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Inverse Parameters Determination Procedure in Material Behavior Model

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ABSTRACT: *Currently, finite element models are commonly used in product design and development processes. The value of material parameters in the material behavior model is one factor determining the accuracy of numerical simulation results. The study proposes a procedure for inversely determining material parameters in the behavior model of anisotropic materials. The obtained results show that the proposed method has accuracy and reliability. This procedure can be applied to many different material behavior models.*

KEYWORDS: *Inverse, Simulation, Material*

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I. INTRODUCTION

Nowadays, in the product design process, the application of finite element simulation helps reduce the time and cost of the testing phase. Therefore, determining the exact values of material parameters in the finite element model is very important. Depending on the material used in the study, the values of the parameters in the behavior model are determined. For example, the Johnson-Cook behavior model is used in many studies related to the need to determine material parameters. However, each study uses a different approach to determine the parameters in the model. In particular, in the case of metal forming, a good knowledge of the elastic-plastic material properties is of utmost importance to perform sufficiently accurate simulations. Or in many cases, a complete description of the mechanical behavior of the material can be a difficult task, for materials with anisotropic properties.

Up to now, there have been many studies in which it is necessary to directly determine the parameter values of materials in finite element models [1][2][3][4][5][6]. Based on the Johnson-Cook flow stress model, the values of the parameters in the behavior model for lead-free brass were determined. Finite element simulations with the model were then conducted to compare the results with cutting experiments to estimate the damping effect in metal cutting [7]. A hybrid inverse analysis method to determine the nonlinear material parameters of any individual component from the mechanical responses of a composite material is proposed in the study of A. This method combines experimental approach, numerical simulation with inverse search method. The experimental approach is used to provide the basic data. Then, using the obtained experimental data and inverse search algorithm to determine the elastic-plastic material properties [8]. The parameters in the Johnson Cook model of failure behavior were determined in the study of B. Uniaxial tensile tests and an optimization program were developed in Matlab and based on the inverse method [9]. Johnson-Cook plasticity and damage models were used to predict the material properties and impact behavior of 2024-T3 aluminum alloy. Comparison of finite element analysis results with experiments, under similar material and impact conditions, showed good correlations in impact force, deformation, and failure processes [10].

Most of the above studies have not clearly presented how to determine the values of parameters in the material behavior model. Therefore, in this study, we propose a procedure for determining the values of parameters in the anisotropic behavior model of materials.

II. MATERIAL AND METHODOLOGY

II.1. MATERIAL

Compact cardboard has a linear elastic behavior up to a given limit: the elastic limit. The properties of the fibers and the manufacturing process of the board result in a material that can be considered orthotropic. This means that the materials will have different properties in three main orthogonal directions: MD-machine direction, CD-cross direction and ZD-thickness direction (Fig. 1).

The constitutive law governing the behavior of an orthotropic material can be written in the (x, y, z) frame corresponding to (MD, CD, ZD):

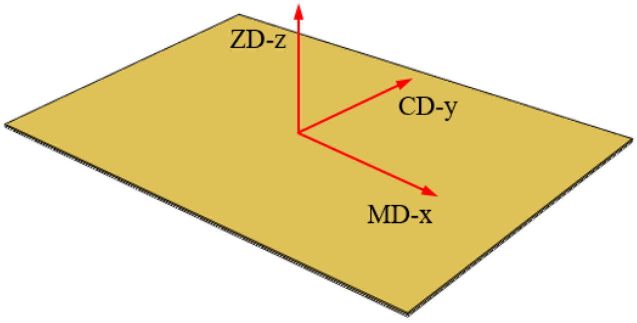

Fig. 1 Three main directions of paperboard

$$\{\boldsymbol{\varepsilon}\} = \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \varepsilon_{xy} \\ \varepsilon_{xz} \\ \varepsilon_{yz} \end{Bmatrix} = [\boldsymbol{S}]\{\boldsymbol{\sigma}\} = \begin{bmatrix} \frac{1}{E_x} & \frac{-\nu_{yx}}{E_y} & \frac{-\nu_{zx}}{E_z} & 0 & 0 & 0 \\ \frac{-\nu_{xy}}{E_x} & \frac{1}{E_y} & \frac{-\nu_{zy}}{E_z} & 0 & 0 & 0 \\ \frac{-\nu_{xz}}{E_x} & \frac{-\nu_{yz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{xy}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{xz}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{yz}} \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \sigma_{xy} \\ \sigma_{xz} \\ \sigma_{yz} \end{Bmatrix} \tag{1}$$

where {σ} is the stress tensor, {ε} is the strain tensor, [s] is the flexibility matrix, E_i are the Young's moduli, ν_{ij} are the Poisson's ratios and G_{ij} are the shear moduli.

