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AN INVESTIGATION OF MATERIAL MODEL PARAMETERS FOR FOAMS OF COMPOSITE SANDWICH STRUCTURES

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Abstract: *The aim of this technical paper is to present a contribution in the study of mechanical behavior of sandwich structures, by investigating intrinsic parameters of a material model for foams. The present research focuses on core modeling, particularly in a closed-cell foam core composed of PVC (polyvinyl chloride). Finite element models were developed using ABAQUS® code in order to simulate the mechanical behavior of the foam. The inelastic behavior for foams is simulated in this package by two complementary relations: a yielding criterion (specified by CRUSHABLE FOAM option and parameters) and an evolution law (specified by CRUSHABLE FOAM HARDENING option and parameters). Experimental tests and finite element models under different boundaries conditions were used for the investigation. The results show that the influence of the material model parameters investigated depends on load modes. Hence, the influence of the material model parameters for uniaxial compression and biaxial compression loads are presented.*

Keywords: *foams; material model; finite element model; sandwich structure; composite.*

1 INTRODUCTION

Nowadays, the development of new materials technologies enables for a given structure to increase relation strength per weight. These are interesting characteristics for a wide range of industrial segments; in particular, they are widely required by marine, aerospace and aeronautical industries, where reducing weight is essential for a remarkable design. The composite sandwich structure concept is a perfect example.

Composite sandwich structures combine properties of two or more materials in order to obtain higher performance than the others, applied individually (Callister, 2002). In general, sandwich structures consists on two skins, which are responsible for bending loads, joined by an interface to a core, which is responsible for shear loads and supporting the skins (Fig. 1). The skin and core can be made from different materials (polymeric, metallic, ceramic or composite). Particularly, in the most applications, the skin is a thin metal sheet or a composite laminate (glass and/or carbon fiber with a polymeric resin); while the core is a cellular solid (honeycomb or foam).

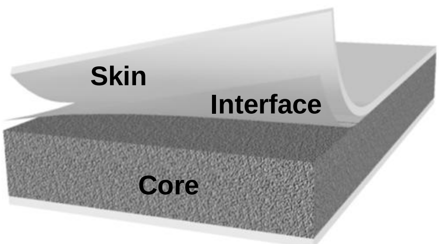


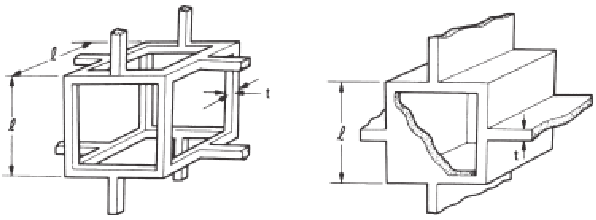
Figure 1. Sandwich structure concept.

An important task to accomplish during the design of structures concerned by the sandwich concept is to understand the behavior of the following components: the skin, the interface and the core. In order to predict the behavior of each part under specific boundaries conditions, material models defined by several parameters are used. Therefore, this technical paper focuses on investigating the model's parameters defining the behavior of the core made from polymeric foam. In this purpose, the CRUSHABLE FOAM model of finite element package ABAQUS® has been used. The results presented in this paper are a part of a main research work, which has as objective to model the behavior of a complete sandwich structure.

2 THEORETICAL FUNDAMENTALS

2.1. Material behavior

The macroscopic behavior of foams (cellular solids) is directly associated with micromechanical phenomena that governs the material response. Thus, for a composite sandwich structure under flexural load, it's important to understand the micromechanics of the material under tensile and compression stress. Cellular solids are materials featuring an interconnected network of solid microstructures, which can be classified as open or closed-cell foams, as explained by micromechanical modeling (Gibson and Ashby, 1988**)** (Fig. 2). Therefore, different behavior under tensile and compressive loads are noticed, function of cell's geometry.



(a) Open cell **(b) Closed cell**

Figure 2. Microstructure of polymeric foams (Gibson and Ashby, 1988).

Under compressive loads, the material has a typical behavior showed on Figure 3 where three stages can be highlighted: linear elastic, plastic plateau and densification. In the linear elastic stage, that is for low strains level ($\epsilon <$ 0.05); the cell's walls bend (Fig. 4). Reached the yield point, the material behavior is characterized by a plastic plateau where the strains increase under a practically constant stress level. In this stage, cells collapsing takes place, reducing considerably the material volume, which is a result of cell's wall buckling (Fig. 5). Finally, once those cells are fully collapsed, the densification stage is observed. The large increase of stress for a small increment of strain is the result of cell's walls crushing together (the volume does not change).

