Modelling of Heat Transfer across Bolted Joints in Abaqus/CAE

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Abstract: *Bolted joints are frequently used connections in many engineering systems, and crucial parts of the heat transfer path in structures. During the design phase, heat transfer across the joints must be modelled properly in order to determine the accurate temperature distribution on components. Usually in finite element models, perfect thermal contact between mating surfaces is assumed. However; this approach is inadequate and may bring on misleading results owing to the equality of temperature assumption between surfaces. Complex configuration of the joints and non-uniform contact pressure distribution due to bolt preload make the prediction of transient heat transfer characteristics across the joints arduous. In this study, transient conduction heat transfer through the bolted joints was modelled in Abaqus/CAE by defining gap conductance between the abutting surfaces. Two correlations were utilized to estimate the thermal contact resistance at joints. Impact of bolt preload and resulting pressure distribution on heat transfer and temperature distribution were investigated. Experiments were performed to verify the analyses results by conducting various temperature measurements. Finally, coupled temperature displacement analysis of a missile guidance section under aerodynamic heating was conducted and results were compared with the results of an uncoupled heat transfer analysis in which perfect thermal contact was assumed at all interfaces.*

Keywords: *Bolted Joints, Gap Conductance, Thermal Contact Resistance*

1. Introduction

Customer requirements lead to more complex missile systems and using components susceptible to temperature. One of the most challenging duties to ensure mission success of missiles is to keep some components such as avionics within their narrow operating temperature range during flight. To determine whether employing thermal management systems is necessary or not, temperature distribution on the components shall be accurately estimated. Accurate estimation of the temperature distribution also enables us to decide which and to where thermal protection systems, e.g. ablative shields and phase change materials, shall be implemented.

Major thermal load a missile is subjected to during its flight at supersonic and hypersonic regimes is the aerodynamic heating which can be briefly described as conversion of the kinetic energy of air into thermal energy due to viscosity (see Figure 1). Aerodynamic heating brings on very high heat flux rates q”, up to several millions W/m^2 which makes thermal contact resistance’s effect at interfaces significant. The higher the heat flux is, the higher temperature drop across an interface takes place due to the following relationship,

$$q^{"} = k_{gap}(T_1 - T_2) = k_{gap}\Delta T$$

where T_1 and T_2 denote the temperatures of the mating surfaces and k_{gap} is the thermal contact conductance which is also called as gap conductance (see Figure 2).

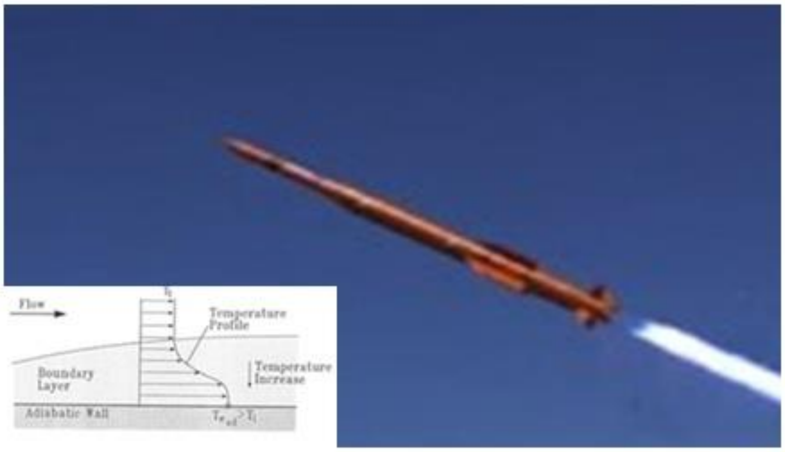

Figure 1. Aerodynamic heating during flight (courtesy of Roketsan).

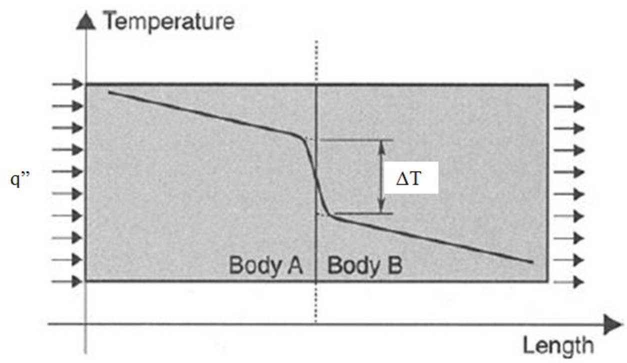

Figure 2. Temperature drop across a joint, (Gilmore, 2002).

