Nonlinear Finite Element Study of Beams with Elasto-Plastic Damage Behavior in the Post-Buckling Regime

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Lattice structures with low density tend to localize under compressive loading. The localizations start in a single cell band due to buckling of the beams and lead to compaction of the cells. To identify an appropriate discretization and to determine the influence of damage in an elasto-plastic material behavior two simple load cases are analyzed with the finite element (FE) method. Simulations of an axial loaded beam in the post-buckling regime with and without damage are carried out. In addition, a triangular cell under compression with different discretizations is analyzed.

1 Introduction

Lattice materials can be described as arrangements of rigid-jointed beams. Loads on the macroscopic level of the lattice can cause a loss of structural stability on the microscopic level. Gümrük et al. [1] have investigated the effect experimentally with samples of lattice structures with different densities. All investigated types of lattices showed localization bands under compression. The localization started with the buckling of beams in one band of cells and progressed up to full compaction of the cell band. The adjacent cell layers experienced the same deformation behavior with increasing load. Similar deformation patterns were shown by Luxner et al. [2] in a numerical study. Also Crupi et al. [3] reported localization bands due to buckling of struts in experimentally investigated lattice samples. Smith et al. [4] determined the buckling of struts in lattices under compression in experiments as well.

Simulating buckling and localization bands in lattices using nonlinear finite element analyses would allow for a systematic investigation of dominating parameters encouraging this failure mode. Of particular interest are lattice structures with an elasto-plastic base material including damage. The aim of the present study is to find a suitable discretization of a single lattice member with this kind of material behavior. A beam under axial loading (Fig. 1a) in the post buckling regime and a triangular cell under compression (Fig. 2a) are numerically investigated. The outcome is supposed to form a basis for future numerical investigations of lattice structures with elasto-plastic behavior with damage. It is assumed that the outcome of the 2D simulations can be easily adopted for 3D lattice structures.

2 Materials and Methods

Both structures have linear elastic perfectly plastic material behavior with and without damage. The Young’s modulus is $E = 2000$ MPa and the Poisson ratio $\nu = 0.2$. The yield stress of the material is 18.4 MPa. A slight hardening of $H = 1$ MPa is applied to prevent numerical instability in the finite element simulations. Damage of the material is defined by the specific fracture energy $G_I = 1$ N/mm and linear softening. The critical strain $\varepsilon^{pl}_{cr} = 10^{-5}$ defines the onset of damage. A 2D 3-node Timoshenko beam element with a quadratic interpolation function is used for all numerical simulations. It is characterized by two integration points along the beam axis per element. In through thickness direction five or 25 integration points are used, which are indicated as section points. All numerical simulations are performed with the finite element software Abaqus/Standard 2018 (Dassault Systèmes Simulia Corp., Providence, RI, USA).

In the first loading scenario, a small horizontal force in the center of the beam is applied as perturbation in addition to the axial displacement (Fig. 1a). The perturbation is only active in the first quarter of the simulation time and ramped down to zero after. The axial displacement is applied up to a maximum of 0.5 mm. The beam has a length of 1 mm and a width of 0.1 mm and is discretized by 25 elements with quadratic interpolation function. The two integration points per element have 25 section points. The beam is analyzed with linear elastic as well as with elasto-plastic behavior once with damage and once without damage.

Moreover, the collapse of a triangular cell under displacement controlled loading is studied (Fig. 2a). A small moment is applied as perturbation at the top corner of the cell in the same way as in the single beam study. The members of the triangular cell have a length of 1 mm and are 0.1 mm in width. To study the influence of the element and section point number three different discretizations are compared. The first one has five elements per side and five section points, the second has five elements and 25 section points, and the third has 25 elements and 25 section points. All three simulations include damage.

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3 Results

Figure 1 b shows the reaction force over the lateral displacement of three FE analyses of a single beam under axial loading. The analysis indicated by El is a simulation with linear elastic material. The one labelled by El-Pl has elasto-plastic material without damage behavior, while El-Pl-Dam is characterized by an elasto-plastic material including damage. After reaching point A the reaction forces of the the simulation El is increasing slightly further to 1.6 N where the curve reaches a plateau. The reaction forces of El-Pl and El-Pl-Dam decrease substantially after point A and both curves are nearly identical up to 0.08 mm displacement. Past 0.08 mm the force-displacement curve El-Pl is characterized by slightly higher values of reaction force compared to the curve El-Pl-Dam. Moreover, the reaction force of the curve El-Pl-Dam drops at point C to almost zero and the analysis stops premature at point D while the simulation El-Pl continues to the applied final displacement. In an early stage of both simulations the deformation begins to localize in an inelastic hinge in a single element. Figure 1 c shows the stresses in axial direction in the localized element for different stages of the simulation El-Pl-Dam. The premature ending in D of the simulation El-Pl-Dam coincides with a fully damaged section point with $S_{11} = 0$ MPa indicated by an $\times$ in Fig. 1 c.

The three discretizations of the triangular cell lead to very similar force-displacement curves (Fig. 2 b). The analyses with 25 elements and 25 section points ends due to numerical instabilities at point A at 0.05 mm displacement. The simulation with five elements and five section points stops at point B at 0.35 mm displacement. Only the FE analyses with five elements and 25 section points reaches the applied displacement of 0.5 mm at point C (gray in Fig. 2 a).

4 Discussion and Conclusion

The aim of the study was to find an appropriate discretization to investigate lattice structures under compressive loading with elasto-plastic material including damage. Therefore, a single beam in the post buckling regime as well as a single triangular cell under compression was investigated. The two simulations of the single beam under axial loading with elasto-plastic material and with and without damage lead to similar force-displacement curves. The significant difference is the sudden drop in reaction force and a premature ending in the simulation including damage. The end of the simulation due to numerical instabilities is assumed to be related with the stresses in the inelastic hinge with one fully damaged section point. The number of elements and section points per side is rather insignificant to predict the reaction force of the triangular cell. This suggests that the mesh adjusted softening works well with the 3-node Timoshenko beam element in Abaqus. However, the numerical stability of the FE analyses seems to benefit from a combination of fewer elements and many section points. The results of the present study give a first indication on how to discretize lattice structures under compressive loading with elasto-plastic material behavior including damage and form a basis for future investigations.

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