Anisotropic plastic behavior model of cardboard following IPE behavior model. The orthotropic elasticity behavior in plane stresses is defined by:

$$\{\sigma\} = \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix} = [H]\{\varepsilon^e\} = \frac{1}{(1-\nu_{xy}\nu_{yx})} \begin{bmatrix} E_x & \nu_{yx}E_x & 0 \\ \nu_{xy}E_y & E_y & 0 \\ 0 & 0 & G_{xy}(1-\nu_{xy}\nu_{yx}) \end{bmatrix} \begin{Bmatrix} \varepsilon_x^e \\ \varepsilon_y^e \\ \gamma_{xy}^e \end{Bmatrix} \tag{2}$$

The deviatoric stresses vector and the IPE plasticity criterion are given by:

$$\{s\} = \begin{Bmatrix} s_x \\ s_y \\ s_z \\ s_{xy} \end{Bmatrix} = [L]\{\sigma\} = \frac{1}{3} \begin{bmatrix} 2A & C-A-B & 0 \\ C-A-B & 2B & 0 \\ B-C-A & A-B-C & 0 \\ 0 & 0 & 3D \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix} \tag{3}$$

$$f = \sigma_{eq} - \sigma_y = \left(\frac{3}{2}\langle s\rangle\{s\}\right)^{1/2} - E_0\left(\varepsilon_0 + \varepsilon_{eq}^p\right)^{1/n} \tag{4}$$

where σ_y is the plasticity threshold, A, B, C, D, E_0 and n are the IPE model parameters which will be determined from the reverse identification procedure proposed in this study. The research material was cardboard with a grammage of 315 g/m^2 and a thickness of 0.55 mm.

II. 2. METHODOLOGY

The values of material parameters in the behavior model directly affect the accuracy of the FEM model when performing numerical simulations. Therefore, it is necessary to accurately determine these values. In this section, an inverse determination method is proposed to determine the values of parameters in the behavior model of the material. Accordingly, a numerical simulation of the tensile test of the material is performed (the values of the parameters in the behavior model are taken arbitrarily). In the next step, the comparison and evaluation of the error between the numerical curve and the experimental curve are performed using optimization algorithms. Thus, the data needed for this identification process are the results of experiments and a behavior model of the material. The general procedure for inverse determination of parameters is shown in Fig. 2.

The objective function of the process is given in expression (5).

$$F_{obj} = \frac{1}{N}\sum_{i=1}^{n}\left(F_{num}(t_i) - F_{exp}(t_i)\right)^2 \tag{5}$$

where N is the number of experimental points, t_i represents the strain corresponding to the experimental point i, F_{num} and F_{exp} are the numerically and experimentally calculated stresses, respectively.

The objective function is the quadratic difference between the numerical and experimental tensile forces. Minimizing this quadratic deviation is performed based on the combination of Abaqus simulation software and modeFRONTIER optimization software. The identification procedure, developed and presented in the modeFRONTIER software environment, is shown in Fig. 3.

