

Efficient Selection Method for Mass Scaling Factor in 3D Microscopic Cutting Simulation of CFRP

Fuji Wang^{*}, Xiang Zhao, Xiaonan Wang, Tianyu Gu and Boyu Zhang

Key Laboratory for Precision and Non-traditional Machining Technology of the Ministry of Education, Department of Mechanical Engineering, Dalian University of Technology, Dalian 116024, China

Abstract: 3D microscopic cutting simulation of CFRP is very important for revealing material removal mechanism and damage suppression, wherein mass scaling is usually adopted for solving the problem of extremely low calculating efficiency. For the simulation with very low cutting speed, a quasi-static criterion is usually adopted for an appropriate mass scaling factor. However, to get closer to real machining processes, there is tendency of simulation with higher cutting speed considering more complicated factors, and the selection of mass scaling factor in this situation is difficult and computationally intensive. To solve this problem, this study aims to propose an efficient method of appropriately selecting mass scaling factor, which is upon the kinetic-to-internal energy ratio in the beginning stage of simulation. Through direct relationship between kinetic energy and cutting speed, the selection method applies under different cutting speeds; with the focus on the beginning stage of calculation, the proposed method requires little calculating work. By verification, such advantages are clearly presented with obviously improved calculating efficiency and limited error. What's more, a set of empirical values of mass scaling factor suitable for different cutting speeds are provided for reference. The findings of this study could make great contributions in facilitating the development of 3D microscopic cutting simulation method of CFRP.

Keyword: Mass scaling, Selection method, 3D microscopic cutting simulation, CFRP, Kinetic-to-internal energy ratio, High-speed cutting simulation.

1. INTRODUCTION

Carbon Fiber Reinforced Polymer/Plastic (CFRP) is regarded as a kind of high-performance structural material in aviation industry for its excellent properties such as high specific strength and strong designability [1-3]. The components made from CFRP are usually near-net shaped, but for meeting the engineering requirements of assembly, processes such as drilling and edge trimming are always inevitable and in great demand. However, due to the inherent characteristics of anisotropy and heterogeneity of CFRP which are totally different from the metal, the CFRP components are very vulnerable to undesirable machining damages like delamination, burrs and fiber pull-out in such processes [4-6], which severely affects the overall performances of the components and further hinders the engineering application of CFRP. Hence, effectively suppressing these damages in machining of CFRP has become one of the key issues remaining to be solved in the worldwide industry.

For seeking the way of suppressing such damages from the source, a lot of studies have been conducted on the material removal process of the anisotropic and heterogeneous CFRP. To date, the simulation method,

especially 3D microscopic cutting simulation of CFRP [1, 7-9] draws more and more attention for its outstanding advantages in intuitively and also conveniently calculating dynamic removal processes of multiple fibers and matrix, which is always regarded as the material removal essence of CFRP. However, since such simulation is based on a model which is very difficult to calculate for its rather small elements of each constituent phase and the rather complicated contacts between the phases, the calculating efficiency is always extremely low, considerably slowing down the research process [10]. Therefore, how to markedly improve the calculating efficiency has been a focus and also an important problem in the field of 3D microscopic cutting simulation of CFRP.

Generally speaking, careful mesh generation and mass scaling are two main methods for improving calculating efficiency of the cutting simulation. In terms of CFRP 3D microscopic cutting simulation, due to the limitation of small geometric dimension and requirements of computational precision, the former method is hard to work. On the other hand, without such limitations, the mass scaling can be expected as an appropriate method for this issue. However, due to its basic principle of artificially modifying the element density, the calculating precision would be affected undoubtedly, particularly in the situation when the cutting speed is very high. In other words, the successful application of such method must be premised on the appropriate selection of mass scaling

^{*}Address correspondence to this author at the Key Laboratory for Precision and Non-traditional Machining Technology of the Ministry of Education, Department of Mechanical Engineering, Dalian University of Technology, Dalian 116024, China; Tel: +86-(0)411-84707743; Fax: +86-(0)411-84707743; E-mail: wfsll@dlut.edu.cn

factor, under which the calculating precision can be guaranteed as much as possible.

On this point, some studies have been conducted for seeking an effective method of selecting appropriate mass scaling factor. To date, the selection is always made based on a quasi-static criterion [11-13]. It considers that for a quasi-static process, with appropriate mass scaling, the inertial effect should be limited. Specifically, it requires that the kinetic energy should remain a small part of the internal energy, typically less than 10%. By this method, some studies introduced mass scaling into the cutting simulation of composites. Rao [14] used mass scaling in two-dimensional microscopic cutting simulation of GFRP on the basis of this quasi-static criterion. Agarwal [15] also used the same criterion in 3D microscopic cutting simulation of CFRP.

Nevertheless, with the quasi-static prerequisite, the cutting speeds used in the above-mentioned studies are very low (about 0.5m/min), far less than the one actually adopted in practical drilling and edge trimming processes of CFRP. In fact, in order to make the model closer to real machining process, there is a trend in simulation with higher cutting speed considering more complicated factors. However, with the increase of cutting speed, the kinetic energy would also increase, and it becomes more and more difficult to satisfy the quasi-static criterion. In a word, for 3D microscopic cutting simulation of CFRP, the quasi-static method only applies to the model with extremely low cutting speed. With a higher cutting speed, for a reliable calculation result, the appropriate mass scaling factor can only be determined through a set of fully calculated models including the one without mass scaling, which usually requires enormous calculation. Hence, it is very necessary to develop a new selection method of mass scaling factor, which is efficient for determining an appropriate mass scaling factor and can be suitable under different cutting speeds in 3D microscopic cutting simulation of CFRP to improve the calculating efficiency and ensuring the calculating precision at the same time. Unfortunately, relevant study is still in infancy.

