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FINITE ELEMENT ANALYSIS FOR A SIMPLIFIED MODEL OF A BLOOD VESSEL WITH LESION

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Abstract: The complications of vascular injuries can be significant. Static behaviour of a blood vessel with different shapes of injury subjected to constant interior pressure is analyzed using a simple elastic two-layer model. The inner layer was considered with lesions, namely a spherical-cap cavity and a cylindrical one with the axis parallel to the vessel. The finite element analysis presents the stresses for the two cases and it is revealed that the spherical-cap model produces stresses less significant than the elongated lesion.

1. ELEMENTS OF BLOOD VESSEL STRUCTURE AND MECHANICAL CHARACTERIZATION

The basic structure of all blood vessels, either delivering oxygenated blood - arteries, arterioles, capillaries or returning with carbon dioxide – veins and venules, consists of three layers: the intima, the media and the adventia, [1]. The materials from the structure of these layers and the size of these three layers distinguish arteries from veins and one artery from another. Arteries have a larger media layer than veins and have more smooth muscle to contract than veins. Arteries have a larger amount of elastin than veins and veins have a thicker adventia layer than the arteries. The intima consists of a single layer of endothelial cells and an underlying very thin basal lamina. The media contains smooth muscle cells and smooth muscle tissue. A large artery may contain 40 to 70 concentric layers. The adventia consists of type I collagen fibers with elastin and fibroblasts and is 0.1 to 0.5 of the thickness in arterial walls.

The arteries can be considered elastic and muscular, [2]; the elastic arteries have larger diameters closer to the heart, such as the aorta, pulmonary artery, common carotids and common iliac artery.

Qualitative observations can be made about blood vessel mechanical behavior considering the tissue constituents role. Fung, [1], one of the initiators in biomechanics, considered the blood vessels for torsional, tensile and pressure testing. The stress-strain curve presented both region of nonlinear and linear character.

More recent experiments, as shown by Vito, [3], reveal that arteries are nonlinear, anisotropic - having different properties in different directions and viscoelastic - exhibiting creep, stress relaxation and hysteresis. They are heterogeneous through the wall and along their length, stressed in the unload state, demonstrate insensitivity to the rate of imposed strain and behave differently in the passive and activated states. Constitutive equations generally account for only a subset of characteristics, a comprehensive constitutive equation remaining an idealistic goal, [3].

Various constitutive models were proposed to describe the tissue mechanical behaviour, [3], such as elastic, pseudoelastic, randomly elastic, hyperelastic, linear viscoelastic model, or more complex models, [4]. Even though the simplified models cannot completely explain the actual behaviour, when simplified assumptions are made some important information is often revealed, [5], [6], [7].

2. MODEL AND ANALYSIS OF A BLOOD VESSEL WITH LESIONS

As people age, they tend to develop fatty plaques within the walls of their blood vessels and when these plaques rupture, they release tissue that can block blood vessels in the heart, causing a heart attack. Smooth muscle cells adapt well, producing substances that form a fibrous cap that contains the plaque and creating a matrix that stabilizes it. In some situations, however, the cells lose their protective ability, and paradoxically begin to secrete substances that dissolve these fibrous caps. When this happens, the plaques become unstable and are prime candidates for rupture, the underlying cause of heart attacks.

The finite element method is a powerful technique for finding approximate solution of a partial differential equation where the domain boundaries of a given problem are so complex that other approaches have difficulties or fail, [8]. It has now become one of the fundamental numerical approaches for solving problems arising in many applications, including biomedical simulation. In the finite element method, a complex domain is discretized into a number of elements, such as that a set of basis functions can be defined on the elements to approximate the solution.

In the present paper, the authors propose to model a blood vessel with inner lesions in order to analyze the stress field produced by the blood pressure using finite element method. It is expected that these injuries will act as stress concentrators and the shape and dimension of the lesions are a few parameters of the study.

For the beginning, the static case is considered, with constant interior pressure. The blood vessel is modeled as a two layer vessel, obtained from two concentric elastic cylinders. The inner cylinder models the intimal-media layer while the outer cylinder models the adventia layer. The dimensions and mechanical characteristics of the layers are modeled according to mean values from literature for an arterial wall, [9].

The finite element analysis is made using Generative Structural Analysis module from Catia environment, [10].

