CHAPTER 16
Damage simulation

16.1 Introduction

In some circumstances it may be useful to see what happens if a part of a structure or component should not only enter the plastic field, as we saw in Chapter 13, but even reach failure. These are clearly very special situations, for which we may consider proceeding by modeling the behavior of the material at failure.

It can easily be seen that the results of these simulations are highly dependent on the input data describing the damage initiation mechanism in the material and its evolution. In the next sections we will see how to model the damage for ductile materials, for composite materials and for bonding between parts.

16.2 Damage in ductile materials

To deal with this case we take the example of figure 13.16 of Chapter 13; we apply to the beam a mechanical machining in the middle in order to reduce its section, as shown in figure 16.1.

Additionally, instead of applying a torque in the z-direction at either end, we apply a rotation so that we have less difficulty with convergence (see also Chapter 11).

Finally, we use a material with an elastic-plastic behavior that can be schematized with a bilinear model, such as the one shown in figure 16.2.

So far nothing too different from what we did in Chapter 13. But if we want to see what happens beyond the limit at failure, we must also build a model of the material to describe its behavior after failure. We can proceed in different ways and some codes already provide models of behavior after breakage: clearly the most general one foresees the insertion of tabular data coming from experimental tests.

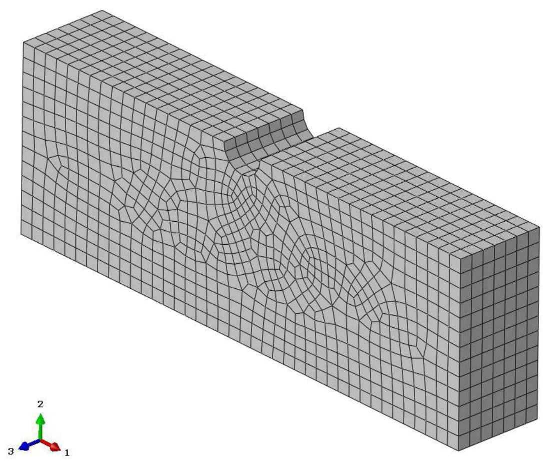

Figure 16.1. Beam modeled with 8-node brick elements. The notch was created to promote the initiation of failure.

The simplest model, which we will use here, involves a linear trend of the damage from 0 to 1.

With reference to figure 16.2, we have assumed that the material is completely damaged (damage equal to 1) after an additional 1% elongation beyond the ultimate tensile strength (whre the damage is equal to 0).

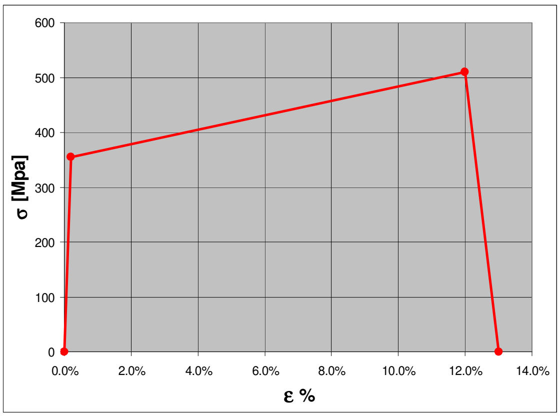

Figure 16.2. Bilinear stress-strain curve for S355 steel. After ultimate tensile stress, the material was assumed to be completely damaged by an additional 1% elongation.

To describe this further part there are at least two different methods: a limit displacement to be imposed in the description of the material or an energy associated to the failure; the first method is more difficult to interpret and could be related to the characteristic dimension of the mesh elements, while the second is more easily understood: in fact, if we look at figure 16.2, we can say that the energy associated to the damage of the material is given by the area of the triangle with base equal to 0.01 and height equal to the ultimate tensile stress, that is $510 \cdot 0.01 \cdot 0.5 = 2.55$ mJ/mm^3.

