ADAPTATION OF A MACHINE LEARNING ASSISTED FAILURE PREDICTION METHODOLOGY TO BOLTED COMPOSITE JOINTS

1st August 2023

Presenter
Omar Imran Azeem

Supervisor
The Late Professor Lorenzo Iannucci

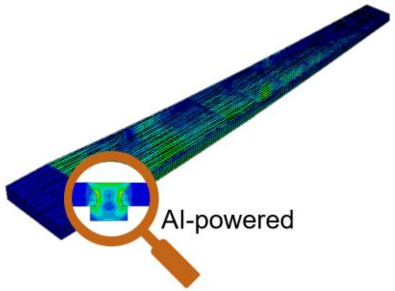
Department of Aeronautics

Imperial College London

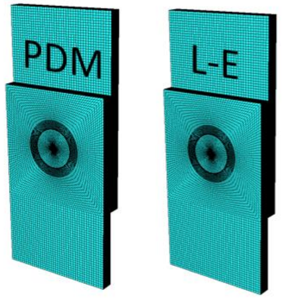
ICCM 23
INTERNATIONAL CONFERENCE ON COMPOSITE MATERIALS
BELFAST 2023
30 JULY – 4 AUGUST

Contents

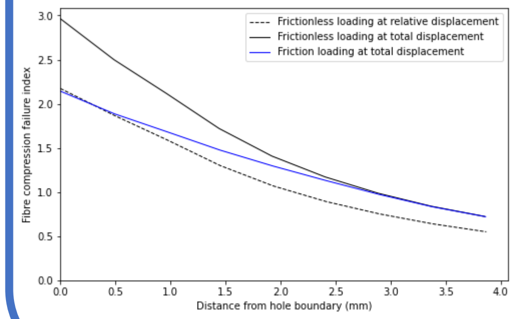
CONTEXT



METHODOLOGY

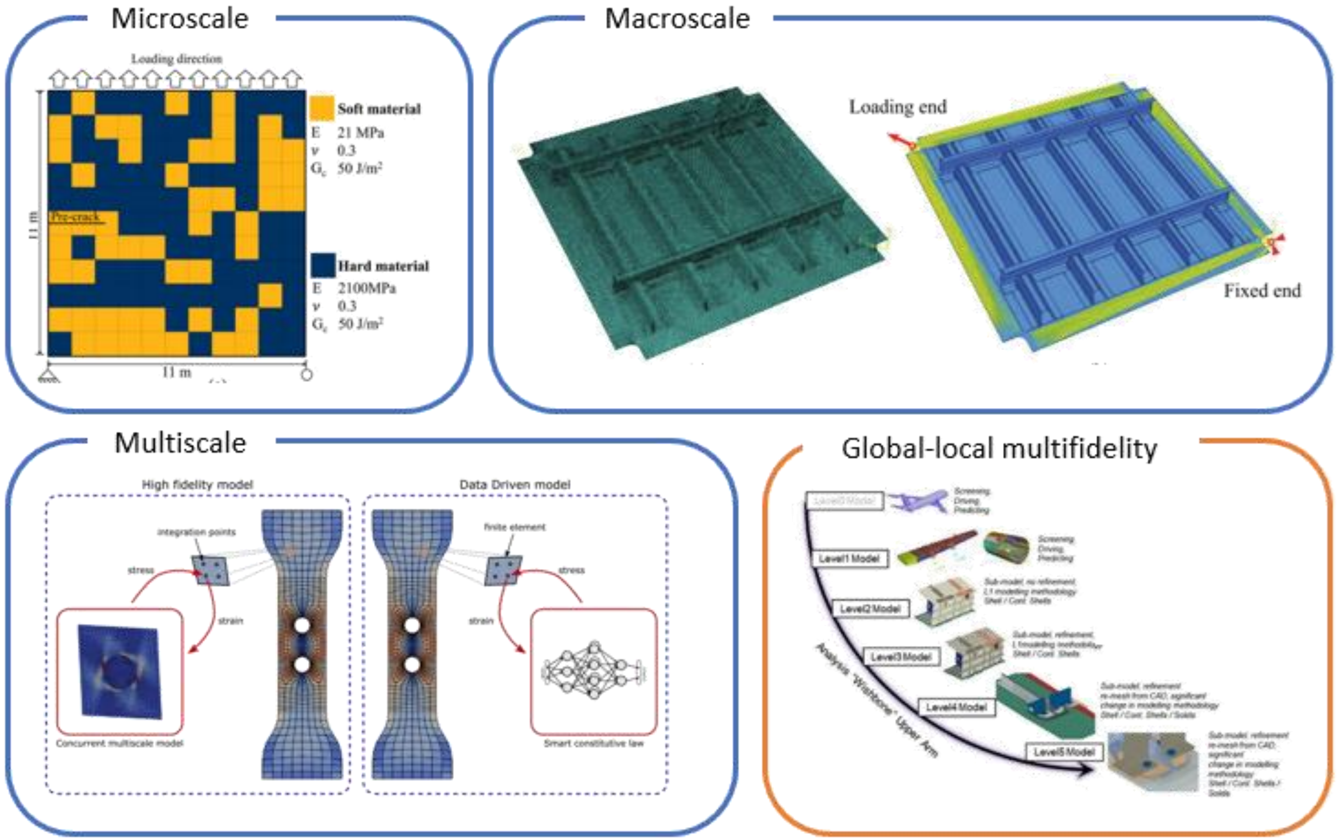


RESULTS



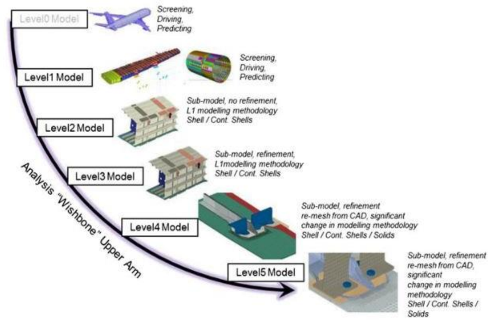
CONCLUSIONS

Machine learning for preliminary design of composite structures



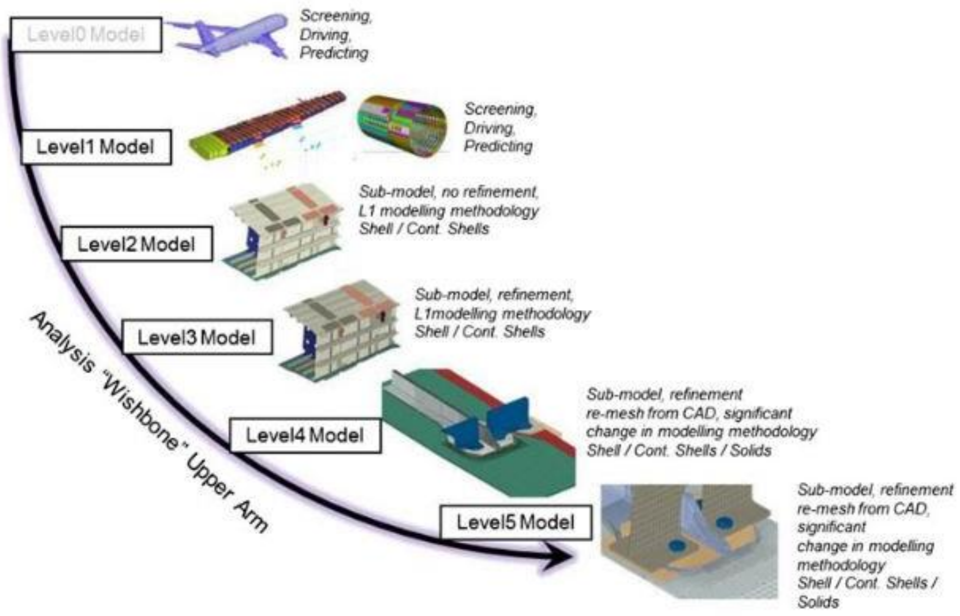
Use of machine learning for composite modelling [Yang et al, 2020], [Sun et al, 2021], [Logarzo et al, 2021], [Ostergaard et al, 2011]

Machine learning for preliminary design of composite structures

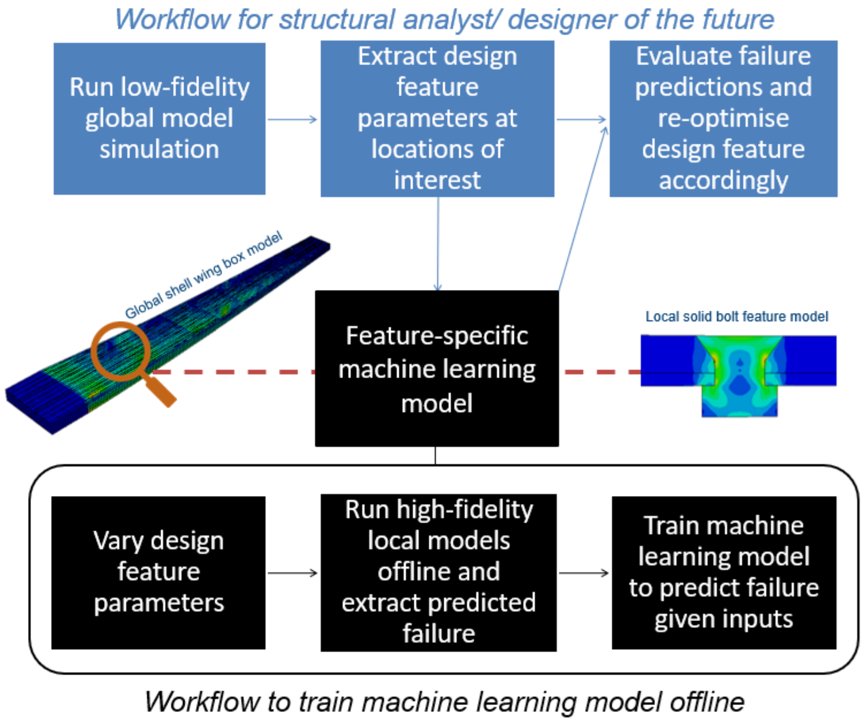


Use of machine learning for composite modelling [Yang et al, 2020], [Sun et al, 2021], [Logarzo et al, 2021], [Ostergaard et al, 2011]

Machine learning for preliminary design of composite structures

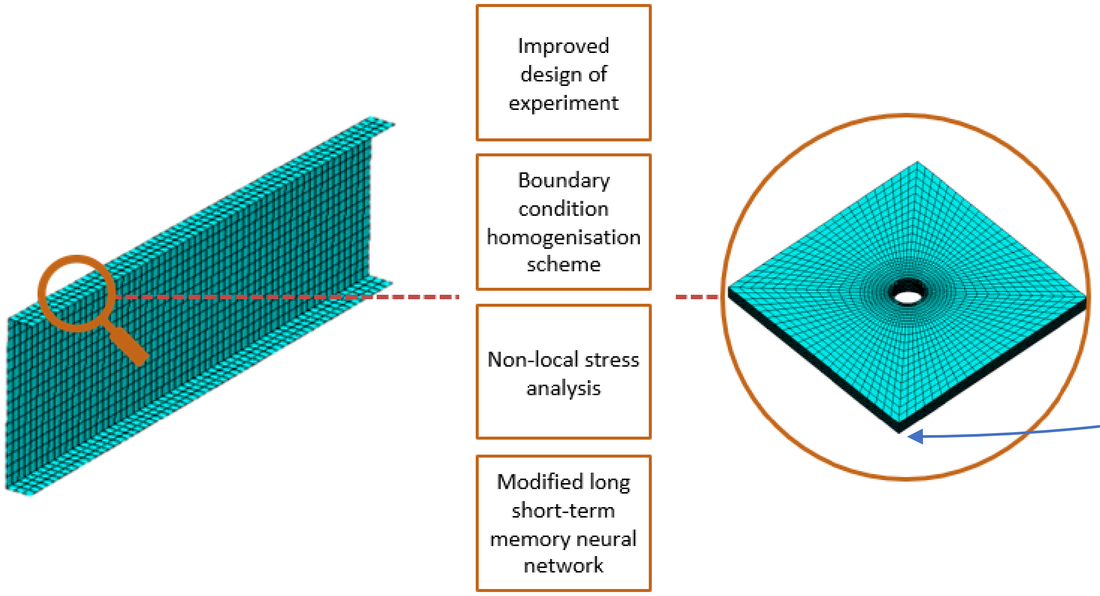


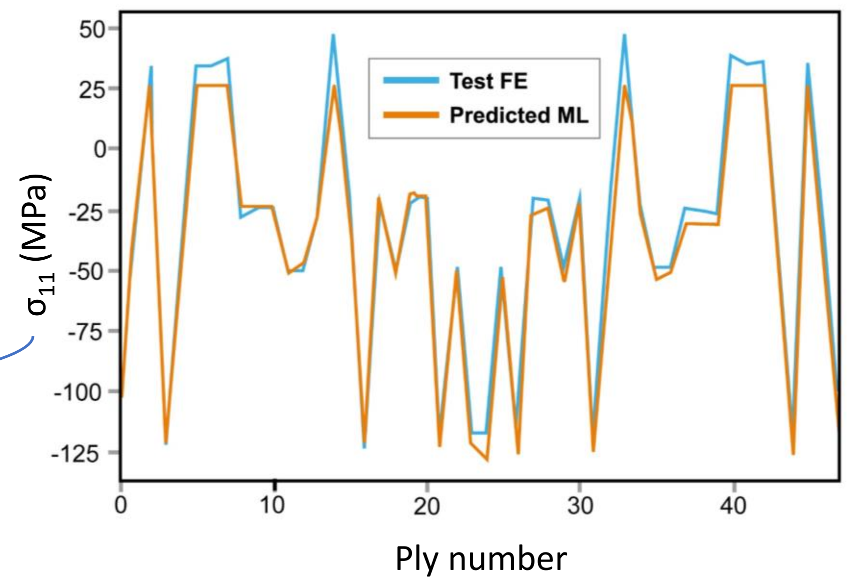
Machine learning for preliminary design of composite structures



The proposed preliminary design process
[Azeem and Iannucci, 2022]

Adapting proof of concept to bolted joints





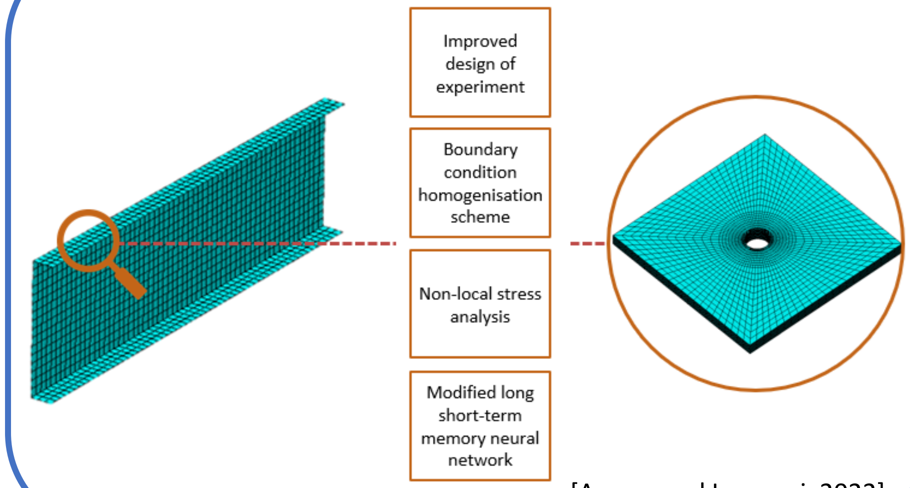
Methodology for ML-assisted stress prediction, based on linear superposition [Azeem and Iannucci, 2022]

Stress component predictions using developed methodology [Azeem and Iannucci, 2022]

Demonstrated the use of machine learning to predict ply-by-ply stress variation at satisfactory accuracy, with reasonable amount of training data

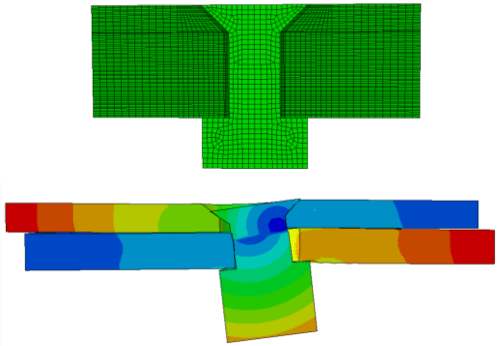
Adapting proof of concept to bolted joints

