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FUNCTIONAL ANALYSIS AND GEOMETRICAL OPTIMIZATION OF THE AUTOMOTIVE'S DOOR INNER WAIST BELT MADE FROM PP/TPV-E USING FEM METHOD

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Abstract: *In this paper the authors present how the inner door waist belt geometry was optimized using car model and FEM (Finite Element Method), so that functional requirements are satisfied. Through this analysis, high costs have been avoided resulting from poor functionality of the component, identified by its practical implementation. The software used was Simulia ABAQUS. The difficulty of the achieved FEM analysis consists in finding the optimal algorithm for modelling a relatively new combination of materials, polypropylene (PP) and vulcanized thermoplastic elastomer (TPV-E) with hyper elastic feature.*

Key words: *TPV-E, PP, FEM, inner waist belt, geometrical optimization.*

1. General Aspects

In technical projects in the automotive industry is often seen the situation where technological requirements, costs and package, impose design and material conditions, which can be varied for this component, only in a limited framework. To avoid situations in which problems are identified by functional component of its practical implementation, it requires a priori simulations of component behaviour, using CAE (Computer Aided Engineering). The engineering art in the use of such methods consists in creating a virtual environment simulation as close to real conditions. In the current paper the authors show how, in the inner door of the inner waist belt geometry was optimized using car model FEM (Finite Element Method), so that functional requirements are satisfied the car. Software was Simulia used ABAQUS. Through this study were found and eliminated virtual risks that would otherwise be caused by quality problems and costs. The difficulty of the FEM analysis performed consists in finding the optimal algorithm for modelling a relatively new combination of materials, polypropylene (PP) and vulcanized thermoplastic elastomer (TPV-E) with hyper elastic feature.

2. Describing the Door's Inner Waist Belt

Figure 1 shows the CAD model of the inner door waist belt and the its outer periphery [1]. It includes the following elements:

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[2] Centre "Automotive HighTech Products", *Transilvania* University of Braşov.

• metallic clamp for fixind on door (gray);
• central rigid zone of the parapet (light brown);
• window contact zone, inner door panel contact zone and grip fins on metallic clamp made from optimum elastic properties material (green);
• sliding surface properties of the higher lip contact with glass (brown);
• surface properties of the lower lip sliding contact with the window (dark blue);
• lateral window of the door (light blue).

The inner waist belt role is to close on the inside space of the metallic structure of the door, side window and the door panel. By closing this area the noise entering the cabin is reduced, and also the vibrations and resonances, and the inner door cavity is protected. The mechanical and electrical drive components of the glass are also protected with this sealing. Due to constant contact with the window and to moving window friction, the lips of the inner door railing must have a surface with sliding properties and also high abrasion resistance.

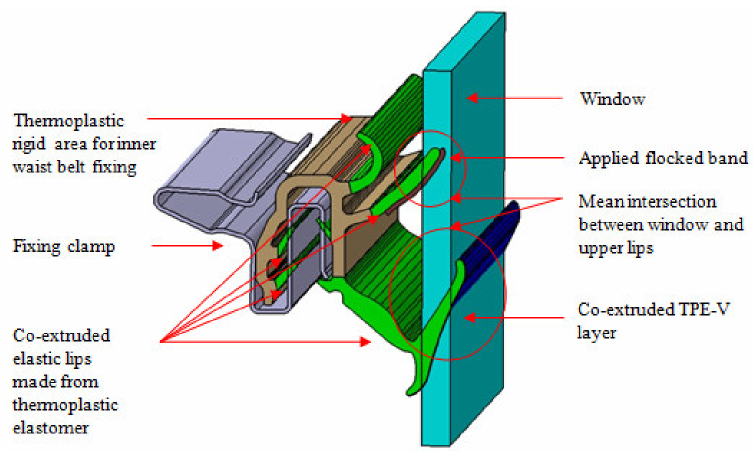


Fig. 1. *Inner door waist belt assembly - fixing method and window interaction* [2]

The way of tensioning the lips in contact area with the window and their position, both in the Free State and in the assembled state, is presented in a transparent manner through statement of the FEM model in Figure 2.

