ON NUMERICAL SIMULATION OF IMPACT IN FACIAL PROTECTORS

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Abstract. *In the last years, sports-related maxillofacial fractures increased. One of the solutions to avoid nose fracture is using an EVA protector (Ethylene Vinyl Acetate). Protectors' geometric and material characteristics are not normalized, although used by many professionals, mainly basketball and soccer players. In order to improve its geometry, based on safety and comfort, an EVA type was chosen and characterized for Ogden model. The effectivness of the model is evaluated based on numerical simulations of a pilot test – an EVA protector over two layers: skin and bones, whose material parameters were obtained from literature.*

Keywords*: EVA, facial protector, Ogden model, numerical simulation.*

1. INTRODUCTION

In recent years it was noticed a significant increase in the number of facial fractures in sports activities (Antoun and Lee, 2008). The face injuries usually occur when colliding with another player, against the ground or against sports equipment and accessories (Frenguelli et al., 1991; Carroll et al., 1995). The impact can result in sudden acceleration or deceleration of the face depending on the relative velocity between the bodies (Park and Levy, 2008). In this process, the kinetic energy is transformed into deformation energy, which is dissipated by the soft tissues and bone structures (Le Fort, 1901). As the nasal bone is located in the face weakness zone and it is its most prominent structure (Higuera et al., 2007), even low-intensity impacts can cause its fracture. This is the reason why the facial bone has a high frequency of injuries in sports activities (Carroll et al., 1995).

After the occurrence of fracture the only possible treatment is surgical. It is recommended to wait at least 4 to 7 days after the surgery for to return the athlete to training and games, and it is also recommended the use of the nasal protector (Chao, 2008), because the fractured bone is only fully consolidated after 30 days (Morita et al., 2007). As the removal jeopardizes the career of the athlete and can lead to great financial loss to the Club (Garza et al., 1993), the National Youth Sports Foundation for the Prevention of Athletic Injuries suggests that the nasal protector should also be used to prevent such injuries.

Studies show that the use of orofacial protectors reduces by 50% all the reported fractures in sports (Flanders and Bhat, 1995). However, to date there is no standardization for the material to be used for the manufacturing of nasal protectors. Among the materials being used there is the ethylene and vinyl acetate copolymer (EVA). Some authors have highlighted the ability of EVA to absorb energy and reduce the transmission of impact (Westerman et al., 2002). Moreover, this material presents the possibility of low temperature conformation, ease of finishing, durability and low cost (Coto, 2006).

In the dental market, the EVA is presented in the form of rigid and flexible plates. The Faculty of Dentistry in the University of São Paulo has alleged the cooption of rigid and flexible plates to manufacture the nasal protectors in order to associate cushion capacity and comfort. In order to optimize this combination it is necessary to understand the mechanical behavior of each material used in the manufacturing of nasal protectors. The main objective of this paper is the characterization of the flexible EVA. Future works will evaluate the mechanical behavior of rigid EVA. As an application, the characterized material is applied to a considered *pilot model*: an EVA protector over two layers: skin and bones, whose parameters and medium thickness were obtained from literature. The protector is impacted by a rigid ball and the failure in the bone layer is studied.

