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Transonic Buffet Effects on Shockwave-Induced Lift Stress Response and Fatigue Life of the SC(2)-0714 Supercritical

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ABSTRACT

Transonic buffet, triggered by shockwave–boundary layer interaction, produces oscillations that cause unsteady lift fluctuations, structural stresses, and accelerated fatigue damage. Understanding this chain—from shockwave to lift, stress, and fatigue—is critical for the durability of modern aircraft wings, especially those employing supercritical airfoils. This study investigates the SC(2)-0714 supercritical airfoil using CFD in ANSYS Fluent at Mach 0.8 with AoA 2°, 4°, and 6°, combined with structural and fatigue analysis in Abaqus and Fe-Safe. Results show stress levels between 1.26 and 12.6 MPa, well below the yield strength of Al 2024-T3, confirming safe static margins. However, fatigue life declined sharply with AoA, from 177,868 cycles at 2° to 130,282 cycles at 6°. These findings emphasize that while stresses remain within limits, transonic buffet–induced lift fluctuations critically reduce fatigue life, underscoring the urgency of incorporating buffet effects into structural durability assessments and airfoil design.

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INTRODUCTION

The Aircraft operating in the transonic regime often face complex unsteady aerodynamic phenomena that affect performance, structural integrity, and safety. One of the most critical phenomena is transonic buffet, caused by the interaction between shockwaves and the boundary layer [1], [2]. Shockwave oscillations generate unsteady lift fluctuations, which are transmitted into the wing as dynamic loads. Although the resulting stresses may remain below the yield strength, the repeated stress cycles accelerate fatigue damage and reduce structural life [3], [4]. In other words, aerodynamic instabilities begin with shockwave oscillations, continue with fluctuations in lift, manifest as structural stresses, and eventually shorten the fatigue life of the airfoil.

The mechanism of this interaction is illustrated in Fig. 1, where transonic buffet induces aerodynamic instability, limits the operational envelope, and increases the risk of structural damage or failure. The figure also highlights the fluid–structure coupling that links shockwave oscillations with lift fluctuations, structural stress response, and fatigue degradation [5].

Transonic buffet has long been a focus in aerodynamics and aeroelasticity due to its impact on flow stability and structural durability. The first identification of shockwave oscillations was reported by Hilton and Fowler [2], followed by numerous experimental and numerical studies to capture buffet onset and frequency [1], [10]. Recent advances in CFD methods, such as Reynolds-Averaged Navier–Stokes (RANS), Large-Eddy Simulation (LES), and Detached Eddy Simulation (DES), have improved prediction accuracy and enabled validation against experiments [6], [13]. Several works have also investigated buffet control using shock-control bumps and trailing-edge modifications [11], [12]. However, research directly linking buffet frequency to fatigue durability remains limited. Most prior studies separated aerodynamic and structural analyses or simplified the problem to static loading without addressing unsteady effects on fatigue [4].

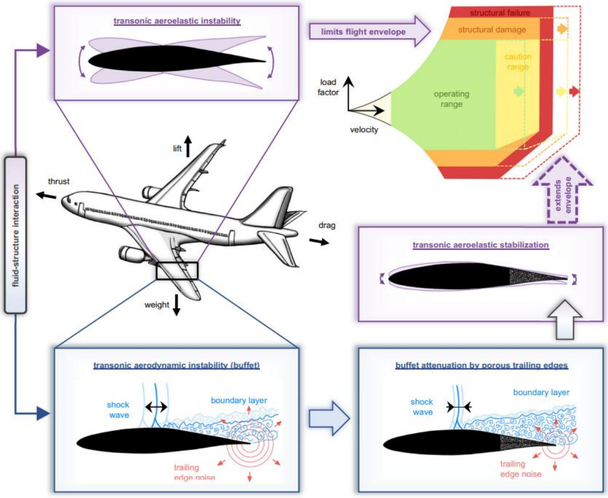


Figure. 1. Effect of transonic buffet on structural response and potential damage in airfoil components [5].

