LOCAL REINFORCEMENT INFLUENCE ON CORRUGATED LAMINATES STRUCTURAL STIFFNESS RESPONSE FOR FLEXIBLE SKINS

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Abstract
Corrugated structures can achieve highly anisotropic structural stiffness properties and hence they are ideal candidates for morphing skins. Corrugations consisting of two almost full circles fulfill the requirements for morphing wings very well, namely a high compliance in and high bending stiffness about chord direction, and provide a favorable behavior concerning interlaminar stresses. A drawback, however, is the relatively low bending stiffness about the span direction. In the present study, we aim to increase this bending stiffness by locally reinforcing the corrugated structures. The geometry is parametrized and a finite element model is implemented. We use a unit-cell approach and assume a generalized plane strain state to reduce the computational costs. An optimization is performed using the successive response surface method to find the best material distribution in order to minimize the axial to bending stiffness ratio. The found optimal shape performs 50 % better than the initial configuration.

1. Introduction

Corrugated laminates are highly anisotropic structural elements. They have a very high axial compliance and very high stiffness about the same direction. Therefore, they are ideal candidates for flexible skins for morphing wing applications [1–3]. Due to their geometry, corrugated structures can undergo high global strains while the local strains remain relatively low [4]. By using composite materials which can withstand material strains up to 1 % this effect can be used optimally [5]. Recently, Dayyani et al. [6] provided a review over composite corrugated structures, summarizing the advantages of corrugated laminates as flexible skins.

Various cross-section shapes for corrugated skins have been suggested in literature. Some authors suggested trapezoidal shapes [7–9], sinusoidal shapes [10, 11] or circular sections [12]. Previtali et al. suggested double-walled corrugation [13]. Lately, we have suggested a corrugation consisting of two almost full circles where interlaminar stresses and hence delamination failure are minimized [14, 15]. Further, this corrugation has a very high compliance in and a very high bending stiffness about the chord direction. However, the bending stiffness about the span direction which contributes to withstanding aerodynamical forces is rather low. Therefore, we aim to increase this bending stiffness with local reinforcements in this investigation.

To model corrugated structures, homogenized models are often used to obtain equivalent stiffnesses. Various analytical models exist for thin structures [12, 16–18] and numerical models for structures of

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arbitrary thickness [19]. In this work we use a commercial finite element code to model the locally reinforced corrugated structures. Due to the periodicity of the structures and to save computational costs, only one unit-cell is modeled and periodic boundary conditions are applied. Further, we can reduce the problem to two independent variables by assuming a generalized plane-strain state.

The current study investigates how the bending stiffness about the span direction can be increased with local reinforcements. The geometry of the corrugation is held constant while the geometry and shape of the reinforcement is parametrized. An optimization is carried out to minimize the ratio between the axial and bending stiffness using the successive response surface method. In the following section the finite element model and the according boundary conditions are explained for the tensile and bending load case. In section 3 the optimization is presented, namely the objective function, the applied constraints, and the initial design. Then, the found optimal shape is shown and the results are discussed. The paper closes with a conclusion and an outlook.

2. Modeling approach

The corrugated structures consist of circular sections and are modeled using a unit-cell approach. Further, we assume a generalized plane-strain state as shown in figure 1.

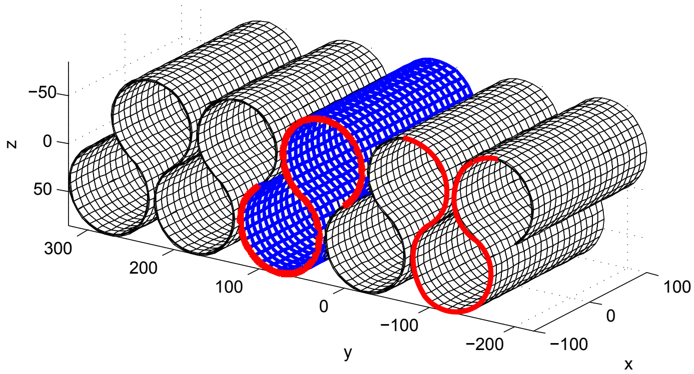

Figure 1. Modeling approach using unit-cell (blue) and generalized plane strain (red). Two different cross-section can serve as a unit-cell (red) where the right one is more favorable for the self contact modeling.