In Fig.1.a, a fragment of the geometrical model is presented. The two cylindrical layers are assumed fastened and the lesions are cavities modeled as cylindrical and spherical cap. The cavities are partially presented from computational reasons. The meshing of the model with the necessary finer elements around concentrators is presented in Fig.1.b.

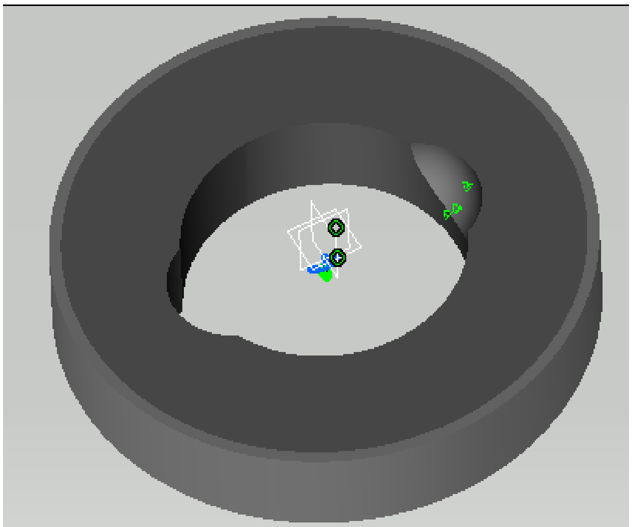

Fig.1.a. Geometrical model

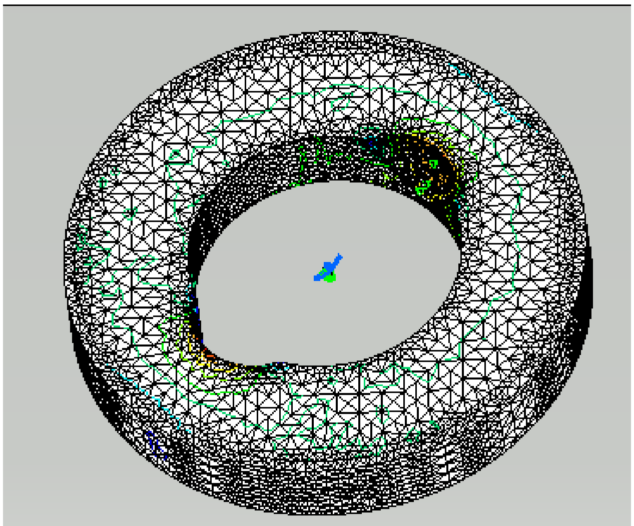

Fig. 1.b. Meshing of the model

Assuming fastened contact condition between the two cylinders, the stresses in the layers were found, as presented in Fig.2. The maximum equivalent von Mises stress occurs in the region of the longitudinal concentrator for the inner layer. For the outer layer, compression stresses are revealed on the radial direction of the concentrators while maximum stresses are found symmetrically with respect to the axis of the main concentrator.

