Design and Test of a Canard for a Missile

A.Yetgin and B.Acar

Roketsan Missile Ind.

***Abstract**: Canards are frequently used control surfaces to steer missiles in the air. They are positioned at relatively forward sections of the body. Considering the mechanical and thermal loadings during the flight of a missile, design of a canard is a challenging process. Guidance of the missile to its target relies on these control surfaces. In case of a malfunction or damage on the structure of it, missile cannot fulfill its mission. Therefore they are crucial components and on critical design path. Canard system which consists of aerodynamic control surface and a rotating base must withstand aerodynamic loadings and rotate within predefined angles to produce steering action. Necessary rotation movement may be provided by mechanical or hydraulic actuators. In this study, canard body and its connection to rotating base were modelled in Abaqus/CAE. Detailed finite element model of bolted connection was created and thermo mechanical strength analyses were performed. Different bolt configurations and loading varieties were analyzed in order to ensure adequacy of the design. Safety of the system was calculated against applied aerodynamic pressure and thermal loadings. Experimental study was conducted in order to obtain ultimate loading of the system. Finally analyses were verified using various measurements during tests such as strain and displacement. At the end of study a good correlation was obtained between analysis and test results.*

***Keywords**: missile, canard, bolted joints*

1. Introduction

Canards are control surfaces that are located at forward sections of the missile body. They have been commonly used in tactical and ballistic missiles although canard control can poses negative effects on roll motion of the missile (Dyer, 2004). A canard controlled missile is shown in Figure 1.

Figure 1. A canard controlled missile (Courtesy of ROKETSAN)

Guidance directs a missile to its target throughout its flight course. Guidance system makes necessary calculations using various methods, in order to keep the missile on track while cruising to its target. Missile maneuvers using aerodynamic control surfaces extending from missile body (Acar, 2013). Therefore, guidance relies on those control surfaces. In case of a malfunction or damage on the structure of them, missile cannot fulfill its mission. That makes these components crucial and critical on design path.

Missiles generally operate on supersonic speeds and hence aerodynamic heating can cause significant thermal loads on missile components (Coskun, 2015). In addition, high maneuverability requires high angle of attack on canards and this eventually leads to high aerodynamic pressure loads at control surfaces. Different types of loading that act on canard body are shown schematically on Figure 2.