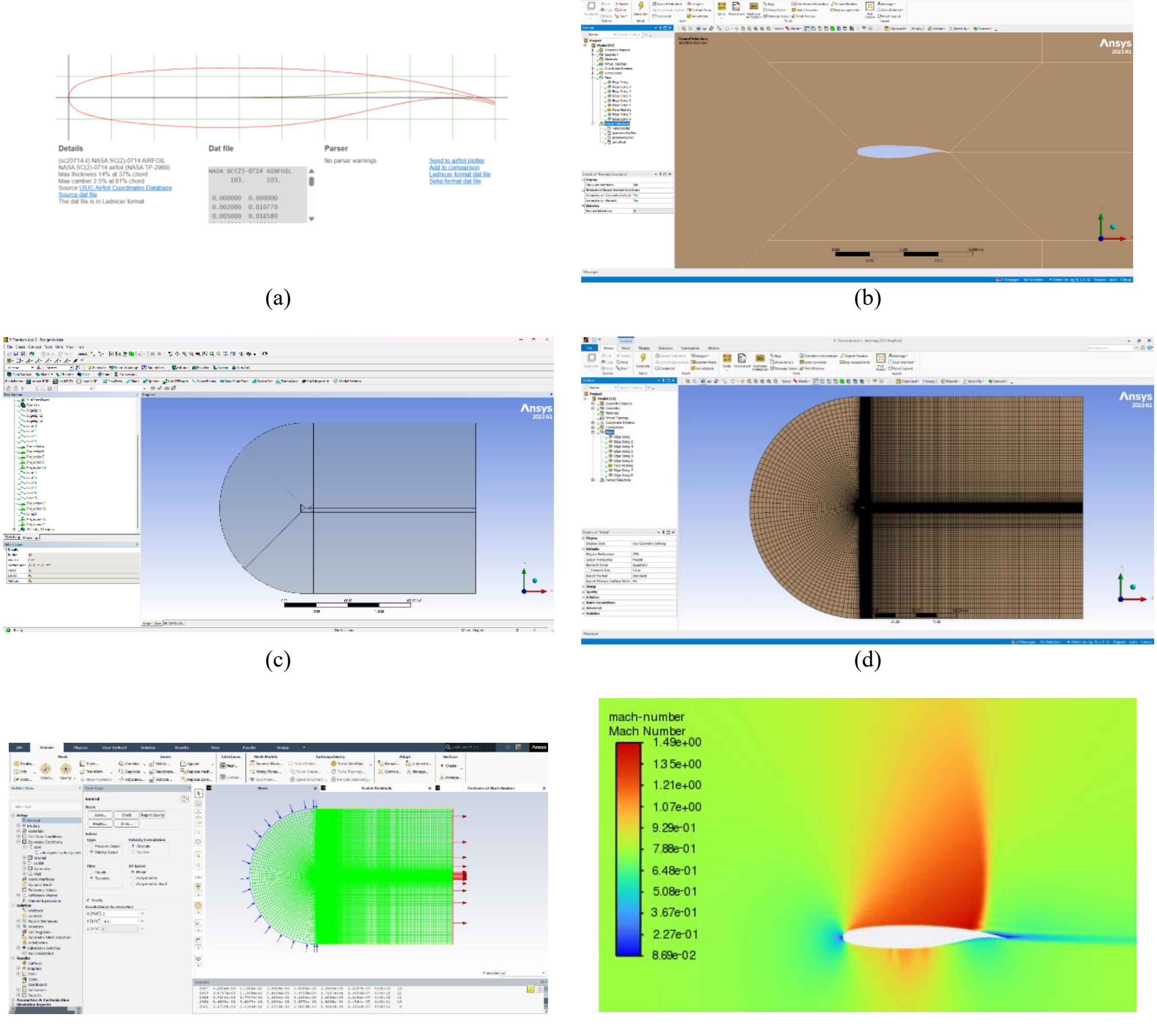
To address this gap, numerical simulations play a crucial role. In this study, Computational Fluid Dynamics (CFD) using ANSYS Fluent is employed to capture shockwave oscillations and the resulting unsteady lift during transonic buffet. The unsteady aerodynamic loads obtained from CFD are then mapped as input for structural analysis. Subsequently, Finite Element Method (FEM) simulations using Abaqus are carried out to evaluate stress distribution and deformation under dynamic loading conditions. Finally, fatigue life estimation with Fe-Safe is performed to assess durability under repeated stress cycles. This integrated CFD–FEM approach enables a direct connection from aerodynamic instability to structural fatigue degradation.

