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# Loading Simulation Study of Auxetic Structures used as a Film Cooling Design

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## Abstract

This study investigates the effects of applying mechanical loads to auxetic designs that could be used as film coolant slots. The auxetic design causes the component to behave as if it has a negative Poisson’s ratio (NPR). The effects of typical mechanical loadings were tested on the following three geometries; an auxetic S-shape pattern, an auxetic ellipsoid pattern and a non-auxetic pattern of inline circles that functioned as a base case. This NPR behavior was studied via Siemens NX Software simulations using finite element analysis (FEA) to study the effect of applying theoretical force and pressure loads on the structures in order to determine the stress concentrations and deformations of each geometry.

The loading stresses were first simulated on a flat coupon and then on an open-ended cylinder to simulate different surfaces of critical turbine components where the auxetic structures could be used. For the flat coupons the simulations demonstrated that when a 10kN axial force was applied to the structures, all three designs expanded laterally, with the S-shape expanding the most followed by the ellipse coupon and then the inline circle coupon. For the cylindrical coupon, the applied 0.04MPa resulted in an increase in radius where the slots were located.

## Introduction

In gas turbines, the highest allowable temperatures at which materials can safely operate is less than the combustion operating temperatures experienced. In order to close this temperature gap, cooling methods are implemented to maintain the integrity of the material. One such cooling method is film cooling. Film cooling provides a thermal barrier between the critical components, such as airfoils and combustor liners, and the hot combustion air. This allows for higher turbine inlet temperatures (TIT), therefore increasing the thermal efficiency.

This coolant air flows from the compressor into the inner coolant chambers and out through the surface of the critical components. The size, shape and number of coolant slots on the critical component surfaces determine the effectiveness of the film cooling. Because the critical components experience significant mechanical and thermal loads, the shape of the coolant holes deform when in loading. This deformation affects the effectiveness of film cooling, and in order to increase the effectiveness when deformed, the use of auxetic structures is studied.

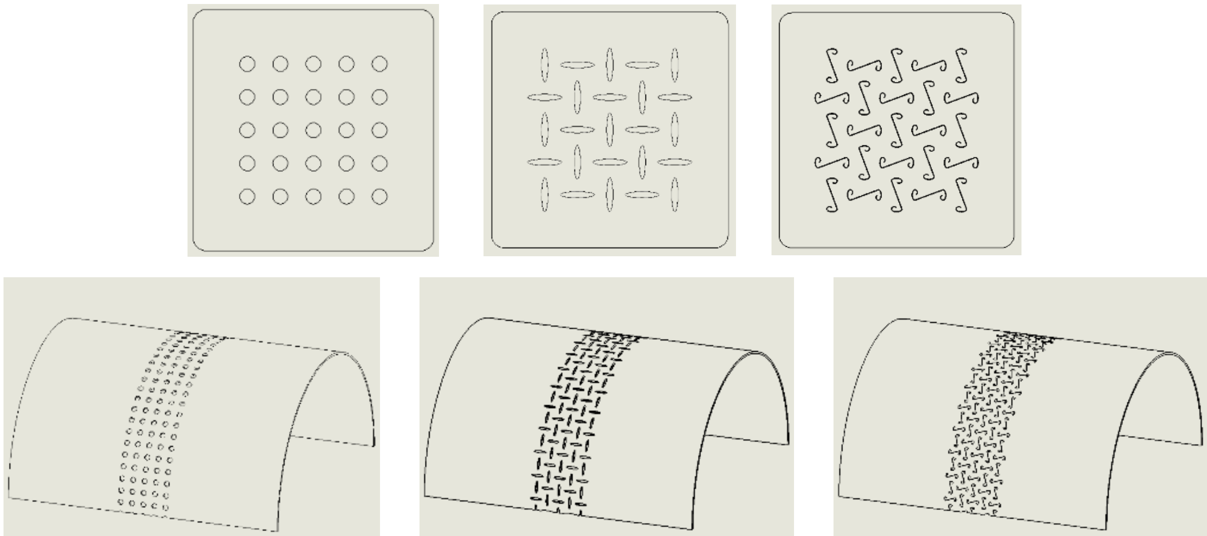

***Figure 1: Flat & Cylindrical Test Coupons***

## Background

Combustion liners and airfoils experience great stress concentrations due to high amounts of mechanical and thermal loading. Having a design that maintains or increases the size of the coolant holes without high concentrations of stress when in tension can potentially lead to increased cooling and part life. The S-shape being used in this study has proven to be an auxetic structure with stress-relief features because of its curved nature and NPR qualities [6]. This auxetic structure opens the possibility for effective cooling with low porosity. Flores et al [1] studied the film cooling effectiveness of the same three geometries, s-shape, ellipse and circles, and found the most efficient coolant and free stream flux ratio, or blowing ratio, range of the undeformed structures to be between .05 and 0.75. To continue auxetic structure research and its potential application, the effectiveness of the deformed structure must be determined. To do so, this research will aim to study how the auxetic structures deform under typical critical component mechanical (force and pressure) loading.