2. MATERIAL CHARACTERIZATION

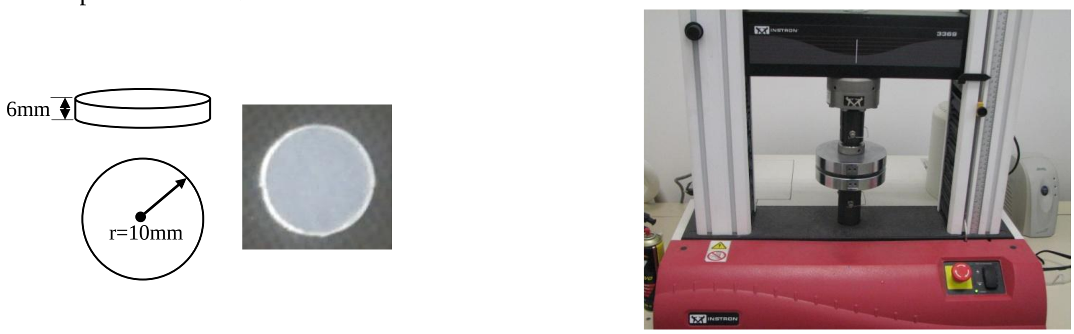
2.1 EVA material

This material is a thermoplastic polymer with linear semi-crystalline structure and therefore its geometry consists of an amorphous part and a crystalline part. As any polymer, the physical properties of EVA depend on its mass, shape and geometry. The EVA is considered a copolymer because it is formed by two monomers, the ethylene and the vinyl acetate, the latter comprises between 18% and 28% of the material. The cushion capacity of the EVA increases as the content of vinyl acetate reduces. It is a macromolecule composed of repeating units linked by a covalent bond. Its raw material is a monomer (molecule with a repeating unit), its physical properties depend on the length of the molecule and its molecular weight. Polymeric materials usually present low density, low temperature resistance and low electrical and thermal conductivity. Among the main features of the EVA the high elasticity, flexibility, good toughness at low temperatures, good mechanical resistance and high fracture resistance at low temperatures can be highlighted. Considering the flexible EVA, some properties such as elasticity are more pronounced, however some properties such as the limit of the mechanical resistance are lower. The EVA has a flexible elastic behavior similar to the elastomers. Thermoplastics are polymers that are able to soften and flow when subjected to high temperature and pressure and away from this situation they solidify in a defined shape, being that a reversible physical transformation, they are called fusible, soluble and recyclable.

Most of the practical conditions in which the polymer is applied or tested mechanically, is possible to observe that their mechanical response is time-dependent, which characterizes them as viscoelastic materials. This means that their behavior is similar to a viscous fluid, giving an instantaneous elastic response. This part that makes the polymer behave as a viscous fluid consume part of the absorbed energy irreversibly. This absorption can occur due to the internal friction between the macromolecules, or by conformational change (rotation of carbon - carbon bonds around its own axis) or by the flow. Moreover, if the power transfer for the polymer is sudden, the elastic response delay will depend on the difference in time between stimulus and response of the polymer for its macromolecules to roll and unroll. This delay on the elastic or mechanical response is due to its viscous portion.

2.1.1 Experimental tests

Compression tests were carried out to determine the material characteristics. The sample dimensions and geometry are showed in Fig.1a. All tests were performed in an Instron machine model 3369 with load capacity of 50kN (see Fig. 1b). The imposed displacement rate of the plates during the quasi-static experiments was 1.0mm/min. The load and displacements were recorded. Figure 2 shows the evolution of the test and Fig. 3 shows the load - displacement curve obtained from the experimental test.



(a) (b)

Figure 1. (a) Compression tests specimens and (b) set up and the experimental apparatus.

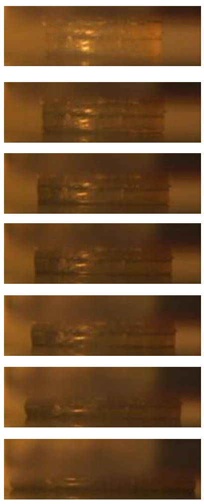


Figure 2. Compression test, recorded by a high velocity camera.

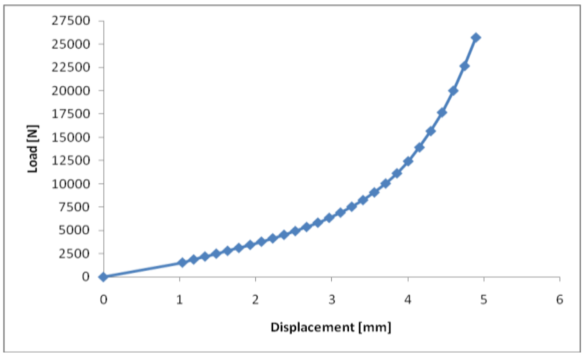


Figure 3. Load-displacement curve for compression test of flexible EVA.