In this study, heat transfer through bolted joints was modelled in Abaqus\CAE by defining gap conductance between mating surfaces. Two models were utilized to estimate the thermal contact conductance at joints. Impact of bolt preload and resulting pressure distribution on heat transfer and temperature distribution were investigated. Experiments were performed to verify the analyses results by conducting various temperature measurements. Finally, coupled temperature displacement analysis of a missile guidance section under aerodynamic heating was conducted and results were compared with the results of uncoupled heat transfer analysis in which perfect thermal contact was assumed at all interfaces.

2. Heat transfer in bolted joints

Bolted joints are crucial parts of the heat transfer path in missile structure. In general, perfect thermal contact between mating surfaces is assumed. However, this approach may bring on misleading results especially when heat fluxes are very high. Complex configuration of the joints and non-uniform pressure distribution due to bolt preload make the prediction of heat transfer characteristics across the joints arduous.

Figure 3 depicts a typical bolted joint construction (a), pressure distribution at the interface (b), and heat flow through the joint (c). Pressure is at its peak near the bolt hole and assumed to be zero outside of the pressure cone. Since gap conductance is a function of pressure, heat flow lines constrict in the region where the pressure is high.

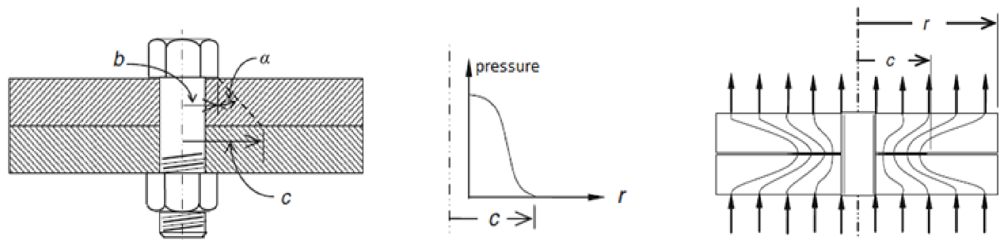

Figure 3. Heat transfer in a bolted joint ((a) a bolted joint, (b) pressure distribution at the interface, (c) heat flow), (Madhusudana, 2014).

There exist several correlations for thermal contact conductance in the literature. They can be broadly classified as ones with elastic deformation assumption and ones with plastic deformation assumption (Hasselström, 2012). They relate gap conductance to the interface pressure, surface quality parameters and material properties.

3. Test sample and FE model

Test sample used in experiments is similar to a pipe flange construction (see Figure 4). While one end of the sample is closed, the other end is open. The test sample was heated at the closed side for a certain time with a hot air gun whose heating power can be adjusted up to several kW, while all other surfaces were insulated. Temperature distribution on the test sample was measured with K type thermocouples. A series of thermocouples placed on the sample were aligned with the bolt centerline, and another series of thermocouples were aligned with an artificial line lying along the mid of the two neighboring bolts.

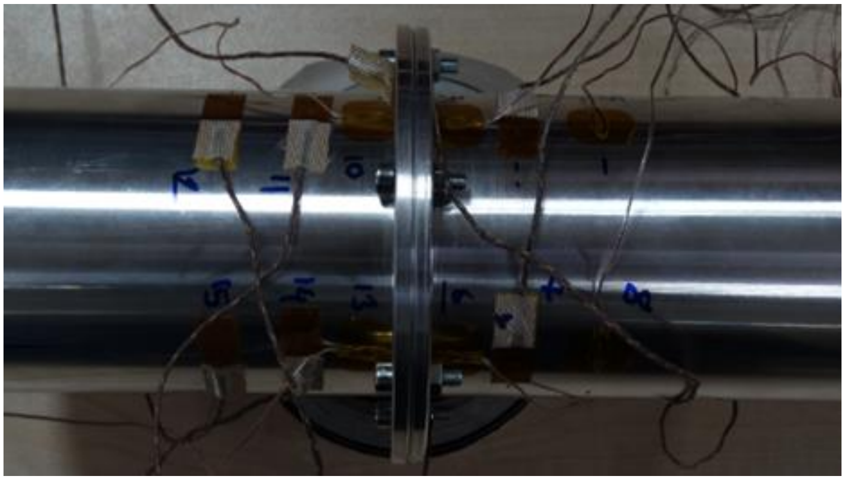

Figure 4. Test sample.