The objective of this paper is to propose such an efficient selection method of mass scaling factor. According to the basic principles of mass scaling, the overall thinking of the selection method is presented, which mainly contains two steps: the one is to determine a selection criterion, under which the appropriate mass scaling factor could be determined efficiently; the other one is to determine the appropriate

mass scaling factor meeting the selection criterion. The core of this paper lies in the first step with two key problems. Firstly, the effect of mass scaling on the calculating precision in 3D microscopic cutting simulation of CFRP is studied through the calculation of a set of models with different mass scaling factors, wherein an appropriate mass scaling factor is obtained. Secondly, for quick determination and clear identification, the ratio of kinetic energy to internal energy in the beginning stage of calculation is analyzed. Based on these analyses, the relationship between the energy ratio in the beginning stage and the calculating precision is revealed, upon which the selection criterion is concluded and verified. With this criterion, for the second step, through calculating the models with different mass scaling factors for a short amount of time, the appropriate mass scaling factor under given cutting speed could be determined. The method proposed in this paper applies under different cutting speeds without enormous trial work, which would reduce calculation load to a great extent and make great contributions in facilitating the development of CFRP 3D microscopic cutting simulation method.

2. RESEARCH SCHEME OF SELECTING MASS SCALING FACTOR BASED ON ITS PRINCIPLES

In CFRP cutting simulations, explicit solution method is usually adopted for its advantages in solving nonlinear problems, for instance, the robust contact analyses [16]. The explicit solution uses the central difference method to explicitly integrate the motion equation over the time domain through many small increments, as shown in Eqs. (1-2) [17].

$$\ddot{u}_{\left(i+\frac{1}{2}\right)}^N = \ddot{u}_{\left(i-\frac{1}{2}\right)}^N + \frac{\Delta t_{(i+1)} + \Delta t_{(i)}}{2} \ddot{u}_{(i)}^N \quad (1)$$

$$u_{(i+1)}^N = u_{(i)}^N + \Delta t_{(i+1)} \dot{u}_{\left(i+\frac{1}{2}\right)}^N \quad (2)$$

where u^N represents displacement or rotation components, i represents increment number and Δt is the time increment. The method uses the values of $\dot{u}_{\left(i-\frac{1}{2}\right)}^N$ and $\ddot{u}_{(i)}^N$ from previous increment to calculate the velocity $\dot{u}_{\left(i+\frac{1}{2}\right)}^N$ and displacement $u_{(i+1)}^N$ explicitly. The acceleration at the beginning of each increment is calculated as follow:

$$\ddot{u}_{(i)}^N = \left(M^{NJ}\right)^{-1} \left(P_{(i)}^J - I_{(i)}^J\right) \quad (3)$$

Where M^{NJ} represents mass matrix, P^J represents applied load and I^J represents internal force.

When the time increment Δt is larger, the total number of increments required for the full calculation is smaller, and the calculating efficiency is higher. However, there is a limitation for the time increment Δt , namely stability limit Δt_{stable} to ensure that the acceleration is as close as possible to a constant in each increment. That is to say, the time increment Δt could only be enlarged at the premise of the increase of the stable time increment Δt_{stable} .

Due to the fact that the stable time increment is related to the highest frequency of the model which is hard to acquire, an approximate and conservative stability limit is always used which could be depicted as the smallest transit time of a dilatational wave across any elements in the model. The expression for this stable limit is shown as follow:

$$\Delta t_{stable} = L^e \sqrt{\frac{\rho}{E}} \quad (4)$$

where L^e is the characteristic element dimension related to the element size, ρ represents material density and E represents the elastic modulus.

Based on Eqn. (4), the methods for improving calculating efficiency are analyzed. Above all, the stable limit would increase with the increase of element size. However, for 3D microscopic model of CFRP, there exist extremely small geometric features. With such kind of geometric structure, the element size and the stability limit are limited, and thus the improvement of calculating efficiency through optimizing mesh generation is also limited. Another method is increasing the stable time limit through modifying the density artificially, namely mass scaling. In this situation, without the limitation of geometric features or other limitations related to further development of the model such as the rate-dependent material properties, mass scaling provides a solution.

However, the introduction of mass scaling would definitely introduce errors which must be controlled for a precise calculating result. The commonly used method for selecting appropriate mass scaling factor is based on the quasi-static criterion. It requires that in terms of the quasi-static process, the effect of introduced mass scaling on the kinetic energy should be small, accounting for a small part of internal energy. While with the increase of cutting speed, the kinetic energy also increases and the quasi-static criterion no longer applies. In this situation, it is difficult to select the appropriate mass scaling factor for the reason that enormous calculation is needed to determine whether

the calculating precision is affected obviously, and the factor should be determined again when some related parameters of the model for instance the cutting speed are changed, which hinders the development and improvement of the microscopic model to a great extent.

To this end, for a reliable selection criterion based on which the appropriate mass scaling factor could be determined efficiently, there are several key problems remaining to be solved. Firstly, the effect of mass scaling factor on the calculating precision should be studied based on a 3D microscopic cutting simulation of CFRP through which the appropriate mass scaling factor can be obtained. Secondly, for quick determination and clear identification purpose, a representative variable which could reflect the effect degree of mass scaling is needed. On referring to the quasi-static criterion, it is found that the kinetic energy is directly affected by mass and velocity while internal energy is almost not and the response of energy is quick with less fluctuation compared with other variables such as the cutting force. Thus the ratio of kinetic energy to internal energy might well be appropriate for the representative variable. Besides, to judge the appropriateness efficiently and reduce trial work, the ratio in the beginning stage of calculation is focused. What's more, the relationship between the representative variable and the calculating precision should be revealed, based on which the selection criterion and thus the selection method for the mass scaling factor are proposed. The above research scheme is concluded as Figure 1.