ML to predict stresses around hole in plate

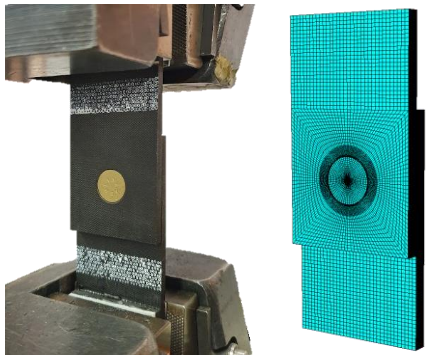


[Azeem and Iannucci, 2022]

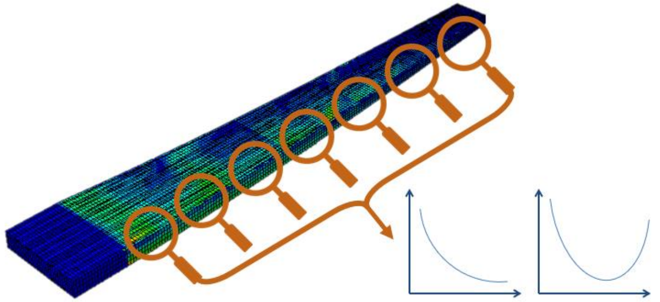
ML to predict stresses around bolted joint



ML to predict stresses at failure around bolted joint

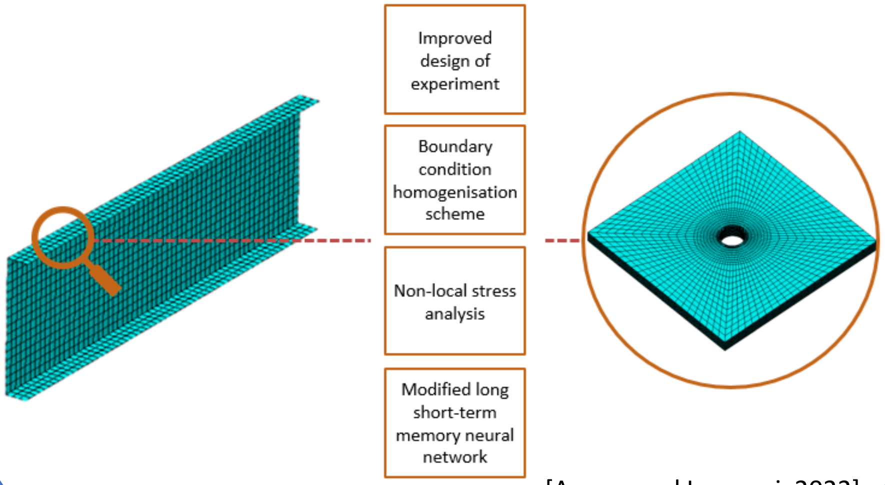


Application of faster analysis capability for wingbox trade-off studies



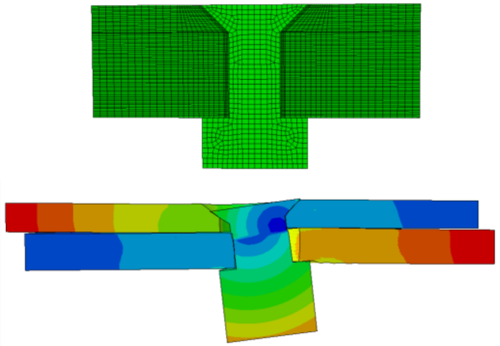
Adapting proof of concept to bolted joints

ML to predict stresses around hole in plate

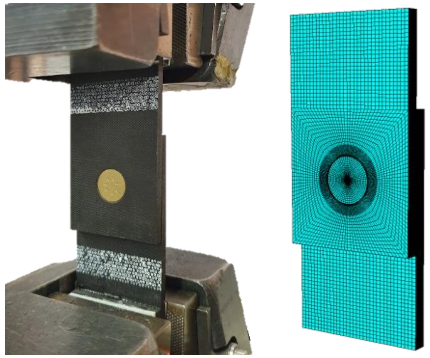


[Azeem and Iannucci, 2022]

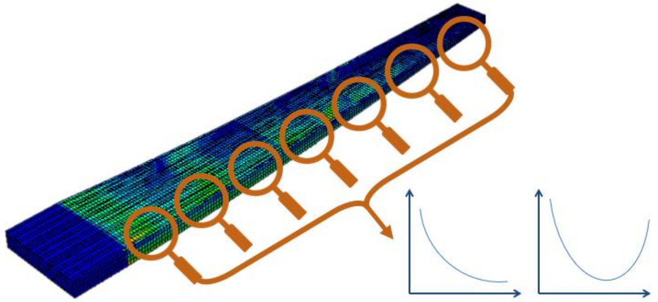
ML to predict stresses around bolted joint



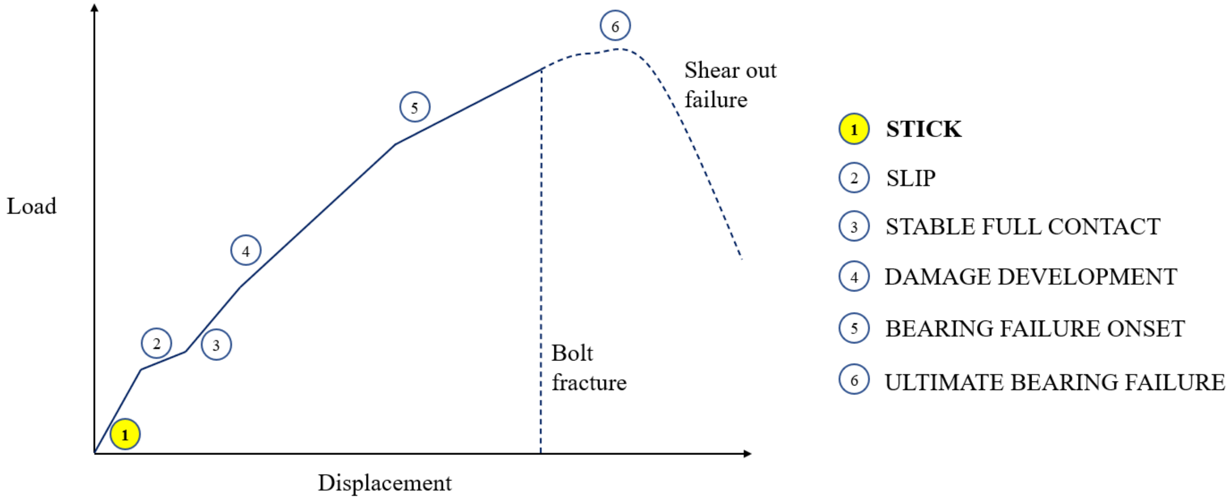
ML to predict stresses at failure around bolted joint



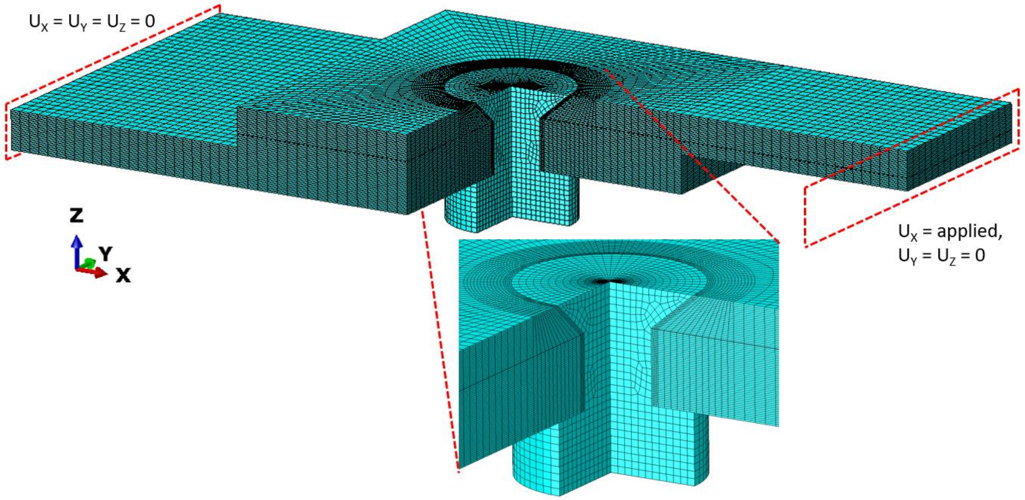
Application of faster analysis capability for wingbox trade-off studies



