Novel Architected Materials for Increase Resilience in Critical Infrastructure

Jens R Knudsen III

The University of Texas at San Antonio, San Antonio TX, 78249

Name: Jens R Knudsen III
Status: *Junior*
Department: *Mechanical Engineering*
Area of Study: *Architected Materials*
USDA/UTSA Mentor(s): *Dr. Restrepo*

AMMS Research Area

The main research interest of the AMMS Lab is to advance in the fundamental understanding of nonlinear behavior and failure mechanisms observed in materials and structures, with the aim of designing new materials that exhibit unprecedented mechanical properties and functionalities. To achieve this goal, our research approach combines computational simulations, theoretical analysis, fabrication, and experimental testing. Applications of interest are in broad areas including healthcare, defense, robotics, civil infrastructure, mechanical engineering, and aerospace engineering.

Motivation or Background

Traditional energy dissipation techniques rely on mechanical failure which result in weakening or destruction of structure. However, materials can take advantage of the elastic nature of some buckling geometries to dissipate energy when loaded and return to their original configuration when the load is removed. For example, energy dissipation can be taken advantage of in low rise buildings to dissipate kinetic energy transmitted by waves during seismic events through control of the bucking behavior of the architectural materials. In order to understand and predict buckling behavior in materials, wave propagation through materials must be understood. Currently, the buckling analysis of large scale periodic structures is time consuming and computationally expensive, leading to trial and error design followed by empirical data collection through modeling and testing. However, Bloch's periodicity has be used in solids physics to analyze the propagation of waves through periodic materials by analyzing a single unit cell of the periodic structure. In an effort to reduce the resource expense when performing buckling analysis, we attempt to apply Bloch's periodicity to a particular geometry. In order to do so, the model must be developed and validated with a simpler geometry before being applied to the model in Figure 1.

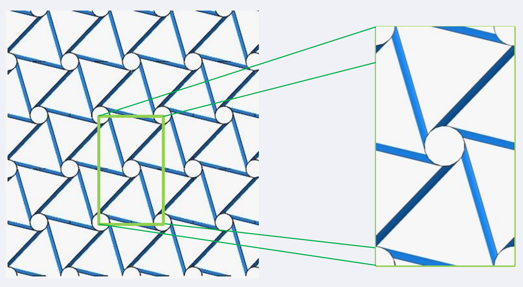

Fig. 1
Complex Geometry requiring a Bloch's model for anlaysis

Objectives

1. Develop a model using Bloch's periodicity to analyze a unit cell representing a periodic material to recover global effects.
2. Validate the model by comparison of recovered buckling shape and buckling strain data.
3. Predict behavior of a periodic material through analysis of a single unit cell.

Methodology

Super Cell Buckling Analysis

A periodic structure of crosses forming a 15 x 15 grid pattern was chosen as the material of interest. The structure and the associated unit cell's detail are displayed in Figure 2. The material properties include a Young's Modulus of 2370 MPa and Poisson's Ratio of 0.32. All simulations were performed using periodic boundary conditions between opposing sides, represented by red and blue zones in Figure 2. First, the base line data on the entire structure's deformation was collected using Abaqus FEA. The data collected was used to facilitate a static test under compressive force from which force and strain data were collected.