Before tests were conducted, the arithmetic average roughness and flatness of the mating surfaces of the flange were measured. Flatness of the surfaces were 0.013 and 0.005 mm. The RMS roughness of the surfaces were calculated as 0.65 and 0.78 μm by assuming a Gaussian distribution of asperities.

Tests were carried out at three different torque levels, i.e. Γ, 2Γ, and 4Γ Nm. After each test, the sample was let cool down for a time to reach ambient temperature and have uniform temperature distribution. Afterwards, torque level was adjusted with a torque meter and a new test was started.

After tests were completed, FE model of the test sample was created in Abaqus/CAE. Since pressure is zero at interfaces in uncoupled heat transfer analysis, coupled temperature-displacement analysis must be conducted to model the pressure dependent thermal contact conductance. Therefore, linear solid coupled temperature-displacement elements (C3D8T) were used to build the model. Since the model is symmetric, only 1/12 of the test sample was built (see Figure 5). Surface-to-surface contacts were defined for all mating surfaces except tie contact was used for the interface between the nut and bolt.

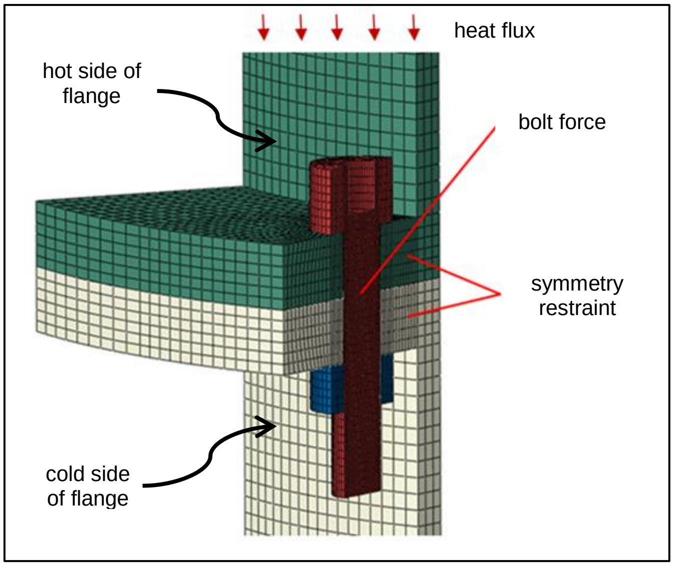

Figure 5. FE model of the test sample.

Two correlations taken from the literature were utilized to define the thermal contact conductance between the mating surfaces. The first correlation, i.e. Mikic's correlation (Gilmore, 2002), is based on the elastic deformation assumption, and the second one, i.e. Tien's correlation (Hasselström, 2012), is based on the plastic deformation assumption. GAPCON subroutine was used to define the gap conductance in Abaqus/Standard, because GAPCON offers flexibility in specifying dependencies of gap conductance on the interface pressure, surface quality parameters and temperature dependent material properties.

4. Results

Three different torque levels and two different thermal contact conductance correlations were used in the simulations. In total, six simulations were conducted and results were compared with the test data. Temperature drop across the two different sections of the flange is chosen for comparison since temperature drop is the major variable related to the gap conductance and interface pressure (see Figure 6). Figure 7, 8 and 9 show the temperature drop across the flange for different torque levels of Γ, 2Γ and 4Γ Nm, respectively.

