

### Project Objectives and Goals

Analyze Leonardo's lintel using modern engineering tools and methods.

Discover how the mechanics of Leonardo's lintel differ from that of an Euler Bernoulli beam.

The tools and methods used are:

- CAD tools to visualize the structure
- 3D printing for structural realization
- Three point bend experiments
- Photoelastic experiments
- Finite element analysis

### Background

Leonardo's lintel is constructed using a series of interlocking blocks to replace beams [1].

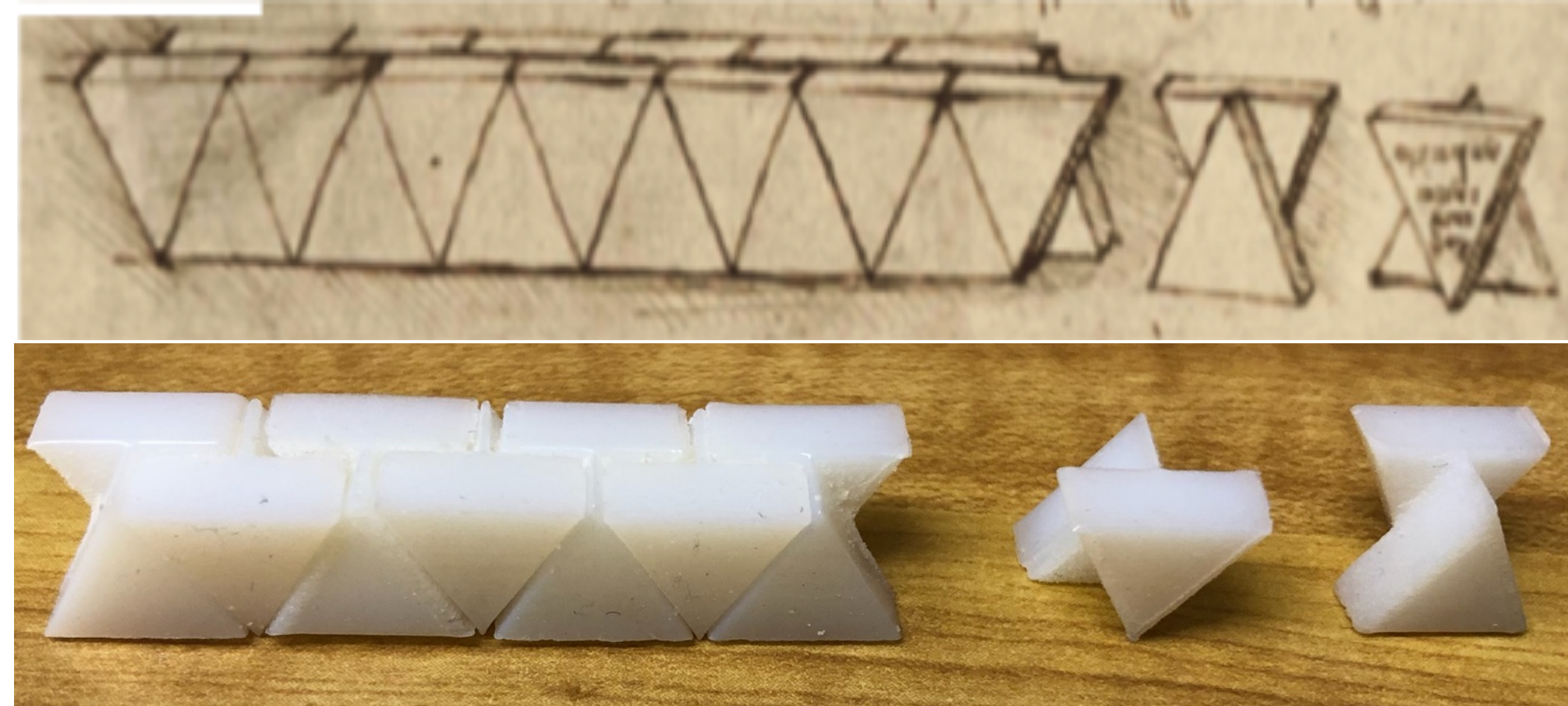


Figure 1: (a) Leonardo's original lintel design and (b) a 3D printed representation

Hypothesize that Leonardo's lintel deforms by compression processes only. Therefore, the response would be similar to that of a van Mises truss.

The van Mises truss would span from the support points to the load point.