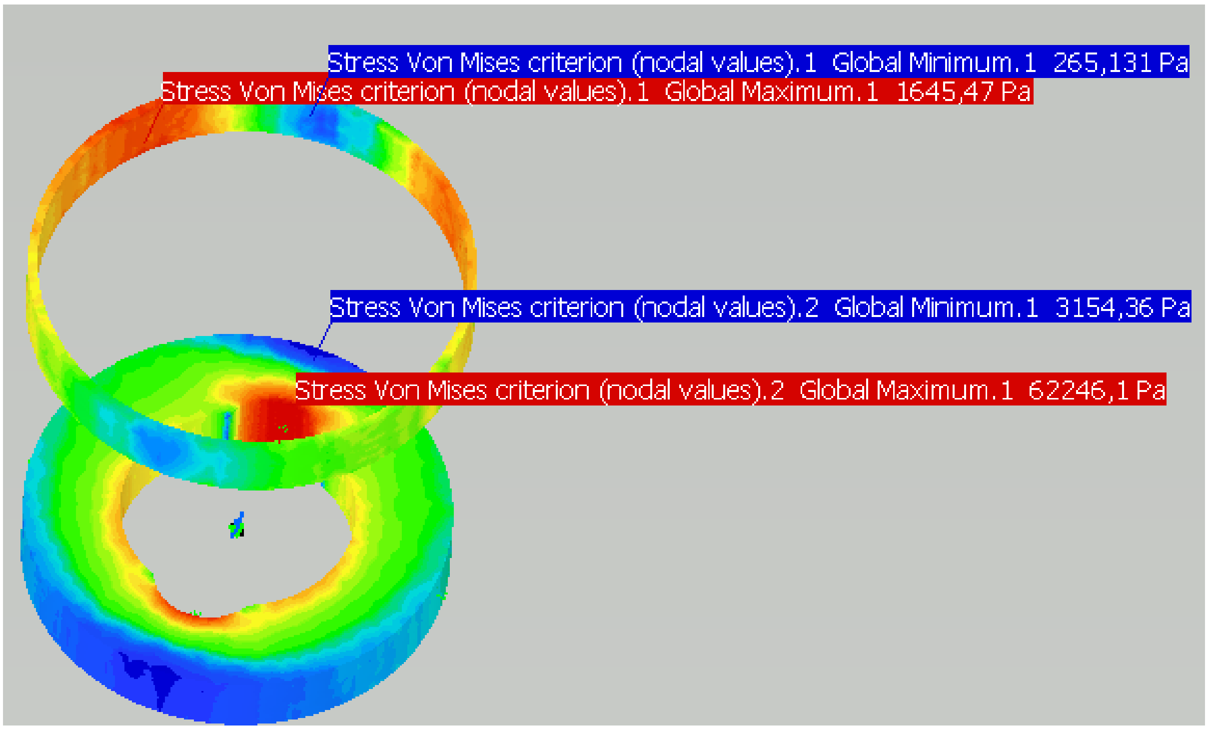

Fig.2. Variation of von Mises stresses and extreme values in both layers of the model

In Fig.3, the radial stress is presented, computed in cylindrical coordinates, and it can be seen that radial stresses the outer layer are insignificant, while for the interior layer it presents both compression values, verifying the applied interior pressure and small traction stresses in the region of the spherical cavity.

