Reduced Ductility due to Local Variation in Material Properties for 3D-printed Components

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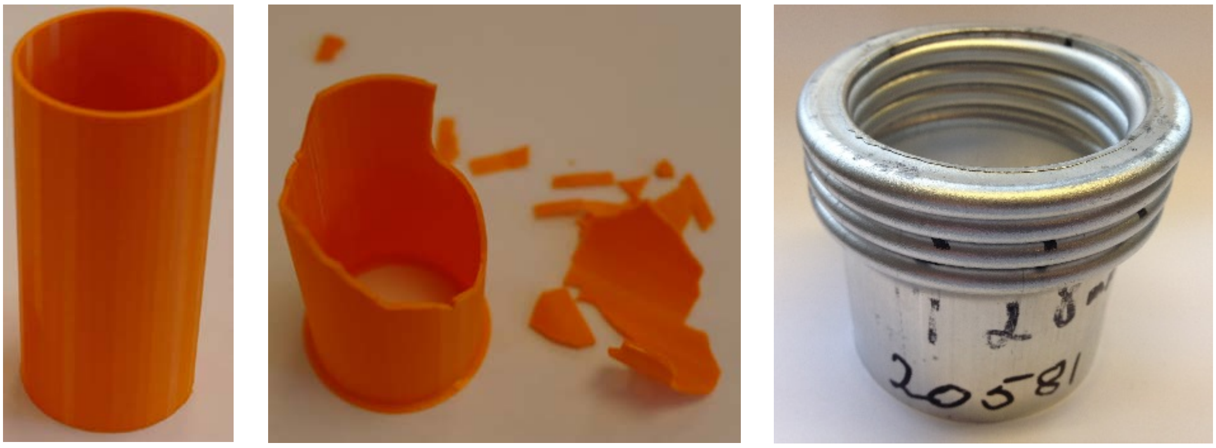
1 Background

It is often useful to have a physical model to display geometry as an alternative to the 3D-model on a computer screen. In addition, 3D-printed components may work well to evaluate the assembly process. The question here is whether parts that are manufactured in this way have representative ductility to give valuable results in structural tests where the material is loaded outside the elastic regime. There is a wide range of processes and printers available, and is it possible to get more realistic material properties with an expensive machine compared with a simpler one? It is likely that 3D-printed components may have local variation in the material properties, and a study on an aluminium alloy for crashboxes shows that this phenomenon may reduce the ductility [1]. Uniaxial tensile tests may not detect the effect due to sufficient strain hardening for small strains. It may be better to use a shear test that evaluate the material into a higher degree of deformation [2]. However, axial compression with a sensitive geometry may clearly demonstrate the effect when the lowest of several deformation modes at the same force level suddenly wins and this result in a brittle behaviour.

2 Specimen geometry and test procedure

Note that axial compression of a circular tube defined by length, diameter and thickness L = 2D = 60T was chosen with purpose to get a sensitive folding pattern and thereby challenge the simulation tool to capture this. This requires a combination of element formulation and element mesh that represent correct local and global stiffness even at severe deformation. It also means that the whole component stores elastic energy that is suddenly released when the capacity is met. The result may be either a brittle behaviour in case the ductility is too low or more or less nice folding in case the ductility is sufficient. However, it is important to remember how geometry and material interact. Aluminium has elastic modulus about 70 GPa, and the result is four concertina rings when this tube is compressed to half of its initial length. Polymer has significantly lower stiffness, and 3-lobe buckling is more likely. The brittle behaviour shown in figure 1 is a result of a specimen geometry that require not only a certain ductility but also local variation in the material properties below a certain value. The 3D-printed part at left hand side was produced by a relative simple printer, and it could be interesting to test components from a more advanced machine to evaluate whether the local variation in ductility is reduced to a level where it folds properly.



Initial geometry | Brittle behaviour | Ductile behaviour

Fig.1: Axial compression of tube defined by length, diameter and thickness L=2D=60T.

