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AN APPROACH OF SENSITIVITY ANALYSIS FOR FINITE ELEMENT SIMULATION OF CFRP DRILLING PROCESS BASED ON SOBOL METHOD

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Finite element (FE) simulation of carbon fiber reinforced plastic (CFRP) drilling process requires numerous mechanical property parameters. It is time costly to obtain every value of the parameters and the impact level of every parameter to the simulation result has not been clear. This paper developed a sensitivity analysis method for FE simulation of CFRP drilling process to rank the parameters in order of importance. Firstly, an order-driven parametric FE model of CFRP is established using ABAQUS/Explicit. The CFRP is modeled as a shell and 2D Hashin Criteria is used to represent the damage. The simulation is carried on using non-GUI module to satisfy the request of large sample size. Secondly, different value combination of mechanical property parameters are assigned according to Sobol method and the corresponding results are extracted from the simulated drilling forces to complete enough samples. Lastly, the sensitivities of mechanical property parameters in the FE model are analyzed using Sobol method using MATLAB. Some tests have been carried out which proved the validity of the approach.

Keywords: CFRP, Drilling, FE simulation, Sensitivity analysis, Sobol method

1. Introduction

With the development of the application of composite materials, composite materials are more and more widely used in the aviation field due to their characteristics such as high specific strength, large specific modulus and corrosion resistance [1]-[3]. At present, Drilling of CFRP, as one of the most common manufacturing process in assembly, has become one of research focuses in this field. Due to the characteristics of anisotropy and non-homogeneity of CFRP, it is difficult to machining and is prone to delamination, tearing and wearing during drilling. The mechanism of CFRP drilling should be studied and finite element (FE) simulation is an effective way to help understanding the mechanism [4],[5].

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However, in the finite element simulation, the drilling model of composite materials involves lots of material parameters, including elastic parameters, fracture parameters and so on. For example, elastic modulus in three main directions, E_1, E_2, and E_3, shear modulus in three planes, G_{12}, G_{13}, and G_{23}, Poisson's ratio in three planes, μ_{12}, μ_{13} and μ_{23}, Shearing strength, L_S, T_S, Compressive strength, T_C, Tensile strength, L_T, T_T. Obtaining these parameters one by one through experiments will undoubtedly results in a great waste of time and resources, which greatly reduces the efficiency of studying the drilling mechanism of composite materials. Therefore, it is necessary to analyze the importance of each material parameter on the drilling force, that is, to calculate the sensitivity of each parameter during the drilling of composite materials. When data acquisition and mechanism research are carried out, the parameters with higher sensitivity could be selected according to the results of sensitivity analysis, and the material parameters with lower sensitivity can be assigned according to experience. Due to the proposed approach, lots of tedious experiments could be reduced and the efficiency of drilling mechanism research could be improved.

Sensitivity analysis is to study the sensitivity of the output change of a model to the change of model parameters. At present, lots of researchers have studied the application of sensitivity analysis method in engineering. For example, in model evaluation and engineering structure optimization, sensitivity analysis method is used to determine which parameters have great influence on the system or model [6]-[10]. Park et al. [11] used the method of global sensitivity analysis to optimize the design of the finite element simulation of convection physical mechanics. Charles et al. [12] used the improved global sensitivity analysis method to analyze the sensitivity of the hydrological model. Bravo et al. [13] optimized the design of the wing structure by using the global sensitivity analysis method. Under the condition of finite element simulation, the sensitivity of the wing structure was calculated and analyzed by using the global sensitivity analysis method based on variance. Ruan et al. [14] analyzed the global sensitivity of composite structure under uncertain conditions, Studied the uncertainty of the input variable of composite material structure response output variance and the influence of the failure probability, considering the material mechanics performance, layer thickness based on the variance and global sensitivity analysis method, and obtained the global sensitivity of input variable sort results.

In conclusion, it can be seen that although the sensitivity analysis method is quite mature and widely used in engineering. However, its application in the research of composite materials is not mature enough; especially the research on the sensitivity analysis of the drilling of composite materials still needs to be studied. This paper aims to analyze the sensitivity of material parameters to the drilling force during CFRP drilling using Sobol method.