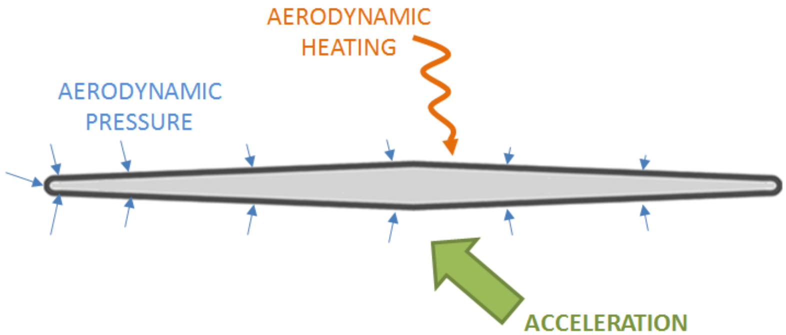

Figure 2. Loads acting on canard

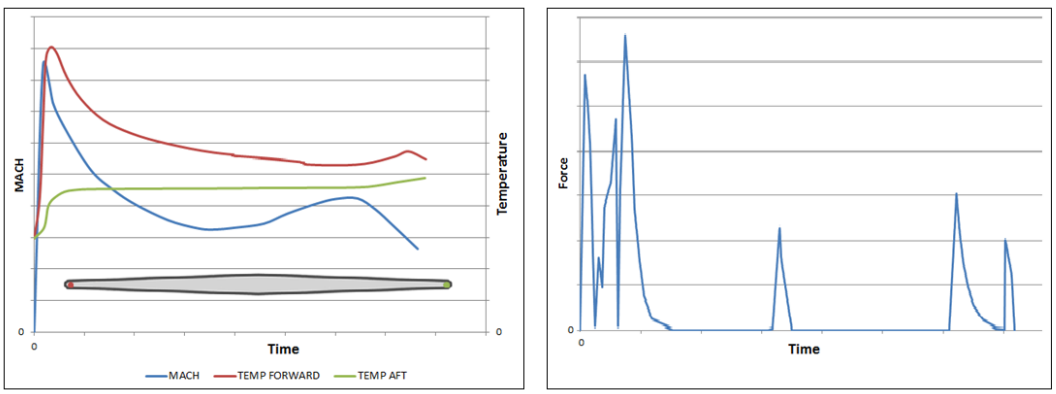

Figure 3. Structural and thermal loads on canard vs. flight time

Missile moves in the air at varying speed and most of the flight time it cruises supersonic. Structural components as well as electronics must operate under certain temperature limit and the design must be checked against thermal loads (Coskun, 2015). At these supersonic speeds a shock wave occurs then pressure and temperature of the surrounding air increase near leading edges where shock wave exists (Simsek, 2012). In Figure 3, temperature of the leading and trailing edges of canard is shown over Mach number versus time plot. It is seen that at the leading edge, temperature profile follows the Mach number profile closely. It is also given in Figure 3 that magnitude of total force acting on canard surface due to aerodynamic pressure. A missile can make different maneuvers depending on mission profile during its flight course. Effects of pressure and heating must be evaluated simultaneously over flight time in order to make an optimized and safe design. In this study finite element analysis model of a test case that represents aerodynamic pressure loading is created. The finite element model includes bolted connections and geometric details as in the real case. That model is verified using data measured during test studies. Effects of different bolt parameters are investigated. Then finite element model of canard connection in the missile body is analyzed against aerodynamic pressure and thermal loadings.

2. Experimental Set up

A test study was conducted in order to determine ultimate loads of the canard and bolted connection. In order to simulate the connection of canard to its base, a test fixture was designed and manufactured. This fixture also ensures correct position of point load that represents the aerodynamic pressure loading. Canard is bolted to the fixture and positioned in a universal tensile testing machine. Experimental set up is shown in Figure 4. Load is applied at a single point using ram that is shown in the figure. The final purpose of this experimental work is to determine the ultimate load carrying capacity of the canard and bolted connection.

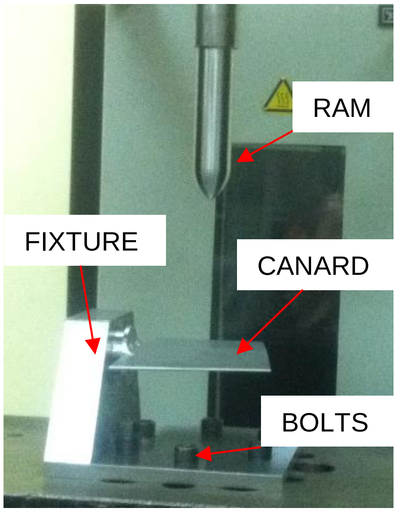

Figure 4. Test setup located in tensile testing machine

Strain gages were located at certain positions to measure strains and compare with finite element calculations. During the test, strains were measured using a data acquisition system. The location of strain gages are shown in Figure 5. Strains are measured in one direction and it is shown as red arrows in the figure. Strain gage positioning was made in such a way that measurement locations and direction matched with highest expected strains and directions.