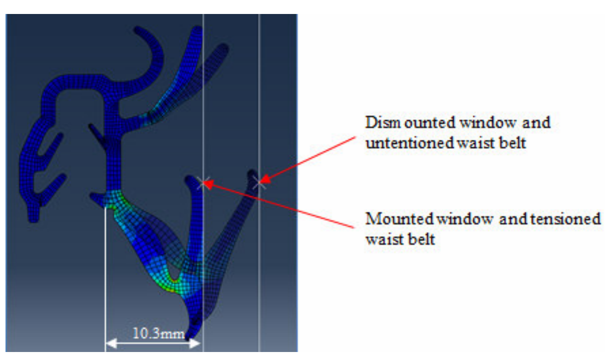


Fig. 2. *Geometrical comparison between free standing parapet and tensioned mounted parapet* [1]

For the FEM model the mounted final position of the window is relevant from the fixing the waist belt. As seen in Figure 2, this dimension is 10.3 mm.

3. Choosing the Mathematical Model and Finite Element Model

As a result of the implementation technology used inside the door waist belt, namely extrusion and co-extrusion zone rigid PP TPV elastic lip-E, it is possible to approach in modelling as a single homogeneous elastic body with cohesion between materials. From FEM simulation performed were excluded for reasons of simplification, flocked band and co-extruded layer of TPV-E slide (see Figure 1). Also, tabs grip the metal clip was integrated in the central rigid model [3].

Because the deformation area of the waist belt is made of incompressible material with hyper elastic behaviour and high strain, the authors chose the Mooney-Rivlin for FEM analysis [4].

Finite element modeling was accomplished by using mesh structure with quadrilateral elements, of the first order, the plane strain condition. Adopting the model as a state plane deformation is appropriate for the inner waist belt structure since:

- two-dimensional (in plan that defines section) are much lower than the third (along waist belt);
- deformation along the waist belt is null.

This model significantly reduces the volume of calculation. Finite element simulation of the plane strain condition has been done considering the dual nonlinearity of material and geometric of the model.

4. Determining the Characteristics for the Hyper-Elastic Material

Elastic characteristics of hyper elastic materials shall be established based on experimental research by simple tensile stresses, biaxial tensile, shear and simple compression (Figure 3).

For performing this FEM modelling, the authors chose the elastic characteristics of Santoprene 121-58 W175, for a strain level for a sample of 50% [5]. According to the manufacturer's certificate of material was determined experimentally after simple tensile tests, strain-tension correlation in Table 1.

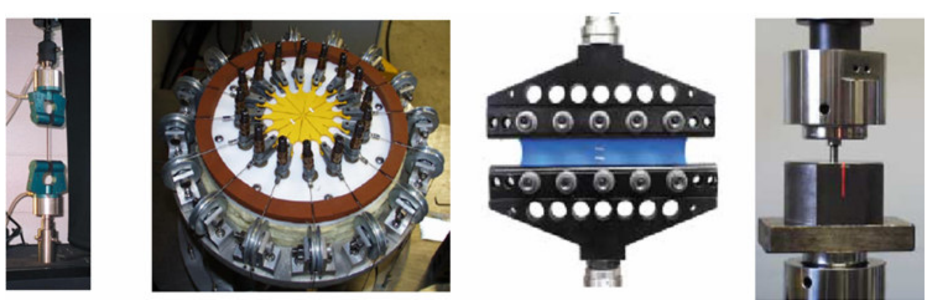


Fig. 3. *Experimental methods for determining the elastic characteristics of hyperelastic materials* [6]

Table 1

Pressure-strain correlation of Santoprene 121-58 W175 material for the 5th cycle test at 23° C and the sample deformation level of 50% [7]

Deformation, [%]	1.86	6.09	10.29	14.61	18.85	23.13	27.22	31.20	36.83
Tension, [Mpa]	0.091	0.201	0.290	0.375	0.461	0.555	0.666	0.805	1.083

For performing these measurements were used 3 samples of material with dimensions 250x250x2 mm.

