coils. The inner and outer legs of the TF coil are connected through a set of flexible straps that allow for the thermal growth of the center stack and the out of plane twisting moments in the TF coils. Electromagnetic interaction of the TF, OH and PF coils results in loads on the TF coil structure. The TF flexible straps and structural components of the machine have to withstand these loads. Coupled electromagnetic, thermal and structural analyses were performed. The results of these analyses, which will be presented in detail in this paper, have led to the validation of the design of TF flexible straps and compliance with the requirements of the NSTX structural design criteria.

Keywords-NSTX; tokmak; modeling; multiphysics; TF coils

I. INTRODUCTION

In NSTX upgrade spherical tokomak, the center stack containing the inner legs of the Toroidal filed (TF) magnets will be replaced by a larger centerstack with larger TF inner legs capable of providing the current for the 1 Tesla central magnetic field. The inner legs of the TF magnets are attached to the outer TF magnets through a set of flexible straps [2] that can accommodate the thermal expansion of the TF inner legs and the central stack.

The current in the straps and the TF magnet also interacts with the Toroidal field and the field from the poloidal field (PF) coils and the Ohmic heating (OH) coil. The result of these interactions is a general twist in the TF inner legs and the TF outer legs. The flexible straps need to withstand this out of plane torque for the projected life of the machine.

II. TF FLEXIBLE STRAPS

There are 36 straps for connecting three TF inner leg blades to each of the 12 TF magnet outer legs (fig. 1). Each strap carries a peak current of 130 kA in a discharge. The U-shaped straps shown in fig. 1 are made of annealed copper zirconium alloy, C18150 H01 Cu-Cr-Zr, with thirty 0.075in thick lamellae with 0.14in gap between lamellae cut using the wire EDM technique to provide vertical and out of plane flexibility.

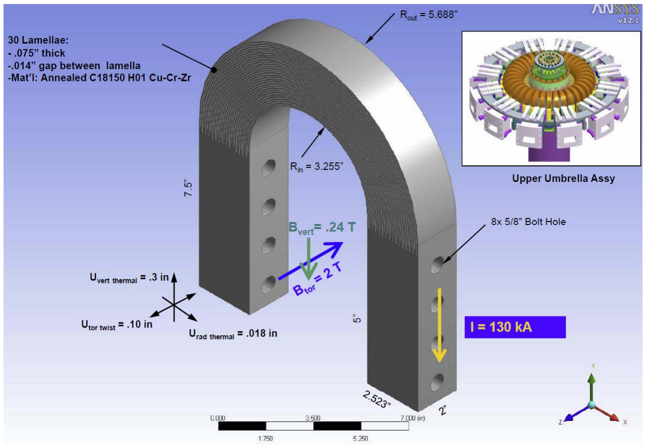


Figure 1. TF flexible straps

Each strap is bolted using eight 5/8-in Inconel 718 Superbolts® [3]. Four of these are on the inner side and go through a copper extension piece into the copper TF inner leg flag (fig. 2). The other four Superbolts are used on the outer side and connect the straps to a copper toroidal positioning extension piece. High strength Inconel thread insets are used to provide high pull-out strength (in the copper-zirconium pieces) for the bolts. The 5/8-in Superbolts are pre-tensioned to 25,000 lbf in order to provide the high contact force necessary to ensure low contact resistance. Nine 3/8-in Inconel 718 bolts are used to connect each extension piece to one of the three turns in the TF outer leg. The 3/8-in bolts are pre-tensioned to 6,700 lbf (fig. 6).

