Using LS-OPT for Parameter Identification and MAT_FABRIC with FORM=-14

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1 Abstract

This work was carried out as a methodology development project in a joint venture between Autoliv and DYNAmore Nordic AB. The outset of the project was to obtain a better component behavior due to a more realistic material behavior in the simulation of airbag models.

The observation underlying the project was that the current fabric model used in most airbag models is *MAT_FABRIC and FORM=14. In FORM=14 there is no consideration taken to a stiffened response due to a bi-axial stress state in the fabric. To consider the bi-axial stress state, FORM=-14 was implemented some years ago but has, until now, not been used. The objective with this implementation is to increase the stiffness in the fabric when subjected to a bi-axial stress state.

This paper presents a resume of the features found in *MAT_FABRIC, a methodology to fit the simulation model to material test data using LS-OPT and finally a comparison between the behavior of the different FORM options.

2 Introduction

The material formulation -14 was implemented some time ago in order to capture the behavior of fabric materials under a bi-axial stress state. This paper describes the work flow when going from material testing to material data input into LS-DYNA when using MAT_FABRIC with FORM=-14.

The material parameters are described as values or load curves in LS-DYNA. In many material models in LS-DYNA these parameters will have to be found using finite element, (FE), simulations models of the material test procedure, i.e. parameter identification optimization problems. Hence, the need for an optimizer such as LS-OPT is obvious.

When using FORM=14 for MAT_FABRIC in LS-DYNA, the user will supply load curves describing the material response for uni-axial loading in terms of a 2'nd Piola-Kirchoff/Green-Lagrange curve. This curve can be converted from a uni-axial test analytically and directly input to LS-DYNA. The LS-DYNA simulation model is then able to exactly reproduce this material test.

When using FORM=-14, the user will also supply load curves which describes the material response for a bi-axial stress state. Typically this will increase the stiffness of the material response. In contrary to the uni-axial test, the results from material tests cannot be converted to input data to LS-DYNA analytically. Instead the load curves to be used in LS-DYNA will have to be found by use of reversed engineering.

Reversed engineering for parameter identification is a well-known area in the field of optimization. In this work we used LS-OPT and Sequential Response Surface Methodology, (SRSM) as optimization technique. The main difficulty with this optimization procedure is to keep the number of design variables as low as possible.

Apart from FORM=14/-14 a number of new features have been added to the material model lately. Therefore, a small description of some of the different features in MAT_FABRIC will be discussed as well in the initial part of the paper.

3 *MAT_FABRIC

The features of *MAT_FABRIC that will be discussed is the liner, coating and form selection and their influence on the material response under compression.

3.1 Liner

The liner in *MAT_FABRIC is a way to deal with compressive loads. The liner is defined by three parameters: EL, PRL and LRATIO which are the Youngs modulus, Poisson’s ration and thickness of the liner, respectively. If the elastic liner is used it will also affect the material response under tension. The material response for the liner is a pure elastic one, including the Poisson’s effect.

3.2 Fabric Coating

For -14 there is a new feature called the coating which is an elasto-plastic material model for representation of the coating of the fabric. Three extra input parameters are read which are the ECOAT, SCOAT and TCOAT which stands for Youngs modulus, yields strength and thickness of the coating respectively. The thickness is applied on both surfaces of the membrane, see Figure 1.. The intention of is to be able to capture the increased bending stiffness due to a coating. Observe, the coating will add membrane stiffness in both tension and compression, unless it is turned off.

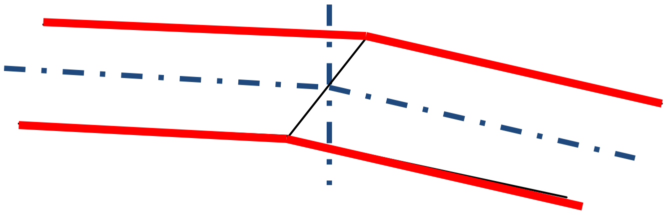


Figure 1: Fabric coating

3.3 FORM 14/-14 under compressive loads

During compression loading there has been an update for both FORM 14 and -14. Earlier the two implementations were intended to define the material response under tension loads using load curves.