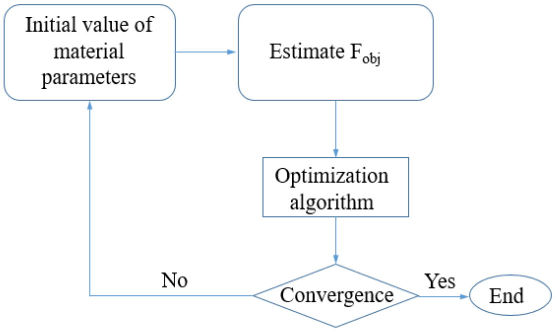

Fig. 2 General procedure for determining parameters

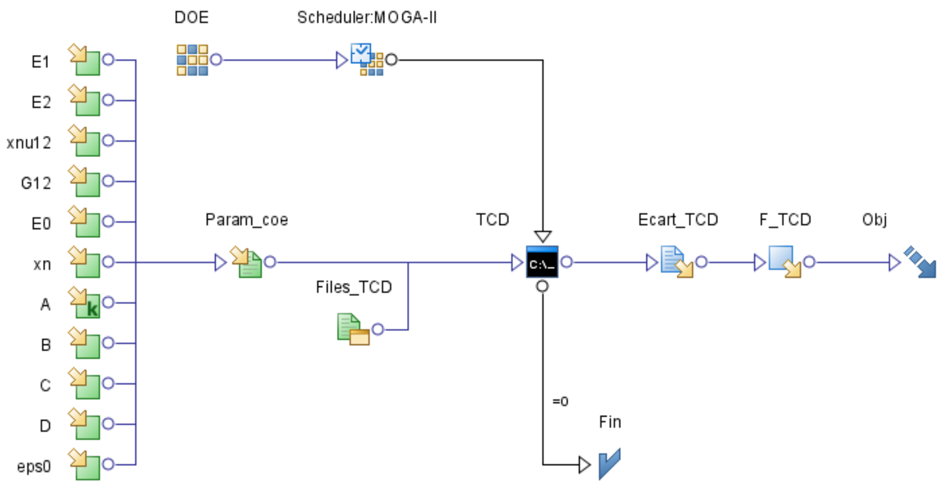

Fig. 3 Flowchart of the inverse determination process in ModeFrontier

The reverse identification process consists of several key steps as follows:

- Optimization Algorithm:

Various standard (Simplex, Levenberg Marquardt, etc.) or advanced (NGSA-II, etc.) optimization algorithms are available in modeFrontier and can be used depending on the complexity of the problem to be solved. In this study, we use the NGSA-II optimization algorithm.

- Parameters to be determined:

Depending on the behavior of each type of material in the behavior model, the number of material parameters to be determined will be determined.

- The FEM models of the tensile specimens are imported as inp files and combined with the VUMAT subroutine
- The script will execute the command as required.

This part is a collection of subroutines such as UMAT, VUMAT for material behavior, programs programmed to read and extract values from Odb files when simulating tensile specimens, experimental values, and other calculation programs.

The objective function values are given and evaluated after each loop.

III. RESULTS AND DISCUSSION

The material used in this study was cardboard. The tensile test specimens were cut in three directions (MD, CD and 450). The experimental tensile tests were performed at a speed of 10 mm/min under standard conditions (23°C and 50% relative humidity). The experimental tensile results are shown in Figure 4.

For paperboard, the parameters in the IPE model are determined based on tensile tests performed in the MD, CD and 450 directions, so the determination of the parameters must take place simultaneously according to the process shown in Figure 5.

