Design of a heterogeneous mechanical test using a nonlinear topology optimization approach

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INTRODUCTION

The design of sheet metal forming parts is increasingly taking advantage of virtual manufacturing tools. An accurate reproduction of the material behavior is required to guarantee the quality of the results.

The actual material characterization process requires the use of several classical mechanical tests to extract all the information about the material behavior. To improve this time-consuming and expensive process, heterogeneous mechanical tests have been proposed [1]. The heterogeneous fields that are induced can be analyzed using full-field measurement techniques. Due to the diversity of mechanical states, a large quantity of relevant information can be extracted from a single test.

To the best of the authors' knowledge, there is still a need for a systematic test design methodology. An optimization approach should be used to search for an optimal test configuration in a more efficient way than trial and error approaches. Therefore, this work aims at filling this gap by proposing a nonlinear topology-based optimization methodology for designing specimen geometries with heterogeneous displacement and strain fields.

METHODOLOGY

This work proposes the coupling between the design by topology optimization and a mechanism design approach. As the main aim is to obtain highly heterogeneous fields, innovative and complex geometries can be obtained with topology optimization, being an extended version of the compliant mechanisms' theory used to introduce more heterogeneity directly through the displacement field [2].

The design by topology optimization starts from a predefined design domain, represented in Fig. 1, and aims at finding its optimal material layout. During the optimization process, a uniaxial tensile loading test is reproduced, being

- $\mathbf{F}_{\text{in}}$, the load applied by the grips of the testing machine;
- u_{in} and u_{out}, two displacements applied in specific locations chosen empirically by the authors. While the first one corresponds to the grips' displacement, the second one is responsible for the way the specimen deforms, being applied preferentially far from the specimen boundaries.

The material layout, **X,** is defined by the design variables, X_e**,** that represent the relative density of each element,

$$X_e = \begin{cases} \rho_{\min} & \text{if void} \\ 1 & \text{if full} \end{cases}$$

The density of each element is updated at each iteration of the optimization process until the material layout that corresponds to the optimum of the objective-function is found.

In this work, it is proposed to maximize the ratio between the displacements in the output, u_{out}, and input, u_{in}, locations in order to enhance the heterogeneity of the displacement field of the specimen,

$$\text{maximize} \quad T(\mathbf{X}) = \frac{u_{\text{out}}}{u_{\text{in}}}$$

$$\text{subject to} \quad \mathbf{R} = \mathbf{0}$$

$$\frac{\sum_{e=1}^{M} X_e V_e}{\sum_{e=1}^{M} V_e} - \mathrm{V}^* \leq 0$$

$$0 \leq \rho_{\min} \leq \mathrm{X_e} \leq 1, e = 1, 2, .., M.$$

where **R** stands for the residual of the structural equilibrium. A volume constraint is set, being V_e, X_e, and V^*, the volume and relative density of each element and the volume fraction required for the specimen, respectively. A minimum value for the relative density, $\rho_{\min}$, is established to avoid numerical issues.