The compression behavior was treated using the liner characteristics and in many cases the material response from the FORM option was turned off in compression.

Now, it is also possible to define the compression behavior using negative stress/strain values in the behavior curves. Still, if a liner is defined, the total behavior during compression will be the cumulative of the liner and the defined behavior curves.

4 Uni-axial behavior: FORM=14

When using FORM=14, the 2’nd Piola-Kirchoff stress versus the Green-Lagrange strain is given using load curves in each fiber direction. To establish these curves, material tests are performed. The results from the test are transformed into load curve data which is entered into the simulation model (input deck) directly.

4.1 Uni-axial test

The uni-axial test is carried out using a strip of fabric material with the initial length, l_0, and cross-section area, A_0, see Figure 2. The measurements taken from the test are the grip handle displacement *d* and the force *f(d)* as a function of the displacement.

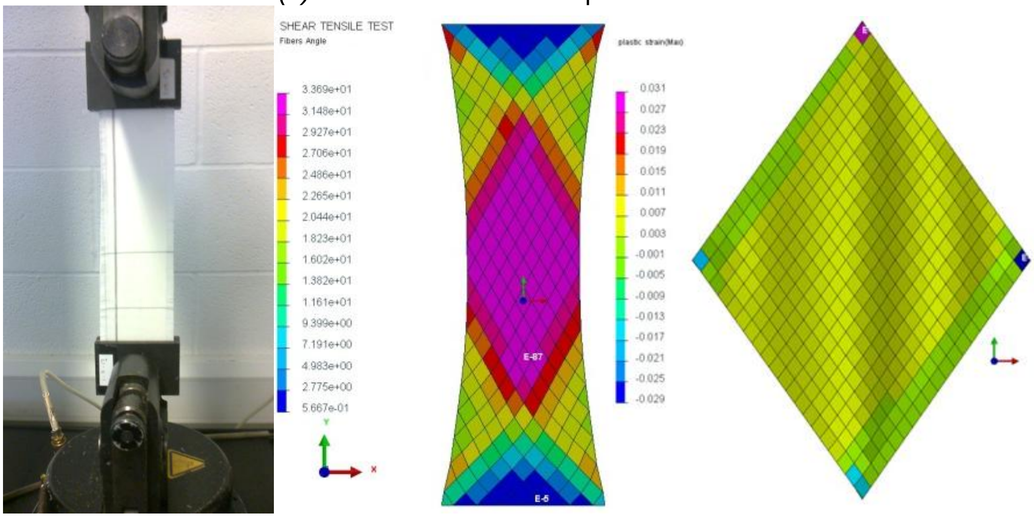


Figure 2 : Uni-axial test, Bias test, Picture frame test configurations

The stress-strain curve to be used in the material model is then obtained by the transformations:

$$E = \frac{1}{2}\left\{\frac{d}{l_0} + 1\right\}^2 - \frac{1}{2} \quad \text{and} \tag{1}$$

$$S = \frac{f(d)}{A_0}\frac{l_0}{(l_0 + d)}. \tag{2}$$

4.2 Shear test

Two types of shear test are presented in Figure 2. A Bias test [1], where the fabric is oriented at 45° compared to the loading direction. A Picture Frame test [2], where the the fabric is clamped in a rigid frame. and a hinge is modeled at each corner of the rigid frame. Two opposite corners are pulled apart. The measurements from the test is the force –displacement curve *f(d)*.

The stress-strain curve to be used in the material model is then obtained by the transformations:

$$E_{XY} + E_{YX} = \left\{\frac{d}{l_0\sqrt{2}} + 1\right\}^2 - 1 \tag{3}$$

and

$$S_{XY} = \frac{f(d)}{t(l_0\sqrt{2} + d)}. \tag{4}$$

5 Bi-axial test – FORM=-14

The aim of FORM=-14 is to capture the stiffening effect found when the fabric is subjected to a bi-axial stress state. Another aspect of FORM=-14 is that in an uni-axial loadcase it should give the exact same result as FORM=14.

The test configuration is given in Figure 3. The force – displacement curves $f_b^X(d)$ and $f_b^Y(d)$ in the two directions are measured.