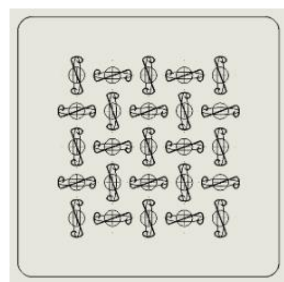

***Figure 2: Relationship of Geometry Design***

## Geometry

The geometry used in this study was adapted from the normalized geometry used by Flores [1]. For each of the three slot designs, the center to center distance of all slots for each pattern is 12.5 mm. All the flat coupons consist of a 5x5 slot design centered at the center of the 90.93 mm x 90.93 mm filleted square coupon. The half cylinders consist of a 36x5 slot pattern with a cylinder radius of 143.239 mm and a cylinder length of 300 mm. The thickness of both coupons was 2 mm. The base case design is a simple pattern of inline circles with diameters of 5.6 mm. Both auxetic designs consist of each consecutive slot oriented at a 90° angle in any direction, starting with an initial 0° angle from the vertical. The ellipsoid pattern is characterized by identical ellipses with a major radius of 6.5 mm and a minor axis of 1.2 mm. The S-slot design consists of the s-shape with an overall height of 13.2 mm, width of 4.19 mm, and a slot thickness of 0.2 mm.

## Methodology & Mesh Refinement

The parts were modeled using SolidWorks and simulation results were obtained using Siemens NX 12 software. The slot designs used were obtained from Flores [1], as well as the dimensions used for the flat coupon. The material assigned for all simulations was Annealed Stainless Steel 304, as provided by NX siemens Software. For all the flat coupons, the left-hand face was fully constrained and a 10kN distributed load was applied to the right-hand face. Each flat coupon simulation used a CTETRA(10) 3D mesh with an element size of 1.0 mm, surface curvature based size variation of 40.4, an internal mesh gradation of 1.05, and a small feature Tolerance of 10.0.

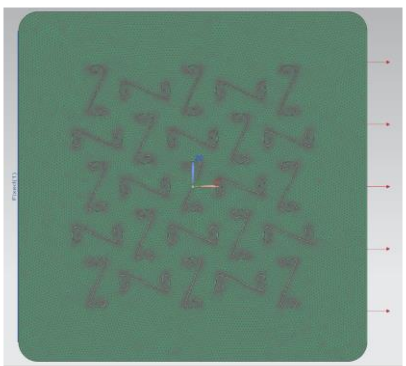

***Figure 3: Flat Coupon NX Simulation Setup***

Because a cylinder is symmetrical and the slot designs are periodic, only half of each cylinder was modeled with a length of 30cm and an outer radius of 14.33 cm and a wall thickness of 2 mm. 3-D CTETRA(10) meshes with element size of 7.0 mm, surface curvature based size variation of 85.6, an internal mesh gradation of 66.4, and a small feature Tolerance of 17.4 were applied to each cylindrical model. A pressure of 0.04MPa, 2% of 20 bar, was applied to the inner surface of each cylinder to simulate the typical pressure experienced by critical components. The hoop edges were fully constrained and the edges where the cylinder would have continued were given symmetrical constraints.

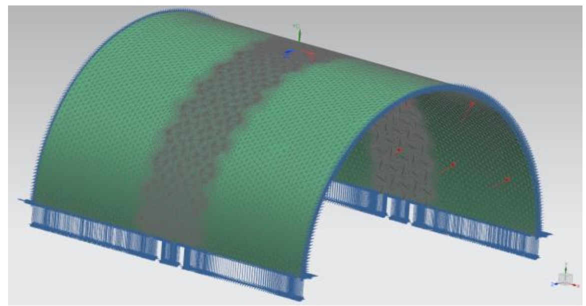

***Figure 4: Cylindrical Coupon NX Simulation Setup***

Mesh specifications were decided based on the accuracy of the mesh around the curved slots and the length of time required for simulations to run, no more than 20min. The following are examples of meshes considered for the cylindrical s-slot coupon. The finer mesh was chosen because it provided finer results without being too costly. A similar process was done for the flat coupon mesh.