Figure 2 shows some pictures from the video take during the test, and it is clear that the behaviour is brittle. Two parallel tests were performed at two different scales defined by diameter about 32 mm and 63 mm, and all test specimens "explode" in the same way. Some of the events were also recorded with high-speed camera, and some pictures are presented in figure 3. Here it is possible to see local buckling into 3-lobe buckling, but it is clear that the ductility is not sufficient to secure one local folding to absorb the elastic energy that is stored in the whole component before something suddenly happens. Remember that the situation that represents the lowest energy level is always found in a test independent of whether this mode is predicted by numerical simulations.

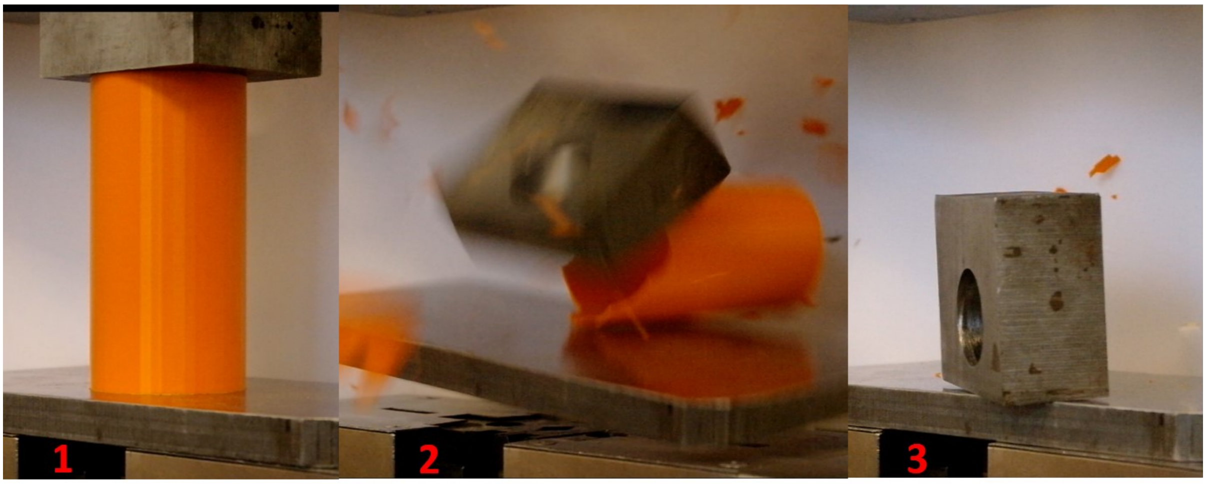
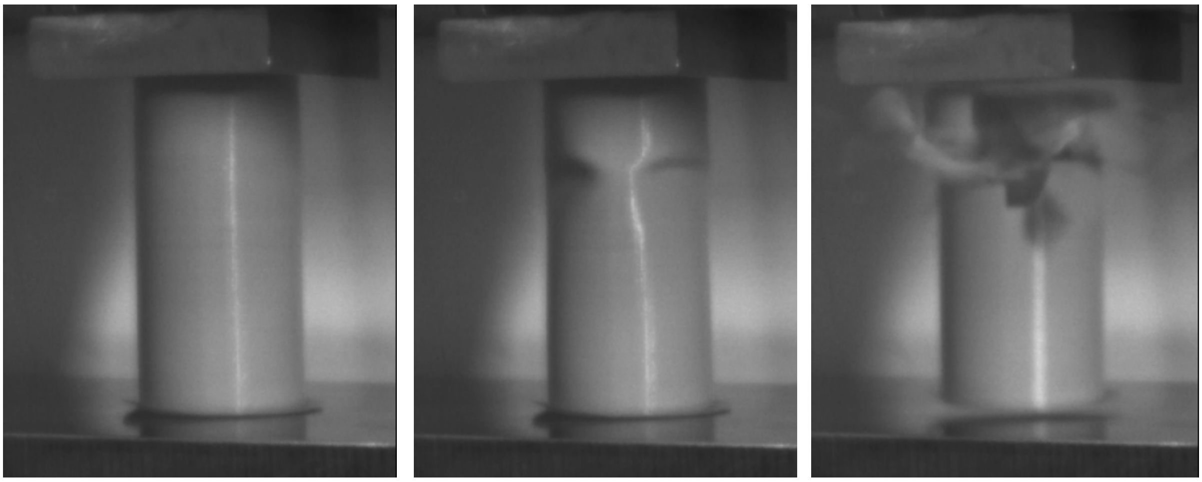


Fig.2: Some pictures form quasi-static compression of a 3D-printed tube with L = 2D = 60T.

