Load Optimisation for Air Bending in the Context of Damage Reduction

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Load optimisation applied to air bending is used to optimise the damage state in the formed component. In [1], *elastomer bending* is presented, where superposed stresses due to the reaction forces of the elastomer cushion lead to reduced damage growth. Replacing the elastomer cushion with compressive loads allows for optimisation of these loads such that the damage, estimated with the stress triaxiality, is reduced. The optimisation is accomplished with the commercial FEM-Software Abaqus as the solver for the mechanical problem where Sequential Quadratic Programming (SQP) is used within Matlab to generate improved loads.

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1 Motivation

The results obtained in [1], where damage evolution in selected forming processes was investigated, show the possibilities of superimposing stresses in bending to yield lesser damaged components, while maintaining the same deformation and final shape. The disadvantage of the elastomer cushion, however, is the inhomogeneous triaxiality distribution and the impossibility to directly define the forces imposed by the elastomer. The objective of load optimisation is to generate loads which yield a reduced damage state and, to later on improve the elastomer cushion for a precise setup of the reaction forces.

2 Theory of load optimization

The main idea for load optimisation has been presented in e.g. [2]. There, the external loads $\mathbf{f}$ within the equilibrium condition of the finite element formulation

$$\mathbf{R} = \mathbf{F}^{\text{int}} - \mathbf{F}^{\text{ext}} = \mathbf{K} \cdot \mathbf{u} - \lambda\mathbf{f} = \mathbf{0} \quad \text{with} \quad \mathbf{f} = a\mathbf{x}^n + b\mathbf{x}^{n-1} + \cdots + j\mathbf{x} + k, \tag{1}$$

can be optimised to generate new improved loads for a given problem. For the optimisation, the external loads are replaced by polynomial functions, with the coefficients of the polynomial as the design variables for the optimisation.

3 Numerical implementation

The main part of this work is the implementation of the optimisation framework. For the sake of comparison with the results in [1], the software Abaqus is used as the solver for the FEM problem. This allows for the use of the same material properties as well as the in-built contact formulations. With this in mind, the optimisation framework is built around Abaqus in order to allow mathematical optimisation. For the optimisation, Matlab is used with its solver *quadprog* for SQP. In order to transfer the data from the simulations for the optimisation within Matlab, the python library and interface provided by Abaqus are utilised.

The problem is defined in the *Complete Abaqus Environment* (CAE) and includes the region for the objective function, the area for the side constraints and the nodes for the load application. The input file created this way can then be altered to allow for optimisation. The complete optimisation framework consists of the following steps:

1. Run a structural analysis (Abaqus) for the material response of the problem with design variables $\mathbf{s}$.

2. Perturb design variable $\mathbf{s}_i$ (Matlab) and calculate the structural response (Abaqus) and the numerical gradient for the corresponding design variable via finite differences.

3. Use the objective functions, side constraints and gradients for SQP and generate a new design (Matlab).

For the mathematical optimisation, the problem is defined as a least square problem, i.e.

$$\begin{aligned} \underset{\mathbf{s}_l \leq \mathbf{s} \leq \mathbf{s}_u}{\text{minimise}} \quad & \|\mathbf{U}(\mathbf{s}) - \mathbf{U}^{\text{pre}}\|_2^2 \\ \text{subject to} \quad & \eta(\mathbf{s}) \leq \eta^{\text{crit}} \end{aligned} \quad \text{with} \quad \eta = \frac{\sigma_h}{\sigma_{vM}} \quad \text{and} \quad \sigma_h = \frac{I_1}{3} = \frac{\text{tr}(\boldsymbol{\sigma})}{3}, \tag{2}$$

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PAMM · Proc. Appl. Math. Mech. 2019;**19**:e201900179. www.gamm-proceedings.com

https://doi.org/10.1002/pamm.201900179 © 2019 The Authors *Proceedings in Applied Mathematics & Mechanics* published by Wiley-VCH Verlag GmbH & Co. KGaA Weinheim
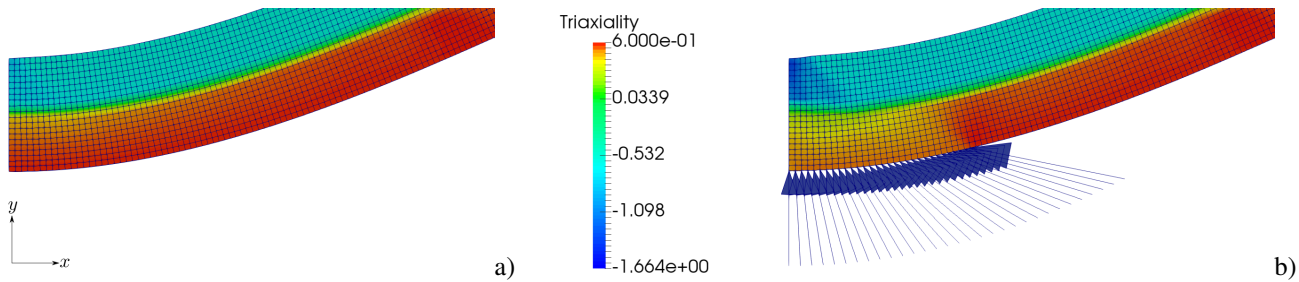
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Fig. 1: Experimental results for the validation of the compliance optimisation. The corresponding simulation is displayed in red. Fig. a) shows the minimisation with only the volume constraint, Fig. b) the results with the additional damage constraint.