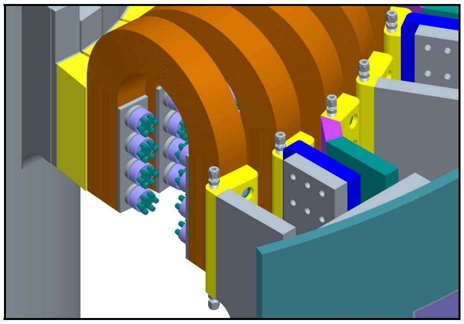


Figure 2. TF straps and Superbolts®

III. MODELING AND ANALYSIS

In order to qualify the TF flexible straps for use in the NSTX upgrade machine we need to predict the stresses in the TF flexible strap assembly and ensure that it complies with the NSTX Upgrade design criteria [4]. Contact pressure and bolt stresses need to be calculated as well. To predict the stresses in the strap assembly we need to simulate in a coupled manner the electrical conduction, electromagnetic loads, thermal, and structural behavior of the assembly. Figure 1 shows the magnetic field components that are present at the center of the straps.

A. *Electromagnetic Analysis*

The geometry of the straps and the lamellae are very fine with high aspect ratios. As such it requires a high fidelity model of the straps and an electromagnetic FEA code that can mesh the fine structure of individual lamellae (and air in between) in order to simulate the behavior of individual lamellae under the large electromagnetic forces. MAXWELL [5] electromagnetic code (also known as Ansys Magnetostatic code) was chosen to do this modeling.

A magnetostatic analysis was performed to simulate the forces in the TF structures. Using symmetry, a 30-degree cyclic symmetric model was made of the geometry in order to reduce the model size for a less expensive computation. Furthermore the up-down symmetry of the geometry was used to reduce the model size further in half. Figure 3 shows the model used in the electromagnetic simulation. The structure of the TF flexible straps has many parts some of which are in the TF conduction path. The electromagnetic simulation only took into account those parts in the TF conduction path.

Figures 4 and 5 show the ohmic heat generation rate, and magnetic field results from the MAXWELL electromagnetic analysis for a combination of TF and PF and OH coil currents for a realistic scenario of machine operation.

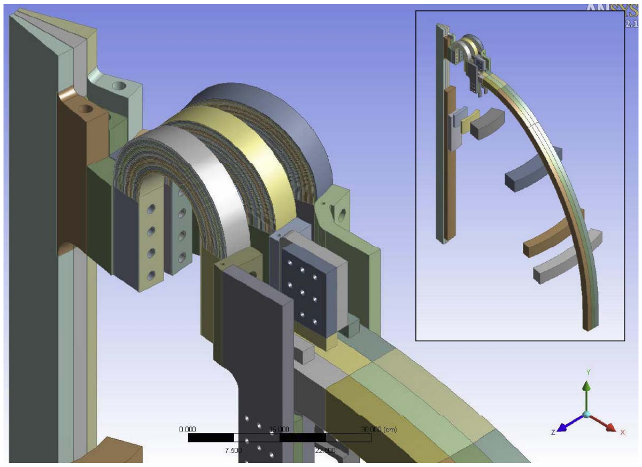


Figure 3. MAXWELL 30° cyclic symmetry geometry

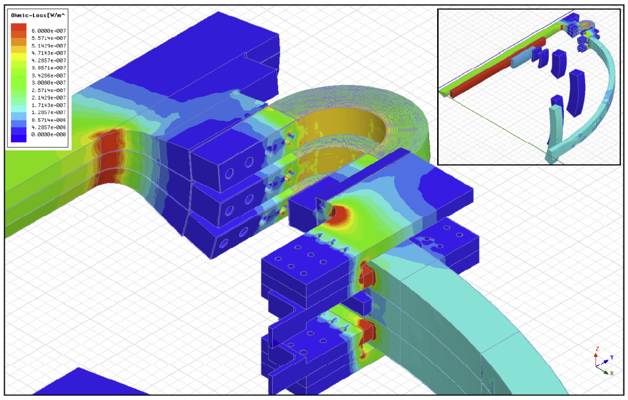
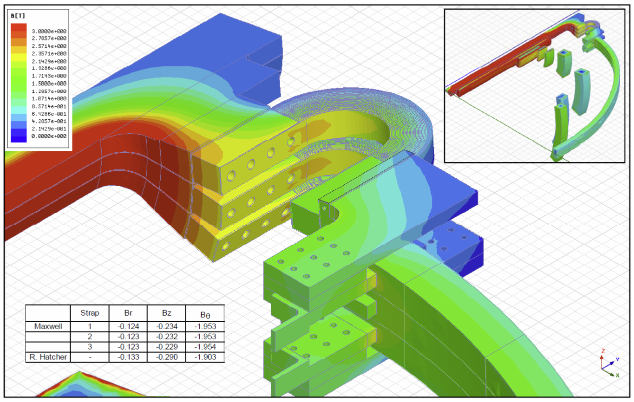