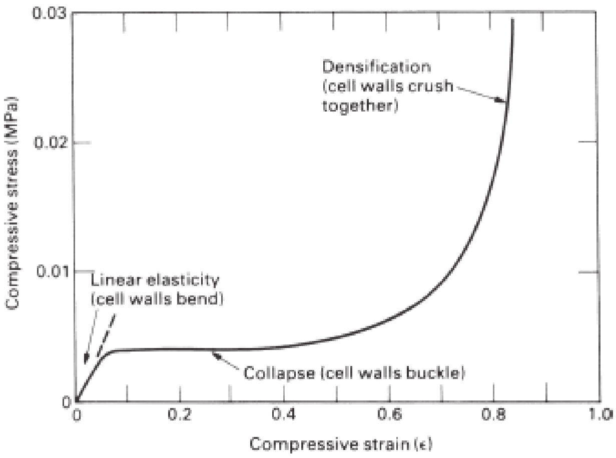


Figure 3. Characteristic stress-strain curve for polymeric foams under compression (Ashby, 1998).

Under tensile loads, the material behavior is essentially brittle and fails by the propagation of a single crack (Gibson & Ashby, 1988), which begins with a rupture of some cell's wall.

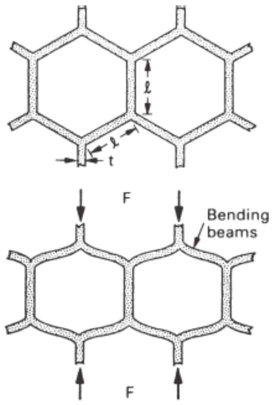


Figure 4. Elastic bending of the cell wall (Gibson and Ashby, 1988).

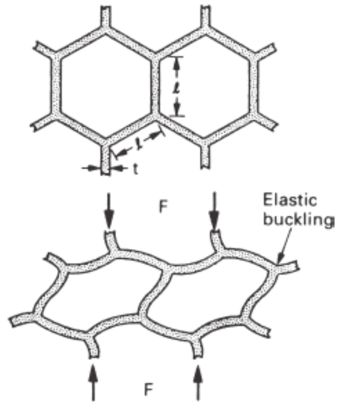


Figure 5. Elastic buckling of cell column (Gibson and Ashby, 1988).

The mechanical behavior of foams enables the material to reach large strains, what explains the reasons for absorbing large energy quantities under compression. Compared to honeycomb cellular solids (2D), foams can absorb energy in many directions; while honeycomb, preferentially just in one direction. The energy absorption is one of the most engineering applications of cellular solids.

2.2. Material Model

The CRUSHABLE FOAM plasticity model from ABAQUS® finite element package was adopted to simulate the material behavior. In this model, as deformations are not recovered instantaneously, a plastic deformation is idealized, and the material behavior is modeled in two stages: linear elastic at first and nonlinear plastic at second.

In the elastic domain, the material behavior is characterized by Young modulus and Poisson ratio, and the foam is considered isotropic. The plastic behavior is described by two complementary relations: a yielding criterion (corresponding to an initial yield surface) and an inelastic evolution law. The yield surface is expressed by an ellipse in the (p-q) stress plane (Fig. 6) as expressed by Eq. (1) (Abaqus® User Manual).

$$F = \sqrt{q^2 + \alpha^2 + (p - p_0)^2} - B = 0 \quad (1)$$

Where:
q: Mises stress,
B: size of the q-axis of the yield ellipse,
α: factor shape of the ellipse,
p_0: center of ellipse on the p-axis, and
p: pressure stress.