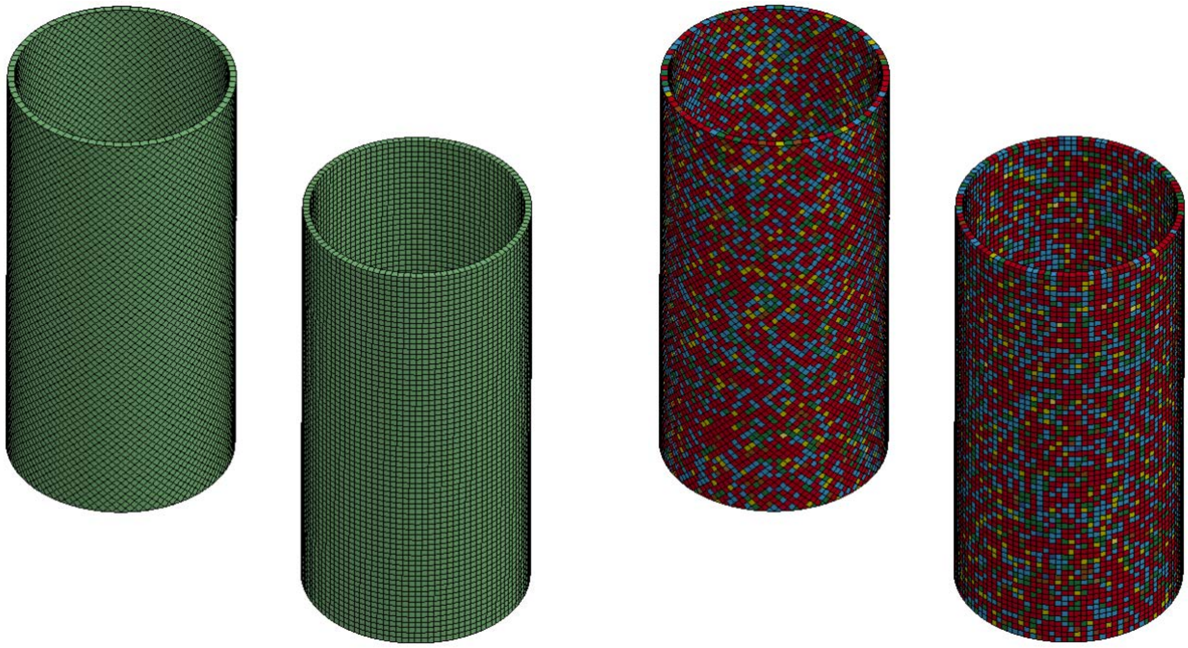


At maximum force | Just before collapse | Just after collapse

Fig.3: Some pictures from the high-speed film show some buckling before collapse.

3 Numerical simulations

Numerical simulations were performed with hexahedron elements to represent the volume of the test specimen and shell elements at the surface to obtain a better estimate for the surface strain, see figure 4. Note that the thin shell elements should not contribute significantly to the stiffness. The part containing solid elements was split randomly into two half whereas the last one was split again into two new parts, and this procedure was repeated until ten parts containing about 0.1%, 0.2 %, 0.4 %, 0.8 %, 1.5 %, 3 %, 6 %, 13 %, 25 % and 50 % were defined. Note that this procedure may result in two neighbour elements with the highest and lowest material properties defined, and this is likely not realistic in case the element mesh are very fine.



Shell elements to capture the surface strain   Randomly order of the elements into ten parts

Fig.4: Ten parts containing 0.1 to 50 % of the elements define the local material variation.

Figures 5 and 6 illustrates how the finite element simulation predicts 3-lobe buckling starting from the upper end while the test in figure 3 shows this mode some distance from the end. Note that the simulation was run with cut angle 0.5° to trigger local buckling from this end, while all four tests show this phenomenon at a distance about half the diameter from the top. The deformation mode is therefore not predicted as accurate as it should be, and it is questionable whether it make sense to predict fracture based on a strain field that is not correct.