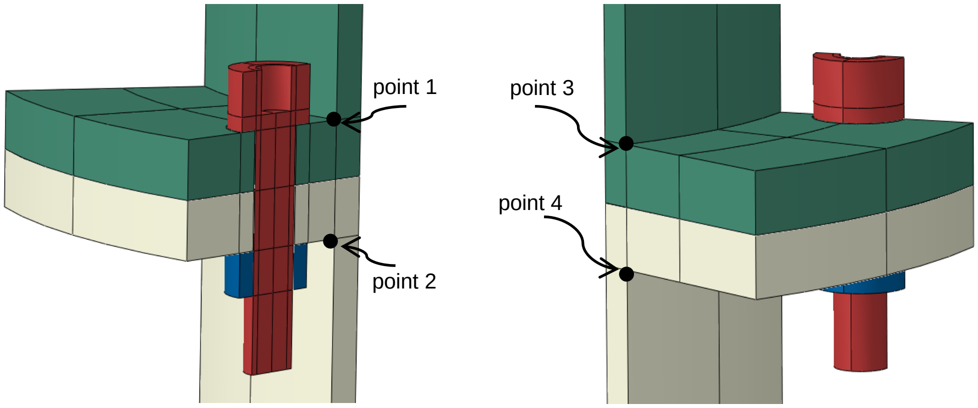

Figure 6. Locations where temperature drops were compared.

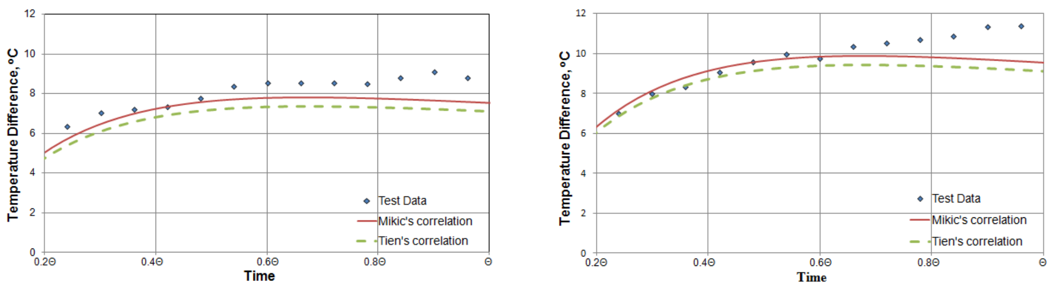

Figure 7. Temperature drop across the flange (Γ Nm) ((a) between point 1 and point 2, (b) between point 3 and point 4).

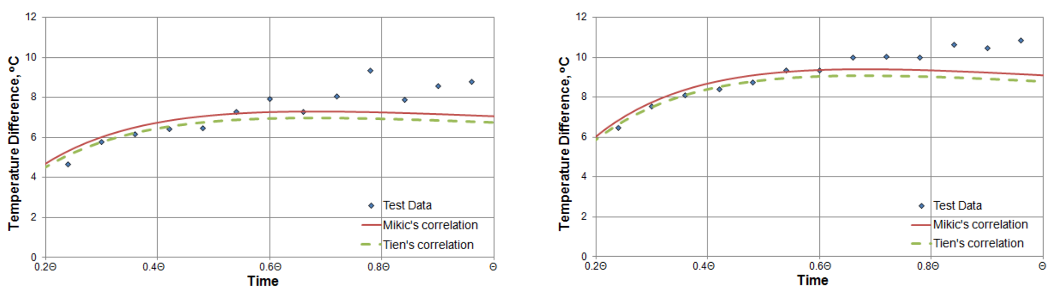

Figure 8. Temperature drop across the flange (2Γ Nm) ((a) between point 1 and point 2, (b) between point 3 and point 4).

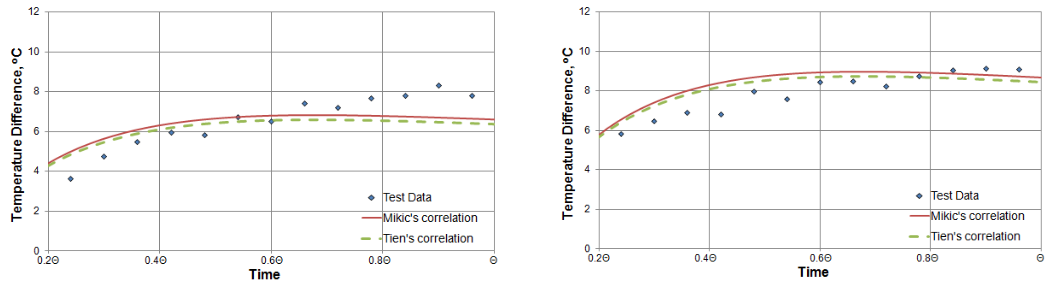

Figure 9. Temperature drop across the flange (4Γ Nm) ((a) between point 1 and point 2, (b) between point 3 and point 4).