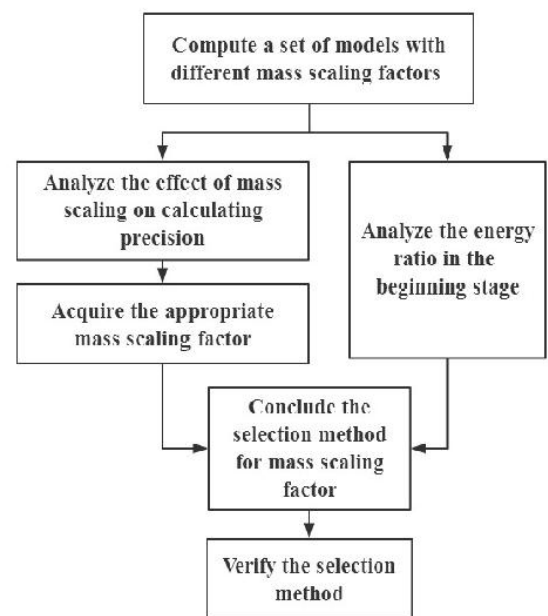


Figure 1: Research scheme.

3. EFFECTS OF MASS SCALING ON CALCULATING PRECISION AND THE APPROPRIATE FACTOR

In this section, a 3D microscopic cutting model is developed and verified firstly based on finite element software ABAQUS. Then, through the calculation of a set of models with different mass scaling factors, the effect of mass scaling factor on the calculating precision is analyzed and the appropriate mass scaling factor corresponding to the current model is determined.

3.1. Establishment of 3D Microscopic Model and the Verification

3.1.1. Geometry Modeling and other Settings

The geometry of the microscopic model is shown as Figure 2. The workpiece is mainly composed of microscopic part which consists of fibers, interfaces and resins (marked as A, B and C respectively in Figure 2) and Equivalent Homogeneous Method (EHM) part (marked as D in Figure 2) which mainly provides support for microscopic part. To study the effect of mass scaling on the calculating precision, this paper is based on a model which originally has very low calculating efficiency with the size of $300 \times 78 \times 13 \mu\text{m}$ and around 600 thousand elements. As for the tool, the rake angle and the clearance angle are 25° and 5° respectively, and the cutting edge radius is $10 \mu\text{m}$.

The element type adopted in each part is 8-node linear brick, reduced integration and hourglass control (C3D8R). The interaction between the tool and workpiece is set as surface-to-surface contact based on penalty contact method. Meanwhile, to prevent the elements from penetrating with each other, the general contact is set. To simulate the clamping state in

experiment, the back and the bottom of the workpiece are fixed.

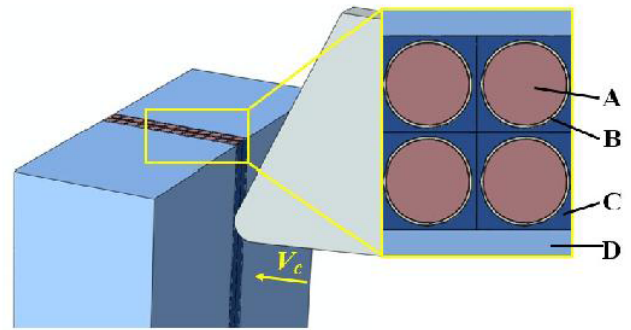


Figure 2: Schematic diagram of geometric model.

3.1.2. Material Modeling

In this paper, the constitutive model of carbon fiber is simplified as linearly elastic and transversely isotropic [18]. The failure criterion used is the maximum stress criterion which is achieved by the user subroutine VUMAT. The resin is simplified into isotropic elastoplastic material, and the shear failure criterion is adopted. When the equivalent plastic strain reaches the failure strain, the material fails and enters the damage evolution stage, and linear damage evolution is adopted. The interface is the material between the resin phase and the fiber phase, which could connect the two phases and transfer the load. Some literatures [19-20] used cohesive element to simulate the cracking of the interface while the cohesive element has the problem of excessive distortion for compressive failure [21]. This paper uses continuum element to simulate the interface, with the material model similar to that of resin, but the strengths are slightly reduced [22-23]. The material properties used in this paper are shown in Table 1.

Table 1: Material Properties used in the Simulation

Carbon Fiber			
Elastic modulus E_1 (Gpa)	295	Elastic modulus $E_2=E_3$ (Mpa)	14
Poisson's ratio $\nu_{12}=\nu_{13}$	0.2	Poisson's ratio ν_{23}	0.07
Tensile strength along fiber direction X_T (Mpa)	5880	Shear strength S_j (Mpa)	380
Density (T/mm^3)	1.7×10^{-9}		
Resin			
Elastic modulus E (Mpa)	3400	Poisson's ratio ν	0.34
Density (T/mm^3)	9.8×10^{-10}	Yield strength (Mpa)	85
Failure strain	0.02		

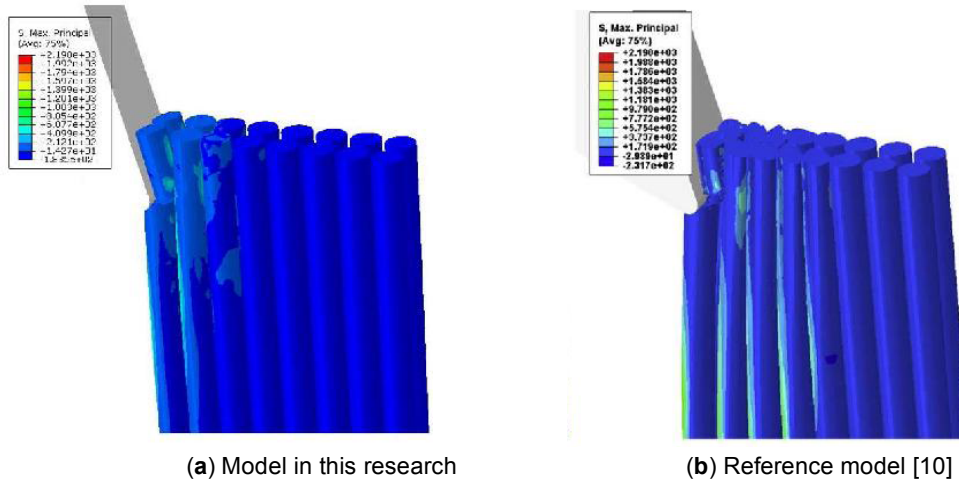


Figure 3: Cutting phenomena of the verification and reference [10].