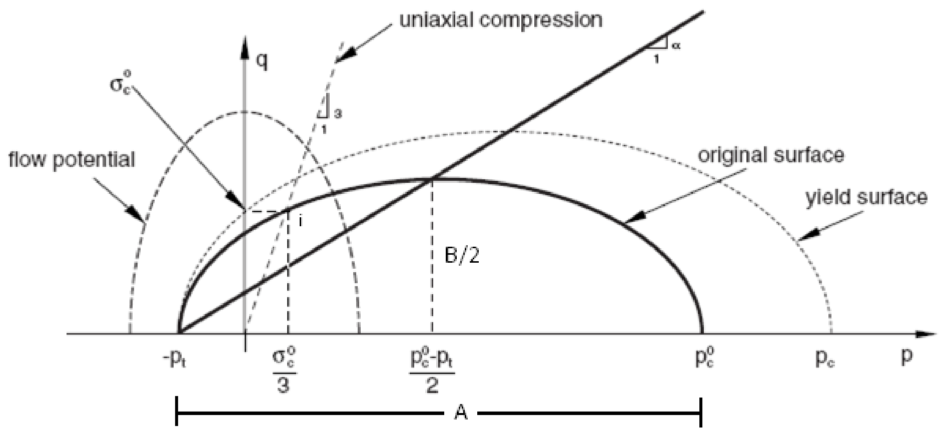


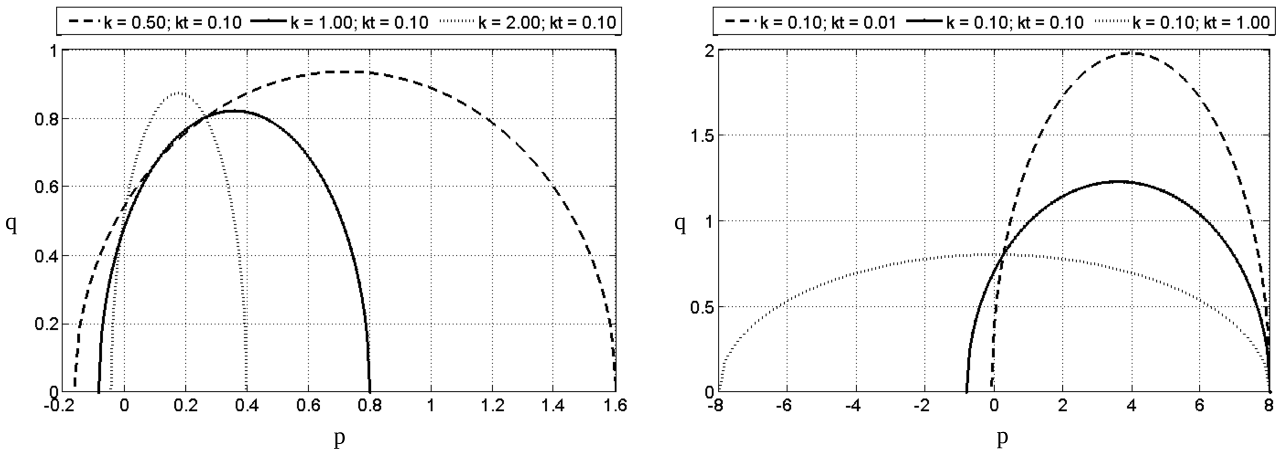
Figure 6. Crushable foam yield surface (Abaqus® User Manual).

The yielding criterion used is defined by two parameters k and k_t which are defined in Eqs. (2).

$$k = \sigma_c^0/p_c^0 \ (0 < k < 3); \qquad k_t = p_t/p_c^0 \ (k_t \geq 0) \tag{2}$$

Where:
σ_c^0: initial yield stress in uniaxial compression,
p_c^0: initial yield stress in hydrostatic compression and
p_t: yield strength in hydrostatic tension (fixed during transformation process).

The parameters k and k_t are directly associated to the initial yield surface, and both parameters can influence the yield surface. In figures 7(a) and 7(b), the sensibility of yield surface to k and k_t is shown by taking different values of one and keeping the other one fixed.



(a) Influence of k (k_t fixed). **(b) Influence of k_t (k fixed).**

Figure 7. Influence of k and k_t on the initial yield surface represented in the p-q plane.

The inelastic evolution law is defined by a volumetric hardening model function of the yield stress in compression written in terms of corresponding plastic strain. This model was developed through the experimental observation that foam structures usually experience a different response in compression and tension, as showed by the initial yield surface in Fig. 6. Hence, the data required by the hardening model just mentioned is the evolution of the true stress as a function of the logarithmic plastic.