The force v. displacement response possesses a peak load at a displacement equal to the half lintel height and fall to zero load at a displacement equal to the lintel height.

Lintel stiffness, maximum force and toughness would be linearly dependent on lintel length.

Leonardo's lintel is a one dimensional topologically interlocking structure. This work expands concurrent research on planar interlocking systems that replace plates [2, 3].

### Methods & Procedures

#### Three Point Bend Experiments:

For three point bend experiments, 8 mm tall lintel pieces were 3D printed. The pieces were arranged into lintels ranging from 7 to 11 pieces. Lintels were placed under a wedge at the lintel center. A force sensor and a displacement sensor were used to collect force and displacement data.

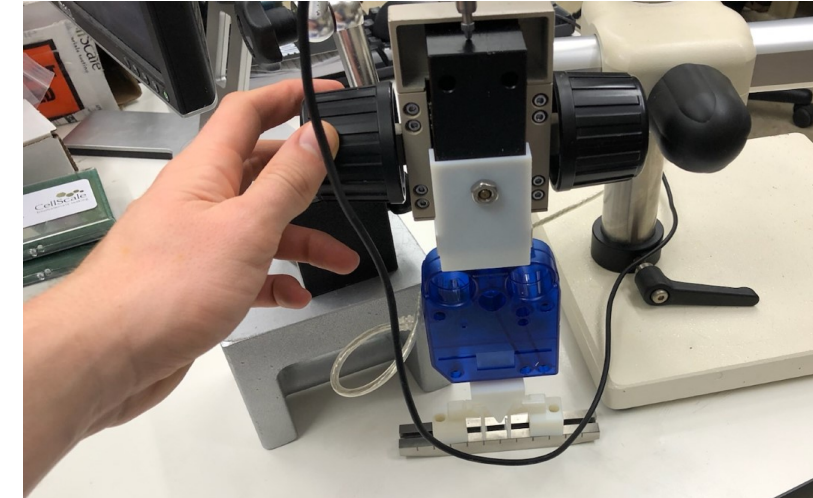


Figure 2: The three point bend experiment set up

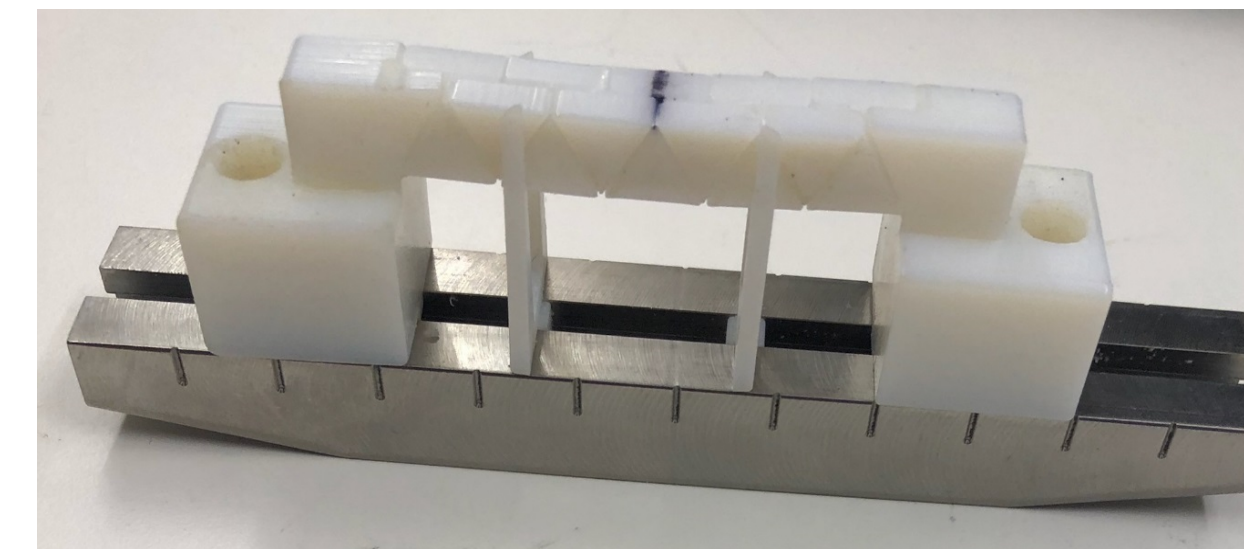


Figure 3: The nine piece lintel

#### Photoelastic Experiments:

For photoelastic measurements, 16 mm tall translucent pieces were 3D printed, arranged into a lintel, and placed under a wedge, bisecting the lintel. Images were taken throughout the loading process.