3.1.3. Verification of the Model

For the verification of the model, mass scaling is not introduced in this section. The model is verified according to reference [10] and the average cutting forces during the fracture of the first fiber are compared. The average force in reference [10] is 0.008096N, and that in this paper is 0.00792, with an error of 2.17% which is rather small. Besides, the cutting phenomena of both the verification model and reference [10] are shown in Figure 3. In this way the model is verified.

3.2. Effects of Mass Scaling on the Calculating Precision and the Appropriate Factor

In this section, the effects of mass scaling on the calculating precision based on the developed 3D microscopic cutting model with cutting speed $V_c = 1$ m/s are investigated. The model without mass scaling is taken as reference in this section for the analyses of calculating precision. The selected mass scaling factors are 1, 2000, 4000, 6000 and 10000 and the CPU times when the cutting length is 11.1 μ m are listed in Table 2. The calculating results and analyses are as follows.

Table 2: CPU Times with Different Mass Scaling Factors

Mass Scaling Factor	CPU Time (h)	Normalized Computational Efficiency
1	50.61	1
2000	1.753	28.87
4000	1.288	39.29
6000	1.078	46.95
10000	0.87125	58.09

The cutting forces with mass scaling factor 1 and 2000 are shown in Figure 4 as an example.

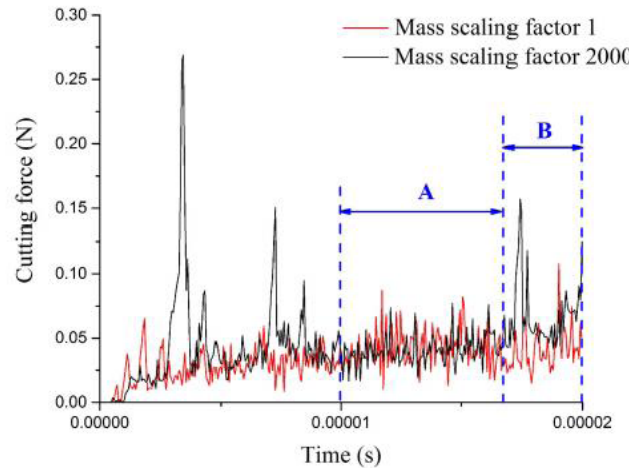


Figure 4: Cutting force with mass scaling factor 1 and 2000.

In order to compare the difference of cutting force quantitatively under different mass scaling factors, the average cutting forces in the same stable stage are compared, which is stage A as shown in Figure 4. As for stage B, there is obvious increase for mass scaling 2000 and it is found that the failure front has already reached the back constraint at this moment. The hindrance to deformation and failure from the boundary condition may as well lead to the increase of the cutting force. For this reason, this paper only focuses on stage A. The average value during this stage and the errors of cutting force under different mass scaling factors are shown in Table 3.

As shown in Table 3, the average cutting force would increase with the increase of mass scaling factor generally and so would the errors. Among them, the

errors of average cutting force with the mass scaling factor of 2000 and 4000 are both within 20%, and especially that of 2000 is very small, only 3.2%.

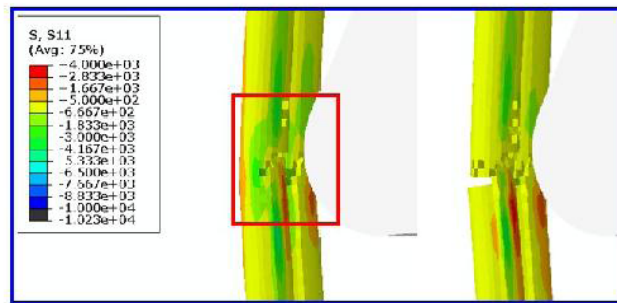
Table 3: Average Values and Errors of the Cutting Force with Different Mass Scaling Factors

Mass Scaling Factor	Average Value of Cutting force (N)	Error (%)
1	0.042167	-
2000	0.040797	3.2
4000	0.047171	11.9
6000	0.052089	23.5
10000	0.072002	70.8

Due to the reason that the material removal mechanism of CFRP has much to do with the deformation and breakage process of fiber, the effect of

mass scaling on the calculating precisions concerned with these processes are analyzed as follows.

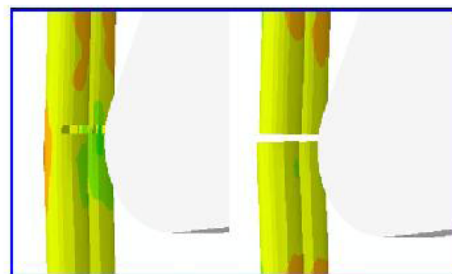
To start with, the intuitive fiber fracture processes are analyzed, as shown in Figure 5. It is shown that excessive mass scaling would change the fiber fracture process. When the mass scaling factor is 1, the elements near the contact area of the tool and workpiece first fail due to shear stress and then the fiber would break along the fracture plane, as shown in Figure 5 (a). When mass scaling factor is 2000, the process is similar to that with mass scaling factor 1 and there is no obvious difference. While when the mass scaling factor is further increased, the elements near the contact area of the tool and workpiece wouldn't fail and the fiber breaks directly. Besides, the stress distributions have obvious difference. Therefore, excessive mass scaling would alter the fiber fracture process.



