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Damage Optimisation for Air Bending

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Load and shape optimisation are applied to the process of air bending to optimise the damage state in the formed component. The enhanced process of *elastomer bending* is optimised, which yields a reduced damage state due to the superimposed radial stresses in the critical area of the forming process. The optimisation presented here is twofold. First, the elastomer is replaced by nodal loads to generate optimised loads for a reduced damage state. Second, the elastomer itself is optimised via shape optimisation by adjusting the layer for two kinds of elastomer of varying stiffness. The optimisation is accomplished with the commercial FEM software Abaqus as the solver for the mechanical problem and Matlab is used for optimisation.

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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. By altering the elastomer cushion to be manufactured with different types of elastomer and thus stiffness, shape optimisation can be utilised to homogenise the triaxiality in the critical area of the bended sheet.

2 Numerical implementation

The main aspect of this work is the implementation of the optimisation framework. For a detailed explanation of the idea of load optimisation see [2] or [3].

In order to allow comparison of the results with [1], the software Abaqus is used as the solver for the FEM problem. This allows for the use of the same material properties while more importantly the use of the in-built contact formulations. The optimisation framework is built around Abaqus, wherein Matlab is used to gather the results from Abaqus and to solve the defined mathematical optimisation problem. In order to transfer the data from the simulations to Matlab, the python library and interface provided by Abaqus is utilised. The FEM problem is defined in the *Complete Abaqus Environment* (Abaqus/CAE) and includes the region for the objective function, the area for the constraints and the nodes for the load application. The input file created this way can then be altered to allow for optimisation, by exchanging either the nodal load values or the optimised nodal coordinates.

Applying the above concept, the complete optimisation framework consists of the following steps:

1. A structural analysis (Abaqus) for the material response of the problem with design variables $\mathbf{s}$.
2. Perturb design variable 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, constraints (and gradients) for the optimisation and generate a new design (Matlab).

Step two of the above enumeration only applies if gradient based optimisation (e.g. Sequential Quadratic Programming (SQP)) is performed. Otherwise the pertubation is skipped.

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

$$\begin{aligned} &\underset{\mathbf{s}_l \le \mathbf{s} \le \mathbf{s}_u}{\text{minimise}} && \|\mathbf{U}(\mathbf{s}) - \mathbf{U}^{\text{pre}}\|_2^2 \\ &\text{subject to} && \eta(\mathbf{s}) \le \eta^{\text{crit}} \end{aligned} \quad \text{with} \quad \eta = \frac{\sigma_h}{\sigma_{vM}} \quad \text{and} \quad \sigma_h = \frac{I_1}{3} = \frac{\text{tr}(\boldsymbol{\sigma})}{3}, \tag{1}$$

where $\mathbf{U}(\mathbf{s})$ is the current deformation with design $\mathbf{s}$ of the sheet and $\mathbf{U}^{\text{pre}}$ 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. This value is set to be equal to $\eta^{\text{crit}} = 0.48$. The final deformation is defined in the objective function

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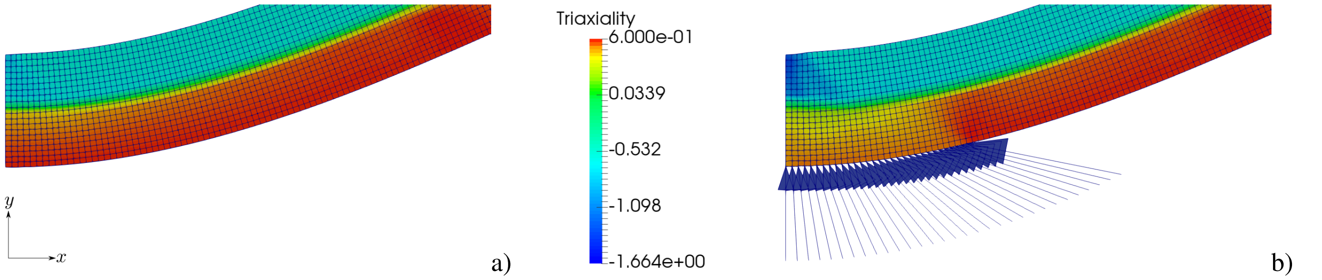

Fig. 1: Results for the load optimisation. The initial deformed sheet with no external loads (left) and the deformed sheet with optimised loads (right). The triaxiality is homogenised around the critical value of $\eta^{\text{crit}} = 0.48$.

since the aim of the initial forming process is to generate a specific geometry for the sheet. Thus, the shape of the optimised sheet must remain as close as possible to the original one.

For the shape optimisation, the optimisation problem is defined as $\underset{\mathbf{s}_l \leq \mathbf{s} \leq \mathbf{s}_u}{\text{minimise}} \|\boldsymbol{\eta}(\mathrm{s}) - \boldsymbol{\eta}^{\text{crit}}\|_2^2$. The deformation is not considered here since it is directly prescribed by the process and the elastomer cushion. Hence, the triaxiality is utilised for the objective function, in order to homogenise the values in the given critical area.

3 Numerical examples

The above framework is applied to air bending to generate optimised loads, as well as *elastomer bending* to generate an optimised layout for the elastomer cushion. The dimensions and specific parameters of the simulation can be taken from [1] and [3].

For the load optimisation, a gradient-based scheme (SQP) is used. The results are presented in Fig. 1. Only the area of the sheet, where damage is likely to accumulate and hence the loads applied, is shown. 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 $\eta^{\max} = 0.58$. The optimised loads are depicted on the right, showing the desired triaxiality distribution, which never exceeds the critical value of $\eta^{\text{crit}} = 0.48$.

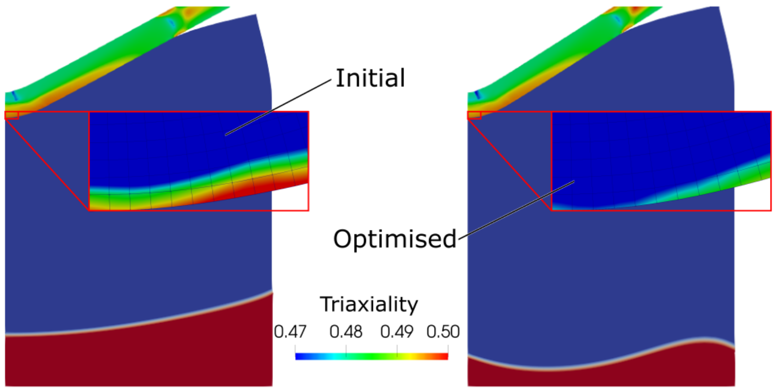

Fig. 2: The initial (left) and optimised (right) elastomer cushion. The blue area is the soft, the red the hard elastomer. The red bordered are shows the homogenised sheet.

For the shape optimisation, gradient-based optimisation did not converge and thus was not applicable. This is likely due to the highly discontinuous nature of contact calculation. While contact is still present in the above load optimisation, it is more severe in this optimisation problem due to the additional elastic-elastic contact of the elastomer and the metal sheet. In order to still be able to generate solutions, gradient-free optimisation in the form of a downhill-simplex [4] has been utilised. The generated results are shown in Fig. 2. The blue area depicts the elastomer of harder stiffness with the red being softer. By rearranging the elastomer parts, the triaxiality can be reduced and homogenised, depicted in the enlarged red-bordered area.

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