The novelty of this research lies in combining transonic aerodynamic analysis with structural and fatigue assessment, specifically focusing on the SC(2)-0714 supercritical airfoil. This type is widely applied in modern aircraft, yet comprehensive studies linking buffet-induced oscillations to fatigue life are still scarce. This study aims to characterize shockwave oscillations during transonic buffet on the SC(2)-0714 supercritical airfoil, evaluate how the resulting lift fluctuations generate structural stresses, and estimate the reduction in fatigue life caused by repeated unsteady loading. Through this objective, the research seeks to provide a comprehensive understanding of how aerodynamic instabilities ultimately translate into structural degradation.

METHODS

Airfoil Geometry and CFD Setup

The SC(2)-0714 supercritical airfoil, obtained from the NASA airfoil database, was used as the reference geometry in this study (Fig. 2a). The airfoil had a chord length of 6.74 m and was modeled with a rectangular wing span of 35.88 m using ANSYS DesignModeler (Fig. 2b). To minimize boundary effects, a C-type computational domain was constructed with sufficient upstream and downstream distances (Fig. 2c). A structured mesh was applied with refinement near the wall and the leading edge to accurately capture boundary-layer development and shockwave interactions (Fig. 2d). Boundary conditions were defined with a far-field inlet at Mach 0.8, a pressure outlet, and a no-slip condition on the airfoil surface. The reference values were determined based on standard cruise flight conditions, including air density of 1.176 kg/m³ and a freestream velocity of 274.4 m/s (Figs. 2e–f). The CFD simulations were conducted in ANSYS Fluent using a density-based transient solver with Detached Eddy Simulation (DES) turbulence modeling, which has been proven effective in resolving shockwave oscillations and buffet dynamics [14].



Details

(sc20714-il) NASA SC(2)-0714 AIRFOIL
NASA SC(2)-0714 airfoil (NASA TP-2969)
Max thickness 14% at 37% chord
Max camber 2.5% at 81% chord
Source UIUC Airfoil Coordinates Database
Source dat file
The dat file is in Lednicer format