Using the ABAQUS software were determined material coefficients C_{01} and C_{10} (Table 2), required for application of Mooney-Rivlin model for FEM simulation of the behaviour of the inner door waist belt.

Table 2

Mooney-Rivlin material coefficients for Santoprene 121-58 W175 for a deformation level of 50%

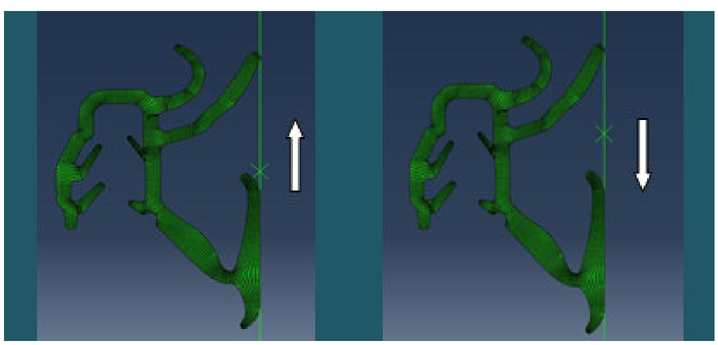
Coefficient	C_{01}	C_{10}
Value	8,5798e-3	1,2106e-2

5. Results of Finite Element Modelling and Optimization of the Geometric Model

In this paper the authors quit giving a detailed description of the steps of modelling and resume to their list:

- importing CATIA model in the ABAQUS software;
- achieving a flat surface model of the inner door waist belt;
- defining all rigid body-deformable body;
- defining discretized model with quadrilateral finite elements for plane strain state;
- define sections with different materials;
- instantiated deformable body (waist belt) and the rigid body (window);
- flush conditions defining the deformable body;
- defining the geometry of the window relative horizontal displacement (see Figure 2);
- defining the vertical translation of the window (Figure 4);
- defining areas of contact and friction between rigid body and deformable body;
- defining the geometry of the interaction between rigid body and deformable body.

Important to note is that, FEM analyzes were performed for three different regimes of friction between deformable body (parapet) and rigid body (glass), as shown in Table 3 [8].



a) *upward vertical move* b) *downward vertical move*

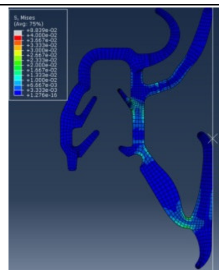
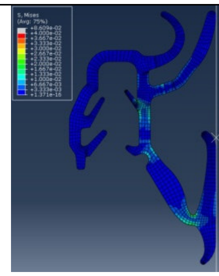
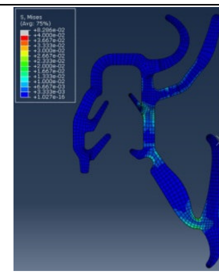
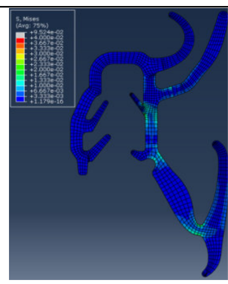
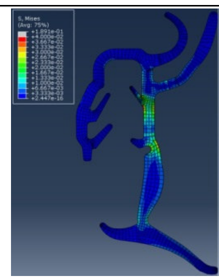
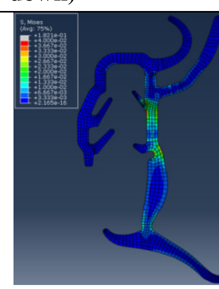
Fig. 4. *Window vertical moving*

Friction regimes utilised for FEM analysis Table 3

Contamination grade	Clean window	Dirty window	Extremely dirty window
Friction coefficient	0.25	0.5	0.75

Following the modelling were obtained for the original geometrical model (Model 1) the results summarized in Table 4.

FEM results for the original geometrical model (*Model 1*) Table 4

Friction coefficient	**0.25**	**0.5**	**0.75**
Upper translation limit of the rigid body (window up)			
Tension in material [Mpa]	 8,839e-2	 8,609e-2	 8,286e-2
Lower translation limit of the rigid body (window down)			
Tension in material [Mpa]	 9,524e-2	 1,891e-1	 1,821e-1

As it can be seen, the lower lip of waist belt is not sufficiently stable to lowering the window. Under the dirty window conditions there is a not allowed tipping to the inside door. The other profile areas acts positive, tensions in the material being in the acceptable limits.

