Chapter 5

Results

Two types of results are shown in this chapter. First, the graphics referring to the "Force-Displacement" behaviour and second, a set of images with the evolution of the damage in a particular tested sample.

5.1 Normalized "Force vs Displacement" Graphics

In order to compare the behaviour of different sizes, a normalization of both Force and Displacement values has to be performed. This is because we impose the same displacement with different cell sizes and the strain rates that we obtain inside the unit cells are different. In a similar fashion, if we impose the same displacement with different cell sizes, the reactions in the boundaries will be different as well. Thus, for small cells we have a larger reaction for a given displacement step than the big cells. In order to be able to compare different sizes with an equivalent rate of strain-stress average we should normalize them dividing by their cell size.

Figures 5.1, 5.2 and 5.3 contain, for each density, the normalized Force-Displacement behaviour for all the tested realizations corresponding to sizes 10 to 25.

First of all some remarks about Figures 5.1, 5.2 and 5.3 have to be made. It can clearly be seen that in one particular density set the behaviour of the samples tested ends in different places in the horizontal axis. This is because, imposing the same displacement in every unit cell, the final normalized value of the displacement is different from size to size. The samples belonging to a bigger cell length have smaller values of the latest normalized displacement than the ones belonging to smaller cell lengths. This is how it can be possible to distinguish the size to which the sample belongs. In both three graphics four groups of 5 realizations appear. Each group belongs to a different cell size.

Another important remark is that in the previous Figures 5.1, 5.2 and 5.3 there are some vertical divisions in which a certain parameter has been measured. These particular divisions refer to a "Elastic", "Hardening", "Softening close to the peak" and "Softening far from the peak" measure points. As it is explained in the next chapter, these are the places in the graphics where the slope (related with the Tangent
Figure 5.1: Material behaviour for density 30 and sizes 10 to 25
Set Rho 45

Figure 5.2: Material behaviour for density 45 and sizes 10 to 25
Figure 5.3: Material behaviour for density 60 and sizes 10 to 25
Stiffness) is measured. The slope of the behaviour graphic is considered as one of the material parameters used to investigate the existence of a RVE.

In order to clarify the results, Figures 5.4, 5.5 and 5.6 are examples of the material behaviour considering only one realization for each cell size.

**Description of the global behaviour of the samples**

From Figures 5.1, 5.2 and 5.3 some global behaviours can be clearly seen. All the samples show a really similar behaviour in elasticity. In these figures it is almost impossible to distinguish one realization from the other. In the hardening part (just before reaching the peak load) results are a little bit more spread and the graphics belonging to different samples can be now distinguished. The peak load, although having a tendency to give similar values, presents also a certain spread between them. This variety between values, as it will be explained next, also depends on the density set that is studied. The main result, although, is the softening branch. It can clearly be seen that there are notorious changes in the slope of the graphic in the softening branch from size to size (Figures 5.4, 5.5 and 5.6). The smallest sizes tend to give flatter slopes and the biggest sizes tend to show larger slopes (i.e. behaving more brittle\(^1\)). A general tendency is also observed in the softening branch for the spread between results. It

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\(^1\)This means that there is a more sudden loss of load carrying capacity once the peak load is reached.
Figure 5.5: Material behaviour for density 45 and sizes 10 to 25 (only one realization for each size).

Figure 5.6: Material behaviour for density 60 and sizes 10 to 25 (only one realization for each size).
seems that when the size of the tested samples increases the results get closer to each other.

**Comparison of the results between different density sets**

Some differences between density sets are shown in Figures 5.4, 5.5 and 5.6. On one hand the smallest density sets ($\rho = 30\%$) present flatter slopes in the softening branch than the greater density sets ($\rho = 45\%$ and $\rho = 60\%$). These last ones, see Figure 5.6, seem to behave, in general, in a more brittle way.

The peak load tend to increase when increasing the density of aggregates in the sample. Moreover the spread between peak load values also increases with the bigger density sets. This is much more evident for the set with $\rho = 60\%$ in Figure 5.3.

The elastic stiffness increases with the density in the sample, although it is difficult to observe from the previous graphics. This seem to be consistent bearing in mind that the particles are defined to be stiffer, so their increment in the cell leads to a grow of the global stiffness.

**5.2 Example of the Damage Evolution in one Cell**

Analyzing one particular sample with $\rho = 30\%$, size 10 (realization 1), the mechanical behaviour for this particular tension test can be seen in Figure 5.7. We can clearly distinguish an elastic branch followed by a hardening part until the peak load is reached and finally a softening behaviour that will approach to a certain constant value of the "Force Average". This last part has a clear exponential shape due to the chosen damage evolution law shown in Eq. (4.5).

Figure 5.8 is a zoom of the previous graphic, Figure 5.7. The first steps of the material behaviour are shown with a better resolution and the graphic is divided in eight parts. These parts refer to the following remarkable stages: "Elastic behaviour", "Damage starting in the ITZ", "Damage starting in the matrix", "Initial Damage Concentration", "Fracture Choice", "Peak Load", "Post-Peak stage with complete damage" and "Strain Concentration in the Failure Band".

**5.2.1 Images of the Damage Evolution**

Figures 5.9, 5.10, 5.11, 5.12, 5.13, 5.14, 5.15 and 5.16 show some interesting information at different stages of the damage evolution referring to the behaviour showed in Figure 5.8. Each figure is composed by a set of 4 images. The top left image shows the distribution of all three materials and the reactions appearing in the boundaries. The top right image 'STRESS 5' shows the distribution of the damage (for that is not appearing in the elastic stage). The two images underneath represent, from left to right, the normal stress distribution in the x-direction 'STRESS 1' and the local equivalent strain distribution 'DISPLACEMENT 3'.
Figure 5.7: Material behaviour: Sample with size=10 and $\rho = 30\%$.

Figure 5.8: Damage Stages for sample with size=10 and $\rho = 30\%$. 
Figure 5.9: Elastic behaviour stage.
Figure 5.10: ITZ starting Damage Stage.