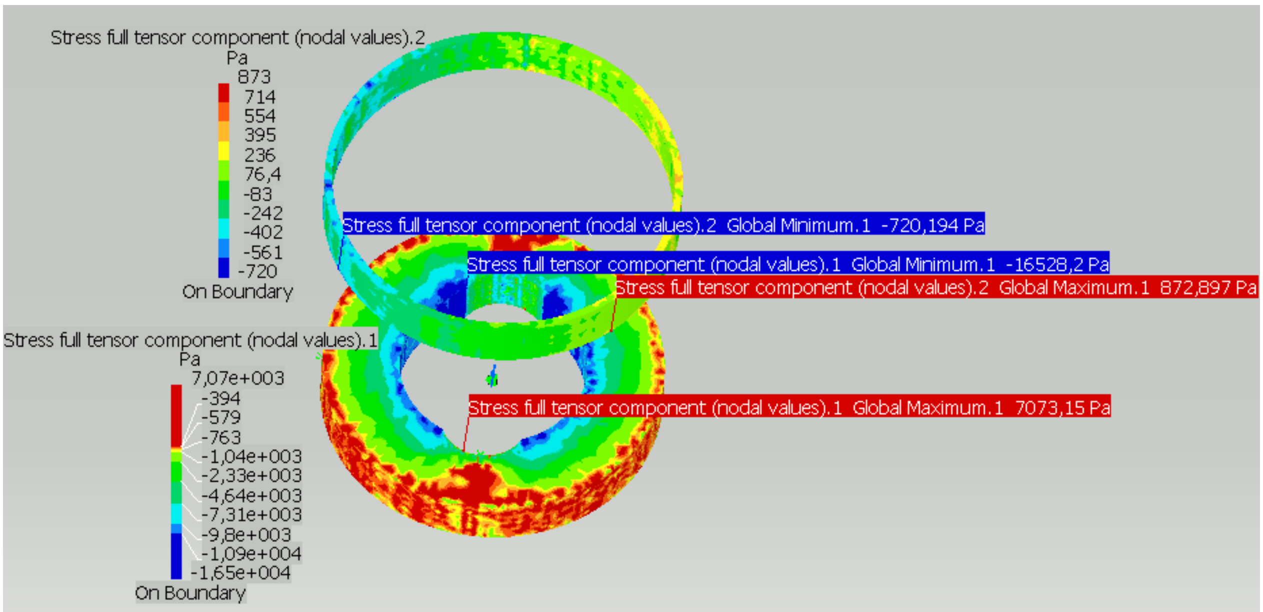

Fig.3. Radial stress in both layers of the model

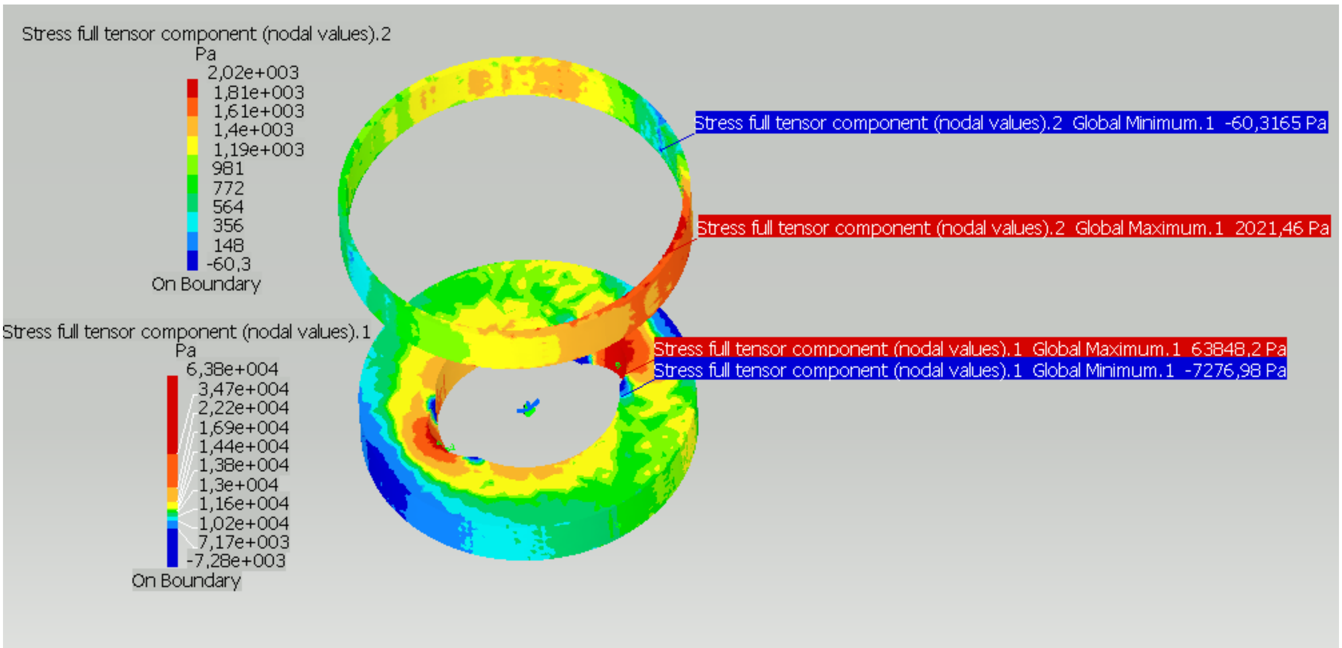

Fig.4. Extreme hoop stresses in both layers of the model

From Fig.5.a., it can be observed that the traction radial stress in the interior layer is most significant in the vicinity of concentrators in the bulk and towards the exterior of the cylinder. Fig.5.b, the hoop stress reaches the most significant values quite on the surface of the concentrators.