Geometric details of the lower lip of the original model can be traced in Figure 5.

By varying the radiuses R1, R2 and R3 is aimed at optimizing the window waist belt lowering behaviour. Summarizing results of five geometric patterns analysed is obtained Table 5.

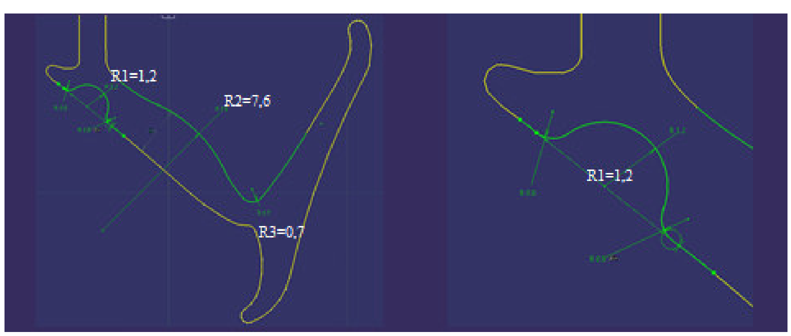


Fig. 5. *Geometrical details of the original model for the inner waist belt - Model 1*

Systematizing the data obtained from FEM modeling Table 5

Model name	Geometrical characteristics, [mm]	Friction coefficient	Maximum material tension, [Mpa]		Observations
			Window up	**Window down**	
Model 1	R1 = 1.2 R2 = 7.6 R3 = 0.7	0.25	8,839e-2	9,524e-2	Tilting the lower lip for μ = 0.5/0.75
		0.5	8,609e-2	1,891e-1	
		0.75	8,286e-2	1,821e-1	
Model 2	R1 = 0.9 R2 = 7.6 R3 = 0.7	0.25	1,523e-1	1,532e-1	Functional geometrical package
		0.5	1,510e-1	1,607e-1	
		0.75	1,489e-1	2,010e-1	
Model 3	R1 = 0.6 R2 = 7.6 R3 = 0.7	0.25	1,520e-1	1,527e-1	Functional geometrical package
		0.5	1,507e-1	1,599e-1	
		0.75	1,486e-1	1,880e-1	
Model 4	R1 = 0.9 R2 = 8.3 R3 = 0.8	0.25	1,425e-1	1,643e-1	Tilting the lower lip for μ = 0.5/0.75
		0.5	1,337e-1	2,831e-1	
		0.75	1,326e-1	2,742e-1	
Model 5	R1 = 0.9 R2 = 8.3 R3 = 0.4	0.25	1,287e-1	1,406e-1	Tilting the lower lip for μ = 0.75
		0.5	1,245e-1	1,593e-1	
		0.75	1,187e-1	2,642e-1	
		0.5	1,128e-1	1,334e-1	
		0.75	1,093e-1	2,497e-1	

According to the above data, can be observed that only models 2 and 3 have a functional geometrical configuration for all regimes of friction, both for high position, but also for the lowered position the window. Considered by the robustness of the technology, the authors consider that the geometry package Model 3 is the optimal solution.

6. Optimizing the Choice for the Material Characteristics

The FEM modelling performed to date had left the premises of material characteristics determined for a strain level of 50%. Determined in real time deformation simulation is however between 15-18% (Table 6.). Therefore it will be performed an additional modelling of the Model 3, using the material characteristics for a level of deformation of 25%. The purpose of this modelling is to reconfirm the functionality of the chosen geometry package.

According to the manufacturer's certificate of material, the strain-tension correlation, determined by simple tensile tests with sample deformation level of 25%, are found in Table 7.