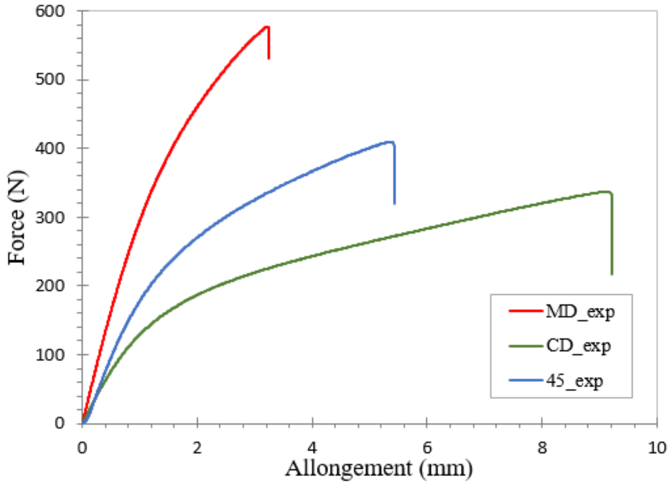

Fig. 4 Force vs displacement curves from tensile tests of paperboard

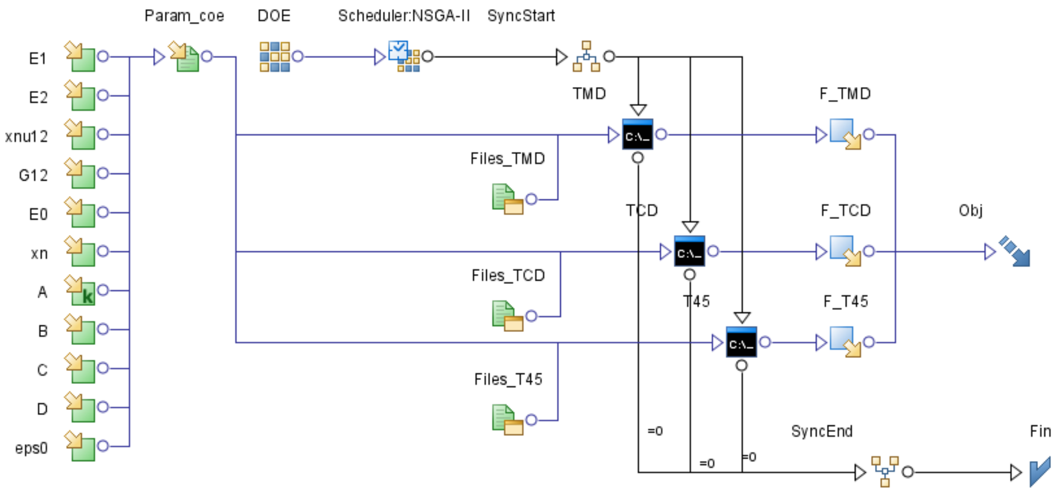

Fig. 5 Reverse identification process in ModeFrontier

Each iteration of the identification process gives a set of corresponding parameter values (Fig. 6, 7, 8, 9, 10). After each iteration of the calculation, a pre-programmed Python code program automatically reads the OBD file in Abaqus to extract the numerical curve of the tensile specimen. This curve is compared with the experimental curve to give the values of the parameters. After more than 48 hours of calculation on a computer with a configuration of Processor Intel(R) Xeon(R) CPU E5-2689 0 @ 2.60GHz 2.60 GHz, RAM 16.0 GB, the results are obtained as shown in Fig. 11 and the values of the parameters in the IPE model are shown in Table 1.

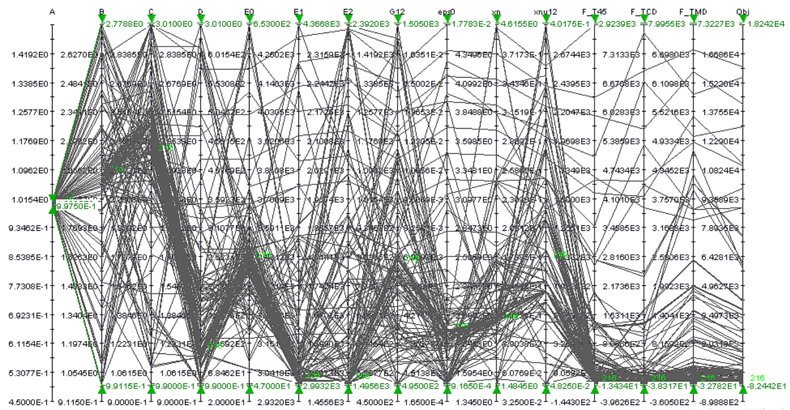

Fig. 6 Changes in input variable values and objective function values

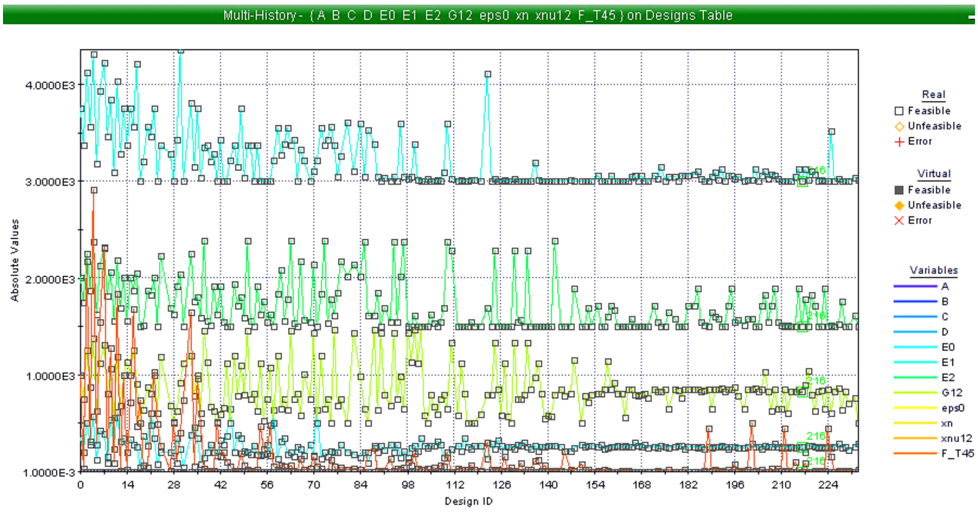

Fig. 7 Changes in input variable values and objective function values (Direction 45^0)