Deleted surface elements define the cracks   Also some volume elements are deleted

Fig.5: The numerical simulation predict 3-lobe buckling starting from the upper end.

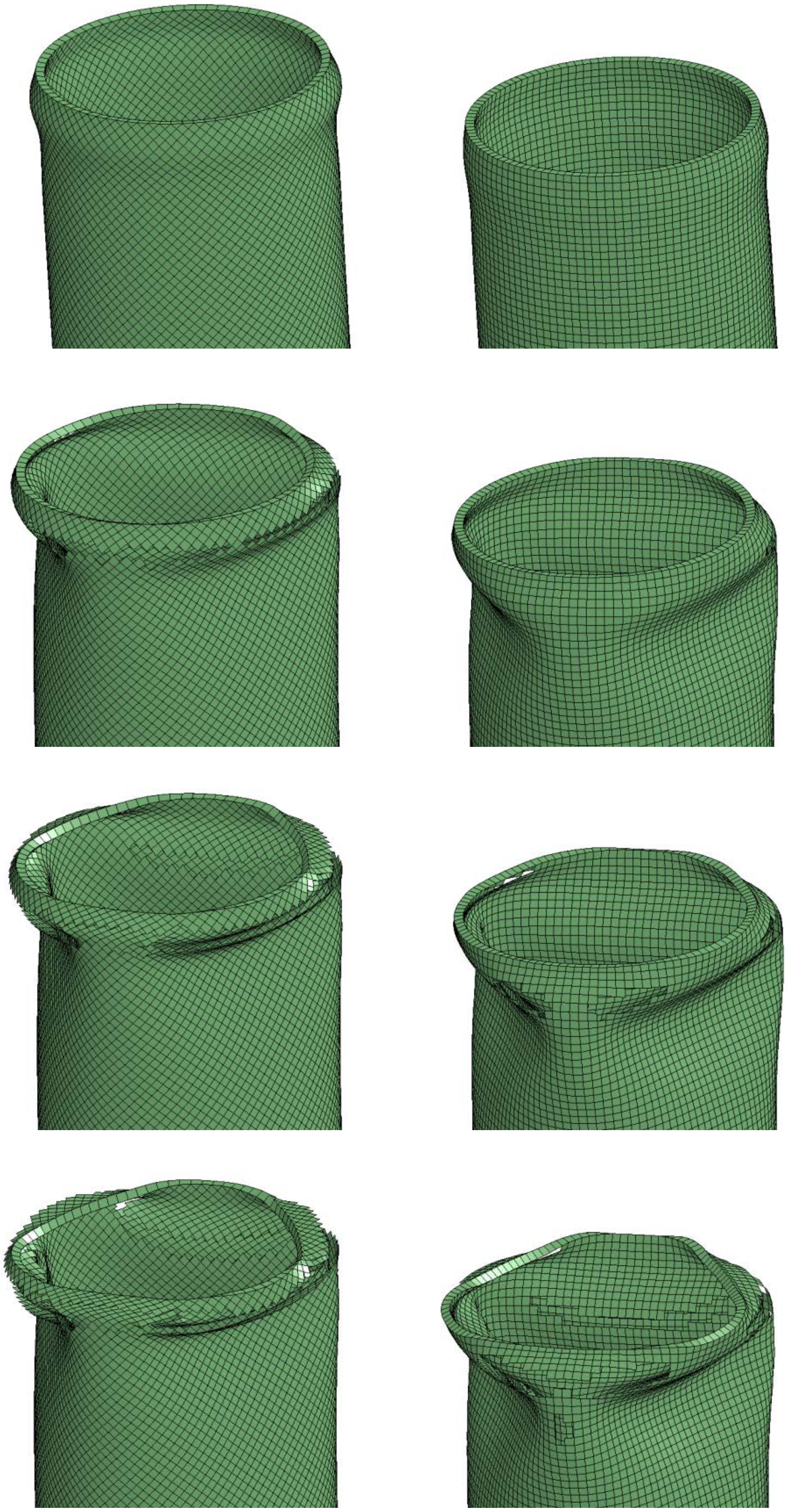


Fig.6: Also the element orientation has some influence on the predicted deformation mode.