From a numerical point of view (ABAQUS®), the linear elastic stage is modeled using *ELASTIC option; whereas the inelastic stage is modeled by *CRUSHABLE FOAM and *CRUSHABLE FOAM HARDENING options. CRUSHABLE FOAM defines a yield criterion and CRUSHABLE FOAM HARDENING a hardening law. It's important to note that the nonlinear behavior is modeled using the plastic strains concept, so, this model is applied essentially for structures under monotonic loads.

3 MATERIALS AND METHODS

3.1. Material

The present research focuses on modeling the core, particularly, in a thermoplastic closed-cell foam core composed of PVC (polyvinyl chloride). The foam investigated is Divinycell H60 (nominal density: ρ = 60 kg/m^3) produced by DIAB® currently used on marine and aeronautics applications. This foam has Young modulus equal to 60 MPa and Poisson coefficient equal to 0.32 (Diab® Divinycell H). The uniaxial compression curve for this foam is shown at the Figure 9 (Rizov, 1996)

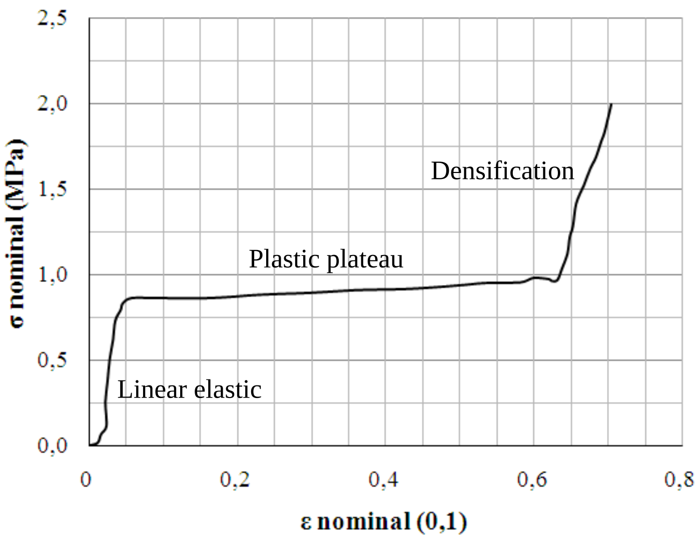


Figure 9. Stress-strain curve – uniaxial compression (Rizov, 1996)

3.2. Finite element model

The parameters used to set up *ELASTIC and *CRUSHABLE FOAM HARDENING options are obtained from uniaxial compression curve. For the latter, the uniaxial compression curve is expressed in terms of true yield stress in uniaxial compression and a volumetric plastic strain (Fig. 10).

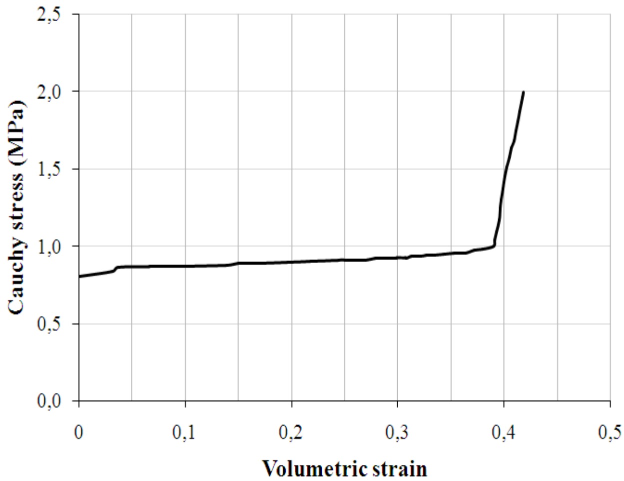


Figure 10. Cauchy stress versus volumetric strain curve.