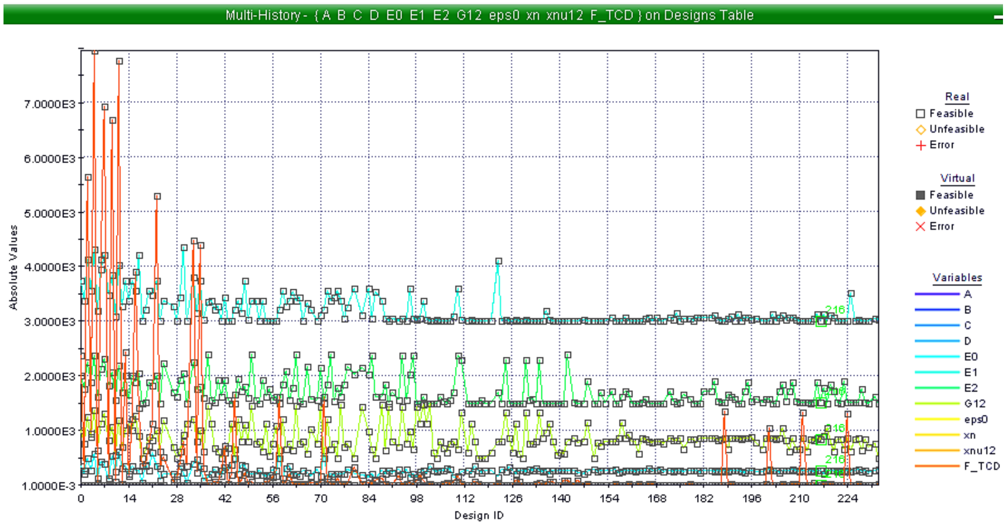

Fig. 8 Changes in input variable values and objective function values (Direction CD)

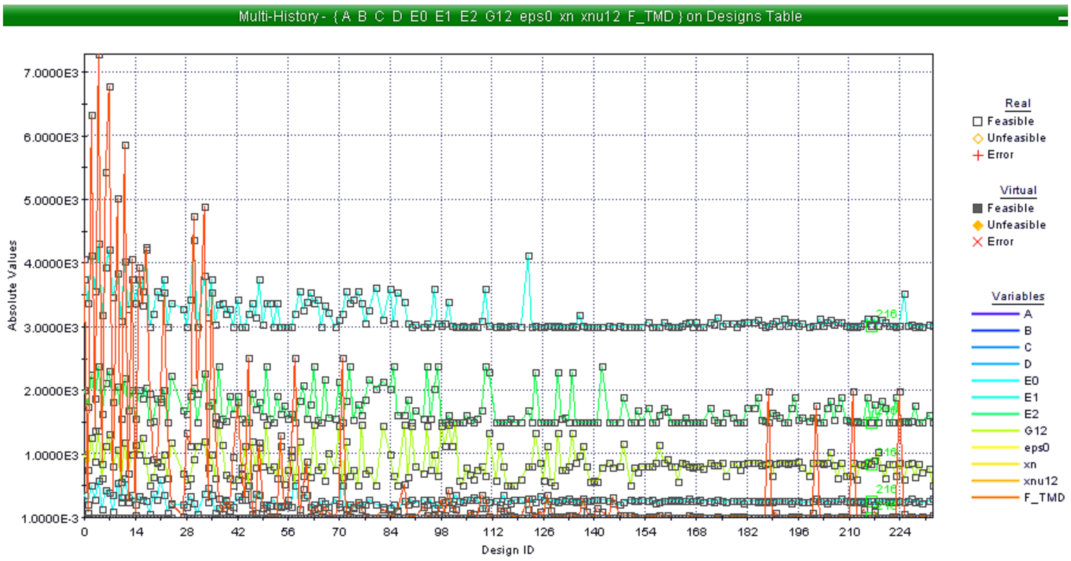

Fig. 9 Changes in input variable values and objective function values (Direction MD)