Dat file

```
NASA SC(2)-0714 AIRFOIL
      103.      103.

 0.000000  0.000000
 0.002000  0.010770
 0.005000  0.016580
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Parser

No parser warnings

Send to airfoil plotter
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(a) (b)

(c) (d)

(e) (f)

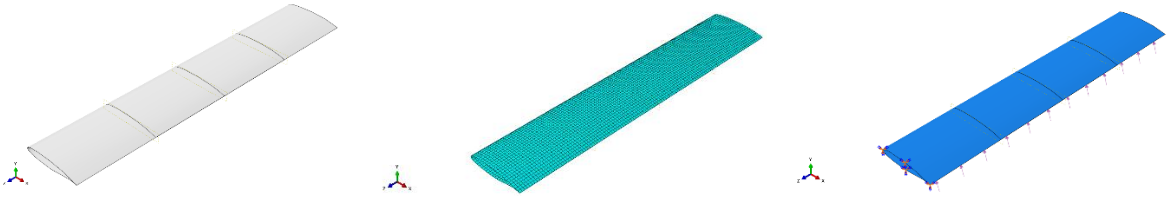
Figure. 2. SC(2)-0714 supercritical airfoil and CFD setup: (a) airfoil profile from NASA database, (b) geometry modeling in ANSYS, (c) C-type computational domain, (d) structured meshing near the airfoil, (e) reference values for CFD simulation, and (f) Mach number contours around the SC(2)-0714 airfoil.

Structural Model and FEM Setup

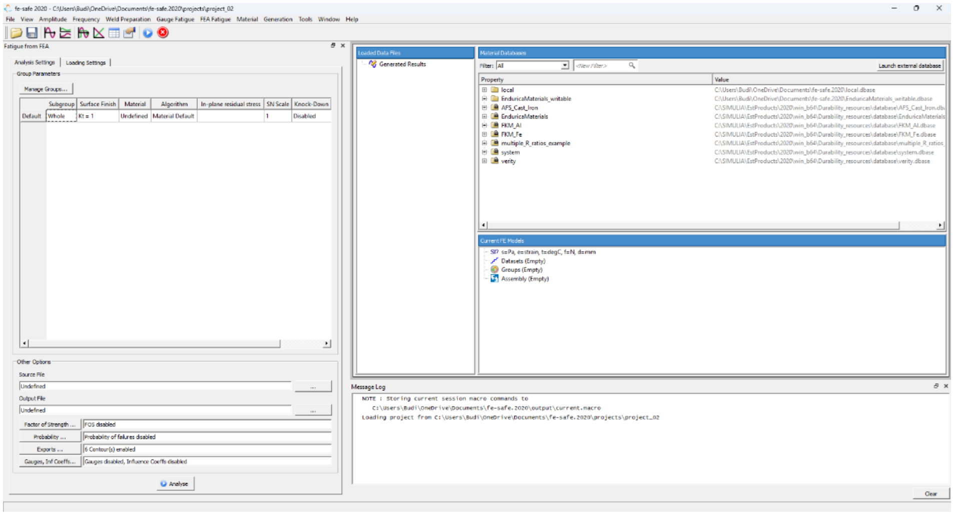
The structural model was developed based on the SC(2)-0714 supercritical airfoil with a wingspan of 35.88 m and chord length of 6.74 m. The wing geometry was constructed in three dimensions to represent the aerodynamic surface (Fig. 3a). The model was then discretized into 26,343 finite elements using a structured mesh to ensure accurate stress and deformation predictions (Fig. 3b). Mesh refinement was applied near the leading edge and wing root to capture local stress gradients that typically govern fatigue initiation.

The material selected for the wing was aluminum alloy 2024-T3, a widely used aircraft-grade alloy with high strength-to-weight ratio and reliable fatigue performance [15]. Both elastic and plastic properties were defined in the model to capture realistic structural response under cyclic aerodynamic loads. Boundary conditions were applied at the wing root using a fixed constraint, restricting translational and rotational degrees of freedom to simulate fuselage attachment. Unsteady aerodynamic loads extracted from CFD simulations were mapped onto the FEM surface as distributed pressures across the wing span for each angle of attack (Fig. 3c). This integration of CFD and FEM has been recognized as an effective approach to quantify structural responses under buffet-induced dynamic loading [16].

Stress histories obtained from Abaqus were subsequently imported into Fe-Safe for fatigue life prediction. The Goodman mean stress correction method was applied, which is suitable for ductile metallic materials such as aluminum alloys. The Fe-Safe environment (Fig. 3d) enabled cycle counting and life estimation under oscillatory buffet-induced loads, thereby completing the analysis chain from shockwave oscillations to lift fluctuations, structural stress, and fatigue life.



(a) (b) (c)



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Other Options
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Output File: Undefined
Factor of Strength ...: FOS disabled
Probability ...: Probability of failures disabled
Exports ...: 6 Contour(s) enabled
Gauges, Inf Coeffs...: Gauges disabled, Influence Coeffs disabled

Filter: All

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verity	C:\SIMULIA\EstProducts\2020\win_b64\Durability_resources\database\verity.dbase

SI? s=Pa, e=strain, t=degC, f=N, d=mm
Datasets (Empty)
Groups (Empty)
Assembly (Empty)

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NOTE : Storing current session macro commands to
   C:\Users\Budi\OneDrive\Documents\fe-safe.2020\output\current.macro
Loading project from C:\Users\Budi\OneDrive\Documents\fe-safe.2020\projects\project_02
```

(d)