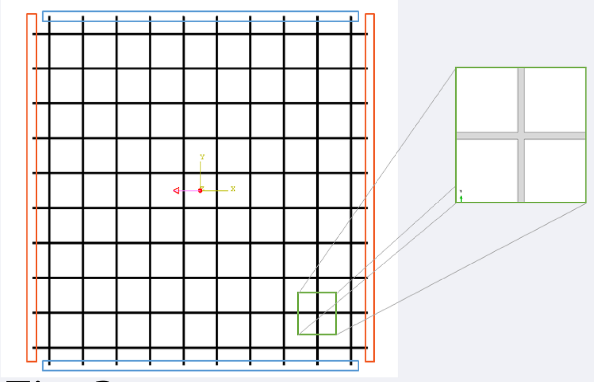

Fig. 2
Supercell Geometry with Unit Cell

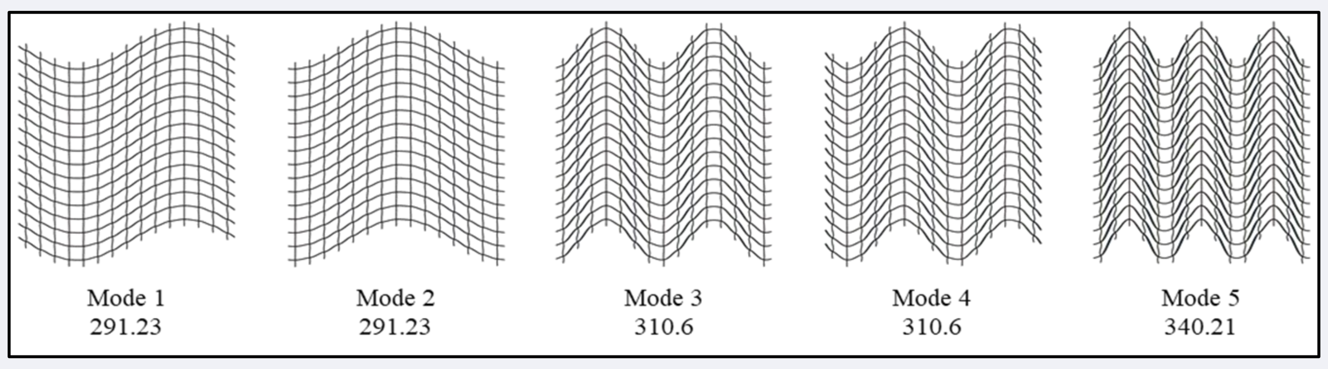

Fig. 3
Supercell Traditional Buckling Analysis

Unit Cell Buckling Analysis

Traditional buckling analysis of the unit cell was performed and the modal results compared to the supercell's. This comparison revealed traditional analysis of the unit cell would not be useful in evaluation of the periodic structure, as the longer wavelengths that cause buckling in the Supercell are not identified as buckle modes (Figure 4).

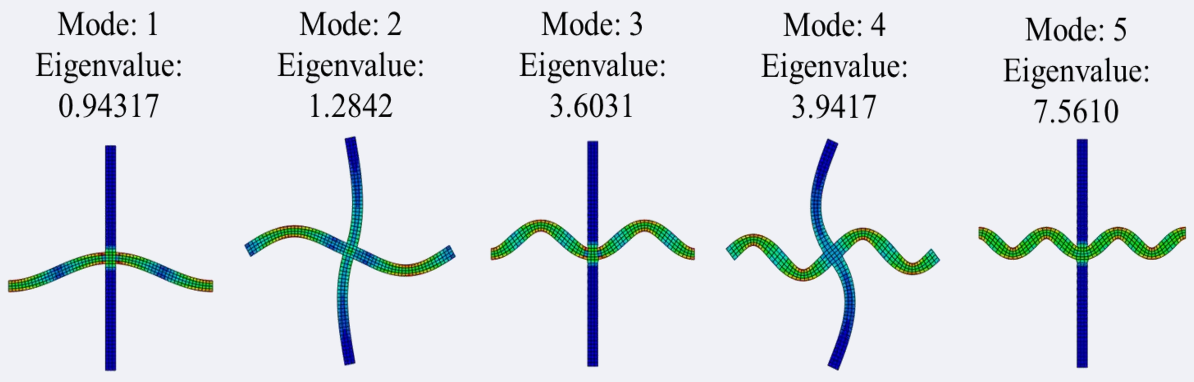

Fig. 4
Traditional Buckling Analysis of the Unit Cell

Unit Cell Analysis with Bloch's Periodic Boundary Conditions

In order to capture data on the buckle modes of the supercell while analyzing on a unit cell, the methods employed by Liu, Bertoldi, et all in "Bloch wave approach for the analysis of sequential bifurcations in bilayer structures" [1] as well as Do and Le Grognec in "Buckling analysis of a reinforced sandwich column using the Bloch wave theory." [2]

Results

Super Cell Buckling Analysis

The buckling modes and eigenvalues of the supercell obtained are shown in Figure 3.
The results of adding these buckle modes as imperfections to the super cell's geometry and performing the static analysis under a compressive force of 295 N is displayed in Figure 5. The deformed geometry matches well with Mode 1 of Figure 3. Additionally, the force strain data identifies the critical strain as 0.001219.

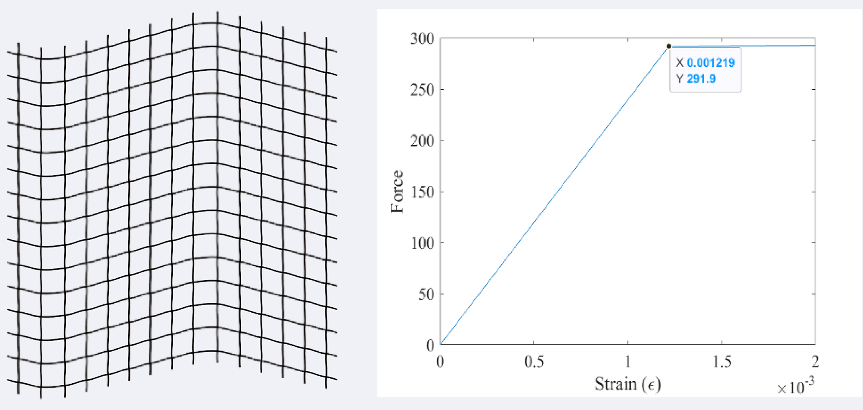

Fig. 5
Supercell with Imperfections Static Analysis Results

The Bloch's Analysis

Figure 6, shows the results of the Bloch's analysis performed across a strain range of [1E-8, 2E-3] and a wavenumber range of [0.0, 0.005*Pi]. The minimum buckling strain, associated with k=0.001592*PI agrees well with the critical strain identified the super cell static analysis (Figure 5).

