A Sensitivity Analysis Method for Finite Element Simulation of 
CFRP Drilling Process

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Abstract. This paper developed a sensitivity analysis method for FE simulation of CFRP drilling 
process to rank the parameters in order of importance. Firstly, a FE model of CFRP is established 
using ABAQUS/Explicit. A standard twist drill is imported from stp-formatted files, then it is meshed 
using C3D4 element and treated as rigid body. The CFRP is modeled as a shell and 2D Hashin 
Criteria is used to represented the damage. Secondly, a back-propagation artificial neural network is 
established and trained with the data generated by the FE models using different parameters, which is 
designed by uniform design method. Lastly, the sensitivity analysis of the back-propagation artificial 
network is carried out using analytical method. The sensitivity of the parameters in the FE 
model is calculated using a MATLAB program.

Introduction

Composite materials, especially carbon fiber reinforced plastics (CFRP), have been become very 
promising materials and have been widely used in the most diverse fields of engineering ranging from 
aviation to automobile. Drilling of CFRP, as one of the most common secondary manufacturing 
process in assembly, has become a hot spot [1]. Finite element (FE) simulation is an economical and 
effective approach to help understand the cutting mechanism of CFRP drilling and optimize the 
technical parameters [2].

Chakladar et al [3] estimated drilling responses using finite element as a numerical simulation tool. 
An equivalent elastic macromechanical model was assumed for the woven composite workpiece. 
Isbilir et al [4] developed a 3D FE model of the process of drilling in CFRP using 2D Hashin Criteria. 
The FE model is used to investigate the effects of cutting speed and feed rate on thrust force, torque 
and delamination. Then, Isbilir et al [5,6] continued their study by establishing the drilling FE model 
based on 3D Hashin Criteria and focused on the relation between delamination and tool geometry. 
Phadnis et al developed [7] a unique three-dimensional (3D) finite element model of drilling in a 
composite laminate, accounting for complex kinematics at the drill-workpiece interface and the effect 
of cutting parameters on drilling thrust force and torque during the machining process was studied. 
Feito et al [8] developed both complete and simplified models and compared in terms of delamination 
prediction, and stated that the simplified model, presenting reduced computational cost, slightly 
overestimates the delamination factor when compared with the complex model. Usui et al [9] 
presented a finite element scheme using a nonlinear, large deformation Lagrangian formulation with 
an explicit time integration, which is employed with cohesive element insertion and structured mesh 
element splitting. The simulation procedure against experiments for four fiber orientations was 
validated.

As we can see from the above, some achievements have been made in this field of FE simulation of 
CFRP drilling, which help understand the mechanism of CFRP cutting. The trend is the establishing 
of more complex and precise models. Nevertheless, the more precise model calls for the more precise 
material property, which has not paid enough attention for nowadays. Most researchers used the
material property derived from earlier literature, even though the batches or the material designation are not the same. The precise material property of CFRP would be very important for the foreseeable future to generalize FE simulation to engineering applications.

However, there are too many parameters to describe the material property of CFRP, Young's modulus, shear modulus and Poisson's ratio in each direction, tensile strength, compressive strength and transverse in each direction, et al. To gained precise value of every parameter is uneconomic and time consuming. Some parameters may contribute a lot to the precision of the simulation, but others not. This means that the key parameters should be paid more attention. This leads to the next topic, how to select the key parameters, which is the innovative work of this paper.

**Analysis of FE Simulation on CFRP Drilling**

In this study a 3D FE model is performed using the commercial FE package, ABAQUS/Explicit, as shown in Figure 1. The mass an inertia effects are included and the dynamic characteristics of the process is proposed.

![Figure 1. 3D FE model of CFRP drilling.](image)

**FE Modeling of CFRP Drilling**

The cutting tool is a 6 mm drill with 118° point angle and 30° helical angle. The drill is constrained in x and y directions (U1=U2=UR1=UR2=0), and the velocity is set -1.5 mm/s in V3 direction and -314 radians/s in VR3 direction. The CFRP laminates is a multi-directional having dimensions of 12 mm×12 mm×5 mm consists of 40 plies with a stacking sequence of [0°/-45°/90°/45°]_{5S}. The encastre boundary of the CFRP workpiece is used, namely U1=U2=U3=UR1=UR2=UR3=0.