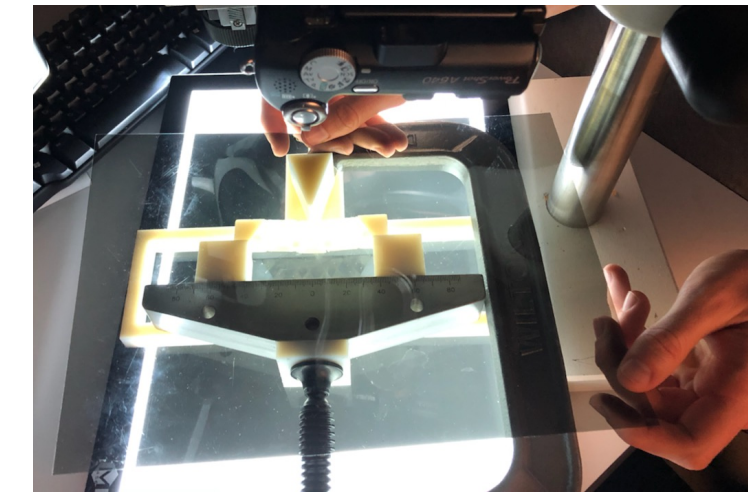


Figure 4: The photoelastic set up with two polarized filter sheets

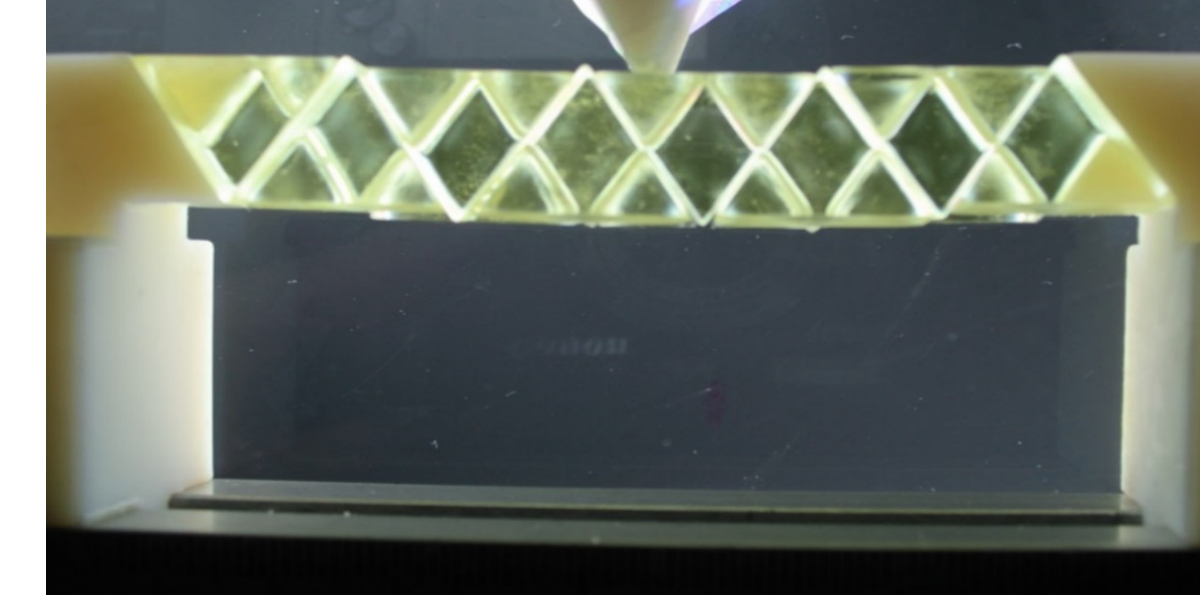


Figure 5: The translucent lintel

#### Finite Element Model:

Finite element models were made using ABAQUS for lintels ranging from 6 to 10 pieces. Models were used to compute the force v. displacement response and the stress distribution.