2.1.2 Numerical simulation

EVA can be considered a hyperelastic material. Very briefly, a hyperelastic material is characterized by a function *W*, called the *strain-energy function*, whose derivative with respect to the strain tensor ε equals the stress tensor σ. Particularly, the Ogden model is suitable for modeling EVA (Verdejo and Mills, 2004). In this way, the previously described compression test was simulated in the FE software LS-Dyna in order to obtain the material parameters for the model. The strain energy function implemented for Ogden model is given by:

$$W^{*} = \sum_{i=1}^{3}\sum_{j=1}^{n}\frac{\mu_j}{\alpha_j}\left(\lambda_i^{*\alpha_j}-1\right)+\frac{1}{2}K(J-1)^2 \tag{1}$$

where μ_j e α_j are the j-th set of model parameters, (n define the number of terms and it can vary from 1 to 8); λ_i refers to the principal stretch in *i* direction; *K* is the bulk modulus, *J* is the determinant of the Jacobian, related to volume variation during deformation.

For material characterization, the software LS-Dyna conducts an iterative process, where the parameters are optimized by giving, as input data, the load-displacement curve and the geometry and boundary conditions of the experimental test. Figure 4 shows the numerical model. The specimen has 5,700 solid finite elements. In order to imitate the experimental test, two infinite rigid planes were created at both ends of the specimen. The inferior plane was fixed while a displacement was imposed to the superior plane. Figure 5a shows the evolution of the numerical test. The parameters are resumed in Table 1. Figure 5b compares numerical and experimental simulation.

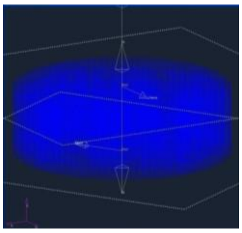


Figure 4. FE model of compression test.

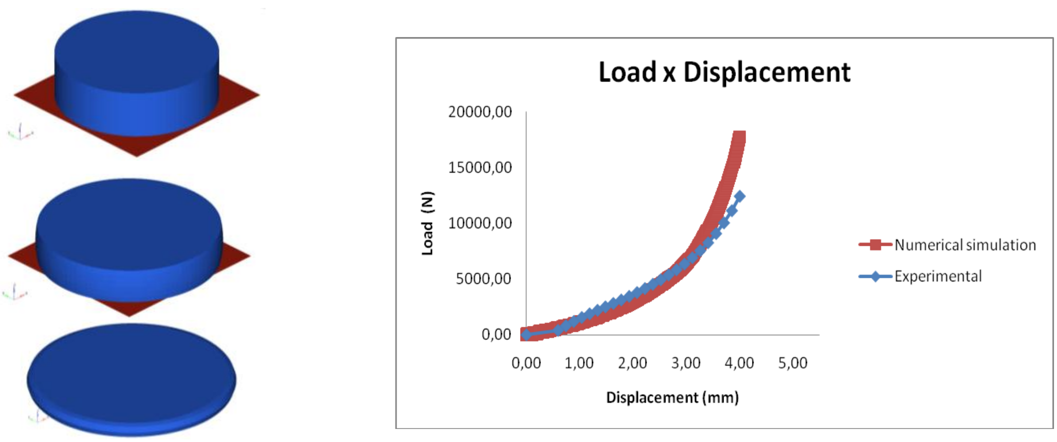


Figure 5. Comparison between numerical and experimental results for compression test.

Table 1. Material model for EVA: elastic and Ogden parameters.

Ogden parameters				Elastic parameters		
μ_1	μ_2	α_1	α_2	G (MPa)	$\rho(t/mm^3)$	ν
7.00	2.60	0.80	2.60	10	2.00E-09	0.48

2.2 Soft tissue and bone

Material properties for the soft tissue and bones model were determined based on published literature. Table 2 presents the material models for the bone, which was modeled as elastic linear, with a failure criteria of maximum principal strain. According to literature, a linear law does not account properly for the mechanical behavior of the human soft tissues, while a hyperelastic material seems to be well adapted. Among the various strain-energy functions which can describe such a mechanical response (see, for example Bonet and Wood, 1997), we focused on the Ogden model and Table 3 resumes the parameters. Bones and soft tissue thickness measurements were taken in computerized tomography and the thinnest values obtained were approximately 0,7mm and 2mm, respectively.

Table 2. Material model for bone: elastic parameters and failure criteria (Verschueren et al., 2007; Lotti et al., 2006; Hanson, 1995).