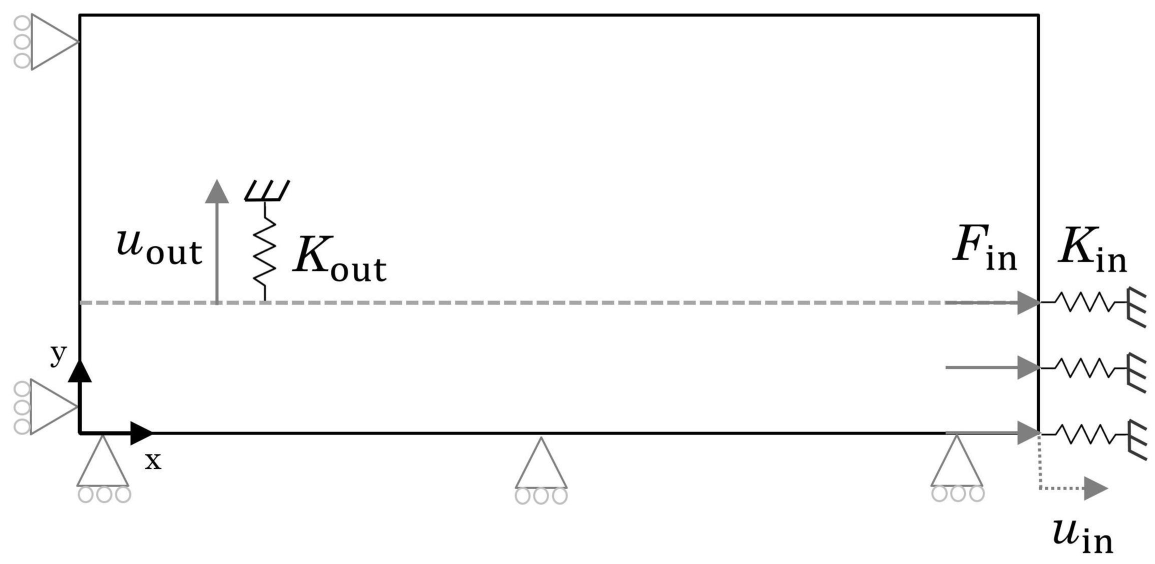

Fig. 1 – Schematic representation of the topology design domain subjected to a uniaxial tensile loading test. Only one quarter of the design domain is represented. Plane stress conditions are considered [2].

RESULTS AND ANALYSIS

From the proposed methodology, an optimal specimen geometry was found. The displacement in the output location is applied in the left symmetry boundary condition, pointing downwards. A volume fraction of 35% of the total volume and a mesh of 50 x 50 elements are used. The elastic properties and the constitutive model parameters related to the Swift's hardening law for DP600 steel are represented in Table 1 [3]. The obtained specimen design is represented in Fig. 2 along with its stress states distribution (tension, compression and shear).

Fig. 2 – Elastic properties and Swift's law parameters for DP600 [3].

		DP600
Elastic	E [GPa]	210
	ν	0.3
Plastic	K [MPa]	979.46
	ε_0	0.00535
	n	0.194

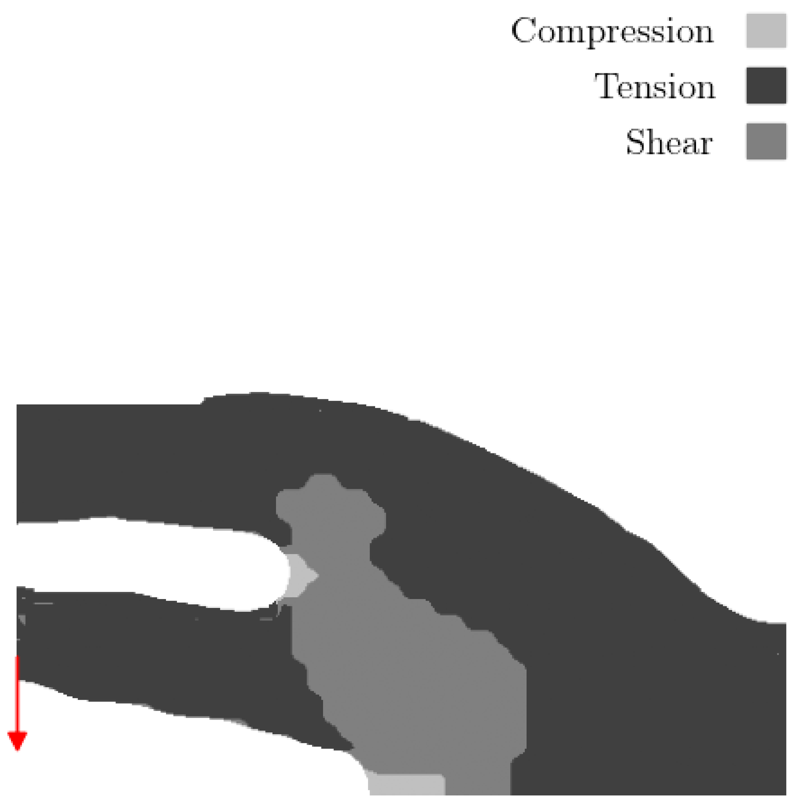

Fig. 2 – Stress states distribution and material distribution of the obtained specimen geometry.