### Data and Results

#### Three Point Bend Experiments:

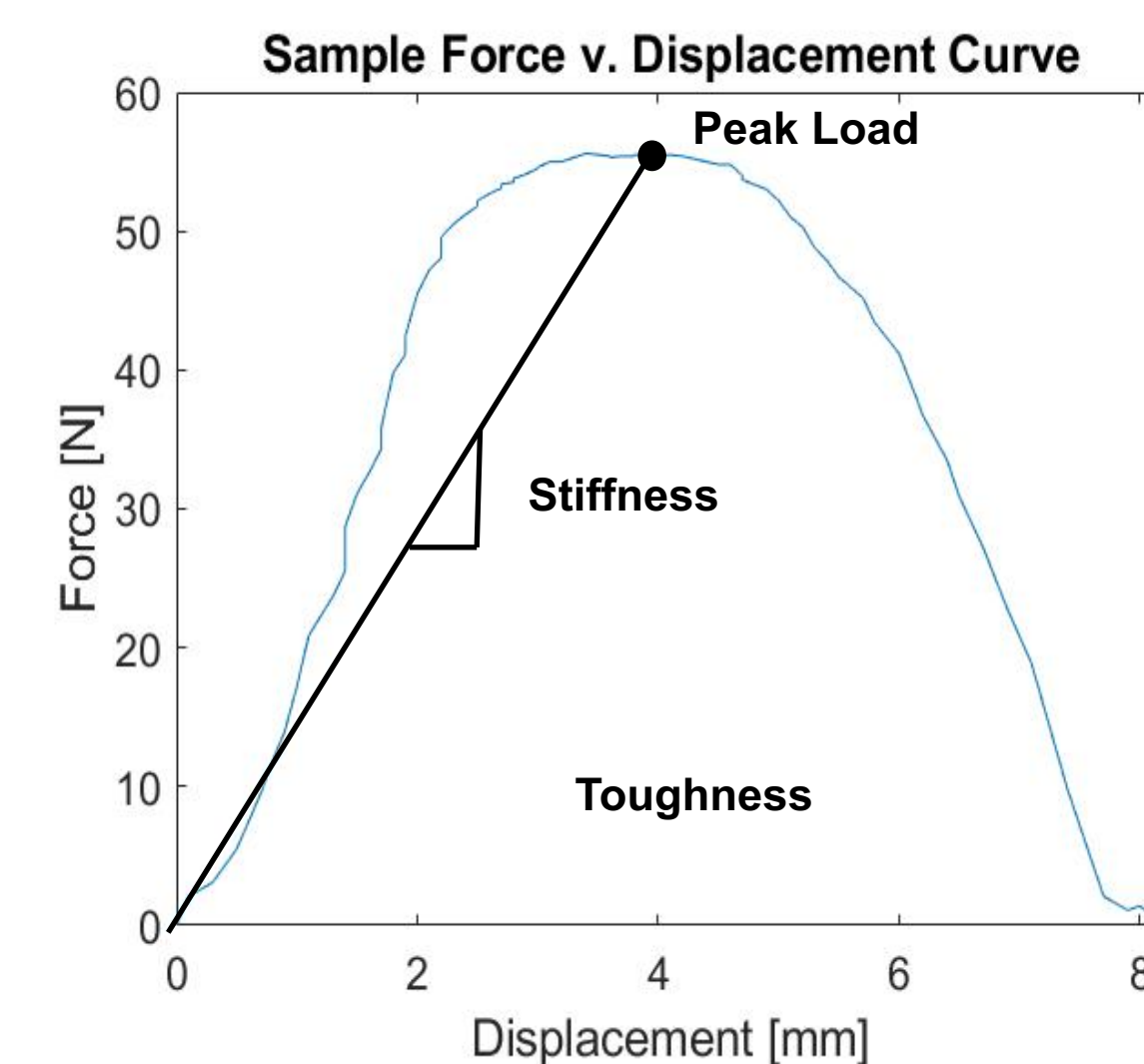


Figure 6: Sample force v. displacement curve