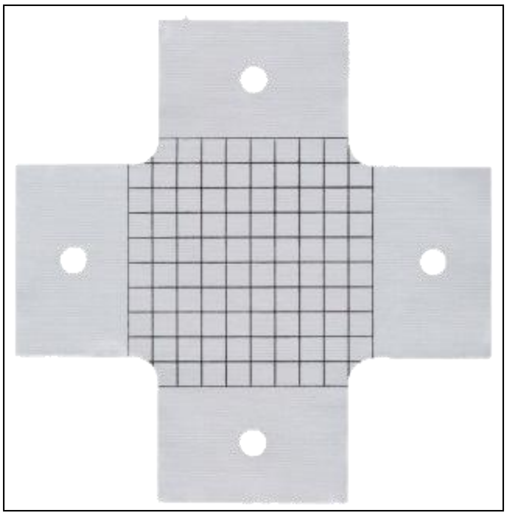


Figure 3 : Bi-axial test configuration.

Two new curves, f'^{X}_{b} and f'^{Y}_{b} are introduced to model the tensile stress-strain curves in the fiber directions when $E_{XX}=E_{YY}$, i.e., in bi-axial strain. Assuming that $E_{XX}>0$ and $E_{YY}>0$, the stress in the fiber directions are computed according to

$$S_{XX} = f_l^X(E_{XX})\max(0,1-E_{YY}/E_{XX}) + f'^X_b(E_{XX})\min(1,E_{YY}/E_{XX}) \tag{5}$$

$$S_{YY} = f_l^Y(E_{YY})\max(0,1-E_{XX}/E_{YY}) + f'^Y_b(E_{YY})\min(1,E_{XX}/E_{YY}) \tag{6}$$

This means that the stress will follow the uni-axial loading curve for uni-axial strain and the bi-axial loading curve for bi-axial strain. The stress is linearly interpolated in between these two curves using the normalized parameters $min(1,E_{XX}/E_{YY})$ and $min(1,E_{YY}/E_{XX})$, respectively.

This means that f’ is a stress/strain relationship that is used in the material definition in LS-DYNA and *f’* cannot be found through a neat equation as for the uni-axial load case. To find *f’* we need to optimize the appearance of *f’* to capture the test configuration material response *f.*

6 Optimization

From the bi-axial test the force displacement curves are known. To determine the optimal curves to use in LS-DYNA in order to capture the material test results the curves to be used must be found through some sort of parameter identification. In this study the SRSM approach in LS-OPT was used.

6.1 Simulation model

As a balanced rate of bi-axiality was used (same prescribed displacements at all four ends), the center of the sample remains in the center of the device. A simplification of the finite element model was then applied.

A quarter of the test piece was modeled, using symmetry conditions and prescribed velocities along the other boundaries, see Figure 4. The element size is chosen to be of the same order as the element size used for the restraint system simulation.

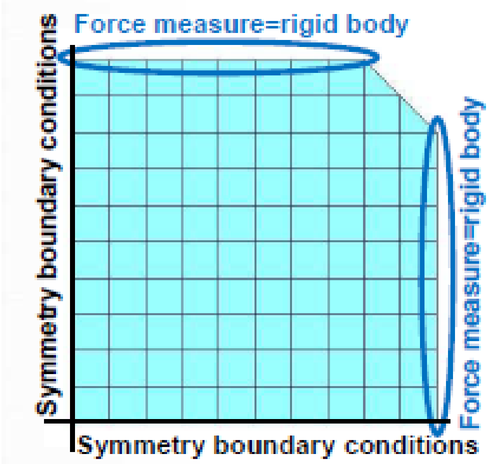


Figure 4: Simulation model for the bi-axial loading case.