The resulting 2D plane model is implemented in Ansys Mechanical 14.5 and periodic boundary conditions are applied as described in the following subsections. The model considers geometric non-linearities and non-linear contact. Since we are interested in the axial to bending stiffness ratio, we consider two load cases: tensile loading in *y*-direction and bending about the *x*-direction as illustrated in figure 2.

2.1. Tensile load case

The tensile load case allows the reduction to a half-cell model as shown in figure 3. A displacement $u_{tensile}$ is applied on the left edge and symmetry boundary conditions are applied on the right edge.

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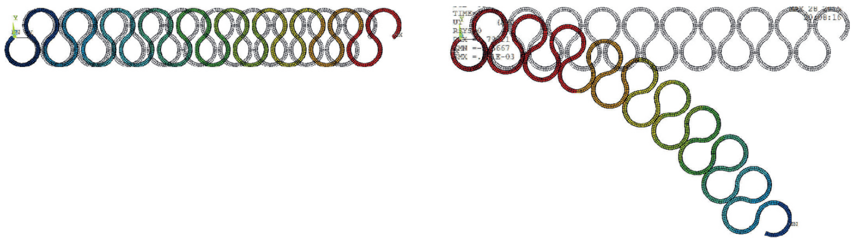

Figure 2. Considered load cases: a) tensile loading and b) bending.

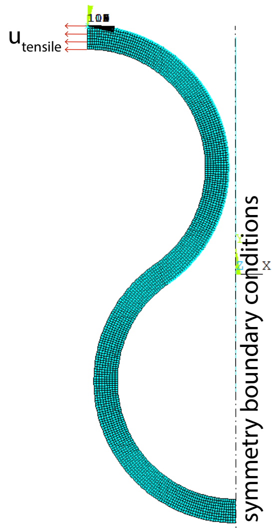

Figure 3. Boundary conditions for tensile load case.

2.2. Bending load case

For the bending load case self-contact between the unit-cells has to be considered. Again this can be realized using the half-cell model and a rigid symmetry wall as illustrated in figure 4.

2.3. Parametrization of the reinforcements

The geometry of the corrugation is held constant. The reinforcements are parametrized as shown in figure 5. In the present study, the number of free geometric parameters is set to seven. The parameters define the supporting points between the edge of the reinforcements and the mid point of the circular sections of the corrugation. The profile between the supporting points is generated by interpolation.

3. Optimization

In this section the optimization algorithm, the objective function, the constraints and the initial design is presented.

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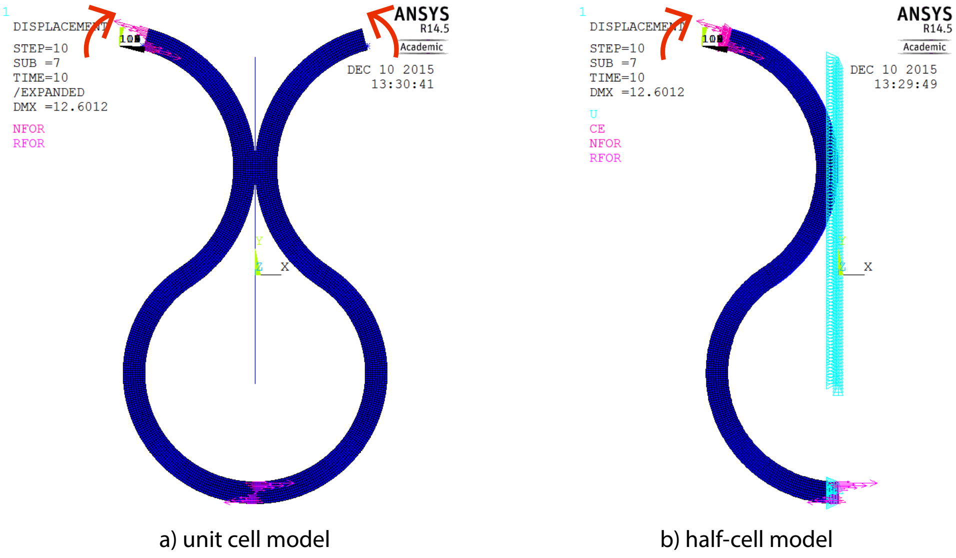

Figure 4. Boundary conditions for bending load case: a) unit-cell with self-contact b) half unit-cell with rigid symmetry wall.