Figure 4. Ohmic heating rates



	Strap	Br	Bz	Bθ
Maxwell	1	-0.124	-0.234	-1.953
	2	-0.123	-0.232	-1.953
	3	-0.123	-0.229	-1.954
R. Hatcher	-	-0.133	-0.290	-1.903

Figure 5. Magnetic field intensities

B. *Multiphysics Analysis*

A coupled multiphysics analysis was set up wherein the result of the electromagnetic analysis force density and ohmic heat generation was imported into Ansys. This was possible through an experimental program from Ansys [6] that maps those quantities from the MAXWELL computational mesh into the corresponding parts in the Ansys mesh. The ohmic heat rates were imported into an Ansys transient thermal analysis in order to obtain temperatures. The force density results from the electromagnetic analysis and the temperature results from Ansys thermal analysis were imported into an Ansys structural analysis in order to calculate the resulting mechanical stress. Figure 8 is a schematic of this multiphysics analysis. The Ansys structural analysis uses all components of the TF structure including the conducting parts and non-conducting structural parts. Figure 6 shows the geometry and fig. 7 shows the Ansys structural FEA mesh.

1) *Stress in the Lamellae*

The structural analysis resulted in detailed modeling of the behavior of the lamellae under realistic electromagnetic and thermal loads. Figure 9 is a plot of stress intensity resulting from the highest loads among the NSTX Upgrade operational scenarios. Figure 10 is a close up of the equivalent stress results in the straps region.