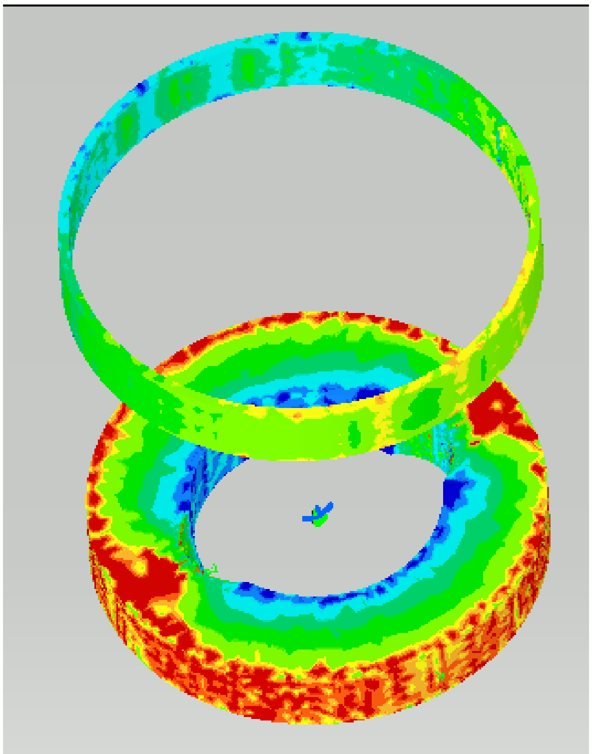

Fig.5.a. Radial stresses in both layers of the model

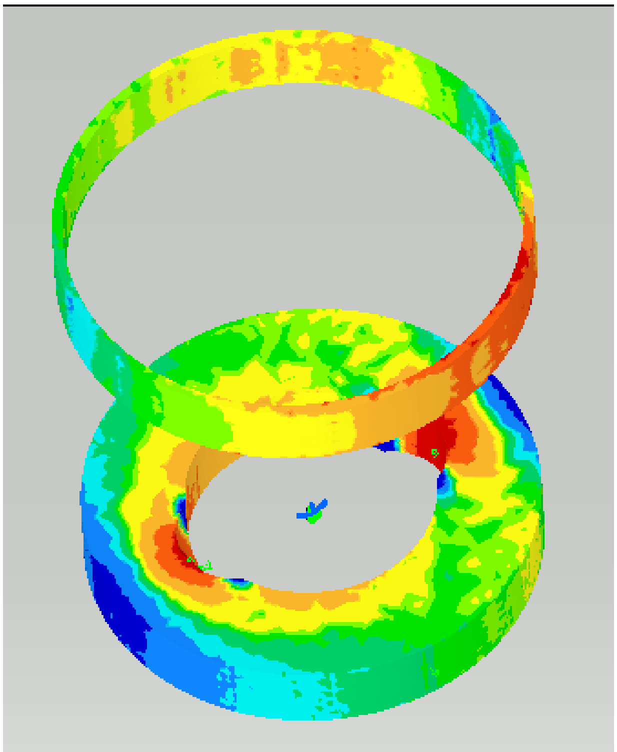

Fig.5.b. Hoop stresses in both layers of the model

In Fig.6 the principal shearing stress variation is presented and it can be noticed that the maxima are obtained for the inner layer in the concentrator regions and there is a similar aspect to the equivalent von Mises stress.