Once these data are given we try to perform the calculation, obtaining the results in figure 16.3.

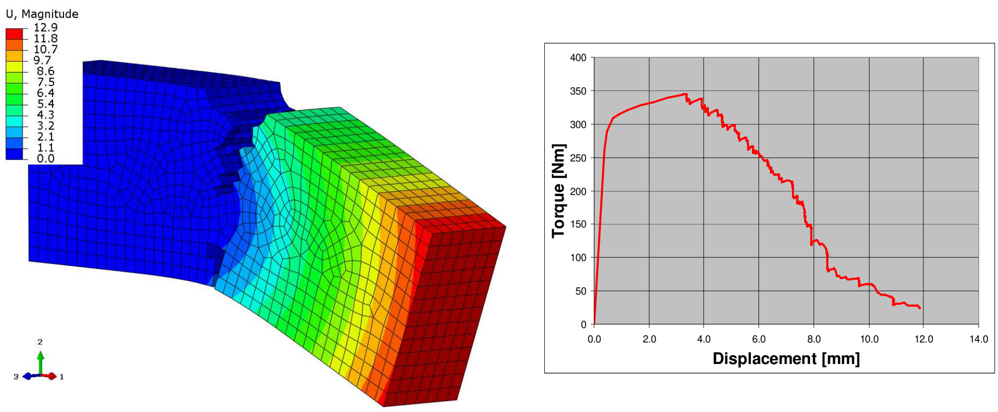

Figure 16.3. Results of the calculation with material damage: deletion of the elements that have damage equal to 1 (left) and trend of the applied torque as a function of the application point displacement (right).

As it can be seen the calculation code deletes the elements whose damage is equal to 1 and, clearly, also in the calculation they are no longer considered. In this way the torque will obviously tend to zero when all the elements of the section have damage equal to 1.

For example, let's see what happens if we pull the plate in figure 16.4, imposing a displacement of 5 mm at the right end. The material used and the damage model are the same as those used for the previous example.

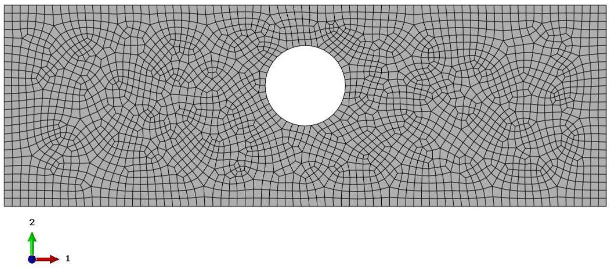

Figure 16.4. Plate with a hole: length = 60 mm, height = 20 mm, thickness = 2 mm, hole diameter = 8 mm; the center of the hole is offset by 2 mm to facilitate the triggering of the failure.

In this case, the code manages to converge all the way to the end and produces the results in figure 16.5, where, as it can be seen, the force drops to zero once the complete section collapse is reached.

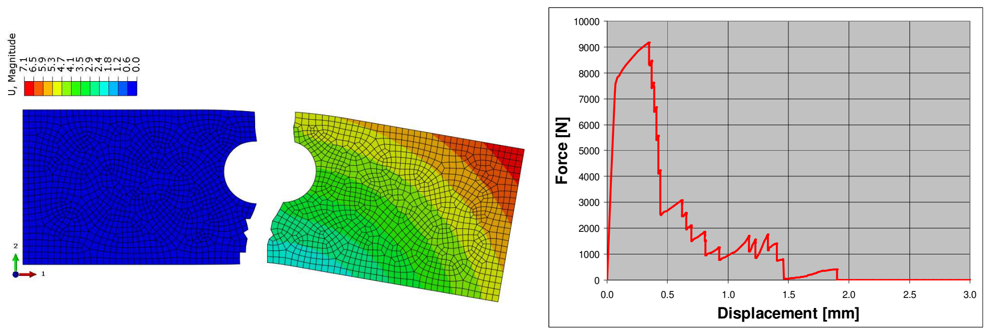

Figure 16.5. Results of the calculation with material damage: deletion of the elements that have damage equal to 1 (left) and trend of the applied force as a function of the application point displacement (right).