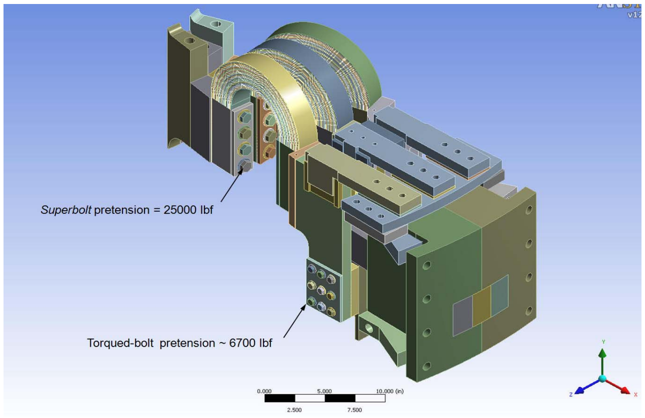


Figure 6. Problem geometry in Ansys

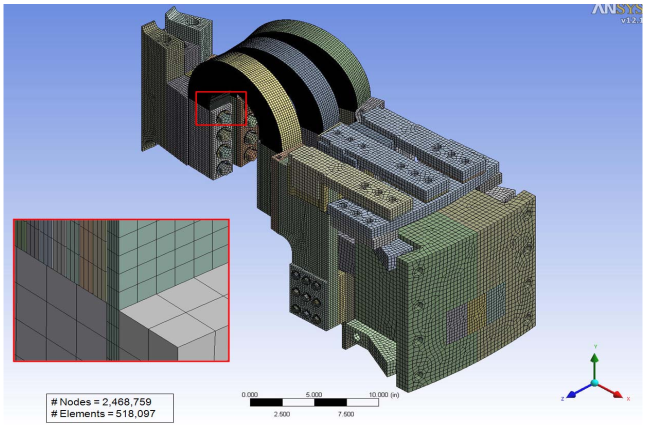


Figure 7. Ansys mesh

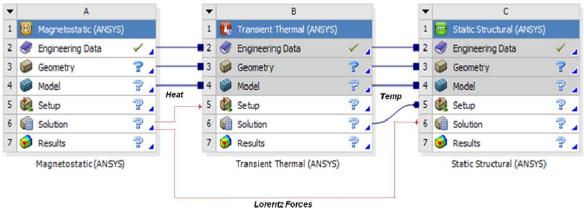


Figure 8. Multiphysics modeling diagram

A plot of stress intensity (Tresca stress) in Fig. 11 shows the highest stress intensity in the lamellae of approximately 19,000 psi (i.e. 130 MPa). To satisfy the requirements of the NSTX Structural Design Criteria, the fatigue strength at 60 K cycles must be greater than twice this stress, or the fatigue strength at 1.2 E06 cycles (20x N) must be equal to or greater than this stress, whichever is the more severe requirement. The fatigue S-N curve for C18150 copper-zirconium, with the max lamella Tresca stress plotted at N = 60 K cycles, is shown in Fig. 12. The maximum lamella stress is slightly below the 2x stress level and meets all the requirement of the Design Criteria.

2) *Contact Status and Pressure*

Another important aspect of the qualification of the TF flexible straps is the requirement that the contact between the straps and the mating parts not separate and a minimum contact pressure of 1,500 psi be maintained in the joints. If the contacts were to separate or the contact pressure drop below 1,500 psi, the condition for validity of a one way coupled multiphysics analysis would be nullified and a dynamic time-dependent fully coupled approach would be necessary. This is in part due to the substantial heat at the joint that will come from a high contact resistant due to lower contact pressure.