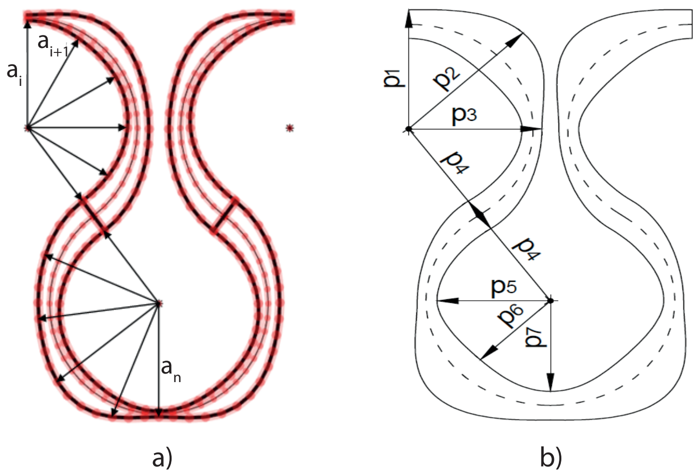

Figure 5. Parametrization of the reinforcements: a) general concept and b) the used seven parameters.

3.1. Objective function

The goal of this optimization is to minimize the ratio between the axial stiffness AS_{chord} and the bending stiffness BS_{span}:

$$min\left(-\frac{BS_{span}}{AS_{chord}}\right) \tag{1}$$

where the axial stiffness AS_{chord} is evaluated by calculating the tangential stiffness within the first 5 % global strain. The bending stiffness BS_{span} is obtained by taking the tangential stiffness of the moment-rotation-curve after self-contact occurred.

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The objective function is minimized applying the successive response surface method and the Latin Hypercube sampling is used to define the supporting points.

3.2. Constraints

The parameters p_i (see figure 5) are varied between t_{min} and t_{max} and some constraints t_{con} have to be defined in order to avoid penetration between two adjacent cells:

$$t_{min} = 1mm <= p_i <= t_{max} = 6mm, p_i <= t_{con} \quad for\ i = 1, 2, ..., 7 \tag{2}$$

The mass is not taken as a constraint since the objective of minimizing AS_{chord} tends to minimize the amount of material while maximizing BS_{chord} leads to an increase of the amount of material. These contradictory objectives should result in a balanced amount of mass.

3.3. Initial Design

Figure 6 shows the initial geometry. All the parameters p_i are set to zero. The amplitude of the corrugation is $80mm$ and the periodic cell length is $100mm$.

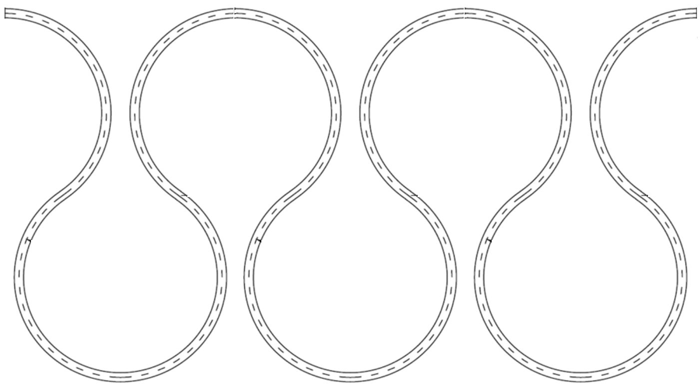

Figure 6. Initial geometry.

4. Results and discussion

Figure 7 shows the optimized shape which performs around 50 % better than the initial shape in terms of axial to bending stiffness ratio. The corrugation is mainly reinforced at the location of the maximum amplitude. Due to the self-contact between the unit-cells in the bending load-case this is the location where we expect the highest changes in the curvatures for the bending load case. Therefore, additional mass in this point increases the bending stiffness BS_{chord}. Also in the tensile load case we expect the highest bending moment at largest amplitude due to the highest lever. Hence, the additional mass also increases the axial stiffness, but by a lower factor than the bending stiffness which results in a lower stiffness ratio. The tensile stiffness of the reinforced corrugation is still low in comparison to a corrugation consisting of semi-circles, since the initial shape has an axial stiffness that is orders of magnitudes lower than corrugated skins consisting of semi-circles.