6.2 Parameterization

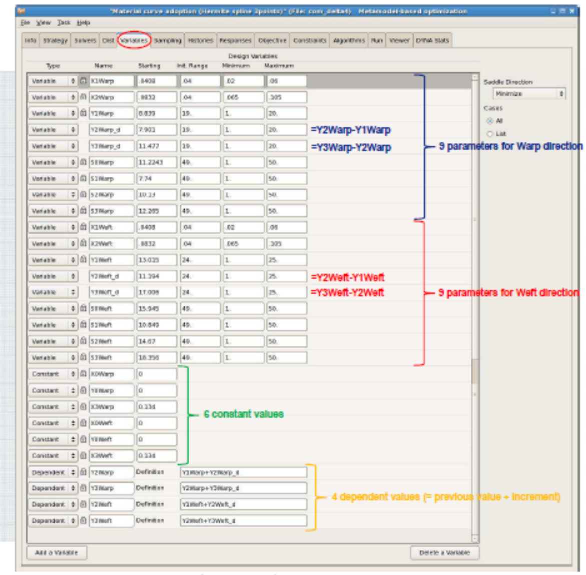
Load curves need to be parameterized. A Hermetic Cubic Spline formulation is used in order to generate continuous load curves form the optimization. Each load curve is divided into 3 segments with a cubic polynomial interpolation for each respective segment, see equations below. C1 continuity criterion was used between the segments.

$$p(t) = h_{00}(t) \times p_o + h_{10}(t) \times m_0 + h_{01}(t) \times p_1 + h_{11}(t) \times m_1$$

with $t \in [0,1]$ and $h_{00}(t) = 2t^3 - 3t^2 + 1$

$$h_{10}(t) = t^3 - 2t^2 + t$$
$$h_{01}(t) = -2t^3 + 3t^2$$
$$h_{11}(t) = t^3 - t^2$$

Shown in Figure 5 is the final parameter definition input needed to LS-OPT. There are 18 independent parameters. Since the simulation model is small the number of parameters is not discarding.



Design Variables

Type	Name	Starting	Init. Range	Minimum	Maximum
Variable	X1Warp	.8408	.04	.02	.06
Variable	X2Warp	.8832	.04	.065	.105
Variable	Y1Warp	8.839	19.	1.	20.
Variable	Y2Warp_d	7.902	19.	1.	20.
Variable	Y3Warp_d	11.477	19.	1.	20.
Variable	S0Warp	11.2243	49.	1.	50.
Variable	S1Warp	7.74	49.	1.	50.
Variable	S2Warp	10.13	49.	1.	50.
Variable	S3Warp	12.285	49.	1.	50.
Variable	X1Weft	.8408	.04	.02	.06
Variable	X2Weft	.8832	.04	.065	.105
Variable	Y1Weft	13.025	24.	1.	25.
Variable	Y2Weft_d	11.394	24.	1.	25.
Variable	Y3Weft_d	17.008	24.	1.	25.
Variable	S0Weft	15.945	49.	1.	50.
Variable	S1Weft	10.849	49.	1.	50.
Variable	S2Weft	14.67	49.	1.	50.
Variable	S3Weft	18.356	49.	1.	50.
Constant	X0Warp	0			
Constant	Y0Warp	0			
Constant	X3Warp	0.334			
Constant	X0Weft	0			
Constant	Y0Weft	0			
Constant	X3Weft	0.334			
Dependent	Y2Warp	Definition	Y1Warp+Y2Warp_d		
Dependent	Y3Warp	Definition	Y2Warp+Y3Warp_d		
Dependent	Y2Weft	Definition	Y1Weft+Y2Weft_d		
Dependent	Y3Weft	Definition	Y2Weft+Y3Weft_d		

Figure 5 : Parameter window in LS-OPT. There are 2 dependent variables, 3 constants and 9 parameters for each yarn direction, hence a total of 22 design variables.

6.3 Responses, Constraints and Objective

The objective is to minimize the difference of the force-displacement curve between the test and the simulation. The measure used in this study is the Root Mean Squared (RMS) error evaluated at each point in the force-displacement curve from the test.

6.4 Results from the optimization

The optimization process runs for 7 iterations using 33 simulations in each iteration, see Figure 6. As it can be seen, the optimization process rapidly reaches the objective. Several different starting positions have been tested but all of them converge to the same solution.