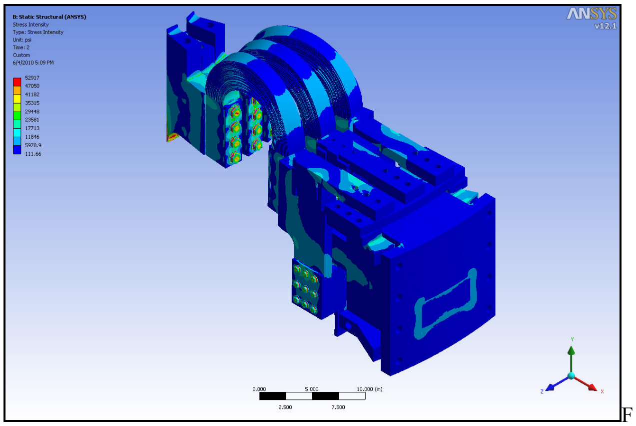


Figure 9. Stress intensity results

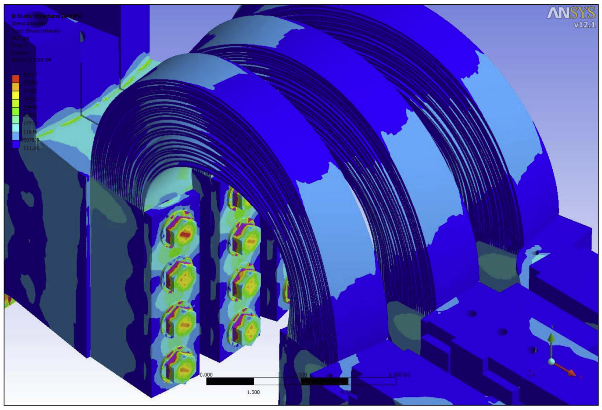


Figure 10. Stress intensity in strap lamellae

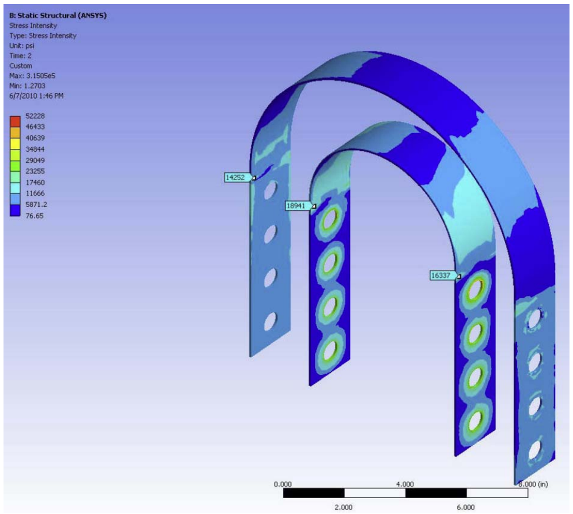


Figure 11. Maximum lamella stress

Results from the analysis shown in figures 13 and 14 demonstrate that none of the TF strap joints separate, and that the minimum local contact pressure under the bolts is approximately 2,500 psi, which is 1000 psi above the minimum requirement. This also shows that our sequential one-way coupled model is valid.

3) Bolt and Thread Stresses

Bolt and thread stresses were calculated by the analysis. The results are shown in stress intensity plot of fig. 15. The average shear stress in the copper threads is 34.8 ksi. To satisfy the design criteria, the shear stress must be less than 0.6 Sm = 0.4Sy = 37.5 ksi. The Modified Goodman diagram for copper-chromium-zirconium, with thread Tresca stress plotted, is shown in fig. 16. The thread stress meets the requirements of the design criteria.

Modified Goodman diagram for the 5/8-in Inconel bolts is plotted in fig. 17. Inconel bolts also meet the requirements of the design criteria.