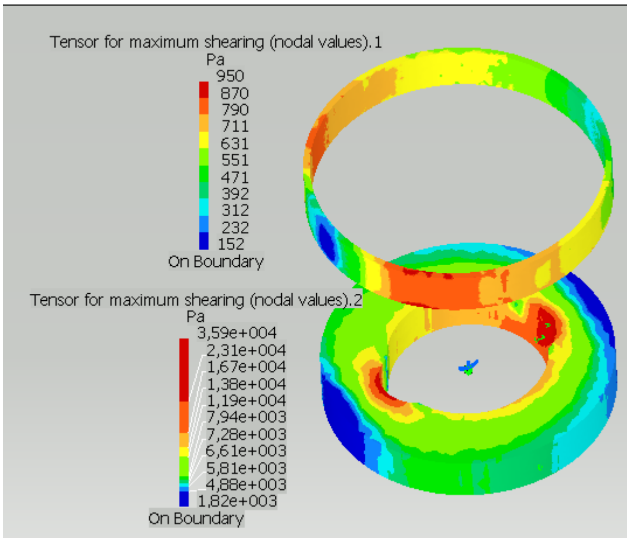

Fig.6. Principal shearing stress

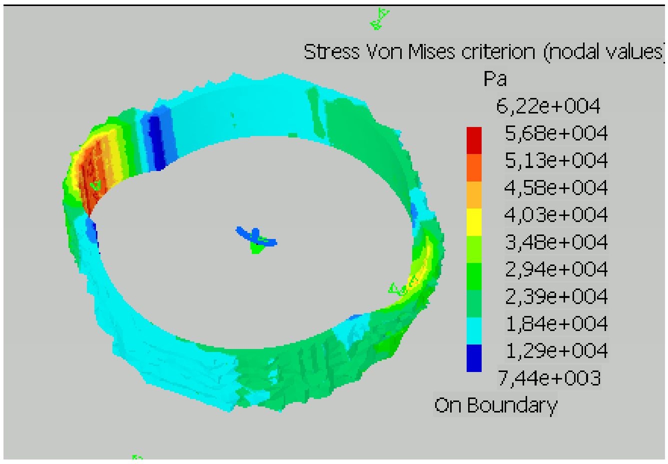

Fig.7. Detail of the von Mises stresses in the vicinity of interior surface

When the equivalent stresses from the two layers are simultaneously represented, Fig. 8, from the longitudinal section it can be seen that compared to the interior of the lesion, the exterior layer is subjected to less important stresses. The continuity of the stresses exists, Figures 9-11, but is more evident to the greater stresses, that is the hoop stresses.

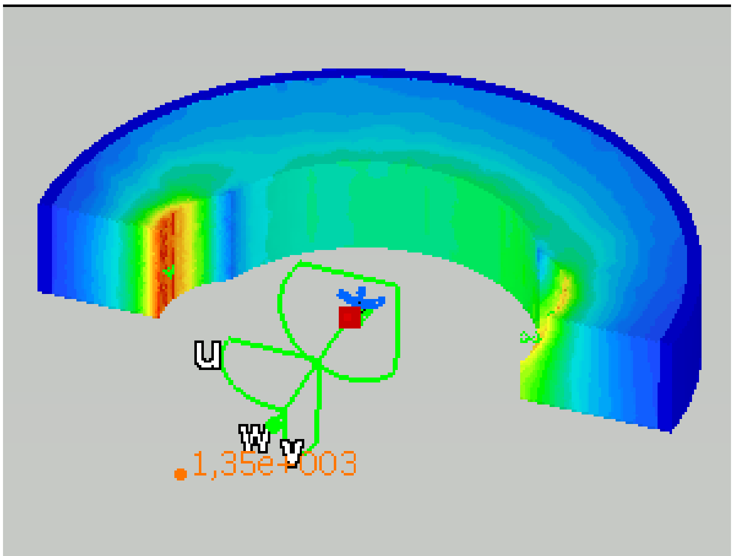

Fig.8. Section of the model for highlighting von Mises stresses for the assembly of two layers