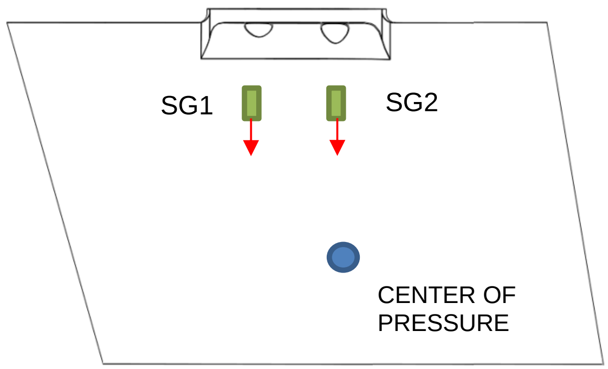

Figure 5. Location of strain gages on canard

Tests were conducted by positioning the fixture in tensile test machine and monotonically increasing load until failure in canard or bolted connections occurs. A typical load vs. time curve is given in Figure 6. Load is increased over time and at a certain point failure occurs at bolts. At some point after load drops, there can be seen an increasing trend because of the canard tip touching the fixture bottom. Picture of failed bolt can be seen in Figure 7. Failure occurred at threaded section of the bolt.

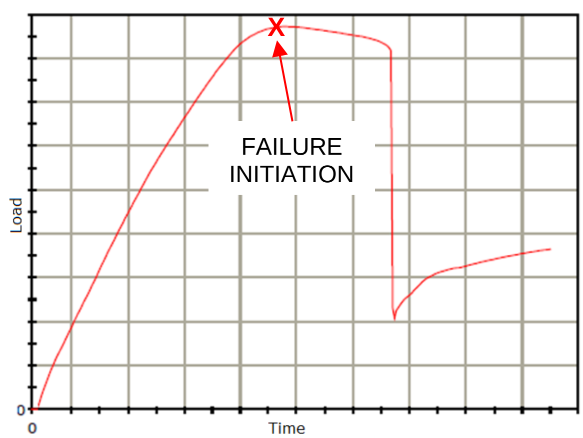

Figure 6. Load vs. Time curve obtained after test

Figure 7. Failed bolt, before and after test

3. Finite Element Model

Finite element model of canard and fixture is created using Abaqus/CAE. Three dimensional full model of the system is meshed using C3D20R and C3D10R elements. Finite element model is shown in Figure 8. Interactions were defined for all touching surfaces. Bolts that are used to mount the canard are included as solid models and preloads are defined. Fixture is mounted to the base with bolts that are modeled using beam elements. Beam bolts are tied to base parts using coupling definitions also given as in Figure 8. The finite element model of the test setup was built in order to validate modeling procedures using measurement data obtained during test. Also ultimate load is determined for bolts and calibrated for model.