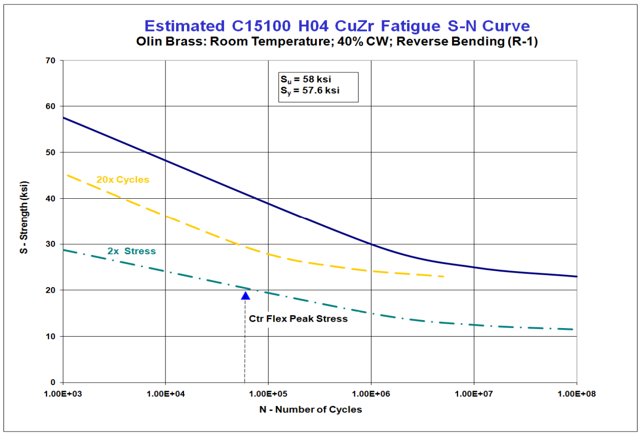


Figure 12. Fatigue curve for copper zirconium alloy

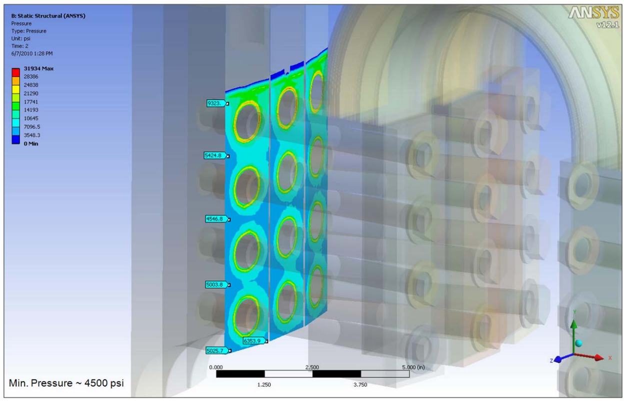


Figure 13. 5/8-in bolt joint contact pressure

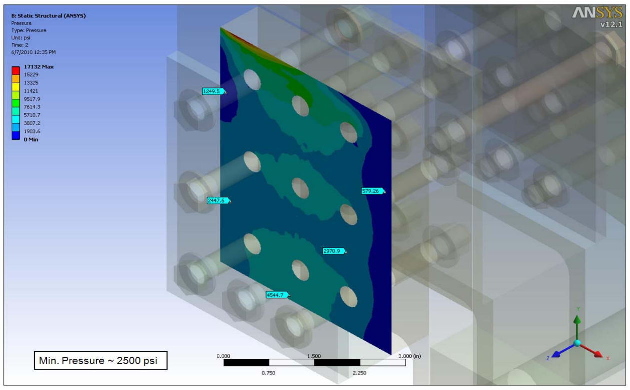


Figure 14. 3/8-in bolt joint contact pressure

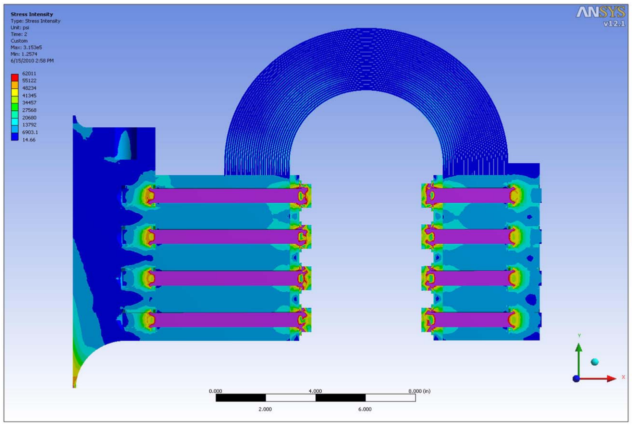


Figure 15. Bolt and thread stress

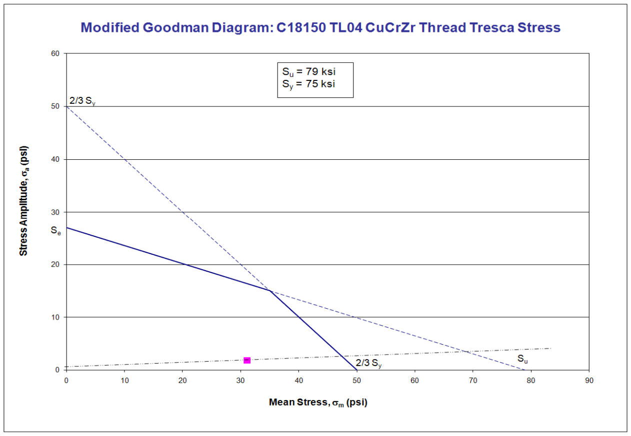


Figure 16. Modified Goodman diagram for Cu-Zr thread stress

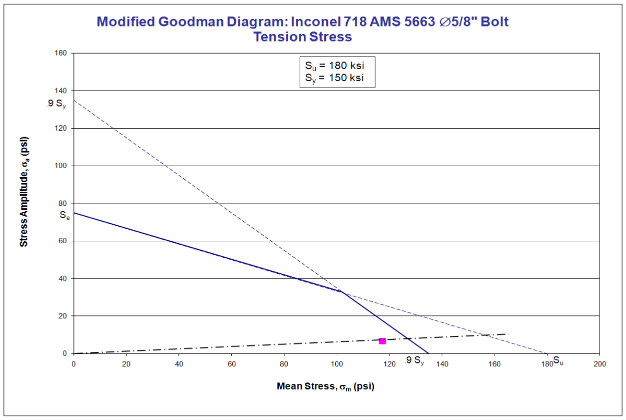


Figure 17. Modified Goodman diagram for 5/8-in Inconel bolts

IV. CONCLUSIONS

A novel multiphysics mode of the NSTX upgrade TF flexible strap has been constructed and simulated. Simultaneous one way coupled simulation of electromagnetic forces and ohmic heat generation along with thermal conduction and structural calculation have been performed on the components of the strap. Mechanical behavior of individual lamellae under load has been modeled in detail. The results of the calculations confirm the qualification of the TF strap assembly design for the following principle objectives:

- Lamella stresses meet the NSTX design criteria for fatigue life.
- None of the joints separate and a minimum contact pressure of 2,500 psi (i.e. 1000 psi higher than the requirement) is maintained in all joints.
- Bolt and thread stress intensities meet the requirements of the NSTX upgrade design criteria.

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