Elastic parameters			Failure mode
$\rho(t/mm^3)$	E (MPa)	ν	Maximum principal strain (%)
7.8500E-08	1,300.00	0.30	0.15

Table 3. Material model for soft tissue: elastic and Ogden parameters (Zahouani1 et al., 2009; Holberg et al. , 2005).

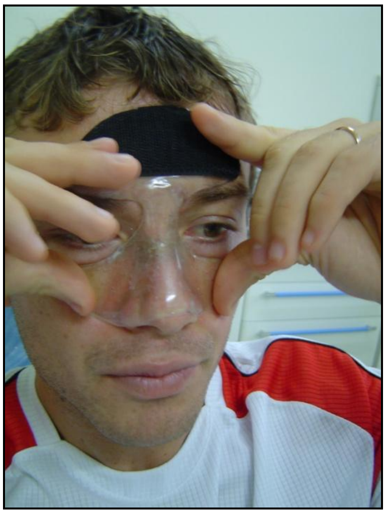
Ogden parameters				Elastic parameters		
μ_2	μ_4	α_2	α_4	G (MPa)	$\rho(t/mm^3)$	ν
0.0059	0.0236	2.00	4.00	0.69	9.5E-10	0.30

3. NUMERICAL MODEL

3.1 Facial protector

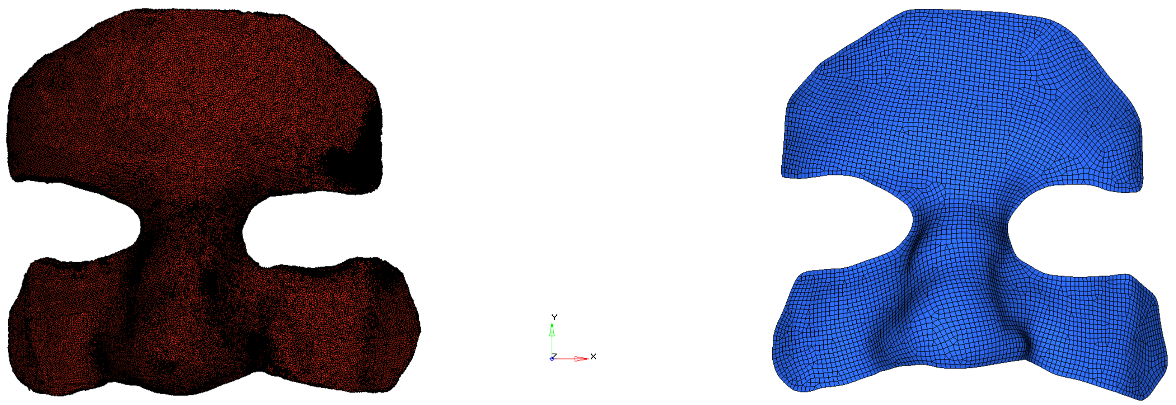
The protector showed in Fig. 6 was digitalized with a three-dimensional scanner. This procedure is highly precise, leading to a very heavy mesh, as can be seen in Fig. 7a. The software Hypermesh® was used to remodel the surface showed in Figure 7, which is composed by 111,990 shell elements. The minimum mesh size (length, width, and height) was determined as 2 mm to accomplish a reasonable time step.

(a)



(b)*

Figure 6. (a) Original protector (b) in use showing the supporting points.
*Picture with copyright holder's permission.



(a) (b)

Figure 7. (a) Digitalized image and (b) Final protector model.

3.2 Pilot model

Fig. 8 illustrates the three different layers of the model - bones, soft tissue and protector. Each layer has 111,990 shell elements. The nodes in the boundary of the bones' layer has restrictions of displacements in any direction. The fixed face, as modeled here, is the most critical condition for the protector. In a real-life situation, if the head is free, the neck forces the head back during the impact, leading, therefore, to a smaller maximum impacting load. However, the objective of the protector should include situations such as the impact on a rigid wall or in the floor. Moreover, the purposed model does not consider the supporting points, as details Fig. 6b.

The contact *surface to surface* is applied between the layers, and friction is considered as 0,1. Smaller friction coefficients lead to more critical conditions, since the protector slip over the skin. The actual friction value is compatible with parameters found in the literature. In Fig. 8 the projectile is represented by a rigid ball with 324 shell elements and diameter of 30mm. The ball has 0.05 Kg and an initial velocity of 20 m/s was imposed.