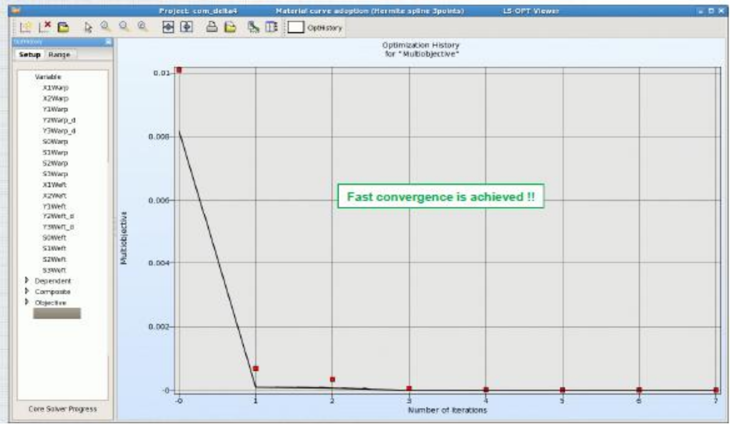


Figure 6 : The optimization history. The optimization history shows that the optimization process converges very fast towards an optimal value.

Shown in Figure 7 are the obtained force-displacement curves from the test as well as the initial and final force-displacement curves from the simulation. The appearance of the load curves used in the material model, LCAA and LCBB in respective yarn direction, in the simulation model are shown in Figure 8.

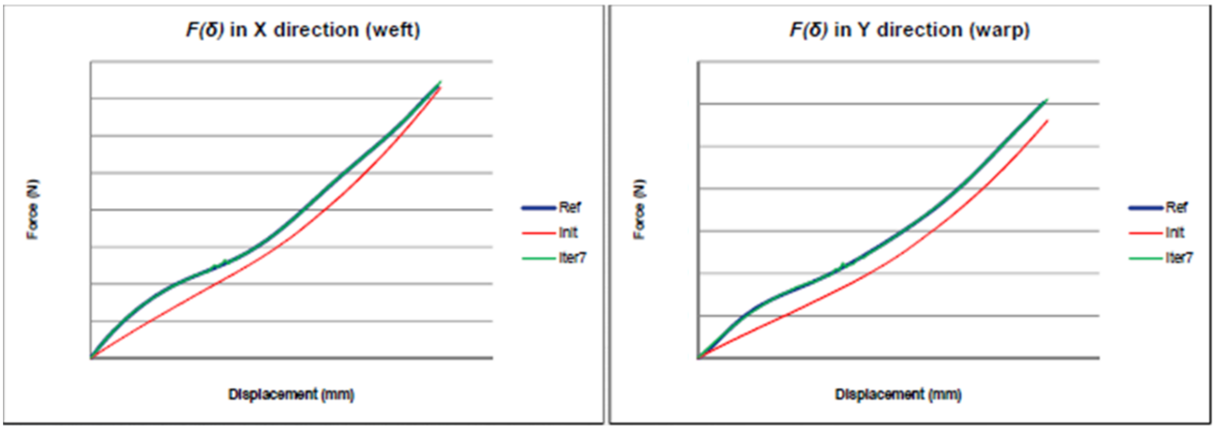


Figure 7: The force-displacement results from test, initial simulation and the optimized simulation results, respectively.

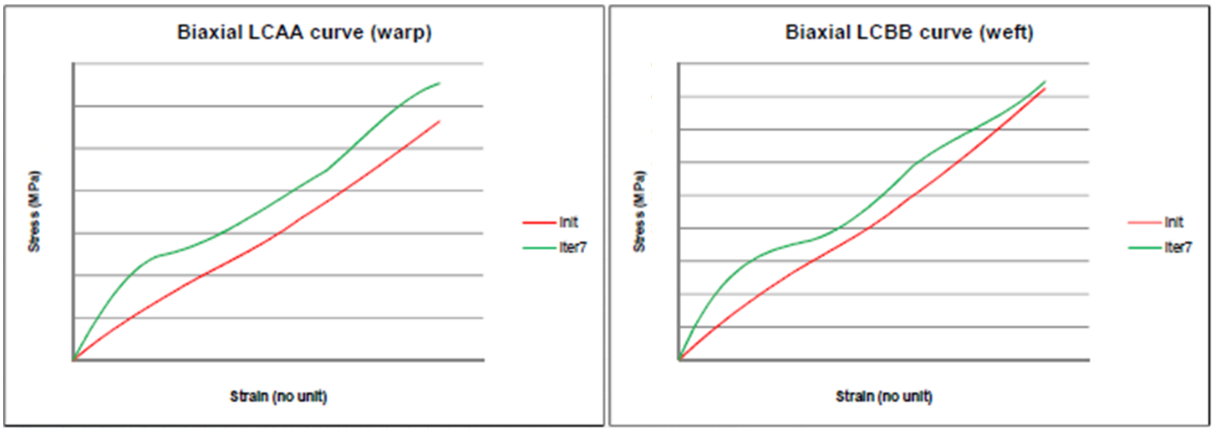


Figure 8: The shape of the used load curves in the material model for the two yarn directions.