Bolted Joint Bearing Failure

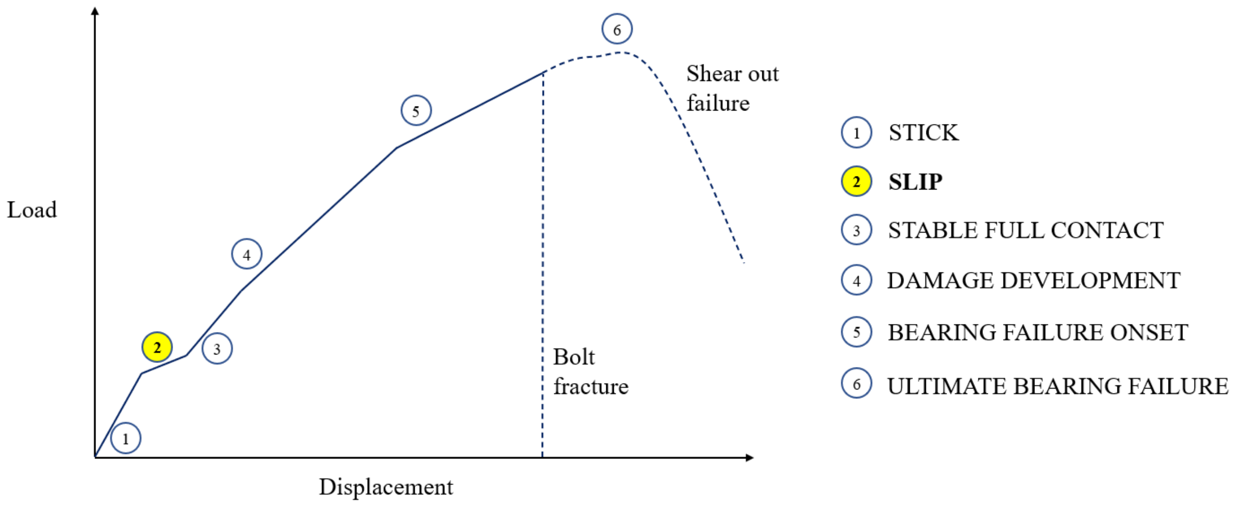


Typical bearing mode bolted joint load-displacement behaviour

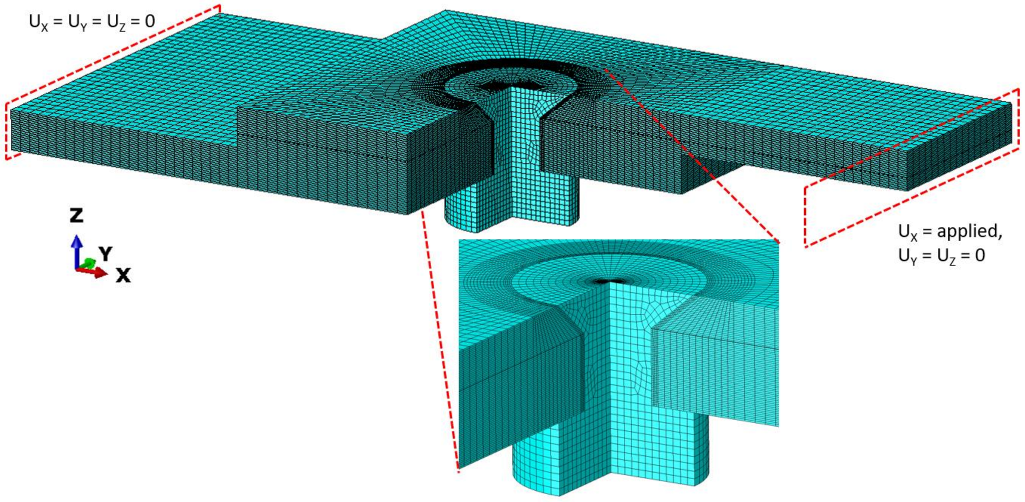


High fidelity model required to predict progressive damage

Bolted Joint Bearing Failure

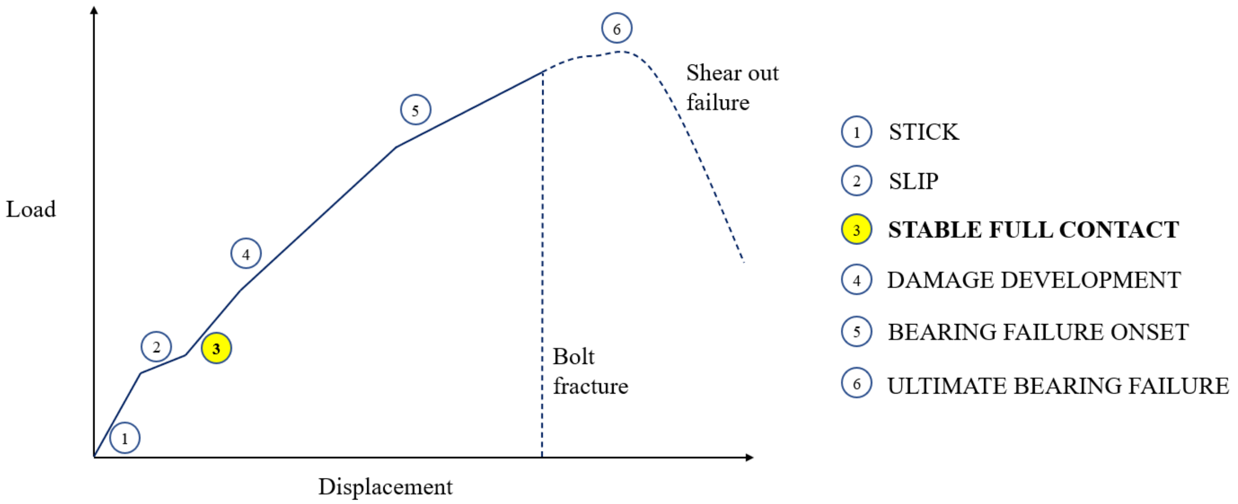


Typical bearing mode bolted joint load-displacement behaviour

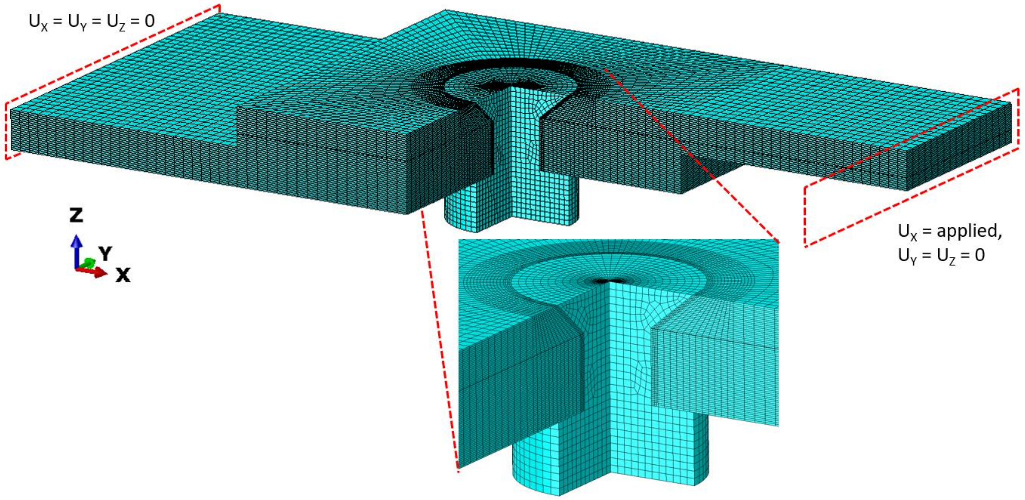


High fidelity model required to predict progressive damage

Bolted Joint Bearing Failure

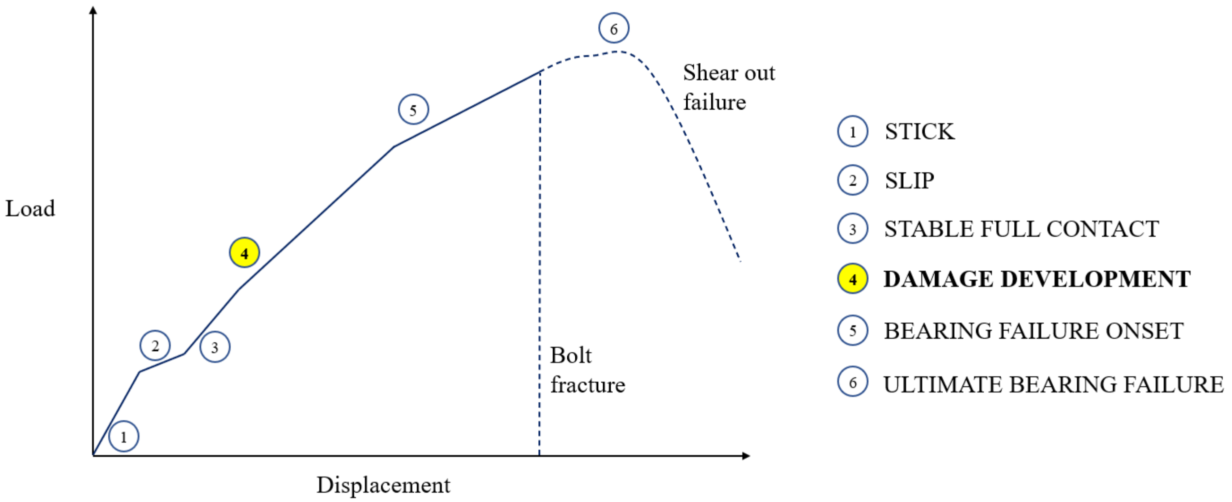


Typical bearing mode bolted joint load-displacement behaviour

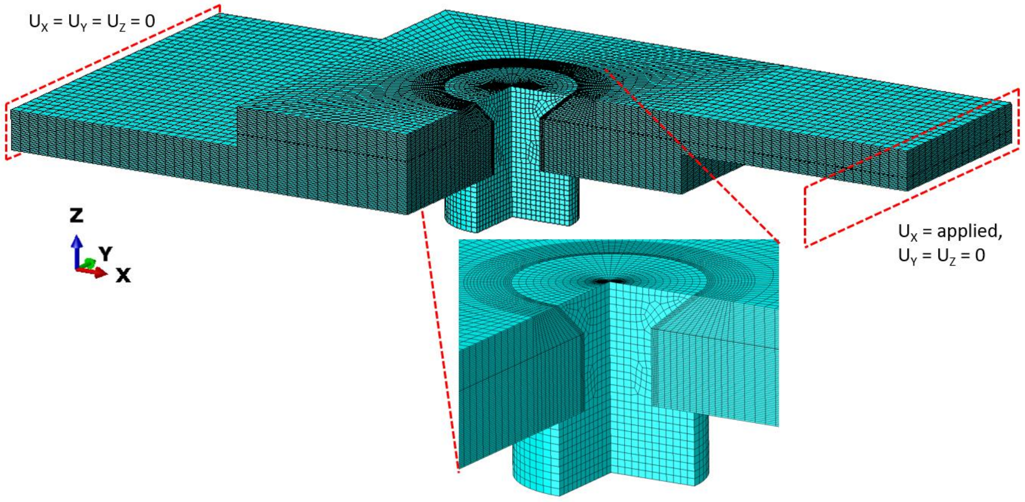


High fidelity model required to predict progressive damage

Bolted Joint Bearing Failure

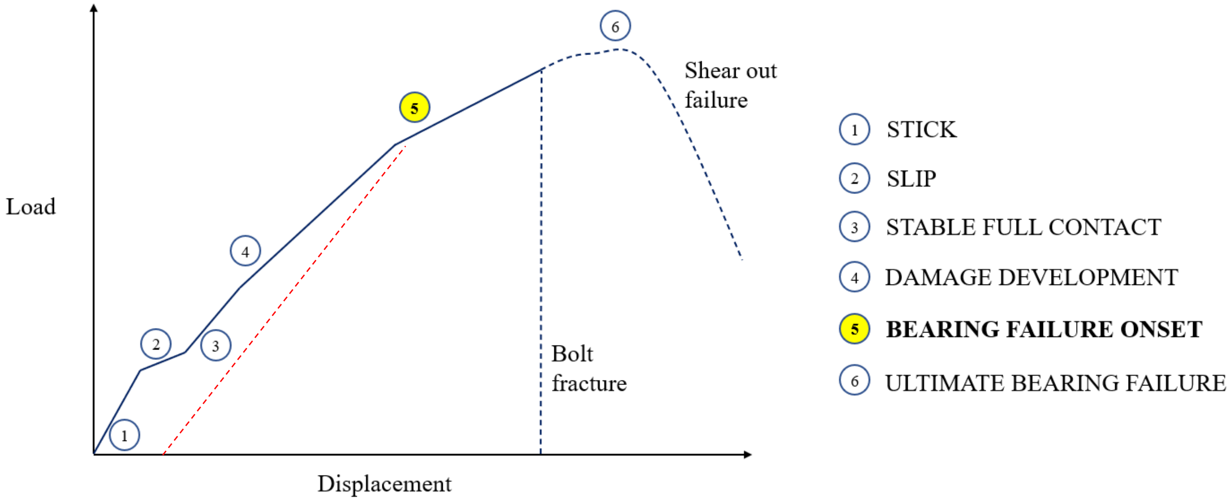


Typical bearing mode bolted joint load-displacement behaviour

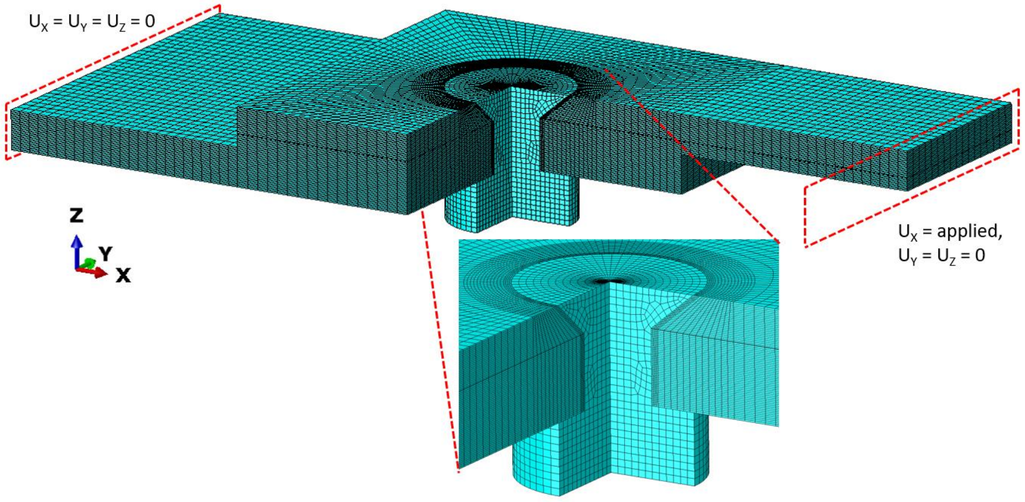


High fidelity model required to predict progressive damage

Bolted Joint Bearing Failure

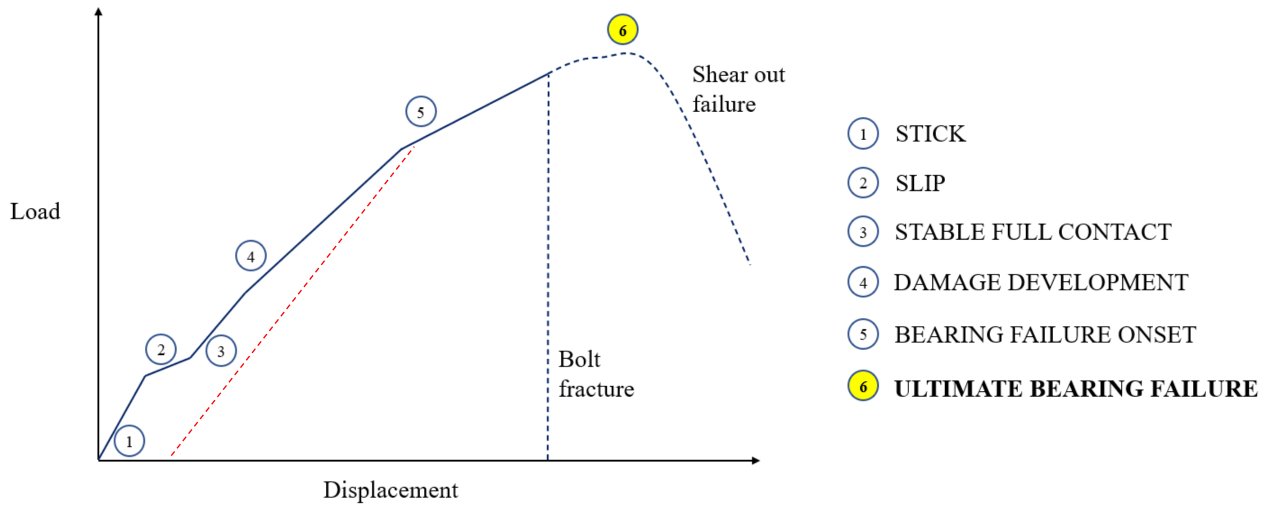