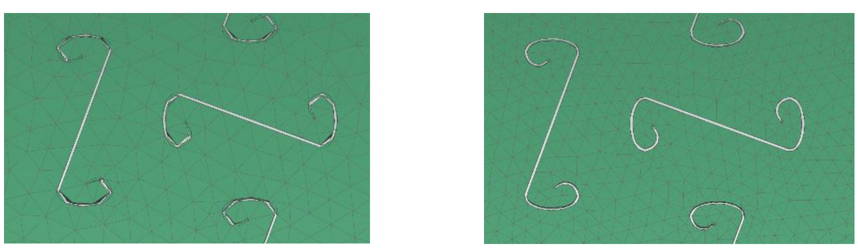

***Figure 5: Rejected Coarse Mesh (Left) & Used Mesh with mentioned specifications (Right)***

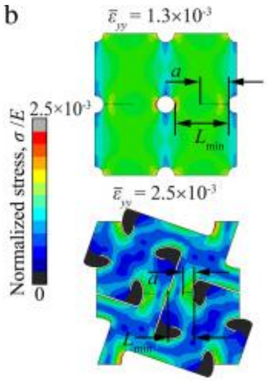


***Figure 6: Simulation Results from Javid [2] Simulations***

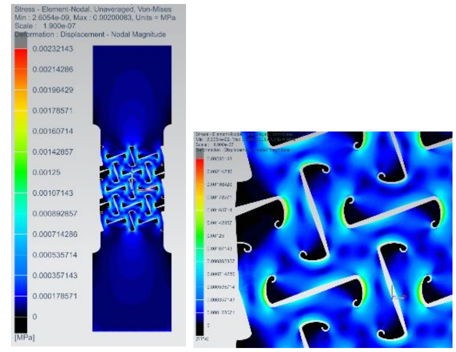

***Figure 7: Comparison Simulation Results***

## Verification

In order to validate the approach used to gain these results, Javid et al's [2] simulation is replicated using NX simulation software instead of ABAQUS to ensure accuracy of methodology that will be used within this study.

Javid focused on a 2D model and modeled it as an infinite periodic section with periodic constraints. For the comparison, the same T-bone shape used in the Javid study was replicated with a 3D mesh used along with non-periodic constraints. The scale obtained from the NX simulation was manipulated to obtain the normalized strain as was done by Javid. As seen, the strain concentrations derived from the NX software match the results from the Javid Harvard study.

## Results & Discussion

The following are the results obtained from the simulations of the three geometries with the two coupon designs.

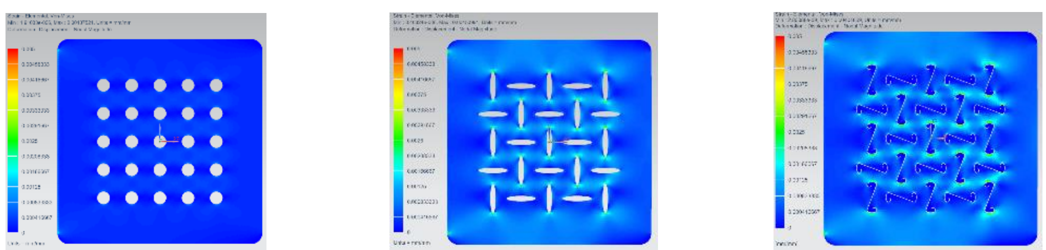

***Figure 8: Flat Coupon Strain Results***

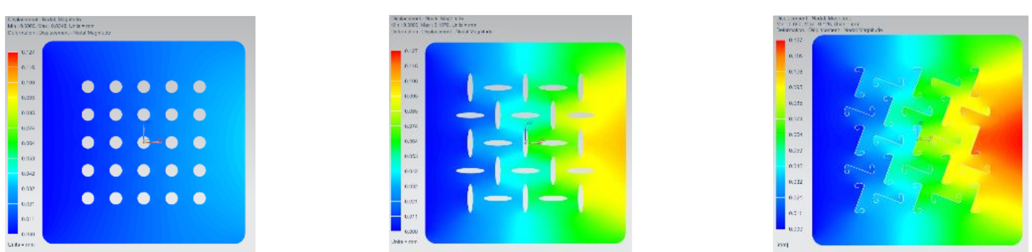

***Figure 9: Flat Coupon Displacement Results***

*Table 1: Flat Coupon Deformations*

| Design | Lateral Deformation [mm] |
|---|---|
| S-Shape | +0.1265 |
| Ellipses | +0.0612 |
| Circles | +0.0454 |

For the flat coupons, the applied force caused each of the structures to deform. From the 10kN force simulations, it is shown that the more auxetic the structure is, the more strain and deflection it experiences. The S-Shape, being the most auxetic, experiences the most strain and deflection while expanding the most laterally and decreasing the least vertically. The Ellipse design and circle design follow that same pattern with the circle design experiencing the least strain and deflection with the least lateral deformation and the most vertical deformation because it is not an auxetic structure.