As seen from the figures, temperature drop between the points 1 and 2 is lower than the temperature drop between the points 3 and 4. This is due to the higher interface pressure and gap conductance in the proximity of the bolt hole. Figure 10 shows the temperature distribution and contact pressure at the flange interface of the cold side when the bolt torque is 4Γ Nm and time is Θ. Higher temperature and contact pressure values are observed near the bolt hole.

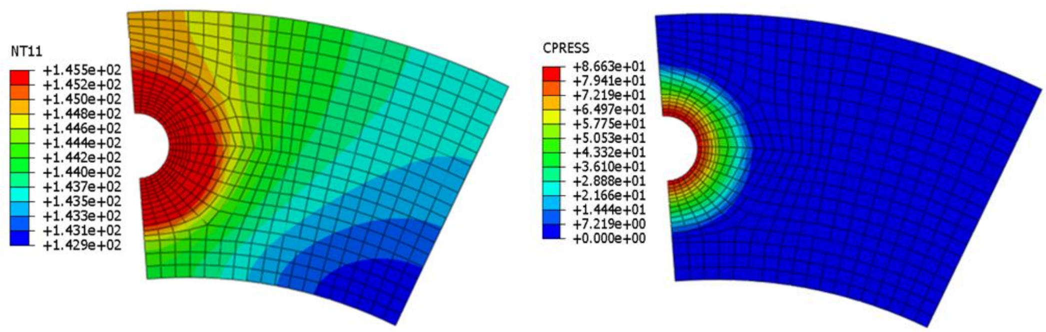

Figure 10. Temperature (in °C) and pressure distribution (in MPa) at the interface.

Fully coupled heat transfer analysis with Abaqus/Standard results in acceptable results compared to the test data especially when time is less than 0.8Θ. The Mikic's correlation yields more satisfactory results than the Tien's correlation when torque level is lower than 4Γ Nm. Difference between the two correlations becomes negligible as torque level is increased.

Figure 11 demonstrates the effect of bolt torque on temperature drop across the flange. As torque level is increased, temperature drop across the flange reduces. It is an expected result since the gap conductance is almost proportional to the interface pressure which is determined by the bolt torque.

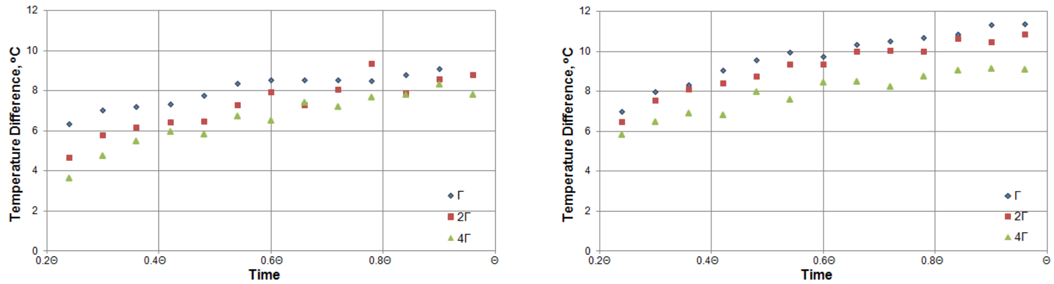

Figure 11. Effect of the bolt torque on temperature drop ((a) between point 1 and point 2, (b) between point 3 and point 4).

5. Aeroheating analysis of a missile guidance section

As stated above, temperature of the avionics shall not exceed the maximum operating temperature during the flight. Therefore, in order to decide the necessity of implementing thermal protection, accurate thermal analysis shall be made. Figure 12 shows the quarter model of a missile guidance section built in Abaqus/CAE. The model consists of two casings fastened with bolts, plate and avionics. Bolted joint connections are also used to fasten the plate to the casing2 and the avionics to the plate (which is not shown in the figure).