The Dynamic/Explicit step is selected and Nlgeom setting is toggled on which means geometric nonlinearity during the step is accounted for. Surface to surface contact is set to describe the interaction between drill and CFRP, and the tangential behavior is described by penalty friction formulation. A rigid body constraint is set up to build the relationship between reference point RP-1 and the drill. The boundary conditions of the drill are imposed on RP-1.

A 4- node doubly curved thick shell, reduced integration, hourglass control, finite membrane element (S4R) is selected for the CFRP workpiece. Element deletion is toggled on to describe the cutting behavior of the element. The element type of the drill is 4-node linear tetrahedron (C3D4).

**Material Parameters Setting and Force Extraction**

The material properties of T700/E-44 graphite/epoxy unidirectional CFRP are given in Table 1. Some engineering constants in different direction are combined because of the orthogonal anisotropy of CFRP laminates.
Table 1. Material properties of T700/E-44.

| E1 [Mpa] | E2/E₃ [Mpa] | Nu12/Nu13 | Nu23 | G12/G1₃ [Mpa] | G23 [Mpa] | LT [Mpa] | LC [Mpa] | TT [Mpa] | TC [Mpa] | LS/TS [Mpa] |
|----------|-------------|-----------|------|---------------|----------|---------|---------|---------|---------|-------------|
| 11200    | 8200        | 0.3       | 0.4  | 4500          | 3000     | 1900    | 1000    | 84      | 250     | 110         |

The simulation result and the thrust force are shown in Figure 2.

Figure 2. Simulation result and the thrust force.

Four parameters of the CFRP properties is pick up to study their effect to the simulation results. Different level of the four factors are organized by uniform design method, as shown in Table 2, and the other factors remain unchanged.

Table 2. Different level of material properties of CFRP.