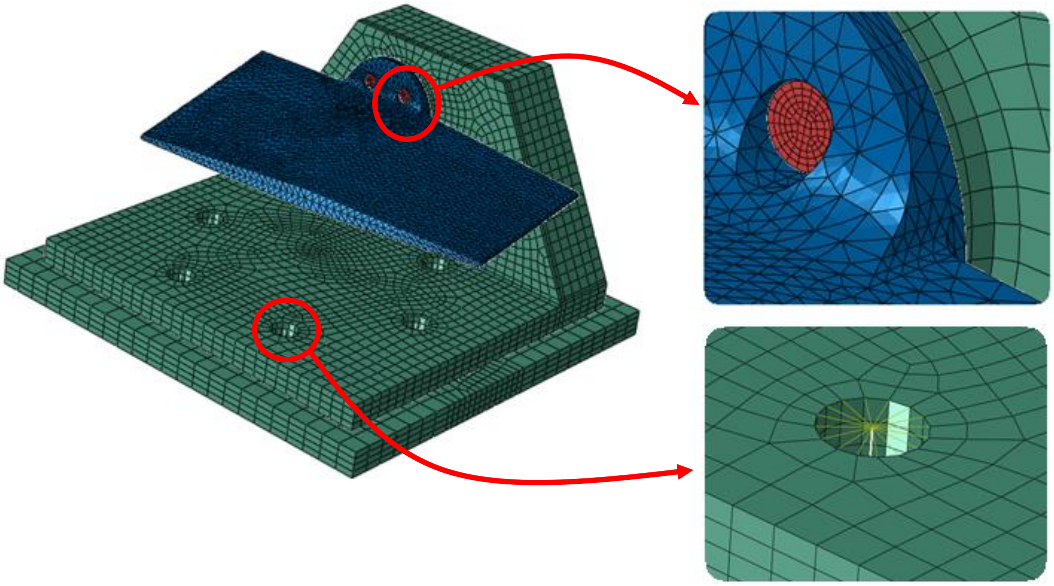

Figure 8. Finite element model of test setup

Interactions are defined for surfaces lying under bolt head and surfaces between canard base and fixture mating surface. Interaction property is defined using “Hard contact” as pressure-over closure method in normal direction, and “Penalty” friction formulation with 0.2 friction coefficient in tangential direction. Threaded section of the bolts that stays in the fixture is tied using tie constraint definition.

While modeling bolts, load carrying cross section is taken into account. Critical cross section diameter is different from nominal size of the bolts. That difference between nominal and critical cross section affects stresses on bolts and also stiffness of the connection. The correlation between nominal diameter and mean, pitch diameters for a metric thread is given in Equation 1 and 2 respectively. Profile of a metric thread is sketched in Figure 9.

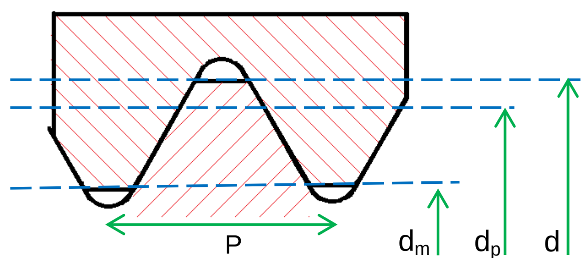

Figure 9. Metric thread profile

$$d_m = d - 1.226869\ P \qquad \text{Equation 1}$$

$$d_p = d - 0.649519\ P \qquad \text{Equation 2}$$

where P is pitch, d is nominal diameter, d_m is minimum diameter and d_p is pitch diameter.

4. Results

Finite element model of test setup is analyzed under increasing point load acting at the same location as tensile test machine. The model consists of nearly 100000 elements and 150000 nodes. Solution for a run takes 4 hours at 16 cpus server. Von mises stress plot obtained at failure load is shown in Figure 10. It is seen that critical stress tend to build up at sections near bolted connection. During the course of loading, upward face of the canard is loaded in tensile direction. Therefore, bolts at the upper row are critically loaded. In the test those bolts failed.