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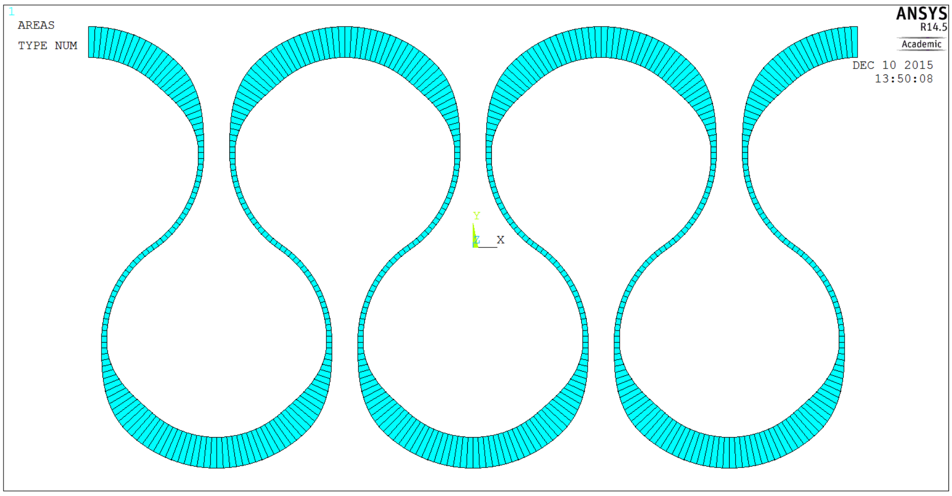
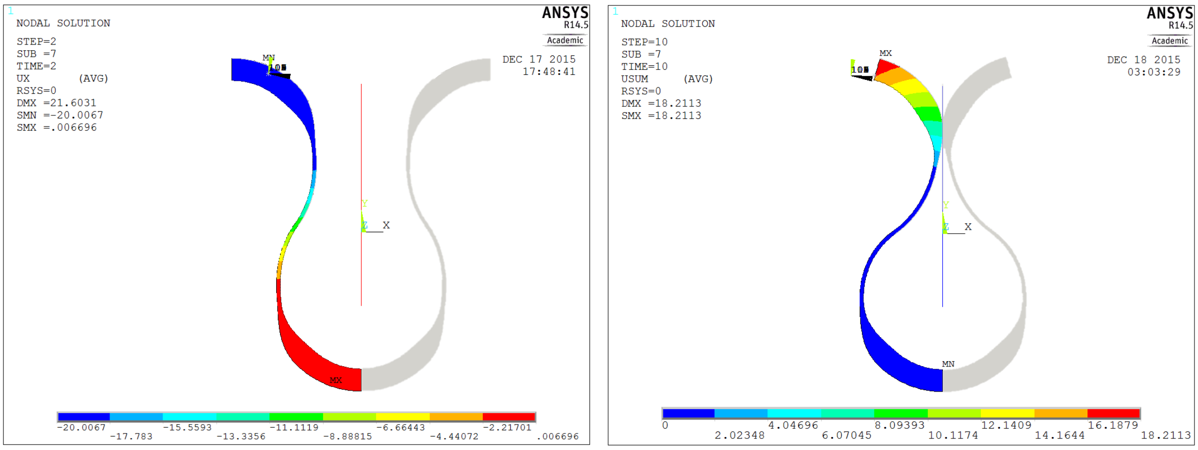


Figure 7. Optimized shape.

Figure 8 shows the deformed shapes for the tensile and the bending load case. We can see that in both load cases the deformation gradient concentrates at the thinner and more compliant part of the corrugation. In the tensile load case the deformation is symmetric about the horizontal axis. In the bending load case mainly the upper part of the thin cross-section is deformed.



a) Deformation in tensile load case

b) Deformation in bending load case

Figure 8. Displacement for a) the tensile load case and b) the bending load case.

5. Conclusion

This study investigates the potential of locally reinforced corrugated structures in order to minimize the axial to bending stiffness ratio. A numerical model is implemented which considers one half-unit-cell of a periodic corrugation and uses generalized plane strain state. The local reinforcements are parametrized and an optimization is run to find a configuration with low axial stiffness in the chord direction, but high bending stiffness about the span direction. The found corrugation performs around 50 % better than the initial configuration. In future studies we aim to refine the present study using more constraints such as mass and manufacturability. Furthermore, the implementation of the found optimal shape in morphing

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wing applications can be considered.

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