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Non-linear stiffness response of corrugated laminates in tensile loading

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1 Introduction

Corrugated structures have been used in morphing wing design, since they provide deformation of the wing skin in chord direction while they behave very stiff in the span direction at low weight. Corrugated laminates can undergo large deformations in tensile loading and hence geometric non-linearities have to be considered. Modeling of corrugated structures by use of commercial FEM software leads to enormous computational costs. Hence the development of new modeling techniques is needed.

2 Governing mechanism and modeling approach

The structural response mainly depends on the geometry parameters, namely corrugation amplitude and laminate thickness and also on laminate design. Fig 1 Illustrates the internal force and moment distributions in a corrugated structure due to tensile loading. Close to the reference configuration the bending moment dominates the structural response. As the corrugation deforms the amplitude decreases and the normal force becomes more and the bending moment less important.

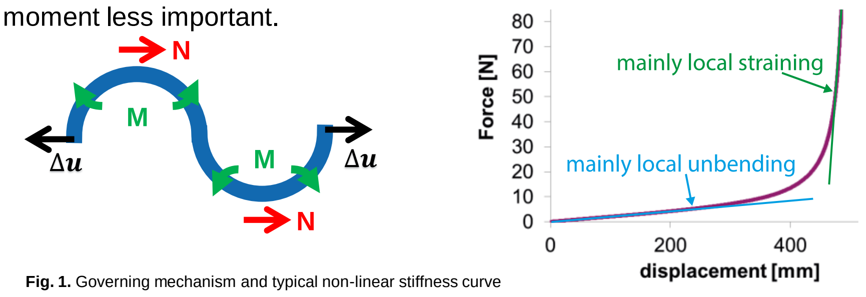

Fig. 1. Governing mechanism and typical non-linear stiffness curve

Our model calculates the mechanical response based on a simplified model consisting of rods and discrete torsional springs (see Fig. 2).

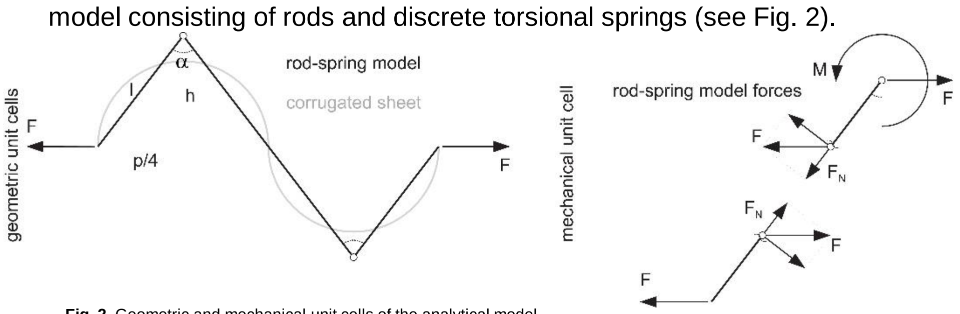

Fig. 2. Geometric and mechanical unit cells of the analytical model

3 Experimental and numerical validation

The analytical model was numerically verified with non-linear structural analysis using FEM. Furthermore, it was experimentally validated using samples manufactured by 3D printing (see Fig. 3). The samples were tested in a tensile machine measuring the non-linear stiffness response.

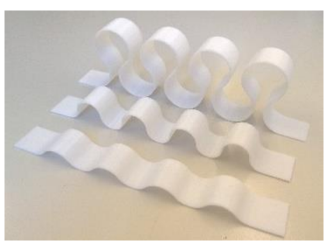

Fig. 3. Test samples

4 Results and discussion

Fig. 4 shows the experimental force-displacement curves for all the three tested samples. In the initial phase, where the sheet bending stiffness controls the behavior, the stiffnesses of the three samples vary significantly due to their different geometry (red). As the displacement increases and the corrugation flattens the stiffness increasingly depends on the sheet membrane stiffness. In this case the results are similar for all the three samples (blue).

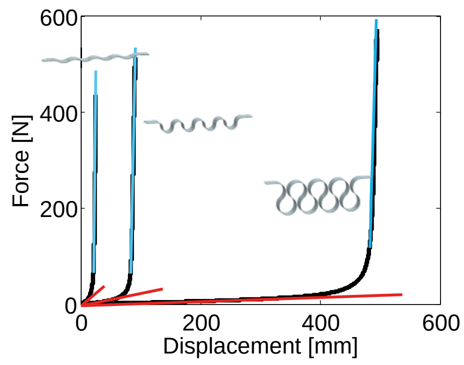

Fig. 4. Typical non-linear stiffness response for three different geometries: while the initial stiffness (red) is mainly driven by the moment and differs between the three geometries, the last part of the stiffness response (blue) is mainly driven by the stiffness of the base sheet which is equal for all three geometries

The verification and validation of the model shows that the analytical model, numerical solution and experimental results show a very good agreement. Fig. 5 displays the comparison of the proposed model with the FE results for three different thicknesses. The results show that the stiffness response is very well reproduced by our model, for both thin and thick laminates.

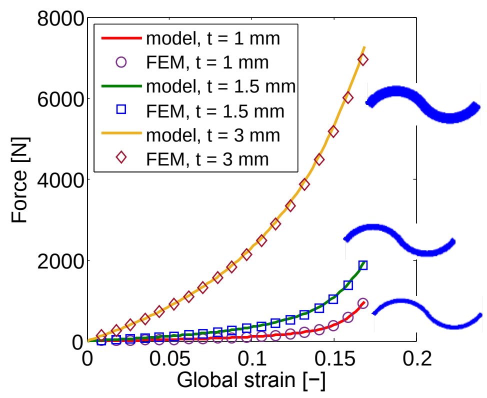

Fig. 5. Validation of the proposed model for different thicknesses

5 Conclusions

Conclusions:

- An analytical model to analyze the non-linear stiffness response of corrugated structures was developed, numerically verified, and experimentally validated
- The model is able to predict the non-linear stiffness response both for thin and thick corrugated multidirectional lamina
- The model is very efficient and much faster than a FEM solution and can directly be used for design purposes

6 References

Thurnherr C., Ruppen L., Kress G., Ermanni P., «Non-linear stiffness response of corrugated laminates», Composite Structures, 157, 244-255, 2016

Partners

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