| No. | Parameters of CFRP |   |   |   |   |   |   |   |
|-----|--------------------|---|---|---|---|---|---|---|
| T1  | E1 [Mpa]           |   |   |   |   |   |   |   |
|     | Nu12/Nu13          | 0.3|   |   |   |   |   |   |
|     | LT [Mpa]           | 1900|   |   |   |   |   |   |
|     | LS/TS [Mpa]        | 110 |   |   |   |   |   |   |
|     | Force [N]          | 328 |   |   |   |   |   |   |
| T2  | E1 [Mpa]           |   |   |   |   |   |   |   |
|     | Nu12/Nu13          | 0.21|   |   |   |   |   |   |
|     | LT [Mpa]           | 1800|   |   |   |   |   |   |
|     | LS/TS [Mpa]        | 450 |   |   |   |   |   |   |
|     | Force [N]          | 424.8|   |   |   |   |   |   |
| T3  | E1 [Mpa]           |   |   |   |   |   |   |   |
|     | Nu12/Nu13          | 0.3|   |   |   |   |   |   |
|     | LT [Mpa]           | 600 |   |   |   |   |   |   |
|     | LS/TS [Mpa]        | 370 |   |   |   |   |   |   |
|     | Force [N]          | 22.78|   |   |   |   |   |   |
| T4  | E1 [Mpa]           |   |   |   |   |   |   |   |
|     | Nu12/Nu13          | 0.39|   |   |   |   |   |   |
|     | LT [Mpa]           | 2000|   |   |   |   |   |   |
|     | LS/TS [Mpa]        | 290 |   |   |   |   |   |   |
|     | Force [N]          | 125.2|   |   |   |   |   |   |
| T5  | E1 [Mpa]           |   |   |   |   |   |   |   |
|     | Nu12/Nu13          | 0.48|   |   |   |   |   |   |
|     | LT [Mpa]           | 820 |   |   |   |   |   |   |
|     | LS/TS [Mpa]        | 210 |   |   |   |   |   |   |
|     | Force [N]          | 109.1|   |   |   |   |   |   |
| T6  | E1 [Mpa]           |   |   |   |   |   |   |   |
|     | Nu12/Nu13          | 0.18|   |   |   |   |   |   |
|     | LT [Mpa]           | 2200|   |   |   |   |   |   |
|     | LS/TS [Mpa]        | 130 |   |   |   |   |   |   |
|     | Force [N]          | 181.6|   |   |   |   |   |   |
| T7  | E1 [Mpa]           |   |   |   |   |   |   |   |
|     | Nu12/Nu13          | 0.27|   |   |   |   |   |   |
|     | LT [Mpa]           | 1000|   |   |   |   |   |   |
|     | LS/TS [Mpa]        | 50  |   |   |   |   |   |   |
|     | Force [N]          | 81  |   |   |   |   |   |   |
| T8  | E1 [Mpa]           |   |   |   |   |   |   |   |
|     | Nu12/Nu13          | 0.36|   |   |   |   |   |   |
|     | LT [Mpa]           | 2400|   |   |   |   |   |   |
|     | LS/TS [Mpa]        | 490 |   |   |   |   |   |   |
|     | Force [N]          | 219.1|   |   |   |   |   |   |
| T9  | E1 [Mpa]           |   |   |   |   |   |   |   |
|     | Nu12/Nu13          | 0.45|   |   |   |   |   |   |
|     | LT [Mpa]           | 1200|   |   |   |   |   |   |
|     | LS/TS [Mpa]        | 410 |   |   |   |   |   |   |
|     | Force [N]          | 107.6|   |   |   |   |   |   |
| T10 | E1 [Mpa]           |   |   |   |   |   |   |   |
|     | Nu12/Nu13          | 0.15|   |   |   |   |   |   |
|     | LT [Mpa]           | 2600|   |   |   |   |   |   |
|     | LS/TS [Mpa]        | 330 |   |   |   |   |   |   |
|     | Force [N]          | 222.6|   |   |   |   |   |   |
| T11 | E1 [Mpa]           |   |   |   |   |   |   |   |
|     | Nu12/Nu13          | 0.24|   |   |   |   |   |   |
|     | LT [Mpa]           | 1400|   |   |   |   |   |   |
|     | LS/TS [Mpa]        | 250 |   |   |   |   |   |   |
|     | Force [N]          | 107.3|   |   |   |   |   |   |
| T12 | E1 [Mpa]           |   |   |   |   |   |   |   |
|     | Nu12/Nu13          | 0.33|   |   |   |   |   |   |
|     | LT [Mpa]           | 2800|   |   |   |   |   |   |
|     | LS/TS [Mpa]        | 170 |   |   |   |   |   |   |
|     | Force [N]          | 228.2|   |   |   |   |   |   |
| T13 | E1 [Mpa]           |   |   |   |   |   |   |   |
|     | Nu12/Nu13          | 0.42|   |   |   |   |   |   |
|     | LT [Mpa]           | 1600|   |   |   |   |   |   |
|     | LS/TS [Mpa]        | 90  |   |   |   |   |   |   |
|     | Force [N]          | 108.3|   |   |   |   |   |   |

Sensitivity Analysis based on Neural Network Method

Sensitivity analysis is heavily dependent on the functional expressions of the input and output data. And unfortunately, the FE model is a very complex nonlinearity system, which means the functional expressions is complex and invisible. Back-propagation artificial neural network is a kind of local...
approximation neural networks. In theory, it can approximate any continuous function if there is enough neuron [10]. The result of the FE model is unique when the input data is given. The train data could be obtained through a serial of FE models. Then the functional expression could be obtained and the sensitivity analysis is available.