Typical bearing mode bolted joint load-displacement behaviour (red-line indicating 2% offset)

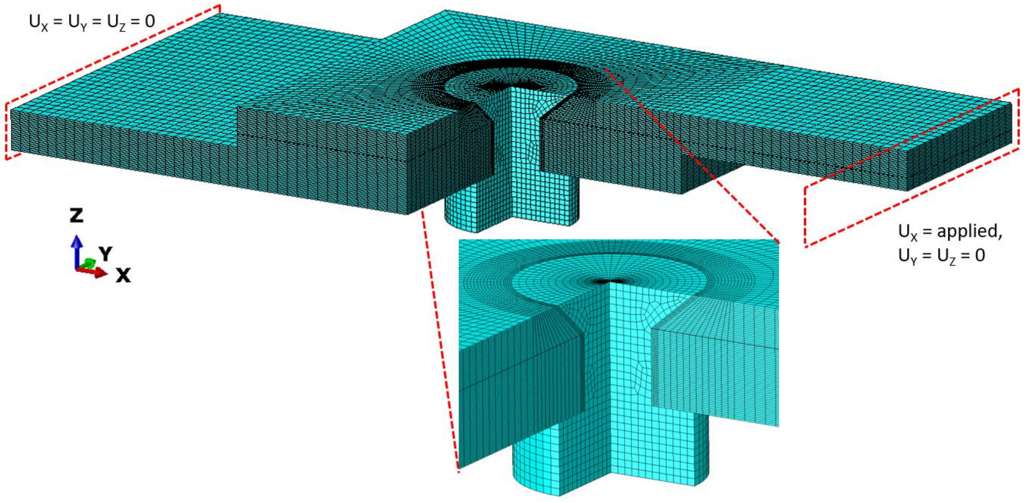


High fidelity model required to predict progressive damage

Bolted Joint Bearing Failure



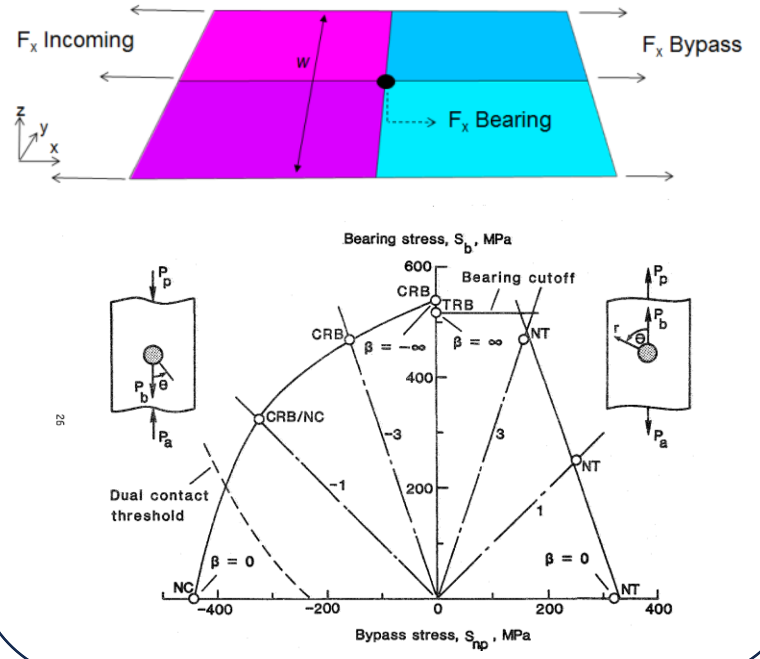
Typical bearing mode bolted joint load-displacement behaviour (red-line indicating 2% offset)



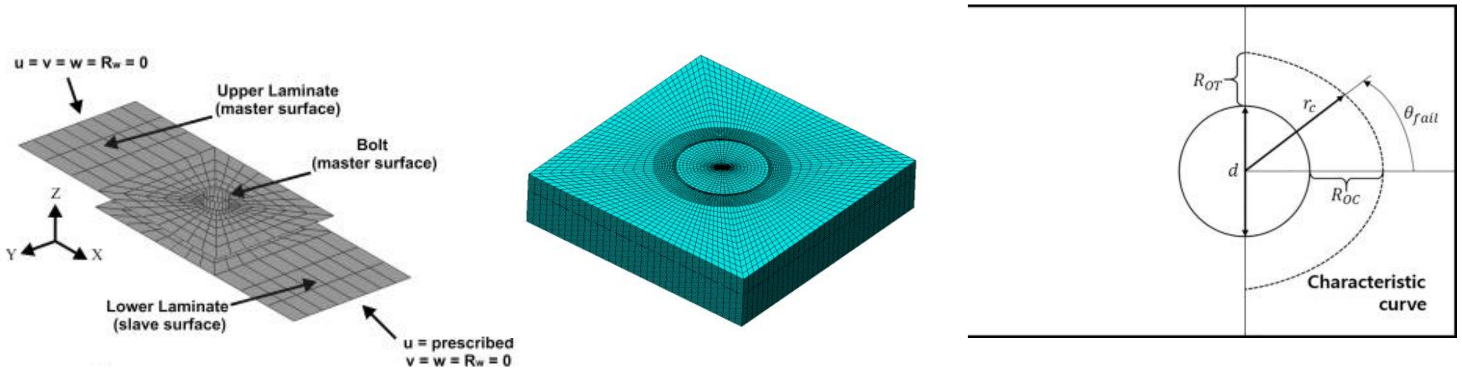
High fidelity model required to predict progressive damage

Bolted joint bearing failure is a non-monotonic and complex process, requiring expensive models to predict accurately

Bolted Joint Bearing Failure



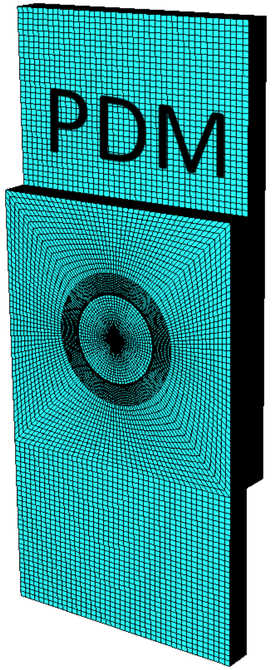
Bearing bypass interaction curve
[Hypersizer, 2014],[J. Crews and R.Naik, 1986]



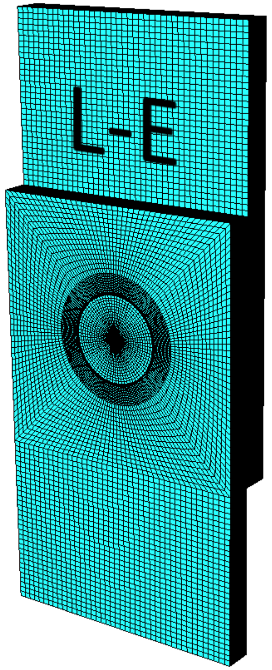
Characteristic length method [P.J. Gray and C.T. McCarthy, 2010],[Choi et al, 2018]

Methods used during the preliminary design of airframes predict stresses with FEA but require knowledge of failure loads and/or characteristic distances.