2. Order-driven parametric FE drilling modeling

In order to realize CFRP drilling sensitivity analysis, many samples are required as analysis data, among which the input samples are different mechanical property parameters and the output samples are the corresponding drilling forces during CFRP drilling. The FE drilling model for CFRP is established. The material parameters could be assigned different value combination, and the boundary conditions of drilling process could be loaded by finite element simulation software. The simulation is submitted to obtain the drilling force results, which lays a foundation for the analysis of drilling sensitivity.

2.1. FE Modeling of CFRP Drilling

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

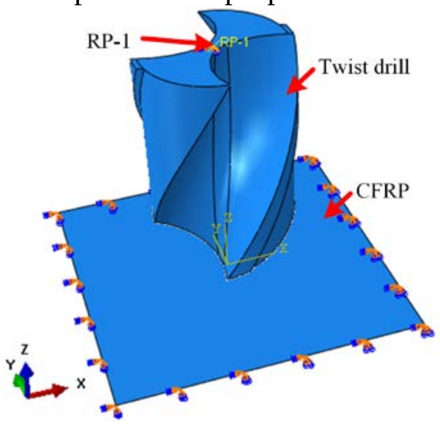

Fig. 1. 3D FE model of CFRP drilling

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 (U_1=U_2=UR_1=UR_2=0), and the velocity is set -1.5 mm/s in V_3 direction and -314 radians/s in VR_3 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 U_1=U_2= U_3= UR_1=UR_2= UR_3=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).

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

E_1 [Mpa]	E_2/E_3 [Mpa]	μ_{12}/μ_{13}	μ_{23}	G_{12}/G_{13} [Mpa]	G_{23} [Mpa]	L_T [Mpa]	L_C [Mpa]	T_T [Mpa]	T_C [Mpa]	L_S/T_S [Mpa]
112000	8200	0.3	0.4	4500	3000	1900	1000	84	250	110

The simulation result and the thrust force are shown in Fig. 2. Thrust force is the force in the axial direction of the drill (*z* direction in Fig. 1), and the radial force is the force perpendicular to the axis (*x/y* direction in Fig. 1). Due to the thickness of the CFRP, it is not appropriate to simulate the whole drilling process using 2D model. However, the highest thrust force, which appears at the entrance of the CFRP, is relatively credible due to the deformation of the laminate and the pushing of the drill tip. The 2D model could be reasonable enough to simulate the highest thrust force since the shell element is defined by reasonable mechanical properties with 40 layers.

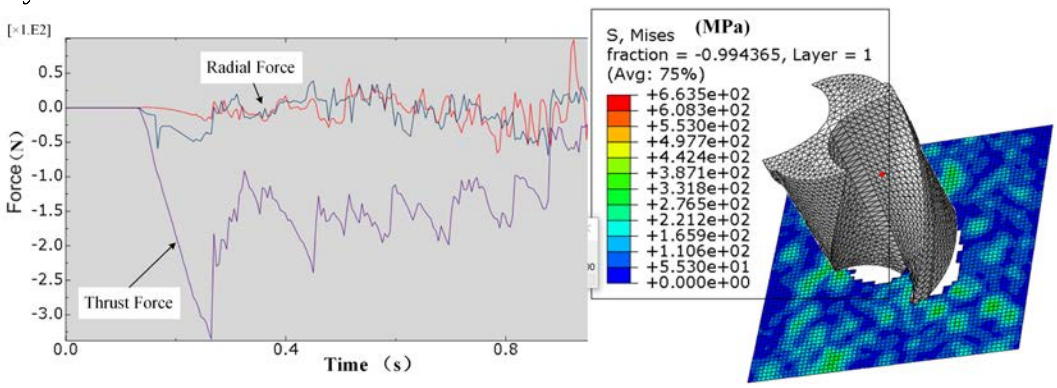

Fig. 2. Simulation result and the thrust force

2.2. Non-GUI module for the FE simulation

The purpose of this study is to analyze and obtain CFRP drilling sensitivity, which requires multiple drilling simulations to generate analysis samples. Due to the complexity of the simulation process, it requires large computer operation cost and time cost working with Abaqus GUI, and manual operation is prone to make mistakes. In addition, due to the large sample size, the manual modification of material parameters and submission of operations in Abaqus GUI become an unreasonable choice. In this paper, batch file is used to make the drilling simulation process run in non-GUI mode, which could solve the above problems.

The job is submitted after the CFRP finite element drilling model is completed, then the drilling process is simulated. The drilling force is extracted from PRT file. Get the RPY file which records the action steps in the Abaqus default storage path and change it into the PY file. Using Abaqus batch file, i.e., bat file, the command from PY file can be used to drive the FE drilling process of CFRP.