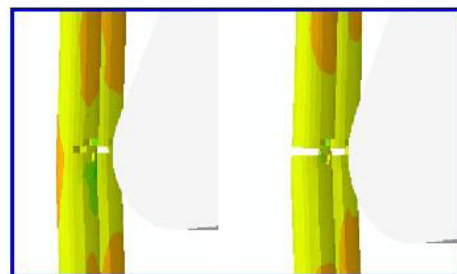
(a) Mass scaling factor 1



(b) Mass scaling factor 2000



(c) Mass scaling factor 4000



(d) Mass scaling factor 6000



(e) Mass scaling factor 10000

Figure 5: Fiber fracture process of the fiber with different mass scaling factors.

Apart from the phenomena, to evaluate the errors quantitatively in terms of fiber deformation and breakage, the relevant variables are measured and analyzed. For the former one, as the fiber would deform continuously with the feed of the tool before fracture, the times when each fiber breaks are analyzed to characterize the deformation of fibers. For the latter one, namely fiber breakage, the lengths from the fracture position to the free end of the fiber are compared. The results are shown as follows.

There are two fibers in each column as shown in Figure 2, and the fracture times might be different. Figure 6 shows the fiber fracture times with different mass scaling factors. When mass scaling factor is 2000, the fracture time of each fiber is generally close to that with mass scaling factor 1. When mass scaling factors are 4000 and 6000, the errors are always larger than that with mass scaling 2000, and the fracture times are relatively close to that with mass scaling factor 1 except for the second fiber with rather large errors. However, for the result of mass scaling factor 10000, the error is always the largest, and fracture times of all the fibers are significantly earlier than others, which implies that the fibers would tend to fracture under little bending when excessive mass scaling is introduced.

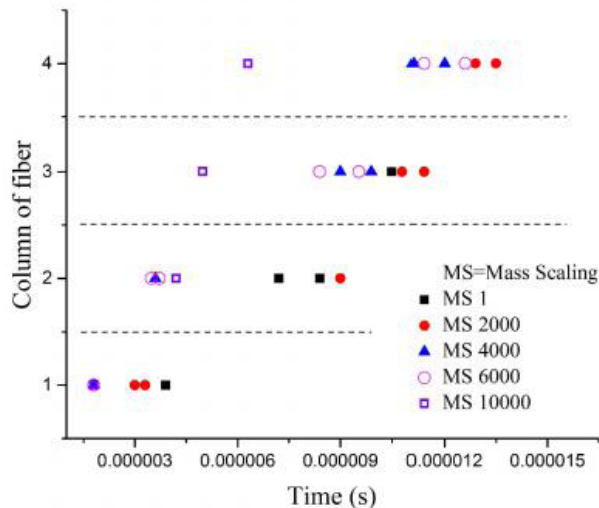


Figure 6: Fiber fracture times with different mass scaling factors.

Figure 7 shows the fiber fracture lengths with different mass scaling factors. The fiber fracture length of mass scaling 2000 is always closest to that of mass scaling factor 1 among those results. With the increase of mass scaling factor, the error of fiber fracture length tends to increase. Besides, the fiber fracture length

increases with the column number of fibers under small mass scaling factors, but that tends to level off for the result with mass scaling 10000.

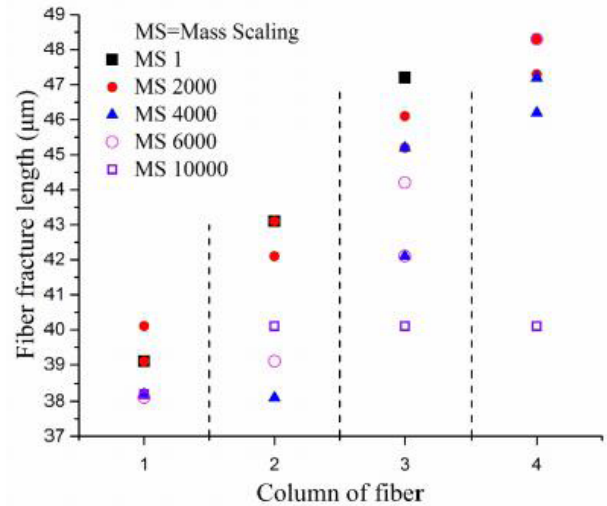


Figure 7: Fiber fracture lengths with different mass scaling factors.

Through the above analyses, it is concluded that mass scaling factor 2000 is appropriate for the current model with cutting speed 1m/s.

4. SELECTION METHOD OF MASS SCALING FACTOR AND VERIFICATION

Combining the analyses of effects of mass scaling on the calculating precision above, this section concludes the efficient selection method of mass scaling factor based on the analyses of the energy ratio in the beginning stage, as depicted in Section 2. Then, the proposed method is verified through another example. Besides, a set of empirical values of mass scaling factors under different cutting speeds are provided based on the proposed method for further improvement of 3D microscopic cutting simulation for long-fiber composite material.

4.1. Analyses of Energy Ratio and Selection Method of Mass Scaling Factor

The ratio of kinetic energy to internal energy at the beginning stage of the workpiece with different mass scaling factors is analyzed firstly, as shown in Figure 8. The beginning stage mentioned here refers to the period from 0 to 3×10^{-6} second, corresponding to the time when the fibers in the first column break.