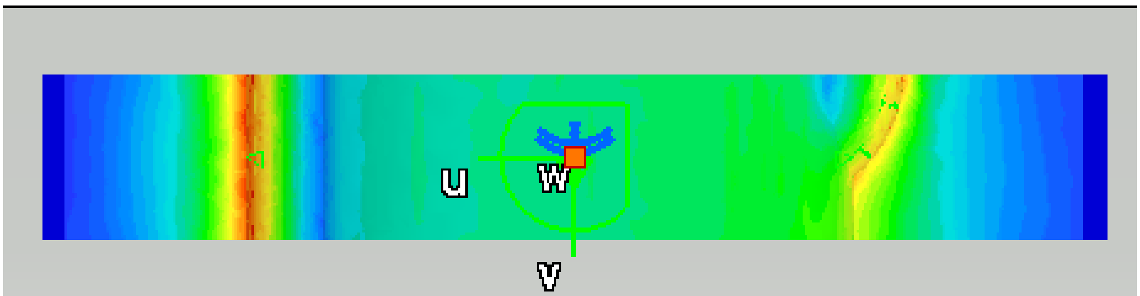

Fig.9 Longitudinal section -von Mises stresses for the two layers

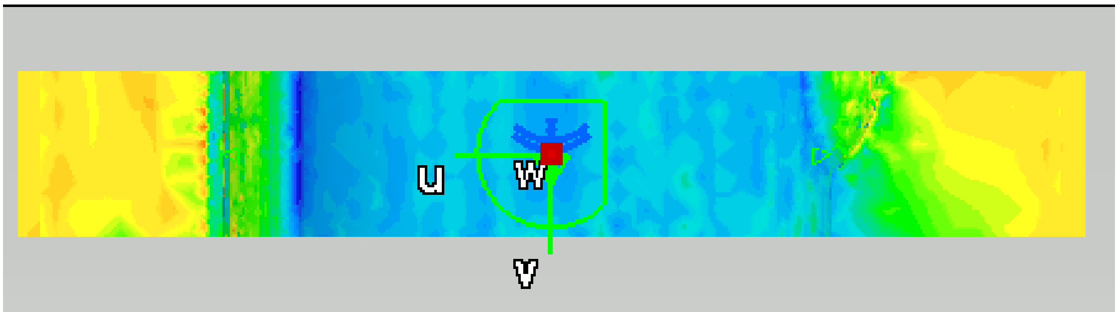

Fig.10. Longitudinal section –Continuity of radial stresses for the two layers

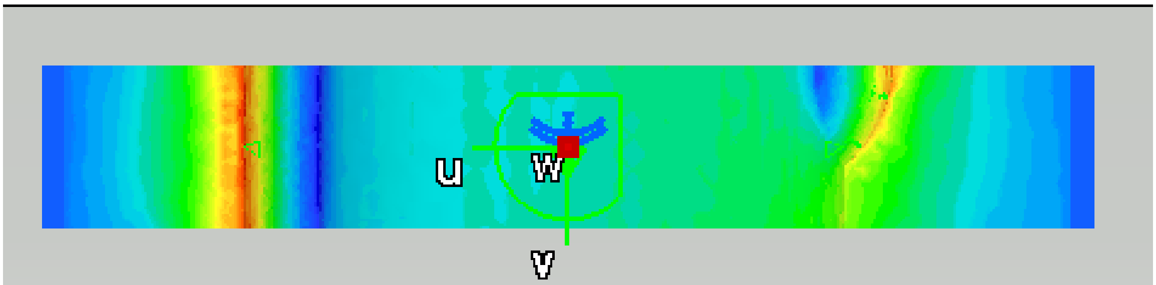

Fig.11. Longitudinal section –Continuity of hoop stresses for the two layers

In order to validate the results, a model for two bonded cylinders without fissures, with the same interior applied pressure, is studied. The radial stresses, Fig. 12, and hoop stresses, Fig.13. were found in good agreement to the analytical results, [11]. The errors (7.5%) are attributed to the coarse meshing adopted by computational reasons. Therefore, the equivalent von Mises stresses Fig.14-15, are considered to be realistic.