Due to the large deformations allowed to the Ogden materials, it was necessary the use of the Adaptative Lagrangian Eulerian (ALE) model.

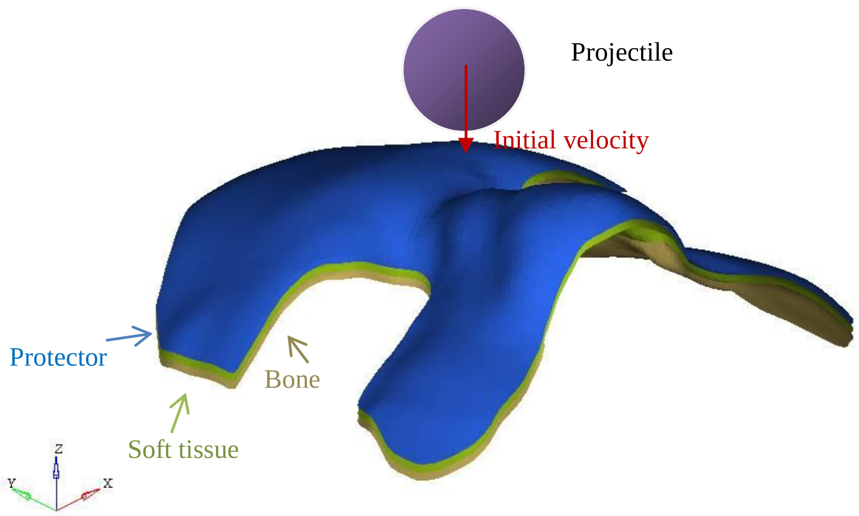
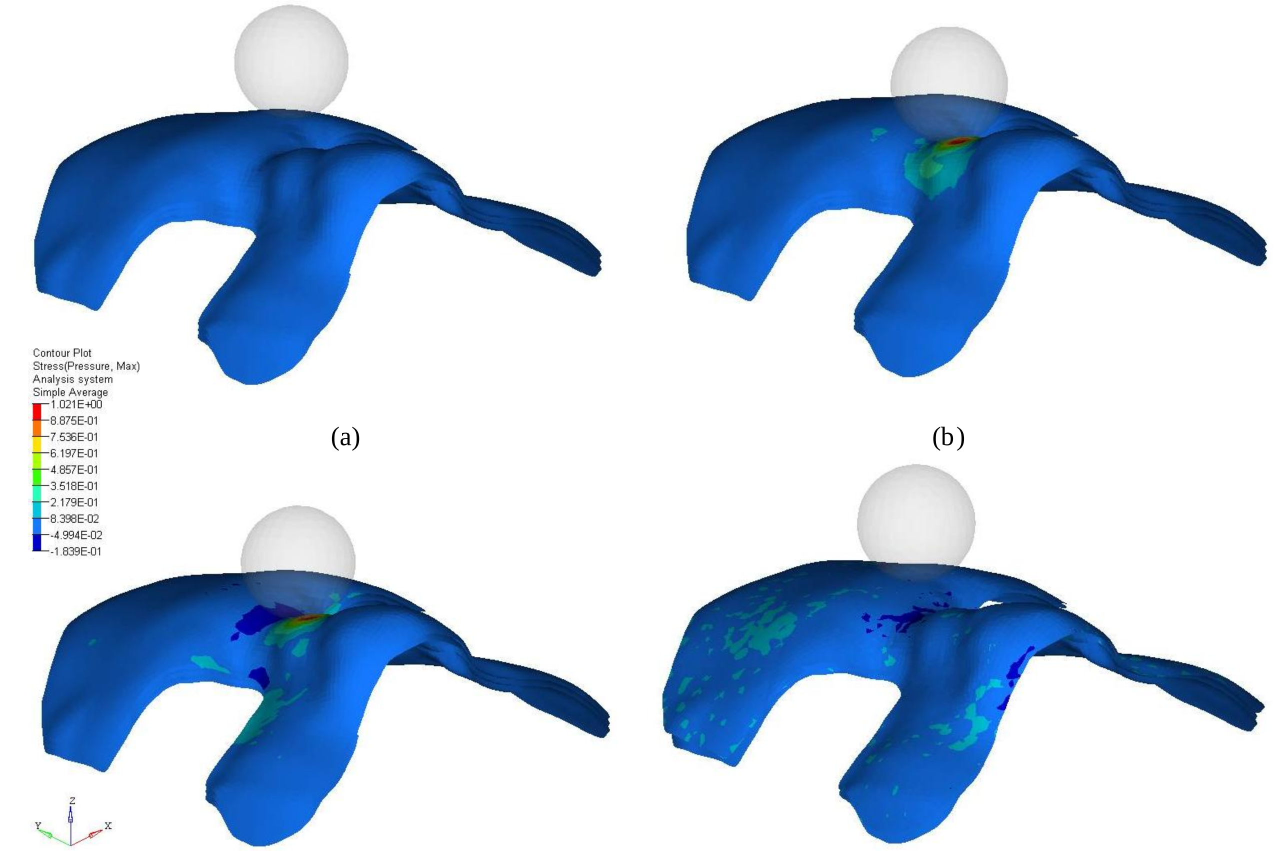