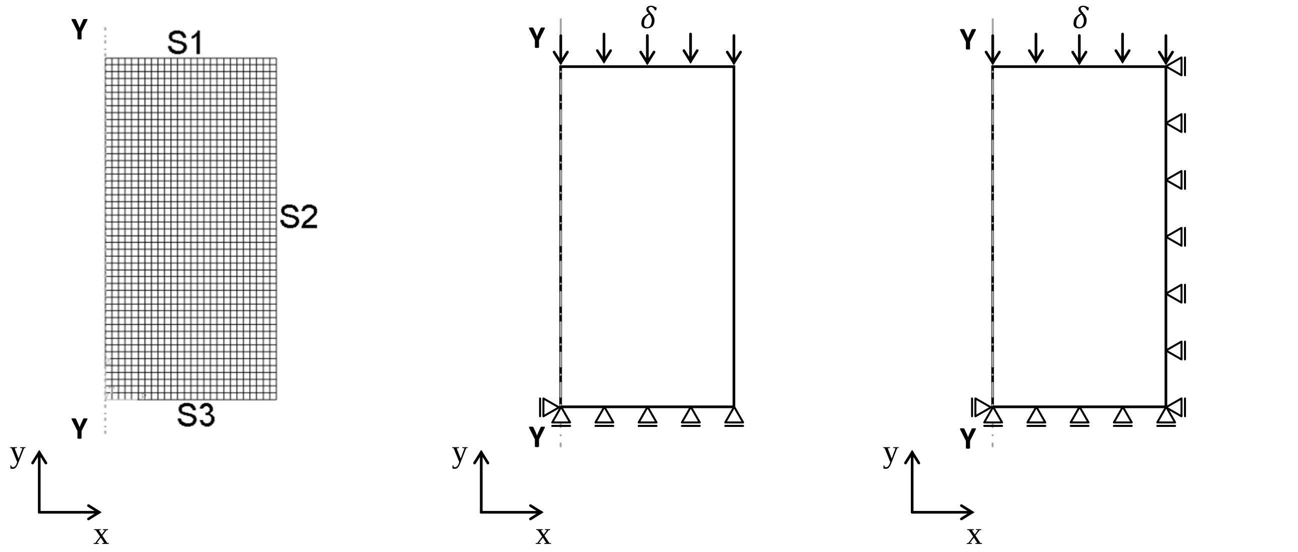
As the evolution of the yield surface is defined in terms of the derivative of plastic strain $\dot{\epsilon}^{pl}$, the parameter representing hardening is p_c , as p_t and σ_c^0 remain constants all over the transformation process. Therefore the evolution of the yield surface is governed by p_c as a function of the volumetric plastic strain ϵ_{vol}^{pl} defined by Eq. (3):

$$p_c(\epsilon_{vol}^{pl}) = f(\sigma^c, \epsilon_{axial}^{pl}, p_t, k, k_t) \tag{3}$$

In uniaxial compression, $\epsilon_{vol}^{pl} = \epsilon_{axial}^{pl}$ (due to Poisson's ratio nearly zero at the plastic stage). Thus, hardening law is obtained by the value of the true yield stress in uniaxial compression as a function of the volumetric plastic strain.

In order to investigate the effects of parameters k and k_t (associated with *CRUSHABLE FOAM option) in the material response, it was developed two finite element models: a uniaxial compression model (Fig. 11b) and an oedometric (Fig. 11c). These models were evaluated for a combination of k and k_t taking the reaction forces as a function of vertical displacement.

These models consist are axisymmetric with 25 mm of radius and 50 mm of height. It was used the same geometry and finite element mesh for both models (Fig. 11a) with the axis Y-Y as the axisymmetric axis. In the uniaxial compression model, the nodes on the edge S3 are restricted in the Y direction; the imposed displacement δ is applied on the nodes on S1 (where the reaction forces are taken); and also, the nodes on S2 aren´t restricted. The oedometric model is similar to the uniaxial compression one, except that, the nodes on the edge S2 are restricted in X direction. The solution is performed by a nonlinear analysis physic and geometric.



(a) – Finite element mesh (b) – Uniaxial compression model (c) – Oedometric model

Figure 11. Finite element model.

4 RESULTS AND DISCUSSION

The uniaxial compression finite element model provides a vertical reaction-vertical displacement evolution for nominal strains minor than 30% (Fig. 12). The latter is barely affected by the variation of k and k_t parameters. As a matter of fact, the response is not sensitive to significant changes on k (one hundred times), and adopts a slightly different form when k bounds are reached. No evolutions are noticed in the response for any variations of the k_t parameter. It is worth mentioning that the results just obtained are a consequence of the choice of numerical modeling as well as its boundaries conditions. In other words, in the uniaxial compression case, the stress states belong to the uniaxial axis (Fig. 6) and modifying k and k_t represents only a change on the initial yield surface. The influence of k and k_t parameters cannot be elucidated using this numerical configuration.