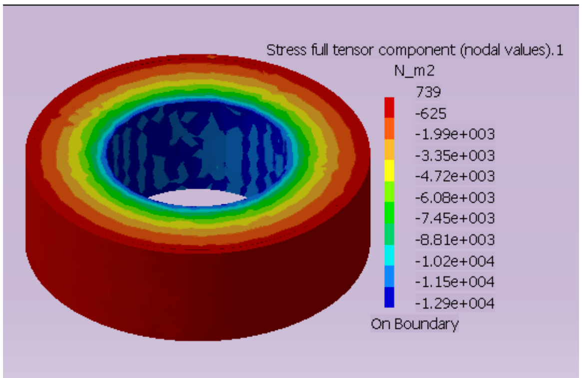

Fig.12. Radial stresses for the two cylinders

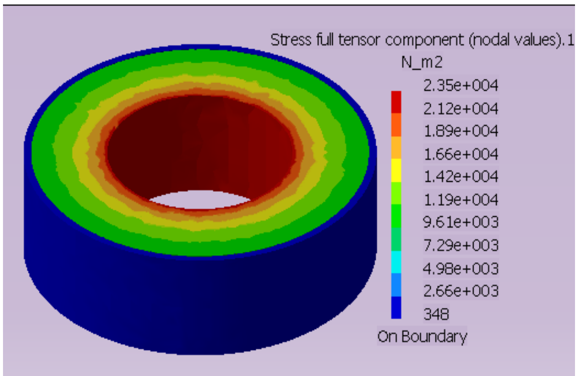

Fig.13. Hoop stresses for the two cylinders

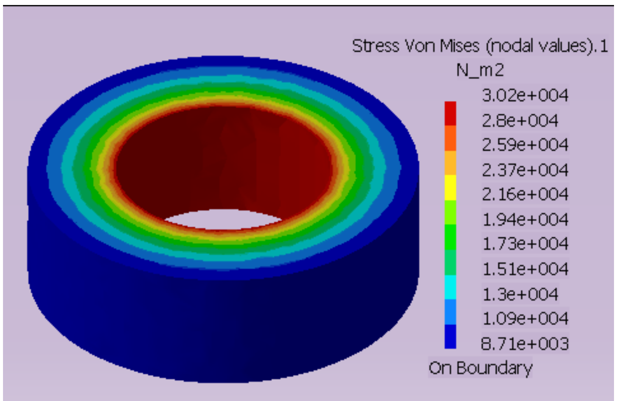

Fig.14. Von Mises stresses for inner cylinder

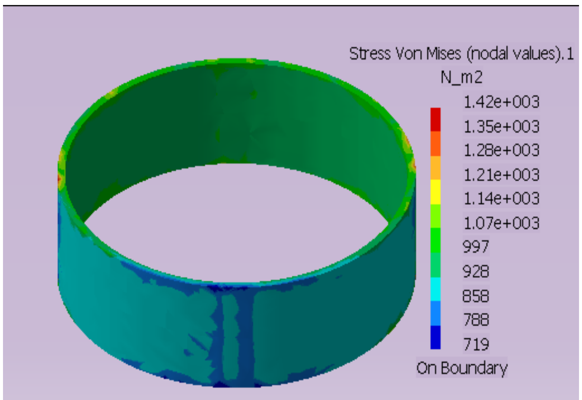

Fig.15. Von Mises stresses for external cylinder

From Fig. 16 and Fig. 17, the continuity of stresses is seen and therefore the validity of connection assumption, namely fastened cylinders.

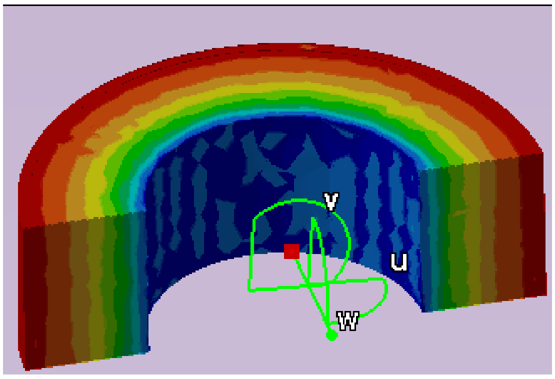

Fig.16. Radial stress continuity for the two cylinders

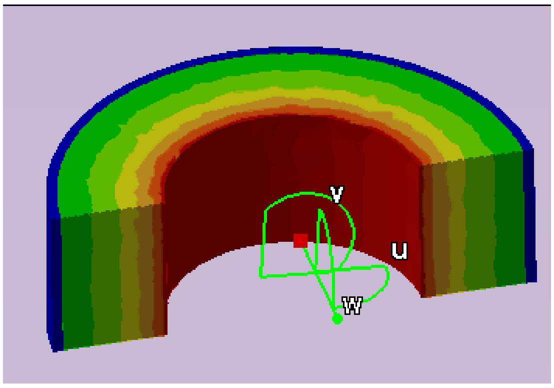

Fig.17. Hoop stress continuity for the two cylinders

CONCLUSIONS

A model of the blood vessel with inner lesions was proposed in order to analyze the stress field produced by the blood pressure.

For the beginning, a simple case is considered, namely the static case of vessel with constant interior pressure. The blood vessel is modeled as a two layer vessel, obtained from two concentric elastic cylinders. The dimensions and mechanical characteristics of the layers are modeled according to mean values from literature for an arterial wall.

The finite element analysis was performed using Generative Structural Analysis module from Catia environment. The stress field was found and details about the equivalent von Mises stresses and stress components for the two layers were observed.

The cavity-shaped injuries act as stress concentrators and the shape and dimension of the lesions are parameters influencing the extreme stresses.

The injury having the shape of spherical cap cavity presents a smaller concentrator effect upon the equivalent stress compared to the elongated cylindrical longitudinal lesion.

The hoop stress presents maximum values in the inner layer in the centre of the cylindrical lesion and its values determines the maximum von Mises stress in the same point.

The analysis can also be performed on a wide range of different blood vessel, allowing for different wall thickness and layer thickness ratio or different lesion dimensions.

For a more realistic modelling, future work is aimed considering the pulsatile blood flow and the viscoelasticity of the blood vessel layers.

From the blood vessel models can benefit other applications, including the creation of new blood vessel substitutes, vascular tissue engineering and aneurysm treatment and prevention. Each of these domains requires comparative and interdisciplinary studies of healthy and diseased vessels.

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