S-shape activation transfer function could be expressed as

$$f(x) = \frac{1}{1 + \exp(-x)}$$  \hspace{1cm} (1)

For a simple 3 layers back-propagation network with S-shape activation transfer function, the output of the output layer could be written as [11]

$$O_k = f\left(\sum_j f\left(\sum_i O_i W_{ij} + \theta_i\right) W_{jk} + \theta_k\right)$$  \hspace{1cm} (2)

where $O_k$ is the output data of the output layer, $O_i$ is the output data of the input layer. $W_{jk}$ stands for the connection weight of the middle layer units to the output layer units, $W_{ij}$ stands for the connection weight of the input layer units to the middle layer units, $\theta_i$ and $\theta_k$ are the threshold of corresponding connection.

Set

$$e_j = \sum_i O_i W_{ij} + \theta_i$$  \hspace{1cm} (3)

Then Eq. 2 could be expressed as

$$O_k = f(e_j) = f\left(\sum_j f(e_j) W_{jk} + \theta_k\right)$$  \hspace{1cm} (4)

The S-shape activation transfer function is continuously differentiable, which makes the partial derivative taking process feasible. The partial derivative of the output data $O_k$ to the input data $O_i$ could be expressed as

$$\frac{\partial O_k}{\partial O_i} = \sum_j \frac{\partial O_k}{\partial O_j} \frac{\partial O_j}{\partial O_i}$$  \hspace{1cm} (5)

For the network more than 3 layers, the partial derivative will be

$$\frac{\partial O_k}{\partial O_i} = \sum_{j_m} \sum_{j_{m-1}} \cdots \sum_{j_1} \frac{\partial O_k}{\partial O_{j_m}} \frac{\partial O_{j_m}}{\partial O_{j_{m-1}}} \cdots \frac{\partial O_{j_1}}{\partial O_{j_1}}$$  \hspace{1cm} (6)

Combined with Eq. 1 and Eq. 2, Eq. 4 could finally be derived to Eq. 7.

$$\frac{\partial O_k}{\partial O_i} = \sum_{j_m} \sum_{j_{m-1}} \cdots \sum_{j_1} W_{jk} G(e_k) W_{j_m} G(e_{j_m}) W_{j_{m-1}} G(e_{j_{m-1}}) \cdots W_{j_1} G(e_{j_1})$$  \hspace{1cm} (7)

where

$$G(e_{j_m}) = \frac{\exp(-e_{j_m})}{[1 + \exp(-e_{j_m})]^2}$$  \hspace{1cm} (8)

Model Calculation and Result Interpretation

Implementation Step of Sensitivity Analysis

ABaqus and MATLAB are combined to carry out the sensitivity analysis, as shown in Figure 3. The results of FE simulation of CFRP drilling are exported to an Excel-format file, which will be used as
the training data. The training data is normalized and the model is trained by back-propagation artificial neural network function in MATLAB. Lastly the partial derivation process is conducted using constant matrices of the network model and the data is written to specified file.

![Flow chart of the sensitivity analysis.](image)

**Result Interpretation**

The results of the sensitivity analysis are plotted in Figure 4. The four selected parameters have their corresponding sensitivity value at each sample point. As we can see, the sensitivity of is not a constant, but a variable depending on the sample, namely the value of all the other parameters.

![Sensitivity value of the parameters of FE model.](image)

![Sensitivity proportion of T1 and average value.](image)

Young’s modulus in the main direction (E1) and shear strength (LT) have the main positive impact on the thrust force. Poisson’s ratio (Nu12/Nu23) has negative impact on the thrust force. And what is
interesting to be mentioned is that the effect of longitudinal tensile strength is not very obvious and ranging around zero.

The sensitivity value is reasonable only if the material parameters of the sample point is close to the real value. In this study, the material parameters of T700/E-44 has been used as the training data T1. The sensitivity proportion of T1 and average value is shown in Figure 5. For CFRP T700/E-44, the order of importance to thrust force is LS/TS(+), E1(+), Nu12/Nu23(-), and LT. This means that to get the more precise FE simulation results, the value of LS/TS(+) and E1(+) must be drew more attention. On the other hand, the value of LT is not so important and has strong error tolerance.

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