Non-GUI mode running does not need to be done on the Abaqus interface, but drives the simulation process through the command line, so that the generated files are saved in the local file and do not occupy the running resources, making the simulation process faster. Therefore, the operation of non-GUI mode lays a foundation for the generation of analysis samples.

3. Sample generation of drilling simulation

3.1. Generation of the input set

In order to realize sensitivity analysis of CFRP drilling simulation, a large number of samples are needed as data support. Considering the uniformity requirements of the samples, the quasi-random sequence, Sobol sequence, are adopted as the input sample, namely the material parameter sample.

Sobol sequence has the advantages of good uniformity of distribution and less time consuming of generating sequence, so it is very suitable to be used as the analysis sample of this study.

Each dimension of the Sobol sequence consists of a basic sequence with a base of 2, but each basic sequence of dimensions has its own matrix [15].

Sobol sequence is based on a set of number dt called direct numbers. Let q_i be positive odd number less than 2^i, then

$$d_i = \frac{q_i}{2^i} \quad (1)$$

Number d_i is generated by means of primitive polynomial of coefficient only 0 or 1. The polynomial could be expressed as

$$f(y) = y^p + a^1 y^{p-1} + \cdots + a^{p-1} y + a^p \quad (2)$$

As for $i>p$, there comes the recurrence formula:

$$d_i = \frac{1}{2}\left(a_1 d_{i-1} \oplus a_2 d_{i-2} \cdots \oplus a_p d_{i-p} \oplus d_{i-p}\right) \quad (3)$$

As for q_i, there comes the corresponding recurrence formula:

$$q_i = 2a_1 q_{i-1} \oplus 2^2 a_2 q_{i-2} \cdots \oplus 2^p a_p q_{i-p} \oplus q_{i-p} \quad (4)$$

According to the above principles and distribution characteristics of CFRP material parameters, 1000 material parameter samples are generated through

Matlab.

3.2. Generation of the output set

The output sample is the drilling force corresponding to 1000 sets of material parameters during CFRP drilling simulation. If these drilling force samples are generated directly through Abaqus simulation, 1000 sets of material parameters need to be artificially input and submitted to the work group by group. The workload is huge and difficult to achieve. In this paper, Isight integrated Abaqus is adopted to generate output samples more conveniently and quickly.

The operation record file PY, batch file BAT and result file PRT are imported into the Simcode module of Isight to achieve the integration with Abaqus. Then, 1000 sets of generated input samples are imported into the DOE module of Isight to realize automatic modification of drilling simulation parameters and submit jobs to generate drilling samples. This method greatly reduces the human workload and improves the research efficiency.

4. Model sensitivity solution and analysis

4.1. Sensitivity solution using Sobol method

The global sensitivity analysis method of Sobol has the following characteristics: (1) the global influence of various factors on the model is studied ; (2) the scope of factors can be extended to the entire domain of factors. All factors can change simultaneously, and the nonlinear, non-superposition and non-monotonic models can be studied and analyzed. It can directly reflect the input variable's contribution to the output response variance and is easy to calculate, which leads to the wide application in engineering practice.

The solution of the sensitivity using Sobol method is the key to this research. To some extent, the accuracy of the final CFRP drilling sensitivity analysis results is determined by this process.

Let $X=(X_1,X_2 \ldots X_n)$ be the input set, namely the material parameters of CFRP, such as young's modulus, poisson's ratio, etc. Assuming Y(X) is the response function of CFRP drilling, namely the drilling force. According to the global sensitivity analysis method based on variance proposed by Sobol method, the influence index of input variable X_i on the variance of output response Y can be established in the composite structure, the expression is:

$$S_i = \frac{V(E(Y \mid X_i))}{V(Y)} \tag{5}$$

where $V(Y)$ is the variance of output drilling force Y, and $V(E(Y|X_i))$ is the variance of conditional expectation E(Y|Xi) of each material parameter X_i to output drilling force Y.

S_i is a first-order sensitivity index (also known as the main effect of input variable's contribution to the variance of output response quantity), which can be used to measure the independent contribution of input variable to the variance of Y, and can reflect the impact of input variable X_i on the uncertainty of Y. From the above formula, the value of S_i is between 0 and 1. The higher the value of S_i, the greater the influence of the corresponding material parameter X_i on the variance of drilling force. Conversely, if the value of S_i is close to 0, the uncertainty of the corresponding material parameter X_i has little influence on the variance of drilling force.