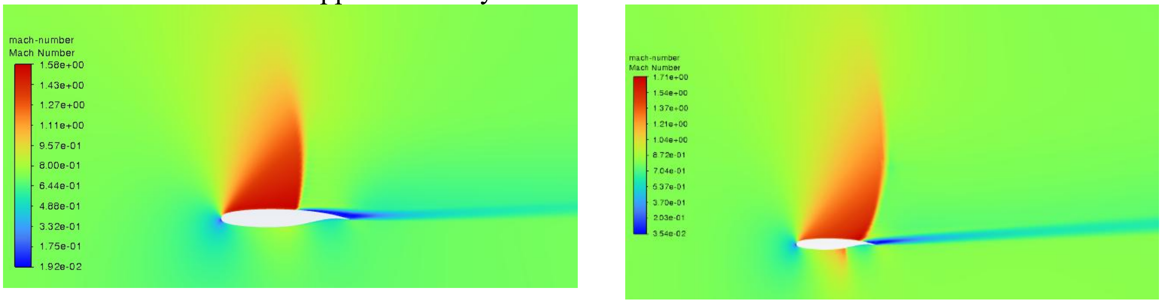
Figure 3. Structural model and analysis of the SC(2)-0714 supercritical airfoil: (a) wing geometry, (b) finite element mesh, (c) structural boundary conditions with aerodynamic loads, and (d) fatigue life simulation in Fe-Safe.

RESULT AND DISCUSSION

This section presents the results obtained from the integrated CFD–FEM–fatigue simulations. The analysis is divided into three main parts: the aerodynamic characteristics of transonic buffet, the structural stress and displacement responses under buffet-induced loads, and the fatigue life estimation of the wing structure. By combining these stages, the results provide a comprehensive view of how shockwave oscillations evolve into lift fluctuations, structural stresses, and ultimately affect the fatigue life of the SC(2)-0714 supercritical airfoil.

Shock Buffet Simulation Analysis

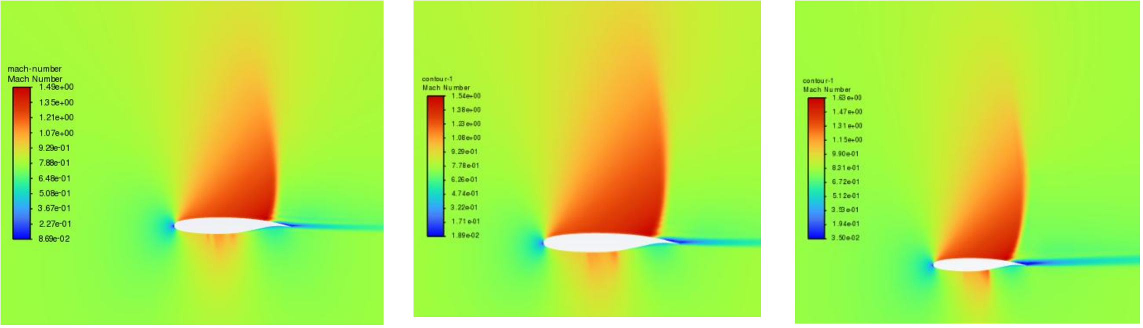
The simulations were conducted at Mach 0.8, representing cruise conditions of a wide-body aircraft such as the Boeing 777, where supercritical airfoils like SC(2)-0714 are typically applied. Three angles of attack (AoA) were examined: 2°, 4°, and 6°. AoA 2° was chosen to observe the onset of buffet, while AoA 4° and 6° were applied to analyze its intensification.



(a) (b)

Figure 4. Visualization of Transonic Buffet at Mach Number 0.8 against AoA 6° (a) Frame 50/1000 and (b) Frame 100/1000

Figure 5. illustrates the temporal evolution of shockwave oscillations at AoA 6°, comparing the flow field at frame 50/1000 and frame 100/1000. It can be seen that the shockwave position fluctuates along the chord, reflecting the unsteady nature of transonic buffet. Further visualizations of Mach number contours at Mach 0.8 for AoA 2°, 4°, and 6° are presented in Figure 3.2. At AoA 2°, a weak shockwave begins to form on the upper surface; at AoA 4°, the shock strengthens and interacts with the boundary layer, producing more pronounced unsteady separation; while at AoA 6°, shock-induced separation becomes significant, indicating stronger buffet effects.