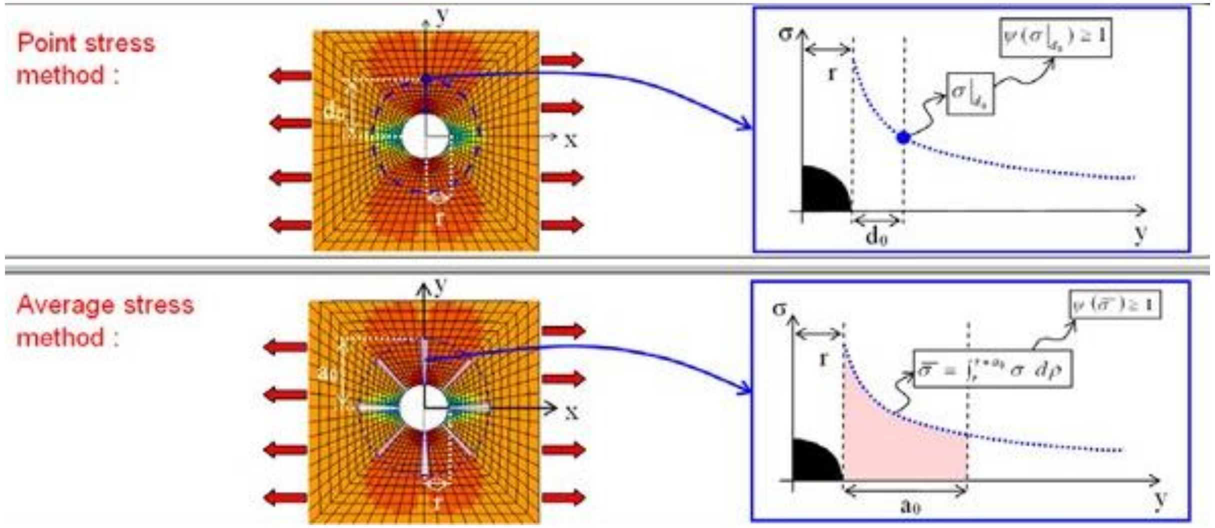
Bolted Joint Bearing Failure



Use a validated progressive damage model to predict failure load



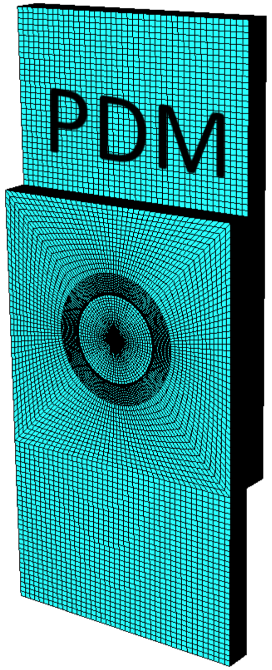
Use a linear-elastic model to predict characteristic distance…

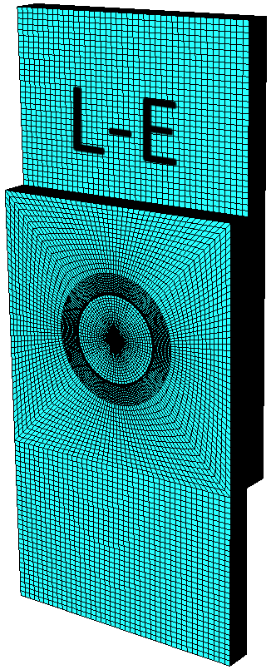


…with either the point stress criterion or the average stress criterion [Laurin et al, 2006]

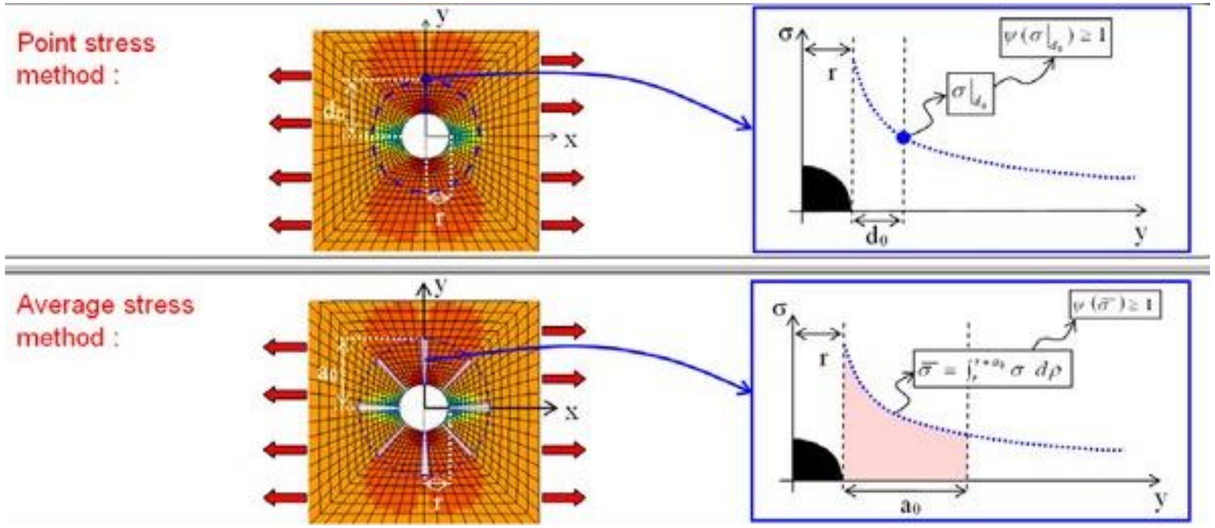
Methods used during the preliminary design of airframes require knowledge of failure loads and/or characteristic distances.

Bolted Joint Bearing Failure





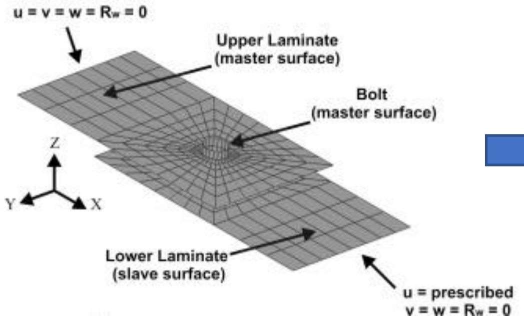
Predict failure load with machine learning
(-> coming soon)

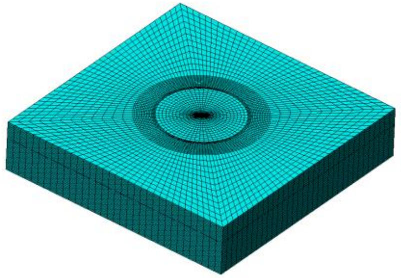


Predict characteristic distance/ stresses at failure with machine learning

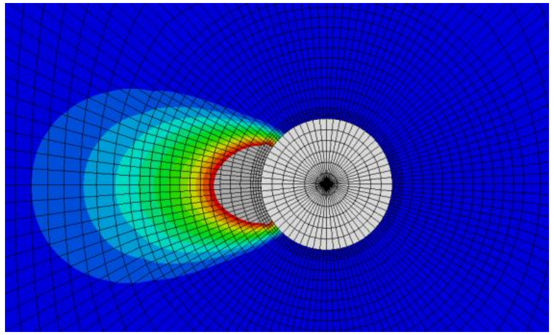
Machine learning could be used to reduce experimental campaign or expert-dependant high-fidelity modelling.

Objectives





Linear frictionless model to train ML for stress prediction



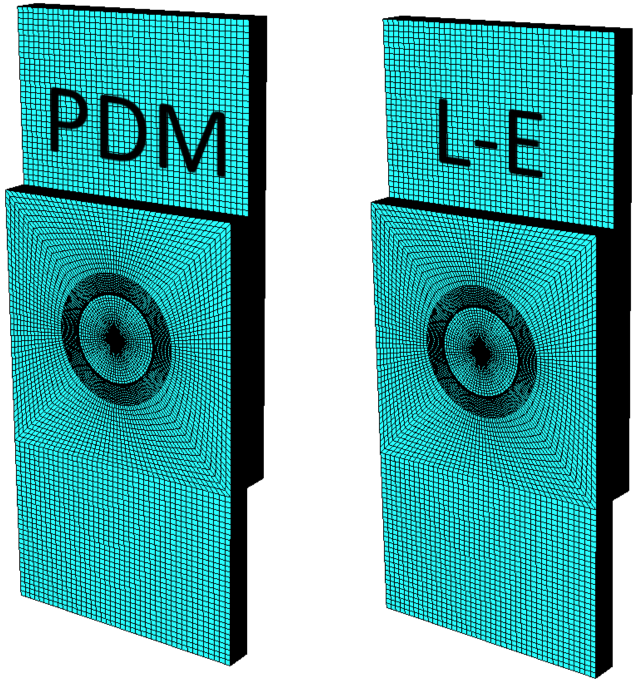
Friction(less?) model to train ML for characteristic distance prediction

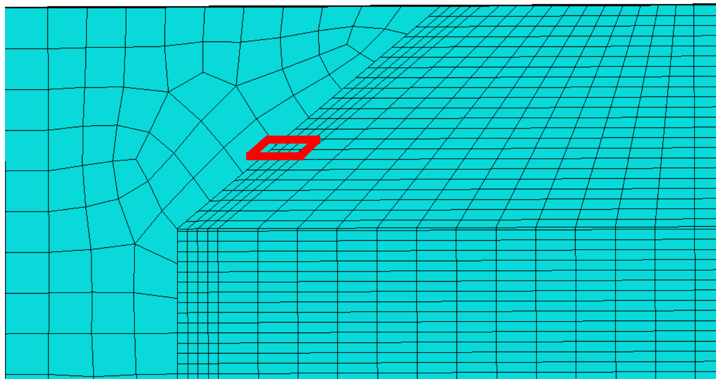
- How does stress development change with varying friction/preload?
- How does failure stresses/characteristic distance change with varying friction/preload?
  - How does failure load change with varying friction and preload?
- Exploring volume averaged stress criterion [stress state, effect of preload, characteristic distance]

How can we adapt our methodology to predict stresses and stress at failure for bolted joints?

Methodology

Fully torqued = 10 Nm
Finger tight = 0.5 Nm

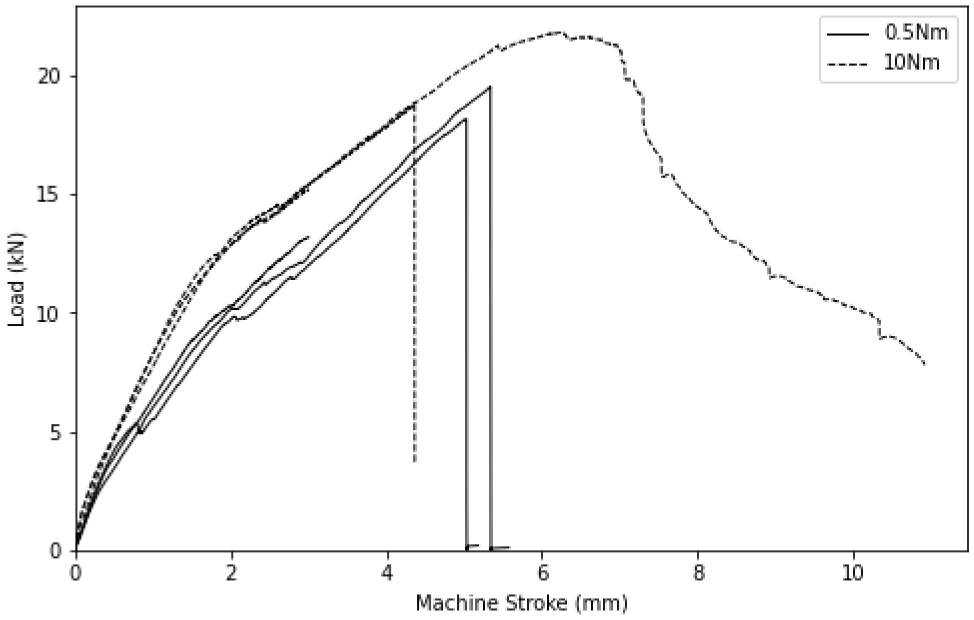


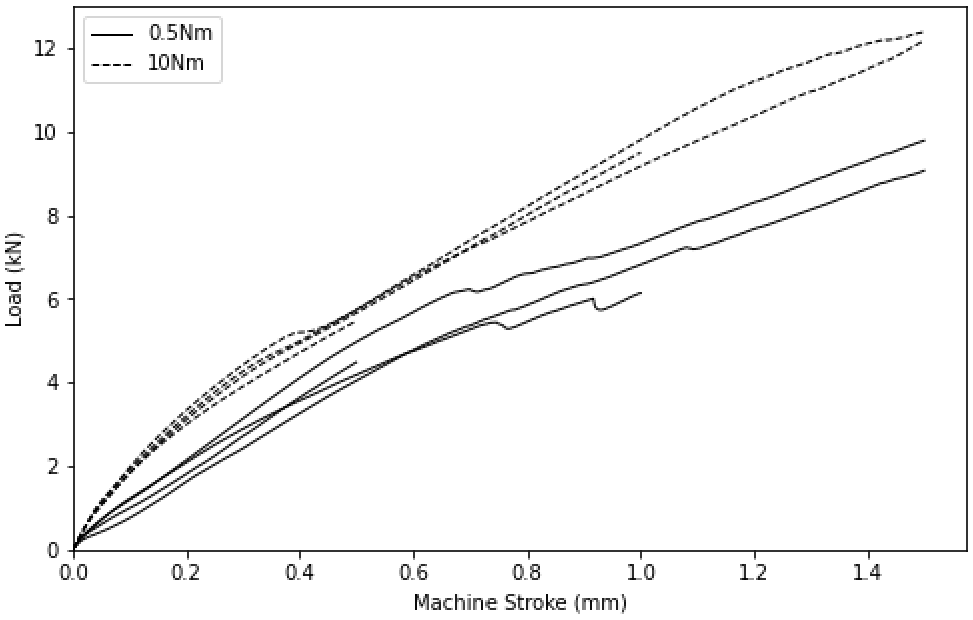


$$\bar{\sigma}_{V,i} = \frac{\sum_{element=1}^{n} \sigma_i * V_i}{\sum_{element=1}^{n} V_i} \quad , \text{ for i in } \{11,22,33,12,13,23\}$$