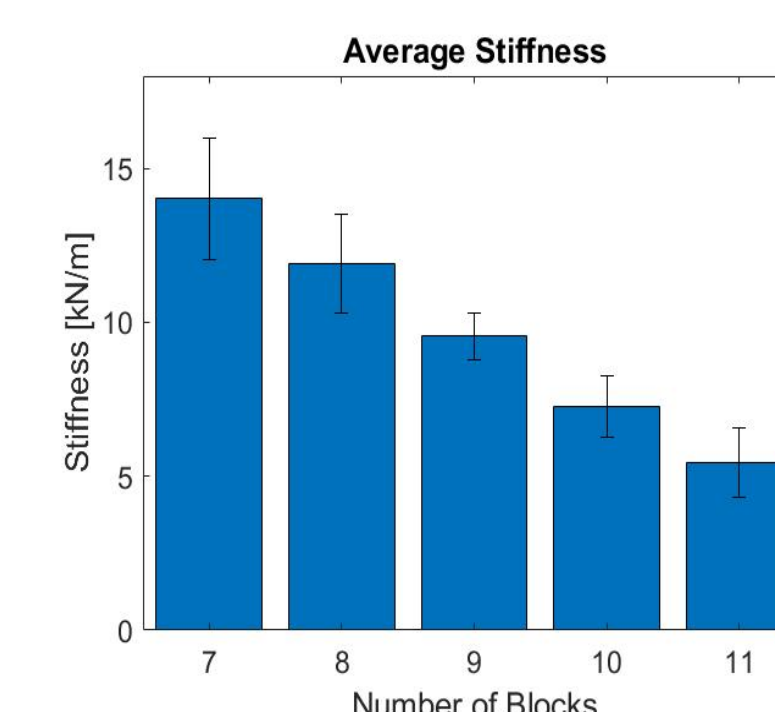
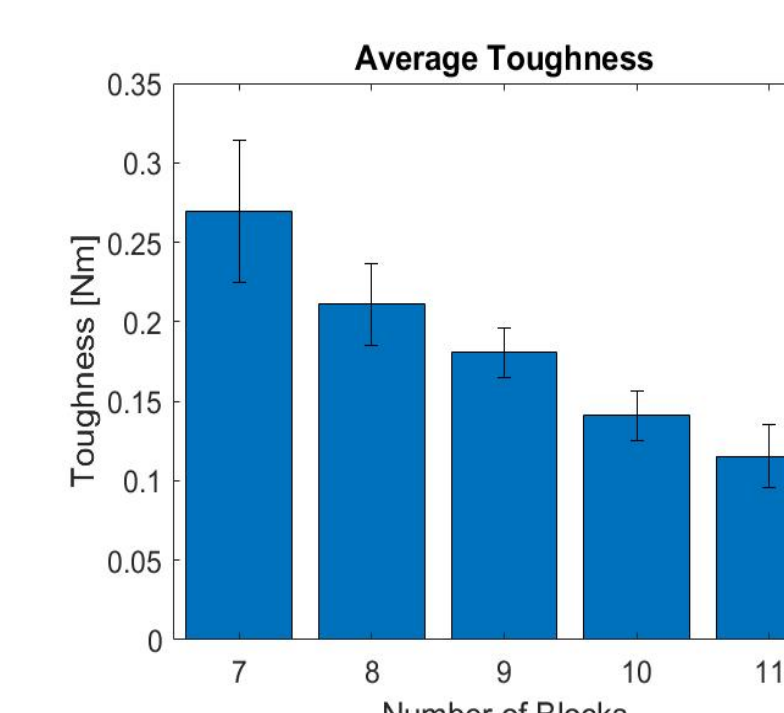
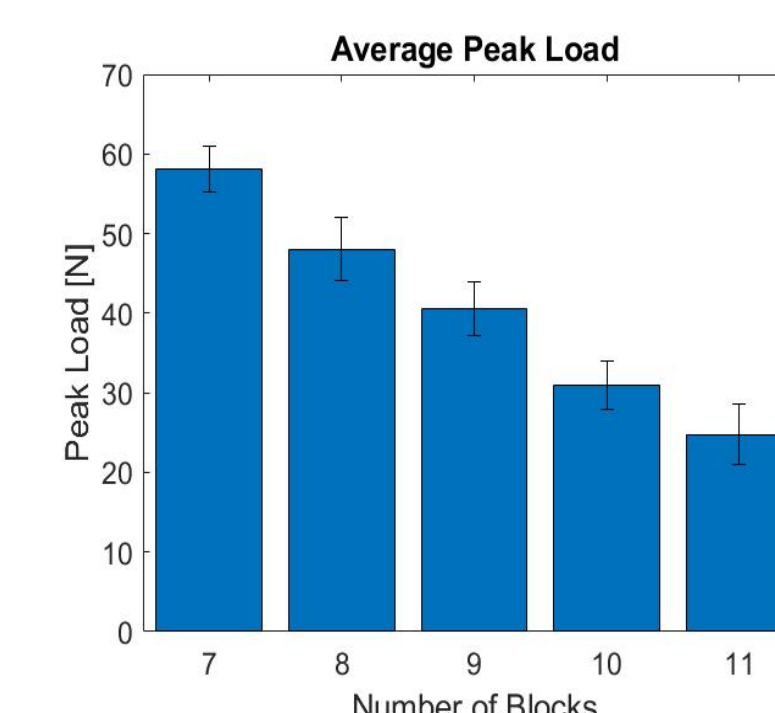