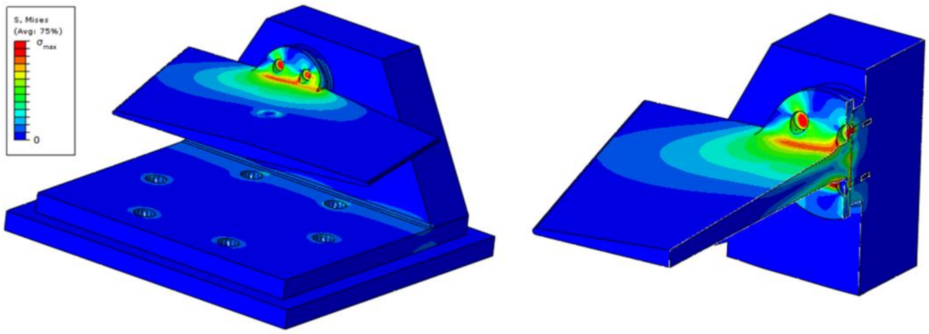

Figure 10. von Mises stress distribution of canard system at test setup

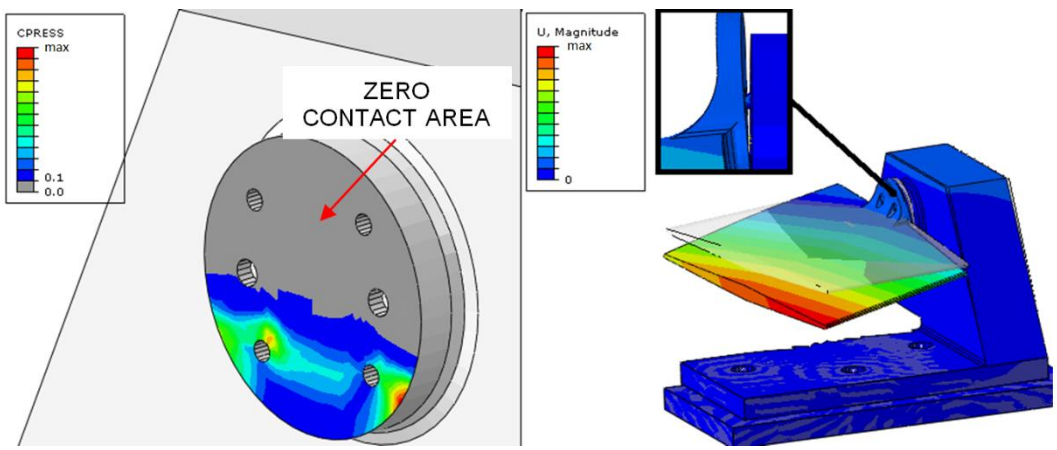

Figure 11. Contact pressure at base surface and displacement of canard

Due to bending effect of loading upper part of the base surface of canard where it is bolted to fixture loses its contact. Contact stress distribution on the base surface and up scaled deformation of the canard and bolts is given in Figure 11. Non contacting zone of the surface is shown as grey color. Separation of the surface at the upper part is clearly seen in the figure. As mentioned before, upper side of canard is loaded in tensile direction and bolts that are at upper portion of base surface are critically loaded.

In Figure 12, measured strains and finite element results are compared against applied point load. As it can be seen from the graph strains agree well with test measurements. It shows that real loading case is captured well in finite element simulations.

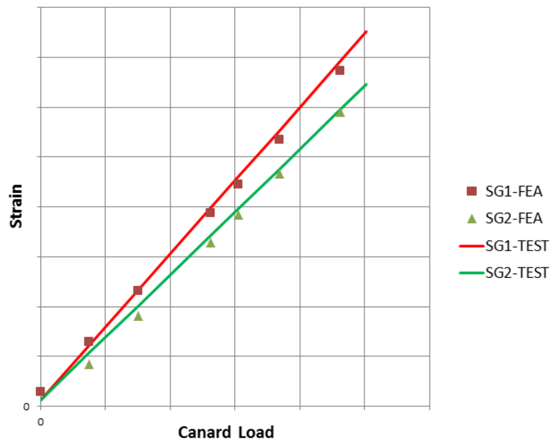

Figure 12. Measured strain comparisons between FEA and test

5. Discussions

In this study, finite element results for a canard and bolted connection loaded aerodynamically is presented. Also an experimental set up is explained and test study has been carried out. Finite element model is verified using data measured during test. At two locations on the canard, strains measured using strain gages during test. It is seen that measured strain values and finite element results are in %5 error band.

For the finite element analysis of test case, ultimate load that causes failure at bolts is determined. In Table 1 predicted load and test result is compared for different preload values. Preload is increased by 16% and 33%. Elasto-plastic material data are used for bolt and canard. Ultimate ram load values are determined within 21%. The main reason for deviation between test and analysis is scatter in the stress strain curve of used materials. However, all predictions are in conservative side and that makes the method used for this model is acceptable for design purposes. Finite element model for canard system mounted on the missile body is created using methodology explained here and analyzed under aerodynamic pressure and thermal loadings. Design iterations are carried out until both maximum equivalent stress on canard stays under allowable limit and the tip deflection is within system requirement limits. After design iterations, geometry was frozen, and the system was tested successfully under real firing conditions.

Table 1. Comparison of predicted ultimate loads to test result

Bolt Preload	Percent Ratio of Expected Canard Ultimate Load to Test Result
Preload	82 %
Preload x 1,16	80 %
Preload x 1,33	79 %

6. References

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