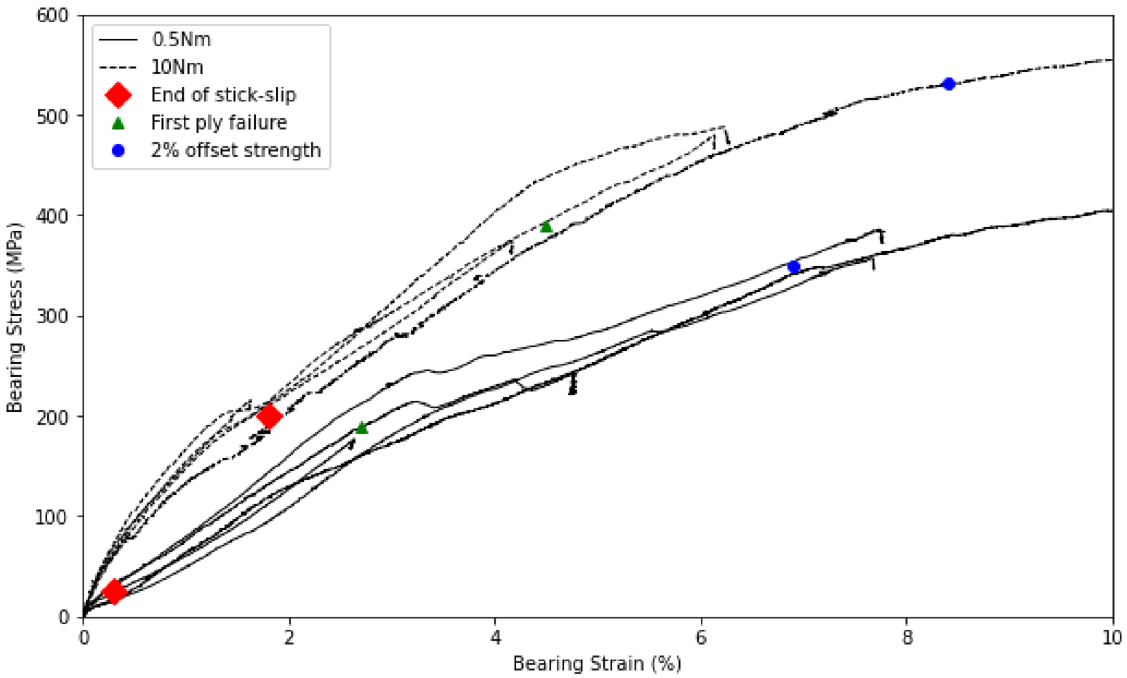
-> Hashin based failure criteria

Effect of preload on bearing strength

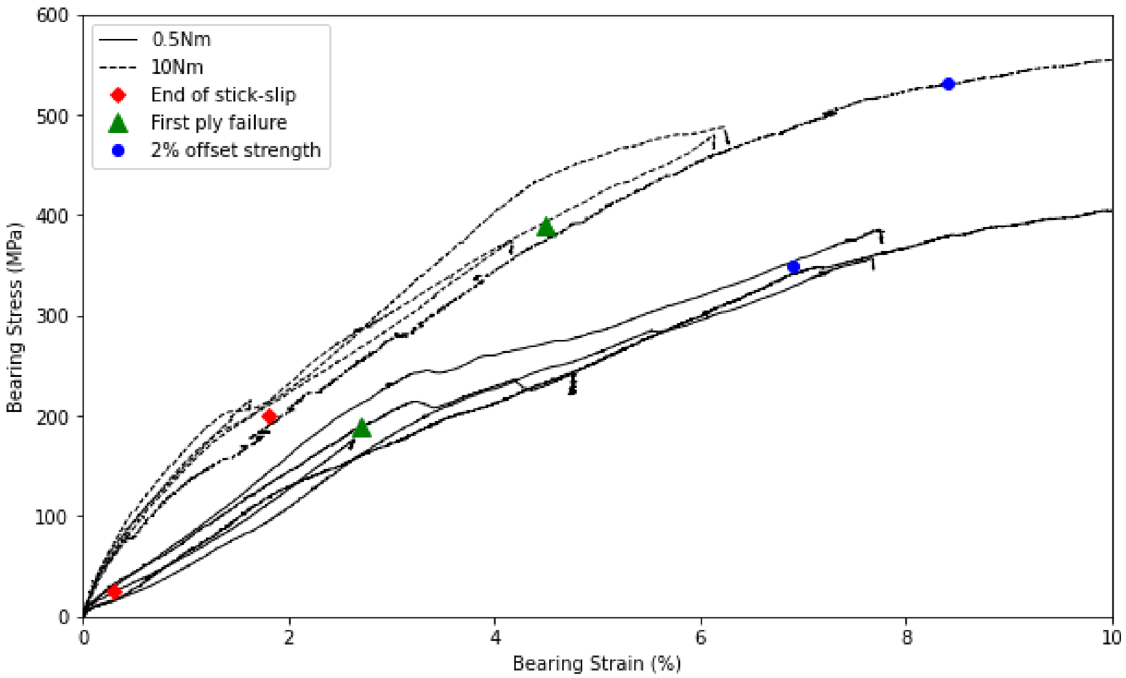




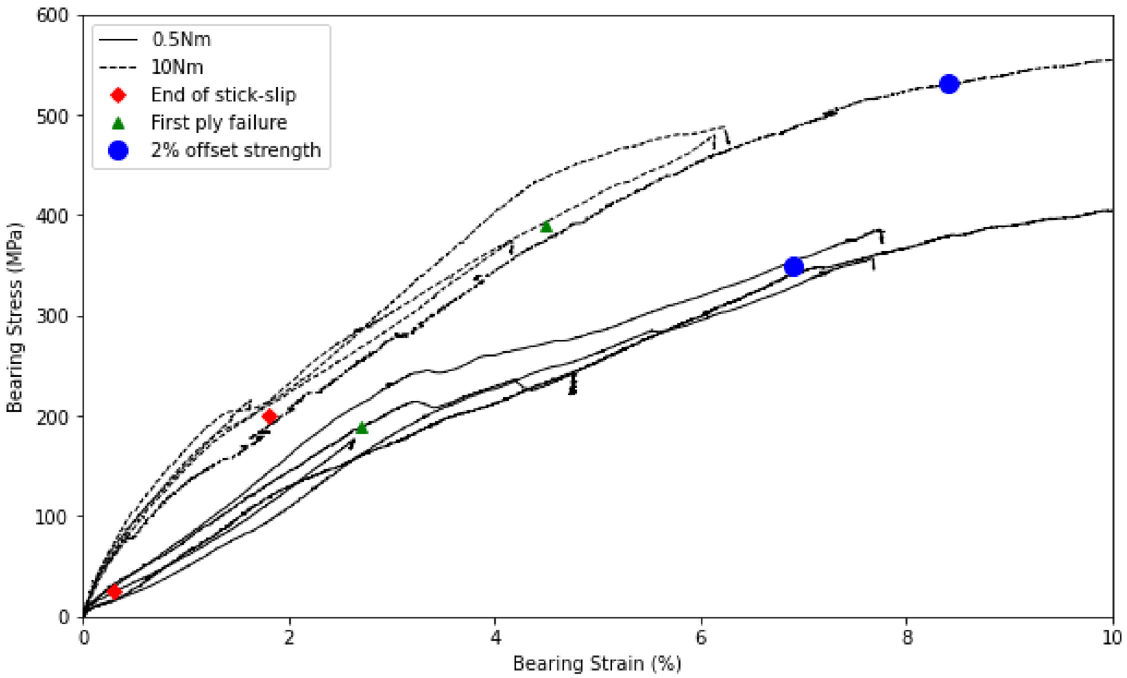
Effect of preload on bearing strength



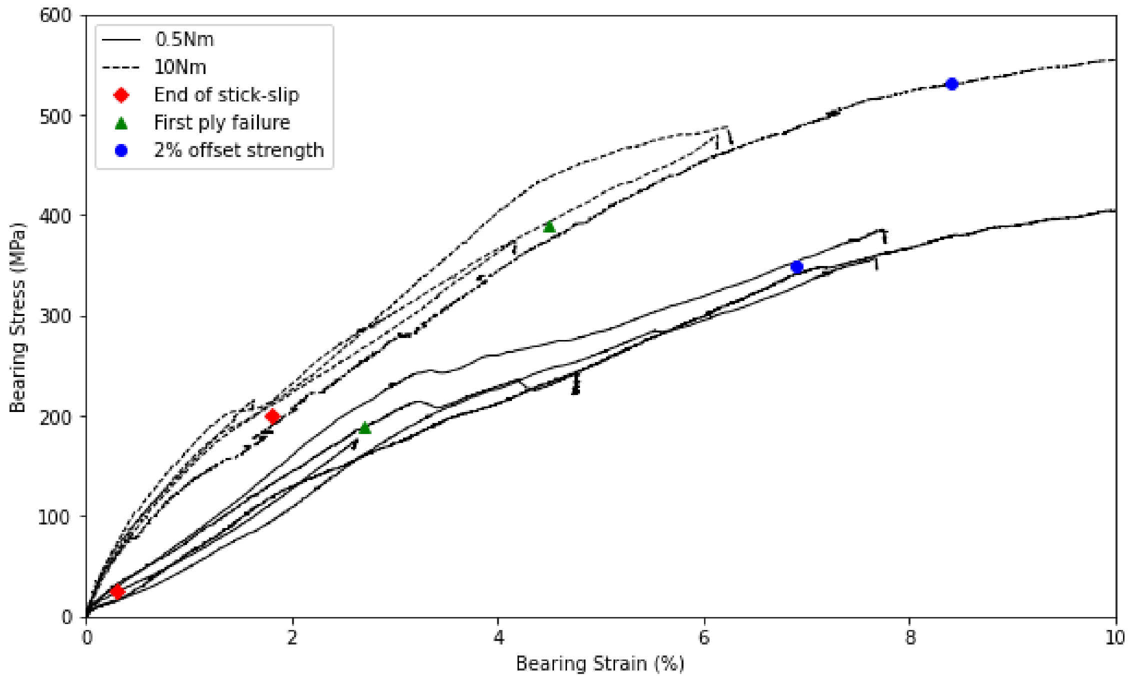
Effect of preload on bearing strength



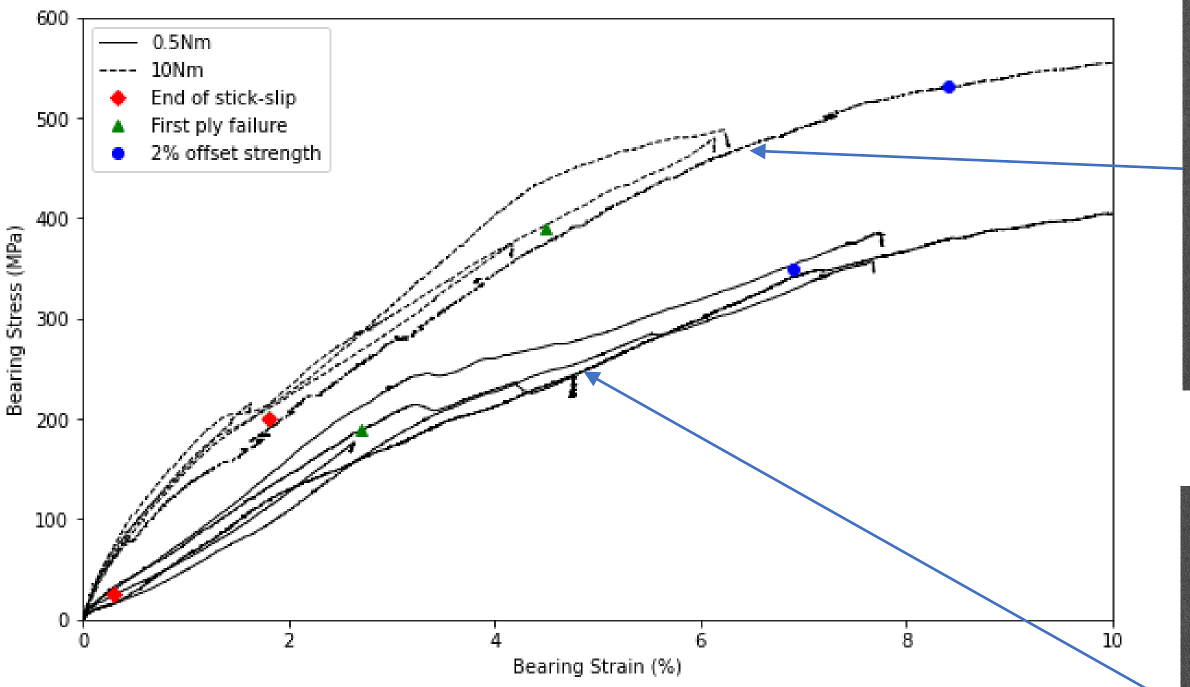
Effect of preload on bearing strength

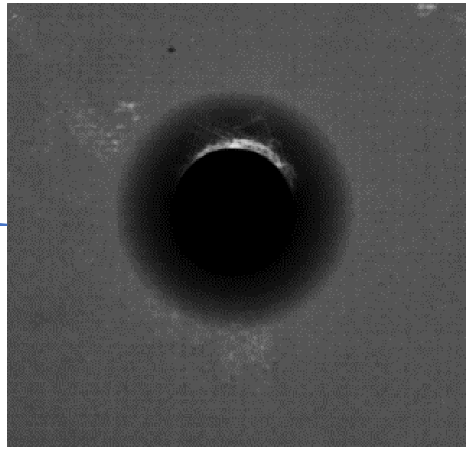


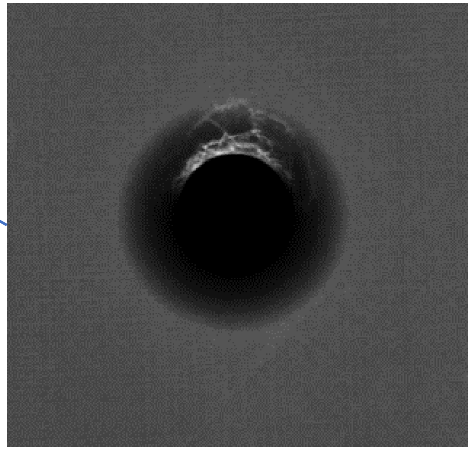
Effect of preload on bearing strength



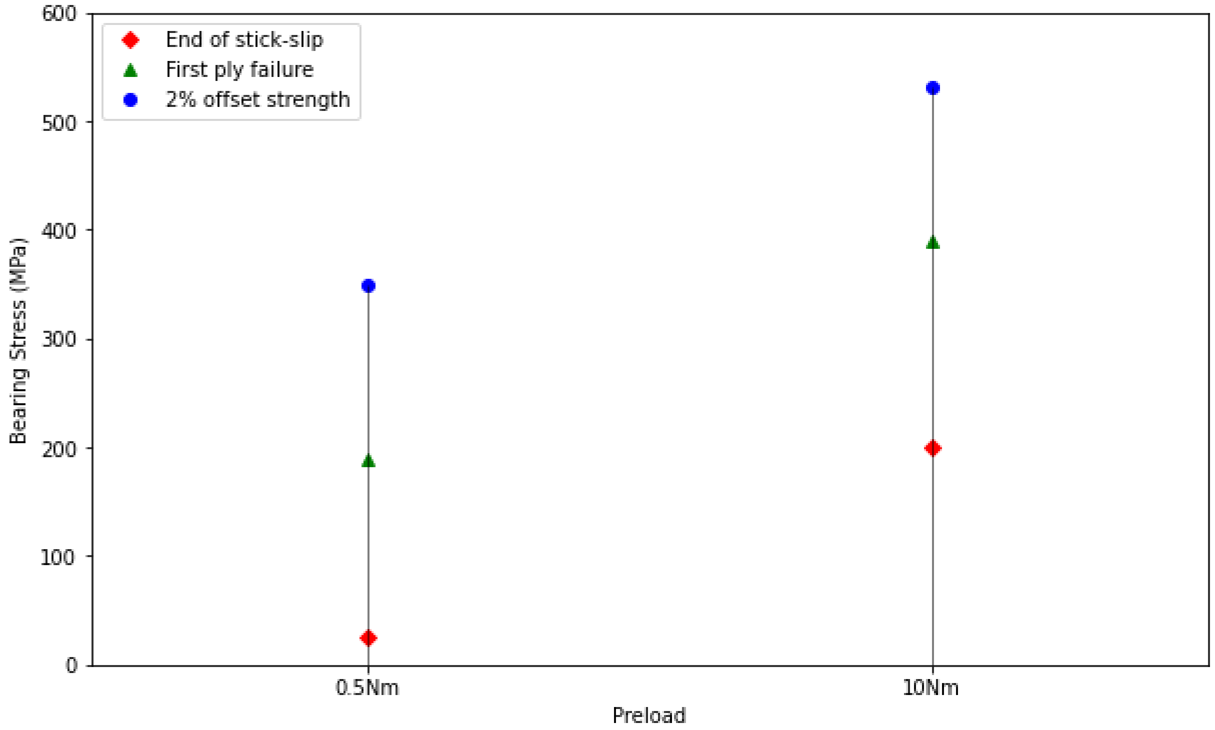
Effect of preload on bearing strength





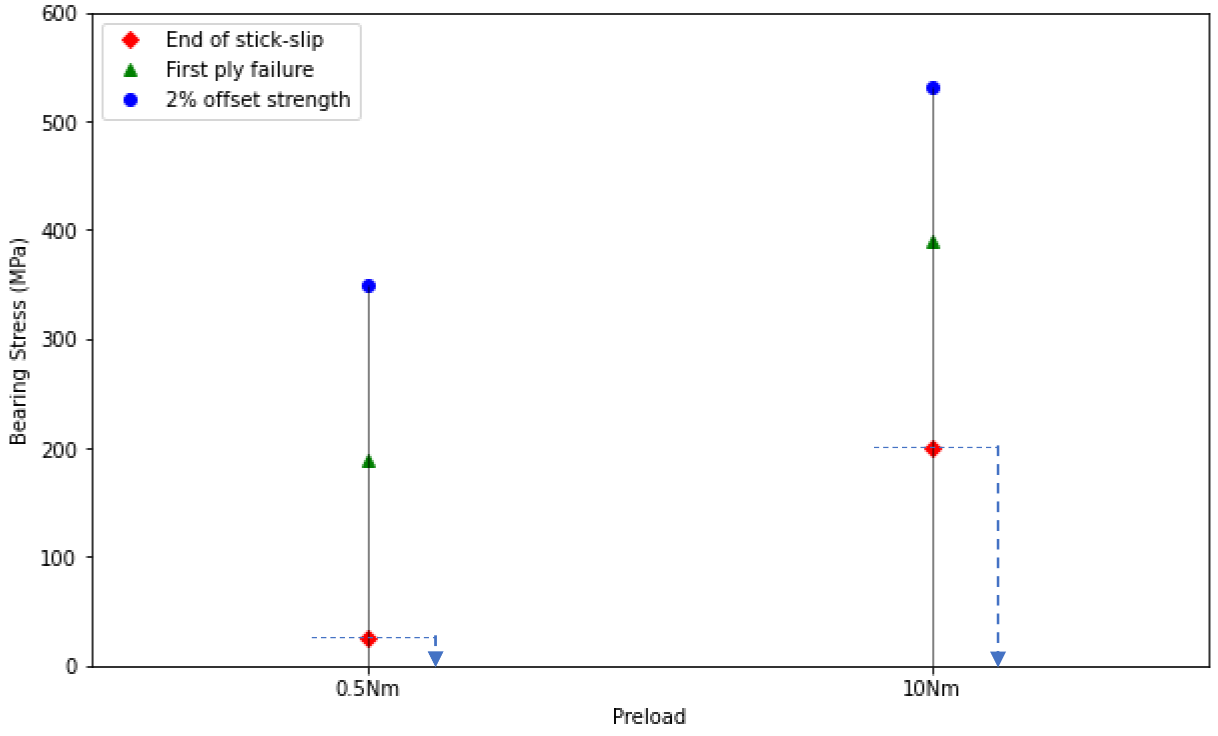


Effect of preload on bearing strength

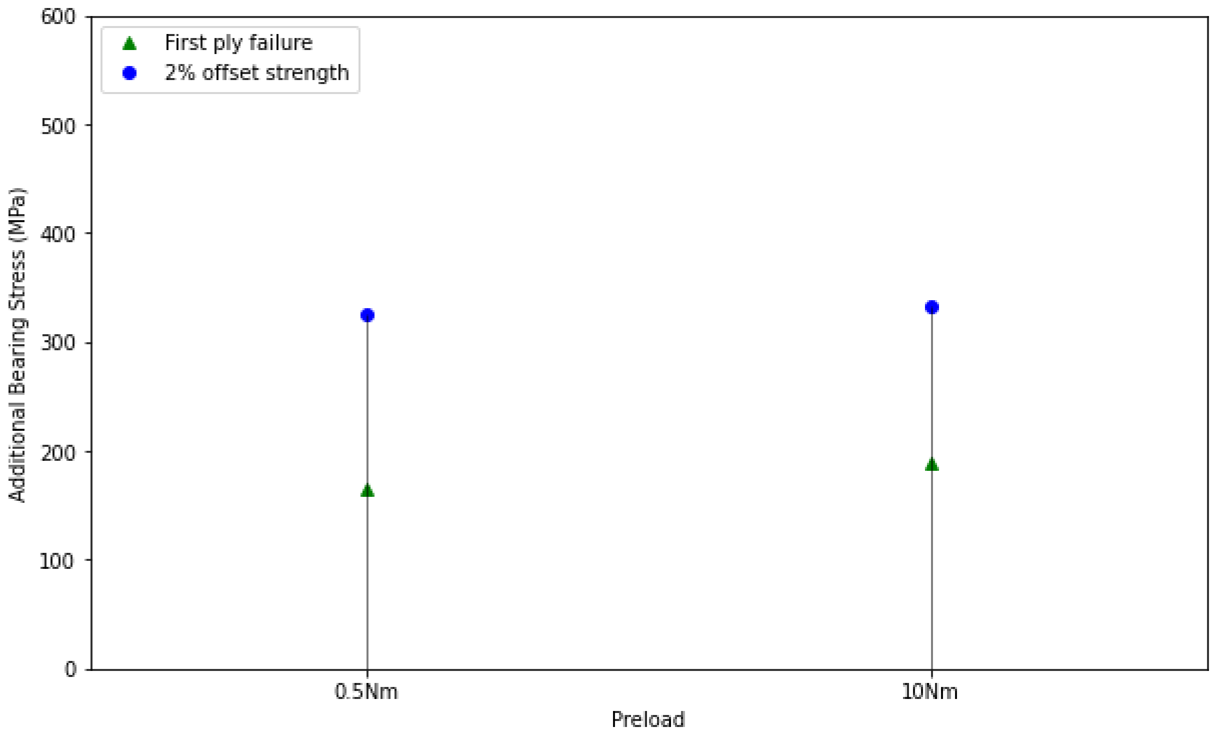


Is the increase in bearing strength a result of the reduction in bearing stress due to friction or also the increased lateral restraint due to preload?