Figure 7: The average peak load, stiffness, and toughness of each lintel



#### Photoelastic Experiments:

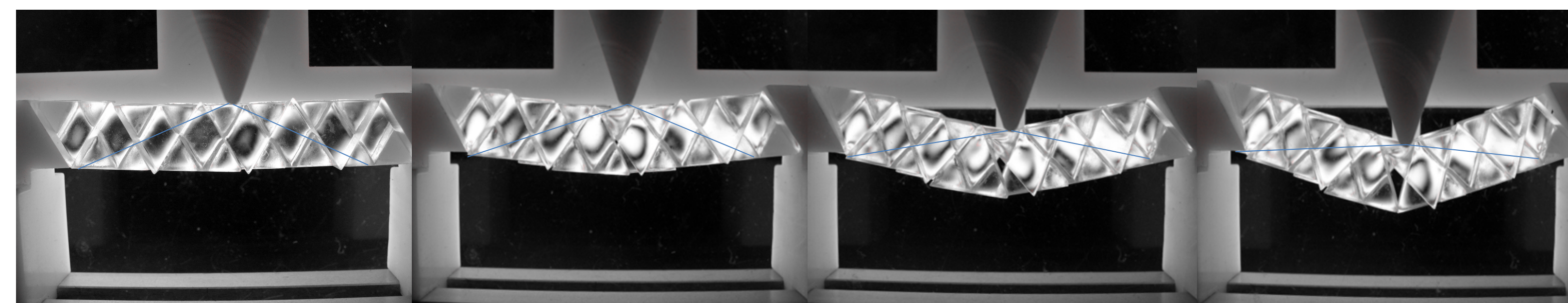


Figure 8: Photoelastic images of a ten piece lintel in deformation

#### Finite Element Model:

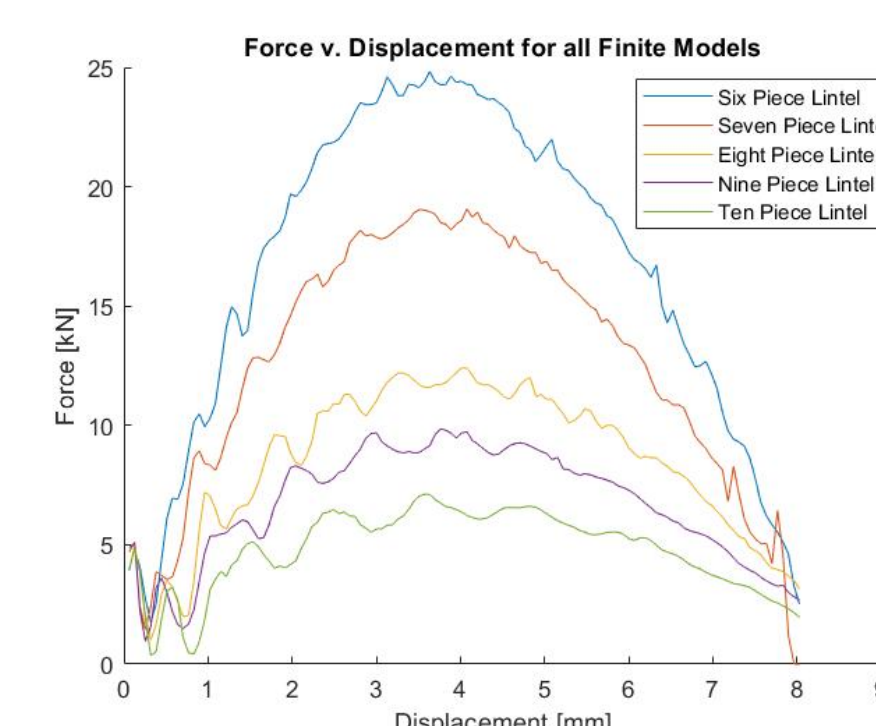


Figure 9: Force v. displacement response of the FE models

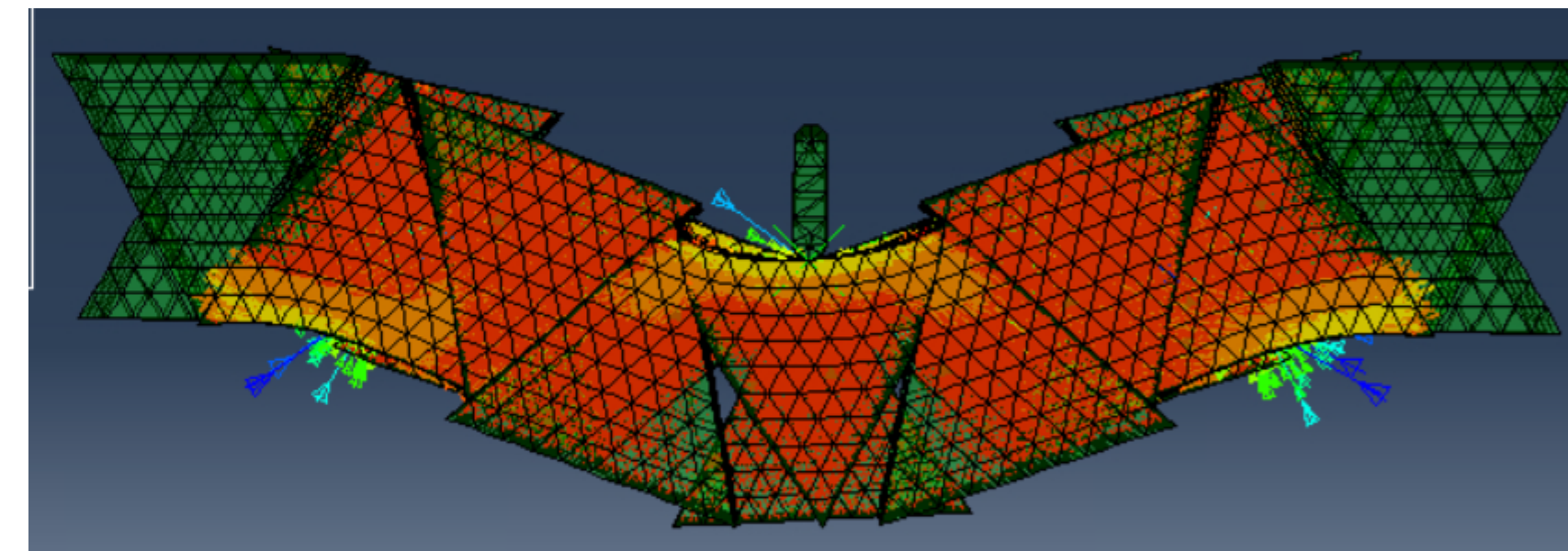


Figure 10: Distribution of compressive principal stress vectors for the seven piece lintel

### Conclusions

Experiments and analysis confirm the initial hypothesis that the load-deflection response of Leonardo's lintel resembles the van Mises truss.

Leonardo's lintel is a compression only structure. Stiffness, strength and toughness emerge as linear dependent on lintel length. The lintel exhibits a gradual failure response.

This behavior is in significant contrast to the Euler-Bernoulli beam, which sees tension and compression stresses, possesses a nonlinear dependence on beam length, and generally fails brittle.

### REU Experience and Highlights

During this research experience I learned:

- How to perform finite element analysis via ABAQUS
- How to perform photoelastic analysis of a structure or member
- How to experimentally determine the force v. displacement response of a structure
- How to redesign an experiment when the original plan for an experiment does not work
- The value of using history to inform design of new technologies

### Acknowledgments

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### References

- [1] www.codex-atlanticus.it, last accessed July 2, 2019.
- [2] Siegmund, T., Barthelat, F., Cipra, R., Habtour, E. and Riddick, J., 2016. Manufacture and mechanics of topologically interlocked material assemblies. Applied Mechanics Reviews, 68(4), p.040803.
- [3] Mirkhalaf, M., Sunesara, A., Ashrafi, B. and Barthelat, F., 2019. Toughness by segmentation: Fabrication, testing and micromechanics of architected ceramic panels for impact applications. International Journal of Solids and Structures, 158, pp.52-65.