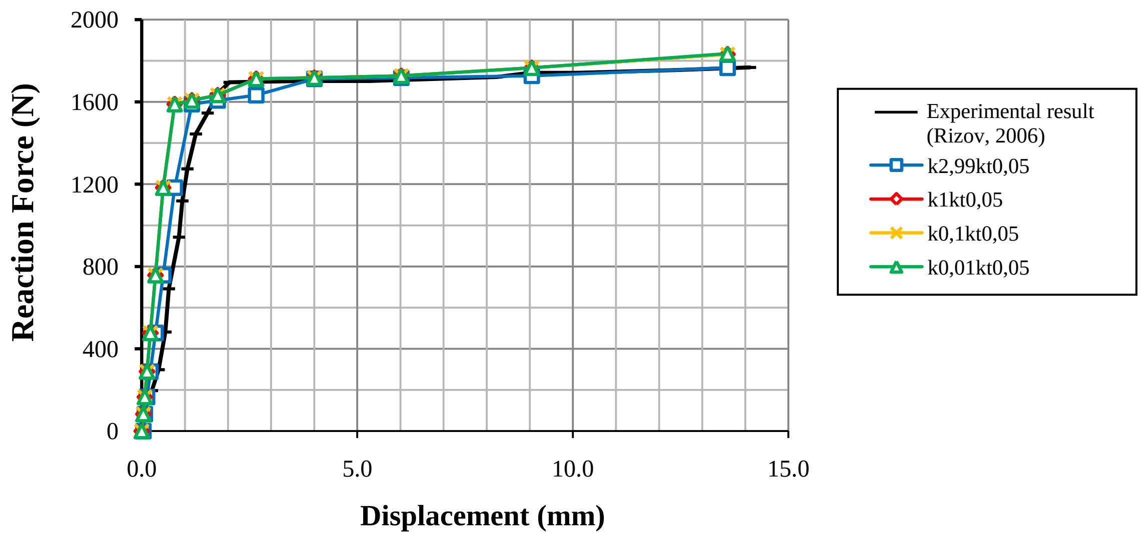


Figure 12. Influence of k on the vertical reaction using the uniaxial compression numerical model (k_t fixed).

Therefore, a change on boundaries conditions of the numerical model should lead to the influence of the material model parameters. In order to approach the hydrostatic axis and test the role of p_c^0 in the response, an oedometric numerical model is built (Fig. 11(c)). The model used here is similar to the uniaxial compression one: the only difference concerns the displacement's restriction on the radial direction.

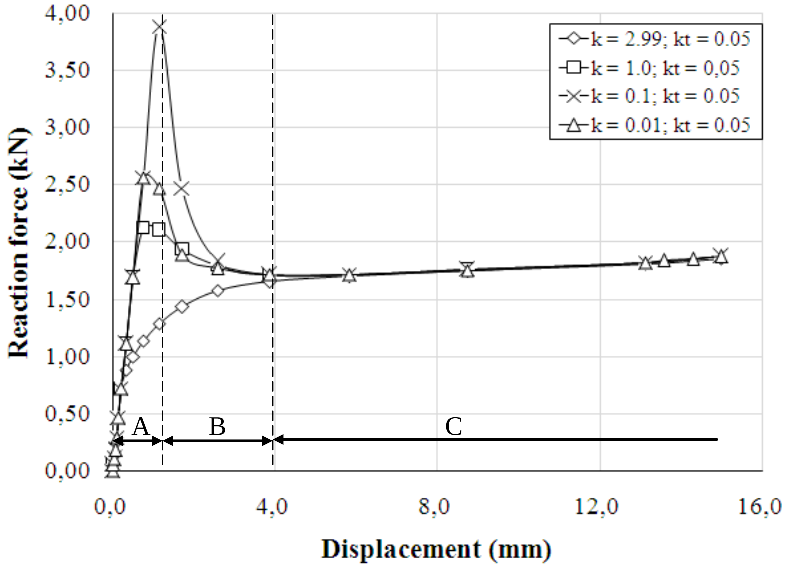


Figure 13. Influence of k on the vertical reaction using the oedometric numerical model (k_t fixed).