7 Component simulations

To check the numerical stability and the stiffening of the material response in case of a distributed loading, a component simulation model was needed. Autoliv's leakage device (GES), developed by Manfred Schlenger [3], was chosen to perform this analysis. This device is regularly used to define the fabric leakage parameters needed to simulate the behavior of uncoated airbags.
It consists of a pressurized metal cone. At one end, a known quantity of gas is released and at the other end, a circular fabric sample is fixed. The pressure history in the cone and fabric bulge amplitude are measured and recorded. These physical measurements are the parameters according to which the Saint Venant-Wantzel leakage coefficients are tuned.

To analyze the local variation of strain due to fabric scrimp interchange, two semicircles with different warp/weft orientations (90°/45°) were used instead of the classical circular fabric sample. To join the two pieces of fabric, a straight line of seam was horizontally sewn.

7.1 Numerical model and sample fiber orientation

The aim of these simulations was to compare MAT34 Form = 14 and Form = -14. The pressure measured during GES tests was applied to the back side of the two semicircular meshes, see Figure 9, right.

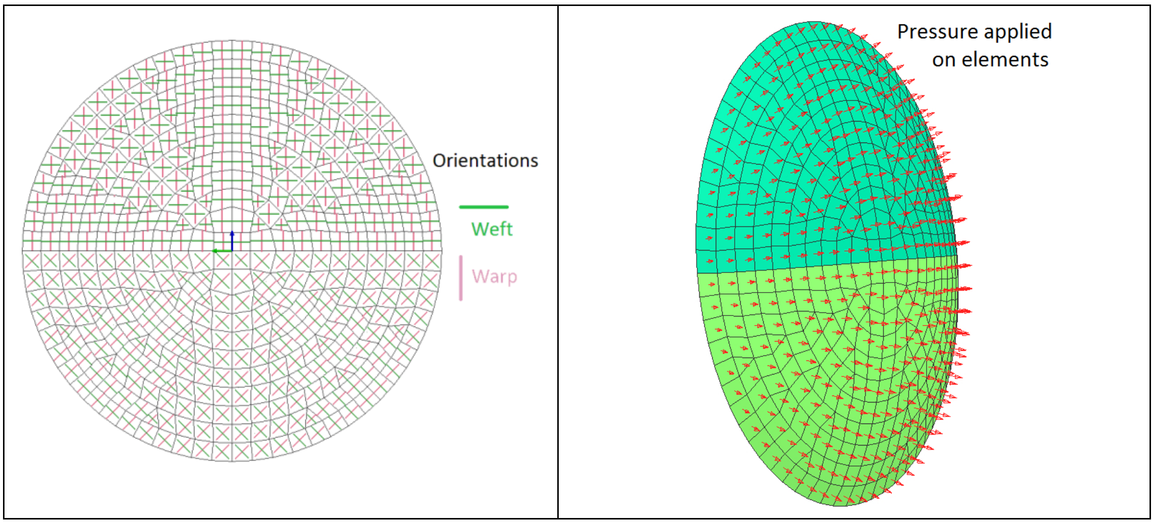
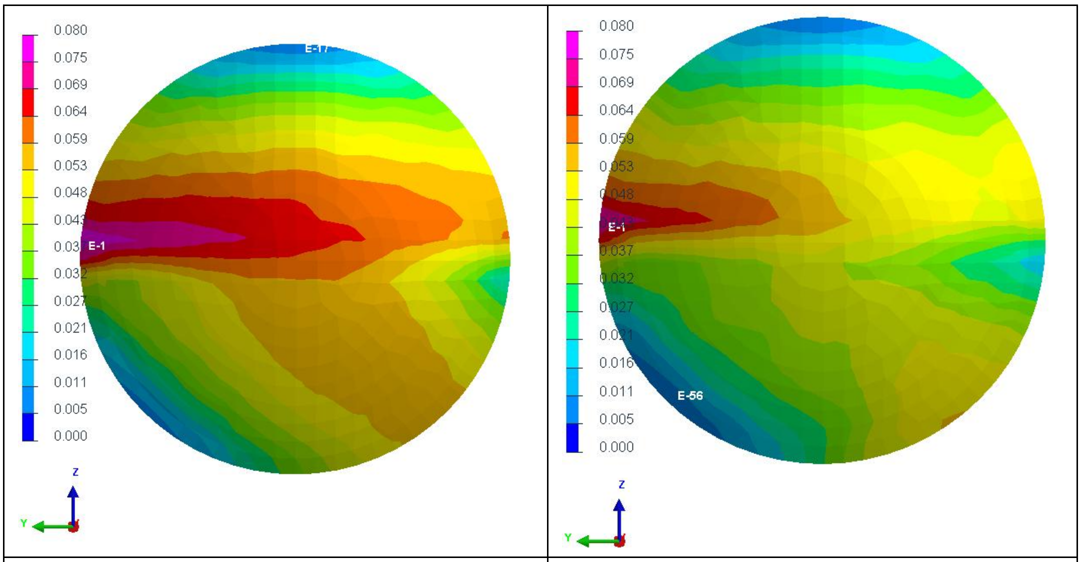