There are always some fluctuations which might be due to the numerical instability at the very beginning of

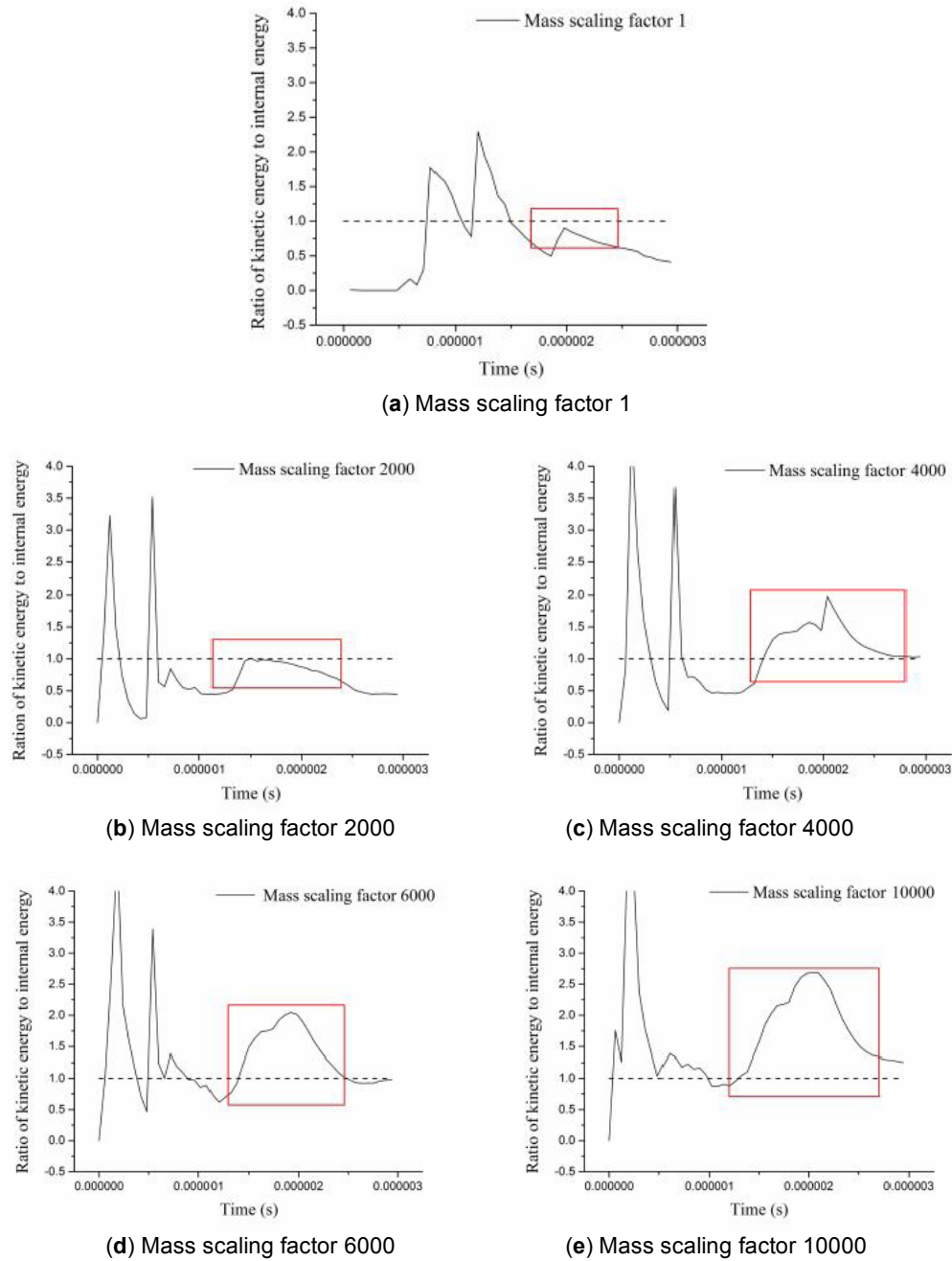


Figure 8: Ratio of kinetic energy to internal energy of workpiece with different mass scaling factors in the beginning stage.

the calculation. According to previous analyses, mass scaling factor 2000 is an acceptable value for the current model, thus mass scaling 1 and 2000 are grouped together and compared with others. In this way, it might be appropriate that the ratio of kinetic energy to internal energy remains below 1 in the beginning stage. Thus the selection criterion of mass scaling factor could be depicted as follows: Ignoring obviously unstable fluctuations, the ratio of kinetic energy to internal energy of workpiece remains below 1 at the beginning stage of calculation. With this criterion,

the appropriate mass scaling factor could be determined efficiently through calculating the model with different mass scaling factors for only a few steps.

4.2. Verification of the Selection Method of Mass Scaling Factor

In this section, an example is provided for verification purpose. As mentioned before, due to the direct relationship between cutting speed and kinetic energy, the proposed method should be able to apply under different cutting speeds. Thus, the model with

different cutting speed is used for verification of the method. The cutting speed chosen is 5m/s.

With the method proposed above, the chosen mass scaling factor is 70 after several attempts and its ratio of kinetic energy to internal energy is shown as follow.

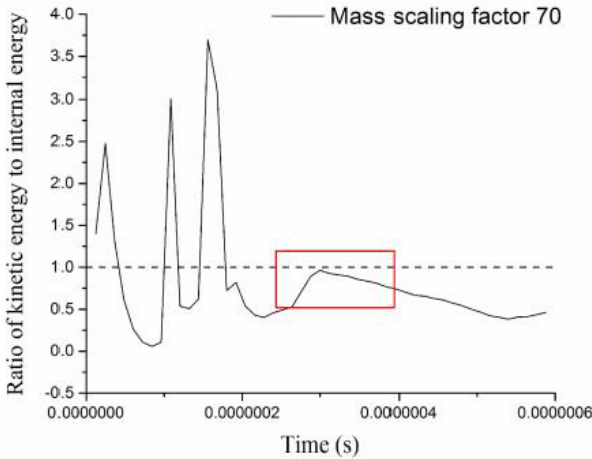


Figure 9: Ratio of kinetic energy to internal energy with mass scaling factor 70 under cutting speed 5m/s.

As shown in Figure 9, the peak value of the ratio is 0.965. Thus the factor 70 is chosen and its calculating precision is analyzed.

The cutting forces under mass scaling factor 1 and 70 are shown in Figure 10. The average cutting forces in stable stage A are 0.0470 and 0.0455 respectively, and the error is 3.3%, which is kept in a small range.

The time and length of fiber fracture are shown in Figure 11. Both results are close to that with mass scaling factor 1, which implies that mass scaling factor

70 is appropriate for the current model with cutting speed 5m/s, and this proves the rationality of the mass scaling selection method proposed in Section 4.1.