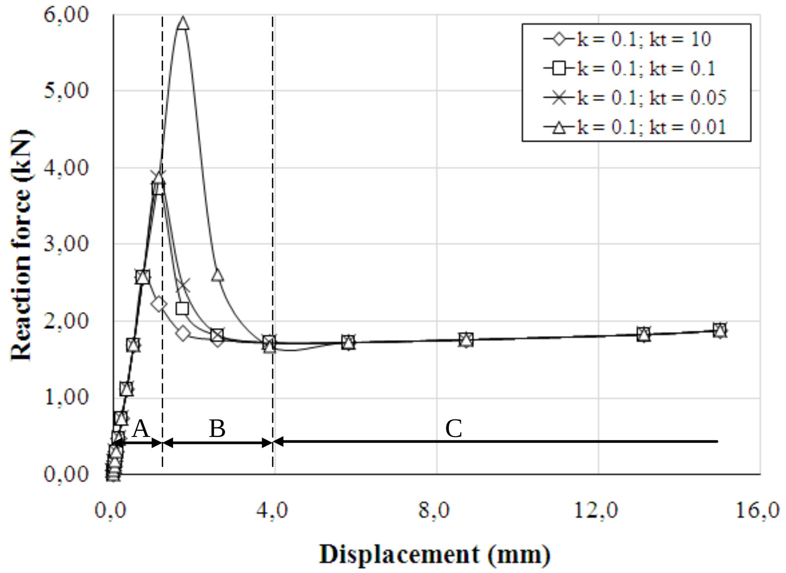


Figure 14. Influence of k_t on the vertical reaction using the oedometric numerical model (k fixed).

The results of numerical analysis for different values of k and k_t constitute a first argument when proving their influence in the characteristic response of the material. Figures 13 and 14 represent the results just mentioned: the evolution vertical reaction vs. vertical displacement is completely influenced by k and k_t for small strains. This can be explained by the stress states of the material when tested under oedometric compression: they are closer to the hydrostatic axis, and consequently the influence of the initial yield surface is well noticed when k and k_t change. Also, in these figures, it is can be highlight three different phases:

- Phase A: linear elastic response
- Phase B: plastic response (vertical displacement approximately between 1.5 mm and 4.0 mm)
- Phase C: plastic response (vertical displacement larger than 4.0 mm)

In the Phase A, the maximum value of vertical reaction force depends on the parameters k and k_t, i.e., the structure maintain a linear and recoverable regime until a maximum level of the reaction force, that occurs when the stress field of a material point is on the original yield surface boundary (see at figures 7(a) and 7(b)).

In the Phase B, the material enters in the inelastic regime (total strains approximately between 3% and 8%) after reached the maximum reaction force, where the evolution of the yield surface is governed by the Eq. 3. Also, numerical simulations showed that the convergence depends on the values of k and k_t, because, in some cases (k = 1.0 and k_t = 0.05), the analysis do not advance to Phase C. Therefore, more numerical analyses need to be performed in the future researches.

Finally, in the phase C, the material is in the inelastic regime (total strains approximately larger than 8% until 30%), and it is not verified the influence by variation of k and k_t. at vertical reaction force. The original yield surface boundary evolutes and the material behavior is governed by the volumetric plastic strain evolution. Probably, the global behavior of the structures is analogous which occurs in the plateau showed at Figure 9. The structure can deform high levels without a considerable increase of the vertical reaction force.

5 CONCLUSIONS

In the uniaxial compression, the influence of the parameters k and k_t on the global structures behavior cannot be evidenced. In the uniaxial compression, there isn't a significant contribution of the hydrostatic axis.

In the oedometric model, the elastic response is influenced by the parameters considerably at Phase A, because the the parameters k and k_t determine the shape of the original yield surface. In the Phase B, the material enters in the inelastic regime and the evolution of the yield surface is function of the plastic strains. Thus, numerical simulations will be developed in order to make investigations, as the influence at convergence of the plastic response by the initial portion of the curve: true yield stress in uniaxial compression versus volumetric plastic strain (Fig. 10). In the phase C, the parameters k and $k_{t.}$ do not influence the value of vertical reaction force, because the strain field at the material is the plateau range, showed at Figure 9. It's very important to note that all simulations do not reach the densification regime. Besides, all the parameters involved in the material models need to be determined by experimental tests. However, it is a difficult task for the foam studied, because it requires complex devices.

As commented on the introduction, this article is inserted in a major project which aims to simulate the mechanical of sandwich structures considering every part (skin, core and interface). Giving continuity, the foam model will be coupled to the skin model in order to compare the results with three point bending tests that have already been done.

6 ACKNOWLEDGEMENTS

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