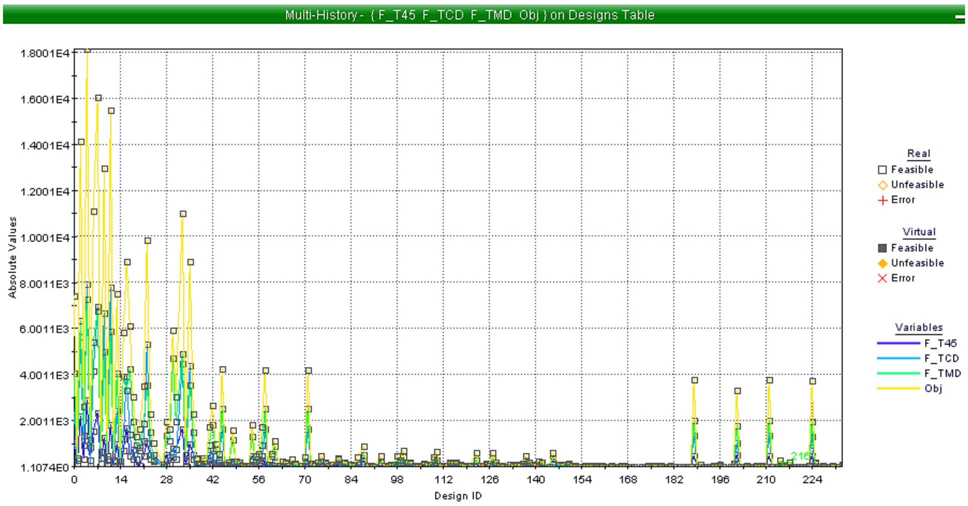

Fig. 10 Optimizing the objective function value (Obj)

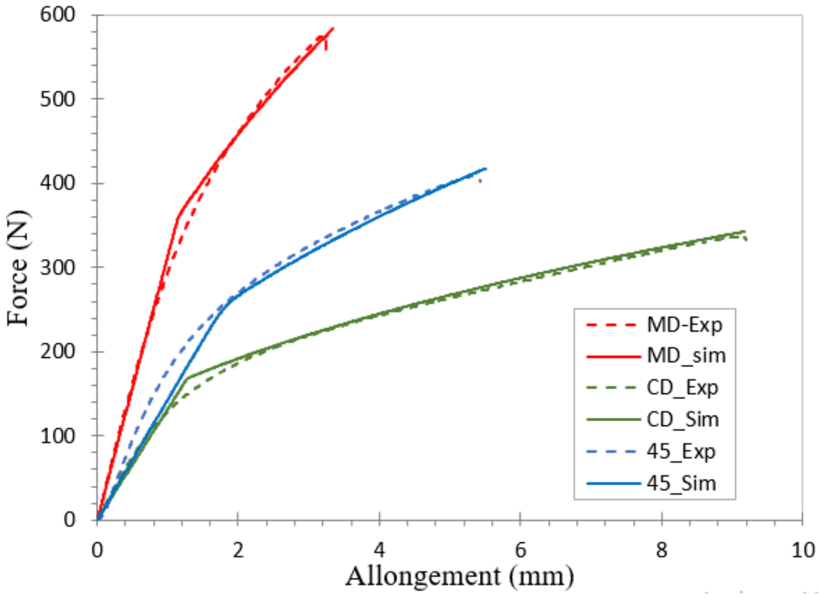

Fig. 11 Experimental and inverse determination curves of papers 1 and 3

Table 1. Properties of cardboard

E_x (MPa)	E_y (MPa)	ν_{xy}	G_{xy} (MPa)	E_0	n	A	B	C	D	ε_0
2350.2	879.91	0.0829	1047.2	91.45	2.3	1.0	2.03	2.35	1.05	0.0045

IV. CONCLUSION

The study has developed a procedure for determining parameter values in the behavior model of anisotropic materials based on experimental curves. The proposed procedure uses the NGSA-II optimization algorithm, so the identification results are reliable. The procedure can be applied to determine material parameters in different behavior models of materials.

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