(a) (b) (c)

Figure 5. Visualization of Mach Number 0.8 Contours against AoA (a) 2°, (b) 4°, and (c) 6°

From these CFD simulations, the aerodynamic forces acting on the wing were extracted and then converted into pressure values by dividing the forces by the wing reference area. These pressure distributions, representing unsteady aerodynamic loads during buffet, were subsequently used as inputs for the FEM simulations in Abaqus to analyze structural stresses and fatigue life

Structural Stress and Displacement Analysis

The unsteady aerodynamic loads extracted from CFD were applied to the structural model in Abaqus to evaluate stress distribution and displacement. From ANSYS Fluent, the aerodynamic force acting on the airfoil was first obtained and then normalized by the wing reference area to calculate the corresponding pressure distribution. This pressure data was subsequently used as the input load in the FEM simulations in Abaqus.

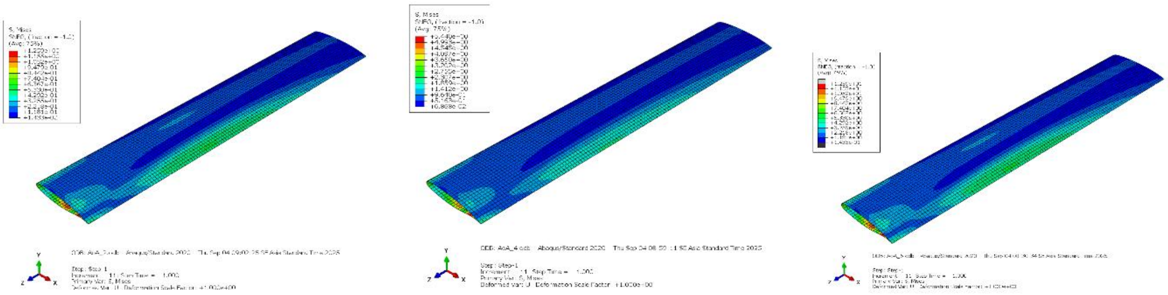

(a) (b) (c)

Figure 6. Result of structural stress for Aoa: (a) 2°, (b) 4°, and (c) 6°

The results of structural stress are shown in Figure 6 for AoA 2°, 4°, and 6°, respectively. The stress values ranged between 1.26 MPa and 12.6 MPa, which remain far below the yield strength of aluminum alloy 2024-T3 (345 MPa). This indicates that under static considerations, the structure remains within safe operational limits.

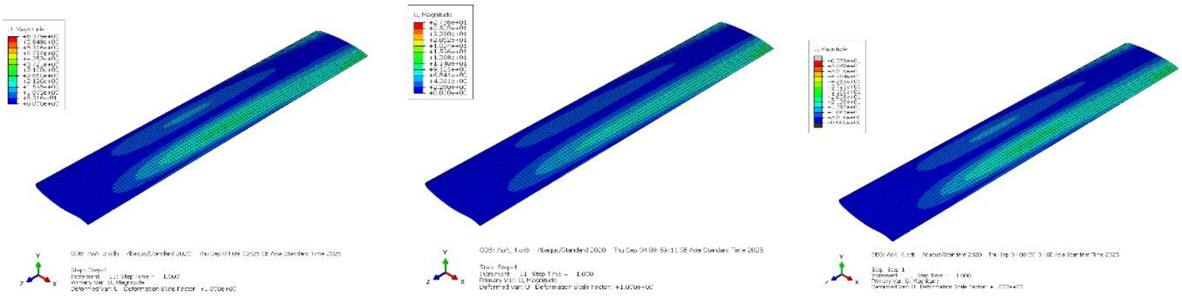

(a) (b) (c)