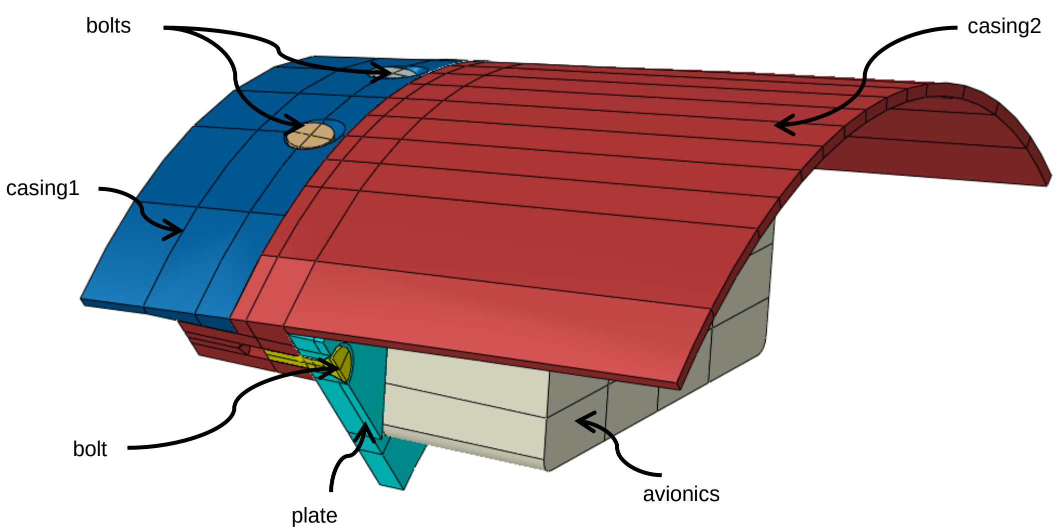

Figure 12. Quarter model of the guidance section.

Aerodynamic heating environment the missile is subjected to was determined via CFD analysis in the form of recovery temperature and heat transfer coefficient versus time. This thermal load was defined in Abaqus/Standard by introducing surface film condition on the outer surfaces of the casings. All other surfaces were assumed to be adiabatic.

Linear solid coupled temperature-displacement elements (C3D8T) were used to build the model. Surface to surface contacts were defined between all mating surfaces except tie contact was used between the threaded regions of the bolts and holes. GAPCON subroutine was utilized to describe the thermal contact conductance according to Mikic's correlation, because Mikic's correlation yields more satisfactory results at lower torque levels and the differences between the correlations becomes negligible at higher torque levels. So it covers broader range of torque levels.

Figure 13 shows the temperature distribution on the guidance section at the end of the flight. Heat flows to the avionics through the bolted joint connection. Therefore, heat transfer in the bolted joints and the thermal contact conductance have a direct impact on the temperature of the avionics.

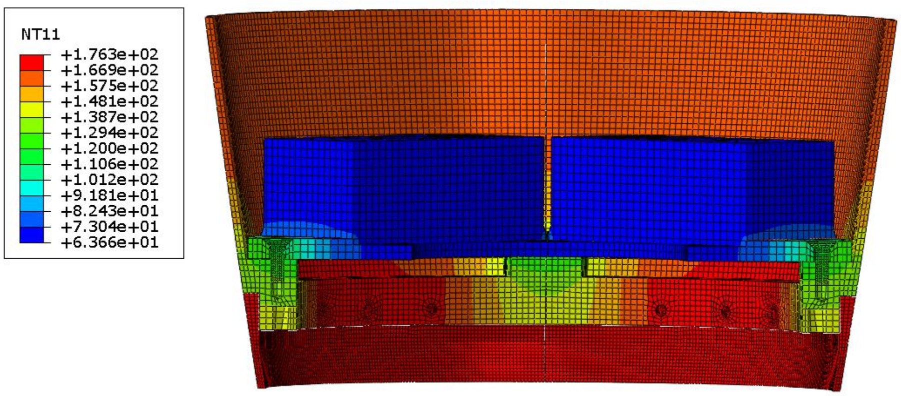

Figure 13. Temperature distribution (in ^{o}C) on the guidance section.

The same aeroheating analysis was also conducted with heat transfer elements (DC3D8) after removing bolt loads and converting all surface to surface contacts to the tie contacts. This is the case in which perfect thermal contact is assumed between all mating surfaces. Figure 14 and Figure 15 compare the results obtained from the fully coupled temperature-displacement analysis and uncoupled heat transfer analysis.