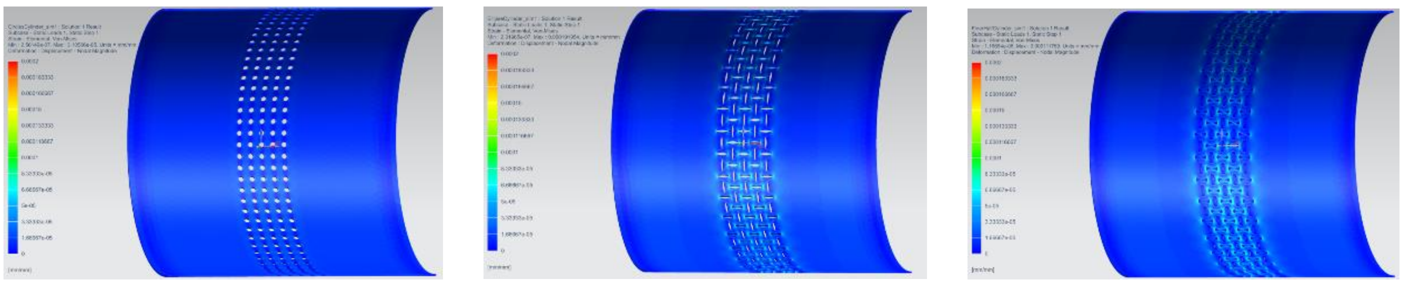

*Figure 10: Cylindrical Coupons Strain Results*

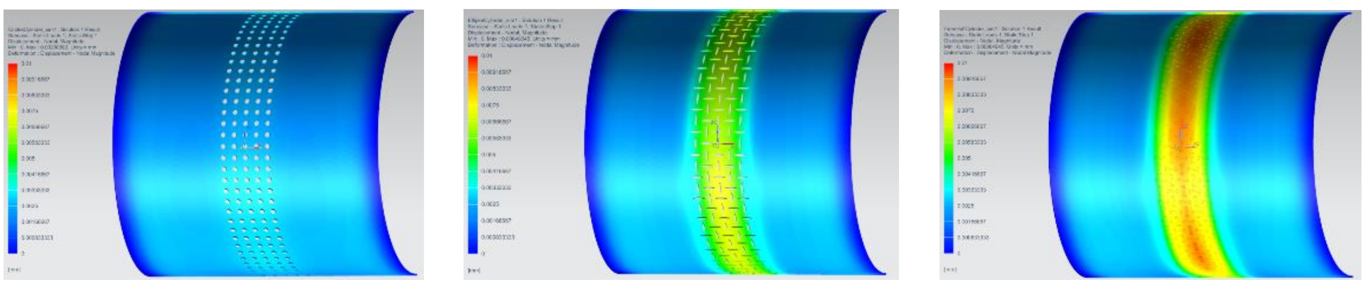

*Figure 11: Cylindrical Coupons Displacement Results*

*Table 2: Radial Deformation Along Center Cross Section of Cylindrical Coupons*

| Design | Radial Deformation [mm] |
|---|---|
| S-Shape | +0.0165 |
| Ellipses | +0.0068 |
| Circles | +0.0044 |

For the cylindrical coupons, the applied 0.04MPa on the inner surface of the coupons resulted in a similar trend of most strain and deformation seen in most the auxetic structure, like the results from the flat coupons. The S-shapes experienced the most outward expansion than the ellipses and circle, respectively.

The S-shape is designed to uncoil and deform, and this tendency is evident from the results. The more the design deforms, the more strain and displacement the material experiences on both flat and curved surfaces. The more force applied to the material, the more the auxetic structures will expand.

## Conclusion and Future Work

This research focused on the deformation of the S-shape on a flat surface in tensile loading and the deformation of a curved surface caused by a pressure difference. Using Siemens NX software to study the deformation will lead to sample deformations of critical components. Once the exact deformations are obtained, sample coupons will be manufactured with the deformed auxetic geometry. These new coupons will then be used to begin to understand the change in film cooling effectiveness as the auxetic structures deform due to mechanical and thermal loading.


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