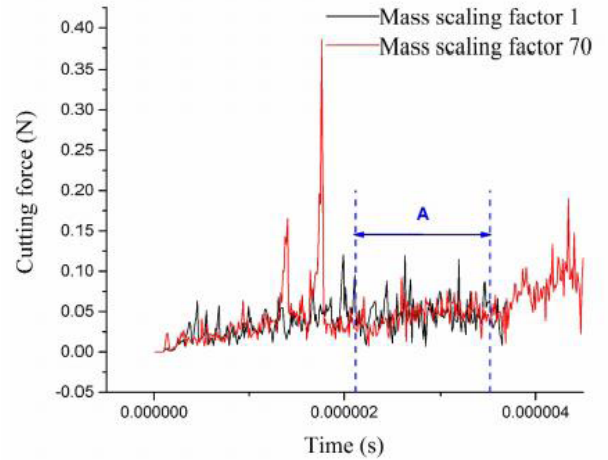
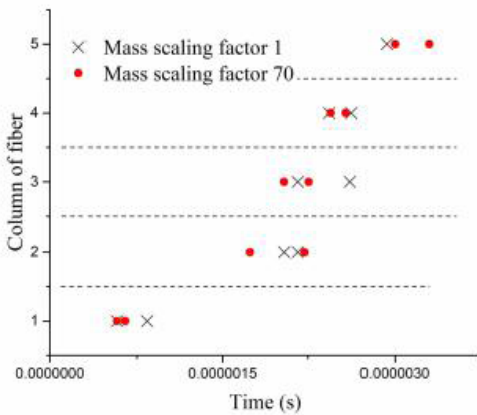


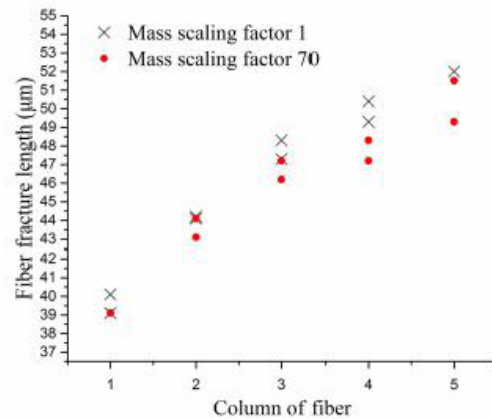
Figure 10: Cutting forces with mass scaling factor 1 and 70.

4.3. Empirical Values of Mass Scaling Factors with Different Cutting Speeds

As mentioned above, the appropriate mass scaling factors with different cutting speed are different due to the direct influence of cutting speed on the kinetic energy. Thus, for giving further references, based on the proposed selection method, a set of mass scaling factors corresponding to a wide range of cutting speeds (from 0.5 m/s to 10 m/s) are determined, as shown in Table 4. With a lower cutting speed, a larger mass scaling factor could be used with little effect on the calculating result. With the increase of cutting speed, the appropriate mass scaling factor drops rapidly. For example, when the cutting speed is 1m/s, the



(a) Fiber fracture times



(b) Fiber fracture lengths

Figure 11: The fracture times and lengths of fiber with mass scaling factor 1 and 70.

appropriate mass scaling factor is 2000; when the cutting speed increases to 5 m/s, the appropriate factor is only 70. Such empirical values could further reduce trial work and provide references on CFRP 3D microscopic cutting simulation.

Table 4: A Set of Mass Scaling Factors with Different Cutting Velocities

Cutting Velocity V_c (m/s)	Mass Scaling Factor
0.5	8000
1	2000
2.5	300
5	70
10	20

5. CONCLUSIONS

This paper firstly develops a 3D microscopic cutting model of CFRP and studies the effects of different mass scaling factors on the calculating precision. What's more, the ratio of kinetic energy to internal energy in the beginning stage of calculation is analyzed. Based on these analyses, an efficient selection method of mass scaling factor with higher cutting speed is proposed. Besides, a set of empirical values are given for a wide range of cutting speed. The conclusions are as follows.

1) Mass scaling would affect calculating precision undoubtedly. As the mass scaling increases, the cutting force generally increases and so would the errors. Excessive mass scaling would affect the process of fiber fracture, causing fiber to fracture with little bending. Besides, the fracture positions of subsequent fibers tend to level off.

2) Based on the analyses of calculating precision and energy ratio, this paper proposes an efficient selection method of mass scaling factor, wherein the selection criterion is depicted as follow: Ignoring obviously unstable fluctuations, the ratio of kinetic energy to internal energy of workpiece remains below 1 at the beginning stage of calculation.

Through the proposed method, the appropriate mass scaling factor could be determined rapidly on the premise of ensuring the calculating precision under different cutting speeds, which could avoid enormous calculation load and greatly facilitate subsequent research for 3D microscopic cutting simulation of CFRP.

ACKNOWLEDGEMENTS

This work is supported by National Natural Science Foundation of China [grant number 51575082]; National Natural Science Foundation of China-United with Liaoning Province [grant number U1508207]; National Innovative Research Group [grant number 51621064]. The authors wish to thank the anonymous reviewers for their comments which lead to improvements of this paper.