The obtained test configuration was submitted to a uniaxial tensile loading test using Abaqus/Standard. The material behavior was described using the parameters presented in Table 1. A forming limit diagram was used to predict when rupture occurs. Fig. 3 represents the ratio between the major and minor principal strains ($\varepsilon_1/\varepsilon_2$), the equivalent plastic strain ($\bar{\varepsilon}_p$), and the von Mises stress distribution (σ_{VM}) at the moment just before rupture.

It can be noticed that most of the specimen is subjected to tension due to the tensile nature of the loading conditions. However, also compression and shear can be observed. An interesting area of the specimen is under plastic strains, which can result in relevant information about the material behavior. A homogeneous von Mises stress distribution, as the one represented, leads to a higher duration of the test and, consequently, to a more informative test.

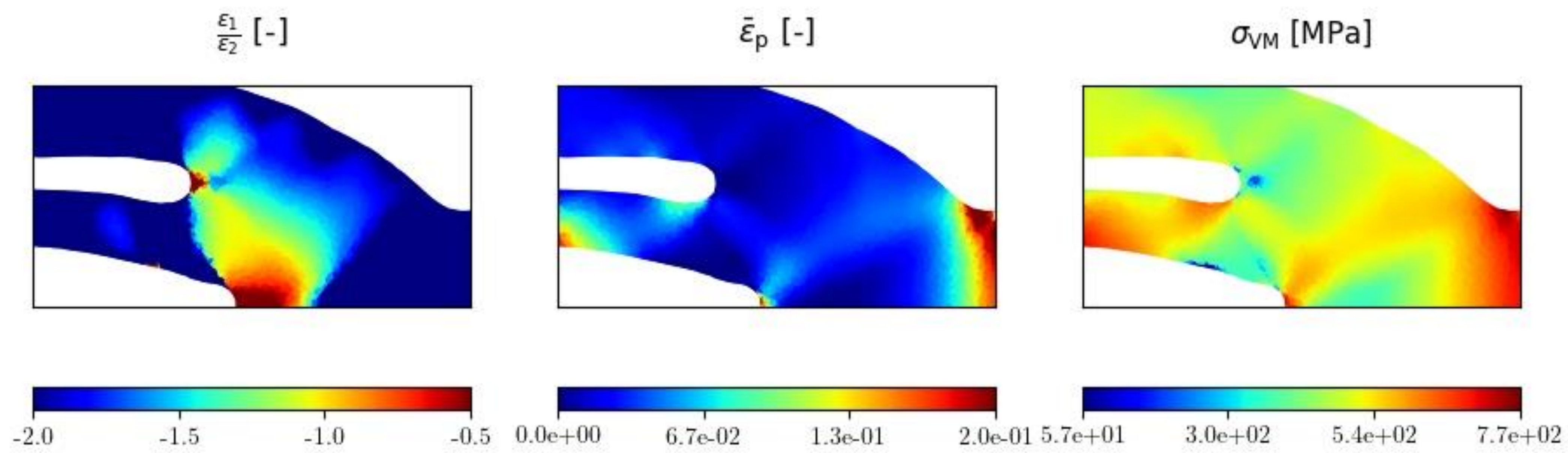

Fig. 3 – Obtained specimen geometry: the ratio between major and minor principal strains ($\varepsilon_1/\varepsilon_2$), the equivalent plastic strain ($\bar{\varepsilon}_p$), and the von Mises stress distribution (σ_{VM}) .

CONCLUSIONS

- A nonlinear topology-based optimization methodology is proposed for the design of a heterogeneous mechanical test;
- Material and geometric nonlinearities are introduced in the test design procedure;
- The obtained specimen geometry has the potential to provide a higher quality and quantity of information about the material behavior, being this methodology of major relevance for an accurate test design.

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