Figure 9 : Numerical model used for the comparison of Form = 14 vs Form = -14

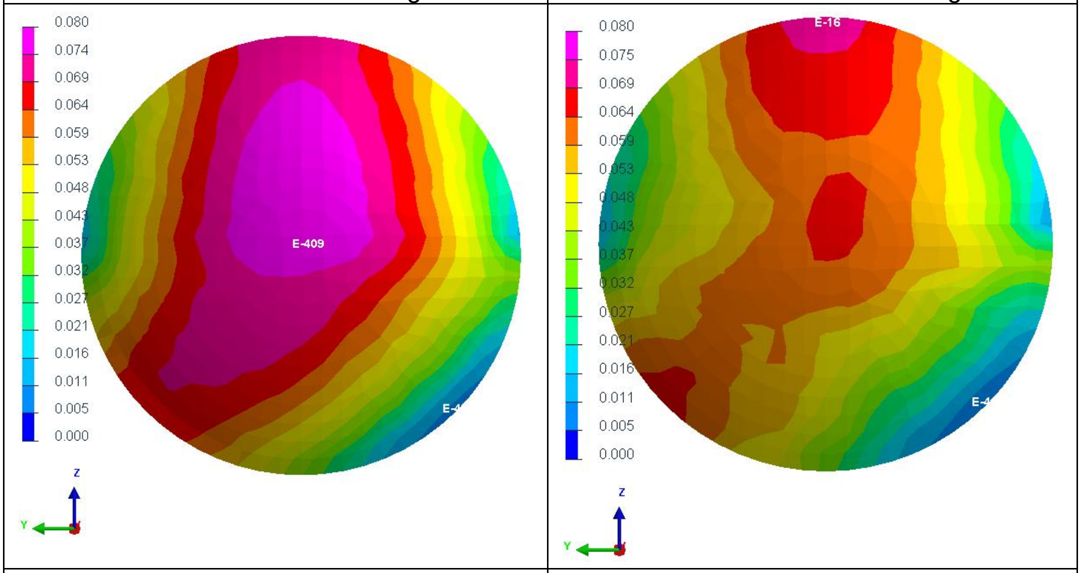
Fixed at their outer diameters, two fabric panels were numerically sewn using a simple line of common nodes. The different fabric orientations (90°/45°) of the two semicircles were taken into by different local warp/weft orientation of the MAT 34 finite elements, see Figure 9, left.

7.2 Strain distribution over the surface

To assess the validity of the new formulation and the set of behavior laws obtained by optimization, the strain distributions over the surface between Mat 34 Form = 14 and Form = -14 were compared as shown Figure 10.