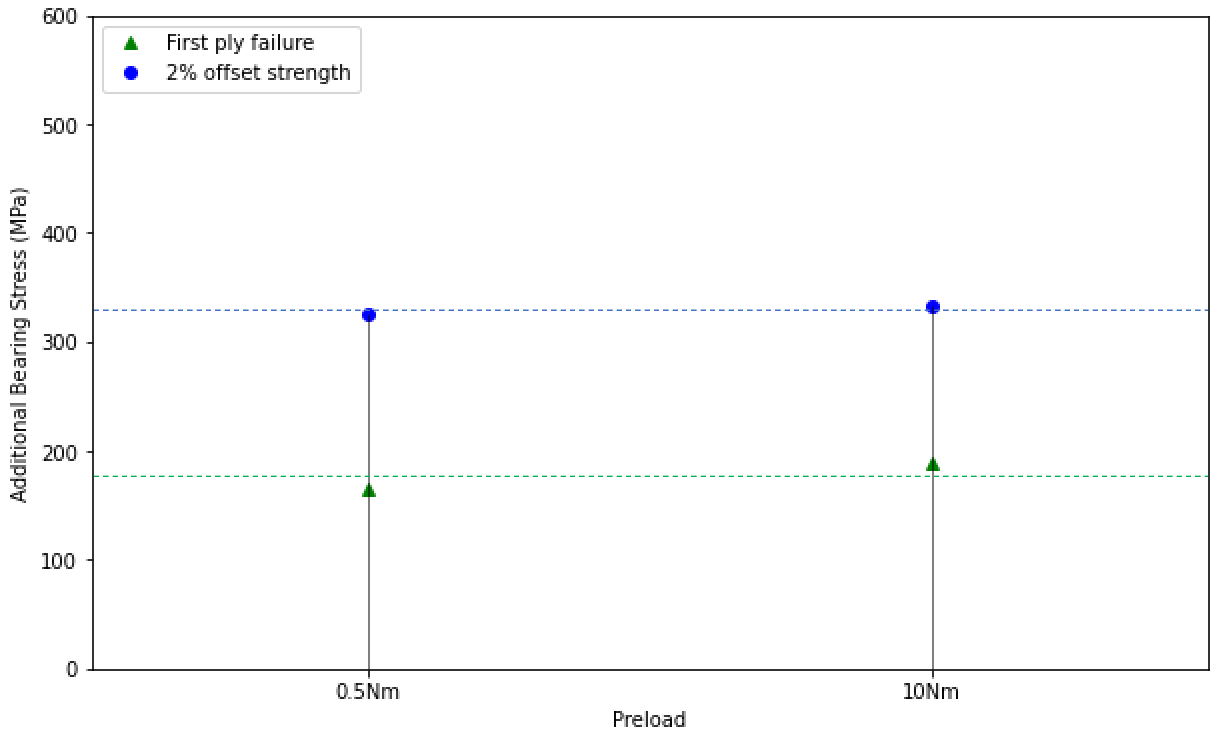
Effect of preload on bearing strength



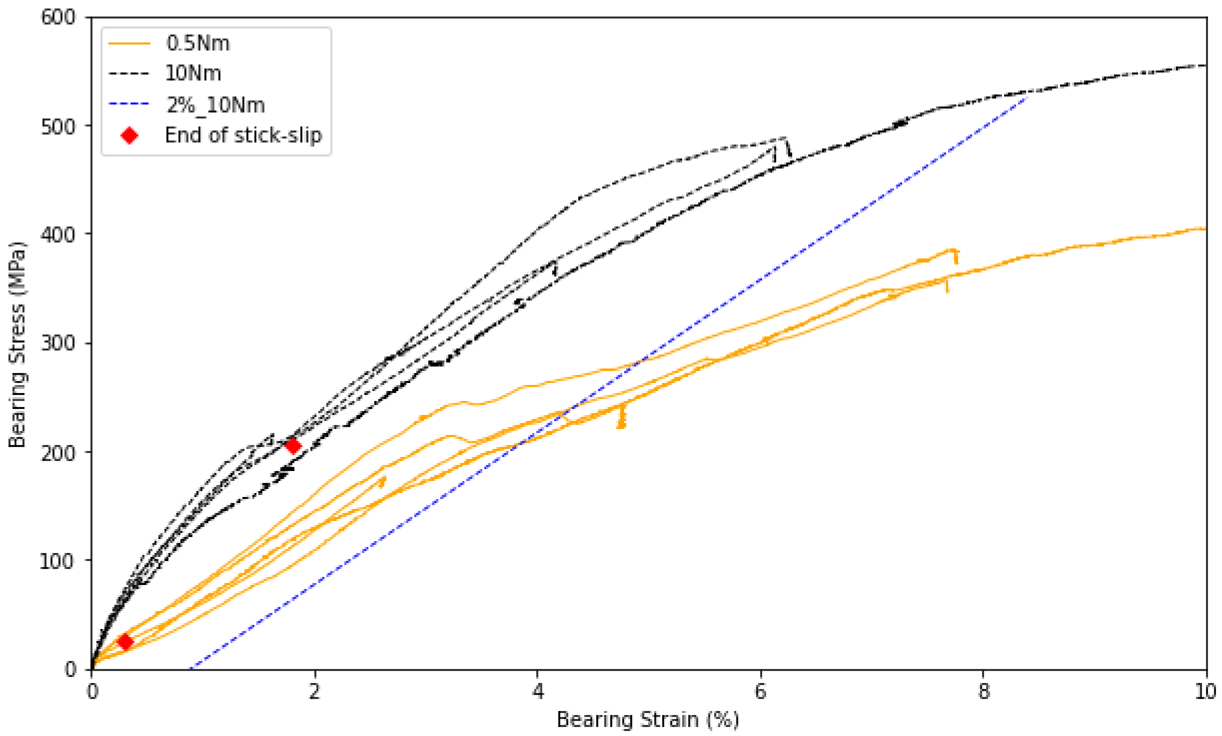
Effect of preload on bearing strength



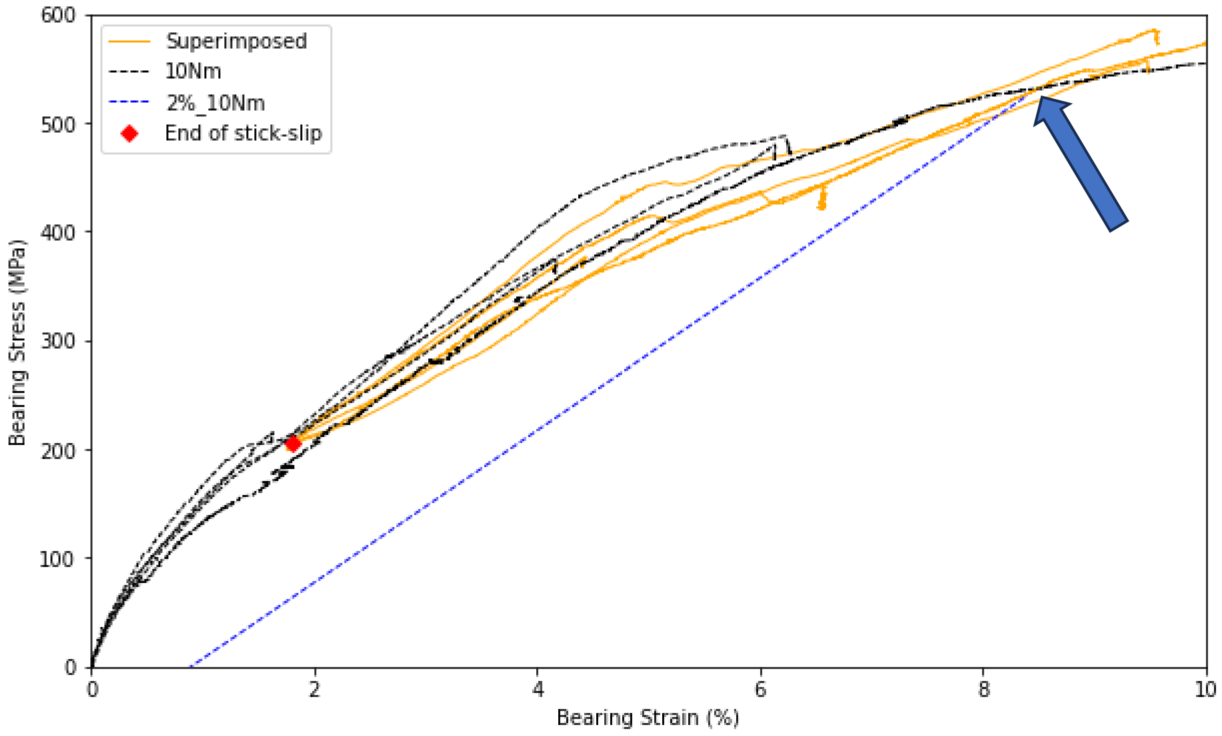
Effect of preload on bearing strength



Effect of preload on bearing strength

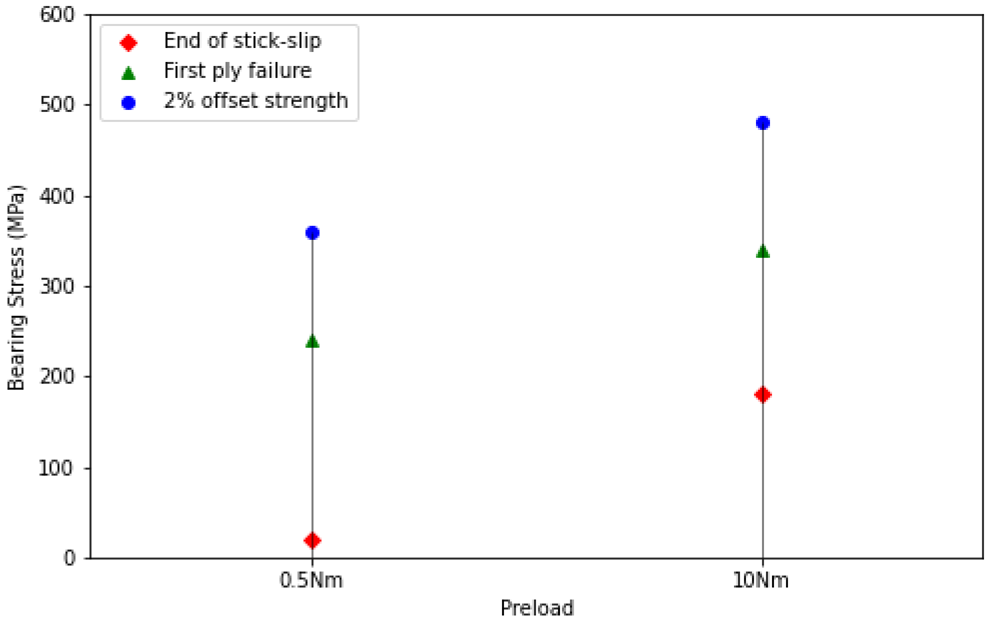


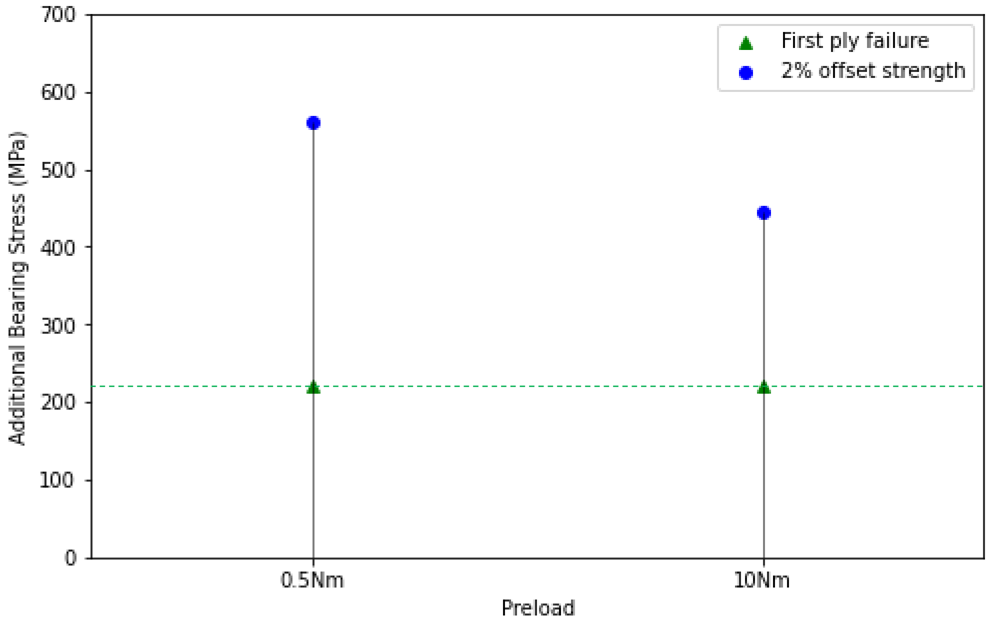
Effect of preload on bearing strength



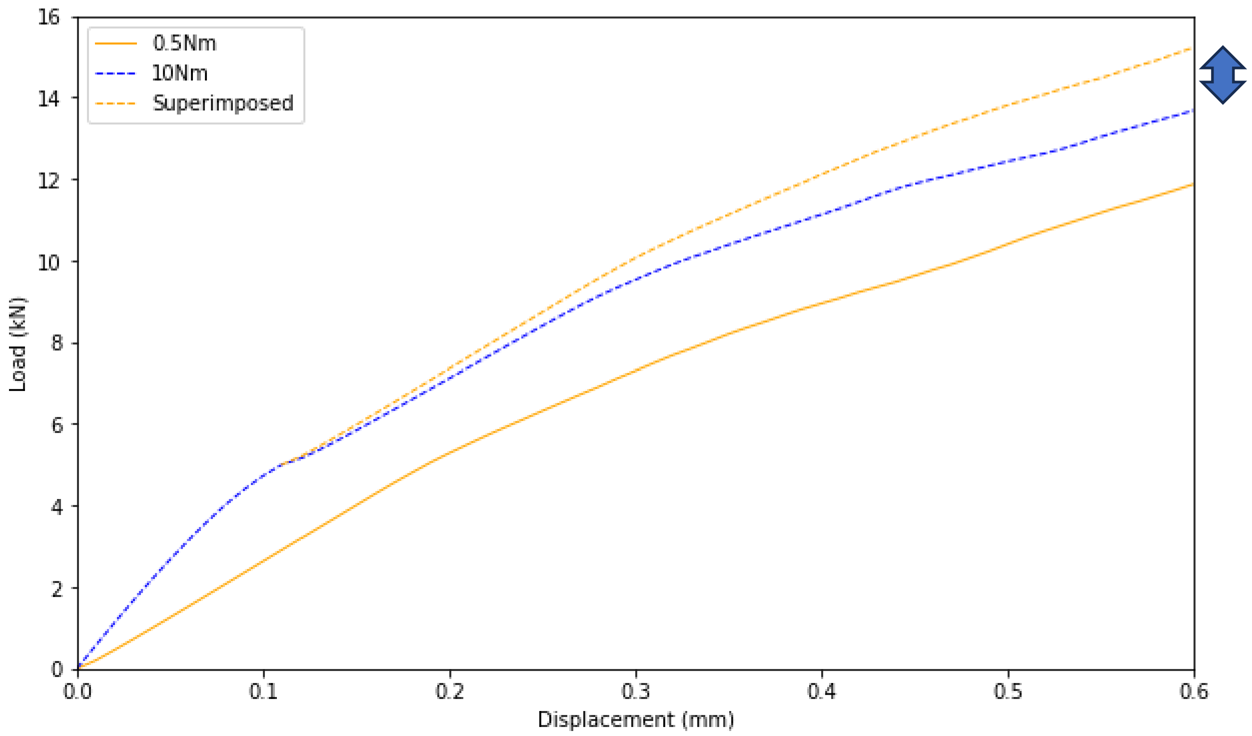
Experimental results indicate stick region plays primary role in increasing bearing strength

Effect of preload on bearing strength



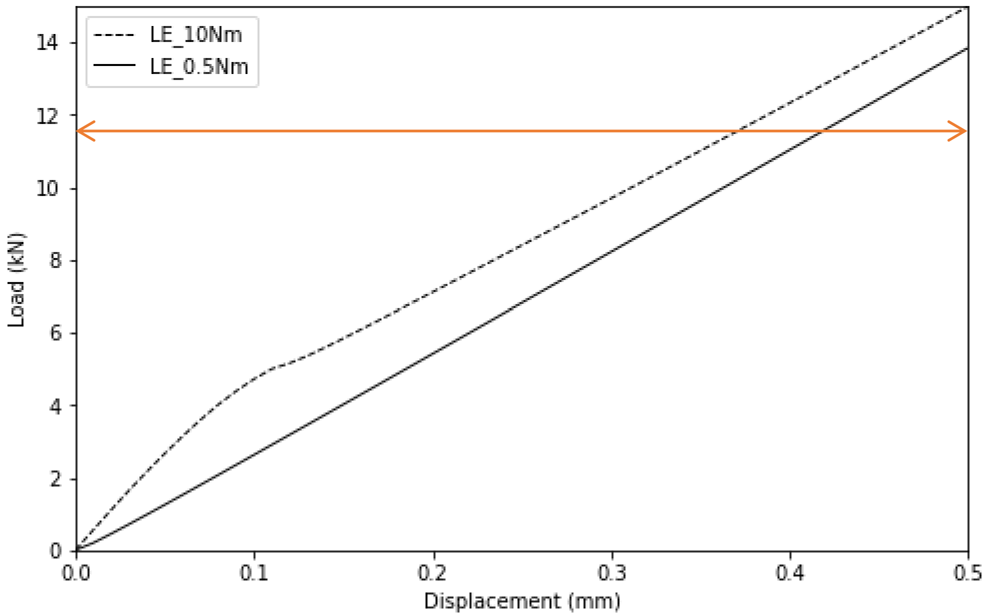


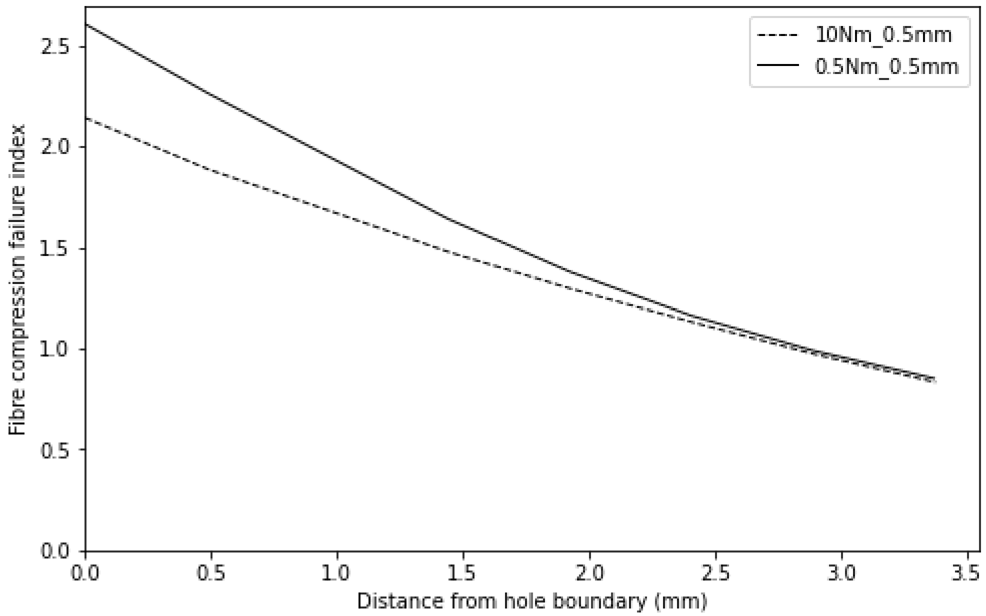
Effect of preload on bearing strength



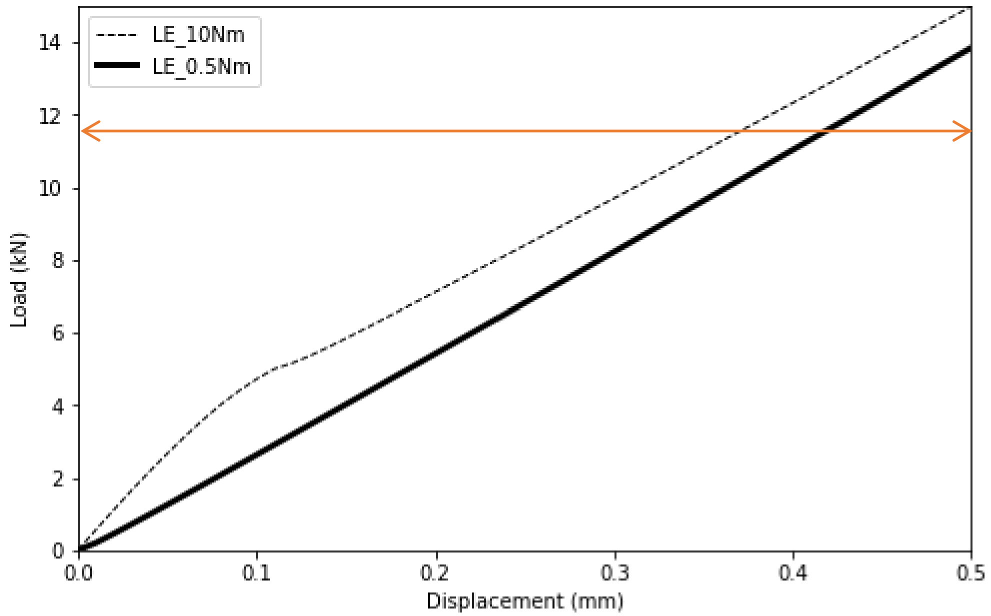
FEA results indicate preload has an adverse effect on joint damage after first ply failure and therefore a reduction in 'additional' bearing strength.