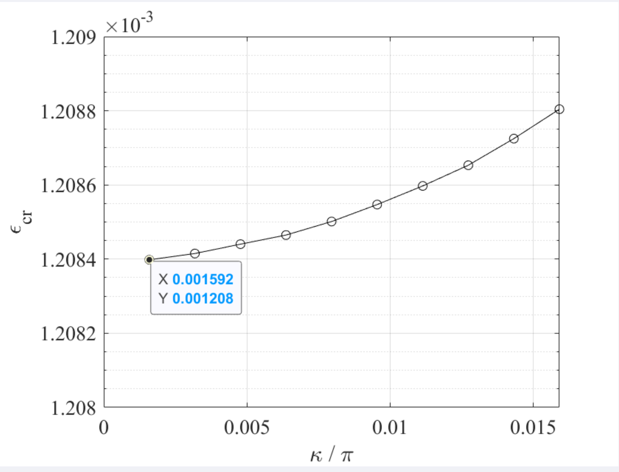

Fig. 6
Critical Strain Identified by Bloch's Analysis

When Bloch's periodic conditions are applied with k=0.001592*PI the structure in Figure 7 is recovered, proving the ability to analyze a single unit cell for the global buckling strain and model the resulting periodic structure.

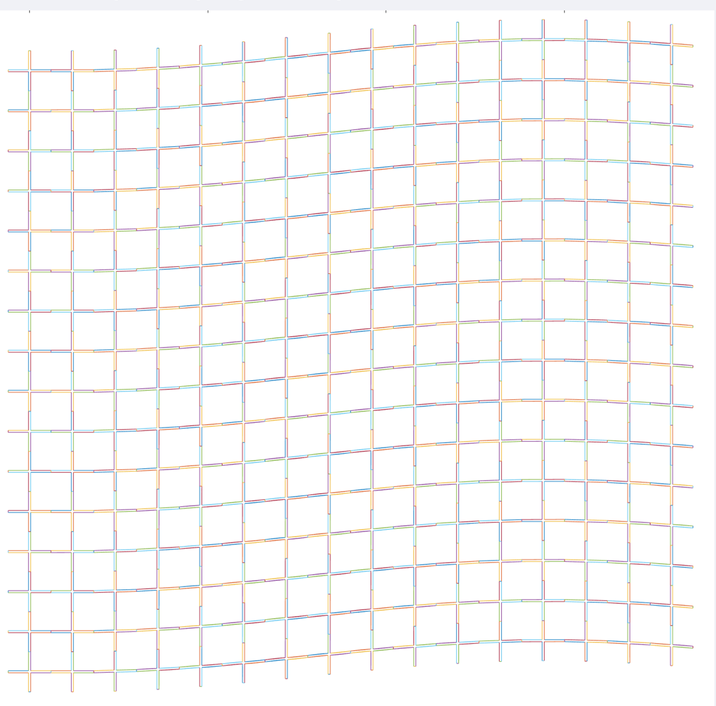

Fig. 7
Supercell created by applying Bloch's Periodicity

Skills and Experience

Throughout the process of this research I developed several new skills. For example, I had never used any finite element analysis software. I now have experience with Abaqus, both using it to create geometries in the CAD environment and in modification of input parameters for finite element analysis. In addition, learned how to perform analysis on periodic structures using periodic boundary conditions. Another finite element analysis skill I developed was extracting, interpreting and communicating data from the computations. Related to data analysis, learned how to extrapolate on the results to improve or drive additional simulations. I also had my first experiences using a super-computer and learning how to maximize efficiency of computations.

What I Learned

I learned a lot from participation in the Advanced Materials and Mechanical Systems Lab research. I was exposed to the concepts of wave propagation and novel concepts to dissipate energy. I gained a greater understanding of buckling mechanics and how buckling can be used to dissipate energy in a system. I also learned about frequency analysis, the meaning of natural frequencies and modal shapes. Additionally, the concept of Bloch's periodicity was introduced to me and I learned how to use the concept to model periodic structures through analysis of a single unit cell.

Future Plans

Future Plans Include:

- Verify how this method can be implemented in a particular hexagonal periodic material.
- Answer: How can the method be related to more complex geometries?
- Answer: Can this method be used to analyze the numerical derivatives of the buckling behavior?
- Use the method to optimize the unit cell geometry and buckling behavior for energy dissipation objectives.

Acknowledgments

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References

[1] J. Liu and K. Bertoldi, "Bloch wave approach for the analysis of sequential bifurcations in bilayer structures," Proc. R. Soc. A Math. Phys. Eng. Sci., vol. 471, no. 2182, p. 20150493, Oct. 2015.

[2] V.D. Do and P. Le Grognec, "Buckling analysis of a reinforced sandwich column using the Bloch wave theory," Thin-Walled Structures, vol. 115, Mar. 2017