Real material deformation level related to friction coefficient Table 6

	Material deformation level for a given friction coefficient		
	0.25	**0.5**	**0.75**
Window up	17%	17%	18%
Window down	15%	15%	17%

Table 7

Tension-strain correlation of the material Santoprene 121-58 W175 for the 5th cycle test at 23° C and the sample deformation level of 25% [7]

Deformation, [%]	1.34	2.66	5.36	7.94	10.55	13.13	15.66	18.18
Tension, [Mpa]	0.068	0.118	0.204	0.228	0.361	0.446	0.544	0.657

Similar to previous modelling were determined the material coefficients C_{01} and C_{10} (Table 8), required for the application of Mooney-Rivlin model.

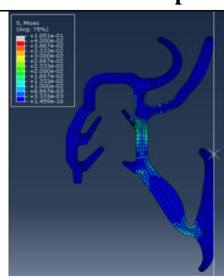
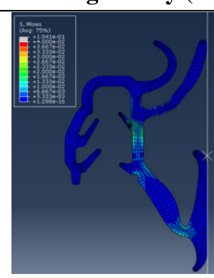
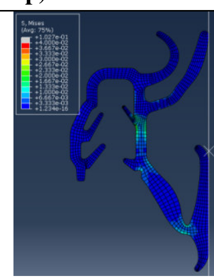
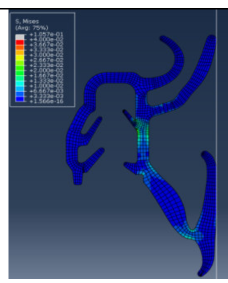
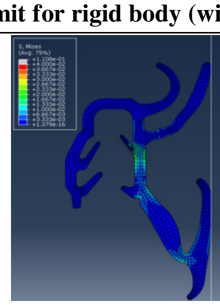
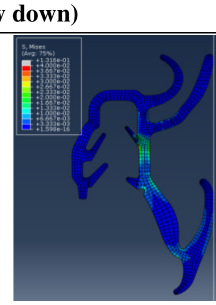
In Table 9 the authors are presenting the summary results from the analysis of Model 3 starting from the material coefficients in Table 8.

Table 8

Mooney-Rivlin material coefficients for Santoprene 121-58 W175 for a deformation level of 25%

Coefficient	C_{01}	C_{10}
Value	-2,1392e-3	1,6407e-2

Model 3 FEM results for a deformation level of 25% Table 9

Friction coefficient	**0.25**	**0.5**	**0.75**
Translation upward limit for rigid body (window up)			
Material tension [Mpa]	 1,051e-1	 1,041e-1	 1,027e-1
Translation downward limit for rigid body (window down)			
Material tension [Mpa]	 1,057e-1	 1,108e-1	 1,316e-1

7. Conclusions

FEM analysis results described above make it possible to draw conclusions as follows:

- the working principle used, i.e. using Mooney-Rivlin model and mesh structure with the first order quadrilateral elements for plane strain condition was correct, being able to discover the functional risk of the initial model;
- geometrical optimizations of the model (model 3) were validated by practical tests in the car;
- combination of materials used is appropriate to ensure functionality of the door waist belt inside the car;
- the chosen design concept, with upper lip contact with the window has a stable positive behaviour for all regimes of friction;

• the chosen design concept, lower lip contact with the window has a stable positive behaviour for all regimes of friction only for R1 values ≤ 0.9 mm;

• R2 and R3 have no influence on functional behaviour of the lower lip contact with the window;

• the deformation caused in the simulation is real but between 15-18%.

Based on these conclusions, the authors recommendation is to use for similar components, FEM modelling method described above, before freezing Catia model. Thus, virtual model geometry can be optimized, up before physical execution of the extrusion tool. This reduces costs due to functional components and optimization by practical tests.

8. Future Research Directions

Figure 1 shows the inner waist belt model car's door and its periphery. As you can see, areas of contact between the waist belt and the lips are covered with glass materials with sliding properties: upper lip with flock band and lower lip coated with sliding TPV-E. These aids were excluded from the present FEM modelling. In order to get the model closer to the actual conditions, the next logical step would be to integrate these materials in the model studied. Through this expansion, the authors do not expect a major change in behaviour of the inner waist belt at lowering, respectively lifting the glass. Differences may occur however at the values of pressure at lip contact on the glass.

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