Figure 8. (a) FE model of the *pilot model*.

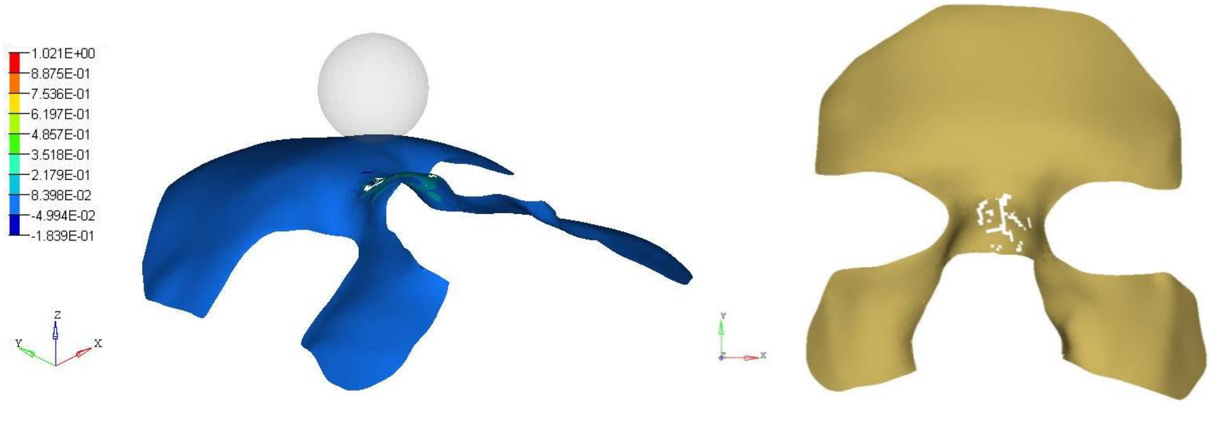
4. NUMERICAL RESULTS

Figure 9 shows the pressure profile in the protector at different analysis instants of the impact of the ball. The impact was analysed during 2ms. The maximum pressure is obtained in the region of the impact. When the maximum strain is reached, fracture in the bone occurs, as shown in Fig. 10.



(c) (d)

Figure 9. (a) Pressure profile at different instants of the impact.



(a) (b)

Figure 10. (a) Failure of the bone in the *pilot model*.

5. CONCLUSIONS

The EVA material was characterized according to Ogden model. The parameters were found by comparison between experimental and numerical simulations, in an optimization process provided by the software LS-Dyna.

As an application, a *pilot model*, including geometry profile, boundary conditions, contact, failure and material model, was proposed from experimental tests, 3d scanning processes and literature references.

Although the numerical analysis can be validated only by confronting the results with experimental tests, the prediction of the simulation in this pilot study can be judged to be satisfactory, due to the coherence of the results and stability of the model.

A detailed structure of the bones and soft tissue are necessary to have any practical conclusion about the effectiveness of the protector. Moreover, in the pilot model, the highest stress occurred in the impact region leading to the bone failure. With the consideration of a second rigid EVA layer and supporting points of the protector in the face, a better distribution of stress is expected. Actual studies are contemplating those hypothesis.

6. ACKNOWLEDGEMENTS

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