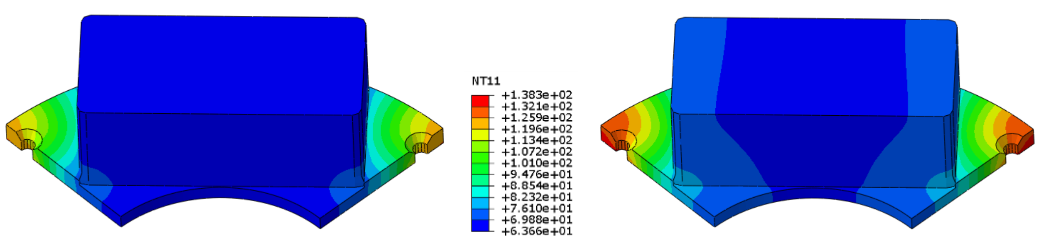

Figure 14. Temperature distribution (in ^{o}C) on the plate and avionics ((a) coupled temperature-displacement analysis, (b) uncoupled heat transfer analysis).

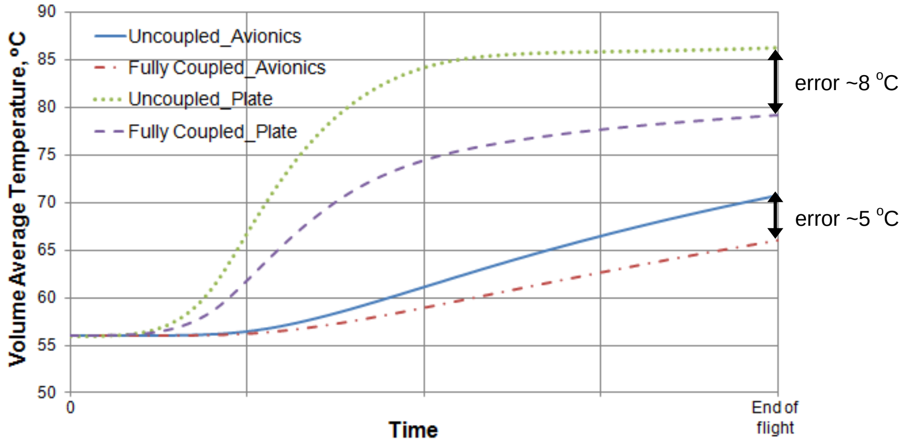

Figure 15. Volume average temperature variation of the plate and avionics.

Figure 14 and Figure 15 show the temperature distributions on the plate and avionics, and volume average temperature variation of the plate and avionics, respectively. As seen clearly, there exists a significant difference between the results of the analyses when taking into account the narrow temperature margin of the avionics. Perfect thermal contact assumption results in higher temperature estimation on the avionics which may lead to the unnecessary use of thermal protection.

6. Conclusion

This paper presents the modelling of heat transfer in bolted joints in Abaqus/CAE by defining pressure dependent thermal contact conductance between mating surfaces in a fully coupled heat transfer analysis. Several tests were conducted by taking numerous temperature measurements on the test sample and measurements were compared with the results of the fully coupled heat transfer analysis. Fully coupled temperature displacement analysis in Abaqus/Standard gave satisfactory results compared to the test data which emphasizes the flexibility and trustworthiness of Abaqus. Furthermore, fully coupled and uncoupled heat transfer analyses of a missile guidance section were conducted. Results indicate that there is a significant difference between the estimated results, as perfect thermal contact assumption overestimates the temperature on the components.

7. References

1. Gilmore, D.G., "Spacecraft Thermal Control Handbook Volume I: Fundamental Technologies," The Aerospace Press, El Segundo, California, 2002.

2. Hasselström, A. J., and Nilsson, U. E., "Thermal Contact Conductance in Bolted Joints," Diploma Work, Chalmers University of Technology, Sweden, 2012.

3. Madhusudana, C. V., “Thermal Contact Conductance,” Springer International Publishing, Switzerland, 2014.
4. Abaqus Users Manuel, Version 6.13-1, Dassault Systemes Simulia Corp., Providence, RI.