Belleville springs or coned disc springs are commonly used in machine design. The geometric dimensions of the spring and the determination of non-linear force–displacement curve are regulated by different standards. However, the theory behind Belleville spring design standards is founded on a study published in 1936. Furthermore, the common spring design with cross-sections of uniform thickness poses problems in terms of non-uniformity of stress distribution. In view of this, non-linear three-dimensional finite element analyses of spring designs including uniform or variable thickness are carried out in this paper. Finite element results are compared with analytical predictions and critically analysed in terms of the effect of Poisson ratio, overall stiffness, and stress distribution in the spring. This is done in order to verify the range of validity of design standards. Finite element analysis emerges as a powerful and computationally cheap approach to assess the structural behaviour of Belleville springs regardless of their geometry and level of non-linearity.