<u>*Remarks*</u>

It is not often that we need to use analyses that go beyond the plastic field of a ductile material; however, sometimes it is necessary to explore the conditions that arise when large parts of a structure have reached collapse; usually this type of analysis is reserved for the simulation of the crash, which however occurs at high speed and it is typically the domain of explicit codes (see Chapter 14).

The accuracy of the results that are obtained is highly dependent on the data entered to model the damage behavior; clearly providing higher energies will result in a longer "life" for the elements that are later cancelled.

From the numerical point of view, then, it should be borne in mind that these are very complex calculations, requiring many iterations with very small increments: it is necessary to introduce a stabilization of the solution (and generally the codes already have a default value that is good in most situations) and perhaps anticipate that the code "is ready" to handle a stiffness matrix that may, in material models involving damage, become non-symmetrical (incidentally, we remember that even contact with friction makes the matrix non-symmetrical).

16.3 Damage in composite materials

Compared to the case of ductile materials, the damage in composite materials has a greater interest because, since composites in general have a brittle behavior, it could be useful to go beyond the criterion of "first ply failure" (see § 10.4), with the intent to further reduce the mass involved, tolerating to have maybe partial failures for all the exceptional loading conditions generated by events after which the inspection and the potential replacement of the part are required. With respect to ductile materials, the data to be provided in order to simulate the damage are multiple, as they concern the compression and tensile behavior in the direction of the fibers and in the transverse one and the shear behavior. Many codes make available the Hashin criterion, valid for unidirectional sheets, but extensible to cloth sheets with due caution; the data to be provided are, in addition to the usual failure limit values, the energies for the various failure modes. If it is necessary to use different criteria, then there is nothing else to do but to create a model of material damage within the code in use, which requires a minimum of programming skills.

In the following we will see in detail an example in which the Hashin criterion is exploited.

In figure 16.6 we report the model of a plate constrained along all sides in the three translations (free rotations) loaded with a pressure of 0.25 MPa and with the laminate reported in the same figure. The material is only one, a unidirectional sheet, whose mechanical characteristics are reported in tables 16.1 and 16.2.

If, however, we have an exceptional pressure condition for which we want the plate not to collapse completely, while tolerating cracks and residual deformations, we can try to model the damage initiation and its evolution to see what happens. We emphasize that we do not report here the values of the energies leading to failure in the different directions for the material used, as they have been assumed and they do not have an actual match with experimental tests.

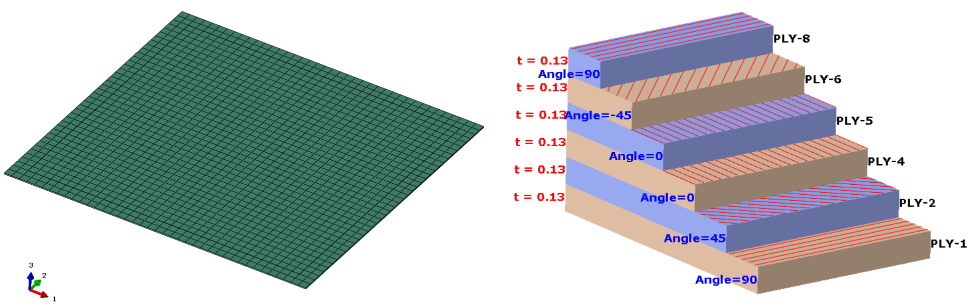

Figure 16.6. Plate (200 x 200 mm) constrained along the four sides in the three translations (left). On the right the laminate is shown: ply number 1 (ply-1) is the one that is below in the 3D view of the model and the total thickness is 0.78 mm (0.13 mm for each ply).