Figure 7. Result of displacement fields for Aoa: (a) 2°, (b) 4°, and (c) 6°

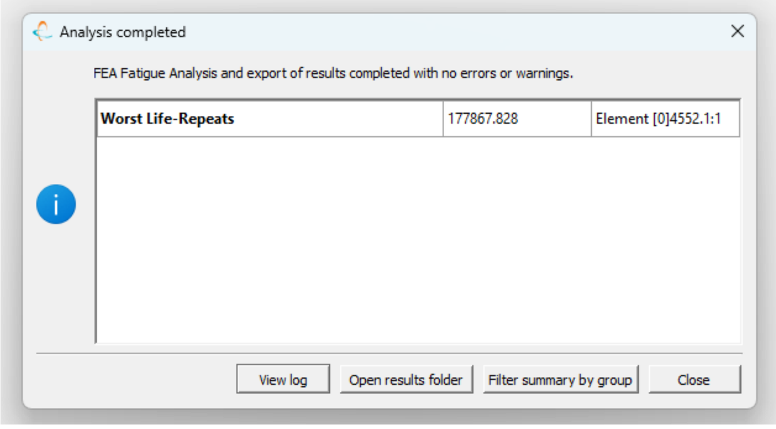
The displacement fields obtained from the FEM simulations are presented in Figures 7. As expected, structural displacement increases with AoA due to higher lift fluctuations. Although the magnitudes of displacement are relatively small compared to the wing span, their oscillatory nature can trigger long-term fatigue accumulation.

Fatigue Life Analysis under Lift-Induced Loading

Stress histories obtained from the FEM simulations were imported into Fe-Safe to estimate fatigue life using the Goodman mean stress correction. The fatigue life results for AoA 2°, 4°, and 6° are summarized in Table 1, while the detailed output displays from Fe-Safe are shown in Figure 8. The results indicate a clear reduction in fatigue life as AoA increases. At AoA 2°, the wing can withstand approximately 177,868 cycles, but this value decreases by ~27% at AoA 6°. This demonstrates that while the stress levels remain below yield, the oscillatory nature of buffet significantly accelerates fatigue degradation.

Table 1. Fatigue life for various AoA

AoA (°)	Fatigue life (cycles)
2	177867.828
4	159436.516
6	130282.117



FEA Fatigue Analysis and export of results completed with no errors or warnings.

Worst Life-Repeats	177867.828	Element [0]4552.1:1

Figure 8 . Wing fatigue life for 2° AoA

The combined results reveal a sequential mechanism: shockwave oscillations during transonic buffet produce unsteady lift, which generates cyclic stresses in the wing structure, ultimately reducing fatigue life. This confirms that buffet effects must be considered in durability assessments of supercritical airfoils. Although the stress levels alone suggest safe operation, the accelerated fatigue reduction highlights the importance of unsteady load modeling in structural design.

CONCLUSIONS

The This study investigated the effects of transonic buffet on the SC(2)-0714 supercritical airfoil by integrating CFD, FEM, and fatigue analysis. The key findings can be summarized as follows:

a. Shockwave Oscillations: CFD simulations using ANSYS Fluent at Mach 0.8 and AoA variations of 2°, 4°, and 6° successfully captured the onset and intensification of transonic buffet. Increasing AoA shifted the shockwave upstream, intensified its oscillations, and promoted stronger boundary layer interaction.
b. Lift Fluctuations to Structural Stress: The unsteady aerodynamic forces obtained from CFD were converted into pressure loads and applied in Abaqus structural simulations. The resulting stresses ranged between 1.26 MPa and 12.6 MPa, remaining well below the yield strength of aluminum alloy 2024-T3, indicating safe static margins.
c. Fatigue Life Reduction: Despite low stress levels, fatigue life estimation using Fe-Safe with the Goodman approach showed a significant decline with increasing AoA. The fatigue life decreased from 177,868 cycles at AoA 2° to 130,282 cycles at AoA 6°, representing a reduction of nearly 27%.

In conclusion, the research confirms that transonic buffet initiates with shockwave oscillations, which propagate as unsteady lift fluctuations, generate cyclic stresses in the wing structure, and ultimately accelerate fatigue degradation. These findings highlight the necessity of incorporating buffet-induced unsteady loads into the structural durability assessment and design of modern supercritical airfoils.

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