FORM = 14 / GL. Strain along Weft | FORM = -14 / GL. Strain along Weft



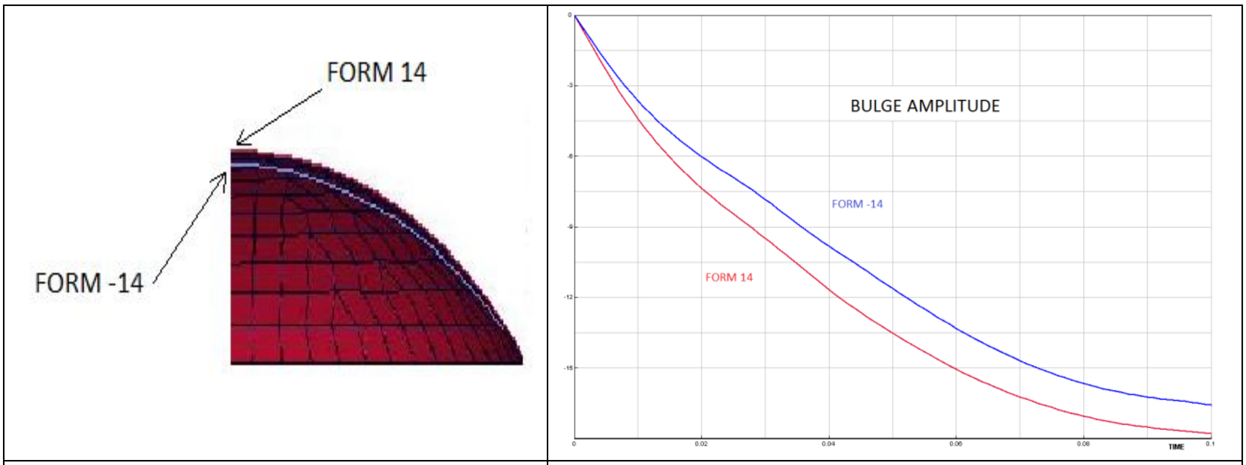
FORM = 14 / GL. Strain along Warp | FORM = -14 / GL. Strain along Warp

Figure 10 : Comparison of strain distribution over the surface at the maximum pressure.

The comparison of the strain distribution over a fabric sample subjected to a pressure field, successfully shows a stiffening of the material properties. Hence the new formulation of the MAT34 enables to simulate the variation of fabric behavior due to the scrimp interchange. In both warp / weft directions, a reduction of a maximum of 20% of the strain values is measured in the center of the circular sample of fabric. This value corresponds to the variance between uni-axial and bi-axial tensile behavior laws.

7.3 Analysis of Bulge amplitudes

To confirm the stiffening of the fabric material using FORM = -14, a global measurement was also assessed. The pressure generated inside the GES, induces a curvature of the circular fabric sample. The amplitude of this bulge experimentally measured by a laser, was compared between the two FORM 14 / -14.



Measurement of the max bulge point

Variation of the bulge amplitude vs. time

Figure 11 : Comparison of Bulge amplitude

Initially equivalent, a stiffening of the fabric property of FORM = -14 compared to FORM = 14 is progressively observed on Figure 11. At the maximum of pressure, a significant reduction of 10% of the bulge amplitude is obtained. This modification of behavior is in accordance with the expected result and validates the whole methodology.

As a consequence, an update of the Saint Venant Wantzel leakage coefficients is needed for un-coated airbag fabric when it is modeled with MAT 34 Form =-14.

8 Summary

This paper describes a methodology to determine material behavior using reversed engineering. The use of automated procedures enables to obtain reliable numerical behavior law and to match test data. The comparison of the strain distribution over a fabric sample submitted to a pressure field shows that the new formulation MAT 34 Form = -14 enables to reproduce the effect on the fabric scrimp interchange. The material becomes stiffen and a global observable, the bulge amplitude, is modified by 10%.

9 Perspectives

The current Form = -14 is a linear interpolation between uni-axial behaviour laws and balanced bi-axial behaviour laws. During the airbag deployment and the restraint phase, various cases of bi-axial loadings are expected. The next development aims at extrapolating this new formulation to the general cases of bi-axiality.

10 Acknowledgement

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11 References

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