where $\mathbf{U}(\mathbf{s})$ is the current deformation with design $\mathbf{s}$ of the sheet and $\mathbf{U}^{\mathrm{pre}}$ the deformation of the sheet when no additional compressive forces are present. η is the so-called stress triaxiality with σ_{vM} as the von Mises stresses and the hydrostatic stresses σ_h. The stress triaxiality is used as the quantity that is controlled to reduce the damage evolution in the forming process. Large triaxiality values are equivalent to a highly tensile oriented stress state, which in turn favours damage evolution, see [1]. This leads to the optimisation problem stated above, where the critical triaxiality value η^{crit} shall not be exceeded in the optimised design. The value is set to be equal to $\eta^{\mathrm{crit}} = 0.48$, which is the maximum value calculated in the simulations for *elastomer bending*. The idea to minimise the displacements of the new design is stated with the basic requirement that the shape of the final sheet must remain as close to the original as possible in order to satisfy prescribed geometric properties for its area of application.
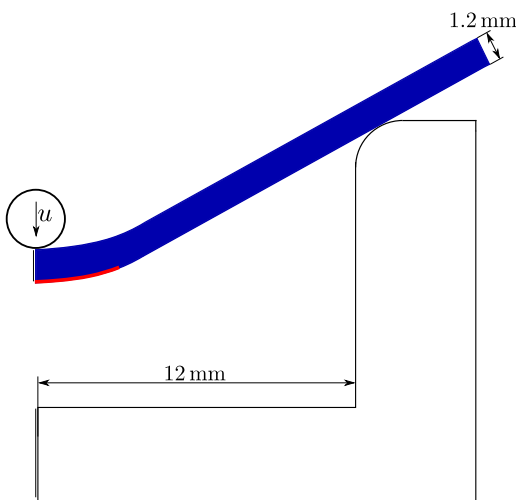
4   Numerical examples

Fig. 2: The simulation and optimisation setup. The deformable sheet is depicted in blue and the loads are applied at the red boundary.

The above framework is used to optimise air bending by applying possible loads in the area, where the elastomer in *elastomer bending* would yield compressive reaction forces. The defined simulation and optimisation problem is depicted in Figure 2. The blue part is the deformable metal sheet that is displaced by $u = 5\,\mathrm{mm}$ by the circular punch. Contact is defined between the punch and the sheet, as well as the die and the sheet. The remaining dimensions are stated in the figure and are taken from [1]. In order to generate loads in x- and y-direction, two sets of forces with polynomial degree $n = 2$, i.e $\mathbf{f}_{x/y} = a_{x/y}\mathbf{x}^2 + b_{x/y}\mathbf{x} + c_{x/y}$, are allowed to be optimised in the red area in Figure 2, resulting in 6 design variables. Each optimisation step requires 7 FEM calculations. The design variables are allowed to change freely, with the exception of the constant c_x in the polynomial for the x-direction. This variable is set to zero, which results in purely vertical forces at the left most point of the sheet, i.e. at the point of the symmetry axis. Initially, no loads are applied to the specified area, resulting in the deformation $\mathbf{U}^{\mathrm{pre}}$.

The results are presented in Figure 1, where only the area around the point of interest is shown since this is where damage is most likely to evolve, which may then lead to failure if the damage becomes to large. Initially, the triaxiality is largely homogeneous in x-direction of the plate. High values of the triaxiality are visible in the lower part of the plate, reaching values of around $\eta^{\mathrm{max}} = 0.58$. The optimised loads are shown on the right, showing the desired triaxiality distribution, which never exceeds the critical value of $\eta^{\mathrm{crit}} = 0.48$. With no further constraint regarding the design variables, loads are generated which are similar to the ones expected in *elastomer bending*, showing the possibilities of this optimisation framework.

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