Figure 7 shows how the finite element simulation underestimates the dramatic behaviour as too many elements are deleted instead of fracture between segments. However, it is likely that this will improve with smaller elements. Alternatively, node splitting could be something to look into. Note that the local variation in material properties was defined randomly in this case. But the tested parts was not produced by layers of powder that is fused together. A simple 3D-printer works more like an inkjet printer, and this production process may influence how the local variation in material properties is distributed.

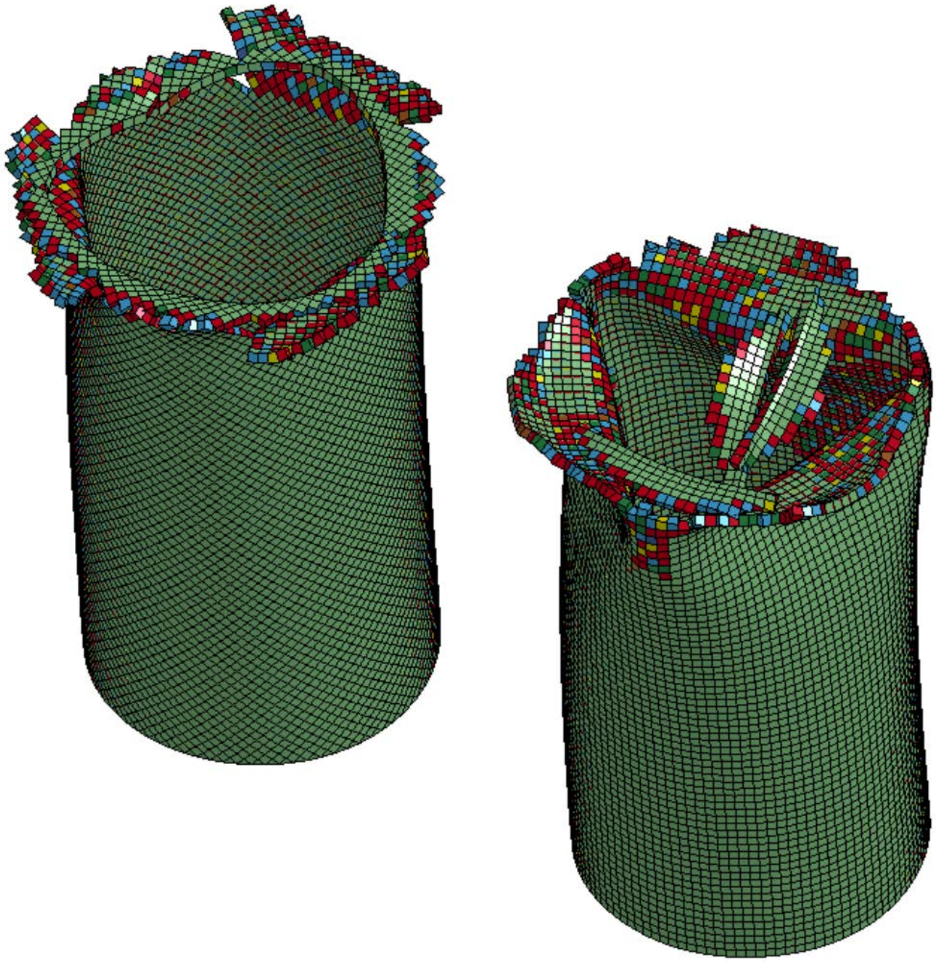


Fig.7: FEM seems to delete too many elements instead of fracture between segments.

4 Summary

Numerical simulations and test results with axial compression of a sensitive tube geometry defined by length, diameter and thickness L = 2D = 30T shows that 3D-printed components may behave brittle due to local variation in material properties that is above a certain limit.

5 Literature

[1] Tryland, T., Berstad, T.: "Keep the Material Model simple with input from Elements that predict the Correct Deformation Mode", 10th European LS-DYNA Conference, Würzburg, Germany, 2015.

[2] Tryland, T., Berstad, T.: "A Simple Shear Test to Evaluate Material Ductility based on Specimens cut from Thin-Walled sections", 11th LS-DYNA Forum, Ulm, Germany, 2012.