REFERENCES

- [1] Mkaddem A, Demirci I and Mansori ME. A micro-macro combined approach using FEM for modelling of machining of FRP composites: Cutting forces analysis. *Compos Sci Technol* 2008; 68: 3123-3127. <https://doi.org/10.1016/j.compscitech.2008.07.009>
- [2] Pérez MA, Oller S, Felippa CA, *et al.* Micro-mechanical approach for the vibration analysis of CFRP laminates under impact-induced damage. *Composites Part B* 2015; 83: 306-316. <https://doi.org/10.1016/j.compositesb.2015.08.059>
- [3] Phadnis VA, Makhadmeh F, Roy A, *et al.* Drilling in carbon/epoxy composites: Experimental investigations and finite element implementation. *Composites Part A* 2013; 47: 41-51. <https://doi.org/10.1016/j.compositesa.2012.11.020>
- [4] Iliescu D, Gehin D, Iordanoff I, *et al.* A discrete element method for the simulation of CFRP cutting. *Compos Sci Technol* 2010; 70: 73-80. <https://doi.org/10.1016/j.compscitech.2009.09.007>
- [5] Isbilir O and Ghassemieh E. Delamination and wear in drilling of carbon-fiber reinforced plastic composites using multilayer TiAlN/TiN PVD-coated tungsten carbide tools. *J Reinf Plast Compos* 2012; 31: 717-727. <https://doi.org/10.1177/0731684412444653>
- [6] Koplev A, Lystrup A and Vorm T. The cutting process, chips, and cutting forces in machining CFRP, *Composites* 1983, 14: 371-376. [https://doi.org/10.1016/0010-4361\(83\)90157-X](https://doi.org/10.1016/0010-4361(83)90157-X)
- [7] Wang F, Wang X, Yang R, *et al.* Research on the carbon fibre-reinforced plastic (CFRP) cutting mechanism using macroscopic and microscopic numerical simulations. *J Reinf Plast Compos* 2016; 36: 555-562. <https://doi.org/10.1177/0731684416684966>
- [8] Calzada KA, Kapoor SG, DeVor RE, *et al.* Modeling and interpretation of fiber orientation-based failure mechanisms in machining of carbon fiber-reinforced polymer composites. *J Manuf Processes* 2012; 14: 141-149. <https://doi.org/10.1016/j.jmapro.2011.09.005>
- [9] Santiuste C, Miguélez H and Soldani X. Out-of-plane failure mechanisms in LFRP composite cutting. *Compos Struct* 2011; 93: 2706-2713. <https://doi.org/10.1016/j.compstruct.2011.05.034>
- [10] Cheng H, Gao J, Kafka OL, *et al.* A micro-scale cutting model for UD CFRP composites with thermo-mechanical coupling. *Compos Sci Technol* 2017; 153: 18-31. <https://doi.org/10.1016/j.compscitech.2017.09.028>
- [11] Wang L and Long H. Investigation of material deformation in multi-pass conventional metal spinning. *Mater Des* 2011; 32: 2891-2899. <https://doi.org/10.1016/j.matdes.2010.12.021>
- [12] Zhu YX, Liu YL, Yang H, *et al.* Improvement of the accuracy and the computational efficiency of the spring back prediction model for the rotary-draw bending of rectangular H96 tube.

- Int J Mech Sci 2013; 66: 224-232.
<https://doi.org/10.1016/j.iimecs.2012.11.012>
- [13] Kim J, Kang S and Kang B. A comparative study of implicit and explicit FEM for the wrinkling prediction in the hydroforming process. *Int J Adv Manuf Technol* 2003; 22: 547-552.
<https://doi.org/10.1007/s00170-003-1540-2>
- [14] Rao GVG, Mahajan P and Bhatnagar N. Machining of UD-GFRP composites chip formation mechanism. *Compos Sci Technol* 2007; 67: 2271-2281.
<https://doi.org/10.1016/j.compscitech.2007.01.025>
- [15] Agarwal H and Gururaja S. Modelling of Orthogonal Cutting of Idealized FRP Composites. In: ASME conference on advanced manufacturing, Quebec, Canada, 14 November-20 November 2014, paper no. IMECE2014-37631, pp.V02AT02A048. New York: ASME.
- [16] Chung WJ, Cho JW and Belytschko T. On the dynamic effects of explicit FEM in sheet metal forming analysis. *Eng Computation* 1998; 15: 750-776.
<https://doi.org/10.1108/02644409810231880>
- [17] ABAQUS analysis user's manual, ABAQUS Inc, 2016.
- [18] Bai X, Bessa MA, Melro AR, *et al.* High-fidelity micro-scale modeling of the thermo-visco-plastic behavior of carbon fiber polymer matrix composites. *Compos Struct* 2015; 134: 132-141.
<https://doi.org/10.1016/j.compstruct.2015.08.047>
- [19] Rao GVG, Mahajan P and Bhatnagar N. Micro-mechanical modeling of machining of FRP composites - Cutting force analysis. *Compos Sci Technol* 2007; 67: 579-593.
<https://doi.org/10.1016/j.compscitech.2006.08.010>
- [20] Dandekar CR and Shin YC. Modeling of machining of composite materials: A review. *Int J Mach. Tools Manuf* 2012; 57: 102-121.
<https://doi.org/10.1016/j.ijmactools.2012.01.006>
- [21] Abena A, Soo SL and Essa KA. Finite element simulation for orthogonal cutting of UD-CFRP incorporating a novel fibre-matrix interface model. *Procedia CIRP* 2015; 31: 539-544.
<https://doi.org/10.1016/j.procir.2015.04.091>
- [22] Gao C, Xiao J, Xu J, *et al.* Factor analysis of machining parameters of fiber-reinforced polymer composites based on finite element simulation with experimental investigation. *Int J Adv Manuf Technol* 2016; 83: 1113-1125.
<https://doi.org/10.1007/s00170-015-7592-2>
- [23] Xu W, Zhang L and Wu Y. Effect of tool vibration on chip formation and cutting forces in the machining of fiber-reinforced polymer composites. *Mach Sci Technol* 2016; 20: 312-329.
<https://doi.org/10.1080/10910344.2016.1168930>

Received on 8-5-2019

Accepted on 14-6-2019

Published on 27-6-2019

DOI: <http://dx.doi.org/10.31875/2409-9848.2019.06.3>© 2019 Wang *et al.*; Zeal Press.

This is an open access article licensed under the terms of the Creative Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/3.0/>), which permits unrestricted, non-commercial use, distribution and reproduction in any medium, provided the work is properly cited.