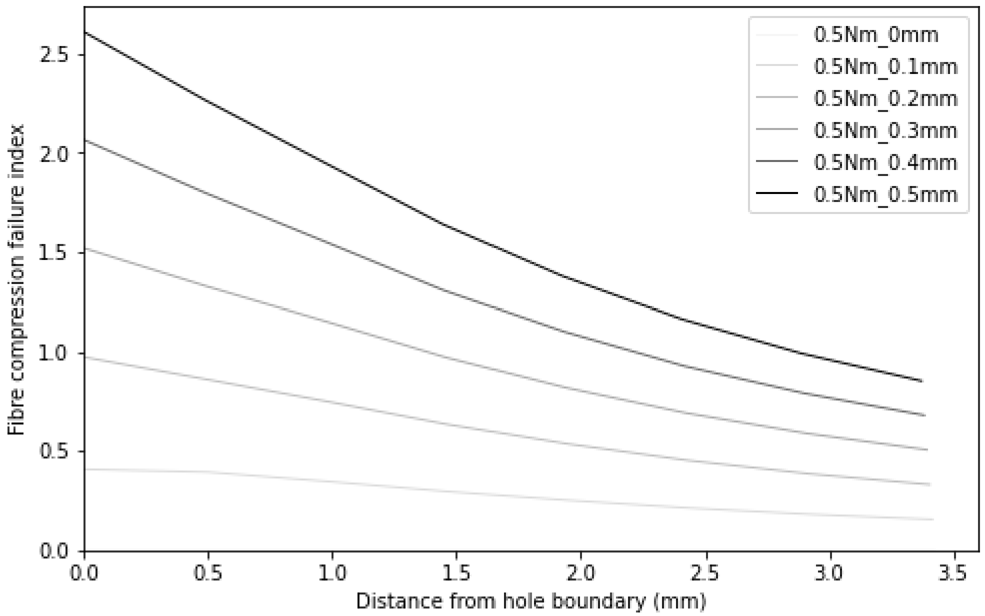
Effect of preload on bearing stress



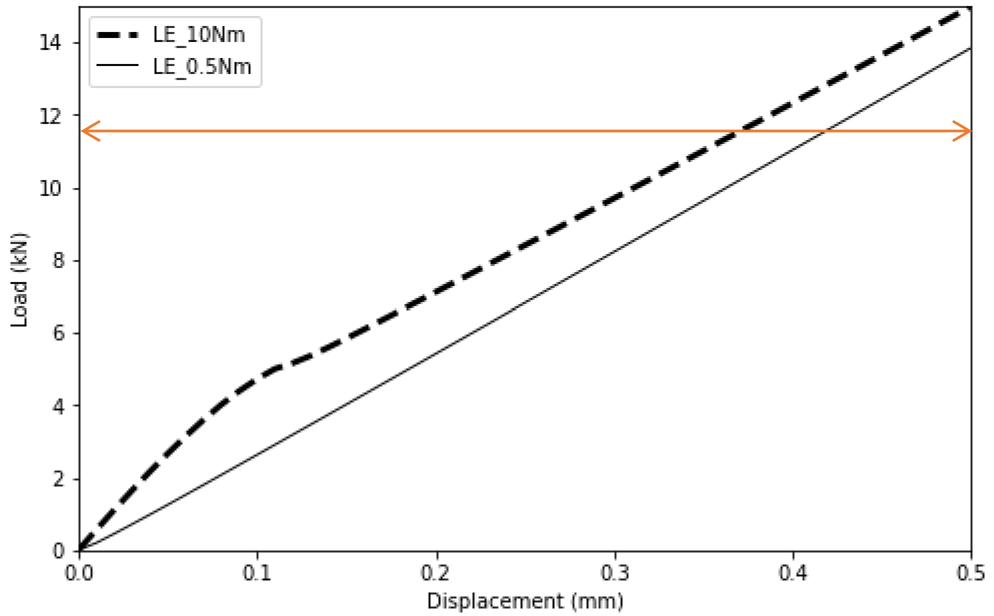


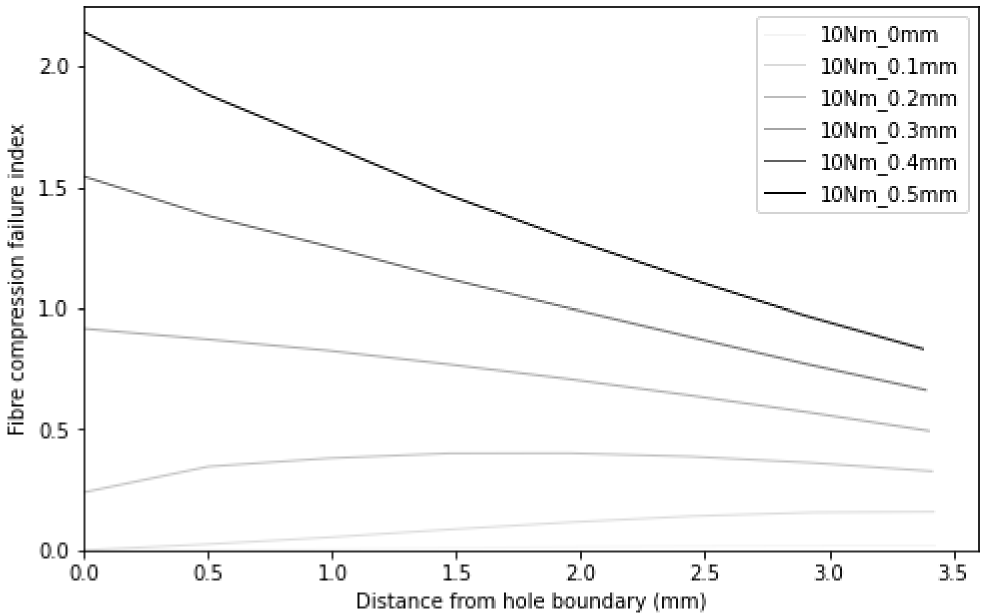
Effect of preload on bearing stress



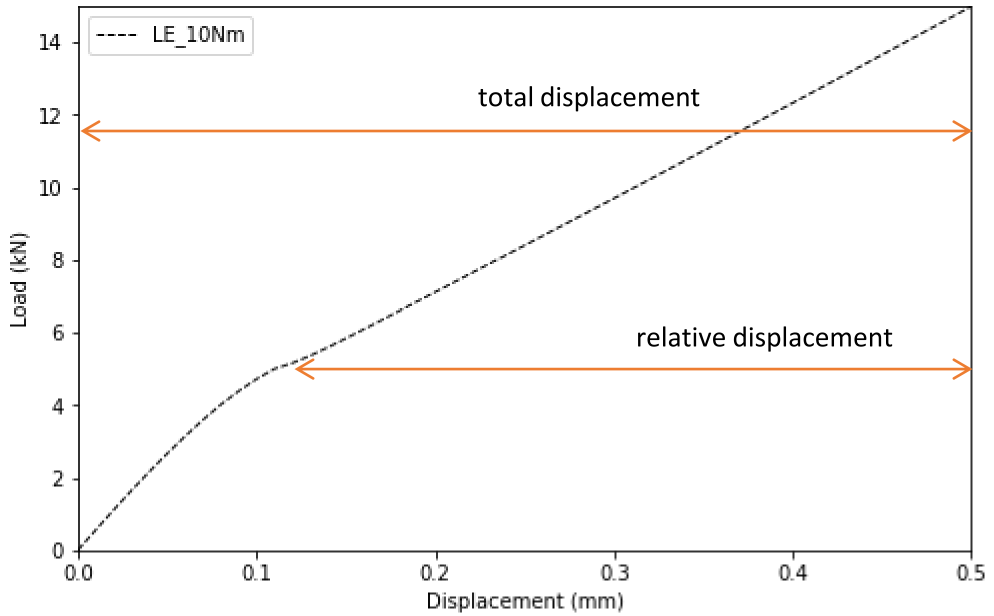


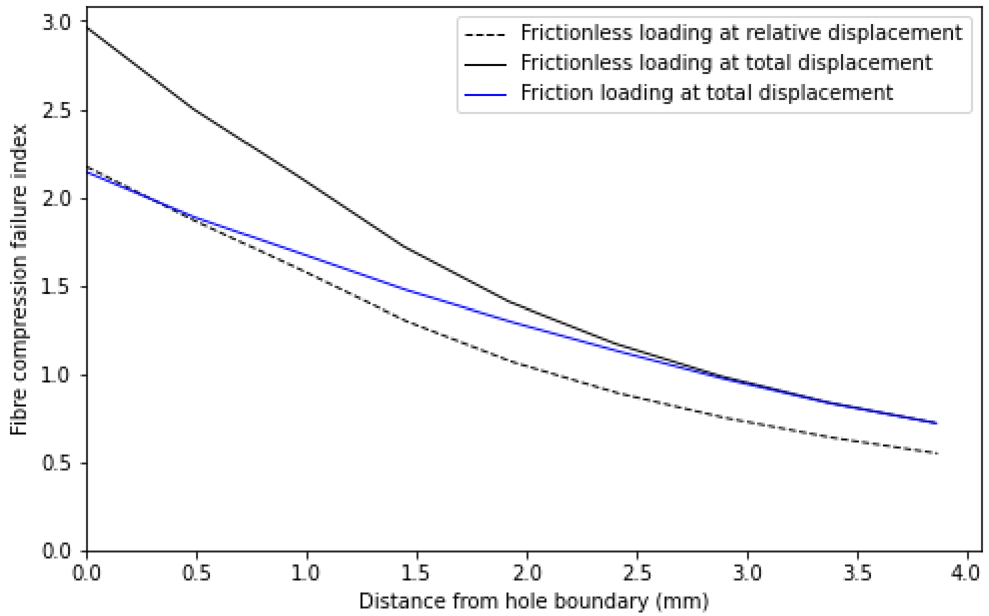
Effect of preload on bearing stress





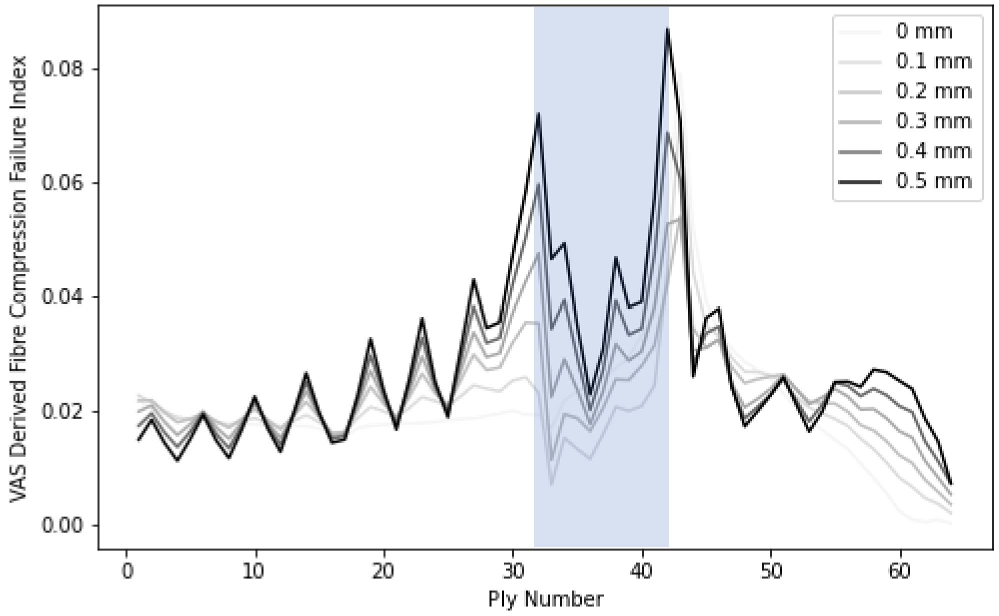
Effect of preload on bearing stress

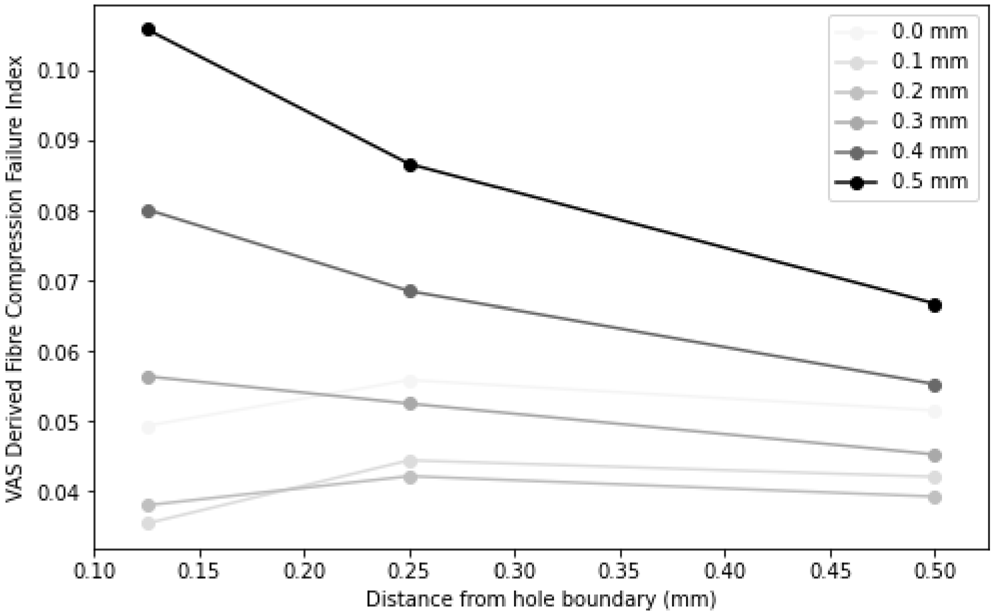




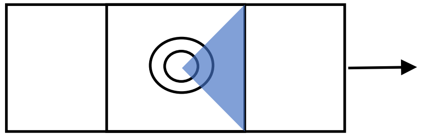
Compressive stresses ahead of hole boundary depend on total displacement, and compressive stresses at hole boundary depend on relative displacement.

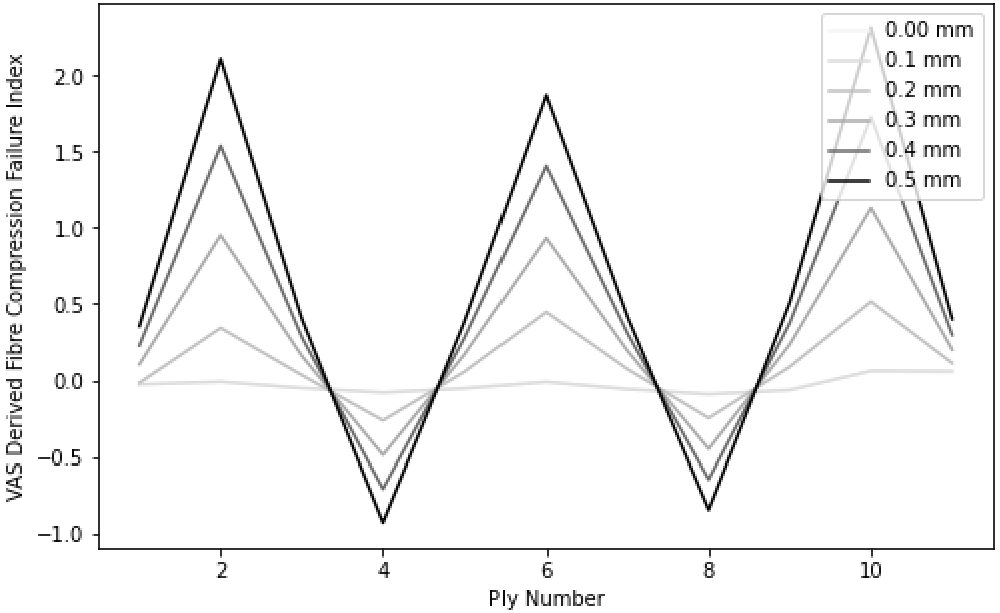
Volume averaged stresses criterion

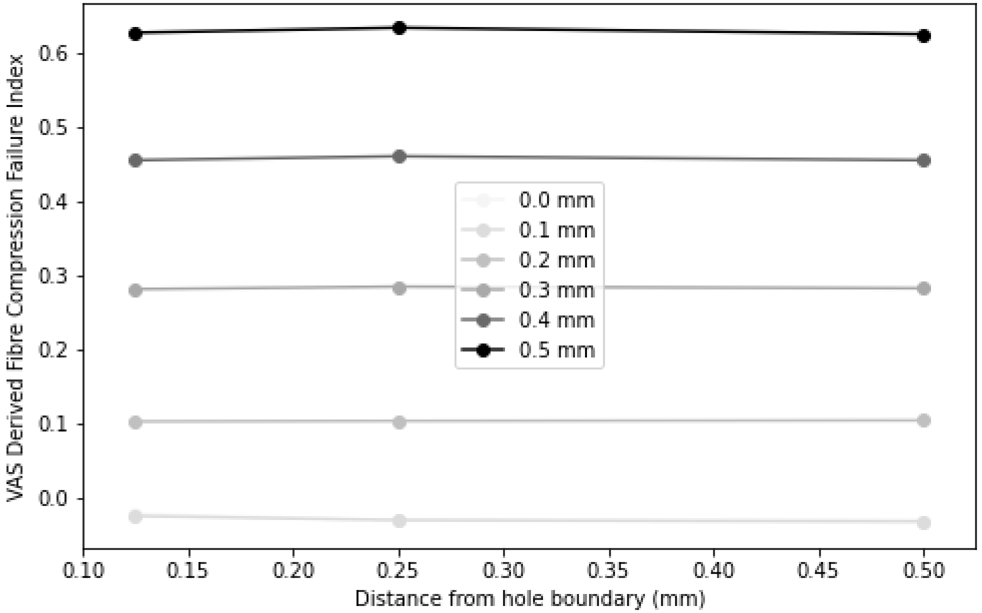




Volume averaged stress criterion





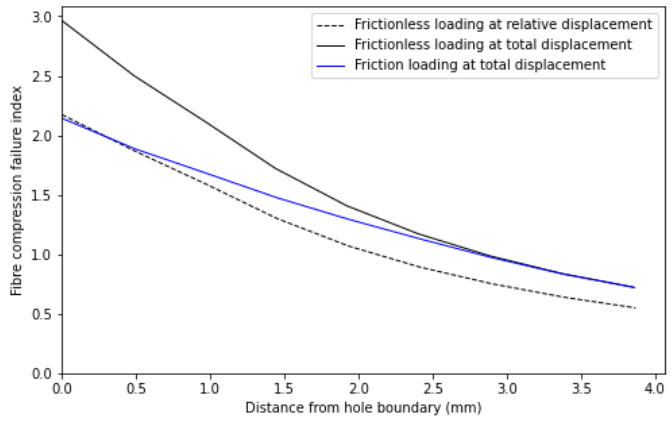


Volume averaging over the bearing quadrant results in higher magnitude indices

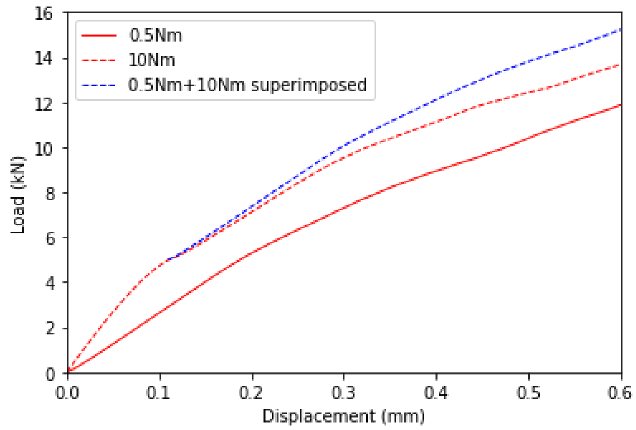
Summary

CONTEXT · · · · | METHOD | RESULTS · · · | CONCLUSIONS · ·

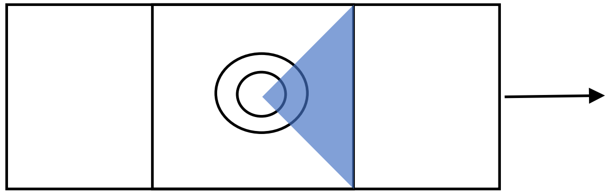
Effect of preload/friction on stresses



Effect of preload on bearing strength

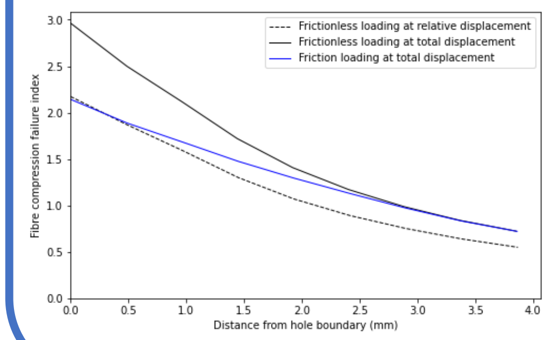


VASC quadrant-based

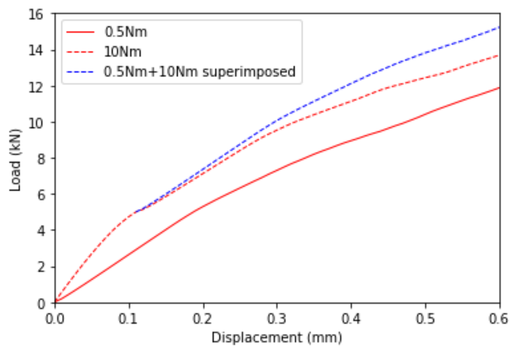


Next steps

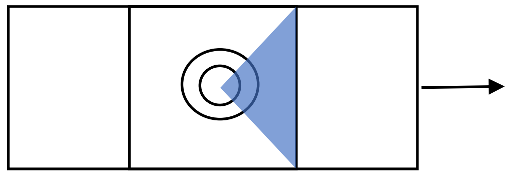
Effect of preload/friction on stresses



Effect of preload on bearing strength



VASC quadrant-based



- Test for different bolted joint configurations
- Vary by-pass loading
- Check effect on tensile plane stresses
- Validate with analytical solutions

- Improve FE correlation with experimental results and convergence
- Further experimental data
- Try different failure models

- Evaluate at larger distances from hole boundary
- Compare with PSC/ASC predictions, at various bypass loadings

References

- AZEEM, O.A.I and IANNUCCI, L, 2022. "A machine learning assisted preliminary design methodology for repetitive design features in complex structures". Design Computation Input/Output Conference 2022.
- CHOI, J et al, 2018. "Failure load prediction of composite bolted joint with clamping force" Composite Structures 2018.
- CREWS, J and Naik, R. 1986. "Combined bearing and bypass loading on a graphite/epoxy laminate" Composite Structures, 1986.
- GRAY, P.J. and McCarthy, C.T. "A global bolted joint model for finite element analysis of load distributions in multi-bolt composite joints". Composites Part B: Engineering, 2010.
- HYPERSIZER, 2014. https://hypersizer.com/help_7.0/Content/Failure/BJSFM/bjsfm-bypass_loads.php
- LAURIN, F. et al, 2006. "Multiscale progressive failure approach for strength analysis of high gradient composite structures" 12th European Conference on Composite Materials, 2006.
- LOGARZO H.J. ET AL, 2021. Smart constitutive laws: Inelastic homogenization through machine learning. Computer Methods in Applied Mechanics and Engineering, (2021), 113482, 373
- OSTERGAARD M.G. ET AL, 2011. Virtual testing of aircraft structures. CEAS Aeronautical Journal 2011
- SUN, Z. ET AL, 2021. Prediction of failure behavior of composite hat-stiffened panels under in-plane shear using artificial neural network. Composite Structures, (2021), 114238, 272
- YANG, C. ET AL 2020. Prediction of composite microstructure stress-strain curves using convolutional neural. Materials and Design, (2020), 189

Thank you for listening!

Any questions?