The difficulty in solving the global sensitivity of CFRP drilling is to calculate the conditional expectation variance $V(E(Y|X_i))$ of the drilling force Y. For the CFRP drilling model, the dimension of random input variables is very high. At present, the State Dependent Parameter (SDP) method is generally adopted in engineering practice to solve the condition expectation, so as to solve the global sensitivity. The complete solution procedure is as follows.

According to the control theory, the SDP model of state space is established as follows:

Observation equation: $$Y_t = P_{i,t} + e_{i,t} \tag{6}$$

SDP model: $$P_{i,t} = P_{i,t-1} + d_{i,t-1} \tag{7}$$

$$d_{i,t} = d_{i,t-1} + \eta_{i,t},\ \eta_{i,t} \sim N(0,\sigma^2) \tag{8}$$

where $P_{i,t}$ are SDP state related parameters varying with state variable $X_{i,t}$, function of basic variable $X_{i,t}$, e_t (observation interference), $\eta_{i,t}$ (system disturbance) are all gaussian white noise input whose mean value is zero and variance is respectively σ^2 and $\sigma\eta^2$, which can be estimated by maximum likelihood optimization.

Then, Kalam Filtreing (KF) and the corresponding recursive Fixed Interval Smoothing (FIS) rule are used to estimate the state related parameters $P_{i,t}$ in the process of circular backward fitting.

Finally, calculate the conditional expectation of each parameter for output

$$E(Y_t \mid X_{i,t}) = Y_t - P_{i,t} \tag{9}$$

Calculate the variance $V(Y)$ of the sample output Y_t and the variance $V(E(Y|X_i)$ of the conditional expectation of X_i for Y.

$$V(Y) = \frac{1}{N-1}\sum_{t=1}^{N}[(Y_t - E(Y_t))]^2 \tag{10}$$

$$V(E(Y \mid X_i)) = \frac{1}{N-1}\sum_{t=1}^{N}[(E(Y \mid X_{i,t}) - E(E(Y \mid X_i))]^2 \tag{11}$$

According to the Equ. (5) of Sobol method, the global sensitivity index S_i of every parameter of composite material to cutting force during drilling is calculated.

According to the above principle, CFRP drilling sensitivity is calculated using Matlab programming to solve the Sobol method.

Input and output samples required for drilling sensitivity have been obtained previously. The input sample X_i and the output sample Y are imported into the Matlab program, and the sensitivity of the drilling simulation could be obtained, shown as Table 2 and Fig. 3.

Table 2

Sensitivity of the property parameters

X_i	E_1	E_2/E_3	G_{12}/G_{13}	G_{23}	L_C	L_S/T_S	L_T	T_C	T_T	μ_{12}/μ_{13}	μ_{23}
S_i	0.162	0.224	0.038	0.068	0.038	0.054	0.055	0.048	0.076	0.167	0.089

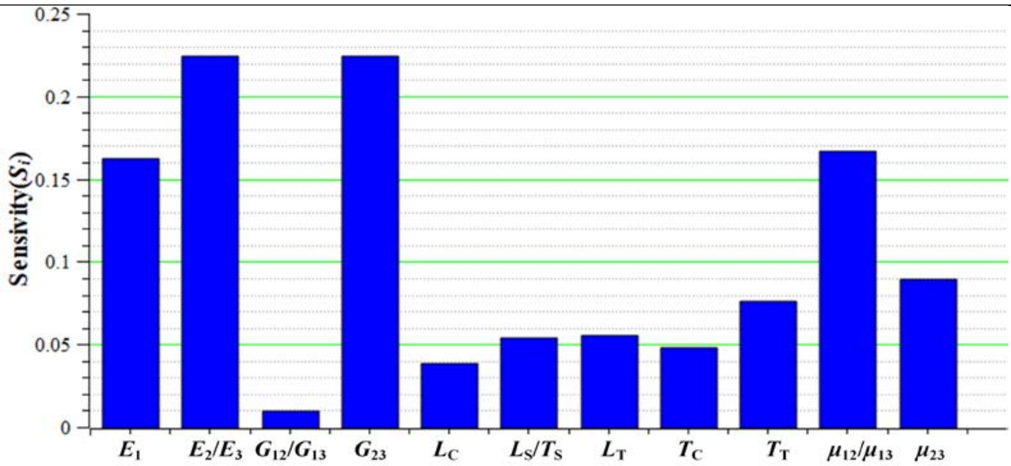

Fig. 3. Sensitivity of the property parameters

4.2. Results analysis and validation

As shown in Fig. 3, the sensitivity of the material parameters to the drilling force is ordered as: $E_2/E_3>\mu_{12}/\mu_{13}>E_1>\mu_{23}>T_T>G_{23}>L_T>L_S/T_S>T_C>G_{12}/G_{13}>L_C$. E_2/E_3, μ_{12}/μ_{13}, E_1 have greater influence on the drilling force, however, G_{12}/G_{13}, L_C have little influence on drilling force.

In order to explore whether the sensitivity results obtained are reliable, the following two groups of drilling simulation were performed with Abaqus for verification.

The validation parameters selected in this paper are E_2/E_3 and L_C. The control variable verification method is adopted, and the properties of the CFRP are shown as Table 3.

Firstly, a set of original parameters (Group 0) are designed, which are imported into Abaqus drilling model for drilling simulation, and the drilling force results are obtained. Then, other parameters are kept unchanged, and only E_2/E_3 is changed to get parameter Group 1, and drilling simulation is carried out to get corresponding drilling force results. After that, other parameters are controlled unchanged and L_C is changed to get parameter Group 2 and drilling simulation is carried out to get corresponding drilling force results. Finally, the variation of drilling force obtained from Group 1 and Group 2 is compared with that of the original drilling force, and the magnitude of variation is compared to observe whether the result is consistent with the theoretical calculation result.

By expanding E_2/E_3 and L_C to 10 times of the original group, and keeping other material parameters unchanged, corresponding drilling force results are obtained through drilling simulation, and the highest thrust forces are as shown in Table 3.

Table 3.

Material parameters and simulation results of verification experiment

	E_1 (Mpa)	E_2/E_3 (Mpa)	G_{12}/G_{13} (Mpa)	G_{23} (Mpa)	T_C (Mpa)	L_S/T_S (Mpa)	L_T (Mpa)	T_C (Mpa)	T_T (Mpa)	μ_{12}/μ_{13}	μ_{23}	Force (N)
0	324000	20000	6200	5600	1400	90	1600	130	170	0.2	0.39	799.15
1	324000	200000	6200	5600	1400	90	1600	130	170	0.2	0.39	1073.89
2	324000	20000	6200	5600	14000	90	1600	130	170	0.2	0.39	752.76

It can be obtained from the table: when other material parameters remain unchanged and only E_2/E_3 is expanded by 10 times, the drilling force changes by 34%. While the drilling force changes by 5.8% when the other parameters are changed by a tenfold reduction of L_C, that is, the sensitivity of E_2/E_3 to the drilling force in CFRP drilling is about 6 times of L_C. In this paper, the sensitivity of E_2/E_3 and L_C to the drilling force is 0.224 and 0.038 respectively by using the Sobol sensitivity analysis method, which is approximately 6 times. It can be concluded that the CFRP drilling sensitivity obtained by Sobol method is reliable.

5. Conclusion

In this paper, the sensitivity of material parameters to the drilling force during CFRP drilling is calculated using the sensitivity analysis method based on Sobol method. When the material parameters required by the mechanism research are obtained through experiments, only the parameters that have a great influence on the drilling force can be considered, which is conducive to improving the efficiency of mechanism research, saving time and materials. The work and conclusions are summarized as follows:

(1) The CFRP FE drilling model driven by instruction is established, the FE model of CFRP drilling is established by Abaqus. CFRP drilling damage is defined according to Hashin failure criteria, and non-GUI mode operation of drilling process is realized through Abaqus batch file.

(2) The input and output samples required for sensitivity analysis is established, and the input samples, namely material parameter samples, are generated according to the principle of Sobol sequence. The autologous modification of the parameters and the drilling force corresponding to the material parameters are generated by the Isight integrated Abaqus.

(3) The sensitivity of CFRP finite element drilling simulation is calculated. According to Sobol method, the sensitivity of the material parameters to the drilling force during CFRP finite element drilling simulation is calculated, and the reliability of the calculated results is verified by finite element simulation.

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